Dark Matter : Properties, Models and Detections

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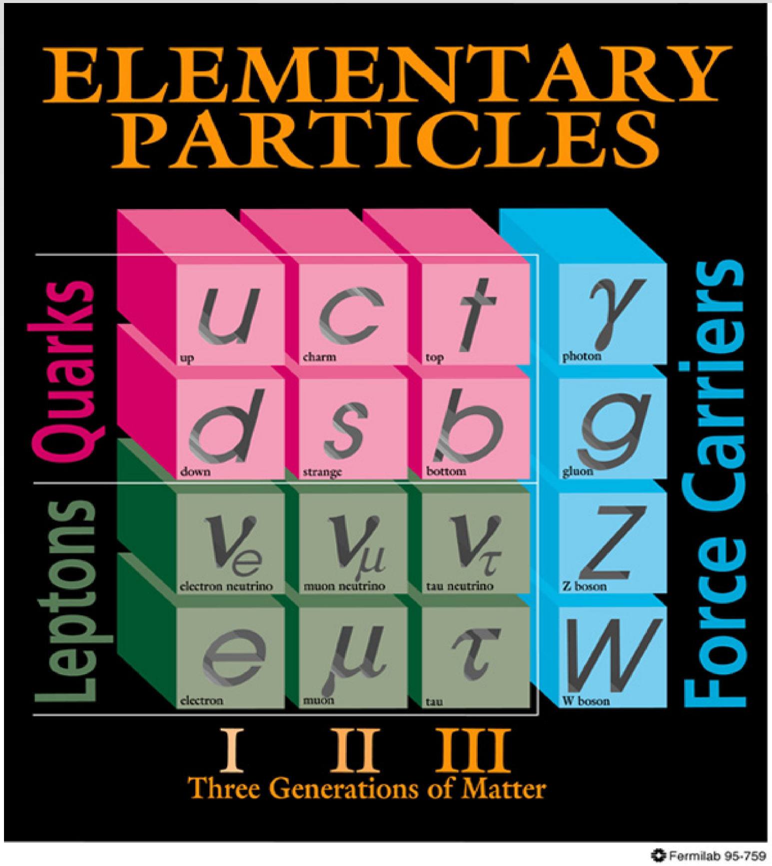
What is *Dark Matter* ?

- An Unknown, non-luminous matter with almost no interactions with other particles except gravity
- Contains more than 80% of the matter content of the universe
- All pervading across the galaxies, clusters, super-clusters

General Properties of Dark Matter

- Should be neutral
- Gravitationally interacting
- Stable
- Very weak interaction with other particles



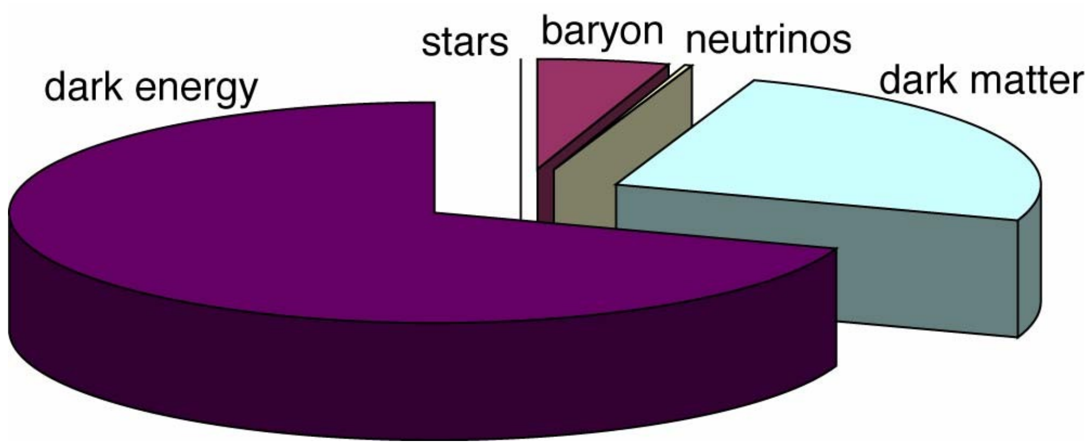
➔ Major constituent is perhaps heavy (massive) particles (non-relativistic while decoupling)

➔ Mainly non-baryonic in nature

Energy Budget of Universe

PLANCK 2013 RESULTS !!!
(March 21, 2013)

- Baryonic Matter are ~ 4.8%
- Dark Matter ~ 26.5%
- Dark Energy ~ 68.4%



“Discovery” of Dark Matter – I
Jan Hendrik Oort (1932)

Jan Hendrik Oort (1900-1992)

11. It is found that the total density of matter near the sun is equal to $6{\cdot}3.10^{-24}$ g/cm^3 or ·092 solar masses per cubic parsec. The observed total mass of the stars down to + 13·5 visual absolute magnitude is found to be ·038 solar masses per ps^3 (Table 34). It is probable that this value would still be greatly increased if we could have taken the next 5 absolute magnitudes into account, so that the total mass of meteors and nebular material is probably small in comparison with that of the stars. There is an indication that the invisible mass is more strongly concentrated to the galactic plane than that of the visible stars (Table 33).

Integrating over a column perpendicular to the galactic plane I find that an average unit of photographic light corresponds to a mass of 1·8 (if both are expressed in the sun as unit), approximately agreeing with the proportion found in the central region of the Andromeda nebula, the only available case where a comparison is possible.

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 Volume VI. No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

Notations.

- z distance from the galactic plane,
- Z velocity component perpendicular to the galactic plane,
- Z_o the value of Z for $z = 0$,
- l modulus of a Gaussian component of the distribution of Z (formula (5), p. 253),
- $K(z)$ the acceleration in the direction of z,
- Δ the star-density,
- ρ the distance of a star from the sun,
- $\Phi(M)$ the number of stars per cubic parsec between $M - \frac{1}{2}$ and $M + \frac{1}{2}$,
- $A(m)$ the number of stars per square degree between $m - \frac{1}{2}$ and $m + \frac{1}{2}$,
- b galactic latitude,
- ϖ distance to the axis of rotation of the galactic system,
- δ $\partial \log \Delta / \partial \varpi$.

Summary of the different sections.

1 and **2.** In these sections a short discussion is given of KAPTEYN's previous investigation on the subject and of the reasons why the problem has been treated anew. In the second section the formulae are given which show the connection between $K(z)$, $\Delta(z)$ and the velocity distribution (formulae (5) and (6)).

3. The distribution of Z and its dependence upon spectral type and visual and photographic absolute magnitude is studied in some detail. The adopted results are in Tables 7 (spectral types), 9 (visual absolute magnitudes) and 11 (photographic absolute magnitudes). The average velocities of giants and dwarfs of the same spectrum appear to be practically identical in the z direction. On account of their irregular distribution the B0 – B5 stars have been excluded in forming the velocity laws for the different groups of absolute magnitude.

It is shown that stars at various distances north and south of the galactic plane indicate no signs of systematic motions in the z-direction (Table 12).

4. From VAN RHIJN's tables in *Groningen Publication* No. 38 the density distribution $\Delta(z)$ has been computed for four intervals of visual absolute magnitude (Table 13 and Figure 1). Figures 2 and 3 show log $\Delta(z)$ for A stars and yellow giants, as derived by LINDBLAD and PETERSSON.

5. With the aid of the data contained in the two preceding sections I have computed the acceleration $K(z)$ between $z = 0$ and $z = 600$. The computations were made by successive approximations; the B stars were eliminated first. The results are in Table 14 and Figure 4, $K(z)$ giving the values finally adopted. The good agreement between the practically independent values of $K(z)$ derived from the separate absolute magnitude groups is a strong argument in favour of the approximate correctness of the data up to $z = 400$. The result may be summarized by stating that the absolute value of $K(z)$ increases proportionally with z from $z = 0$ to $z = 200$; between $z = 200$ and $z = 500$ it remains practically constant and equal to $3{\cdot}8.10^{-9}$ cm/sec^2.

6. In this section the different spectral classes are investigated separately. A comparison of numbers computed with the aid of $K(z)$, with direct counts in high galactic latitude revealed a great discrepancy for the K stars, probably due to an error in the adopted luminosity law (compare *B. A. N.* No. 239). A slight correction to the average velocity of the A stars was also indicated. Both corrections have been applied throughout the greater part of the present investigation.

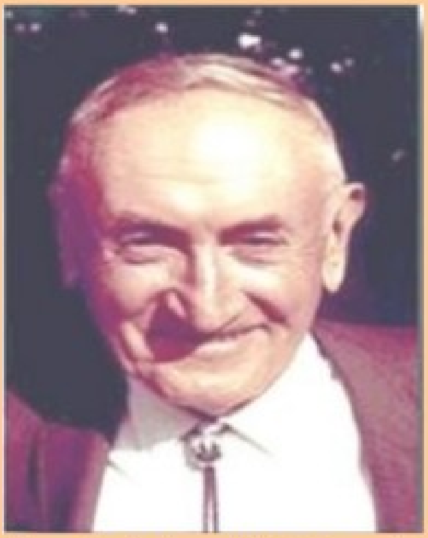
For comparison with future observations of fainter stars the computed numbers of each spectral type and visual apparent magnitude are given in Table 17, for 20°, 40° and 60° galactic latitude. The table also shows the relative numbers of giants and dwarfs to be expected for each magnitude. Finally, Table 18 shows the corresponding average colour indices and the mean square deviations from the average. No great accuracy can be claimed for these values.

7. From the best sources available mean values of log $A(m)$ were computed for visual as well as

249

* Vertical velocities of stars too high – they should have escaped!

* Need “invisible” mass of density ~ 2 GeV / cc ! Modern value ~ 0.3 Gev / cc



“Discovery” of Dark Matter – II
Fritz Zwicky (1933)

F. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta 6: 110–127 (1933)

F. Zwicky, "On the Masses of Nebulae and of Clusters of Nebulae", Astrophysical Journal 86: 217 (1937)

Fritz Zwicky (1898 - 1974)

Coma Cluster

$$\begin{aligned} N &> 1000\,\text{galaxies} \\ D &\sim 100\,\text{Mpc} \\ M &\sim 10^{14} M_\odot \end{aligned}$$

Virial Theorem $\Rightarrow \langle v^2 \rangle \sim \frac{1}{2} \frac{GM}{\langle r \rangle}$

Measured $\langle v^2 \rangle^{\frac{1}{2}} \sim 1000\,\text{km}\,\text{s}^{-1} \Rightarrow M \sim 400 M_{\text{visible}}$!!

— Radial velocities of galaxies in the Coma cluster are too large for the galaxies to be bound in the cluster with the known "visible" mass of the cluster.

Note: Zwicky used (wrong!) $H_0 = 558\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ (as measured by Hubble!). Correct result

$$M_{\text{Coma cluster}} \sim 50 M_{\text{visible}}$$

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal viscosity due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_\odot$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

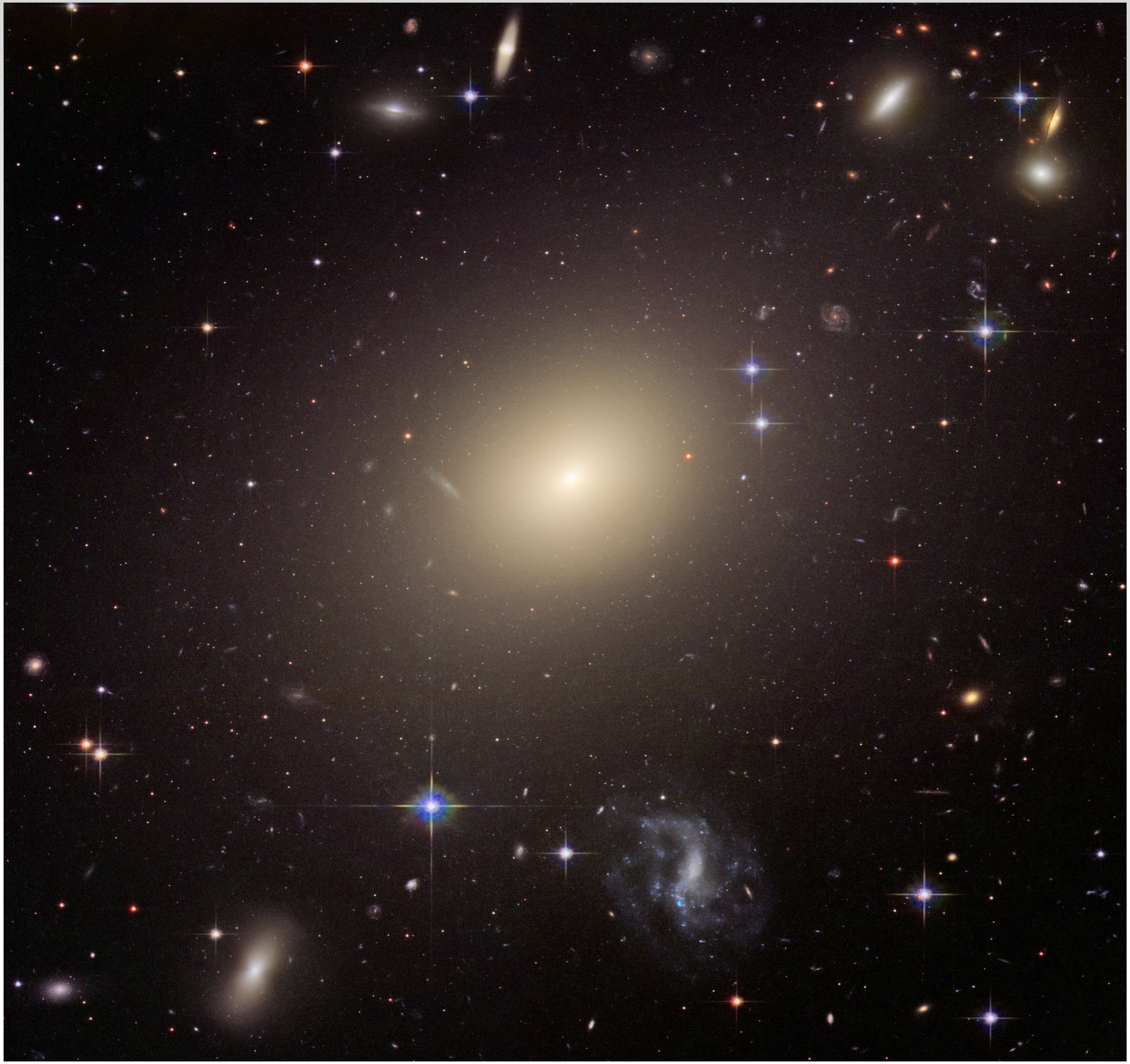
As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar.

Evidence of Dark Matter in the Universe

- Flatness of the rotation curves of spiral galaxies at large radius
- Gravitational lensing
- Bullet Clusters
- Anisotropy of cosmic microwave background radiation.
- Difference in gravitational mass and luminous mass in galaxy clusters
- Difference in total mass and observed mass

Spiral Galaxy

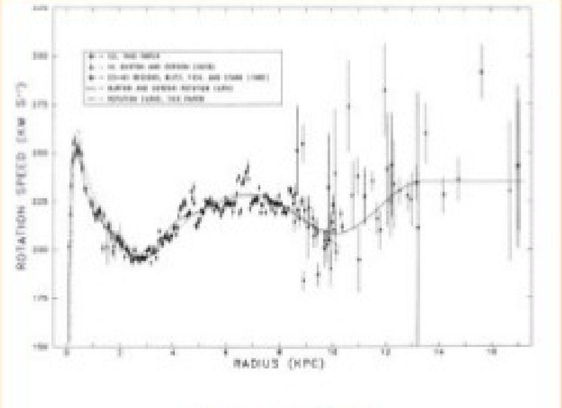
Elliptical Galaxy



Rotation Curve of Spiral Galaxies and Dark Matter

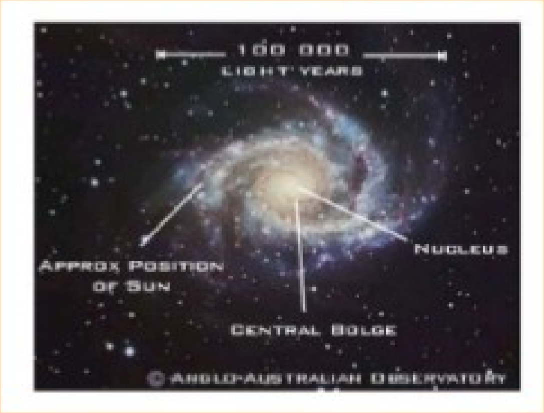
Galactic scale Dark Matter seriously studied only begining early 1970s: Vera Rubin: Rotation Curve of Spiral galaxies.

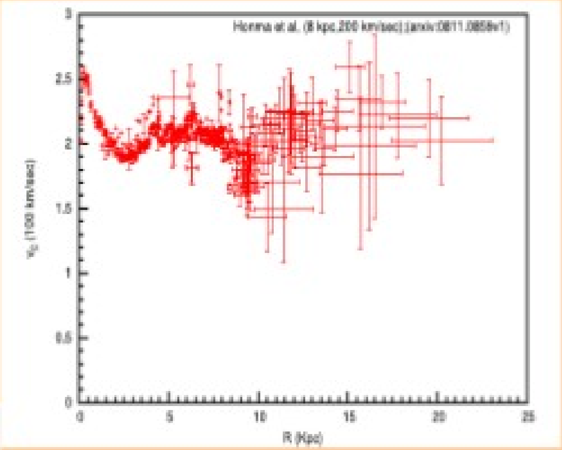
Circular Rotation Speed: $v_c^2(R) = R\frac{\partial \phi}{\partial R} = G\frac{M(R)}{R}$

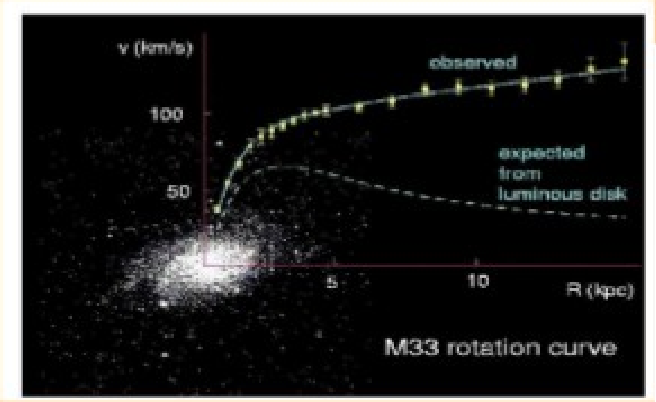


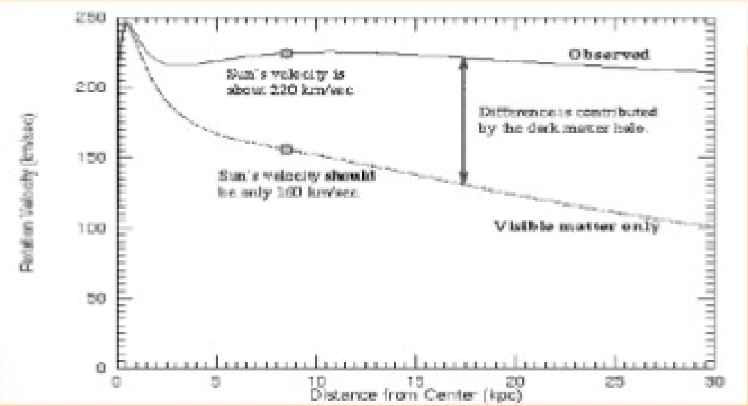
Clemens (1985)

Rotation Curve of Milky Way

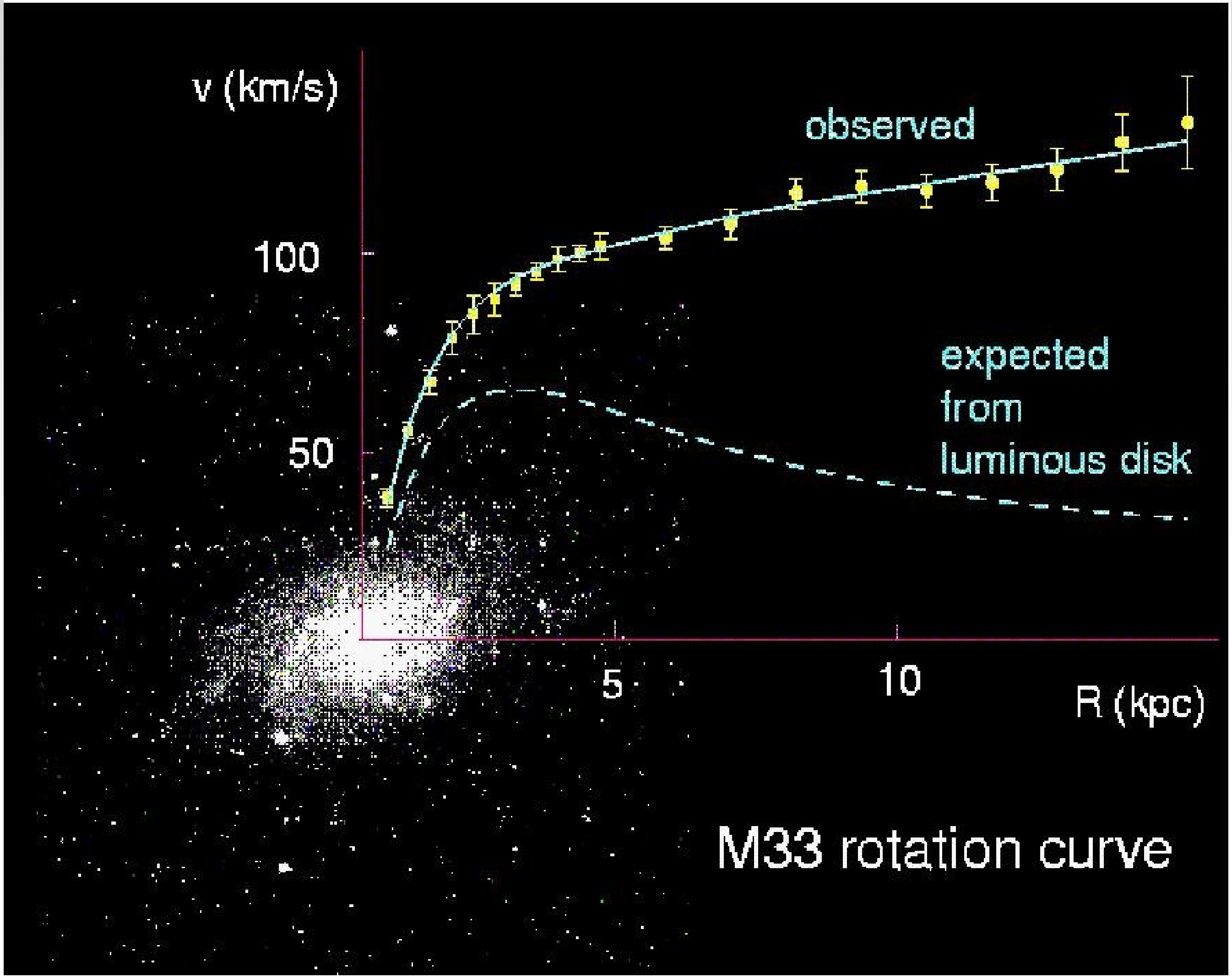








Flatness of Rotational Curve



Flatness of Rotational Curve

$$\frac{mv_r^2}{r} = \frac{GM_r m}{r^2}$$

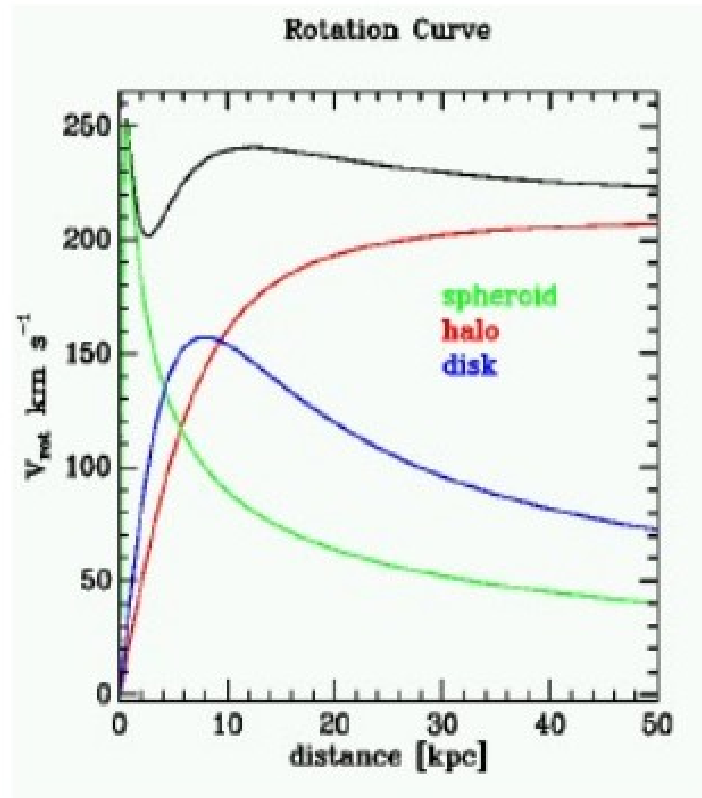
$$M_r = \frac{4}{3}\pi r^3 \rho$$

$$v_r \sim r$$

$$v_r \sim \frac{1}{r^{1/2}} \quad \text{(Keplerian Decline)}$$

$$M_r \sim r$$

Mass Models : Dark Matter Halo



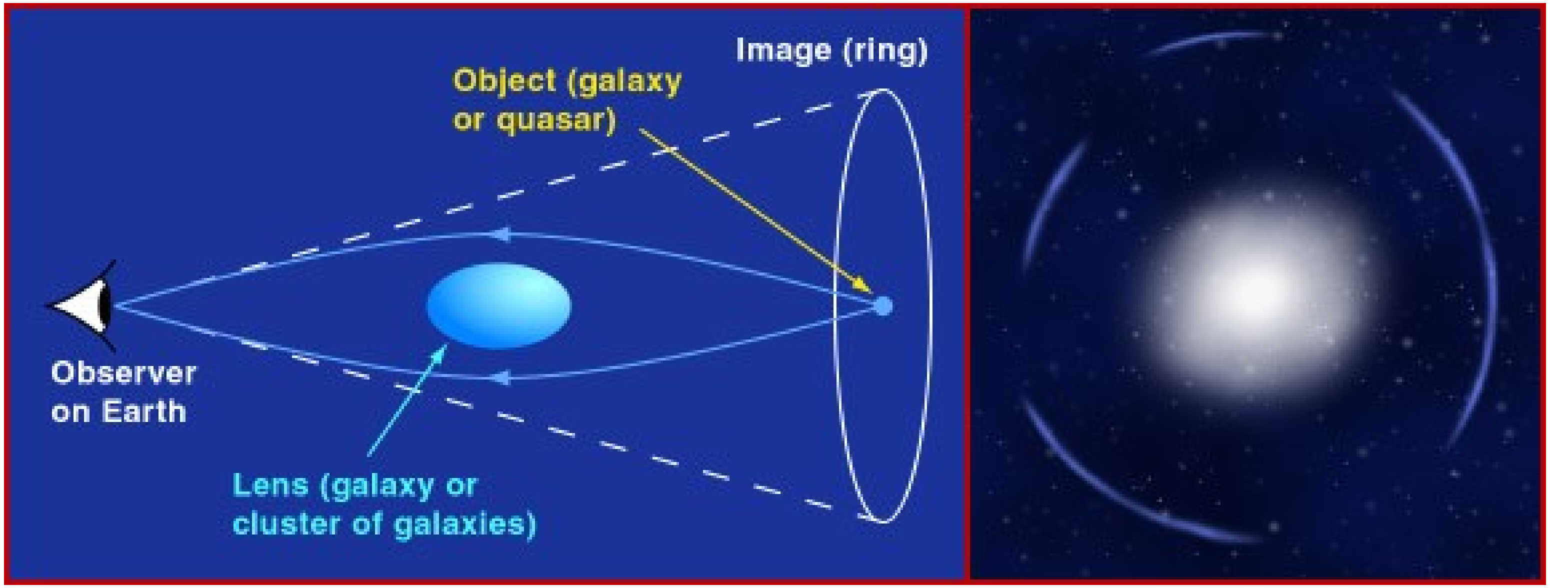
$$\Phi_{\rm total} = \Phi_{\rm visible} + \Phi_{\rm DarkMatter}$$

