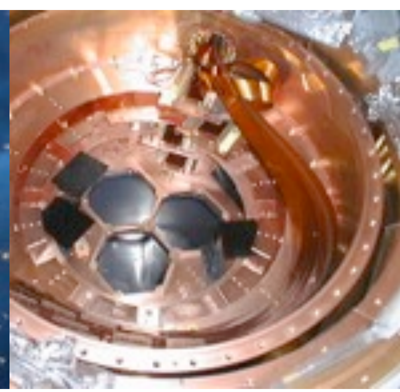
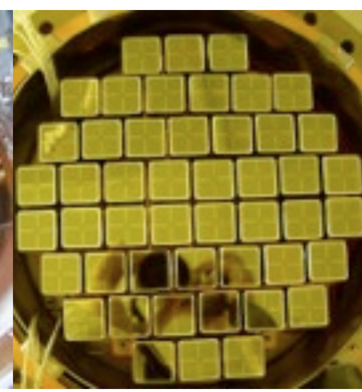
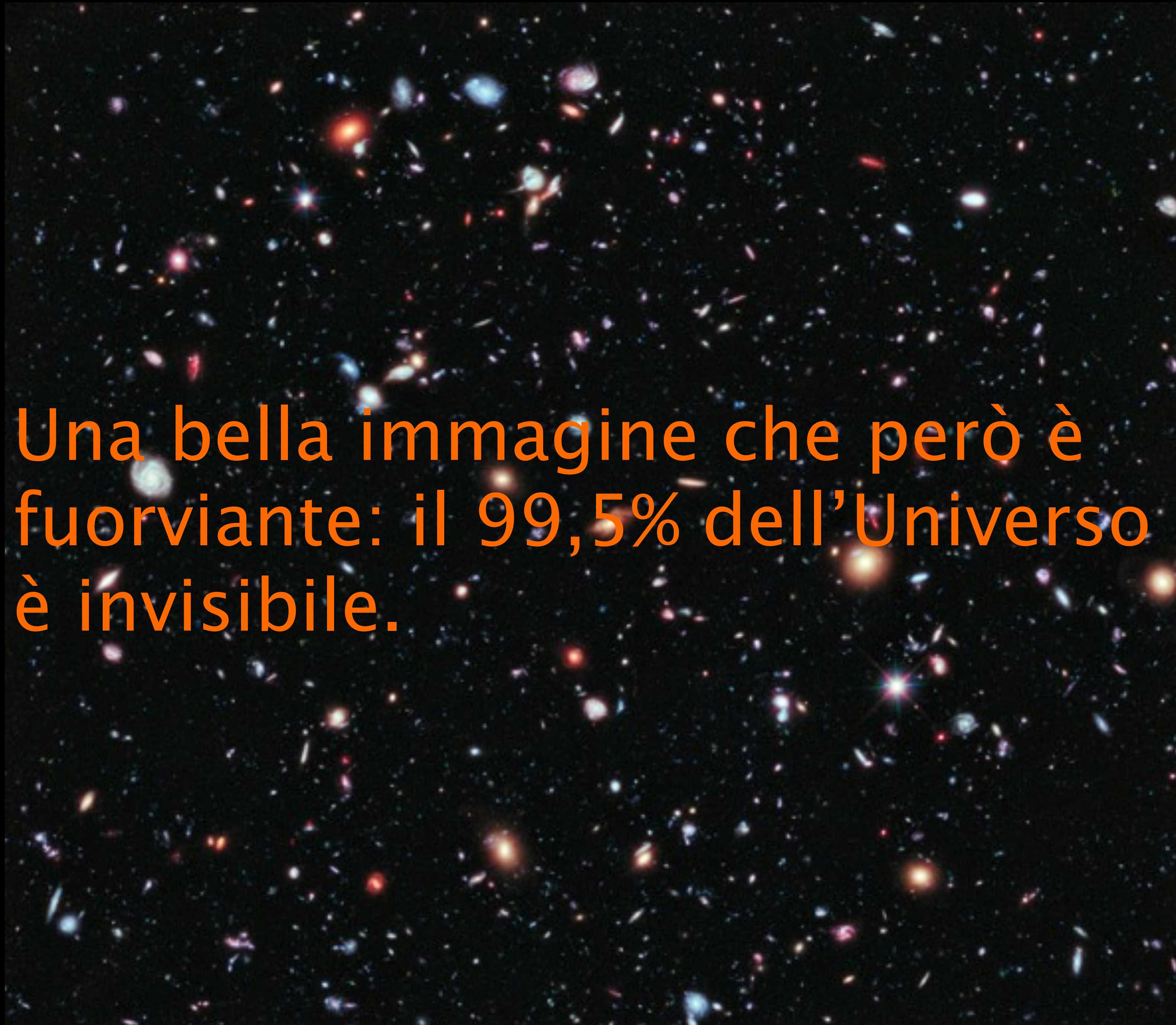
Dark matter: direct searches with underground detectors

Giuliana Fiorillo
Università degli Studi di Napoli "Federico II"

June 28, 2013


- Concordance Model

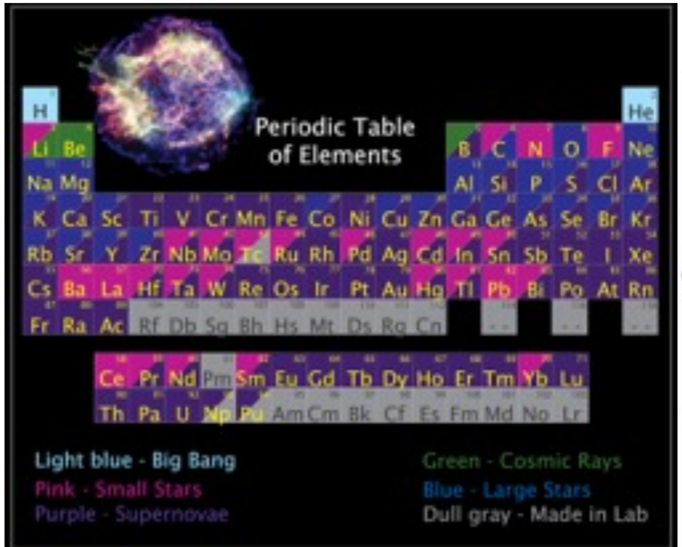


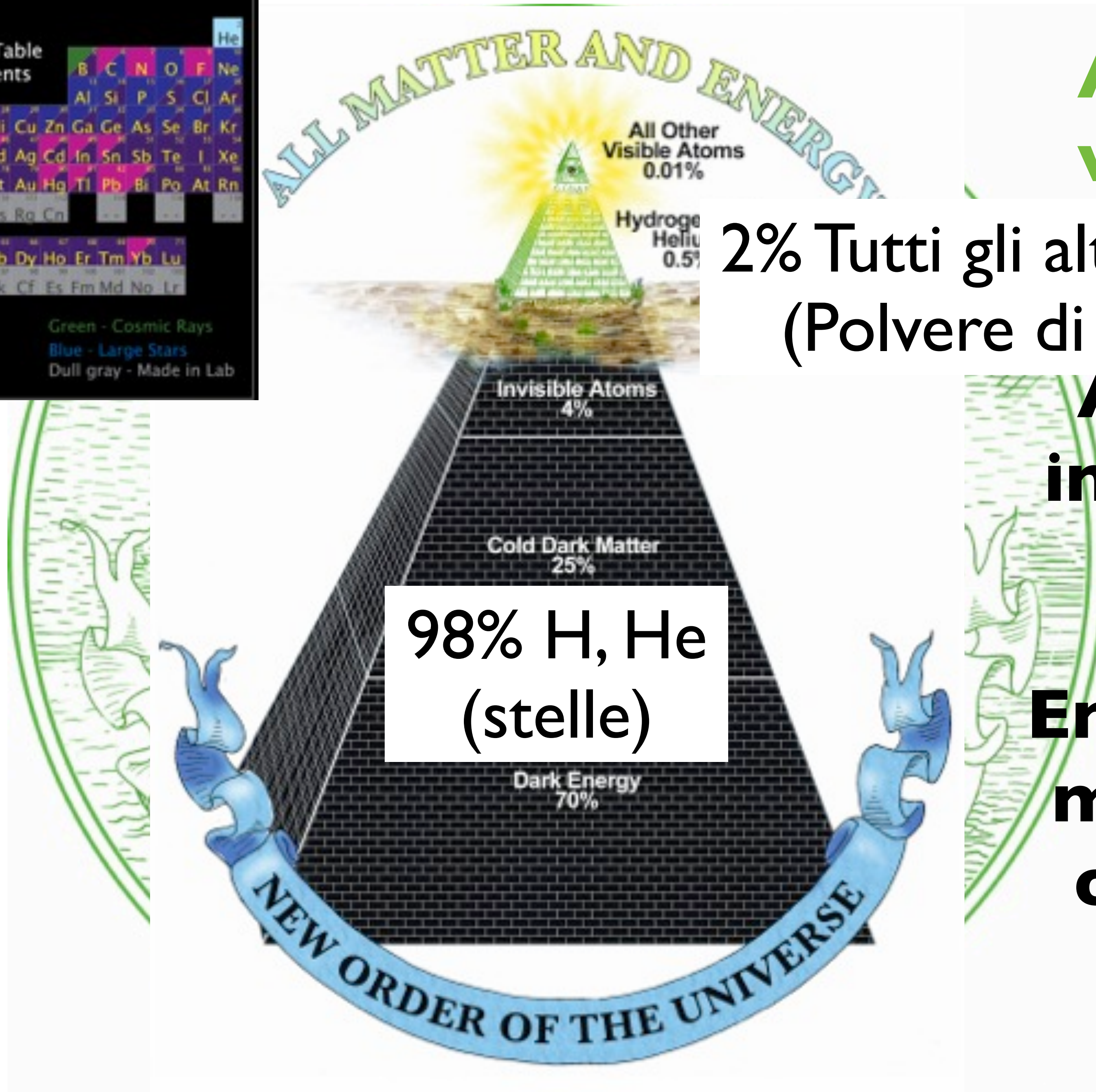
Una bella immagine che però è fuorviante: il 99,5% dell’Universo è invisibile.

Credit: credit: NASA, ESA, G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz), R. Bouwens (Leiden University), and the HUDF09 Team

Pilastri della creazione: Nebulosa della Carena
(luce visibile)

Pilastri della creazione: Nebulosa della Carena
(luce infrarossa)





Atomi visibili

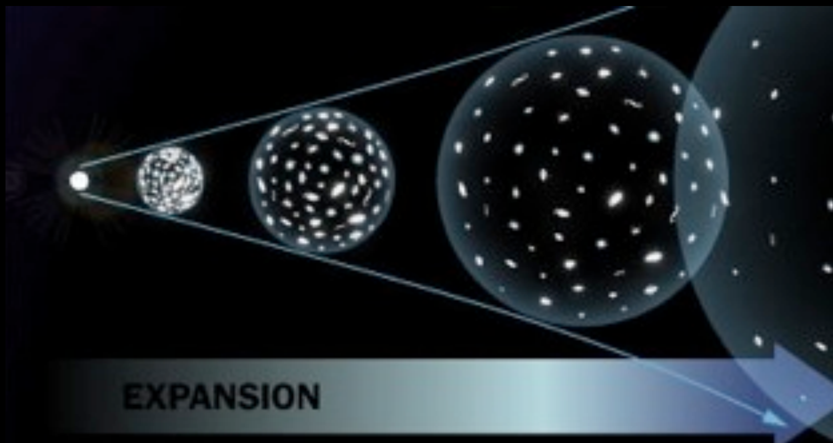
2% Tutti gli altri atomi
(Polvere di stelle)

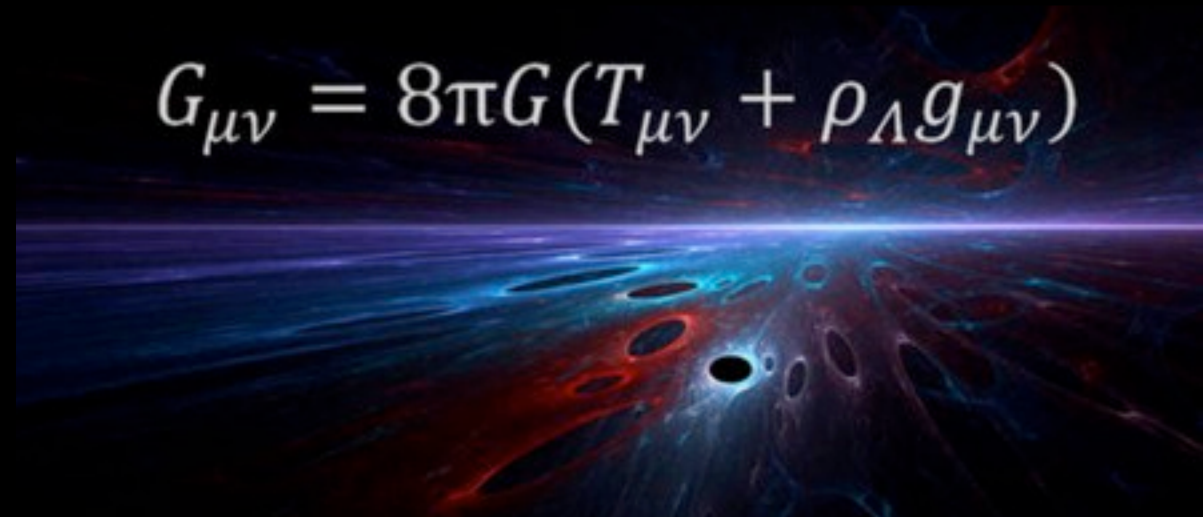
98% H, He
(stelle)

Atomi invisibili 4%

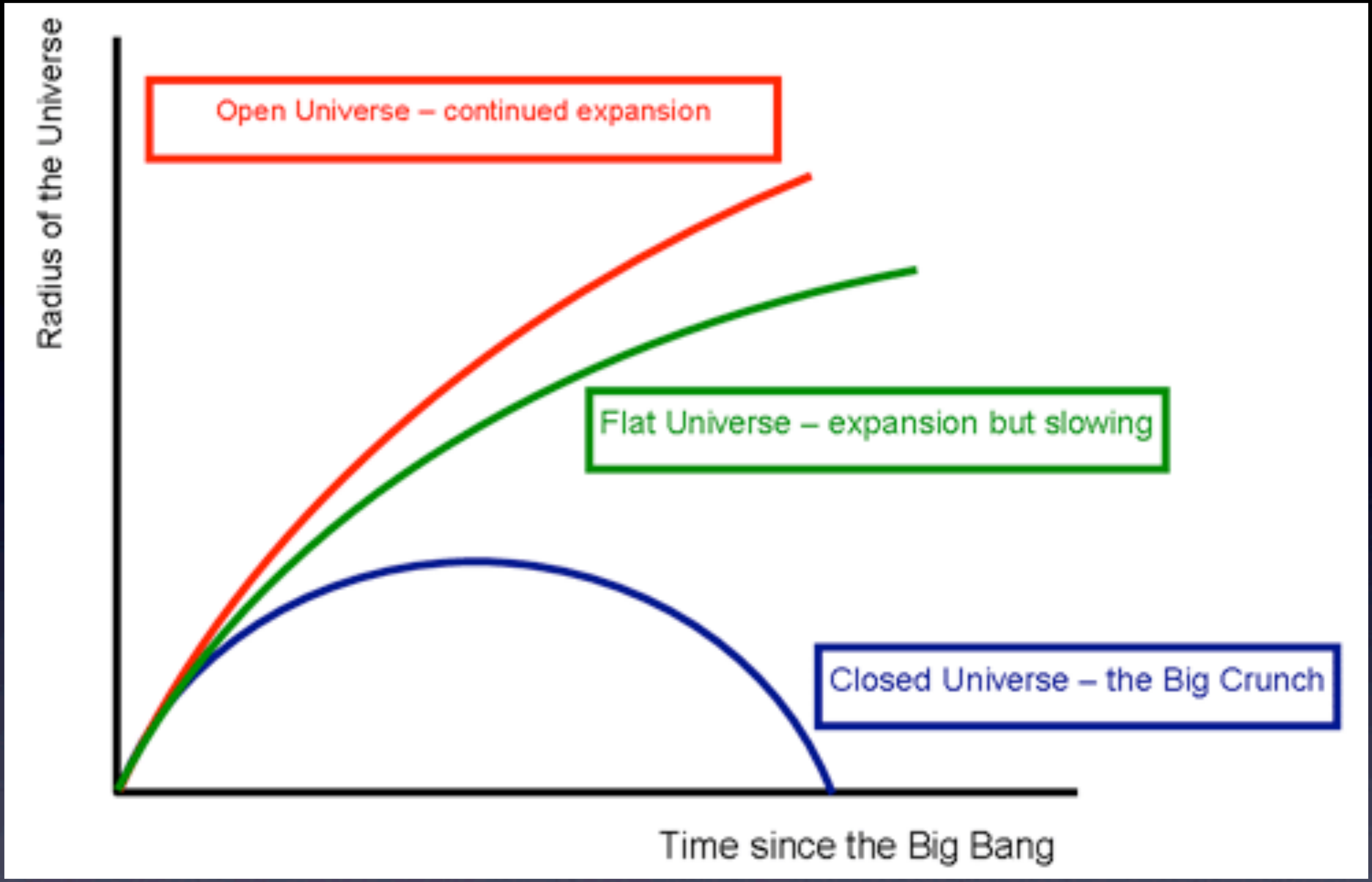
Energia e materia oscura 95%

- L’Universo visibile:
  - su larga scala ci appare omogeneo ed isotropo
  - le galassie lontane mostrano una velocità di recessione direttamente proporzionale alla distanza (legge di Hubble)
  - radiazione di fondo nella banda delle microonde isotropa (Cosmic Microwave Background, CMB)
  - contiene più ^4He di quanto possa essere stato prodotto all’interno delle stelle per processi di fusione nucleare

