Dark Matter

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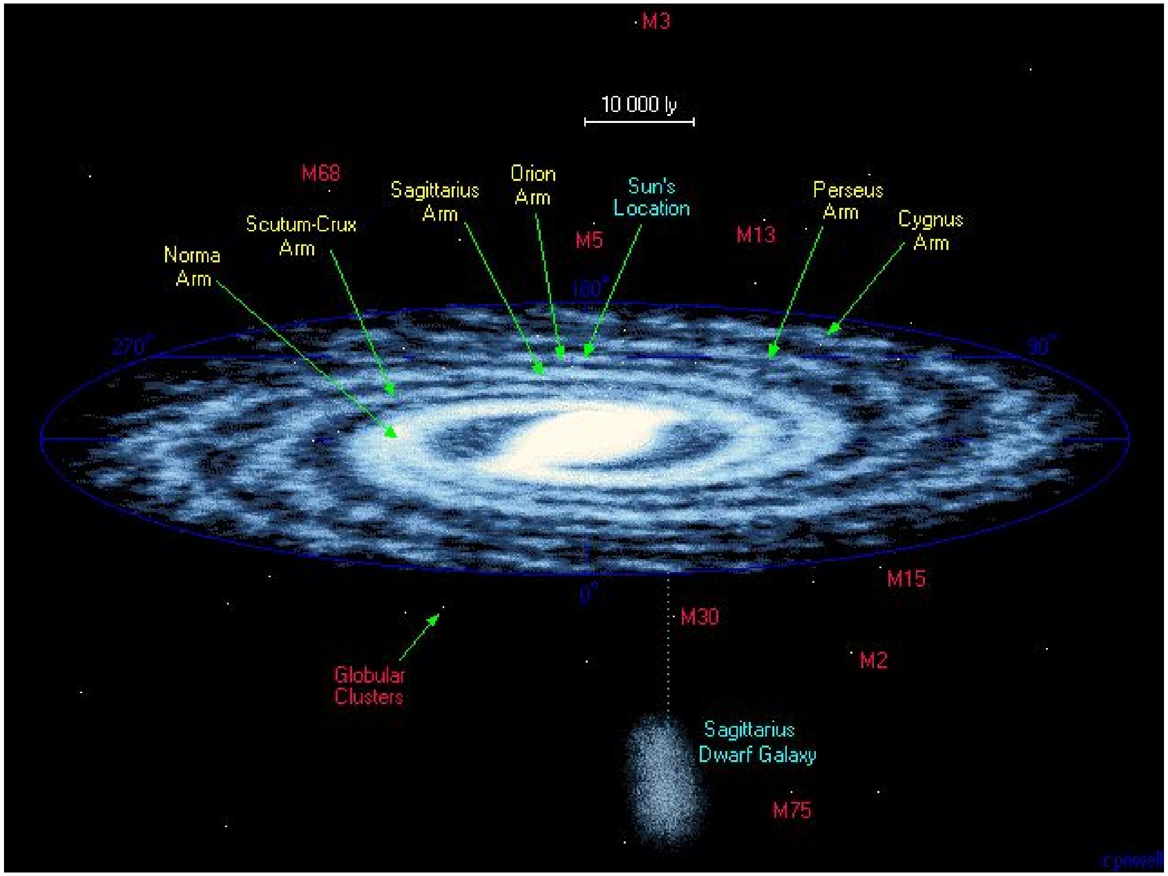
Content:

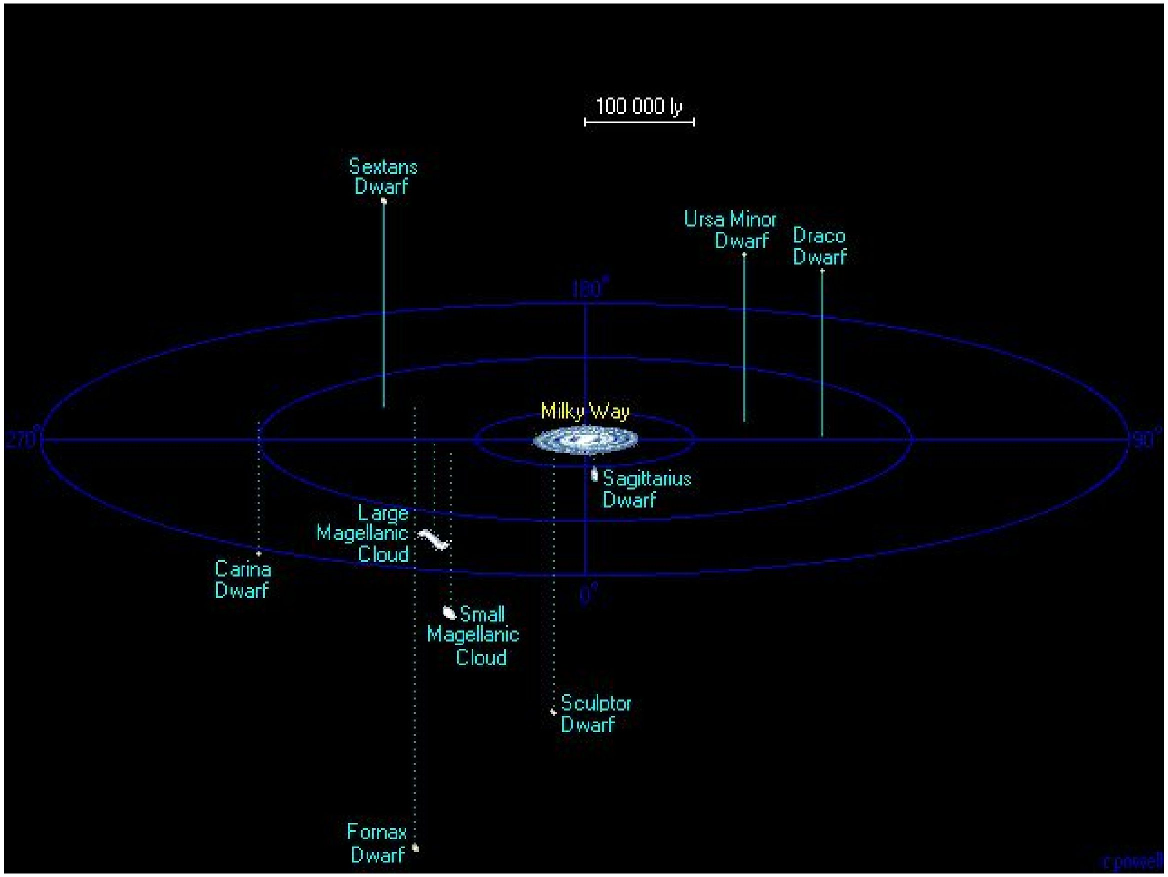
- Dark Matter: what we know
- Particle DM candidates require BSM physics
- WIMP searches at the LHC
- WIMP direct searches ("Light WIMPs"?)
- WIMP indirect searches ("Light WIMPs in the sky?, Fermi Space Telescope bound on "WIMP Miracle", 130 GeV line (or lines) in the Fermi data?, new IceCube bounds)

(Subject is too vast for the time- so idiosyncratic choice of subjects. Citations disclaimer)

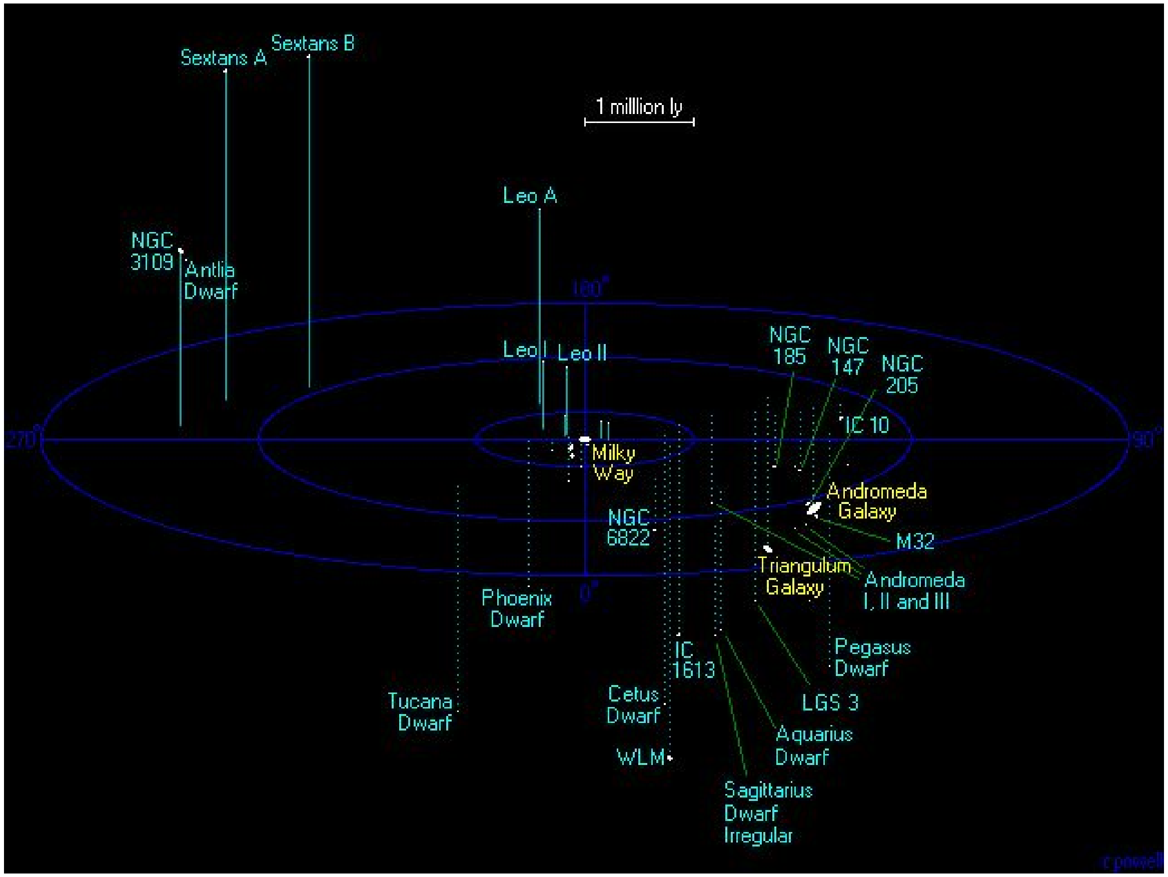
The Universe around us Galaxies are the building blocks of the Universe. The Milky Way and the Sagittarius Dwarf galaxy its nearest satellite galaxy



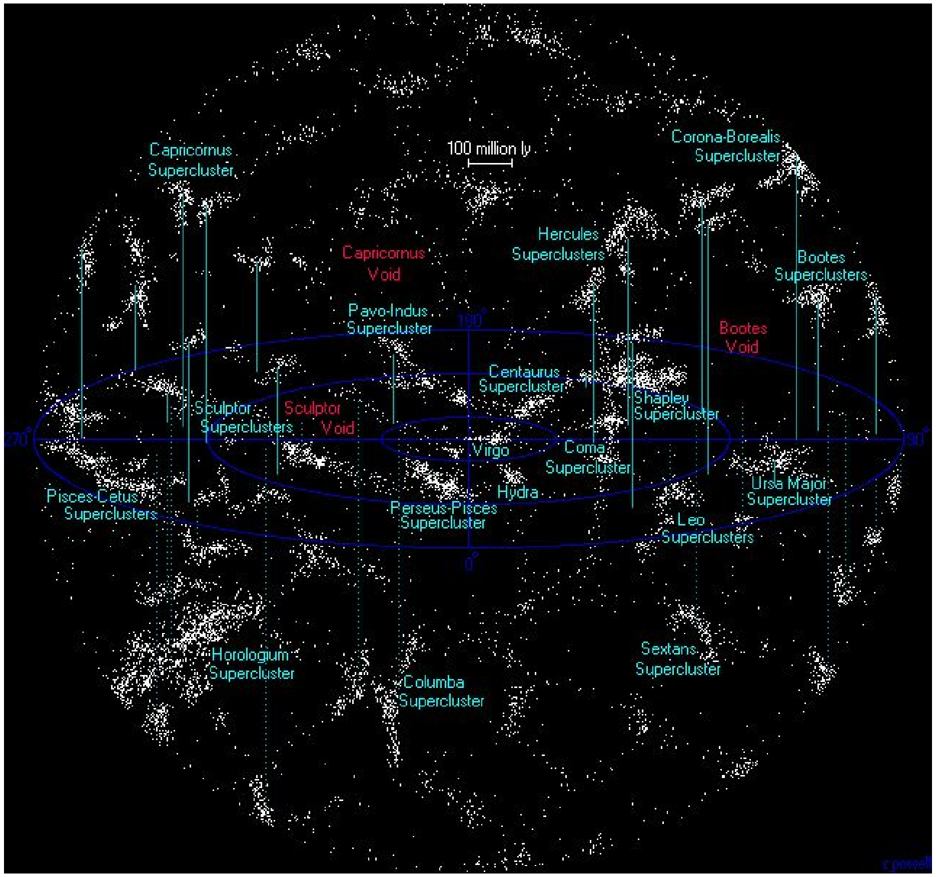
The Milky Way has many small satellite galaxies (many more smaller satellites have now been found (SDSS)!)



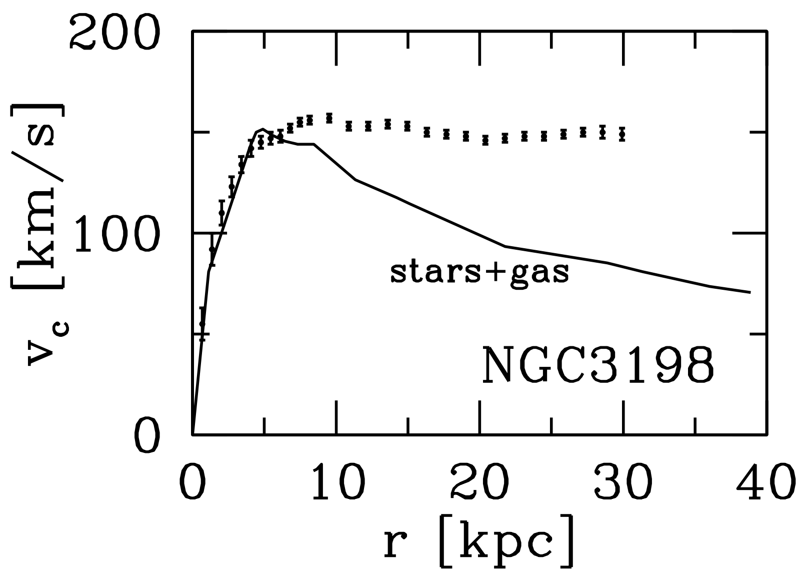
Galaxies come in groups, clusters, superclusters......Our Local Group of galaxies



Galaxies are the building block of the Universe: they come in groups, clusters, superclusters, " filaments, walls and voids")



Rotation curves of galaxies ARE FLAT! Vera Rubin in the 1970'



$$\frac{GMm}{r^2} = m\frac{v^2}{r} \Rightarrow v = \sqrt{\frac{GM(r)}{r}}$$

$$v = const. \Rightarrow M(r) \sim r$$

even where there is no light!

