Dark Matter

The missing piece of the Standard Model

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References

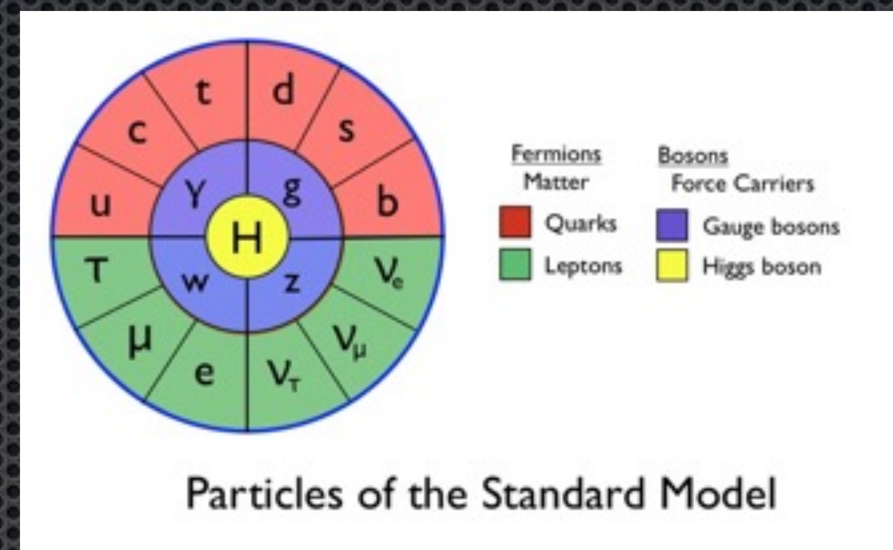
- On the history of Dark Matter: J. Einasto, “Dark Matter,'' Braz. J. Phys. 43 (2013) 369 [arXiv:1308.2534 [astro-ph.CO]].
- On the astrophysics of Dark Matter : J. Silk, “Dark matter: The astrophysical case, “ Comptes Rendus Physique 13 (2012) 724.
- On the cosmology of Dark Matter: S. Profumo, “TASI 2012 Lectures on Astrophysical Probes of Dark Matter,” arXiv:1301.0952 [hep-ph].
- On direct searches: M. Schumann, “Dark Matter 2014,” arXiv:1501.01200 [astro-ph.CO].

http://www.theo.phys.ulg.ac.be/wiki/index.php/Dark_Matter

The problem of Dark Matter

Standard Model

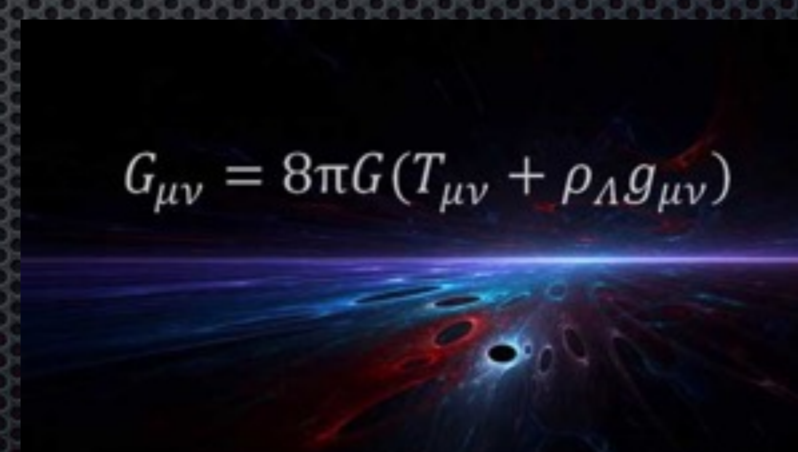
Content



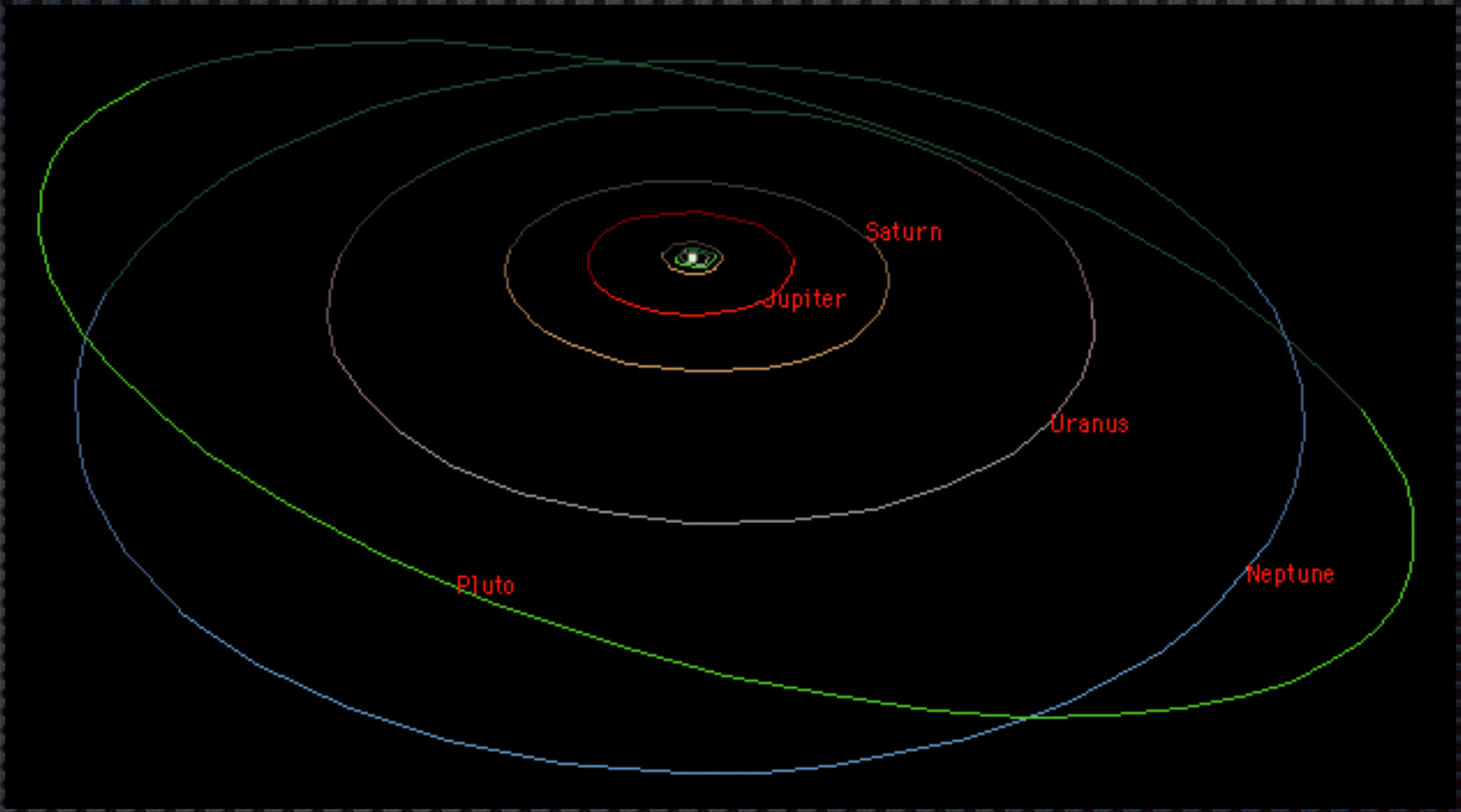
Dynamics

$SU(3) \otimes SU(2)_L \otimes U(1)_Y$

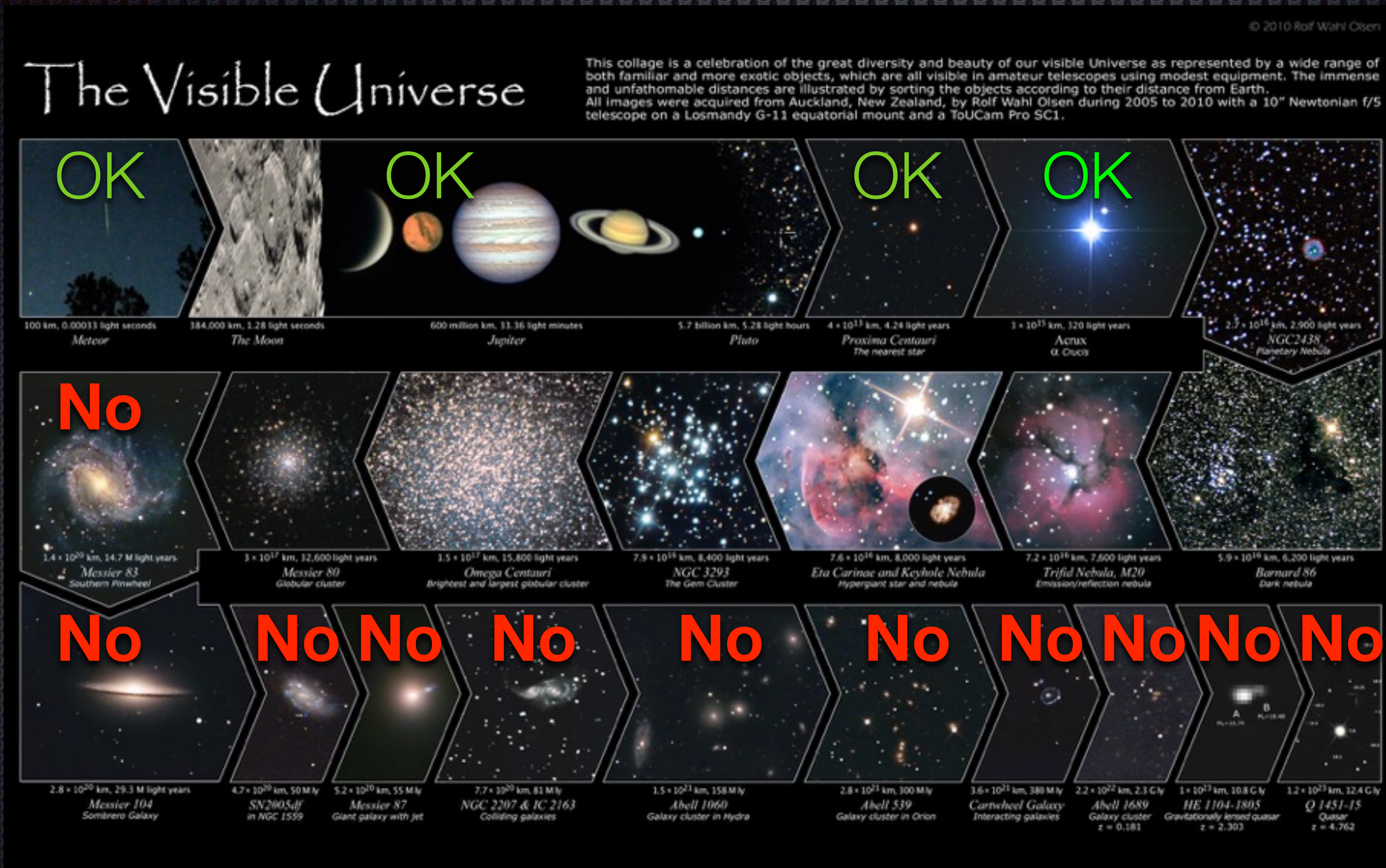
Background



It works perfectly *locally*



It does not work on larger scales



Plan

- Direct evidence
- Possible causes
- Searches
- How to build a model

Plan

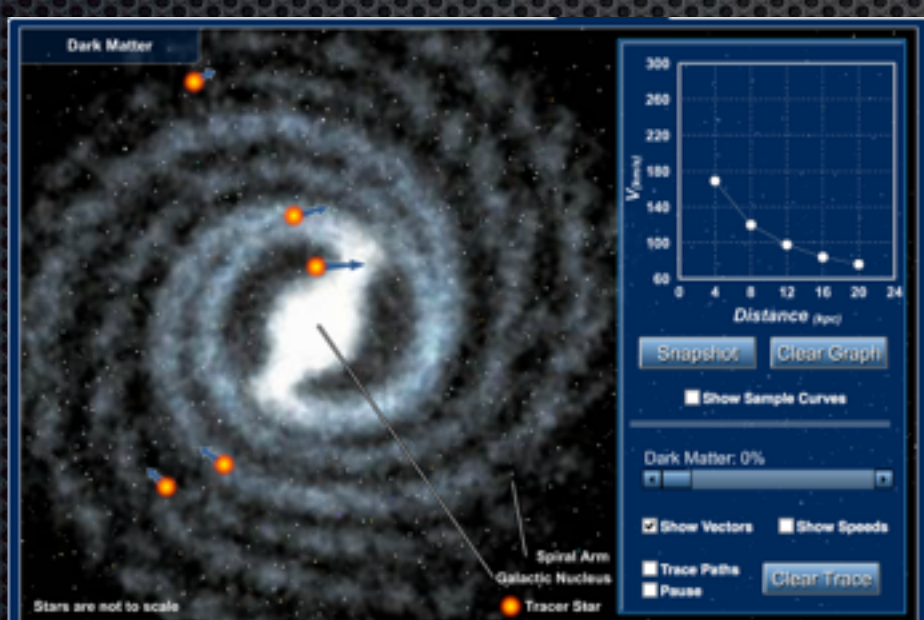
- **Direct evidence**
    - **Galaxies (Rubin)**
    - **Cluster of galaxies (Zwicky)**
    - **Colliding clusters of galaxies**
    - **Milky Way (Oort)**
- Possible causes
- Searches
- How to build a model

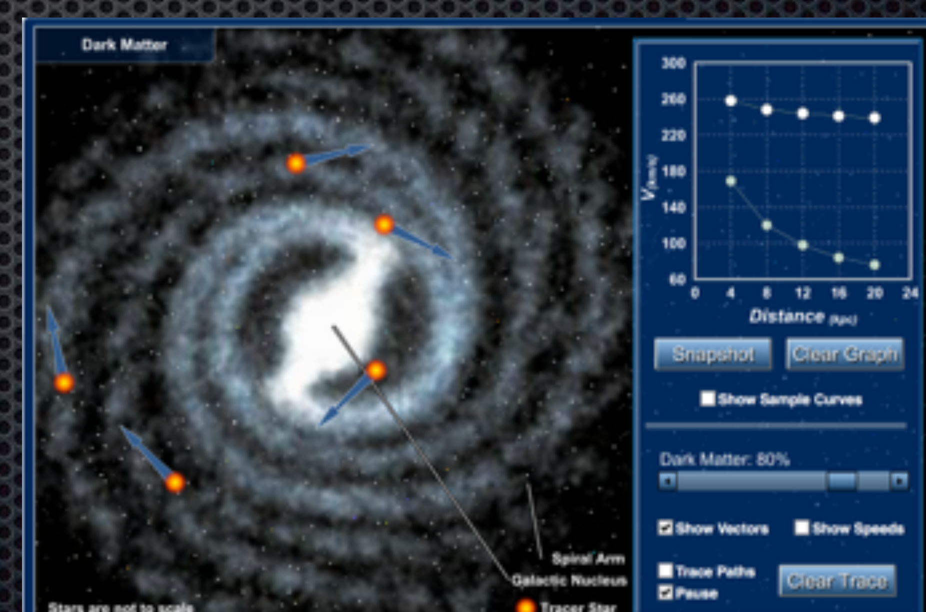
Galaxies *

*http://highered.mheducation.com/olcweb/cgi/pluginpop.cgi?it=swf::100%::100%::/sites/dl/free/007299181x/78778/DarkMatter_Nav.swf::Dark%20Matter%20Interactive

Rubin,V.C., Ford, W.K. & Thonnard, N. 1978, Astrophys. J. 225, L107

“Extended rotation curves of high-luminosity spiral galaxies”





Theory

$M_{bulge} \approx 2\ 10^{10} M_{sun}$, $R_{bulge} \approx$a few kpc

$M_{disk} \approx 6\ 10^{10} M_{sun}$, $R_{disk} \approx 15$ kpc, falling off exponentially

density of stars $\sim \exp(-R/3\,\text{kpc})$

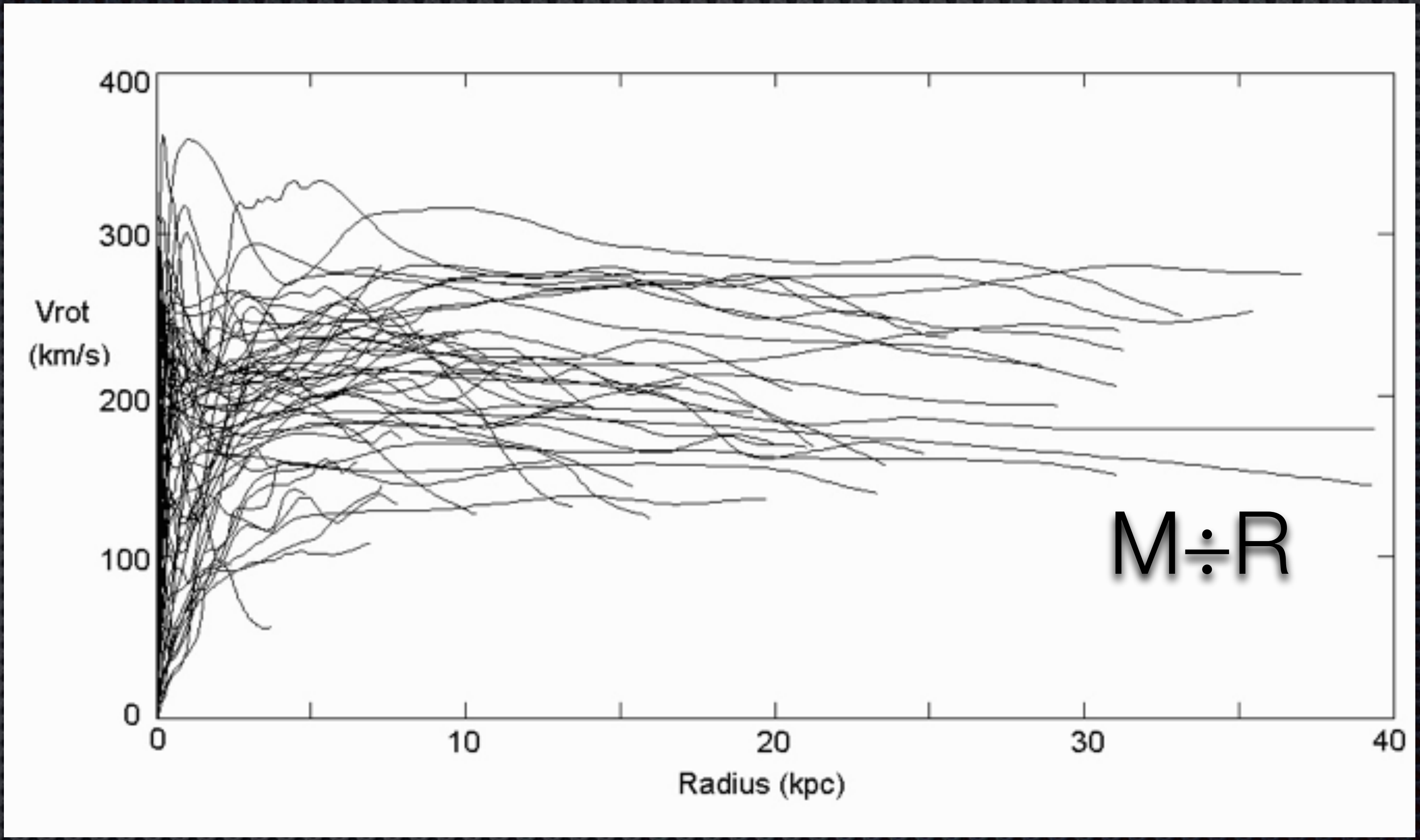
$\vec{F}_c = \vec{F}_{grav}$

$$\frac{mv^2}{R} = G\frac{M(R)m}{R^2} \implies v = \sqrt{G\frac{M(R)}{R}}$$

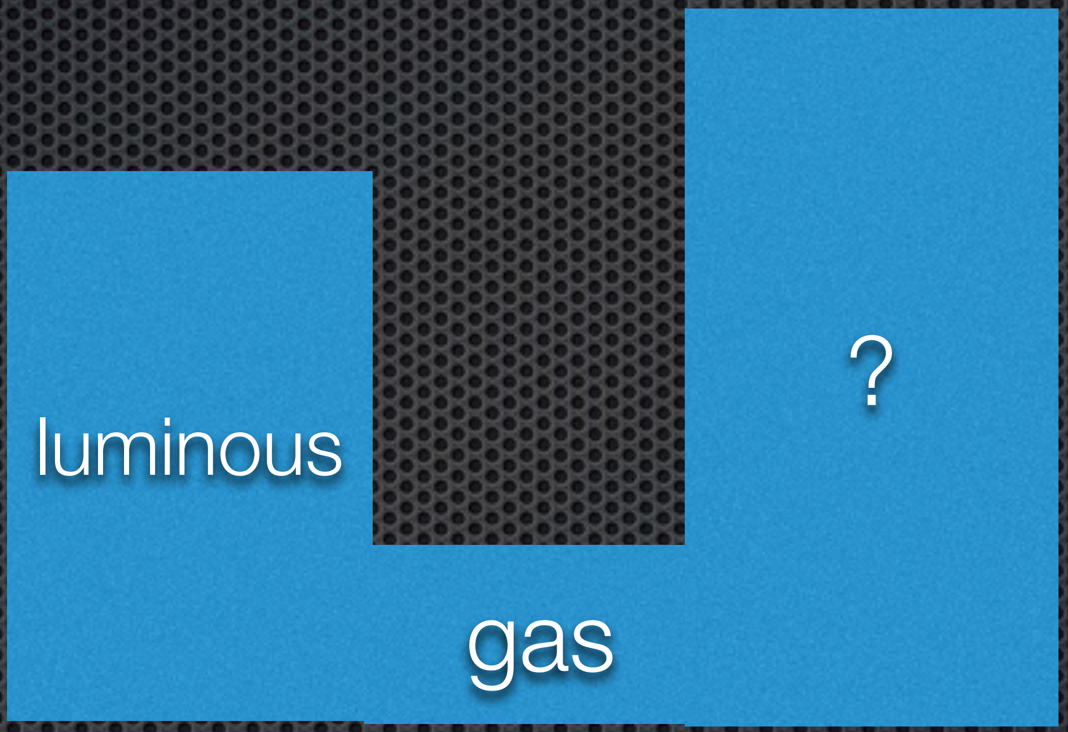
Effective mass

Data

"Rotation Curves of Spiral Galaxies," Y.Sofue & V.Rubin 2001, ARAA 39, 137-174



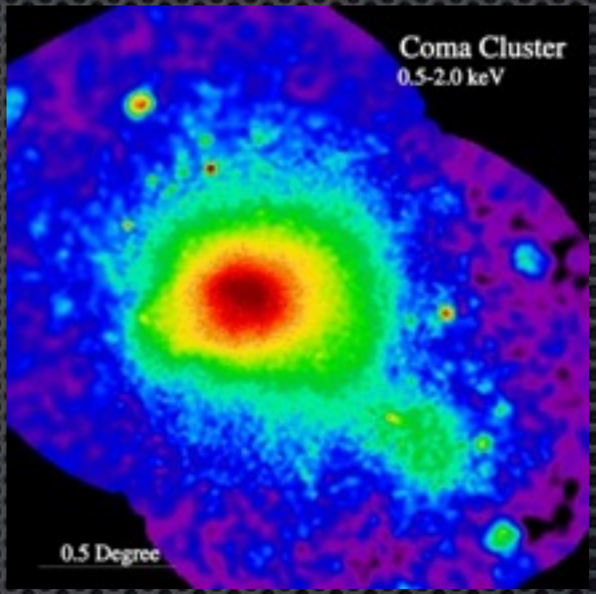
Galactic stuff



Galaxy clusters:

- Zwicky, F. 1933, Helv. Phys. Acta 6, 110, "The redshift of extragalactic nebulae": coma cluster

HUBBLE satellite



ROSAT satellite

Virial theorem: relation kinetic energy-gravitational potential

- peculiar velocities
- X-ray temperature of hot gas

Theory

Let $G = \sum_i \vec{p}_i \cdot \vec{r}_i$ assumed bounded in time. One has

$$\frac{dG}{dt} = 2K + \sum_i \vec{F}_i \cdot \vec{r}_i$$

Average over time.

$$\left| \frac{G(T) - G(0)}{T} \right|_{T\to\infty} = 0 = 2\langle K \rangle + \left\langle \sum_{i\neq j} -\vec{\nabla} V_{ji} \cdot \vec{r}_i \right\rangle$$

$$2\langle K \rangle = \left\langle \sum_{i\neq j} \vec{\nabla} V_{ji} \cdot \vec{r}_i \right\rangle = \left\langle \sum_{i<j} \vec{\nabla} V_{ij} \cdot (\vec{r}_i - \vec{r_j}) \right\rangle$$

V is gravitational, so $\vec{\nabla} V_{ij} \cdot (\vec{r}_i - \vec{r_j}) = -V_{ij}$, so that

$$2\langle K \rangle = -\left\langle \sum_{i<j} V_{ij} \right\rangle = -\langle V \rangle$$

Coma cluster

- age > 9 10^9 years ⇒ equilibrium OK

Kinetic energy
$$K = \frac{1}{2}\sum_i m_i v_i^2 = \frac{1}{2} M \left\langle v^2 \right\rangle$$

Where m_i, v_i are mass, velocity of each galaxy
and M, $\langle v^2 \rangle$ are total mass, average velocity

How to find $\langle v^2 \rangle$?
Can measure only line of sight velocity
$\langle v^2 \rangle = \langle v_x^2 + v_y^2 + v_z^2 \rangle = 3 \langle v_z^2 \rangle = 3\ \sigma^2$
where σ is the "velocity dispersion"

Kinetic energy $K = \frac{3}{2} M\sigma^2$

Potential energy $U = -0.4 \frac{GM^2}{r_h}$

where r_h = "half-light radius"

$2K+U = 0$ gives $2\frac{3}{2} M\sigma^2 - 0.4\frac{GM^2}{r_h} = 0$

$$M = 7.5 \frac{\sigma^2 r_h}{G}$$

$r_h = 1.5$ Mpc

$\sigma = 880$ km/s

Calculate $M = 2\times10^{15}\ M_\odot$

Mass to light ratio of cluster is $250\ M_\odot/L_\odot$

X-ray emitting gas is at 100,000,000 K.

