The Dark Side of the Universe - II

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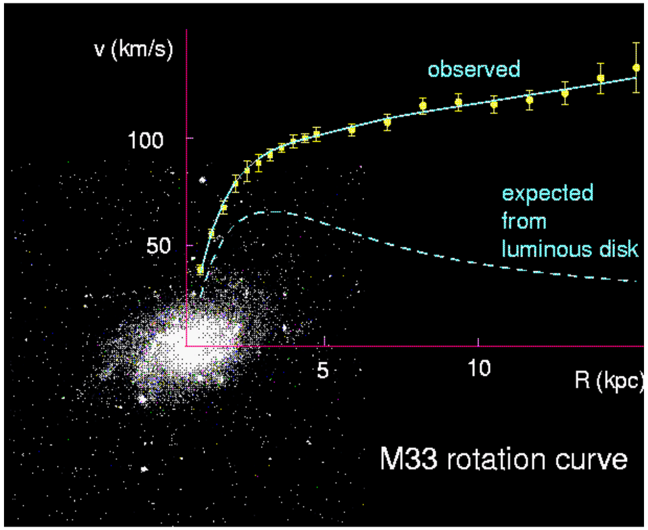
15/12/2013

Dark matter exists

Evidence from many different sources at different scales

Dispersion velocity of galaxies in clusters (30's)

Galaxy rotation curves (70's)



Gravitational lensing

The DARK MATTER problem has been with us since the 1930's, name coined by Fritz Swicky in Helvetica Physica Acta Vol6 p.110-127, 1933

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

On page 122

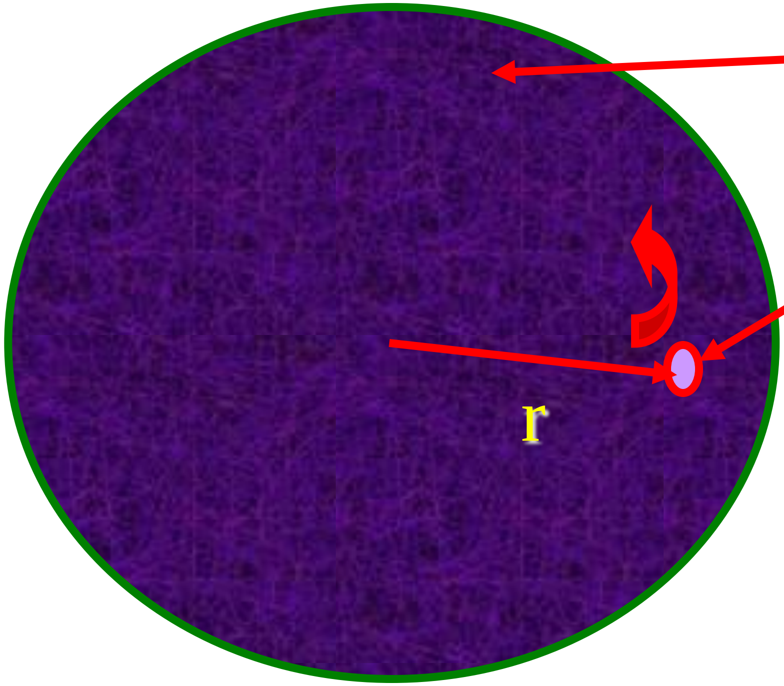
gr/cm³. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}$ gr/cm³ erscheint daher nicht

He used the Virial theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only

Dunkle = dark
Kalte = cold!!

Gelmini WIN 2013

Galaxy rotational curves



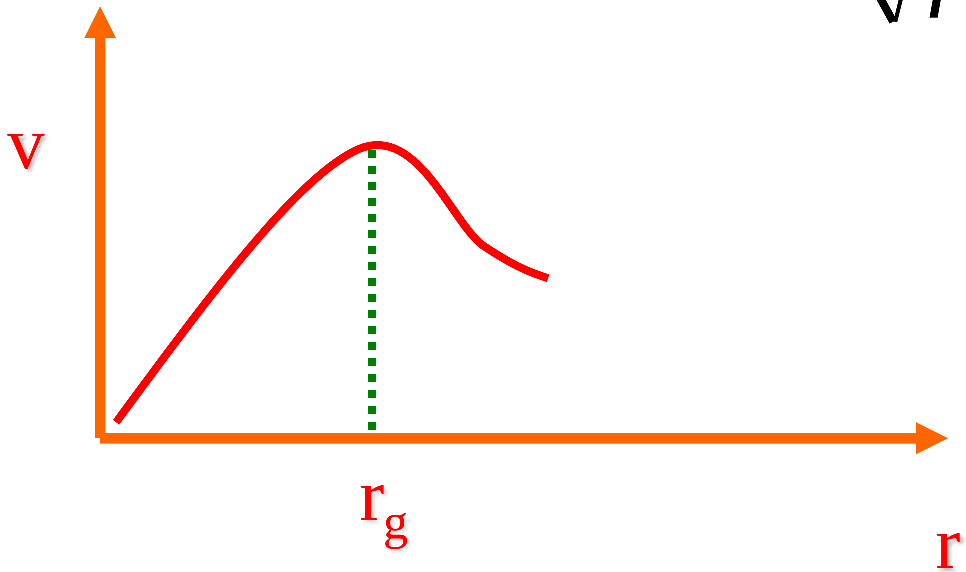
$$m\frac{v^2}{r} = \frac{GmM(r)}{r^2}$$

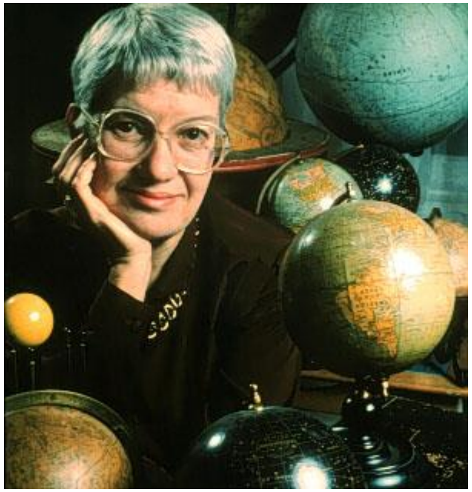
“Inside” the galaxy:

$$M(r) = \frac{4\pi}{3} r^3 \rho \Rightarrow v \propto r$$

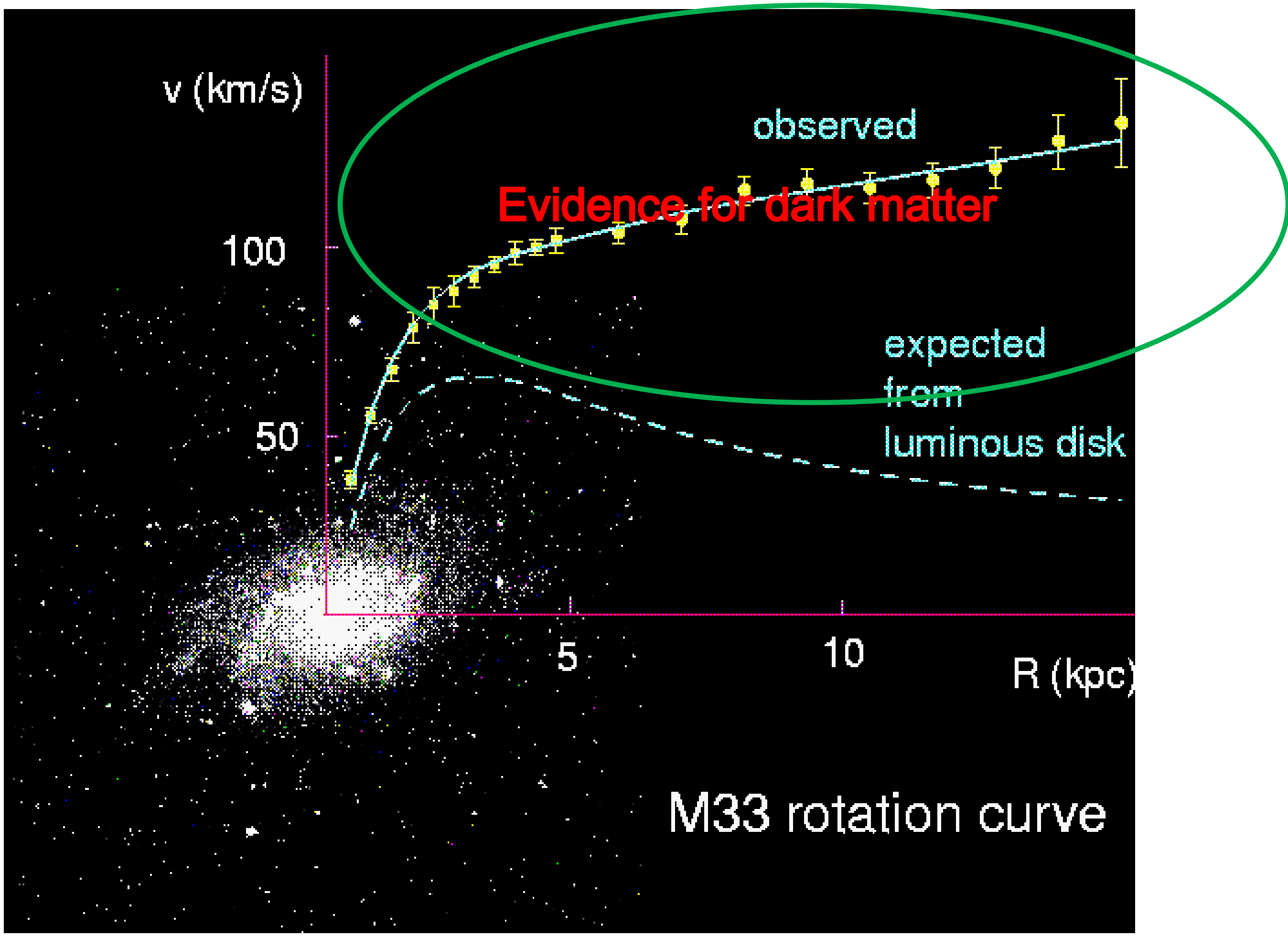
“Outside” the galaxy:

$$M(r) = M \Rightarrow v \propto \frac{1}{\sqrt{r}}$$





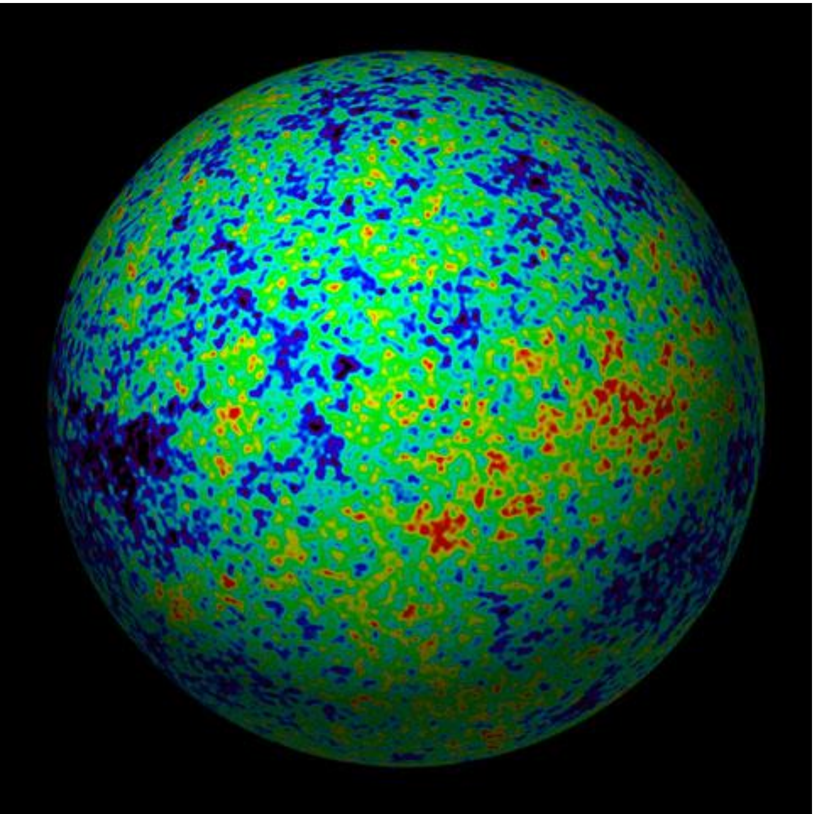
Vera Rubin
1928-



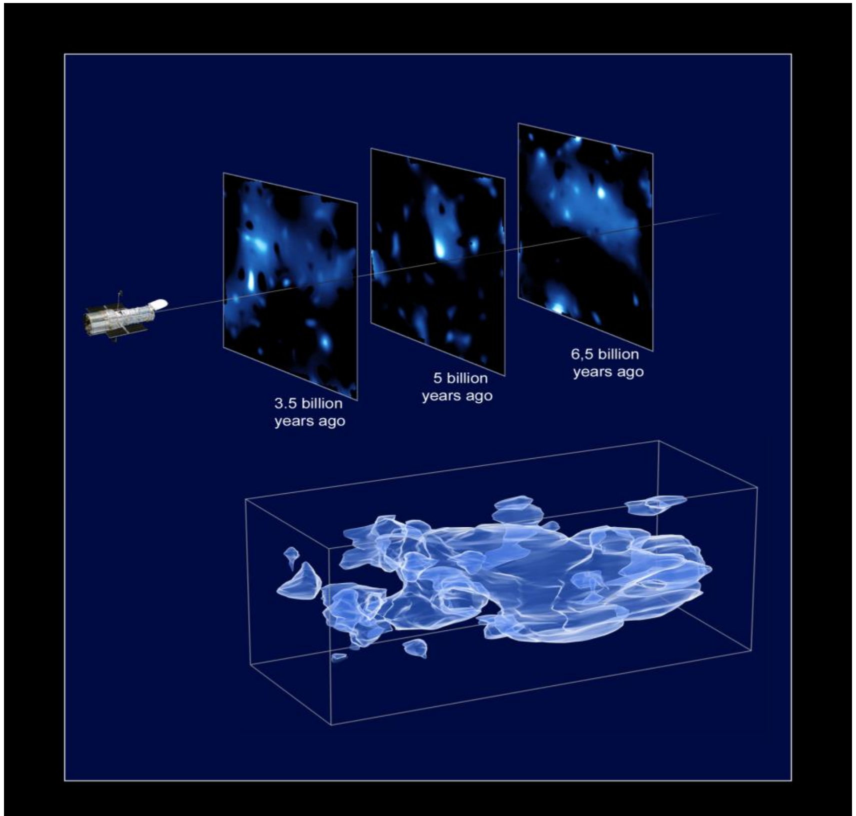
1970's and 1980's

Evidence from many different sources at different scales

Cosmic microwave background (90's)



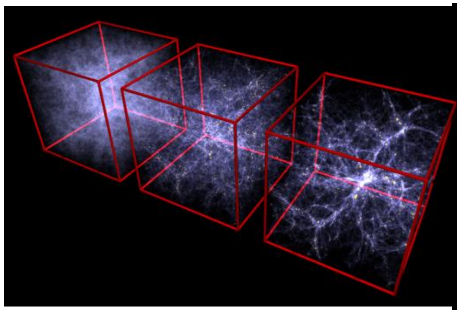
Dark matter distribution in the universe Cosmic Evolution Survey – COSMOS-HST - *Nature 2007*



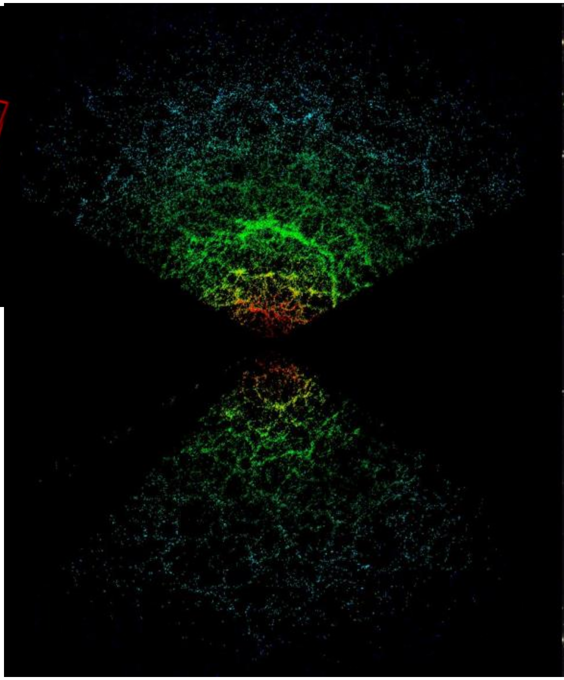
Evidence from many different sources at different scales

Structure formation in the universe

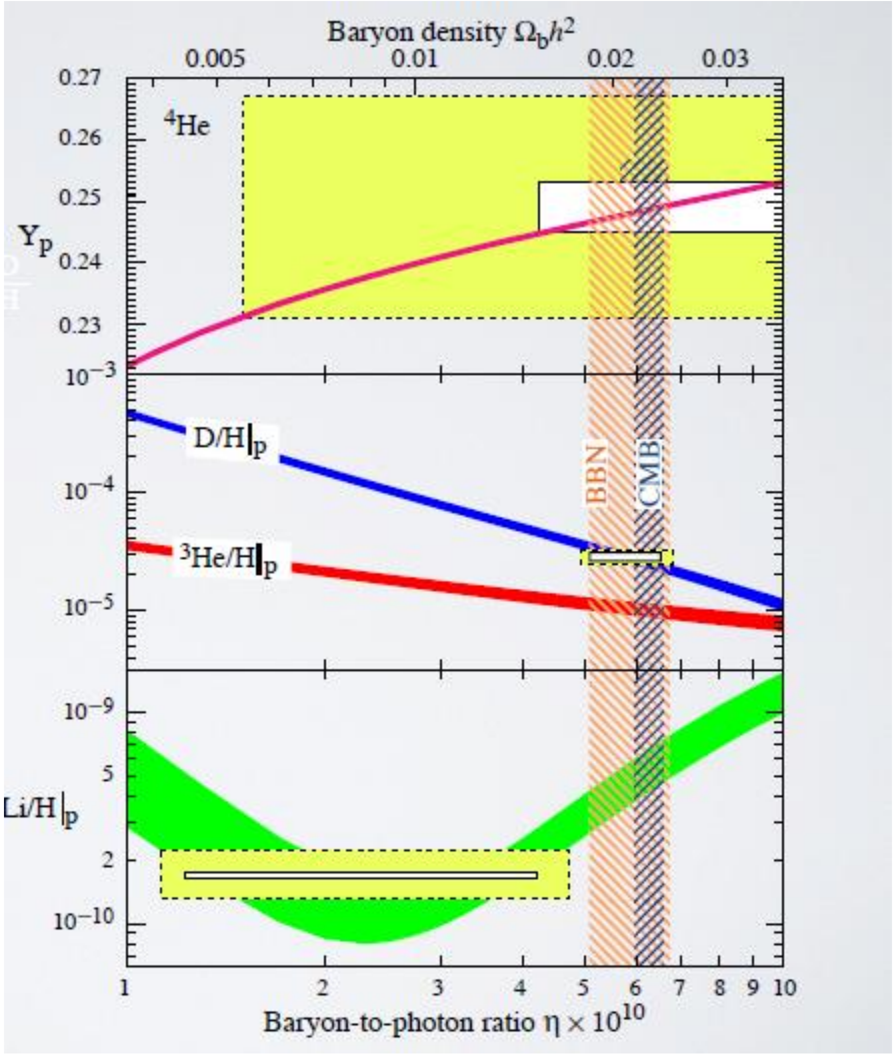
Millenium simulation



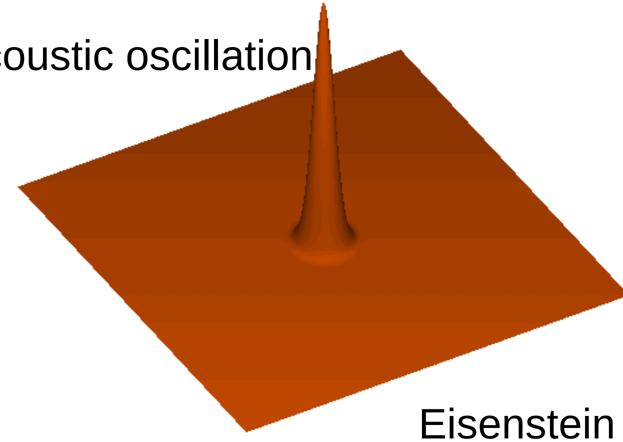
SDSS



Big bang nucleosynthesis



Baryon acoustic oscillation



Eisenstein

Baryon Acoustic Oscillation

- Preferred scale emerges in galaxy distribution: sound horizon at decoupling.