Dark Matter dominates in galaxies e.g. in NGC3198

$$M = 1.6 \times 10^{11} M_\odot (r/30\mathrm{kpc})$$

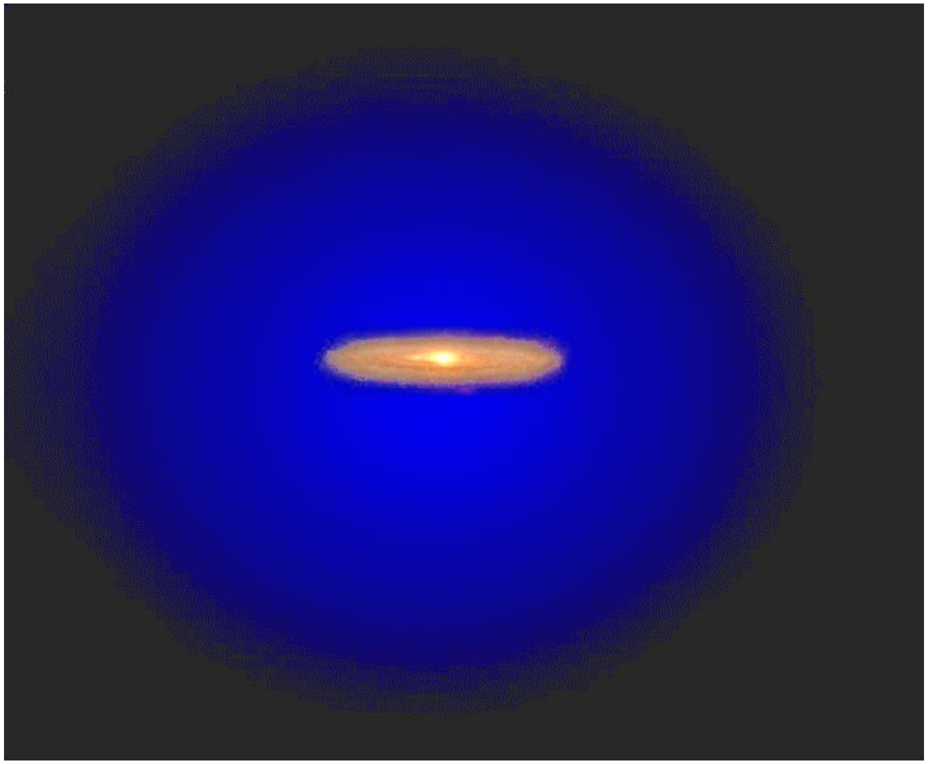
$$M_{\mathrm{stars+gas}} = 0.4 \times 10^{11} M_\odot$$

$$\frac{M}{M_{\mathrm{vis}}} > 4$$

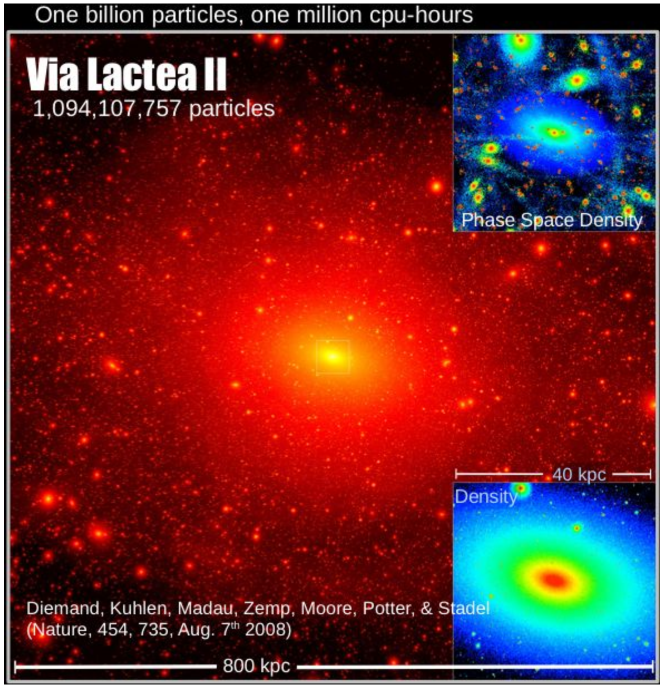
$1\mathrm{pc} = 3.2\ell\mathrm{y}$

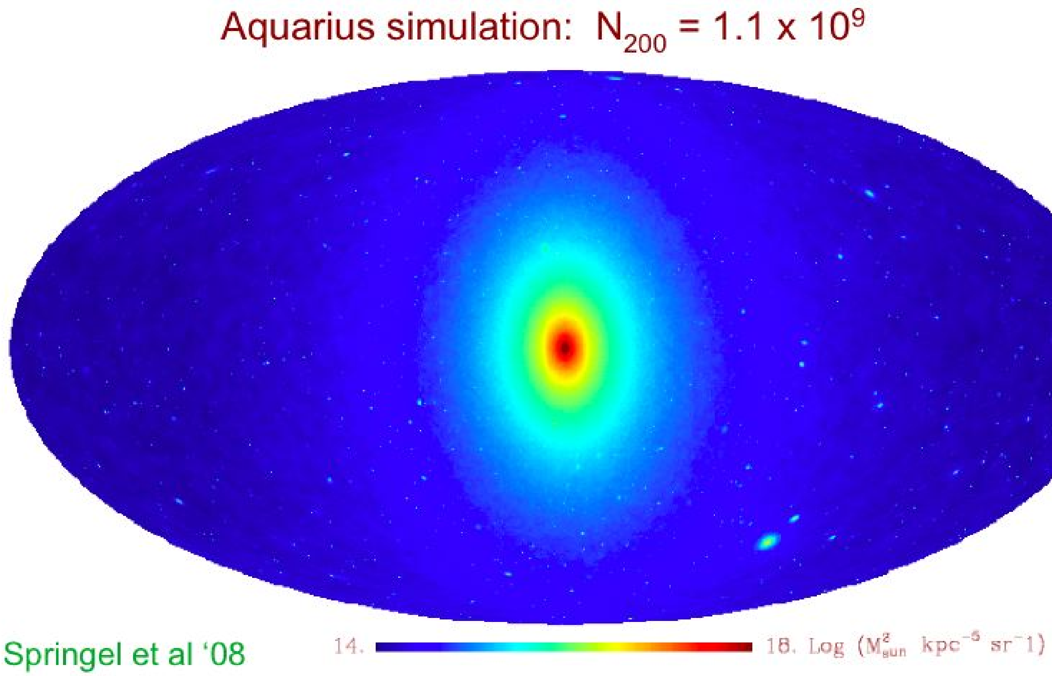
Galaxies have a Dark Halo containing 70 -80% of its mass

Artist view: visible disk surrounded by a DM halo



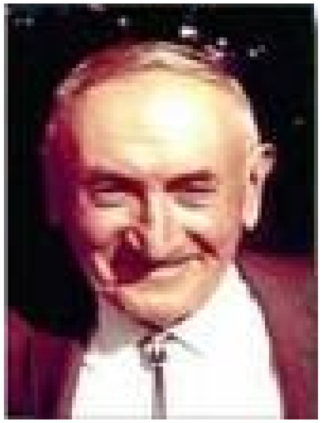
State of the art non-linear N-body simulations of Dark Haloes No baryons included (so no disk)! Sun at 8kpc from the center





Lots of subhalos and tidal streams at large distances from the galactic center. The chance of a random point close to the Sun lying in a substructure is $< 10^{-4}$

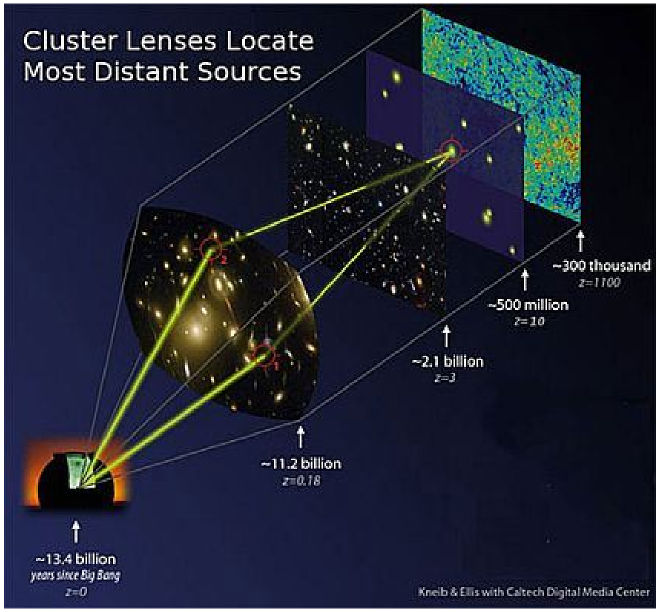
In galaxy clusters?



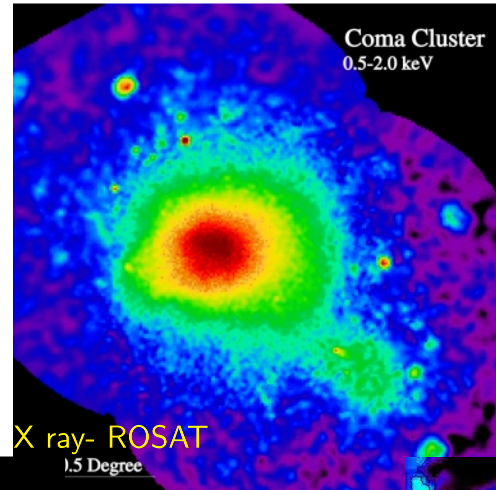
In 1933 Fritz Zwicky found the first indication of the DM.
Used the Virial Theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only

Later: also gas in clusters moves too fast (is too hot - as measured in X-rays) to remain in it, unless there is DM.

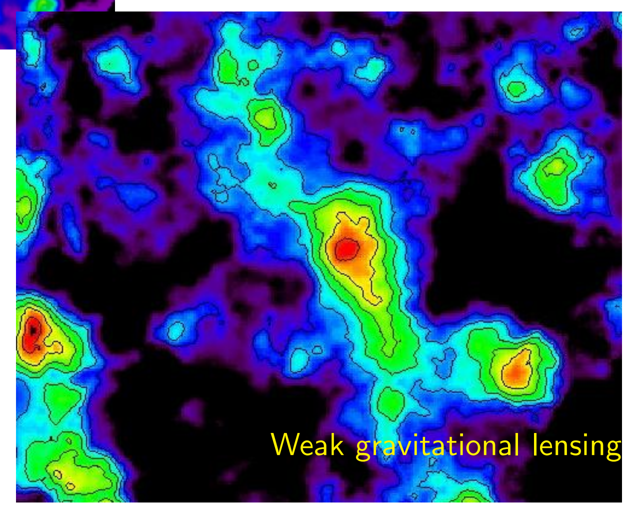
Another method:
gravitational lensing
depends on all the intervening mass



DM dominates in galaxy clusters



$$\frac{M}{M_{\rm vis}} \simeq 6$$

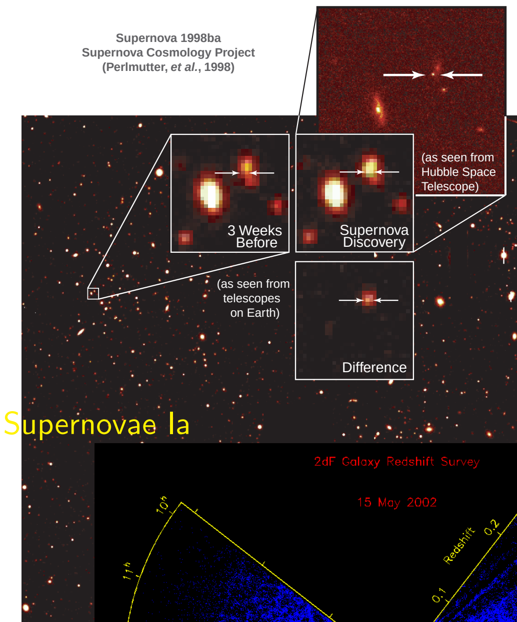


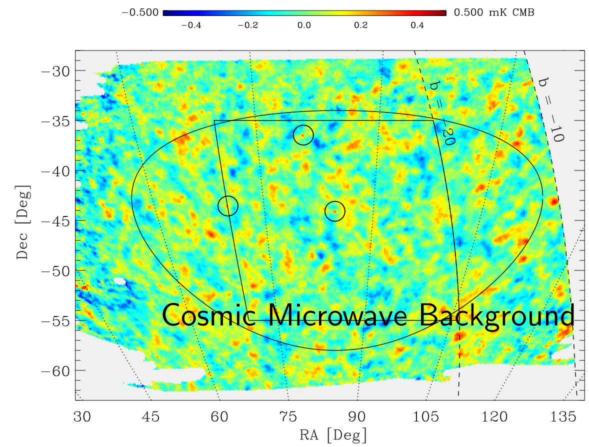
Dark Matter or MOND? "bullet cluster" August 2006

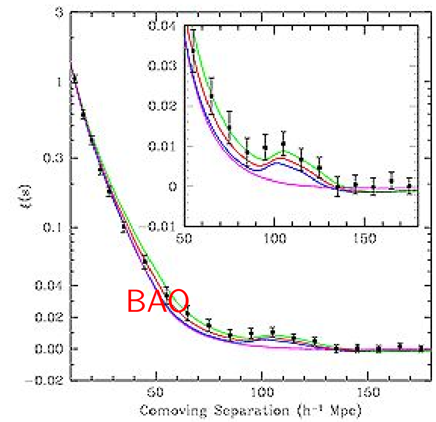
Two galaxies collided leaving the visible (interacting) matter (hot gas detected by Chandra in X-rays -pink) behind, NOT WHERE MOST OF THE MASS of the cluster (seen through gravitational lensing-blue) IS. (Bound on DM self-interaction: $\sigma/m < 0.7$cm^2/g=1.3 barn/GeV, S.Randall et al. 0704.026, Spergel Steinhardt-2000 range was 0.5 to 6 cm^2/g)

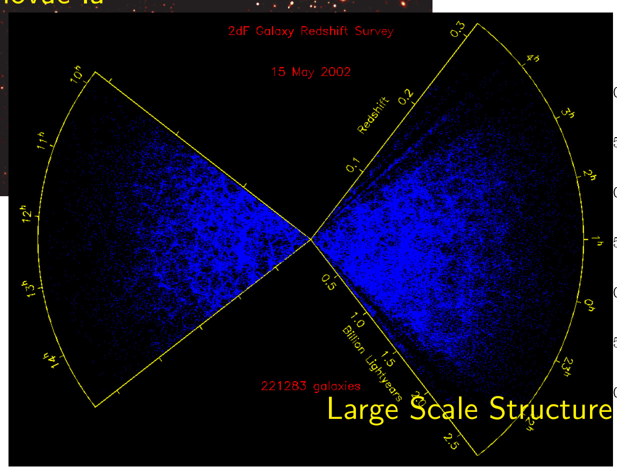
MOND (MOdified Newtonian Dynamics- $F_{Grav} \not\propto$ accelerationMordehai Milgrom,1983) with only baryons cannot explain this system (needs 2-3$\times$ more matter and propose $\sim$eV ν_s, or some Dark Cluster Baryonic Matter?)-Successful up to galactic scales.

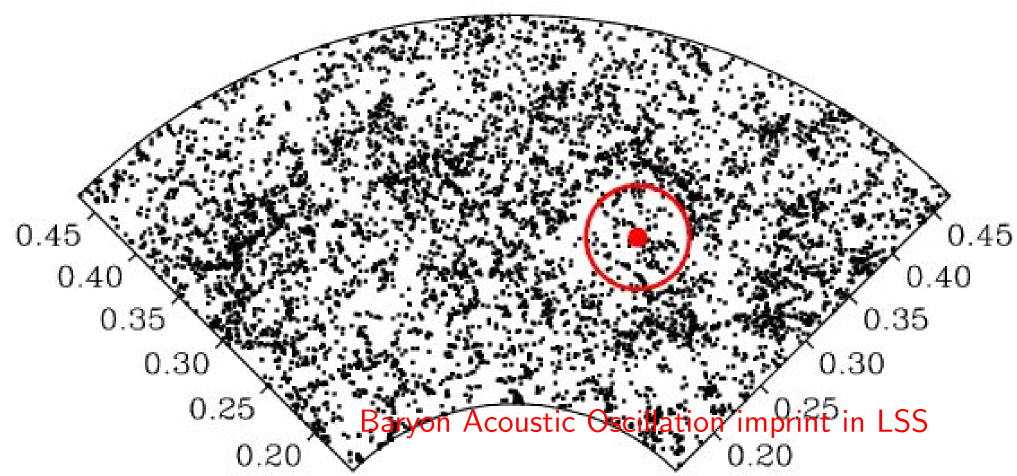
At the largest scales











At the largest scales: concordance cosmology

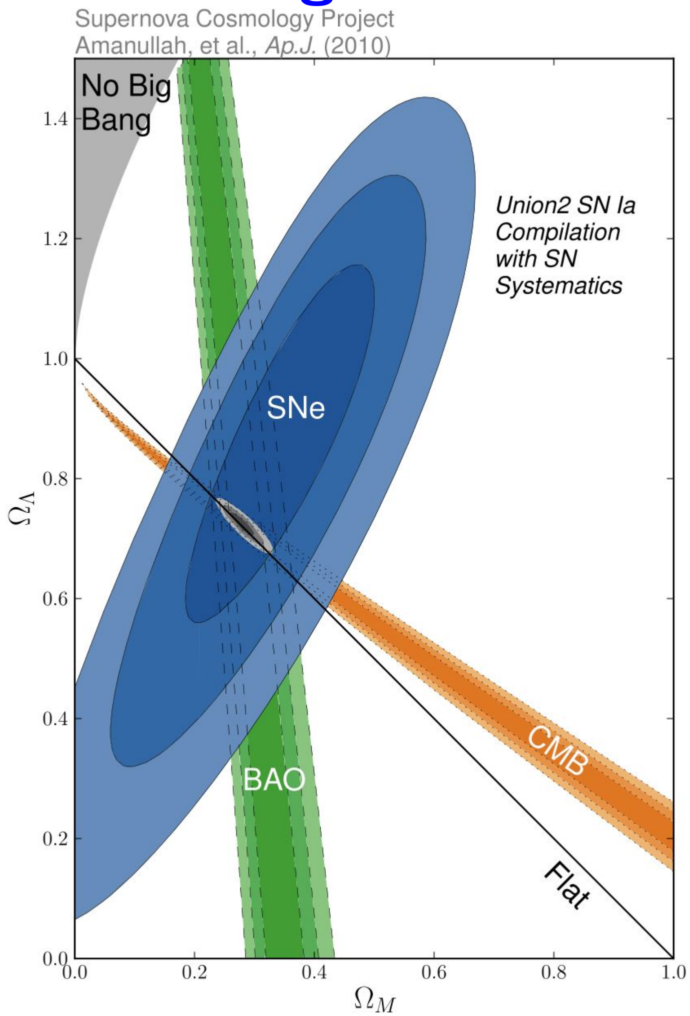


Fig: Amanullah et al 2010 (The Supernova Cosmology Project)

