Dark matter:
direct searches with underground detectors

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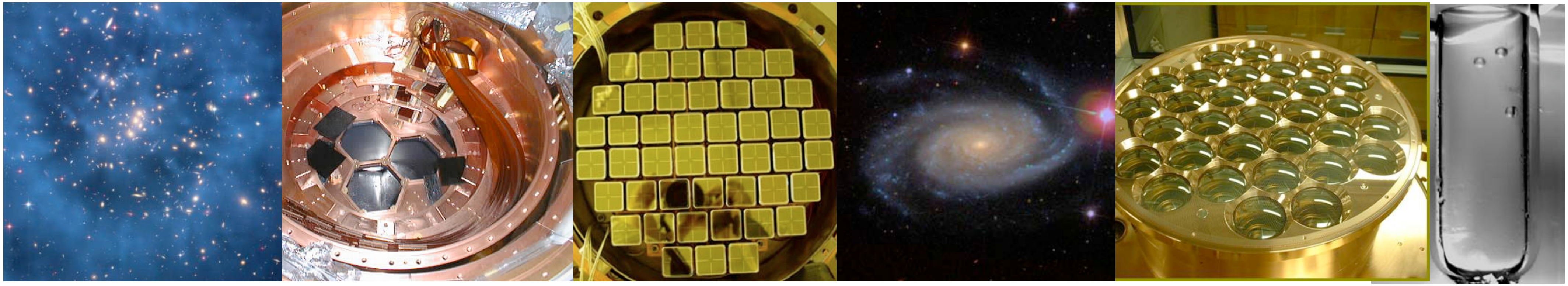
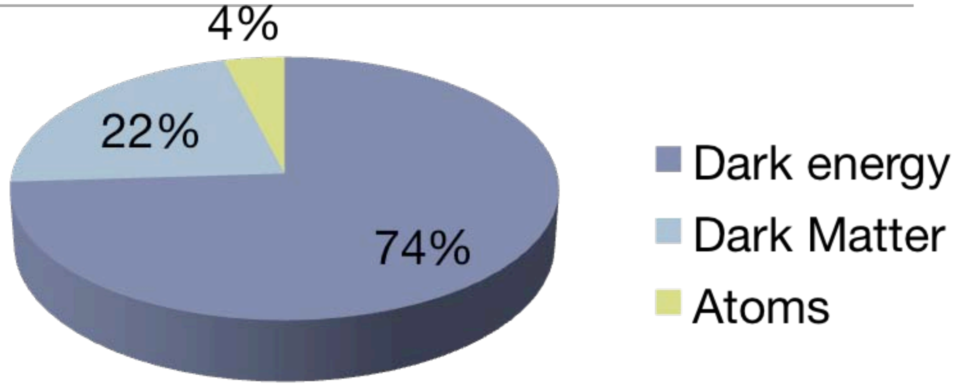


Outline

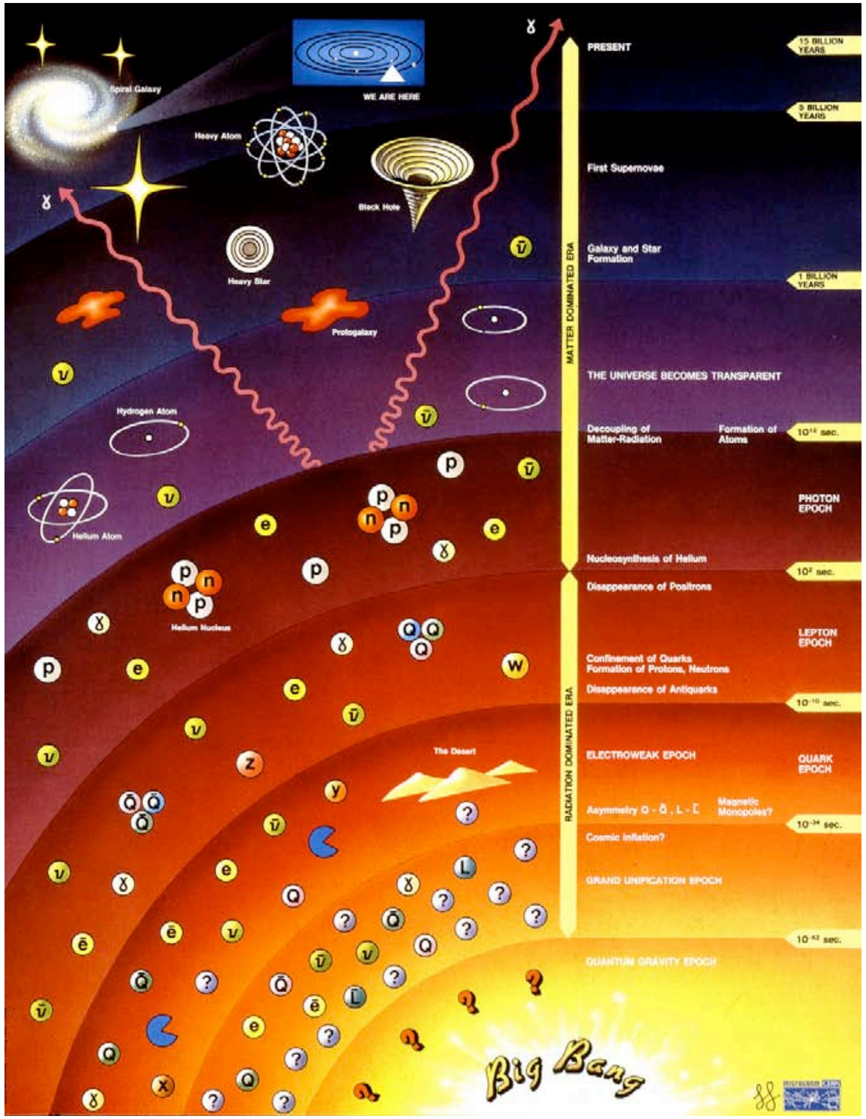
1. Scientific background
    - Cosmology
    - Cosmological parameters
    - DM evidence
    - Non baryonic DM
2. Direct WIMP detection
    - Nuclear recoil detectors
    - Minimizing backgrounds
    - Detection techniques and experimental results

What is our universe made of?



Introduction to Standard Cosmology

- Observations:
  - Universe expansion
  - CMB
  - Relative light elements abundances
  - Age of stellar objects
- Theory:
  - General Relativity
  - Quantum Field Theory



Einstein equations for the gravitational field

$$\boxed{G_{\mu\nu} = -8\pi G T_{\mu\nu}}$$

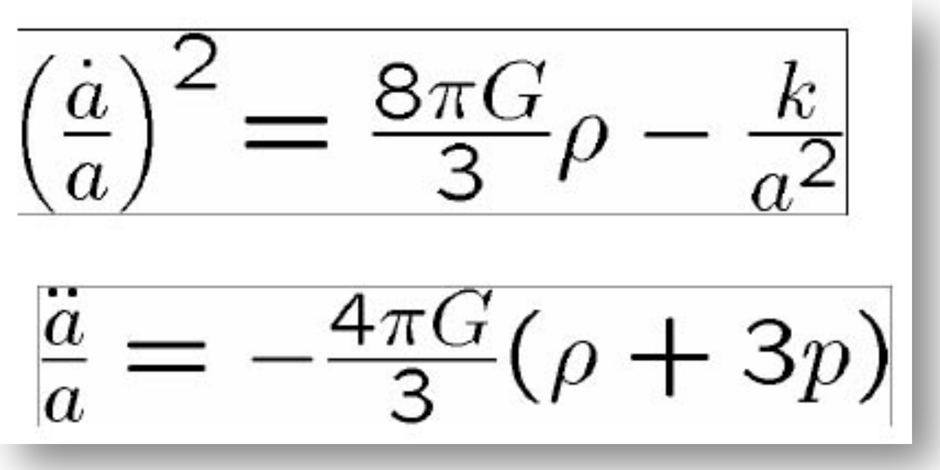
$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$ from the metric

$T_{\mu\nu} = p g_{\mu\nu} + (p+\rho) u_\mu u_\nu$ & $u_\mu = (1,0,0,0)$

Energy-momentum

↓

Source term



$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

Friedmann, Robertson, Walker equations

Cosmological parameters: the density fractions

critical density $\rho_c(t) = \frac{3H^2}{8\pi G} \longrightarrow \Omega = \frac{\rho}{\rho_c}$

➔ express the energy content in terms of the critical density

$$\left.\begin{aligned}
\Omega_m &= \frac{\rho_m}{\rho_c} \\
\Omega_{rad} &= \frac{\rho_{rad}}{\rho_c} \\
\Omega_\Lambda &= \frac{\rho_\Lambda}{\rho_c} = \frac{\Lambda}{3H^2} \\
\Omega_k &= -\frac{k}{a^2H^2}
\end{aligned}\right\}$$

$$\Omega_m + \Omega_{rad} + \Omega_\Lambda + \Omega_k = 1$$

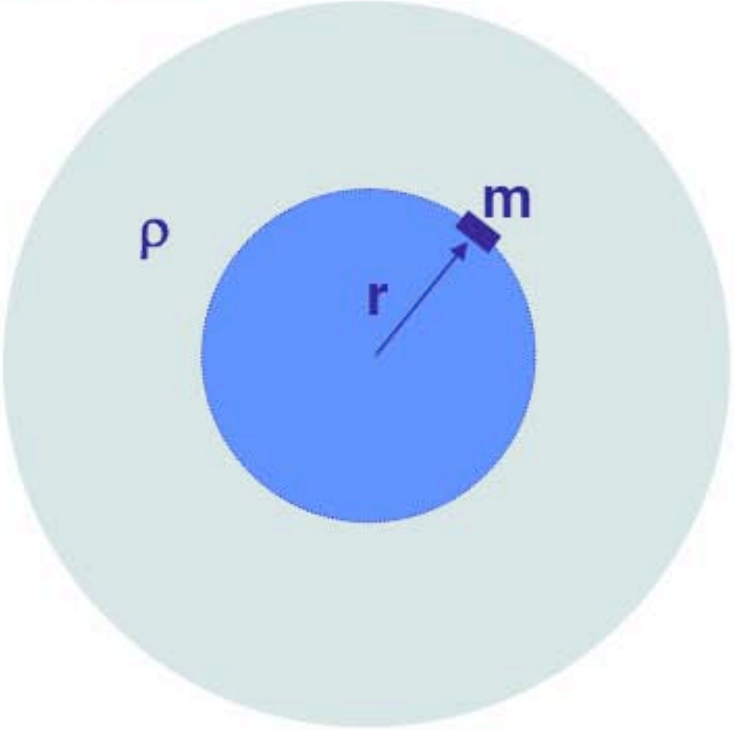
$$q = -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}\Omega_{mat} + \Omega_{rad} - \Omega_\Lambda$$

the first Friedmann equation can be written as

$$\Omega - 1 = \frac{k}{a^2H^2}$$

Qualitativamente : formulazione Newtoniana

Impostiamo le equazioni che governano la dinamica gravitazionale di un generico elemento *m* (ρ dV) dell'universo partendo dall'azione che su di esso viene esercitata da una distribuzione sferica di densità ρ:



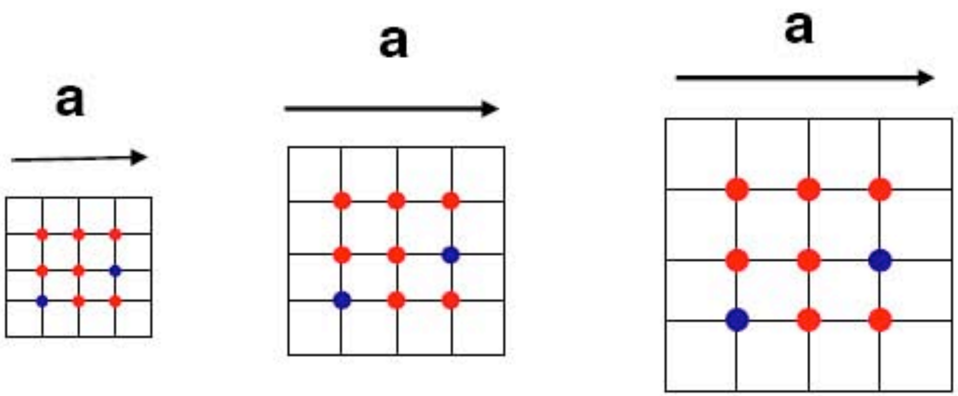
$$\boxed{F(r) = G\frac{Mm}{r^2}}$$

con $\boxed{M = \frac{4}{3}\pi\rho r^3}$

$$\boxed{V(r) = -G\frac{Mm}{r}}$$

$$\boxed{U = T + V = \frac{1}{2}mv^2 - \frac{4\pi}{3}G\rho m r^2} \quad \boxed{= \frac{1}{2}m\dot{r}^2 - \frac{4\pi}{3}G\rho m r^2}$$

Legge di Hubble:
→ ogni massa si allontana dalle altre perché è l'universo stesso ad espandersi, la distanza tra due oggetti r(t) deve essere legata alla legge di espansione dell'universo



Formalizziamo l'espansione dell'universo separando la scala a(t) nell'espressione del vettore di posizione:

$$\vec{r}(t) = a(t)\vec{x}$$

sostituendo nell'espressione dell'energia:

$$U = \frac{1}{2}m\dot{a}^2x^2 - \frac{4\pi}{3}G\rho m a^2 x^2 \longrightarrow \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

avendo posto:

$$kc^2 = -\frac{2U}{mx^2}$$

→ non può dipendere da x

→ non può dipendere dal tempo (U è conservata)

4

B. Bertucci

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

Equazione di Friedman

$$\boxed{H(t) = \frac{\dot{a}}{a}}$$ è il parametro di Hubble

→ l'evoluzione del fattore di scala e la densità di massa sono strettamente legate

→ k è una costante che determina la classe di soluzioni (espansione, espansione accelerata, contrazione) dell'equazione

k=0 → U=0 T=V espansione indefinita ($v=v_{fuga}$)
k>0 → U<0 T<V contrazione finale
k<0 → U>0 T>V espansione indefinita ($v>v_{fuga}$)

N.B. varia anche la densità di materia ρ(t) : l'energia totale è costante ma il volume aumenta nel tempo.

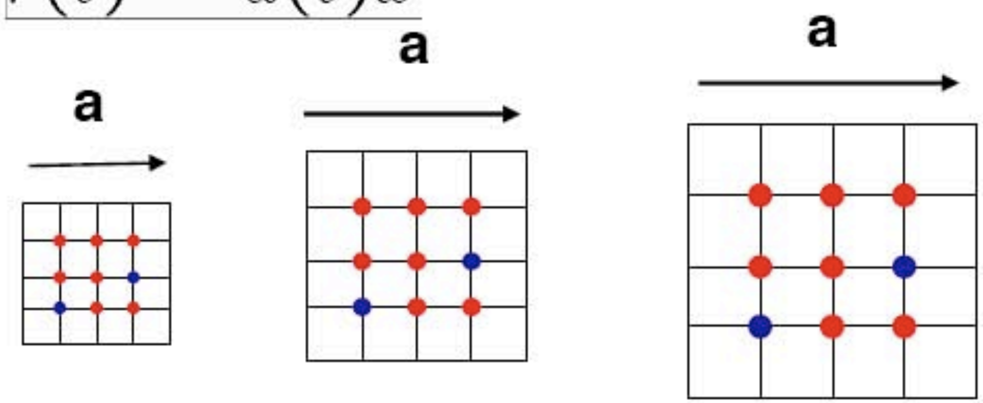
la modalità con cui ρ dipende da a è determinata dalla natura della materia stessa

Qualitativamente : formulazione Newtoniana

Abbiamo impostiamo le equazioni che governano la dinamica gravitazionale di un generico elemento m (ρ dV) dell'universo partendo dall'azione che su di esso viene esercitata da una distribuzione sferica di densità ρ:

$$U = \frac{1}{2}m\dot{r}^2 - \frac{4\pi}{3}G\rho m r^2$$

La velocità di allontanamento di m è legata all'espansione dell'universo nel suo insieme: $\vec{r}(t) = a(t)\vec{x}$



$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

Equazione di Friedman

Qualitativamente: espansione adiabatica di un fluido

Pensiamo al processo di espansione di un gas in un pistone:
→ diminuisce la densità ρ
→ viene compiuto del lavoro (legato alla pressione)
→ viene eventualmente scambiato del calore con l'esterno

Il tutto viene regolato dalla prima legge della termodinamica :

$$\boxed{dE = \delta Q - W} \longrightarrow \boxed{dE = -W}$$

Applichiamola all'espansione di una distribuzione sferica di raggio *a:*

$$\boxed{V = \frac{4}{3}\pi a^3} \rightarrow \boxed{dV = 4\pi a^2 da} \rightarrow \boxed{W = pdV = p4\pi a^2 da}$$

$$\boxed{E = \frac{4}{3}\pi a^3 \rho c^2} \rightarrow \boxed{dE = 4\pi \rho c^2 a^2 da + \frac{4}{3}\pi a^3 c^2 d\rho}$$

In dt avremo dunque :

$$\boxed{(\rho + \frac{p}{c^2})\frac{da}{dt} + \frac{a}{3}\frac{d\rho}{dt} = 0}$$

Evoluzione dell'universo:

$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}} \quad + \quad \boxed{\dot{\rho} + 3(\rho + \frac{p}{c^2})\frac{\dot{a}}{a} = 0}$$

Le due relazioni si combinano quando andiamo a considerare l'accelerazione $\boxed{\ddot{a}}$

Differenziamo rispetto al tempo
l'eq.ne di Friedmann

$$\boxed{2\frac{\dot{a}}{a}(\frac{\ddot{a}}{a} - \frac{\dot{a}^2}{a^2}) = \frac{8\pi G}{3}\dot{\rho} + 2kc^2\frac{\dot{a}}{a^3}}$$

e sostituendo $\boxed{\dot{\rho}}$ dall'equazione del fluido:

$$\frac{\ddot{a}}{a} - \boxed{(\frac{\dot{a}}{a})^2} = -4\pi G(\rho + \frac{p}{c^2}) + \frac{kc^2}{a^2}$$

$$\Downarrow$$

$$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + \frac{3p}{c^2})}$$

l'equazione che descrive l'accelerazione dell'espansione

Le equazioni in gioco nella descrizione dell'evoluzione dinamica del fattore di scala (e della densità di energia) dell'universo:

1) $$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

2) $$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

3) $$\dot{\rho} + 3\left(\rho + \frac{p}{c^2}\right)\frac{\dot{a}}{a} = 0$$

IPOTESI:
- Principio cosmologico
- Leggi di conservazione
- Espansione dell'universo

Quali sono gli elementi per specificare una soluzione?

→ relazione tra pressione e densità $p=w\rho$ ≡ ipotesi sulle proprietà di ρ

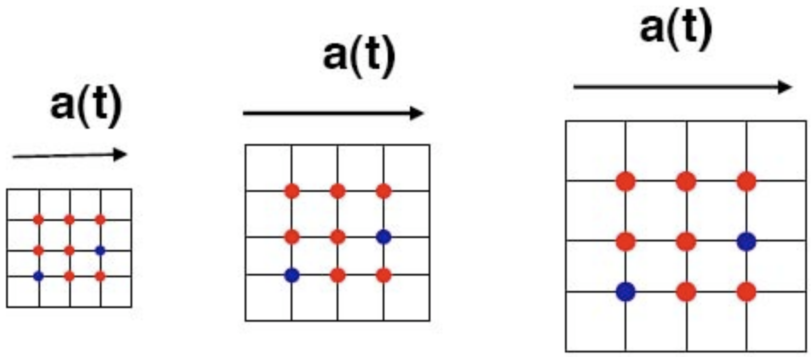
inserita nella 3) ci permette di ricavare $\rho=\rho(a)$

→ nota $\rho=\rho(a)$ otterremo diverse classi di soluzioni al variare di k

→ la 1) e la 2) ci forniscono la velocità e l'accelerazione dell'espansione del fattore di scala. Sono le grandezze che cerchiamo di misurare sperimentalmente e con cui confrontare la correttezza delle nostre ipotesi

Robertson-Walker metrics

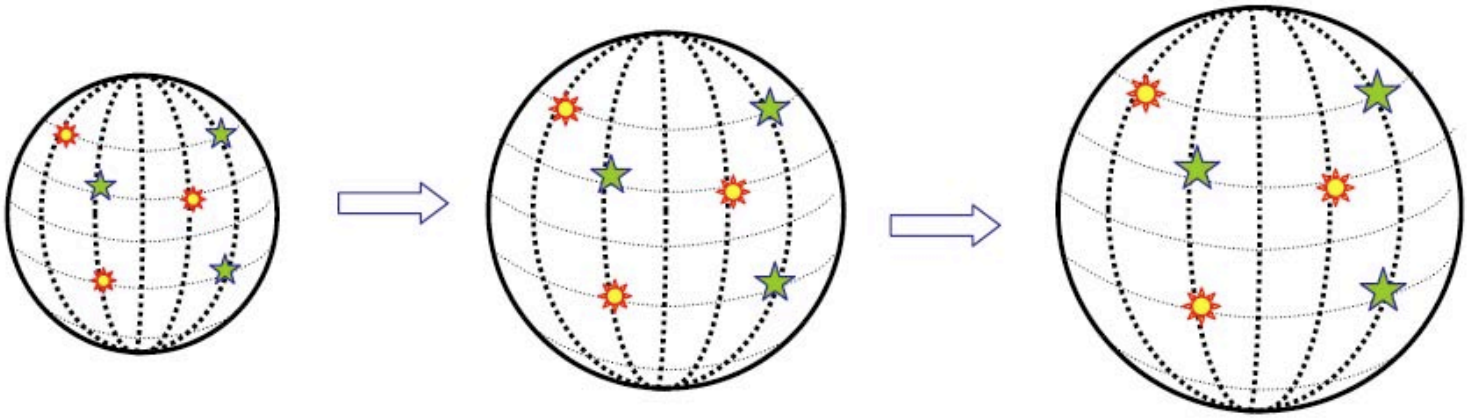
$$\boxed{\vec{r}(t) = a(t)\vec{x}}$$



$$d\tau^2 = dt^2 - a^2\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sen^2\theta d\phi^2)\right]$$

k=0 : spazio Euclideo
k=1 : spazio con curvatura positiva
k=-1 : spazio con curvatura negativa

r,θ,φ → coordinate adimensionali
a → fattore di scala



Friedmann-Lemaitre equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$$\dot{\rho} + 3(\rho + p)\frac{\dot{a}}{a} = 0$$

⟺

$$d\tau^2 = c^2 dt^2 - a^2 \left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

$k = 0, \pm 1$

$a=a(t)$

$$+$$

$$p = w\rho$$

$$+$$

$\rho\, a^{3(1+w)}$=cost

⟺

$$\begin{cases} \rho = \rho_{\text{radiazione}} \\ \rho = \rho_{\text{materia}} + \rho_{\text{radiazione}} \\ \rho = \rho_{\text{vuoto}} \\ \rho = \rho_{\text{materia}} + \rho_{\text{radiazione}} + \rho_{\text{vuoto}} \end{cases}$$

w=0, 1/3, -1 per materia, radiazione, vuoto

Cosmological model

Radiation dominated Universe: $\rho \propto \frac{1}{a^4}$

Matter dominated Universe: $\rho \propto \frac{1}{a^3}$

Cosmological constant dominated Universe: $\rho \propto \text{const.}$

The scale a(t) is time increasing for an expanding Universe → distances are multiplied by a(t)

$$v = \frac{d_2 - d_1}{t_2 - t_1} = \frac{a(t_2) - a(t_1)}{t_2 - t_1} s \xrightarrow[t \to 0]{} \frac{\dot{a}}{a} as = Hd$$

$$\text{Hubble law } H = \frac{\dot{a}}{a}, \;\; d = as$$

The scale time evolution can be determined from acceleration eqn and state eqn

Per evidenziare l'andamento dell'espansione nei diversi modelli abbiamo riportato il termine della densità di materia al valore attuale ρ_0

$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}} \longrightarrow \boxed{\dot{a}^2 = \frac{8\pi G\rho_0 a_o^3}{3a} - k + \frac{\Lambda a^2}{3}}$$

$$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)} \longrightarrow \boxed{\ddot{a} = -\frac{4\pi G\rho_0 a_0^3}{3a^2} + \frac{\Lambda a}{3}}$$

Facciamo la stessa operazione, ma con le densità espresse in relazione alla densità critica:

$$\boxed{\rho_c(t) = \frac{3H^2}{8\pi G}} \longrightarrow \boxed{\Omega = \frac{\rho}{\rho_c}}$$

Definiamo : $\boxed{\rho_c(t = oggi) = \rho_{oc} = \frac{3H_0^2}{8\pi G}}$, $\boxed{\Omega_0 = \frac{\rho_o}{\rho_{oc}} = \frac{8\pi G\rho_o}{3H_0^2}}$

per le singole componenti : $\boxed{\Omega_{om} = \frac{\rho_{om}}{\rho_{oc}}}$ $\boxed{\Omega_{orad} = \frac{\rho_{orad}}{\rho_{oc}}}$ $\Omega_{o\Lambda} = \frac{\rho_{o\Lambda}}{\rho_{oc}} = \frac{\Lambda}{3H_o^2}$

e viene definita : $\Omega_{0k} = -\frac{k}{a_o^2 H_0^2}$

$$\Omega_{om} + \Omega_{orad} + \Omega_{o\Lambda} + \Omega_{ok} = 1 \longrightarrow \Omega_o = 1 - \Omega_{ok}$$

⇨ valida ∀ t : $\Omega_m + \Omega_{rad} + \Omega_\Lambda + \Omega_k = 1$

Come riferire l'equazione di Friedmann per un generico istante t (parametro di scala a) riferita alle Ω attuali?

$$H^2 = \boxed{\frac{8\pi G}{3}}\left(\boxed{\rho_m} + \rho_{rad} + \boxed{\rho_\Lambda}\right) \boxed{-\frac{k}{a^2}}$$

$$\frac{8\pi G}{3} = \frac{H_0^2}{\rho_{oc}}$$

$$\rho_m \rightarrow \rho_{om}\frac{a_o^3}{a^3} \rightarrow \rho_{oc}\Omega_{om}\frac{a_0^3}{a^3}$$

$$\rho_\Lambda \rightarrow \frac{\Lambda}{8\pi G}$$

$$-\frac{k}{a^2} \rightarrow = \frac{\Omega_{ok}H_o^2 a_o^2}{a^2}$$

$$\Downarrow$$

$$H^2 = H_o^2\left[\Omega_{om}\left(\frac{a_o}{a}\right)^3 + \Omega_{orad}\left(\frac{a_o}{a}\right)^4 + \Omega_{o\Lambda} + \Omega_{ok}\left(\frac{a_o}{a}\right)^2\right]$$

N.B. Normalmente quando si considera il valore di una variabile a(t) al tempo odierno si pone $a(t=t_{oggi})=a_0$ MA : quando si parla di densità critica, spesso il pedice viene omesso

$$H^2 = H_o^2\left[\Omega_m\left(\frac{a_o}{a}\right)^3 + \Omega_{rad}\left(\frac{a_o}{a}\right)^4 + \Omega_\Lambda + \Omega_k\left(\frac{a_o}{a}\right)^2\right]$$

$$\Omega_m + \Omega_{rad} + \Omega_\Lambda + \Omega_k = 1$$

Ricordando che: $\Omega_{ok} = 1 - \Omega_o$

$$H^2 = H_o^2 \left[\Omega_m \left(\frac{a_o}{a}\right)^3 + \Omega_{rad}\left(\frac{a_o}{a}\right)^4 + \Omega_\Lambda + \Omega_k \left(\frac{a_o}{a}\right)^2\right]$$

$$\Updownarrow$$

$$\boxed{H^2 = H_o^2 \left[\Omega_m \left(\frac{a_o}{a}\right)^3 + \Omega_{rad}\left(\frac{a_o}{a}\right)^4 + \Omega_\Lambda + (1 - \Omega_o)\left(\frac{a_o}{a}\right)^2\right]}$$

Anche in questo formalismo è immediato vedere come per t≪ t_o (a≫ a_o) :

→ il termine legato alla curvatura è trascurabile, la dinamica è quella di uno spazio piatto

→ il contributo della costante cosmologica è dominante per a > a_o

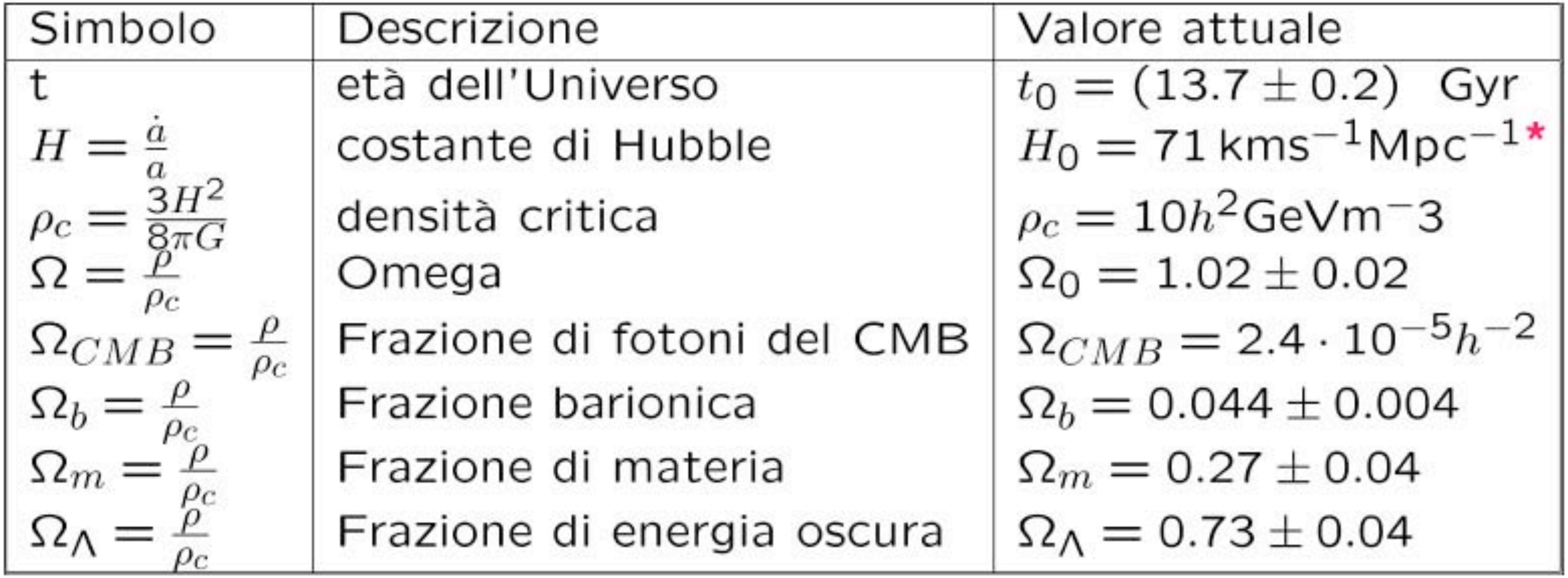
Come si trasforma l'equazione dell'accelerazione in termini di Ω ?

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}\Big(\underbrace{\rho_{mat}}_{\rho_c\Omega_{mat}} + \underbrace{\rho_{rad}}_{\rho_c\Omega_{rad}} + \underbrace{\frac{3p_{rad}}{c^2}}_{\rho_c\Omega_{rad}} + \underbrace{\rho_\Lambda}_{\rho_c\Omega_\Lambda} + \underbrace{\frac{3p_\Lambda}{c^2}}_{-3\rho_c\Omega_\Lambda}\Big) = -H^2\left(\frac{1}{2}\Omega_{mat} + \Omega_{rad} - \Omega_\Lambda\right)$$

$$\rho_c = \frac{3H^2}{8\pi G}$$

$$\boxed{q = -\frac{\ddot a a}{\dot a^2} = \frac{1}{2}\Omega_{mat} + \Omega_{rad} - \Omega_\Lambda}$$

The cosmological parameters

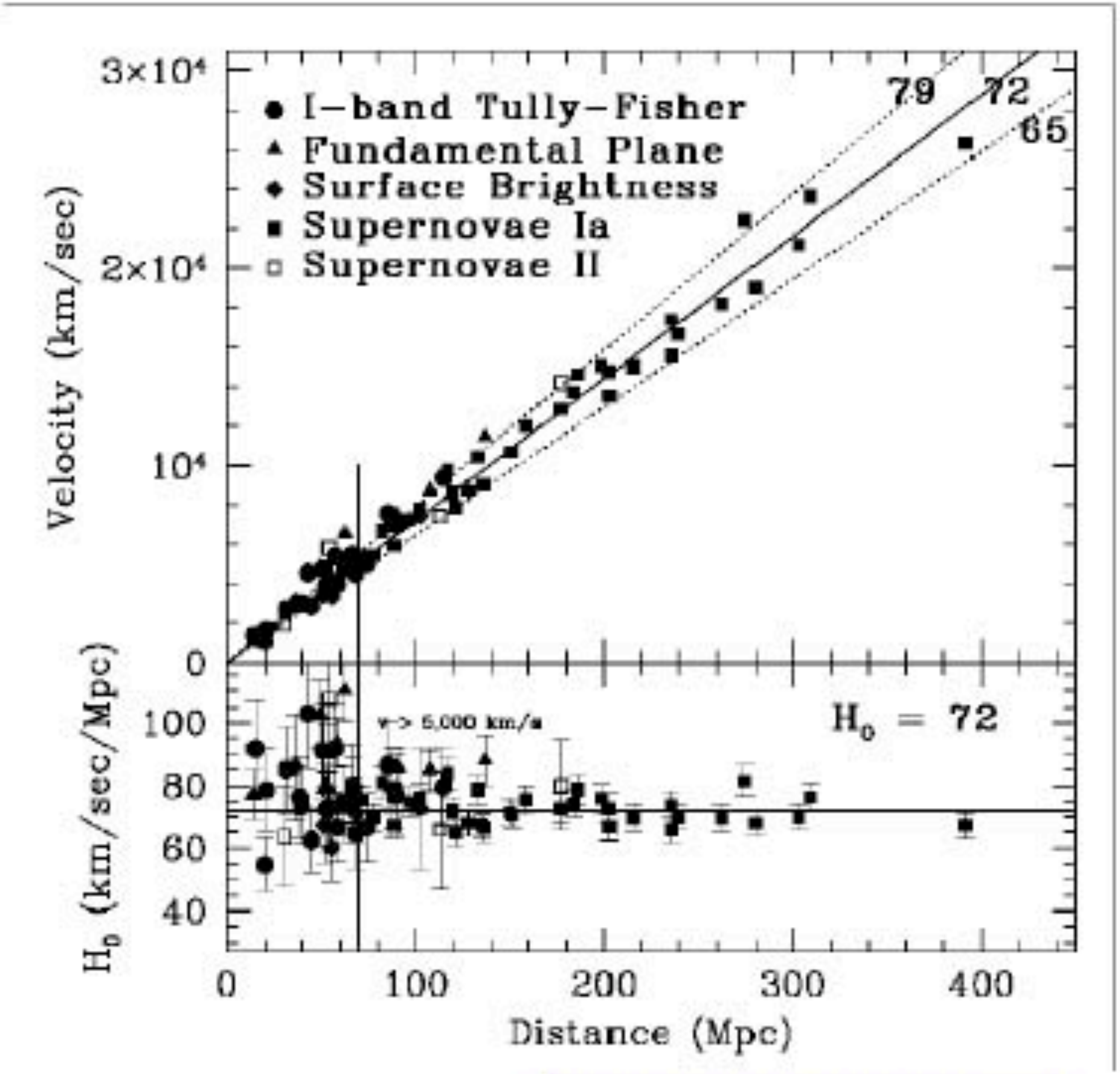


Simbolo	Descrizione	Valore attuale
t	età dell'Universo	$t_0 = (13.7 \pm 0.2)$ Gyr
$H = \frac{\dot{a}}{a}$	costante di Hubble	$H_0 = 71\,\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$*
$\rho_c = \frac{3H^2}{8\pi G}$	densità critica	$\rho_c = 10h^2\mathrm{GeVm}^{-}3$
$\Omega = \frac{\rho}{\rho_c}$	Omega	$\Omega_0 = 1.02 \pm 0.02$
$\Omega_{CMB} = \frac{\rho}{\rho_c}$	Frazione di fotoni del CMB	$\Omega_{CMB} = 2.4 \cdot 10^{-5} h^{-2}$
$\Omega_b = \frac{\rho}{\rho_c}$	Frazione barionica	$\Omega_b = 0.044 \pm 0.004$
$\Omega_m = \frac{\rho}{\rho_c}$	Frazione di materia	$\Omega_m = 0.27 \pm 0.04$
$\Omega_\Lambda = \frac{\rho}{\rho_c}$	Frazione di energia oscura	$\Omega_\Lambda = 0.73 \pm 0.04$

$$\boxed{H_0 = 100\,h\,\mathrm{km\,s}^{-1}\,\mathrm{Mpc}^{-1}} \longrightarrow \text{h=0,71}$$

$$d_L = a_0 r(1+z) = \frac{c}{H_0}\left(z + \frac{1}{2}(1-q_0)z^2 + \ldots..\right)$$

A basso z (z < 0.1) → comportamento lineare per misurare H

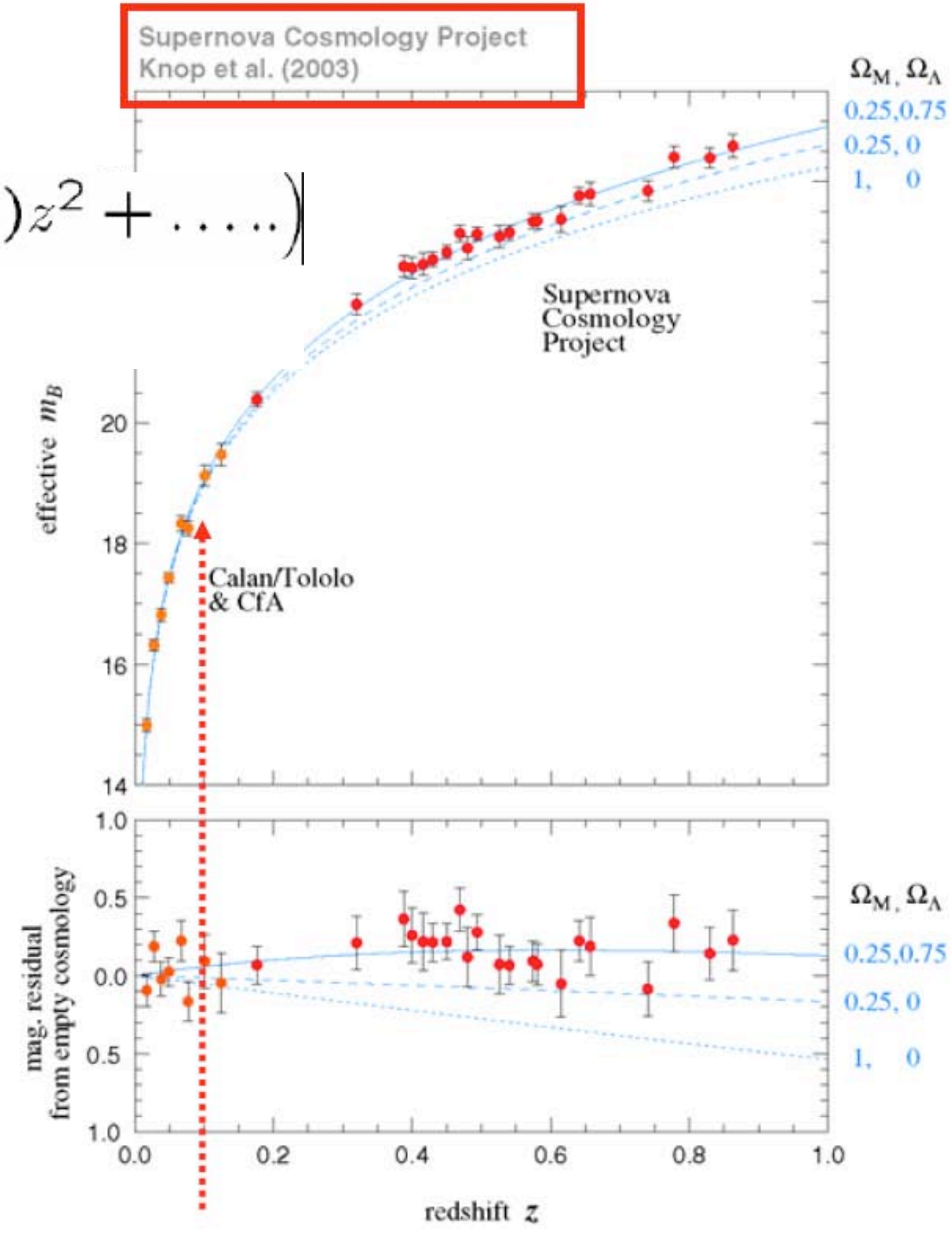


HST Key project

Ad alto z (z>0.1) deviazione dalla legge di Hubble e sensitività a q_0

$$d_L = \frac{c}{H_0}\left(z + \frac{1}{2}(1 - q_0)z^2 + \ldots\ldots\right)$$

$$q_0 = \frac{1}{2}\Omega_m - \Omega_\Lambda$$



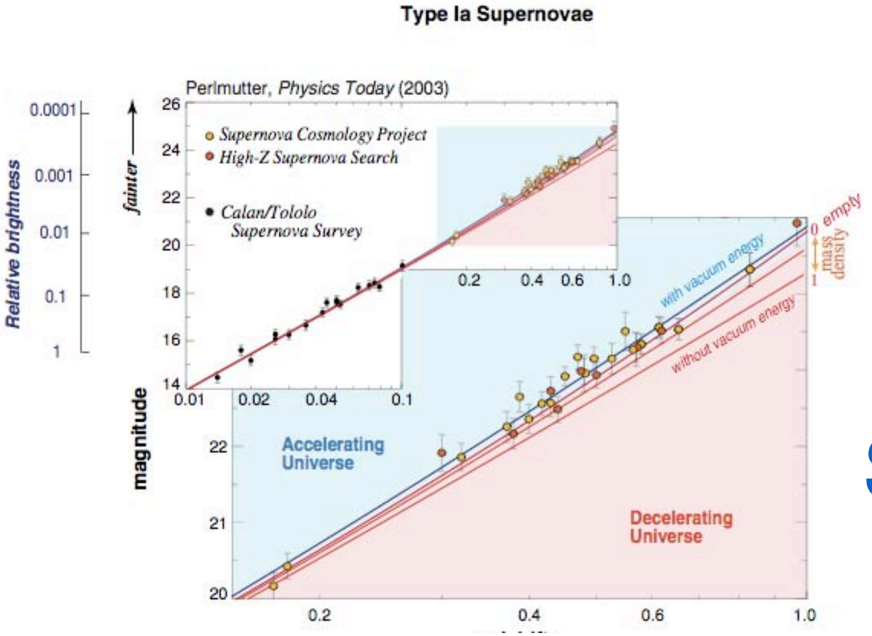
$$m - M \simeq 25 - 5logH_0 + 5logcz + 1.086(1 - q_0)z + \ldots$$