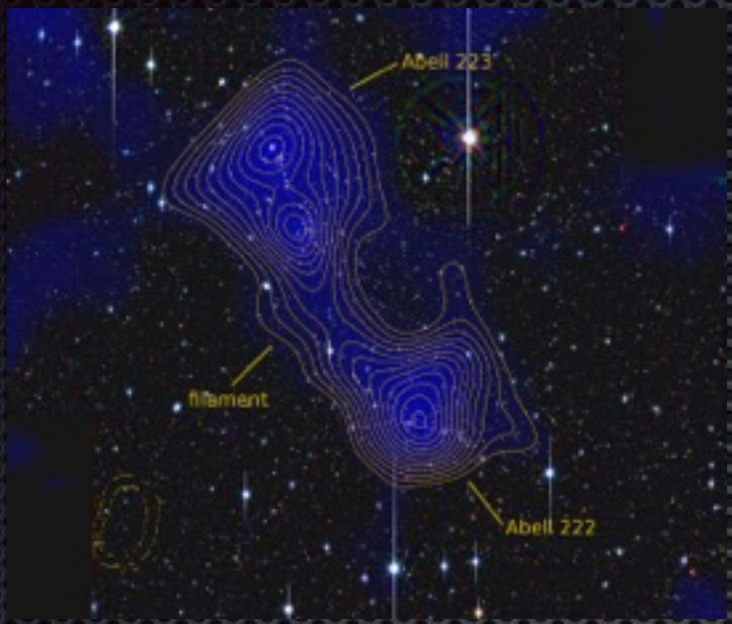
Amount of X-ray emitting gas can be calculated to be $2\times10^{14}\ M$

Modern techniques: gravitational macro- and micro-lensing

Abell 383

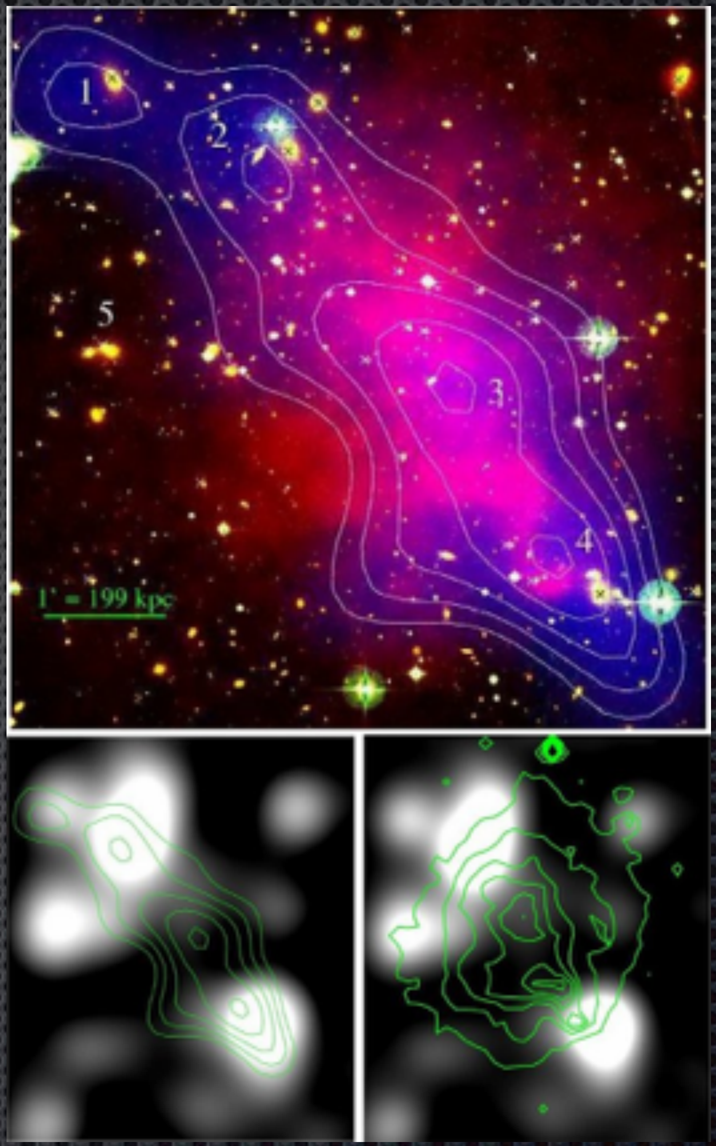
see http://www.spacetelescope.org/images/?search=lensing

Maps of Dark Matter



Jörg Dietrich et al, Nature 487, 202–204 (12 July 2012)

Dark matter map in galaxy cluster Abell 1689
E. Jullo , P. Natarajan and J.-P. Kneib



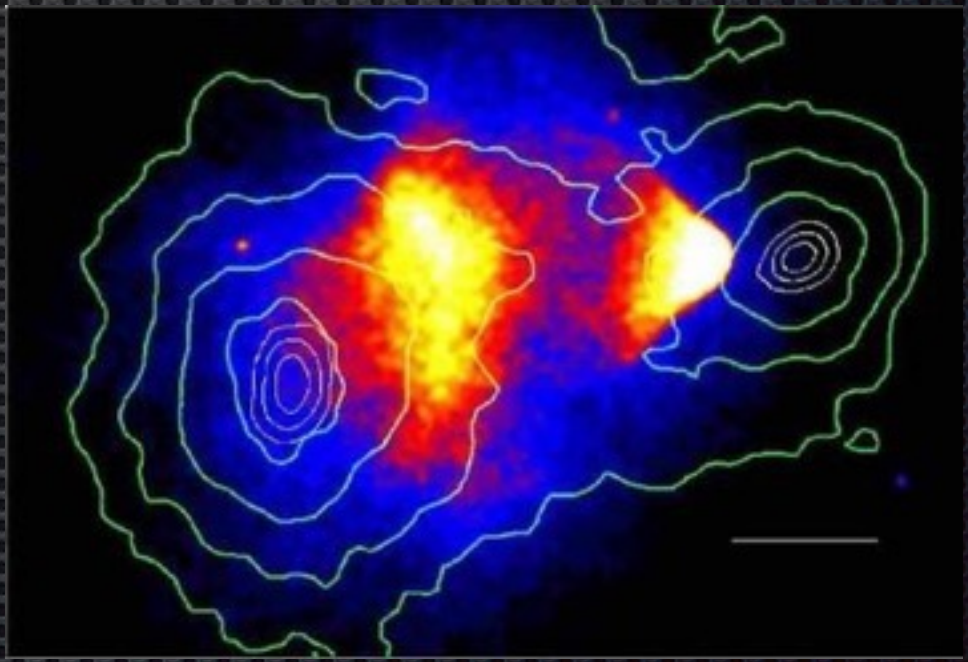
The galaxy cluster A~520 (the cosmic train wreck),
in which the galaxies are seen displaced from the
dark matter (lower left panel) and the X-ray gas (lower right panel).
In the top panel, the lensing signal (blue) and its contour lines are
superposed on the X-ray image (red) and the cluster galaxies (orange).

Gravitational Lensing - Bartelmann, Matthias
Class.Quant.Grav. 27 (2010) 233001
arXiv:1010.3829 [astro-ph.CO]

Cluster Collision

Chandra satellite

Bullet cluster

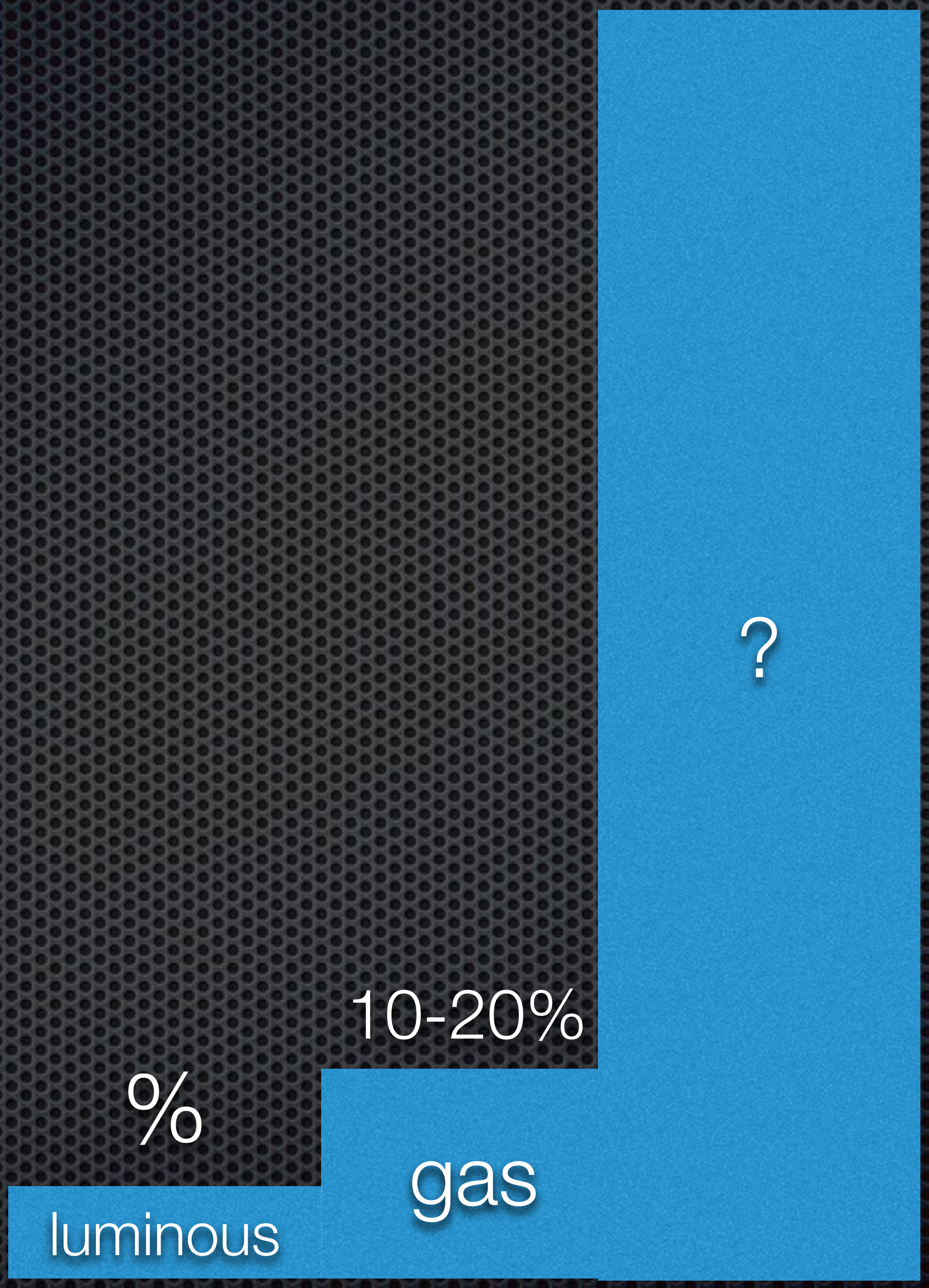


Musket Ball cluster

Dawson, W. et al, 2012, ApJ 747, 42; arXiv:1110.4391

Spherical halos

Galaxy cluster stuff



Milky way

J.H. Oort, 1932, Bull. Astr. Inst. Netherlands, 6, 249 “The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems”

LETTERS NATURE PHYSICS DOI: 10.1038/NPHYS3237

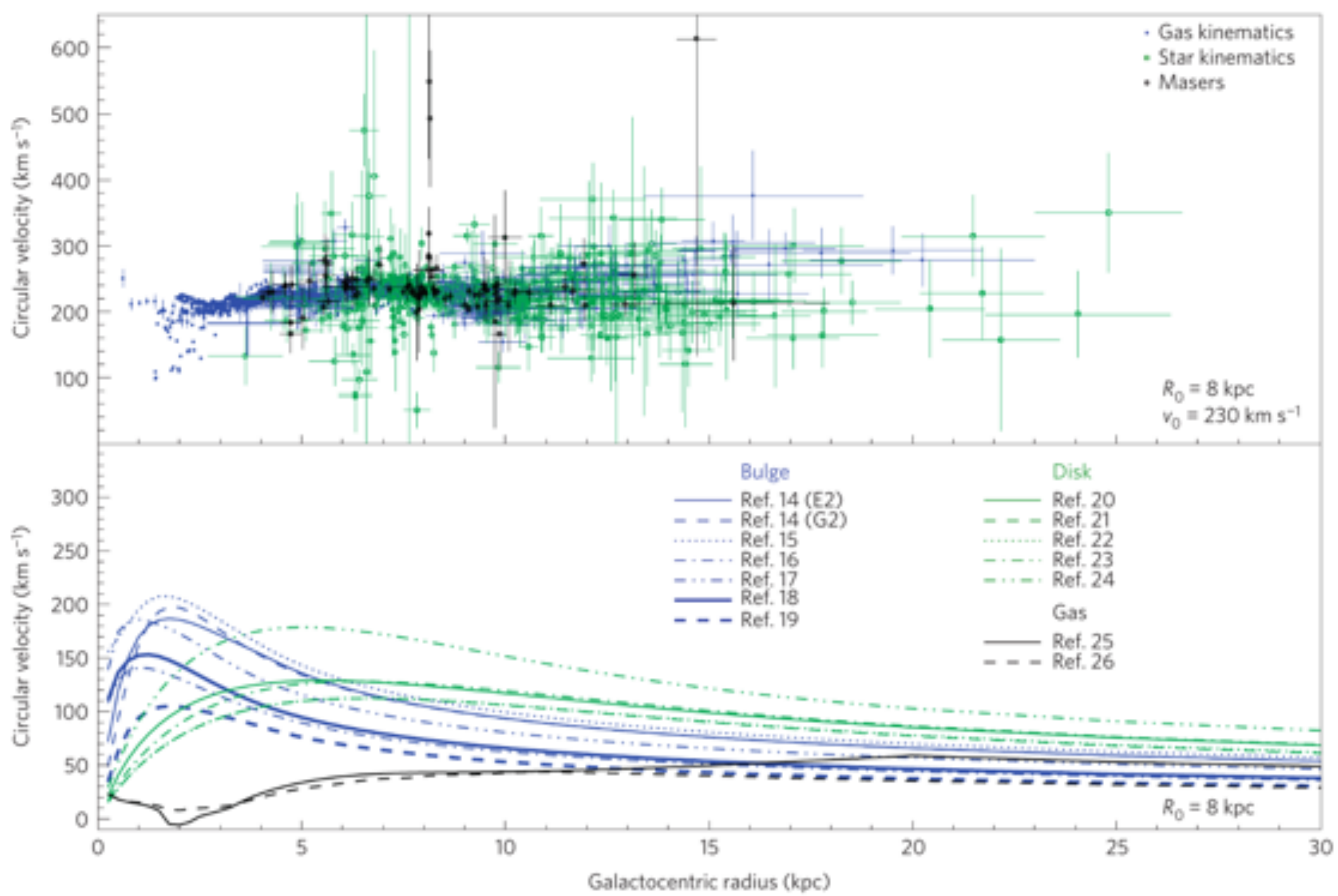


Figure 1 | The rotation curve of the Milky Way. In the top panel we show our compilation of rotation curve measurements as a function of Galactocentric radius, including data from gas kinematics (blue dots; HI terminal velocities, CO terminal velocities, HI thickness, HII regions, giant molecular clouds), star kinematics (open green squares; open clusters, planetary nebulae, classical cepheids, carbon stars) and masers (open black circles). Error bars correspond to 1σ uncertainties. The bottom panel shows the contribution to the rotation curve as predicted from different models for the stellar bulge (blue), stellar disk (green) and gas (black). We assume a distance to the Galactic Centre $R_0 = 8$ kpc in both panels, and a local circular velocity $v_0 = 230$ km s^{-1} in the top panel.

Fabio Iocco, Miguel Pato & Gianfranco Bertone (15 Feb. 2015)

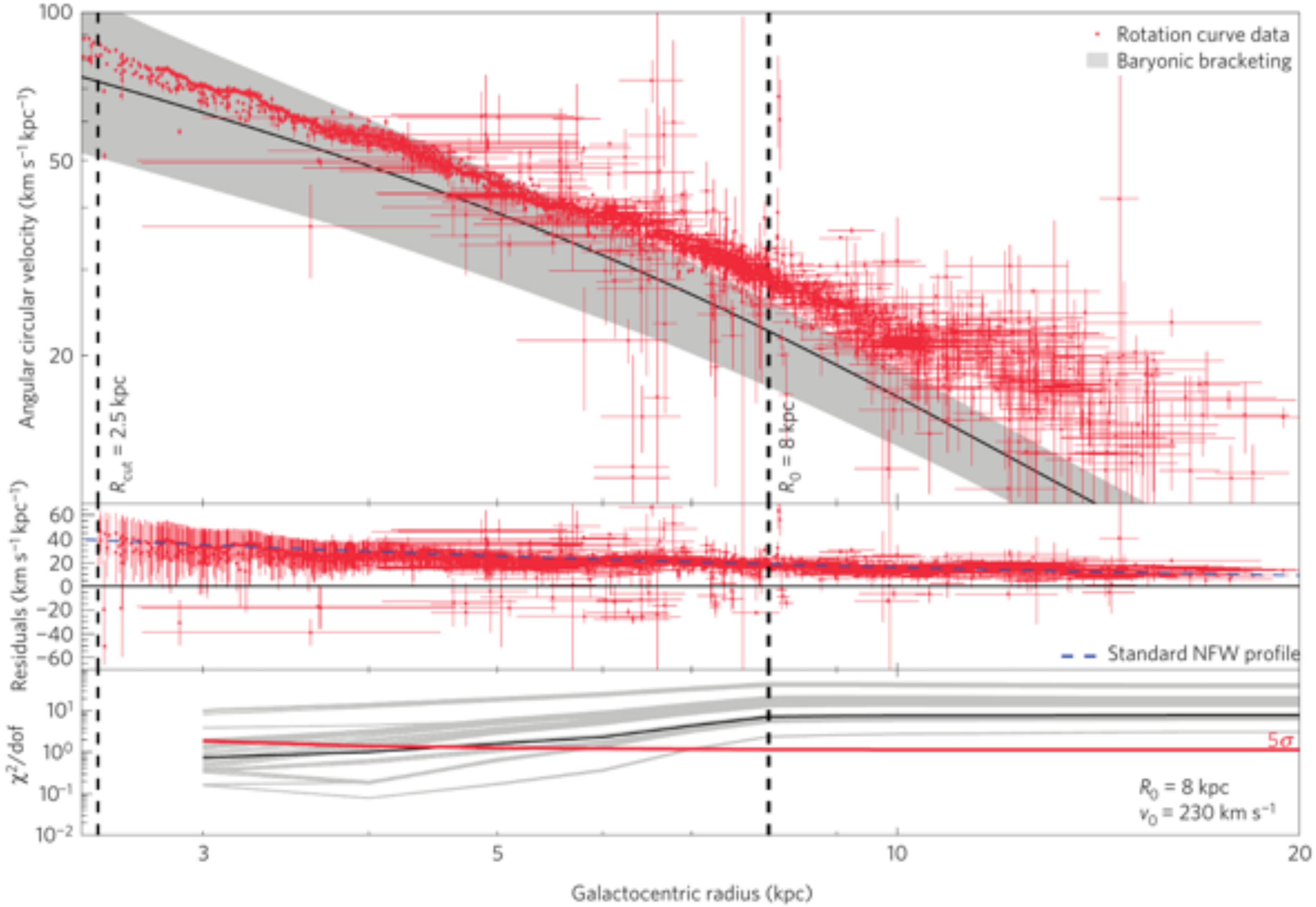
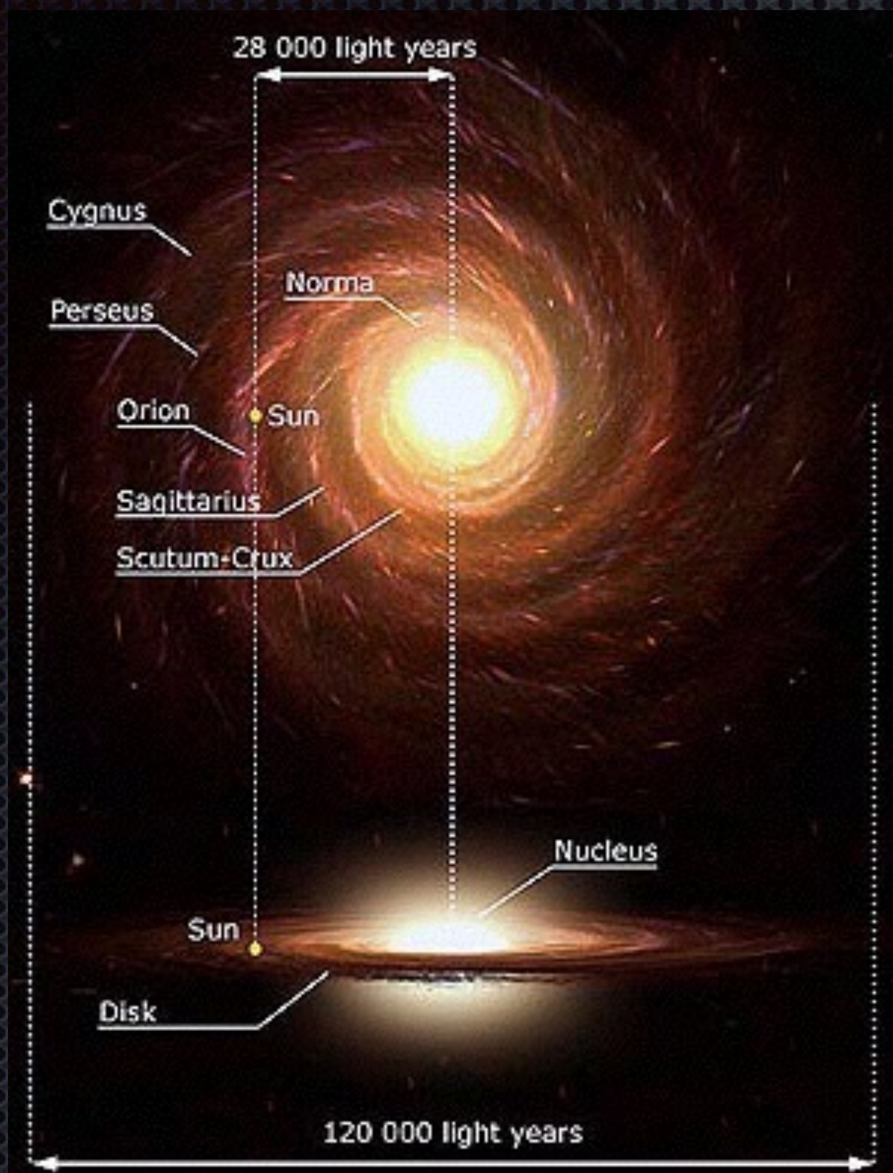
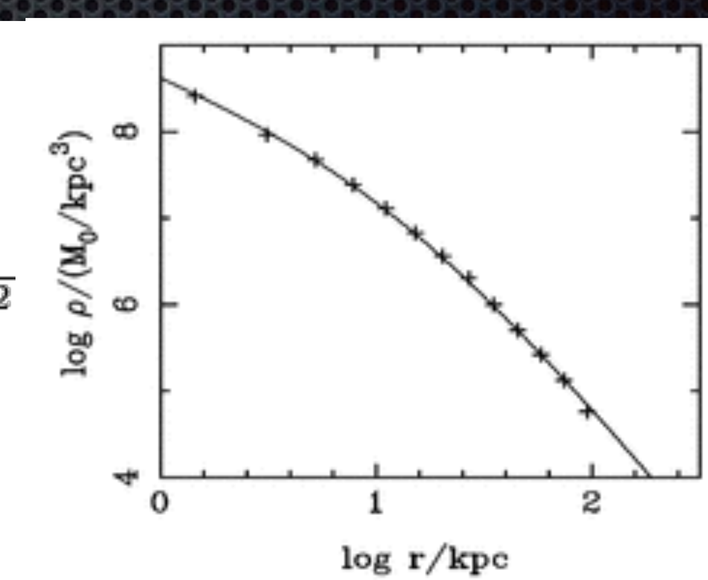


Figure 2 | Evidence for dark matter. In the top panel we show the angular velocity measurements from the compilation shown in Fig. 1 (red dots) together with the bracketing of the contribution of all baryonic models (grey band) as a function of Galactocentric radius. Error bars correspond to 1σ uncertainties, and the grey band shows the envelope of all baryonic models including 1σ uncertainties. The contribution of a fiducial baryonic model is marked with the black line. The residuals $(\omega_c^2 - \omega_b^2)^{1/2}$ between observed and predicted angular velocities for this baryonic model are shown in the central panel. The blue dashed line shows the contribution of a Navarro-Frenk-White profile with scale radius of 20 kpc normalized to a local dark matter density of 0.4 GeV cm^{-3}. The bottom panel shows the cumulative reduced χ^2 for each baryonic model as a function of Galactocentric radius. The black line shows the case of the fiducial model plotted in black in the top panel, and the thick red line represents the reduced χ^2 corresponding to 5σ significance. In this figure we assume a distance to the Galactic Centre $R_0 = 8$ kpc and a local circular velocity $v_0 = 230$ km s^{-1}, and we ignore all measurements below $R_{cut} = 2.5$ kpc.