$\Omega = \rho/\rho_c \qquad \rho_c \simeq 5\ \mathrm{keV/cm^3}$

68.3%, 95.4%, 99.7%CL constraints on Ω_Λ vs. Ω_M obtained from Cosmic Background Radiation Anisotropy CMB (orange), Baryon Acoustic Oscillations BAO (green), and the Union Compilation of 413 Type Ia supernovae (SNe Ia) (blue); Ω_m =0.285$^{+0.020}_{-0.019}$(stat)$^{+0.011}_{-0.011}$(sys) assuming DE is a cosmological constant

WMAP7, BAO, SN1a: E. Komatsu, et al., 2010

$\Omega_\Lambda = 72.2 \pm 1.5\%$ $\Omega_M = 27.8 \pm 1.5\%$

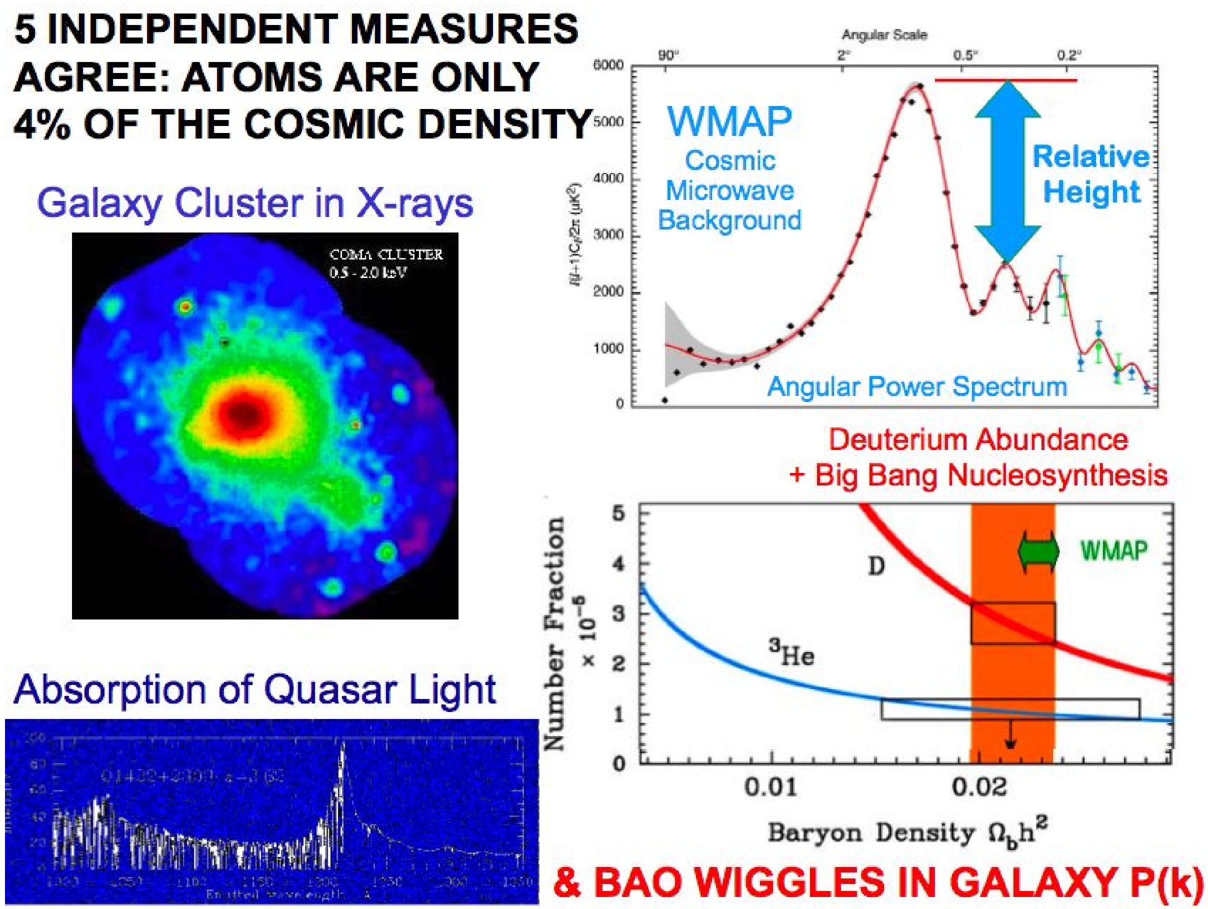
where Ω_M is:

$\Omega_b = 4.61 \pm 0.15\%$

$\Omega_{\rm DM} = 23.2 \pm 1.3\%$

"Double-Dark" model: dark energy+ DM

Our type of matter is only $< 5\%$. Fig: from J. Primack 2010



so most of the DM is non-baryonic

Conditions on DM particle candidates

- **Stable** (or lifetime $>> t_U$)
- **Neutral, colorless**
- 10^{-31} GeV $\leq$**mass**$\leq 10^{-7} M_\odot = 10^{50}$GeV (limits on MACHOS astro-ph/0607207) ("Fuzzy DM", boson Bohr radius= size of galaxy Hu, Barkana, Gruzinov, astro-ph/0003365)

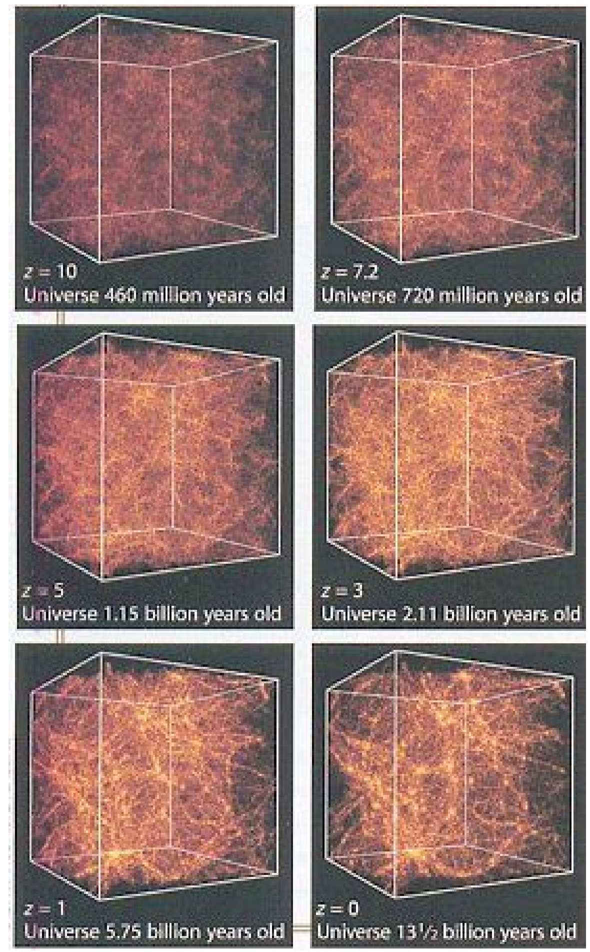
  0.2 -0.7 keV$\leq$ mass (for particles which reached equilibrium - depending on boson-fermion and d.o.f. Tremaine-Gunn 1979; Madsen, astro-ph/0006074)
- With the **right relic abundance** $\leq \Omega_{DM}$ (but not necessarily calculated with the "STANDARD" pre BBN era assumptions)
- **Self interactions with** $\sigma_{\rm self}/{\rm m}$ $\leq$**0.1cm^2/g=0.7 barn/GeV** (from non-sphericity of galaxy and cluster halos) Peter et al 1208.3026
- **Cold or Warm, thus not included in the Standard Model of EP**

Structure Formation is due to primordial inhomogeneities in the DM

CMB anisotropies: $\Delta T/T \simeq 10^{-5}$

In baryons $\delta\rho_B/\rho_B \simeq 3\Delta T/T$ at "recombination" when the CMB was emitted (atoms formed) +gravitational collapse, not enough to form the structure we see: at "recombination" baryons must fall into already formed potential wells of DM.

Observed structure $\Rightarrow$
DM must be "COLD" (non relativistic) or "WARM" (almost non-relat.) when galactic size perturbations enter into the horizon, at $T \sim 1\text{keV}$ (active neutrinos are HOT DM!)



"Double-Dark" model works well with CDM or WDM above galactic scales, distinction at sub-galactic scales

Fig: from Tegmark ("Standard model" with ΛCDM: with Cold DM)

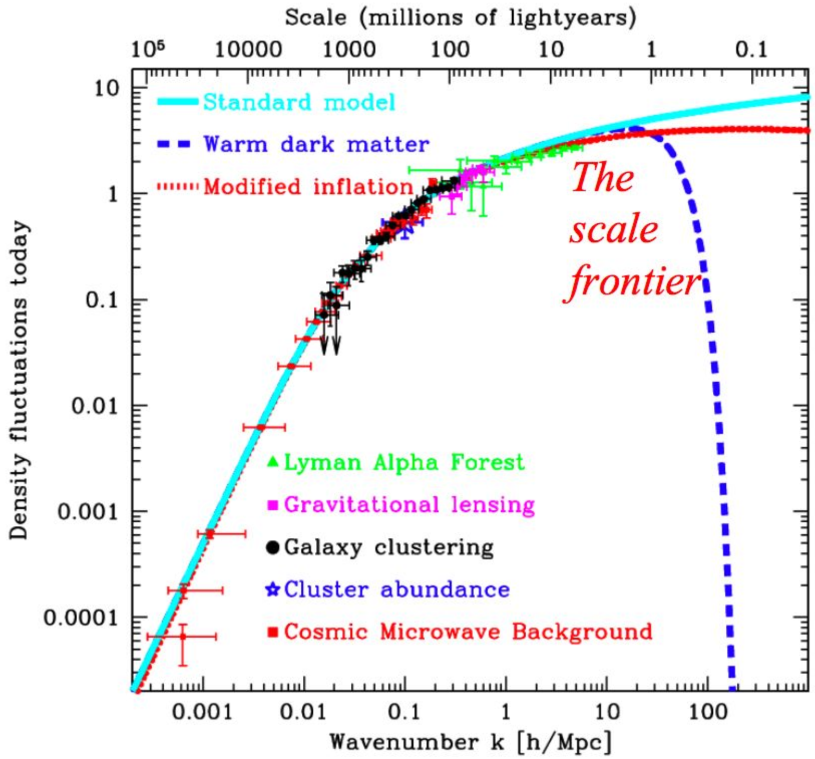
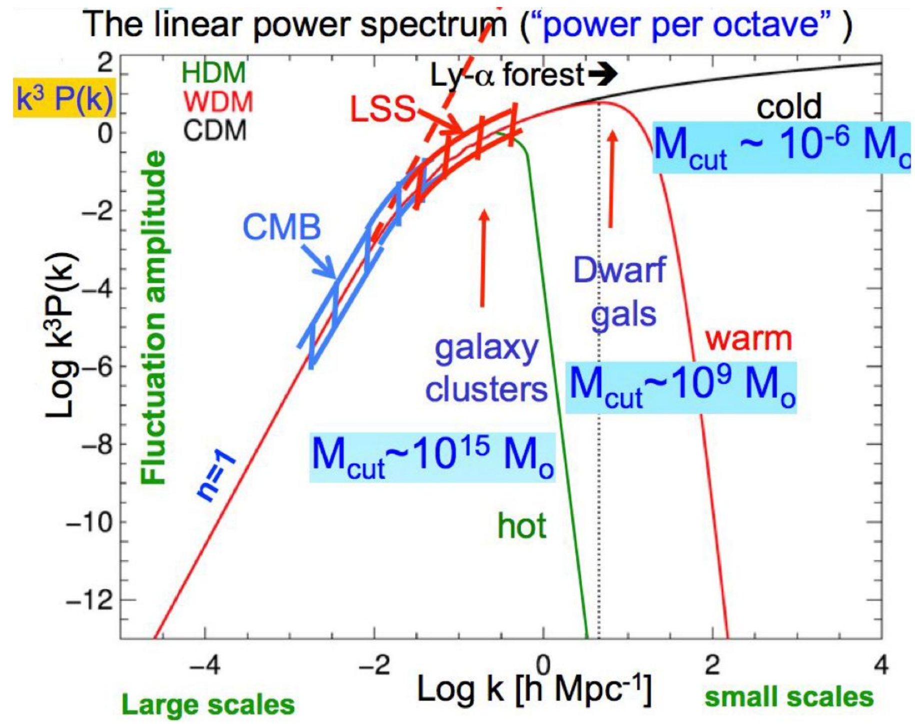


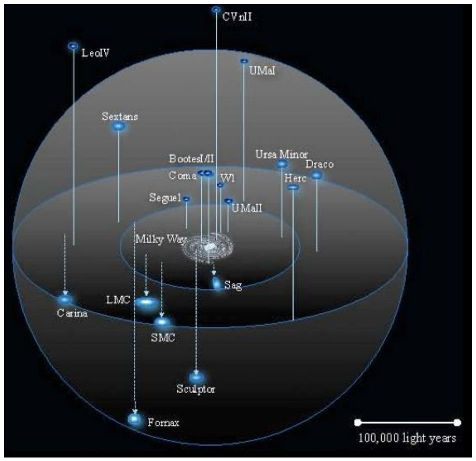
Fig: from Carlos Frenk

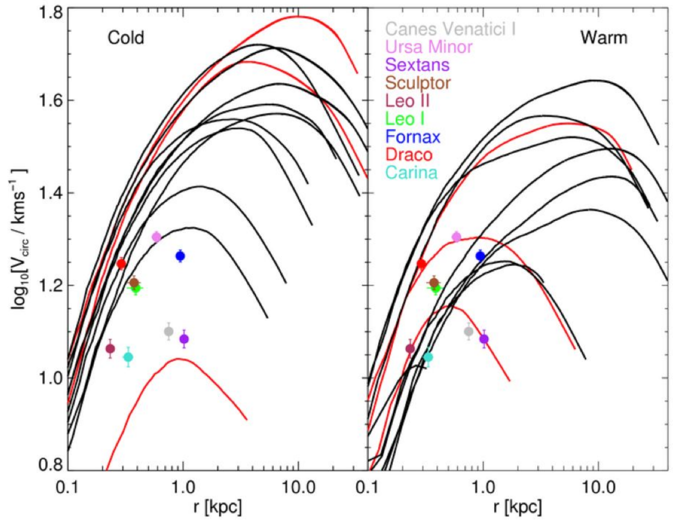


Potential problems for CDM in Milky Way Dwarf Galaxies

Very high resolution simulation (with only DM) find massive dense subhaloes **"too big to fail"** to form lots of stars, but none of the observed satellites of the Milky Way or Andromeda have stars moving as fast as would be expected in these densest sub-halos.

Lovell et al. '11 and 12; Fig: from Carlos Frenk





CDM rejected unless effect of baryons is important, or Milky Way mass $< 10^{12} M_\odot$ (rather than 2×10^{12} $M_\odot$) Vera-Ciro et al 1202.6061; Wang teal 1203.4097 Otherwise:
WDM or velocity dependent DM self interactions with huge $\sigma \simeq 0.1$ to 1 barn/GeV

No CDM or WDM particle candidate in the SM!

active neutrinos are light and in equilibrium until BBN, $T \simeq 1$ MeV thus they are HDM

But many in extensions of the SM!

Warm dark matter:

- sterile neutrino, gravitino, non-thermal WIMPs...

Cold dark matter:

- WIMPs (Weakly Interacting Massive Particles)

Particle DM requires new physics beyond the SM!

New physics at the EW scale?

Expected at $\mathrm{O(TeV)}$ scale because of Spontaneous Symmetry Breaking arguments (totally independently of the DM issue)

BSM models such as Supersymmetry, Technicolor, large extra spatial dimensions (possibly warped), "Little Higgs" model... which provide the main potential discoveries at the LHC and also DM candidates...

mostly WIMPs: LSP, Lightest Technibaryon, LKP (Lightest KK Particle) or LZP (in Warped SO(10) with Z3), LTP (Lightest T-odd heavy γ in Little Higgs with T-parity)...

New physics to explain DM?

May be different...., for example many new models trying to account for "hints" of light WIMPs in several dark matter searches...e.g. "secluded" or "intermediate state" models with DM charged under a broken hidden gauge symmetry and interacting with the SM through a light scalar ("dark photon")...