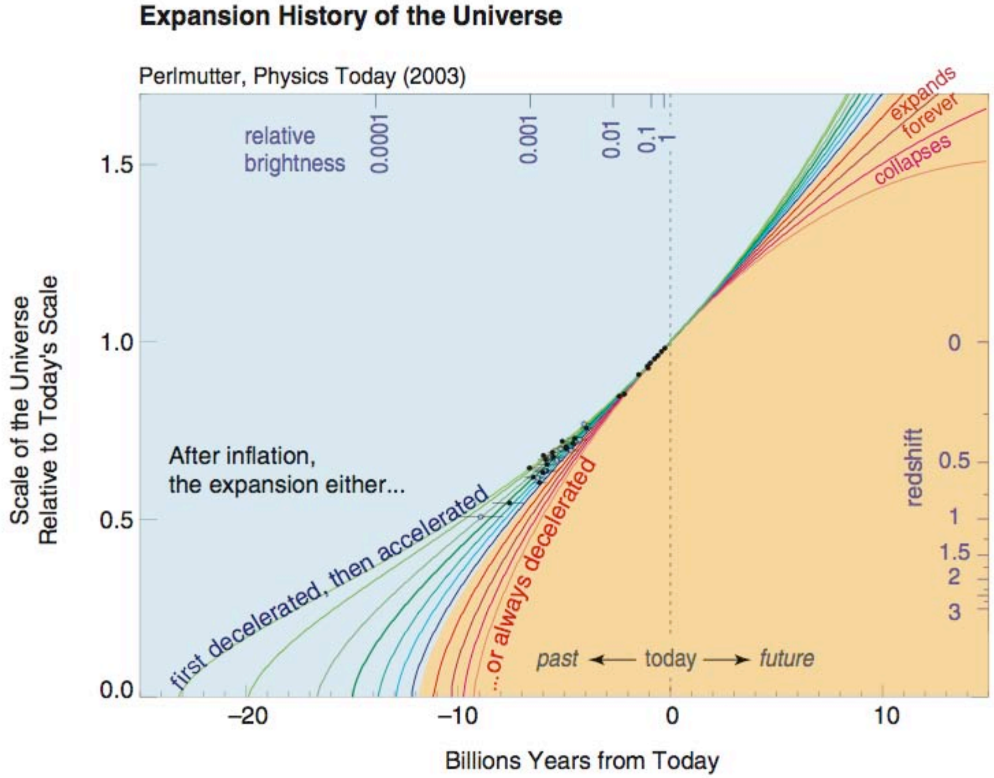
From all observations:

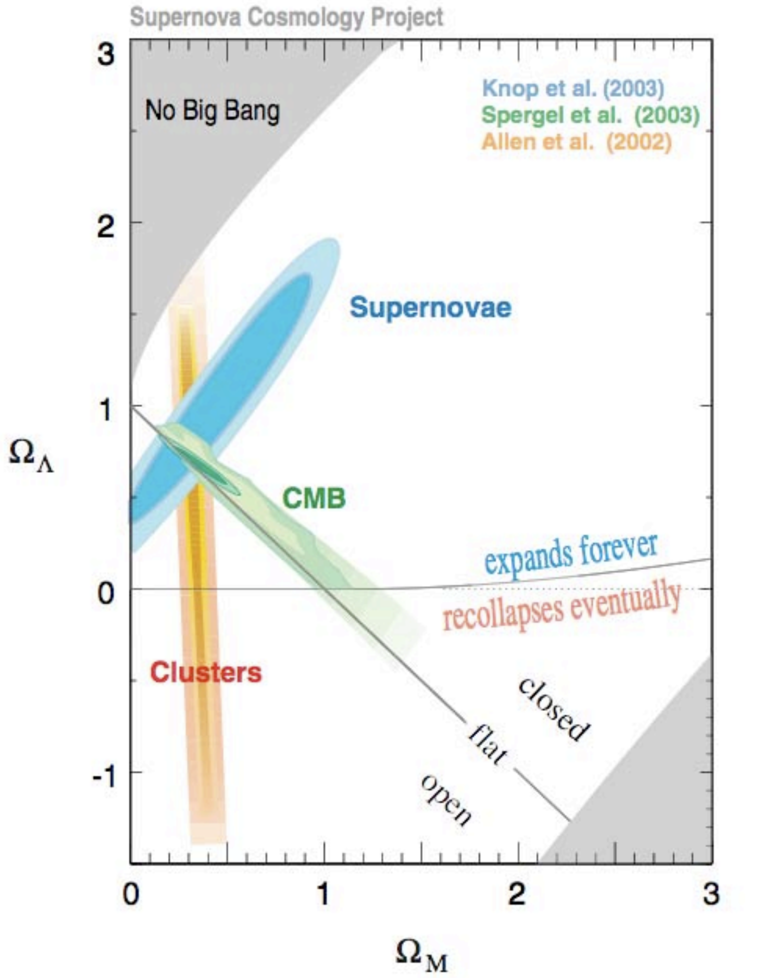
WMAP → Ω_T

X-ray clusters → Ω_m

SN Cosmology project → Ω_Λ

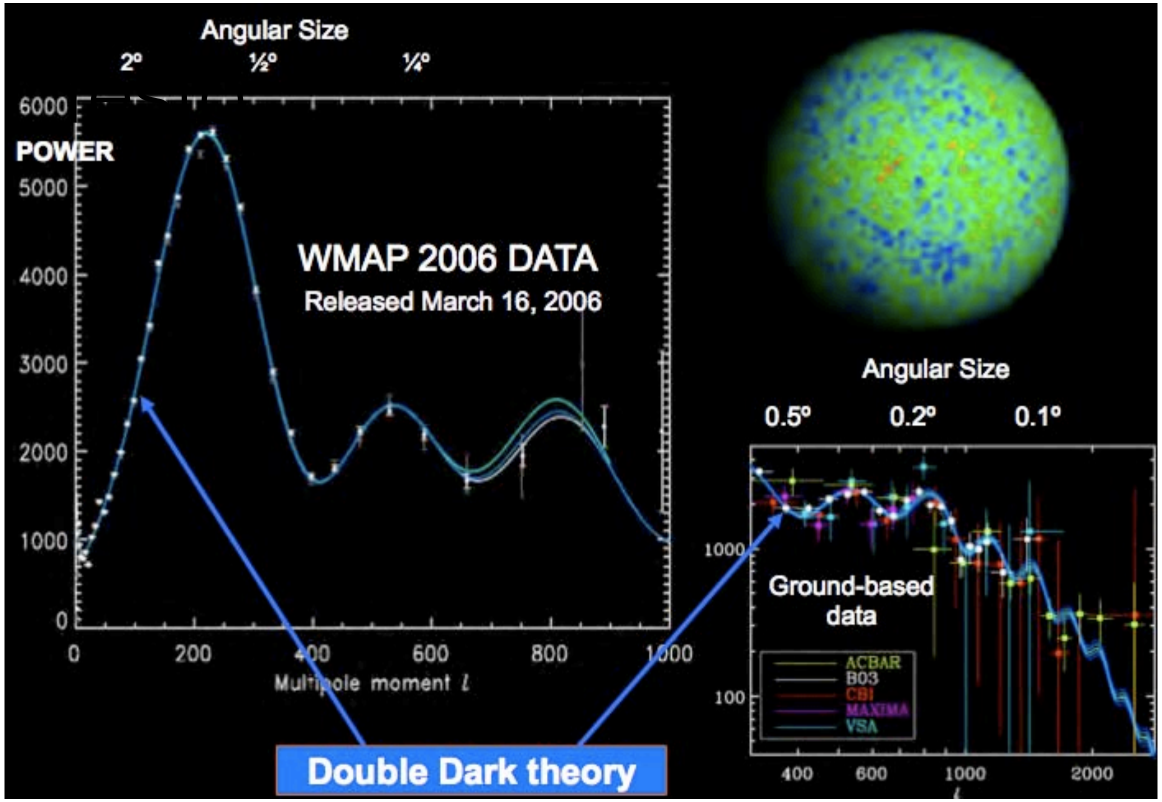






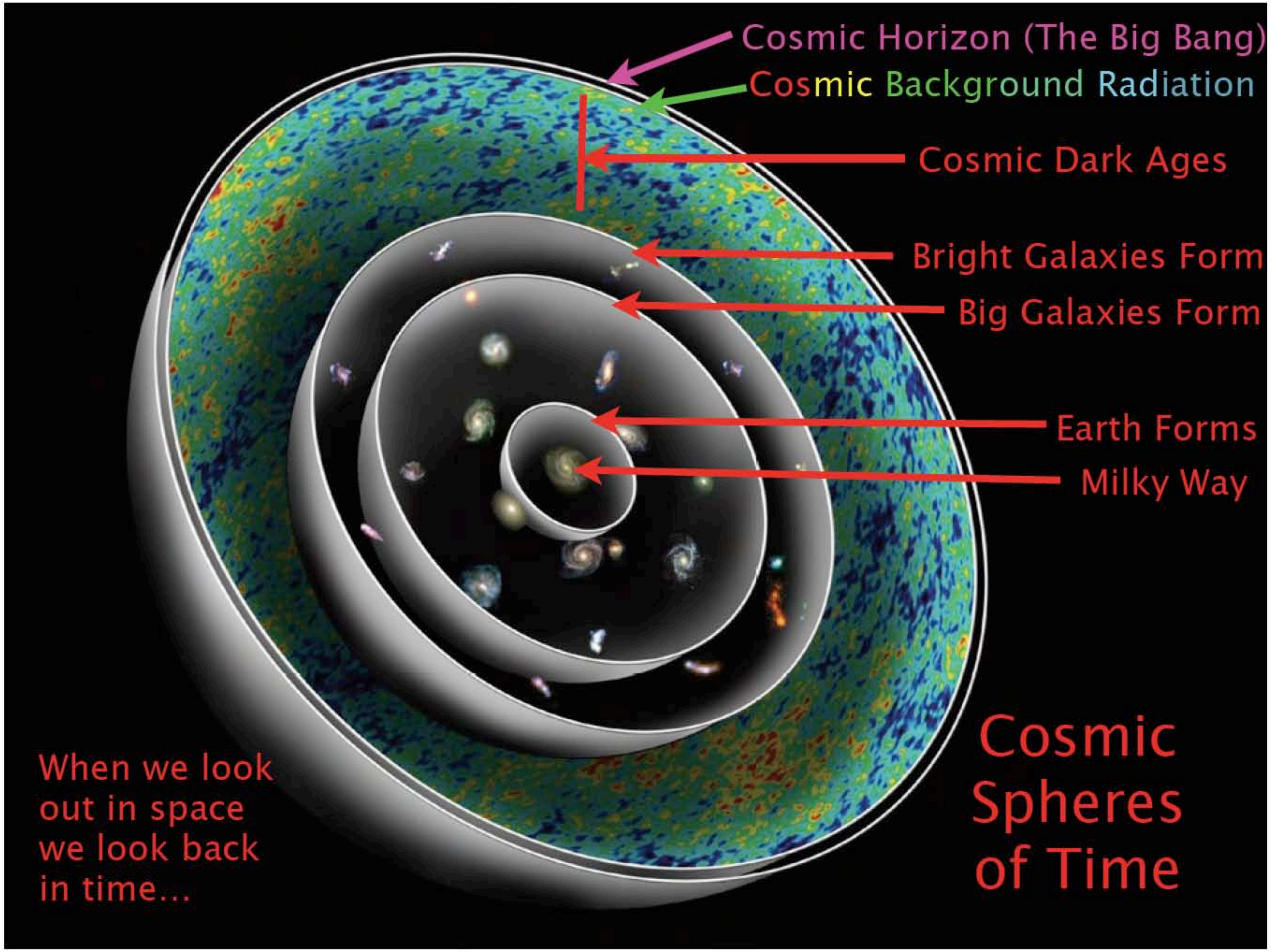
The era of “concordance” cosmology

- Standard Hot Big Bang
- Flat, accelerating Universe
- Composed of: atoms, exotic dark matter, and dark energy
- Precision set of cosmological parameters:
  - $\Omega_0 = 1.00 \pm 0.01$
  - $\Omega_M = 0.24 \pm 0.02$
  - $\Omega_B = 0.042 \pm 0.002$
  - $\Omega_\Lambda = 0.76 \pm 0.02$
  - $H_0 = 73 \pm 2$ km/s/Mpc
  - $t = 13.7 \pm 0.2$ Gyr



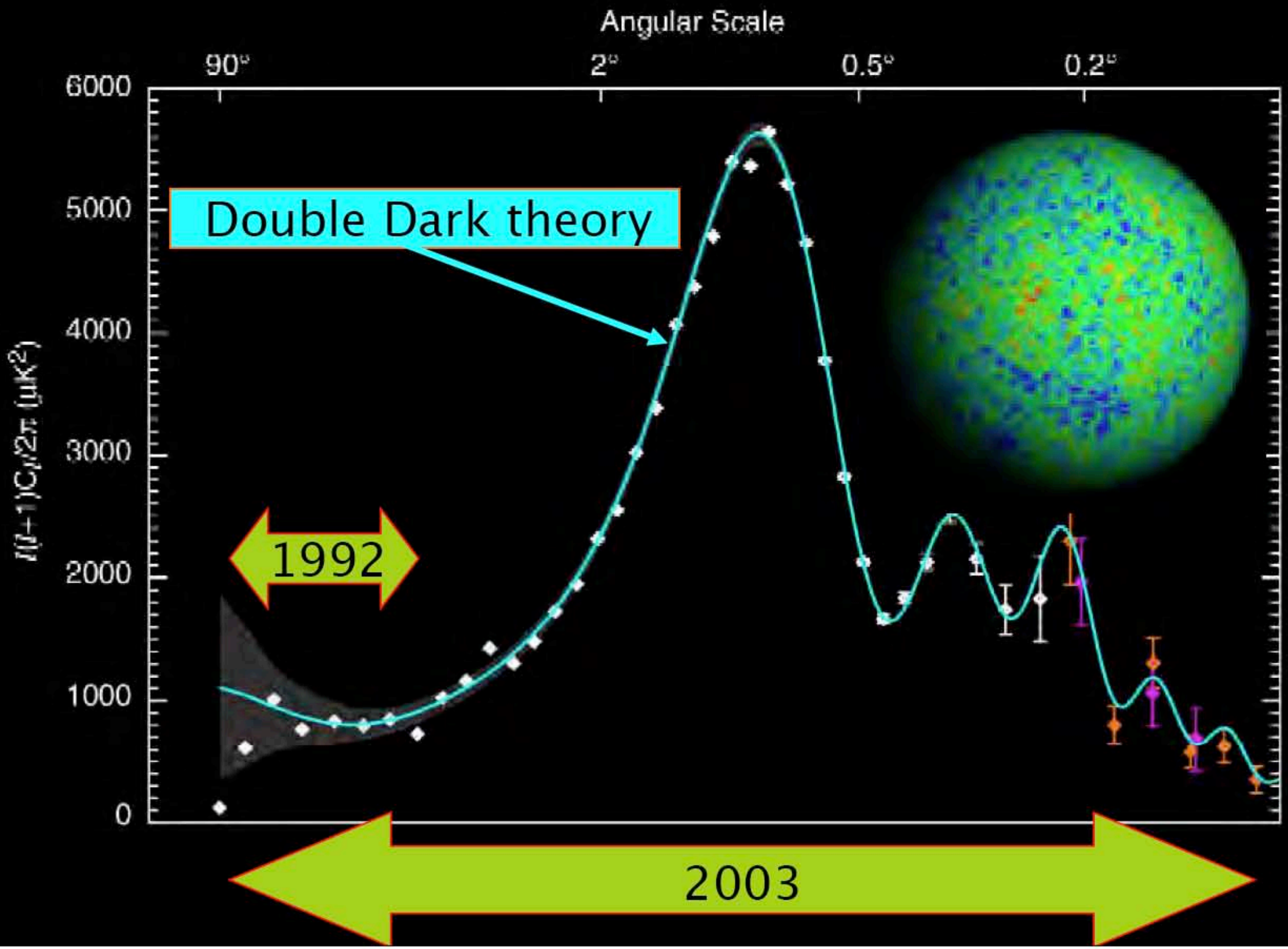
J.Primack

Double Dark Theory



J.Primack

Big Bang Data Agrees with Double Dark Theory!



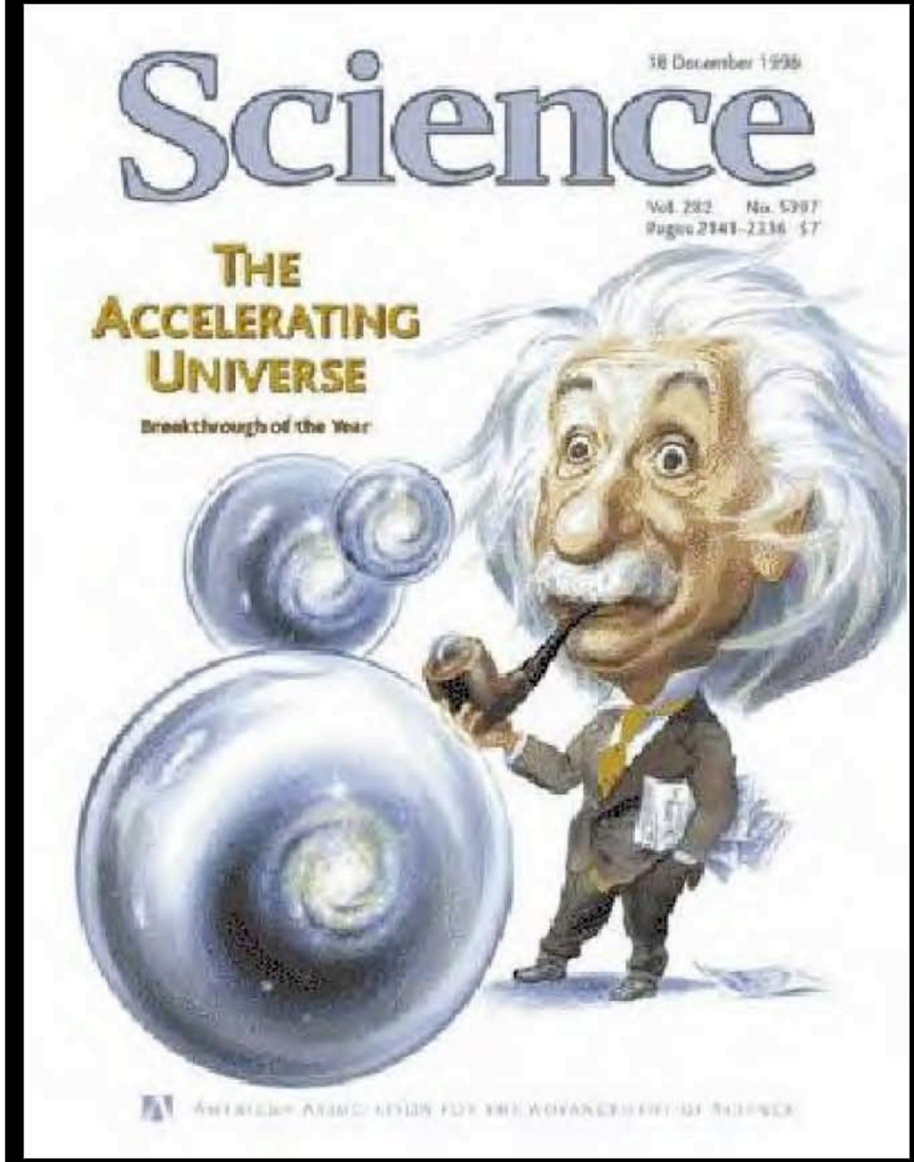
Double Dark theory

1992

2003

J.Primack

1998 BREAKTHROUGH OF THE YEAR 2003



Science

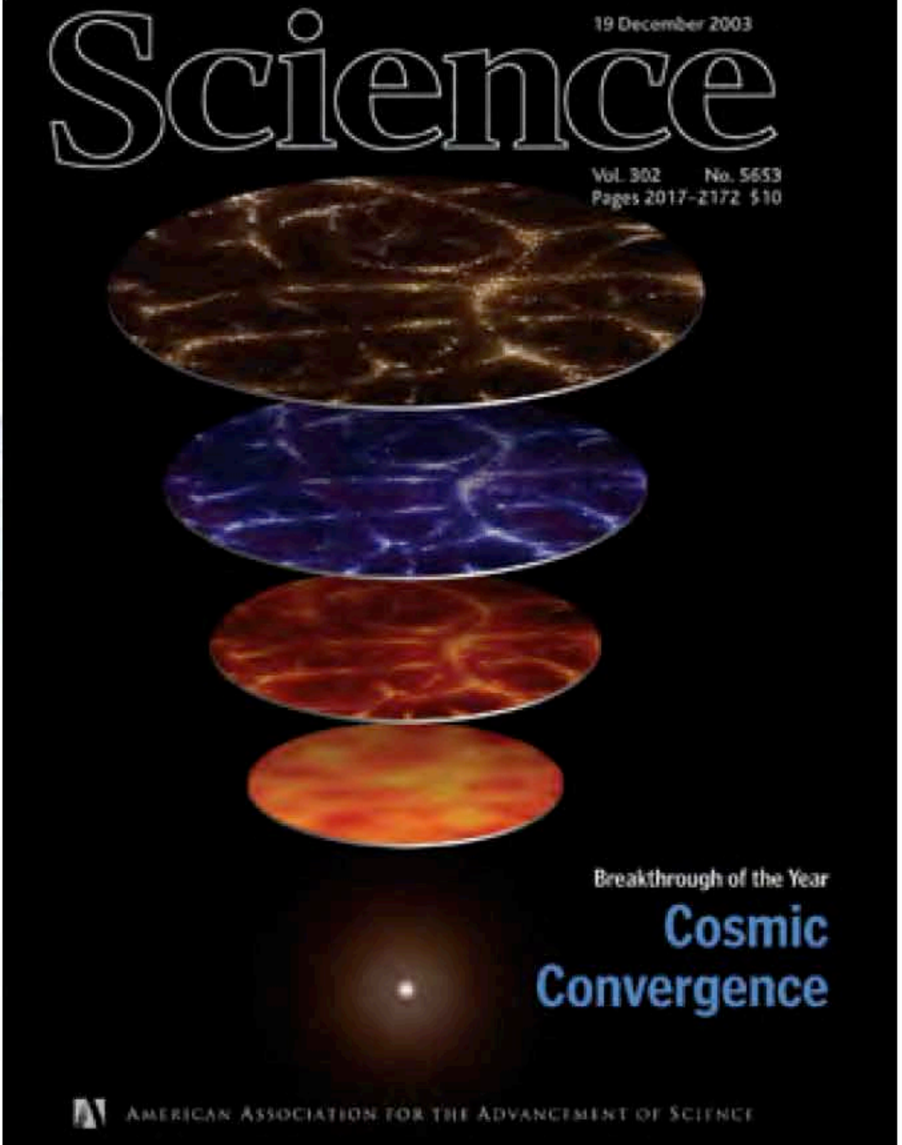
18 December 1998

Vol. 282 No. 5397
Pages 2141–2336 $7

THE ACCELERATING UNIVERSE

Breakthrough of the Year

American Association for the Advancement of Science



Science

19 December 2003

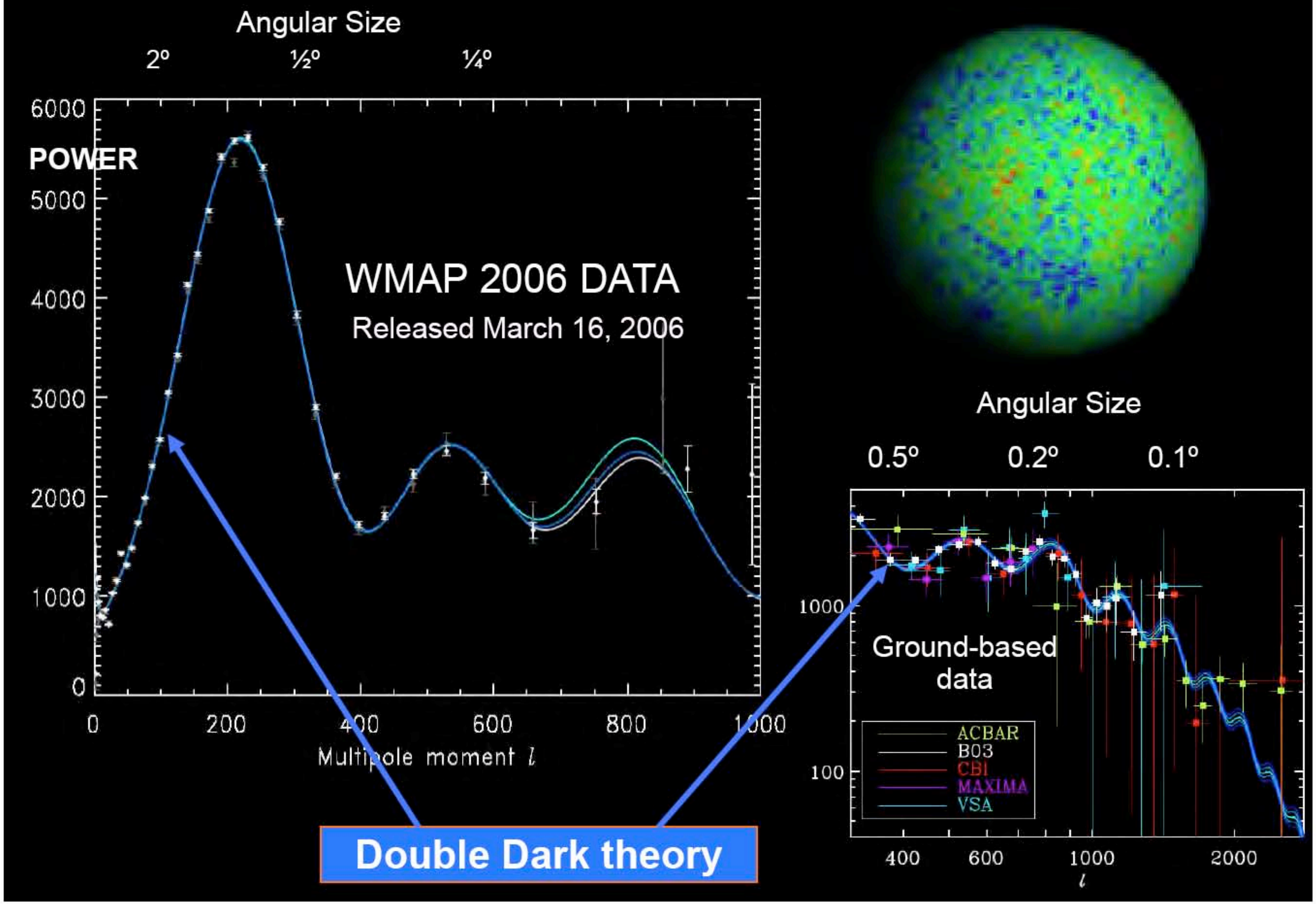
Vol. 302 No. 5653
Pages 2017–2172 $10

Breakthrough of the Year

Cosmic Convergence

American Association for the Advancement of Science

Latest Big Bang Data Strengthens the Agreement!



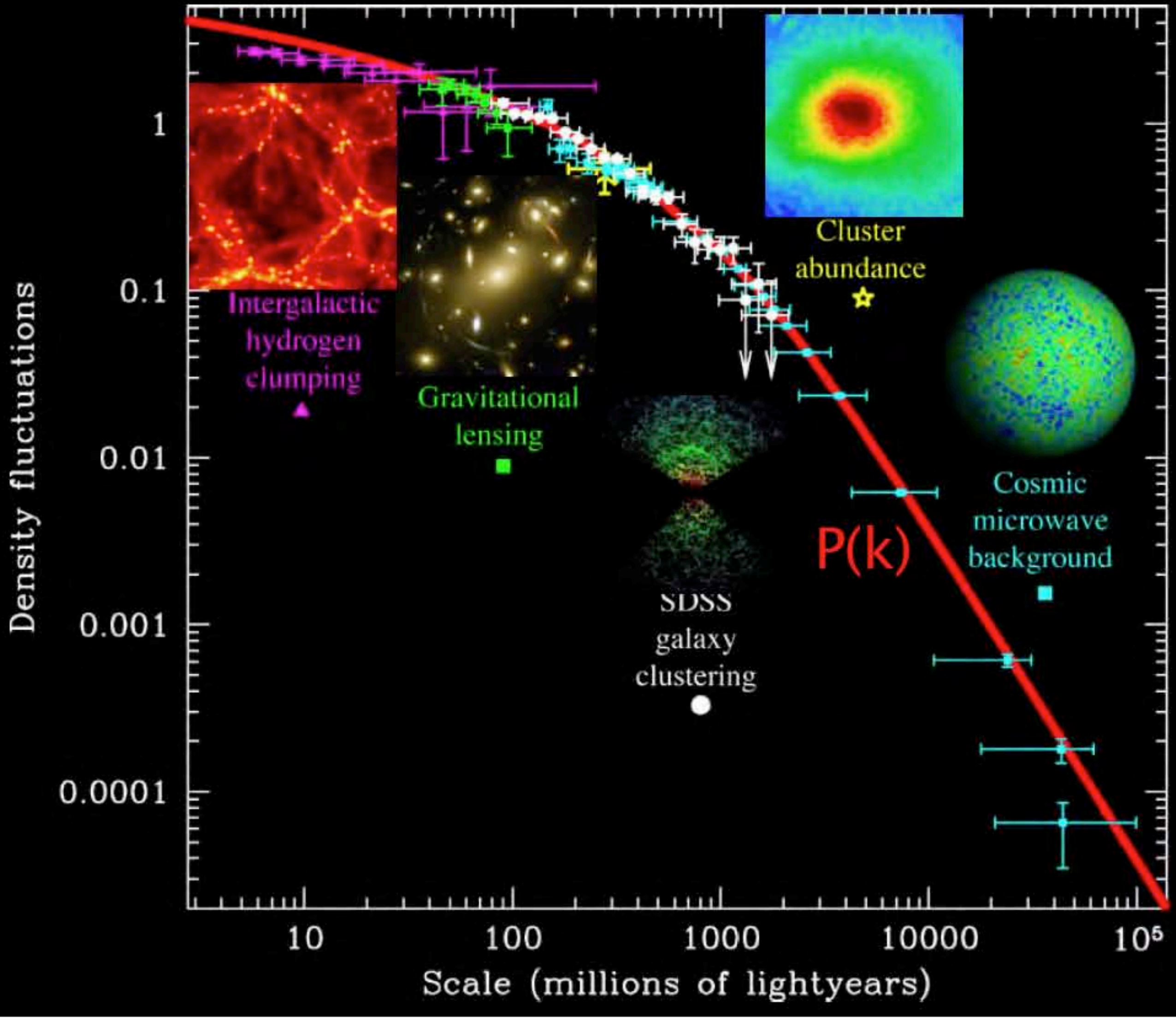
WMAP 2006 DATA

Released March 16, 2006

Ground-based data

Double Dark theory

Distribution of Matter
Also Agrees with Double Dark Theory!



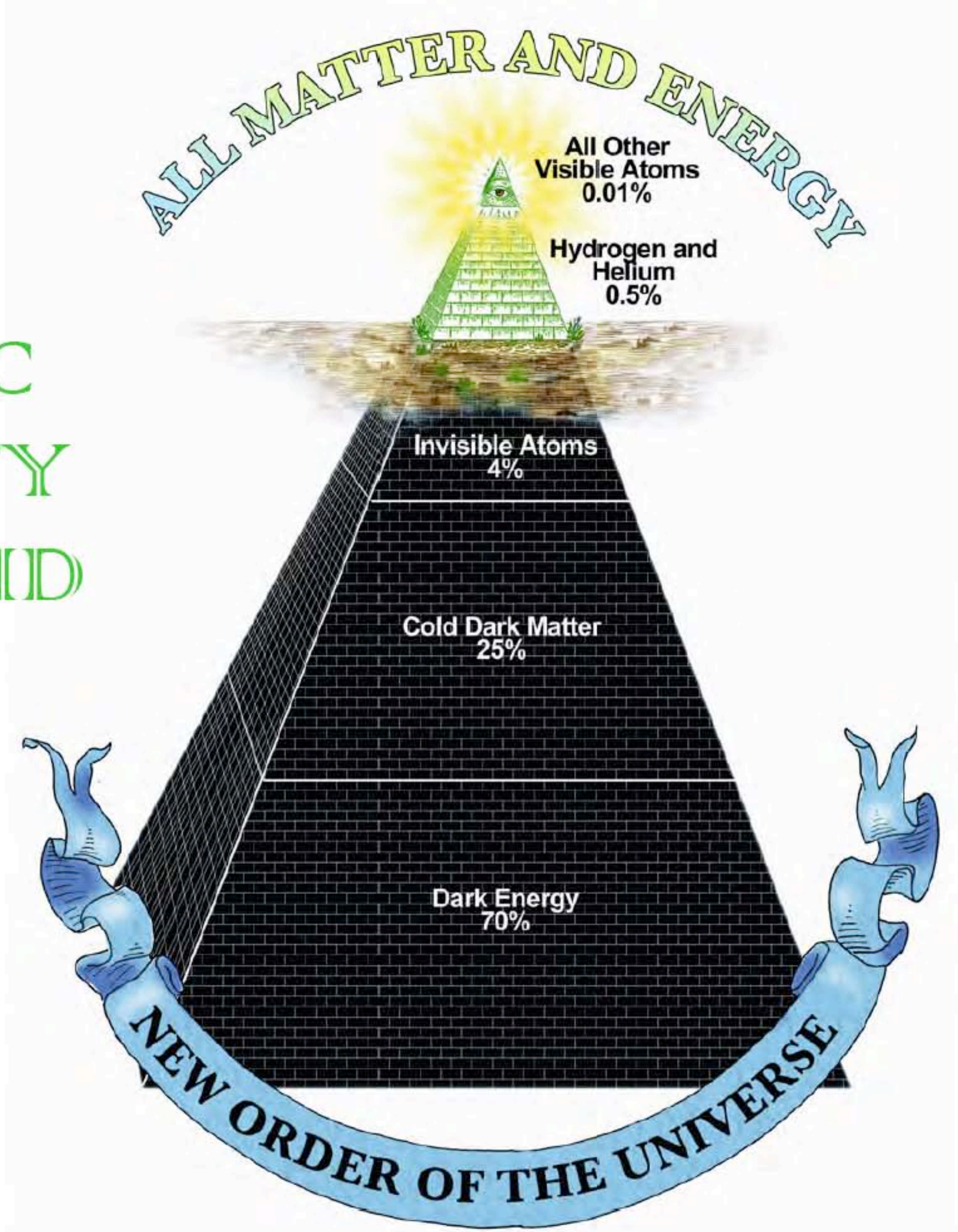
Max Tegmark

stardust

stars

J.Primack

COSMIC DENSITY PYRAMID

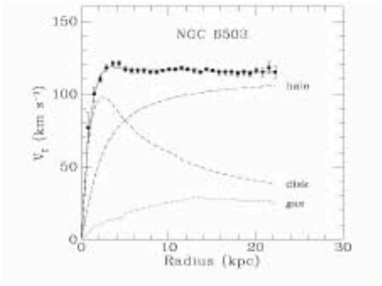


J.Primack

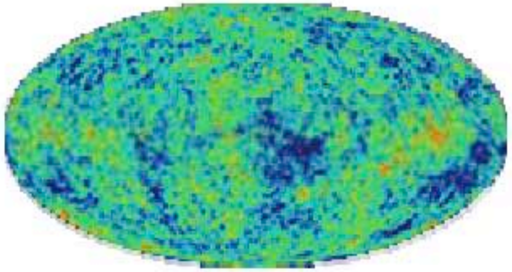
Evidenze di una componente oscura di materia nell'universo:

Osservazioni indipendenti a scale di lunghezza differenti indicano che $\sim$ 30 % dell'energia dell'universo è dovuta a materia non luminosa

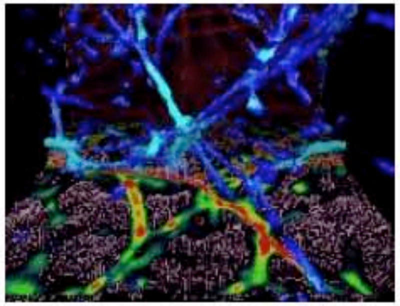
- Rotation curves of galaxies



- CMB



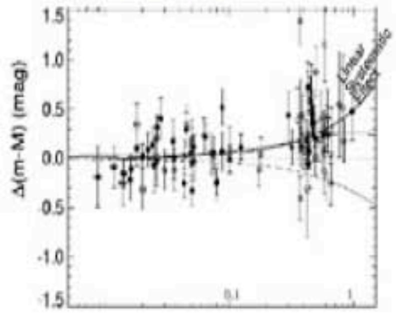
- Large Scale Structure



- Galaxy clusters

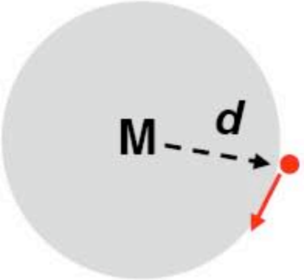
- Lensing

- SN Ia



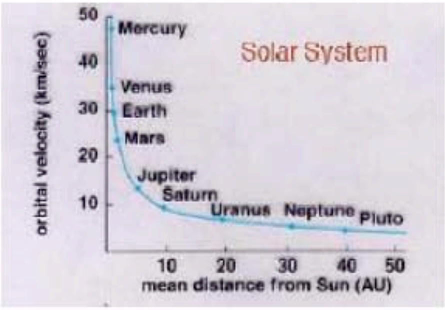
MATERIA OSCURA : evidenze dinamiche

Consideriamo una particella di prova orbitante attorno ad una massa M



sarà: $$\boxed{\frac{mv^2}{d} = \frac{GmM}{d^2}} \longrightarrow \boxed{v^2 = \frac{GM}{d}}$$

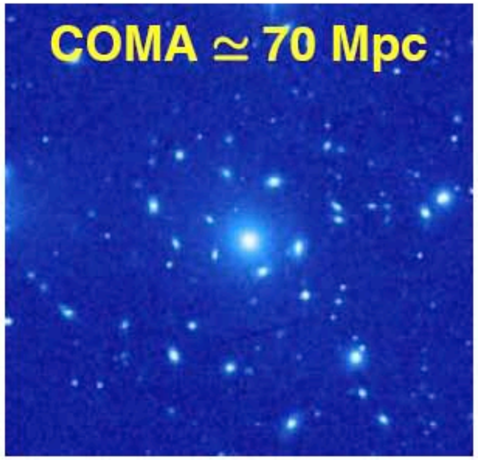
La misura di velocità di un corpo rappresenta una stima della massa a cui è legato



⏩ Applicazione “semplice” :
velocità dei pianeti nel sistema solare

⏩ Applicazioni generali :

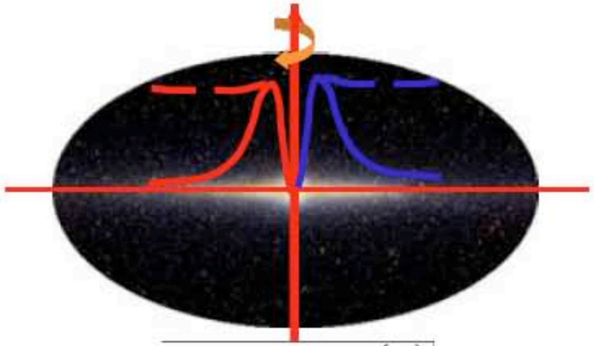
- Curve di rotazione delle galassie
- Distribuzione di velocità delle galassie negli ammassi
  F.Zwicky Helv.Phys.Acta 6(1933) 110
- Emissione termica di gas galattico / intergalattico



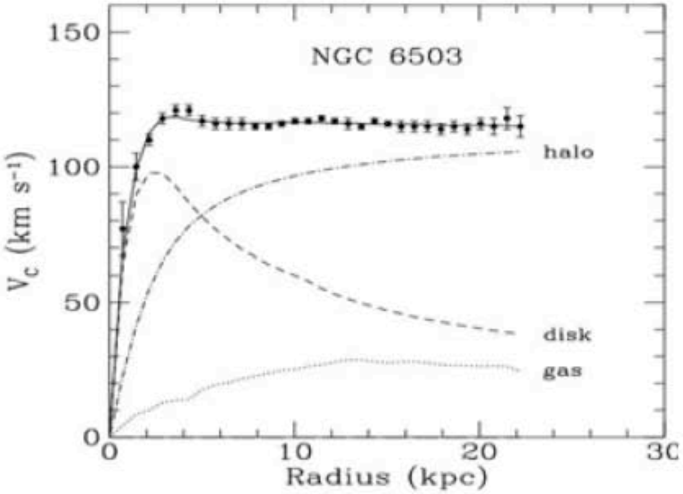
⏩ Conclusione:.
materia oscura > 10 volte la materia luminosa

MATERIA OSCURA : evidenze dinamiche

→ Curve rotazionali delle galassie



$$v^2 = \frac{GM(r)}{r}$$



Cosa ci aspettiamo in maniera naif ?
Dove c'e luce c'e materia :