- Before recombination, baryons and photons were strongly coupled, forming a single fluid with pressure and speed. Dark matter, neutrinos and other forms were decoupled.

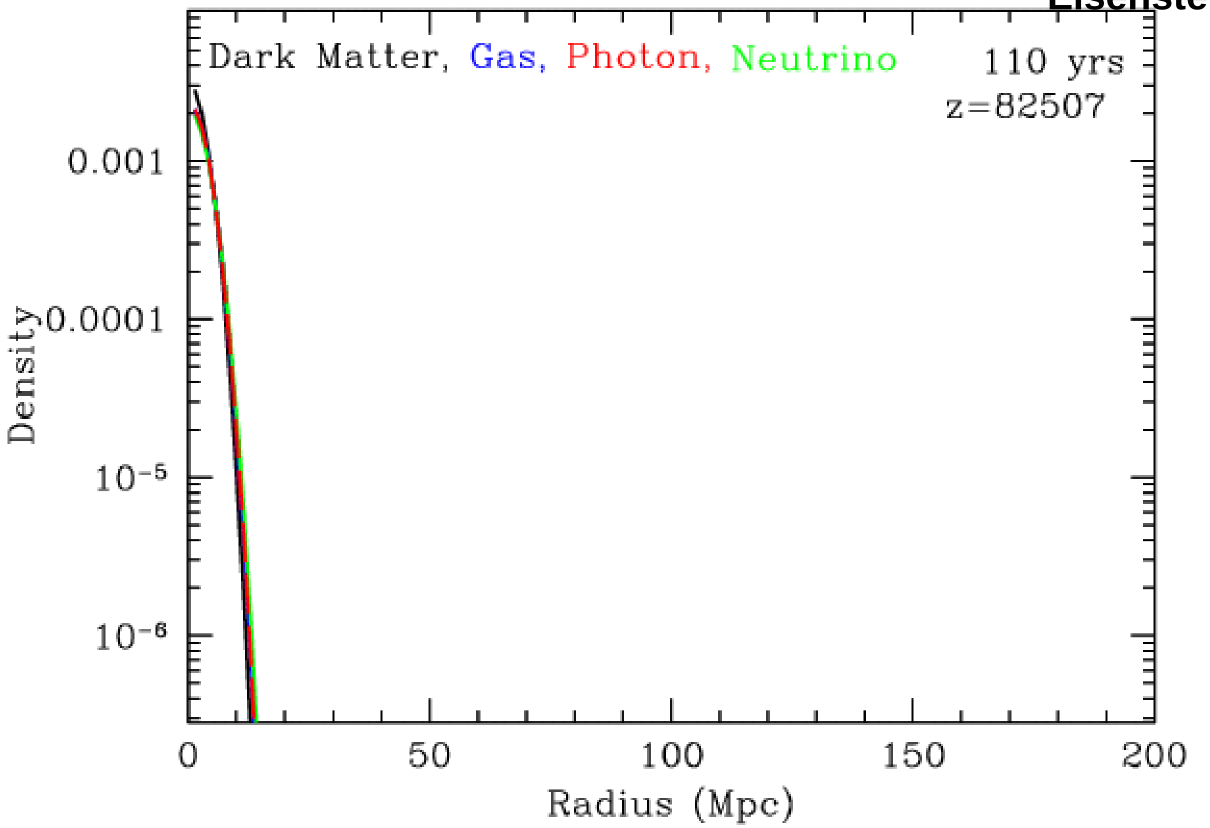
$$c_s^2 = \frac{\partial(p_\gamma + p_b)}{\partial(\rho_\gamma + \rho_b)} \sim \frac{1}{3}$$

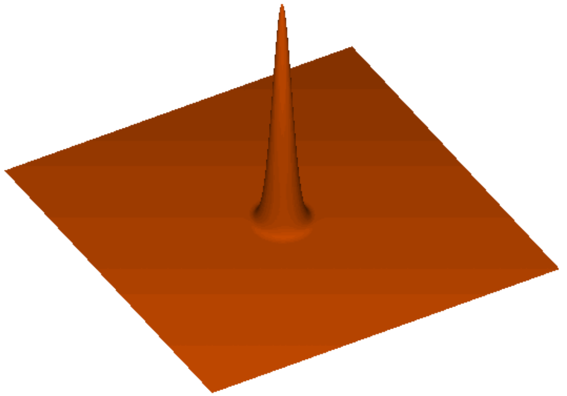
$$r_{BAO} = \int_{z_{rec}}^{\infty} \frac{c_s(z)dz}{H(z)} \approx 150 \text{ Mpc}$$

Cosmological parameters

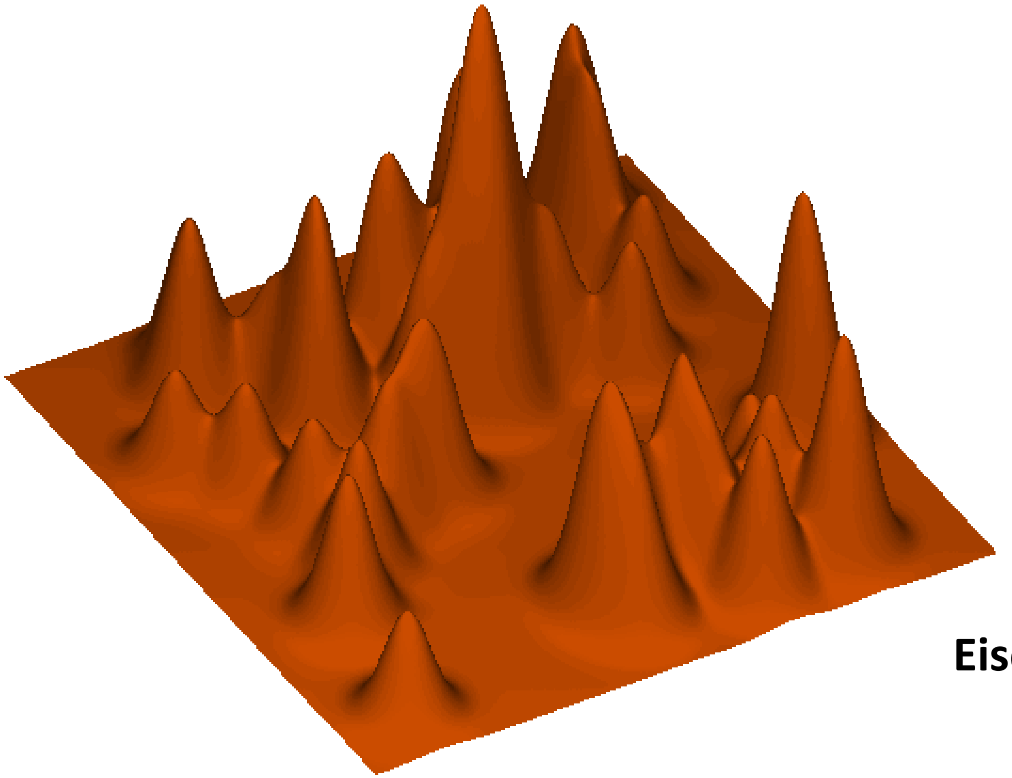
Evolution of one spherical perturbation

Eisenstein

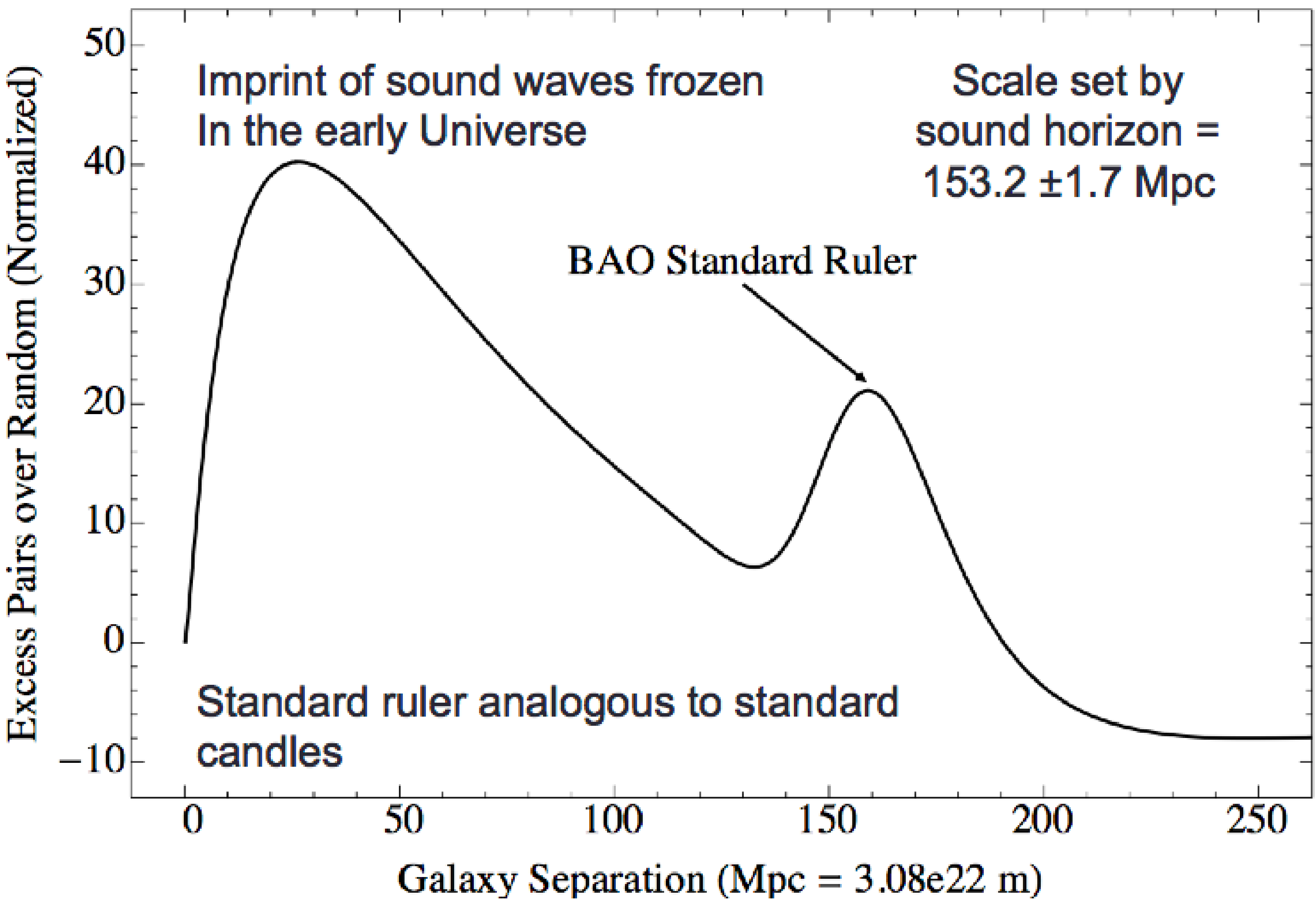




Things are more complicated: superposition of shells with different locations and different amplitudes



Eisenstein

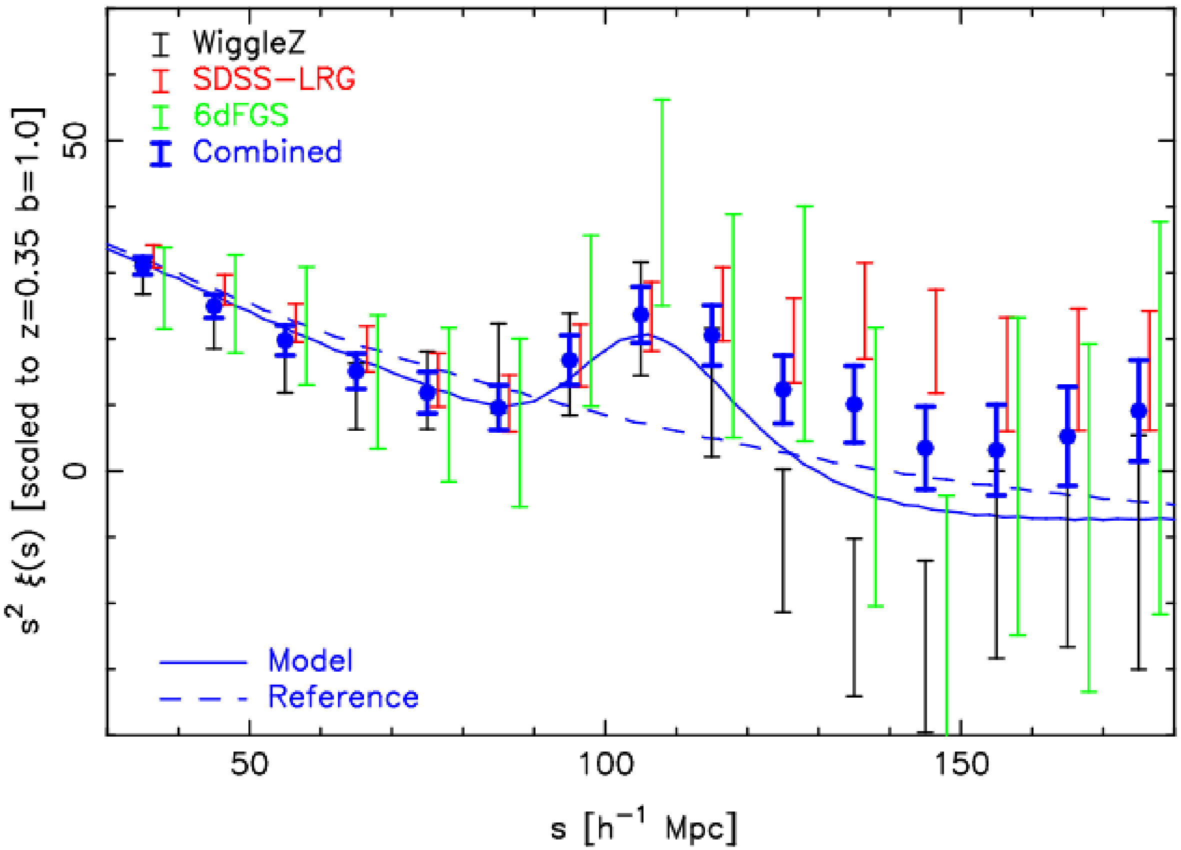


Imprint of sound waves frozen
In the early Universe
Scale set by
sound horizon =
153.2 ±1.7 Mpc
BAO Standard Ruler
Standard ruler analogous to standard
candles
Excess Pairs over Random (Normalized)
Galaxy Separation (Mpc = 3.08e22 m)
50
40
30
20
10
0
−10
0
50
100
150
200
250

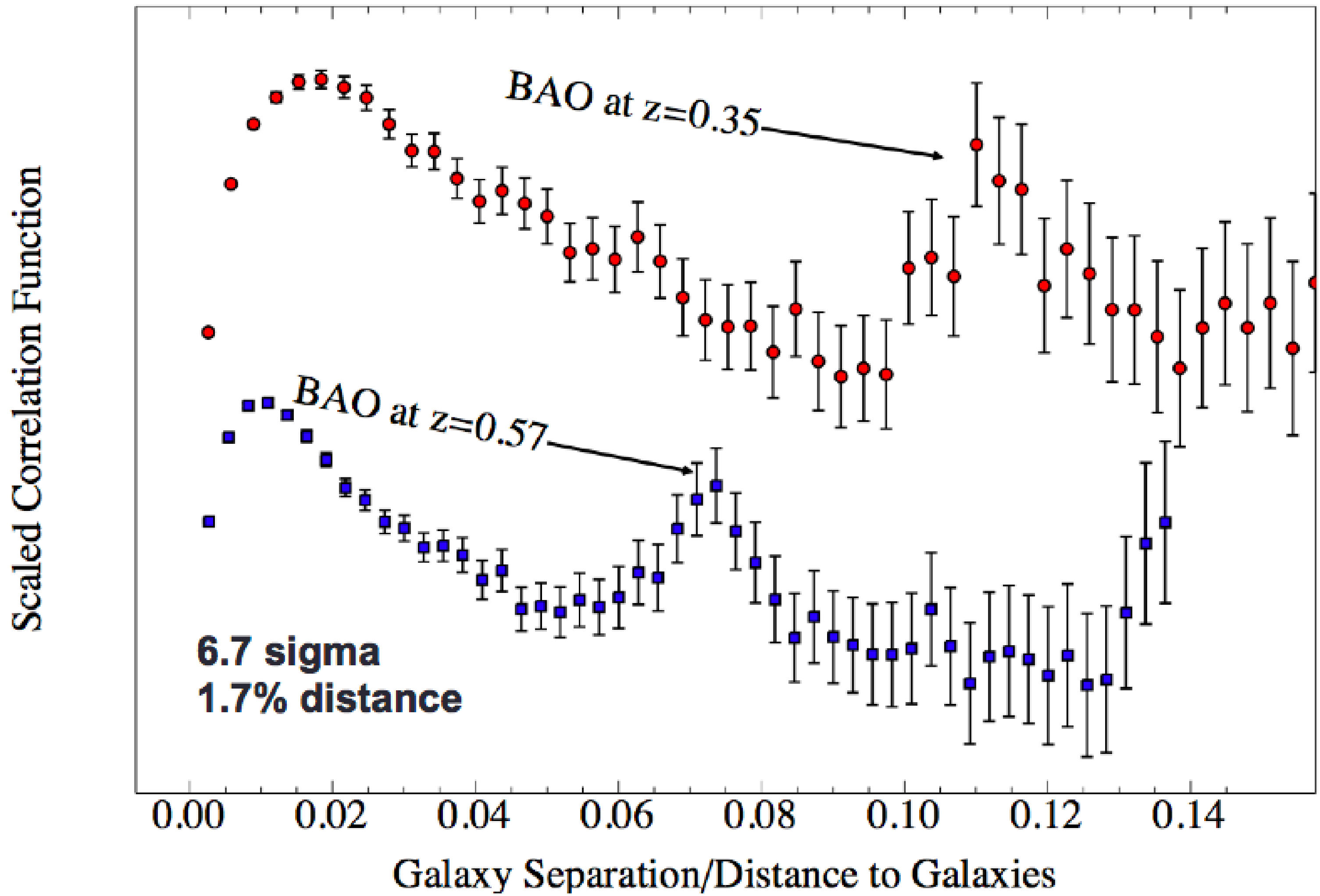
Results from WiggleZ(1108.2635):