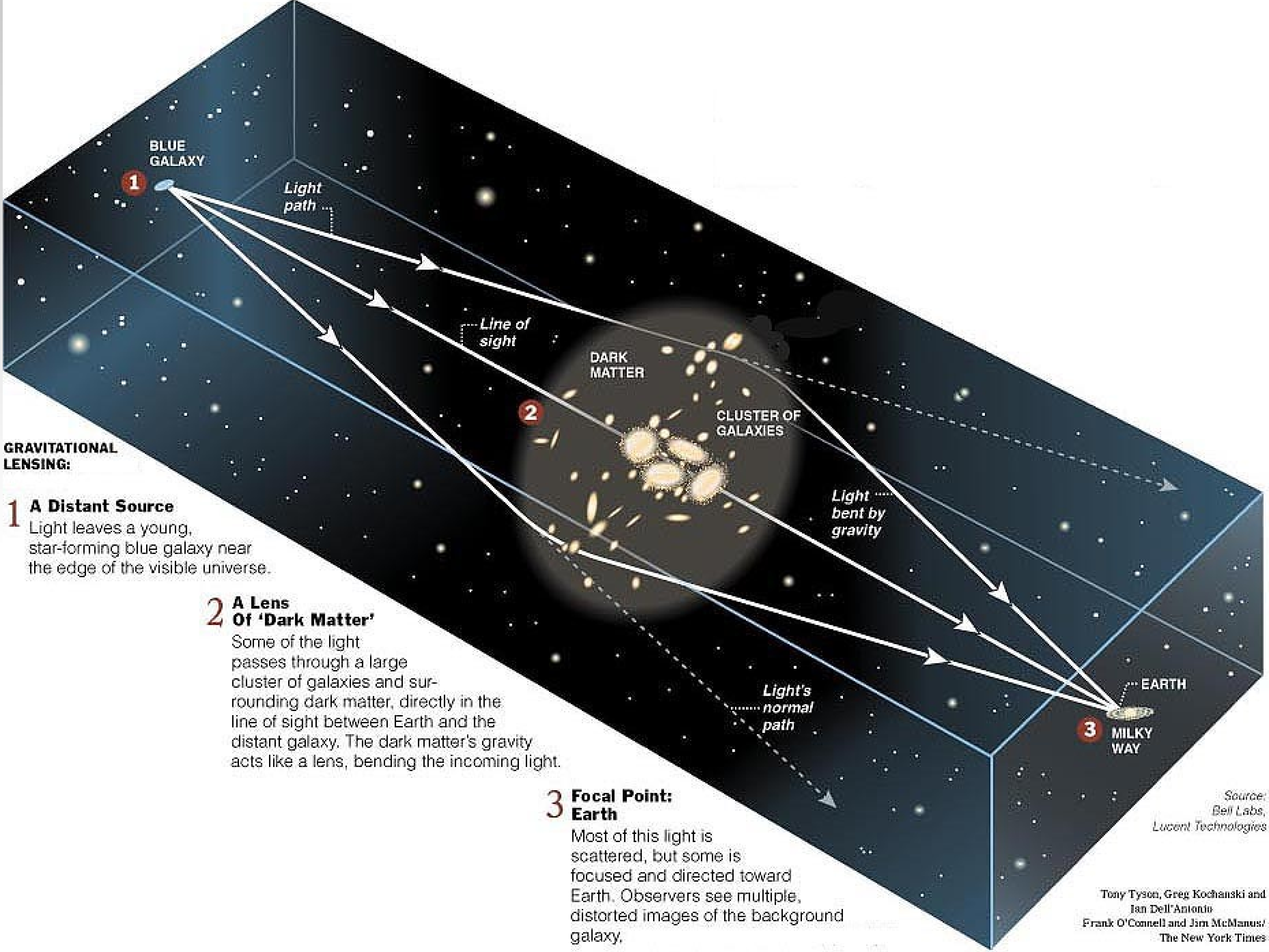
$$v_c^2 = (v_c^2)_{\rm vis} + (v_c^2)_{\rm DM}$$

Lensing

Another method used to study mass/distance relationships among the far reaches of our Universe is called lensing.

Lensing occurs when an object's gravity distorts light behind it.

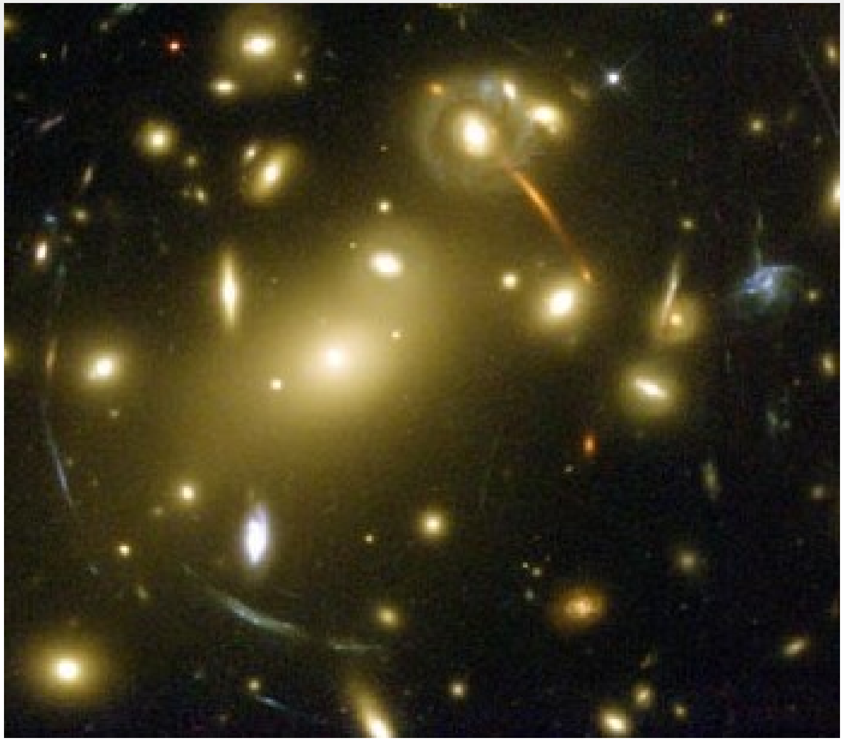



BLUE
GALAXY
1
Light
path
Line of
sight
DARK
MATTER
2
CLUSTER OF
GALAXIES
Light
bent by
gravity
Light's
normal
path
EARTH
3
MILKY
WAY
GRAVITATIONAL
LENSING:
1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.
2 A Lens Of 'Dark Matter'
Some of the light 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

In 1997, a Hubble Space Telescope image revealed light from a distant galaxy cluster being bent by another cluster in the foreground.

Based on the way the light was bent, it is estimated the mass of the foreground cluster to be 250 times greater than the visible matter in the cluster.

It is believed that dark matter in the cluster accounts for the unexplained mass.



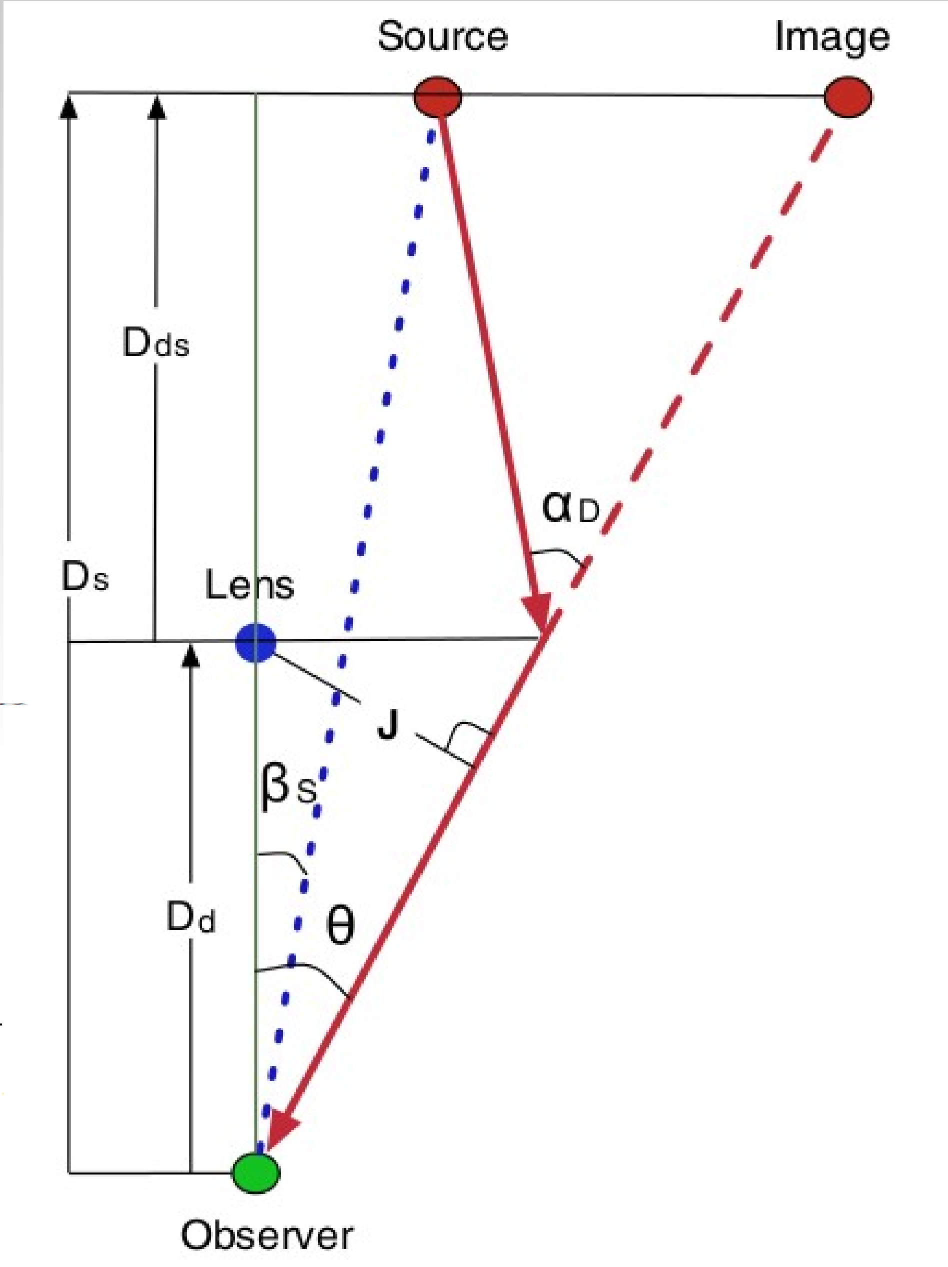
Gravitational Lens Created by Galaxy Cluster Reveals Presence of Dark Matter

$$\alpha_D(R) = \frac{4GM_{<R}}{Rc^2}$$

$$D_S\theta = D_S\beta + D_{dS}\alpha_D$$

$$\alpha = \frac{D_{dS}}{D_S}\alpha_D$$

Lens Equation $$\beta = \theta - \alpha$$

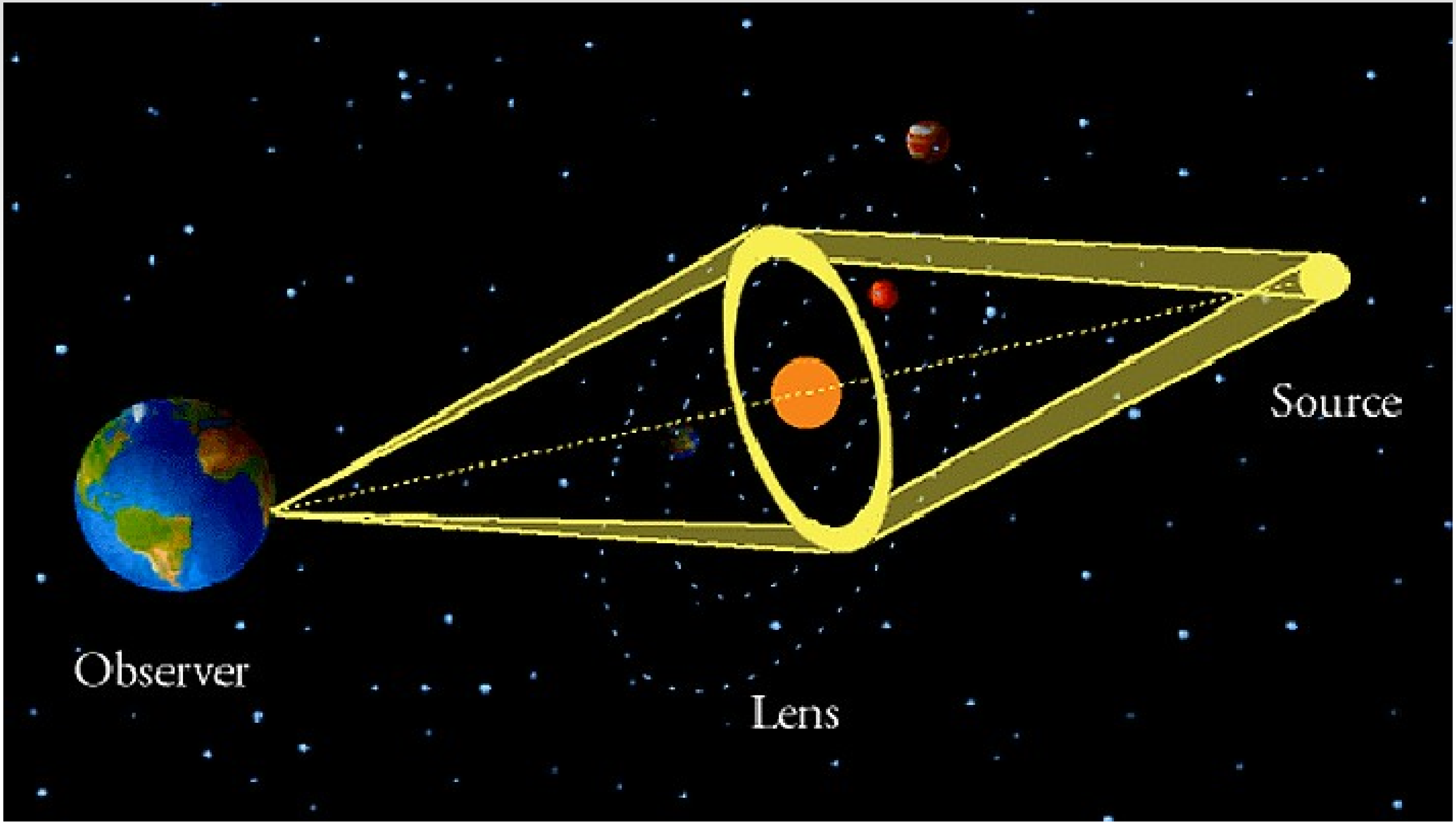


$$\beta = \theta - \frac{4GM}{c^2\theta}\frac{D_{LS}}{D_L D_S}$$

$$\theta^2 - \beta\,\theta - \theta_E^2 = 0 \qquad \theta_E \equiv \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}}$$

$$\theta_\pm = \frac{\beta}{2} \pm \sqrt{\frac{\beta^2}{4} + \theta_E^2}$$

Lensing



Bullet Cluster

WHO: The "Bullet Cluster," named for its distinctive shape, is formally known as 1E 0657-56, and is the result of the collision of two enormous clusters of galaxies.

WHAT: The collision that created the Bullet Cluster was one of the most energetic events since the Big Bang.

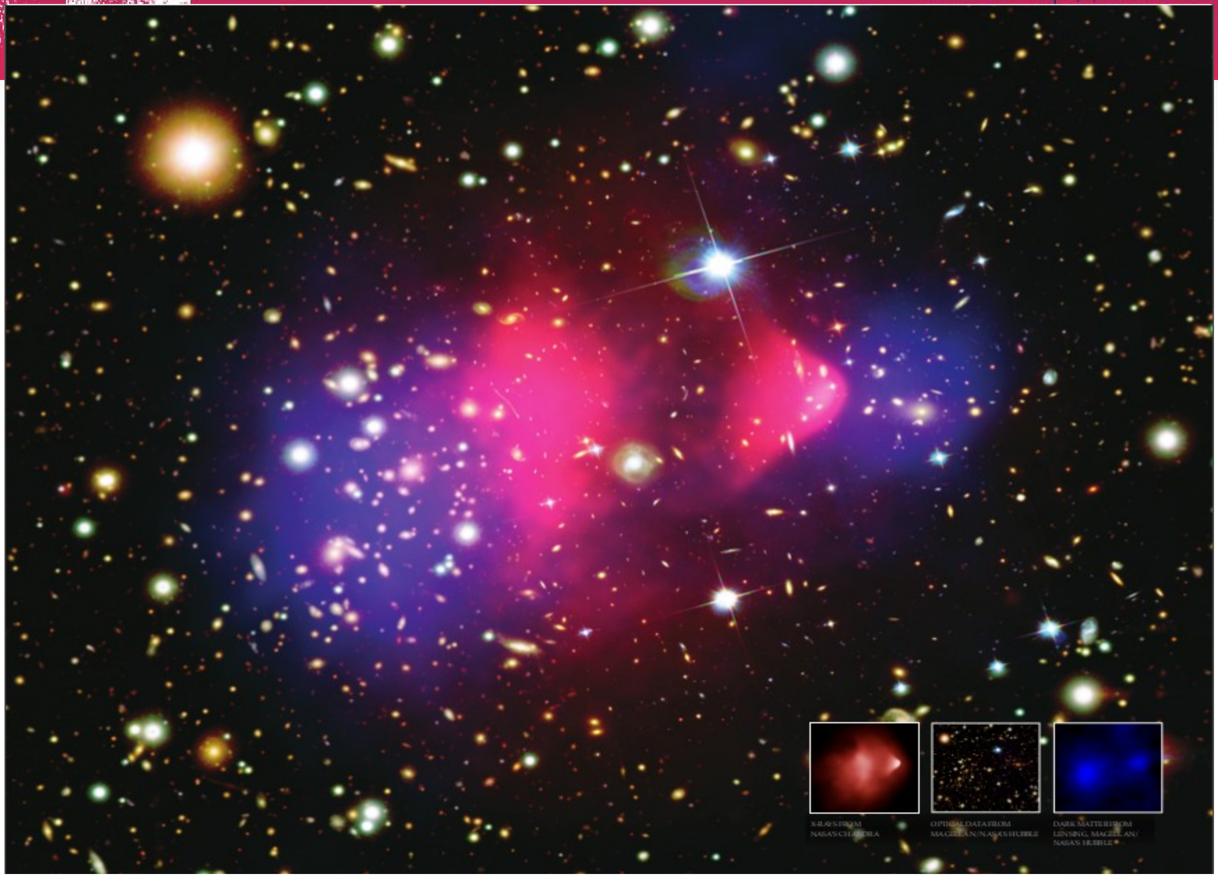
WHERE: At a distance of nearly 4 billion light years from Earth, the Bullet Cluster is located in the constellation Carina, or the "keel" (bottom of a ship).

WHEN: The speed and shape of the bullet, and other information from various telescopes suggest that the smaller cluster passed through the core of the larger one about 150 million years earlier.

HOW: When these two enormous objects collided, they did so at speeds of several million miles an hour. The force of this event was so great that it wrenched the "normal" matter in the form of hot gas (seen in pink) away from the dark matter (blue).

WHY: The separation between the hot gas and the dark matter in this system is direct evidence that dark matter does, in fact, exist. The exact nature of dark matter remains unknown, but it is thought to account for about 25% of the matter in the Universe.

More at: http://chandra.harvard.edu



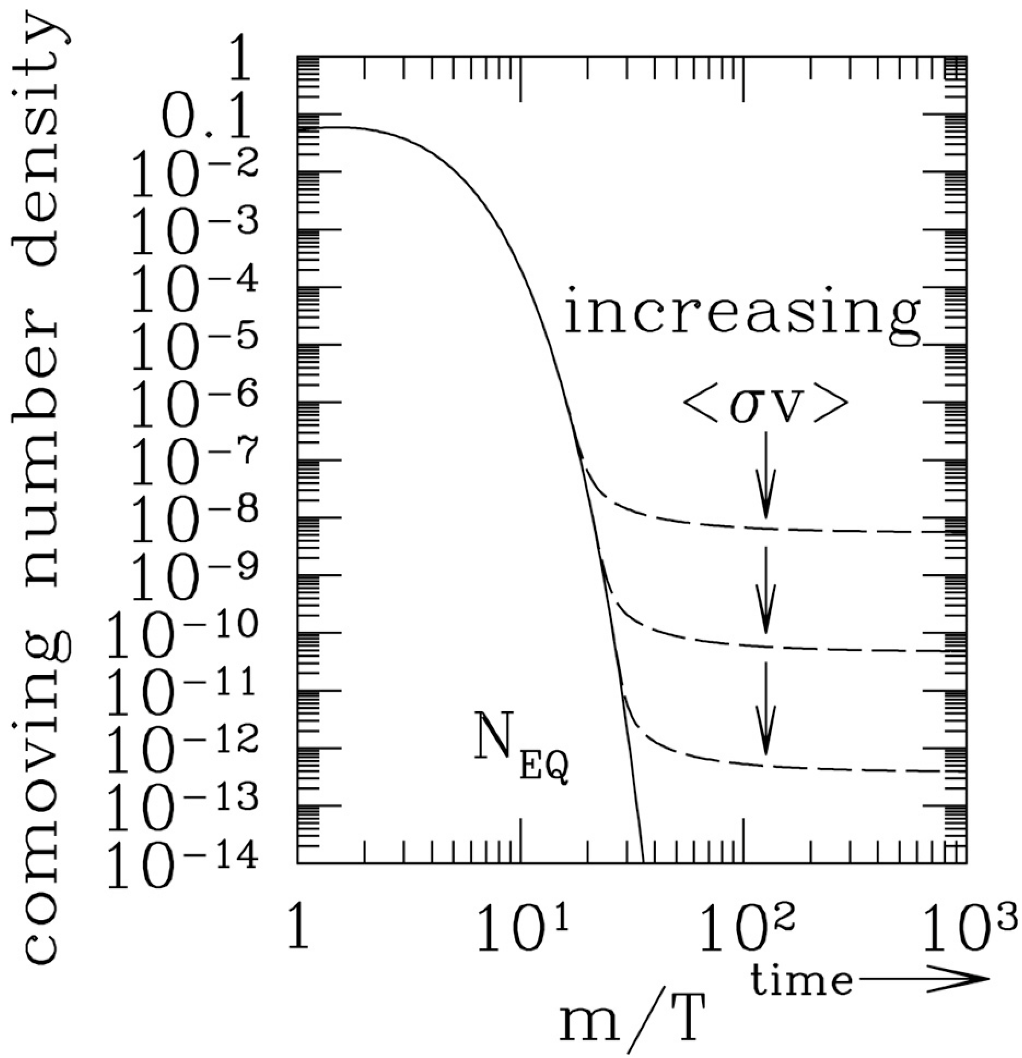
Thermal WIMP Paradigm

- So, the evolution of number density, n(t) is quantitatively given by,

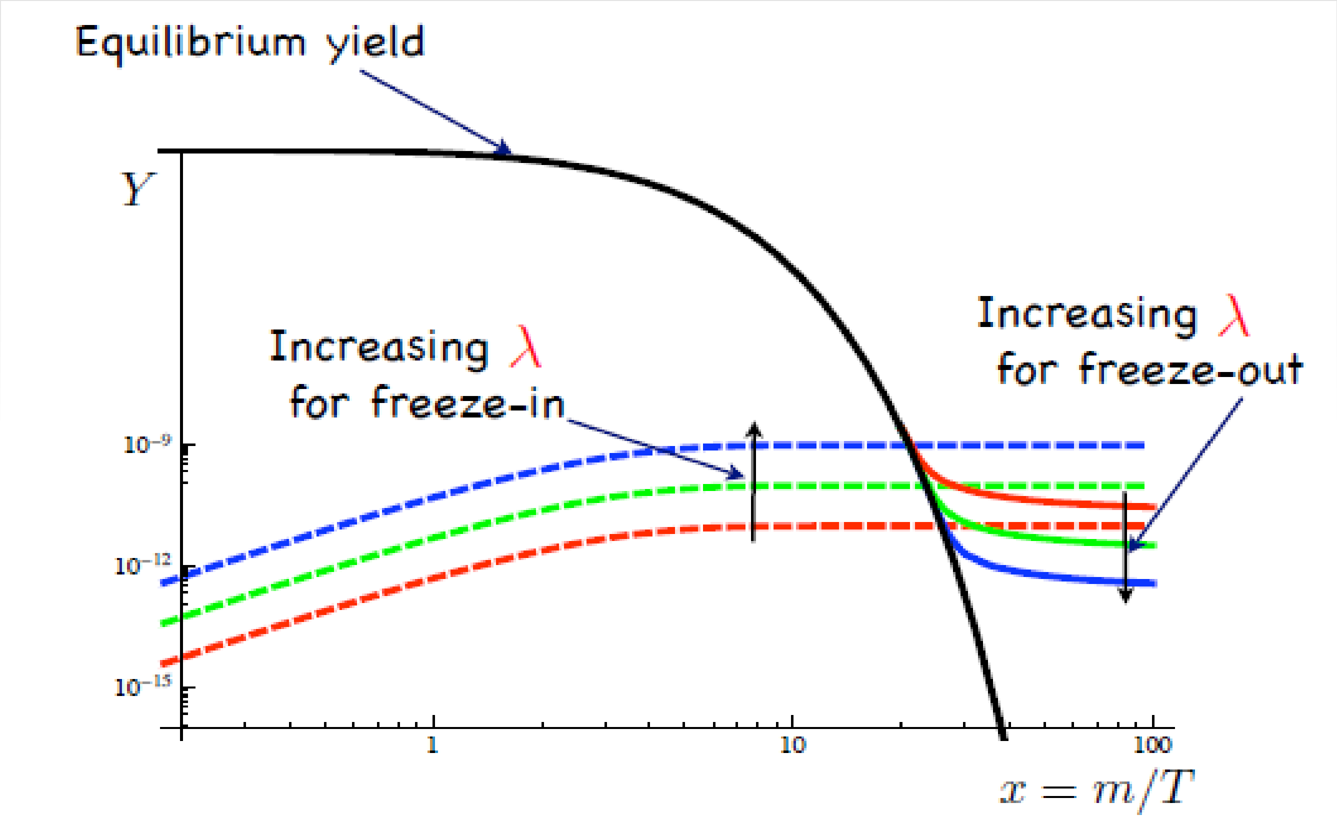
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle[(n_\chi)^2 - (n_\chi^{eq})^2]$$

- Thus, the relic density (DM) is set by,

$$\Omega_{DM} \sim \frac{1}{\langle\sigma v\rangle}$$



Non-thermal vis-a-vis Thermal



Types of Dark Matter

- *Cold Dark Matter (WIMP)*

  moves very non-relativistically, so has a short free-streaming length

- *Hot Dark Matter*

  moves relativistically

- *Warm Dark Matter*

- *Baryonic DM*
- *Non-baryonic DM*

Baryonic Dark Matter

MACHOs – Massive Astrophysical Compact Halo Objects

Brown Dwarfs: with $m < 0.08\ M_\odot$
(no H-burning)

Jupiters: with $m < 0.001\ M_\odot$

Black Holes with $m \sim 100\ M_\odot$
(not sufficient to close the universe)

Quark Nuggets (?) with $m \sim 0.1\ M_\odot$ (MNRAS 340 (2003) 284)

clouds of molecular hydrogen (?)