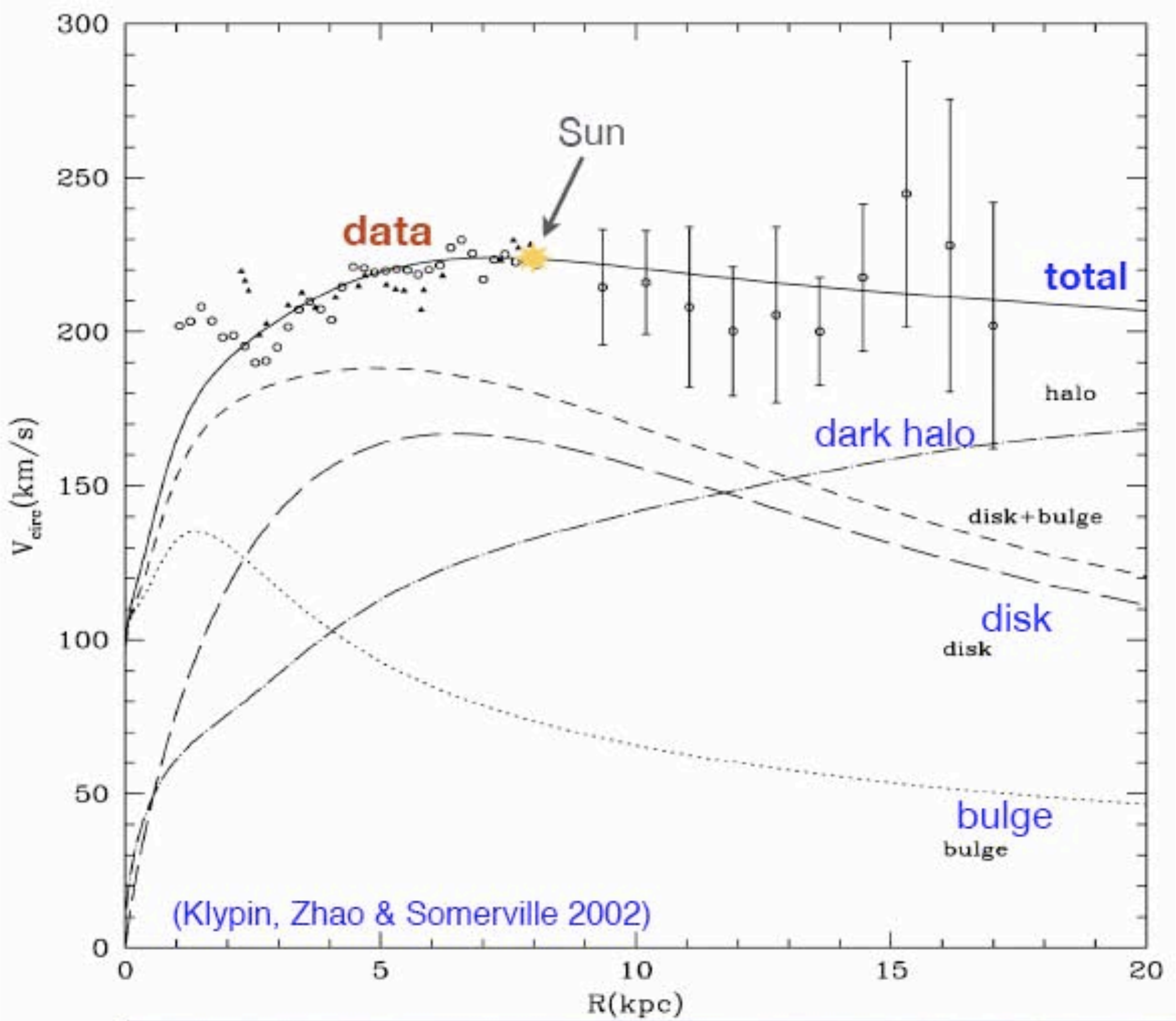
Per $r < R$: $\rho(r)$=cost
$M(r) \propto r^3$
$v(r) \propto r$

$r>R$: $\rho(r) = 0$
$M(r)$=cost
$v \propto 1/r^{1/2}$

Osserviamo: $M(r) \propto r$
$\rho(r) \propto 1/r^2$
$v(r)$ = cost

C'è un alone di materia oscura che si estende ben oltre i pochi Kpc del disco, ma non è chiaro quale debba essere il suo profilo per r →0 e per r→∞

Dark Matter in the Milky Way



$$M_{tot,lum} \approx 9\times10^{10}\, M_\odot$$

$$M_{virial} \approx 1...2\times10^{12}\, M_\odot$$

$$\rho_{dark} \simeq 0.3-0.6\ GeV\cdot cm^{-3}$$

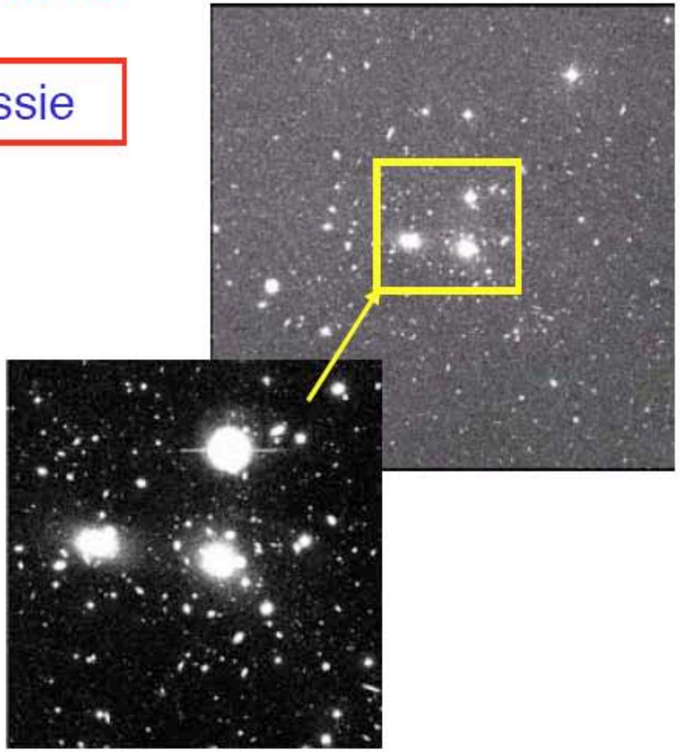
≅ 3000 WIMPs/m^3

(M_{WIMP}=100 GeV)

L. Baudis

MATERIA OSCURA : evidenze dinamiche

→Distribuzione delle velocità negli ammassi di galassie



Per un sistema a simmetria sferica di N corpi di eguale massa m legato gravitazionalmente vale il teorema del viriale:

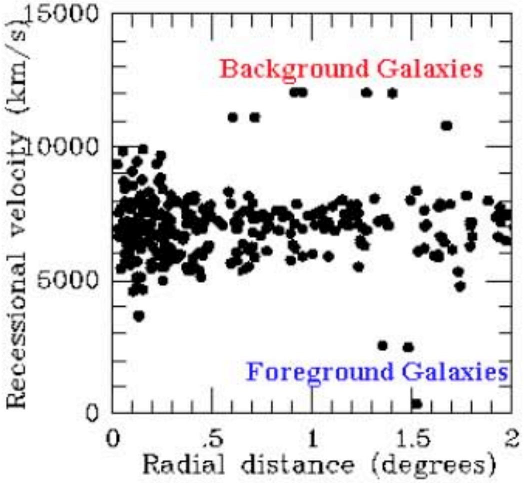
$$E_{kin} - \frac{1}{2}E_{pot} = 0$$

$$E_{kin} = N\frac{1}{2}m < v^2 >= \frac{1}{2}M < v^2 >$$

$$E_{pot} = -\frac{1}{2}G\frac{Nm^2}{<r>} = -\frac{1}{2}G\frac{N^2m^2}{R} = -\frac{1}{2}G\frac{M^2}{R}$$

$$M = \frac{2R<v^2>}{G}$$

Distribuzione delle velocità attorno del coma cluster →



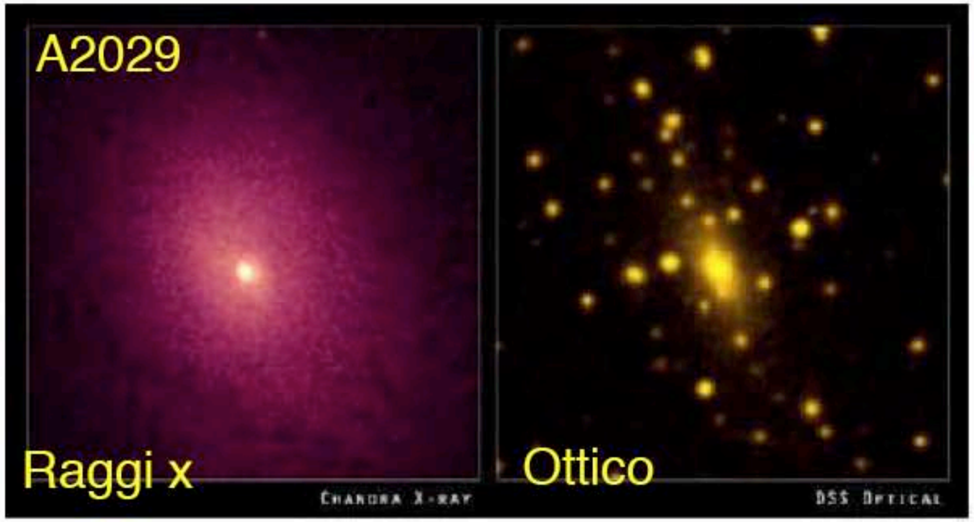
$M \gg M_{luminosa} + M_{gas}$

MATERIA OSCURA : evidenze dinamiche

→ Emissione termica di gas nel potenziale gravitazionale

Condizione di equilibrio per un gas intrappolato nel potenziale gravitazionale:

$$\frac{1}{\rho_g(r)}\frac{dP_g(r)}{dr} = -\frac{GM(<r)}{r^2}$$



Spettro termico nella banda x:
→ T : dalla forma dello spettro
→ ρ : dalla luminosità

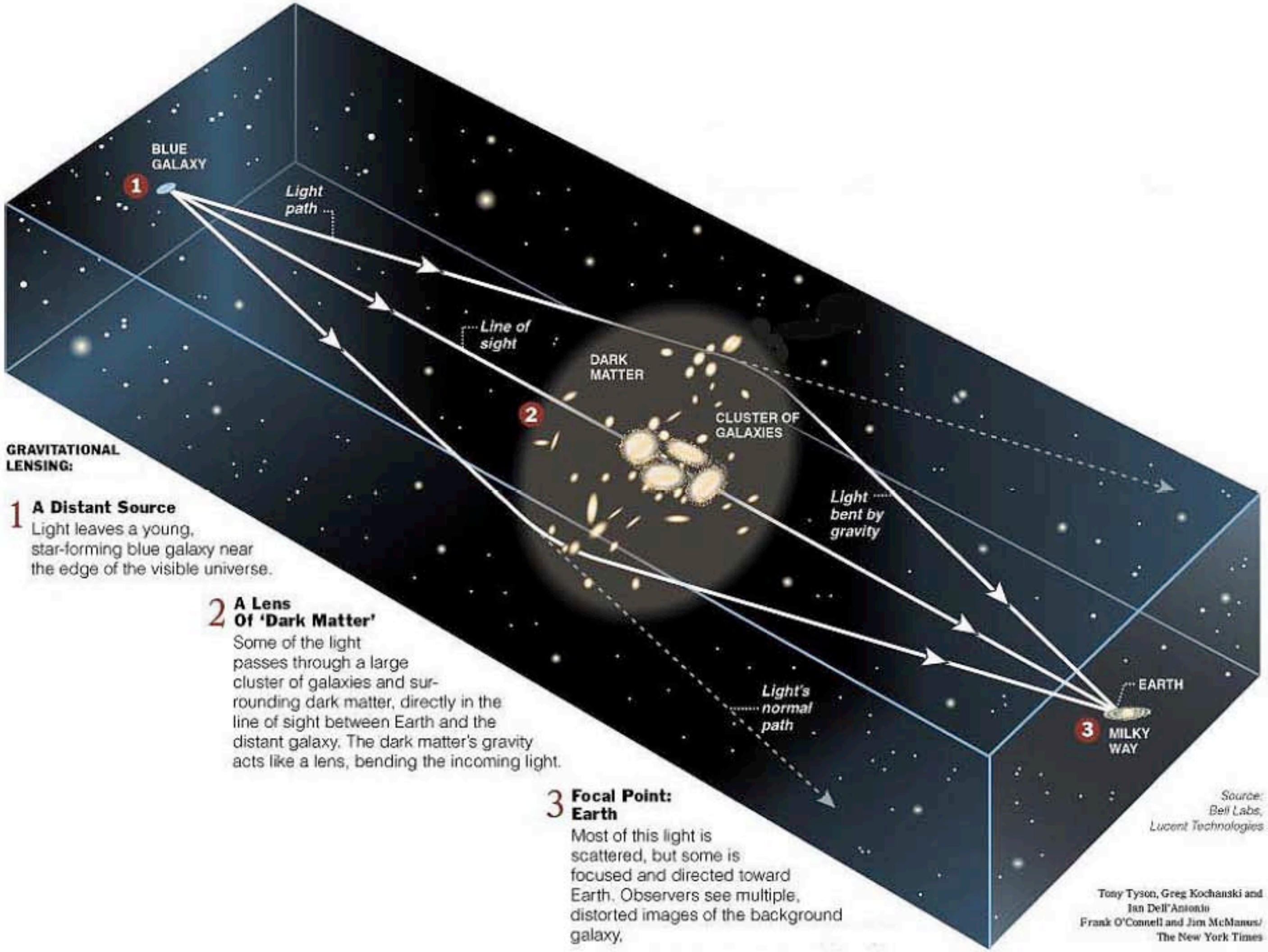
Ricostruendo il profilo di pressione del gas → stima di $\rho(r)$

$$\rho \propto \frac{1}{r/a(1+(r/a)^2)}$$

a=540 kpc

MATERIA OSCURA : lensing gravitazionale

La presenza di materia oscura curva lo spazio-tempo e devia i raggi di luce delle sorgenti sullo sfondo



GRAVITATIONAL LENSING:

1 **A Distant Source**
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

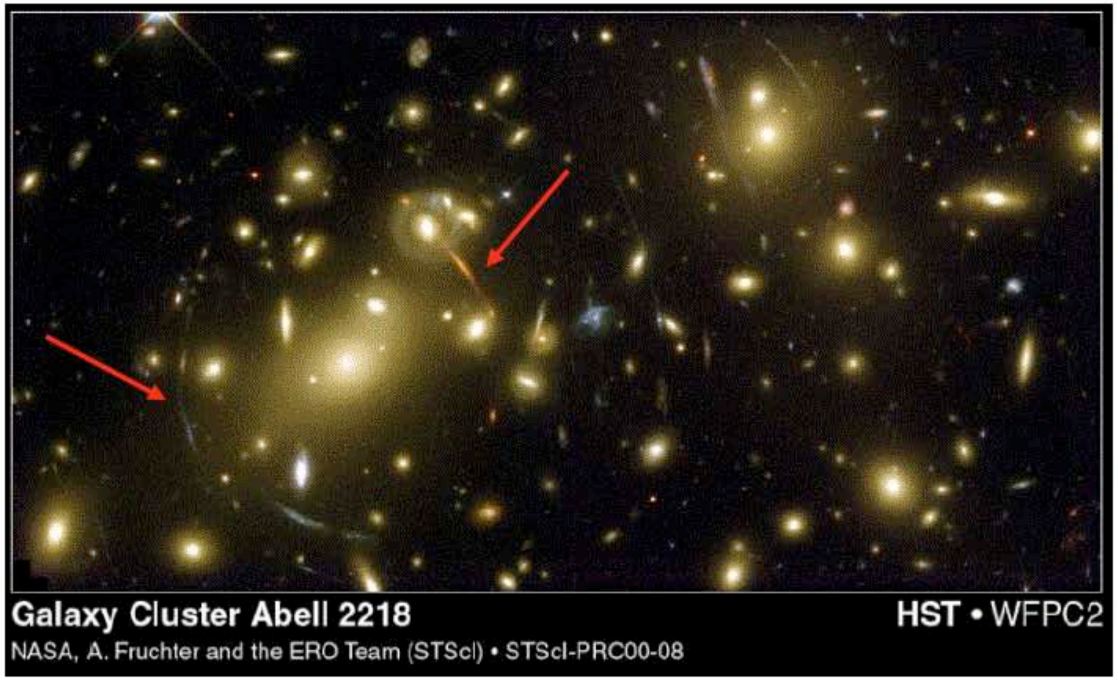
2 **A Lens Of 'Dark Matter'**
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times

MATERIA OSCURA : lensing gravitazionale



→ La geometria della distorsione gravitazionale può essere utilizzata per ricostruire il profilo della massa che l'ha generata.
Cfr. astro-ph/9507008
→Osservando attraverso la stessa lente oggetti a red-shift sostanzialmente diversi, si ricavano dettagli sulla geometria della propagazione (Ω_M, Ω_Λ)
Cfr. astro-ph/0402658

Although the idea that the dark matter may be the lightest supersymmetric WIMP (Pagels & Primack 1982) remains popular with particle theorists, we still have no experimental evidence on what the dark matter is, and there may be problems with the standard ΛCDM Double Dark theory on small scales ...

Are we on the right track? Or should we take seriously Modified Newtonian Dynamics (MOND) or other alternatives to the Double Dark theory?

The Astrophysical Journal, 604:596–603, 2004 April 1

Bullet Cluster 1E 0657-558

More Evidence Against MOND

and also against Self-Interacting DM:
Markevich et al. 2004, ApJ, 606, 819

WEAK-LENSING MASS RECONSTRUCTION OF THE INTERACTING CLUSTER 1E 0657−558: DIRECT EVIDENCE FOR THE EXISTENCE OF DARK MATTER[1]

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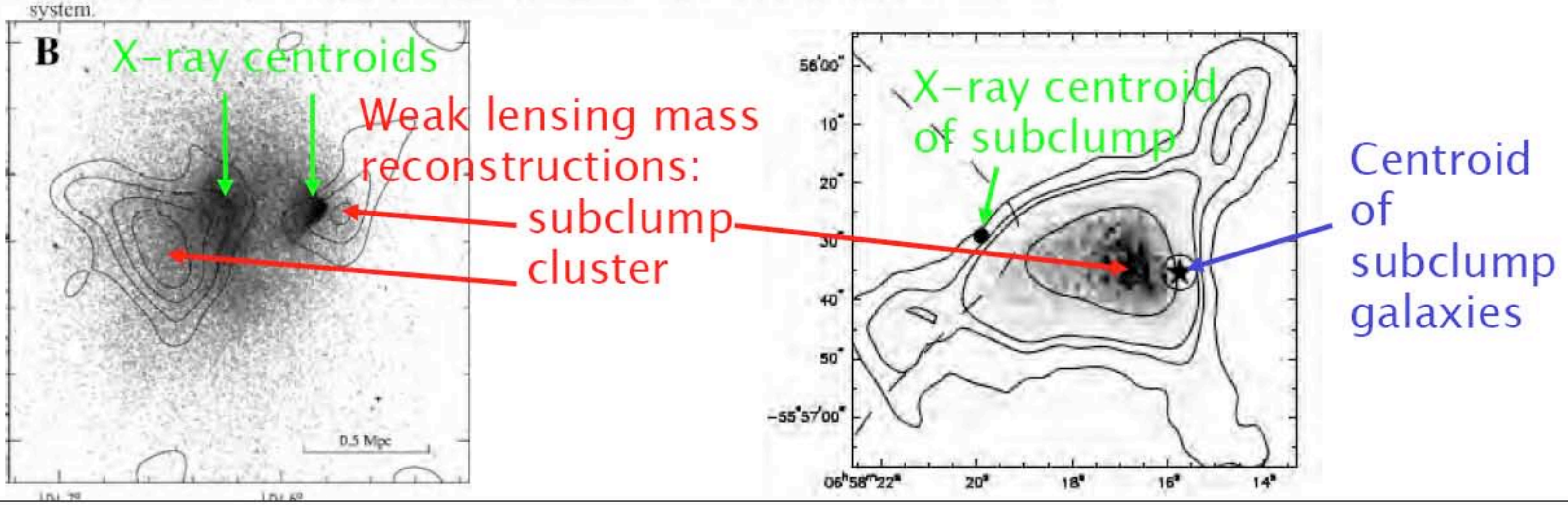
ABSTRACT

We present a weak-lensing mass reconstruction of the interacting cluster 1E 0657−558, in which we detect both the main cluster and a subcluster. The subcluster is identified as a smaller cluster that has just undergone initial infall and pass-through of the primary cluster and has been previously identified in both optical surveys and X-ray studies. The X-ray gas has been separated from the galaxies by ram pressure–stripping during the pass-through. The detected mass peak is located between the X-ray peak and galaxy concentration, although the position is consistent with the galaxy centroid within the errors of the mass reconstruction. We find that the mass peak for the main cluster is in good spatial agreement with the cluster galaxies and is offset from the X-ray halo at 3.4 σ significance, and we determine that the mass-to-light ratios of the two components are consistent with those of relaxed clusters. The observed offsets of the lensing mass peaks from the peaks of the dominant visible mass component (the X-ray gas) directly demonstrate the presence, and dominance, of dark matter in this cluster. This proof of dark matter existence holds true even under the assumption of modified Newtonian dynamics (MOND); based on the observed gravitational shear–optical light ratios and the mass peak–X-ray gas offsets, the dark matter component in a MOND regime would have a total mass that is at least equal to the baryonic mass of the system.

In a purely baryonic MOND universe the X-ray and galaxy centroids would still be separated as the galaxies are still collisionless particles in the interaction. However, because the X-ray halo is the dominant mass component of the visible baryons in the cluster, in the absence of a dark mass component the vast majority, ~ 85 − 90%, of the mass of the subclump would be with the X-ray gas. Thus, any direct method to measure the mass of the system would detect a higher mass about the stripped X-ray halo than around the galaxies. This is not what is observed in this system

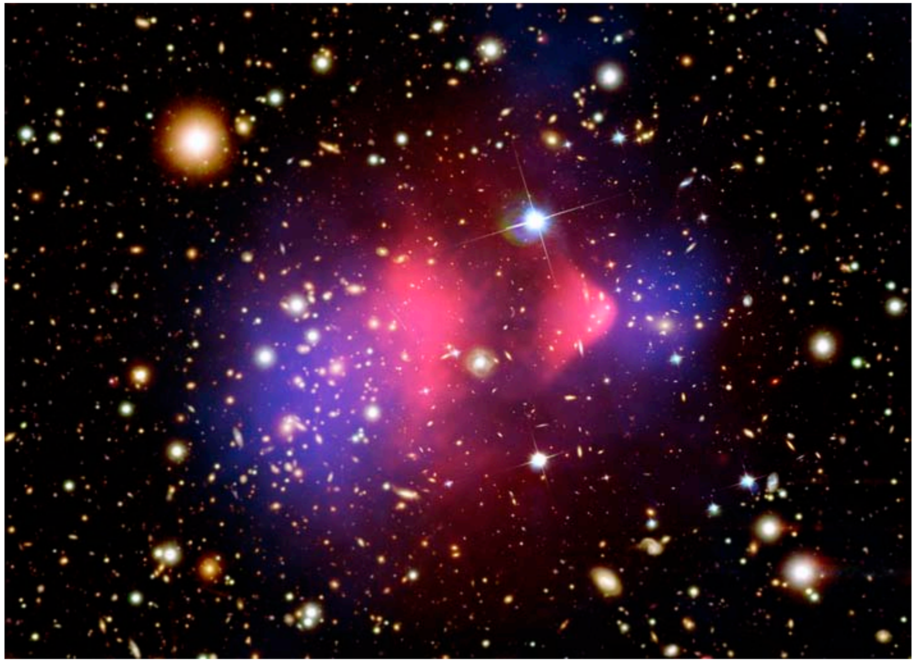


X-ray centroids

Weak lensing mass reconstructions:
subclump
cluster

X-ray centroid of subclump

Centroid of subclump galaxies

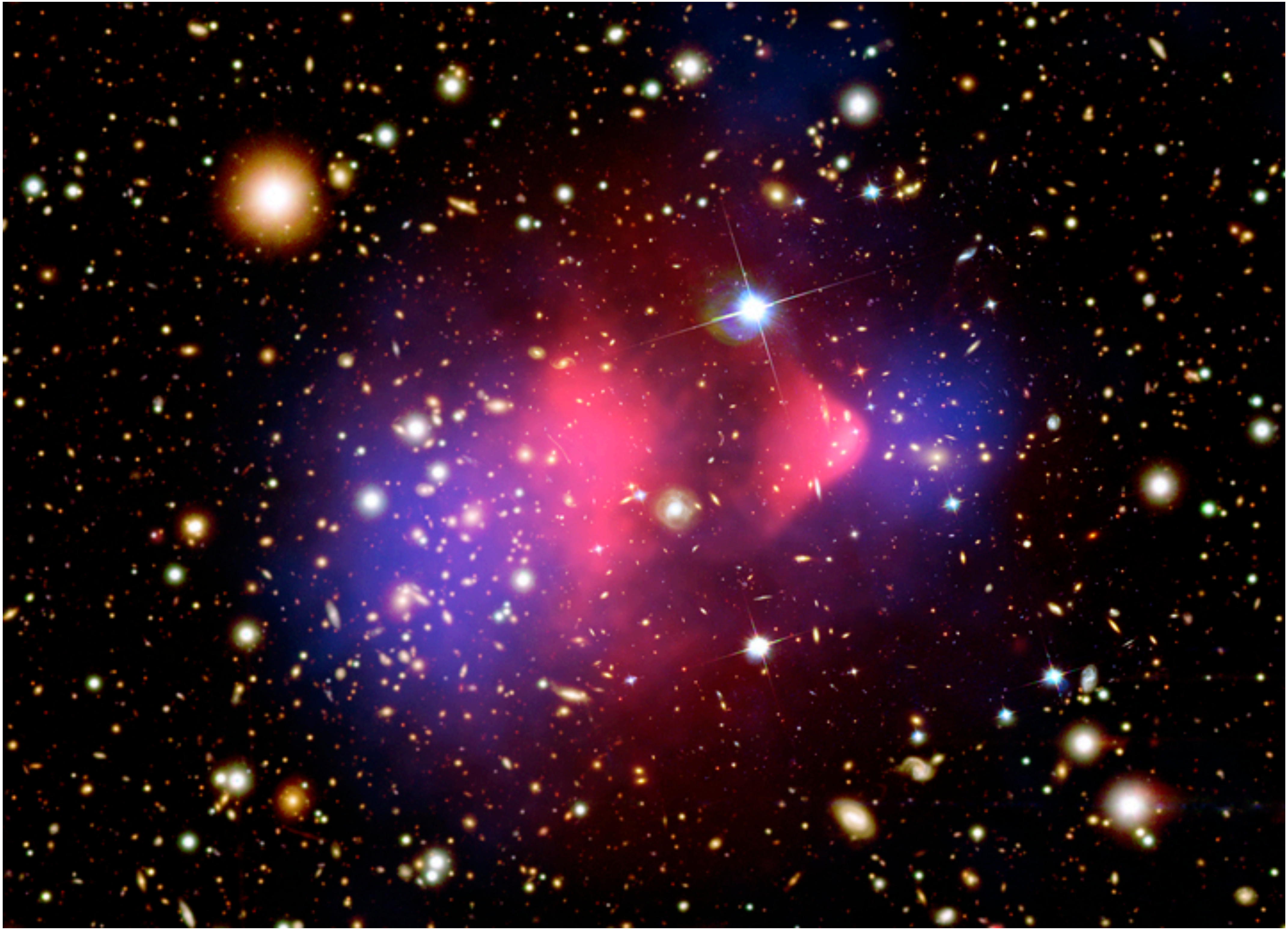


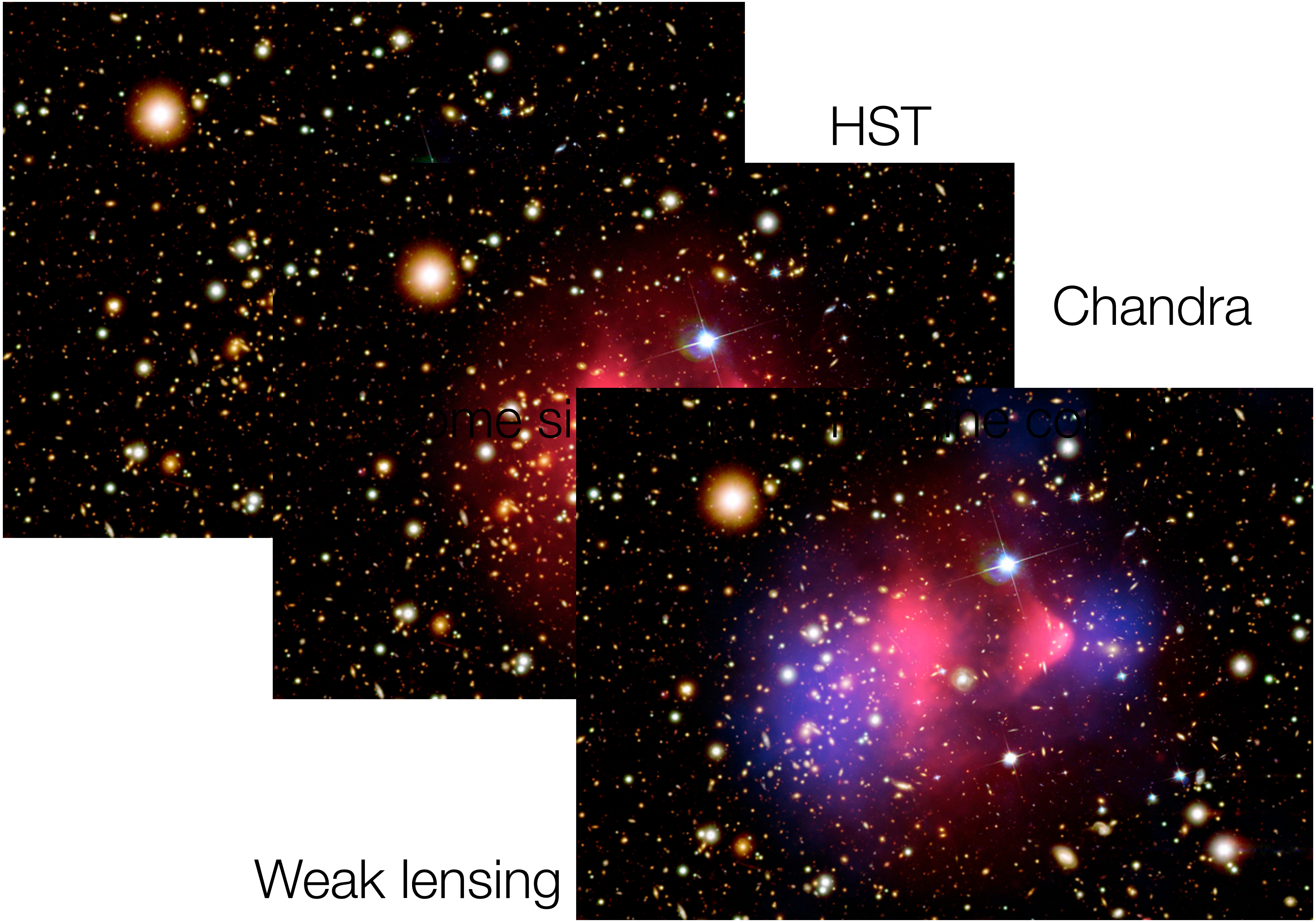
1E 0657-56

This composite image shows the galaxy cluster 1E 0657-56, also known as the "bullet cluster." This cluster was formed after the collision of two large clusters of galaxies, the most energetic event known in the universe since the Big Bang.

Hot gas detected by Chandra in X-rays is seen as two pink clumps in the image and contains most of the "normal," or baryonic, matter in the two clusters. The bullet-shaped clump on the right is the hot gas from one cluster, which passed through the hot gas from the other larger cluster during the collision. An optical image from Magellan and the Hubble Space Telescope shows the galaxies in orange and white. The blue areas in this image show where astronomers find most of the mass in the clusters. The concentration of mass is determined using the effect of so-called gravitational lensing, where light from the distant objects is distorted by intervening matter. Most of the matter in the clusters (blue) is clearly separate from the normal matter (pink), giving direct evidence that nearly all of the matter in the clusters is dark.

The hot gas in each cluster was slowed by a drag force, similar to air resistance, during the collision. In contrast, the dark matter was not slowed by the impact because it does not interact directly with itself or the gas except through gravity. Therefore, during the collision the dark matter clumps from the two clusters moved ahead of the hot gas, producing the separation of the dark and normal matter seen in the image. If hot gas was the most massive component in the clusters, as proposed by alternative theories of gravity, such an effect would not be seen. Instead, this result shows that dark matter is required.





HST

Chandra

Weak lensing

MATERIA OSCURA : dove si trova ?

Generico profilo: $$\rho(r) = \frac{\rho_0}{(r/a)^\gamma[1+(r/a)^\alpha]^{(\beta-\gamma)/\alpha}}$$

r≫ a $$\rho(r) \propto \frac{\rho_0}{x^\beta}$$

r≪ a $$\rho(r) \propto \frac{\rho_0}{x^\gamma}$$

α,β,γ,a
parametri liberi da determinare in base alle osservazioni

Fits to N-body simulations

$$\rho_{\text{Moore}}(r) = \frac{c}{r^{3/2}(a^{3/2}+r^{3/2})};$$

$$\rho_{\text{NFW}}(r) = \frac{c}{r(a+r)^2};$$

Fits to rotation curves

$$\rho_{\text{Burkert}}(r) = \frac{c}{(r+a)(a^2+r^2)};$$

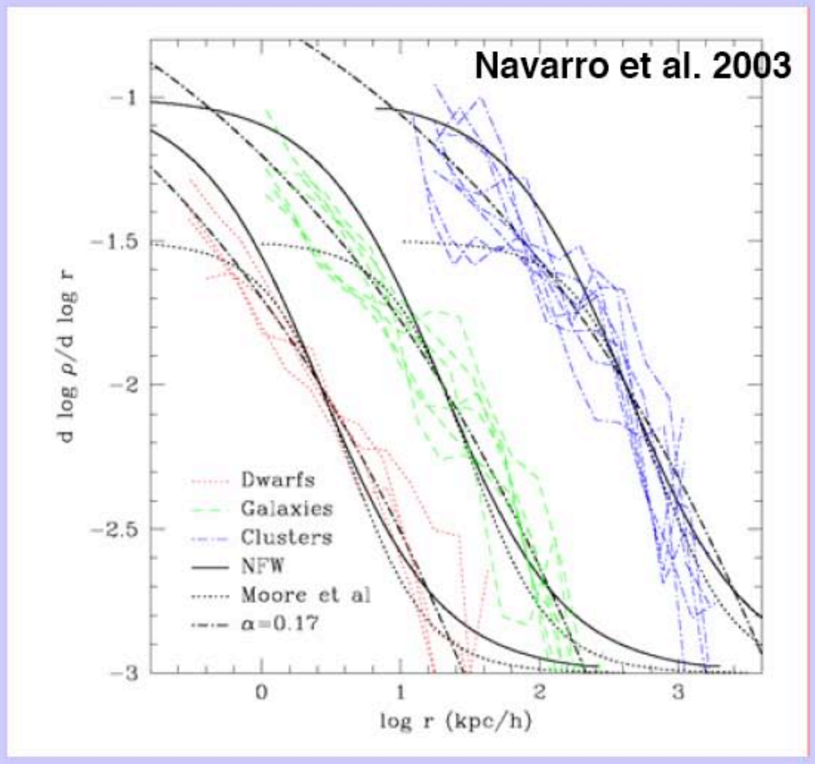
$$\rho_{\text{CIS}}(r) = \frac{c}{a^2+r^2};$$

Fit to lensing (elliptical galaxies)

$$\rho_{\text{SIS}}(r) = \frac{c}{r^2};$$

Berezinsky, Gurevich, Zybin model

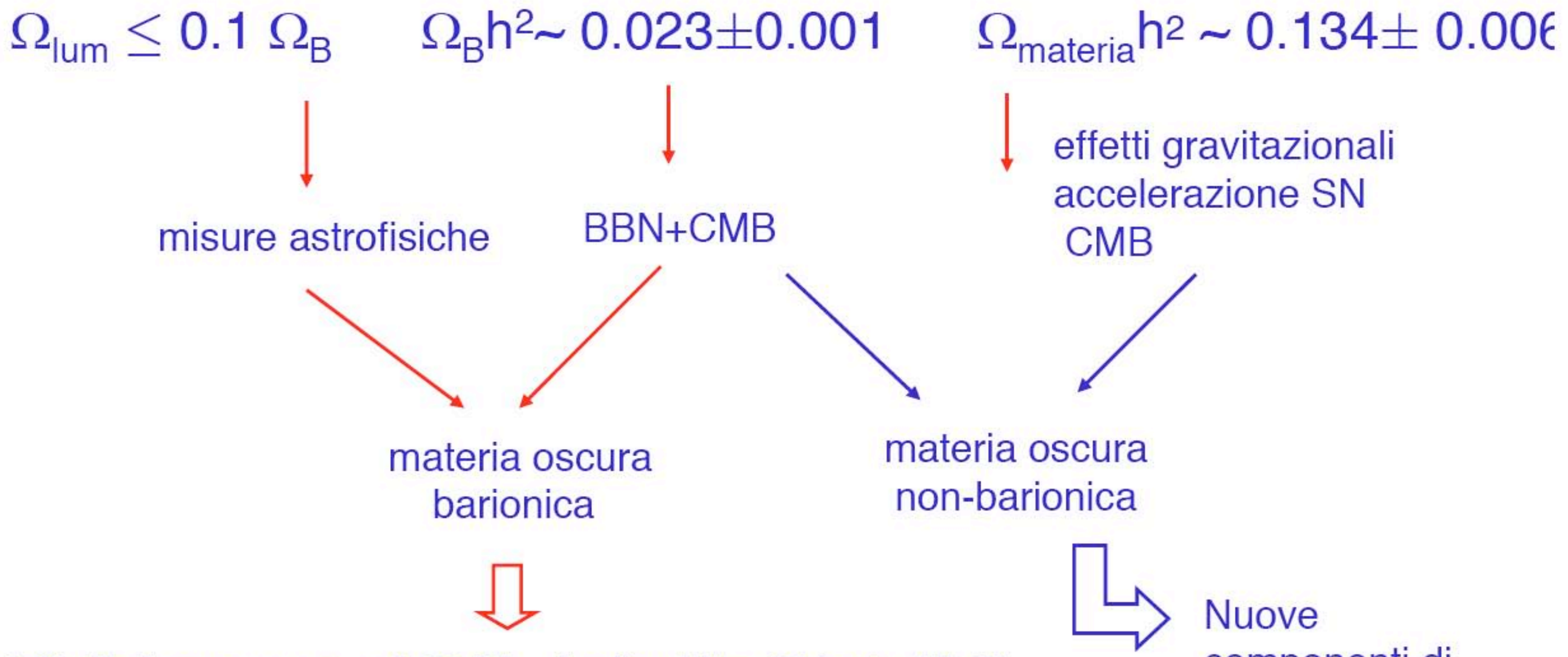
$$\rho_{BGZ}(r) = \frac{c}{r^{1.8}};$$



+ sovradensità locali, deformazioni dovute alla presenza di buchi neri super massicci…

B. Bertucci

MATERIA OSCURA : di cosa è fatta ?



$\Omega_{lum} \leq 0.1\ \Omega_B$ $\Omega_B h^2 \sim 0.023 \pm 0.001$ $\Omega_{materia} h^2 \sim 0.134 \pm 0.00$

misure astrofisiche

BBN+CMB

effetti gravitazionali
accelerazione SN
CMB

materia oscura
barionica

materia oscura
non-barionica

- → Stelle leggere : $m < 0.08\ M_\odot$ Jupiter Like Objects (JLO)
- → MAssive Compact Halo Objects (MACHOs)
- → Resti di stelle
- → Buchi neri
- → Nubi di gas troppo freddo per essere rivelato

Nuove
componenti di
materia !

B. Bertucci

MATERIA OSCURA : i candidati

Identikit:

- ♣ Neutri : - privi di carica elettrica → altrimenti interagirebbero e.m.
  - privi di carica di colore → altrimenti potrebbero formare stati legati nucleari anomali
- ♣ Stabili : altrimenti sarebbero già decaduti
- ♣ Debolmente interagenti con la materia ordinaria
- ♣ Rivelabili (!) : un buon candidato deve essere anche rivelabile

Meccanismo di formazione:

- ♣ Freeze out quando viene raggiunta la condizione di uscita dall'equilibrio :

$$\dot{n} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{EQ}^2)$$

- ►► M.O. CALDA : se relativistici al momento del congelamento.
  mantengono lo spettro termico al disaccoppiamento

- ►► M.O. FREDDA : se non relativistici al momento del disaccoppiamento
  la popolazione viene congelata, e la densità si diluisce con $1/a^3$

Materia Oscura (fredda) & formazione delle strutture

La struttura “discreta” del nostro universo oggi può essere caratterizzata in termini di contrasto di densità : $\delta \rho / \rho \geq 1$ e nasce a partire da perturbazioni iniziali $\delta \rho/\rho \sim O(10^{-5})$.

Il contrasto di densità può crescere effettivamente solo nell’epoca della materia: $\delta \rho/\rho \propto a \propto 1/z$

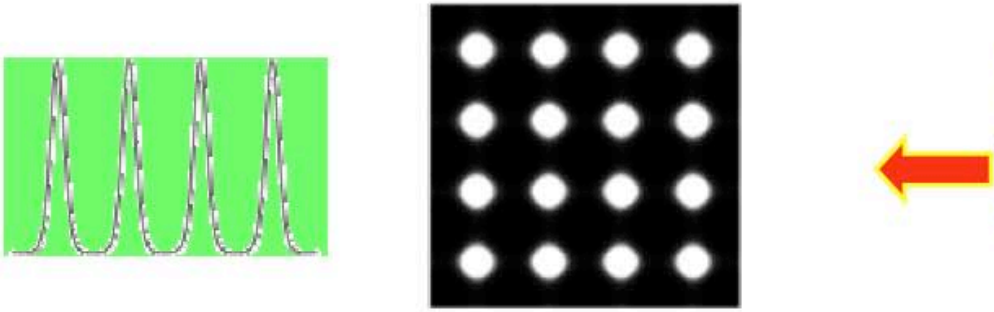
e solo quando essa si sia disaccoppiata dalla radiazione

La materia barionica può realmente iniziare ad addensarsi solo dopo la ricombinazione, le perturbazioni di densità della materia barionica si riflettono in perturbazioni dello stesso ordine nella distribuzione termica della radiazione

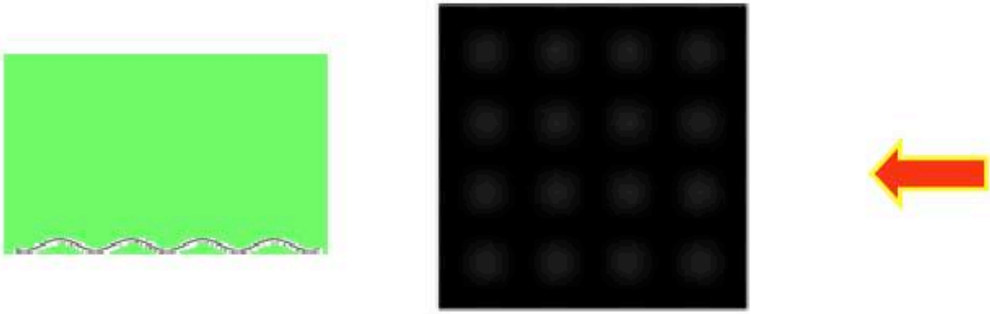
$$@\ z \sim 1000\ \delta \rho_B/\rho_B \sim 10^{-5} \Longrightarrow @\ z \sim 0\quad \delta \rho_B/\rho_B \sim 10^{-2}$$

→ Evolvendo il contrasto di densità barionica dalla ricombinazione ad oggi non possiamo giustificare l’attuale struttura del nostro universo

Il contrasto di densità deve iniziare a crescere PRIMA della ricombinazione.