(N = 158,741 galaxies in the redshift range 0.2 < z < 1.0)

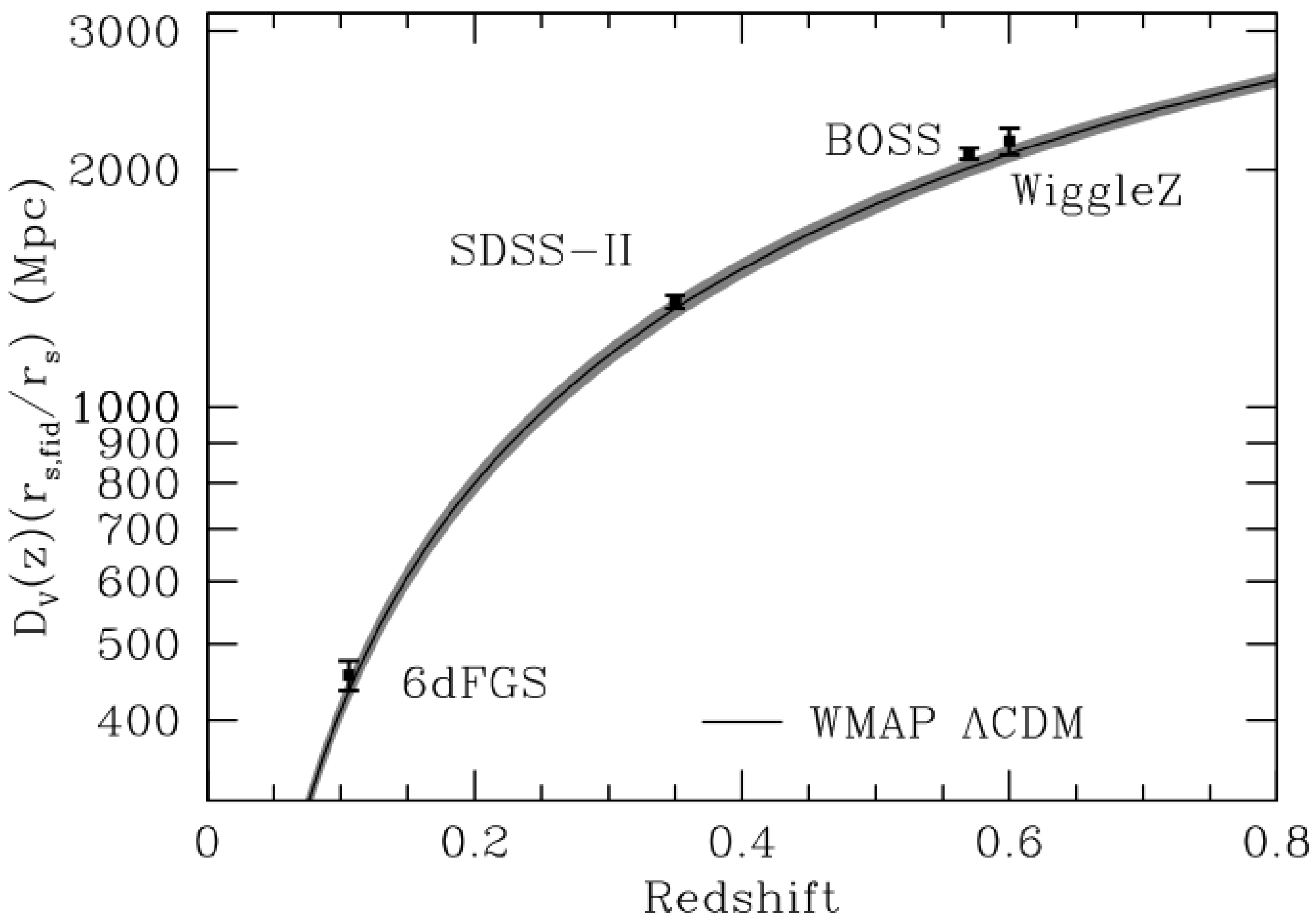
4.9σ significance



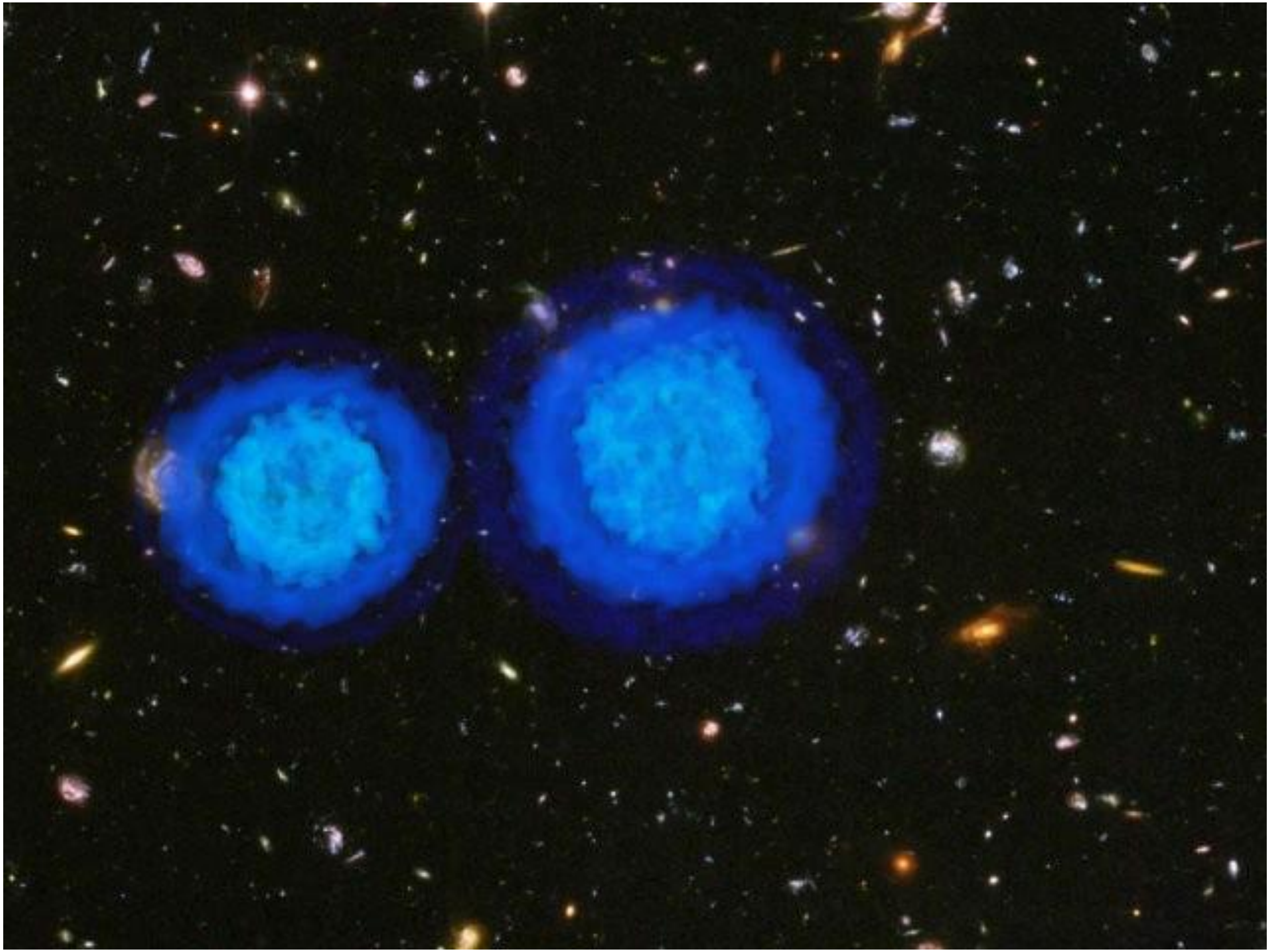
SDSS-II and SDSS-III (BOSS): 6.7σ detection



BAO Hubble diagram



Bullet cluster



Observational evidences for DM

I. Dynamics of clusters of galaxies

II. Rotational curves of galaxies

III. Gravitational lensing

IV. Cosmic microwave background

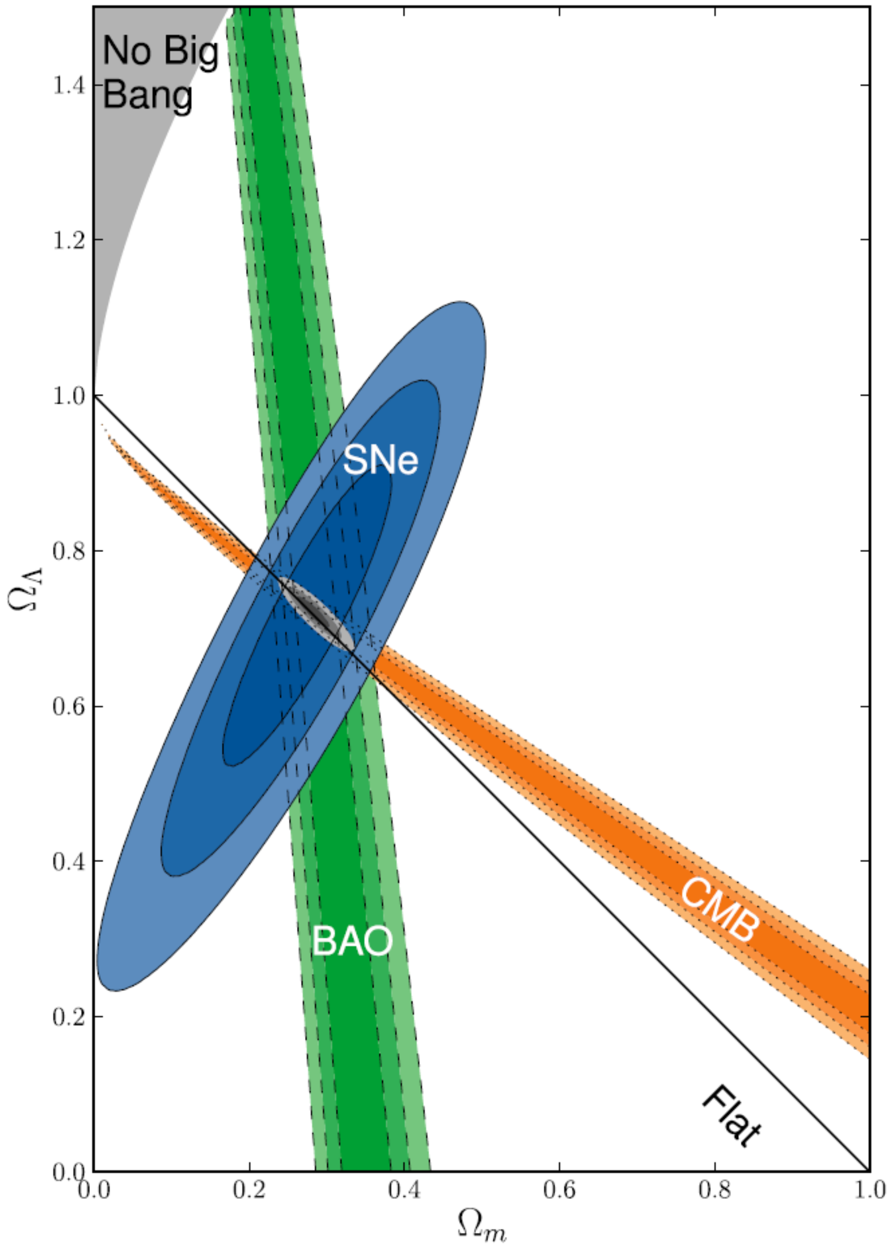
V. Big bang nucleosynthesis

VI. Structure formation in the universe

VII. Baryon acoustic oscillations

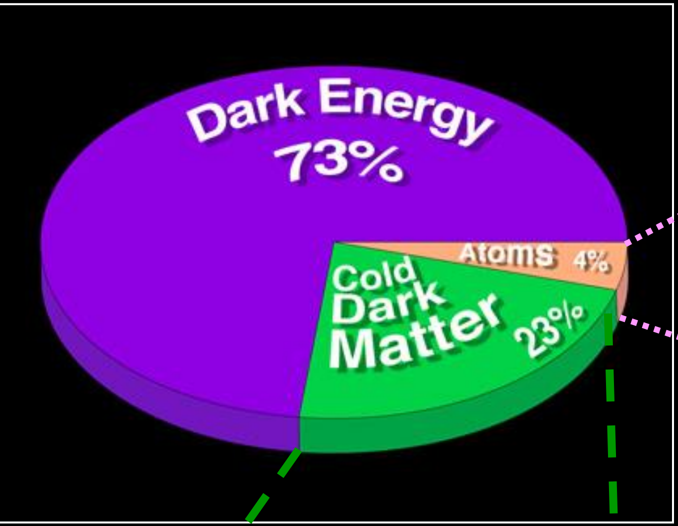
VIII. Bullet cluster

Best fit Universe



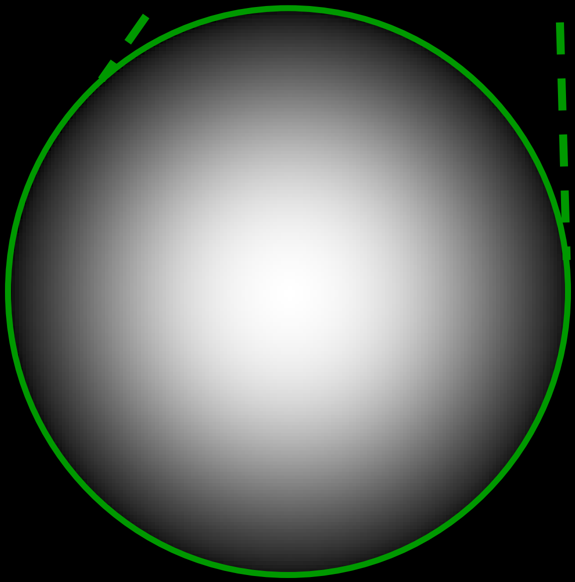
arXiv:1105.3470

What's the universe made of?

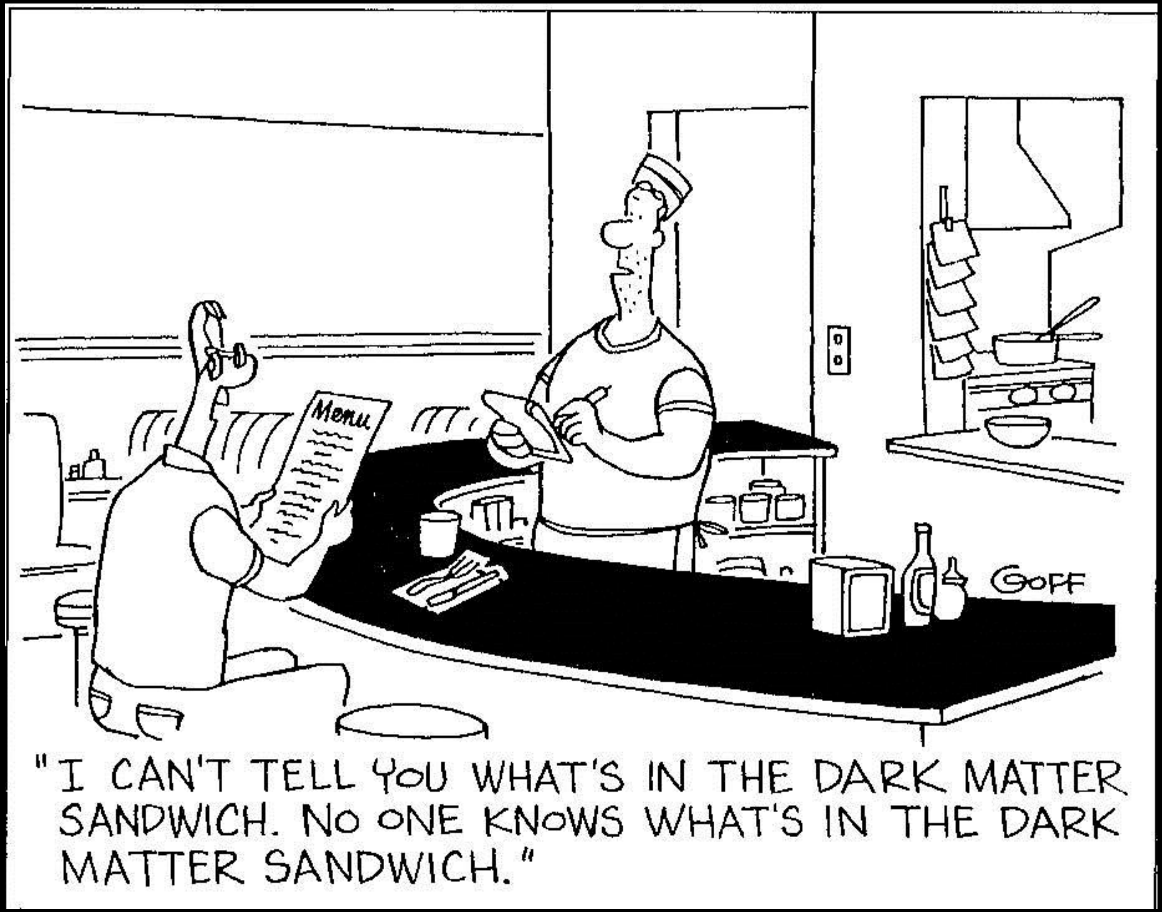


4%

Of all the matter in the universe, only 17% is made of particles we know!!



What is dark matter??