$\rho_{DM,Sun} \approx 0.4$ GeV/cm^3 $\quad$ $v_{Sun} \approx 230$ km/s



$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$



Conclusion 1

Dark Matter/Standard Matter=1 in our galaxy;

=5 in clusters

in clusters $\rho \approx 6\ 10^{-28}$ g/cm^3=400 GeV c^{-2} m^{-3}

Locally $\rho_{DM} \approx 6\ 10^{-25}$ g/cm^{3}=0.4 10^6 GeV c^{-2} m^{-3}

NB: Solar system

Planet motion => density$<1.4\ 10^{-20}$ g/cm^3

(N. P. Pitjev, E. V. Pitjeva, http://arxiv.org/abs/1306.5534)

Plan

- Direct evidence
- **Possible causes**
  - **MACHOS**
  - **Gravity**
  - **WIMPS -> ΛCDM**
- Searches
- How to build a model

Blame astrophysics

Massive Astrophysical Compact Halo Object (MACHO)

Microlensing studies by several groups: rules out more than 20% for $2\ 10^{22}$ kg (0.3 lunar masses) < M < to $2\ 10^{32}$ (100 solar masses)

- red dwarfs, white dwarfs: no (Hubble NICMOS)
- brown dwarfs, asteroids…

Primordial black holes: 10^{17} kg<m<10^{22} kg
(Primordial Black Holes: sirens of the early Universe, Anne M. Green
http://arxiv.org/pdf/1403.1198.pdf)

Caveat

- MACHO collaboration: less than 20% of matter is from compact objects (15 microlensing events observed)
- OGLE, EROS: limit is even lower
- New paper in A&A 575, A107 (2015): "A new look at microlensing limits on dark matter in the Galactic halo," M. R. S. Hawkins. "*an all-MACHO halo can no longer be ruled out with any confidence*"

Blame gravity

- Modified Newtonian dynamics (MOND), Milgrom 83

& Tensor–vector–scalar gravity (TeVeS), Bekenstein 2004

$$\vec{F} = m\vec{a} \rightarrow \vec{F} = mf(\frac{a}{a_0})\vec{a}$$

$a\ large: \ f \rightarrow 1$

$a\ small: \ f \rightarrow \frac{a}{a_0}$

Rotation

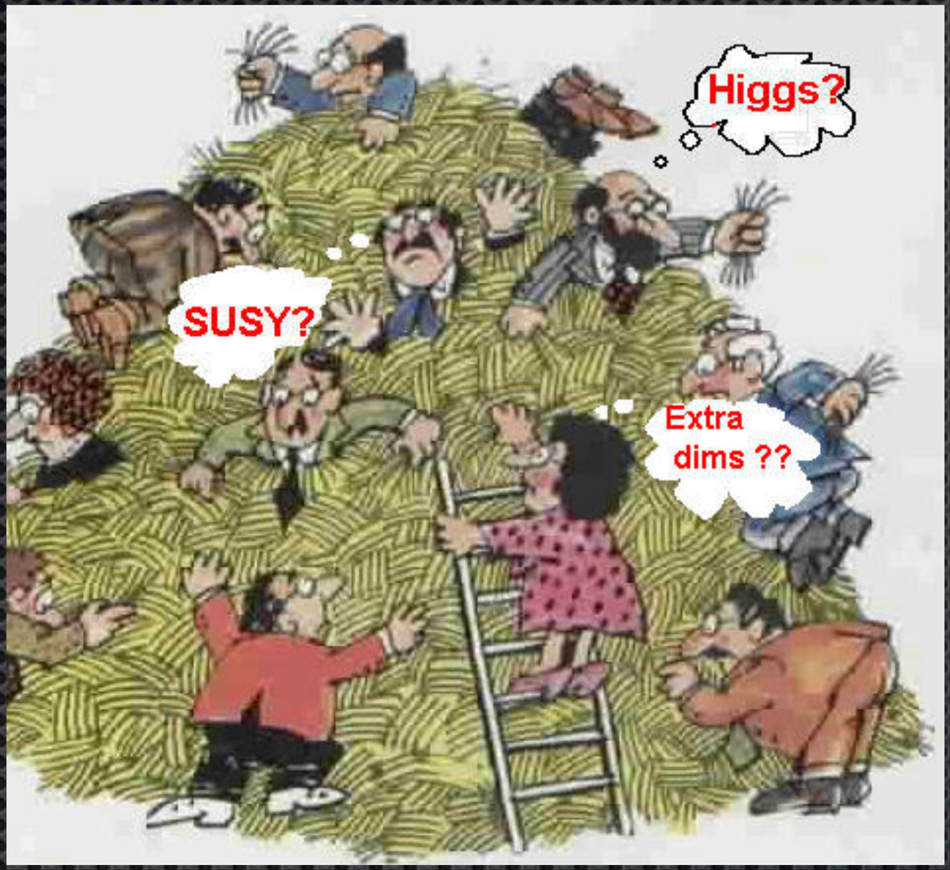
$$\frac{v^2}{r} f(\frac{v^2}{a_0 r}) = \frac{GM}{r^2}$$

$$\frac{v^4}{a_0} = GM$$ at large r (small a)

TeVeS (or MOND)

- does not explain galaxy clusters (need *some* dark matter)
- does not explain bullet cluster
- does not explain dark-matter poor ellipsoidal galaxies

Blame particle physics



- Nobody thinks the Standard model is complete
- Many possibilities

Musket Ball cluster

Dawson, W. et al, 2012, ApJ 747, 42; arXiv:1110.4391

Dark matter has a small self-interaction probability:

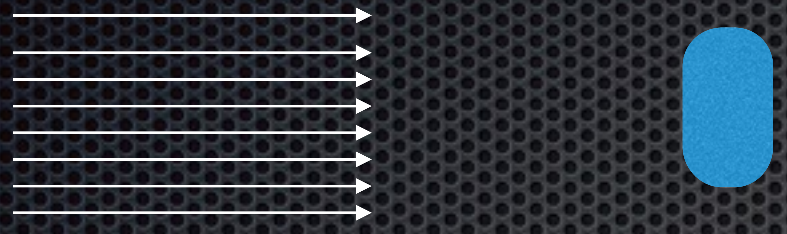
$\sigma/m_{DM} < 1\ \mathrm{cm}^2/\mathrm{g} = 1.8\times10^{-21}\ \mathrm{cm}^2/\mathrm{TeV} = 1.8\ \mathrm{kb/TeV}$

⇒spherical halo

+no pressure

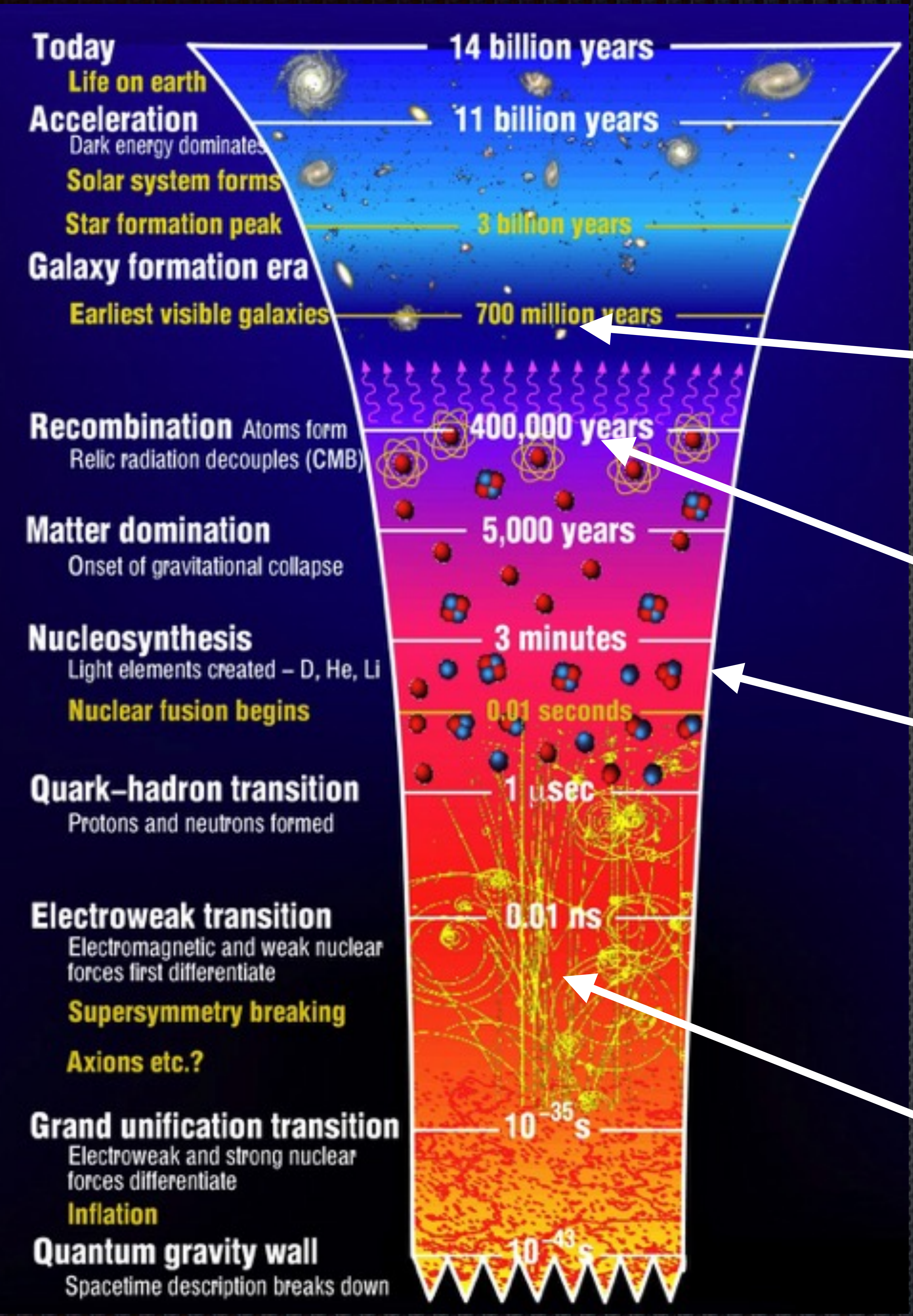
WIMP=Weakly Interacting Massive Particle

Note on cross sections



- Number of events/s $$\frac{dN}{dt} = \Phi_{in} \times N_{target} \times \sigma$$ $$= \rho_{in} N_{target} \times (\sigma v)$$

Cosmology



Structure formation

Cosmic Microwave Background

Big Bang Nucleosynthesis

Abundance of thermal DM

NB: axions & black holes are different

Abundance: the WIMP miracle

$$\frac{M_{DM}}{T_{f.o.}} \in [20, 50]$$

$$< \sigma v >= 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

$$M_{DM} \leq 100 \mathrm{TeV}$$

Works for typical electroweak cross sections with masses of 100-1000 GeV

Big Bang Nucleosynthesis

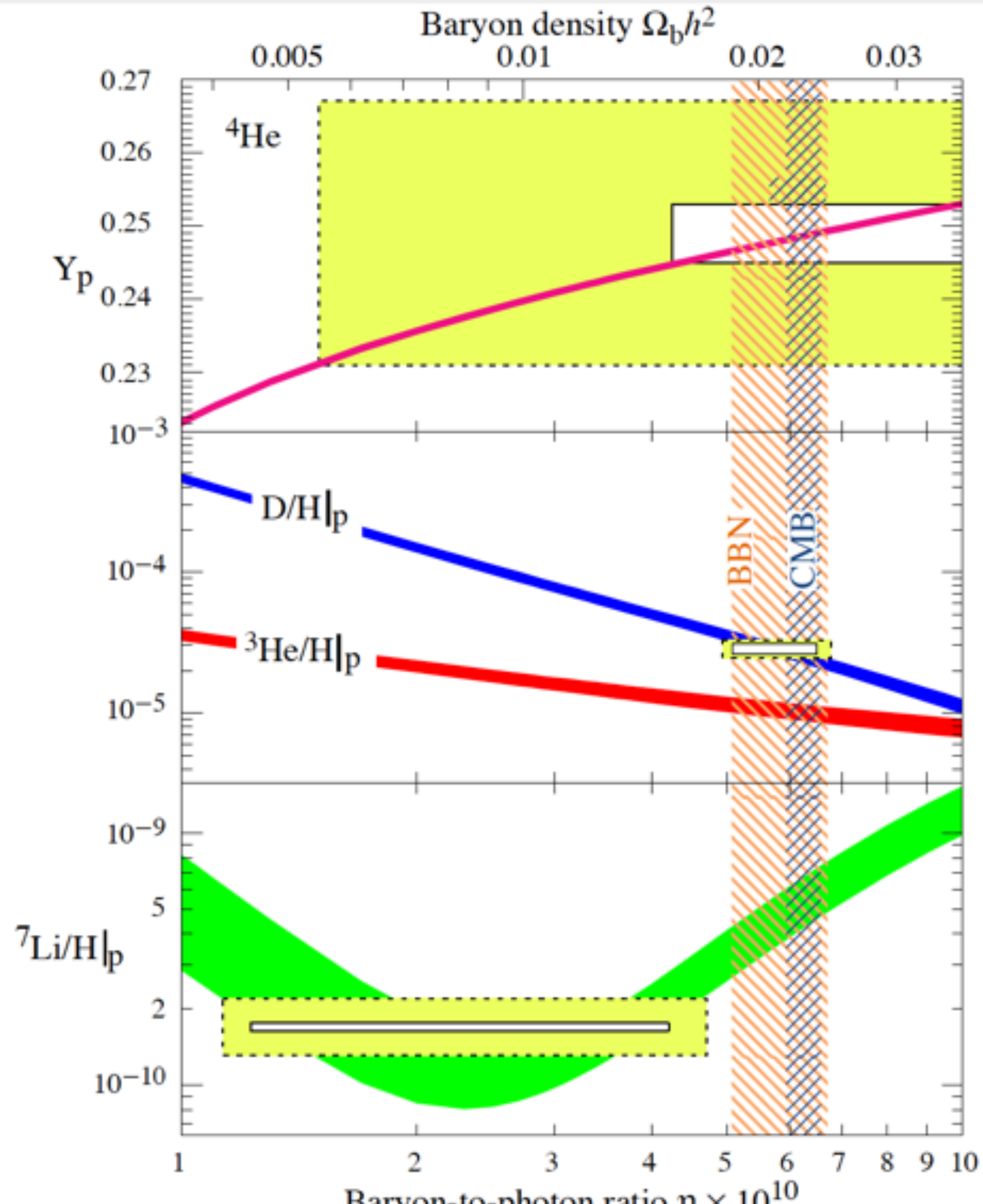


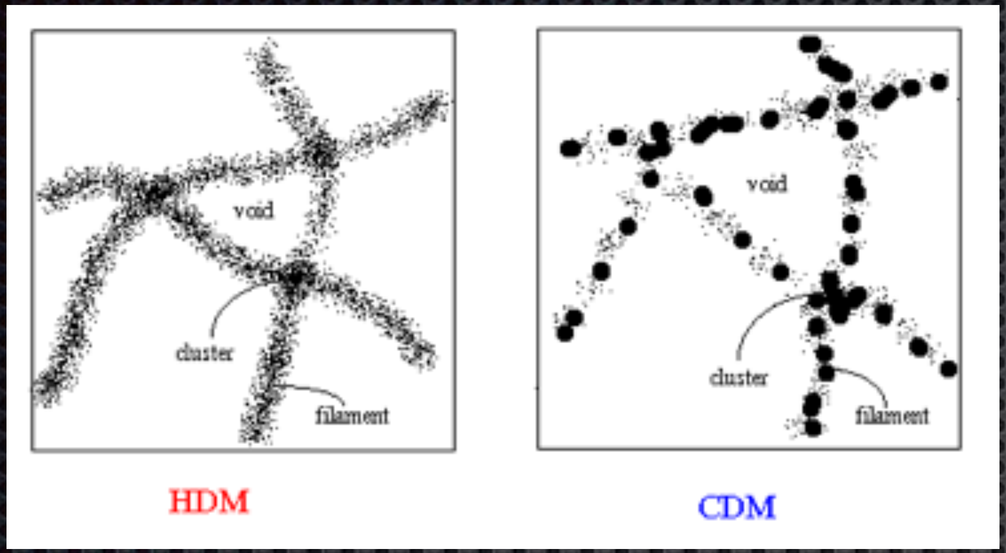
Figure 22.1: The abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis [14] – the bands show the 95% CL range. Boxes indicate the observed light element abundances (smaller boxes: $\pm 2\sigma$ statistical errors; larger boxes: $\pm 2\sigma$ statistical *and* systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN concordance range (both at 95% CL).

Review of Particle properties 2012

Provides the baryon abundance of the Universe 0.23 GeV c^{-2} m^{-3}

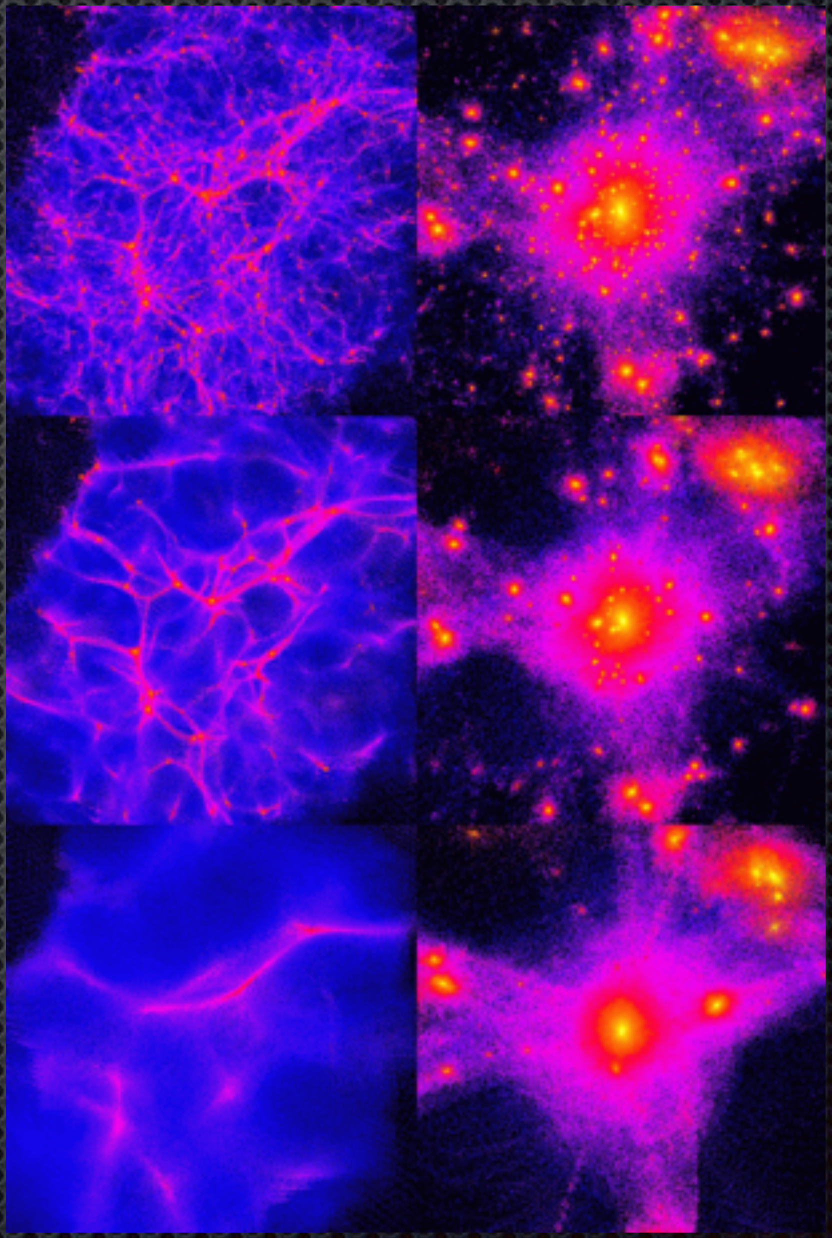
+ DM is non baryonic

Large Scale Structures



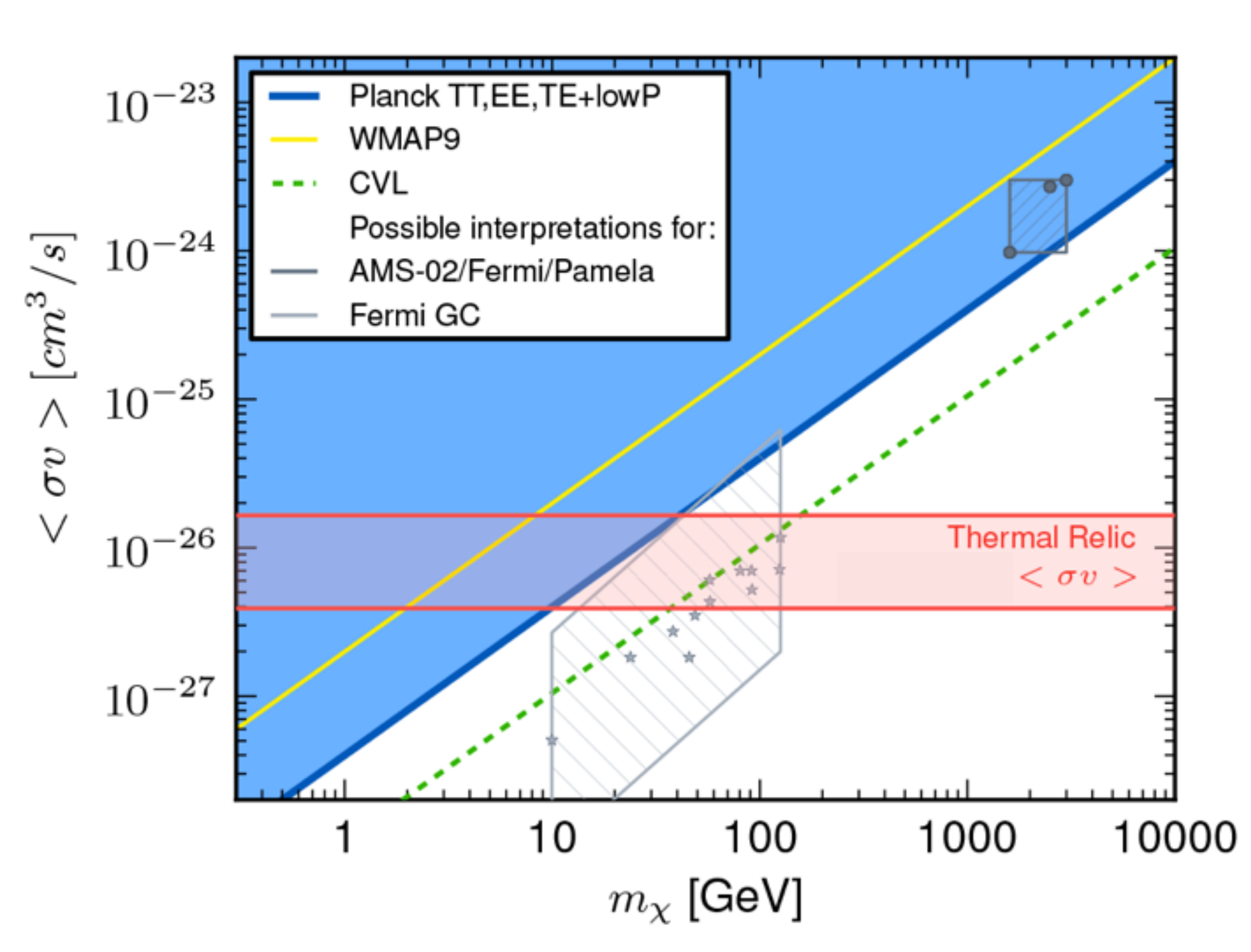
v<<<<c at freeze-out

v≈mm/s



From top: Cold, Warm, and Hot dark matter simulations, credit ITP, University of Zurich.