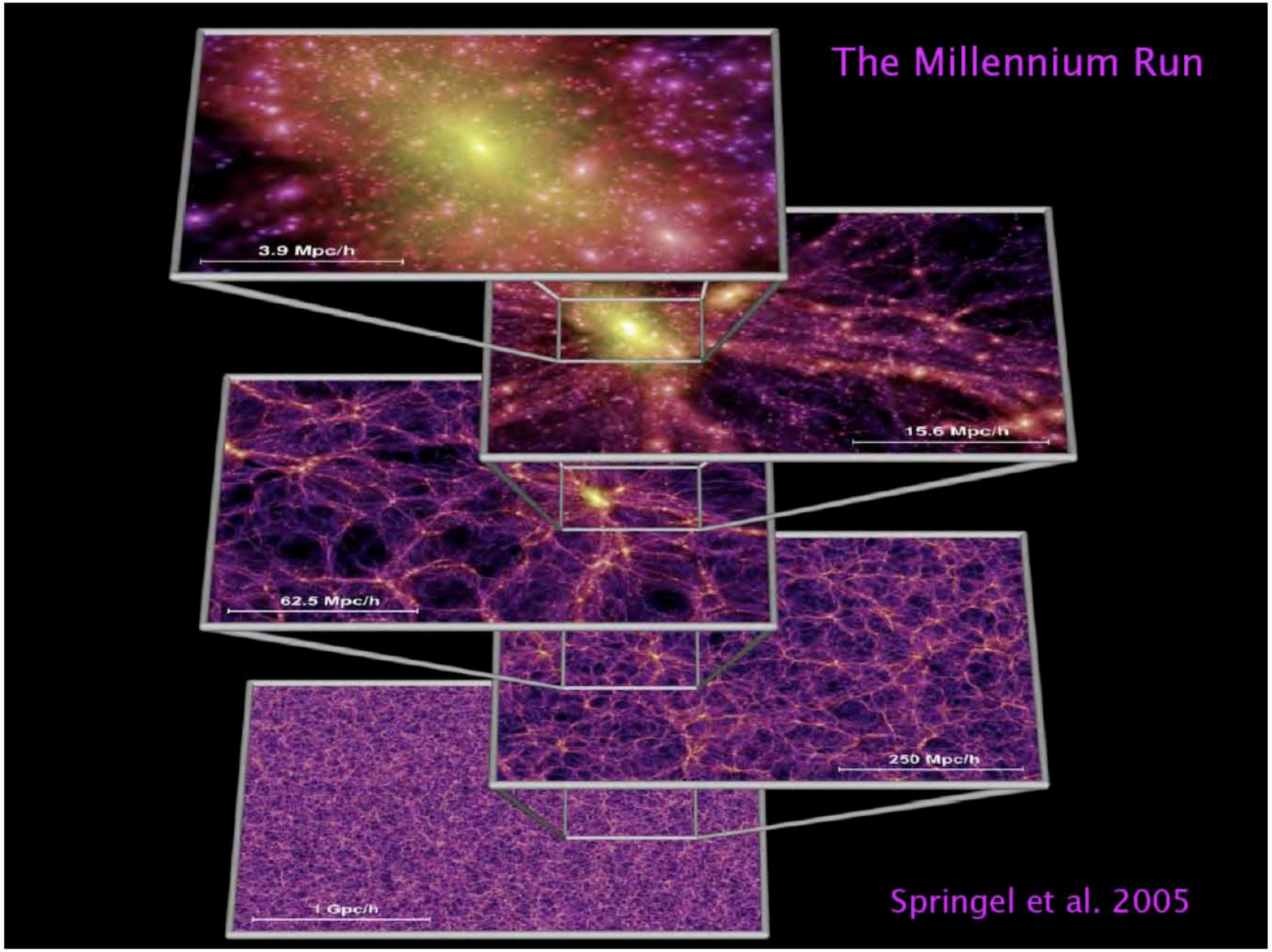
M.O. Fredda aumenta il contrasto di densità delle perturbazioni iniziali



M.O. calda (i.e. ν) tende a diminuire il contrasto iniziale ($v^2 >> 10^{-5}$).

I processi di formazione di strutture a larga scala richiedono la **materia oscura fredda**

Structure formation



Formation of the large-scale structure in the Universe: filaments

For example, here is a simulation running forward in time which shows how particles collect and enhance small initially small wrinkles

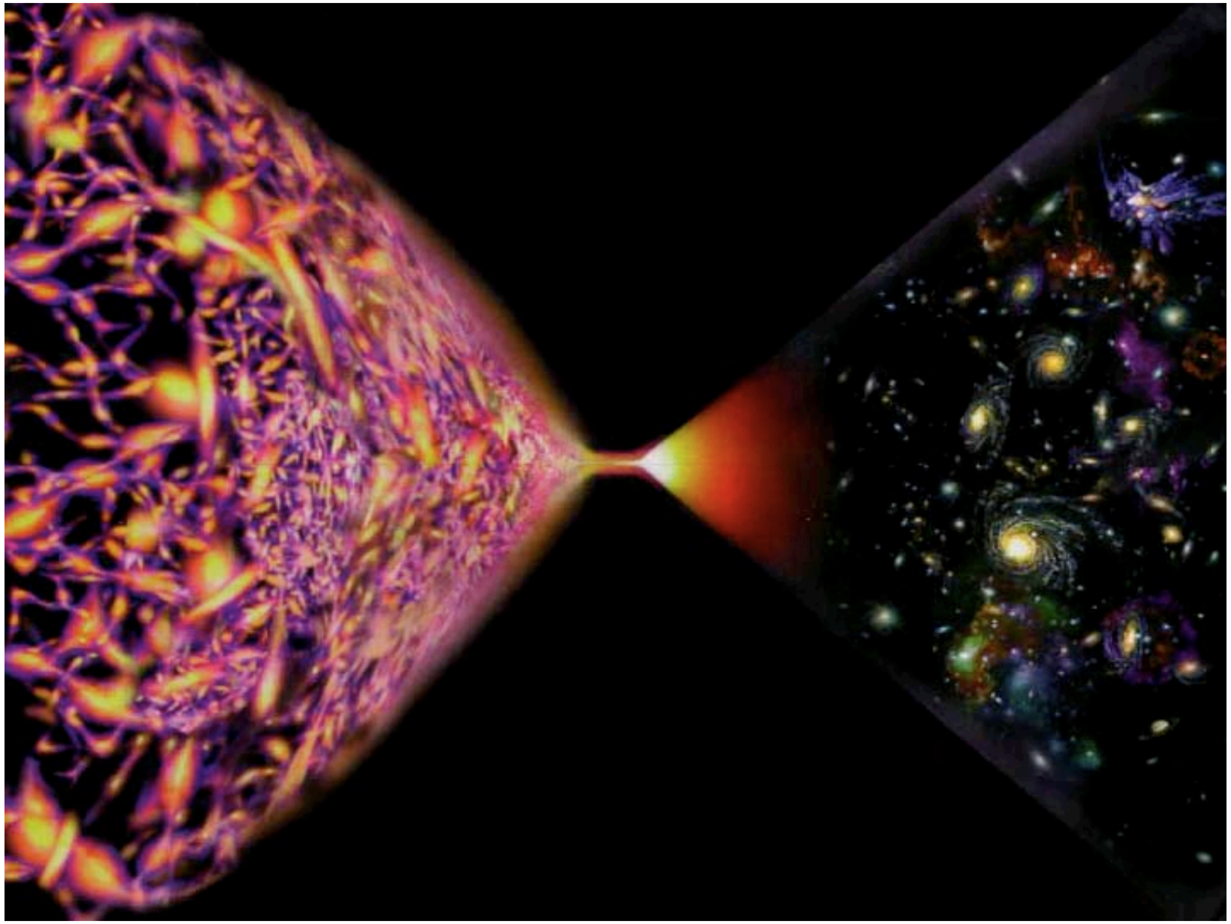
(simulation and movie courtesy of Andrey Kravtsov)

Non baryonic dark matter: WIMPs

- Cold thermal relics from the early Universe are perfect candidates for DM, explaining the LSS

- To account for Ω_M masses should be O(0.1-1 TeV) and cross-sections at the electroweak scale:

Weekly Interacting Massive Particles



Cold Thermal Relics and the Weak Scale

- if a **massive, weakly interacting particle** (WIMP) existed in the early Universe

$$\chi + \bar{\chi} \leftrightarrow X + \bar{X}$$

- it was in equilibrium as long as the **reaction rate** was larger than the **expansion rate**

$$\Gamma \gg H$$

- after Γ drops below H ⇒ "freeze-out", we are left with a **relic density**

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3\times 10^{-27} cm^3 s^{-1}}{\langle \sigma_A \mathrm{v} \rangle}$$

$$\Omega_\chi \sim 0.2 \Rightarrow \langle \sigma_A v \rangle \sim 1 \text{ pb}$$

$$\sigma_\mathrm{A} \sim \frac{\alpha^2}{m^2} \Rightarrow m \sim 100 \text{ GeV}$$

⇒ the relic density and mass point to the **weak scale**
⇒ the new physics responsible for EWSB likely gives rise to a **dark matter candidate**
⇒ examples: LSP (neutralino), LKP (KK-partner of photon, or KK-partner of Z-boson)

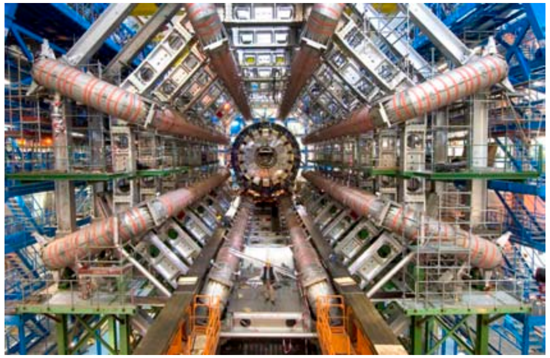
WIMP detection

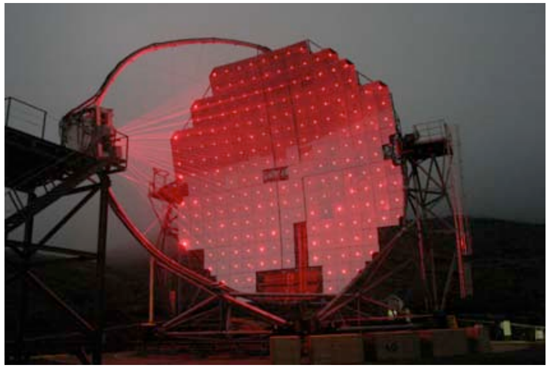
- Huge worldwide effort, complementary methods

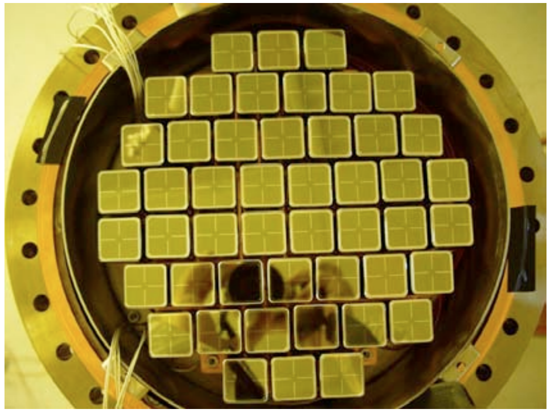
  1. artificially produce SUSY particles at colliders

  2. indirect searches through detection of neutralino annihilation products in astrophysical objects

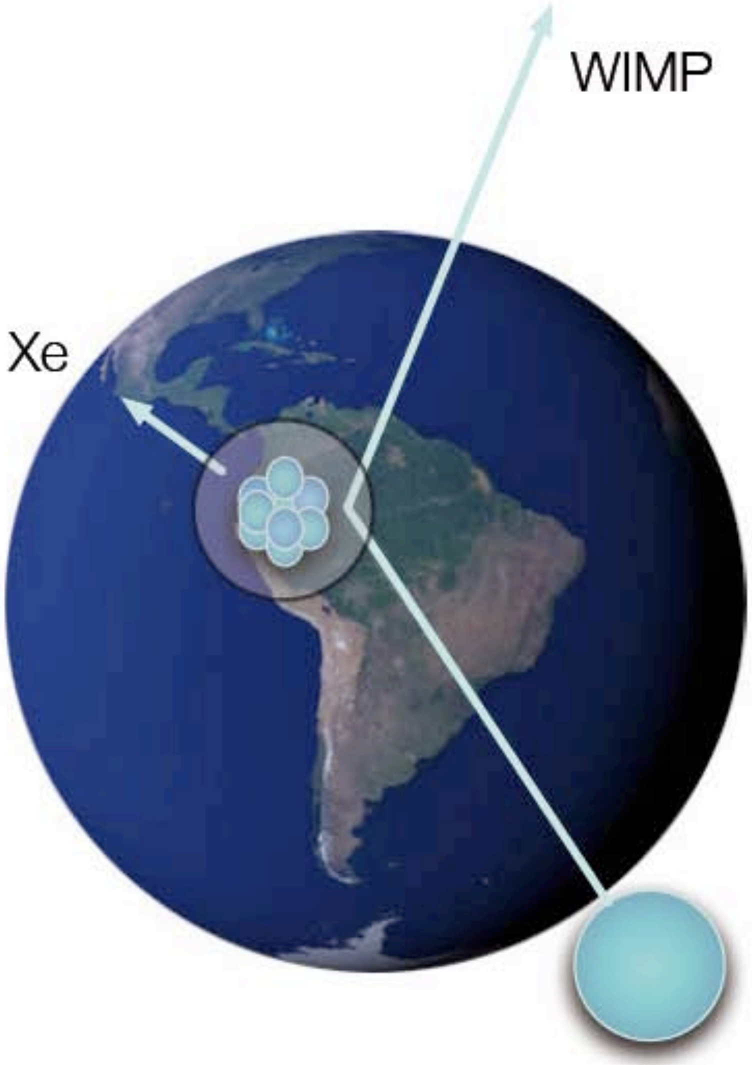
  3. direct searches in underground laboratories







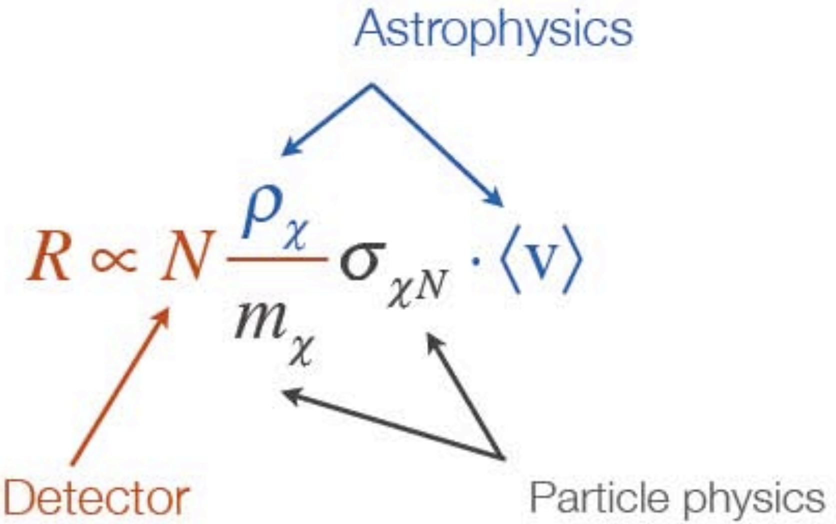
Strategy for WIMP Direct Detection



- Elastic collisions with atomic nuclei
- The recoil energy is:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \leq 50\ keV$$

- and the expected rate:



Astrophysics

$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$$

Detector

Particle physics

Expected Scattering Cross Sections

- A general WIMP candidate: fermion (Dirac or Majorana), boson or scalar particle
- The most general, Lorentz invariant Lagrangian has 4 types of interactions (S, P, V, A)
- In the extreme NR limit relevant for galactic WIMPs ($v_{WIMP} \sim 10^{-3}c$), the interactions leading to WIMP-nuclei elastic scattering are classified as:

➡ **scalar interactions** (WIMPs couples to nuclear mass; from the scalar and vector part of L)

$$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2}\left[Zf_p + (A-Z)f_n\right]^2$$

$f_{p,n}$ = effective couplings to p, n

➡ **spin-spin interactions** (WIMPs couples to nuclear spin J_N, from the axial part of L)

$$\sigma_{SD} = \frac{32}{\pi}G_F^2\frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2}\frac{J_N+1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

$\langle S_{p,n}\rangle$ = expectation values of the spin content of the p, n in the target nucleus

large hadronic uncertainties in the cross section
J. Ellis, K.A. Olive, C. Savage, arXiv:0801.3656v2

$a_{p,n}$ = effective couplings to p, n

Expected Interaction Rates

- Integrate over WIMP velocity distribution; in general assumed to be a simple 1D Maxwellian (good approximation for isothermal halo with ideal WIMP gas):

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2 m_\chi \mu^2} F^2(E_R) \int_{\mathrm{v} > \sqrt{m_N E_R / 2\mu^2}}^{\mathrm{v}_{\max}} \frac{f(\vec{\mathrm{v}},\mathrm{t})}{\mathrm{v}} d^3\mathrm{v}$$

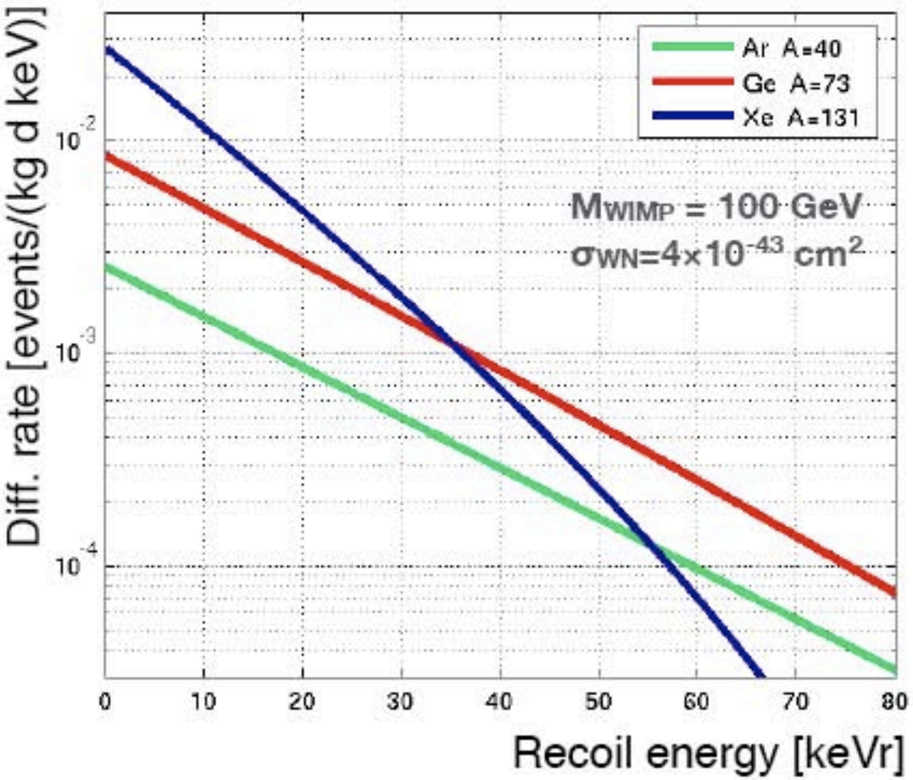
$$f(\vec{\mathrm{v}},\mathrm{t}) \propto \exp\left\{ \frac{-(\vec{\mathrm{v}} + \vec{\mathrm{v}}_E(t))^2}{2\sigma^2} \right\}$$

$$F^2(E_R) = \left[\frac{3 j_1(qR_1)}{qR_1} \right]^2 \mathrm{e}^{-(qs)^2}$$

- with WIMP-nucleon cross sections $< 10^{-7}$ pb, the expected rates are

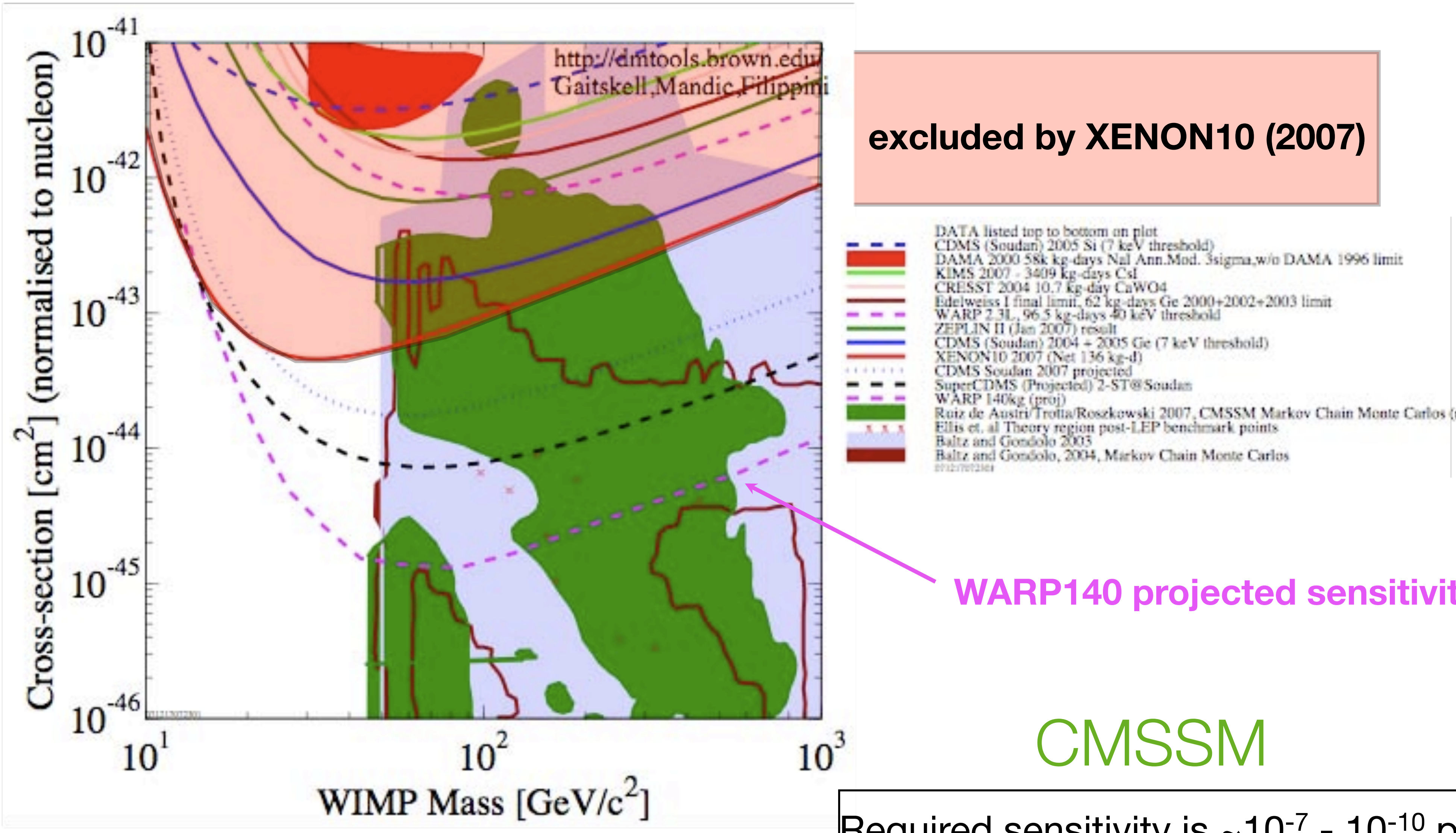
< 1 event/100kg/day

Differential rates for different targets (SHM)



L. Baudis

SUSY predictions for elastic scattering cross section



excluded by XENON10 (2007)

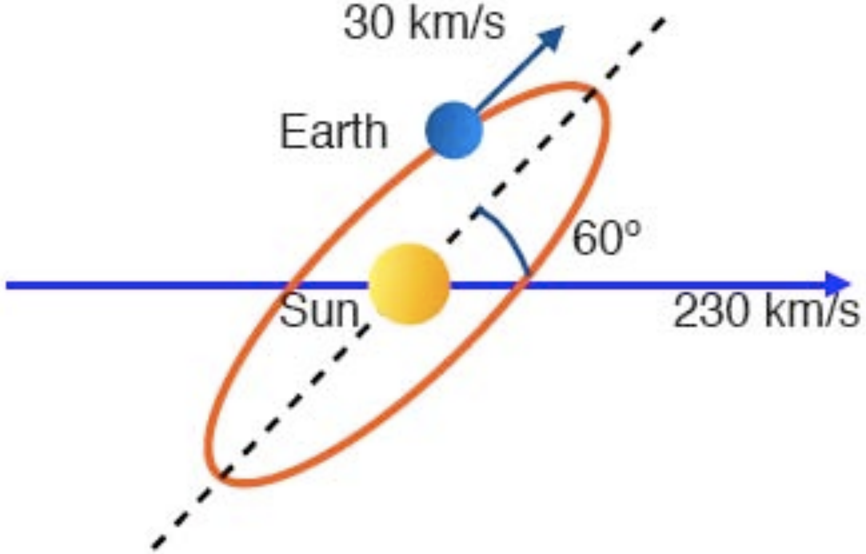
WARP140 projected sensitivity

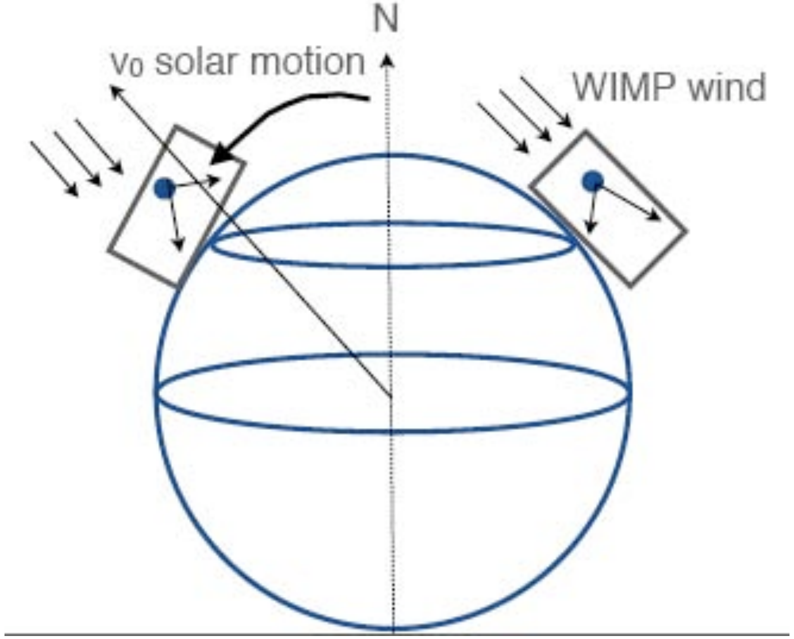
CMSSM

Required sensitivity is ~10^{-7} - 10^{-10} pb

Expected WIMP Signatures

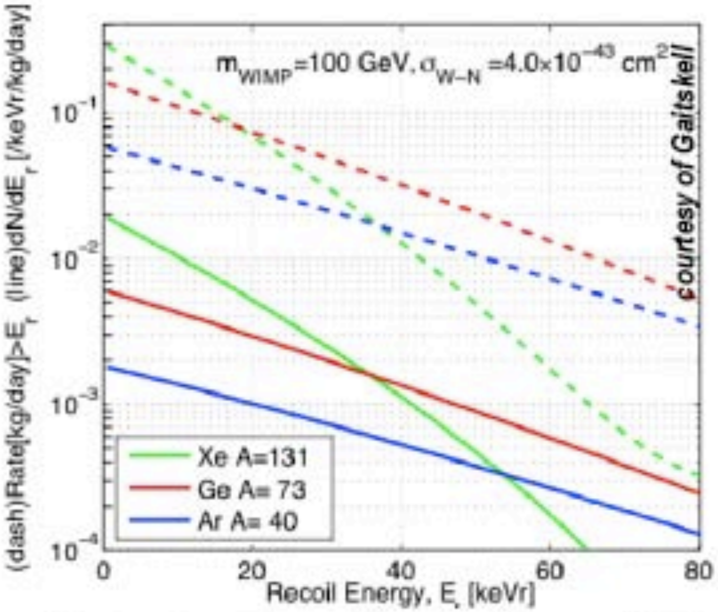
- **WIMP interactions in detector should be:**
  - nuclear recoils
  - single scatters, uniform throughout detector volume
- **Spectral shape** (exponential, however similar to background)
- **Dependance on material** (A^2, $F^2(Q)$, test consistency between different targets)
- **Annual flux modulation** (~ 3% effect, most events close to threshold)
- **Diurnal direction modulation** (larger effect, requires low-pressure gas target)



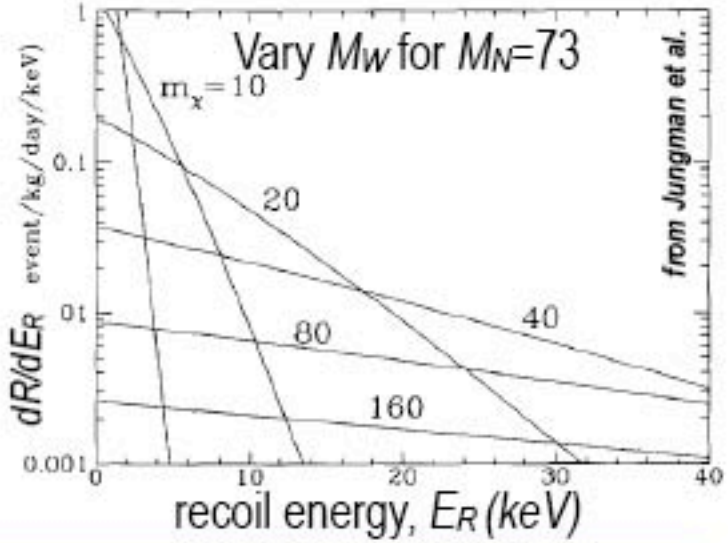


signal characteristics

- ***A^2* dependence**
  - coherence loss
  - relative rates
- ***M_W* relative to *M_N***
  - large *M_W* - lose mass sensitivity
  - if ~100 GeV
- **Present limits on rate**
- **Following a detection (!), many cross checks possible**
  - *A^2* (or *J*, if SD coupling)
  - WIMP mass if not too heavy
    - different targets
    - accelerator measurements
  - galactic origin
    - annual
    - diurnal/directional - WIMP astronomy



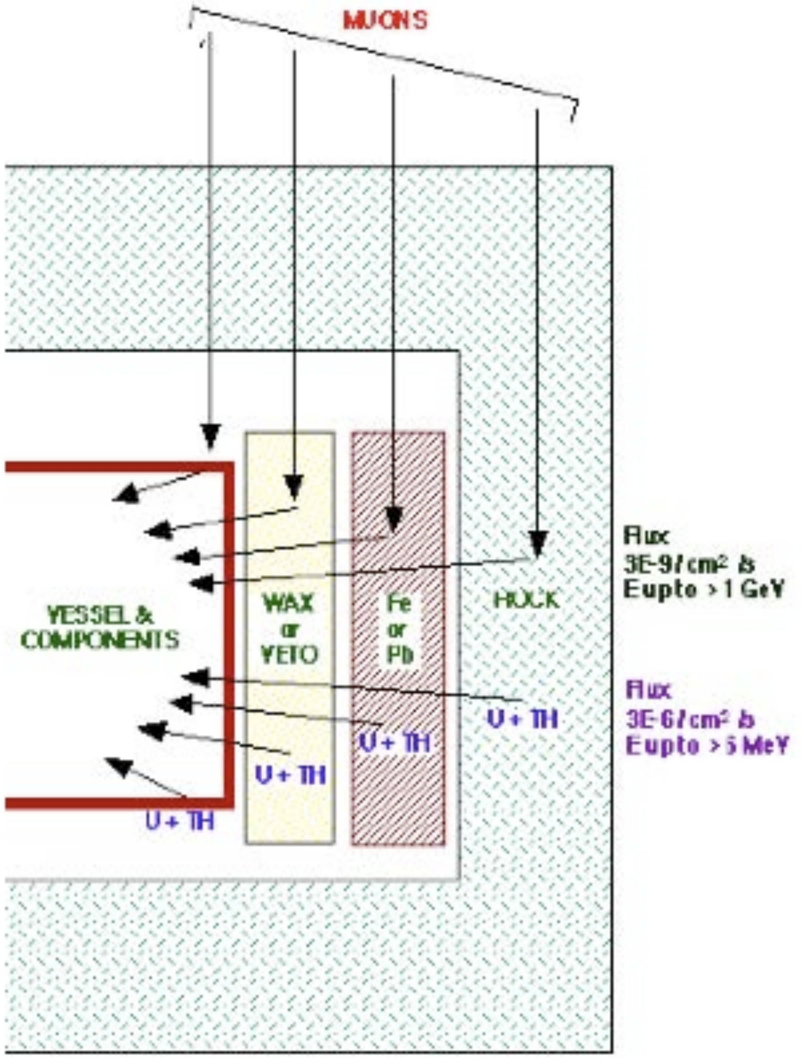
courtesy of Gaitskell



from Jungman et al.

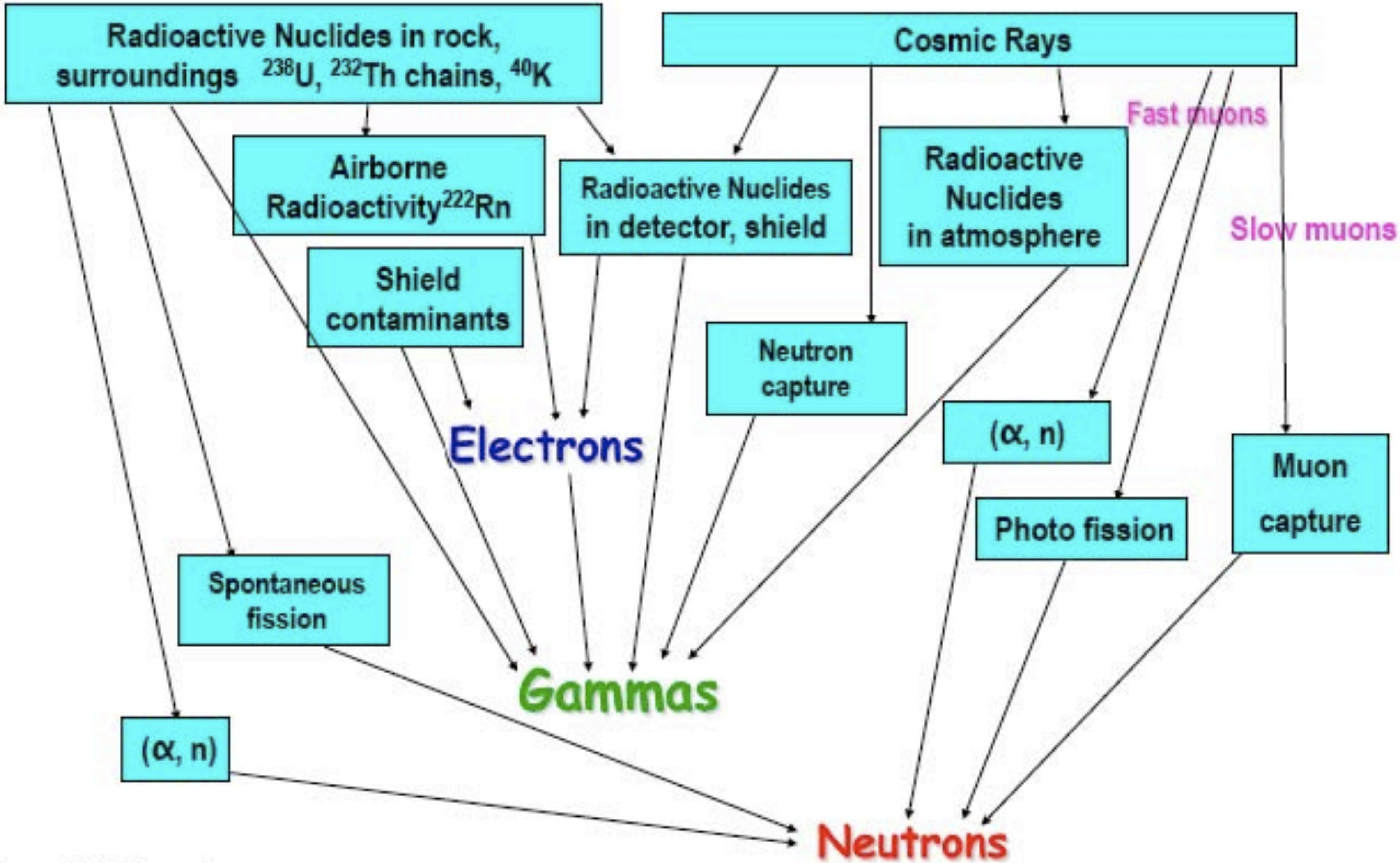
Experimental challenges

- To increase sensitivity over lower regions of parameter space:
  - small event rate and small deposited energy
- Large scale detectors
  - target masses of ton scale to provide count rate
- Low (keV) energy threshold for nuclear recoils
- Low background, especially neutrons, from natural radioactivity and cosmic rays
  - intrinsic activity from detector
  - external activity from surroundings
  - μ spallation
- Good background rejection
  - (α), β, γ rejection
  - control/rejection of surface events
  - position sensitivity, segmentation, fiducialisation / self shielding



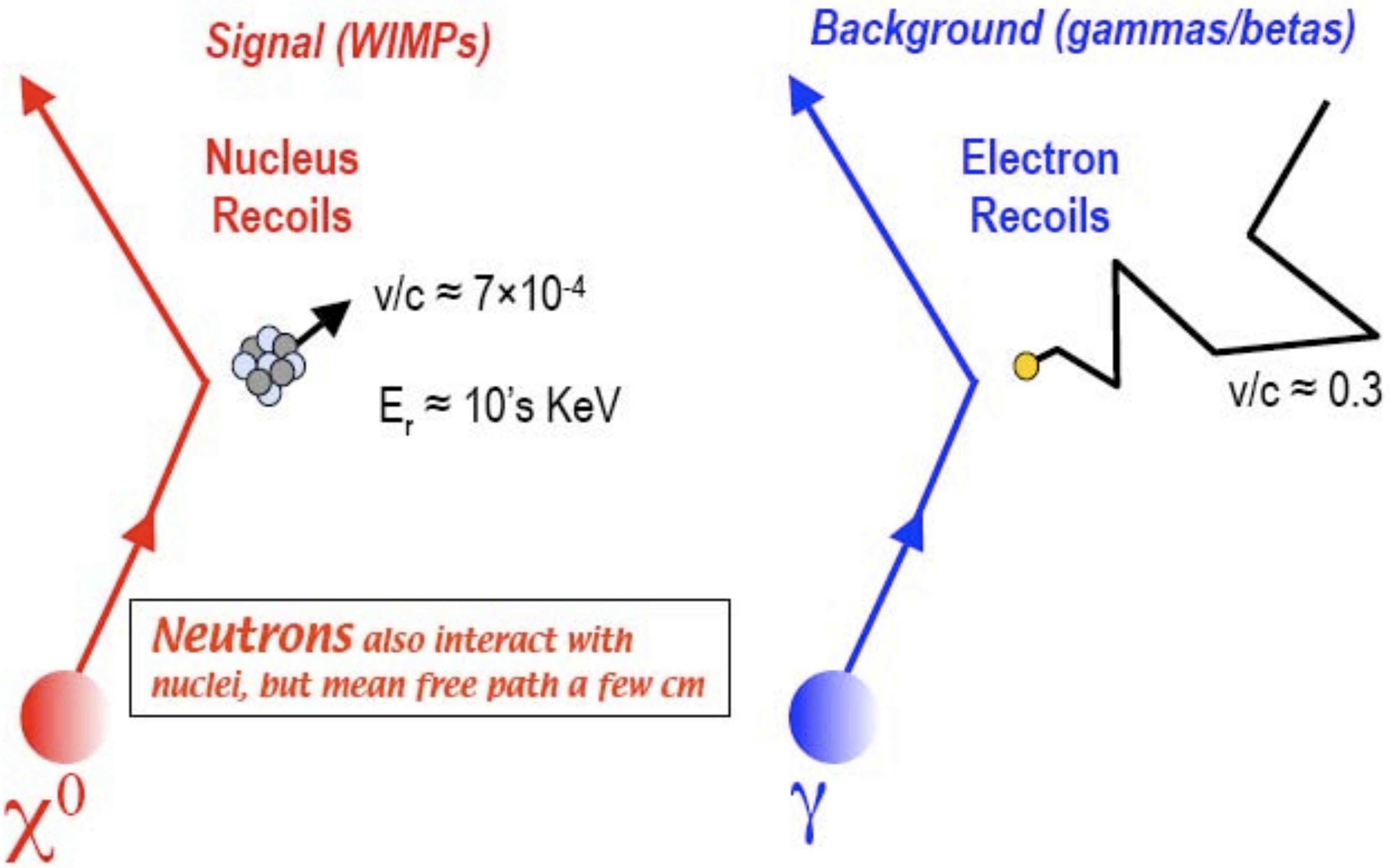
Backgrounds: cosmic rays and natural radioactivity

WIMP scatters (< 1 evts /10 kg/ day) swamped by backgrounds (> 10^{6-7} evts/kg-d)



courtesy of S. Kamat

The Signal and Backgrounds



Signal (WIMPs)