Particle dark matter

Hot dark matter

- relativistic at kinetic decoupling
- large free streaming length
- cannot cluster on galaxy scales

e.g. light neutrinos

Cold dark matter

- non-relativistic at kinetic decoupling
- possible to cluster in small scales

Cold ($v < 10^{-8}$ c)

e.g. neutralinos, axions, KK particles

Warm dark matter

- semi-relativistic at kinetic decoupling

e.g. sterile neutrinos, gravitinos

Neutrino Dark Matter

Structure formation

There is a lower limit on particle mass for smallest scale structure

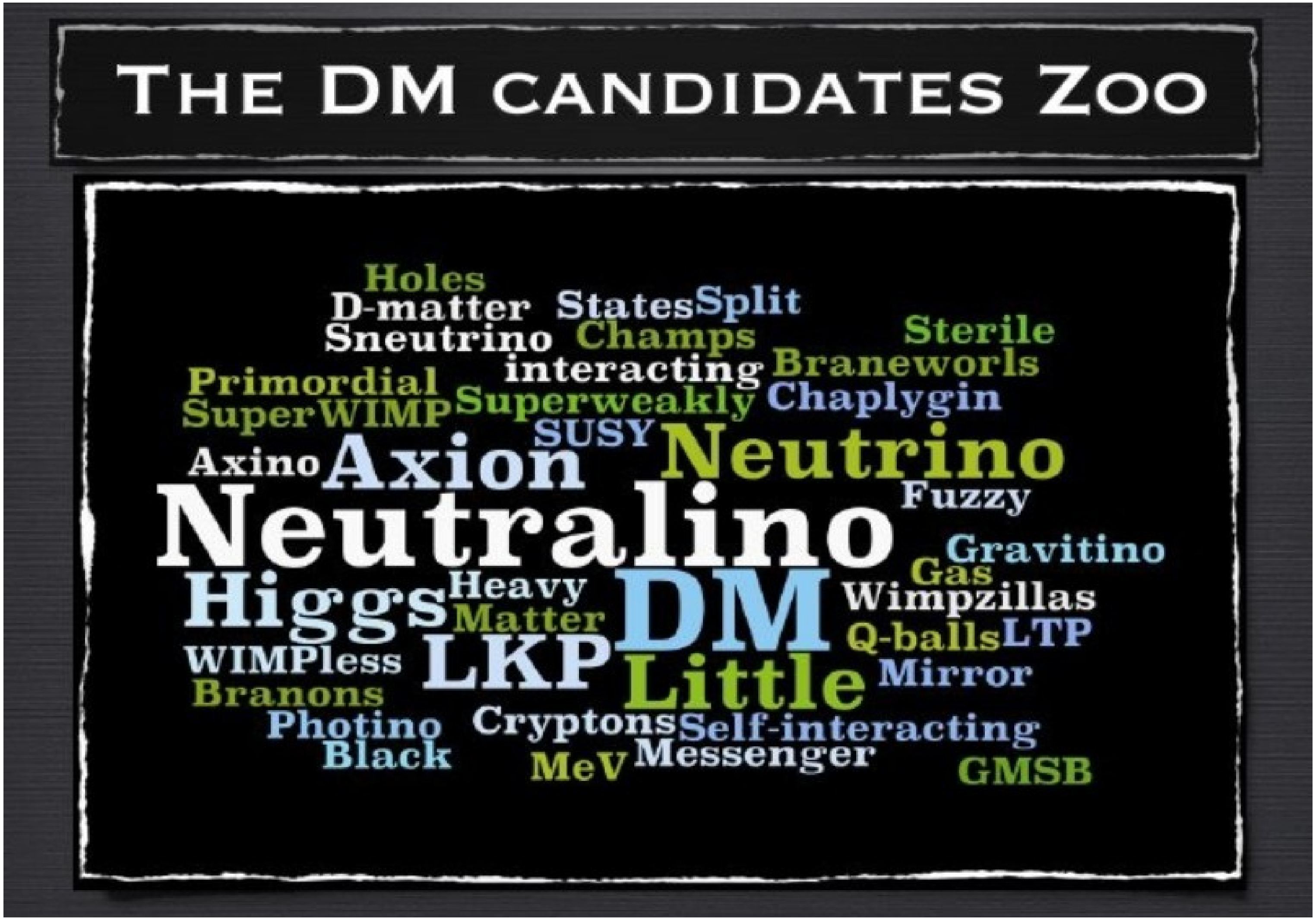
For small scale structures at $z \sim 3$: mass of dark matter $\geqslant 2$ keV

Neutrinos being low mass and high speed

travels large distances
density perturbations may be washed out

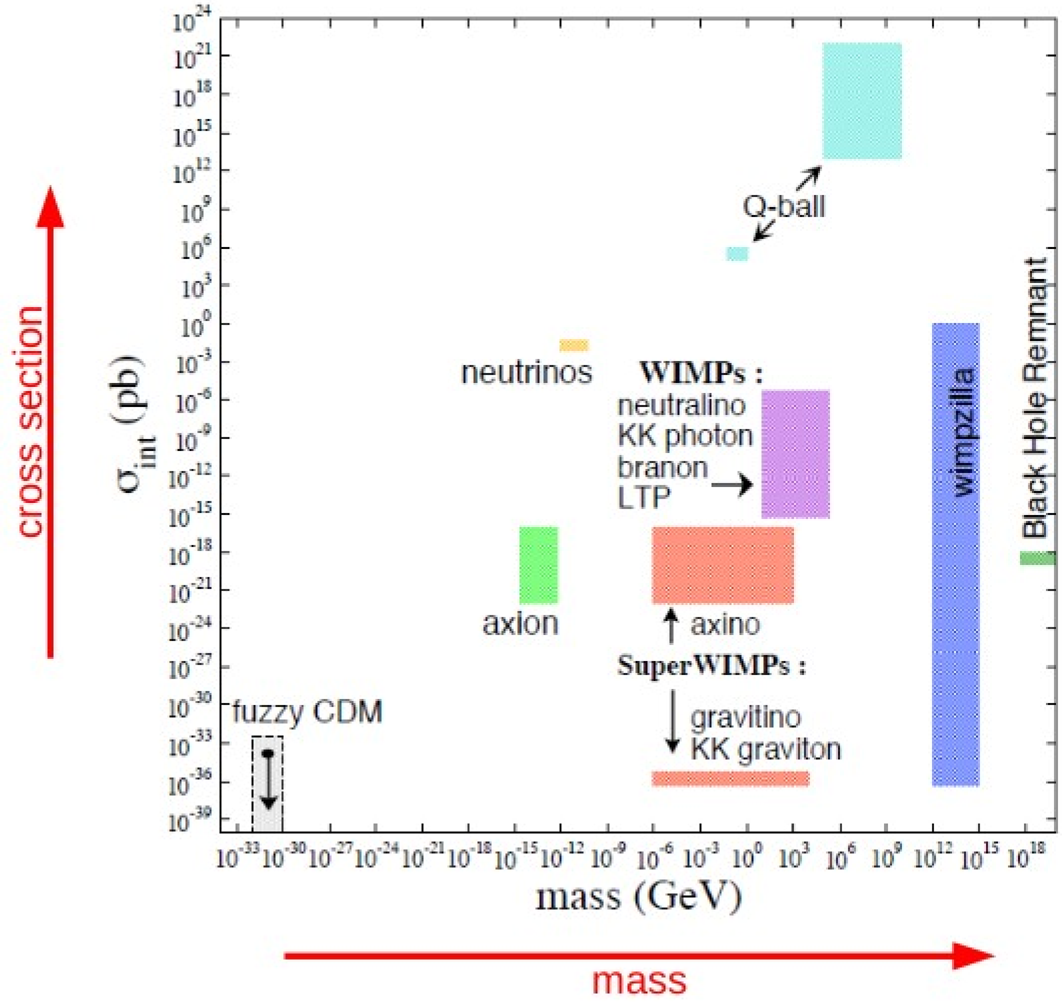
Non baryonic Dark Matter

Explore beyond Standard Model



from Gianfranco Bertone

(Some) Dark Matter Candidates



- Axion
- WIMPs
  - Neutralino
  - (LKP)
- sterile neutrinos

from Marc Schumann

Particle dark matter

Thermal relics

- in thermal equilibrium with the plasma in the early universe
- produced in collision of plasma particles
- insensitive to initial conditions

e.g. neutralinos, other WIMPs, ...

Non-thermal relics

- not in thermal equilibrium with the plasma in the early universe
- produced in decays or out-of-equilibrium decays of heavier particles

e.g. Axions ....

Axion Dark Matter

There are CP violating terms in the QCD Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + \Theta\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu a} + \overline{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

since no strong CP violation is observed, Θ must be very small or zero
but in general Θ can take any value

Strong CP Problem

introduce the global U(1) symmetry (Peccei-Quinn Symmetry)

this symmetry is spontaneously broken at some large scale

dynamical interpretation of the angle Θ

$$\mathcal{L}_{QCD} = -\frac{1}{2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + \overline{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi + \left(\Theta - \frac{a}{f_a}\right)\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu a} + \frac{1}{2}\partial_\mu a\partial^\mu a$$

for $a = \Theta f_a$ CP symmetry is restored

a is the axion field

this theory has a pseudo-scalar boson (the axion) of the spontaneously broken PQ symmetry

Neutral SUSY Particles: LSP Candidates

Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2		Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$				$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

Dark Matter Candidates in the MSSM

1. sneutrino (spin 0)
would have relatively large coherent scattering with nuclei direct DM expts exclude sneutrinos between a few GeV and several TeV

2. neutralino (spin 1⁄2) → the favourite

3. gravitino (spin 3/2)

Sterile Neutrinos

Motivation:

- We know that neutrinos exits, and that they have a mass
  → the only solid lab evidence for beyond SM physics
- Maybe this is a sign for existence of a new *E* scale (GUT?)
- Assume
  - ν masses come from existence of new unseen particles
  - complete theory is a renomalizable extension of the SM
- Introduce sterile neutrinos or heavy neutral leptons N_I
  (=singlet [w. respect to the SM gauge group] Majorana fermions → no weak i/a)
- Number of singlet fermions unknown → choose 3 in SM analogy

$$\mathcal{L} = \mathcal{L}_{SM} + \overline{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\overline{L}_\alpha N_I \tilde{\Phi} - \frac{M_I}{2}\overline{N}_I^c N_I + h.c.$$

Kinematics

Couplings (F) to leptons L
And the Higgs field Φ

Majorana mass term:
N_I is SU(3)xSU(2)xU(1) inv.
→ consistent with the SM symmetry

- νMSM: neutrino minimal SM

Taken from Marc Schumann

Dark Matter models in simple extension of SM

Scalar Higgs-portal dark matter
Fermionic dark matter
....

➔*Scalar Singlet Dark Matter*
(SM+extra scalar singlet)

The most general form of the potential

$$V(H,S) = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_1}{2}H^\dagger H S + \frac{\delta_2}{2}H^\dagger H S^2 + \left(\frac{\delta_1 m^2}{2\lambda}\right)S + \frac{\kappa_2}{2}S^2 + \frac{\kappa_3}{3}S^3 + \frac{\kappa_4}{4}S^4$$

➔Apply Z_2 symmetry ($S \to -S$) ensures stability of DM

Inert Higgs Doublet Model

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h^0 + \mathrm{i}G^0\right) \end{pmatrix}, \qquad \Phi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + \mathrm{i}A^0\right) \end{pmatrix};$$

$$H = (0, v) \qquad \Phi = -\Phi \qquad \Phi = (0, 0)$$

$$V_0 = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + \mathrm{h.c.}\right]$$

$$M_{h^0}^2 = -2\mu_1^2 = 2\lambda_1 v^2 \,,$$

$$M_{H^0}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2 = \mu_2^2 + \lambda_L v^2 \,, \qquad \lambda_L = \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_5\right),$$

$$M_{A^0}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2 = \mu_2^2 + \lambda_S v^2 \,, \qquad \lambda_S = \frac{1}{2}\left(\lambda_3 + \lambda_4 - \lambda_5\right).$$

$$M_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2 \,.$$

Six independent parameters in this model

$$\{M_{h^0}, \; M_{H^0}, \; M_{A^0}, \; M_{H^\pm}, \; \lambda_L, \; \lambda_2\}$$

Inert Higgs doublet Model --- Ma and Rajasekaran
Ambar Ghosal and DM (2008)
Tytgat et al
Anirban Biswas, Arunansu Sil, DM (2013)
Amit Dutta Banik and DM (2014, 2015)

Singlet Fermion in a Two-Higgs Doublet Model --
Amit Dutta Banik and DM (2015)

Two Component Dark Matter Model with Two Scalar Singlets

We Propose SM with additional 2 SM gauge singlets S_1 , S_2

Stability ensured by $\mathbb{Z}_2 \times \mathbb{Z}_2$ or $\mathbb{Z}_2 \times \mathbb{Z}_2'$

$$\begin{pmatrix} S \\ S' \end{pmatrix} \xrightarrow{\mathbb{Z}_2 \times \mathbb{Z}_2} \begin{pmatrix} -S \\ -S' \end{pmatrix} \qquad S \xrightarrow{\mathbb{Z}_2} -S \text{ and } S' \xrightarrow{\mathbb{Z}_2'} -S'$$

K. P. Modak, D. Majumdar, S. Rakshit,
JCAP 1503 (2015) 011

The Scalar Potential

$$V(H,S,S') = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$
$$+\frac{\delta_1}{2}H^\dagger H S + \frac{\delta_2}{2}H^\dagger H S^2 + \frac{\delta_1 m}{2\lambda}S + \frac{k_2}{2}S^2 + \frac{k_3}{3}S^3 + \frac{k_4}{4}S^4$$
$$+\frac{\delta'_1}{2}H^\dagger H S' + \frac{\delta'_2}{2}H^\dagger H S'^2 + \frac{\delta'_1 m}{2\lambda}S' + \frac{k'_2}{2}S'^2 + \frac{k'_3}{3}S'^3 + \frac{k'_4}{4}S'^4$$
$$+\frac{\delta''_2}{2}H^\dagger H S' S + \frac{k''_2}{2}SS' + \frac{1}{3}(k_3^a SSS' + k_3^b SS'S')$$
$$+\frac{1}{4}(k_4^a SSS'S' + k_4^b SSSS' + k_4^c SS'S'S')$$

$$\mathbb{Z}_2 \times \mathbb{Z}_2 \longrightarrow \delta_1 = k_3 = \delta'_1 = k'_3 = k_3^a = k_3^b = 0$$

$$\mathbb{Z}_2 \times \mathbb{Z}'_2 \longrightarrow \delta''_2 = k''_2 = k_4^b = k_4^c = 0 \quad \text{(in addition)}$$

A fermionic DM Model in hidden sector

Dark Matter candidate belongs to a dark sector

Proposed: The existence of a `hidden' dark sector

The Lagrangian of this hidden sector remains invariant under local $\mathrm{SU(2)_H}$

The Lagrangian is also invariant under a global $\mathrm{U(1)_H}$

Two fermion generations

$$\chi_{1L} = \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}_L , \quad \chi_{2L} = \begin{pmatrix} f_3 \\ f_4 \end{pmatrix}_L$$

$f_{i\mathrm{L}}$ transforms like a part of a doublet under $\mathrm{SU(2)_H}$

$f_{i\mathrm{R}}$ singlet under $\mathrm{SU(2)_H}$

Both $f_{i\mathrm{L}}$ and $f_{i\mathrm{R}}$ are charged under $\mathrm{U}(1)_{\mathrm{H}}$

$\mathrm{SU}(2)_{\mathrm{H}}$ Scalar doublet Φ Does not have global $\mathrm{U}(1)_{\mathrm{H}}$ charge

The dark sector is connected to the visible sector through the gauge invariant Interaction term, $\lambda_3 H^\dagger H \Phi^\dagger \Phi$

$$\rightarrow \mathrm{mixing\,between}\ \Phi\ \mathrm{and\,SM\,Higgs}\ H$$

Global $\mathrm{U}(1)_{\mathrm{H}}$ does not break spontaneously

Local $\mathrm{SU}(2)_{\mathrm{H}}$ breaks spontaneously when neutral component of Φ gets a VEV

Three dark gauge bosons $A'_{i\mu}(i = 1, 2, 3)$ get mass

Φ Also possesses a custodial SO(3) symmetry

$\rightarrow A'_{i\mu}(i = 1, 2, 3)$ become degenerate in mass

No mixing between $\mathrm{SU}(2)_{\mathrm{H}}$ gauge bosons and SM gauge bosons

Dark Sector fermions $f_i, i = 1, 4$ are charged under global $\mathrm{U(1)_H}$

Invariance of dark sector Lagrangian under $\mathrm{U(1)_H}$ requires equal and opposite $\mathrm{U(1)_H}$ charges between each fermion and its antiparticle.

Dark sector fermions are Dirac type (not Majorana).

Dark sector fermions can interact by exchanging dark gauge bosons $A'_{i\mu} (i = 1, 2, 3)$

Heavier fermions decays into the lightest fermion f_1

f_1 gets mass by the VEV of Φ when $\mathrm{SU(2)_H}$ of hidden sector breaks spontaneously

$$m_{f_1} = \frac{y'_1 v_s}{\sqrt{2}}.$$

Amit Dutta Banik, DM, Anirban Biswas (2015)

Some possible indirect signatures

- 1-3 GeV gamma ray excess reported by Fermi-Lat from the direction of Galactic Centre (GC).

- 3.55 keV X-ray line from Perseus, Andromeda etc. and 74 other galaxy clusters observed by Newtown X-ray observatory and Chandra Telescope.

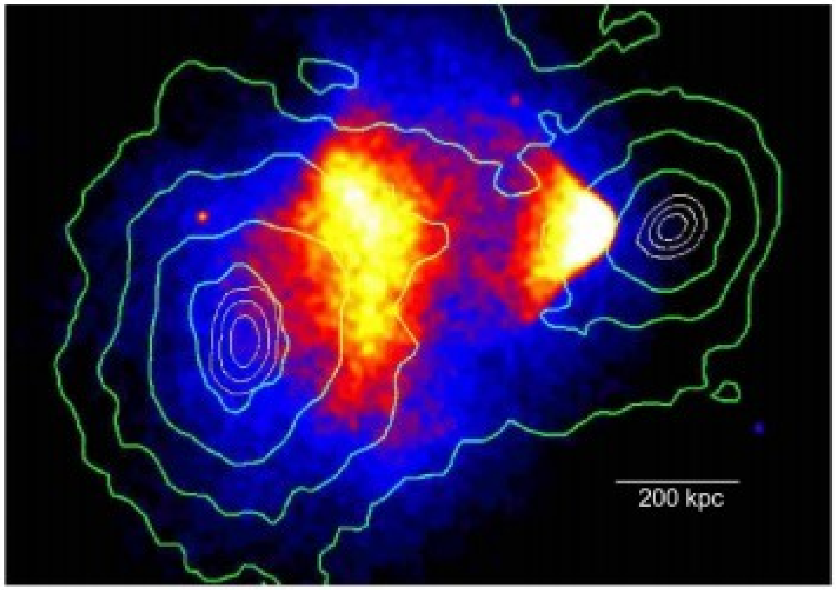
Babu, Mahapatra (PRD 2014), Anirban Biswas, DM, Probir Roy (JHEP 2015)

- Observational evidence for DM self-interaction in Abell and other galaxy clusters.

Self Interacting Dark Matter

Does it interact with itself (collisions)?

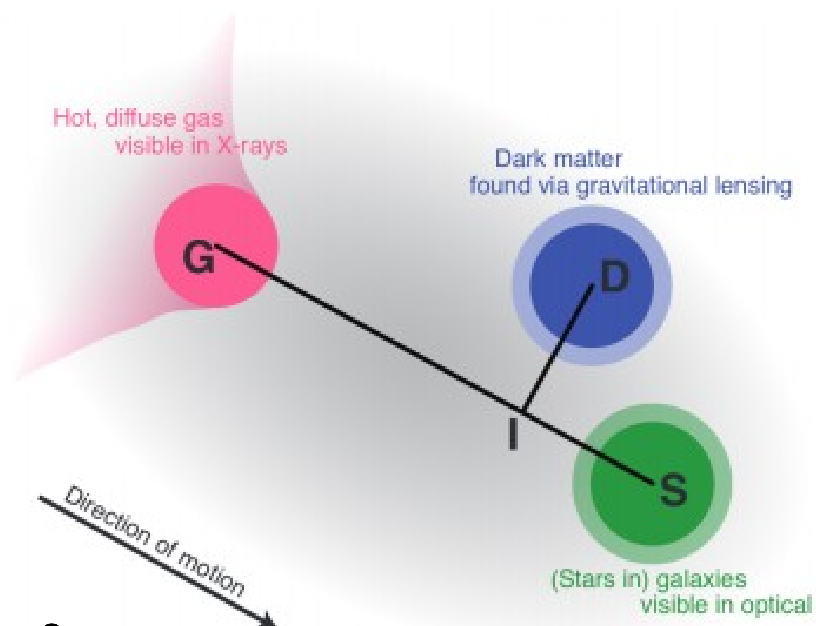
Bullet Cluster (Clowe+ 2006)



$\sigma/m < 0.7\ \mathrm{cm^2/g}$ mass loss in Bullet Cluster *Randall et al 2008*

$\sigma/m < 0.47\ \mathrm{cm^2/g}$ 72 cluster collisions *Harvey et al 2015*

$\sigma/m = (1.7\pm0.7)\times10^{-4}\ \mathrm{cm^2/g}$ in Abell 3827 (?) *Massey et al 2015*



Non-thermal dark matter?

A. Biswas, DM, P. Roy, Europhys.Lett. 113 (2016) no.2, 29001

Madhurima Pandey, DM (2017) (Two component FiMP DM)

THE MODEL
(WIMP-FImP model)

Two component DM model → a fermion and a scalar.

The Model :- SM+ χ + S + Φ.

- χ : Dirac Fermion, S scalar, Φ : a pseudo scalar
- χ singlet under SM gauge group, global $\mathrm{U(1)_{DM}}$ symmetry (global $\mathrm{U(1)_{DM}}$ charge), doesn't talk to SM.
- χ interacts with Φ via Yukawa interaction.
- Impose a discrete $\mathbb{Z}_2$ symmetry on the scalar S (singlet). $\mathbb{Z}_2$ is spontaneously broken & develops a VEV for S
- The Lagrangian is CP invariant but CP symmetry breaks spontaneously when Φ acquires a VEV.