Cosmic Microwave Background



Densities in the Universe

- dark matter: $1.3\ \mathrm{GeV}\ c^{-2}\ m^{-3}$
- protons&neutrons: $0.23\ \mathrm{GeV}\ c^{-2}\ m^{-3}$
- neutrinos: $0.026\ \mathrm{GeV}\ m^{-3}$
- photons: $0.00025\ \mathrm{GeV}\ m^{-3}$

Dark Matter/Standard Matter=1 in our galaxy; 5 in clusters, 5.6 overall

M>10 GeV

Standard Model Candidate

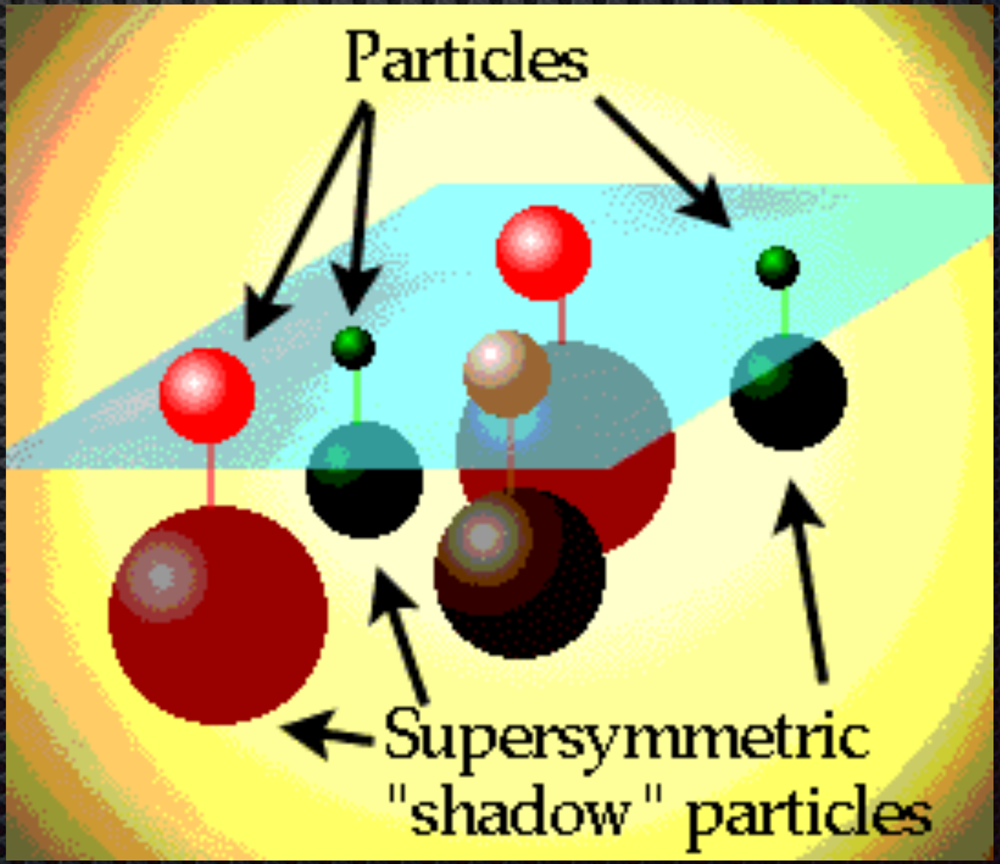
Neutrino

- Dark! No bare electric charge
- Stable or very very long-lived
- Associated with matter (as abundances are similar)
- Small self-interactions
- Created before Big Bang Nucleosynthesis
- Non relativistic (heavy)
- Right abundance

No other candidate

Canonical candidate: LSP

- Superstring theory needs supersymmetry
- To avoid proton decay limits, one must produce the susy particles in pairs (R parity)
- The lightest susy particle is stable



Conclusion 2: Identity card of dark matter

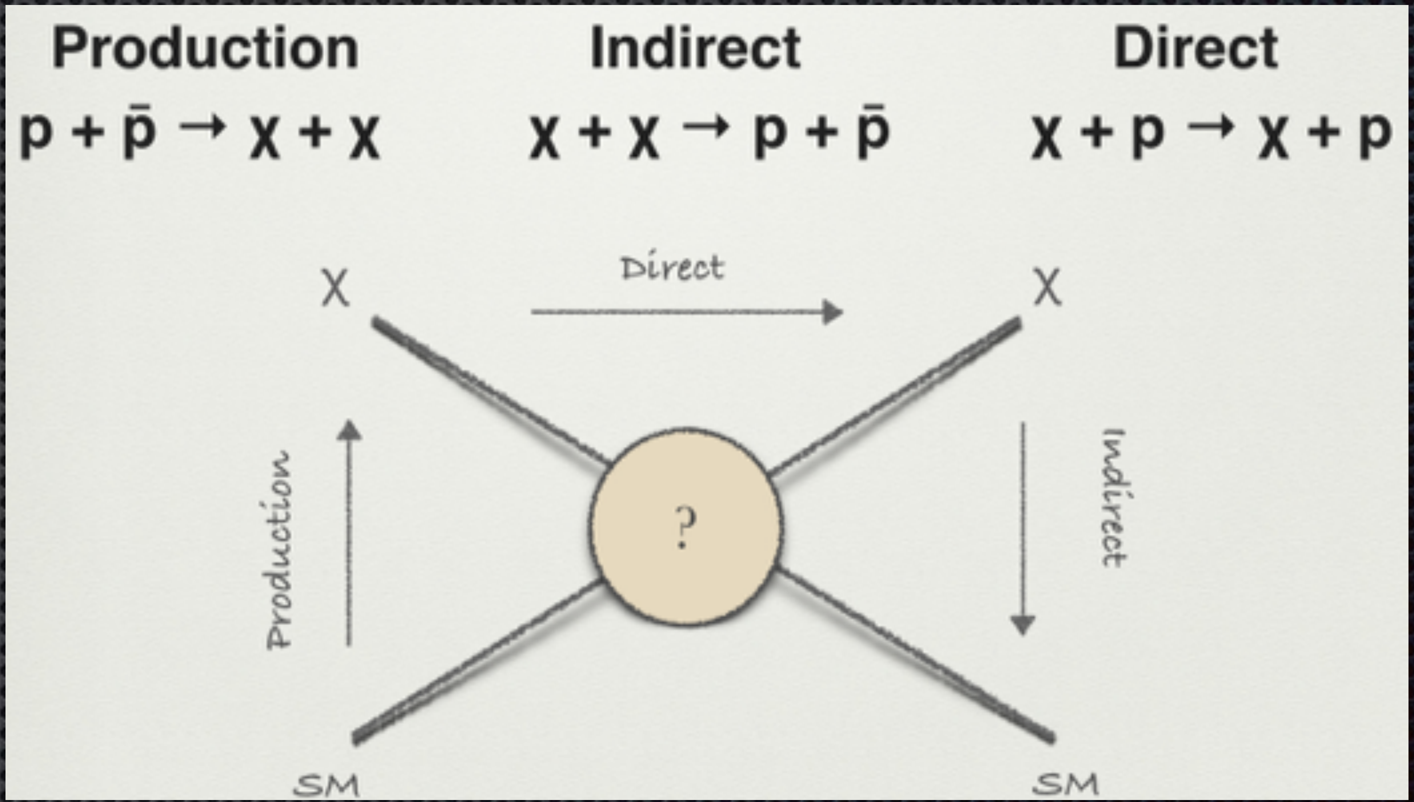
- Dark! No bare electric charge: composite or neutral
- Stable or very very long-lived: new quantum number/symmetry
- Associated with matter (as abundances are similar): weakly coupled to normal matter
- Frozen out before Big Bang Nucleosynthesis: 10 MeV < M
- Non relativistic (heavy): 10 GeV < M <100 TeV
- “Small” self-interactions: (nuclear 0K: 100 b to 10 kb)
- Right abundance: $< \sigma v >= 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$

Plan

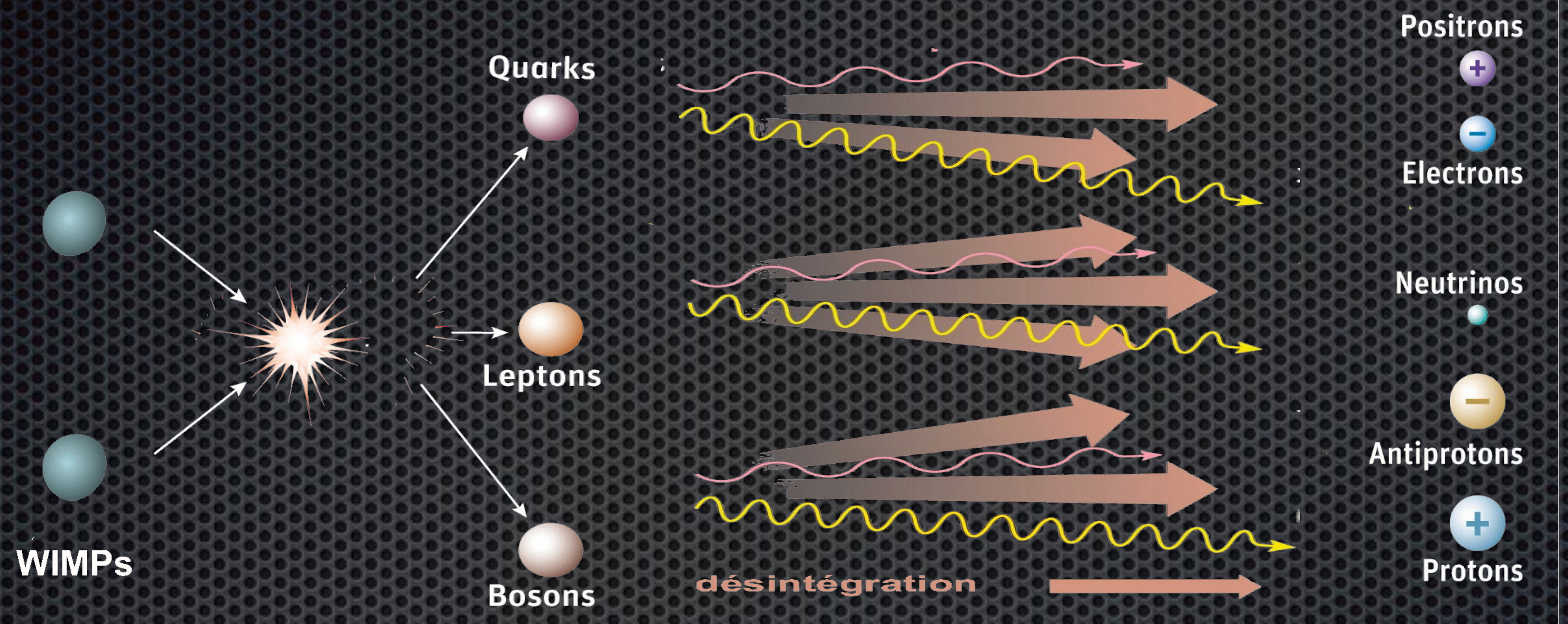
- Direct evidence
- Possible causes
- Searches
  - Indirect: cosmic rays, gamma rays
  - LHC
  - Direct: DAMA vs LUX
- How to build a model

Searches for Dark Matter

- Indirect detection
- Accelerator searches
- Direct searches

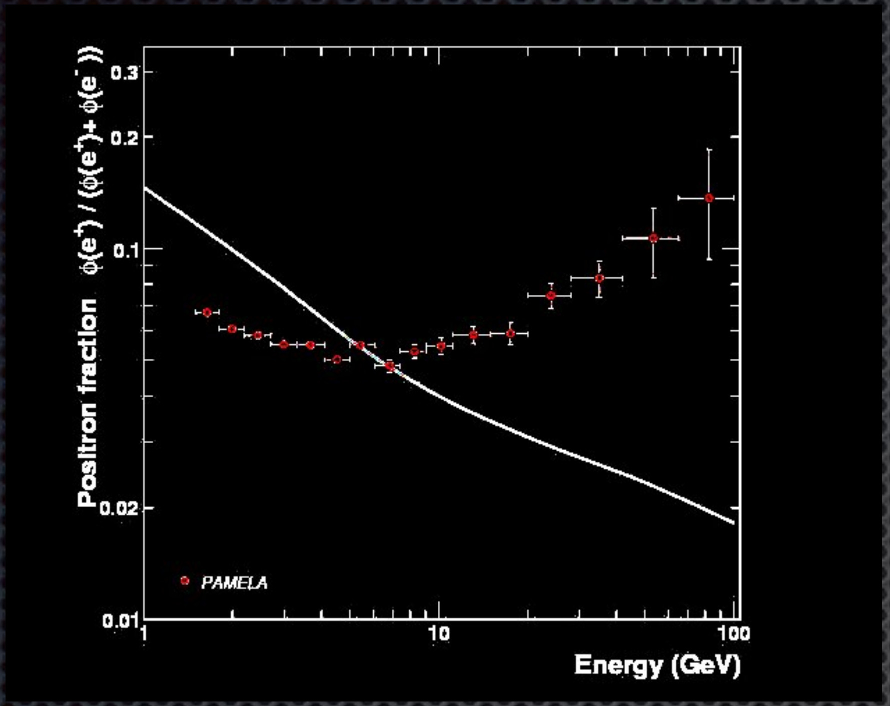


Indirect searches

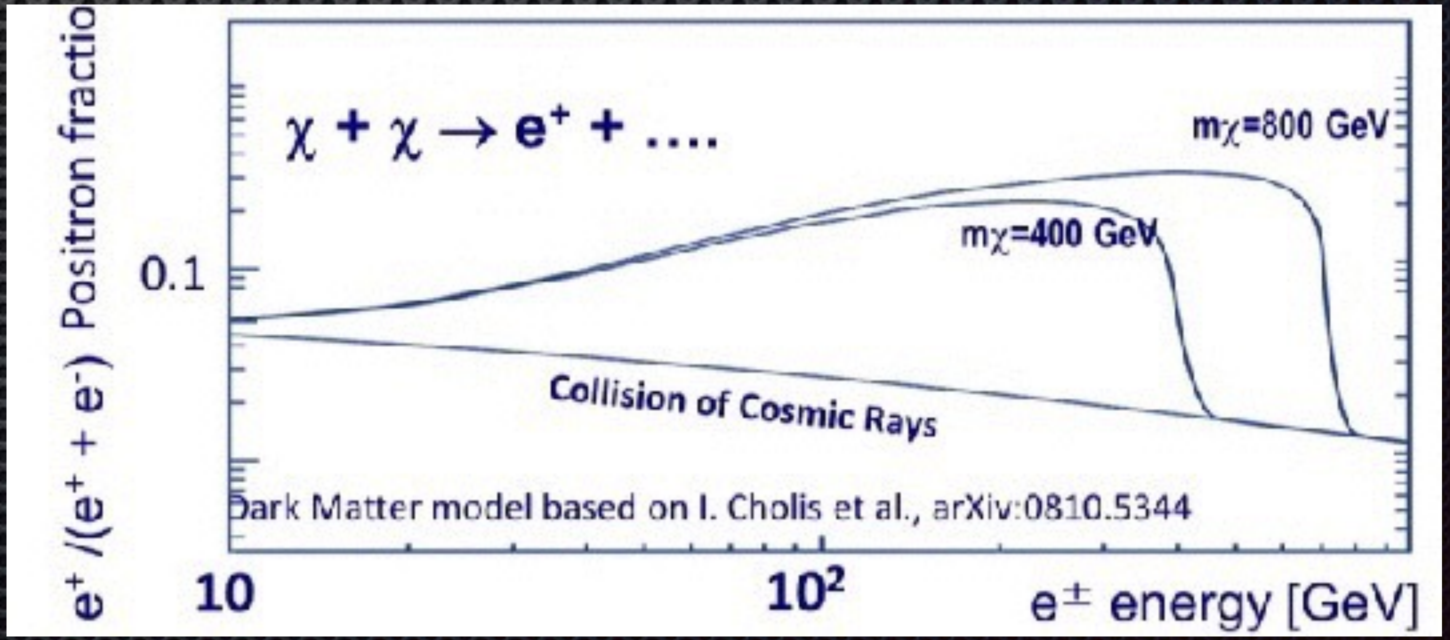


PAMELA: positron

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

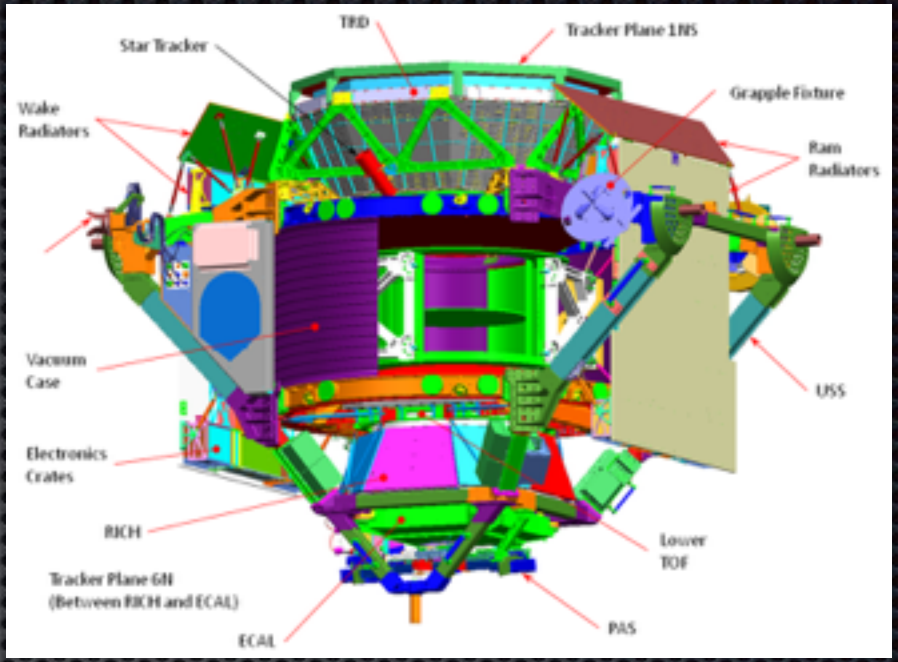


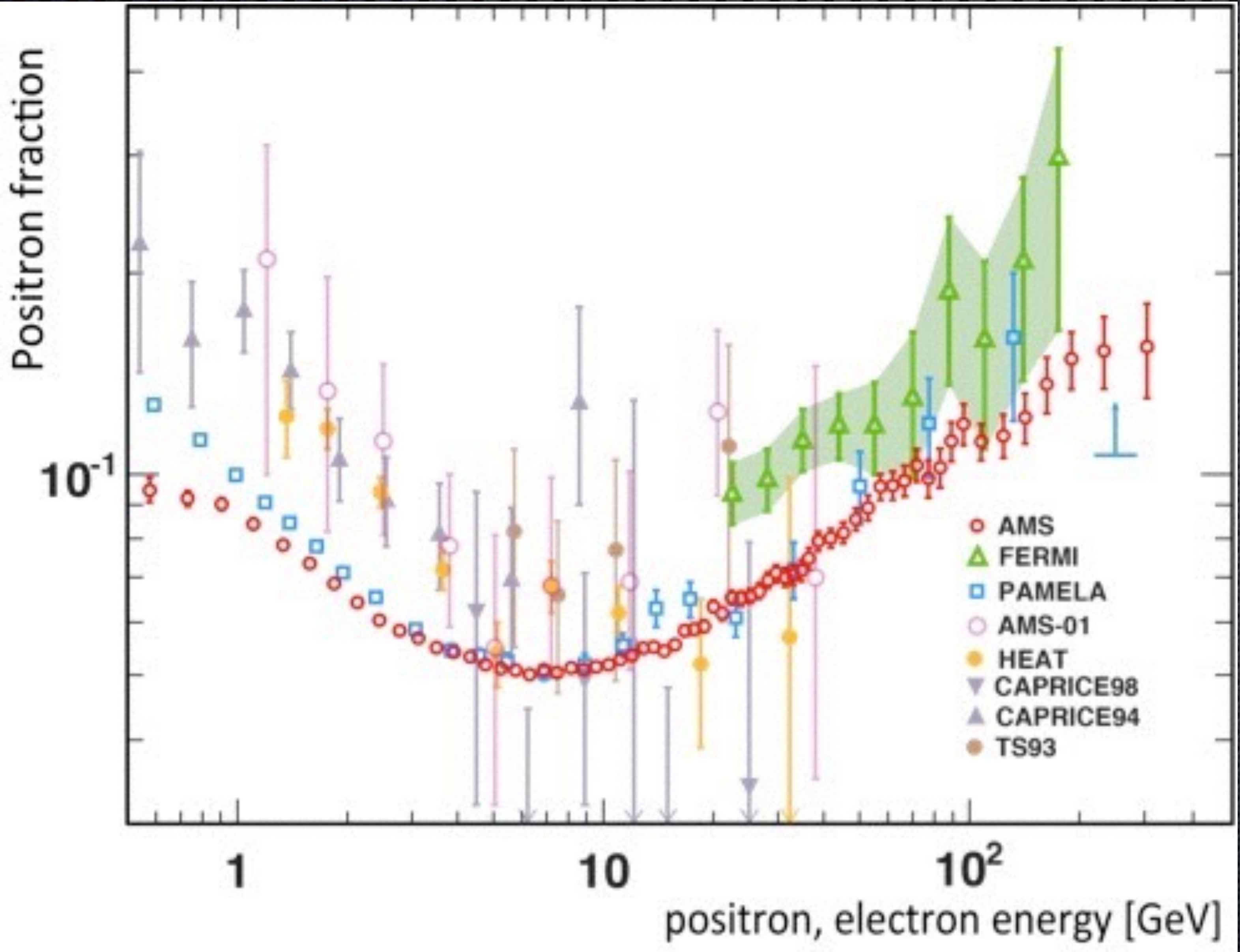
$$\chi\bar{\chi} \rightarrow e^{+}e^{-}$$