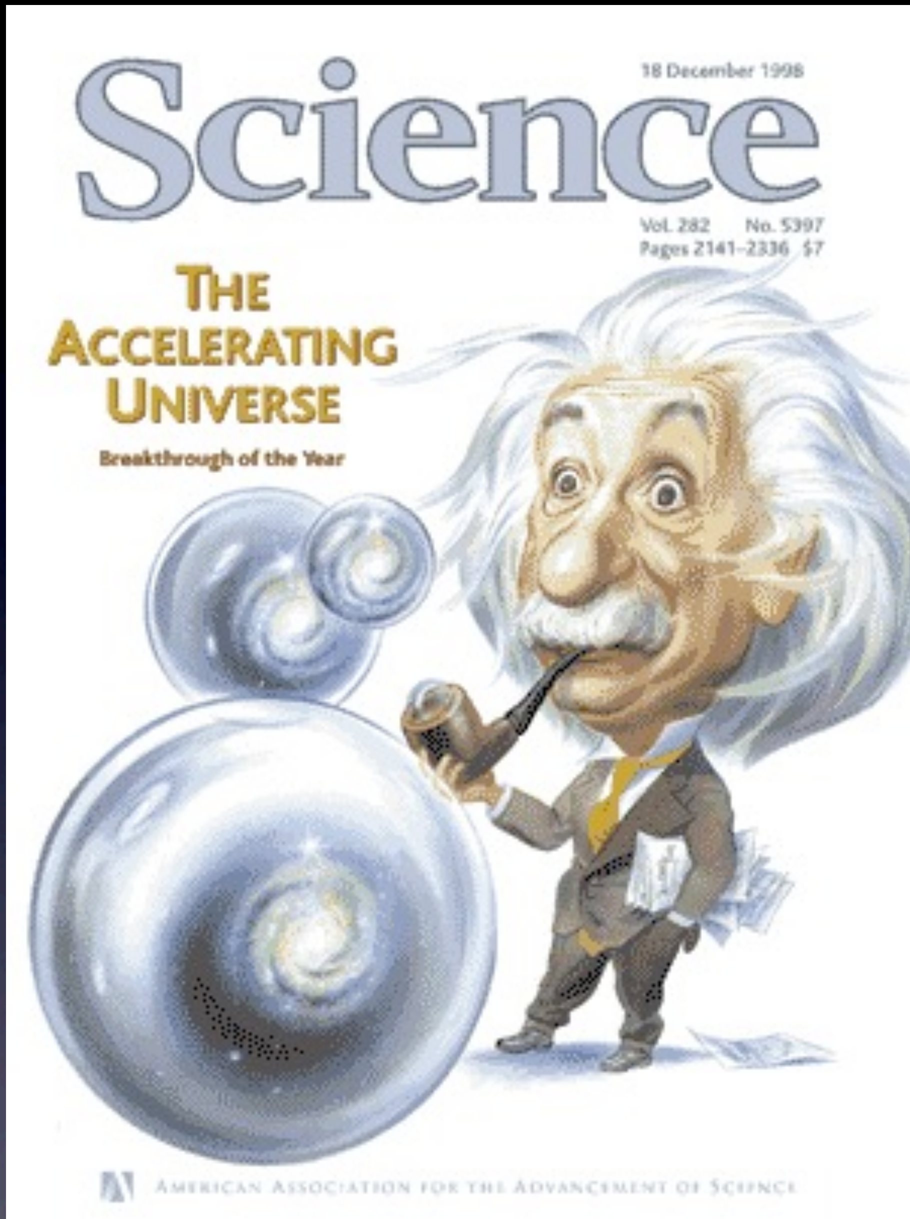


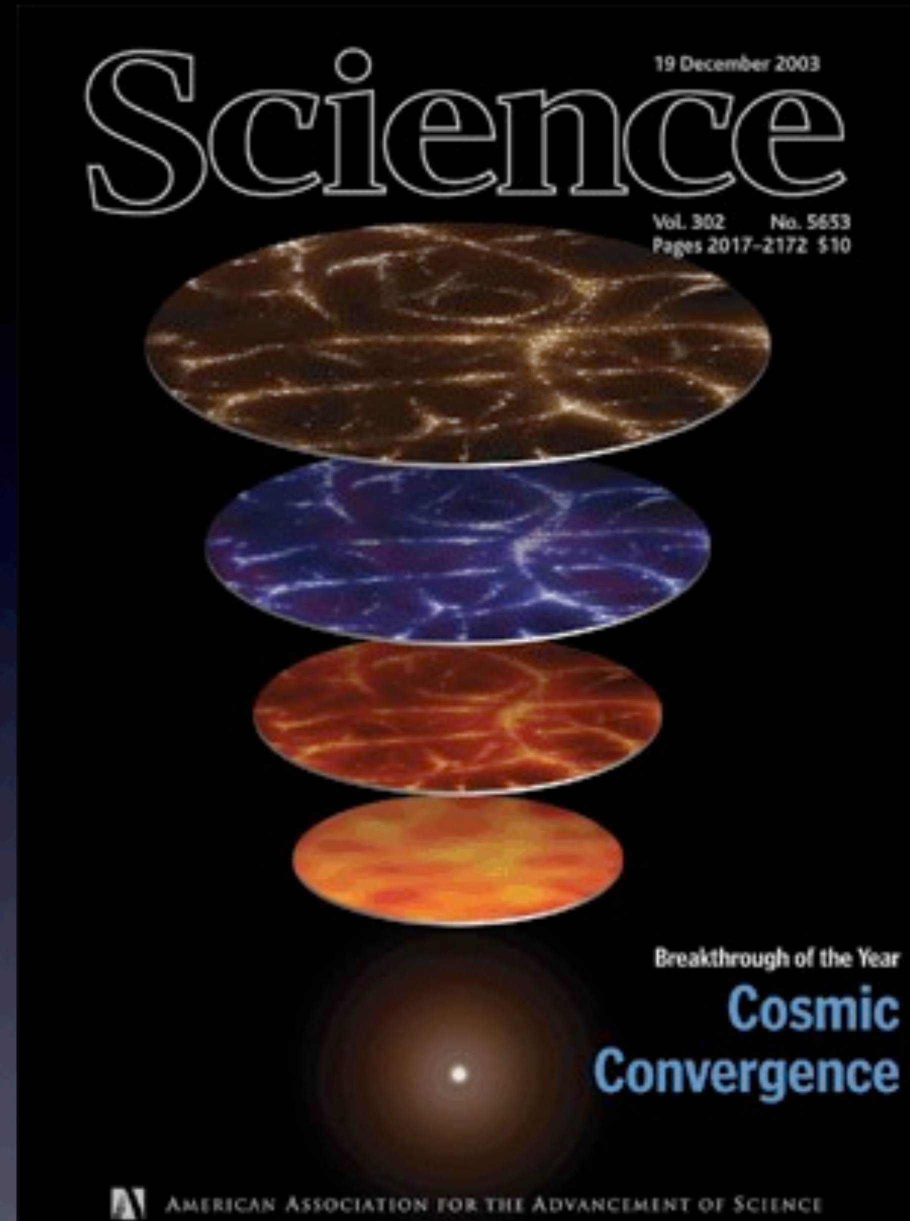


dalla relatività generale



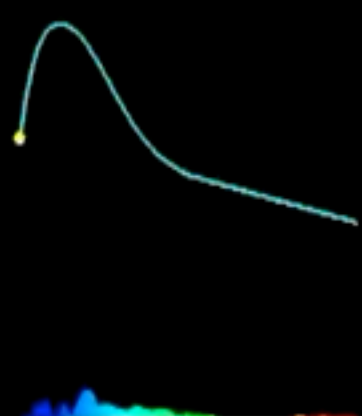
il destino dell'Universo

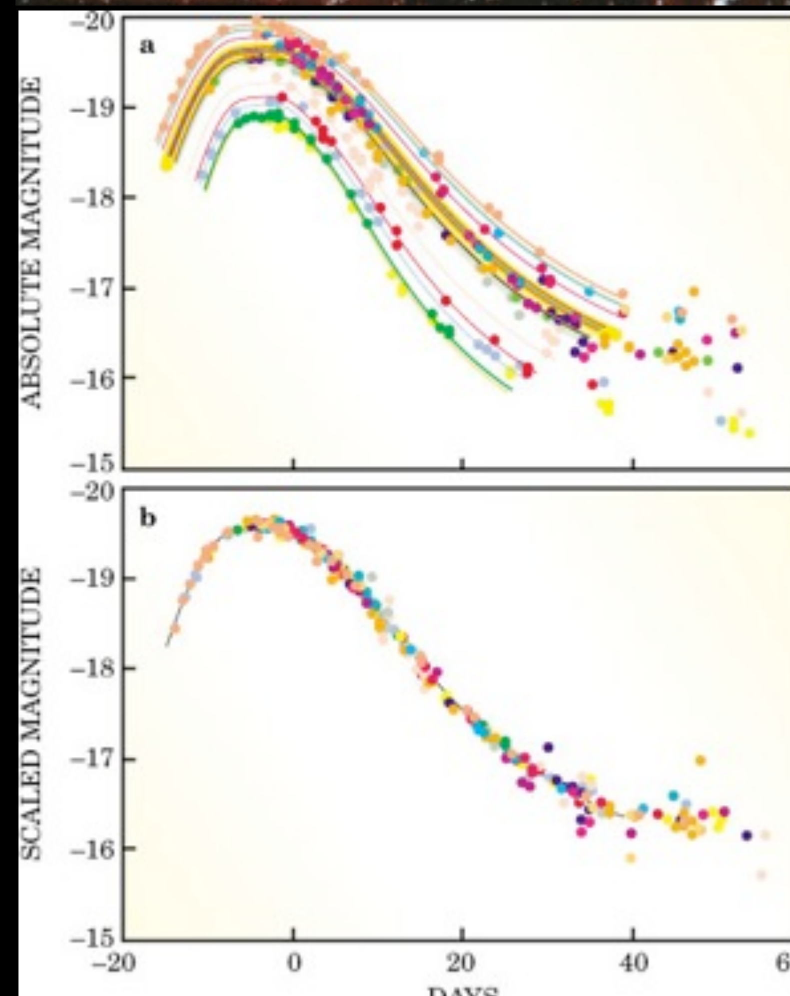




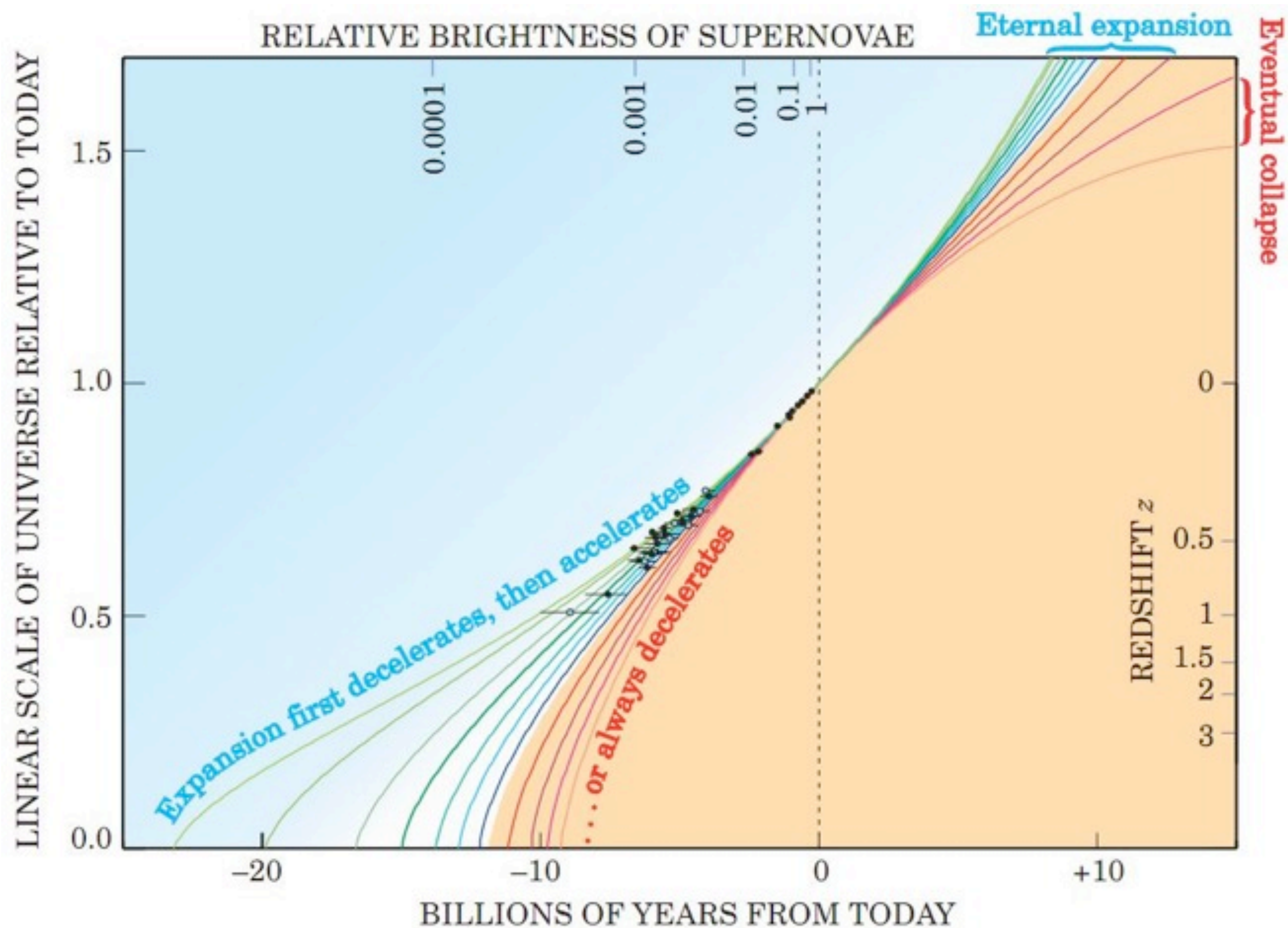
1998 NOTIZIA DELL'ANNO 2003

Supernovae come candele standard

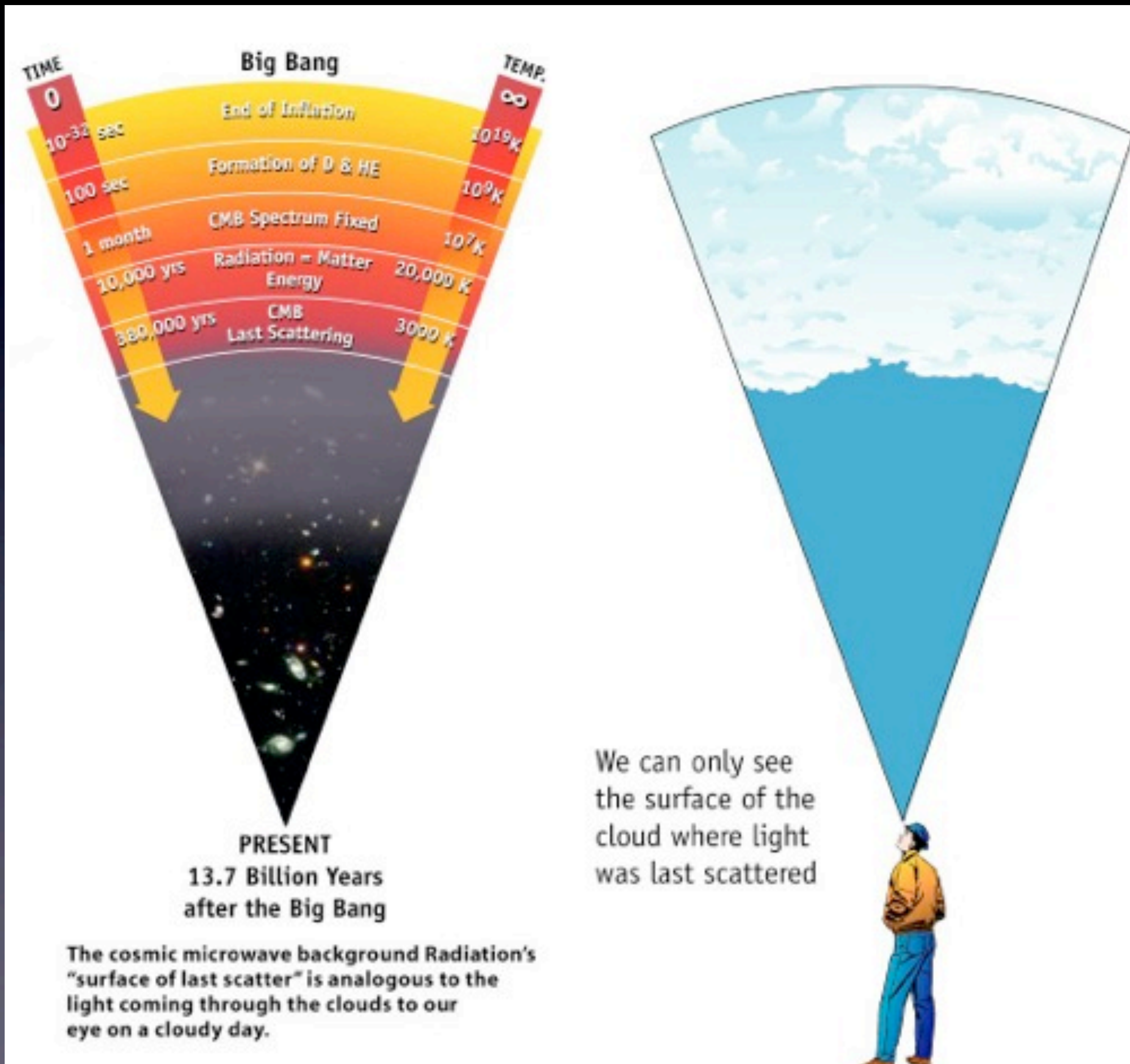




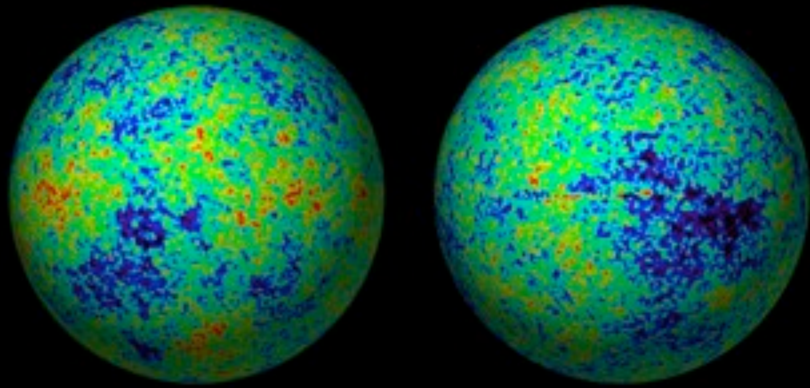
La misura contemporanea di velocità e distanza, per galassie a distanze diverse molto lontane nel passato, permette di misurare il tasso di accelerazione dell'Universo, e di predirne l'evoluzione futura!

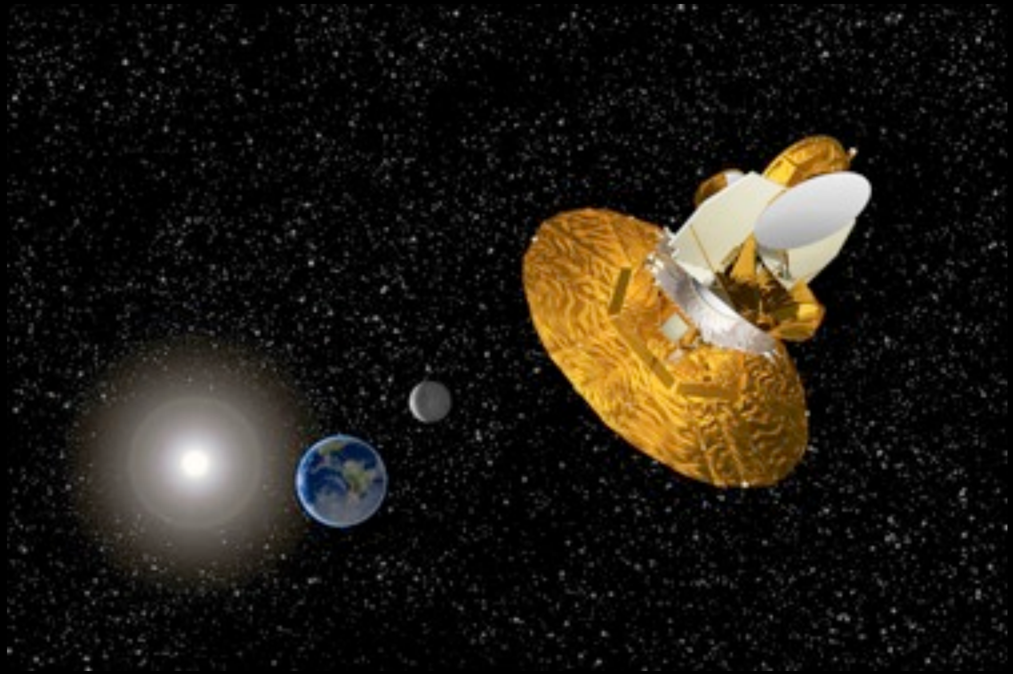


Un’altra finestra sull’Universo primordiale: la radiazione cosmica di fondo

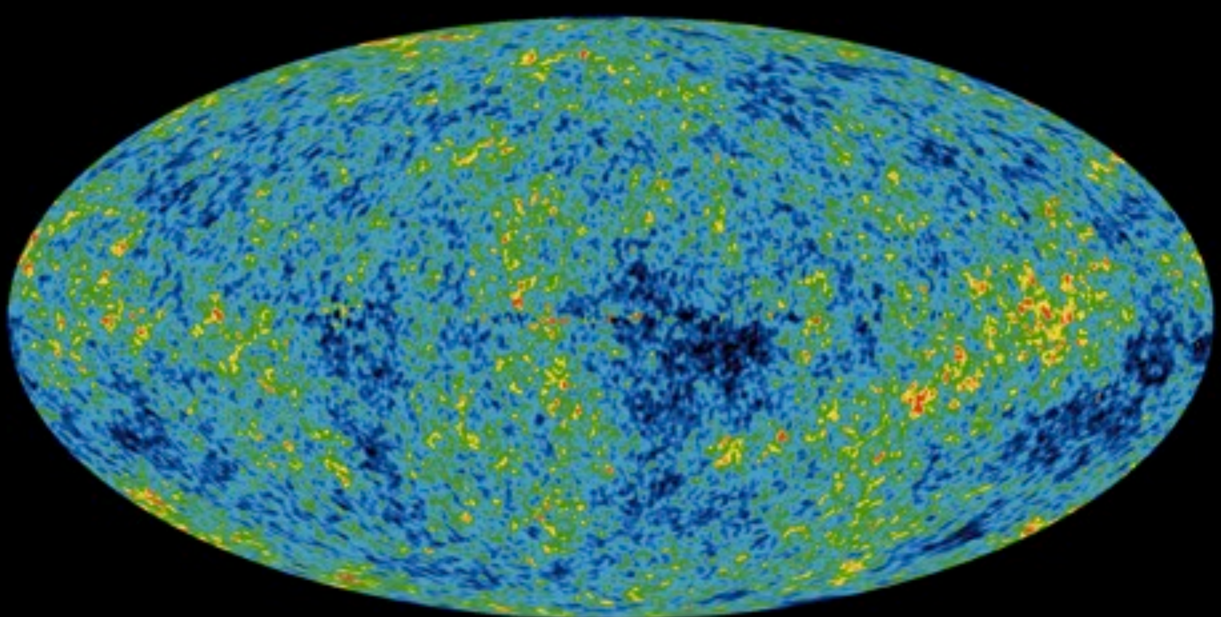


Fossile delle fluttuazioni quantistiche 10^{-34} secondi dopo il Big Bang, congelate dopo l’inflazione e manifeste nelle fluttuazioni di temperatura nell’Universo