Amit Dutta Banik, Madhurima Pandey, DM, Anirban Biswas (2017)

Two Component DM Model

Lagrangian of the model can be written as

$$\mathcal{L} \;=\; \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_{\Phi} + \mathcal{L}_{\rm int} \;, \qquad ...1)$$

$\mathcal{L}_{\rm DM}$ has two parts namely the fermionic and the scalar, which are given by,

$$\mathcal{L}_{\rm DM} \;=\; \bar{\chi}(i\gamma^{\mu}\partial_{\mu} - m)\chi + \mathcal{L}_{S} \;, \qquad .....2)$$

With

$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4}S^4 \,. \qquad .....3)$$

The Lagrangian $\mathcal{L}_{\Phi}$ for the pseudo scalar boson Φ is given by

$$\mathcal{L}_{\Phi} \;=\; \frac{1}{2}(\partial_\mu \Phi)^2 - \frac{\mu_\phi^2}{2}\Phi^2 - \frac{\lambda_\phi}{4}\Phi^4 \;. \qquad 4)$$

$$\mathcal{L}_{\rm int} = -i\,g\,\bar{\chi}\gamma_5\chi\,\Phi - V'(H,\Phi,S)\,,$$

$$V'(H,\,S,\,\Phi) = \lambda_{H\Phi}H^\dagger H\,\Phi^2 + \lambda_{HS}H^\dagger H\,S^2 + \lambda_{\Phi S}\Phi^2\,S^2\ .$$

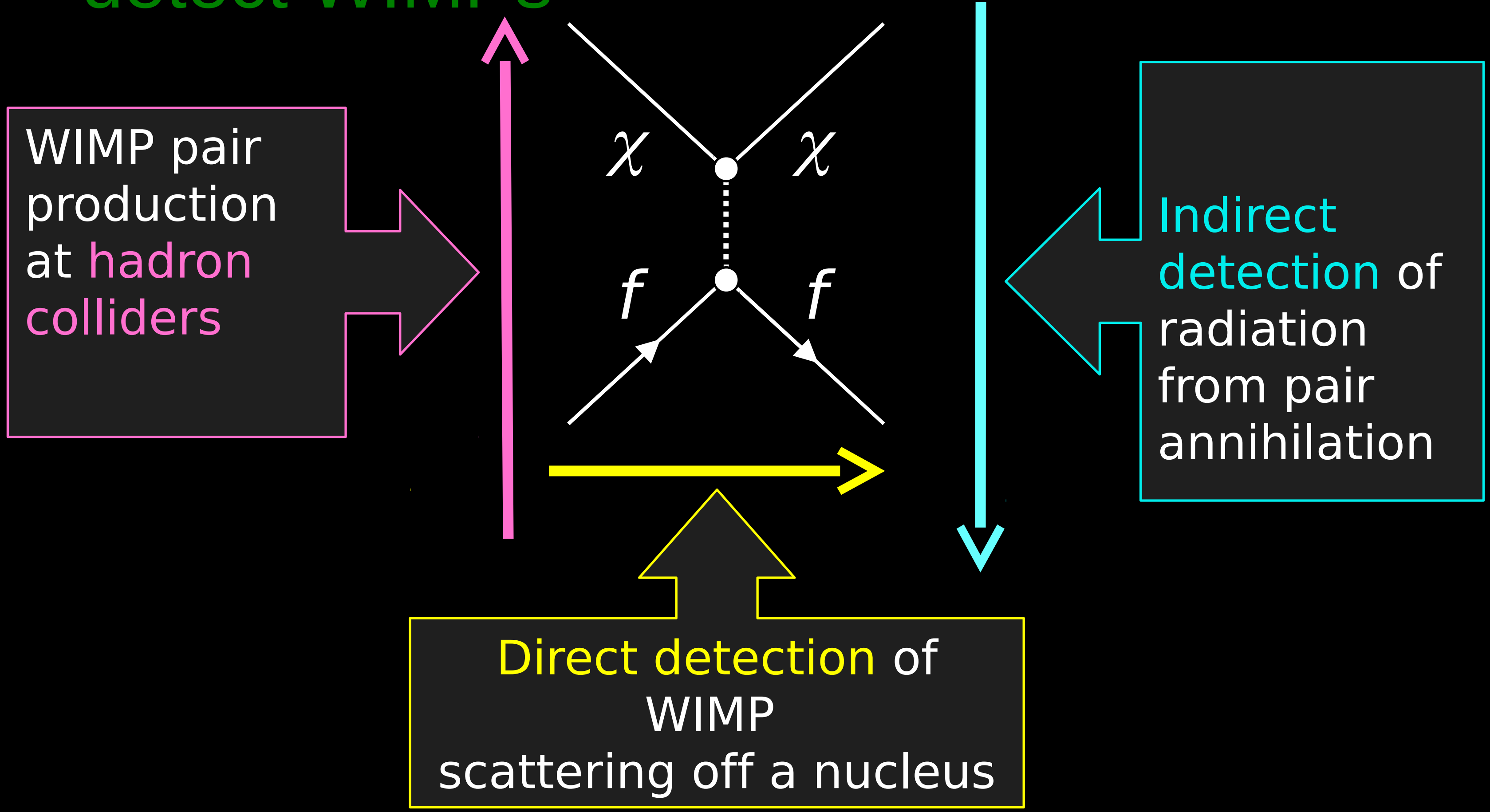
$$H = \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ v_1 + h \end{array}\right)\,,\ \Phi = v_2 + \phi\ ,\ \ S = v_3 + s\ .$$

$$\begin{aligned} V \;&=\; \mu_H^2\,H^\dagger H + \lambda_H\,(H^\dagger H)^2 + \frac{\mu_\phi^2}{2}\Phi^2 + \frac{\lambda_\phi}{4}\Phi^4 + \frac{\mu_s^2}{2}S^2 + \frac{\lambda_s}{4}S^4 \\ &+\lambda_{H\Phi}H^\dagger H\,\Phi^2 + \lambda_{HS}H^\dagger H\,S^2 + \lambda_{\Phi S}\Phi^2\,S^2\,. \end{aligned}$$

$$\begin{aligned} V \;&=\; \frac{\mu_H^2}{2}(v_1+h)^2 + \frac{\lambda_H}{4}(v_1+h)^4 + \frac{\mu_\Phi^2}{2}(v_2+\phi)^2 + \\ &\frac{\lambda_\Phi}{4}(v_2+\phi)^4 + \frac{\mu_S}{2}(v_3+s)^2 + \frac{\lambda_S}{4}(v_3+s)^4 + \\ &\frac{\lambda_{H\Phi}}{2}(v_1+h)^2(v_2+\phi)^2 + \frac{\lambda_{HS}}{2}(v_1+h)^2(v_3+s)^2 + \lambda_{\Phi S}(v_2+\phi)^2(v_3+s)^2\ . \end{aligned}$$

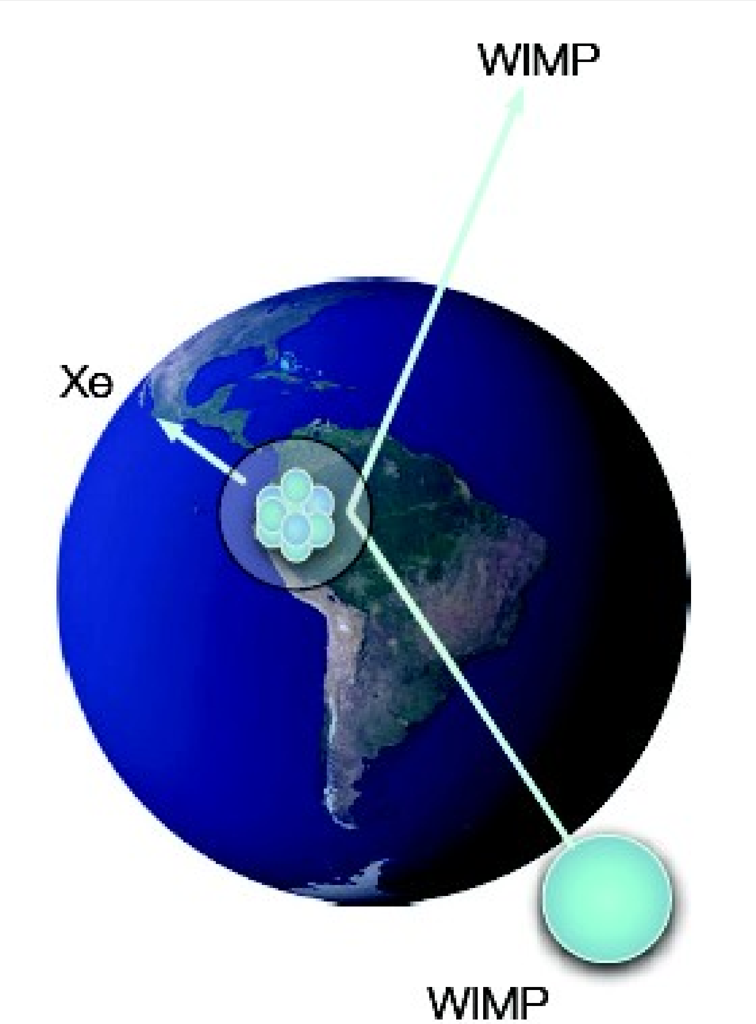
WIMP Hunting

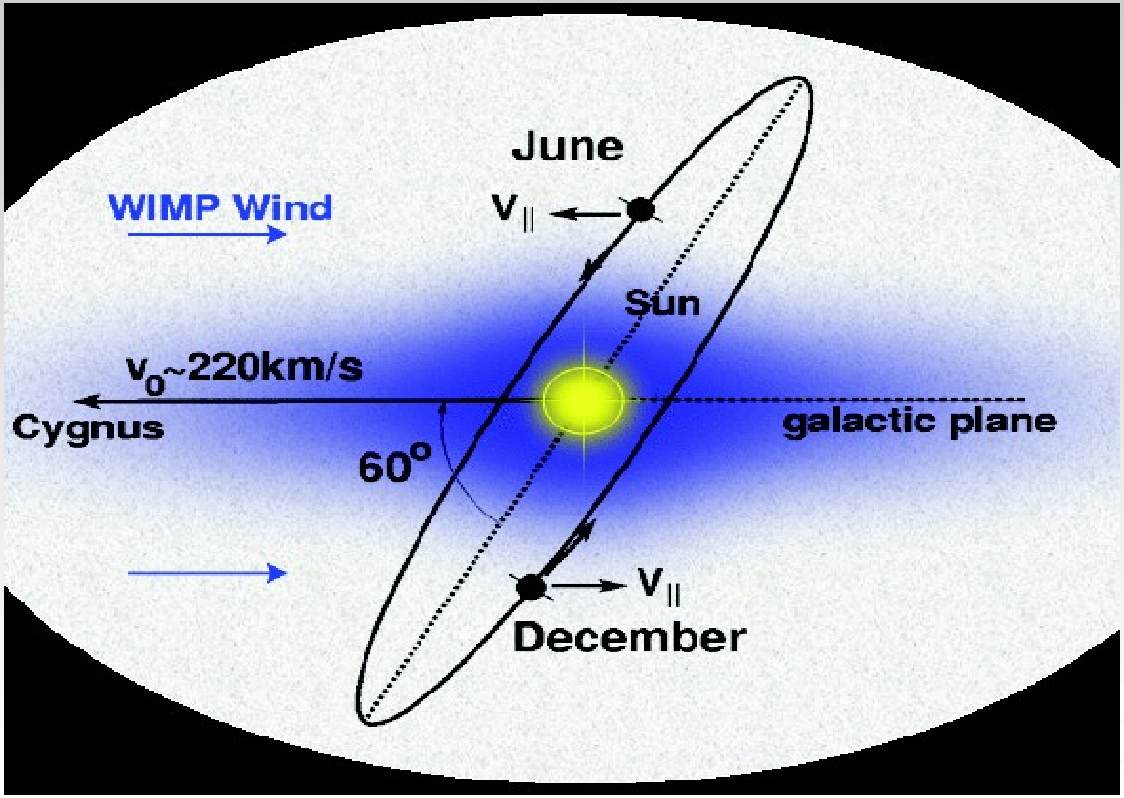
Going beyond gravity, three ways to detect WIMPs

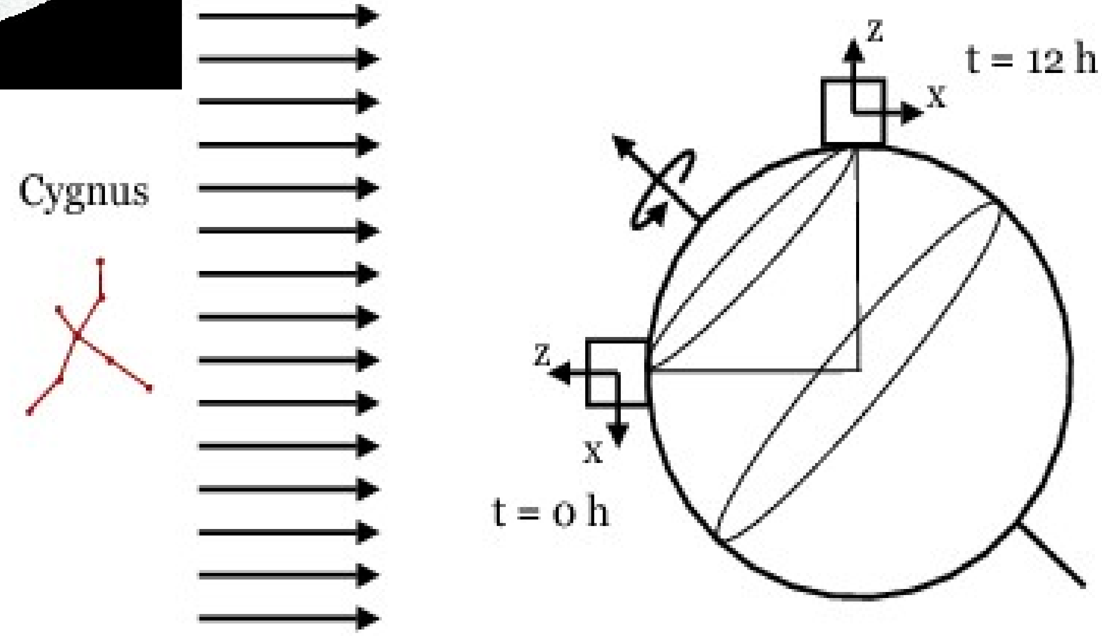


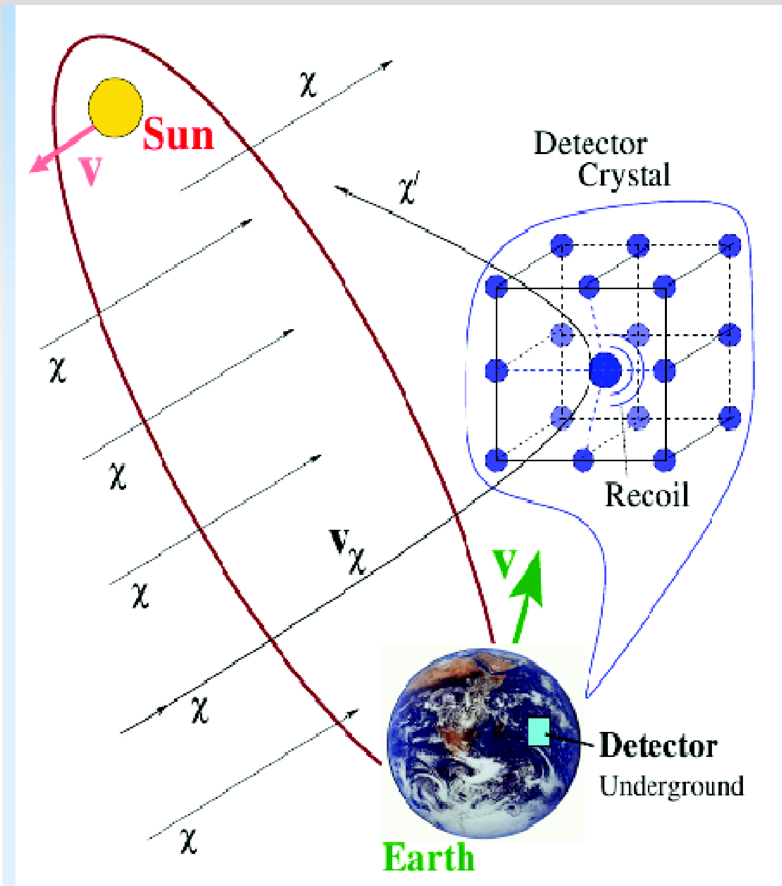
Detection of Dark Matter
Direct Detection

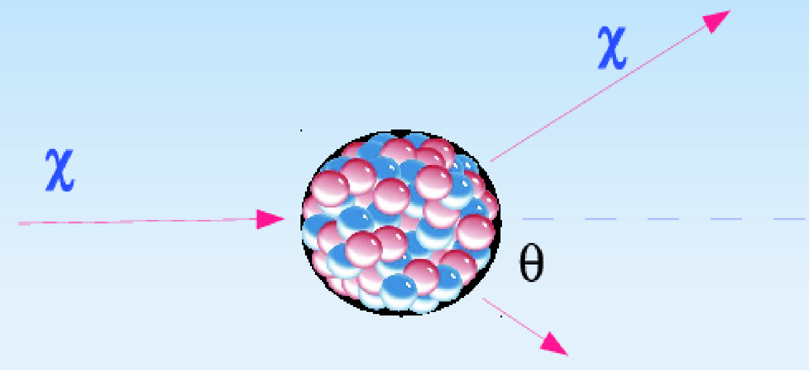
- Rotation of galactic disc through the halo of Dark Matter causes the earth to experience an apparent wind of Dark Matter
- Elastic collision of WIMP with detector nuclei
- The recoil energy of the nucleus is measured




June
WIMP Wind
Sun
v_0~220km/s
Cygnus
galactic plane
60°
December


Cygnus
z
x
t = 12 h
t = 0 h





$$q = |\vec{q}| = 2\mu_A v_\chi \cos\theta$$

$$E_R = \frac{q^2}{2m_A}$$

Non relativistic WIMP scatters elastically with nuclei. The recoil of the nucleus deposits a tiny amount of energy in the detector: recoil energies are from few to 100 keV

Types of Direct Detection

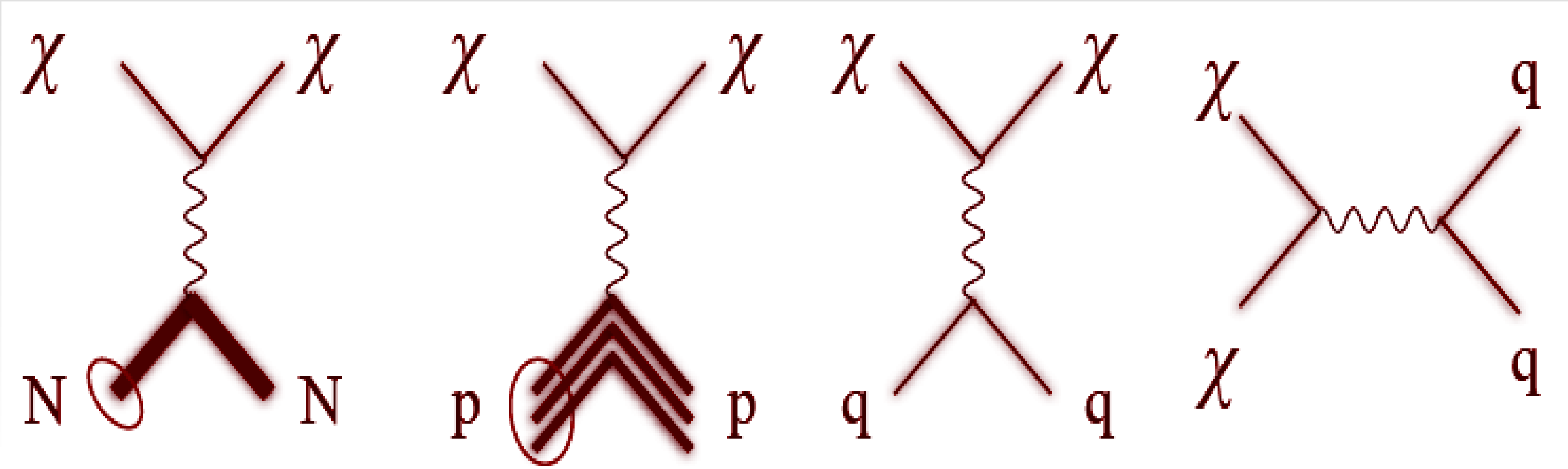
1. *Spin Independent (SI)*
ground state spin of detecting nucleus is zero

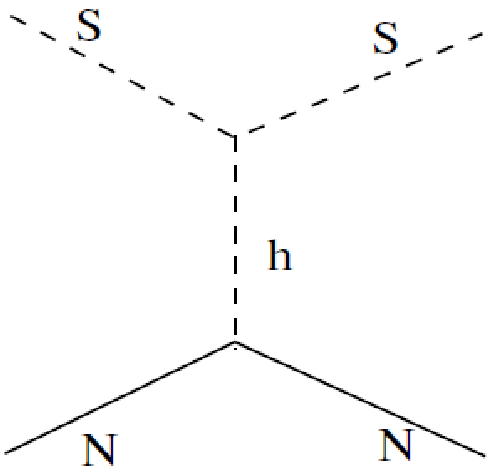
2. *Spin Independent (SD)*
ground state spin of detecting nucleus is non-zero

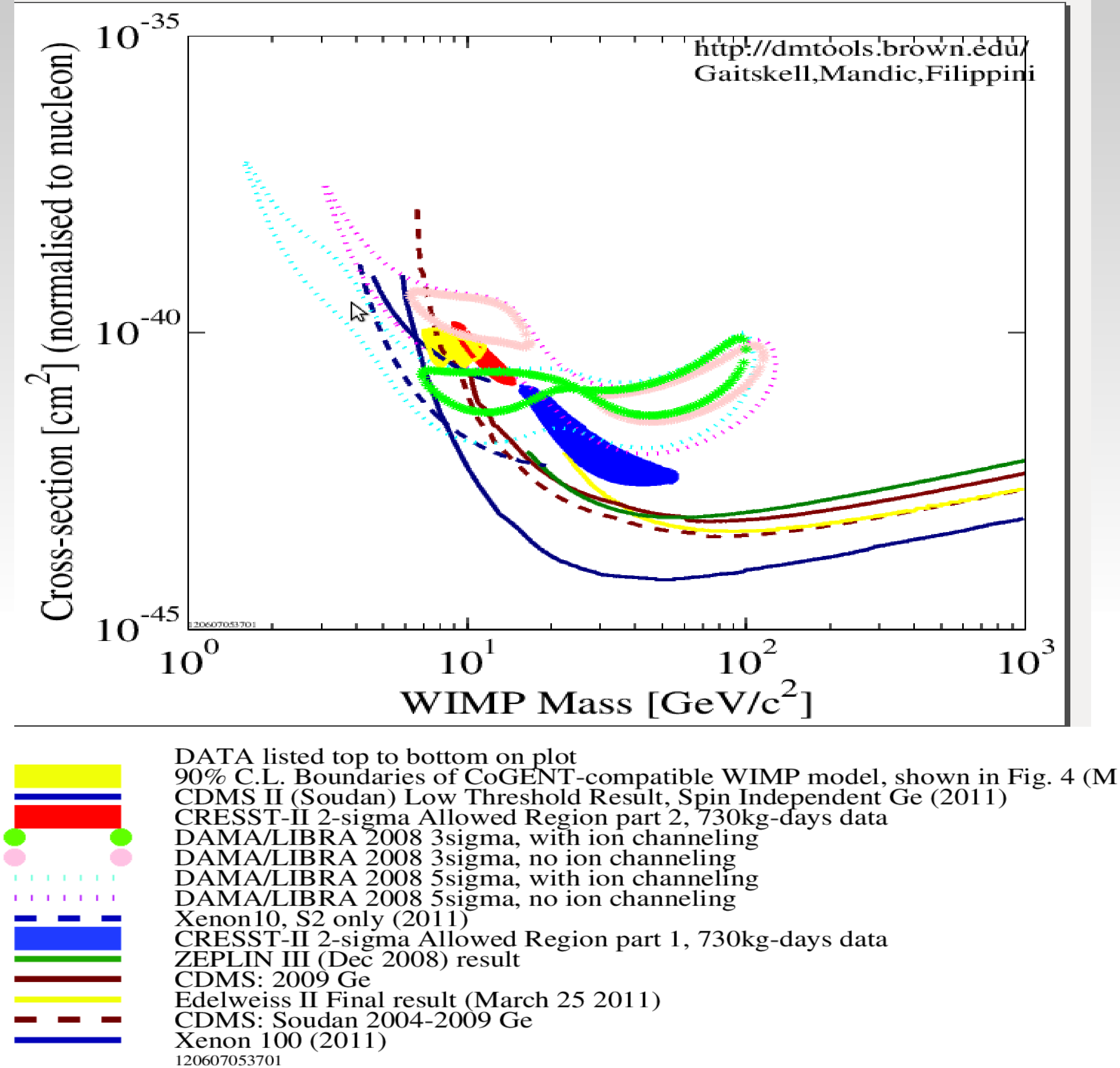
$$\sigma_{SD} = \frac{4M_\chi^2 M_N^2}{\pi(M_\chi + M_N)^2} \times 3|A^{SD}|^2$$

$$\sigma_{SI} = \frac{4M_\chi^2 M_N^2}{\pi(M_\chi + M_N)^2} \times |A^{SI}|^2$$

WIMP-nucleus Interaction






http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
10^{-35}
10^{-40}
10^{-45}
Cross-section [cm^2] (normalised to nucleon)
10^{0}
10^{1}
10^{2}
10^{3}
WIMP Mass [GeV/c^2]
120607053701
DATA listed top to bottom on plot
90% C.L. Boundaries of CoGENT-compatible WIMP model, shown in Fig. 4 (M
CDMS II (Soudan) Low Threshold Result, Spin Independent Ge (2011)
CRESST-II 2-sigma Allowed Region part 2, 730kg-days data
DAMA/LIBRA 2008 3sigma, with ion channeling
DAMA/LIBRA 2008 3sigma, no ion channeling
DAMA/LIBRA 2008 5sigma, with ion channeling
DAMA/LIBRA 2008 5sigma, no ion channeling
Xenon10, S2 only (2011)
CRESST-II 2-sigma Allowed Region part 1, 730kg-days data
ZEPLIN III (Dec 2008) result
CDMS: 2009 Ge
Edelweiss II Final result (March 25 2011)
CDMS: Soudan 2004-2009 Ge
Xenon 100 (2011)
120607053701

Differential detection rate of Dark Matter per unit detector mass

$$\frac{dR}{d|\mathbf{q}|^2} = N_T \Phi \frac{d\sigma}{d|\mathbf{q}|^2} \int f(v) dv$$

NT denotes the number of target nuclei per unit mass of the detector

$$\begin{aligned} E_R &= |\mathbf{q}|^2 / 2m_{\rm nuc} \\ &= m_{\rm red}^2 v^2 (1 - \cos\theta) / m_{\rm nuc} \\ m_{\rm red} &= \frac{m_L m_{\rm nuc}}{m_L + m_{\rm nuc}} \end{aligned}$$

$$\frac{dR}{dE_R} = 2\frac{\rho_\chi}{m_L}\frac{d\sigma}{d|\mathbf{q}|^2}\int_{v_{min}}^{\infty} v f(v) dv$$

$$v_{\rm min} = \left[\frac{m_{\rm nuc}E_R}{2m_{\rm red}^2}\right]^{1/2}$$

$$N_T = 1/m_{\rm nuc}$$

$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{\sigma_{\rm scalar}}{4m_{\rm red}^2 v^2}F^2(E_R)$$

$$F(E_R) = \left[\frac{3j_1(qR_1)}{qR_1}\right]\exp\left(\frac{q^2s^2}{2}\right)$$

$$R_1 = (r^2 - 5s^2)^{1/2}$$

$$r = 1.2A^{1/3}$$

$s \simeq 1$ fm

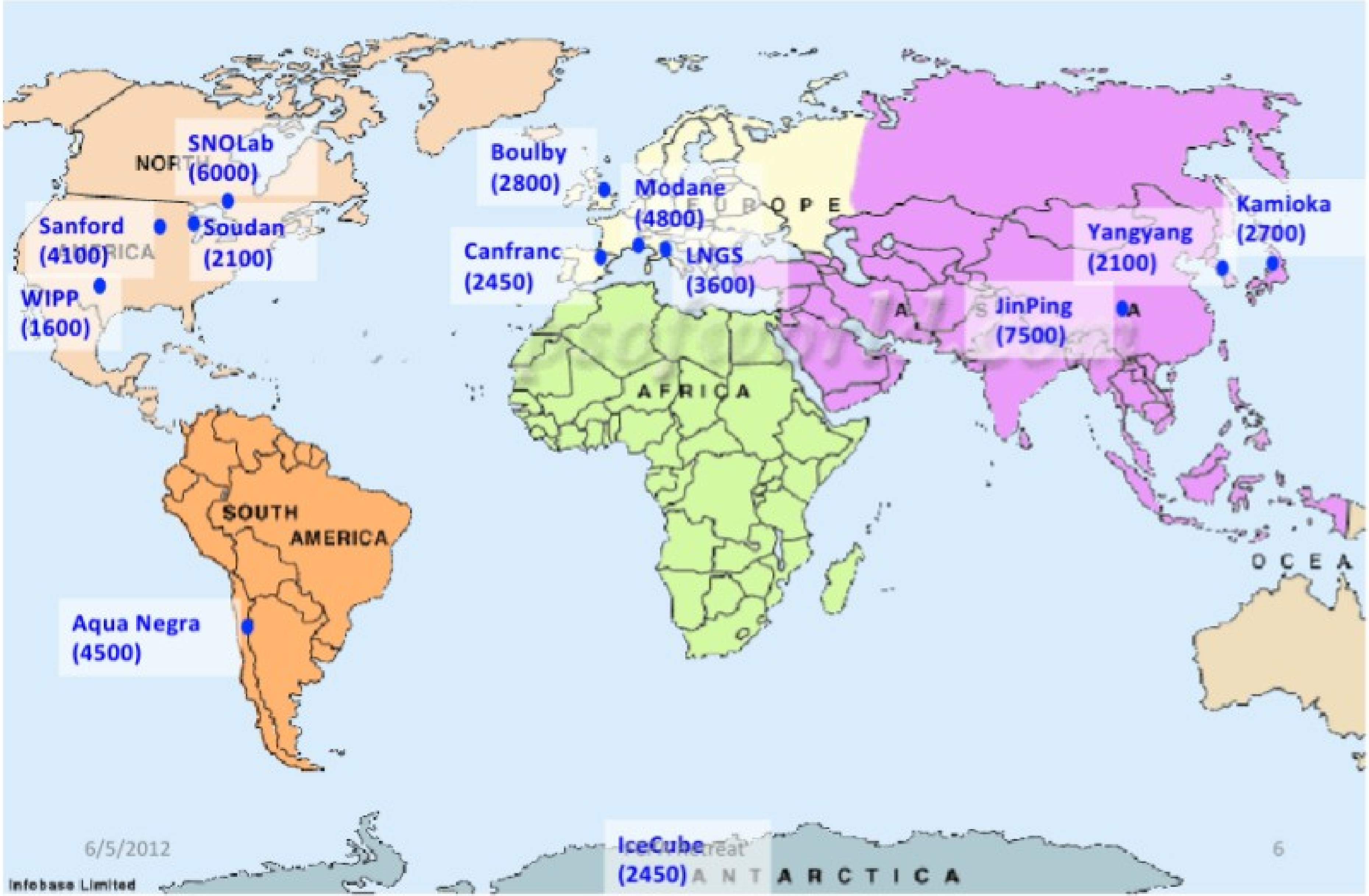
$$\mathbf{v} = \mathbf{v}_{\rm gal} - \mathbf{v}_{\oplus}$$

$$v_{\oplus} = v_{\odot} + v_{\rm orb} \cos\gamma \cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

$$\frac{dR}{dE_R} = \frac{\sigma_{\rm scalar}\rho_\chi}{4 v_{\oplus} m_L m_{\rm red}^2} F^2(E_R) \left[\mathrm{erf}\left(\frac{v_{\rm min} + v_{\oplus}}{v_0}\right) - \mathrm{erf}\left(\frac{v_{\rm min} - v_{\oplus}}{v_0}\right)\right]$$