All we know is that dark matter should be made of stable (or very long lived), neutral particles whose abundance today is ~23%

The “miracle”

If dark matter particles were in thermal equilibrium

$$\chi\bar{\chi} \leftrightarrow f\bar{f}, VV, \ldots$$

$$\Gamma = n\langle\sigma \mathrm{v}\rangle >> \mathrm{H}$$

Interaction rate

Density of particles

Scattering cross section (thermal average)

velocity

Expansion rate

If number of dark matter particles does not change (reactions that can change it are inneficient)

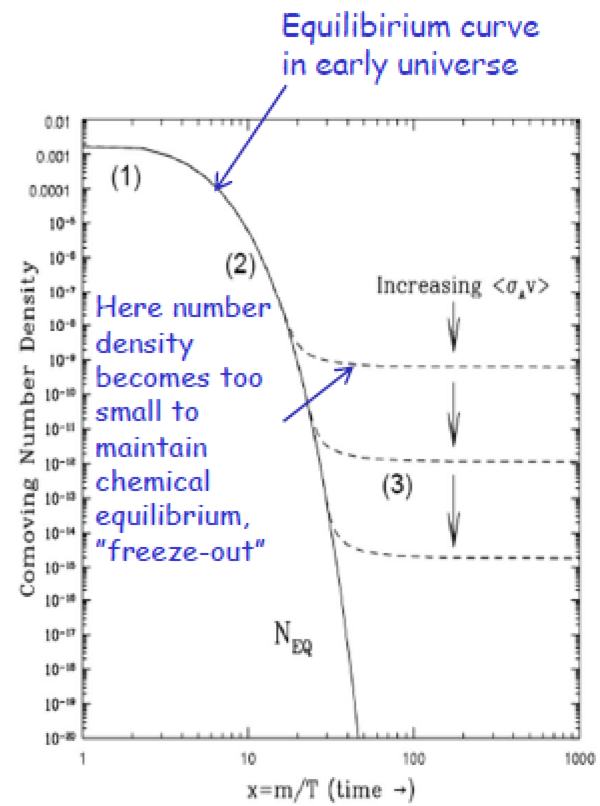
DM DM $\rightleftarrows$ SM

$$\Gamma \approx H$$

Number is frozen (out of chemical equilibrium)

Equilibrium abundance: Boltzmann factor $e^{-m/kT}$ for non-relativistic particles

The longer the particle stays in thermal equilibrium, the smaller is its final abundance



survival of the weakest

Typical cross section for weak interactions

$$\Omega h^2 \approx 0.1 \times \left(\frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle} \right)$$

$$\approx 0.1 \times \left(\frac{\alpha^2 / (200\mathrm{GeV})^2}{\langle \sigma v \rangle} \right)$$

Weakly interacting massive particles (WIMPS) are natural DM candidates

Dark matter candidates

No dark matter candidate in the Standard Model:

New physics!!

- Lightest supersymmetric particle (LSP): neutralino
- Axion
- Lightest KK particle
- Inelastic dark matter
- New scalars (phion, inert Higgs)
- Multicomponent

⋮

Given a model with a DM candidate: many codes that compute the abundance of DM today (MicroOmegas, DarkSUSY, …)

Dark matter candidates

arXiv:0711.4996

DM candidate	I. Ωh^2	II. Cold	III. Neutral	IV. BBN	V. Stars	VI. Self	VII. Direct	VIII. γ-rays	IX. Astro	X. Probed	Result
SM Neutrinos	×	×	✓	✓	✓	✓	✓	–	–	✓	×
Sterile Neutrinos	~	~	✓	✓	✓	✓	✓	✓	✓!	✓	~
Neutralino	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Gravitino	✓	✓	✓	~	✓	✓	✓	✓	✓	✓	~
Gravitino (broken R-parity)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sneutrino $\tilde{\nu}_L$	~	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	~	–	✓!	✓	✓	✓	~
B^1 **UED**	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
Axion	✓	✓	✓	✓	✓	✓	✓!	✓	✓	✓	✓
Heavy photon (Little Higgs)	✓	✓	✓	✓	✓	✓	✓	✓!	✓!	✓	✓
Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	~

I: Test performance of selected DM candidates. The ✓symbol is used when the candidates satisfy the corresponding
ement, and it is accompanied by a ! symbol, in the case that present and upcoming experiment will soon probe a

Production in lab.

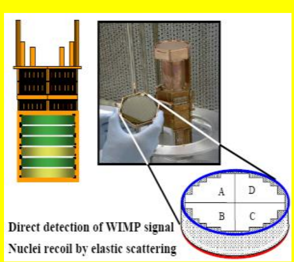
$$SM + SM \to DM + DM$$

Dark Matter

$$SM + DM \to SM + DM$$

$$DM + DM \to SM + SM$$

Direct detection



Indirect detection

Direct detection

Dark matter is all around us

Can we feel the halo?

Answer to Beyoncé

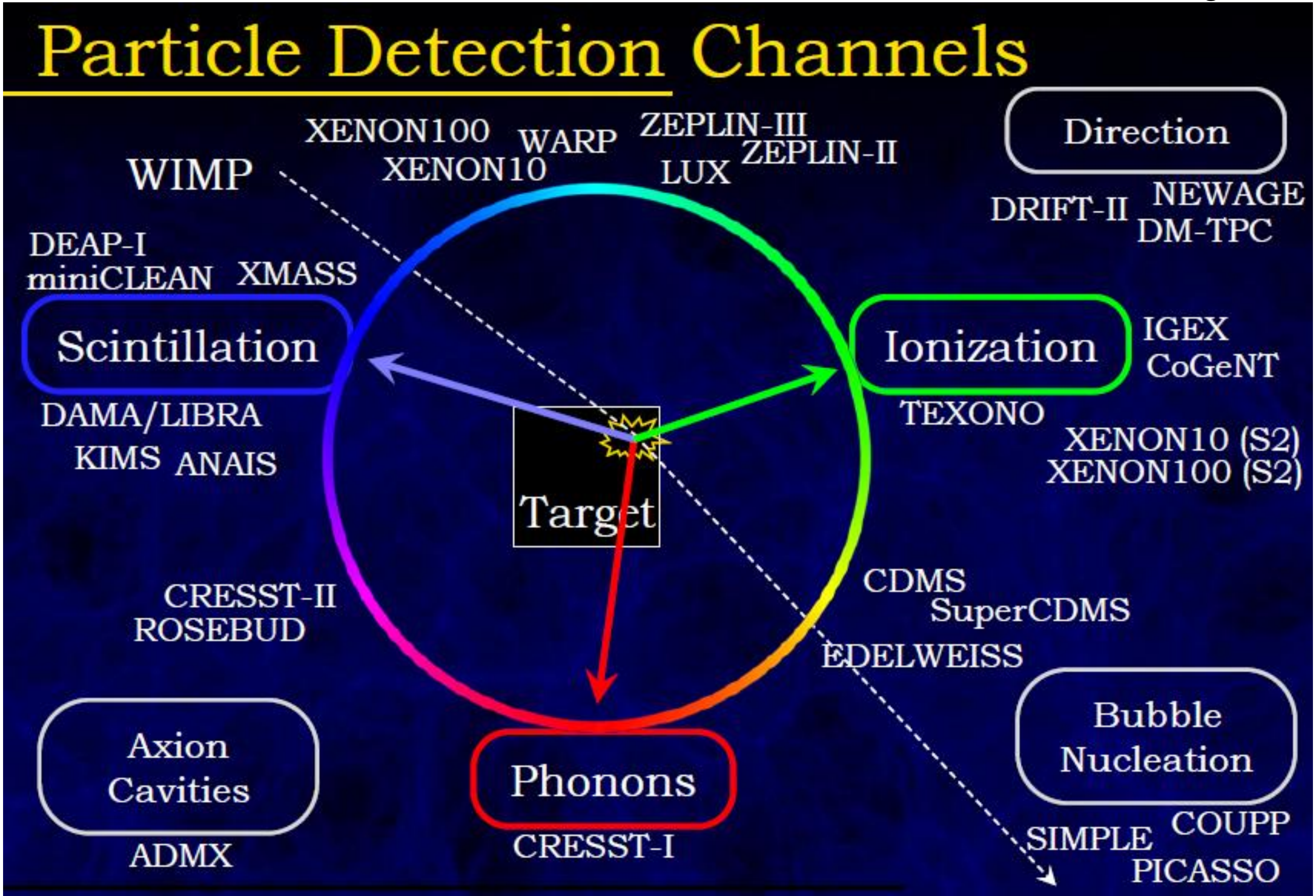
Dark matter particles move in our halo with a typical speed of 240 km/s.

Dark matter density around our solar system is of the order of 0.4 GeV/cm^3.

Approximately 1 billion DM particles crosses a person every second!

A large number of detectors

Lang 2011



In more detail:

1311.4247

The WIMP-nucleus scattering rate within a detected energy interval $[E'_1, E'_2]$, expressed in counts/kg/day, is

target properties

$$R_{[E'_1,E'_2]}(t) = \frac{\rho}{m}\sum_T \frac{C_T}{m_T}\int_0^\infty \mathrm{d}E_\mathrm{R} \int_{v \geqslant v_\mathrm{min}(E_\mathrm{R})} \mathrm{d}^3v\, f(\mathbf{v},t)\, v\, \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}}(E_\mathrm{R},\mathbf{v})\, \epsilon_2(E_\mathrm{R}) \int_{E'_1}^{E'_2} \mathrm{d}E'\, \epsilon_1(E') G_T(E_\mathrm{R}, E').$$

ρ: local dark matter density
m: dark matter mass

Velocity distribution of DM in halo

Detector resolution and efficiencies

Earth's velocity in the galatic frame

Standard halo model

$$f(\mathbf{v},t) = f_\mathrm{G}(\mathbf{u} = \mathbf{v} + \mathbf{v}_\mathrm{E}(t))$$

$$f_\mathrm{G}(\mathbf{u}) = \frac{\exp(-u^2/v_0^2)}{(v_0\sqrt{\pi})^3 N_\mathrm{esc}}\,\theta(v_\mathrm{esc} - u)$$

$$\rho = 0.3\ \mathrm{GeV}/c^2/\mathrm{cm}^3$$

$$v_0 = 220\ \mathrm{km/s}$$

$$v_\mathrm{esc} = 544\ \mathrm{km/s}$$

$$|\mathbf{v}_\odot| = 232\ \mathrm{km/s}$$

The differential cross section for SI interactions is

$$\frac{d\sigma_T}{dE_R} = \sigma_T^{SI}(E_R)\frac{m_T}{2\mu_T^2 v^2},$$

Nuclear form factor

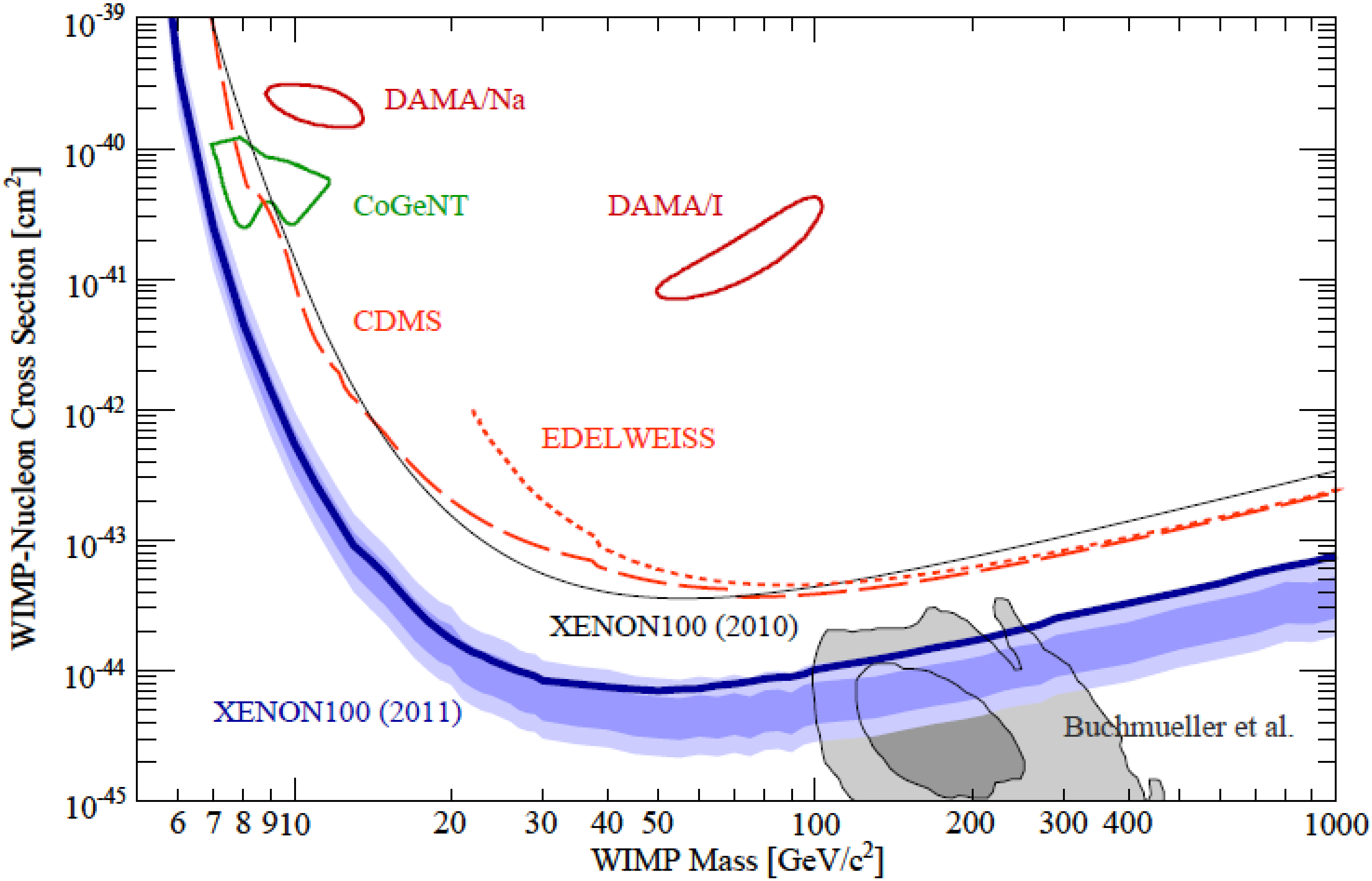
with

$$\sigma_T^{SI}(E_R) = \sigma_p \frac{\mu_T^2}{\mu_p^2}[Z_T + (A_T - Z_T)(f_n/f_p)]^2 F_{SI,T}^2(E_R)$$

Plots for DM mass (m) against DM-proton cross section (σ_p).

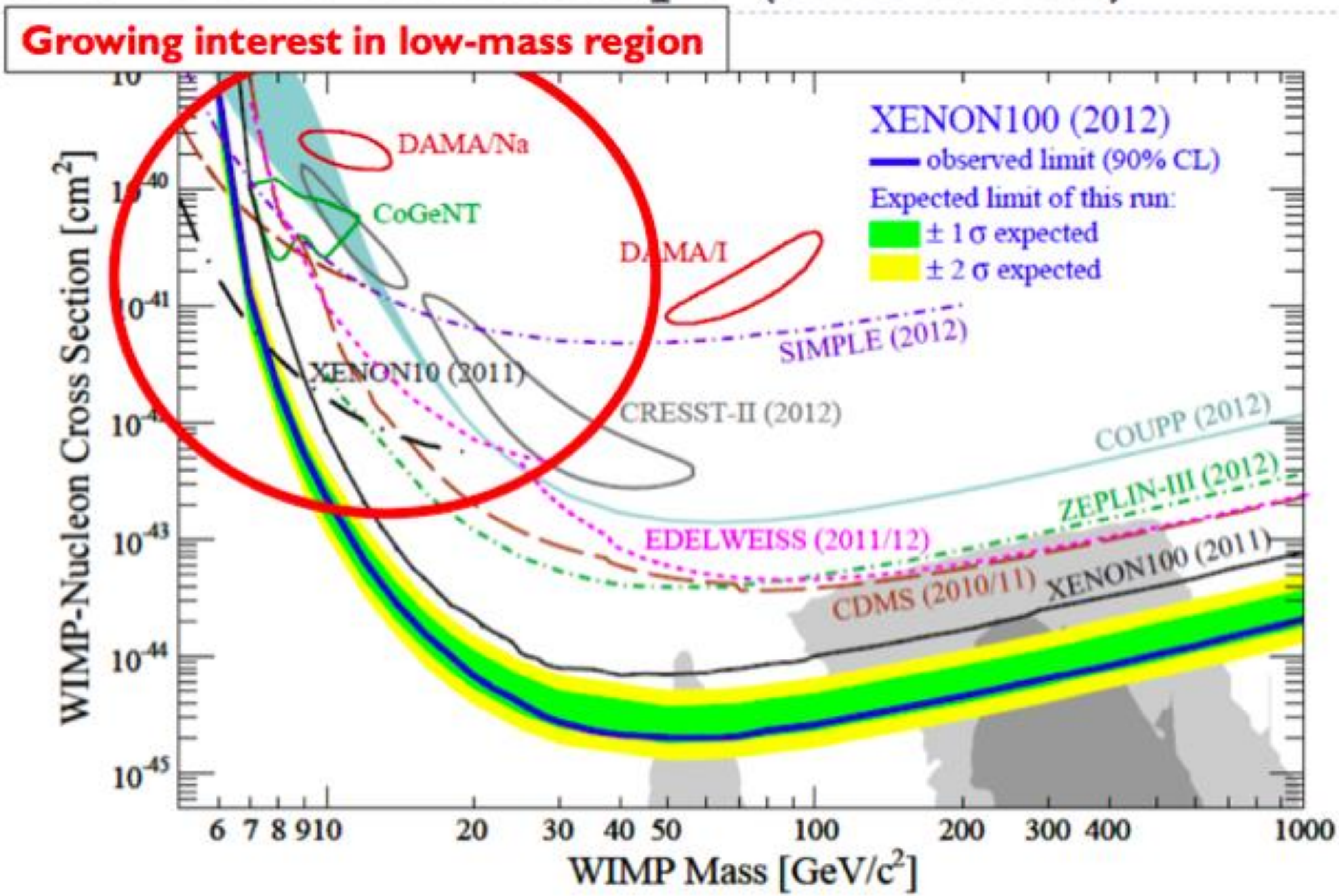
Typical plot

1104.2549



Results are shown in a plot of DM particle-nucleon cross section against its mass

The WIMP landscape (late 2012)



Recent results in direct detection

<u>Cryogenic Dark Matter Search – CDMS II</u> – germanium and silicon detector

Science ***327, 1619 (2010):*** **2 events found with an expected background ~1**

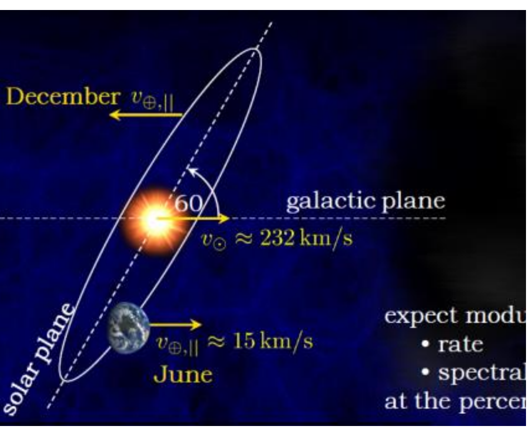
0912.3592

<u>DAMA/LIBRA</u> – NaI crystals

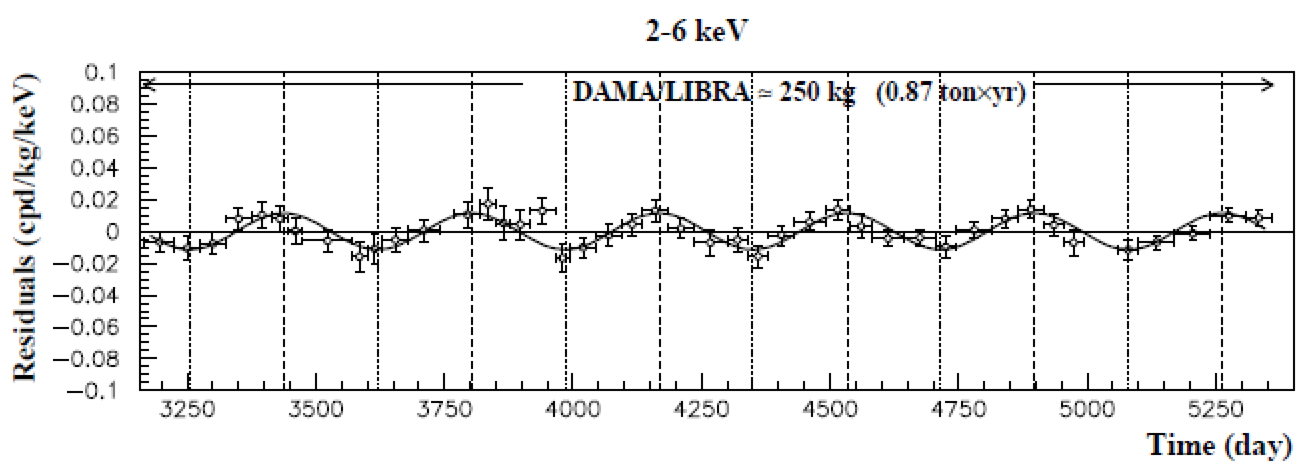
Annual modulation of DM signal due to Earth motion around the Sun.