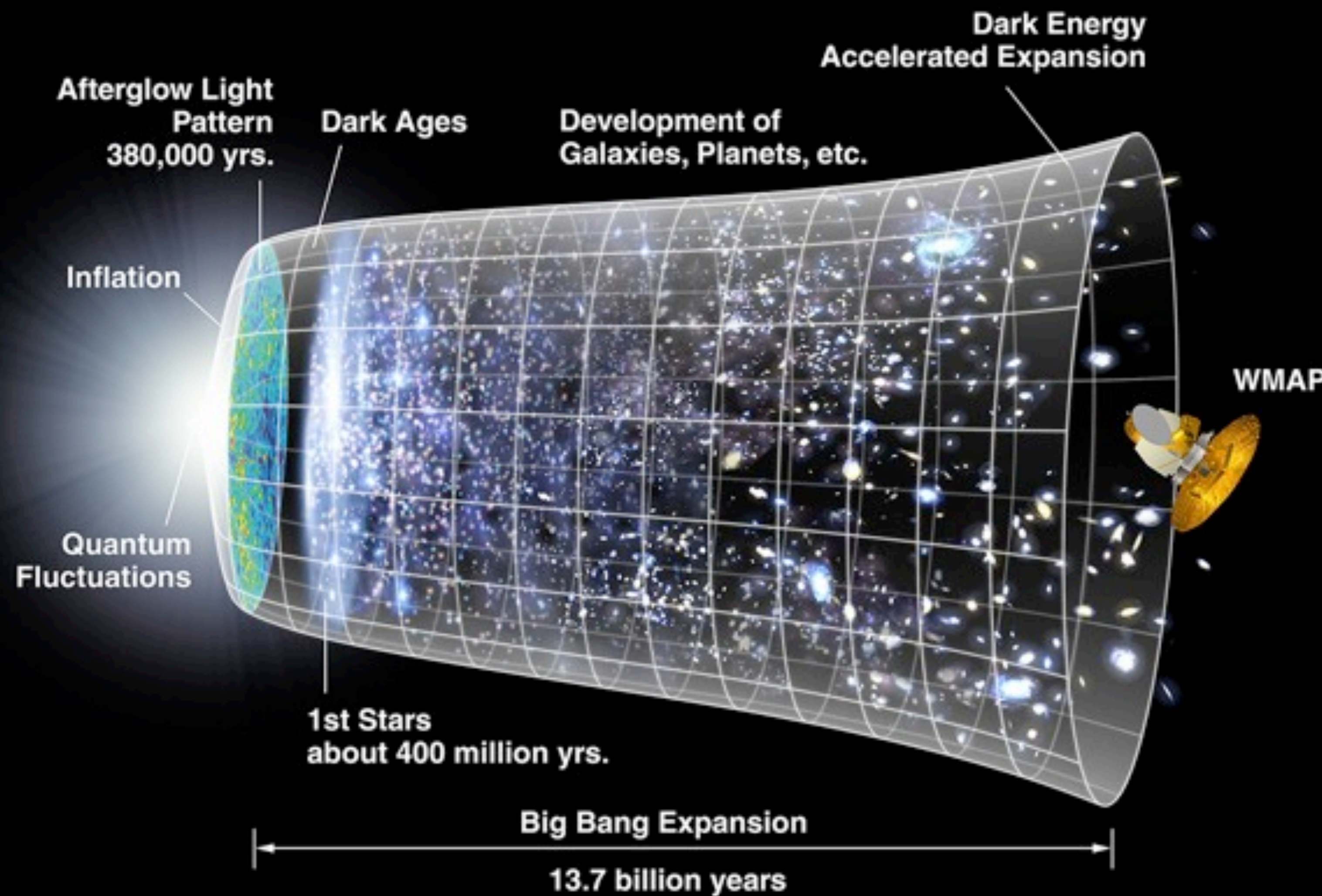




la mappa della radiazione cosmica di fondo

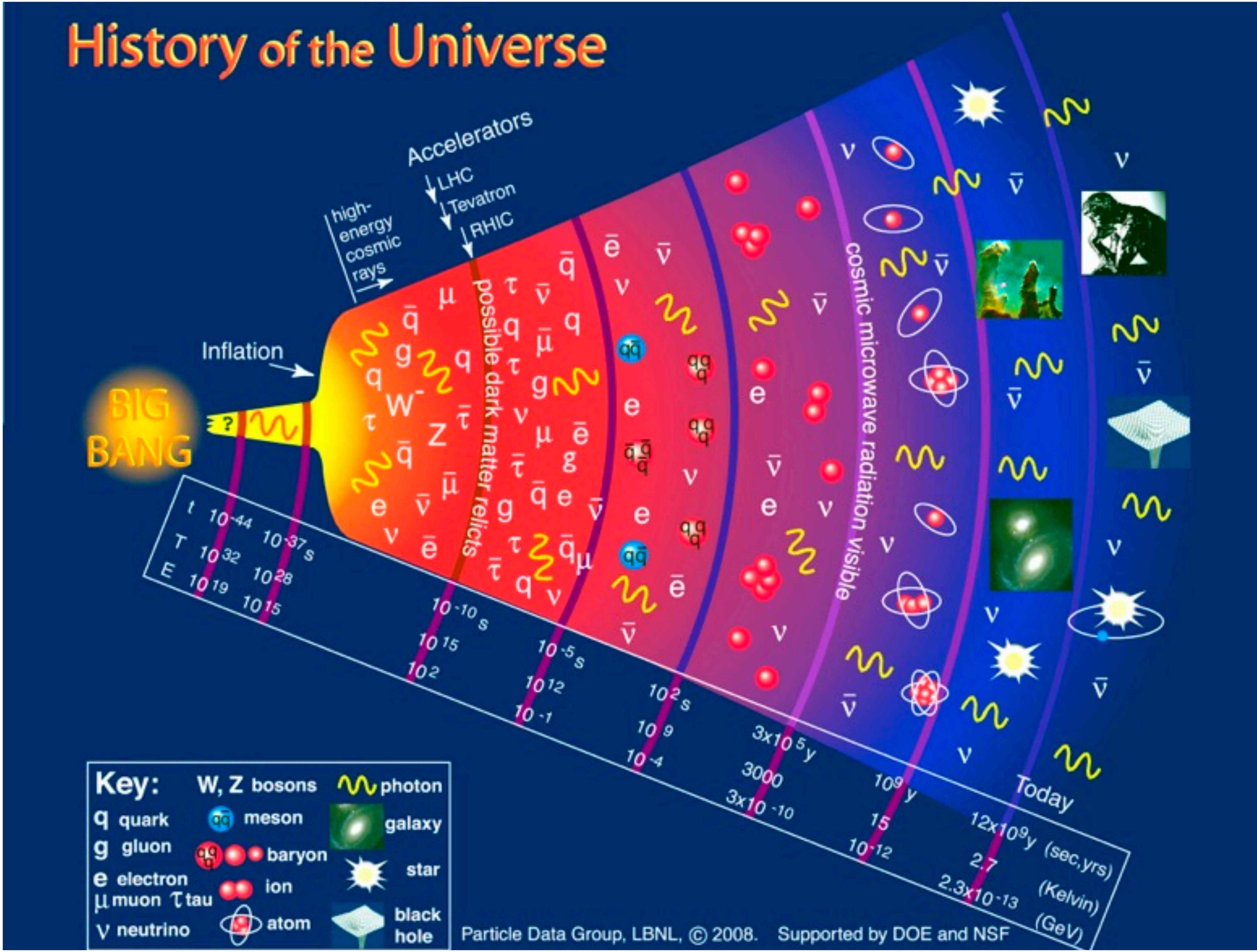


WMAP



Storia dell'Universo

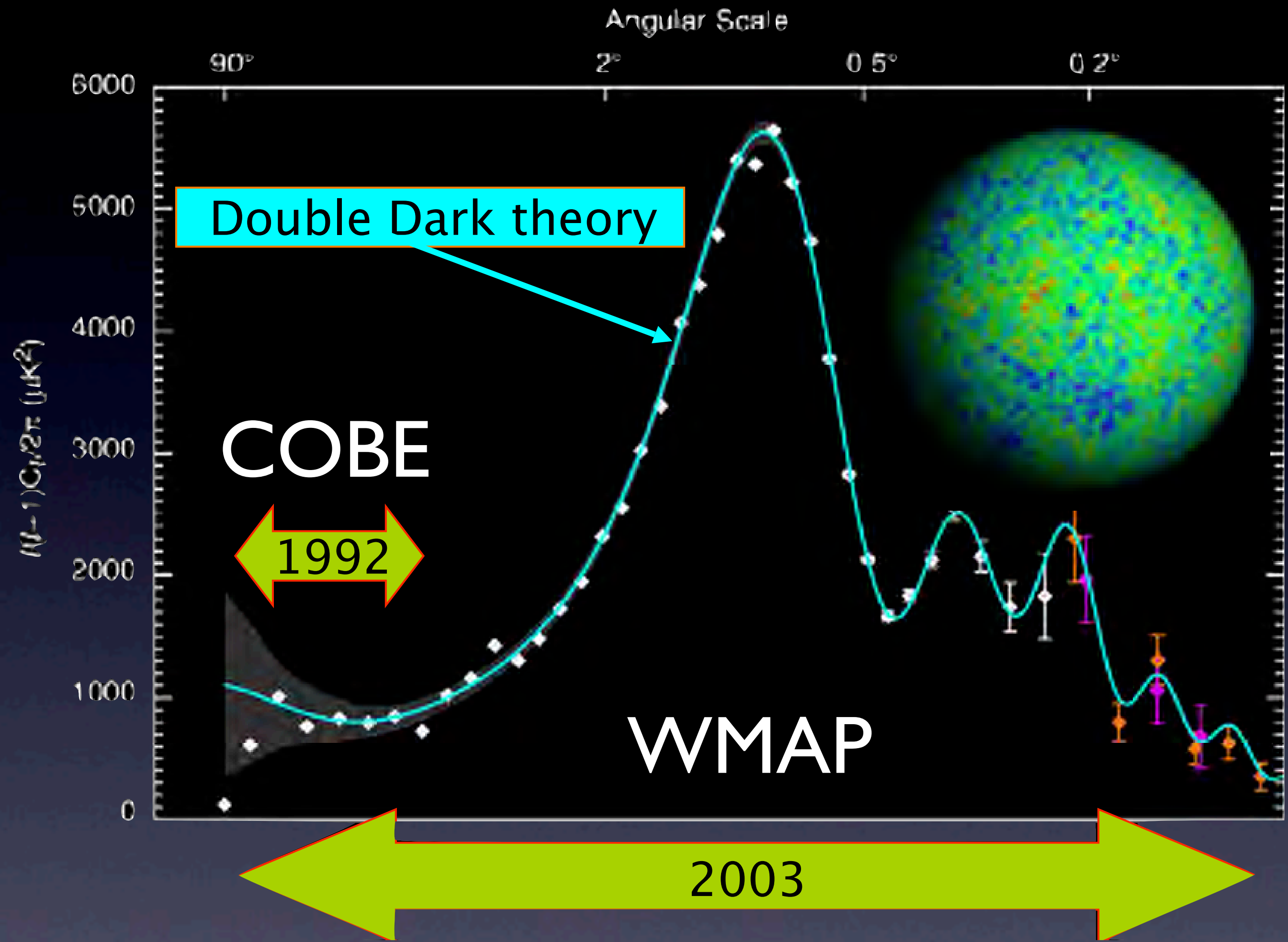
NASA/WMAP Science Team


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Dark Matter + Dark Energy = Double Dark Theory

(Il modello standard della cosmologia)

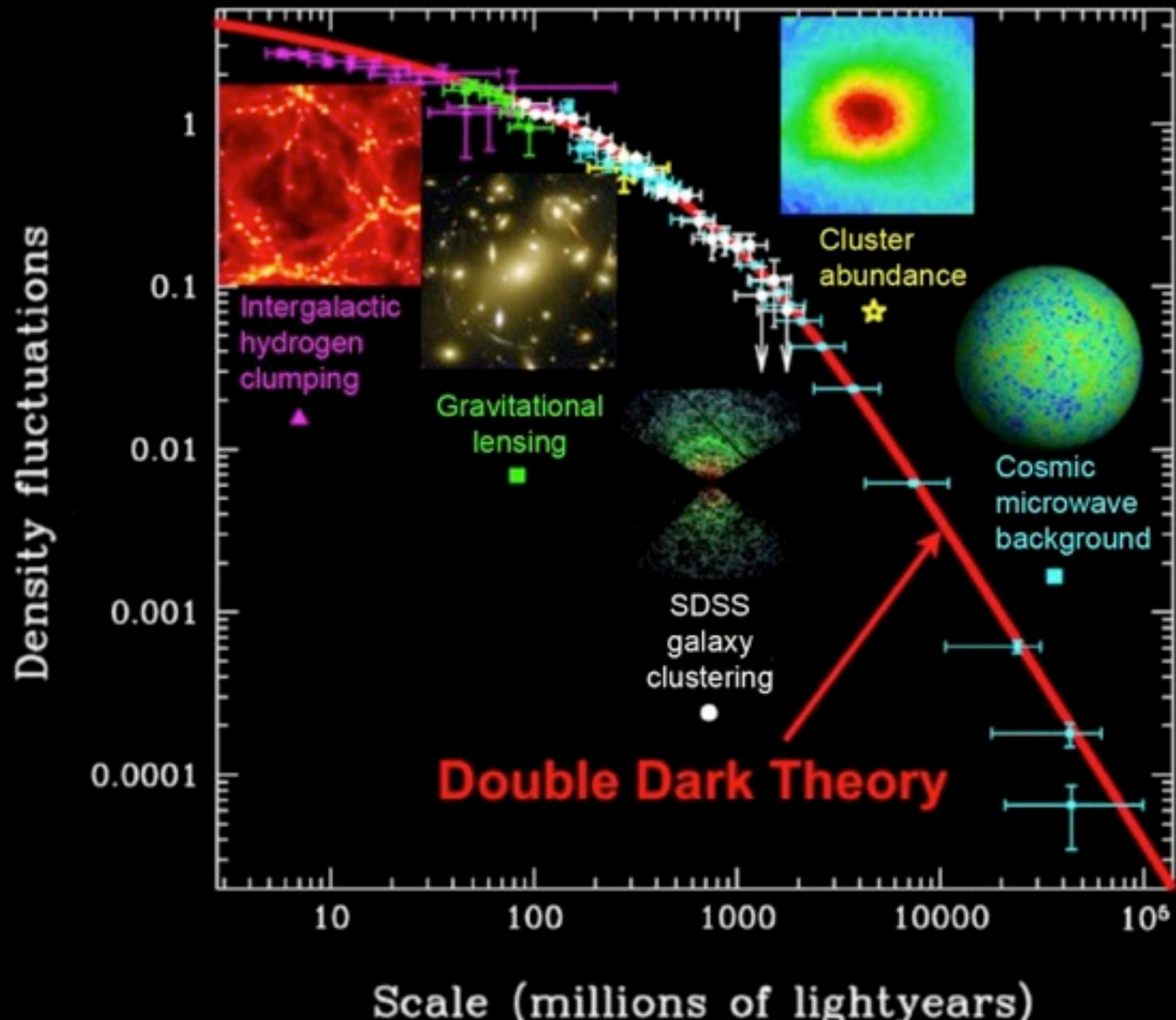
Big Bang Data Agrees with Double Dark Theory!



Il modello standard della cosmologia

ΛCDM: Double Dark Theory

La distribuzione della Materia conferma la teoria ΛCDM a tutte le scale



M. Tegmark

Convergenza cosmica: il parametro di densità Ω

Dalle osservazioni:

Radiazione cosmica di fondo (CMB)

Struttura su grande scala dei cluster di galassie (BAO)

Supernovae (SNe)