Some Ongoing Dark Matter Direct Detection Experiments

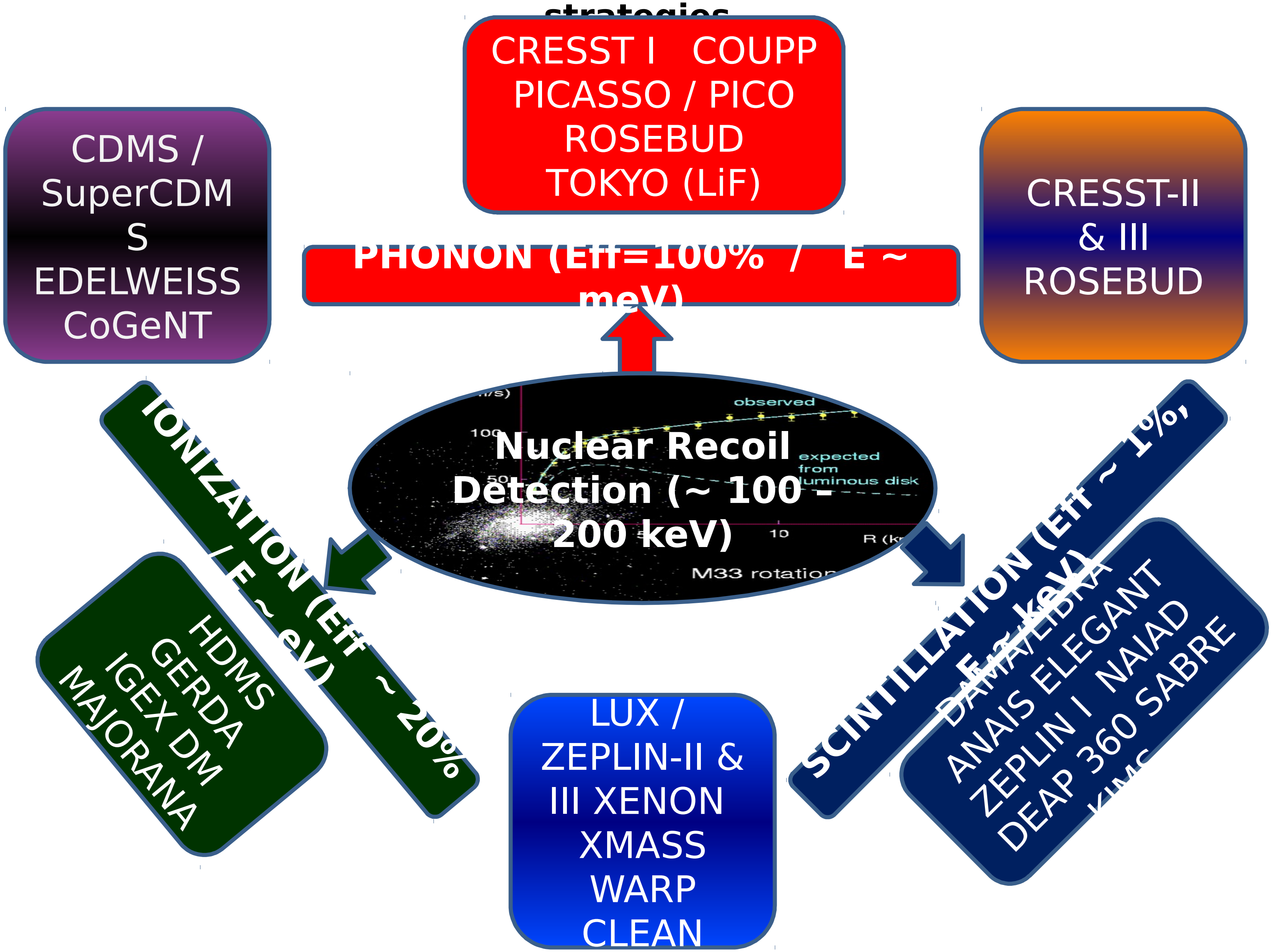
Underground Laboratories



Current direct detection experimental details

Discrimination	Name	Location	Technique	Material	Status
None	CUORICINO	Gran Sasso	Heat	41 kg TeO_2	running
	GENIUS-TF	Gran Sasso	Ionization	10 to 40 kg Ge in N_2	running ???
	HDMS	Gran Sasso	Ionization	0.2 kg Ge diodes	stopped
	IGEX	Canfranc	Ionization	2 kg Ge Diodes	stopped
Statistical	DAMA	Gran Sasso	Light	100 kg NaI	stopped
	LIBRA	Gran Sasso	Light	250 kg NaI	running
	NaIAD	Boulby mine	Light	46 kg NaI	stopped
	ZEPLIN-I	Boulby mine	Light	4 kg Liquid Xe	stopped
Event-by-event	XENON	Surface to GS	Light+ Ionization	3 to 10 kg Liquid Xe	running
	ZEPLIN II	Boulby mine	Light+ Ionization	6 kg Liquid Xe	running
	CDMS-I	Stanford	Heat + Ionization	1 Kg Ge + 0.2 Kg Si	stopped
	CDMS-II	Soudan mine	Heat + Ionization	2 to 7 kg Ge + 0.4 to 1.4 Kg Si	running
	CRESST-I	Gran Sasso	Heat + Light	0.262 kg Al_2O_3	stopped
	CRESST-II	Gran Sasso	Heat + Light	0.6 to 9.9 kg $CaWO_4$	running
	EDELWEISS-I	Modane	Heat + Ionization	1 kg Ge	stopped
	EDELWEISS-II	Modane	Heat + Ionization	10 to 30 kg Ge	In istallation
	PICASSO	SNO	Bubble chamber	20 g Freon	running
	ROSEBUD	Canfranc	Heat + Light	50 g Al_2O_3 + 67 g Ge + 54 g $CaWO_4$	running

Classification of Direct detection experiments based on detection strategies



Liquid Xenon

Xe (A = 131.3) gives a high signal cross section $\sigma \propto A^2$

- 100 kg-year exposure can probe 10^{-45} cm^2

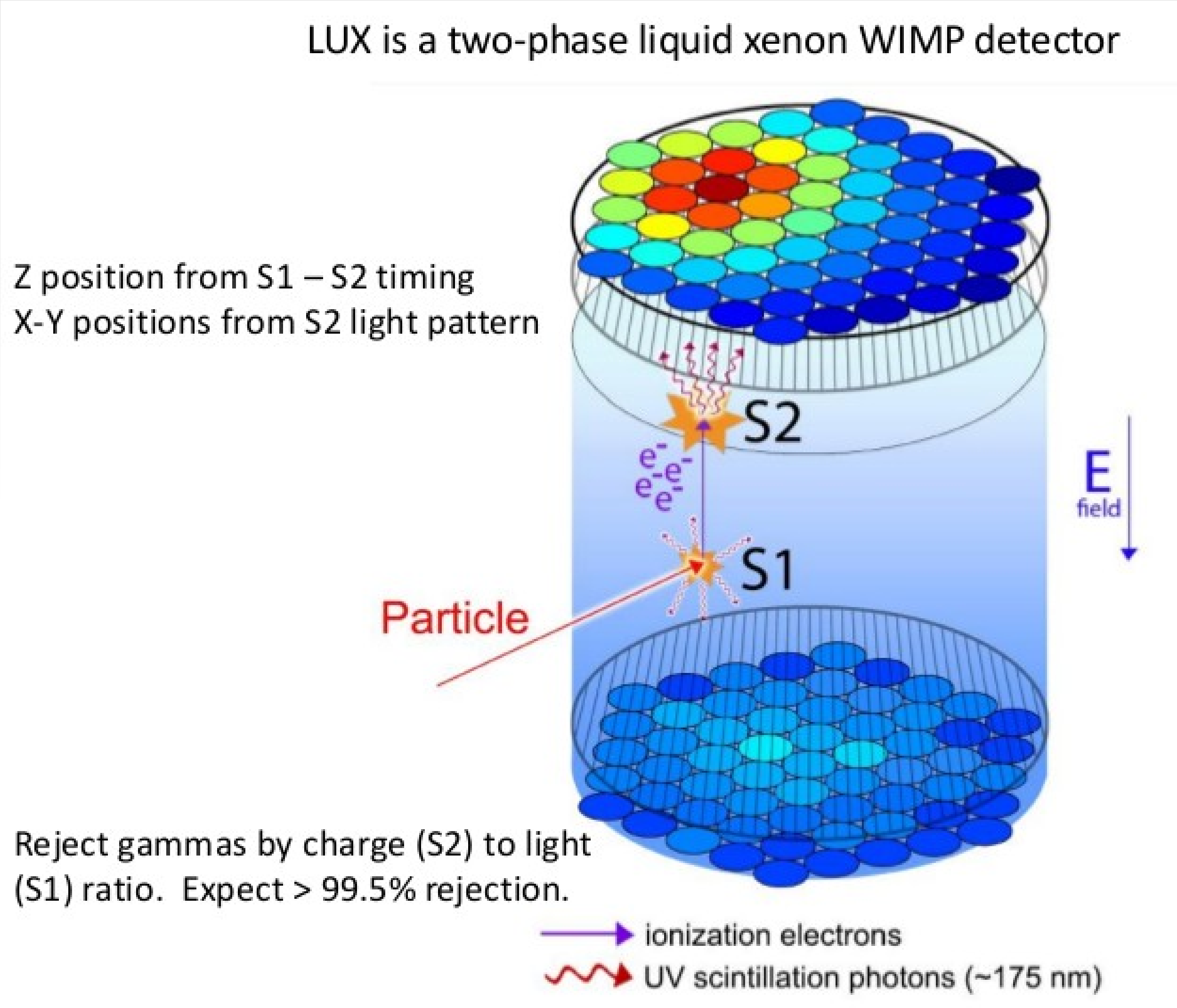
Attractive liquid Xe properties

- High density: 3 g/cm^3 → Compact detector
- Boiling point: 165 K is warmer than liquid N_2 (77 K) → Simpler cryogenics
  - Liquid Ar is 87 K. Ge (CDMS) is 10 mK
- Good scintillator: 42 photons/keV at 175 nm
  - PMTs have good (~30%) quantum efficiency at this wavelength
  - Ar scintillates at 128 nm → Need wavelength shifter
- High ionization yield: 64 electron-ion pairs/keV
- Short radiation length: 2.77 cm → Self shielding
  - Background γ rays and neutrons cannot reach the fiducial volume

LUX Detector

Located at Sanford Lab at Davis

4850 feet (1478 m) underground



XENON100

- Reuse techniques and technologies developed for the XENON10 prototype to build a detector with a $\times 10$ increase in fiducial mass and a $\times 100$ reduction in background.
- Reduce the background from internal components
  - Pulse tube refrigerator and motor valve outside the shield,
  - All signal and HV feedthroughs also outside the shield,
  - Extensive material screening program to choose materials,
  - Kr distillation column to reduce Kr contamination in Xe.
- Reduce the background contribution from external sources
  - New 5 cm layer of copper to the XENON10 shield to reduce the contribution from the the polyethylene,
  - LXe Active veto surrounding the target.
- 170 kg LXe total mass consisting of a 65 kg target surrounded by a 105 kg active veto. 15 cm radius, 30 cm drift length active volume.

CDMS (Cryogenic Dark Matter Search) at SOUDAN mines

The CDMS II experiment looks for heavy, slow moving WIMPs using unique ZIP detectors. The detectors are hockey puck-sized disks of silicon and germanium, kept cold by a special cryogenic apparatus at about .04 degrees K.

Each 250g germanium or 100g silicon crystal provides two sets of information about interactions with incident particles.

When the incident particle, perhaps a WIMP, hits the nucleus of an atom in the detector it generates vibrations called phonons. The phonons are detected by thin films of tungsten metal. These phonons travel to the opposite side of the detector.

Each 250g germanium or 100g silicon crystal provides two sets of information about interactions with incident particles.

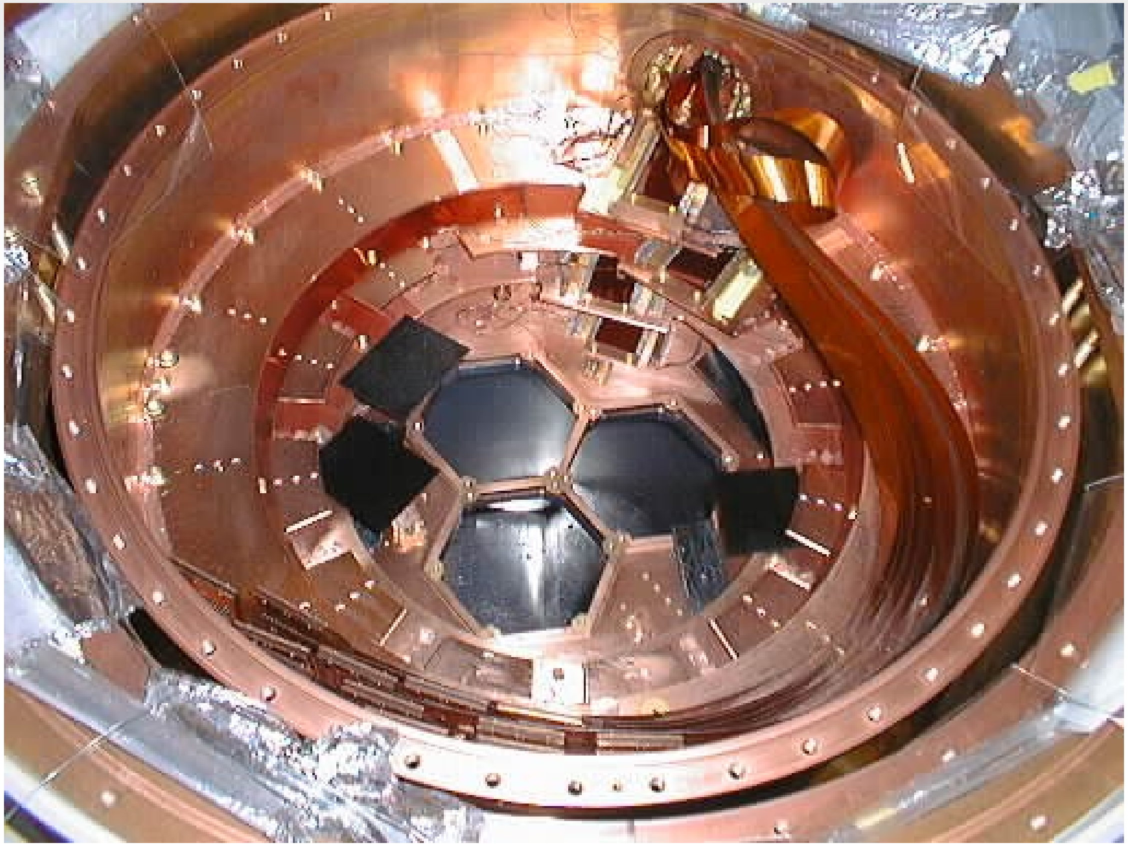
When the incident particle, perhaps a WIMP, hits the nucleus of an atom in the detector it generates vibrations called phonons. The phonons are detected by thin films of tungsten metal. These phonons travel to the opposite side of the detector.

As the phonon travels to the opposite side it excites the electrons in thin aluminum films.

This energy is transferred to the tungsten which is “biased” with some electrical energy already; the energy pushes it right near the brink of going through a transition from being a superconductor to a closer to normal conductor .

The Zip detectors are placed in a container called a cryostat.

The cryostat is constructed of radiopure copper, ensuring a low-radioactivity environment for the extremely sensitive CDMS detectors.



Other Detectors

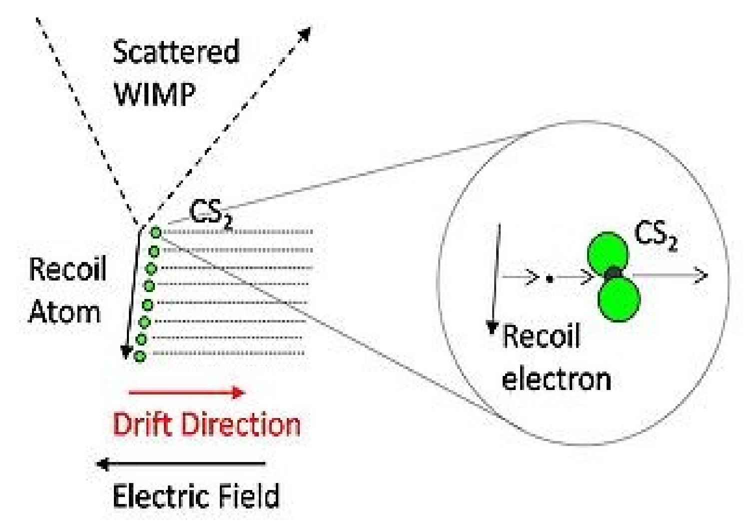
DRIFT Detector

Located at Boulby mines (1100 metre deep) at Great Britain.

Uses low pressure elctronegative CS2 gas as detector material

Drifts CS2 ions instead of free electrons

Enables discrimination of directional events



NEWAGE (New generation WIMP search with an advanced gaseous tracker experiment) Detector

Located at Japan

Uses CF4 gas at 150 Torr.

Direction sensitive micro TPC detector

PICASSO at SNOLAB uses CS2 gel (Superheated droplet)

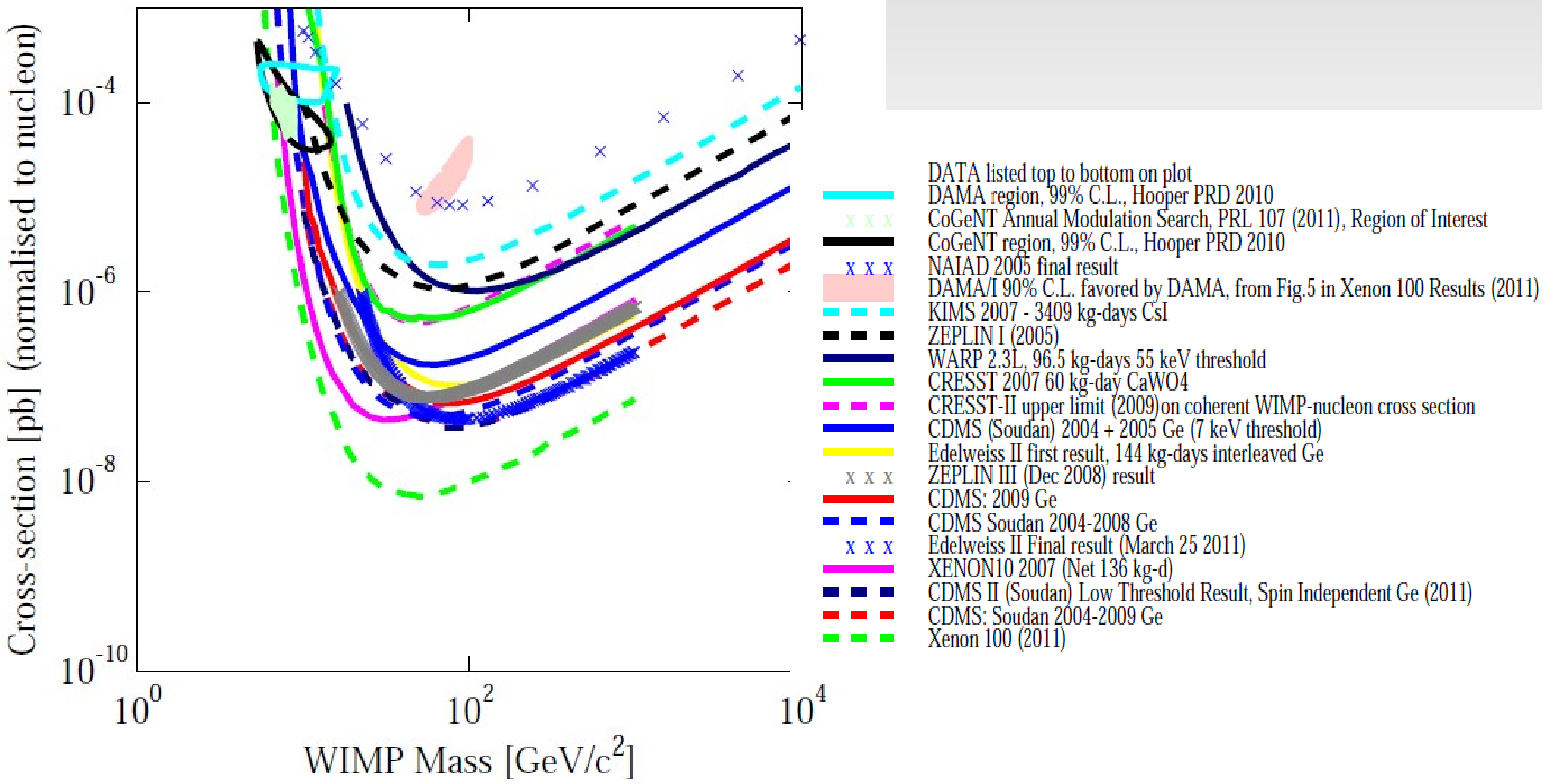
CoGeNT at Soudan mines uses Ge

DAMA at Gran Sasso uses NaI

SIMPLE at France uses C2ClF5 droplets (Superheated droplet)

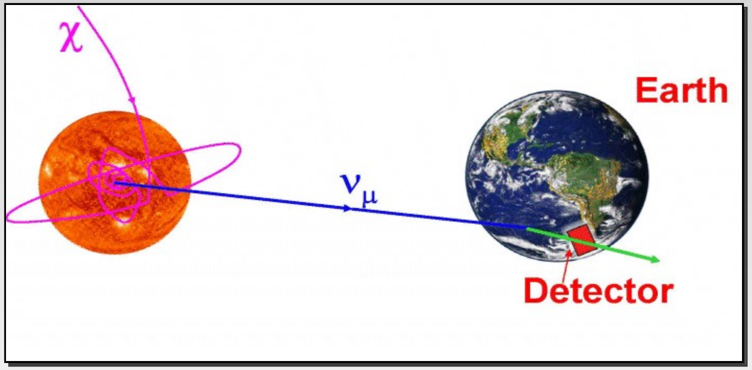
PANDAX at China uses Xe TPC

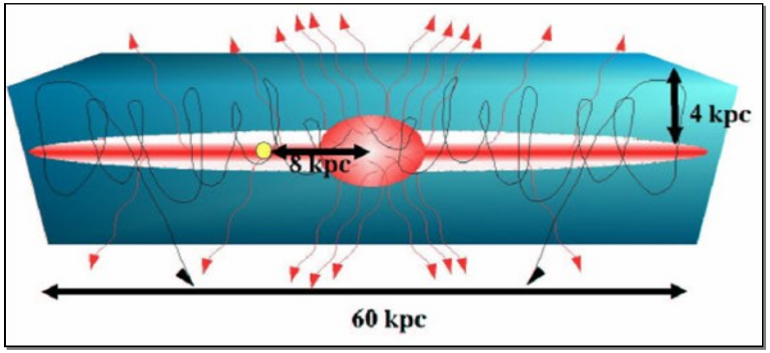
Mass-SI Scattering cross section $\sigma_{SI} - M_{\chi}$



Indirect Detection of DM

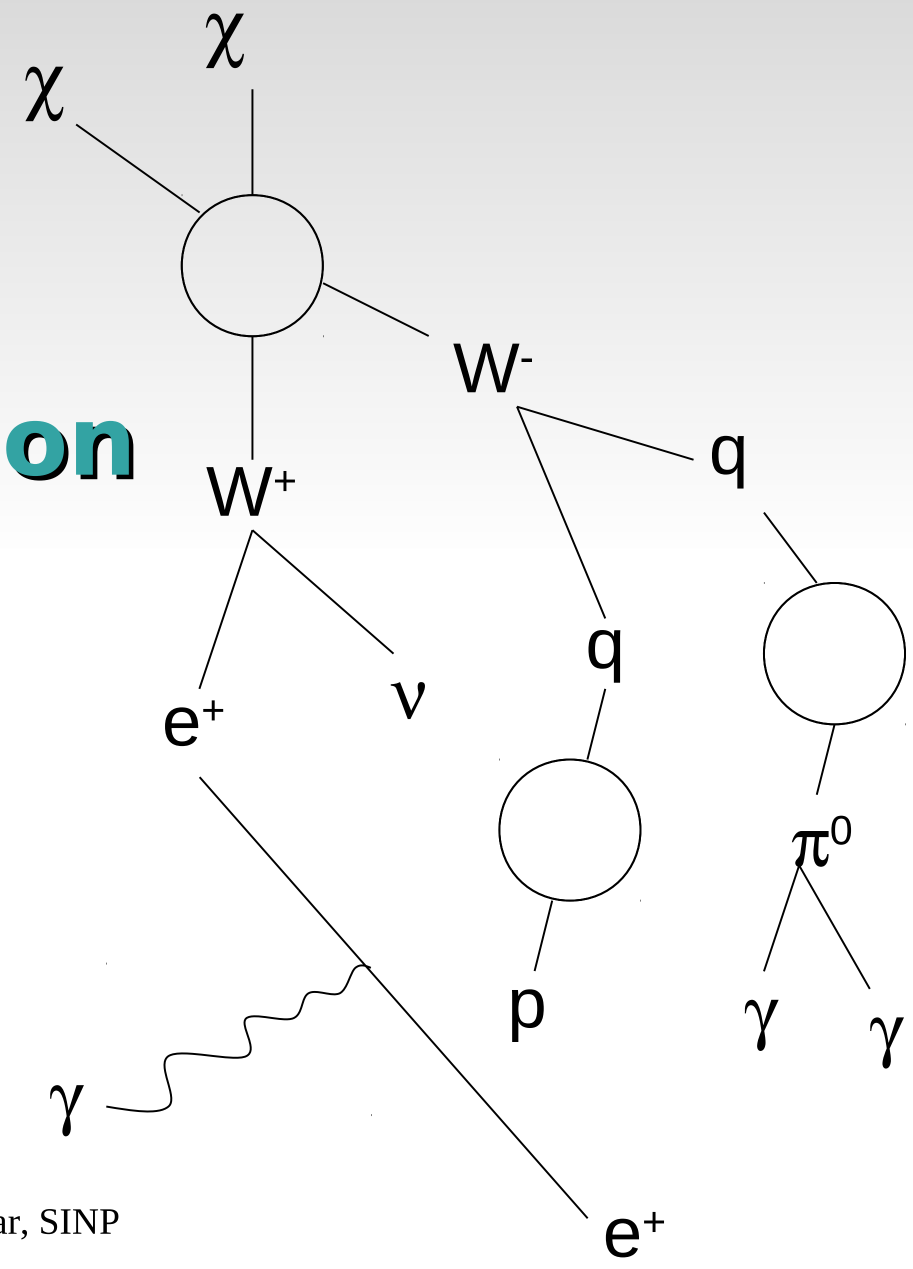
- **Neutrinos** from annihilations in the core of the Sun
- **Gamma Rays** from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc.
- **Positrons/Antiprotons** from annihilations throughout the galactic halo
- **Synchrotron Radiation** from electron/positron interactions with the magnetic fields of the inner galaxy





Indirect Detection of DM

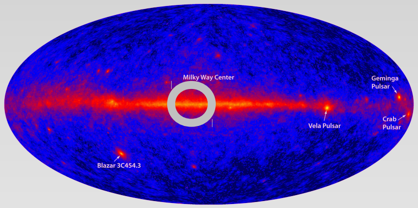
- **Annihilation**
- **Fragmentation**
- **Synchrotron Radiation**



Gamma Ray Flux from DM annihilation From the Galactic Centre And Detection in Gamma Telescopes

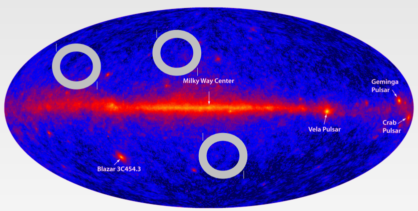
Targets for Indirect Detection of Dark Matter

Galactic Centre



Strongest signal expected, most difficult background
Hard sources, not well understood diffuse emission

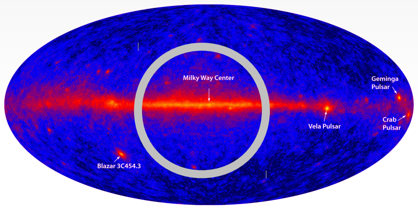
Dwarf galaxies and Galaxy Clusters



Dwarfs: weak signal, but relatively well controlled Dark Matter Distribution and essentially no background (if at high latitude).