Made to fit DM-not to solve the EW hierarchy (attest to the ingenuity of theorists to explain everything)... may provide novel signatures for the LHC

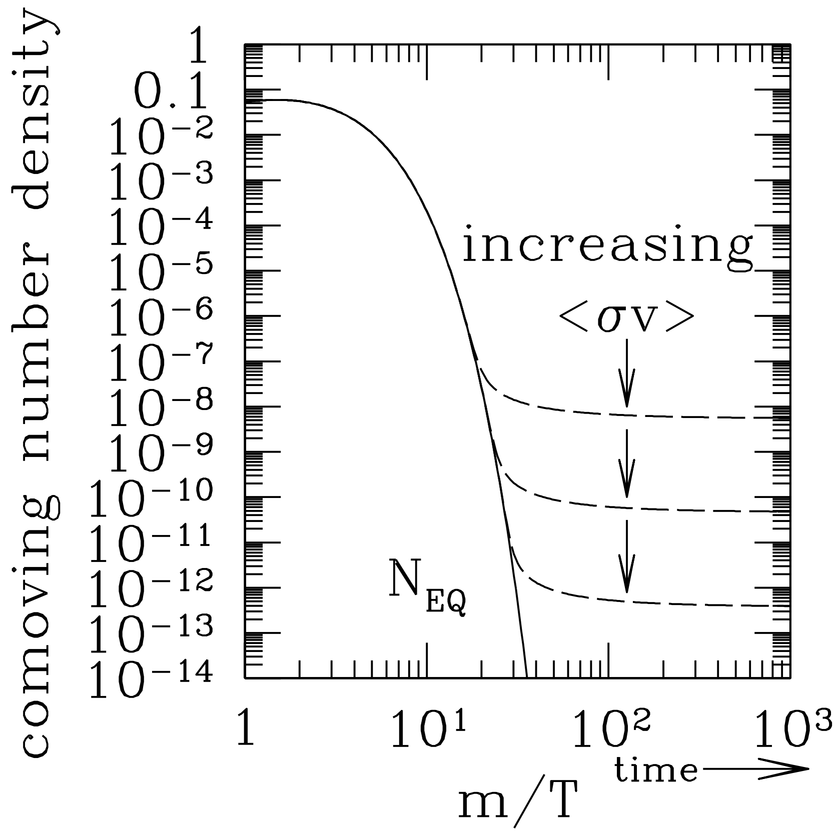
Thermal WIMPs are Cold Dark Matter

Standard calculations: start at $T > T_{f.o.} \simeq m_\chi/20$ and assume that

- WIMPs reach equilibrium while Universe is radiation dominated
- No particle asymmetry
- Chemical decoupling (freeze-out) when $\Gamma_{\rm ann} = \langle \sigma v \rangle \, n \leq H$,
- No entropy change in matter+radiation

$$\Omega_{\rm std} h^2 \approx 0.2 \, \frac{3 \times 10^{-26} {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle}$$

Weak annihilation cross section
$\sigma_{\rm annih} \simeq G_F^2 T^2 \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm s}$
is enough to get $\Omega = \Omega_{DM} \simeq 0.2$!
"WIMP Miracle" (Fermi: m>20 GeV)

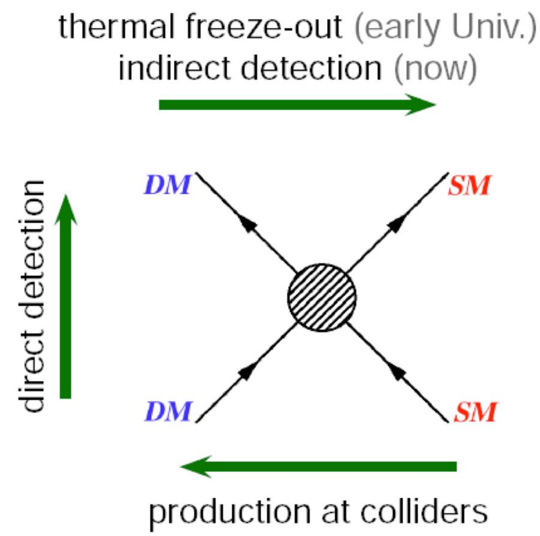


Caveats to Thermal WIMPs as Dark Matter

- Non-Standard Pre Big-Bang Nucleosynthesis (pre-BBN) cosmology
  BBN, at T$\simeq$ MeV, is the earliest episode in the Universe from which we have data. WIMP relic abundance is fixed at $T_{f.o.} \simeq m_\chi/20$, before BBN. If the standard pre BBN assumptions do not hold (i.e. in low reheating temperature models) relation between $\sigma_{\rm annih}$ and density can be very different. (See e.g. Gelmini et al hep-ph/0605016, or Gelmini, Gondolo 1009.3690 and refs. therein)
- Asymmetric DM Only particles remain (no antiparticles). We owe our very existence to a particle-antiparticle asymmetry so why not also the DM? (Requires non-self conjugated DM candidates- neutralinos are Majorana particles instead) (Nussinov 85; Gelmini, Hall, Lin 87; Kaplan 92; Barr, Chivukula, Fahri 90; Enkvist, MacDonald 98; Gudnason, Kouvaris , Sannino 05; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)
- WIMPs can be produced in decays of other particles (Sigurdson, Kamionkowski 04; Kaplinghat 05)
- WIMPs may be unstable and decay into the present DM (Super-WIMP scenario) (Feng, Rayaraman, Takayama 03; Feng, Smith 04)

If DM is Warm, WIMP CDM could be a subdominant DM component or be created in decay and be WDM, but models very different from usual

WIMP DM searches:



- At colliders as missing transverse energy
  (Caveat: the DM mass may be above 2 TeV)

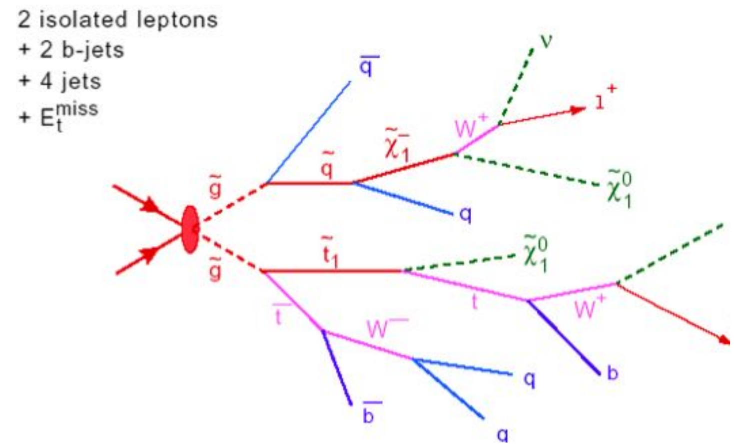
- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way
  (Caveat: the DM interaction might be too weak to detect)

- Indirect Detection- looks for WIMP annihilation (or decay) products
  (Caveat: if DM is asymmetric, it does not annihilate)

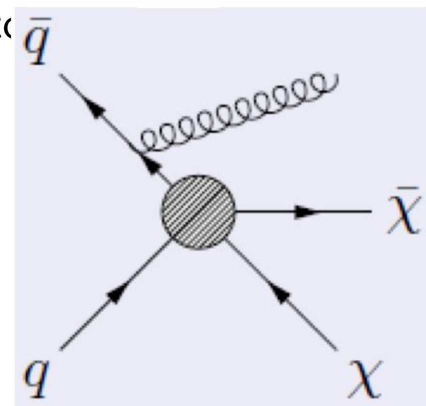
Even if the LHC finds a DM candidate, in order to prove that it is the DM we will need to find it where the DM is

Searches at the LHC

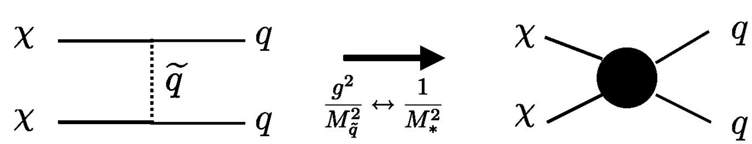
either DM through known decay chain
(specific models, SUSY, simplified)



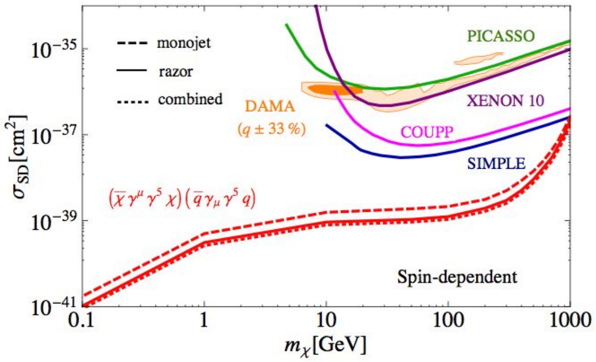
or direct DM production plus a photon
or gluon (monophoton or monojet
signal) so far down only for
CONTACT INTERACTIONS

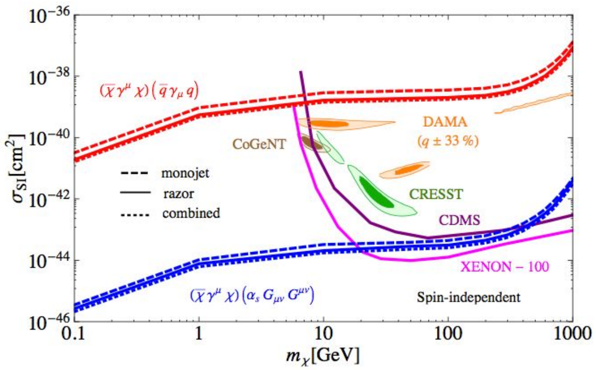


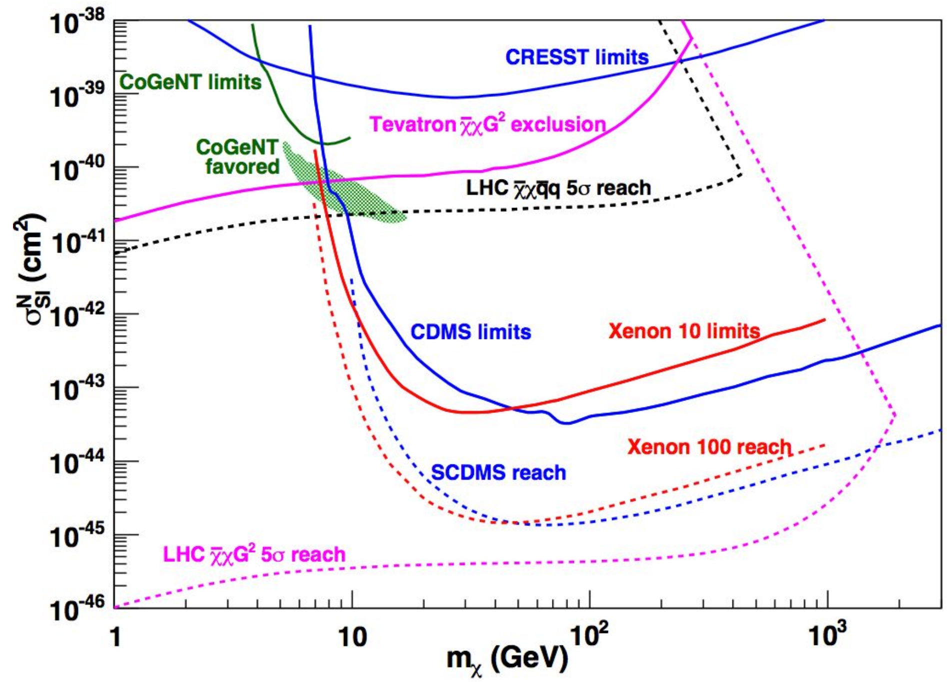
qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$



Searches at the LHC direct production plus a photon or gluon (monophoton monojet signal) so far down only for CONTACT interactions Beltran et al 1002.4137; Fox et al 1203.1662

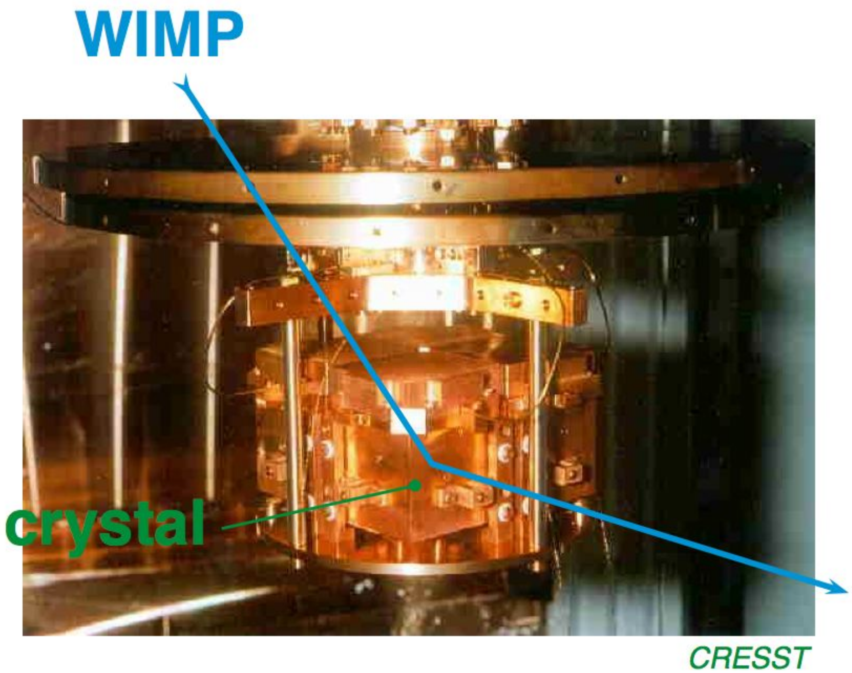






CAVEAT: in direct DM "contact interaction" if mediator M $> q >$ MeV but here mediators mass $>$ 100's GeV

Direct DM Searches:



- Small $E_{\mathrm{Recoil}} \leq 50$keV(m/100 GeV)
- Rate: depends on WIMP mass, cross section, dark halo model, nuclear form factors...
  typical... $<$ 1 event/ 100 kg/day
  (need to go underground underground to shield from cosmic rays)
- Single hits: single scatters, uniform through volume of detector
- Annual flux modulation (few % effect)
- Most searches are non-directional but some are directional (try to measure the recoil direction)

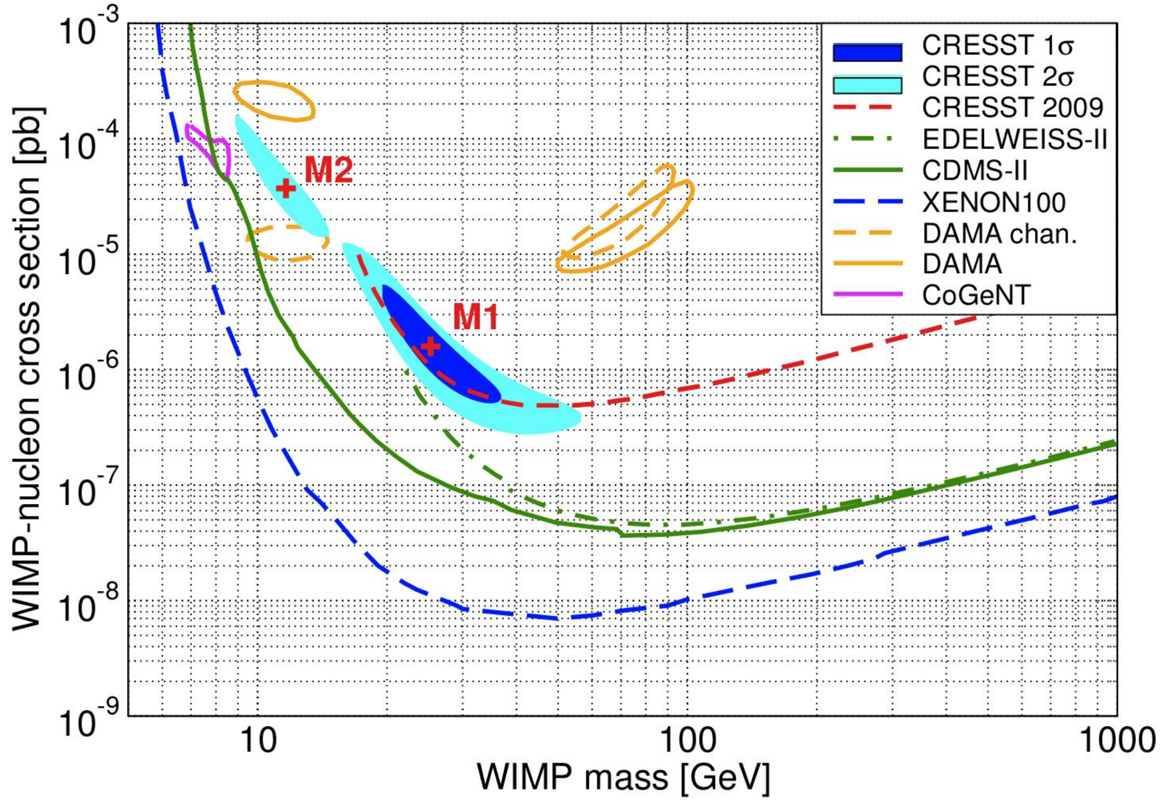
Direct DM detection

DAMA (NaI), CoGeNT (Ge), CRESST II ($CaWO_4$) have detection claims.... point to WIMPs with m< 10 GeV. Are they DM signals or backgrounds?