AMS-02

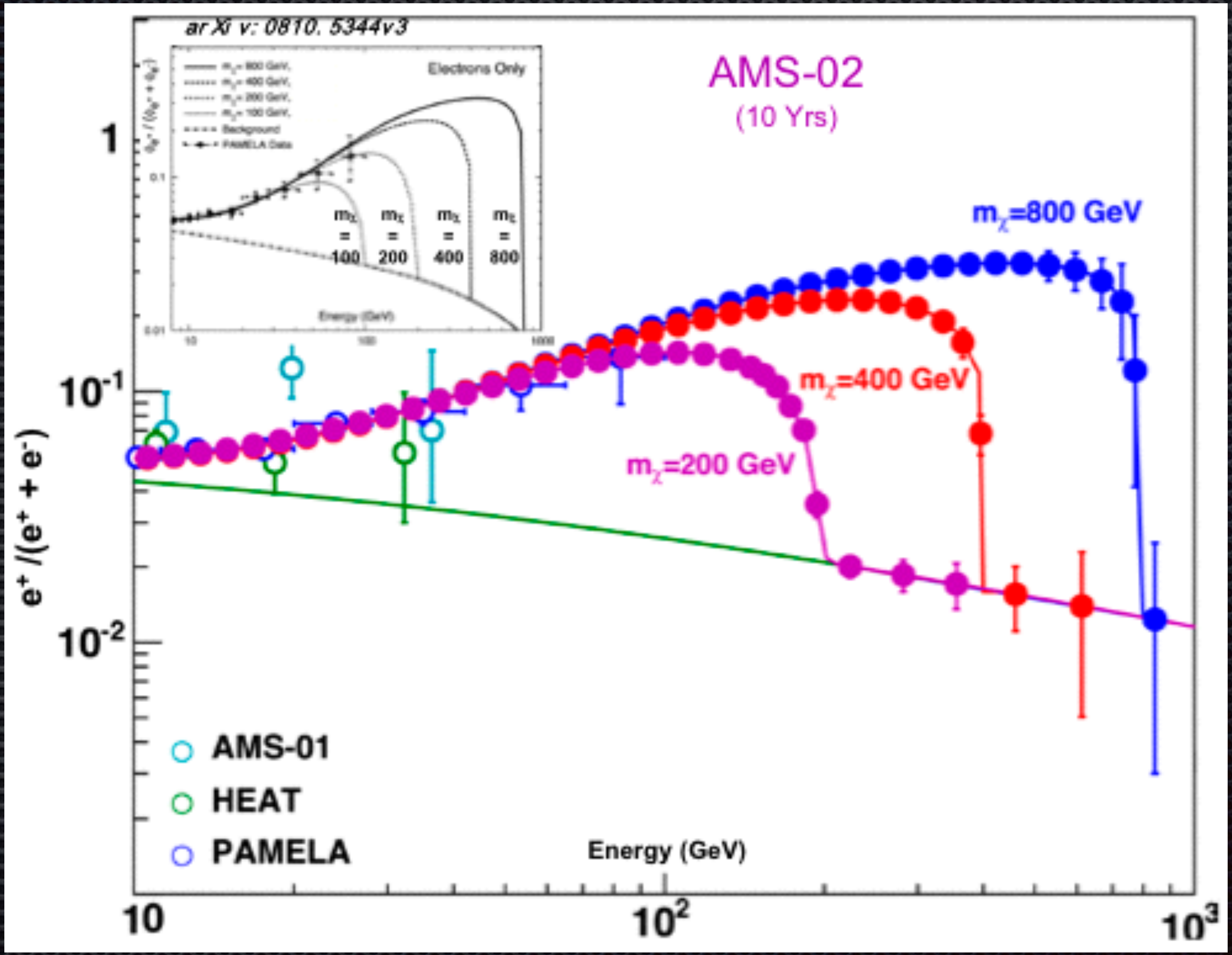
Alpha Magnetic Spectrometer



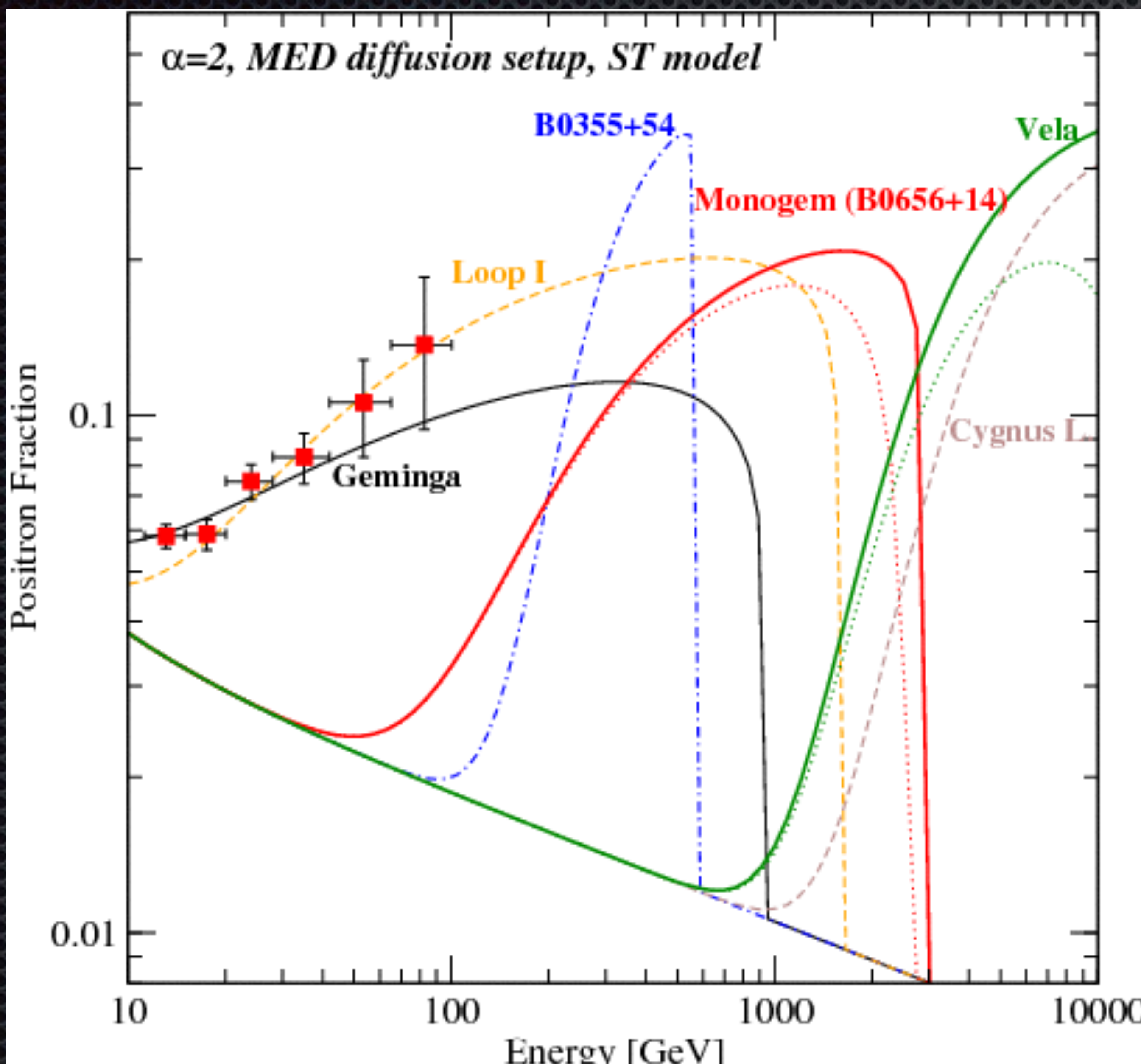


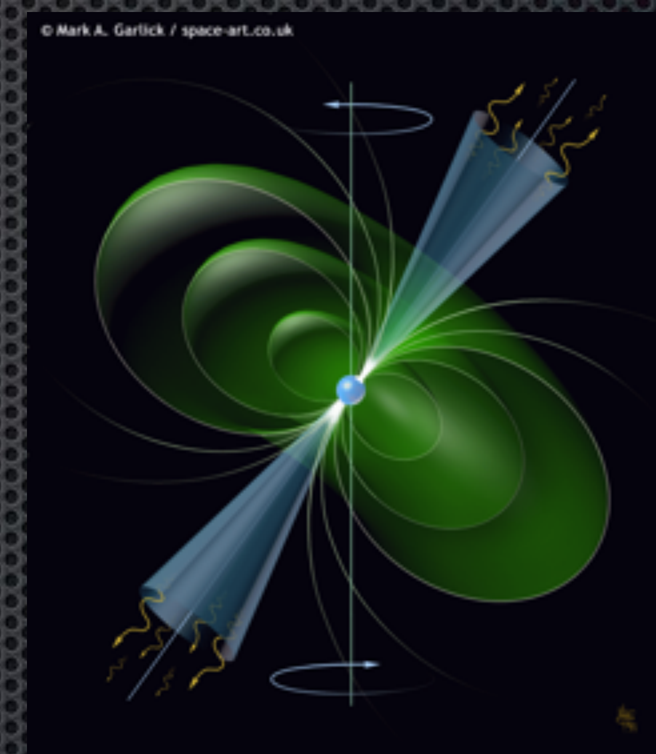
Signal confirmed

Can be explained by WIMPS->e^+e^-+…



Can be explained by pulsars

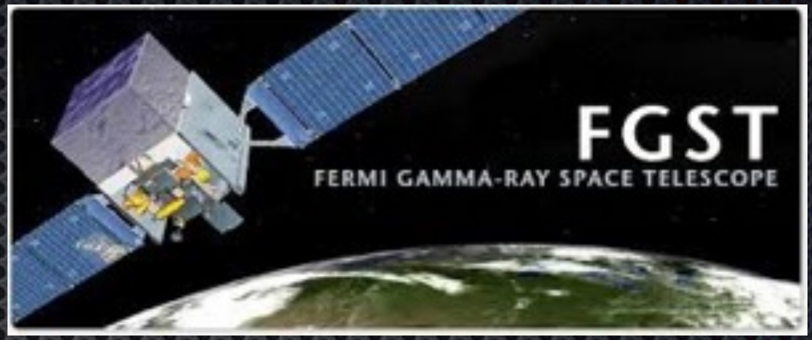


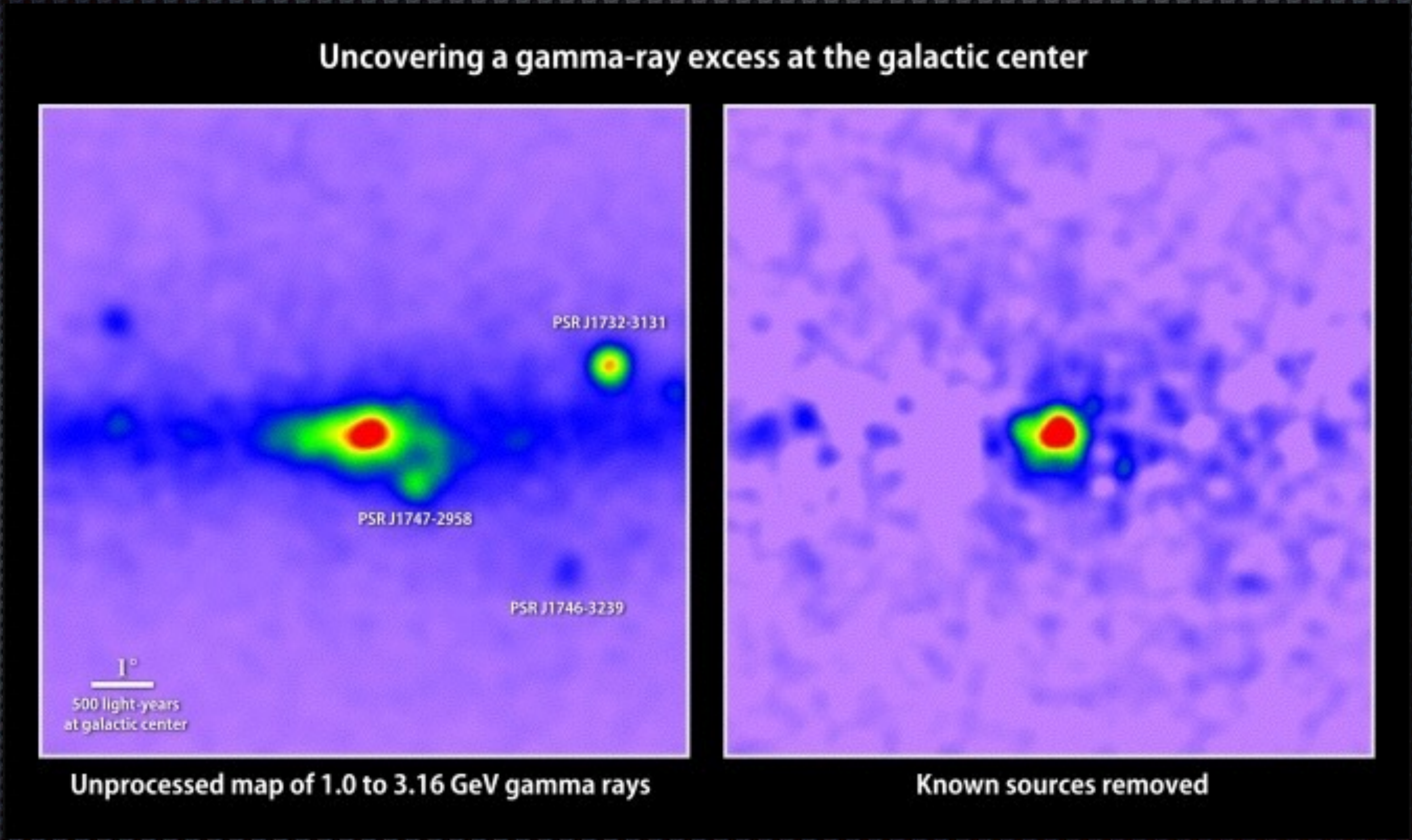


Uncertainties in models & propagation

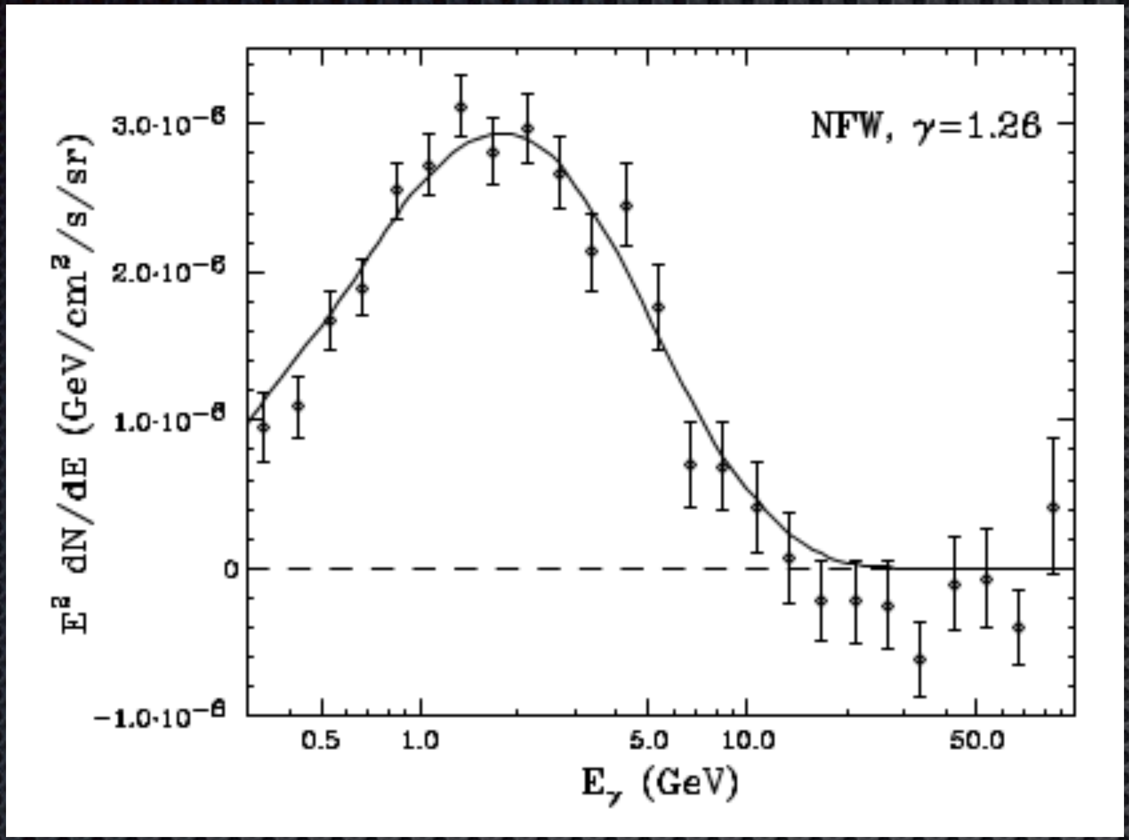
S. Profumo, "Dissecting cosmic-ray electron-positron data with Occam's Razor: the role of known Pulsars," Central Eur. J. Phys. 10 (2011) 1 [arXiv:0812.4457 [astro-ph]].

Fermi: γ rays from the galactic center





Can be explained by DM annihilation

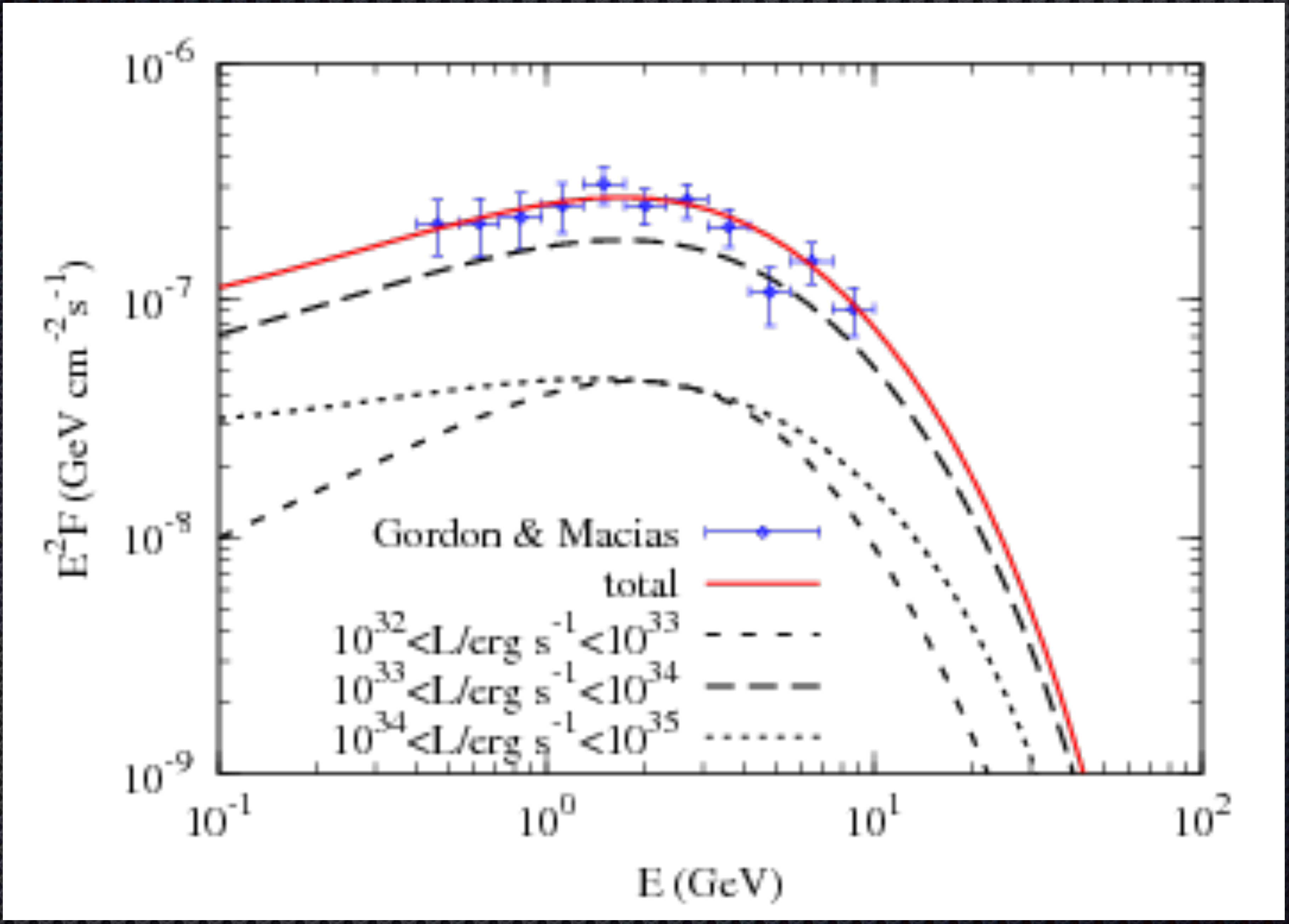


M= 31-40 GeV

Depends (a lot) on the unknown density of DM at the galactic center

T. Daylan, D.P. Finkbeiner, D. Hooper, T. Linden, S.K.N. Portillo, N.L. Rodd and T.R. Slatyer, "The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter," arXiv:1402.6703 [astro-ph.HE]; L. Goodenough and D. Hooper, "Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope," arXiv:0910.2998 [hep-ph].

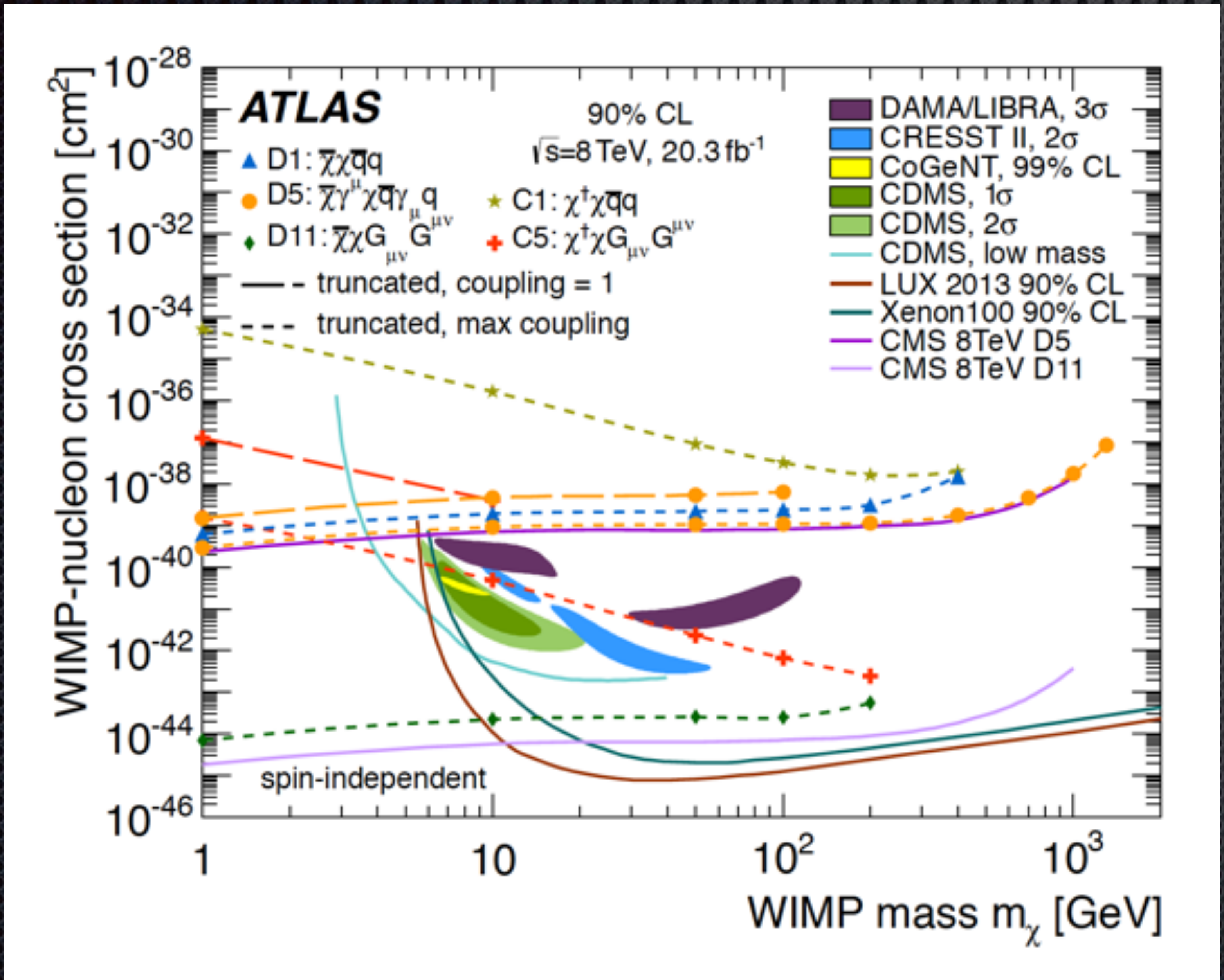
Or by pulsars…



Q. Yuan and B. Zhang, "Millisecond pulsar interpretation of the Galactic center gamma-ray excess," JHEAp 3-4 (2014) 1 [arXiv:1404.2318 [astro-ph.HE]].

Accelerator searches

$$pp \rightarrow \chi X \rightarrow X + \ \ missing\ energy$$



X=photon, jet, W or Z

The limits depend on the way DM couples to p

G. Aad et al. [ATLAS Collaboration], "Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at sqrt(s)=8 TeV with the ATLAS detector," arXiv:1502.01518 [hep-ex].

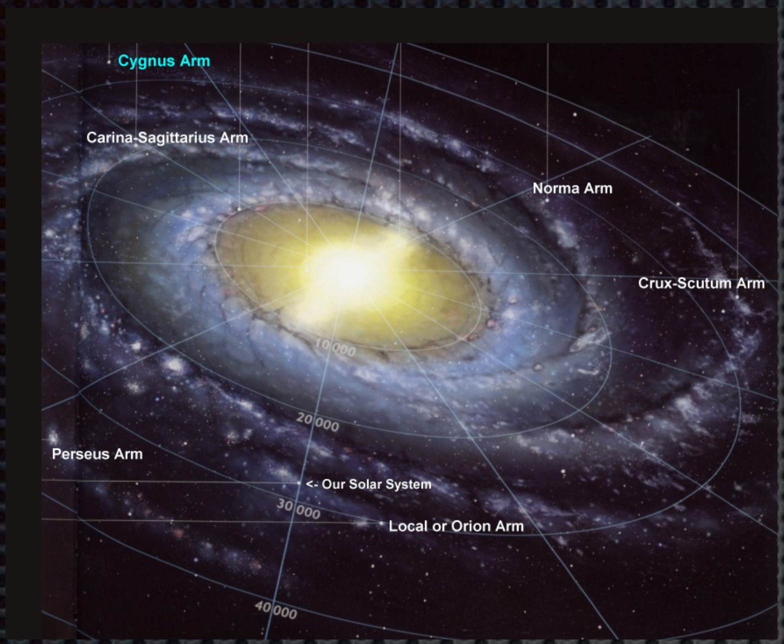
Direct searches

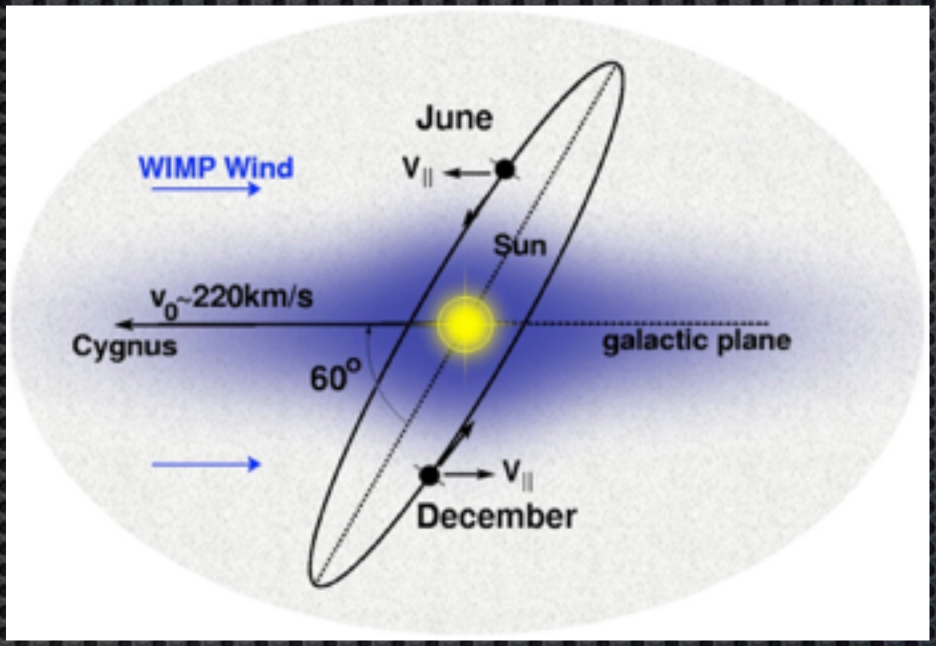
1. ANAIS
2. ArDM
3. ADMX
4. COUPP
5. CDEX / PANDA-X / TEXONO
6. **CoGeNT**
7. **CDMS**
8. CRESST
9. **DAMA/LIBRA**
10. DARWIN
11. DEAP
12. DarkSide
13. EDELWEISS
14. EURECA
15. UNK
16. KIMS
17. **LUX**
18. PICASSO
19. SIMPLE
20. XENON
21. XMASS

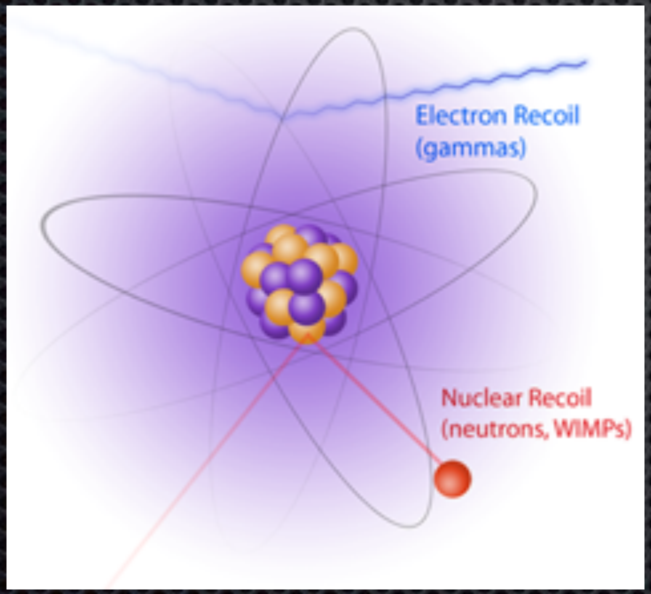
Detection!