Clusters: DM density not well constrained, but provides boost factor (extended emission), so good for discovery (if lucky)

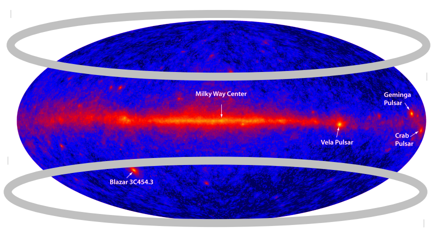
Galactic Halo



Fermi-LAT: spatial and spectral discrimination, good statititstics, extreme freedom in galactic diffuse emission.

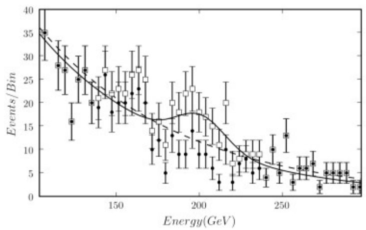
IACT: best potential, small systematics due to diffuse emission, ~100 hour observation time (GC halo)

Extra Galactic



Very model dependent, good as target for spatial analysis.

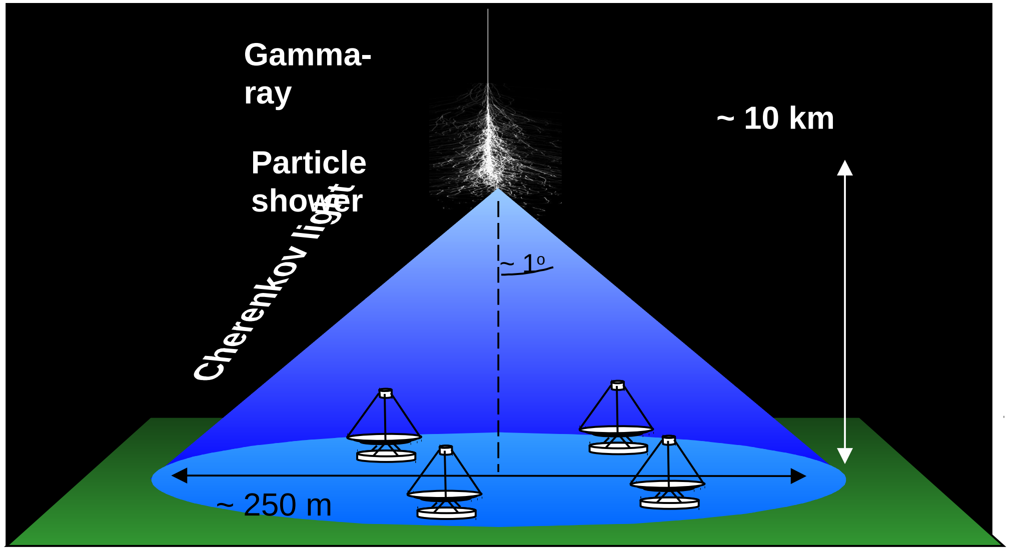
Lines



Smoking gun*, got to get lucky.

Galactic Centre : a suitable target

High Energy Stereoscopic System (H.E.S.S.)

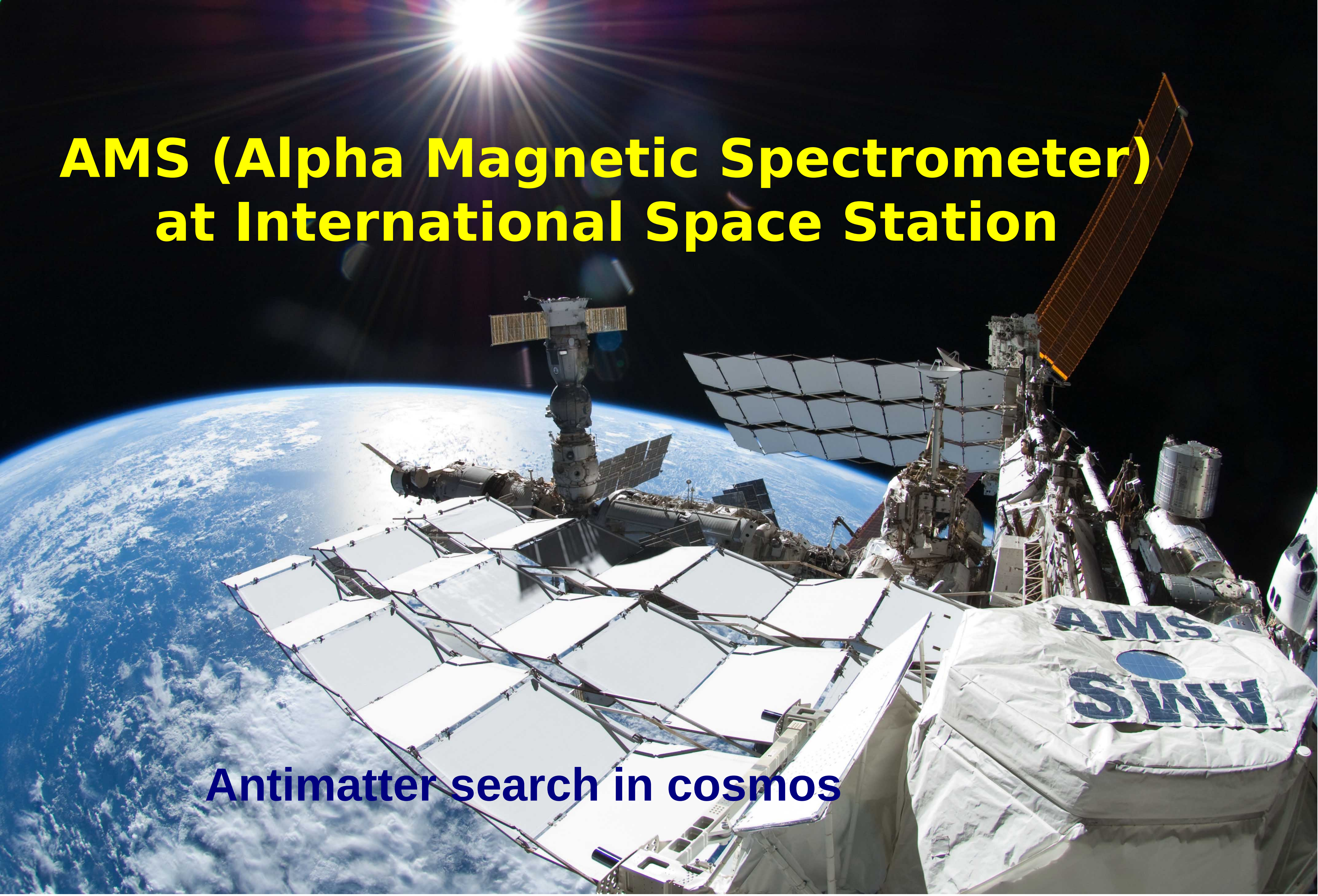


- Ground based Cherenkov telescopes of four detectors for investigation of cosmic gamma rays in the hundreds of GeV to TeV energy range (located at Namibia)

- Gamma ray interacts with atmosphere – secondary particles produced – result in air shower – Cherenkov light is produced that on the ground illuminates an area of diameter 250 m

- The four detectors detect the Cherenkov light

AMS (Alpha Magnetic Spectrometer) at International Space Station



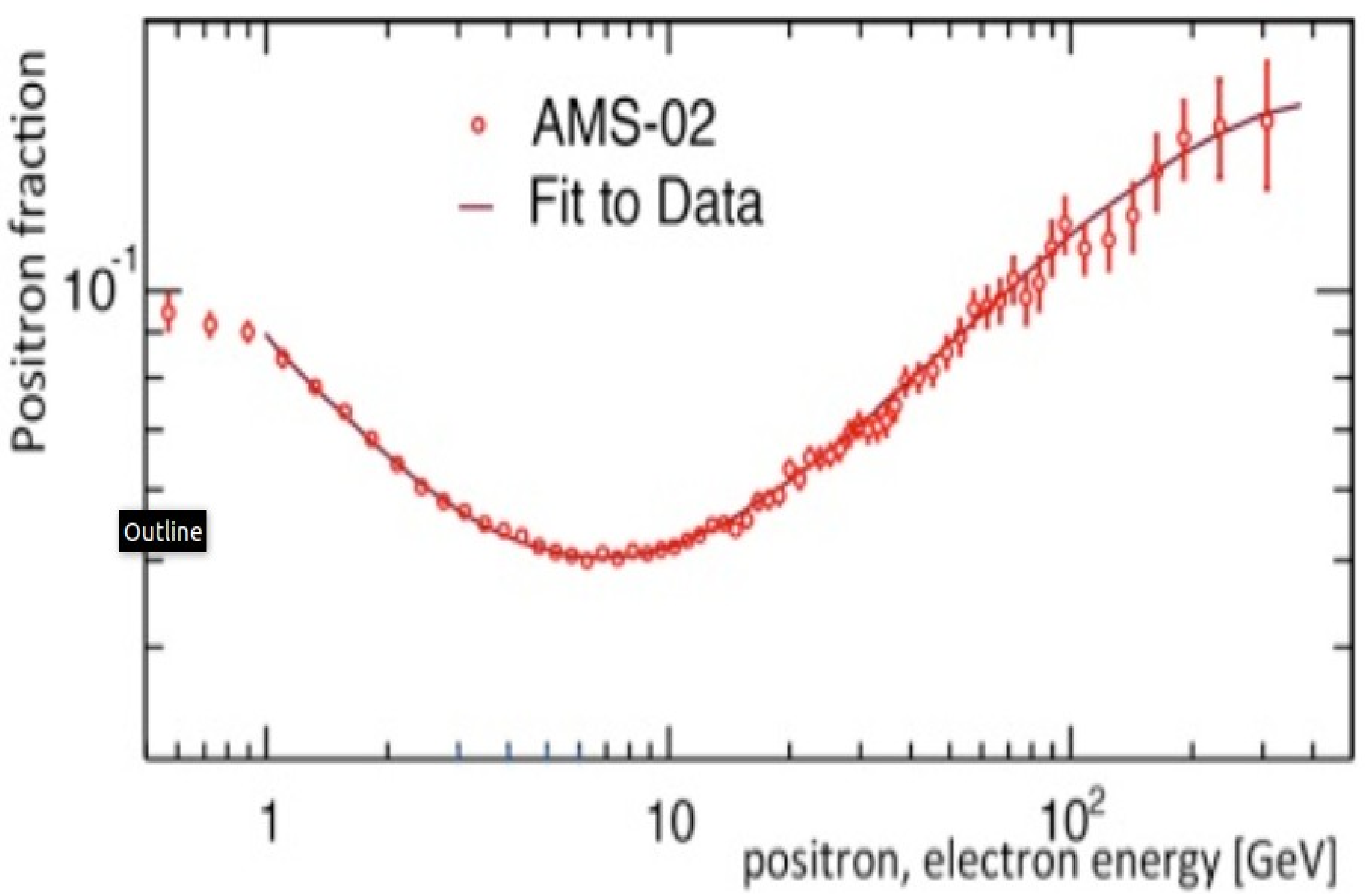
Antimatter search in cosmos

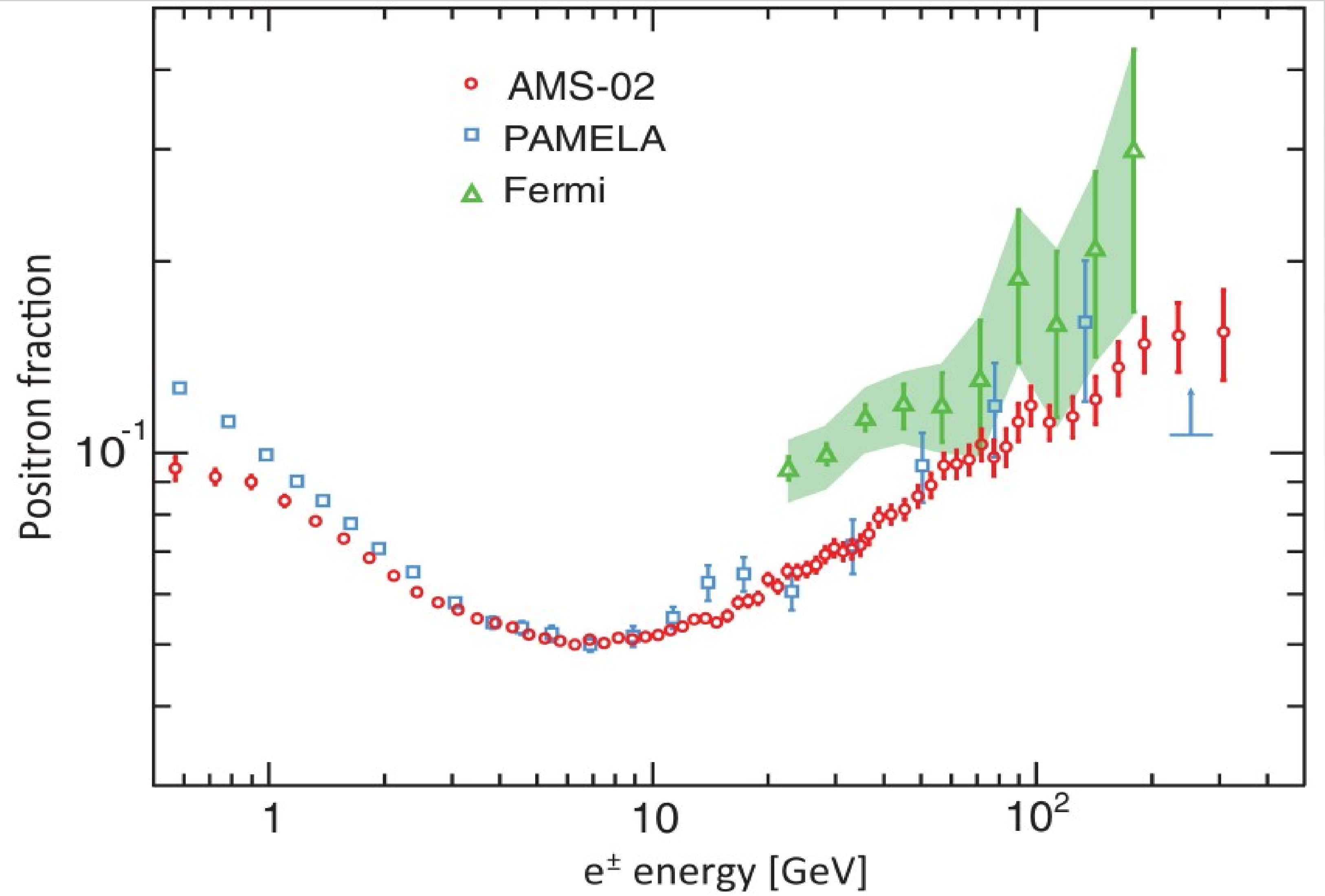
- **AMS searches for Antimatter**
- **The Primordial Antimatter content of the Universe is unknown.**
- **~100 MeV γ flux excludes wide antimatter regions up to 20-100 Mpc**
- **Sakharov's 3 Principles of Baryogenesis :**

  1. **Baryon Number Violation (not confirmed….)**
  2. **C and CP Violation (strong….)**
  3. **Deviation from Thermal Equilibrium**

  … but alternative models predict distant Antimatter local domains !

- **Single anti-He Cosmic Rays nucleus → Strong Evidence for Large Anti-matter Domains in the Universe**
- **AMS probes antimatter domains to the edge of the universe**


Positron fraction
AMS-02
Fit to Data
10^{-1}
1
10
10^2
positron, electron energy [GeV]
Outline



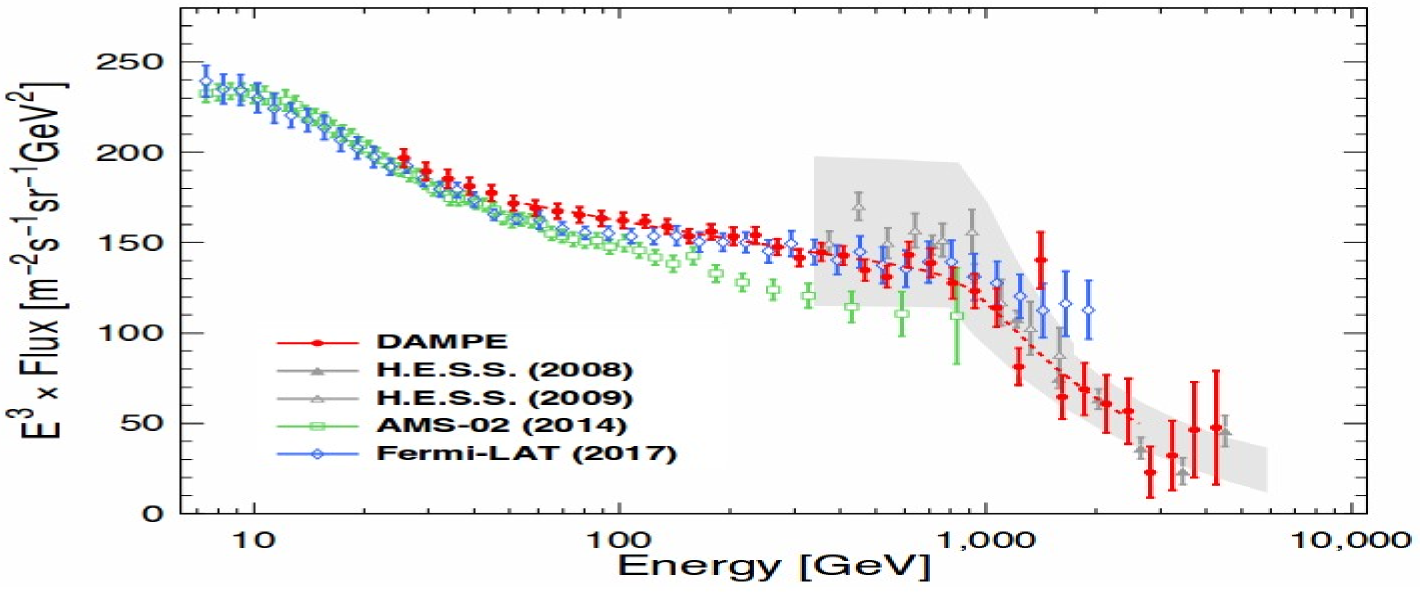
AMS-02
PAMELA
Fermi
Positron fraction
10^{-1}
1
10
10^{2}
$e^{\pm}$ energy [GeV]

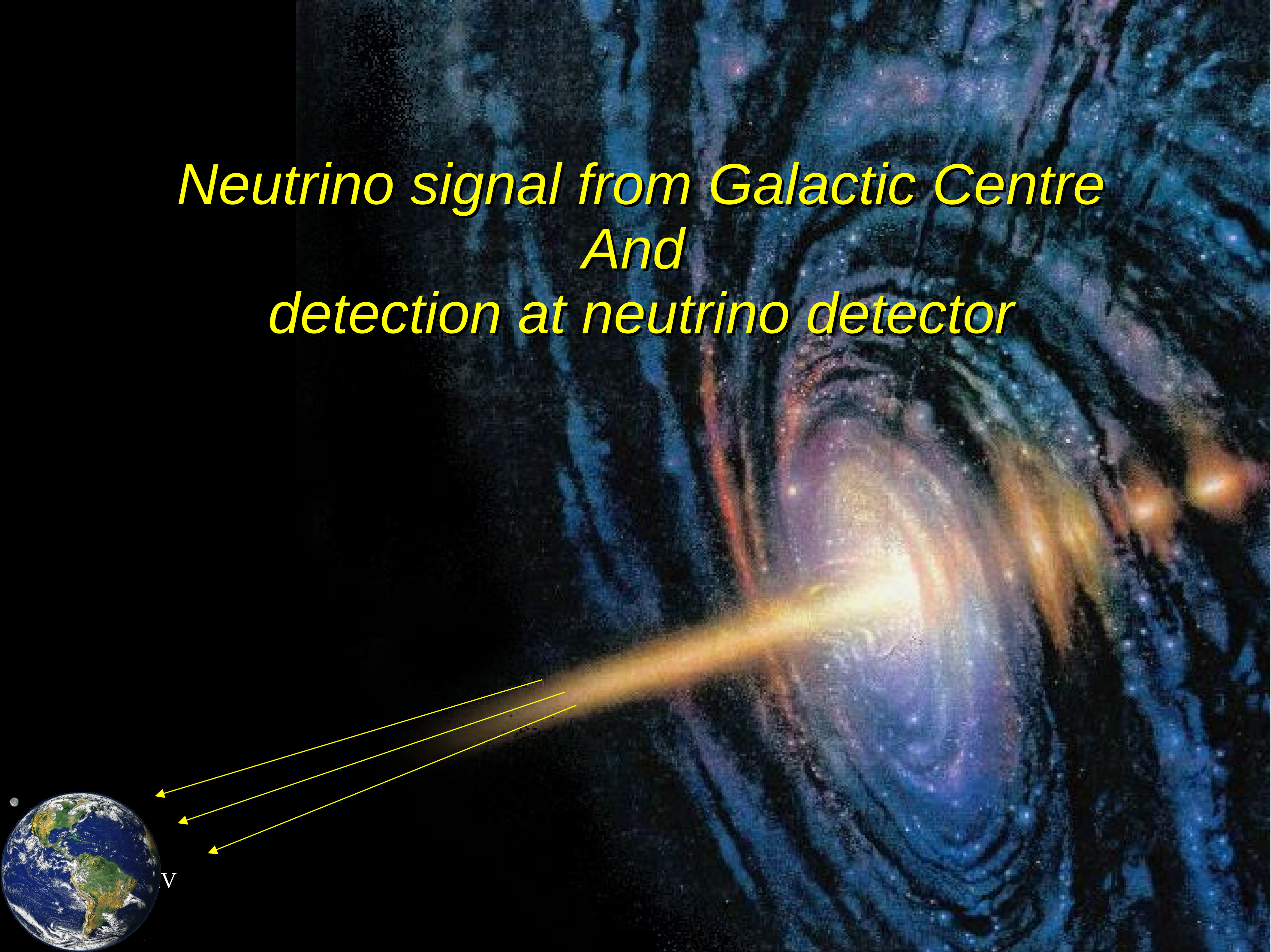
DAMPE Experiment (Dark Matter Particle Explorer)