CDMS (Ge, Si), XENON 10 (Xe), XENON 100 (Xe), SIMPLE (C_2ClF_5).... have upper bounds...
Can all signals and bounds be reconciled? Some of them?

Maybe for "Light WIMPs" (mass $\simeq 10$ GeV).

Light WIMPs DAMA, CoGeNT, CRESST II, DM or backgrounds?



(figure from CREST II, Angloher et al. 1109.0702)

Regions disjoint and already rejected?- The devil is in the details-

(disclamer about citations!! 430 for the CoGeNT Feb 2010 paper alone!)

Recall event rate: events/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nvf(\mathbf{v},t)d^3v$$

$$= \frac{\sigma(q)\rho}{2m\mu^2}\int_{v>v_{\rm min}} \frac{f(\mathbf{v},t)}{v} d^3v = \frac{\sigma(q)}{2m\mu^2}\ \rho\eta(v_{\rm min})$$

if $\sigma(q)$ is v independent. Here $\frac{N_T}{M_T}$ = Avogadro's number per mol = Number of atoms per gram; $\mu = mM/(m+M)$; $v_{\rm min}$ is the min. WIMP speed to get an ion recoil energy E. For elastic scattering $v_{\rm min} = \sqrt{ME/2\mu^2}$

$\rho = nm$, $f(\mathbf{v},t)$: local DM density and $\mathbf{v}$ distribution depend on halo model

- for spin-independent (vector and scalar couplings) $\sigma(q) = \sigma_0 F^2(q)$ where

$\sigma_0 = \Big[\langle Z f_p + (A-Z) f_n\Big]^2 (\mu^2/\mu_{\rm p}^2)\sigma_{\rm p} = A^2(\mu^2/\mu_{\rm p}^2)\sigma_{\rm p}$ for $f_p = f_n$

Thus, for a given halo model the plots are in the $m, \sigma_{\rm p}$ plane.

Notice $\rho\eta(v_{\rm min})$ encodes all the Dark Halo dependence of the rate.

"Halo model independent analysis": compares predictions of $(\sigma_p \rho\eta/m)$ for fixed m.

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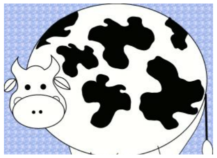
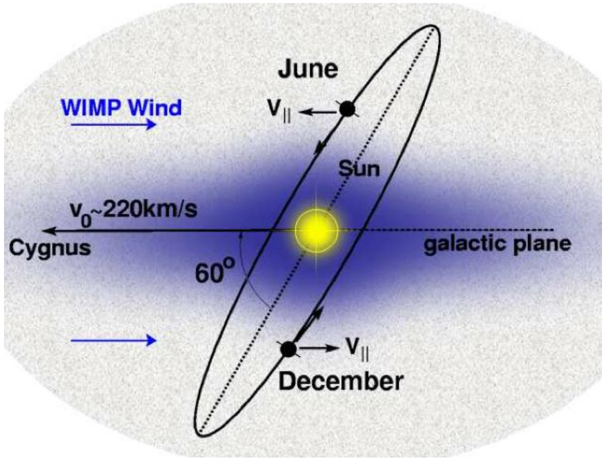
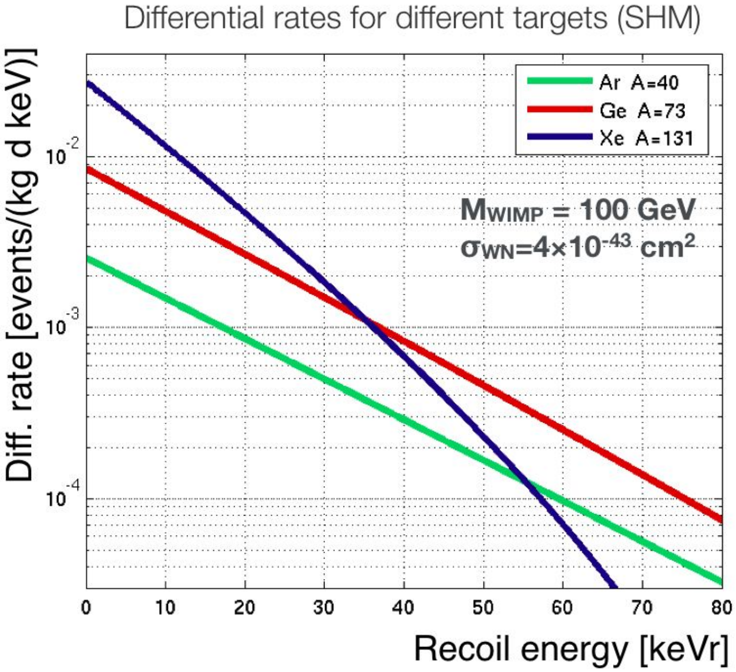
Standard Halo Model (SHM) The  of halo models

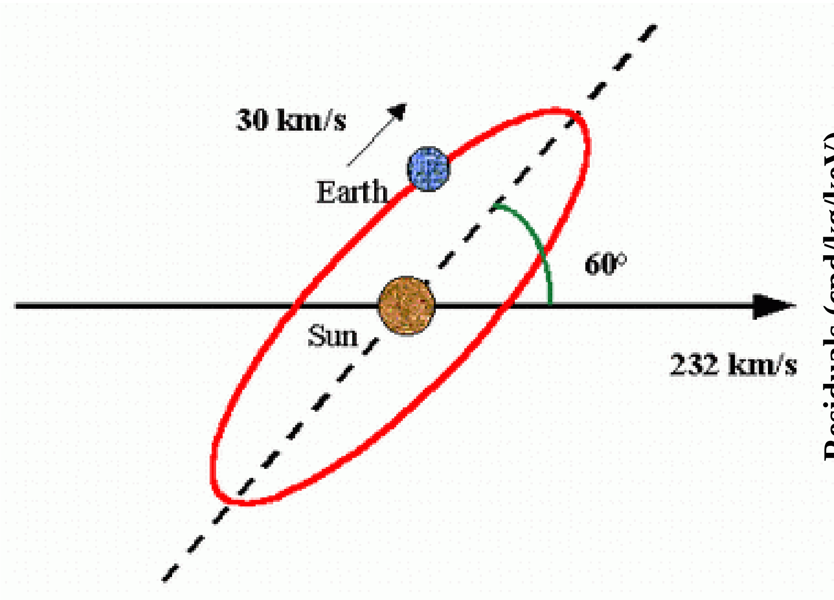


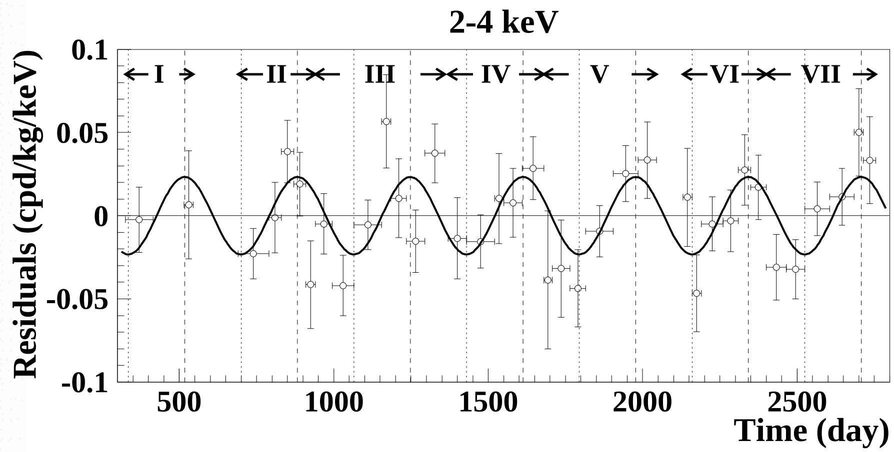


- $\rho_{SHM} = 0.3^{+0.2}_{-0.1}$ GeV/cm^3
- $f(\mathbf{v}, t)$: Maxwellian $\vec{v}$ distribution at rest with the Galaxy $v_\odot \simeq$220km/s (190 to 320km/s), $v_{esc} \simeq$500-650km/s

ANNUAL MODULATION: max in May, min in Dec.(Drukier, Freese, Spergel 1986)
Local ρ, $\mathbf{v}$, modulation phase and amplitude could be very different if Earth is within a DM clump or stream or if there is a "Dark Disk". Other: anisotropic models, velocity tails...

Older DM hint: DAMA/NaI annual modulation





By 2002: 7 years of DAMA/NaI showed a 6σ modulation signal compatible with the Standard Halo Model.

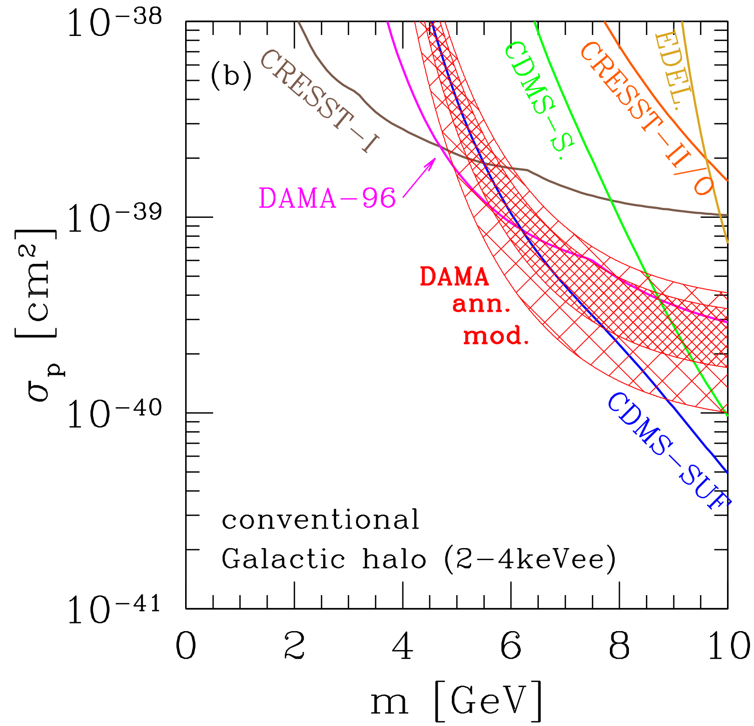
Old DAMA SI WIMPs? Start of the “Light WIMP” saga

“DAMA dark matter detection compatible with other searches,” Gelmini, Gondolo hep-ph/0405278; Gondolo Gelmini hep-ph/0504010

“Los muertos que vos matais gozan de buena salud” Gelmini, TAUP2005, Zaragoza

The bounds had never been extended to m< 10GeV before, because of theoretical prejudices.

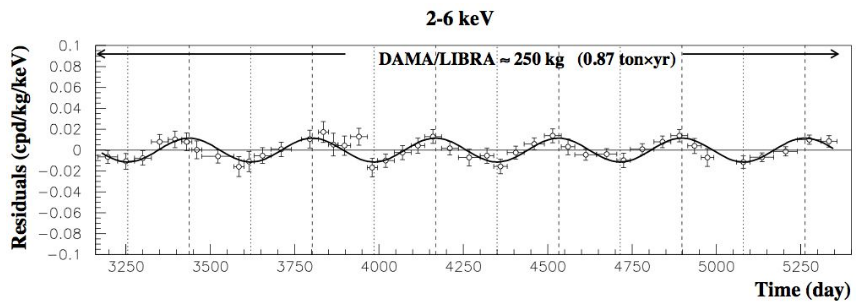
Due to its Na, DAMA could see a signal that was under threshold for Ge in CDMS and EDELWEISS



The Saga of the "Light WIMPs"

April. 2008 DAMA/LIBRA confirmed the DAMA/NaI results 25 NaI (Tl) crystals of 9.5 kg each, 4y of LIBRA, 11 in total, 8.2σ modulation signal(Bernabei et al. 0804.2741)
Explosion of interest on light WIMPs favored by "channeling", proven to be negligible in 2010 (Bozorgnia, Gelmini, Gondolo, 1006.0288)

Feb. 2010 DAMA/LIBRA 25 NaI (Tl) crystals of 9.5 kg each, 6y in LIBRA,13 years total, 1.17 ton $\times$ year, 8.9σ modulation signal
(Bernabei et al. 1002.1028)



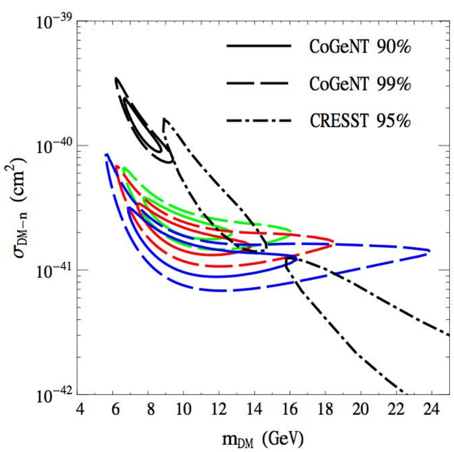
Feb 2010 CoGeNT "irreducible excess"
440g Ge detector in the Soudan Mine with
extremely low threshold, 0.4 keVee, 56 days of data Aalseth et al. 1002.4703
Feb 2010 CRESST II irreducible excess 564 kgd $CaWO_4$ at LNGS, preliminary results
W.Seidel in WONDER, LNGS; Nov. F.Probst in Princeton
Sept. 2011 effect confirmed with 730 kg d (Angloher et al. 1109.0702)

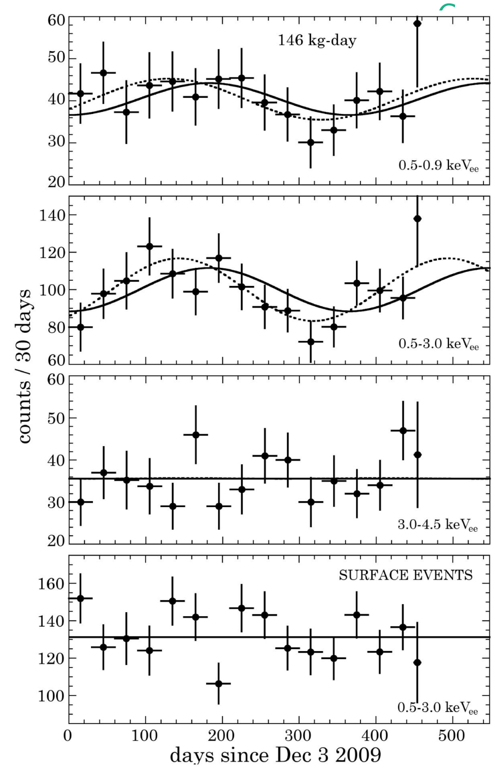
June 2011 CoGeNT annual modulation

15 months (442 d) "irreducible excess"
has a 16.6±3.8 % annual modulation
peaking at 4/18±16 d, a phase
compatible with DAMA's Aalseth et al.1106.0650

Sept 2011 CoGeNT rate revised down

Collar talk at TAUP 2011; Kelso, Hooper, Buckley, 1110.5338



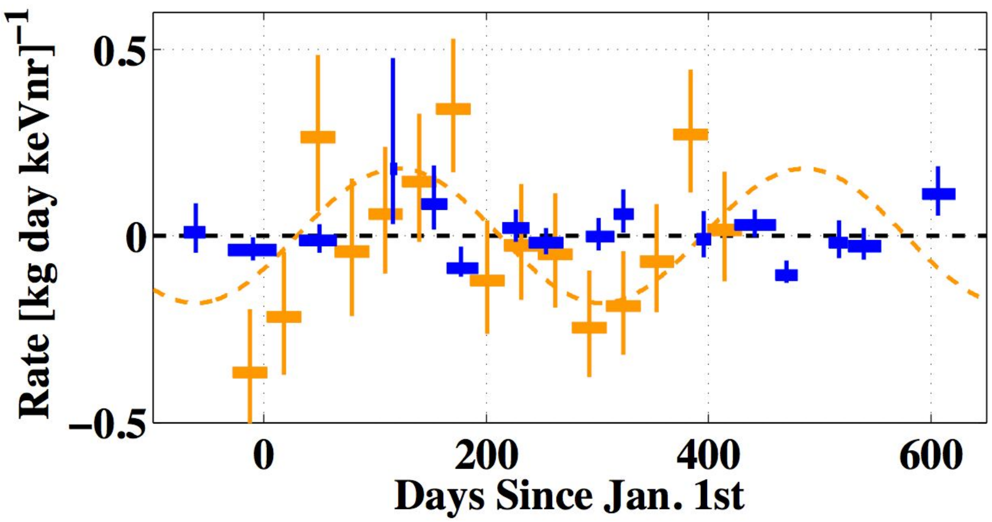


Main negative searches:
XENON10, XENON100, CDMS (Ge) both bound on rate and on an annual modulation

Before last act in the saga so far...