Nucleus Recoils

$v/c \approx 7\times10^{-4}$

$E_r \approx$ 10's KeV

***Neutrons** also interact with nuclei, but mean free path a few cm*

χ^0

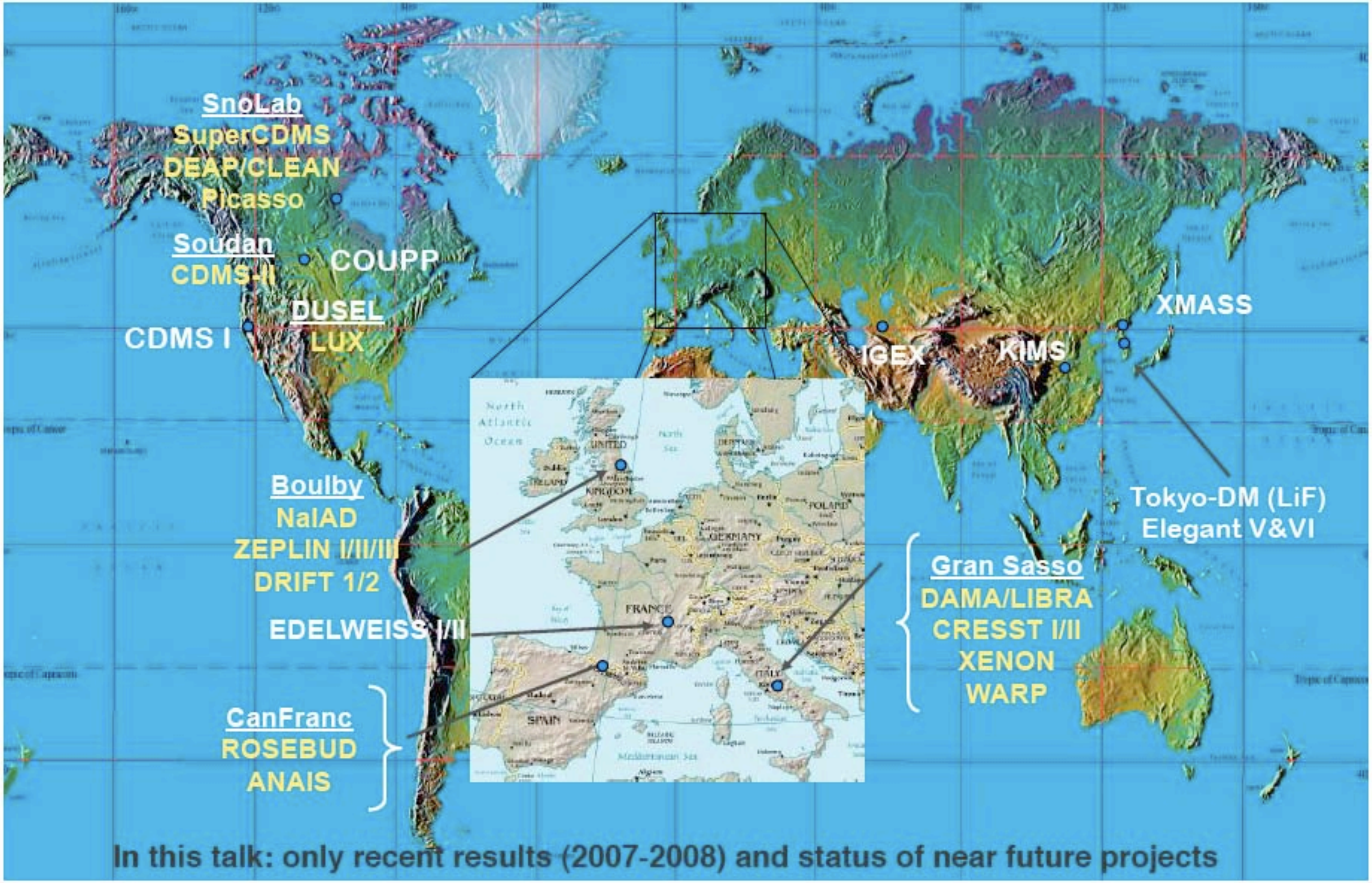
Background (gammas/betas)

Electron Recoils

$v/c \approx 0.3$

γ

World wide WIMP search



In this talk: only recent results (2007-2008) and status of near future projects

Single channel techniques

Ionisation Detectors

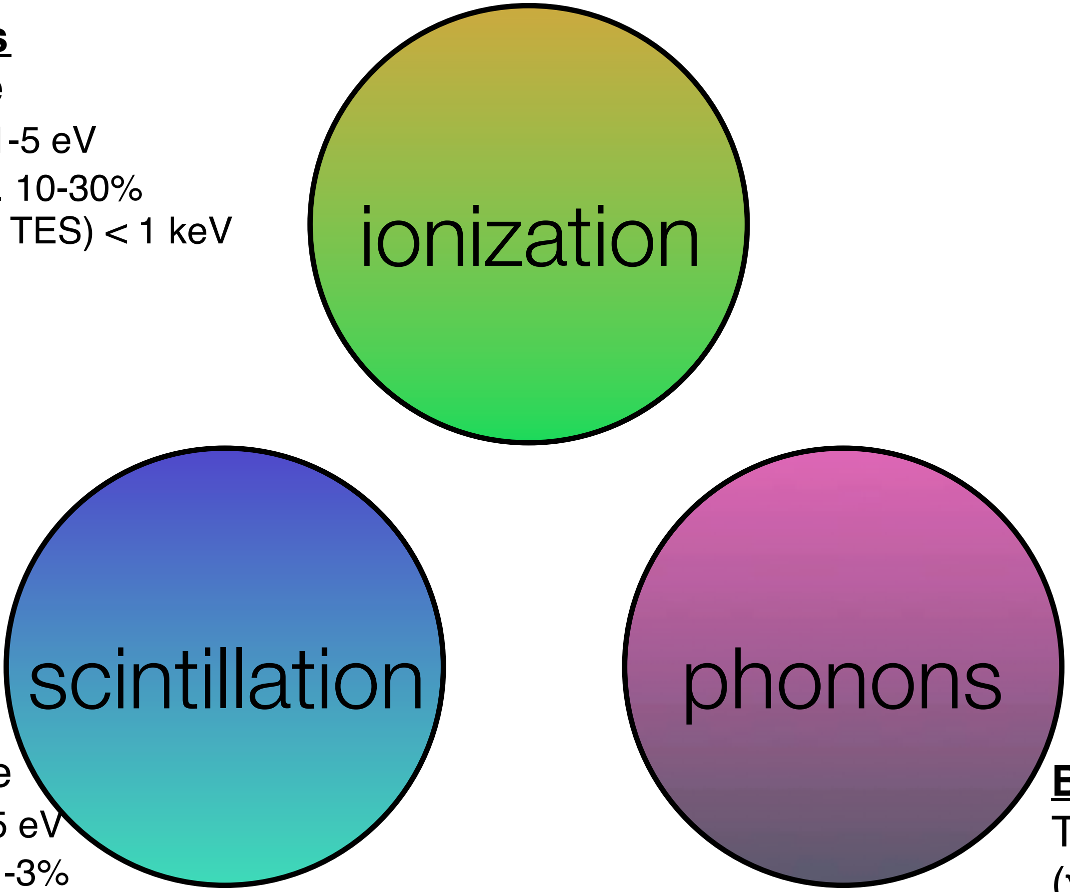
Targets: Ge, Si, CdTe

(γ) Energy per e/h pair 1-5 eV

NR energy collection eff. 10-30%

Sensitivity (HEMT JFET, TES) < 1 keV

IGEX (4 keV), HDMS,
GENIUS (3.5 keV)



Scintillators

Targets: NaI, Xe, Ar, Ne

(γ) Energy per photon ~15 eV

NR energy collection eff. 1-3%

Light gain 2-8 phe/keV

Sensitivity (PMTs) ~1 keV

ZEPLIN I (2 keV), NAIAD (4 keV)

DAMA (2 keV), DEAP, CLEAN, XMASS (5 keV)

Bolometers

Targets: Ge, Si, Al2O3, TeO2

(γ) Energy per phonon ~meV

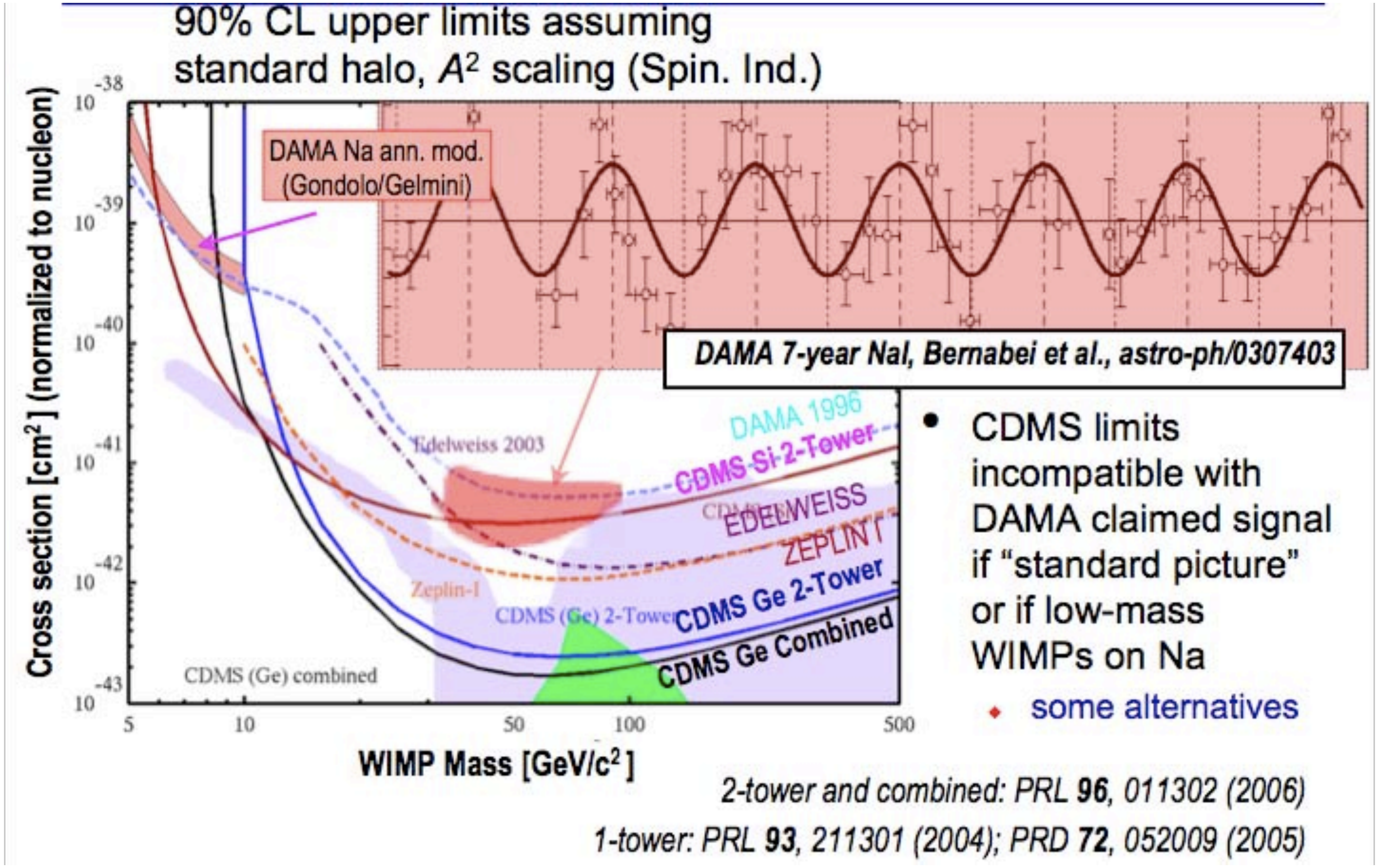
NR energy col. eff. (th.) ~100%

Sensitivity (TES) << 1 keV

(FWHM 4.5 eV @ 6 keV x-rays)

CRESST-I (0.6 keV),
CUORICINO, CUORE (5 keV)

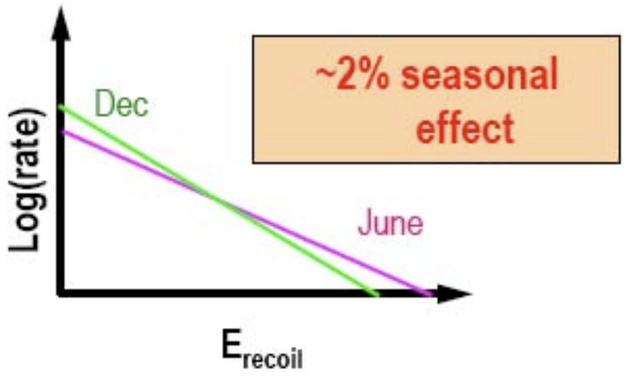
DAMA/NaI: annual modulation



- CDMS limits incompatible with DAMA claimed signal if "standard picture" or if low-mass WIMPs on Na
  - some alternatives

2-tower and combined: PRL ***96****, 011302 (2006)*

1-tower: PRL ***93****, 211301 (2004); PRD* ***72****, 052009 (2005)*

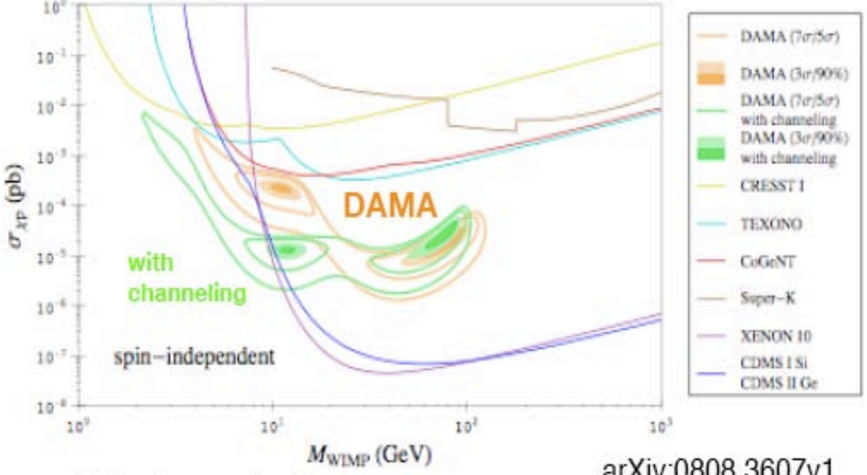


~2% seasonal effect

- 100 kg detector mass
  - measure energy for each event but no rejection of gamma background
- LIBRA: 250 kg operating since 2003

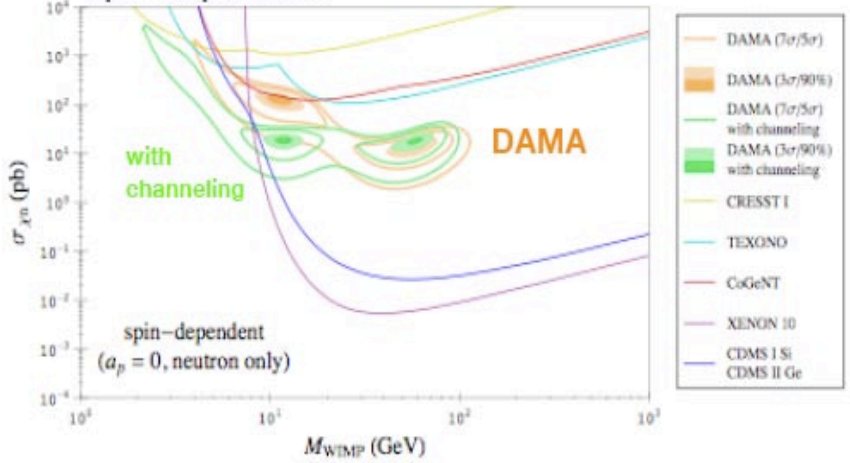
DAMA/LIBRA 2008

- 25 NaI detectors, 4 yrs of data taking: 192 x 10^3 kg days
- Modulation of event ate confirmed



Spin-independent

arXiv:0808.3607v1

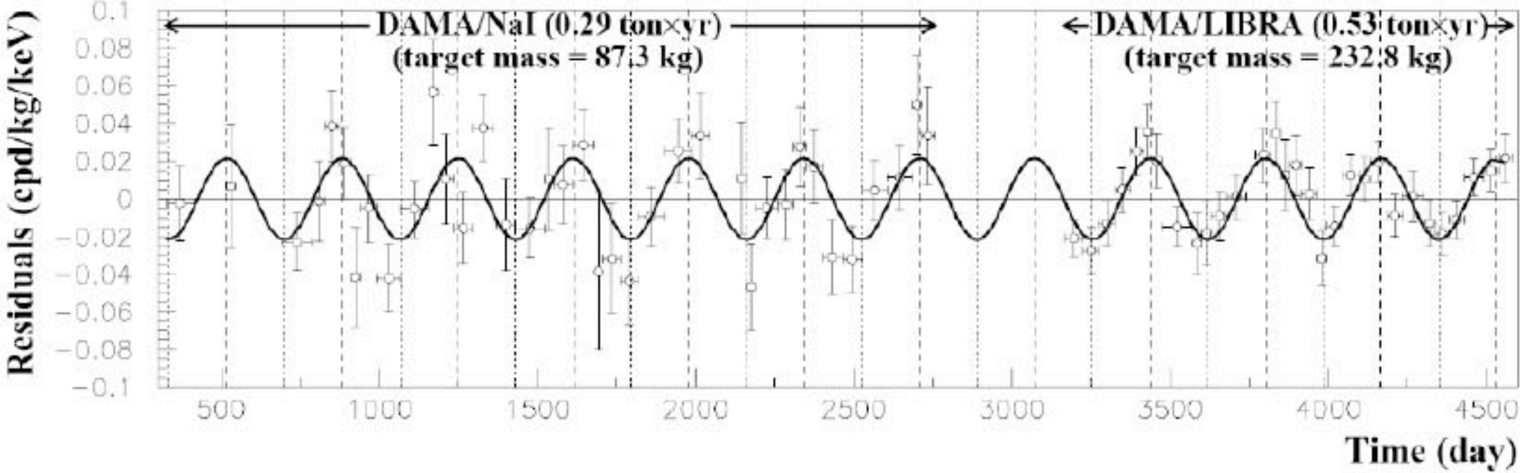


Spin-dependent

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t-t_0)$$

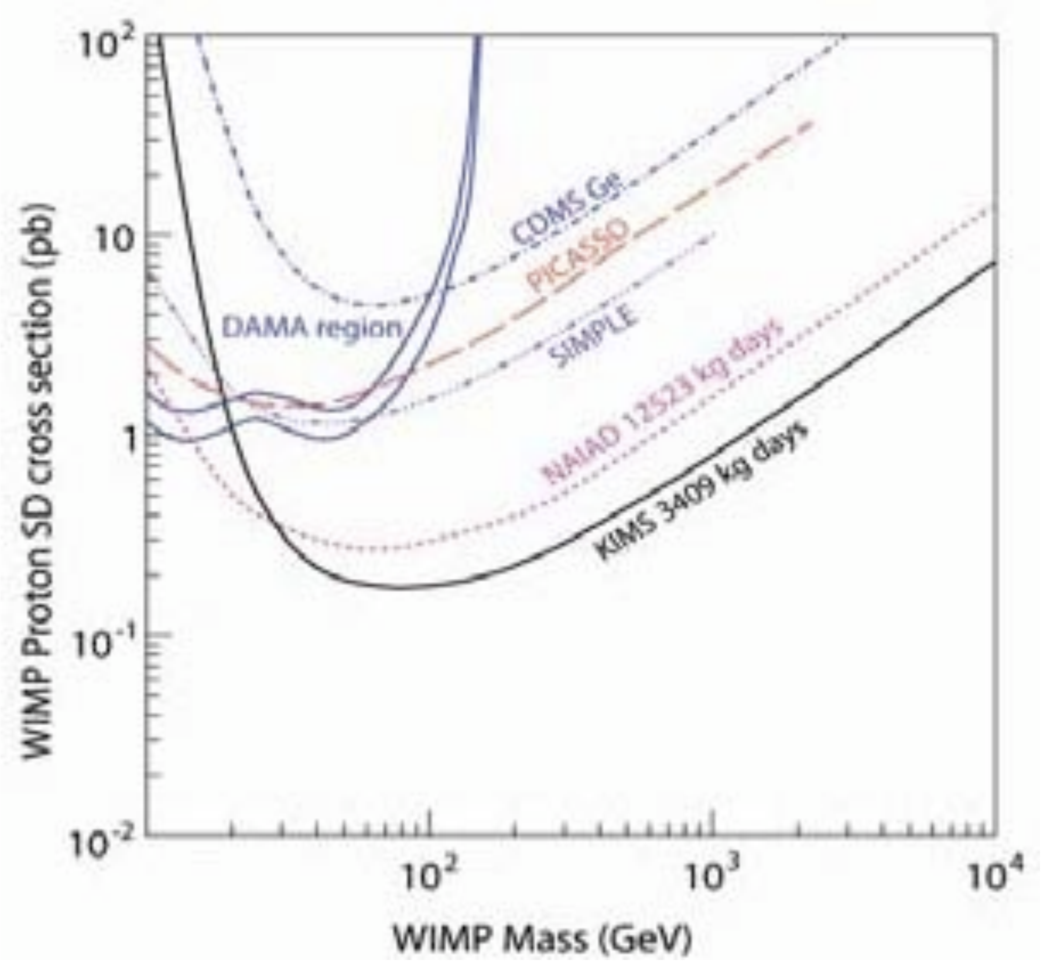
S_m = (0.0215 ± 0.0026) counts/(day kg keV)

residuals from average rate **2-4 keV**



KIMS/CsI(Tl)

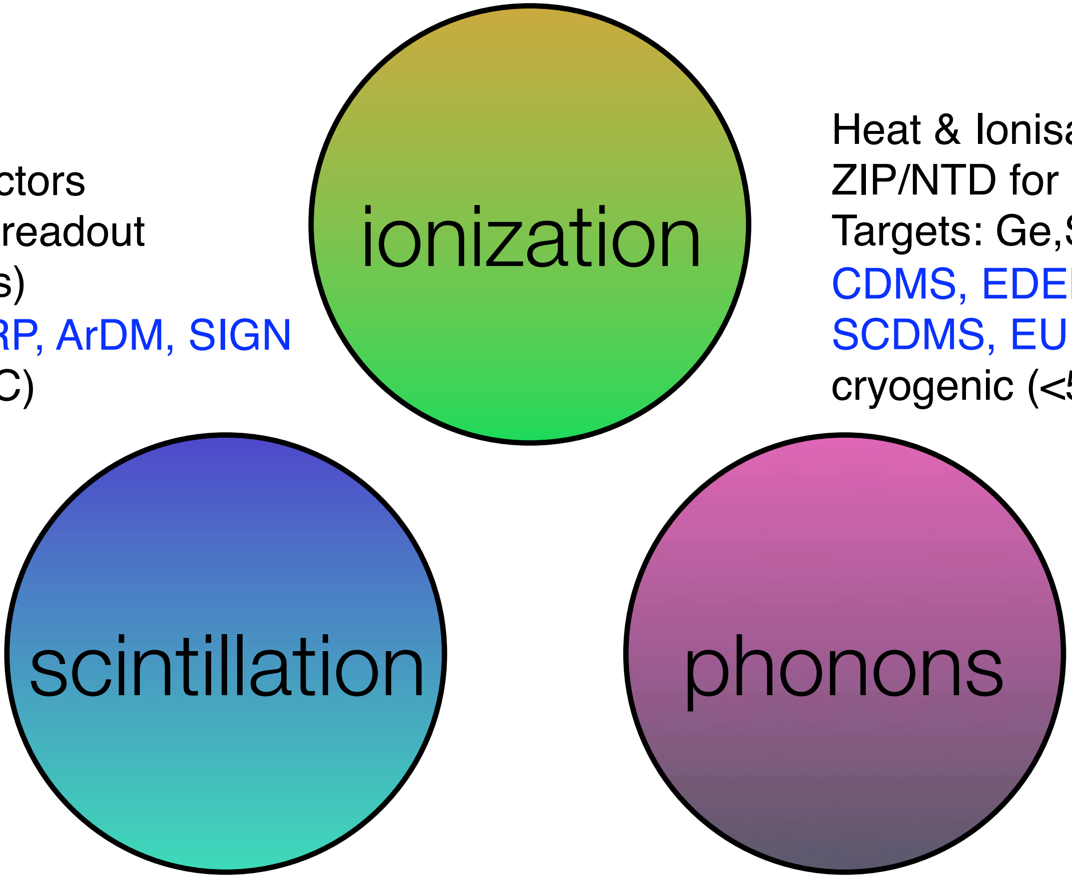
- **Similar to DAMA but CsI**
- **Success in reducing intrinsic radiocontaminants**
  - ^{137}Cs - water purity during prep
  - ^{87}Rb - reduced through repeated re-crystalization
- **New results from 35 kg**
  - 4 x 8.7 kg crystals
  - 3409 kg-days
- **Building 100 kg array**
  - target of 2 cts/(keV kg day)
- **Cross check of DAMA**
  - Iodine couplings
  - annual modulation



S K Kim *et al* PRL 99, 091301 (2007)

Hybrid techniques: nuclear recoil discrimination

- All hybrid techniques have >99% nuclear recoil discrimination at 10keV NR

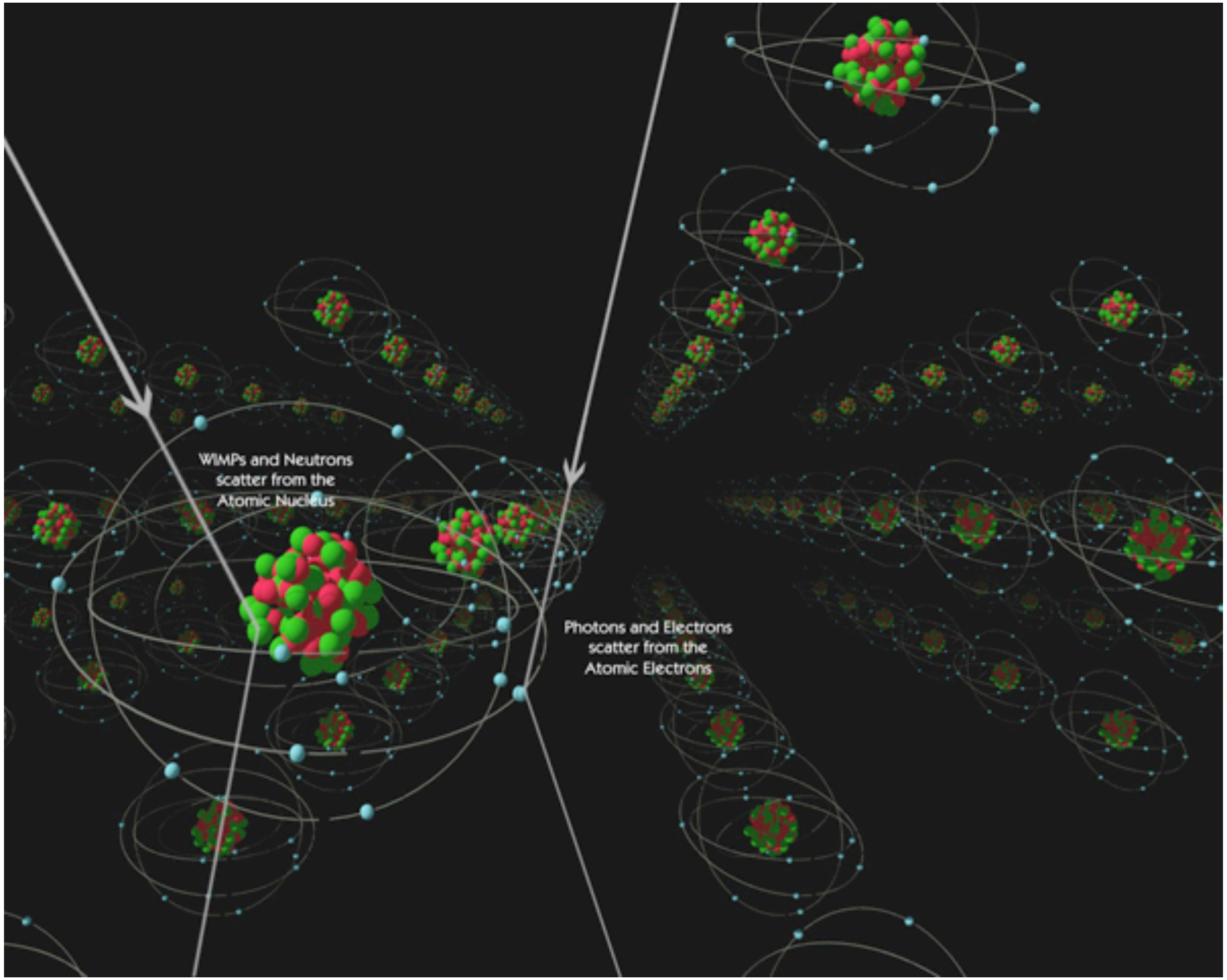


Light & Ionisation Detectors
PMTs for both channel readout
Targets: L(Noble Gases)
ZEPLIN, XENON, WARP, ArDM, SIGN
mildly cryogenic (-100 C)

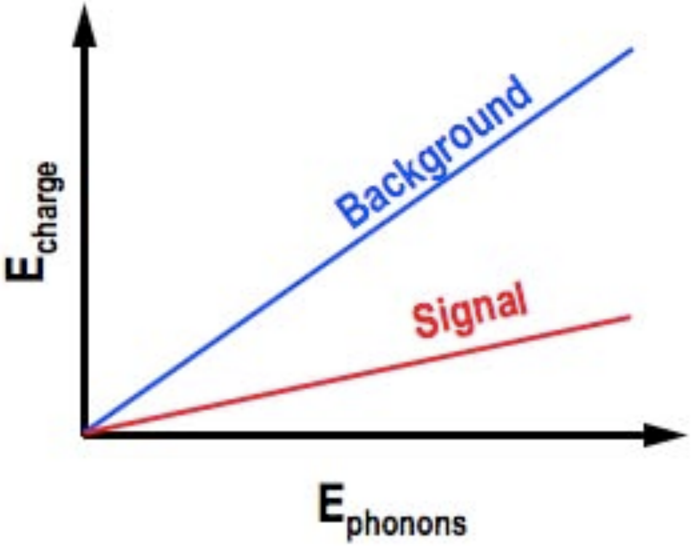
Heat & Ionisation Bolometers
ZIP/NTD for Q & H channels
Targets: Ge,Si
CDMS, EDELWEISS,
SCDMS, EURECA
cryogenic (<50 mK)

Light & Heat Bolometers
TES/NTD for L & H channels
Targets: CaWO4, BGO, Al2O3
CRESST, ROSEBUD
even more cryogenic (~10 mK)

Hybrid techniques: nuclear recoil discrimination



- WIMPs and neutrons scatter off nuclei
- Photons and electrons scatter off electrons

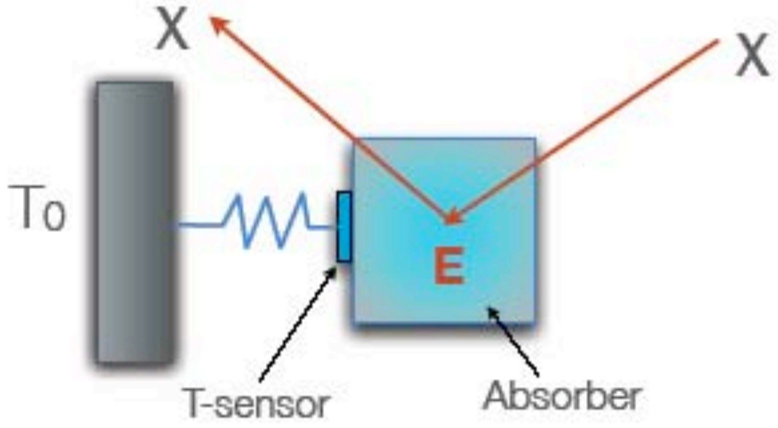


M.Attisha

NTD= Neutron Transmutation Doped (thermal phonons) crystals
TES= Transition Edge Sensors (athermal phonons)
SPT= Superconducting Phase Transition thermometers

Bolometers

- **Principle:** a deposited energy E produces a temperature rise ΔT



$$\Delta T \propto \frac{E}{C(T)}$$

$$T \ll T_c \Rightarrow C(T) \propto T^3$$

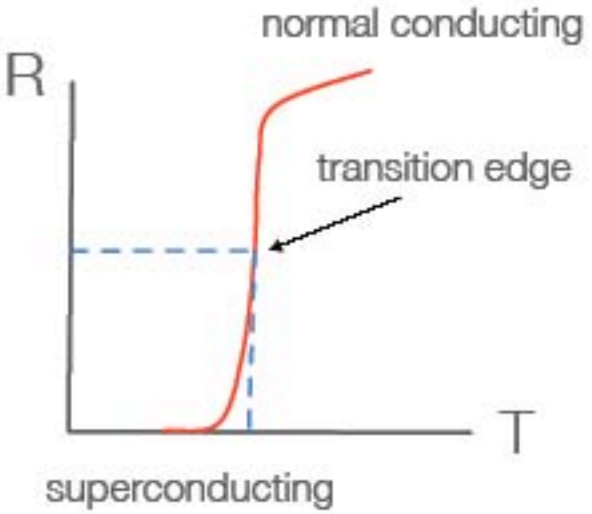
=> the lower T, the larger ΔT per unit of absorbed energy

- **T-sensors:**
  - **superconductor thermistors**

    (highly doped superconductor): NTD Ge → EDELWEISS
  - **superconduction transition sensors**

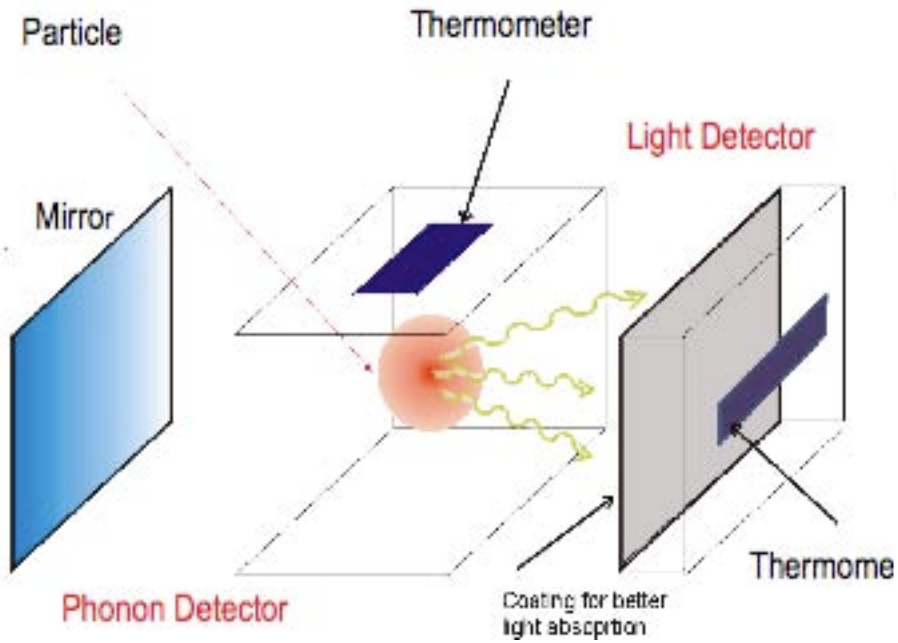
    (thin films of SC biased near middle of normal/SC transition):

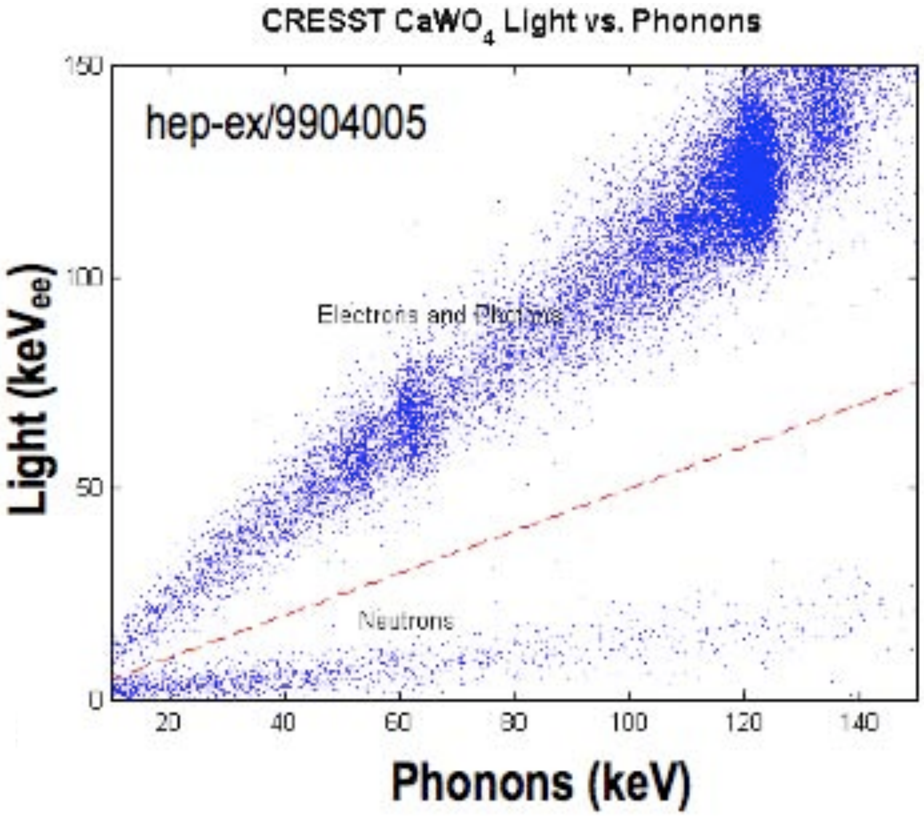
    TES→CDMS, SPT→CRESST



CRESST II at LNGS: light and phonons

- Phonons and scintillation in $CaWO_4$ targets (300g) at ~ 10 mK
- Phonon detector: W-SPT (Superconducting Phase Transition) thermometers (Tc at 15 mK)
- Light detector: Si wafer read out by W-SPT(E_{thr} → few optical γ, ~ 20eV)
- No dead layer effects



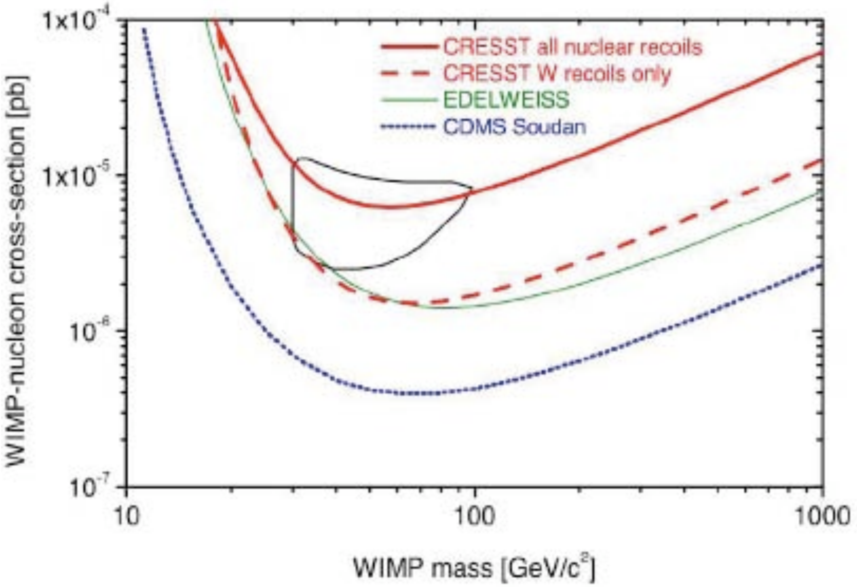


- Nuclear recoils have much smaller light yield than electron recoils
- Photon and electron interactions can be be distinguished from nuclear recoils (WIMPs, neutrons)

Upgrade to 10 kg target mass, with neutron shield and muon veto, new limit published in 2008, arXiv:0809.1829v1

EDELWEISS at LSM: charge and phonons

- EDELWEISS-I: Ge NTD heat and ionization detectors (3 x 320 g at 17 mK)
  - Data taking 2000-2003
  - Backgrounds from neutrons, alpha and surface electron recoils
- EDELWEISS-II: 10 kg (30 modules) of NTD and NbSi Ge detectors in new cryostat
  - New charge electrodes
  - 100 kg d under analysis
  - Data taking in progress



CDMS

Superconducting films that detect minute amounts of heat

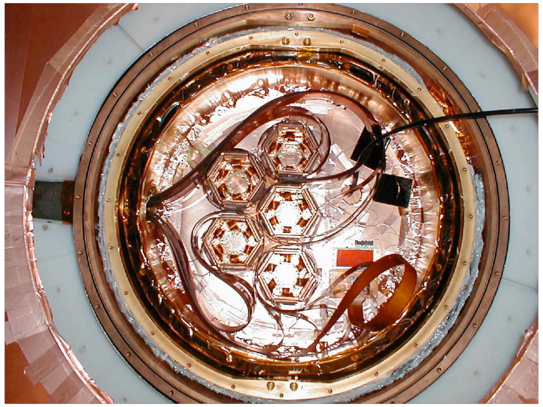
Transition Edge Sensor sensitive to fast athermal phonons

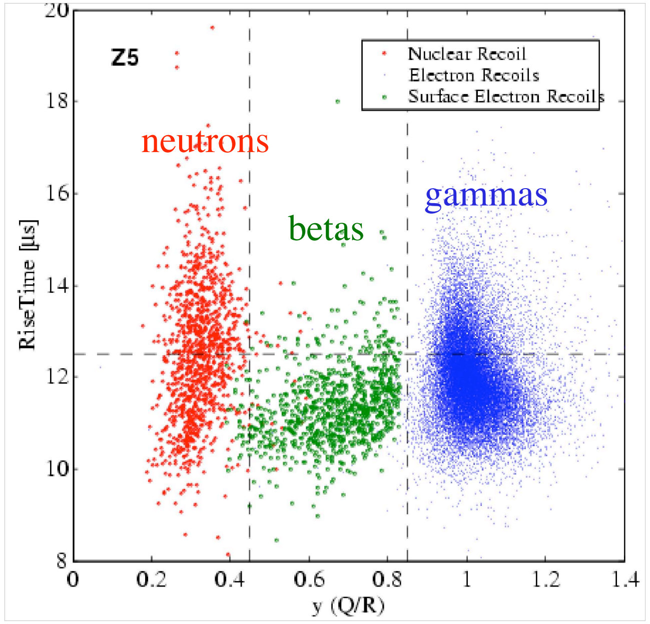
ZIP: Z-dependent ionization and phonon detectors

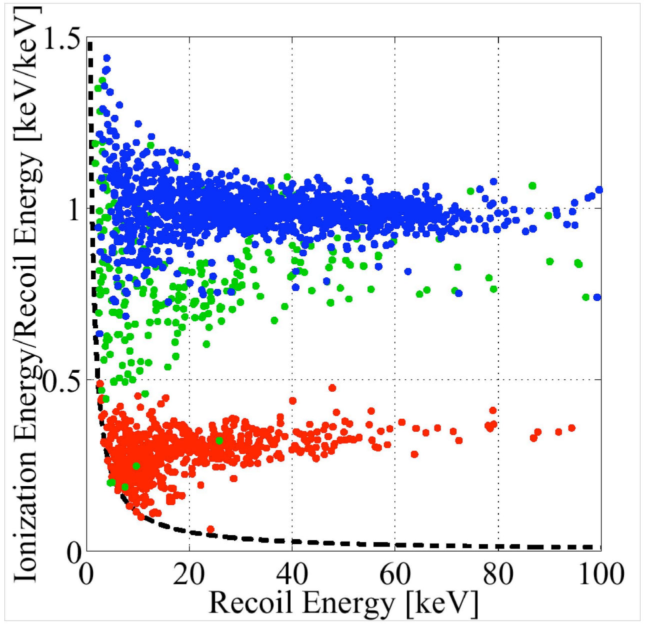
- Charge/phonon AND phonon timing different for nuclear and electron recoils; event by event discrimination!
- Measured background rejection still improving!