8.9 σ CL detection of annual modulation over 13 cycles!!

$$v_e = v_\odot + v_{\mathrm{orb}} \cos\gamma \cos[\omega(t - t_0)]$$

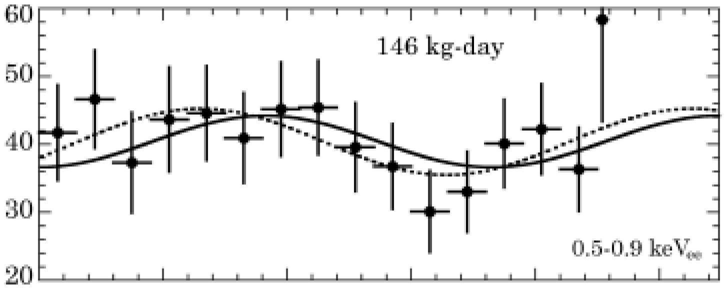


Lang 2011



CoGeNT - Contact Germanium Dark Matter Detector: 2.8 σ signal of annual Modulation (preprint June 3 2011)

1106.0650



XENON 100 – 161 kg liquid xenon - 100.9 live days of data

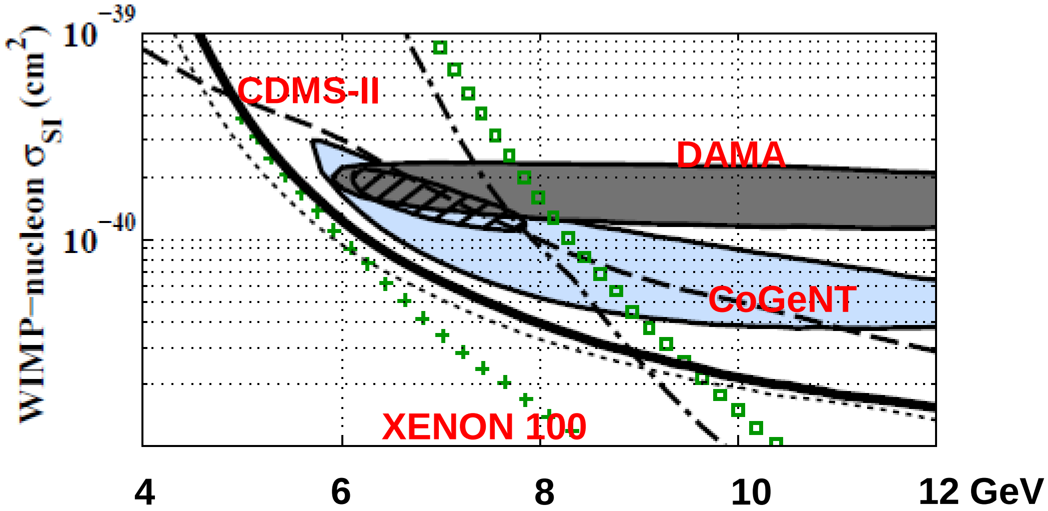
No evidence for dark matter

1104.2549

Some controversy about low mass WIMPS

Low-Energy Analysis of the CDMS II Germanium Data (april 2011)

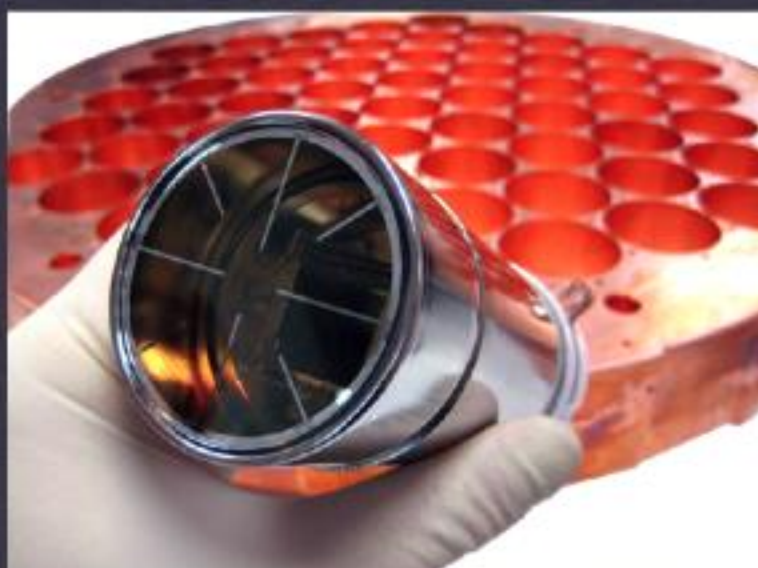
1011.2482v3

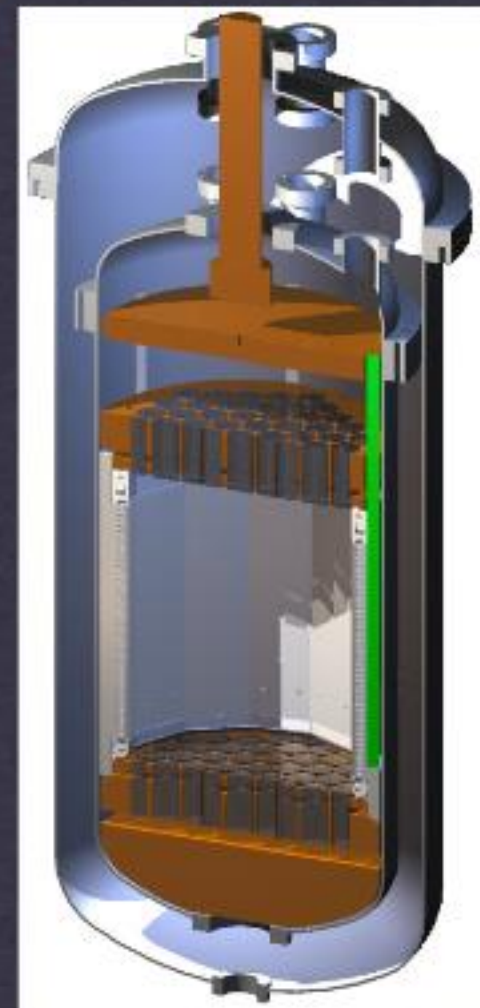


XENON100 and CDMS II Germanium exclude DAMA and CoGeNT regions (even with iDM hypothesis - 1104.3121)

The LUX detector

- 350 kg of xenon, ~100 kg fiducial
- radio-pure titanium cryostat
- internal copper shield
- 122 ultra low background PMTs





LUX first results 1310.8214

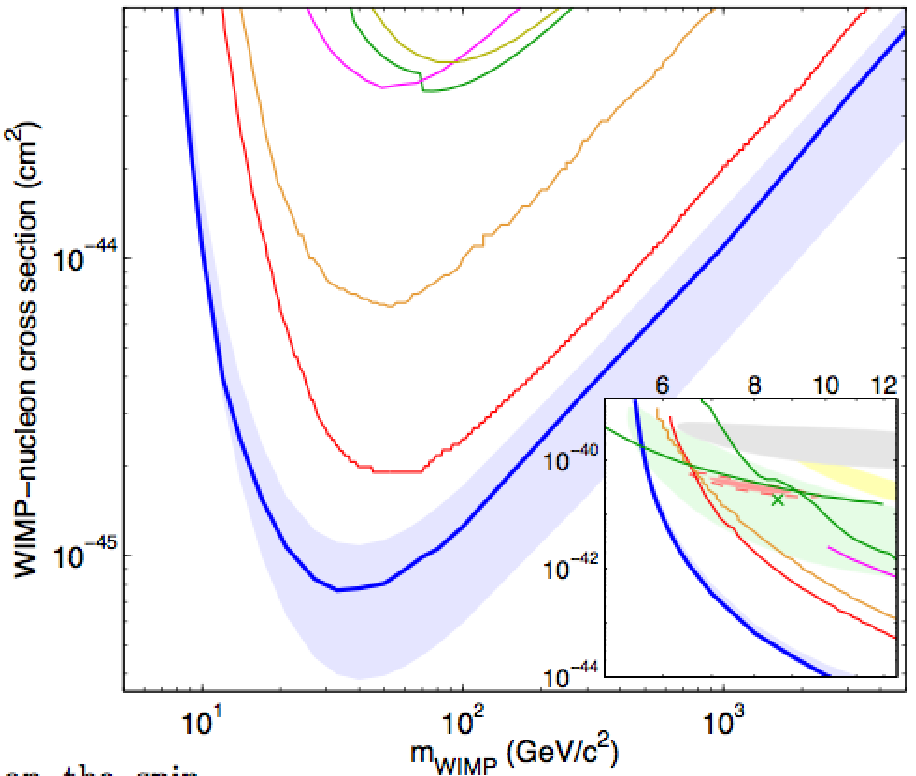
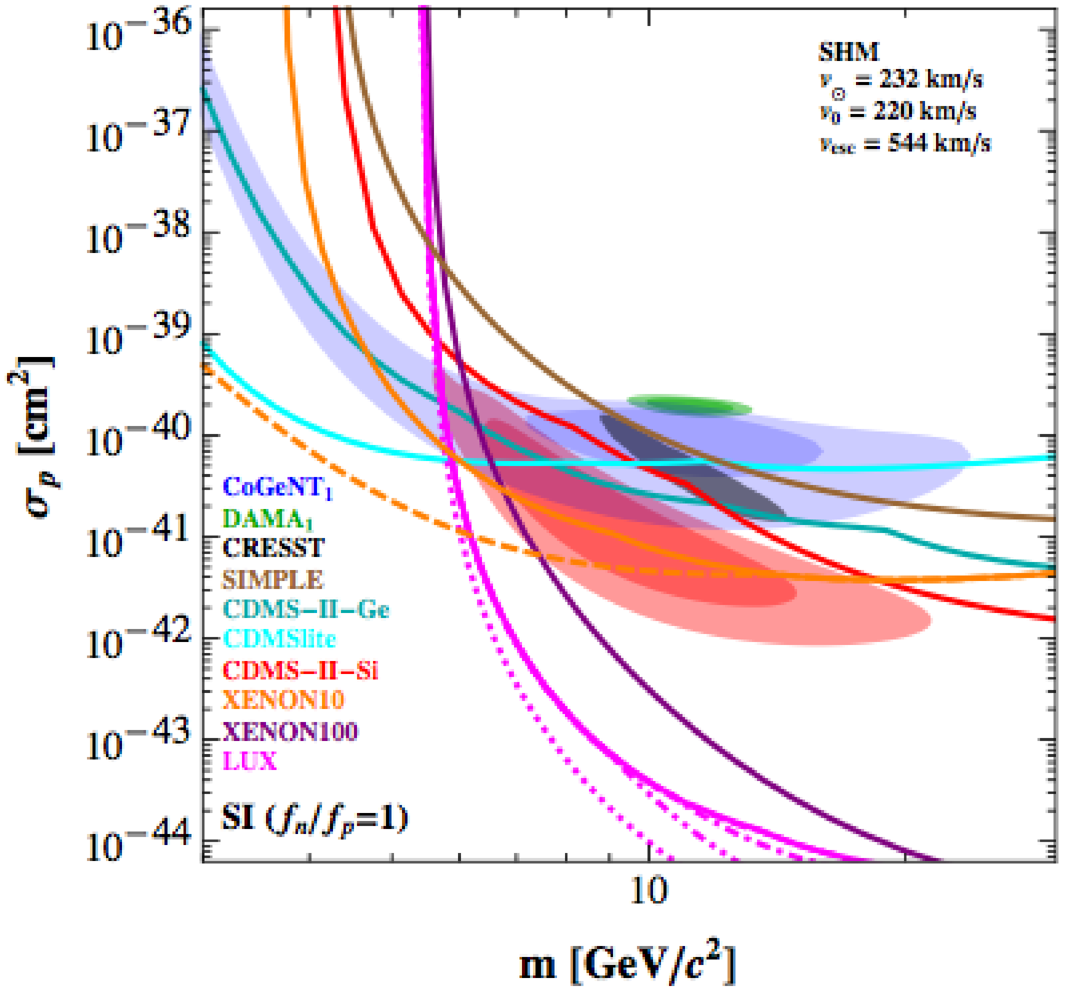


FIG. 5. The LUX 90% confidence limit on the spin-independent elastic WIMP-nucleon cross section (blue), together with the $\pm1\sigma$ variation from repeated trials, where trials fluctuating below the expected number of events for zero BG are forced to 2.3 (blue shaded). We also show Edelweiss II [41] (dark yellow line), CDMS II [42] (green line), ZEPLIN-III [43] (magenta line) and XENON100 100 live-day [44] (orange line), and 225 live-day [45] (red line) results. The inset (same axis units) also shows the regions measured from annual modulation in CoGeNT [46] (light red, shaded), along with exclusion limits from low threshold re-analysis of CDMS II data [47] (upper green line), 95% allowed region from CDMS II silicon detectors [48] (green shaded) and centroid (green x), 90% allowed region from CRESST II [49] (yellow shaded) and DAMA/LIBRA allowed region [50] interpreted by [51] (grey shaded).

1311.4247

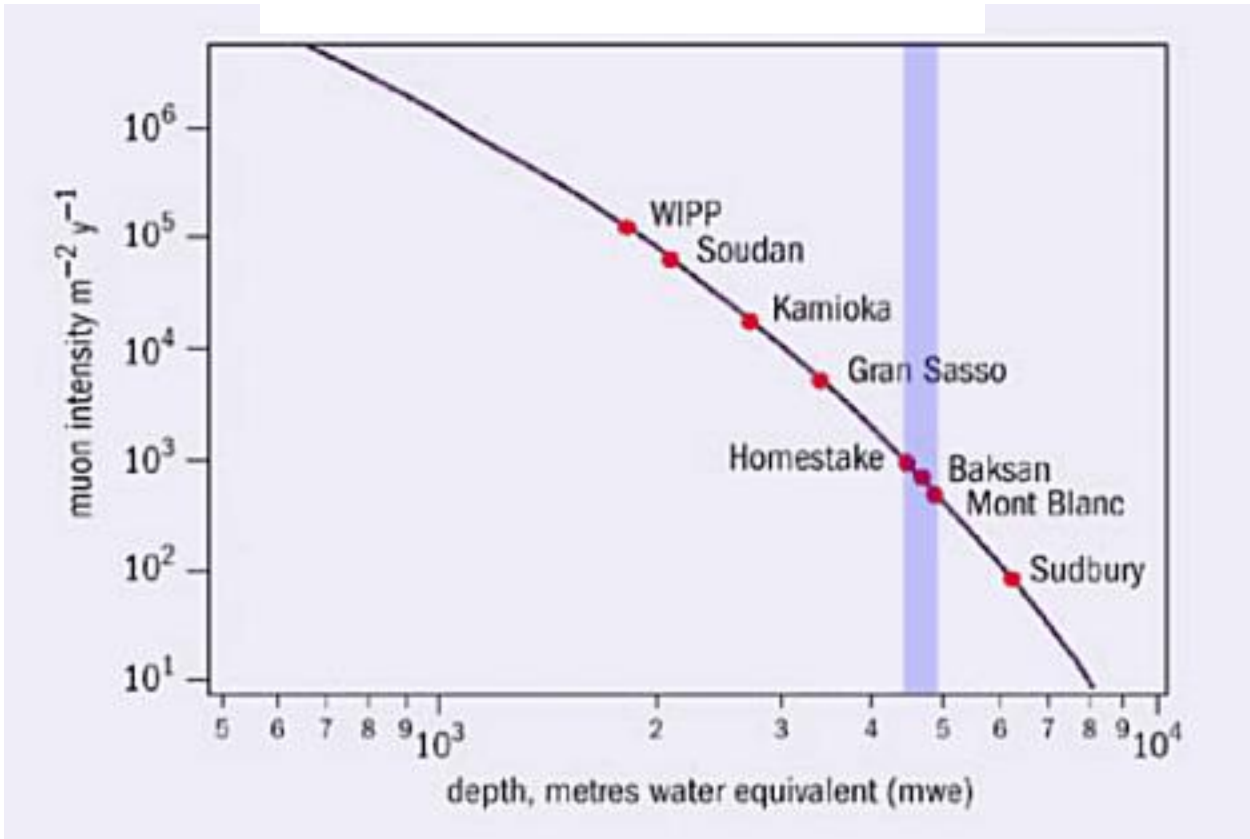


SHM
$v_\odot$ = 232 km/s
v_0 = 220 km/s
v_{esc} = 544 km/s
CoGeNT$_1$
DAMA$_1$
CRESST
SIMPLE
CDMS−II−Ge
CDMSlite
CDMS−II−Si
XENON10
XENON100
LUX
SI (f_n/f_p=1)
σ_p [cm^2]
m [GeV/c^2]
10
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}


ANDES
Agua Negra Deep Experiment Site
AN UNDERGROUND LABORATORY IN THE
AGUA NEGRA TUNNEL