CDMS negative annual modulation search

March 2012: 1203.1309 CDMS (Ge): no modulation $>$ 0.06 ev./keVnr kg day in 5 to 11.9 keVnr (CoGeNT thres. 0.4 keVee $\simeq$ 1.6 keVnr) to 99%CL.



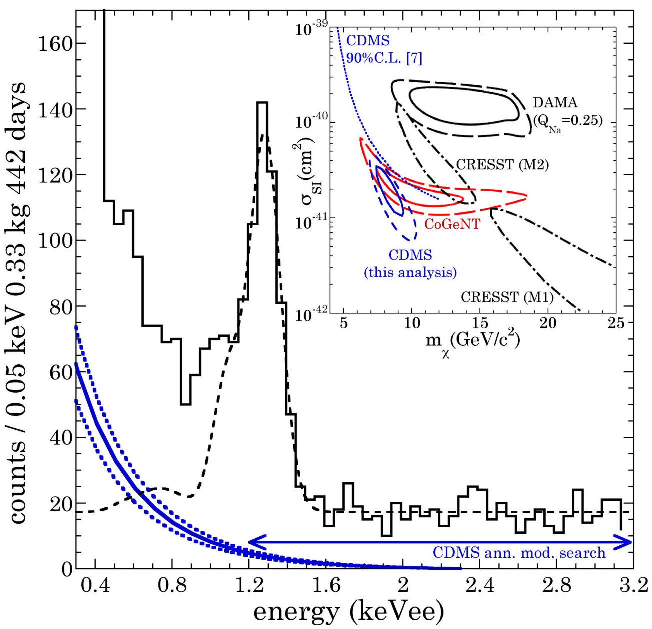
CoGeNT rate (orange)
CDMS rate (blue)

CDMS II 1203.1309

Last act in the saga so far...

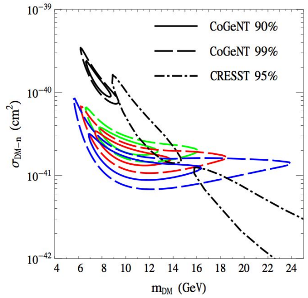
Signal of Light WIMPs in CDMS??

April 2012: 1204.3559 Collar and Fields read off CDMS data from figure in their March 2012 paper (published for the first time), reanalyzed CDMS Ge data
AND CLAIM FIT TO DATA IS MUCH BETTER ADDING A LIGHT WIMP SIGNAL!

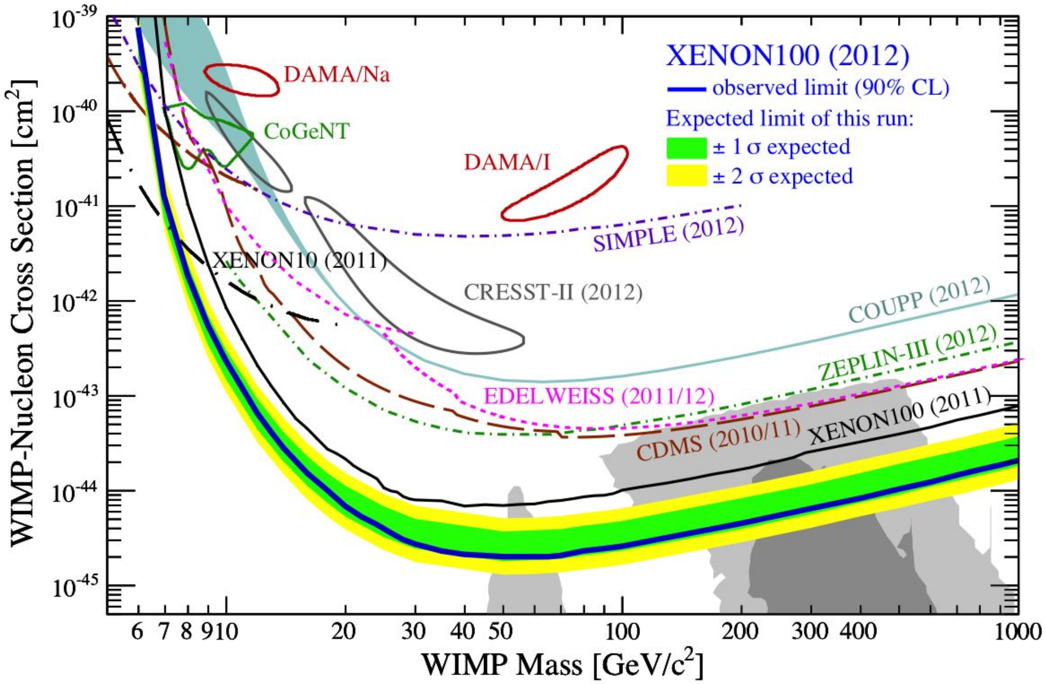


"CDMS signal" shown overlapped to CoGeNT rate- CDMS and CoGeNT $\sigma - m$ regions would overlap!!!
The modulation of this signal would be below the negative modulation CDMS search limit (0.06 events/keVnr kg day)

Latest XENON100 bounds July 2012

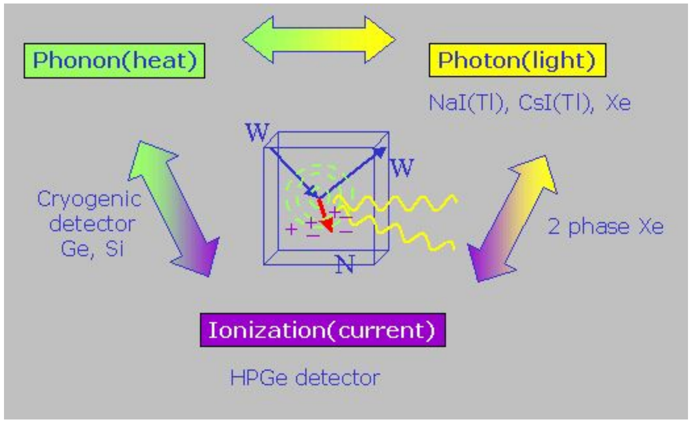


Kelso, Hooper, Buckley, 1110.5338



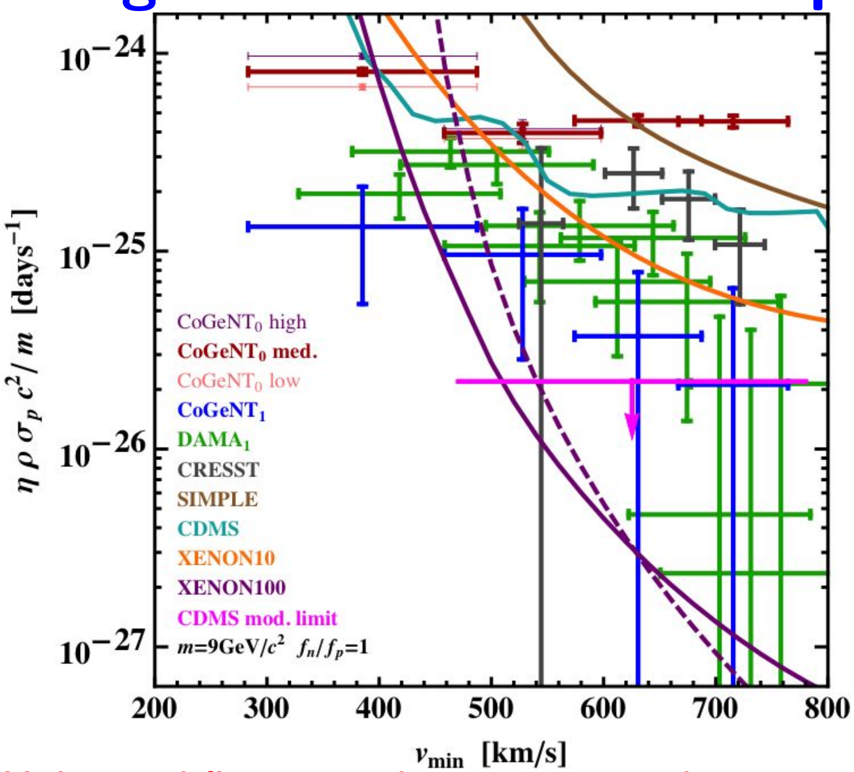
Uncertainties in regions and bounds

- Signals: WIMPs interact with nuclei. In crystals: most of the recoil energy goes usually to phonons, but a fraction Q goes into ionization/ scintillation
  In Xe: $L_{\rm eff}$ measures scintillation efficiency of a WIMP there is also delayed ionization.
  Q's and $L_{\rm eff}$ have large uncertainties at low E. (Collar 1010.5187, 1106.0653)



- Characteristics of the Dark Halo Xe is heavy, thus only sensitive to high v WIMP tail, which may be missing: make a "halo independent analysis" when possible (Fox, Liu, Weiner 1011.1915; Frandsen et al 1111.0292; Gondolo, Gelmini 1202.6359)
- Type of DM interaction Inelastic (iDM)? isospin violating (IV)? Magnetic moment?

SI light WIMPs "halo independent analysis" Fox, Liu, Weiner 1011.1915



$m = 9$ GeV $f_n = f_p$

Gondolo Gelmini 1202.6359

CoGeNT rates and CRESST rate

CoGeNT modulation compatible with DAMA but > 25 % of rate!

DAMA modulation

and CDMS mod. limit

mapped into v_{min}-space

We plot weighted average η_{i0}, η_{im}

$\eta_i = \eta_{i0} + \eta_{im} \cos(\omega t - t_0)$

Bins extended by E-resolution ΔE on both sides

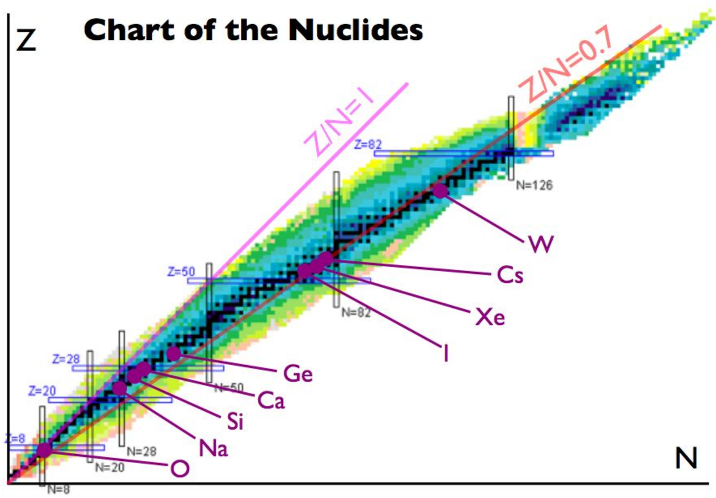
Halo modifications alone not enough to escape Xenon100 bounds - Other problems:

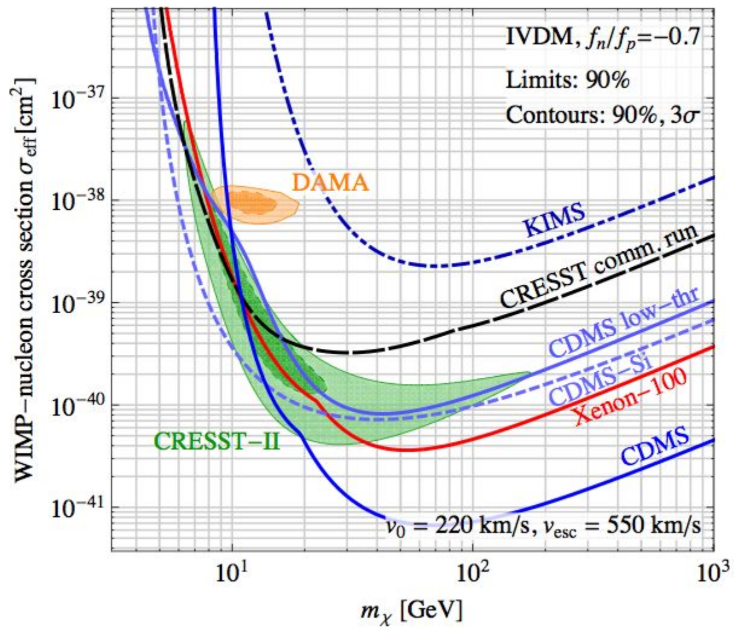
- CoGeNT rate could be lowered but then modulation too high;

-CRESST unmodulated is on top of CoGeNT modulation! so they are incompatible

Isospin violating (IV) light WIMP? Kurilov, Kamionkowski 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010, Feng et al 2011

Coupling $\left[\langle Z f_p + (A-Z) f_n\right] \simeq 0$ for $f_n/f_p \simeq -Z/N$, not all because of isotopes

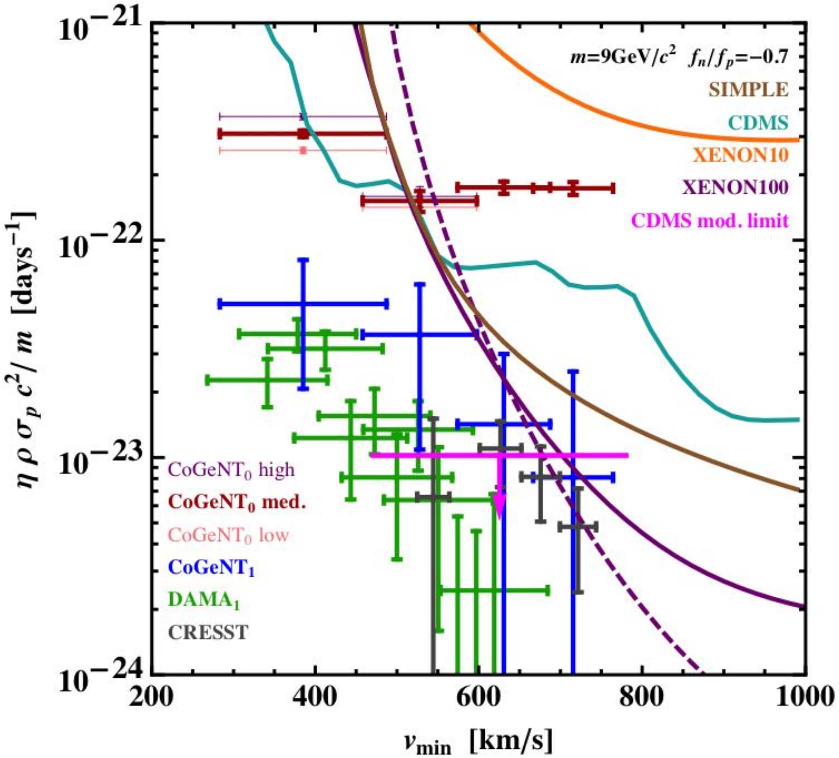




Kopp, Schwetz, Zupan 1110.2721

Best bounds from CDMS now, Ge and Si similar to Na and O!

IV light WIMPs "halo independent analysis" Fox, Liu, Weiner 1011.1915



$m = 9$ GeV Gondolo Gelmini 1202.6359

CoGeNT rates and CRESST rate

CoGeNT modulation compatible with DAMA but $>$ 25 % of rate!

DAMA modulation

and CDMS mod. limit

mapped into v_{min}-space

We plot weighted average η_{i0}, η_{im}

$\eta_i = \eta_{i0} + \eta_{im}\cos(\omega t - t_0)$

Bins extended by E-resolution ΔE on both sides

With IV modulations compatible with all rate bounds! - Problems:

- CoGeNT rate could be lowered but then modulation too high;

-CRESST unmodulated is on top of CoGeNT modulation! so they are incompatible

I agree with the statement of Juan Collar (CoGeNT) at IDM2012 last July

> this speaker does not know how to reconcile DAMA, CoGeNT and CRESST:
>
> Either we are to learn something subtle about the halo, couplings, or detector effects, or...
>
> their observations have nothing in common.