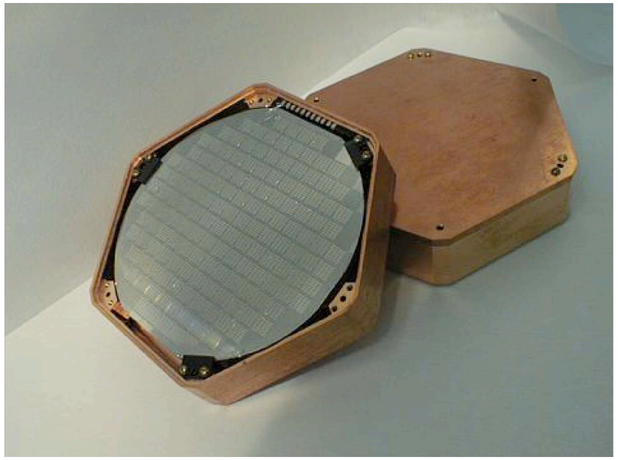
  99.9998% for γ’s, 99.79% for β’s
- Clean nuclear recoil selection with ~ 50% efficiency

  Can tune between signal efficiency and background rejection





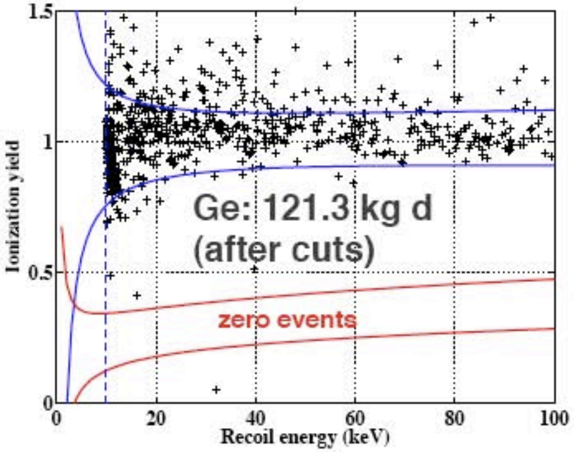


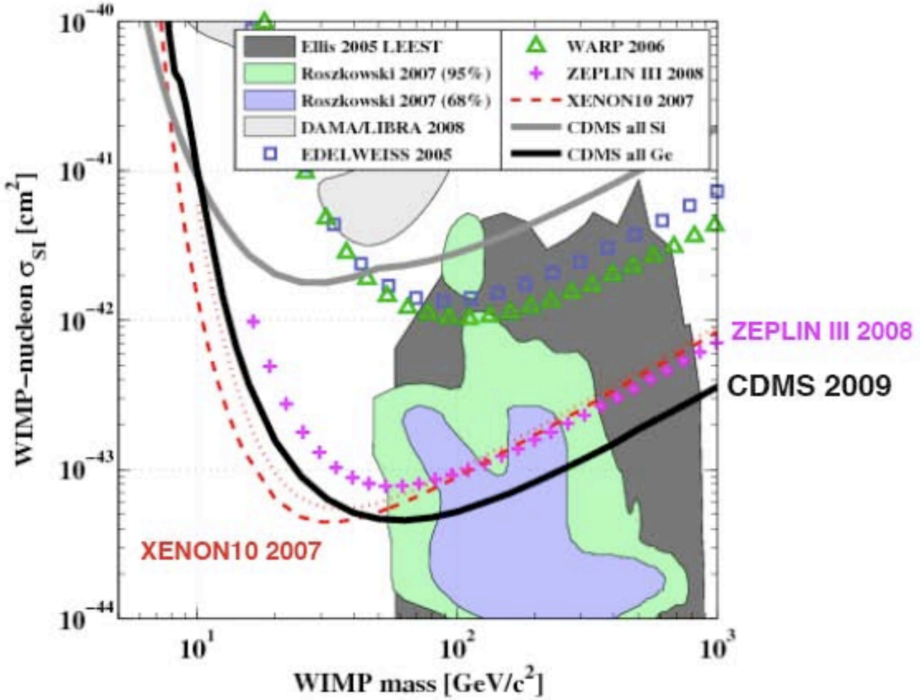


CDMS-II at Soudan

- 250 g Ge, 100 g Si crystals with Al+W TES collecting athermal phonons
- Phonon sensors: 4 quadrants, each 1036 TES in parallel => x-y position of events
- Charge electrodes: inner, disk shaped, outer, ring-like; e--h drift in E-field (3V/cm)
- Surface event rejection based on phonon timing (2 x 10^{-3} misidentified events)

  - **30 Ge (4.75 kg) and Si (1.1 kg) detectors in 5 towers**
  - **Run 123+124:** 163 live days, results published in PRL102 (2009) 011301
  - **Run 125-128:** 240 live days under analysis, first results in summer 09 (sensitivity reach ~ 1×10^{-44} cm^2)

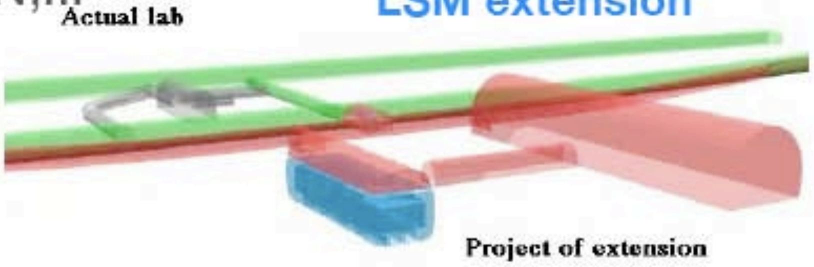




Future mK Cryogenic Dark Matter Experiments

- **EURECA (European Underground Rare Event Calorimeter Array)**
- Joint effort: CRESST, EDELWEISS, ROSEBUD, CERN,...
- Mass: 100 kg - 1 ton, multi-target approach
- FP7 proposal for design study submitted

LSM extension



Lombardi 2007 for LSM

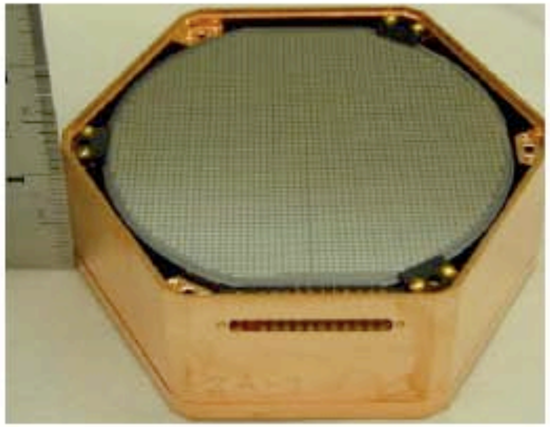
- **SuperCDMS (US/Canada):** 3 phases 25 kg - 150 kg - 1 ton
- 640 g Ge detectors with improved phonon sensors
- 4 prototype detectors built and tested

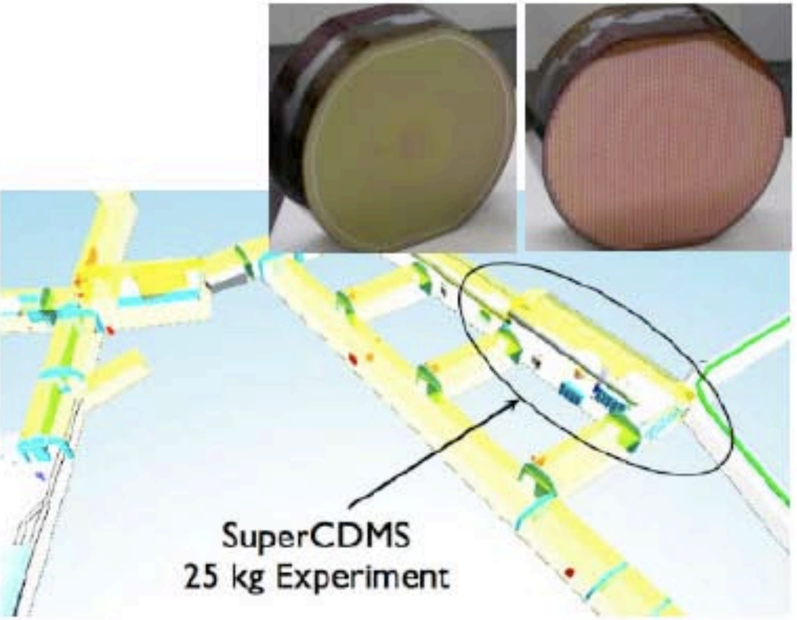
R&D for SuperCDMS:

1” thick **SuperZIPs** (0.64 kg)

2 SuperTowers at Soudan

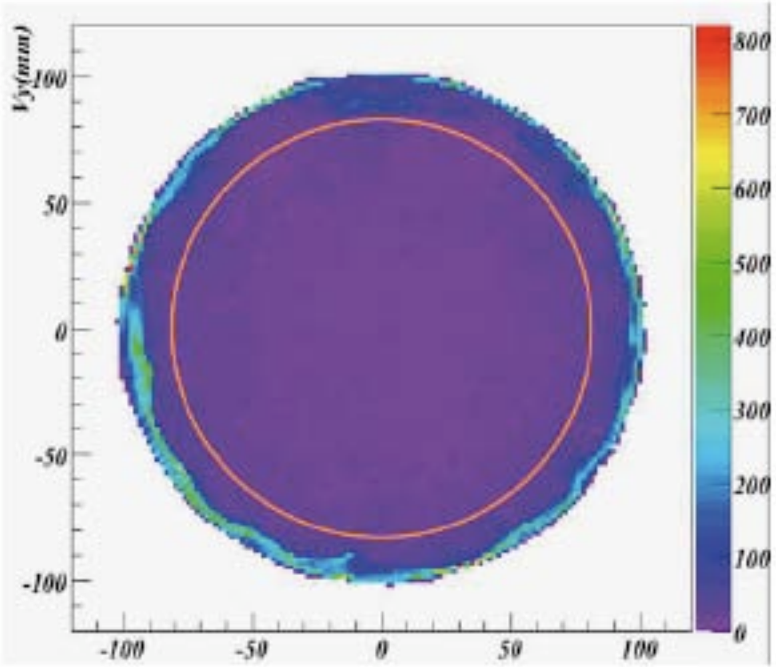
7 SuperTowers at SNOLAB





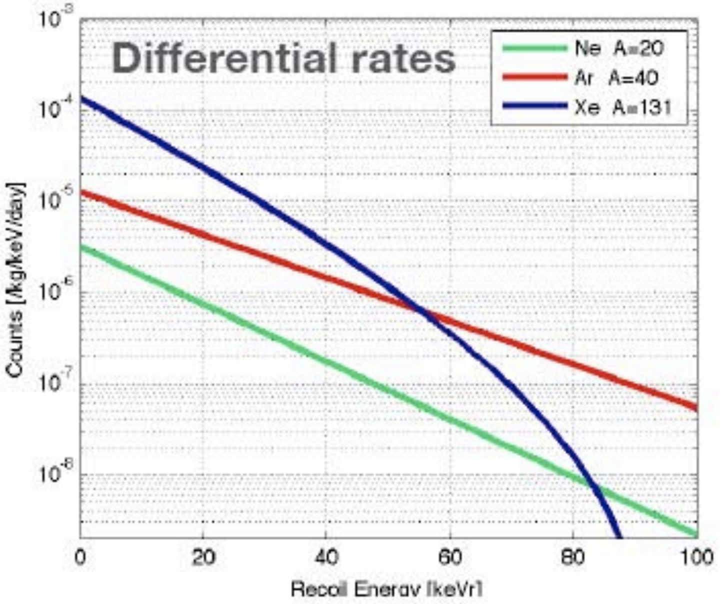
Noble Liquid detectors: advantages

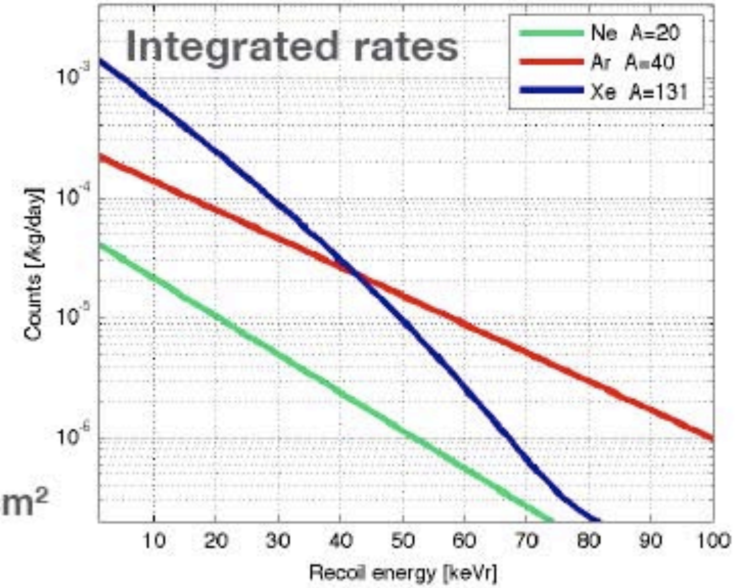
- Liquid noble gases yield both charge and light
- Good Nuclear versus Electron Recoil discrimination
    - scintillation pulse shape
    - ionization/scintillation ratio
- High Scintillation Light Yields
    - low energy thresholds
- Large Detector Masses
    - self-shielding
    - good position-resolution in TPC operation mode (ionization)
- Ionization Drift >> 1 m achieved
    - corresponding to << ppm electronegative impurities
- Competitive Costs



Noble Liquids as Dark Matter Detectors

	Scintillation Light	**Intrinsic Backgrounds**
Ne (A=20) $60/kg 100% even-even nucleus	**85 nm** requires wavelength shifter	Low BP (20 K), all impurities frozen out No radioactive isotopes
Ar (A=40) $2/kg 100% even-even nucleus	**128 nm** requires wavelength shifter	Natural Ar contains ^{39}Ar at 1Bq/kg, corresp. to ~150 ev/kg/day/keV at low energies
Xe (A=131) $800/kg 50% odd nuclei (^{129}Xe, ^{131}Xe)	**175 nm** UV quartz PMT window	No long lived isotopes ^{85}Kr can be removed by active charcoal filter or distillation

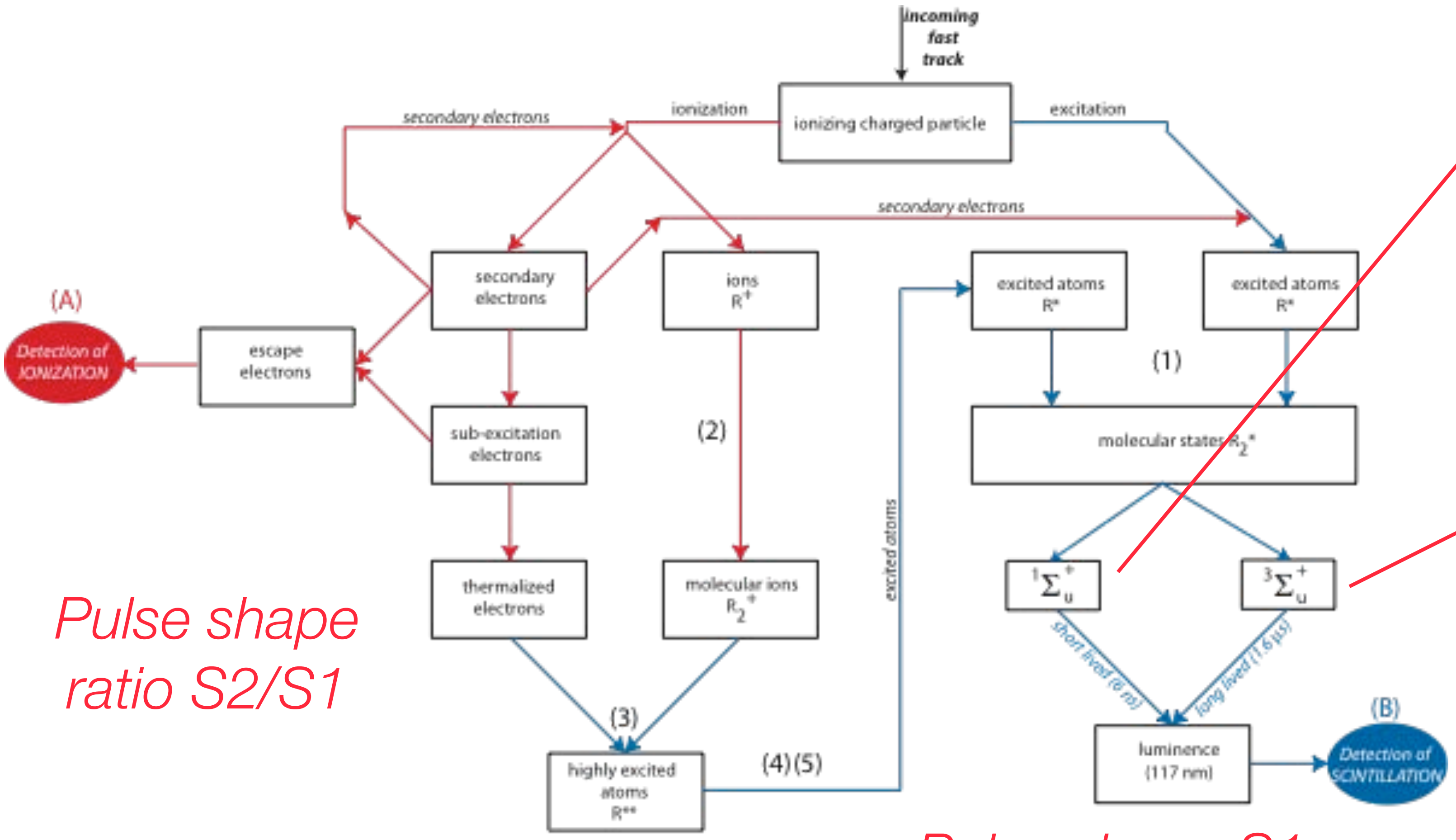


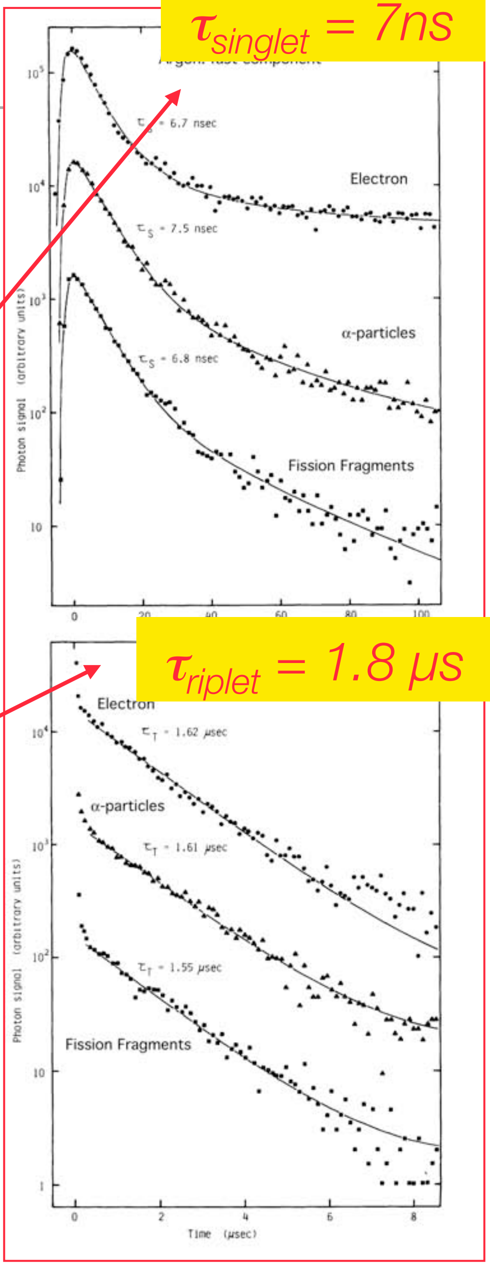


M_{WIMP} = 100 GeV
$\sigma_{WIMP-N}=4\times10^{-43}$ cm^2

L. Baudis

Scintillation and ionization in noble liquids





$\tau_{singlet}$ = 7ns

$\tau_{triplet}$ = 1.8 µs

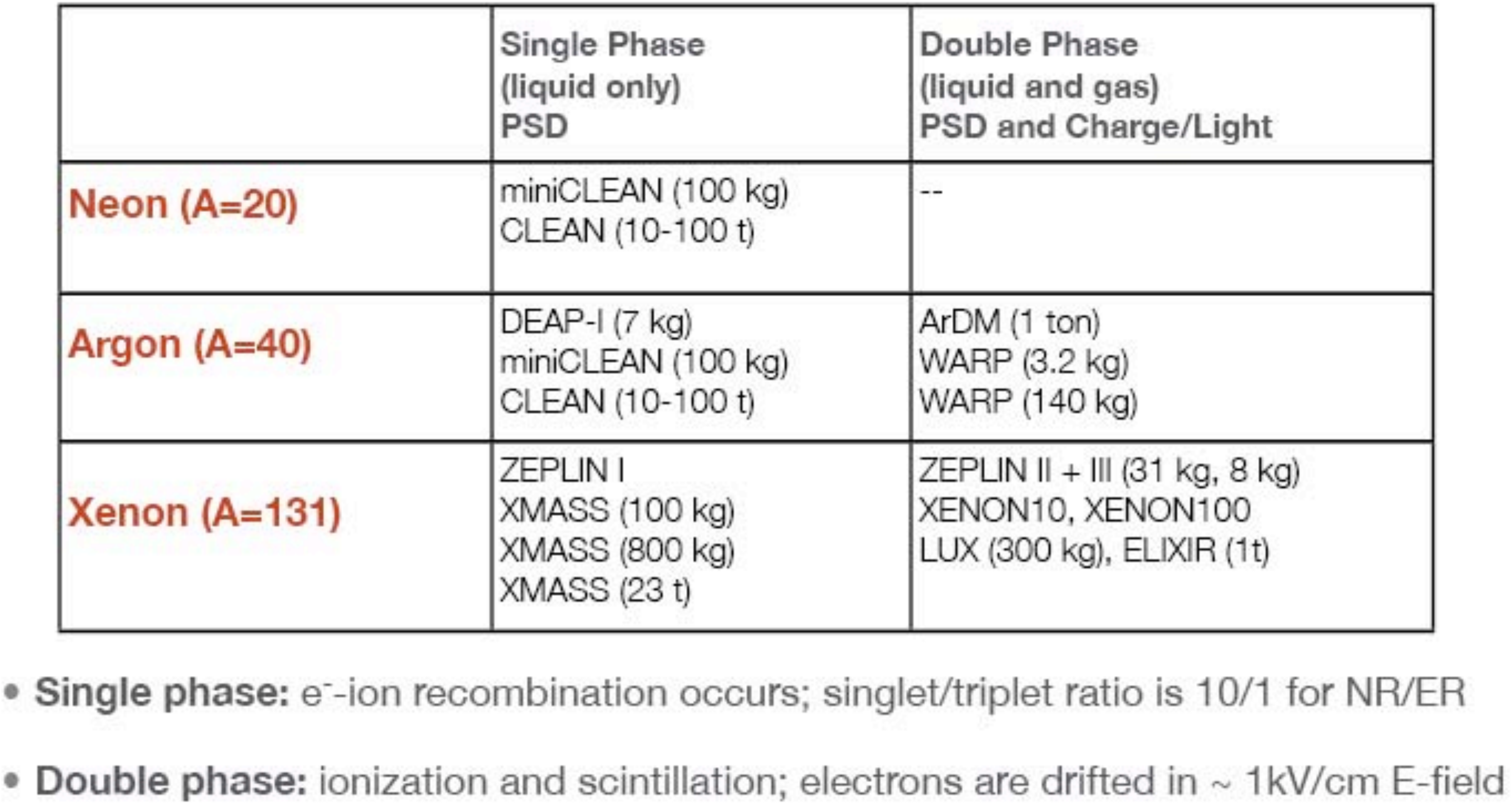
Pulse shape ratio S2/S1

Pulse shape S1

In LAr:
I_s/I_t = 0.3 (e), 1.3 (α), 3.0 (ff)

PSD

Existing and proposed projects

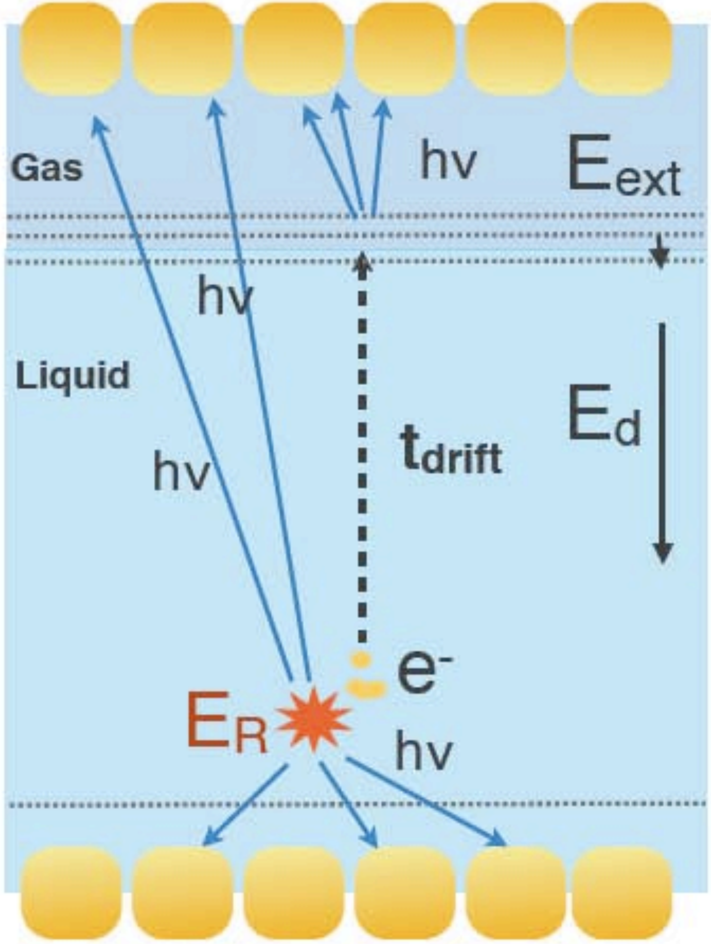


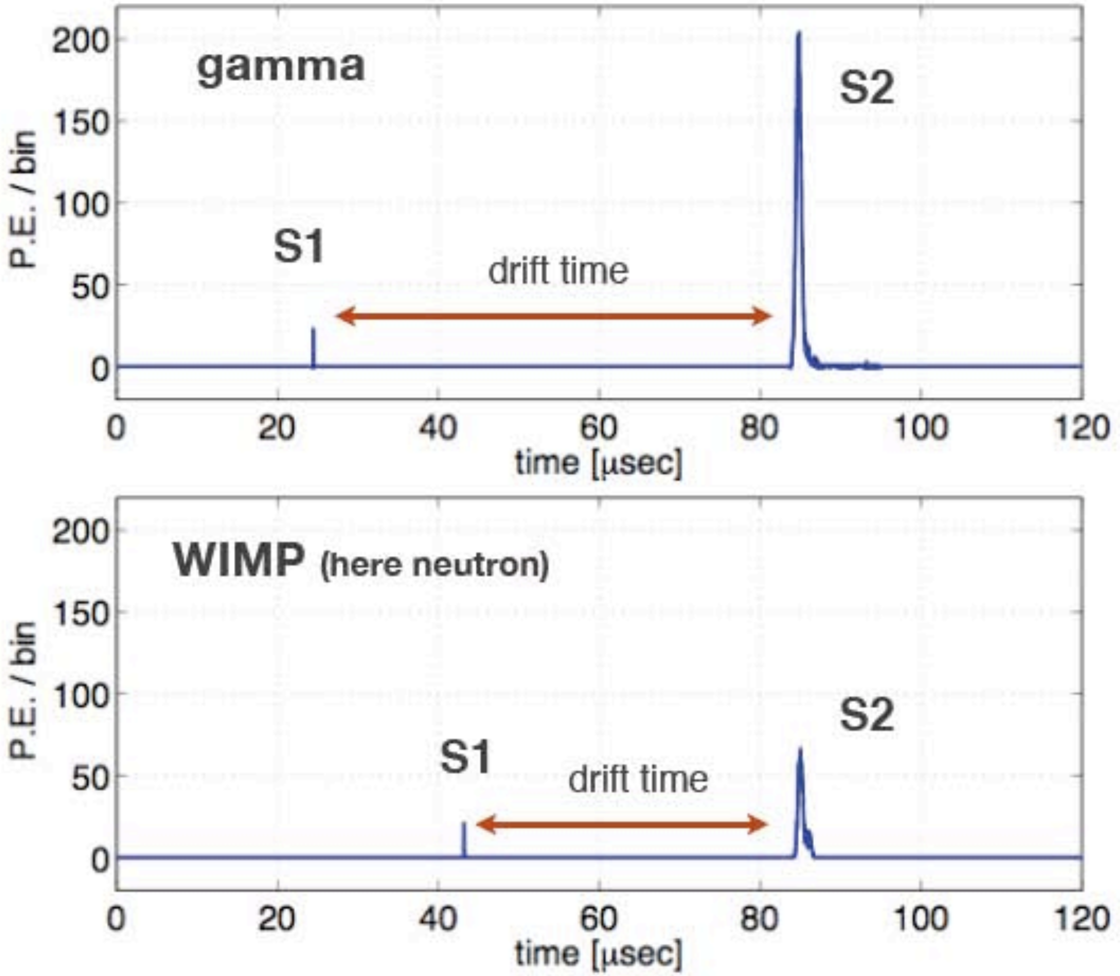
	Single Phase **(liquid only)** **PSD**	**Double Phase** **(liquid and gas)** **PSD and Charge/Light**
Neon (A=20)	miniCLEAN (100 kg) CLEAN (10-100 t)	--
Argon (A=40)	DEAP-I (7 kg) miniCLEAN (100 kg) CLEAN (10-100 t)	ArDM (1 ton) WARP (3.2 kg) WARP (140 kg)
Xenon (A=131)	ZEPLIN I XMASS (100 kg) XMASS (800 kg) XMASS (23 t)	ZEPLIN II + III (31 kg, 8 kg) XENON10, XENON100 LUX (300 kg), ELIXIR (1t)

- **Single phase:** e^--ion recombination occurs; singlet/triplet ratio is 10/1 for NR/ER
- **Double phase:** ionization and scintillation; electrons are drifted in ~ 1kV/cm E-field

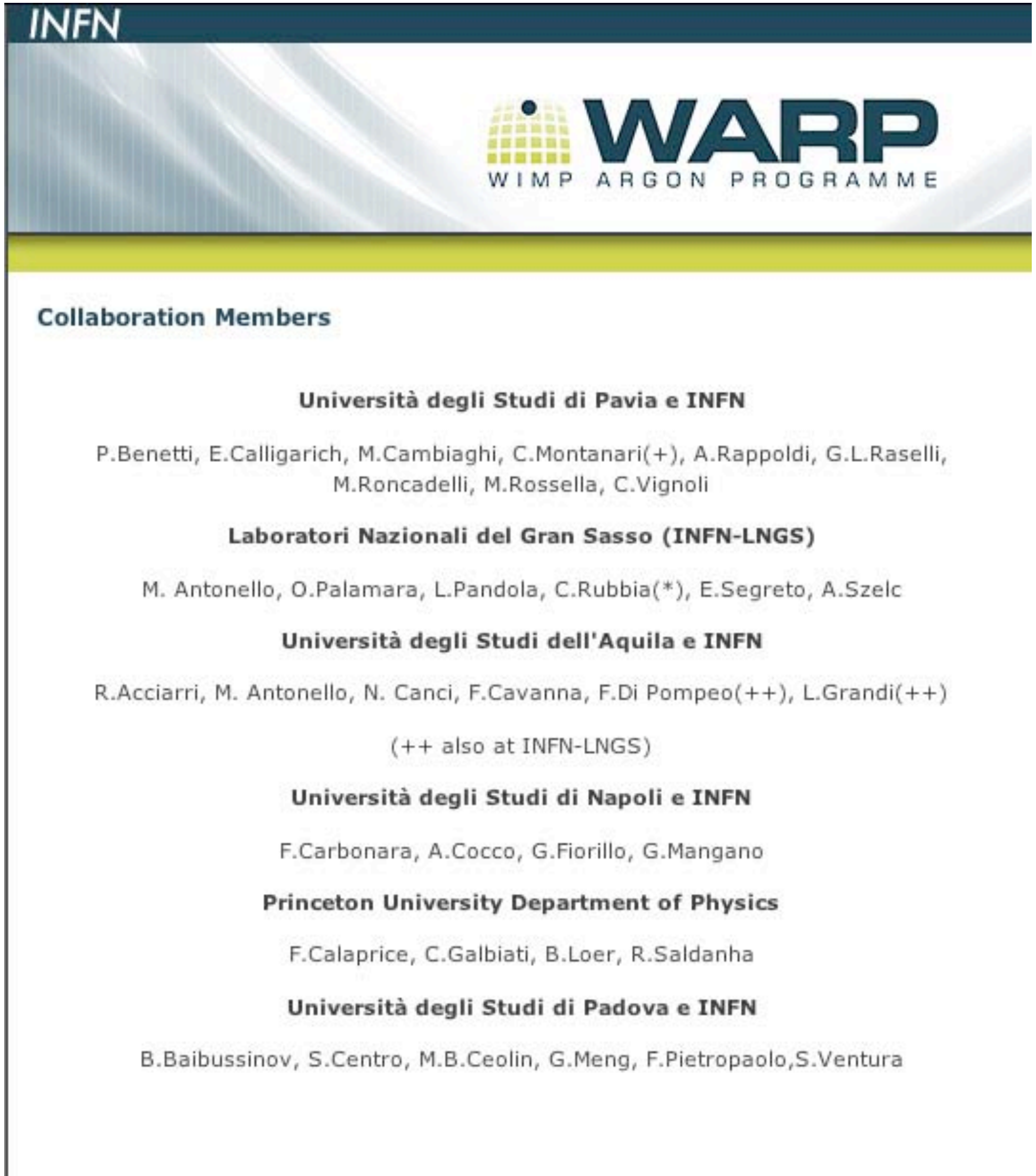
The Double-Phase Detector Concept

- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected either **directly with LEMs**, or as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e$^-$





Two-phase Ar: WARP



INFN

WARP

WIMP ARGON PROGRAMME

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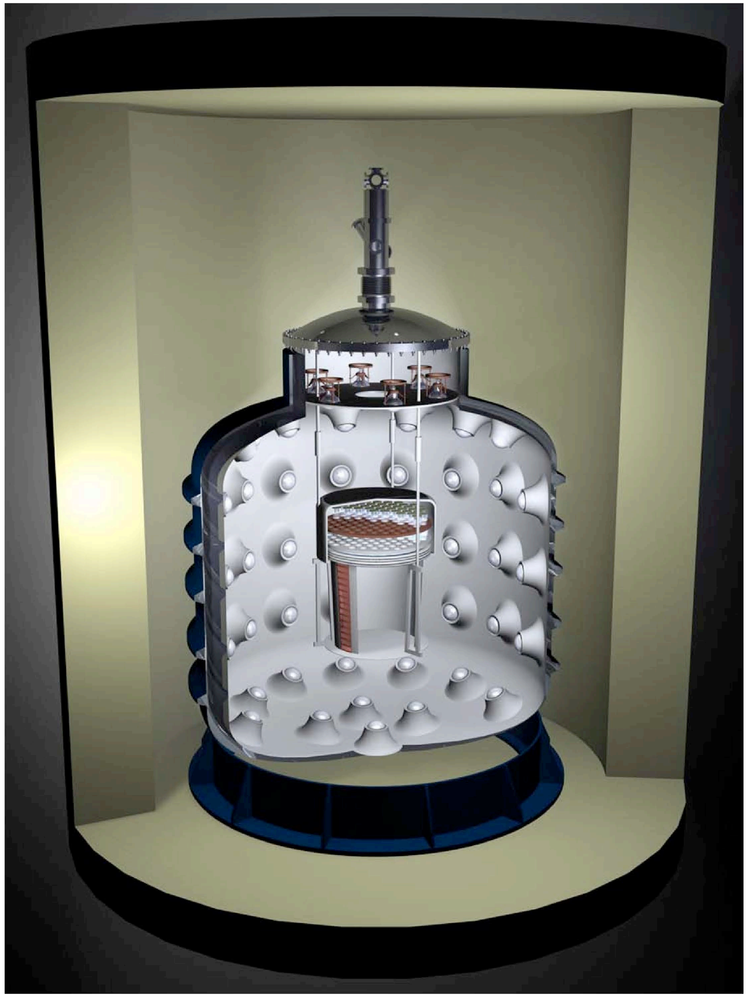
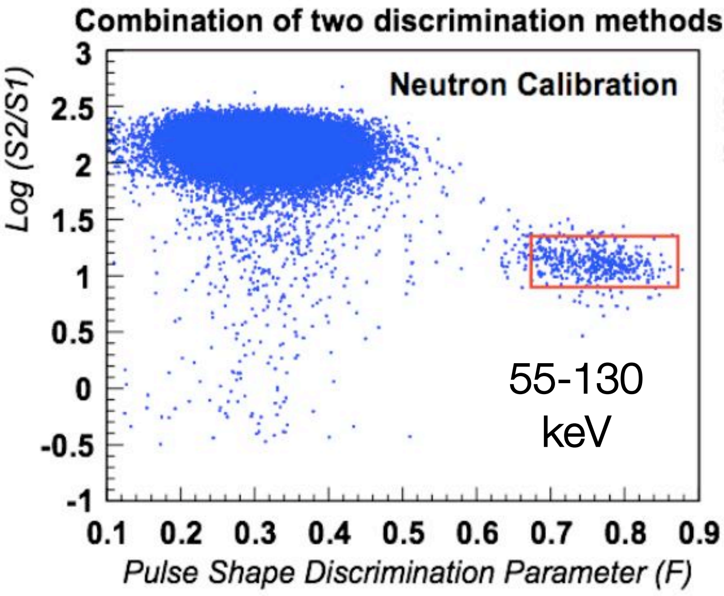
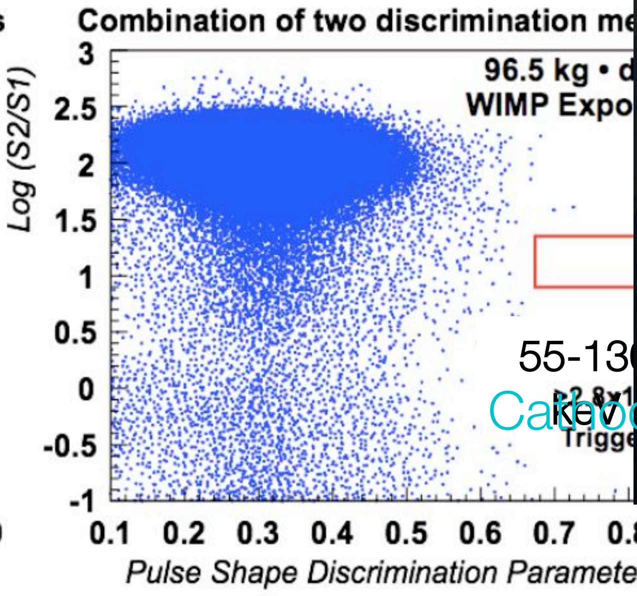
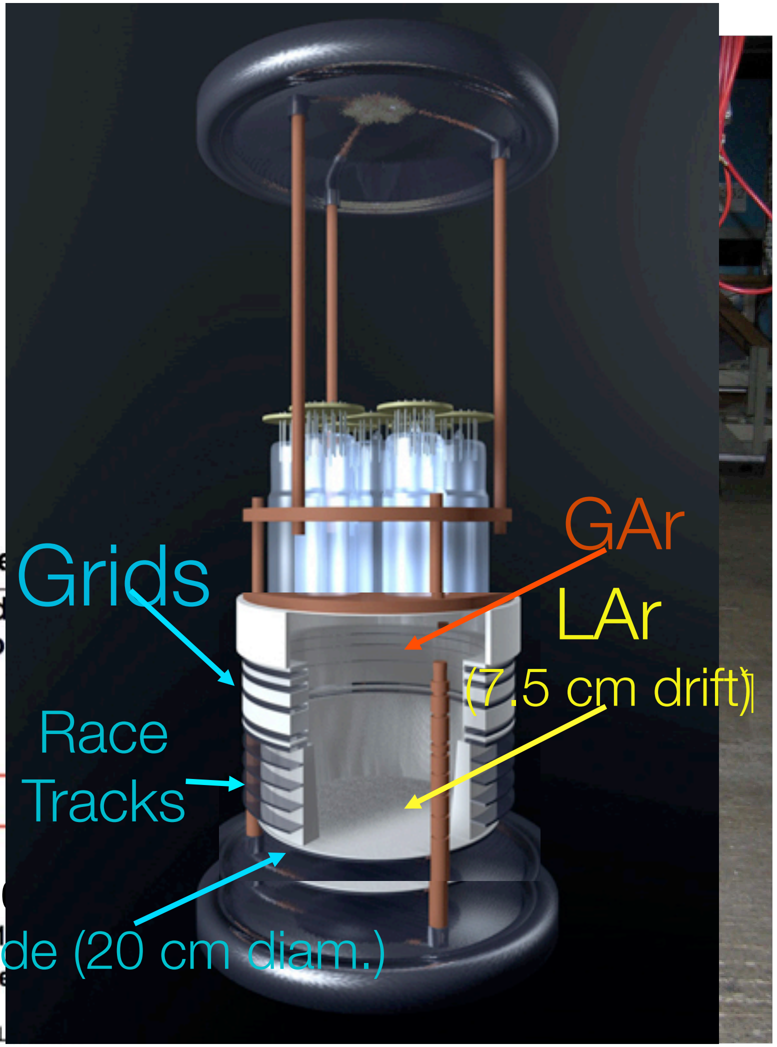


WARP 3.2 kg

- The WArP 3.2 kg prototype uses the same detection principle as the 140 kg detector.
- Operational since may 2005 at LNGS.
- First LAr detector to publish DM search results (3 months WIMP search).
- Serves as testing ground for the 140 kg detector.