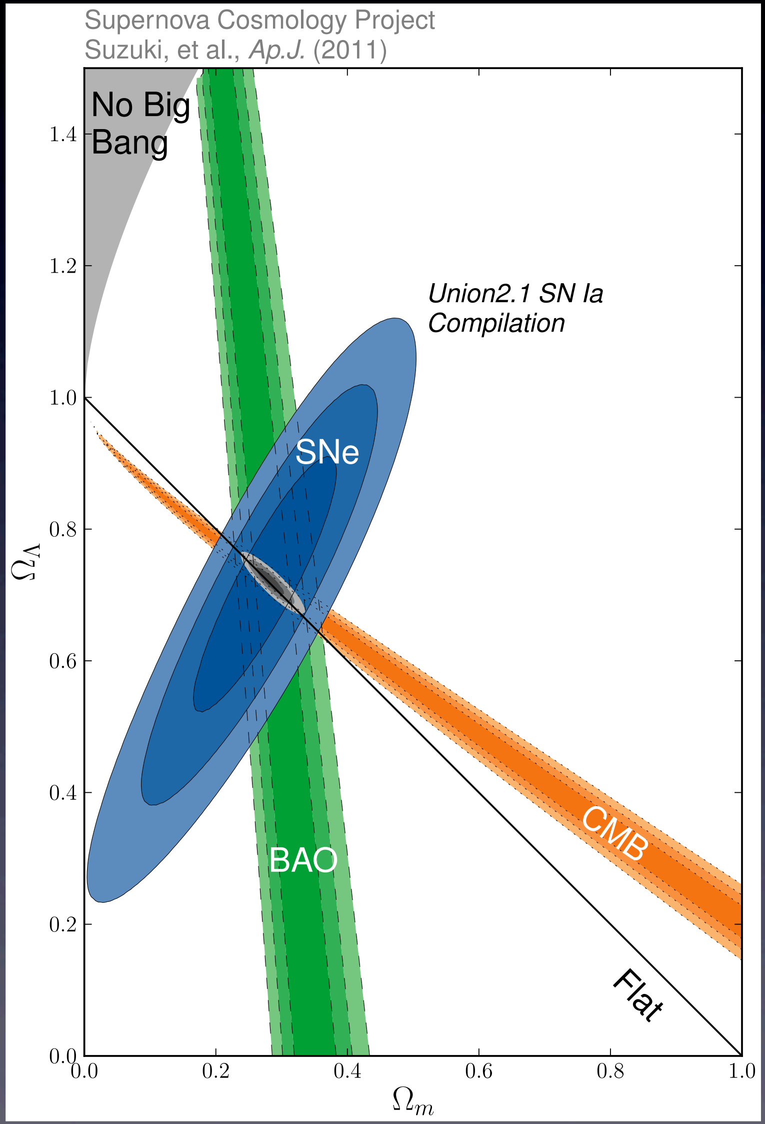
$\Downarrow$

due componenti principali

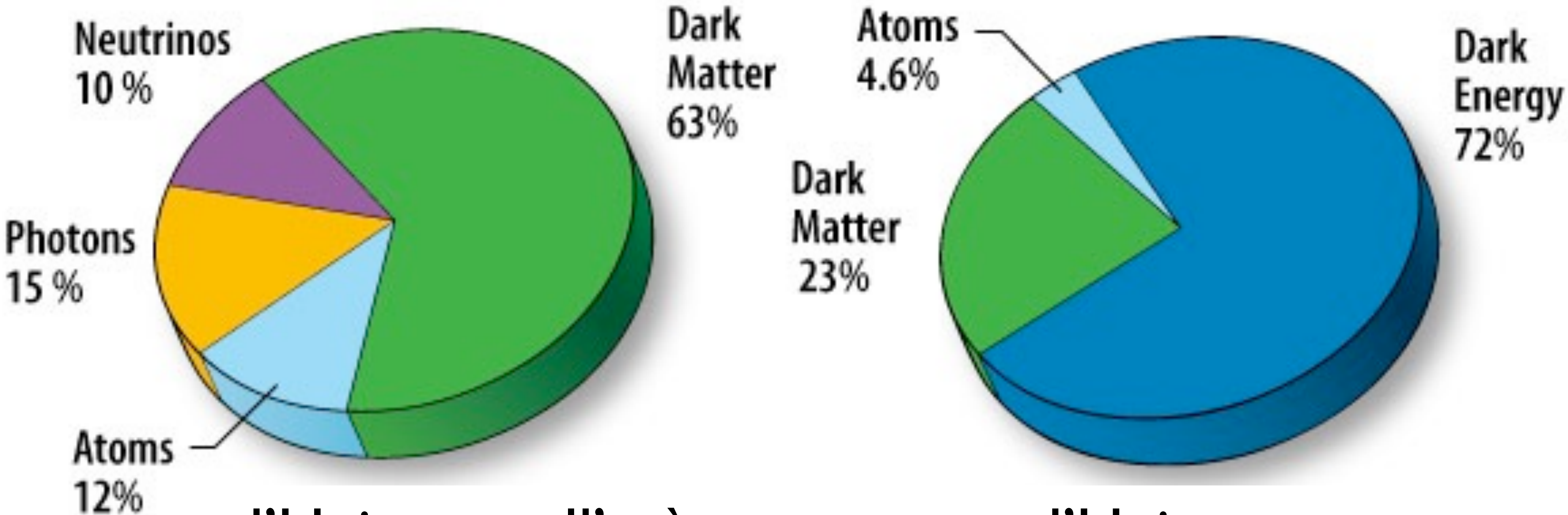
materia totale $\Omega_m \sim 0.3$

energia oscura $\Omega_\Lambda \sim 0.7$

Ω_Λ



Ω_m

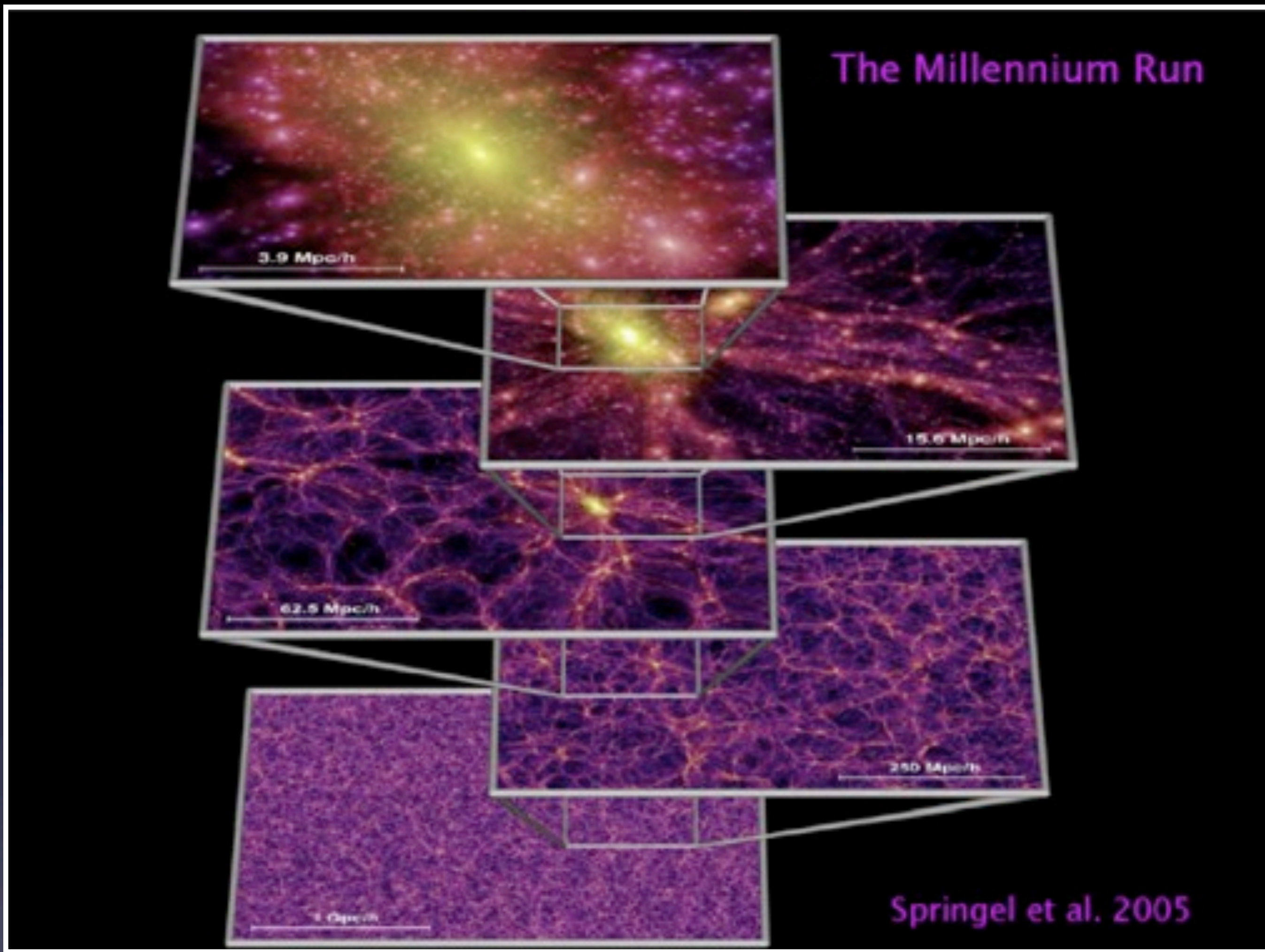


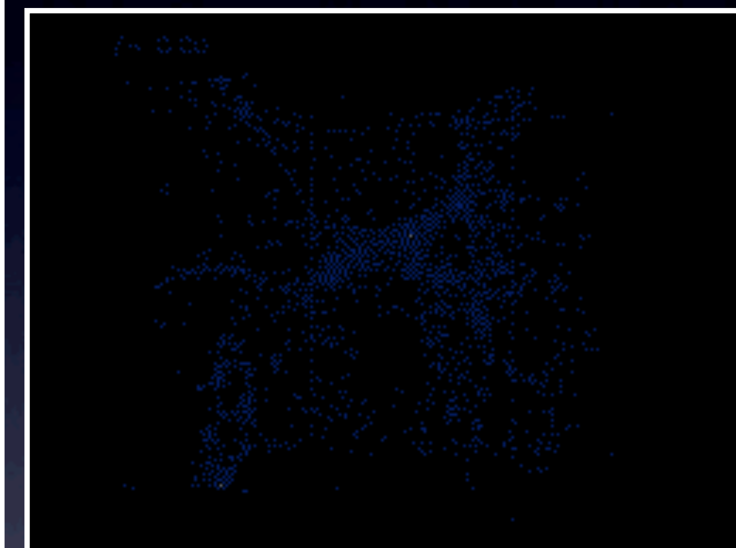
l'Universo all'età
di 380000 anni

l'Universo
oggi

Il contenuto dell'Universo

Formazione delle strutture: simulazioni N-body

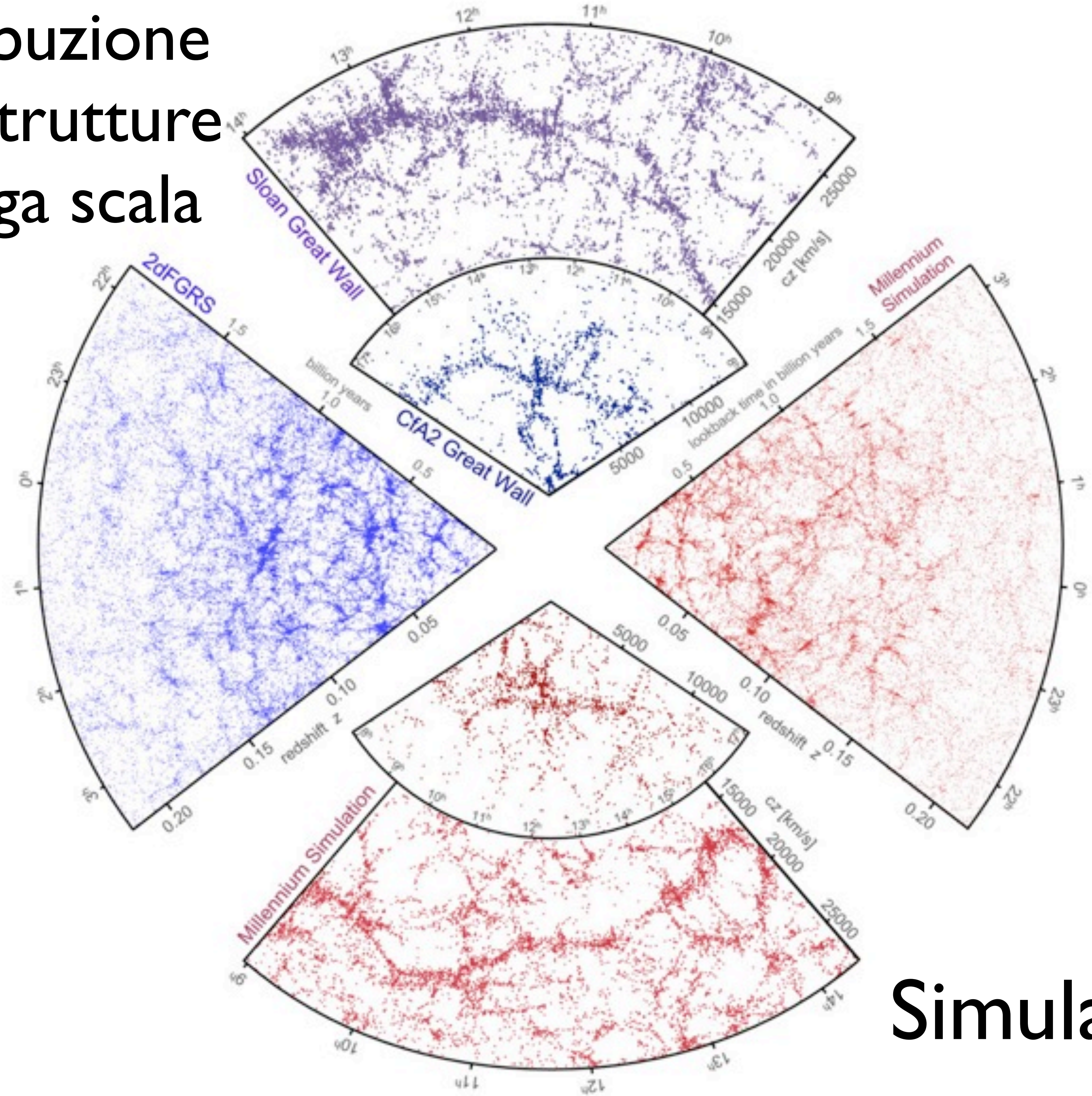




simulations performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.

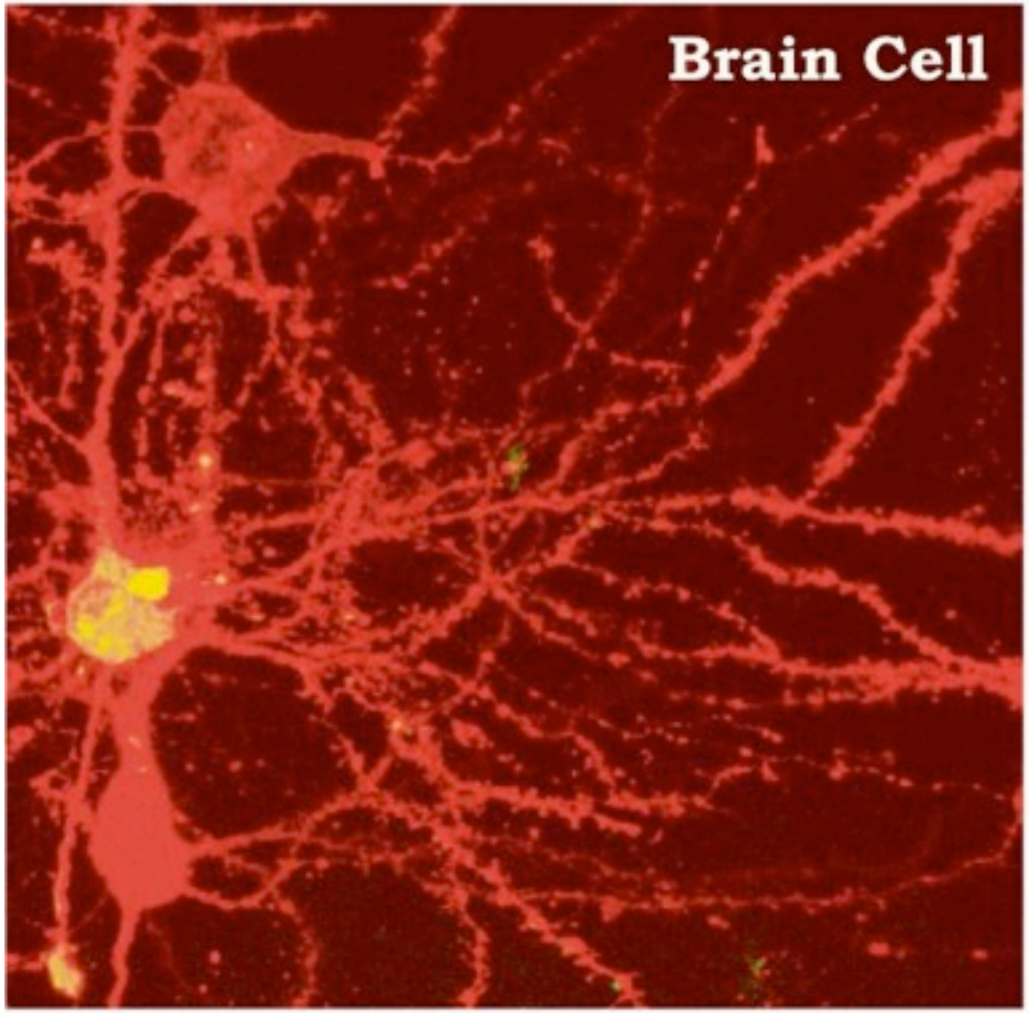
Evoluzione delle perturbazioni assumendo un universo piatto in cui il 30% della densità è dovuto alla materia e il 70% all'energia del vuoto. La maggior parte della materia si suppone nella forma di CDM - particelle massive non interagenti e "fredde" (ossia non-relativistiche).
Vi sono circa due miliardi di particelle nella scatola (140 milioni di anni luce). Il filmato mostra l'evoluzione in coordinate comoventi.

Distribuzione delle strutture su larga scala



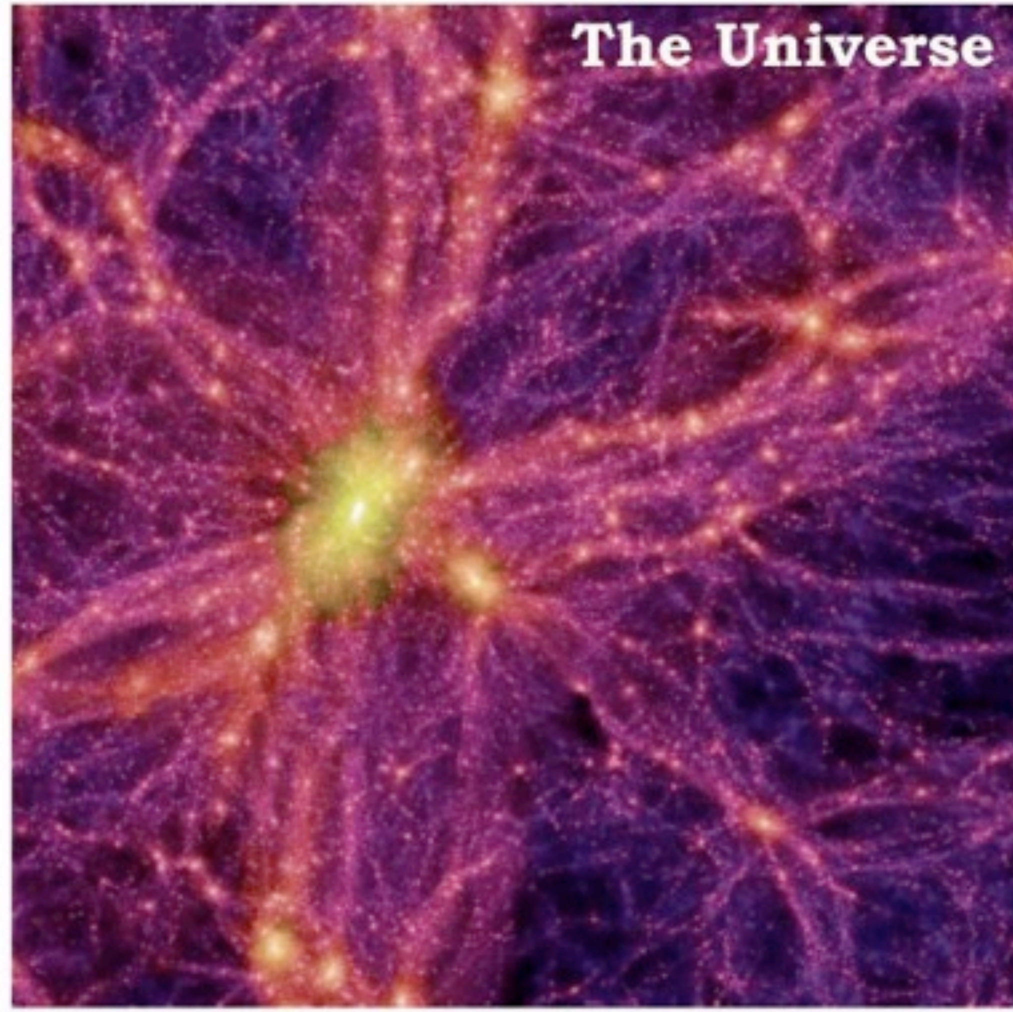
Simulazioni

One is only micrometers wide. The other is billions of light-years across. One shows neurons in a mouse brain. The other is a simulated image of the universe. Together they suggest the surprisingly similar patterns found in vastly different natural phenomena. *DAVID CONSTANTINE*



Mark Miller

Mark Miller, a doctoral student at Brandeis University, is researching how particular types of neurons in the brain are connected to one another. By staining thin slices of a mouse's brain, he can identify the connections visually. The image above shows three neuron cells on the left (two red and one yellow) and their connections.



Virgo Consortium

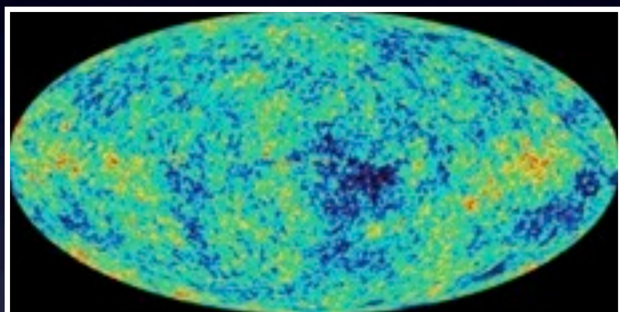
An international group of astrophysicists used a computer simulation last year to recreate how the universe grew and evolved. The simulation image above is a snapshot of the present universe that features a large cluster of galaxies (bright yellow) surrounded by thousands of stars, galaxies and dark matter (web).

Source: Mark Miller, Brandeis University; Virgo Consortium for Cosmological Supercomputer Simulations; www.visualcomplexity.com

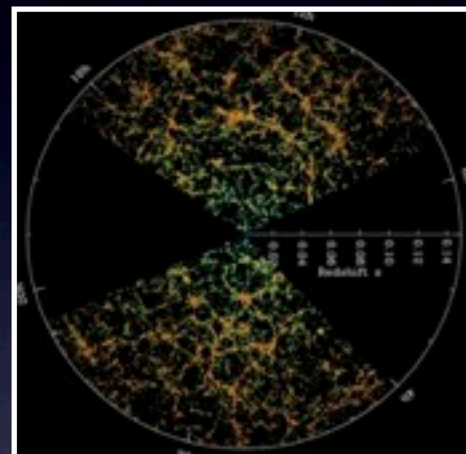
The New York Times

Observational evidence for DM

CMB

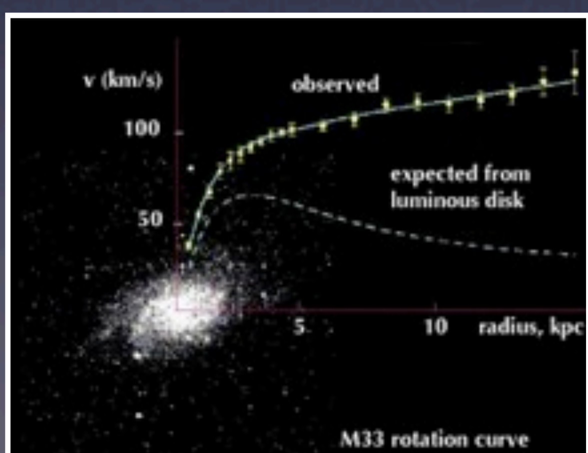


Structure

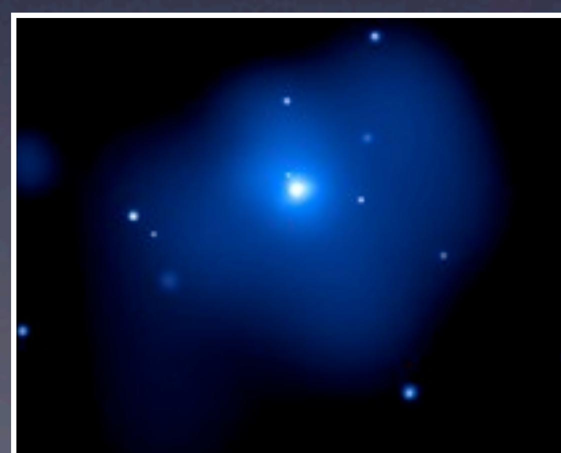


Supernovae

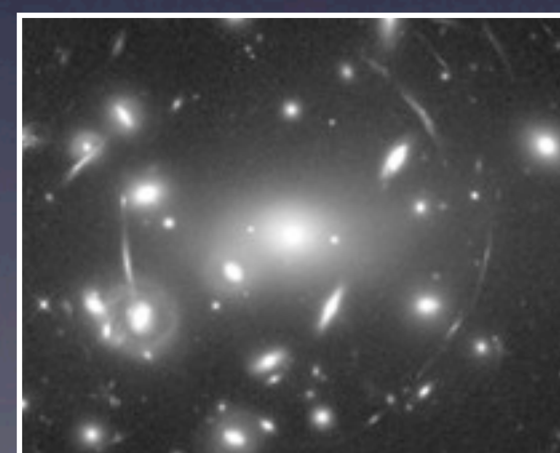
Galaxies



X-rays

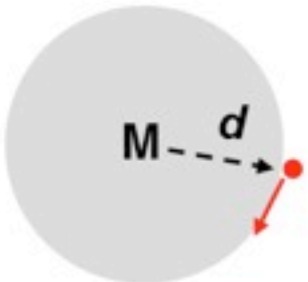


Lensing



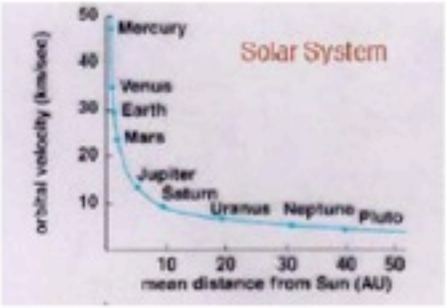
MATERIA OSCURA : evidenze dinamiche

Consideriamo una particella di prova orbitante attorno ad una massa M



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

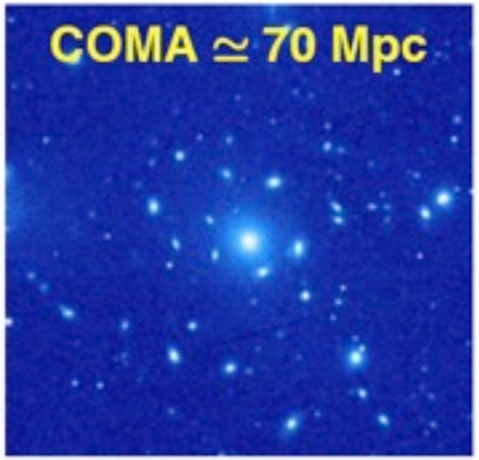
La misura di velocità di un corpo rappresenta una stima della massa a cui è legato