Excess electron-positron flux at ~ 1.4 TeV

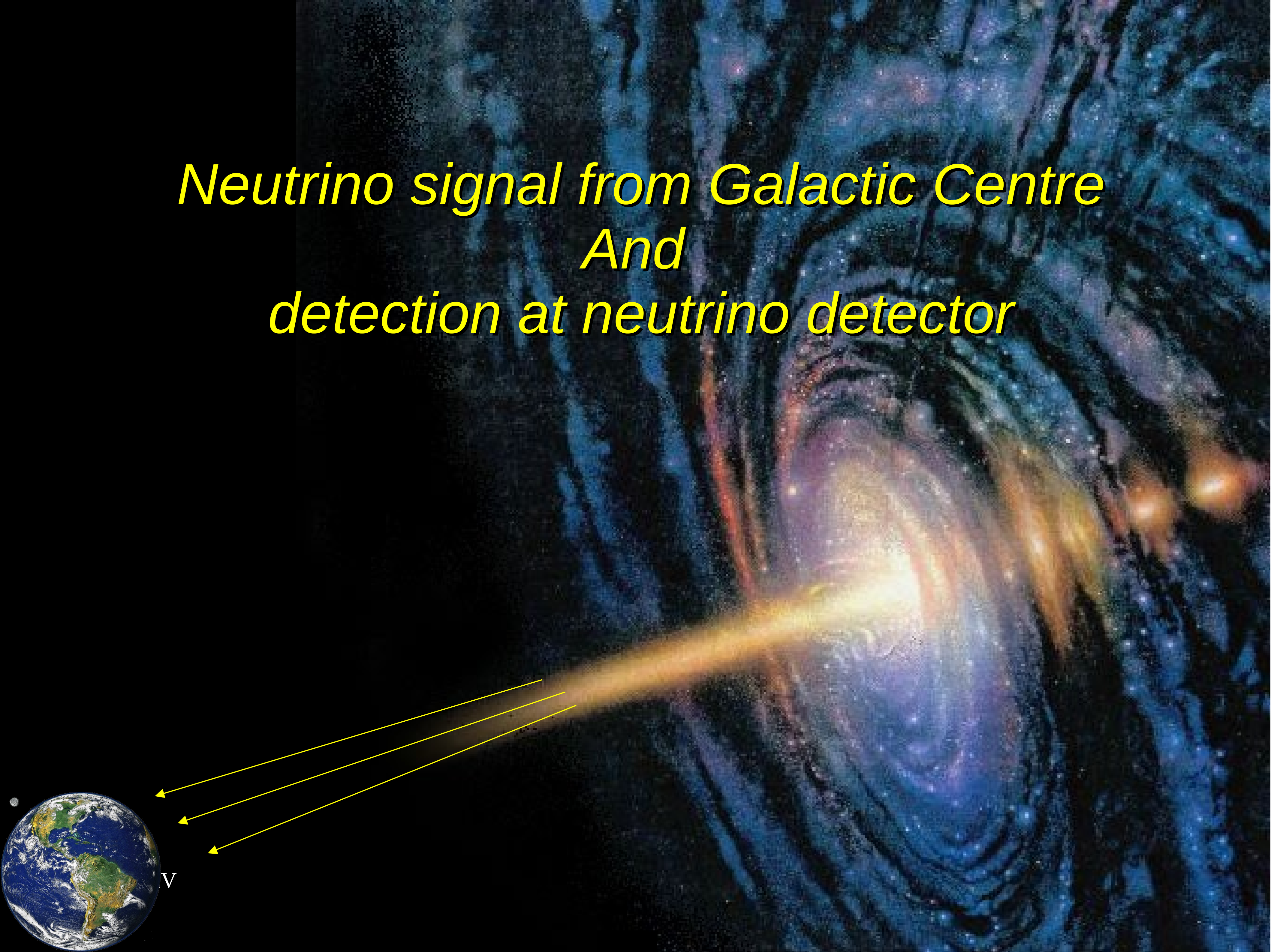
Break at 1 TeV

1.4 TeV Dark Matter ?




Neutrino signal from Galactic Centre
And
detection at neutrino detector
V

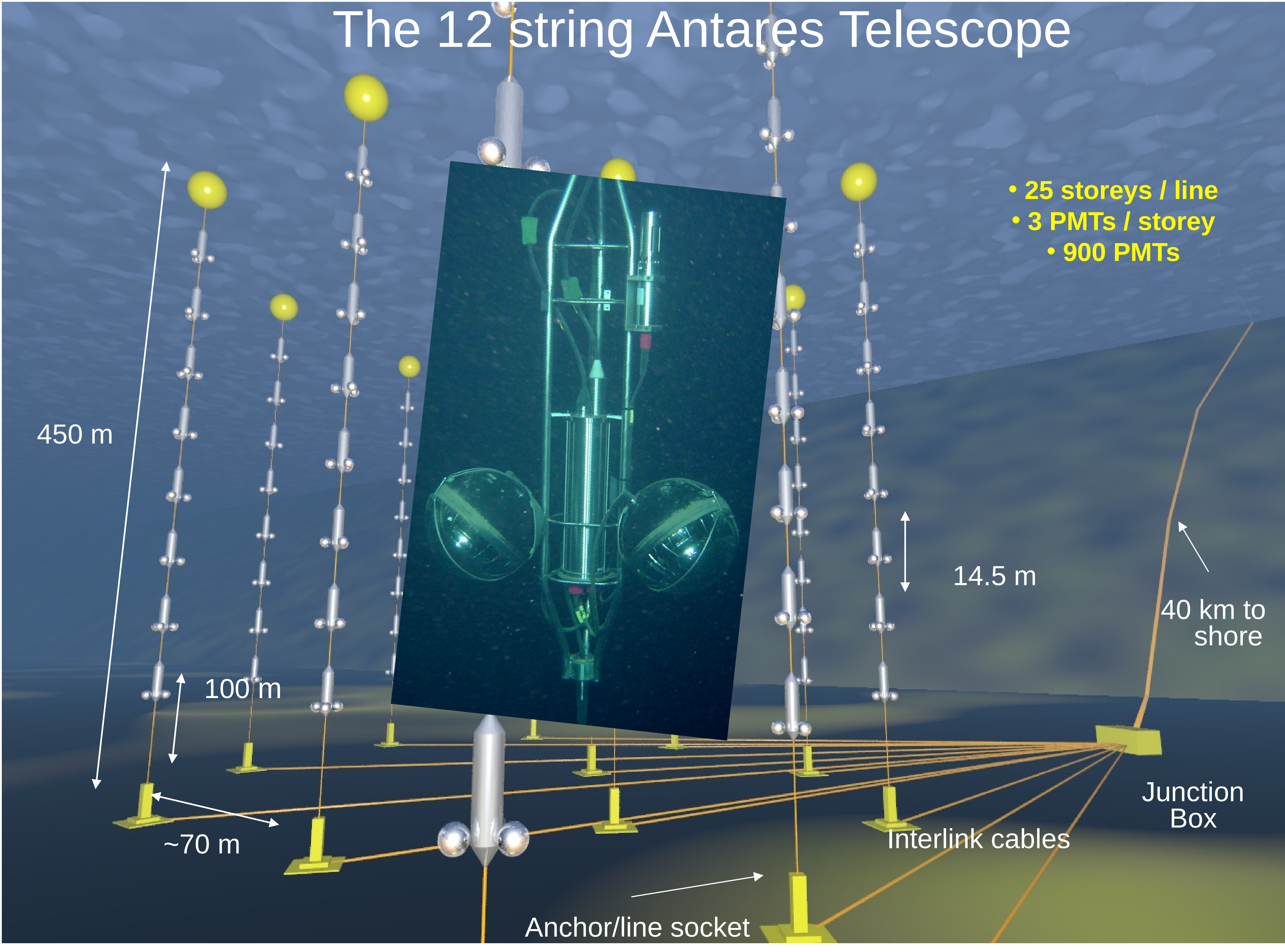
Neutrino signal from Galactic Centre And detection at neutrino detector



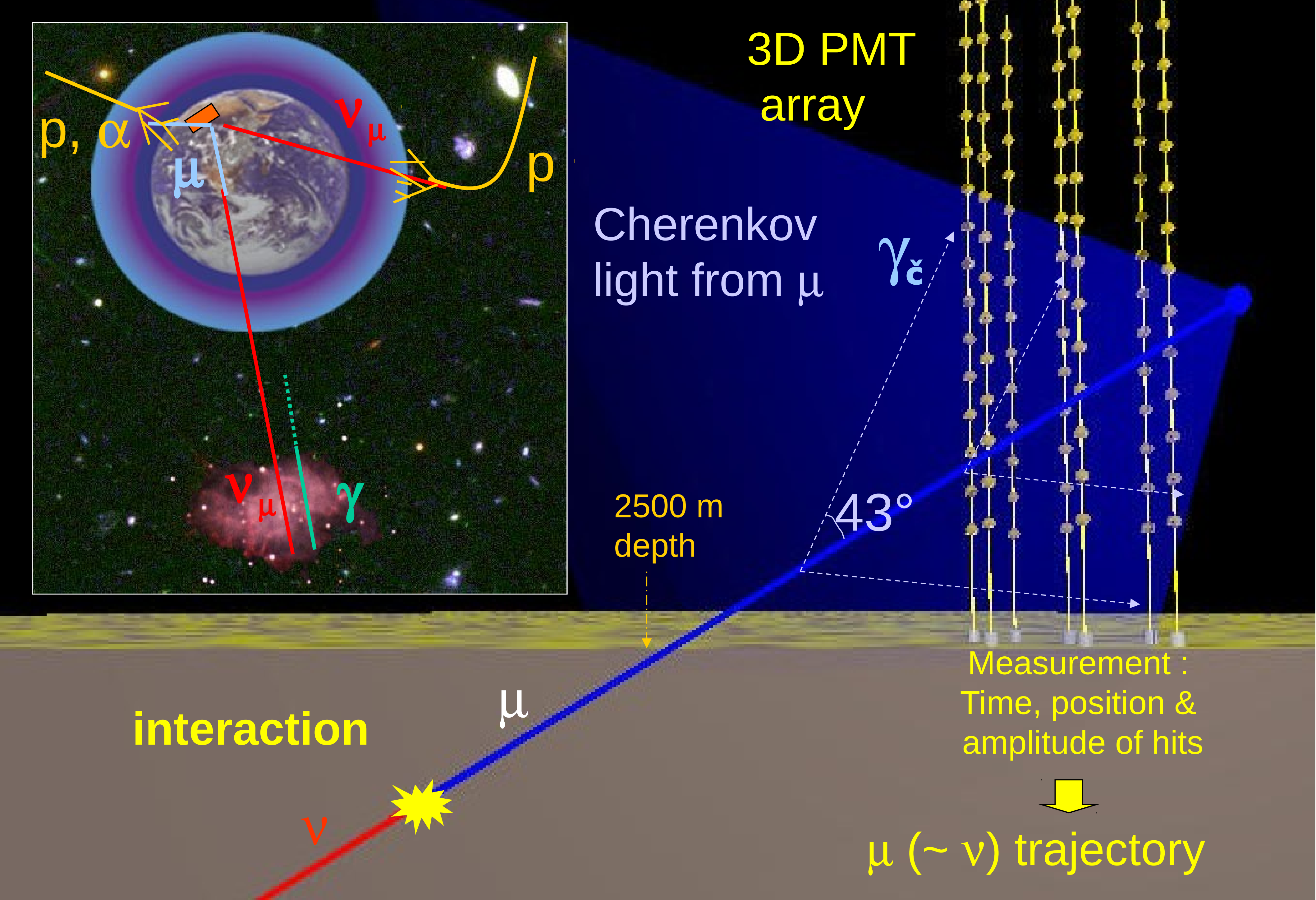
Astronony with a Neutrino Telescope and Abyss environmental RESearch proect (ANTARES)

- Water Cherenkov detector at a depth of around 2.5 km under the Mediterranean Sea off the French coast

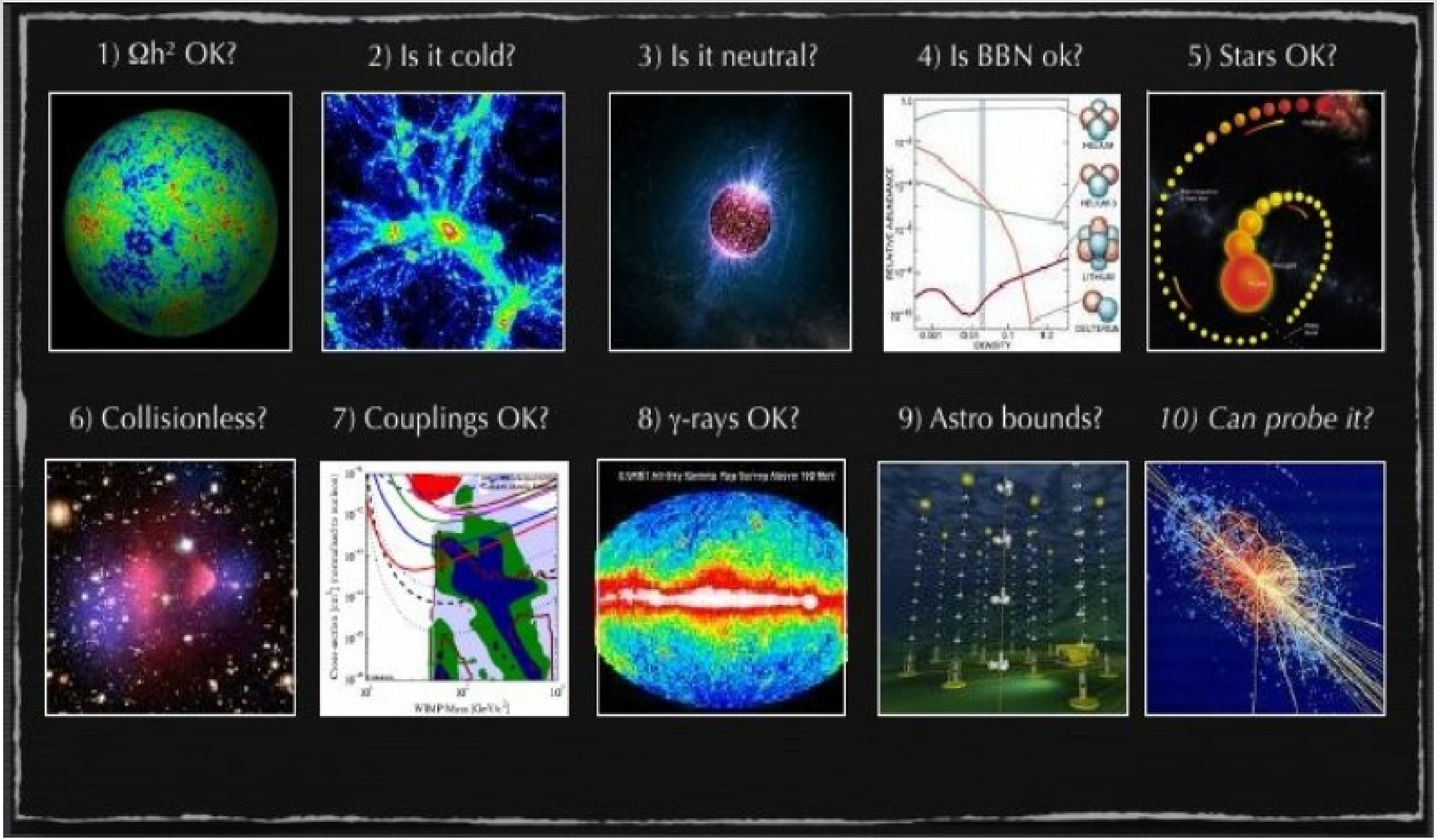
- Designed to detect neutrinos with high energy (~100 GeV to ~100 TeV)


The 12 string Antares Telescope
• 25 storeys / line
• 3 PMTs / storey
• 900 PMTs
450 m
14.5 m
40 km to shore
100 m
~70 m
Junction Box
Interlink cables
Anchor/line socket

Neutrino detection principle

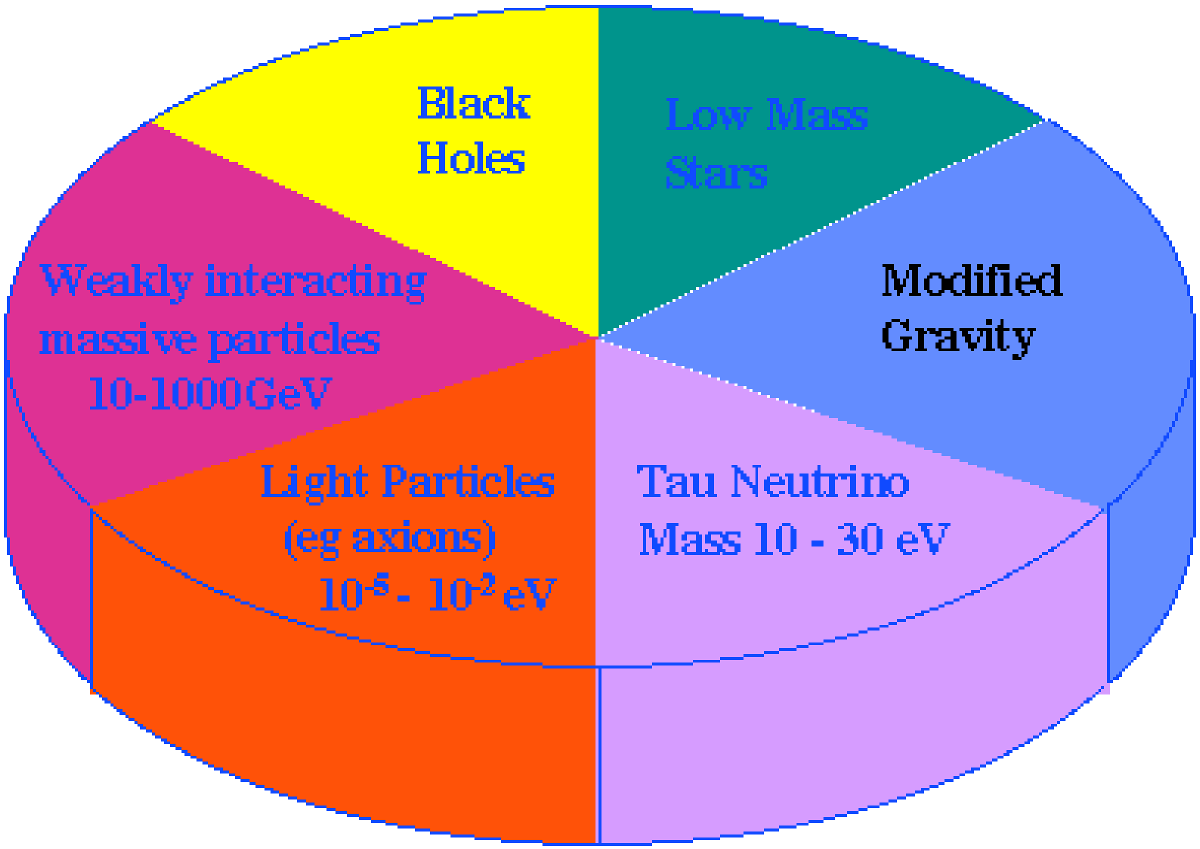


Tests for DM Particles



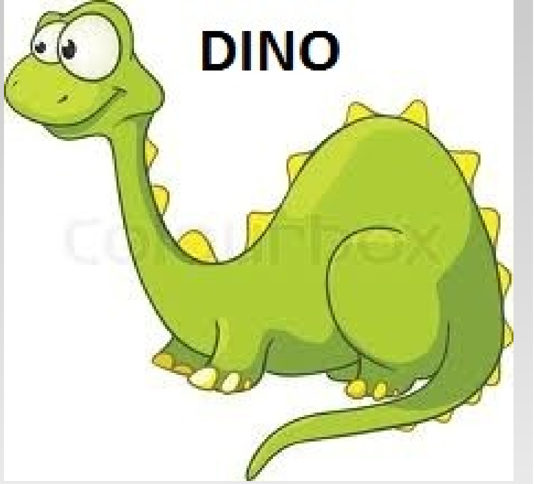
Taken from Gianfranco Bertone, arXiv:0711.4996

Likely Candidates for Dark Matter



Indian Endeavour in DM Search

Dark Matter @ INO (DINO)



Shielding of the detector is required for rock muons, cosmogenic muons and more hazardous neutrons (radiogenic and cosmogenic)

Cooling is proposed to be by He (4 K and below)

Proposed to be housed at horizontal shaft 550 metre underground at UCIL

Required is testing of rock composition, rock radioactivity.

Determination of neutron background, other radioactive backgrounds

Simulation required for determination of thickness of the shielding

Dark matter search at INO (DINO): A proposed dark matter search experiment in India

Proposed in 2 phases: miniDINO and DINO

MiniDINO: Scintillator for DM search R & D for prototype experiment at 555 m depth of UCIL mine with ~ 1-10 kg active mass

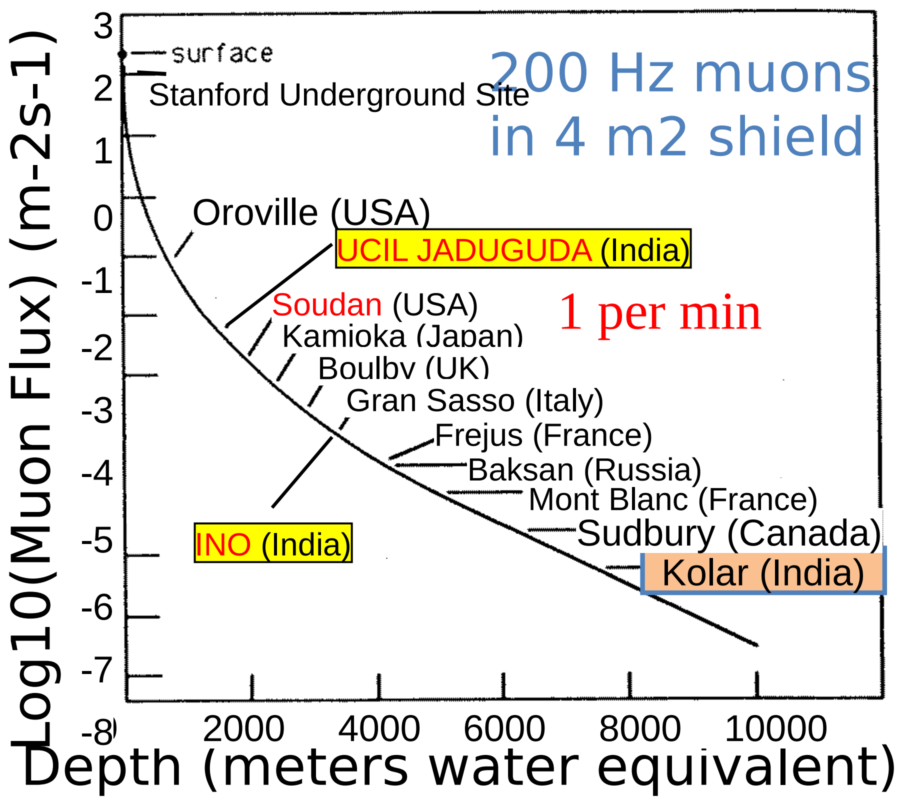
Phase I: room temp.

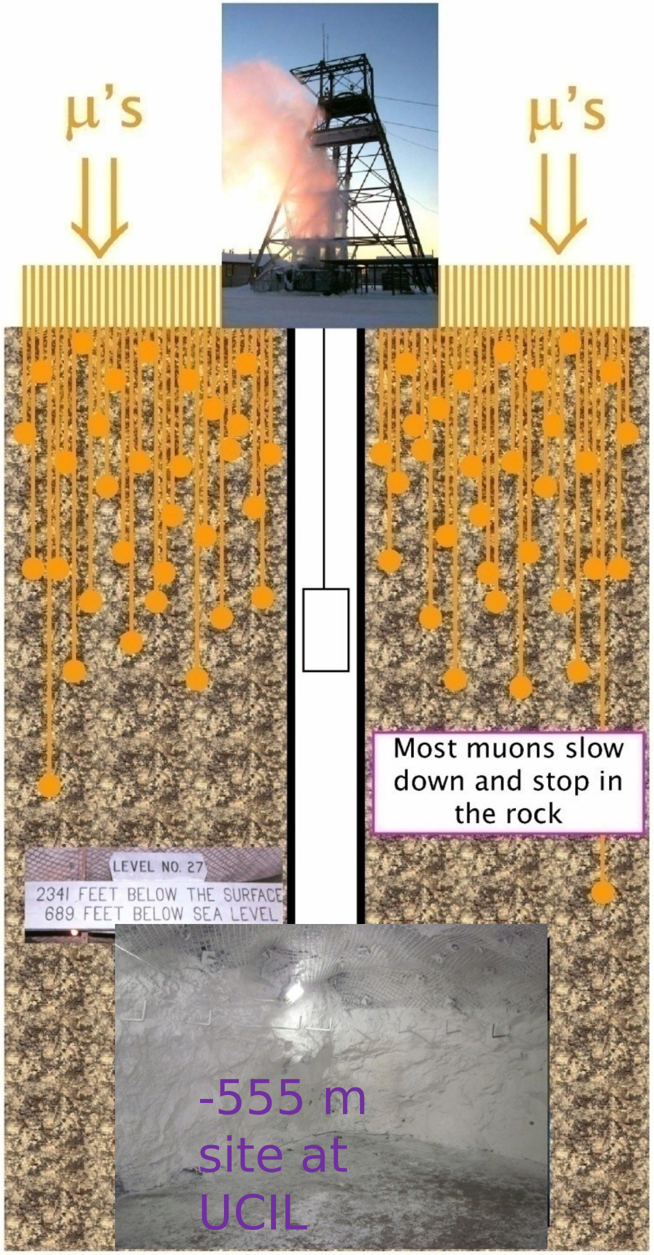
Phase II: Cryogenic expt.