WIMP search results from WARP 3.2 kg

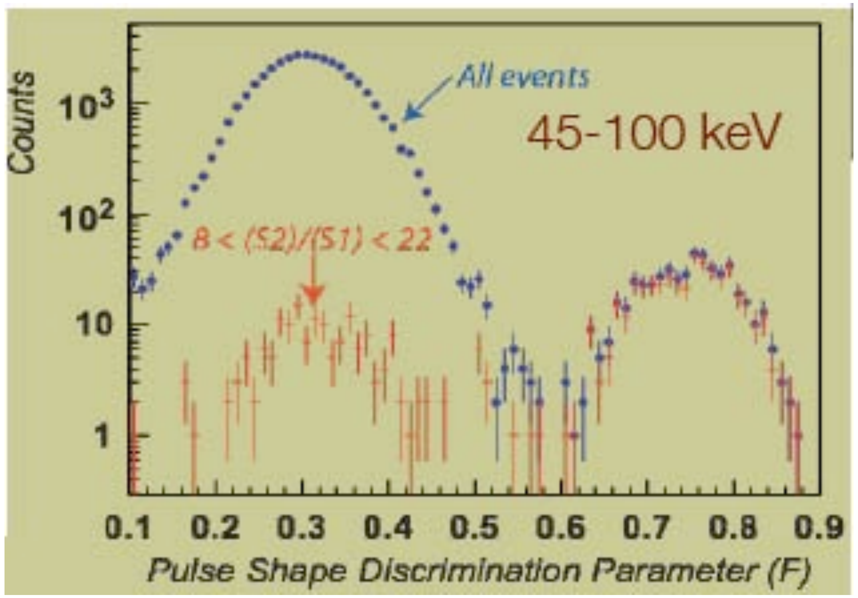
Very good test of the detection principle.

Served as proof of concept:

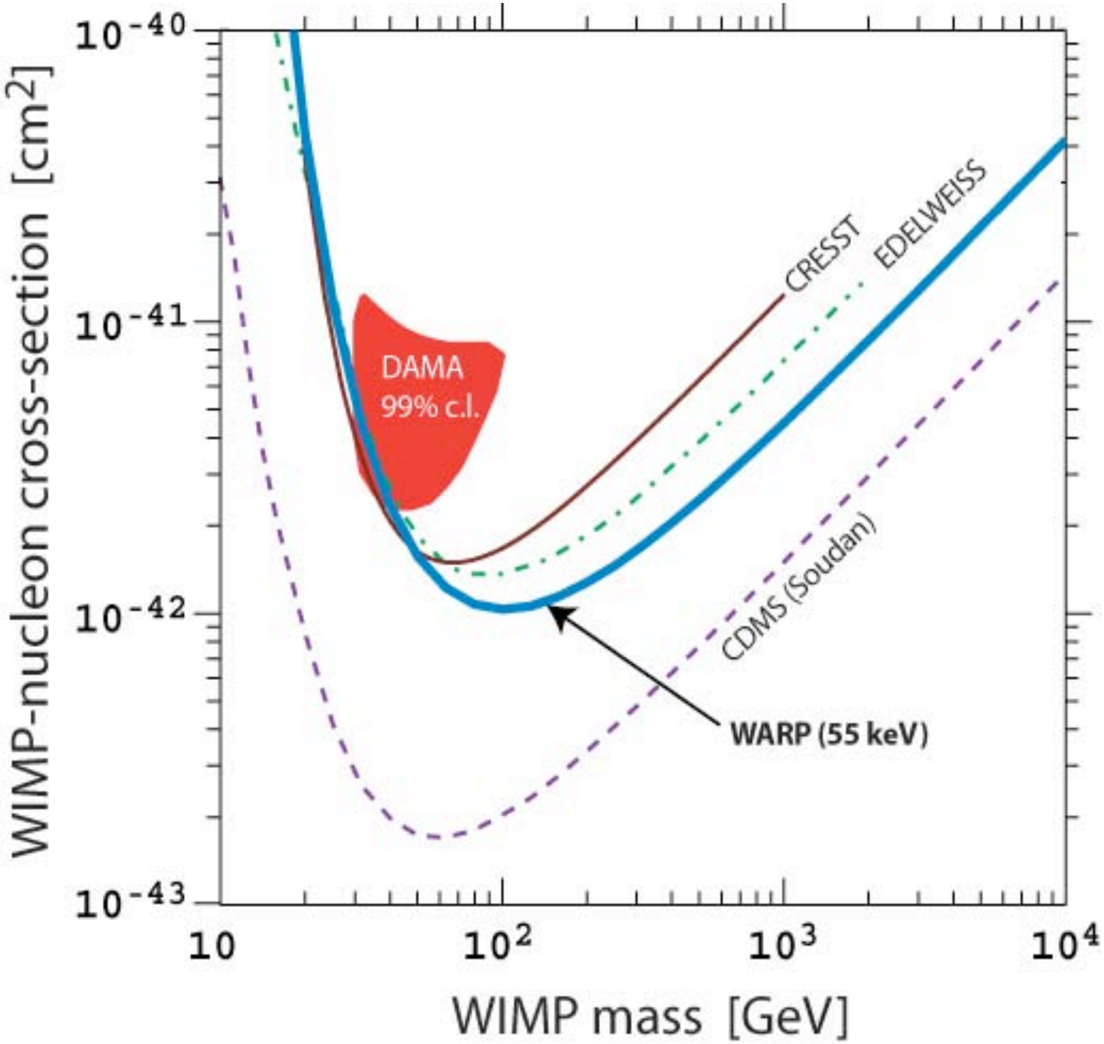
- Excellent results from study of discrimination power between nuclear recoils and γ-betas:

  10^{-8} pulse shape discrimination,

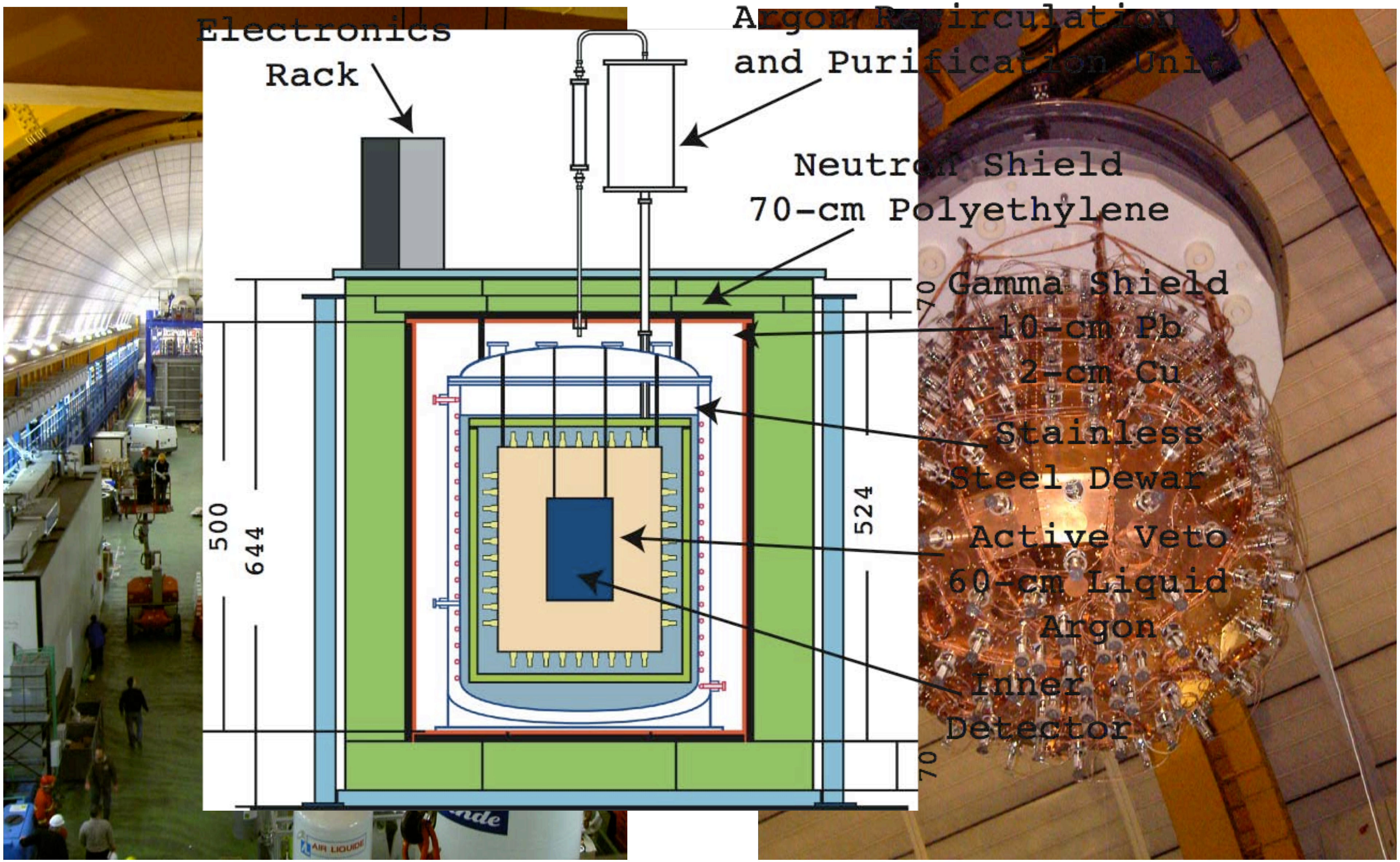
  $5\text{x}10^{-3}$ ionization/scintillation



P. Benetti et al., Astrop. Phys. 28 (2008) 6.

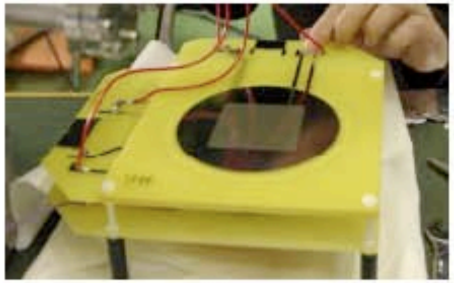


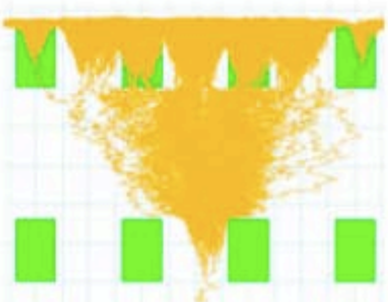
WARP 140 kg

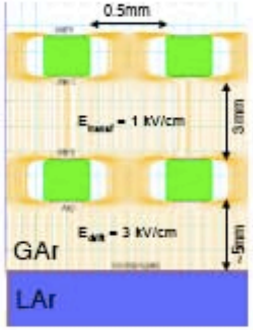

Electronics Rack
Argon Recirculation and Purification Unit
Neutron Shield 70-cm Polyethylene
Gamma Shield 10-cm Pb 2-cm Cu
Stainless Steel Dewar
Active Veto 60-cm Liquid Argon
Inner Detector
70
500
644
524
70
AIR LIQUIDE

Two-Phase Argon: ArDM

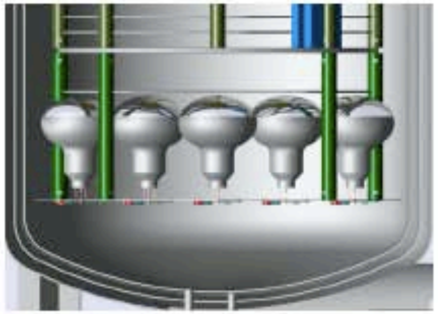
- 1 ton prototype under construction at CERN
- Direct charge readout with 2 stage, thick LEM (macroscopic GEM, gain up to 10^4)







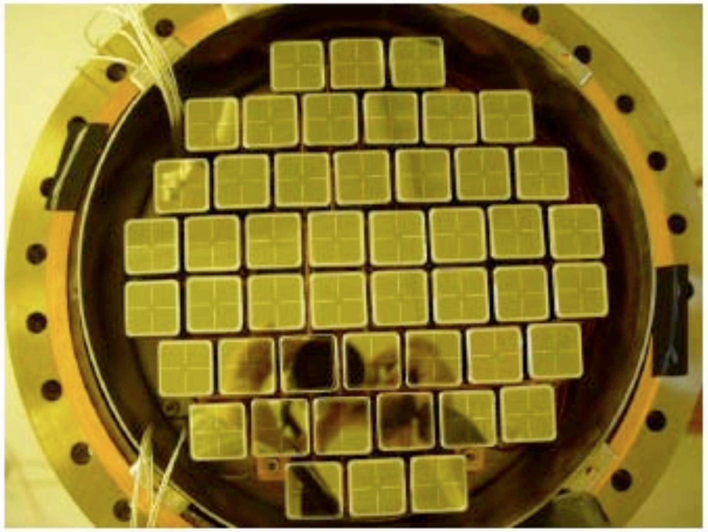
- Photon readout: 85 tetra-phenyl-butadiene coated PMTs: shift λ 128 nm -> 430 nm (20%QE)



- Field: Greinacher Chain + field shapers
- Goal: test at CERN (2007), then move to Canfranc (07-08)

M. Laffranchi et al., astro-ph/0702080

Two-phase Xe: XENON



- **Operated at LNGS in 2006-2007**
- **22 kg of liquid xenon**
    - ➡ 15 kg active volume
    - ➡ 20 cm diameter, 15 cm drift
- **Hamamatsu R8520 1"× 3.5 cm PMTs**
    - ➡ bialkali-photocathode Rb-Cs-Sb, Quartz window; ok at -100ºC and 5 bar, QE > 20% @ 178 nm
- **48 PMTs top, 41 PMTs bottom array**
    - ➡ x-y position from PMT hit pattern; $\sigma_{x\text{-}y} \approx$ 1 mm
    - ➡ z-position from Δt_{drift} ($v_{d,e-} \approx$ 2mm/µs), $\sigma_Z \approx 0.3$ mm
- **Cooling: Pulse Tube Refrigerator (PTR),**

90W, coupled via cold finger (LN_2 for emergency)

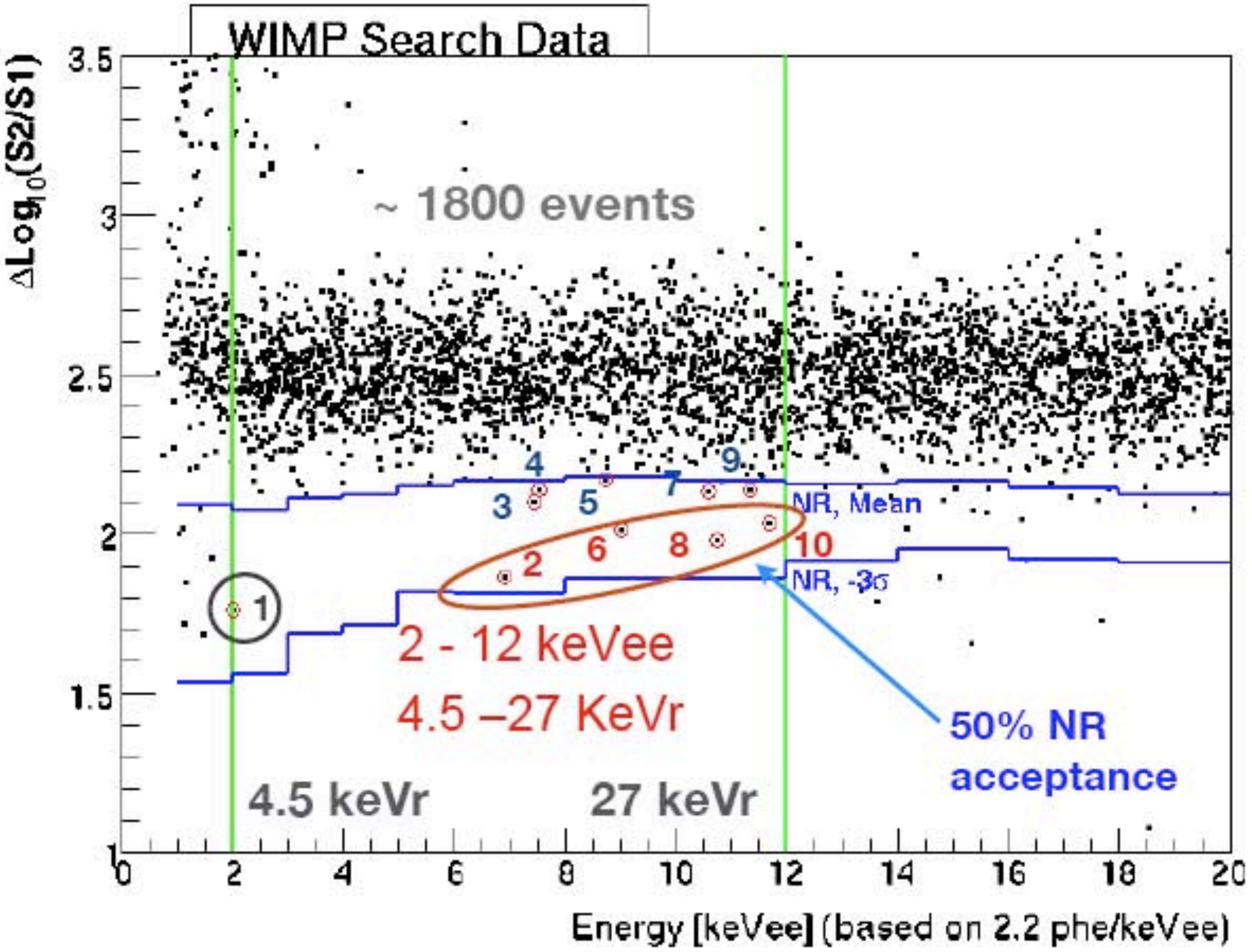
- ➡ LXe maintained at T = 180 K and P=2.2 atm

- **12 kV cathode:** E_d=0.73 kV/cm (drift), E_{gas}=9kV/cm (S2)

L. Baudis

XENON10 WIMP Search Data

- WIMP search run Aug. 24. 2006 - Feb. 14, 2007: ~ **60 (blind) live days**
- **136 kg-days exposure** = 58.6 live days × 5.4 kg × 0.86 (ε) × 0.50 (50% NR acceptance)



WIMP 'Box' defined at

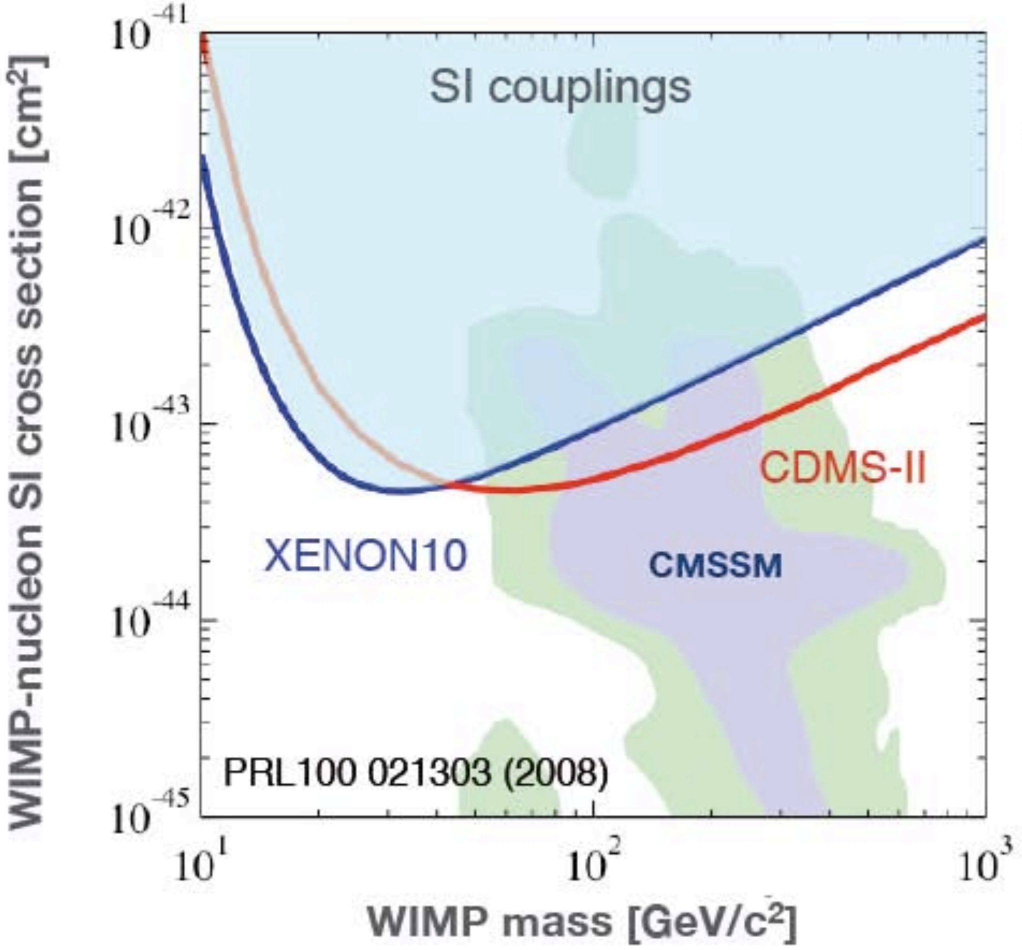
50% acceptance of NRs (blue lines): [Mean,-3σ]

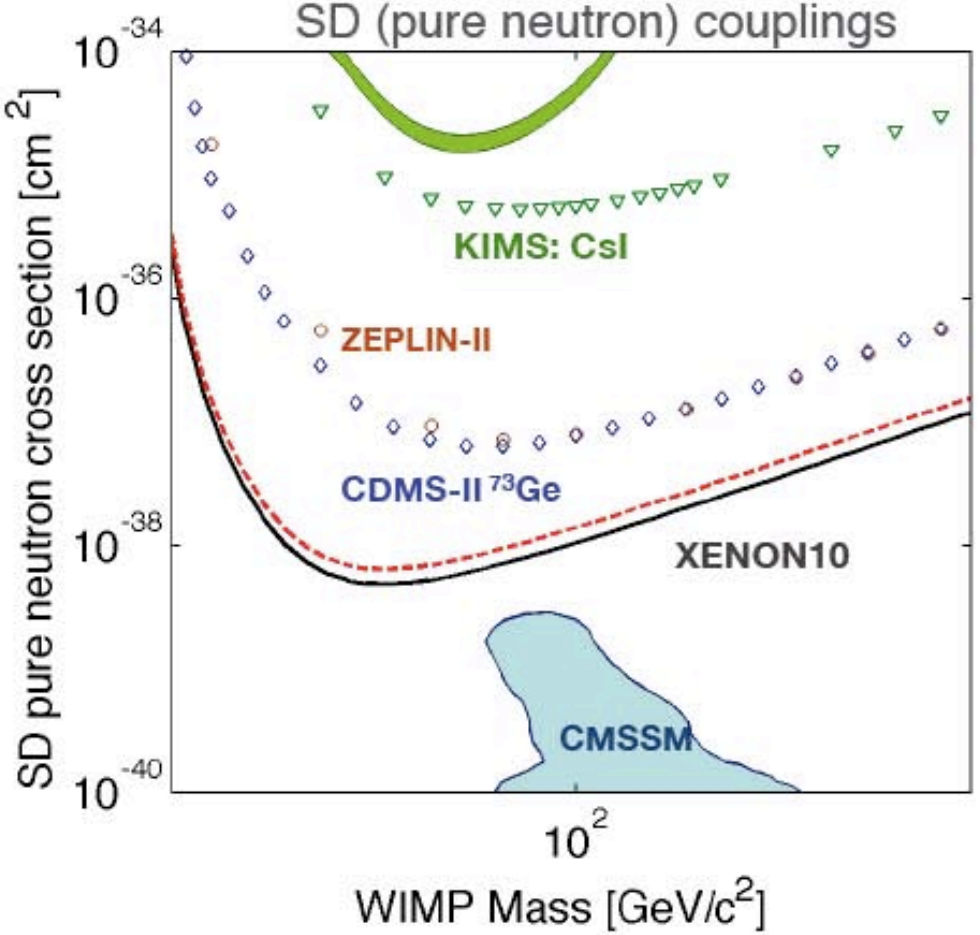
10 events in 'box' after all cuts
7.0 ($^{+1.4}_{-1.0}$) statistical leakage expected from the gamma (ER) band

NR energy scale based on constant 19% QF

XENON10 WIMP Search Results for SI and SD Interactions

- To set limits: all 10 events considered, thus no background subtraction performed
  ➡ probed the elastic, SI WIMP-nucleon σ down to ≈ **4×10^{-44} cm^2** (at $M_{WIMP} = 30$ GeV)
- natural Xe: ^{129}Xe, 26.4 %, spin 1/2, ^{131}Xe, 21.2%, spin 3/2
- use shell-model calculations by Ressel and Dean [PRC 56, 1997] for $\langle S_n \rangle$, $\langle S_p \rangle$

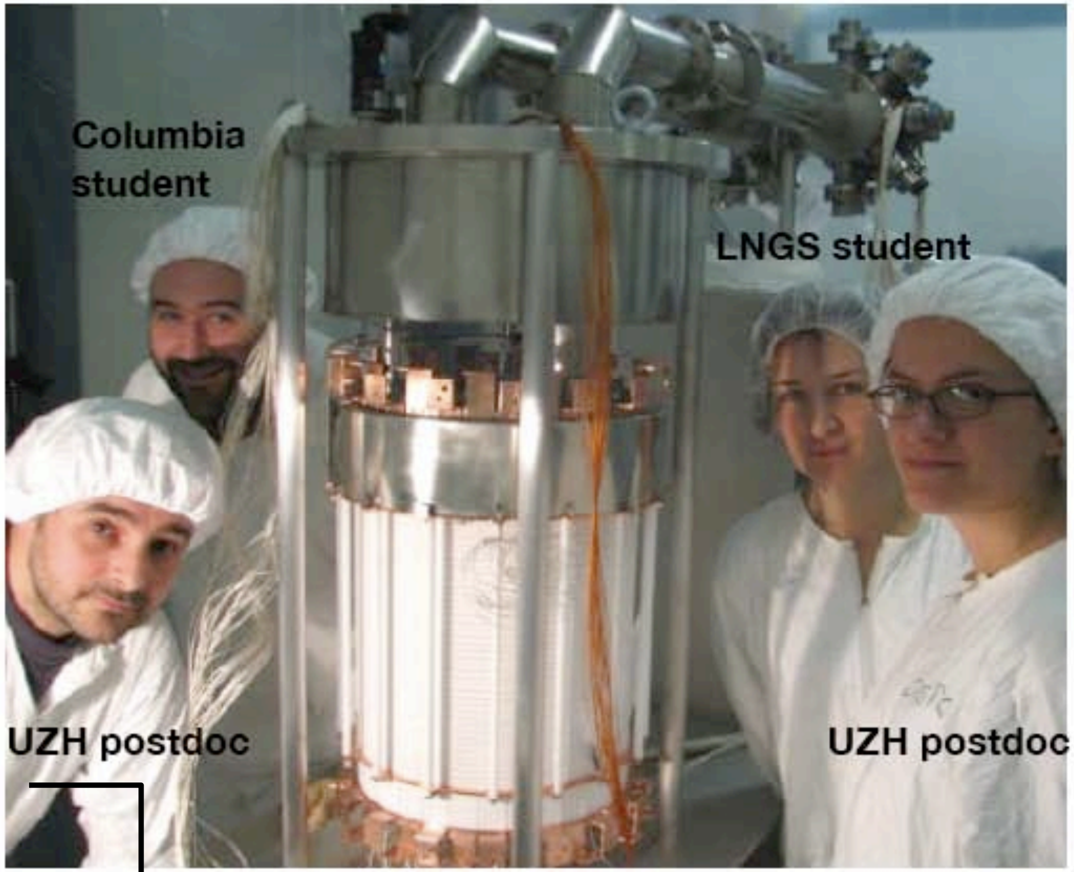




LXe TPCs: near future

- **XENON100:** under commissioning at LNGS, expected to start WS run in spring 2009
- 170 kg (100 kg in active veto) LXe, viewed by 242 PMTs, 30 cm ⌀, 30 cm drift
- **Goal: factor 100 lower background, factor 10 higher mass than XENON10**

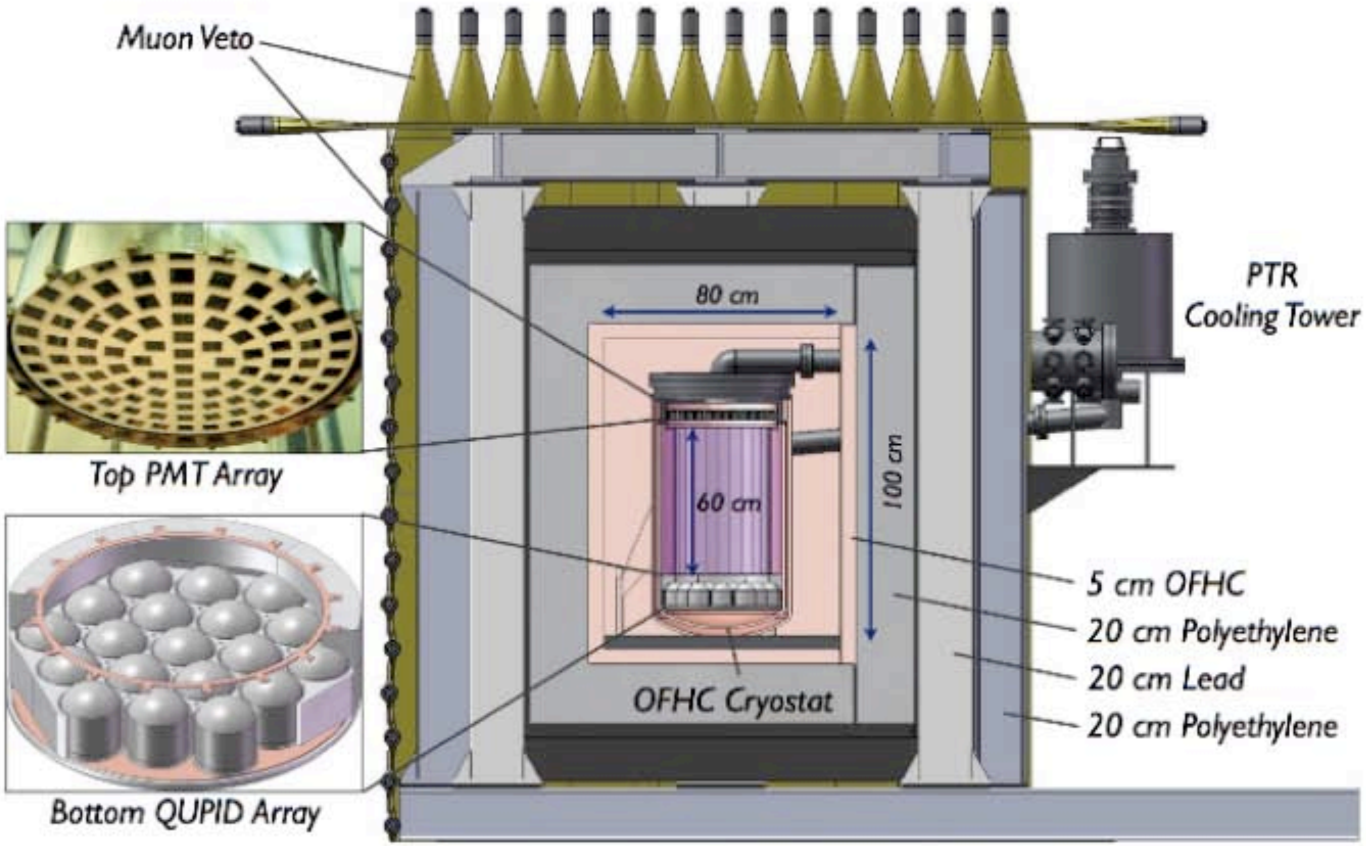
XENON100 in its shield

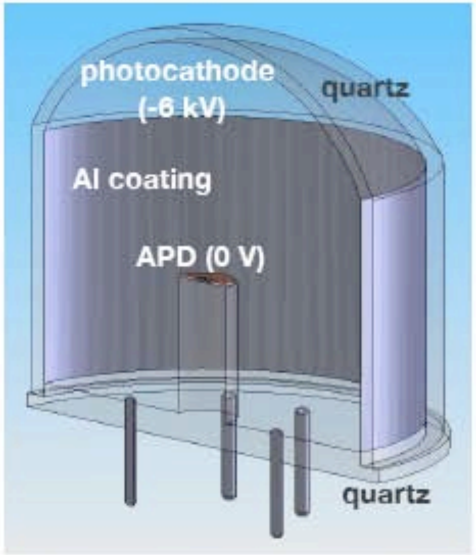


Roberto Santorelli

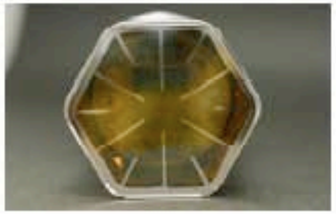
Next Step: The Xenon100 Upgrade

- **100 kg fiducial mass (total of 260 kg LXe), background 5×10^{-4} events/(kg day keV)**
- new photon detectors, QUPIDs; ultra-low BG Cu cryostat, new shield, including muon veto
- **construction 2010; WIMP search 2011-2012**





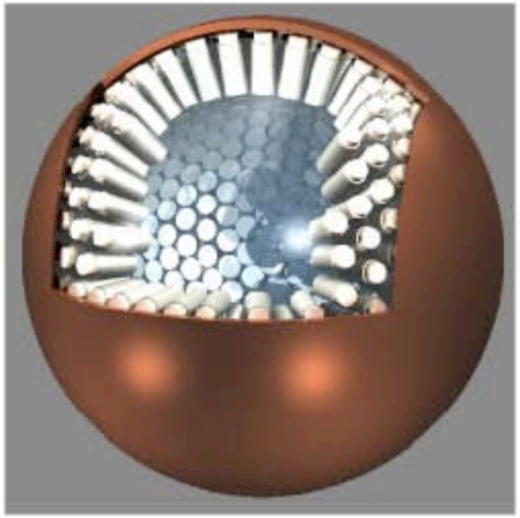
Single-Phase Xenon: XMASS



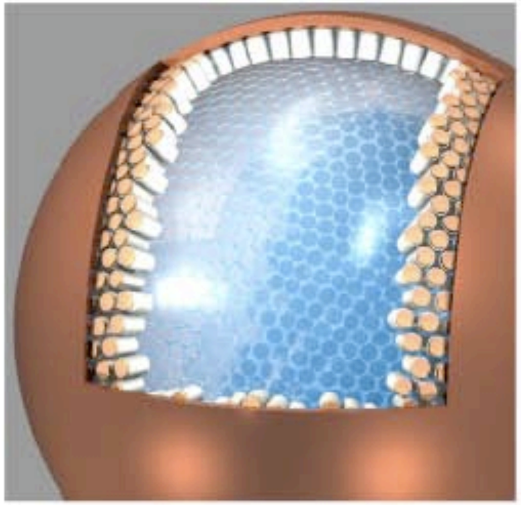
- 100 kg (3 kg fiducial mass) prototype operated (52 2” Hamamatsu R8778 PMTs)
  - the PMT coverage was limited, thus also the position reconstruction of edge events
- **next step:** 850 kg (100 kg fiducial mass) with 642 PMTs (64% photo coverage)
  - basic performance confirmed with prototype
  - vertex reconstruction, self-shielding, BG level are being studied with MCs
- detector is being designed, new hall in Kamioka is ready since February 08

Y. Suzuki, IDM08, Stockholm

100 kg (3 kg fiducial)



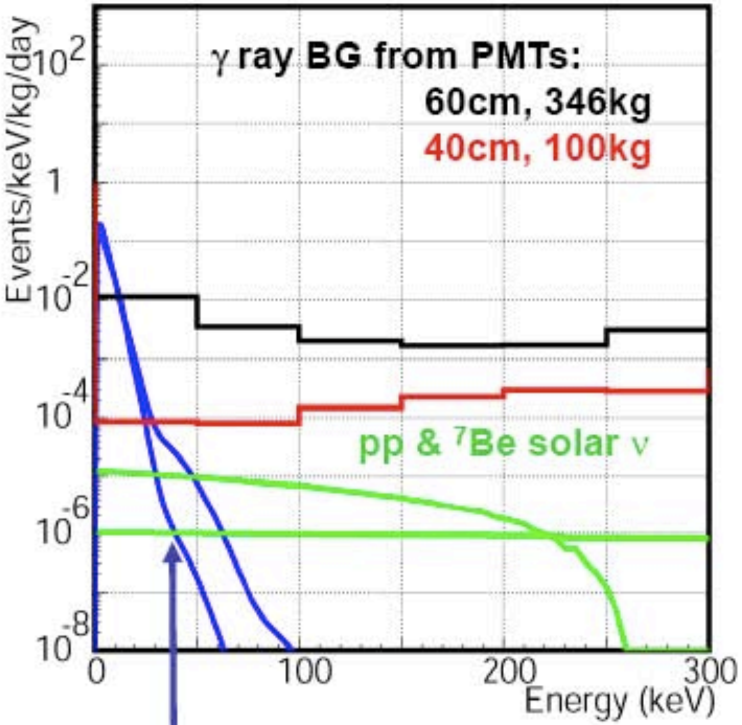
850 kg (100 kg fiducial)



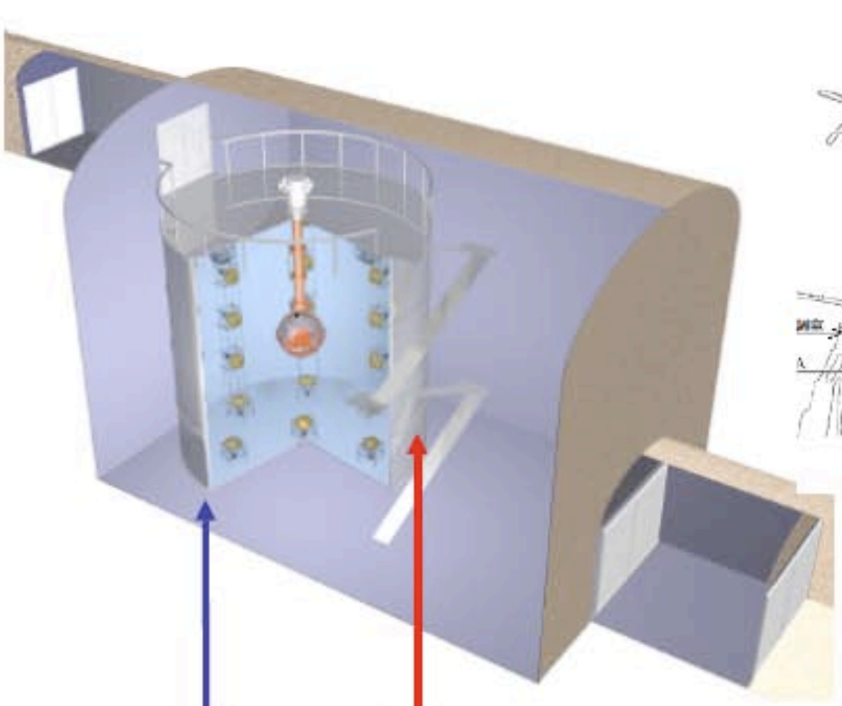
23 t (10 t fiducial)

Single-Phase Xenon: XMASS

- Active and passive water shield in new experimental hall at KAMIOKA - almost ready
- Construction of 10 m x 10 m water tank by February 2009; BG aim: 10^{-4} dru
- Expected WIMP sensitivity: 1×10^{-45} cm^2 for 0.5 ton × year exposure (100 GeV WIMP)

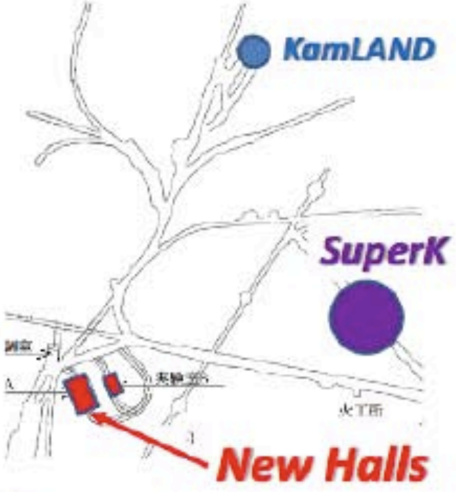


Expected dark matter signal
(assuming 10^{-42} cm^2, Q.F.=0.2, M_χ=50,100GeV)



~10m diameter, ~10m high pure water tank.