- Applicazione "semplice" :
velocità dei pianeti nel sistema solare

- Applicazioni generali :

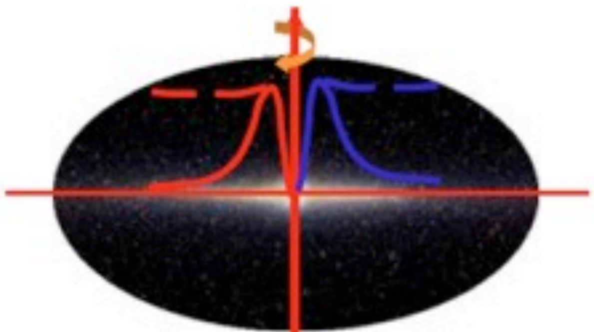
- Curve di rotazione delle galassie
- Distribuzione di velocità delle galassie negli ammassi
  F.Zwicky Helv.Phys.Acta 6(1933) 110
- Emissione termica di gas galattico / intergalattico



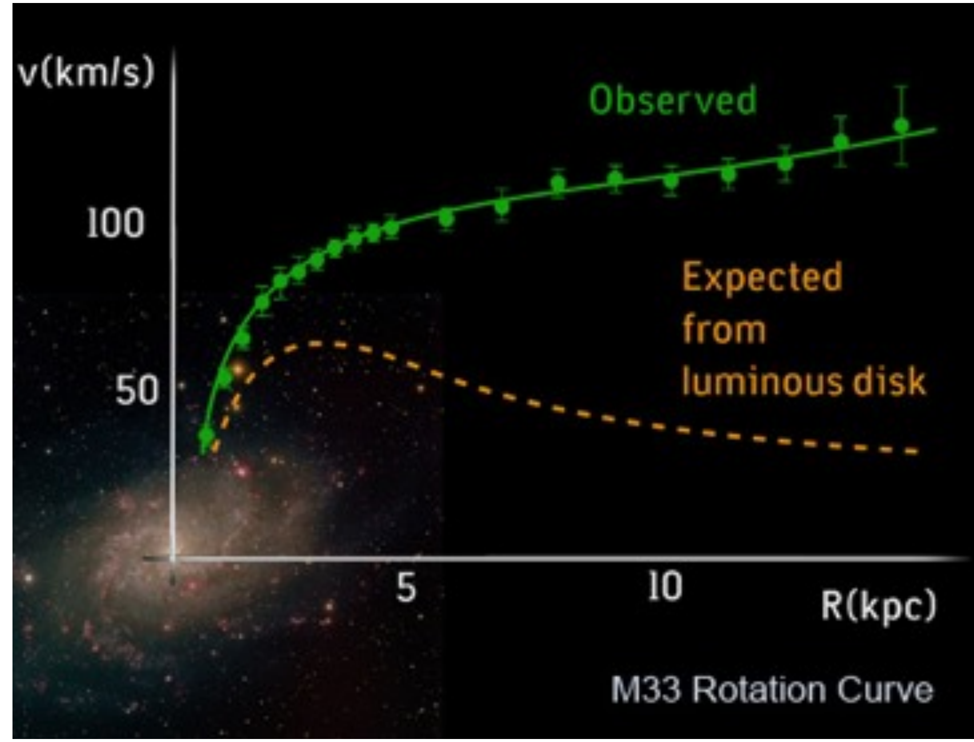
- Conclusione:.
materia oscura > 10 volte la materia luminosa

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 :

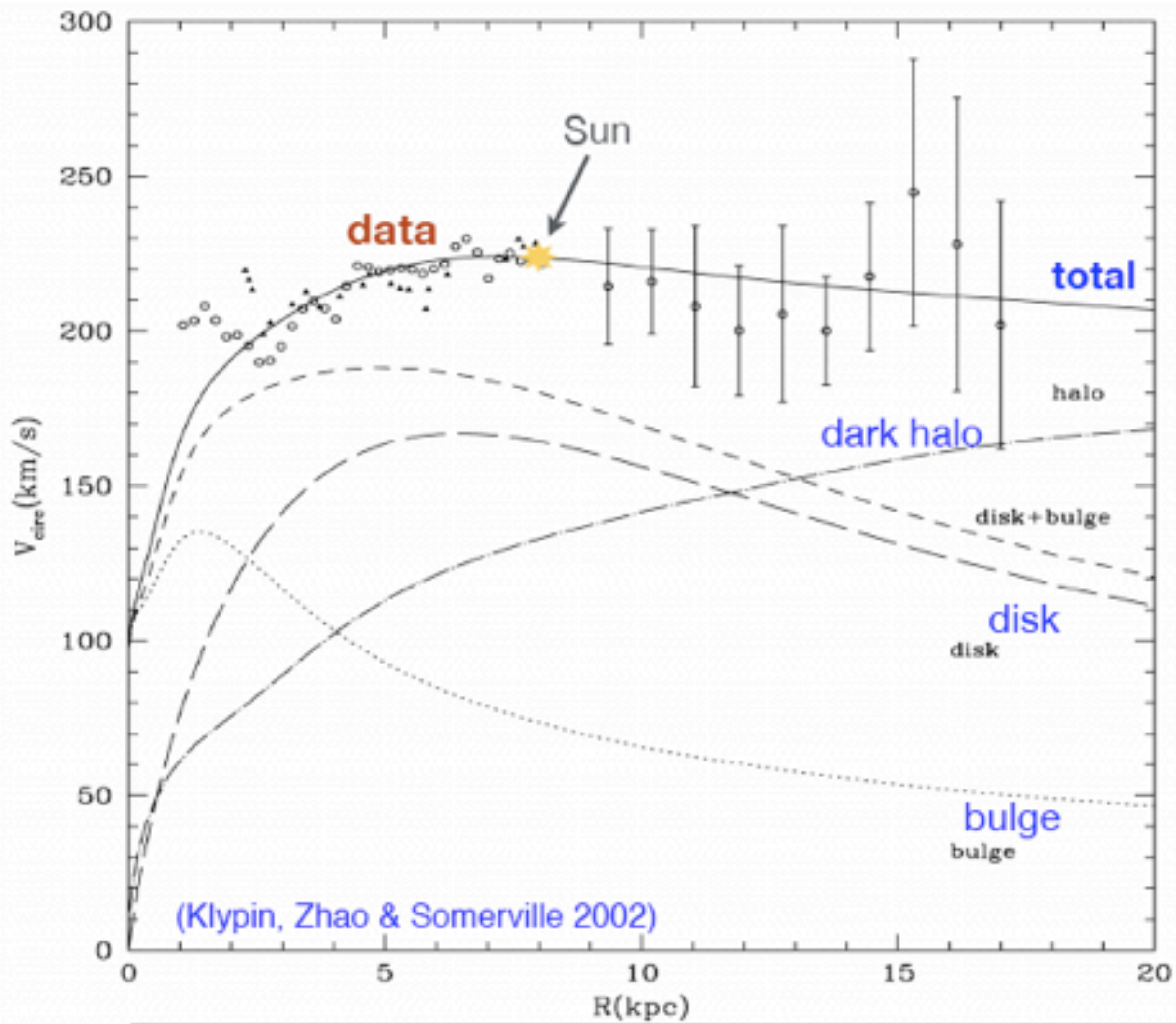
Per $r < R$: $\rho(r)$=cost
$M(r) \propto r^3$
$v(r) \propto r$

$r>R$: $\rho(r) = 0$
$M(r)$=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 $r \to 0$ e per $r \to \infty$

Dark Matter in the Milky Way



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

$$M_{virial} \approx 1...2 \times 10^{12} M_\odot$$

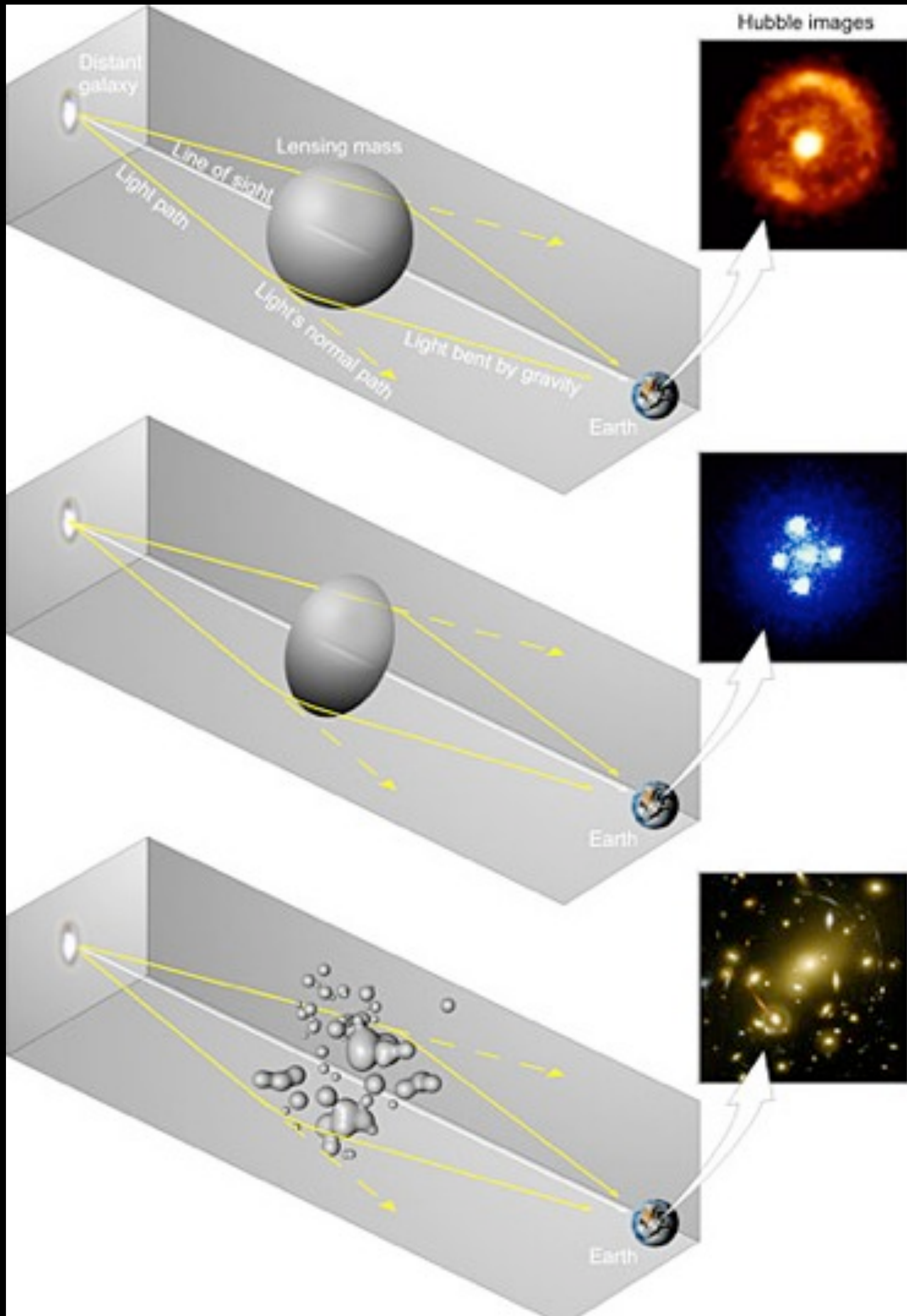
$$\rho_{dark} \simeq 0.3 - 0.6\ GeV \cdot cm^{-3}$$

$\cong$ 3000 WIMPs/m^3

(M_{WIMP}=100 GeV)

L. Baudis

Lensing gravitazionale



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

Bullet Cluster 1E 0657−558

More Evidence Against MOND

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

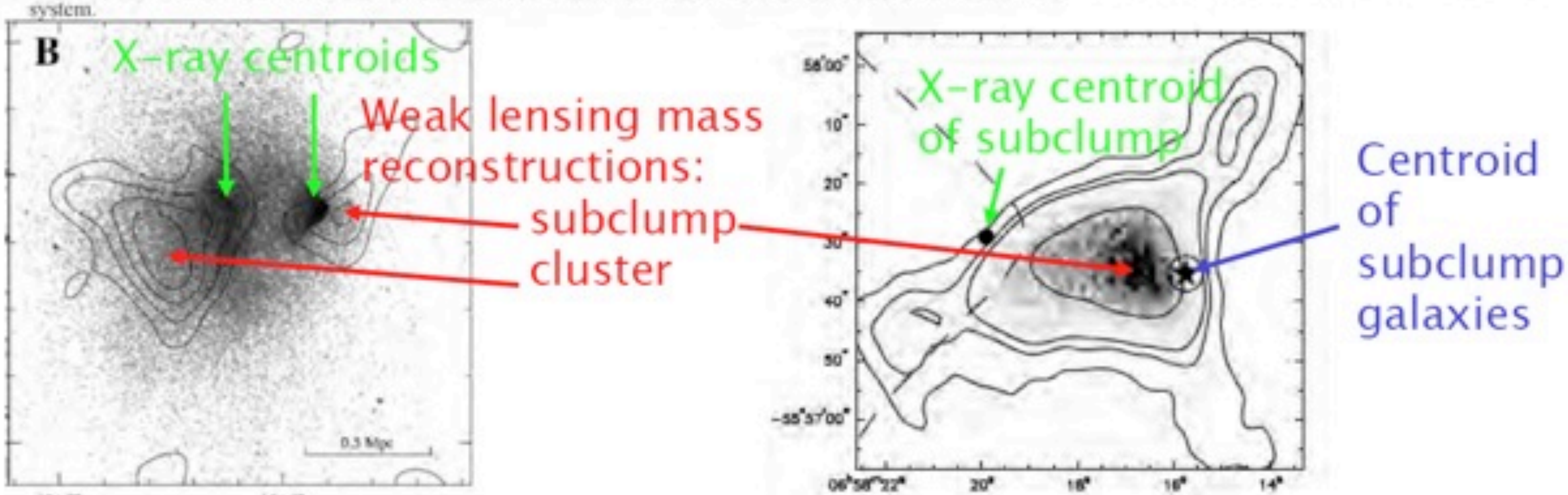
Douglas Clowe[2]
Institut für Astrophysik und Extraterrestrische Forschung der Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany; dclowe@as.arizona.edu
Anthony Gonzalez
Department of Astronomy, University of Florida, 211 Bryant Space Science Center, Gainesville, FL 32611-2055
and
Maxim Markevitch
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
Received 2003 October 28; accepted 2003 December 11

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.

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

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

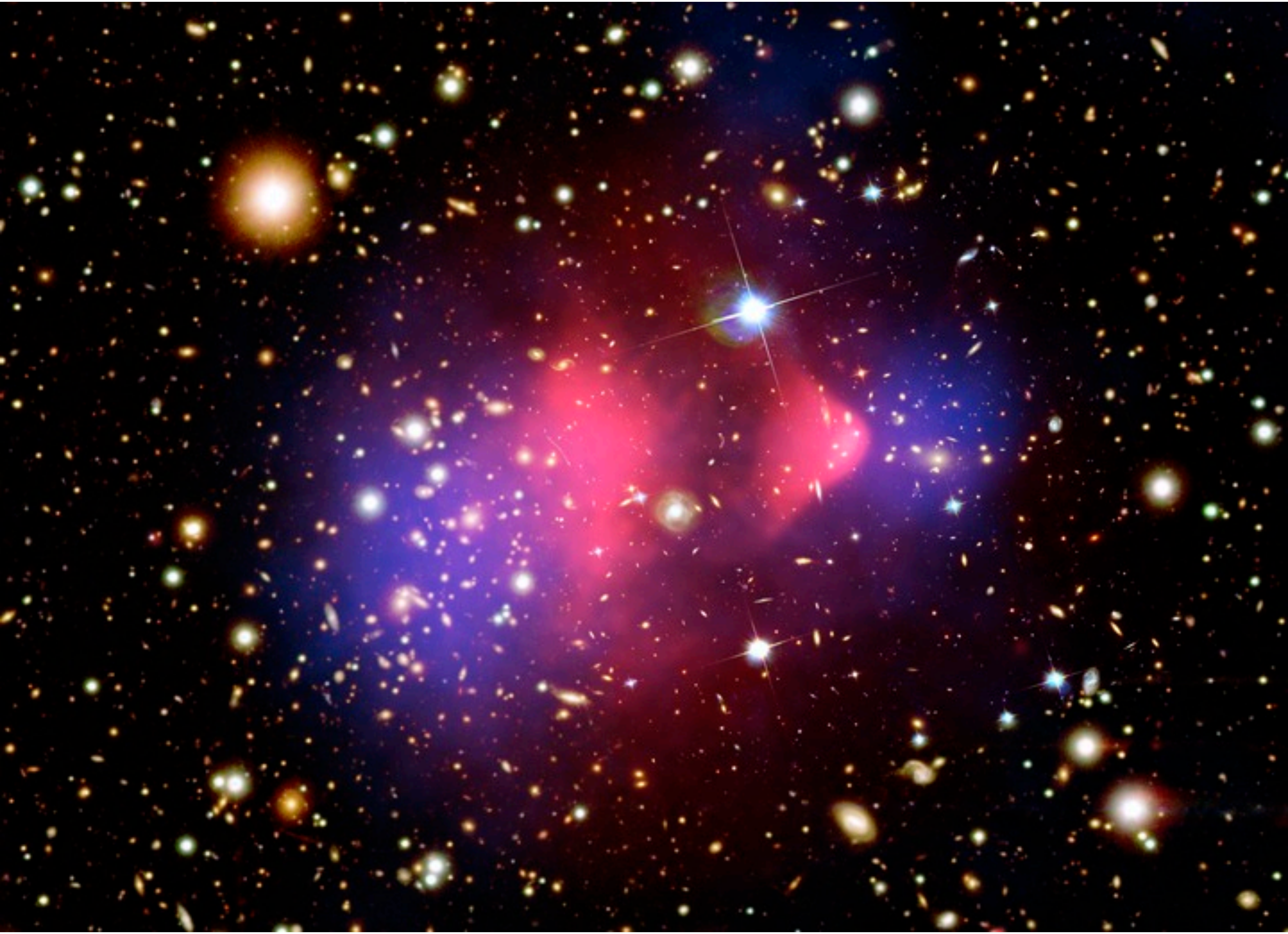


1E 0657-56

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.



Gravitational lensing on galaxy clusters: the bullet cluster

optical from
Magellan and HST
(orange and white)

X-ray from
CHANDRA (pink)

weak lensing (blue)

Cosa è la materia oscura?