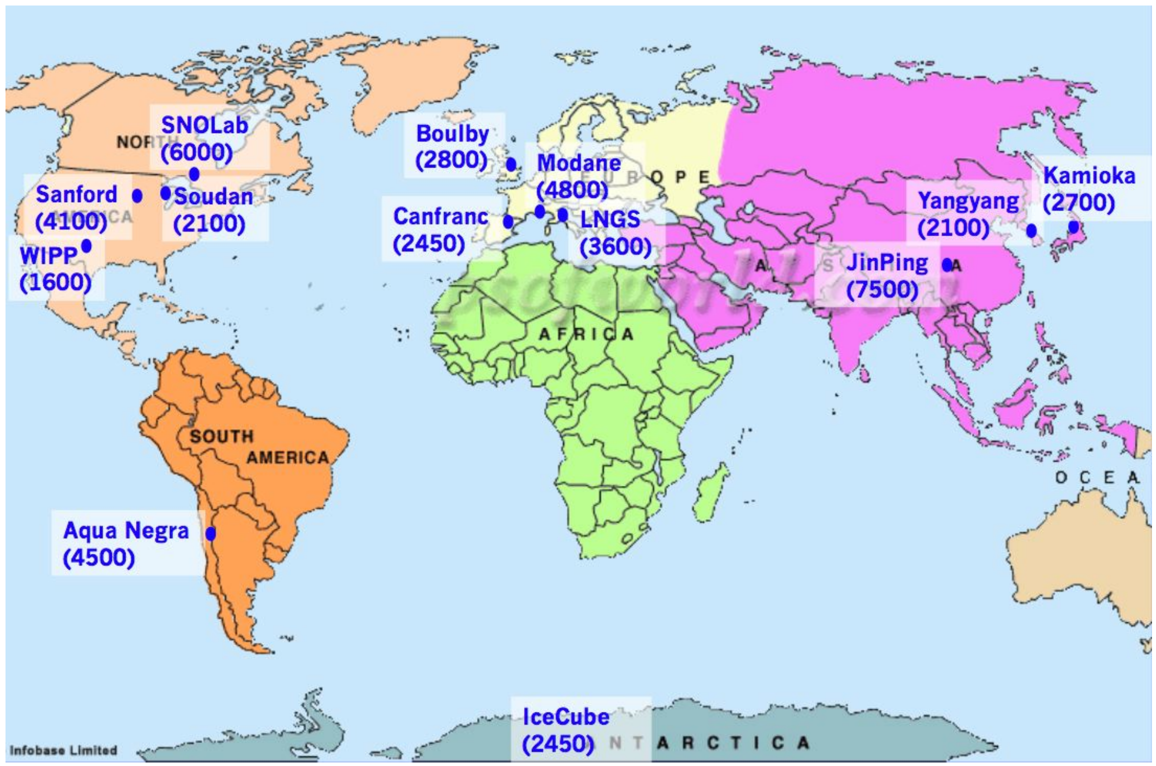
SAGA of "Light WIMPs": WILL CONTINUE.

Light WIMPs or Backgrounds? At this point the situation is confusing and exciting.... Light WIMPs are interesting- however its signal is close to threshold where background is difficult to understand.

There have been many objections to the DAMA result over the years, none conclusive... now extended to CoGeNT too... could they be observing annually modulated backgrounds?

- O(10 MeV) ambient neutrons at the LNGS or Soudan Mine (via scattering or neutron capture and activation- Auger electrons) J. P. Ralston arXiv1006.5255
- $>$TeV cosmic ray μ's which reach the LNGS or Soudan Mine underground facility and
  -either produce secondary neutrons via spallation in the detector or surrounding rock J. P Ralston arXiv1006.5255, K. Blum arXiv1110.0857
  -or deposit their energy directly into the detector D, Nygren arXiv1102.0815 (2011)
- - correlation does not mean causation DAMA refuted each claim...technical issue...
  -is the temporal correlation strong enough? theoretical issue... phase if a bit off... Can including the stochastic nature of muon induced neutron production and interaction lead to agreement in phase with DAMA and CoGeNT modulation?
  K. Blum 1110.0857: YES, S. Chang, J. Pradler and I. Yavin arXiv:1111.4222: NO

Light WIMPs or Backgrounds? A definitive way to eliminate the doubt that the annual modulation in a direct DM detector is due to seasonal backgrounds: make the experiments in the Southern Hemisphere. Problem is, all underground laboratories are in the North- Opportunity for ANDES

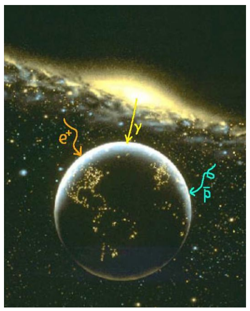


Indirect detection through γ and anomalous cosmic rays

Main detectors: PAMELA, Fermi (FST), HESS, VERITAS, CANGAROO, MAGIC

Look for an excess of γ, e^+, $\bar{p}$ over expected, and a bump at $E \sim m$

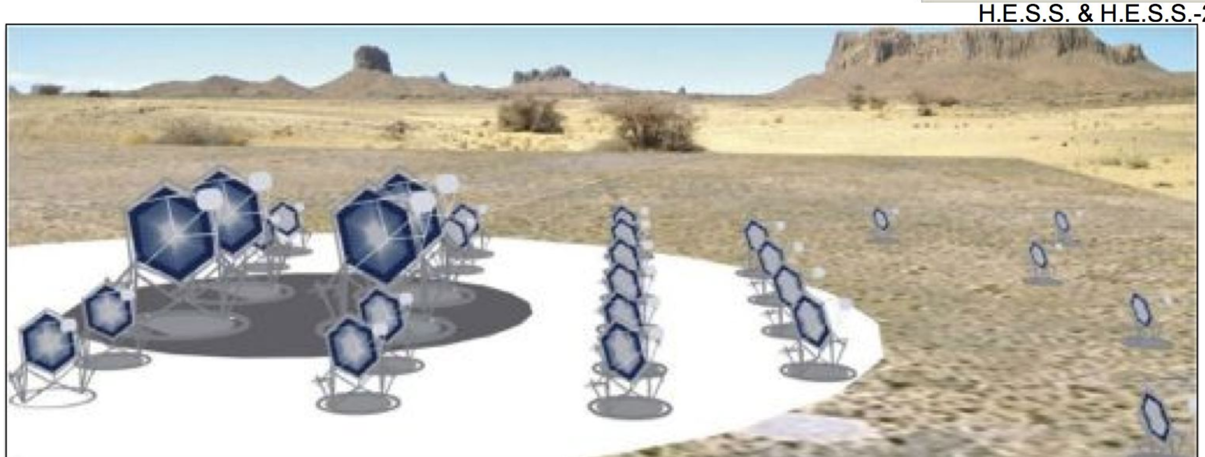
(Fig. from G. Gondolo)



Fermi-LAT (Fermi Large Area Telescope)

H.E.S.S. & H.E.S.S.-2

Maybe in Argentina?

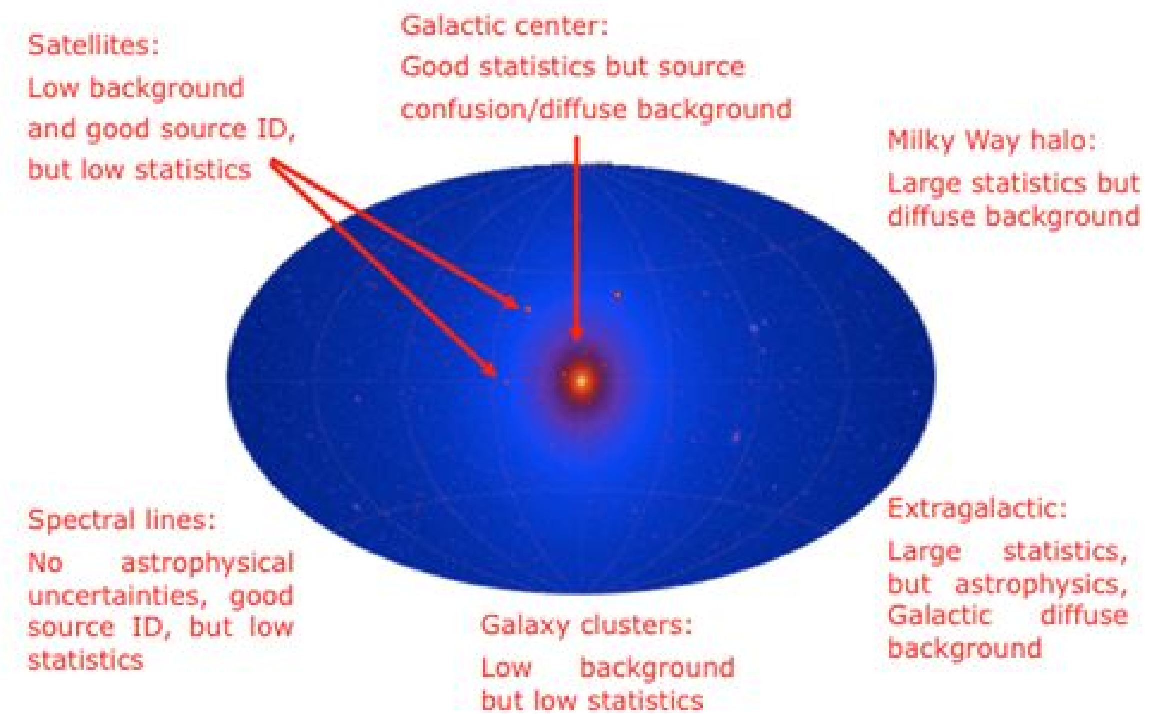


CTA (Cherenkov Telescope Array)

Indirect detection through γ

$$\Phi_\gamma \sim < \sigma_{anih}|v| > \int_{\text{los}} \rho^2(r)\, dl(\theta) d\theta.$$

ρ: DM density. Denser sources are best: GC, minihalos, dwarf galaxies, extragalactic γ



Indirect DM Searches: recent round of WIMP signals?

- PAMELA e$^+$ 2008 excess from the halo CONFIRMED BY FERMI
  But no $\bar{p}$ excess-No bump in spectrum seen by Fermi and HESS- "Leptophilic" (mostly to τs), $m >$TeV mass DM, with large annihilation σ? Difficult! or astrophysical (pulsars).
- "WMAP haze" at the GC CONFIRMED BY PLANCK Finkbeiner et al. 2004
  part of Fermi-Bubbles?Dobler et al 0910.4583; Su et al. 1005.5480
  Most WIMP models could explain it as synchrotron from e produced in annihilations
- GeV's from extended region at the GC, "Light WIMPs" in FERMI data? (Hooper, Linden 1110.0006; D.Hooper 1201.1303; Abazajian, Kaplinghat 2012...))
- 130 GeV line from the GC in FERMI data? Bringmann et al 1203.1312; Weniger 1204.2797; Tempel, Hector, Raidal 1205.1045; Boyarsky, Malyshev, Ruchayskiy 1205.4700; Geringer-Sameth, Koushiappas 1206.0796, Su, Finkbeiner 1206.1616,

“WMAP-Haze” Dobler, Finkbeiner 2007

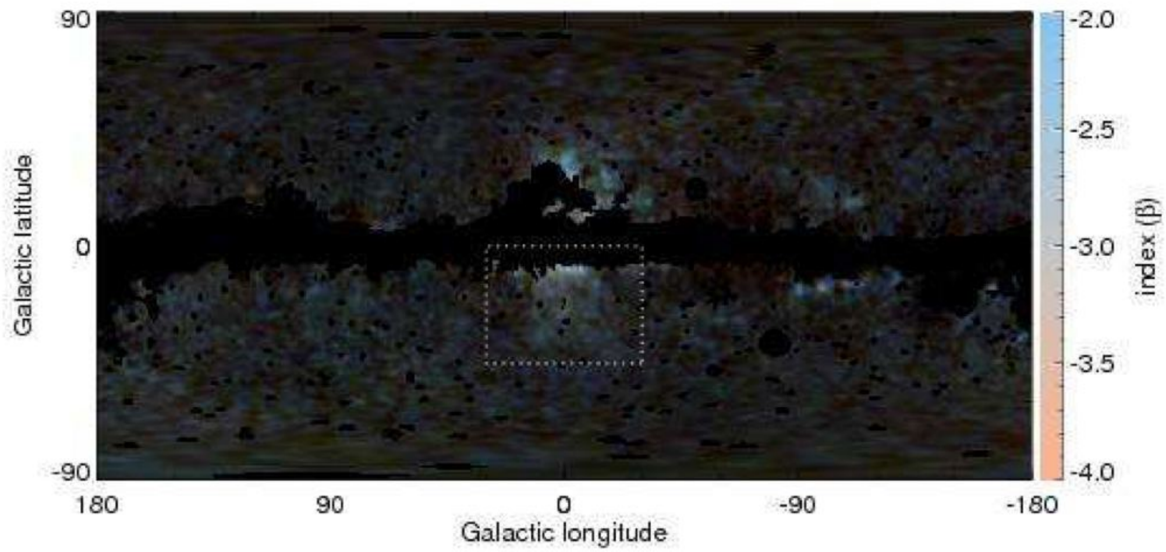


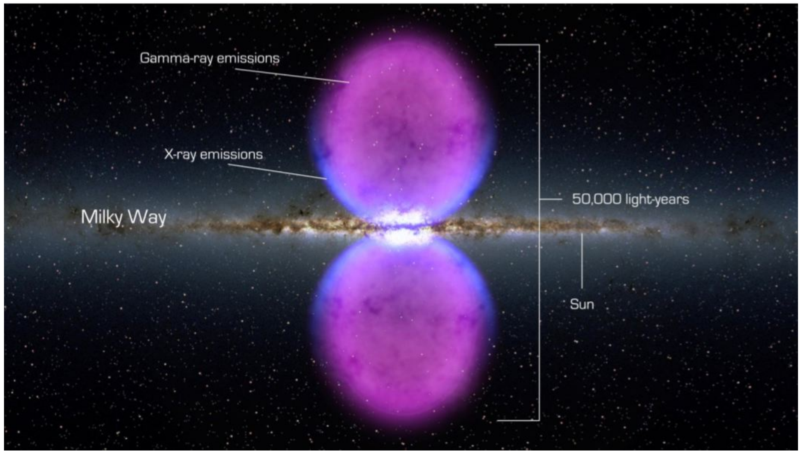
FIG. 7.— An RGB representation of $\mathbf{r}_H$ and $\mathbf{r}_{H+S}$ for RG8 with CMB5. The color coding indicates the spectral index, in antenna temperature, of a given pixel. In particular, the bluer haze region (*box*) indicates a harder spectrum than the redder synchrotron emission.

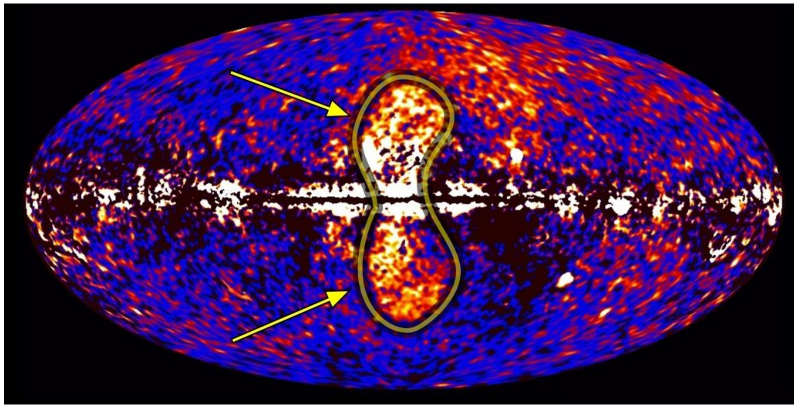
Extra microwave component near the GC found in WMAP data, now confirmed by PLANCK, part of the Fermi-Bubbles?

If DM almost any WIMP annihilating into e could produce it!

FERMI-Bubbles due to a past AGN phase of central black hole?