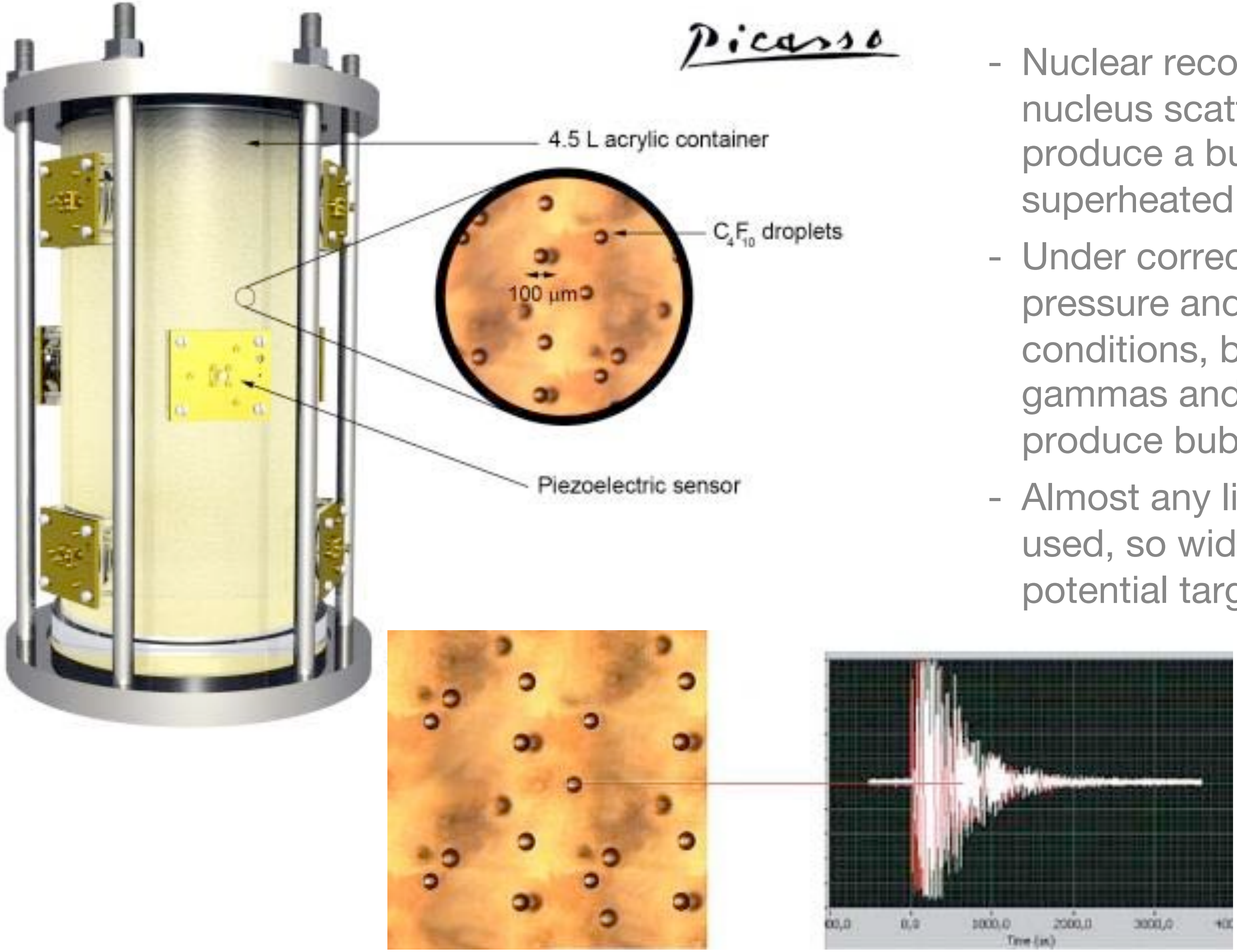
20-inch PMTs for veto counter.



Y. Suzuki, IDM08, Stockholm

Threshold detectors: SIMPLE, PICASSO

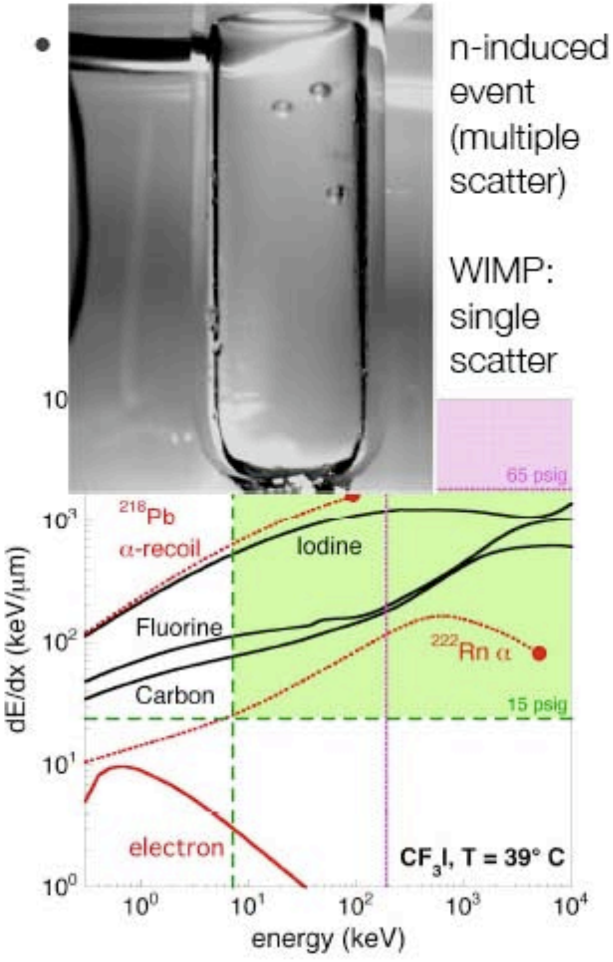
- Nuclear recoils from WIMP nucleus scattering can produce a bubble in a superheated liquid.
- Under correctly chosen pressure and temperature conditions, background gammas and betas can not produce bubbles.
- Almost any liquid can be used, so wide choice of potential target nuclei.



piezoelectric readout of acoustic signal

The COUPP Experiment

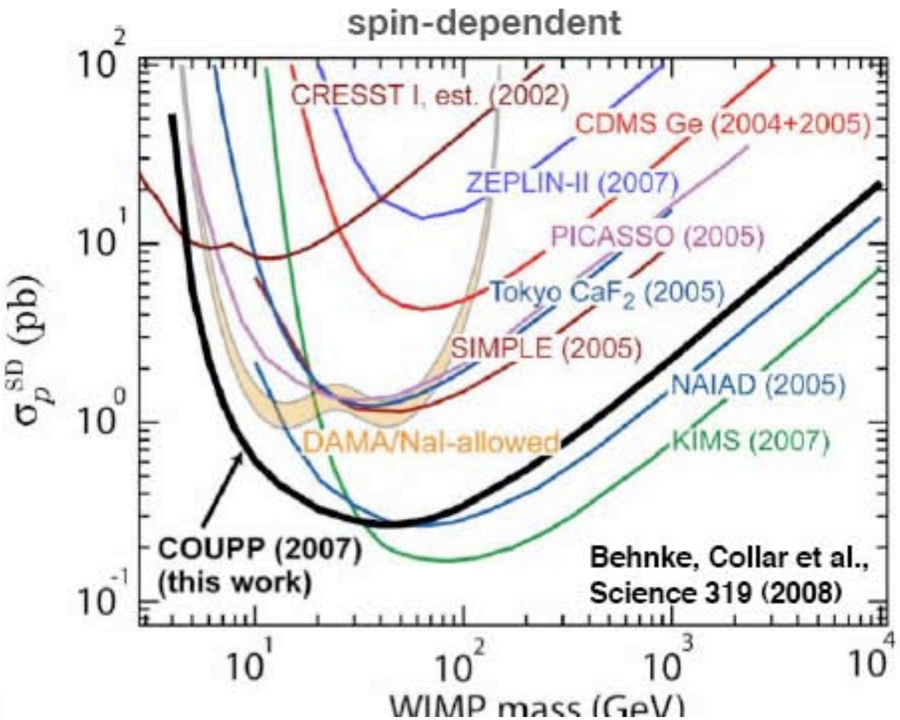
- superheated liquid -> detects single bubbles induced by high dE/dx nuclear recoils; **advantage:** large masses, low costs, SD, SI (I, Br, F, C), high spatial granularity, 'rejection' of ERs 10^{10} at 10keV$_r$; **challenge:** reduce alpha background



- n-induced event (multiple scatter)

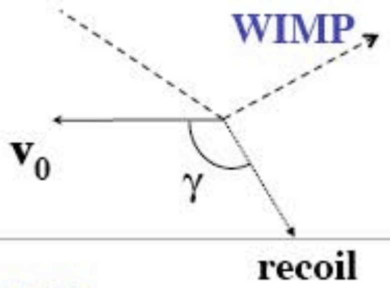
  WIMP: single scatter

2 kg detector at 300 mwe in 2006: α BG from walls
^{222}Rn decays -> ^{210}Pb plate-out + ^{222}Rn emanation
run with 2 kg in 2007/2008 (reduced backgrounds)
60 kg module under construction at FNAL -> 3 x 10^{-8}pb



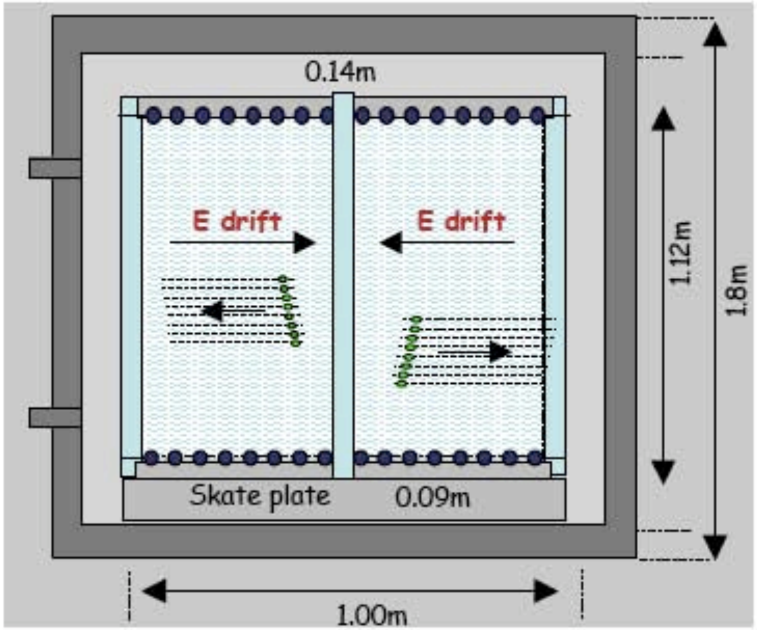
Laura Baudis, University of Zurich, ENTApP DM Worksho

Directional Detectors: gas TPCs



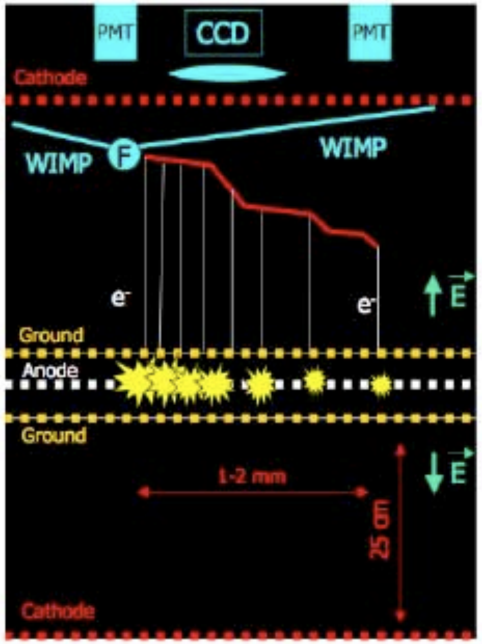
DRIFT at Boulby

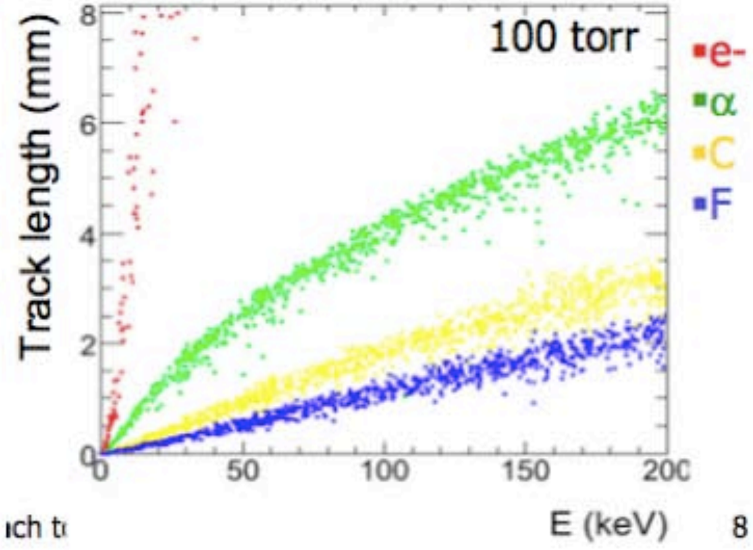
negative ion (CS$_2$) TPC: 1 m^3 40 Torr CS$_2$ gas (0.17 kg); 2 mm pitch anode + crossed MWPC
- NR discrimination via track morphology
- 3D track reconstruction for recoil direction: find head-tail of recoil based on dE/dx
- new run in 2007/08 at Boulby with strongly reduced Rn backgrounds



DM-TPC

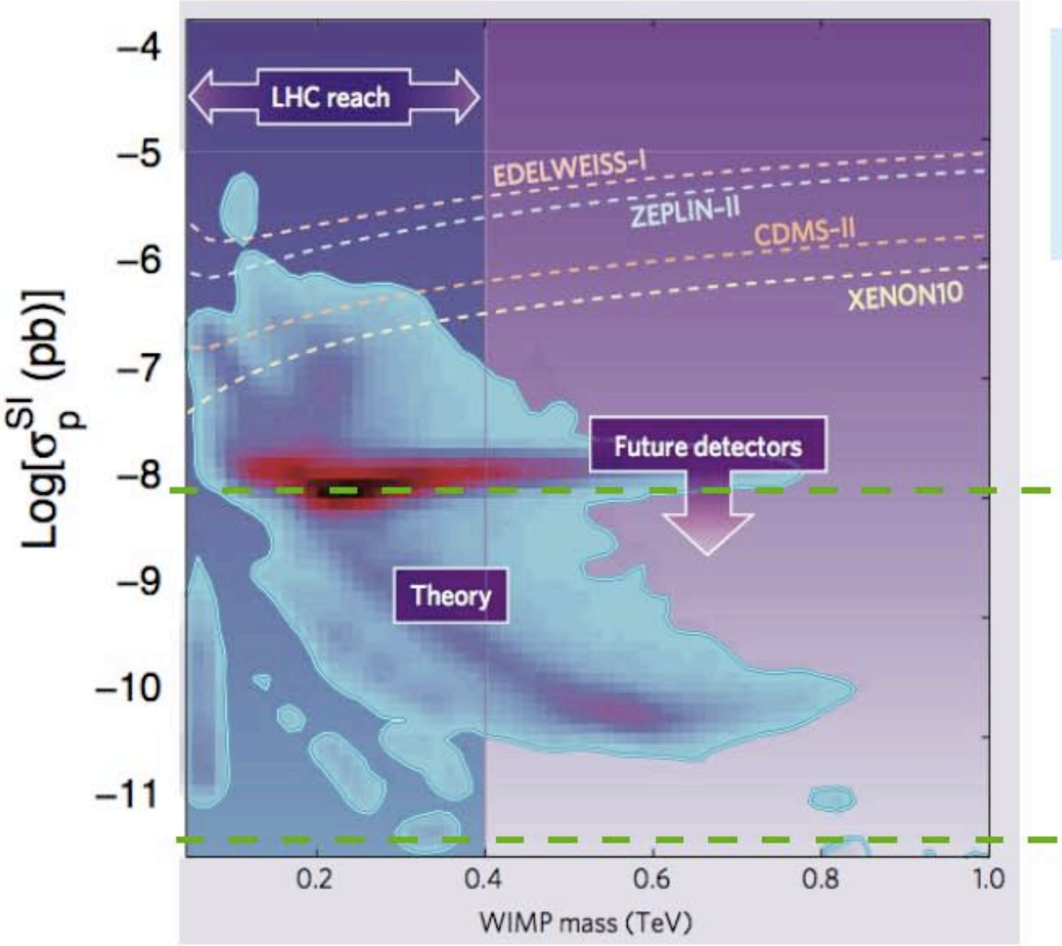
low-pressure CF$_4$ gas TPC: 50 Torr
- 40 keV recoil ~ 1-2 mm track
- PMTs for trigger => z - information
- CCD images avalanche region => E and x-y
- head-tail of recoil based on dE/dx
- 2 x 10^{-2} m^3 modules under commissioning at MIT and ready for operation at WIPP in 2009
- 1 m^3 detector being designed (0.25 - 0.5 kg/m^3)





Conclusions

- Many different techniques/targets are being employed to search for dark matter particles
- Experiments are probing some of the theoretically interesting regions for WIMP candidates
- Next generation projects: should reach the ≲ 10^{-10} pb level => WIMP (astro)-physics



Theory example: CMSSM (Roszkowski, Ruiz, Trotta)
see also: Balz, Baer, Bednyakov, Bottino, Cirelli, Chattopadhyay, Ellis, Fornengo, Giudice, Gondolo, Massiero, Olive, Profumo, Santoso, Spanos, Strumia, Tata,...+ many others

1 event/kg/yr WARP-140

sensitivity of existing experiments:
CDMS-II, XENON100, ArDM, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III,...

1 event/t/yr

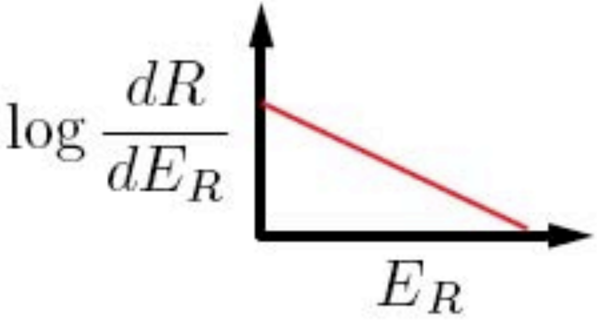
sensitivity of near-future projects
SuperCDMS1t, WARP1t, ArDM
XENON1t, EURECA, XMASS, ...

References

- References and notation - generally following the treatment of two key review articles:
  - J.D. Lewin and P.F. Smith, Astroparticle Physics 6 (1996)
  - G. Jungman, M. Kamionkowski and K. Griest, Physics Reports 267 (1996)
- Textbooks
  - D. Perkins, ‘Particle Astrophysics’, Oxford University Press, ISBN 0-19-850952.
  - L. Bergström and A. Goobar, ’Cosmology and Particle Astrophysics’, J. Wiley & Sons, ISBN 0-471-970542.
- See also
  - R.J. Gaitskell (experiment review) in Ann. Rev. Nucl. Part. Sci. 54 (2004)

Differential energy spectrum (simplified)

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r}$$



R = event rate per unit mass

E_R = recoil energy

R_0 = total event rate

E_0 = most probable incident energy (Maxwellian)

$r = \frac{4 M_W M_N}{(M_W + M_N)^2}$

M_W = mass of WIMP

M_N = mass of target nucleus

$$\int_0^\infty \frac{dR}{dE_R} dE_R = R_0$$

$$\begin{aligned} \langle E_R \rangle &= \int_0^\infty E_R \frac{dR}{dE_R} dE_R \\ &= E_0 r \end{aligned}$$

Typical numbers

For:

$$\begin{aligned} M_W &= M_N = 100\,\mathrm{GeV/c^2} \\ &\Rightarrow r = 1 \end{aligned}$$

$$\beta \sim 0.75 \times 10^{-3} = 220\,\mathrm{km/s}$$

$$\begin{aligned} \langle E_R \rangle = E_0 &= \tfrac{1}{2} M_W \beta_0^2 \mathrm{c}^2 \\ &= \tfrac{1}{2}\, 100\, \frac{\mathrm{GeV}}{\mathrm{c}^2} \left(0.75 \times 10^{-3}\right)^2 \mathrm{c}^2 \\ &= 30\,\mathrm{keV} \end{aligned}$$

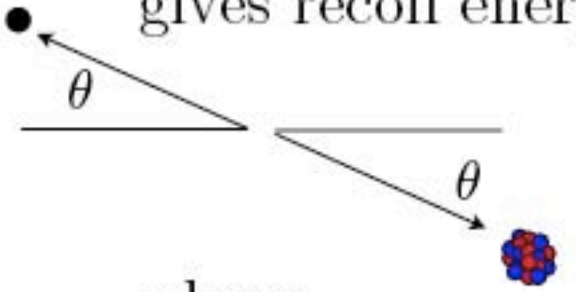
Refinements

$$\left.\frac{dR}{dE_R}\right|_{OBS} = R_0\, S(E_R)\, F^2(E_R)\, I$$

$$\begin{aligned} S(E_R) &= \text{spectral function — masses and kinematics} \\ F^2(E_R) &= \text{form factor correction, with } E_R = q^2/2M_W \\ I &= \text{interaction type} \end{aligned}$$

Kinematics

DM particle with velocity v and incident KE $E_i = \frac{1}{2} M_W v^2$
scattered at angle θ in CM frame
gives recoil energy in lab frame



$$E_R = E_i \, r \, \frac{(1 - \cos\theta)}{2}$$

where

$$r = \frac{4m_r^2}{M_W \, M_N} = \frac{4 \, M_W \, M_N}{(M_W + M_N)^2}$$

and

$$m_r = \frac{M_W \, M_N}{M_W + M_N}$$

is the reduced mass

Kinematics

Isotropic scattering: uniform in $\cos\theta$

Incident WIMP with energy E_i gives recoil energies uniformly in

$$E_R = 0 \rightarrow E_i\, r$$

Recall "familiar" case for equal masses ($r = 1$), target at rest, head-on collision

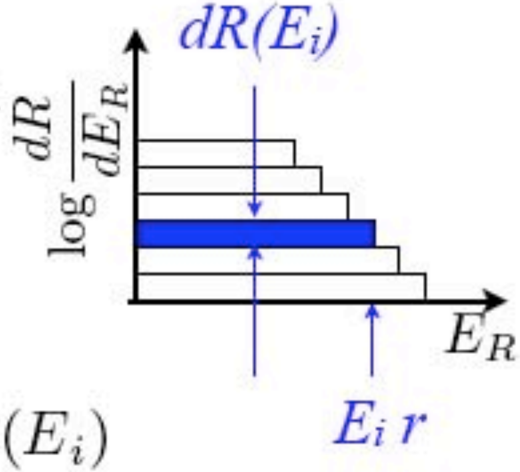
$$E_R = E_i$$

Overall spectrum? —sample incident spectrum

In each interval $E_i \rightarrow E_i + dE_i$

contribution to spectrum in $E_R \rightarrow E_R + dE_R$

at rate $dR(E_i)$ of



$$d\Big(\frac{dR}{dE_R}(E_R)\Big) = \frac{dR(E_i)}{E_i\, r}$$

Kinematics

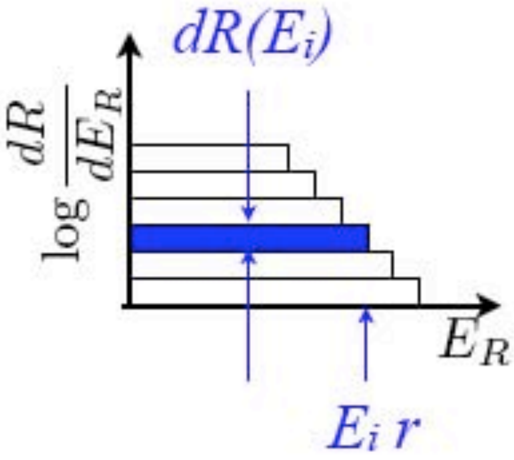
Need to integrate over range of incident energies

$$\frac{dR}{dE_R}(E_R) = \int_{E_{min}}^{E_{max}} \frac{dR(E_i)}{E_i\, r}$$

For E_{max} use ∞ or v_{esc} (later…)

For E_{min}, to get recoil of energy E_R need incident energy

$$E_i \geq \frac{E_R}{r} \equiv E_{min}$$



and also need differential rate…

Differential rate

In a kilogram of detector of nuclear mass number A

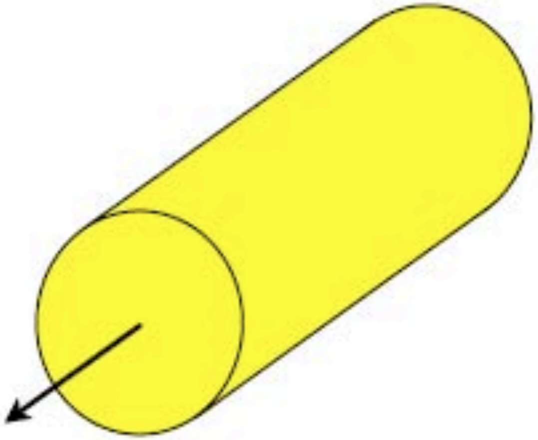
$$dR = \frac{N_0}{A} \sigma \, v \, dn$$

where the differential density dn is taken as a function v

$$dn = \frac{n_0}{k} f(\vec{v}, \vec{v}_E) \, d^3\vec{v}$$

with $n_0 = \rho_{DM}/M_W$ and normalization

$$k = \int f \, d^3\vec{v}$$



volume σv swept per unit time contains dn(v) particles with velocity v

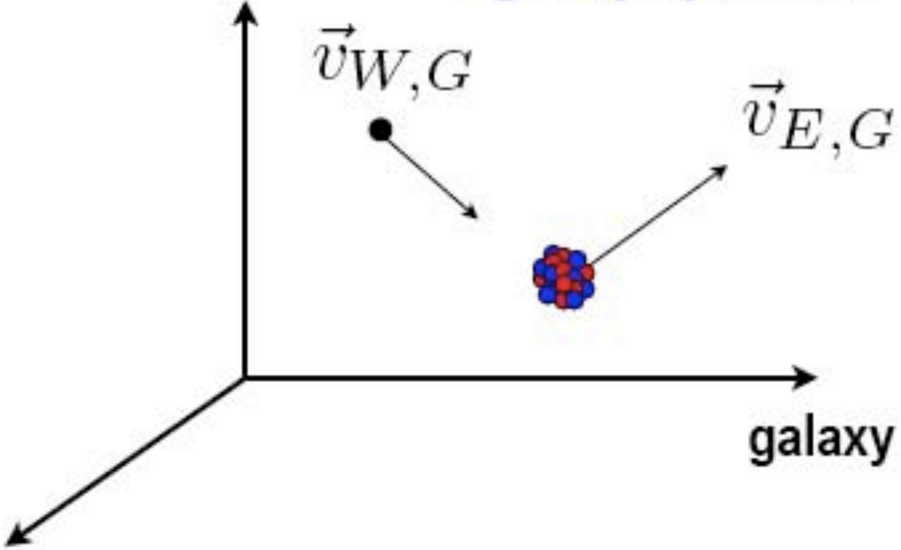
Coordinate system

collision kinematics

$$\begin{aligned}\vec{v} \quad = \quad \vec{v}_{W,E} &= \text{WIMP velocity in the target/Earth frame}\\ \vec{v}_{E,G} &= \text{Earth velocity in the Galaxy frame}\\ \vec{v}_{W,G} &= \text{WIMP velocity in the Galaxy frame}\end{aligned}$$

galaxy dynamics

$$\begin{aligned}\vec{v}_{W,G} &= \vec{v}_{W,E} + \vec{v}_{E,G}\\ &= \vec{v} \qquad + \vec{v}_E\end{aligned}$$



$$f(\vec{v}, \vec{v}_E) = e^{-(\vec{v}+\vec{v}_E)^2/v_0^2}$$

Maxwellian velocity distribution

Differential rate

For simplified case of $v_E = 0$ and $v_{esc} = \infty$

$$dR = R_0 \frac{1}{2\pi v_0^4} \, v \, f(v,0) \, d^3v$$

with $R_0 = 2\pi^{-\frac{1}{2}} \frac{N_0}{A} \frac{\rho_{DM}}{M_W} \sigma_0 v_0$

For Maxwellian $f(v,0) = e^{-v^2/v_0^2}$,
isotropic $d^3v \rightarrow 4\pi v^2 dv$,
$E_i = \frac{1}{2} M_W v^2$ and $E_0 = \frac{1}{2} M_W v_0^2$:

$$\begin{aligned} \frac{dR}{dE_R}(E_R) &= \int_{\frac{E_R}{r}}^{\infty} \frac{dR(E_i)}{E_i \, r} = \frac{R_0}{r(\frac{1}{2} M_W v_0^2)^2} \int_{v_{min}}^{\infty} e^{-v^2/v_0^2} v \, dv \\ &= \frac{R_0}{E_0 r} e^{-E_R/E_0 \, r} \end{aligned}$$

$$v_{min} = \sqrt{2E_R/rM_W}$$

Corrections: escape velocity

For finite v_{esc}

$$\frac{dR}{dE_R} = \frac{k_0}{k_1(v_{esc}, 0)} \frac{R_0}{E_0 r} (e^{-E_R/E_0 r} - e^{-v_{esc}^2/v_0^2})$$

but $\frac{k_0}{k_1} = 0.9965$ for $v_{esc} = 600\,\mathrm{km/s}$,

and for $M_W = M_N = 100\,\mathrm{GeV/c^2}$,
maximum $E_R = 200\,\mathrm{keV}$

$$\Rightarrow \text{cutoff energy} \gg \langle E_R \rangle = 30\,\mathrm{keV}$$

Corrections: earth velocity

Clearly $\vec{v}_E \neq 0$ — but $\sim v_0 = 230\,\mathrm{km/s}$. Full calculation yields:

$$\frac{dR(v_{esc}, v_E)}{dE_R} = \frac{k_0}{k_1}\frac{R_0}{E_0 r}\left(\frac{\sqrt{\pi}}{4}\frac{v_0}{v_E}\left[\mathrm{erf}\left(\frac{v_{min}+v_E}{v_0}\right) - \mathrm{erf}\left(\frac{v_{min}-v_E}{v_0}\right)\right] - e^{-v_{esc}^2/v_0^2}\right)$$

where $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$, $v_{min} = v_0\sqrt{E_R/E_0 r}$, $k_0 = (\pi v_0^2)^{\frac{3}{2}}$
and

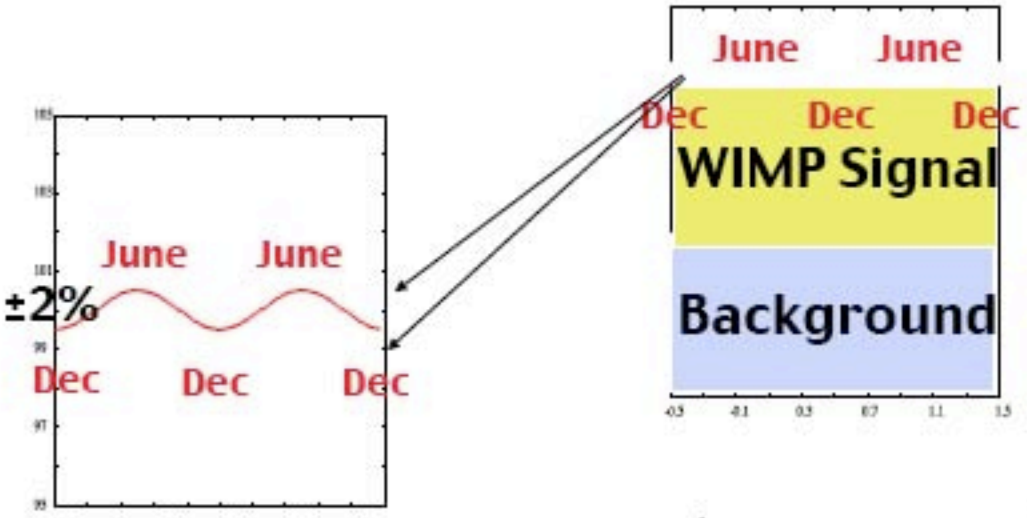
$$k_1 = k_0\left[\mathrm{erf}\left(\frac{v_{esc}}{v_0}\right) - \frac{2}{\sqrt{\pi}}\frac{v_{esc}}{v_0} - e^{-v_{esc}^2/v_0^2}\right]$$

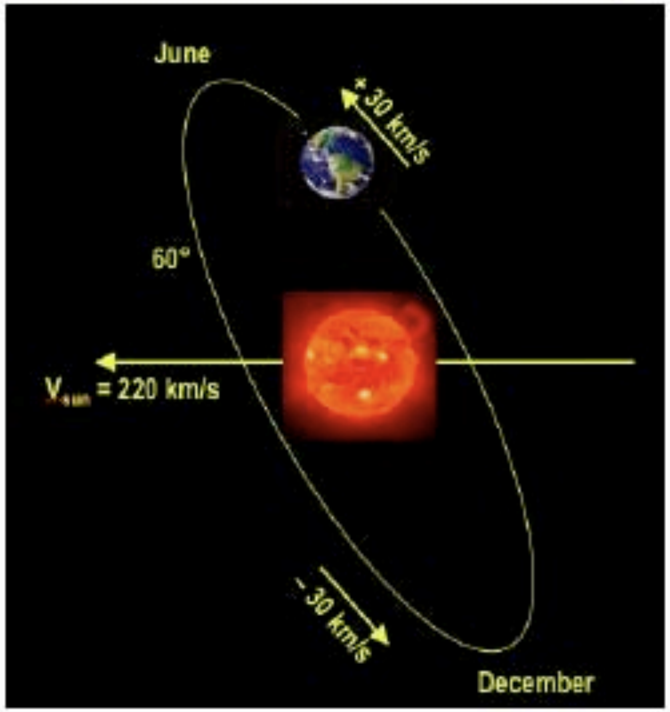
Fortunately, average value well approximated by numerical fit

$$\frac{dR(v_{esc} = \infty, v_E)}{dE_R} = c_1\frac{R_0}{E_0 r}\,e^{-c_2 E_R/E_0 r}$$

~30% increase in integrated rate = c_1/c_2 = 0.751/0.561
and harder spectrum

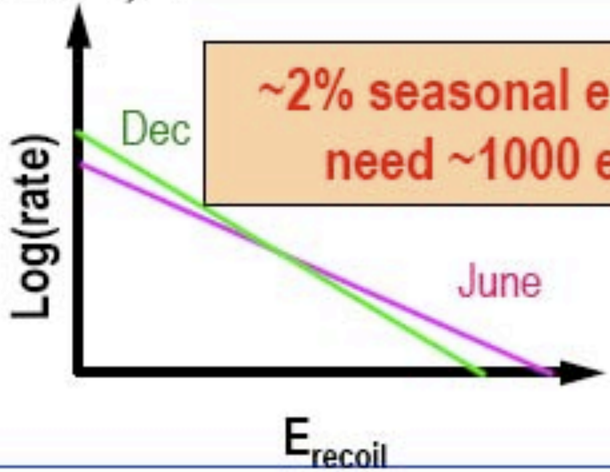
Signal modulations: annual effect





$$v_E(t)[\mathrm{km/s}] = 232 + 15\cos\left(2\pi\,\frac{t-152.5}{365.25}\right)$$

t in days after January 1



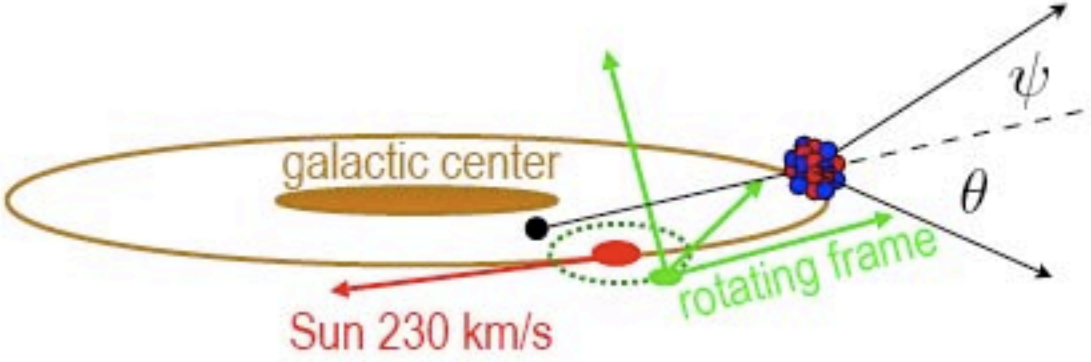
~2% seasonal effect - need ~1000 events

Signal modulations: recoil direction

- **Differential angular spectrum:**

$$\frac{d^2R}{dE_R d(\cos\psi)} = \frac{1}{2}\frac{R_0}{E_0 r}e^{-(v_E\cos\psi - v_{min})^2/v_0^2}$$

- **Asymmetry → more recoils in forward direction by 5x: ~10 events**
- **Orientation of lab frame rotates relative to forward direction**
  - eg, definition of forward/backward in lab frame changes as earth rotates
  - ⊥ versus || reduces asymmetry to 20% effect: ~300 events



Refinements

$$\left.\frac{dR}{dE_R}\right|_{OBS} = R_0\, S(E_R)\, F^2(E_R)\, I$$

✓ $S(E_R)$ = spectral function — masses and kinematics

time dependence

$F^2(E_R)$ = form factor correction, with $E_R = q^2/2M_W$

I = interaction type

in zero-velocity limit (v<<c), scalar and axial vector interactions dominate → **spin independent** and spin dependent couplings

these dominate

Nuclear form factor and Spin Ind. interactions

- **Scattering amplitude: Born approximation** $\vec{q} = \hbar\,(\vec{k}' - \vec{k})$
- **Spin-independent scattering is coherent** $\lambda = \hbar/q \sim \text{few fm}$

$$M(\vec{q}) = f_n\, A \underbrace{\int d^3x\, \rho(\vec{x})\, e^{i\,\vec{q}\cdot\vec{x}}}_{F(\vec{q})} \quad \Rightarrow \quad \sigma \propto |M|^2 \propto A^2$$

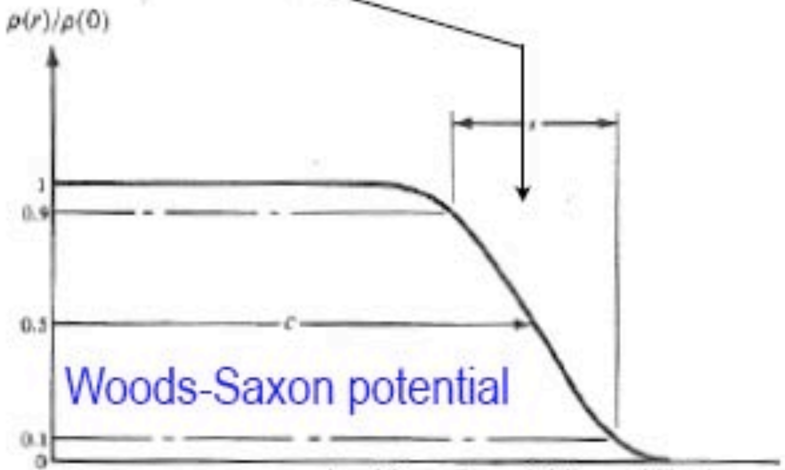
fundamental coupling to nucleon

mass number

"Helm" form factor

$$F(qr_n) = \underbrace{\frac{3[\sin(qr_n) - qr_n\cos(qr_n)]}{(qr_n)^3}}_{j_1(qr_n)}\, e^{-(qs)^2/2}$$

- **j_1 exact for 'sharp' density cutoff**
  - ***r_n* nuclear radius**
  - ***s* skin thickness parameter**



Woods-Saxon potential

swiped from Fraunfelder and Henley

SI cross section

- Now have dependence on q^2 and nucleus → separate out fundamental WIMP-nucleon cross section
- Differential cross section can be written

$$\frac{d\sigma_{WN}(q)}{dq^2} = \frac{\sigma_{0WN}\,F^2(q)}{4m_r^2 v^2}$$

rel. velocity in CM frame

where σ_{0WN} is total cross section for $F = 1$.
From Fermi's Golden Rule

$$\frac{d\sigma_{WN}(q)}{dq^2} = \frac{1}{\pi v^2}|M|^2 = \frac{1}{\pi v^2} f_n^2 A^2 F^2(q)$$

- Can identify "unity-form-factor" cross sections:

$$\sigma_{0WN} = \frac{4m_r^2}{\pi} f_n^2 A^2 = \underbrace{\frac{4}{\pi} m_n^2 f_n^2}_{\sigma_{Wn}} \frac{m_r^2}{m_n^2} A^2$$

nucleus

nucleon

all the particle physics, here

SI cross section and differential rate

- **Putting this all together**

$$\frac{d\sigma_{WN}(q)}{dq^2} = \frac{1}{4m_n^2 v^2}\sigma_{Wn} A^2 F^2(q)$$

- **Recall**

$$\frac{dR}{dE_R} = \int \frac{dR(E)}{Er} \qquad \text{(where } dR(E) \text{ contained } \sigma\text{)}$$

- **The *Er* factor was from isotropic scattering - corresponds to the *v*^{2} in the differential cross section. Including now the FF:**

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r} F^2(q)$$

particle physics

$$R_0 = \frac{2}{\sqrt{\pi}} \frac{N_0}{A} n_0 \sigma_0 v_0 \qquad \sigma_{Wn} \frac{A^2}{m_n^2}\left(\frac{M_W\, M_N}{M_W + M_N}\right)^2$$

halo

detector

Nuclear form factor and Spin Dep. interactions

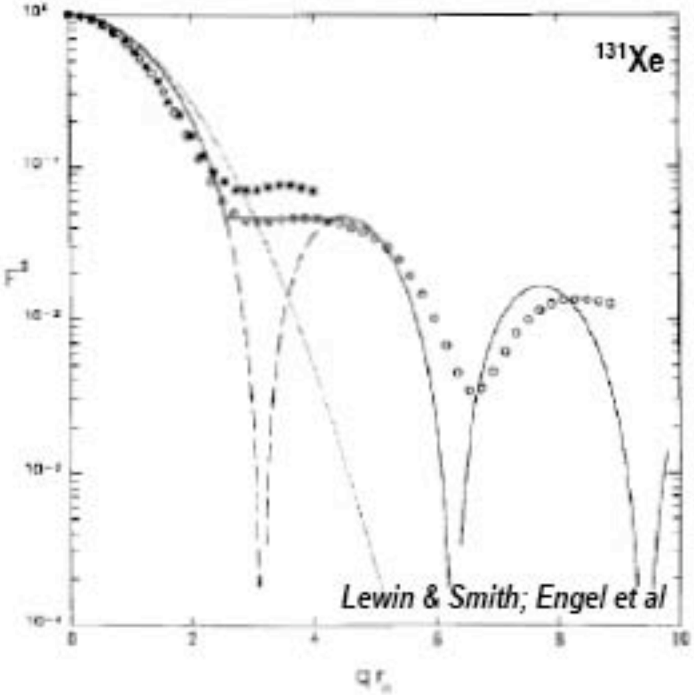
- **Scattering amplitude dominated by unpaired nucleon**
  - paired nucleons ↑↓ tend to cancel -- couple to net spin *J*

$$\frac{d\sigma}{dq^2} = \frac{8}{\pi v^2}\Lambda^2 G_F^2 J(J+1)F^2(q)$$

- **Simplified model based on thin-shell valence nucleon**

$$F(qr_n) = j_0(qr_n) = \frac{\sin(qr_n)}{qr_n}$$

- **Better: detailed nucleus specific calcs.**
  - average over odd-group nucleons
  - use measured nuclear magnetic moment



Lewin & Smith; Engel et al