- Materia invisibile (DM) è necessaria per spiegare gli effetti gravitazionali
- DM costituisce il 23% della densità massa-energia dell’Universo
- DM è circa l’85% della materia totale nell’Universo
- deve essere:
  - **non-barionica** (cioè fatta di materia diversa da protoni e neutroni),
  - **neutra** (non emette né assorbe radiazione)
  - **non interagente** (ossia interagente con se stessa e con le altre particelle solo attraverso la gravità) e
  - **fredda** (cioè non-relativistica all’epoca dell’equivalenza radiazione-materia T~3eV)

Materia oscura particellare

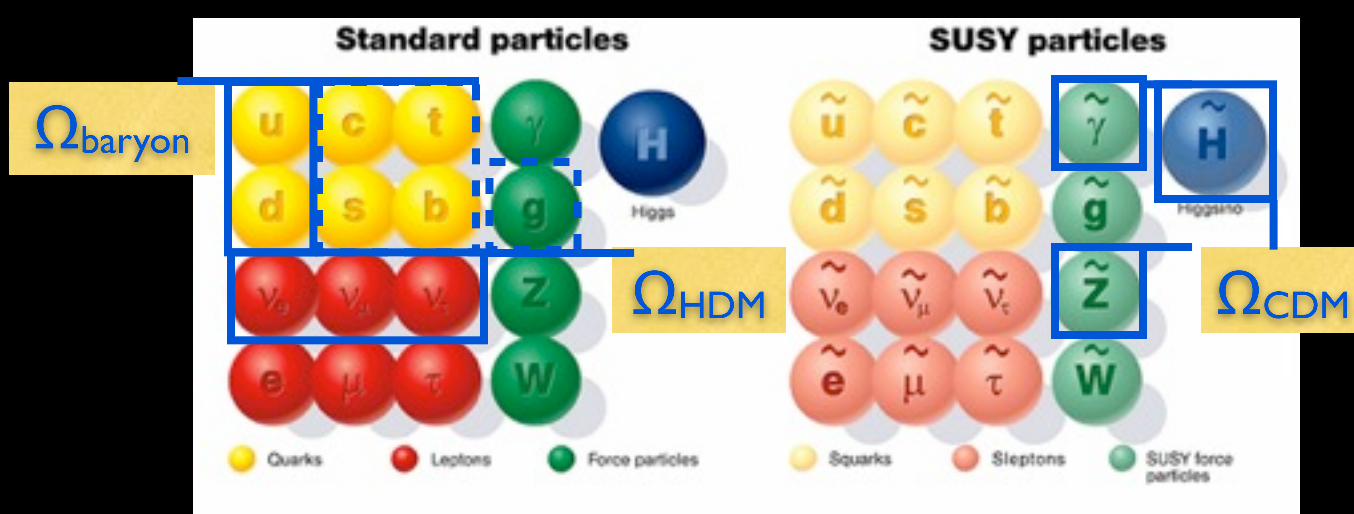
Il Modello Standard delle particelle elementari:

- Una teoria di successo, descrive tutte le osservazioni fino a ≈ 1 TeV
- Però è una teoria efficace alle basse energie, ci aspettiamo nuove particelle e fenomeni ad energie più alte
- Nessuna delle particelle del modello standard è un buon candidato per la materia oscura!

La Supersimmetria fornisce un candidato “naturale” per la DM:

LSP (lightest super-symmetric particle)

LSP creato al Big Bang ha circa la corretta abbondanza relica

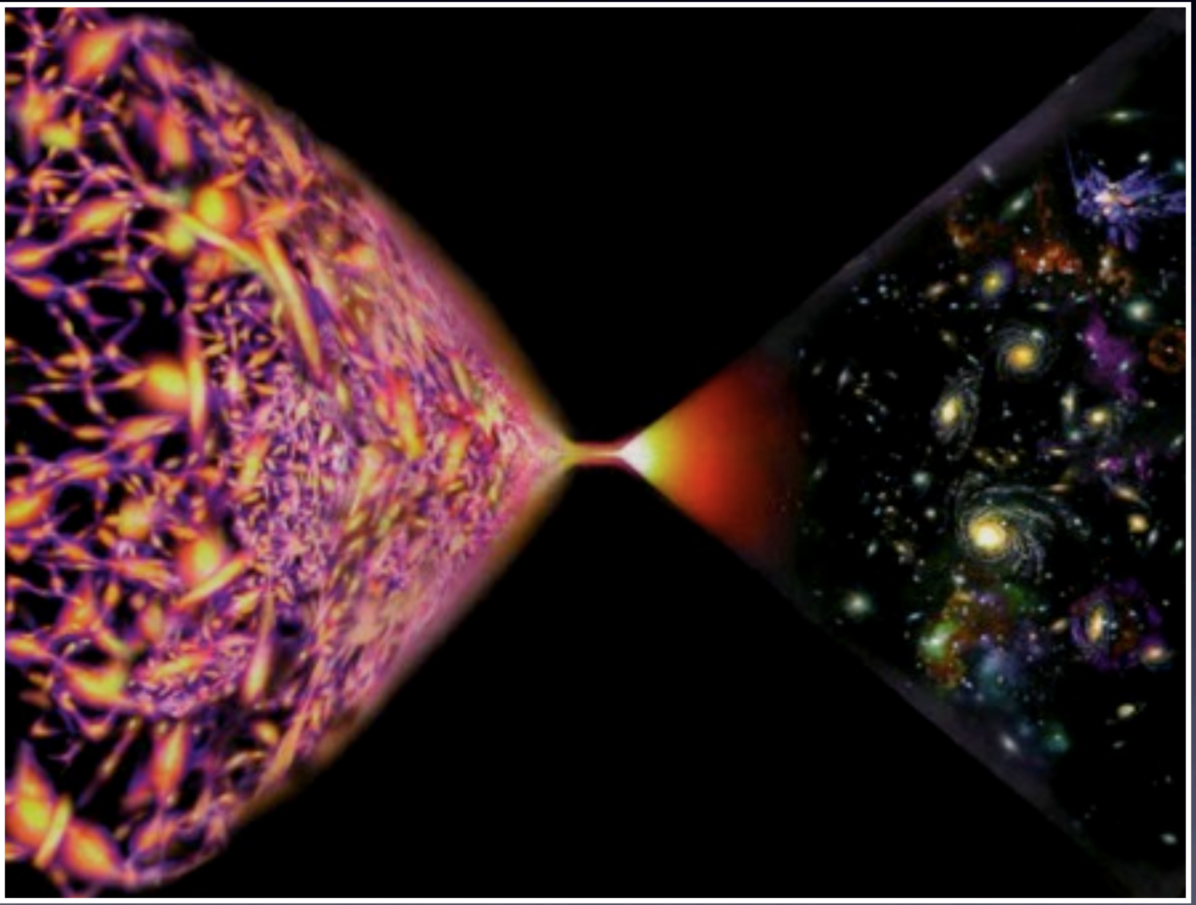


SUSY in a nutshell

WIMPs

Particelle non-barioniche, relitti freddi del Big Bang sono candidati perfetti per DM

- le masse dovrebbero essere circa 10-1000 GeV e
- le interazioni alla scala elettrodebole



Weakly **I**nteracting **M**assive **P**articles

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**

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

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

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

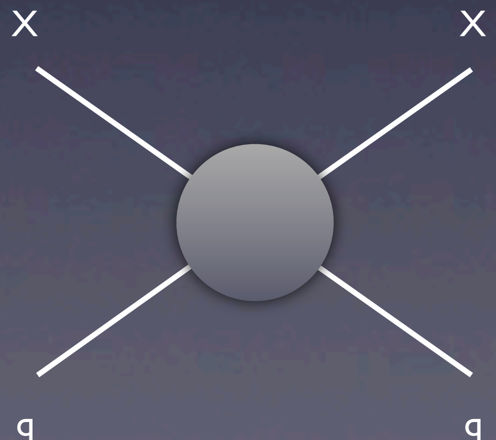
⇒ the relic density and mass point to the **weak scale**
⇒ the new physics responsible for EWSB likely gives rise to a **dark matter candidate**
⇒ examples: LSP (neutralino), LKP (KK-partner of photon, or KK-partner of Z-boson)

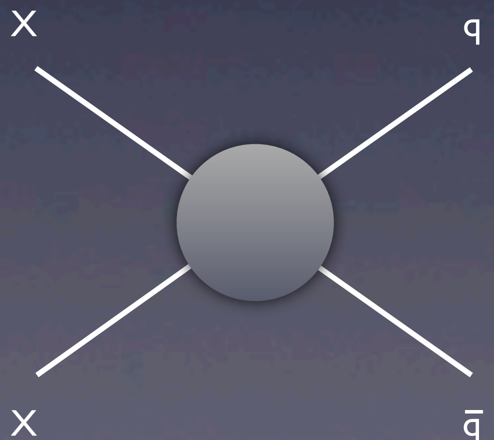
WIMP detection

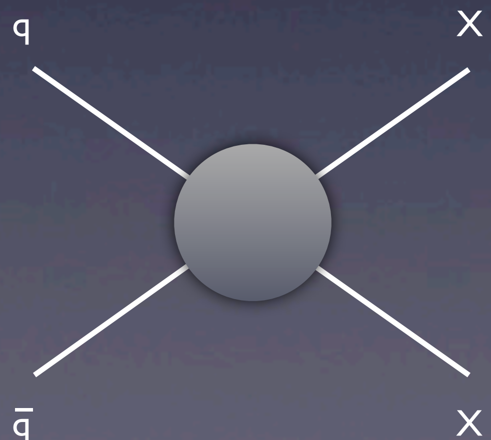
underground

in space

at accelerators

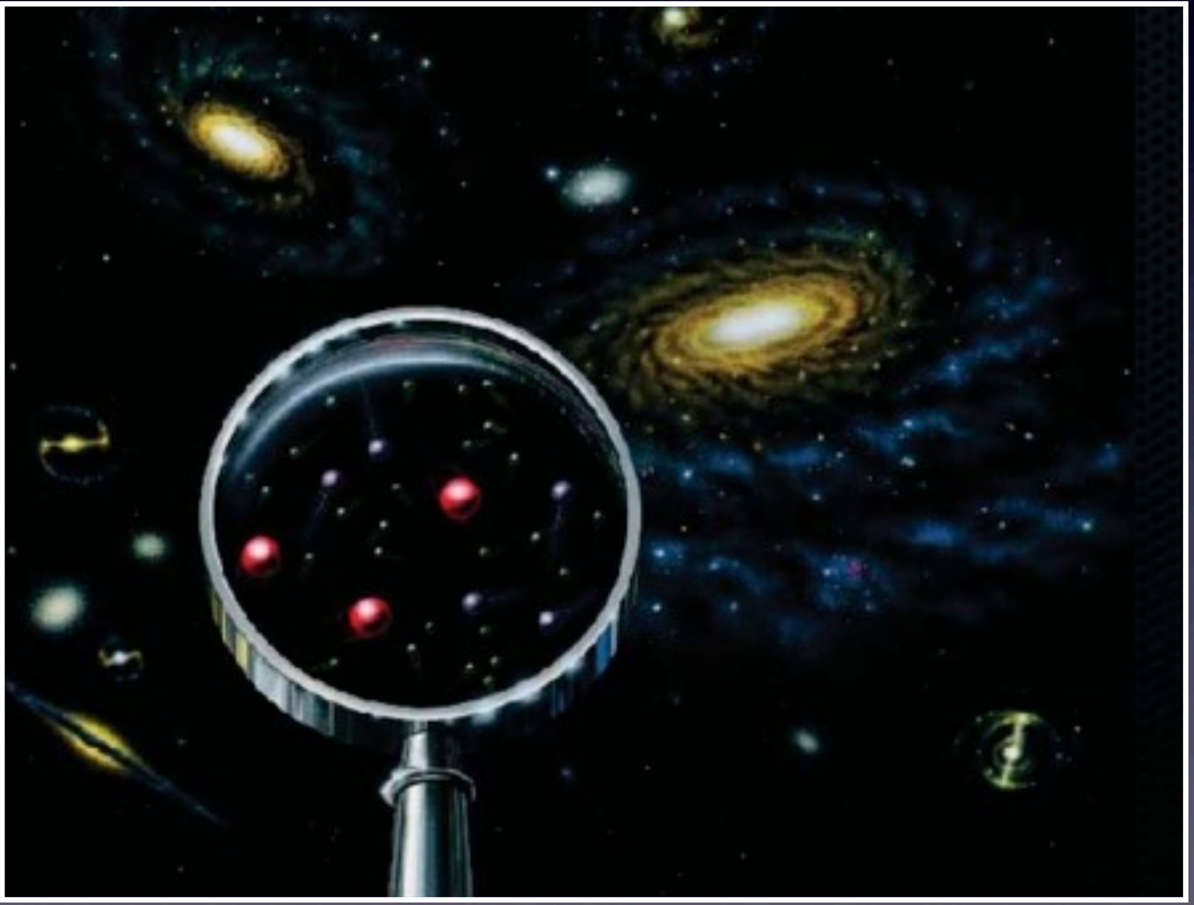


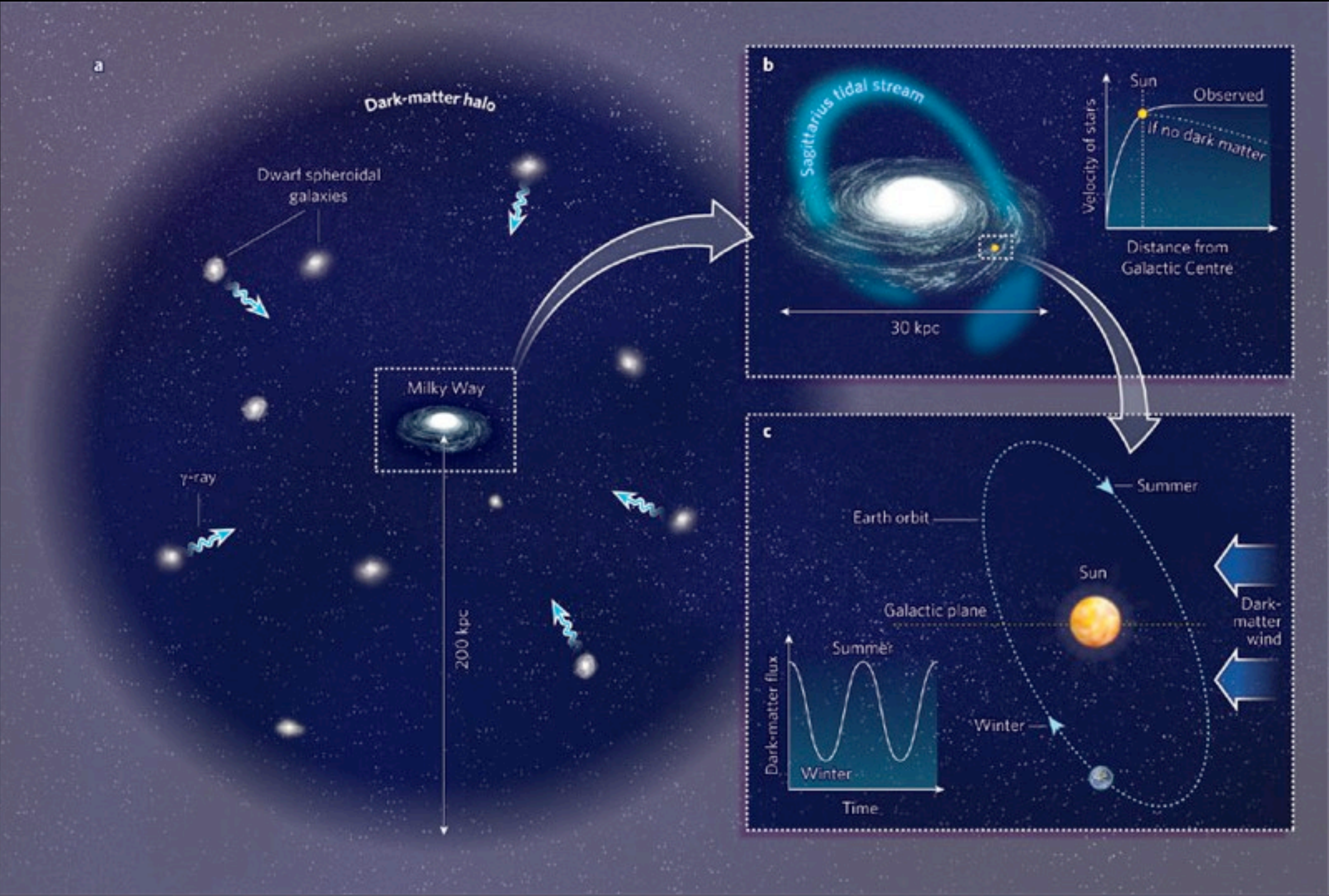




ricerca delle WIMP galattiche

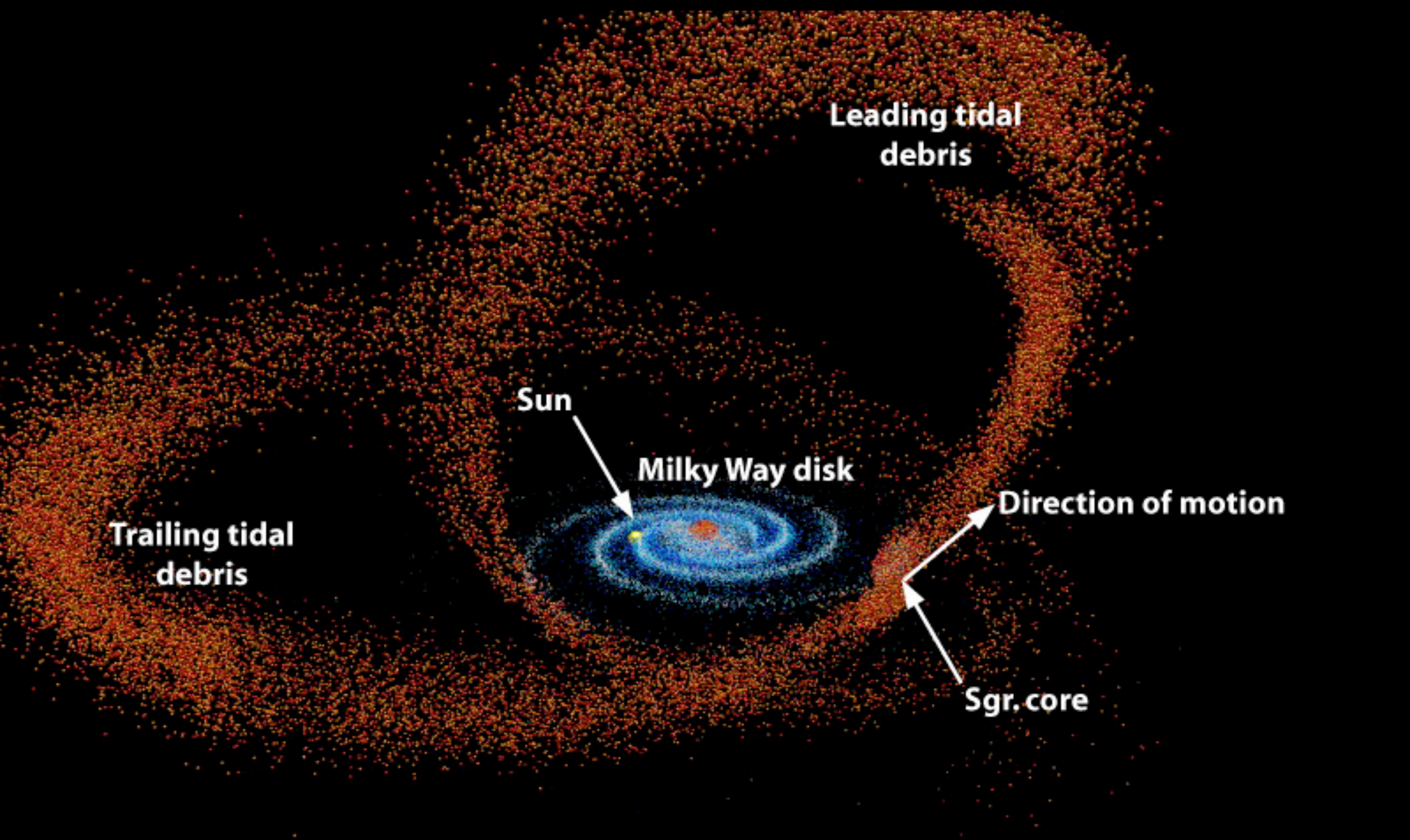
- 10^5 al sec attraversano un pollice
- 10^{15} al giorno attraversano il corpo, solo 5 interagiscono
- come possiamo rivelarle?