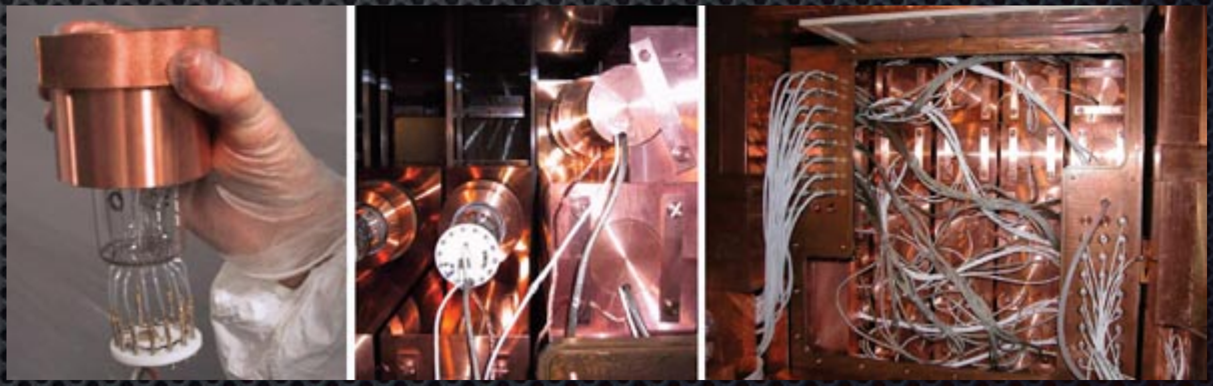
see http://www.interactions.org/cms/?pid=1034004

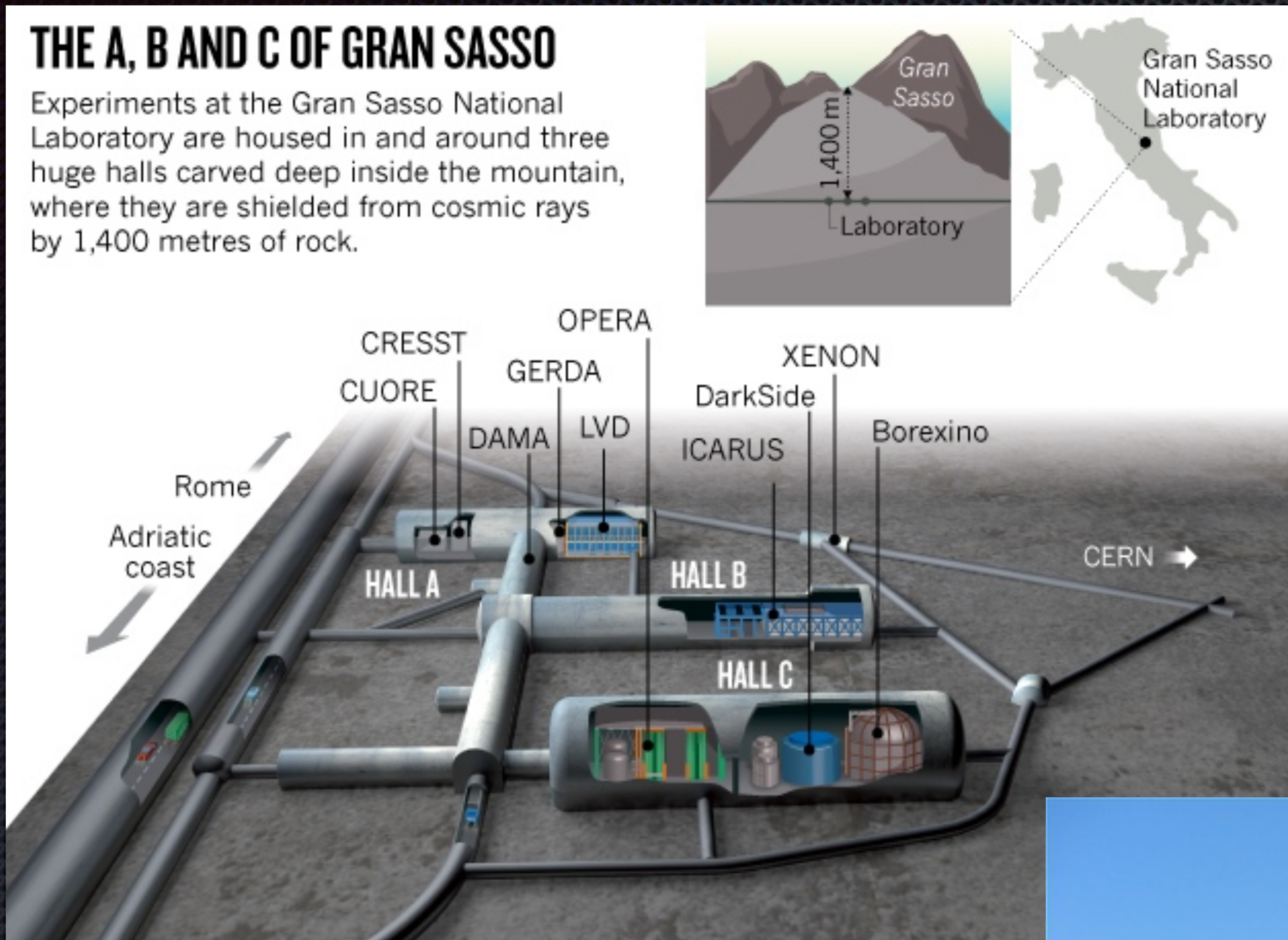
DArk MAtter

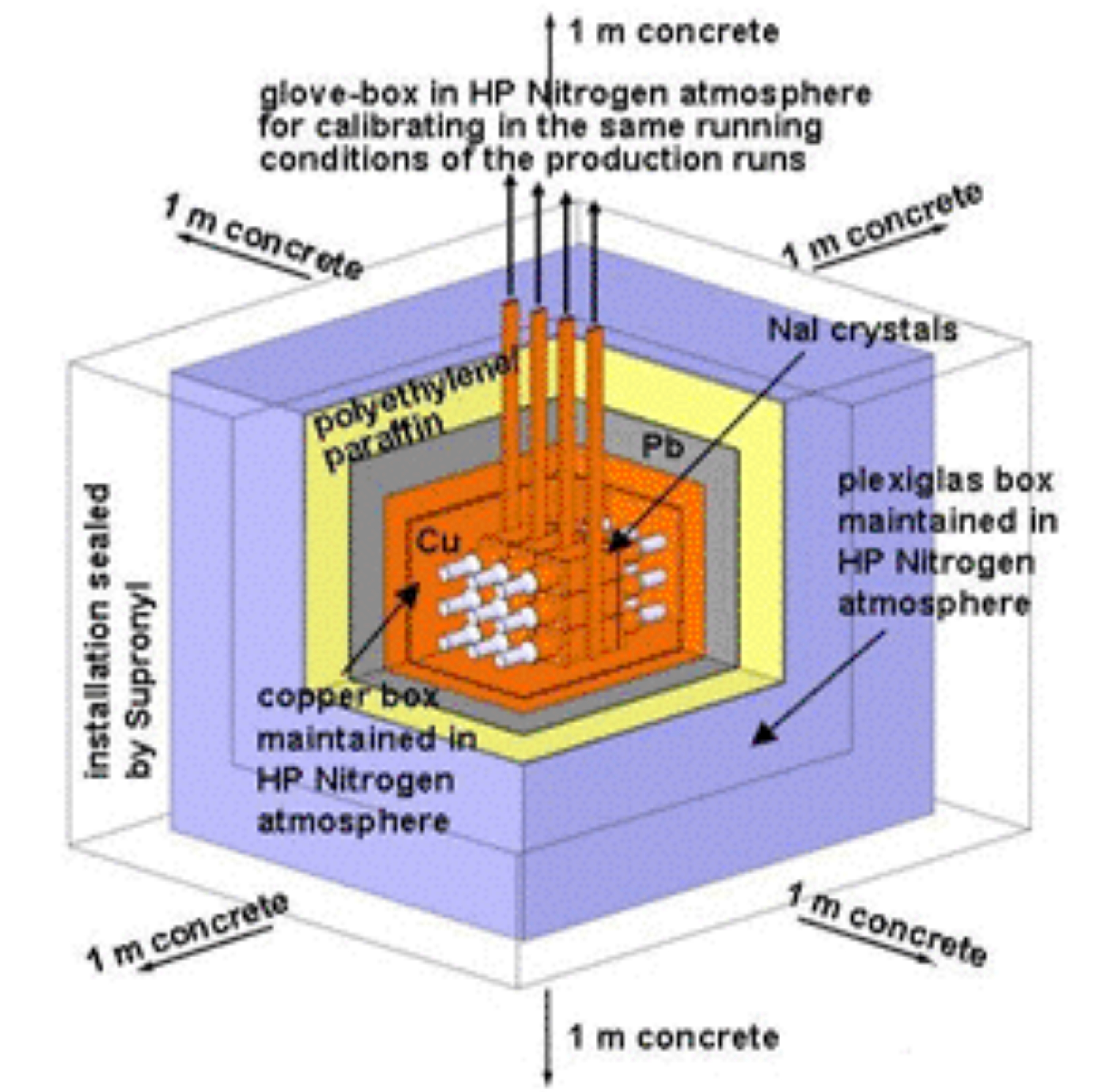

Cygnus Arm
Carina-Sagittarius Arm
Norma Arm
Crux-Scutum Arm
Perseus Arm
<- Our Solar System
Local or Orion Arm
10 000
20 000
30 000
40 000


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


Electron Recoil
(gammas)
Nuclear Recoil
(neutrons, WIMPs)

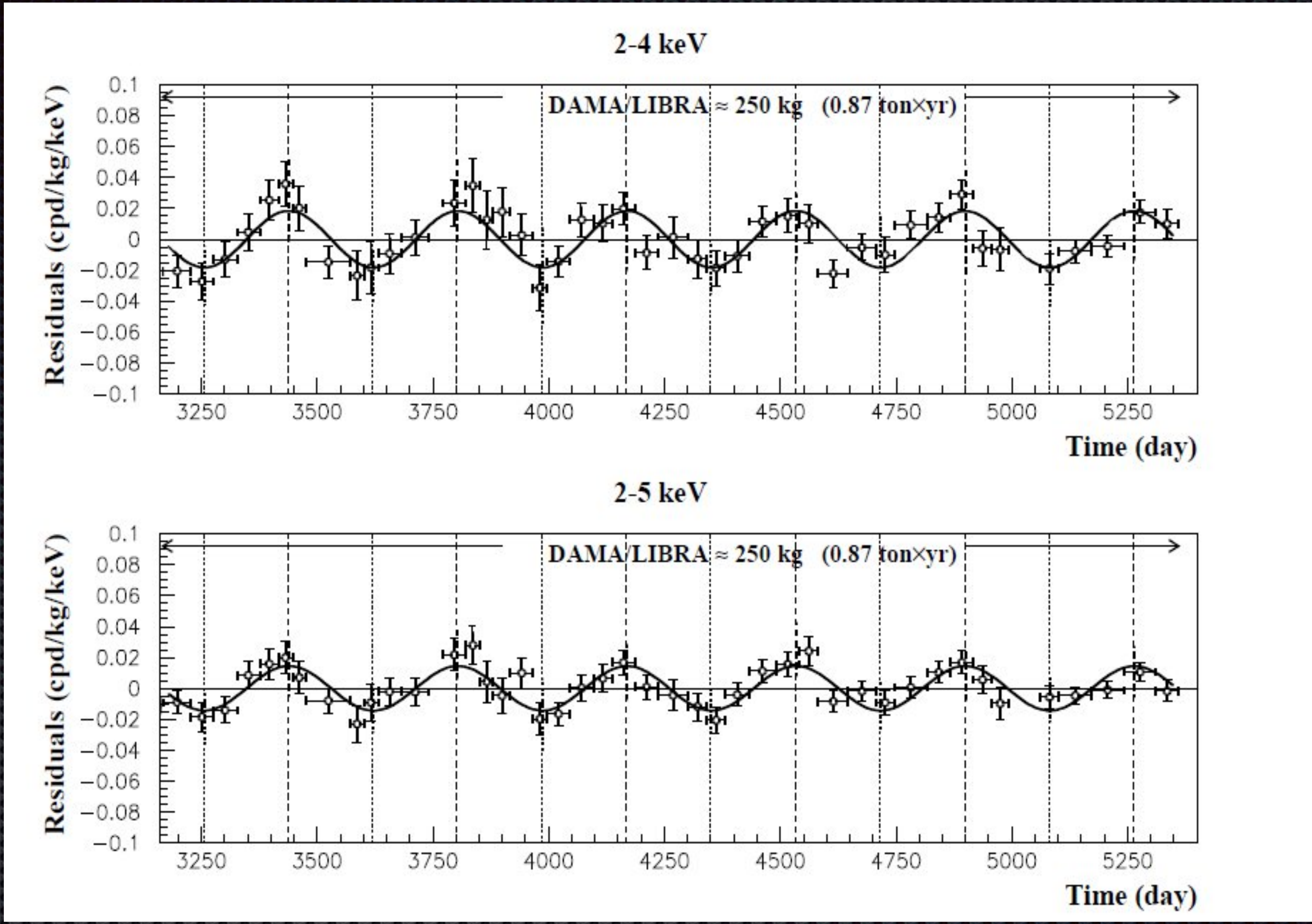



THE A, B AND C OF GRAN SASSO
Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.
Gran Sasso
1,400 m
Laboratory
Gran Sasso National Laboratory
OPERA
CRESST
GERDA
XENON
CUORE
DarkSide
DAMA
LVD
Borexino
ICARUS
Rome
Adriatic coast
HALL A
HALL B
HALL C
CERN



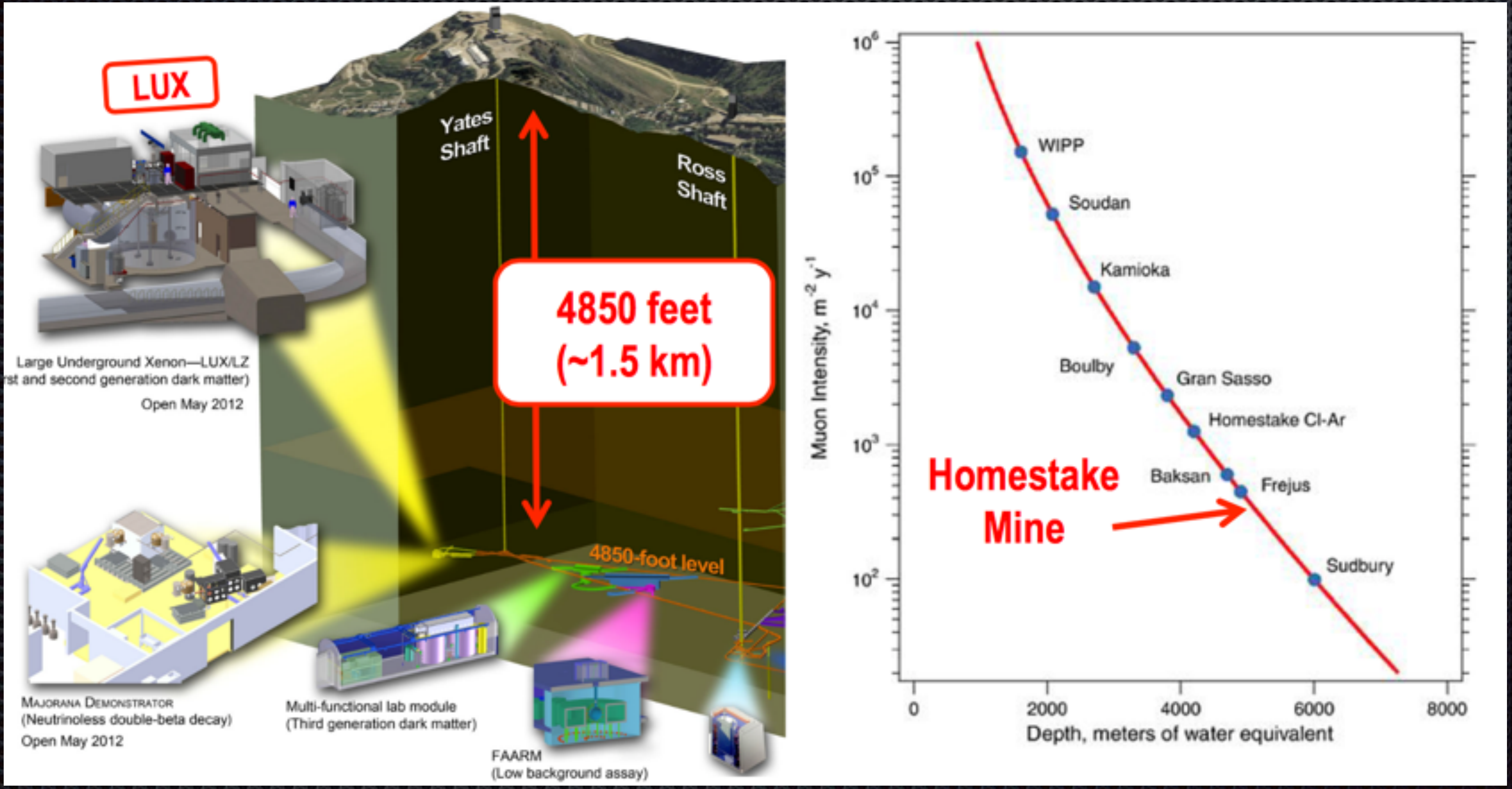
Simplified schema of ~ 100 kg NaI(Tl) set-up

Detects single-hit photon



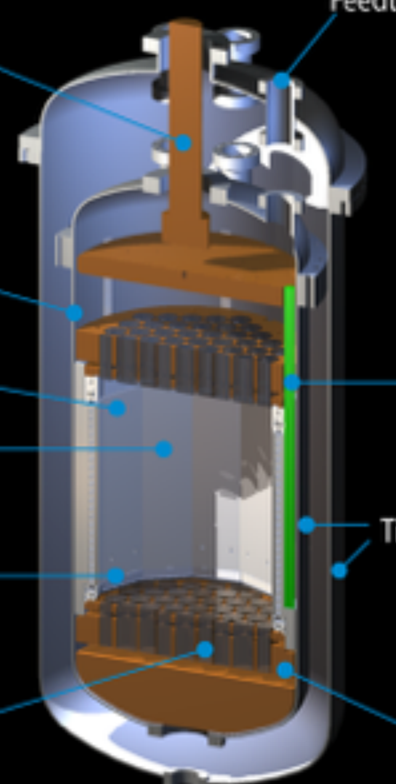
Significance: 9 σ, correct phase, correct period

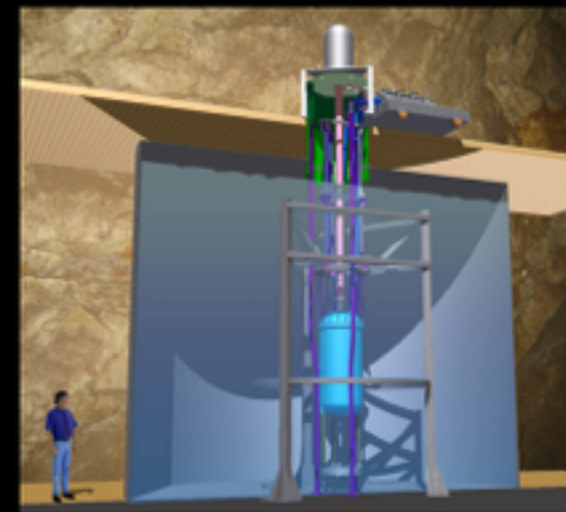
But…


LUX
Yates Shaft
Ross Shaft
4850 feet
(~1.5 km)
4850-foot level
Large Underground Xenon—LUX/LZ
rst and second generation dark matter)
Open May 2012
MAJORANA DEMONSTRATOR
(Neutrinoless double-beta decay)
Open May 2012
Multi-functional lab module
(Third generation dark matter)
FAARM
(Low background assay)
WIPP
Soudan
Kamioka
Boulby
Gran Sasso
Homestake Cl-Ar
Baksan
Frejus
Sudbury
Homestake Mine
Muon Intensity, m^-2 y^-1
Depth, meters of water equivalent
0
2000
4000
6000
8000
10^2
10^3
10^4
10^5
10^6

LUX Anatomy

Brown University, Case Western Reserve University, Harvard University, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, South Dakota School of Mines & Technology, Texas A&M University, University of California Davis, University of Maryland, University of Rochester, University of South Dakota, Yale University





Water Shield

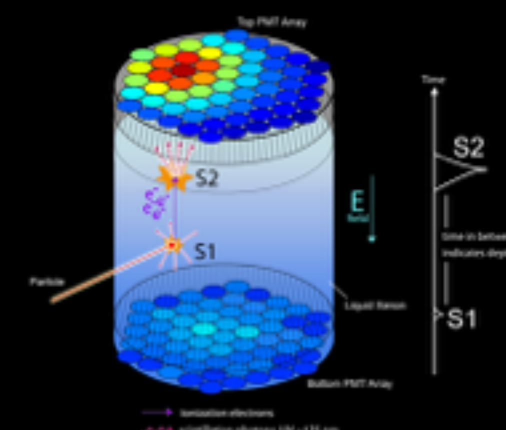
1 In addition to liquid xenon's self-shielding, the 8-meter diameter by 6-meter height water tank reduces gamma background by 7 orders of magnitude.

Thermosyphon

2 Closed loop of liquid nitrogen condensation/evaporation. Provides 1 kW cooling power to the detector.

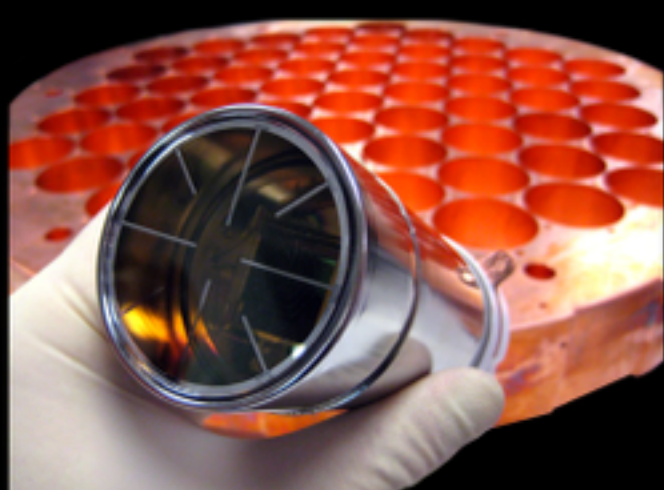
Xenon Recirculation and Heat Exchanger

3 Xenon is constantly being recirculated in and out of the detector for purification (gas panel for recirculation shown above, with the xenon-purifying getter on the right). Inside the detector, the heat exchanger transfers the heat load from the incoming hot xenon to the outgoing cold xenon from the detector.



Time Projection Chamber

4 The PMT hit pattern provides x-y localization of an event, while the time between primary (S1) and secondary (S2) scintillation signals provides z-localization.