DINO: Approx 10 kg to Ton Scale experiment at INO cavern

Collaboration (MiniDINO): SINP, UCIL, BARC, NISER, …

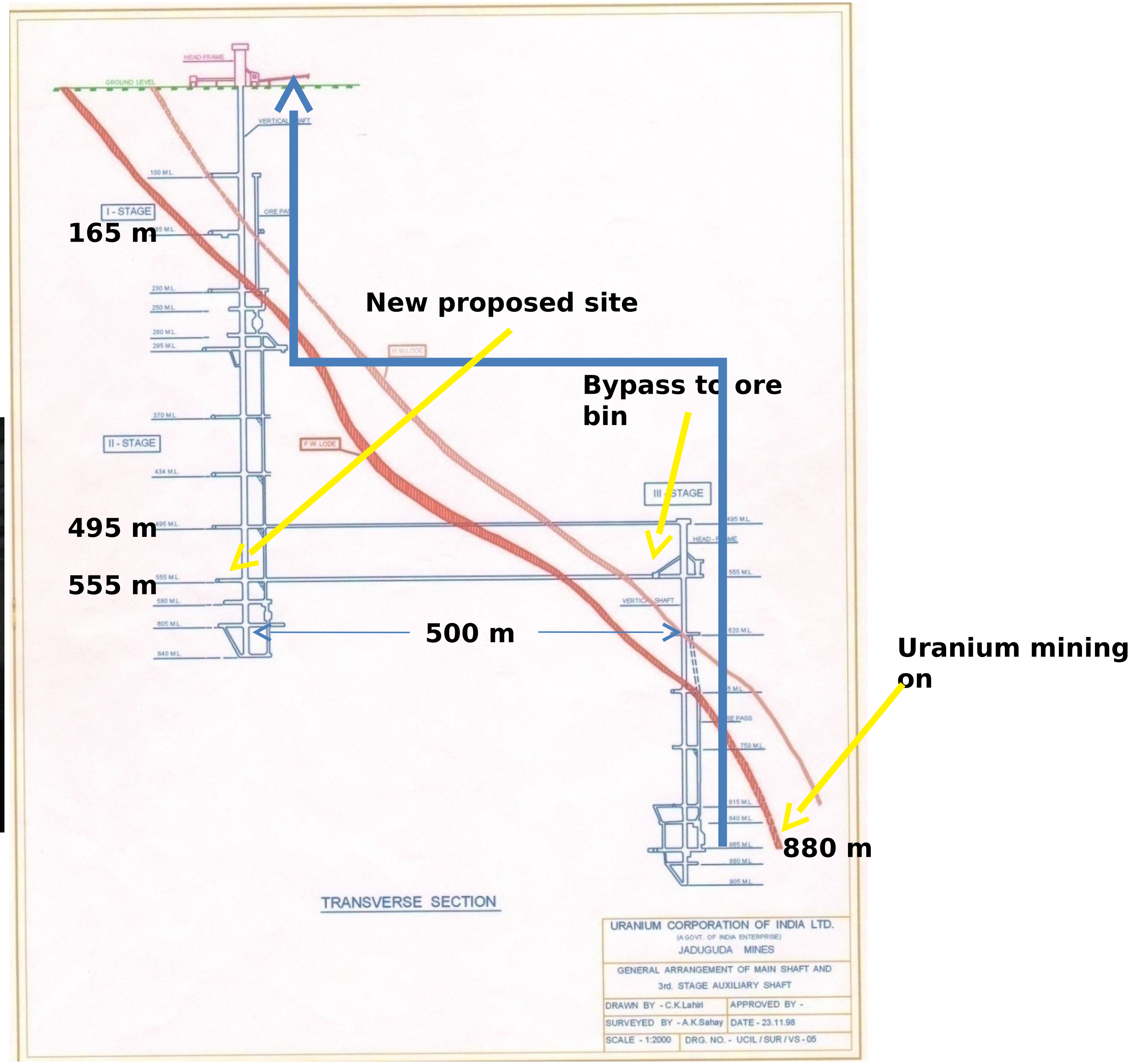
Reducing Cosmogenic Background : shielding of cosmic ray particles by rock



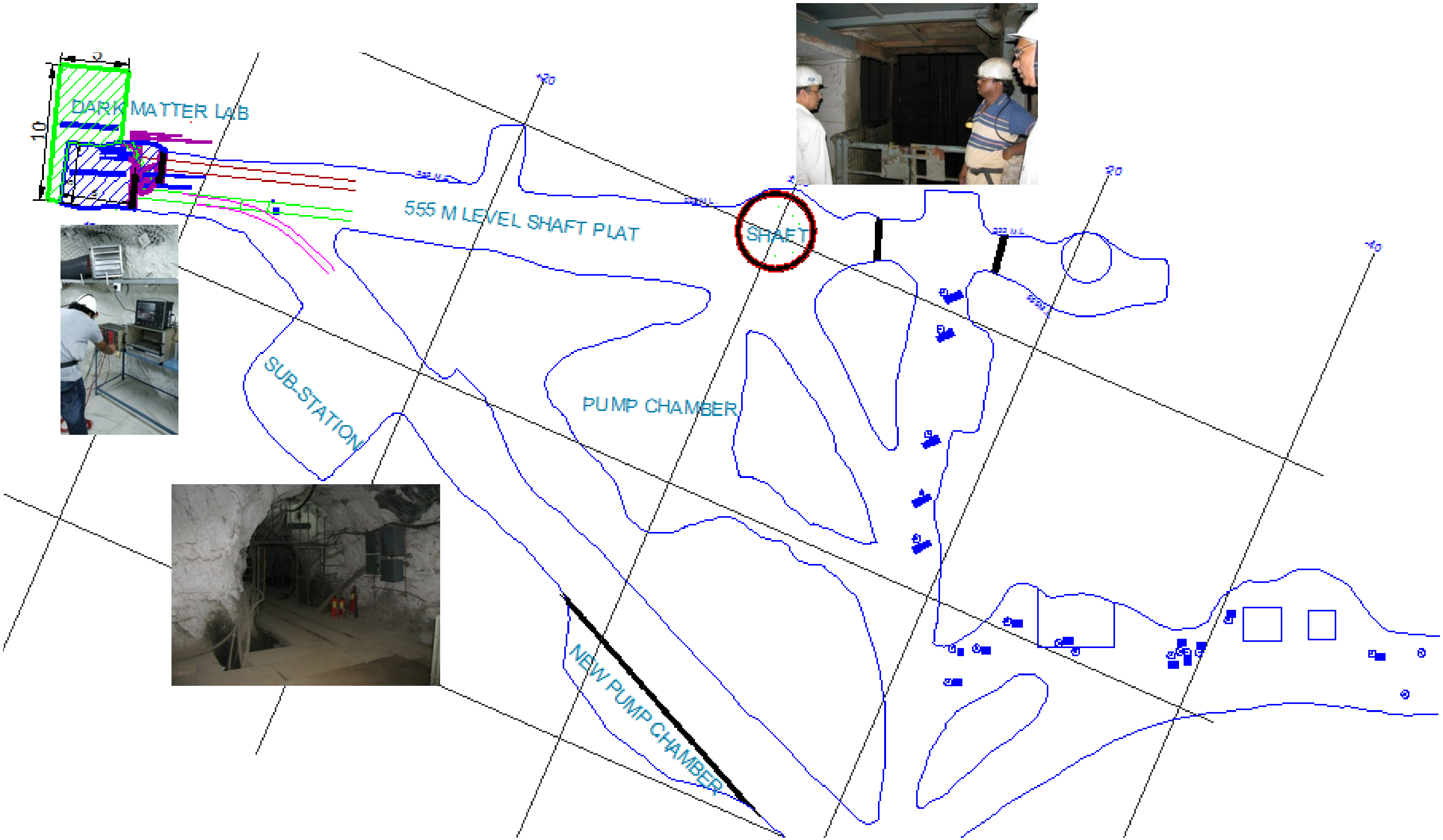


Second underground laboratory for Astroparticle Physics in India.

JADUGUDA MINE ELEVATION DRAWING



LAY-OUT OF -555 M LEVEL AT JADUGUDA AND LOCATION OF LAB



COURTESY: UCIL, Jaduguda

miniDINO & DINO Experiment: Challenges ahead

- Detector material and fabrication: surface lab based prototyping
  Scintillators: **CsI(Tl) / CsI** **GGAG(Ce) / GGAG**
  Tungstates
  Read-outs: Scintillation signals (PMT, Si-PMT, Si photodiode)
  Phonon signals (cryogenic phonon sensors)

- Cryogenics:
  Dilution refrigerator to cool detector stack ~ 10 mK.
  Cryogen-free 4 K refrigerator (suggested alternative for mini-DINO)

- Shielding against background radiation (simulation, passive & active shielding):
  Cosmogenic background (muons, neutrons)
  Radiogenic background (alphas, neutrons)
  Gamma rays, surface beta particles

- Site choice and preparation for experiment:

  UCIL, JADUGUDA (UNDERGROUND LAB) INO CAVERN

Various Shielding

Surround detectors with active muon veto

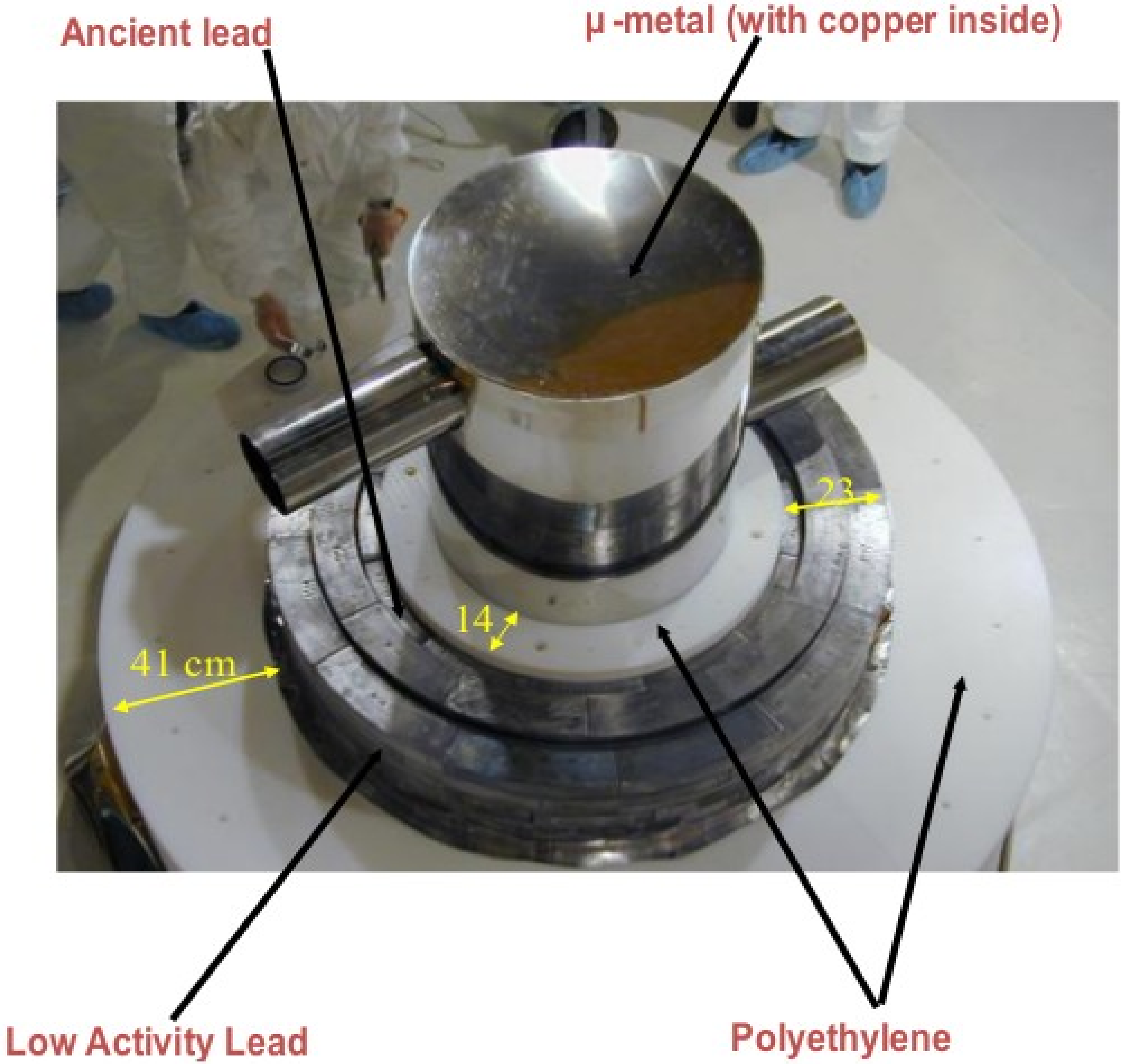
Use passive shielding to reduce γ/Neutrons

•Lead and Copper for photon

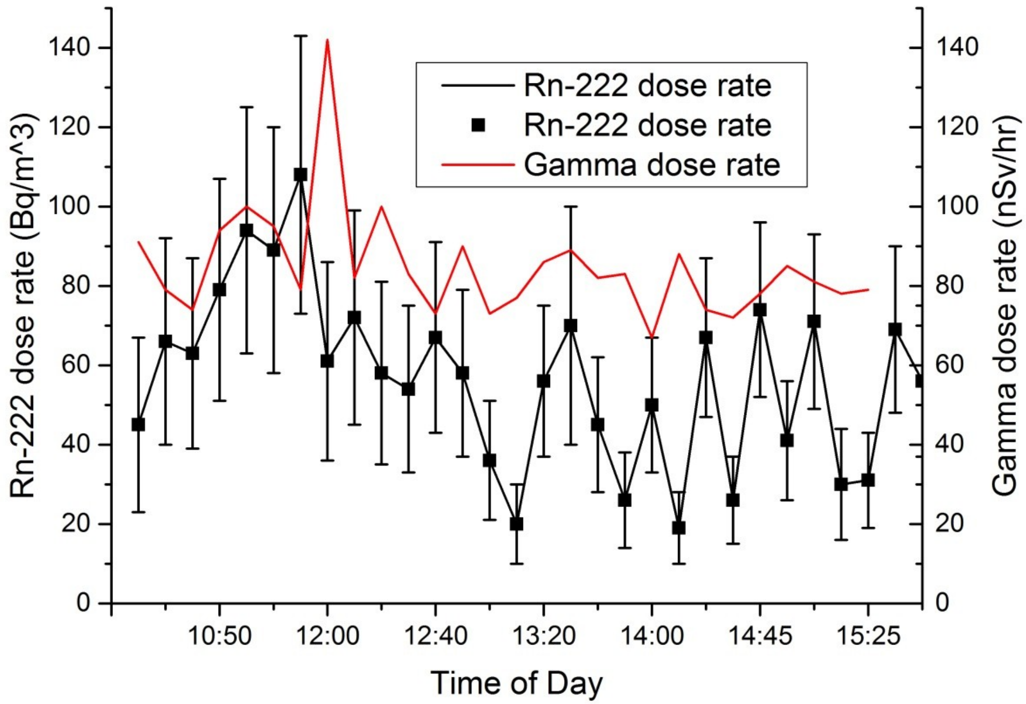
•Polyethylene for low-energy neutron

Neutron background negligible in Soudan, for recent runs

UCIL may be decent



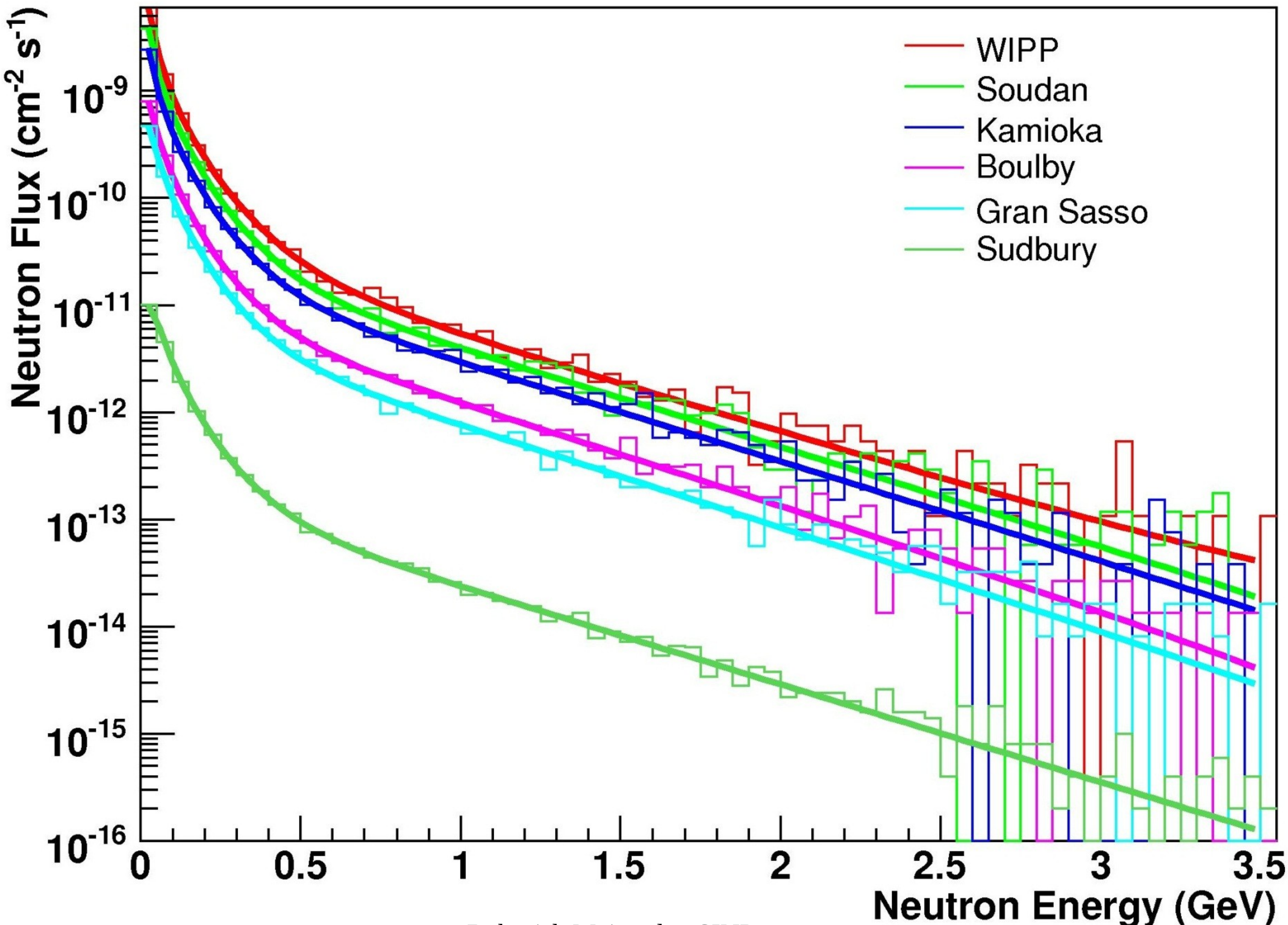
Radon monitoring at -555 m level



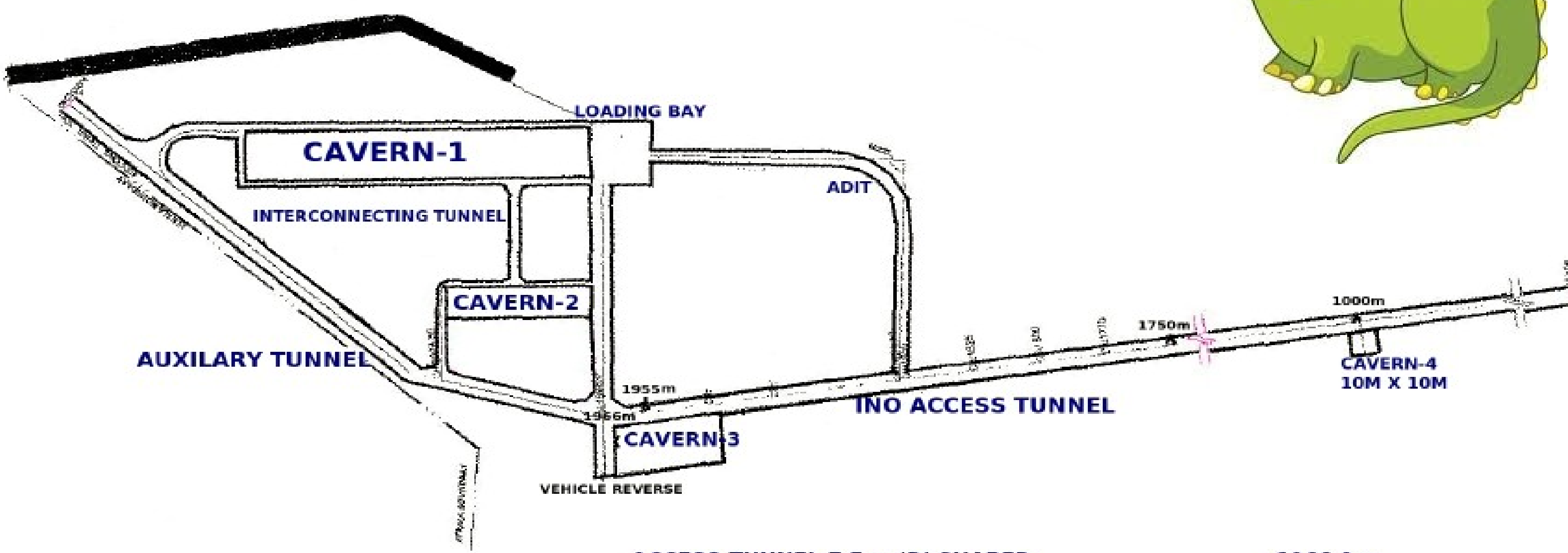
Preliminary measurements:
Average radon level within the laboratory = 56.7 +/- 22.0 Bq/m^3 (1.53 +/- 0.62 pCi/L)
Average radon level outside the laboratory = 111 +/- 31 Bq/m^3 (3.0 +/- 0.9 pCi/L)

Comparable or better with respect to SNOLAB radon background (3.3 +/- 0.4 pCi/L).

Underground Neutron Flux (Mei & Hime)



Dark-matter@INO (DINO) Ton-scale 2020



DINO

ACCESS TUNNEL 7.5m, 'D' SHAPED :1966.0m
ADDITIONALLY DRIVEN INT. TUNNEL 5.5m 'D' SHAPED: 175.4m
AUXILARY TUNNEL 7.5m 'D' SHAPED : 224.6m
INTERCONNECTING TUNNEL 3.5m 'D' SHAPED : 72.5m
ADDITIONAL TUNNEL 7.5m 'D' SHAPED (future expn) : 50.0m

CAVERN -1 : 132m x 26M x 32.5m
CAVERN -2 : 55m x 12.5m x 8.6m
CAVERN -3 : 40m x 10m x 10m
CAVERN -4 : 10m x 10m x 10m

- **INO Lab Depth 1.3km**

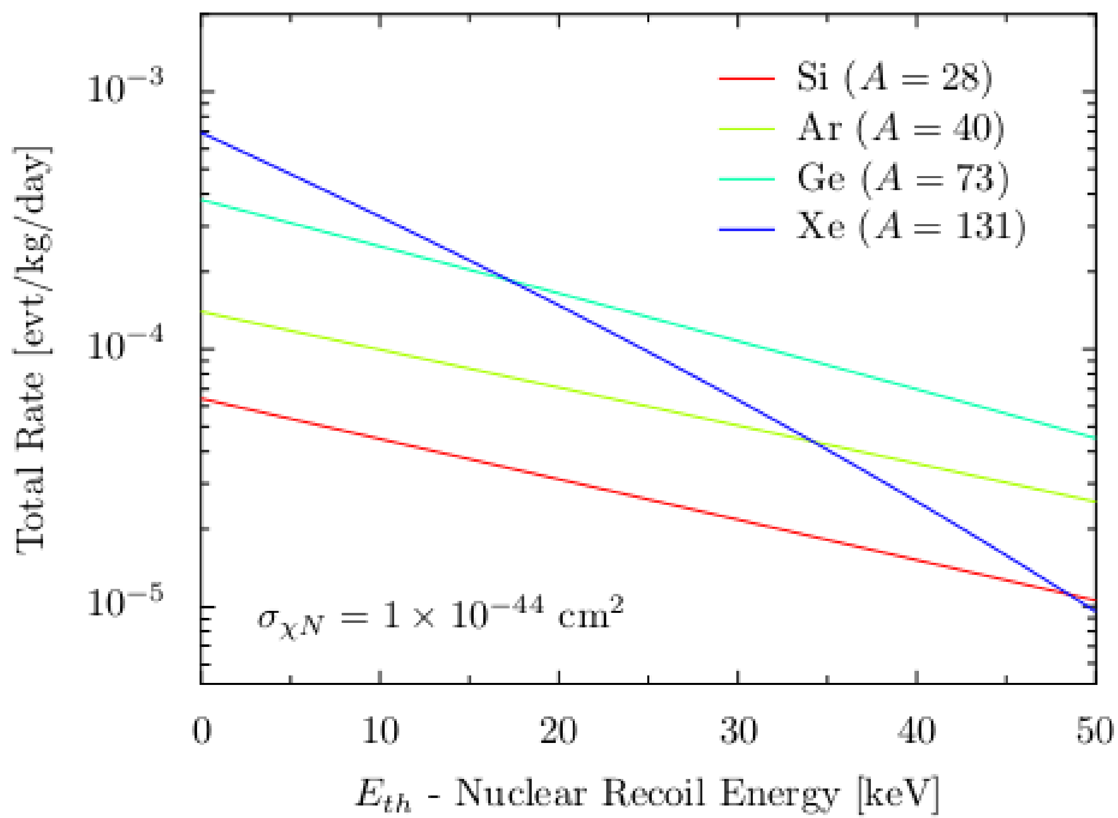
Pottipuram in Bodi West hills

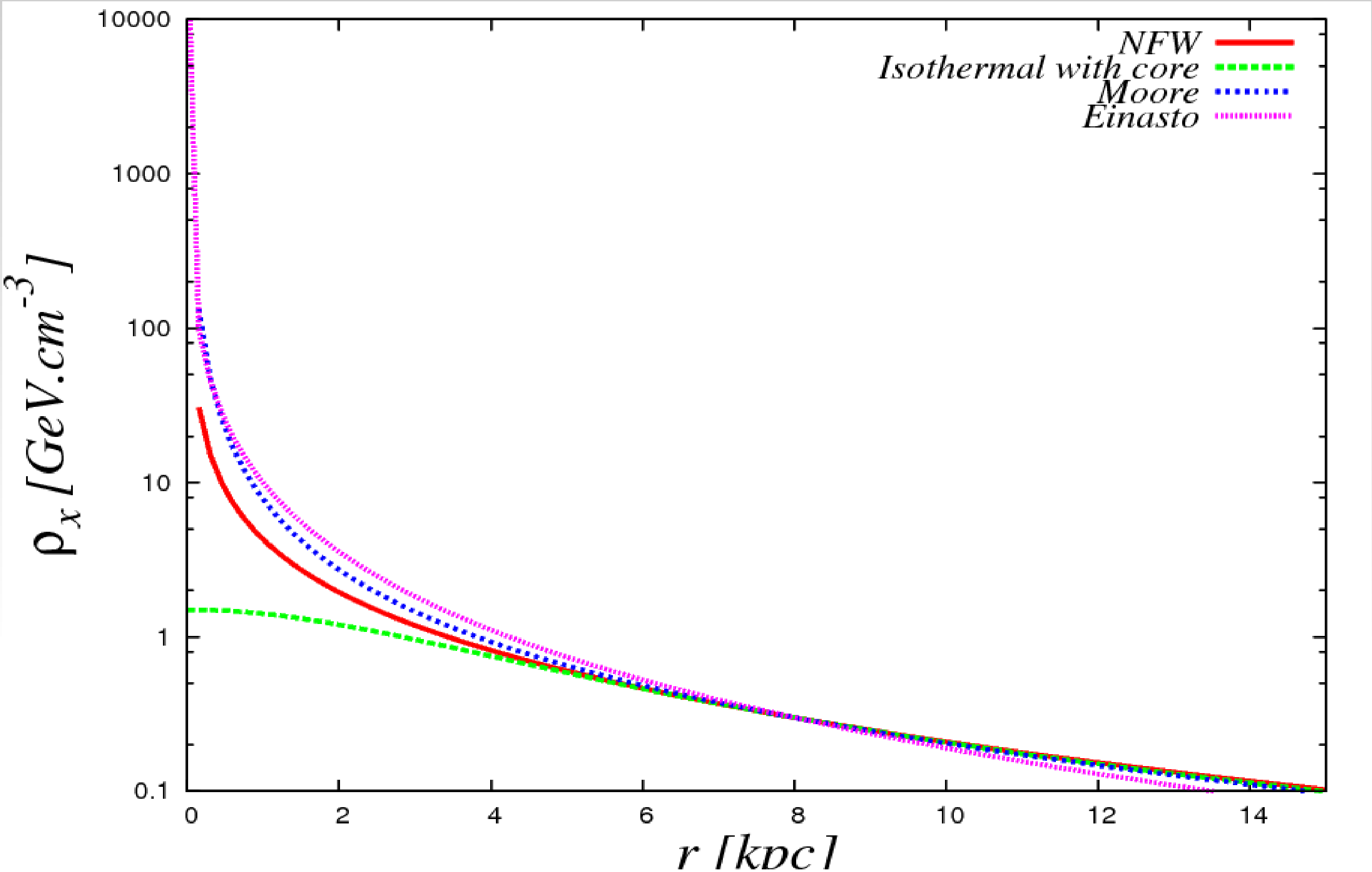
THANK YOU

Back Up Slides

Why Xenon?

- Large mass number A (~131), expect high rate for SI interactions ($\sigma \sim A^2$) if energy threshold for nuclear recoils is low
- ~50% odd isotopes (^{129}Xe,^{131} Xe) for SD interactions
- No long-lived radioisotopes, Kr can be reduced to ppt levels
- High stopping power ($Z = 54$, $\rho = 3\,\mathrm{g\,cm^{-3}}$), active volume is self shielding
- Efficient scintillator (~80% light yield of NaI), fast response
- Nuclear recoil discrimination with simultaneous measurement of scintillation and ionization





Variation of Dark Matter Halo densities for various Halo Profiles

Mass-SI Scattering cross section

$$\sigma_{SI} - M_\chi$$