From Cosmology: Dark matter and dark energy
Robert Caldwell & Marc Kamionkowski
Nature 458, 587-589(2 April 2009)
doi:10.1038/458587a

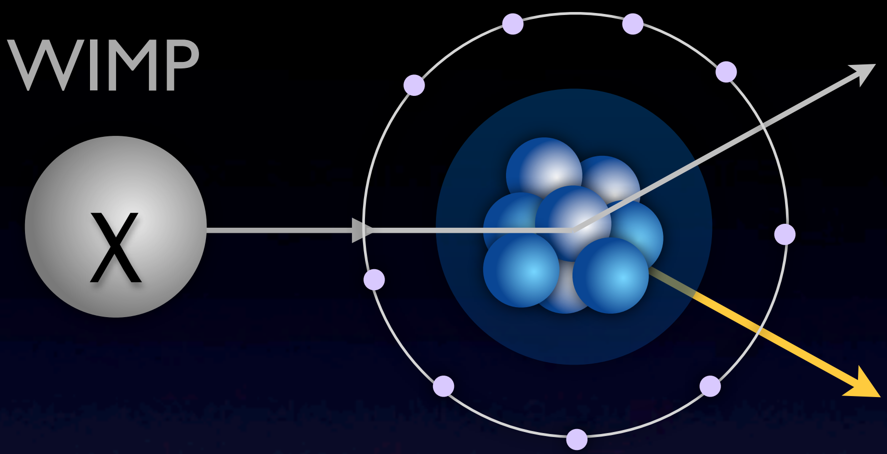
Rivelazione delle WIMP galattiche



Un vento di WIMP

David R. Law
UCLA

WIMP direct detection



$\chi N \to \chi N$

elastic scattering off nuclei

M. Goodman, E. Witten, PRD 1985

$$E_0 = \frac{1}{2} m_\chi c^2 \beta^2$$

$$r = \frac{4 m_\chi m_N}{\left(m_\chi + m_N\right)^2}$$

$$E_R = E_0 r \frac{\left(1 - \cos\theta\right)}{2}$$

$\beta \approx 10^{-3}$

$m_\chi \approx 100$ GeV

Nucleus recoil energy < 100 keV

Spin Independent:

χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$

Spin Dependent:

only unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

Measurement

Integral rate (as a function of E_R) <1 ev/kg/yr

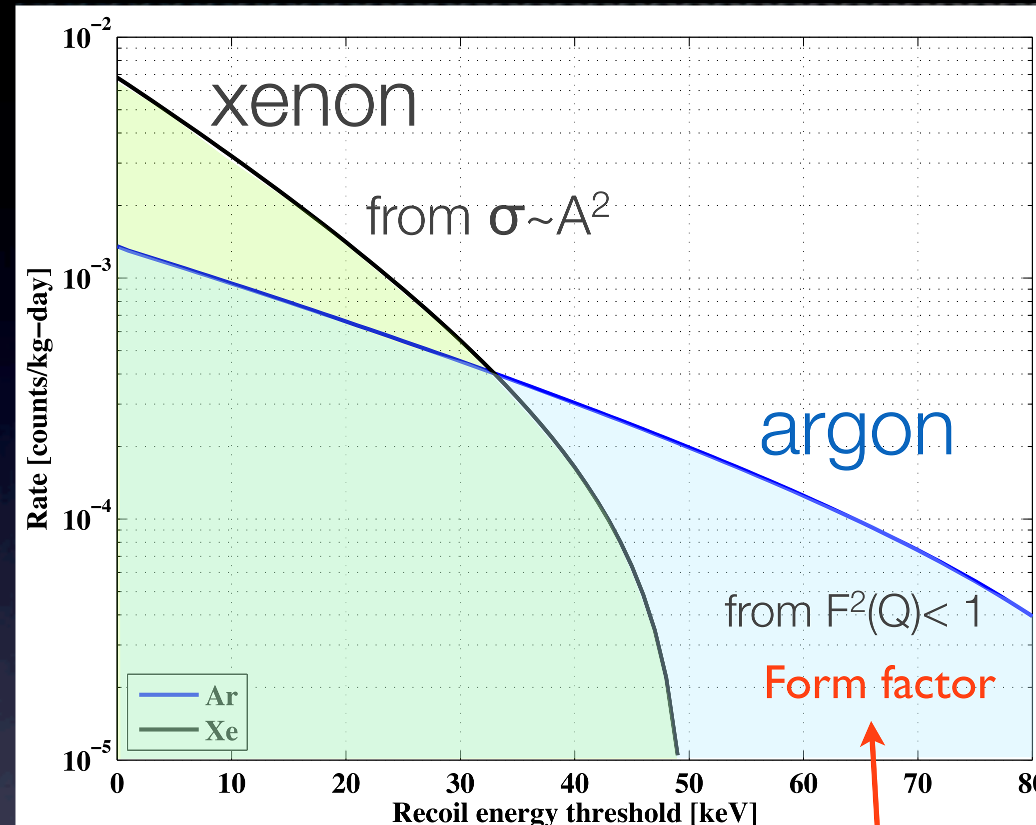
Expected rate

Astrophysics

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

Detector

Particle physics



$$\left.\frac{dR}{dE_R}\right|_{Ideal} = \frac{R_0}{E_0 r} \exp\left(-\frac{E_R}{E_0 r}\right)$$

$$\left.\frac{dR}{dE_R}\right|_{True} = \left.\frac{dR}{dE_R}\right|_{Ideal} \times \left[S(E_R) F^2(q^2) I\right]$$

Sun's velocity around the galaxy

$\langle v \rangle \approx 230$ km/s

WIMP energy density

$\rho_\chi \approx 0.3$ GeV/cm^3

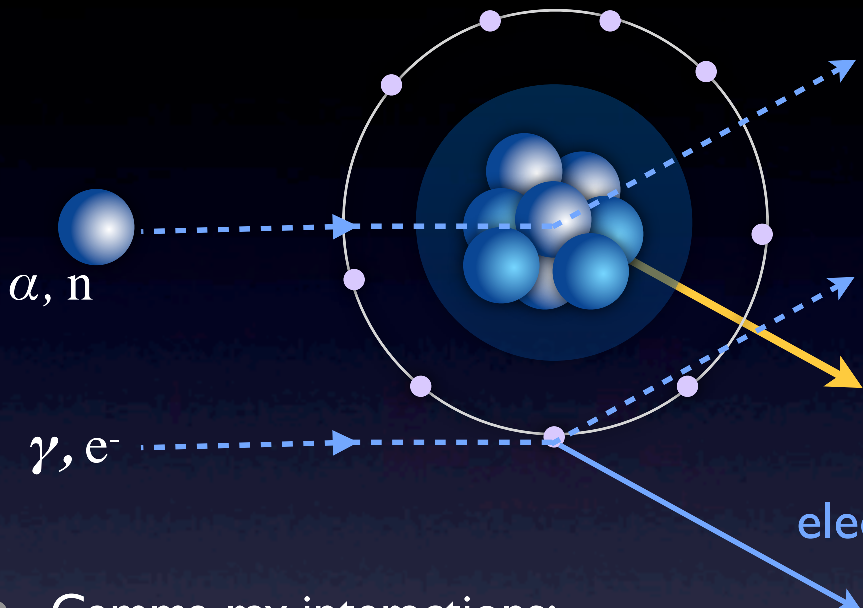
Background

from natural radioactivity:

$\gamma\, e^- \rightarrow \gamma\, e^-$

$nN \rightarrow nN$

$N \rightarrow N' + \alpha, e^-$



- Gamma ray interactions:

  mis-identified electrons mimic nuclear recoil signals

- Neutrons:

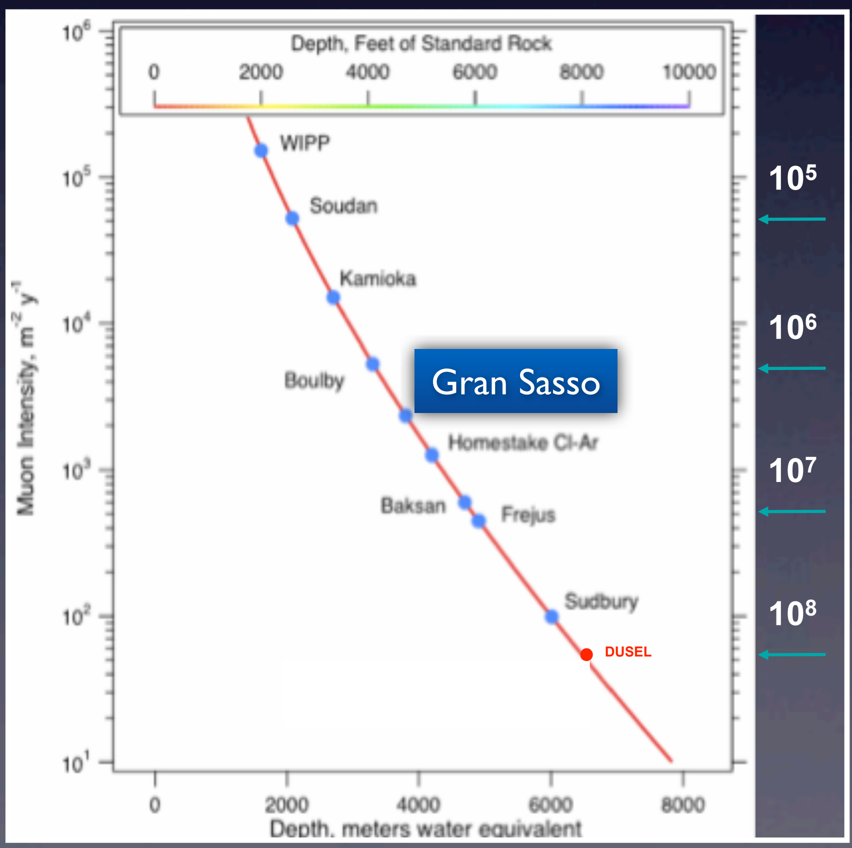
  (α,n), U, Th fission, cosmogenic spallation

- Contamination:

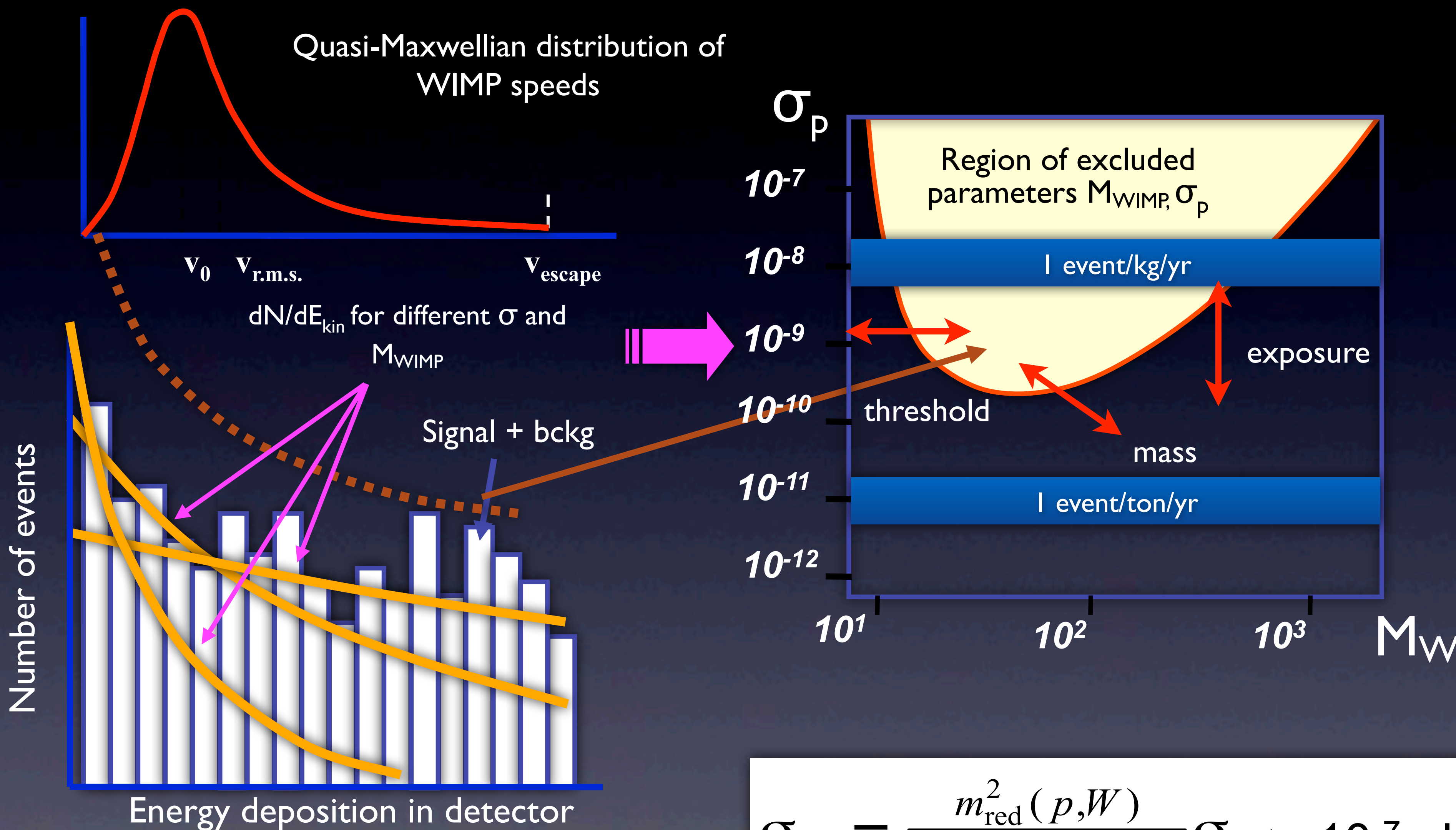
  ^{238}U and ^{232}Th decays, recoiling progeny mimic nuclear recoils

Underground labs

reduction of muon flux by:



Vanilla model: exclusion plot



Exponential behavior is very similar to that of bckg of various origins.

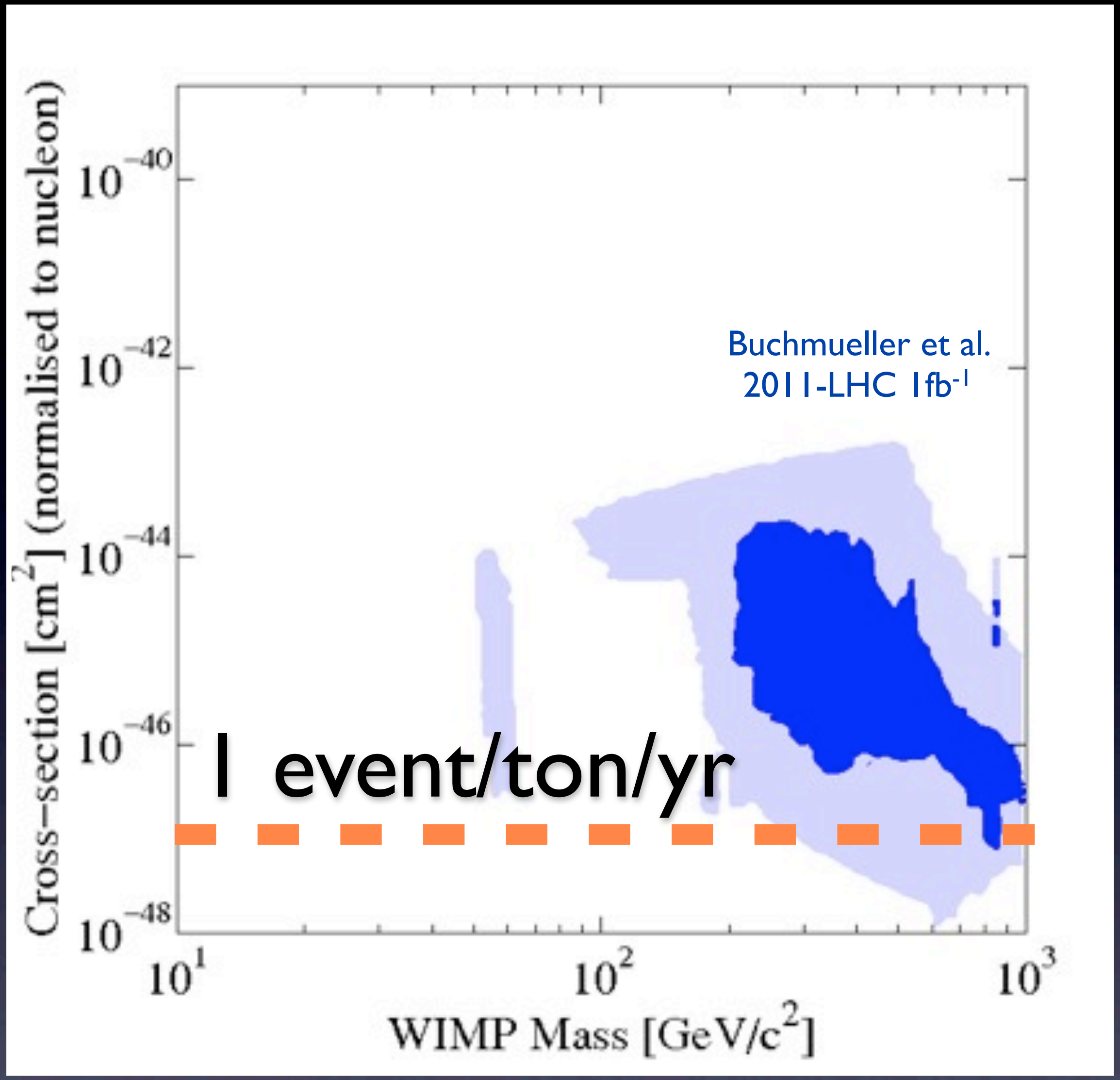
$$\sigma_p = \frac{m^2_{\mathrm{red}}(p,W)}{C m^2_{\mathrm{red}}(Nucl,W)}\sigma <\sim 10^{-7}\ \mathrm{pb}$$