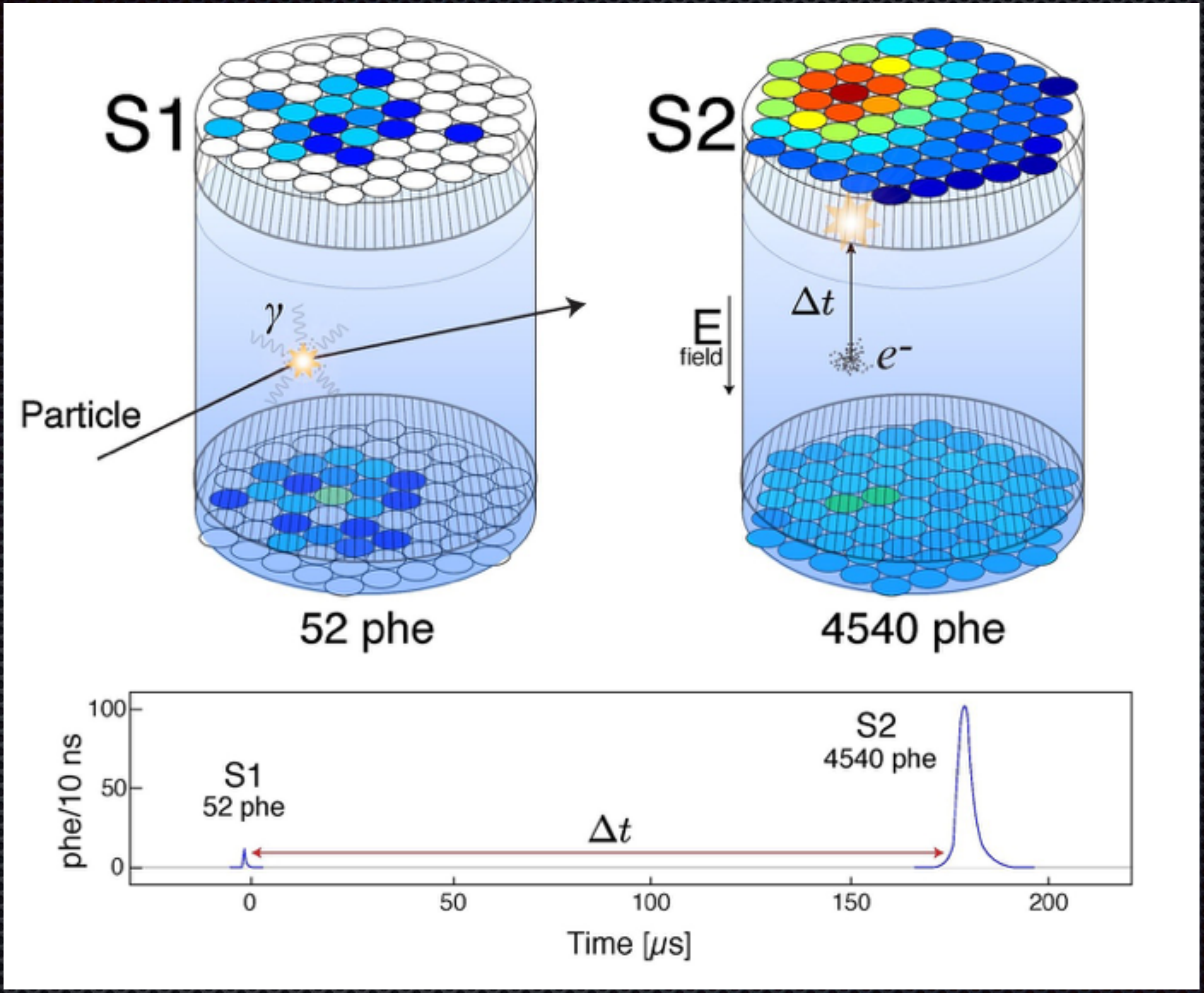


5 Photomultiplier Tubes (PMTs)

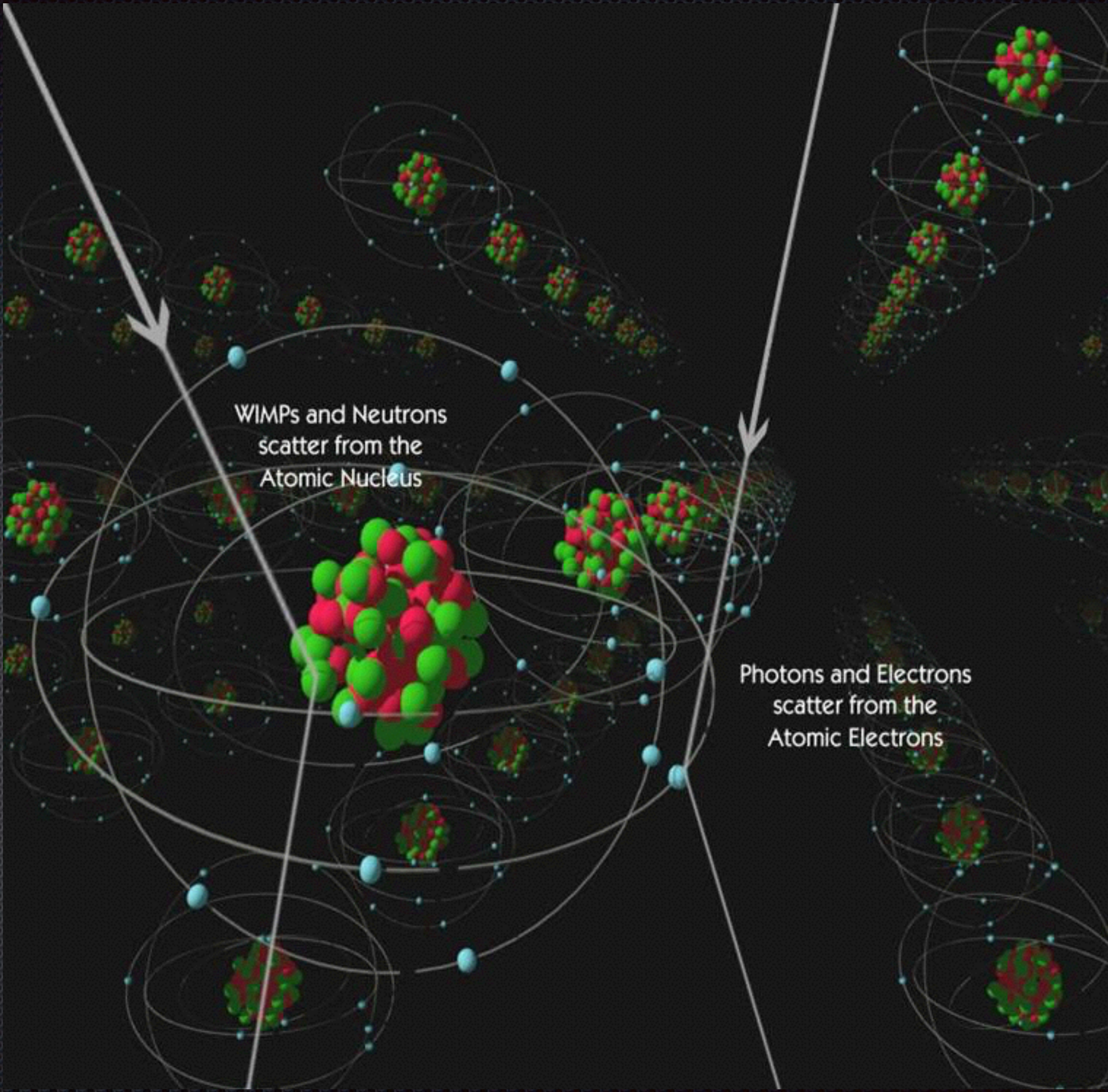
Detect scintillation and ionization light of events inside the detector. They are sensitive to xenon 175 nm (UV) light and are able to detect single photons. They have a typical Quantum Efficiency (QE) of 33%. There are 122 PMTs (61 top and 61 bottom) in the detector.

CHF, 20091112LUXAnatomy

Detects nuclear recoils:
light+charge

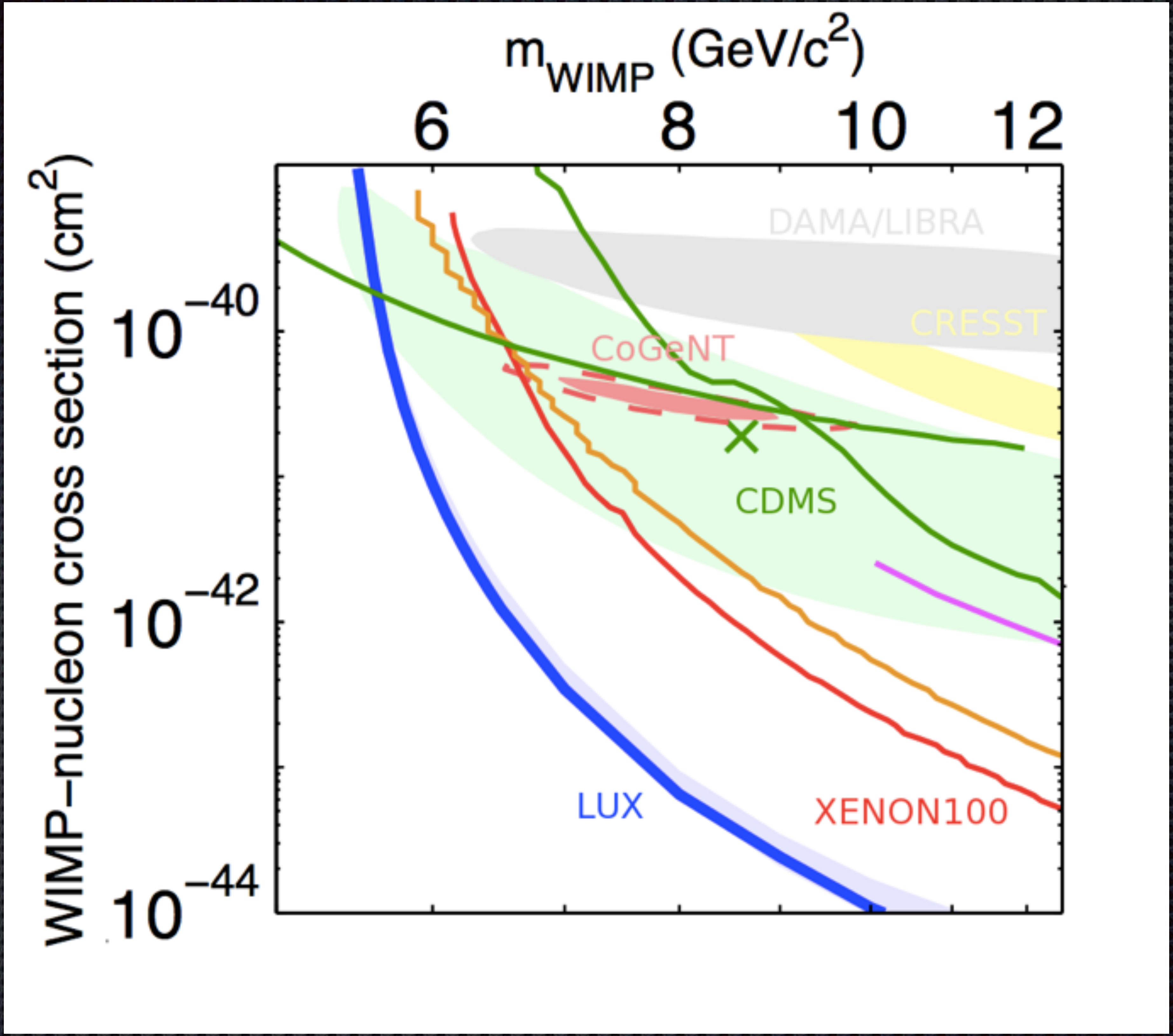


S1
S2
γ
Particle
Δt
E field
e⁻
52 phe
4540 phe
S1
52 phe
S2
4540 phe
Δt
phe/10 ns
Time [μs]

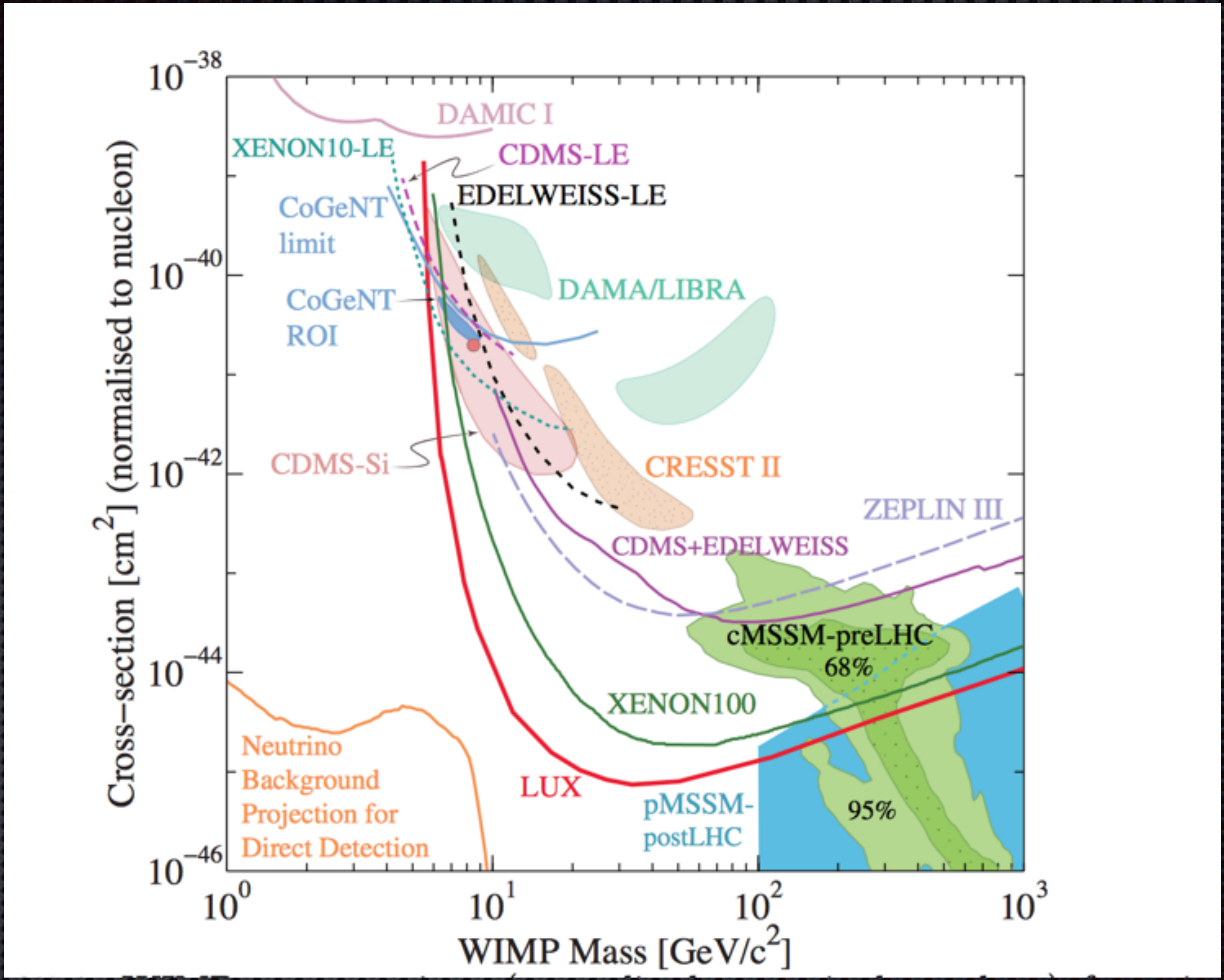

WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons

LUX sees nothing!!!!

- Yes: DAMA/LIBRA (9 σ), CoGent (2 σ?), CDMS Si (3 events)
- No: all others (Xenon 100, LUX, EDELWEISS, CRESST, etc.)



m_WIMP (GeV/c²)
6
8
10
12
WIMP–nucleon cross section (cm²)
10⁻⁴⁰
10⁻⁴²
10⁻⁴⁴
DAMA/LIBRA
CRESST
CoGeNT
CDMS
LUX
XENON100



K.A. Olive *et al.* (Particle Data Group) Chin. Phys. C, 38 (2014) 090001

Consensus ?!

- DAMA due to something else
- Heroic efforts to explain it by muons giving neutrons (wrong rate&phase)
- Plus neutrinos (wrong rate, by 1 million)
- “Many things have a period of 1 year on Earth”
- “Everybody believes in SUSY and CDM”

Conclusion 3

- Great success of CDM / WIMPS
- Inconclusive evidence from indirect searches
- No sign of WIMPS at the LHC
- Confusing situation in Direct Searches

Plan

- Direct evidence
- Possible causes
- Searches
- How to build a model
    - Beyond CDM
    - How to avoid recoils
    - How to have a signal in DAMA only

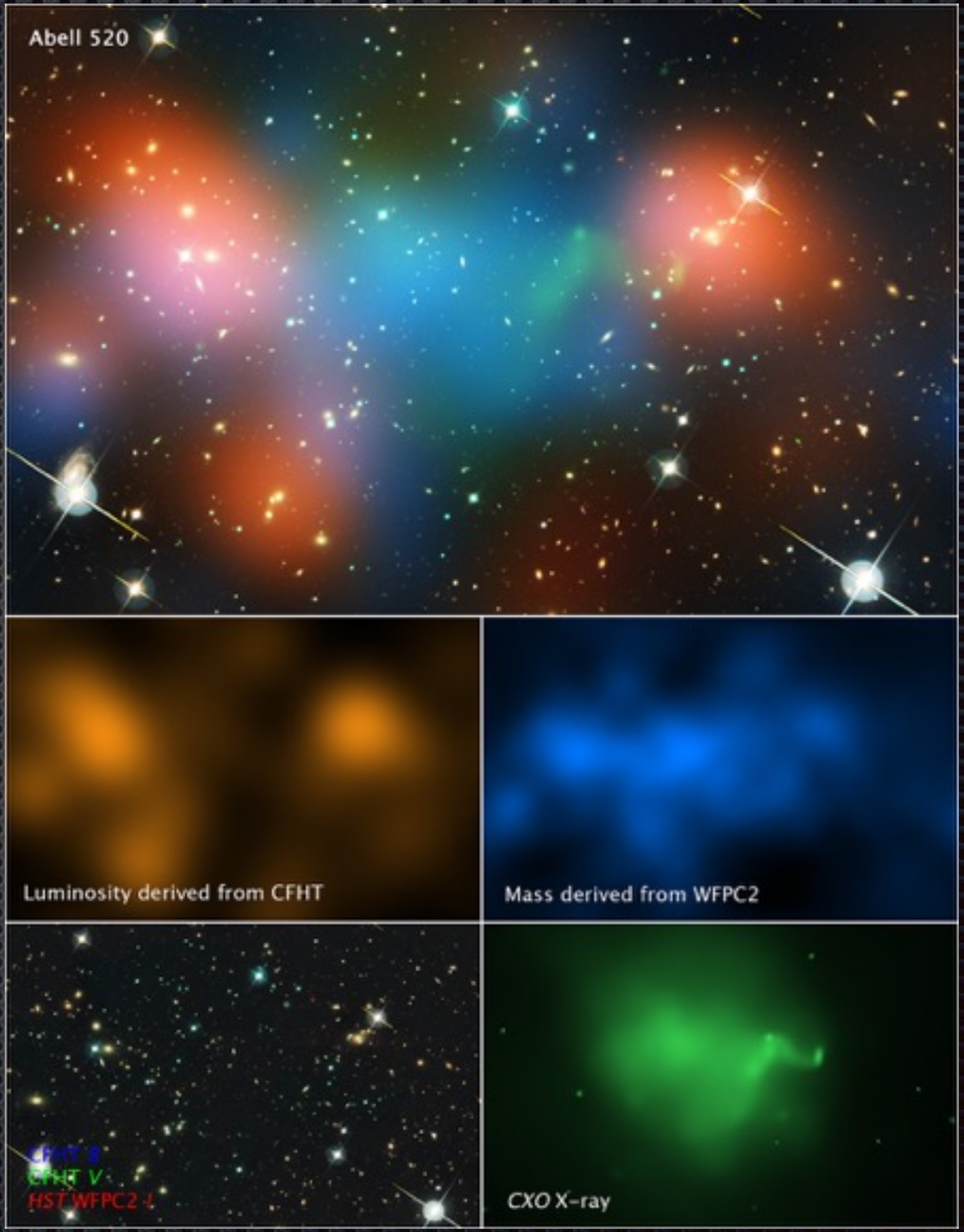
CDM has problems, too:

a) **The cusp/core problem:** the distribution of dark matter in dwarf galaxies is approximately constant in the inner parts of galaxies, while computer simulations predict a steep power-law-like behaviour (cusp).

b) **The satellite problem:** The excessive predicted numbers of dwarf galaxies. The discrepancy amounts to orders of magnitude.

c) **The “too big to fail” problem**: some of the predicted galaxies are just so massive that there’s no way they could not have visible stars.

puzzle of Abell 520



Douglas Clowe1, Maxim Markevitch, Maruša Bradač, Anthony H. Gonzalez, Sun Mi Chung, Richard Massey, and Dennis Zaritsky. The Astrophysical Journal. doi:10.1088/0004-637x/758/2/128

SUSY

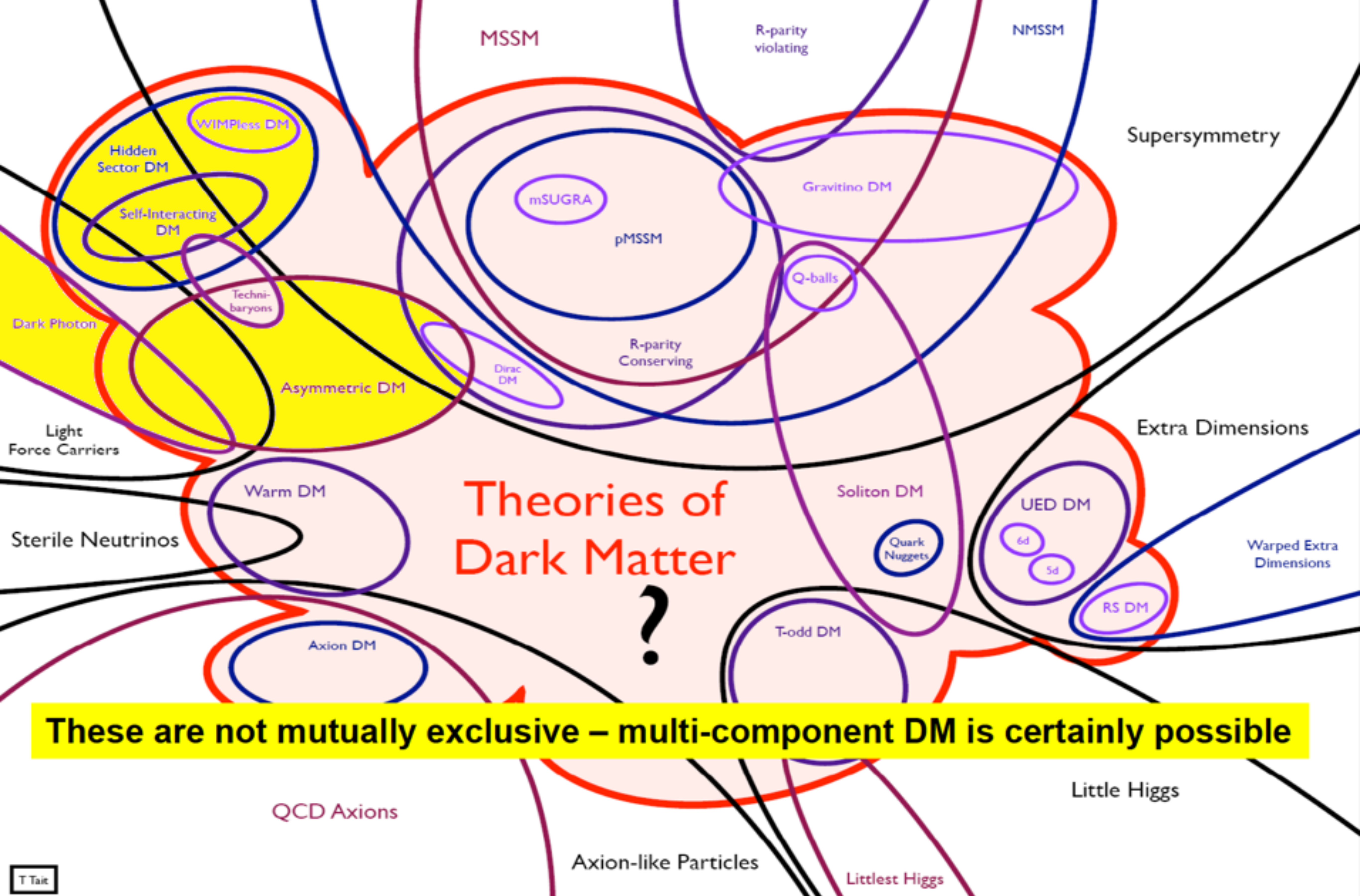
- No predicted scale: could be much further than the reach of the LHC.
- “A global likelihood analysis including this, other electroweak precision observables and B-decay observables suggests that the LHC might be able to discover supersymmetry with 1/fb or less of integrated luminosity. The LHC should be able to discover supersymmetry via the classic missing-energy signature, or in alternative phenomenological scenarios. The prospects for discovering supersymmetry at the LHC look very good.”, J. Ellis, 2007, http://arxiv.org/abs/0810.1178
- "It's better to have loved and lost than not to have loved at all," he says. "Obviously we theorists working on supersymmetry are playing for big stakes. We're talking about dark matter, the origins of mass scales in physics, unifying the fundamental forces. You have to be realistic: if you are playing for big stakes, very possibly you're not going to win.”, J. Ellis, 2014, The Guardian

A solution

- There could be another kind of dark matter with much larger interactions. That would have pressure, and solve the structure problems. Maybe that kind of dark matter is more concentrated in Abell 520.

New classes of models

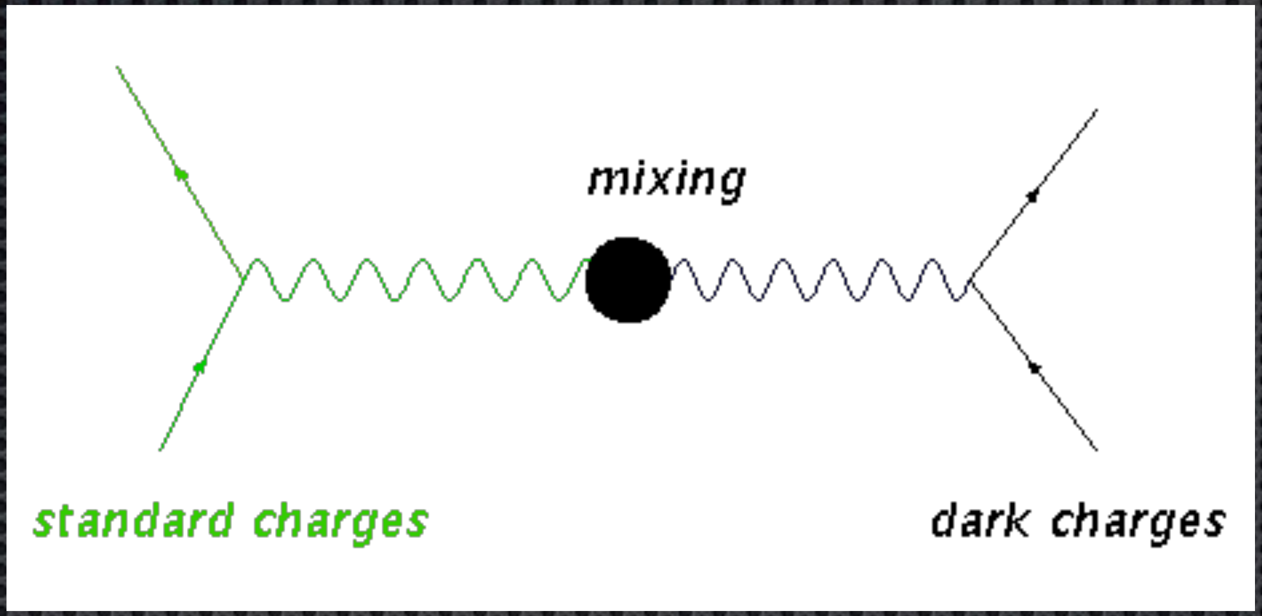
The Standard sector represents 17% of matter and is very complicated.
Why would the other 83% be so simple??


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Soliton DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
These are not mutually exclusive – multi-component DM is certainly possible
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

What are Dark Atoms?