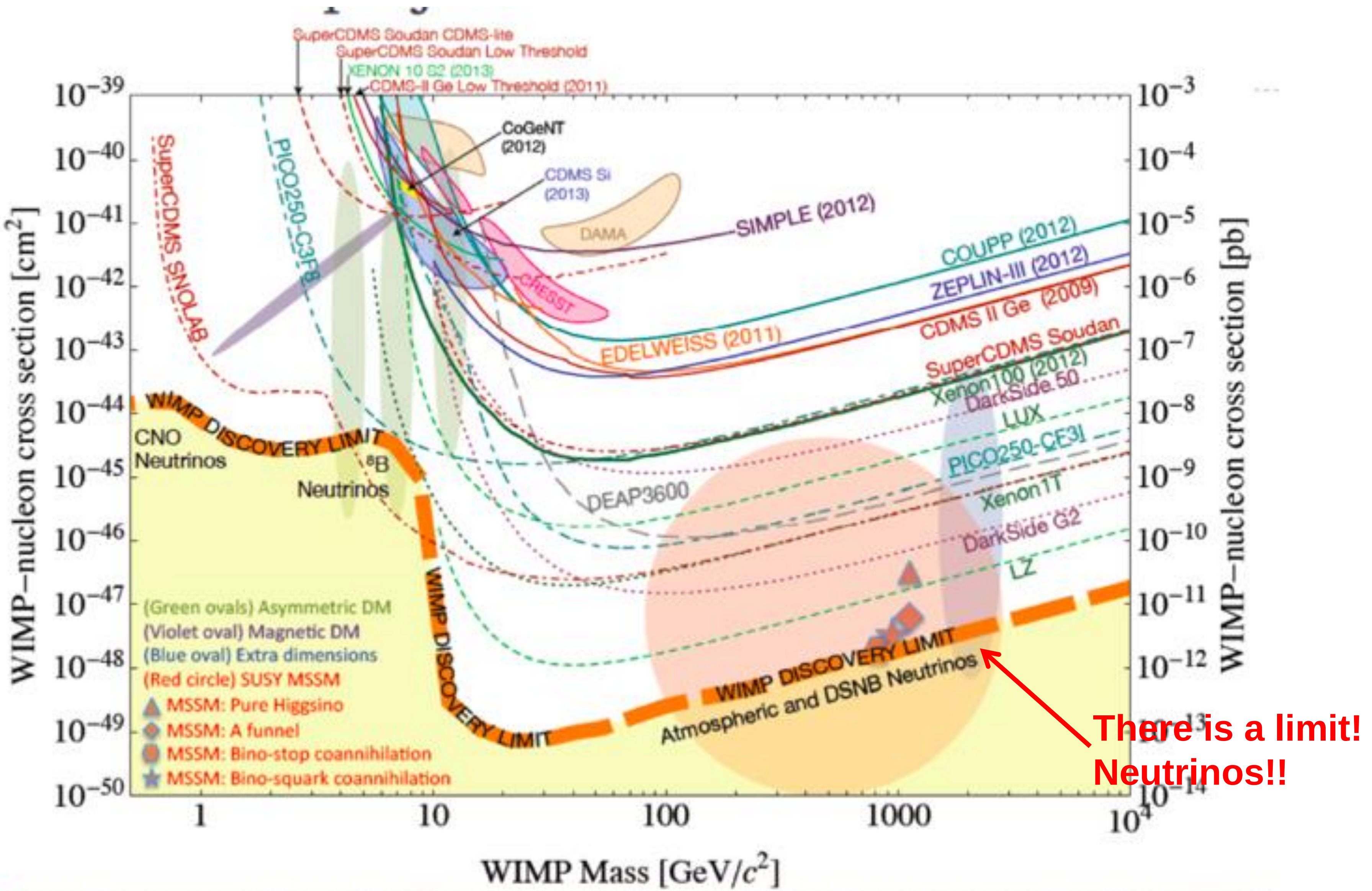
4500-4800 mwe

- World class location



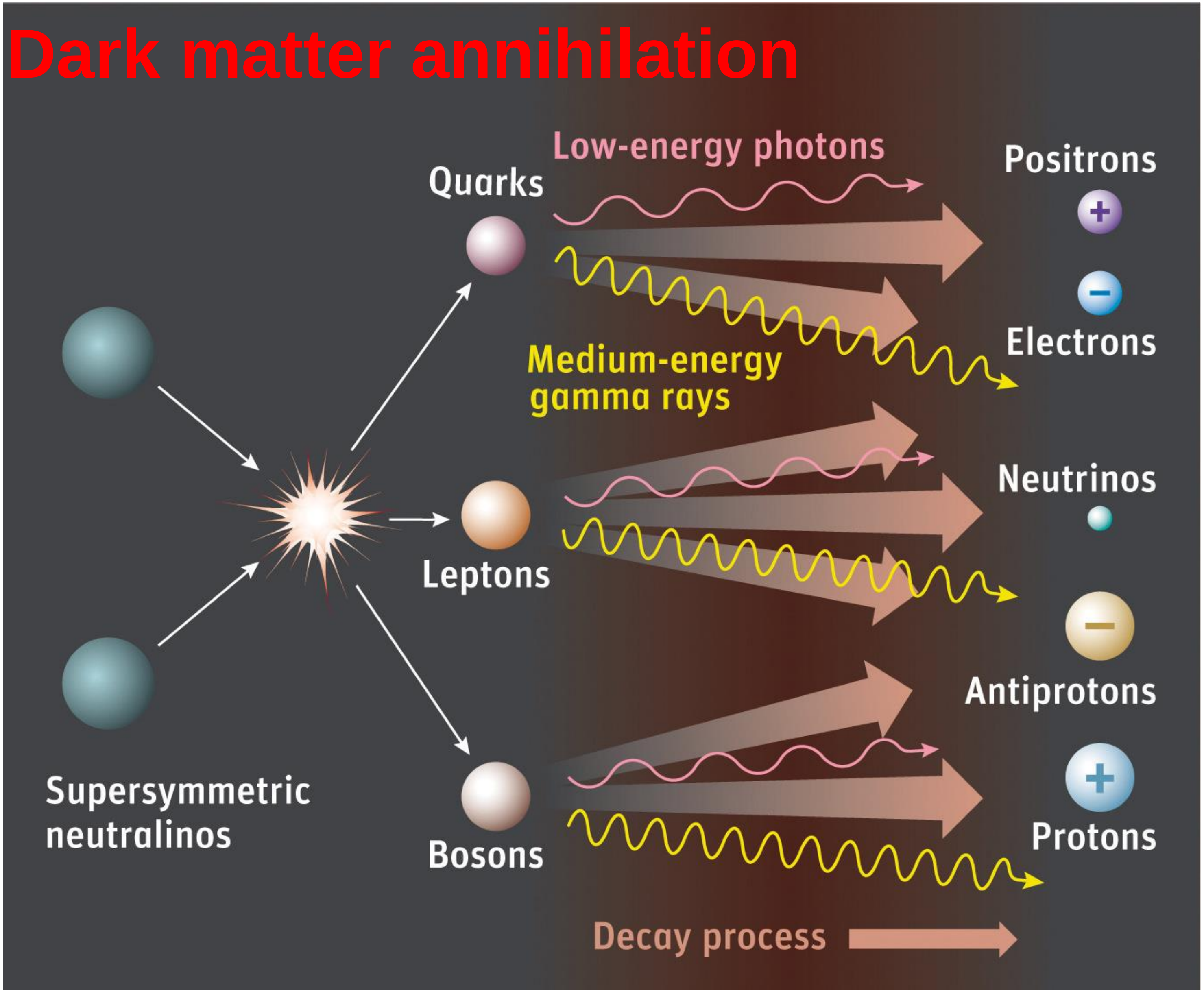
It is important to have a DM detector in the southern hemisphere to study the effects of sazonality in the modulation of DM signal

The future



SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
SuperCDMS SNOLAB
PICO250-C3F8
WIMP DISCOVERY LIMIT
CNO Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
There is a limit! Neutrinos!!

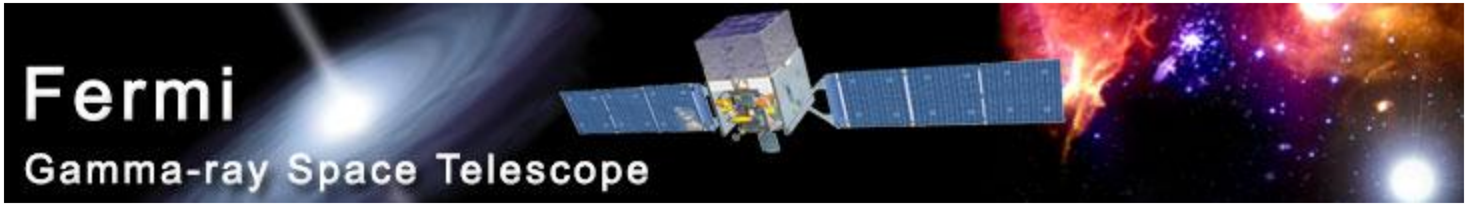
Indirect detection of dark matter



Sky & Telescope / Gregg Dinderman

Indirect detection of dark matter: photons

Launched in 11/06/2008

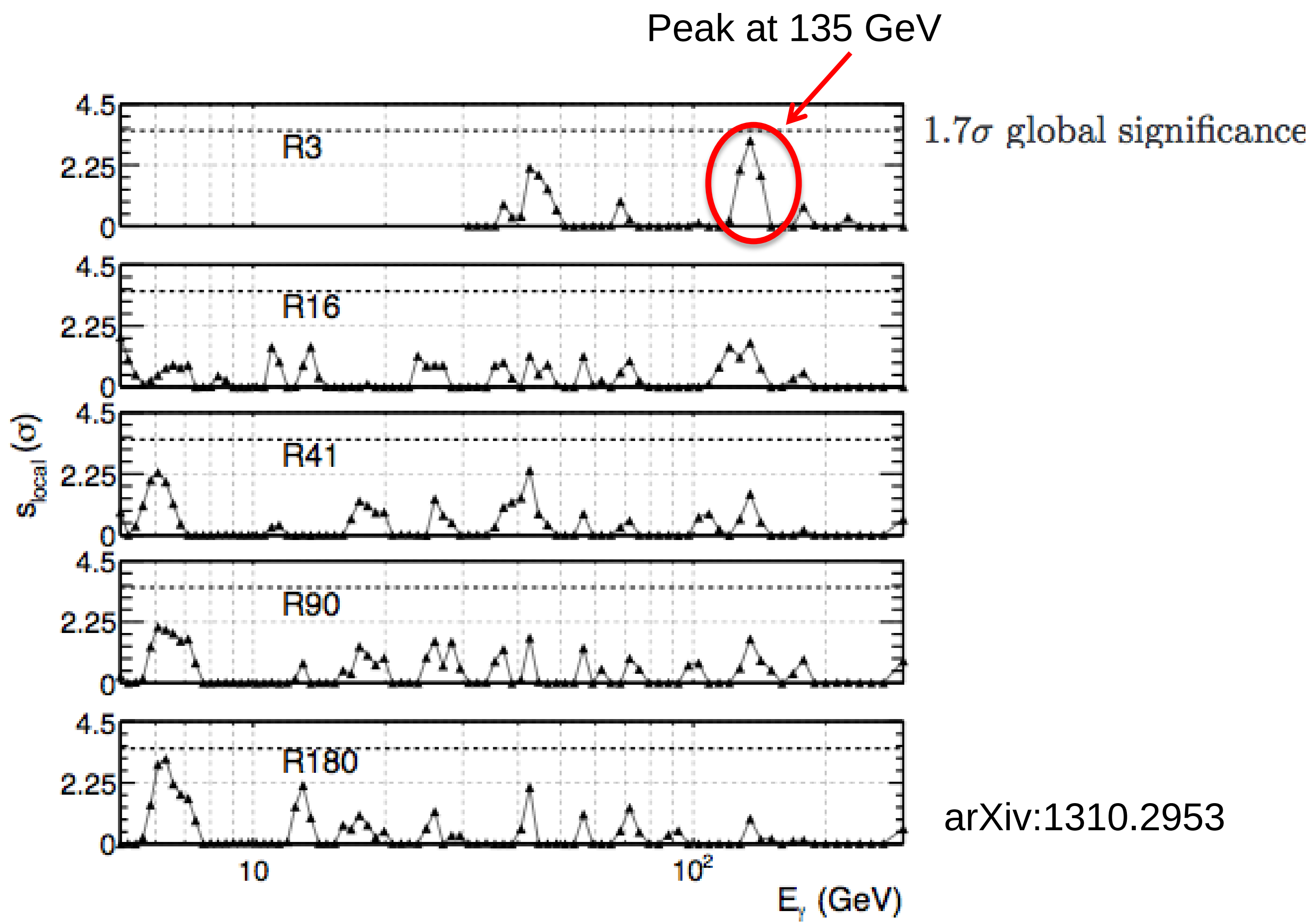


Large Area Telescope (LAT)- 20 MeV to 300 GeV photons

γ lines: tell-tale of DM annihilation

$$\chi\bar{\chi}\rightarrow\gamma\gamma, Z\gamma$$

- A lot of noise about a possible signal from the galactic center – where there is the largest concentration of DM (annihilation is proportional to the square of the density)



I wouldn't get too excited...

Photons from "dwarf" Milky Way sattelite galaxies using Fermi LAT – 1310.0829

The dwarf spheroidal satellite galaxies of the Milky Way are especially promising targets for the indirect detection of dark matter annihilation due to their large dark matter content, proximity, low diffuse Galactic γ-ray foregrounds, and lack of conventional astrophysical γ-ray production mechanisms.

$$\chi\bar{\chi} \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \bar{u}u, \bar{b}b, W^+W^-$$

These decay products also generate photons with "continuum" energy. Photon flux depend on the particle physics model (annihilation cross section, BR's, DM mass) and astrophysical model (halo density profile)

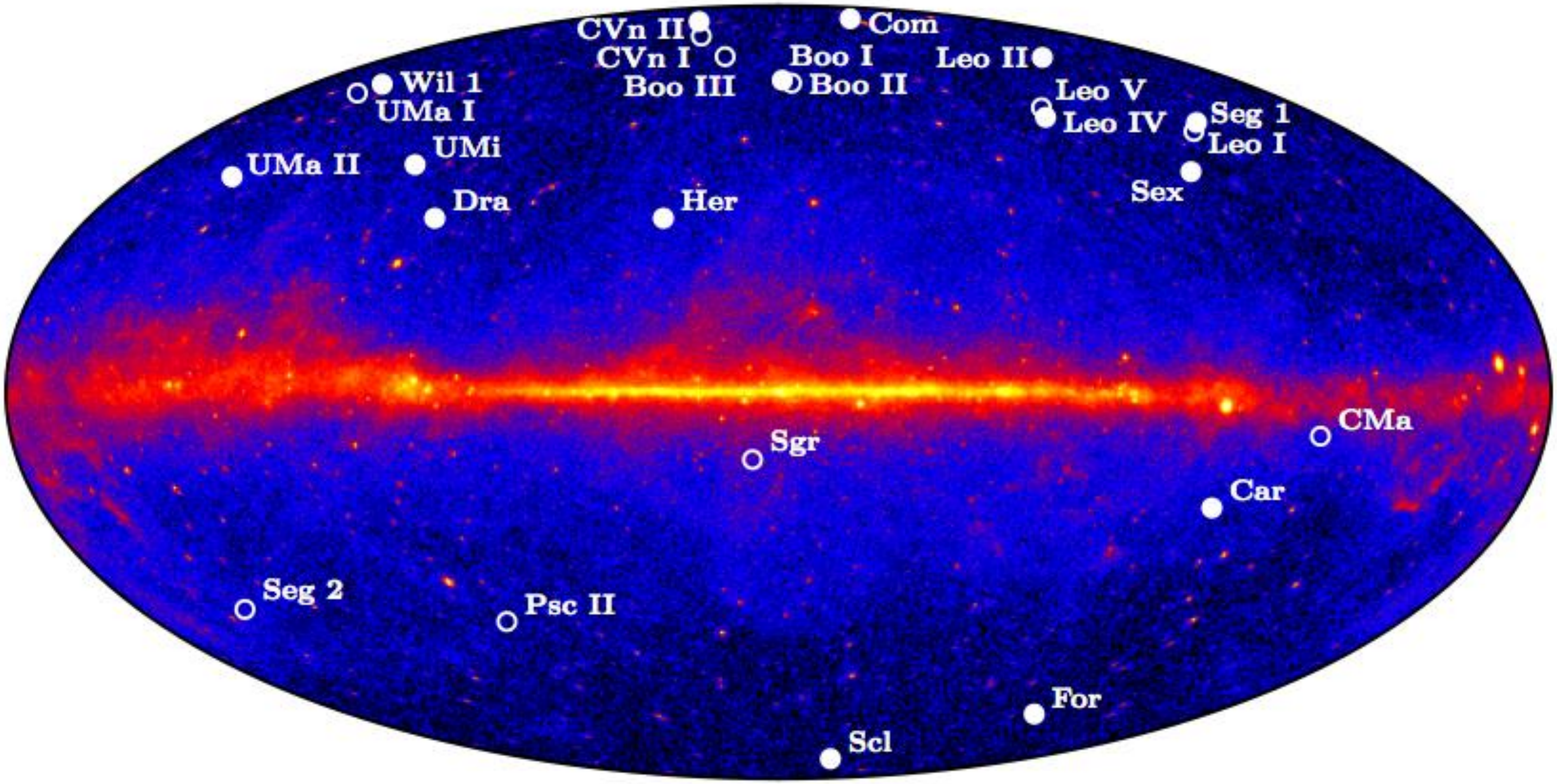
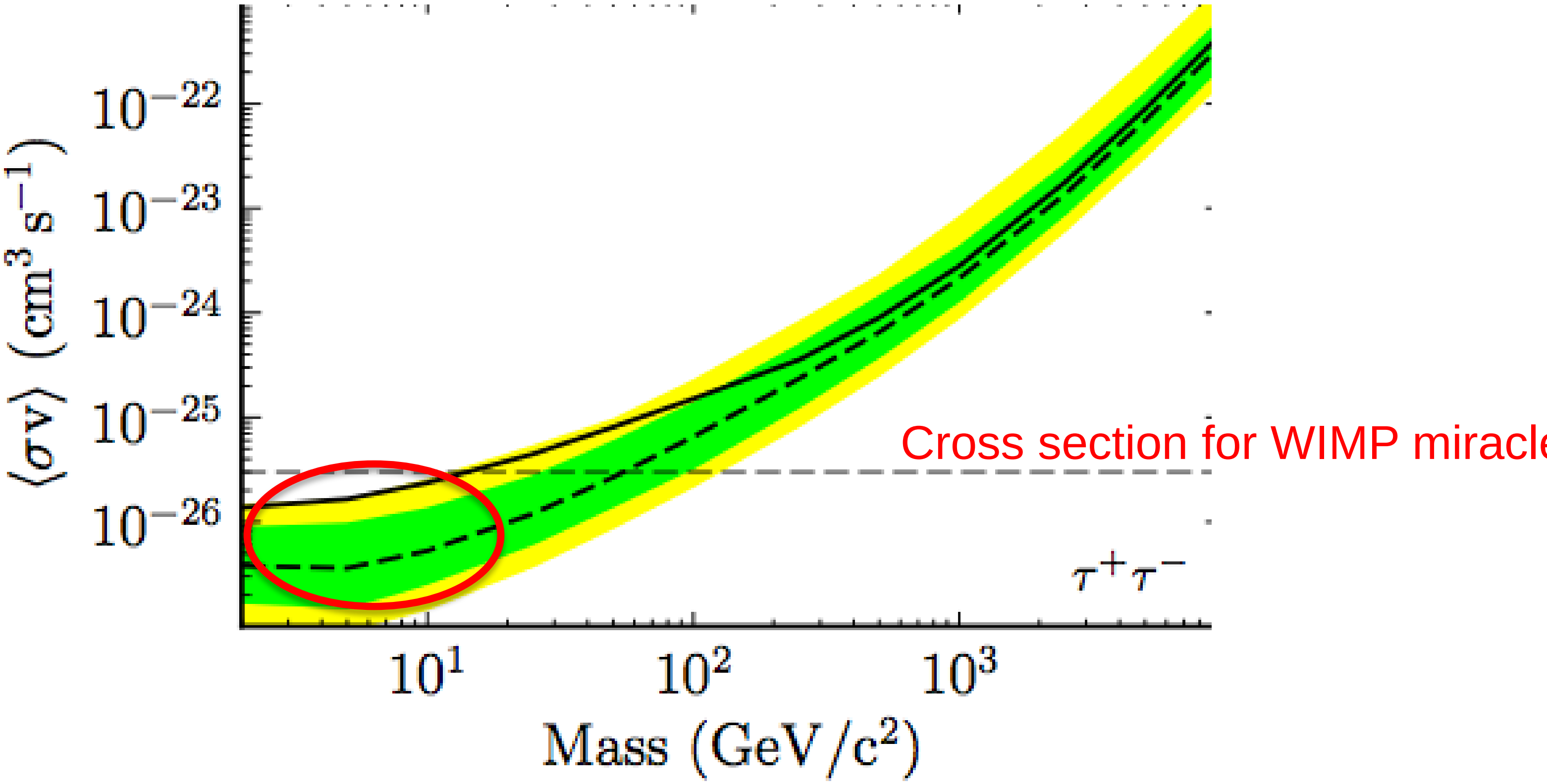


FIG. 1. Known dwarf spheroidal satellite galaxies of the Milky Way overlaid on a Hammer-Aitoff projection of a 4-year LAT counts map ($E > 1$ GeV). The 15 dwarf galaxies included in the combined analysis are shown as filled circles, while additional dwarf galaxies are shown as open circles.