coherent interaction $\longrightarrow C = A^2$

D. Akimov

$\sigma_p(cm^2)$

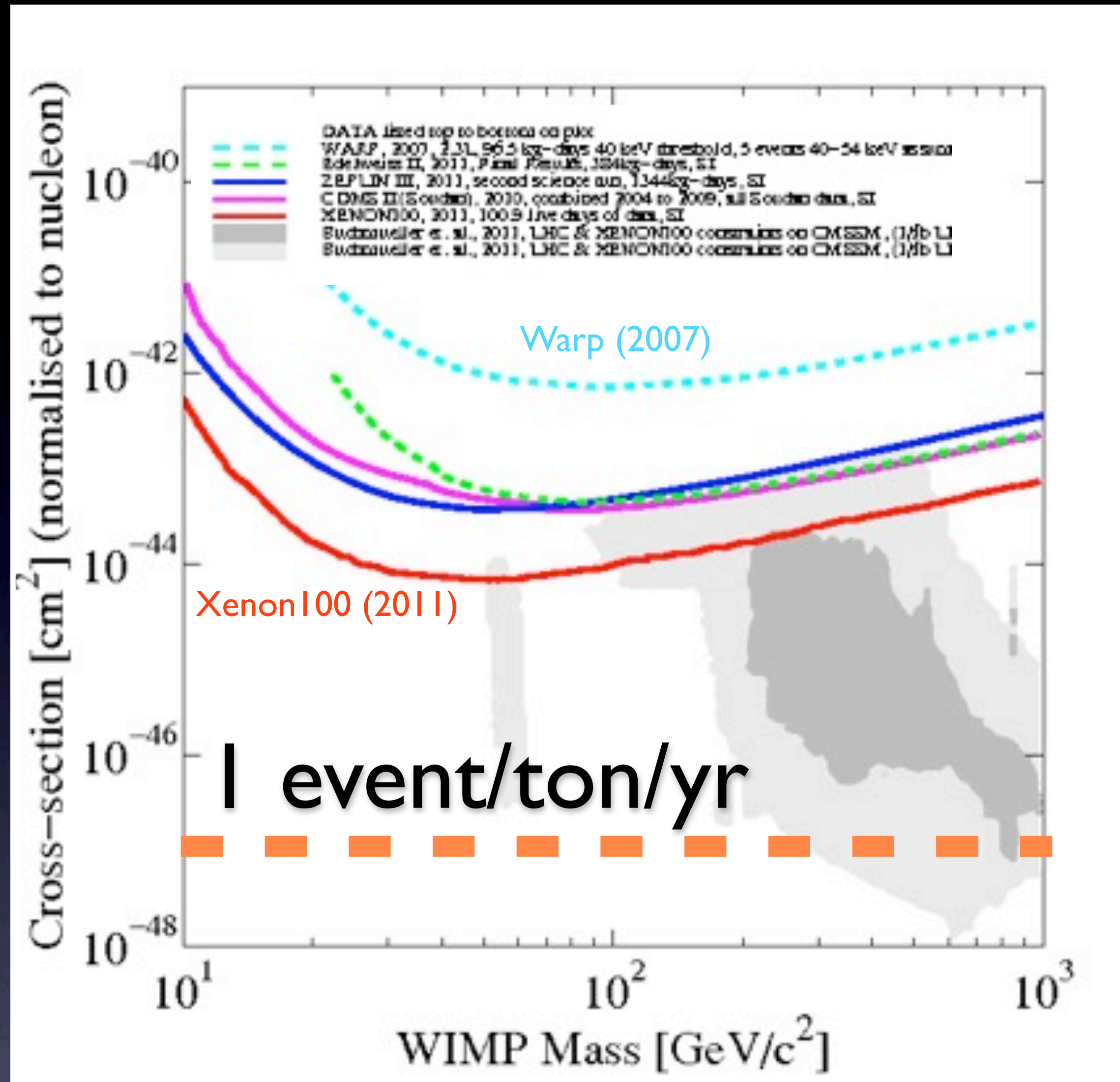
The interesting region for σ_p, m_χ



Our goal:
theoretical predictions for SUSY

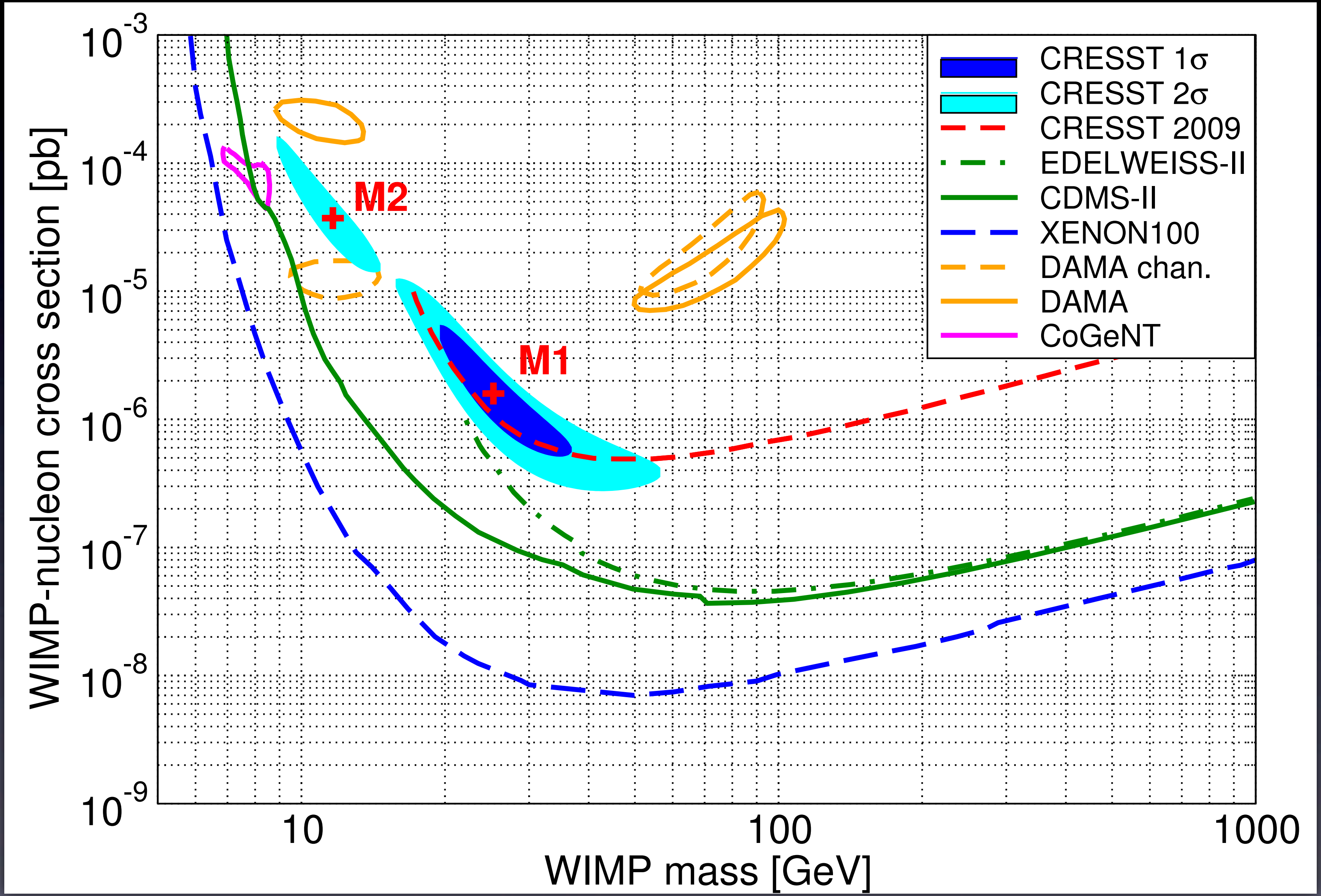
$\sigma_p (cm^2)$

The interesting region for σ_p, m_χ



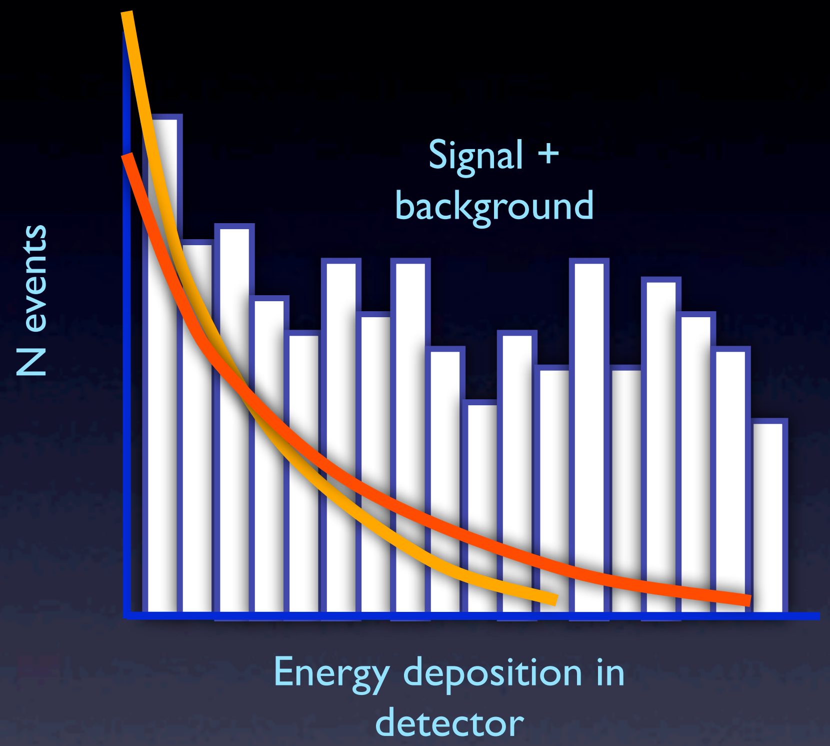
Current experimental limits

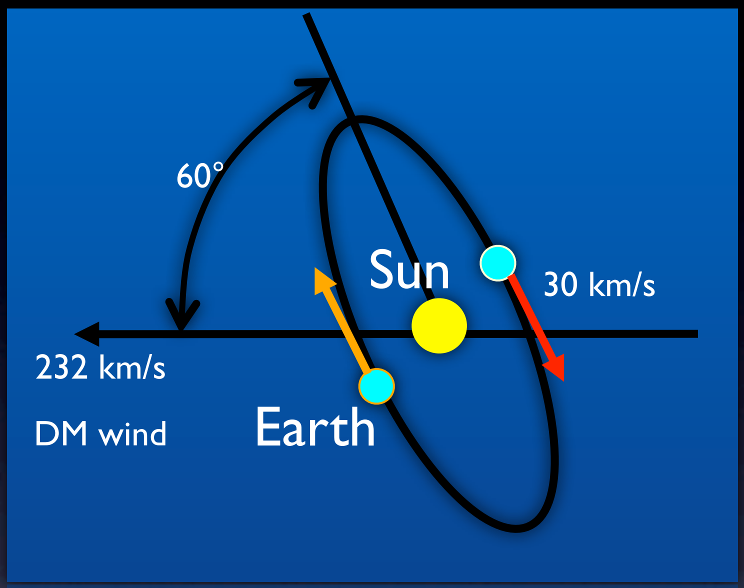
A low mass signal?



2011 CRESST-II (Angloher et al. 1109.0702)

Annual flux modulation



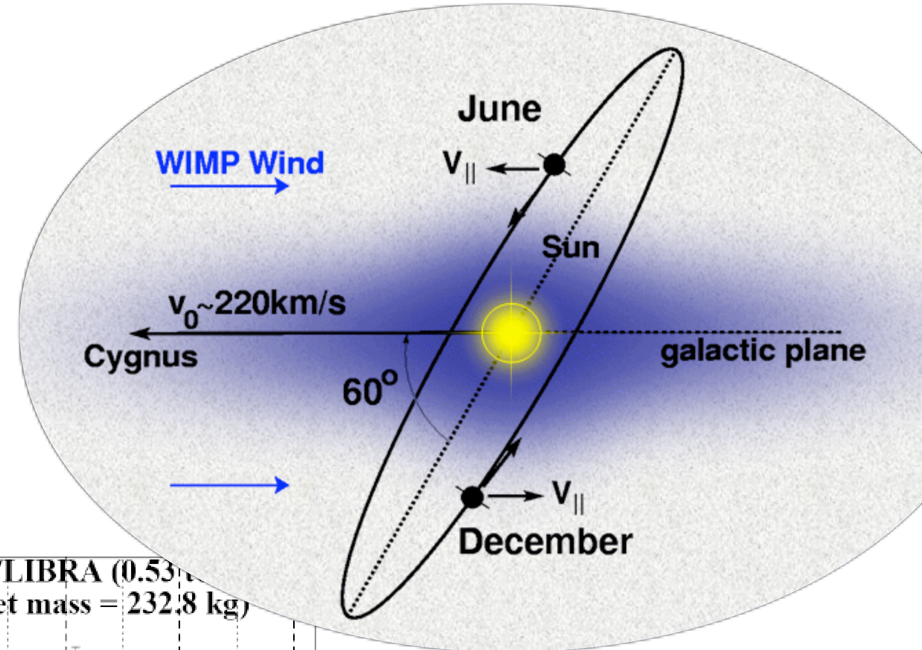


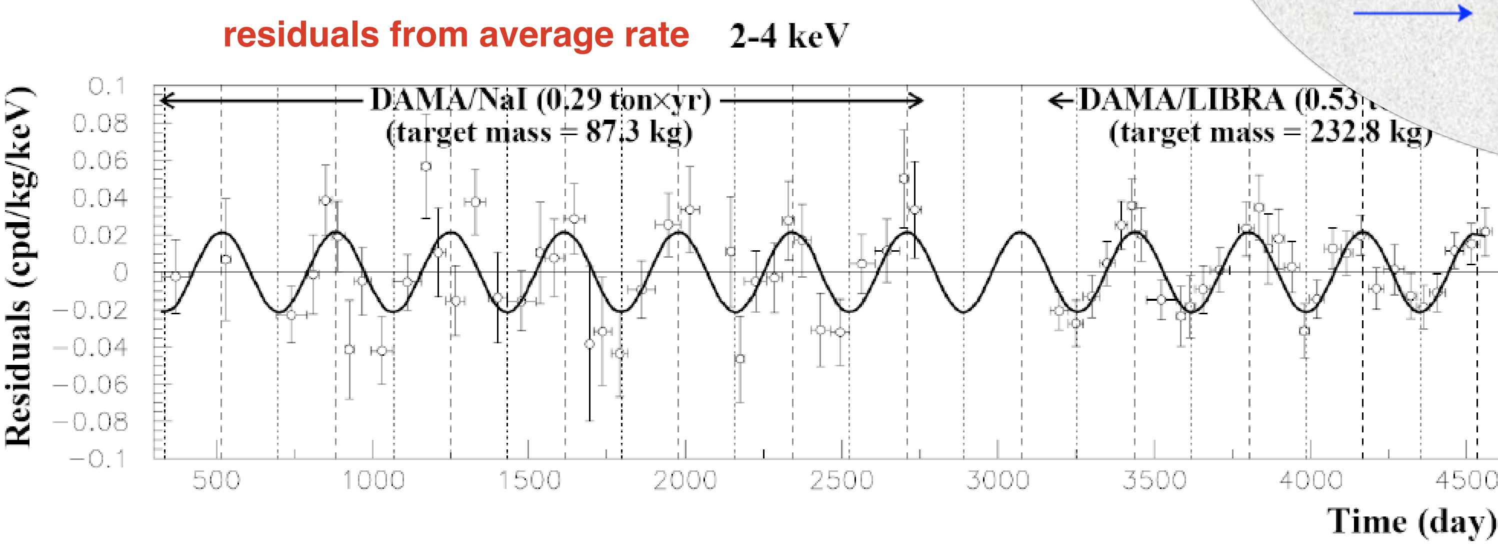
Expected variation of WIMP count rate ± 3%

2010 DAMA/LIBRA (Bernabei et al. 1002.1028)

25 NaI (Tl) crystals of 9.5 kg each, operated at Gran Sasso Underground Lab

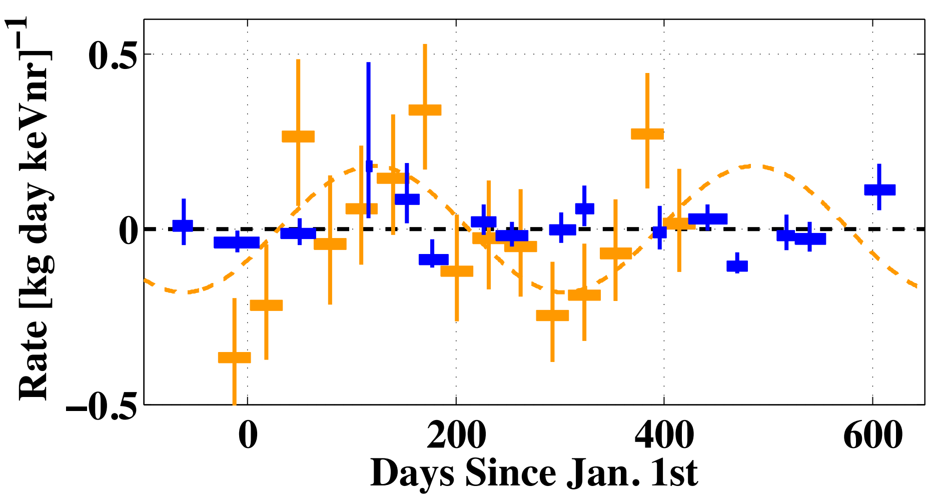
6y in LIBRA (13 years total), 1.17 ton × year, 8.9 σ modulation signal





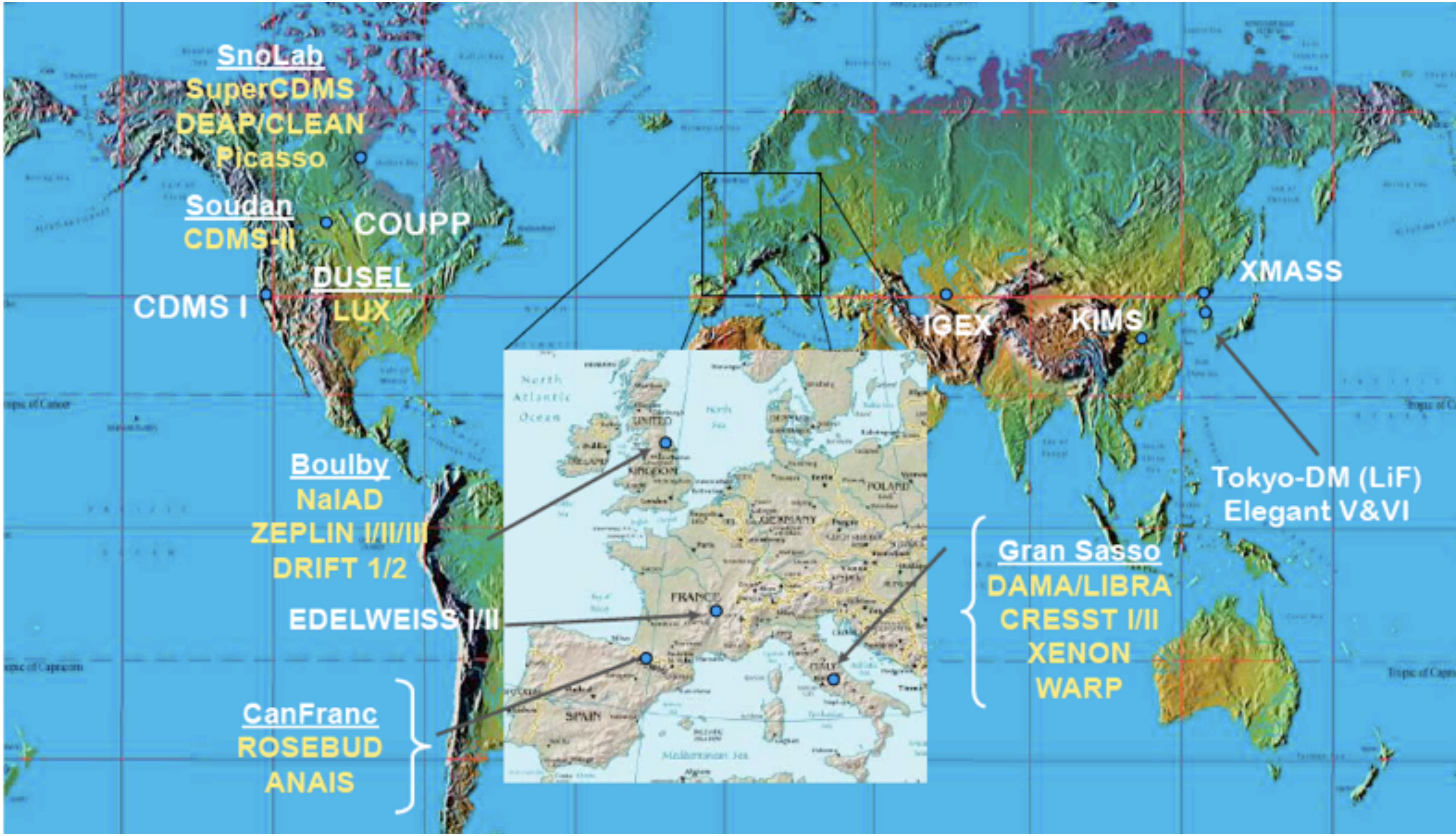
2012 CDMS vs COGENT

(Ahmed et al. 1203.1309)

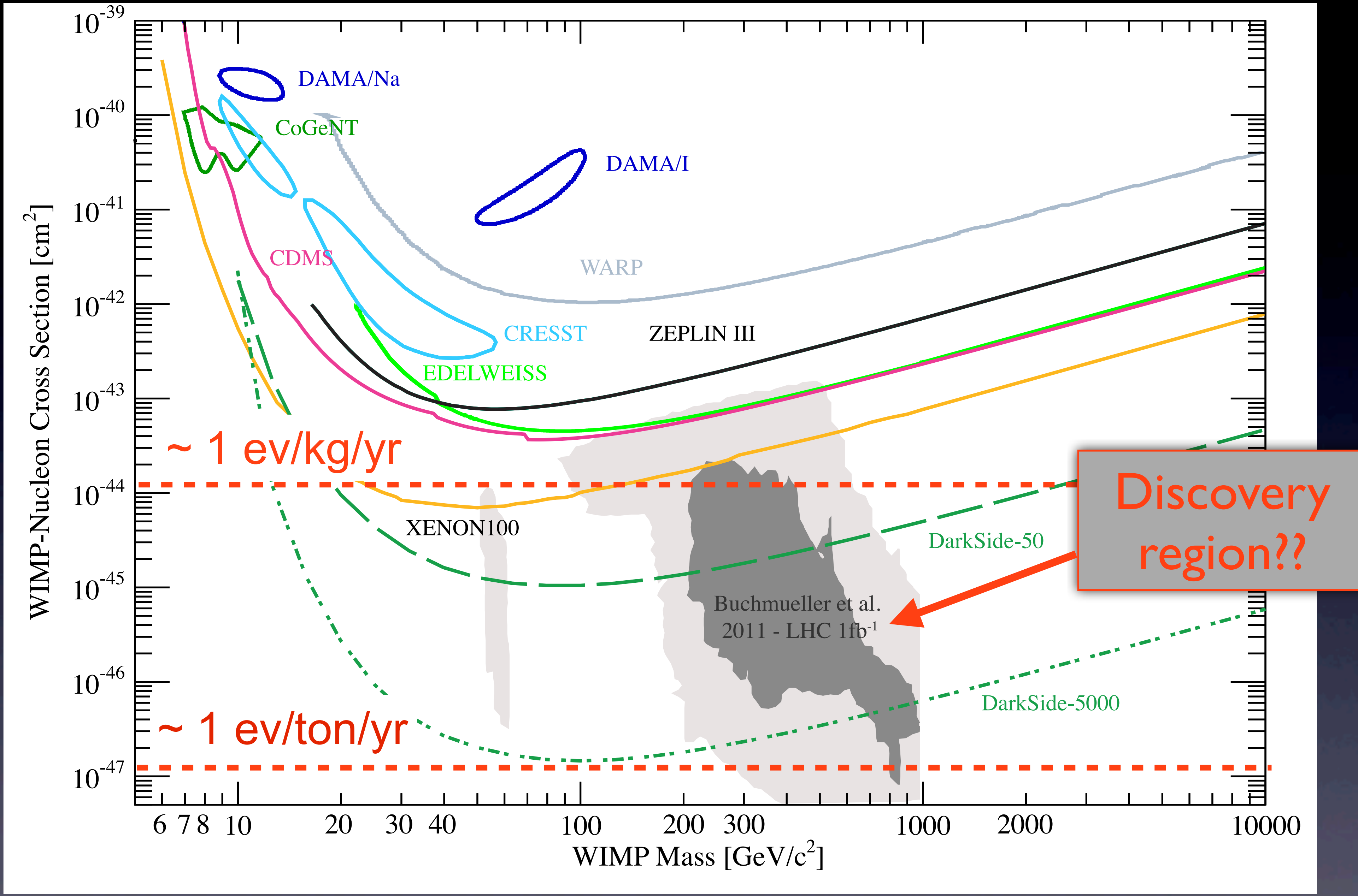


P-type Point Contact (PPC) HPGe Detector, 440g/detector operated in Soudan Underground Lab, 15 months of data

~2.8σ modulation in the low energy range (0.5~3.0 keV)



La ricerca mondiale delle WIMP



The current status