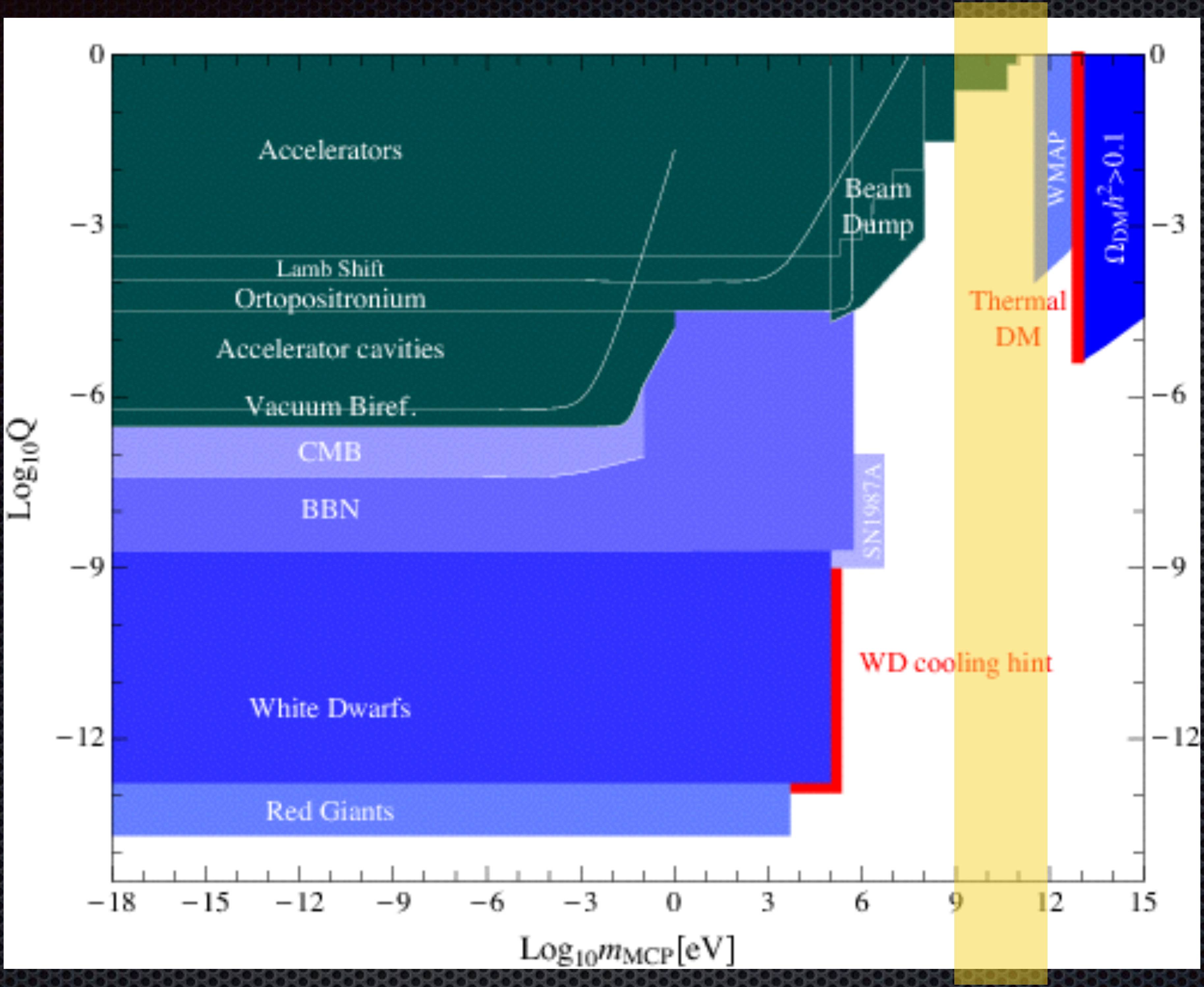
Different mass scales

Photon-Dark photon mixing



$$\mathcal{L} = \epsilon F_{\mu\nu} F^{\mu\nu}_{Dark}$$

Dark charges look to us as millicharges



m=GeV to TeV

ε=0.001-0.01

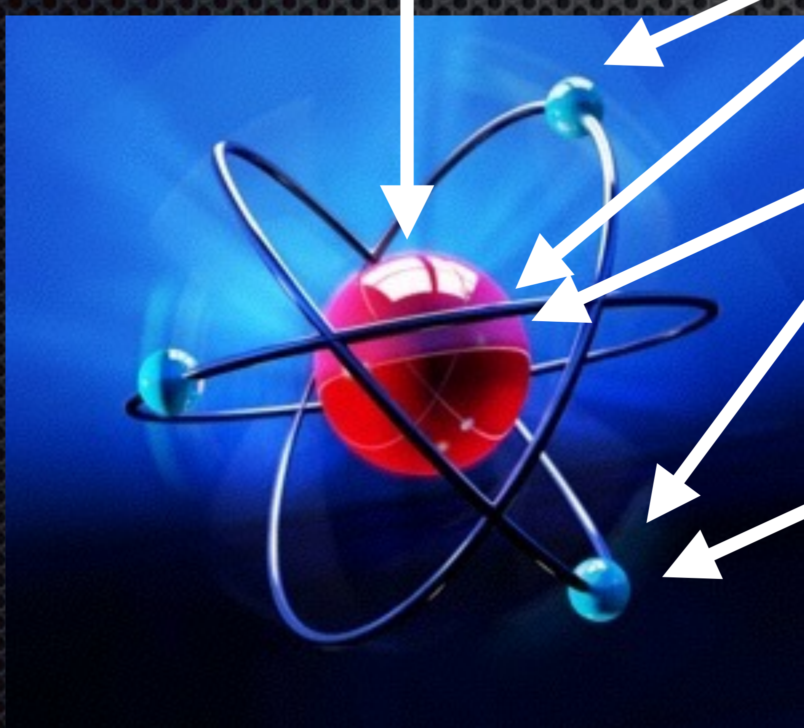
Working Group Report: New Light Weakly Coupled Particles - Essig, Rouven *et al.* arXiv:1311.0029 [hep-ph] YITP-SB-36

- WIMP: mass, cross section

Atomic Dark Matter: many scales!

Excited states

2 mass scales



Binding cross sections

Excited states

Cross section

Can one produce a signal in DAMA, and only in DAMA?

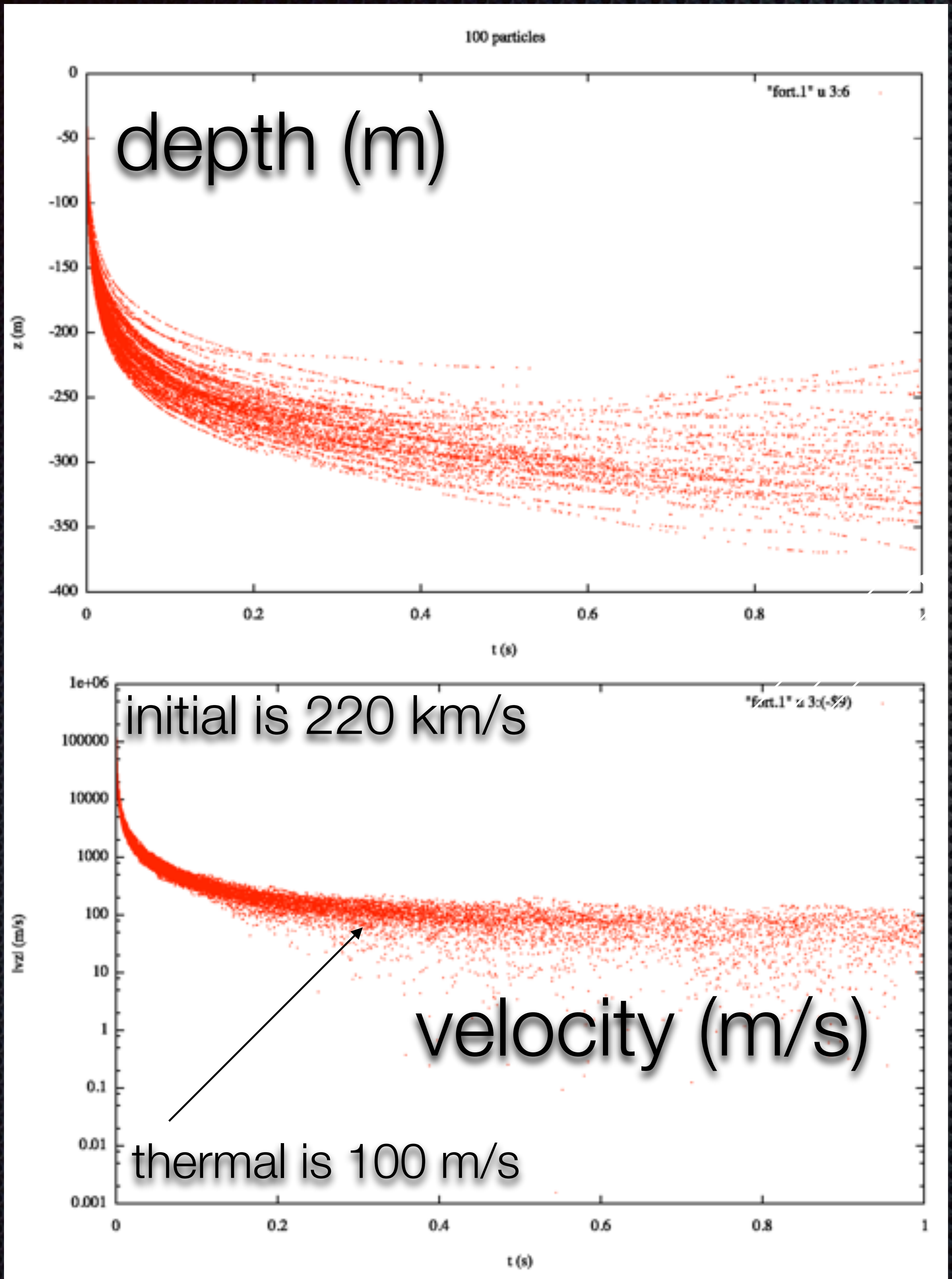
Q. Wallemacq and J.R.C., “Dark antiatoms can explain DAMA,” JCAP 1502 (2015) 02, 011 [arXiv:1411.3178 [hep-ph]].

- DAMA: room temperature, NaI(Tl), any photon
- LUX: cryogenic, Xe, nuclear recoils

=> the DAMA signal is *not* nuclear recoil

How to avoid nuclear recoil

- depth of DAMA~1 km
- thermalize at 1 km=>mean free path $\lambda < 3.4$ m
- $\sigma > 1/(\lambda$*number density$) = 2.2\ 10^{-26}\ cm^2$
- nuclear recoils become undetectable



λ =1 m

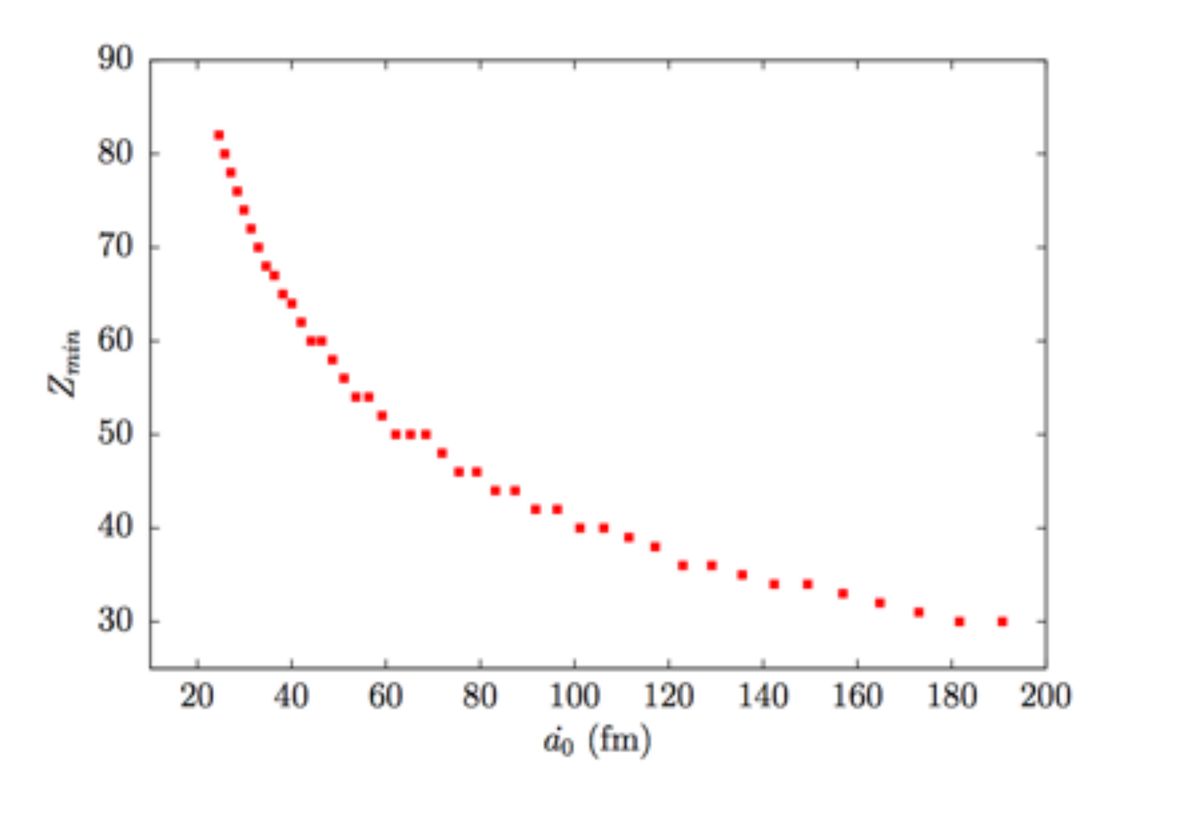
Thermal cloud then slowly drifts down v_d=8.6/s λ

How to obtain a signal

- Other physical process: binding.
- Binding OK if dark matter is composite.
- Could via electromagnetism (dark atoms)
- Need a TeV antiproton->dark anti-atoms

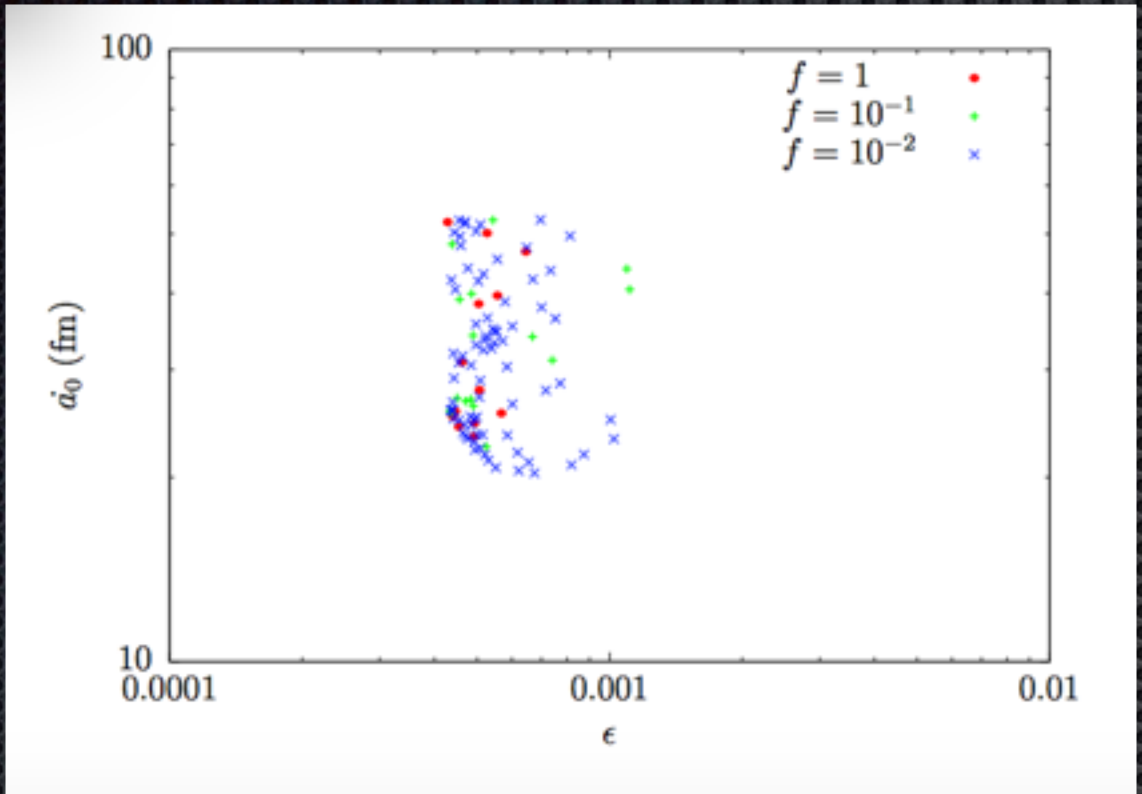
Why DAMA is special

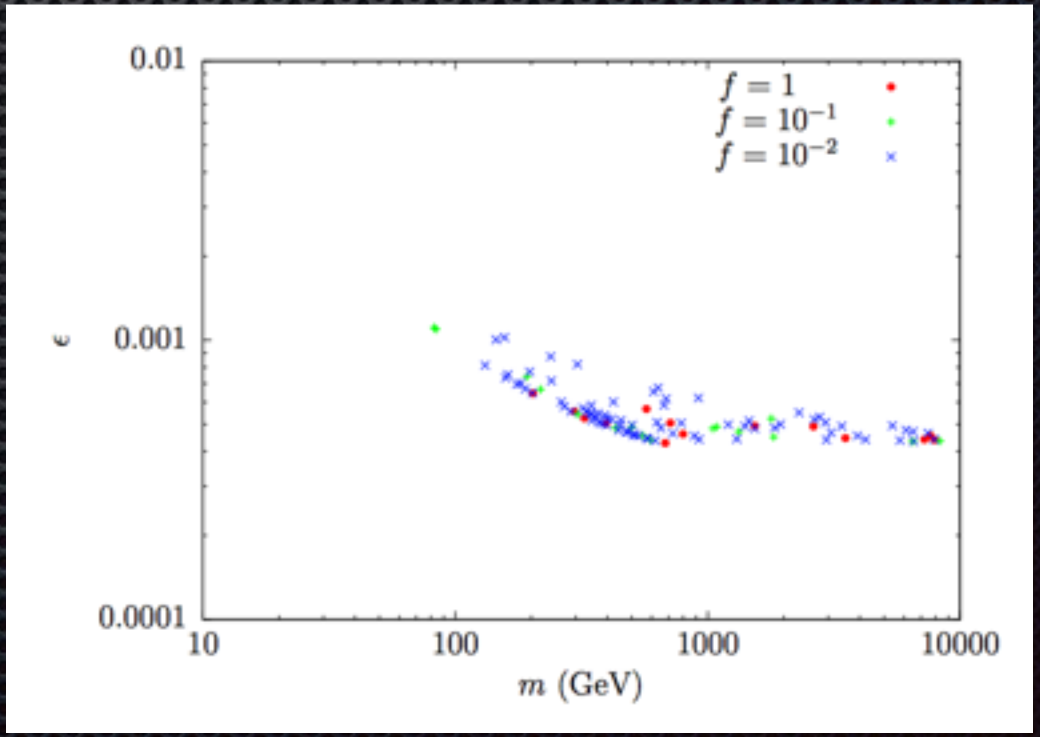
- Binding to high-Z nuclei: depends on the radius
- DAMA contains Thallium (Z=81) impurities



For m=100 GeV,
ε=0.0005

To get the correct event rate





Checks

- Anomalous elements abundance < $2.7\ 10^{-10}$
- Limit on Gold → m > 300 GeV
- Absorption by the Earth and the lead shielding: OK

$$300\ \text{GeV} \leq m \leq 10\ \text{TeV},$$
$$\varepsilon \sim 5\ 10^{-4}$$
$$20\ \text{fm} \leq a_0 \leq 50\ \text{fm}$$

self-interaction $10^{-20}\ \text{cm}^2$ => subdominant

Conclusion 4

- Many possibilities exist
- They should reproduce the data!

Conclusion

- Astrophysical explanation: maybe, but hard to see where all these pebbles come from
- Gravity solution: still need some dark matter
- Particle physics solution: only unusual models can reproduce the data

Future A: Business as usual

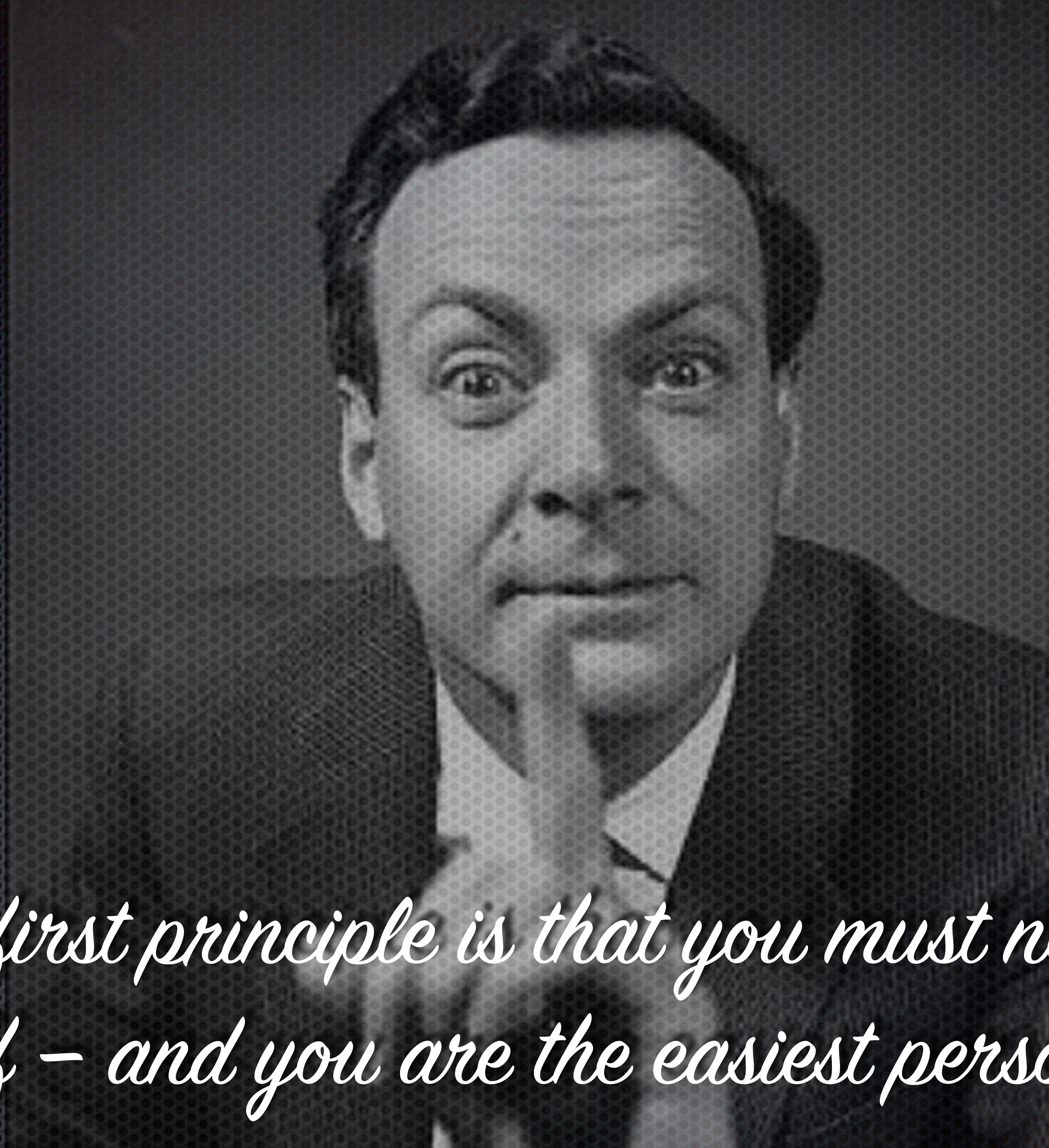
- The LHC finds supersymmetry
- DAMA finds the person who turns off the detector once a year
- Supernovae are frequent enough to flatten the DM profile

Future B: back to the 70’s

- Other direct detection experiments confirm DAMA
- Millicharged particles/anomalous elements are found
- A whole new sector needs to be mapped

Future C: Biology

- The LHC finds nothing further
- DAMA finds a mistake in the data analysis
- MACHOs explain Dark Matter



The first principle is that you must not fool yourself – and you are the easiest person to fool.

R.P. Feynman, “Cargo Cult Science”, adapted from a 1974 Caltech commencement address; also published in Surely You're Joking, Mr. Feynman!, p. 343

Liège Master in Space Sciences

Astrophysics

- Switch to 70% English next year;
- **Long** tradition of astrophysics in Liège, with *Founding Fathers* such as Paul Ledoux and Polydore Swings;
- Programme with a high level of **customization** including many options in various fields related to astrophysics, planetology, astroparticle physics & instrumentation;
- Education programme supported by **active researchers;**
- Connections with **international** research centers and international agencies (ESA, ESO, NASA);
- **Mobility** agreement with several European universities;
- Research-oriented focus with Master thesis fully immersed in **research teams;**
- Opportunities to develop **technical aspects** exportable in private space companies (internships, technical courses...)

Master in Space Sciences

Optional courses (63 credits)

- **Inter-disciplinary courses**
- **Cosmology and astroparticles**
- **Astronomy and astrophysics**
- **Planetology and planetary systems**
- **Climate, environment and oceanography**
- **Intrumentation and methods for space sciences**

30 credits

Research focus module

Courses selected in the above optional boxes, or in the programme of other Masters (science programmes, engineering programmes...)

27 credits

Master thesis

Topic selected among proposals from internal researchers, or from partners in other institutions