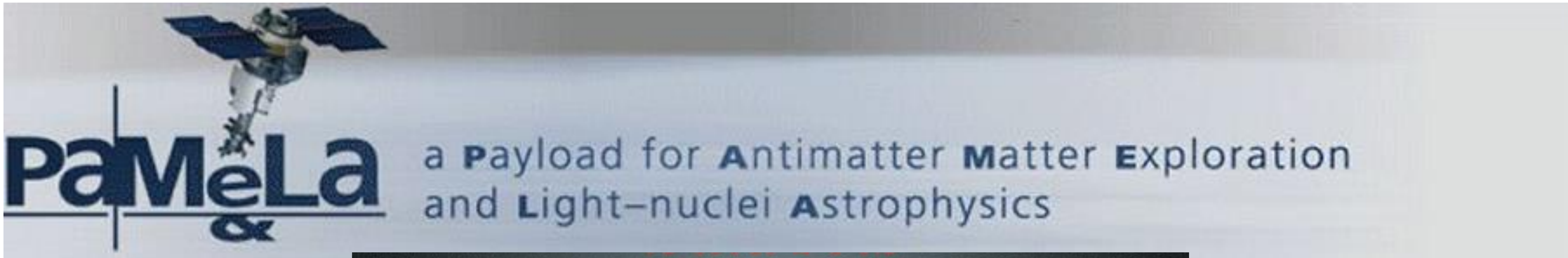
One example

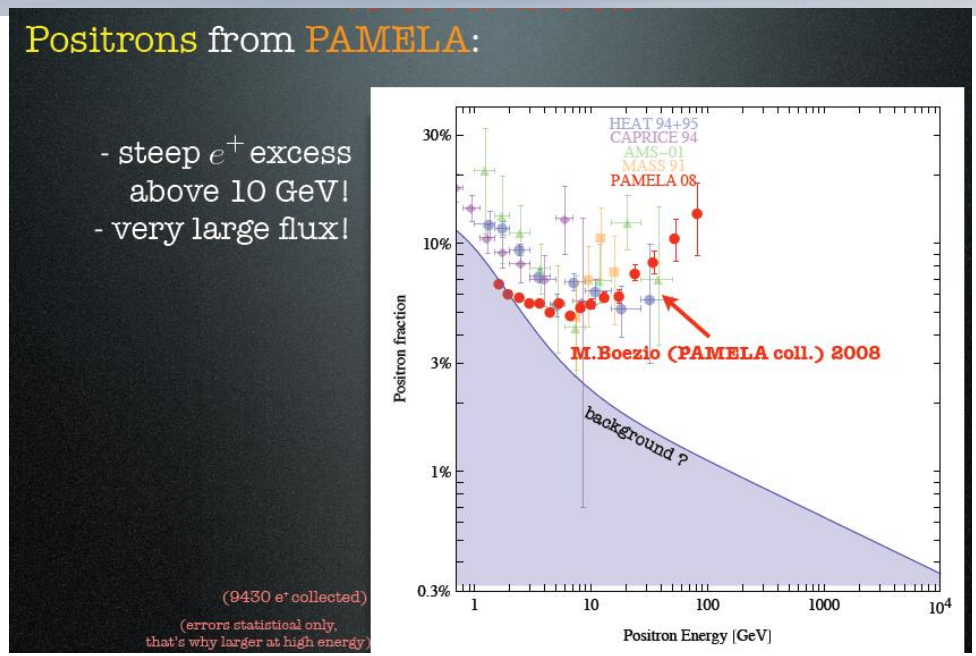


Masses less than ~10 GeV are excluded

But be careful with assumptions

Indirect detection of dark matter: anti-matter





Advanced Thin Ionization Calorimeter (ATIC)
Small excess in the 700 GeV region.

AMS

Selected for a Viewpoint in *Physics*

PRL 110, 141102 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–350 GeV

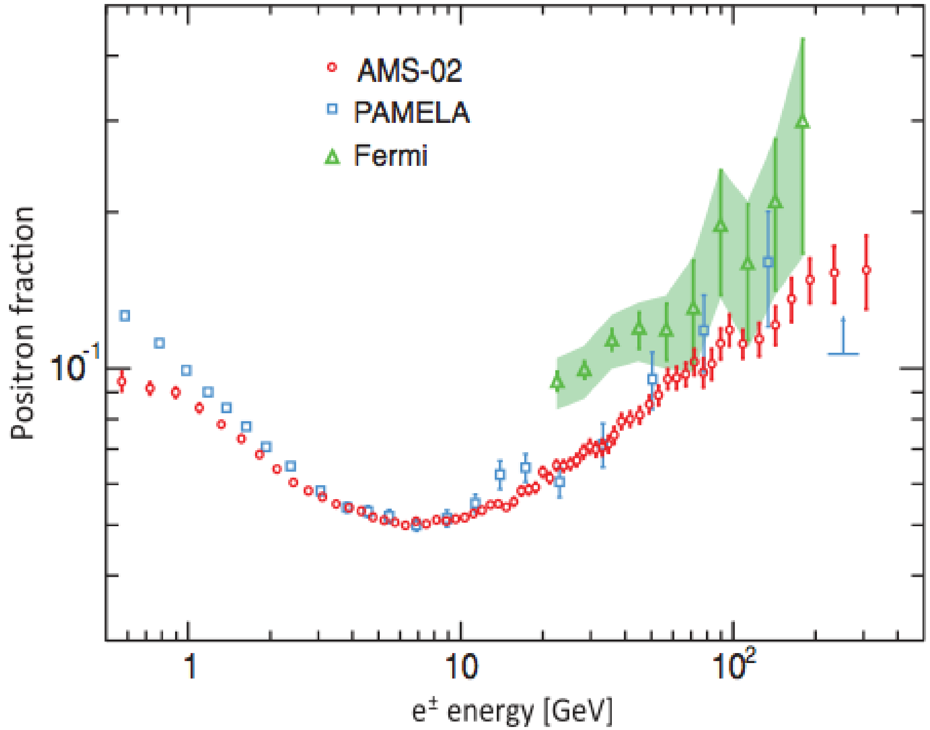
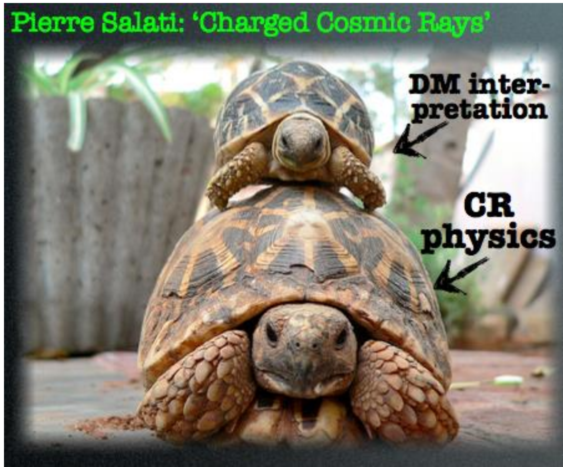
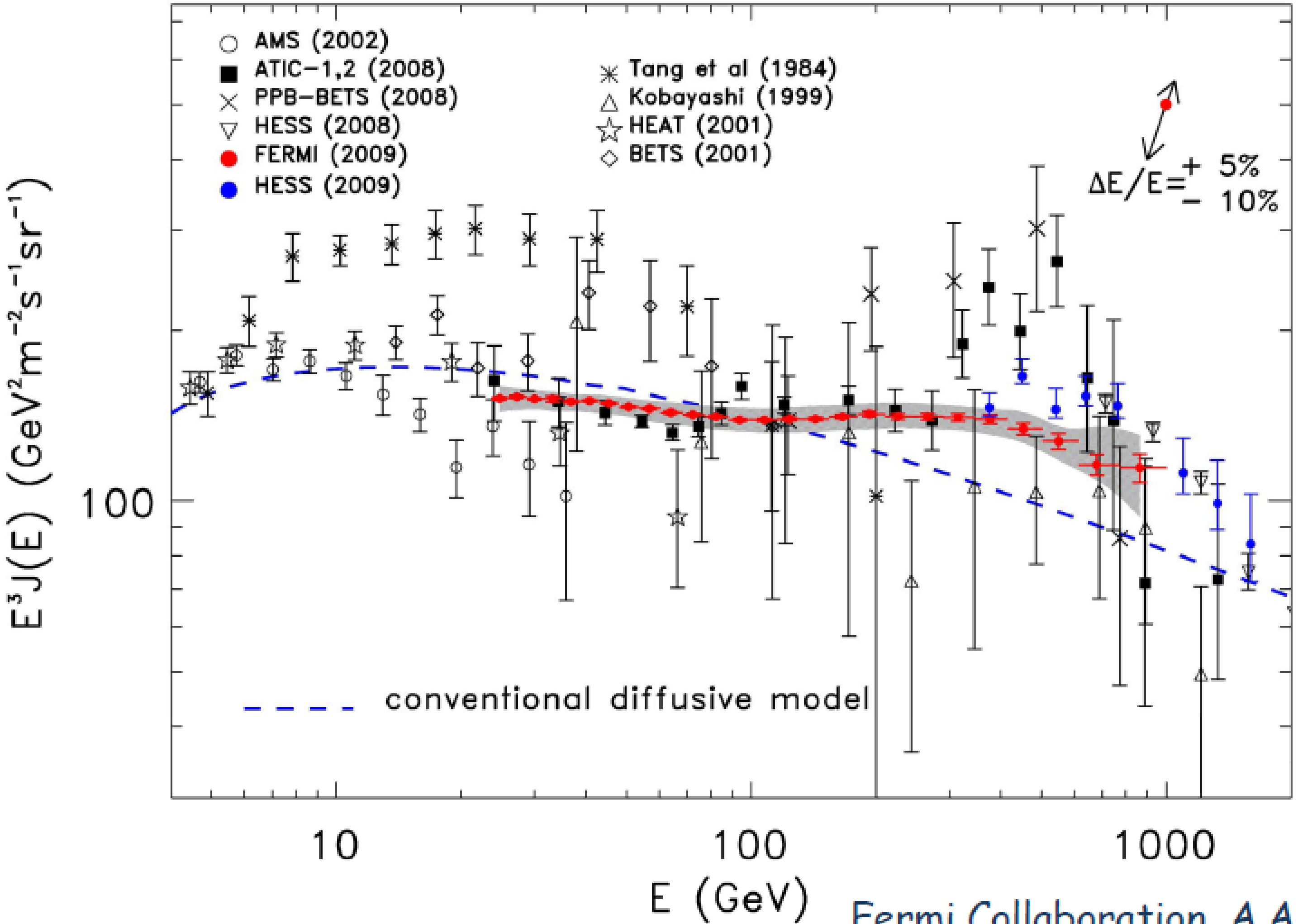


FIG. 5 (color). The positron fraction compared with the most recent measurements from PAMELA [22] and Fermi-LAT [23]. The comparatively small error bars for AMS are the quadratic sum of the statistical and systematic uncertainties (see Table I and [13]), and the horizontal positions are the centers of each bin.

But what is the expected background??



Sum of electron and positron flux versus energy:

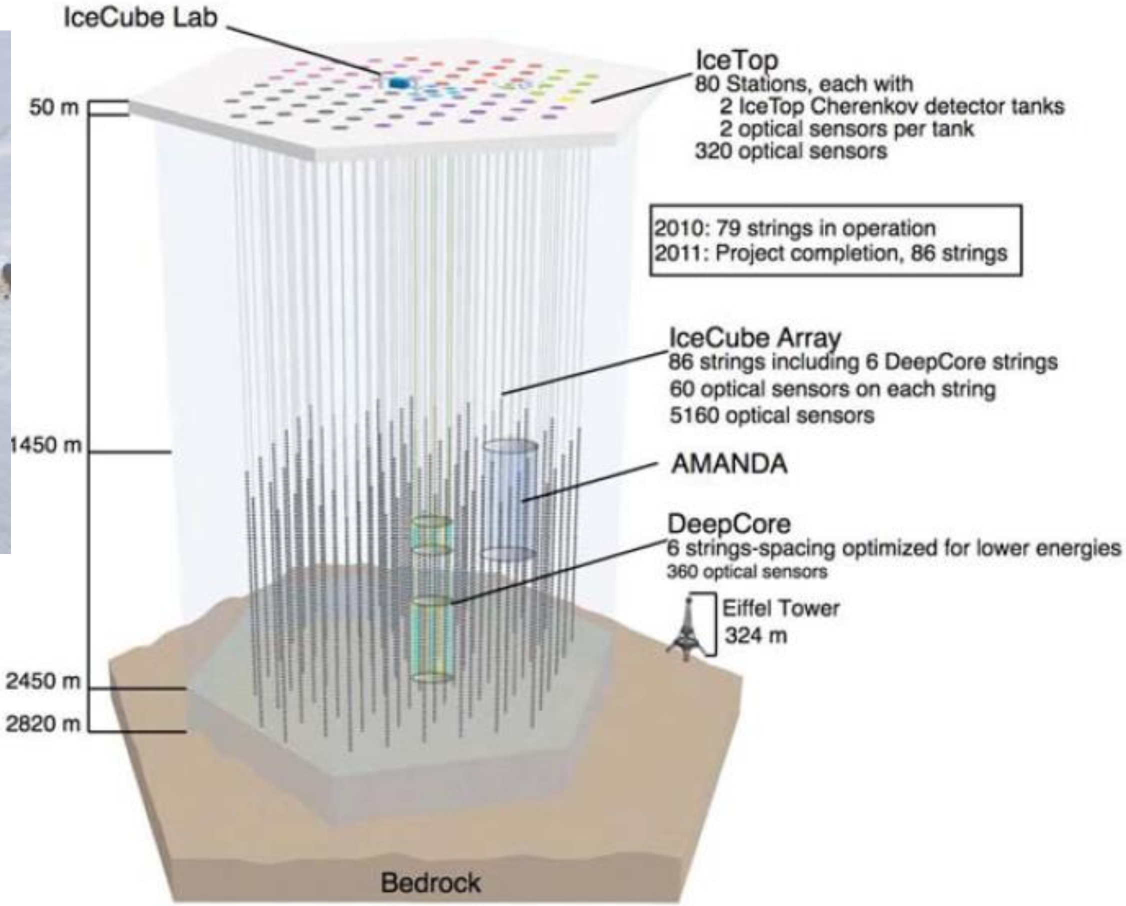


Fermi Collaboration, A.A. Abdo & al, Phys. Rev. Lett., May, 2009

Astrophysical explanation is more plausible: local pulsars?

Indirect detection of dark matter: neutrinos

IceCube: neutrino detector with 1 km^3 in South Pole. It has 5,160 digital optical modules suspended along 86 strings.

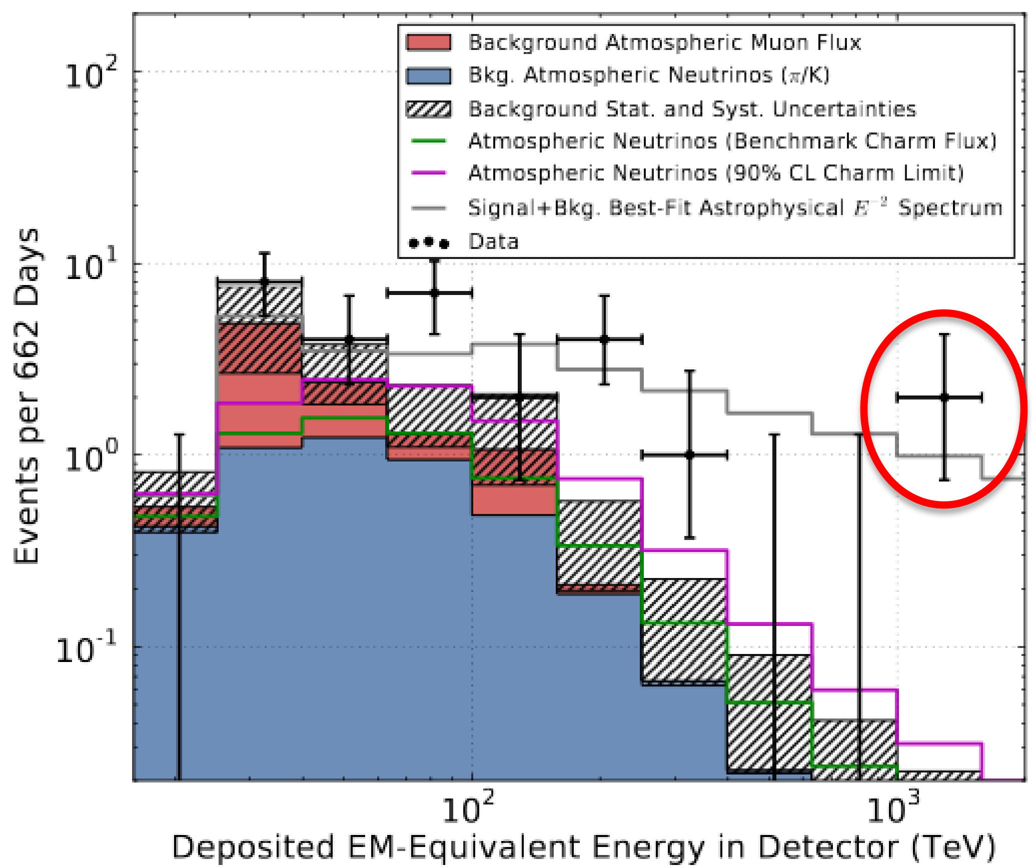


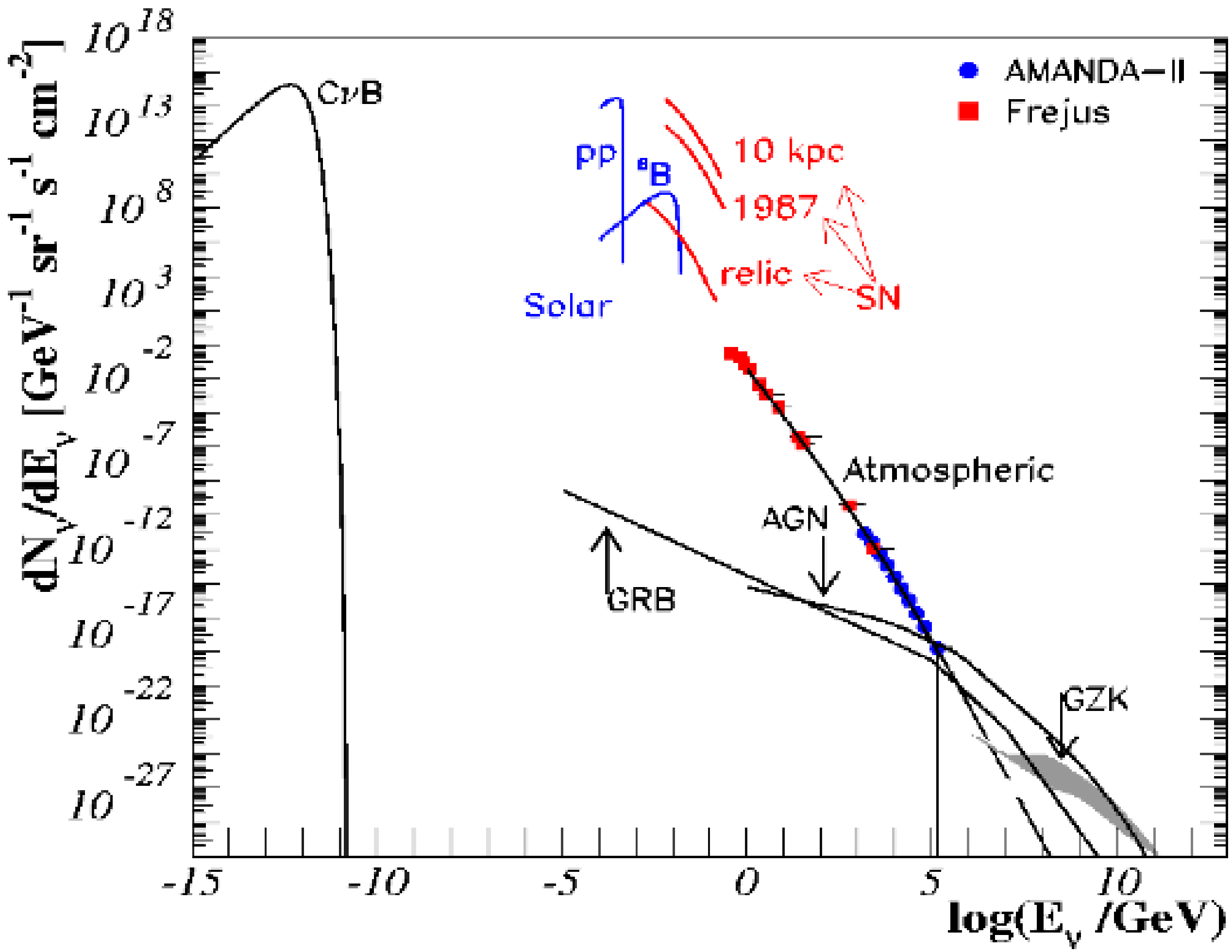
Indirect detection of dark matter: neutrinos

Article in Science – November 22 2013
First detection of neutrinos of cosmic origin (?)

arXiv:1311.5238

Excess of 28 neutrinos observed with energies above 60 TeV.





1311.6350

Figure 1: The cosmic-neutrino spectrum. Sources are the Big Bang (CνB), the Sun, supernovae (SN), atmospheric neutrinos, gamma-ray bursts (GRB), active galactic nuclei (AGN), and cosmogenic (GZK) neutrinos. The data points are from a detector at the Fréjus underground laboratory [17] (red) and from AMANDA [18] (blue). Figure courtesy of J. Becker [5].

Making dark matter at the LHC

LHC results - 7/8 TeV

Discovery of the Higgs particle !

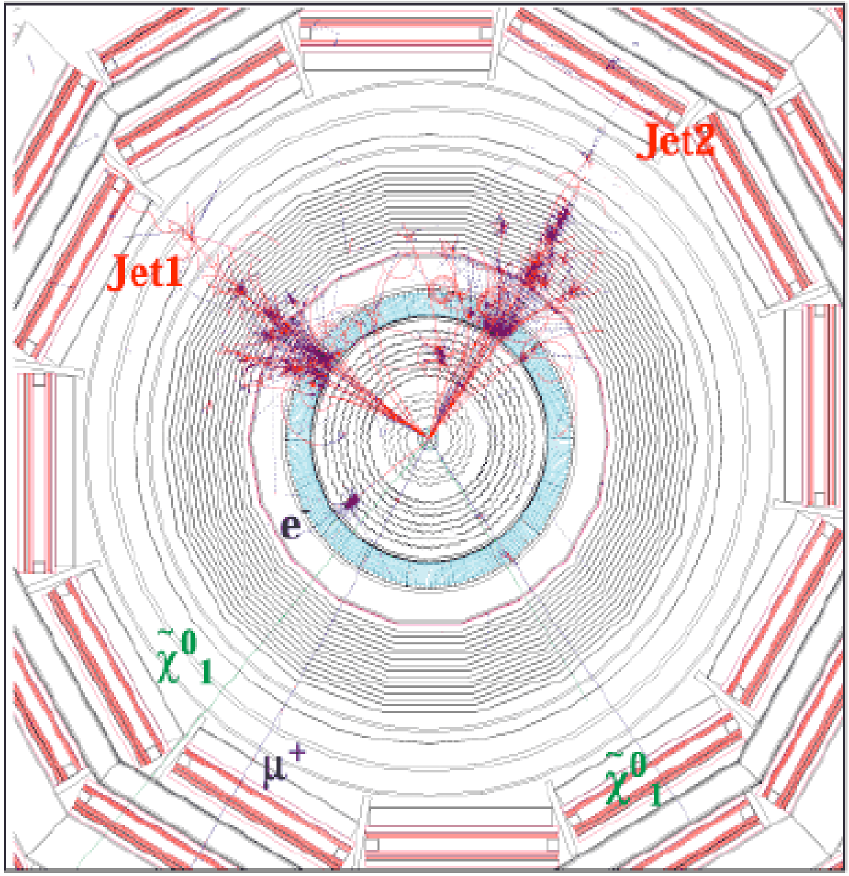
First sign of headache?

- No SUSY ?
- Nothing else ?

Heidi Sandeker – WIN2013

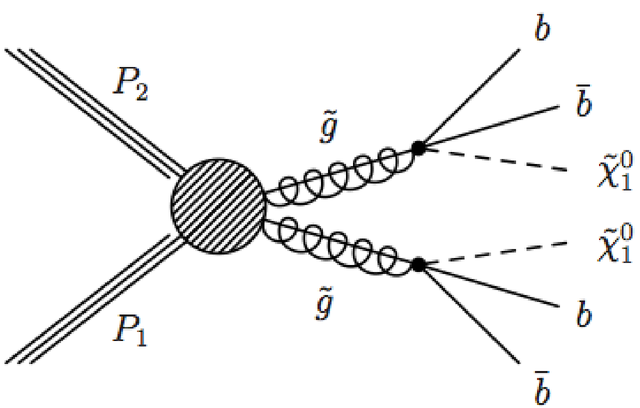
Making dark matter at the LHC

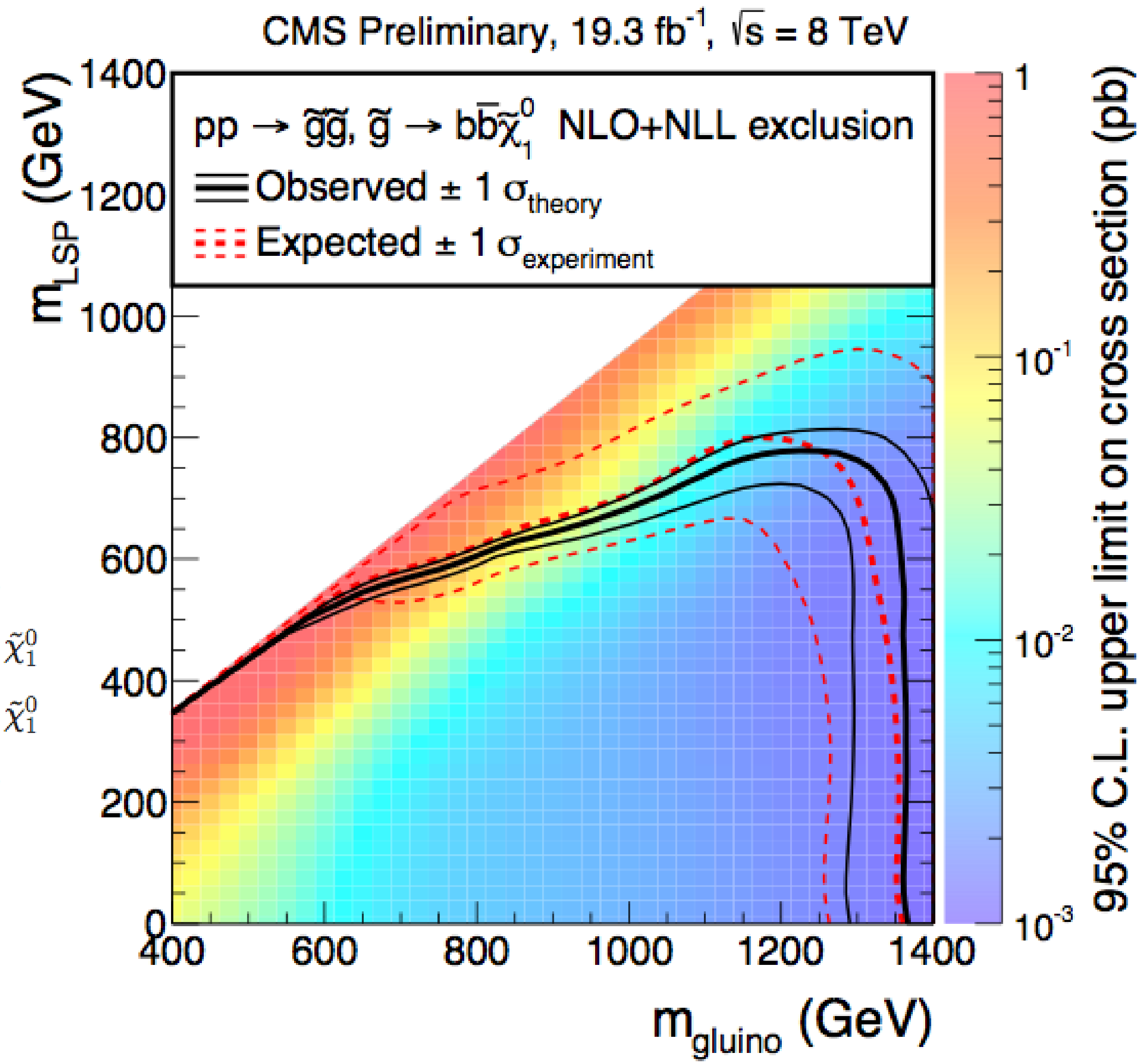
Signal for WIMPS: missing energy



Making dark matter at the LHC

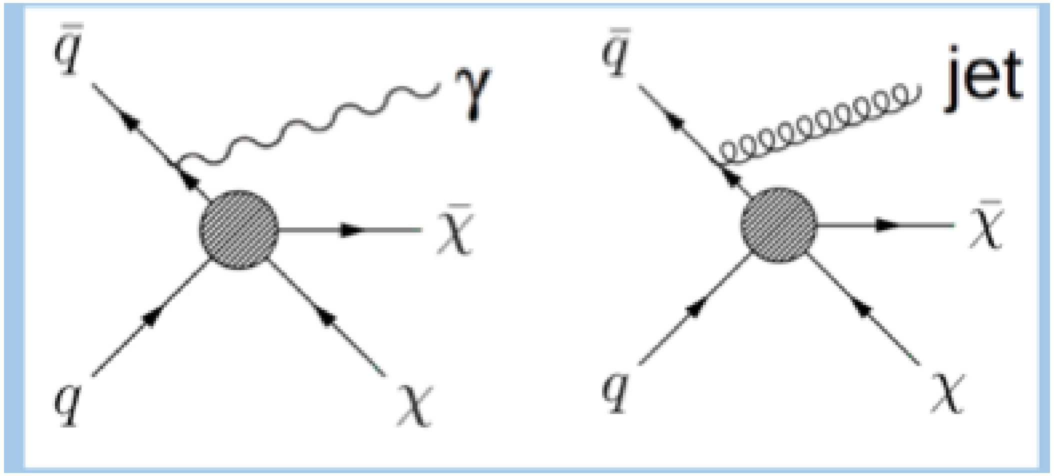
Many SUSY searches. Example: dark matter from gluino pair production





Making dark matter at the LHC

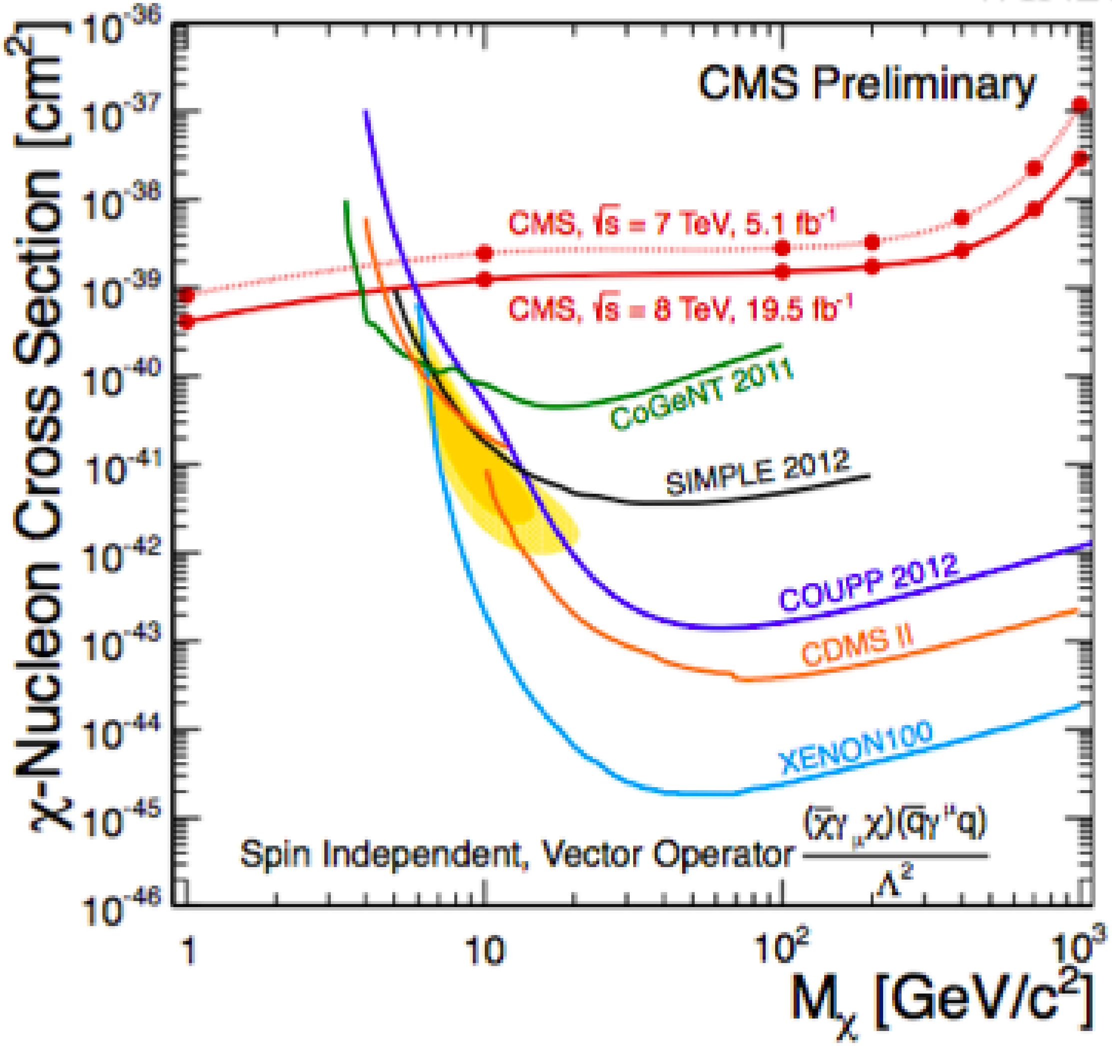
Signal for WIMPS: monojets, monophotons



qqDMDM effective interaction is probed – "model-independent"

Monojet searches

WIN2013

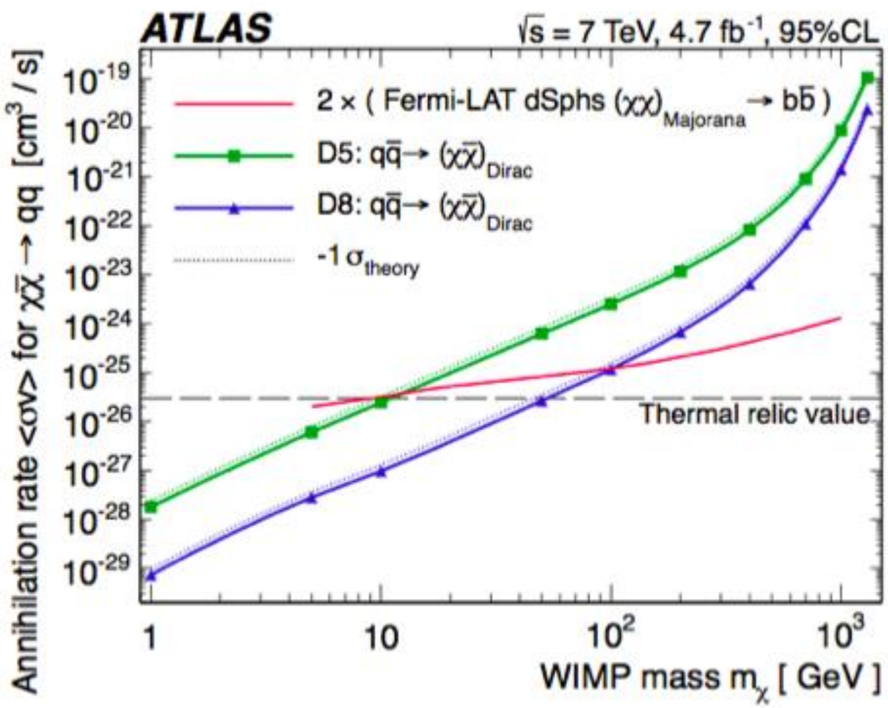


Not yet competitive with direct searches

LHC results - Example Mono-Jet

James Pearce
WIN2013

WIMP Annihilation Limits



- Comparison with FERMI-LAT is possible through our EFT

- The results can also be interpreted in terms of limits on WIMPs annihilating to light quarks
- All limits shown here assume 100% branching fractions of WIMPs annihilating to quarks
- Below 10 GeV for D5 and 70 GeV for D8 the ATLAS limits are below the values needed for WIMPs to make up the DM relic abundance

Conclusions

- Dark matter exists – New Physics BSM!

- We do not know what it is…

- There are good and sometimes well motivated candidates

- Huge activity in direct, indirect and LHC searches – beware of nightmare scenarios

- Discovering the identity of dark matter will bring a major advance in Particle Physics & Cosmology!