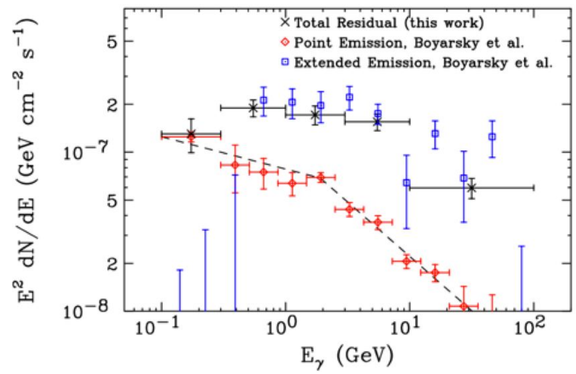
NASA Artist's Conception





Signals of Light WIMPs in Fermi ST data too?

from the Galactic Center (Hooper, Linden 1110.0006; D.Hooper 1201.1303)

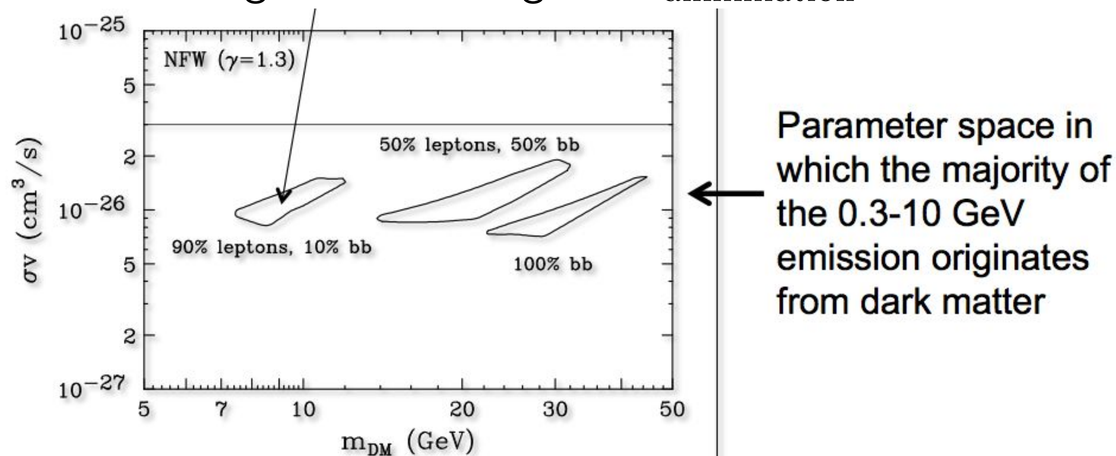


Extended spherically symmetric symmetric excess in GeV's gamma rays! Confirmed independently by a different group Abazajian, Kaplinghat 2012

Signals of Light WIMPs in Fermi ST data too?

few degrees extended source at GC (Hooper, Linden 1110.0006; D.Hooper 1201.1303)

"Light WIMP" region- $\sigma_{\rm annihilation} = 10^{-26}$cm^3/s of "Thermal WIMP Miracle"



(Abazajian, Kaplingat find larger mass range depending on the annihilation mode)

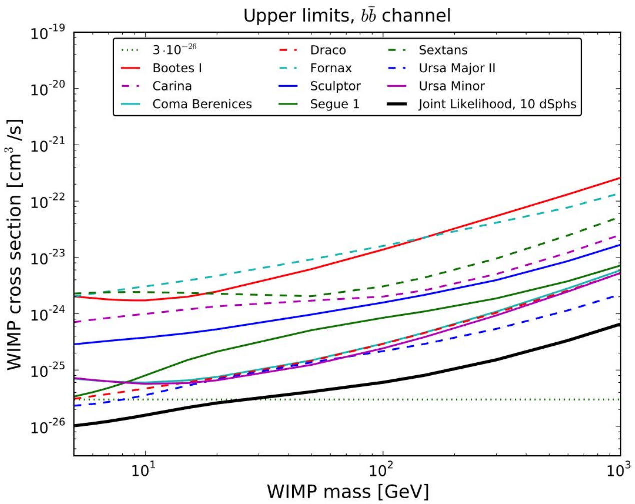
and from galaxy clusters "compatible with Hooper's GC signal" (Han et al 1112.2220)

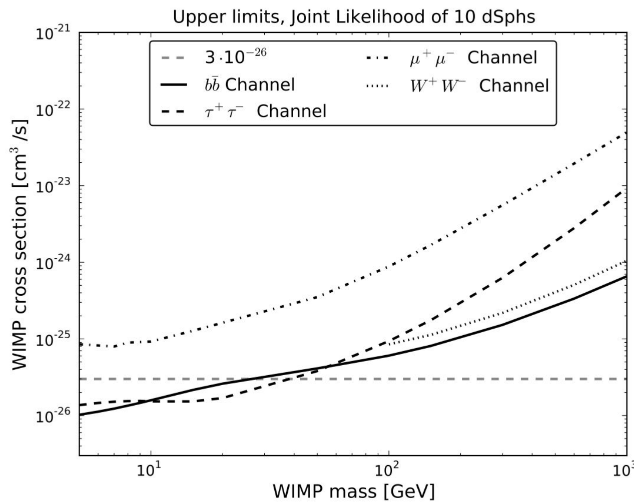
CAVEATS: Results not confirmed by the Fermi collaboration- They have produced only upper bounds. To improve need better energy and angular resolution: CTA could clarify this signal in a few days!

If the signal is there, a population of millisecond pulsars could also produce it...

Upper bounds from Fermi ST Fermi-LAT coll.1108.3546

Exclude Thermal WIMPs with $m < 20$ GeV The Galactic Center is a complicated place: the DM is not gravitationally dominant so large uncertainties in the DM profile, and there are other sources. Dwarf galaxies are simpler and DM dominated.



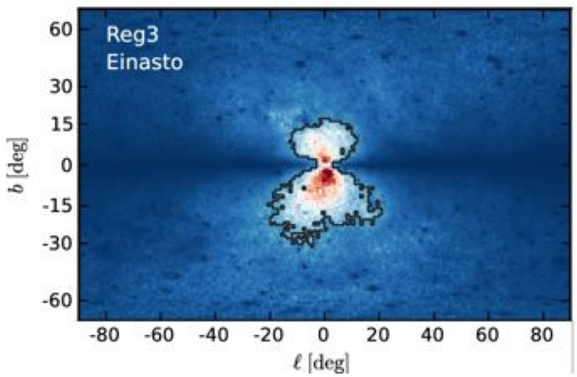


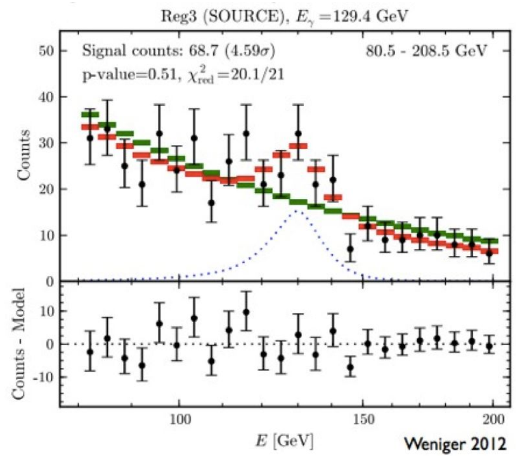
FERMI could exclude the "Thermal WIMPs" with $m <$ few 100 GeV in 6 y.

A 130 GeV line from the GC in the FERMI LAT data? Two lines?

Bringmann et al 1203.1312; Weniger 1204.2797; Tempel, Hector, Raidal 1205.1045; Boyarsky, Malyshev, Ruchayskiy 1205.4700; Geringer-Sameth, Koushiappas 1206.0796, Su, Finkbeiner 1206.1616,

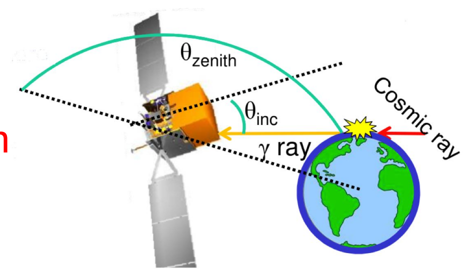
Weniger 4/12: 4.6σ line (3.3σ with "look elsewhere")





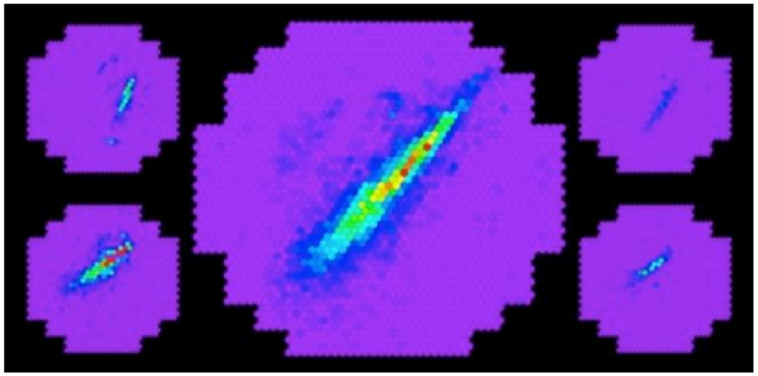
Su, Finkbeiner 6/12 confirmed the result+hint of 111 GeV line too: $\gamma\gamma$ and γZ???

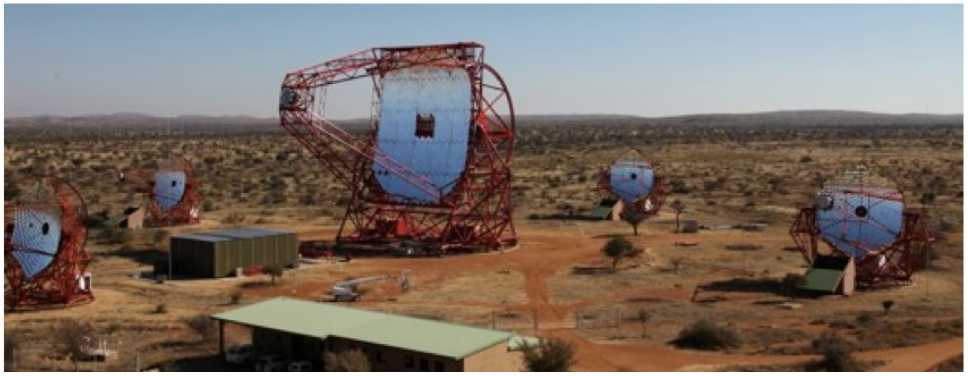
CAVEATS: No convincing evidence for the same lines anywhere else (clusters, unassociated point sources) and Su & Finkbeiner found a marginal 130 GeV line in the Earth Lim (if confirmed it is a clear indication of a systematic error)



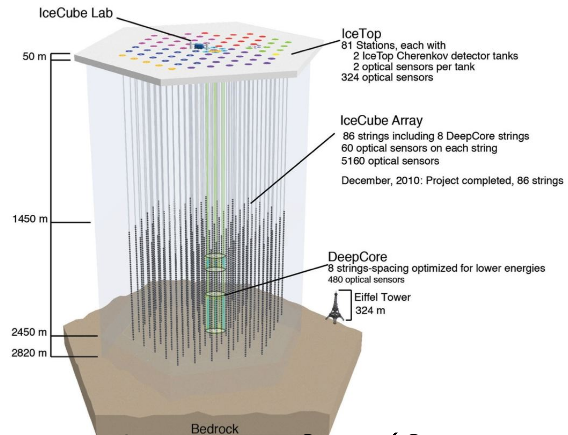
A 130 GeV line from the GC in the FERMI LAT data? Two lines?

HESS-II in Namibia (with a new 28m segmented telescope added to the four 12m ones) operating since July 2012 will confirm or rule out the presence of this line(s) by the end of the year (5σ detection in 50 hours of observation- CTA in 2018 would need less than 5 hours)! Bergtrom et al 1207.6773

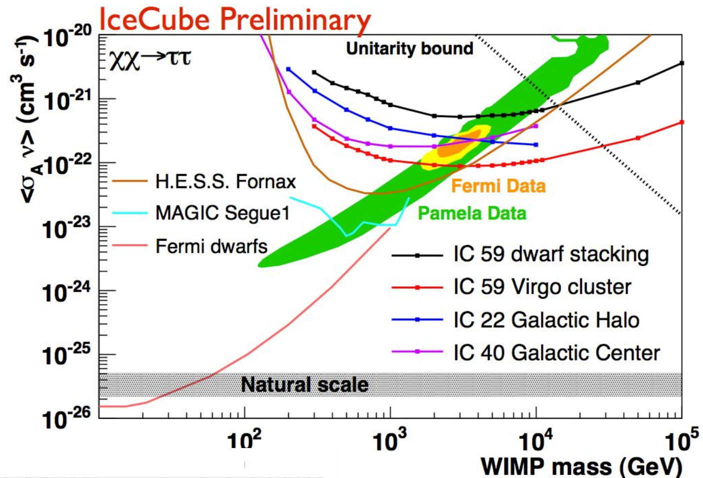




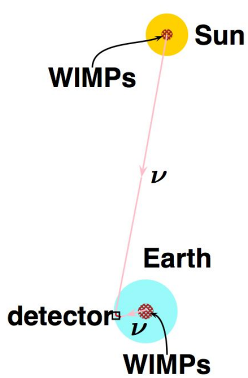
Indirect detection: ν's in IceCube

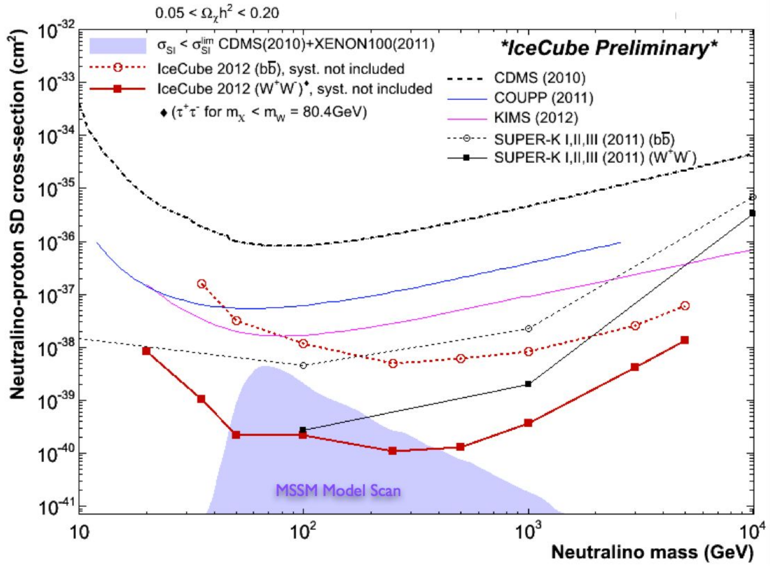


from the Galactic Center,
Dwarf Galaxies, Clusters



from the Sun (SD bounds)





OUTLOOK

So far many hints but no firm DM signature found. In all cases, more data will help clarify the situation.

DM searches are advancing fast in all fronts, the LHC, direct and indirect detection, astrophysical observations and modeling. Lots of data necessarily lead to many hints... hopefully at some point several of them will point to the same DM candidate!

EXTRA SLIDES

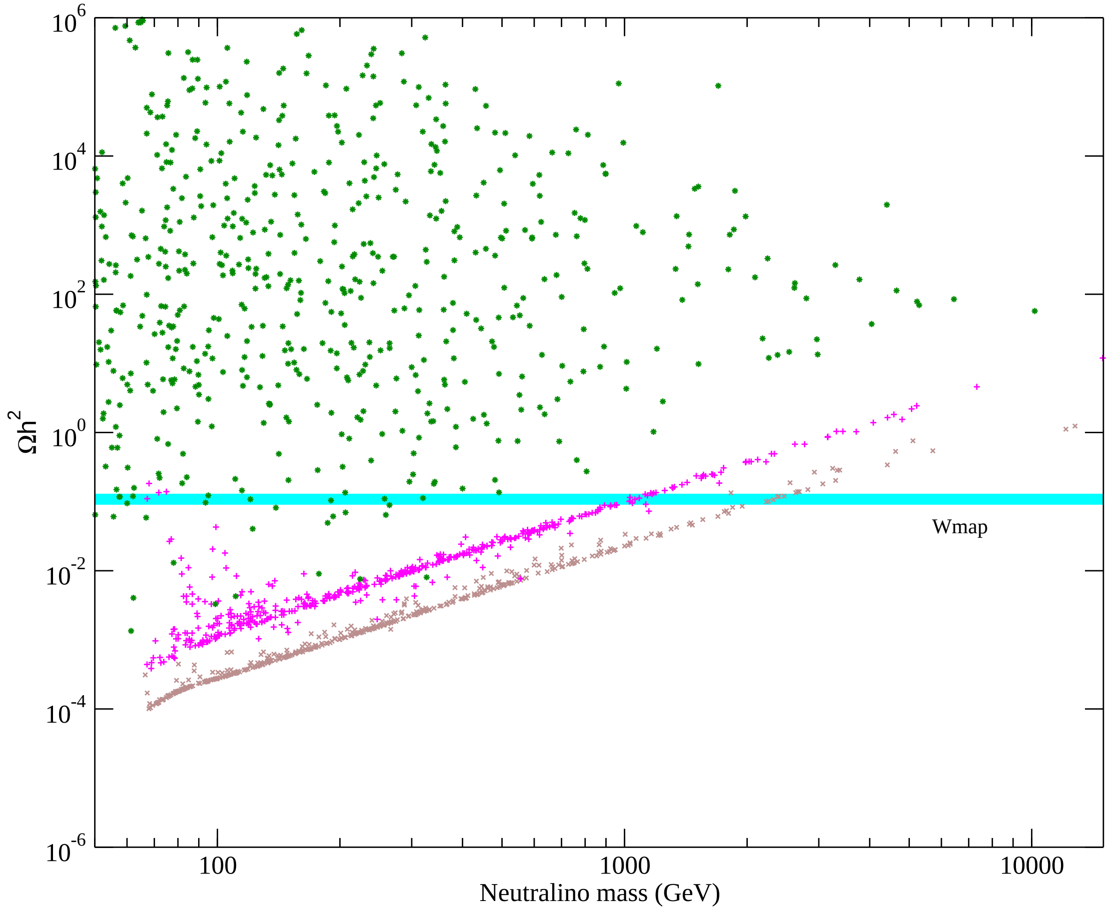
Standard pre-BBN cosmology

MSSM
(9 param.)

Standard cosmology
1700 models / (points)

G.G. etal PRD 74: 083514, 2006

bino-like
higgsino-like
wino-like



Same models in Non-Standard pre-BBN cosmology

MSSM SAME

1700 models (points)

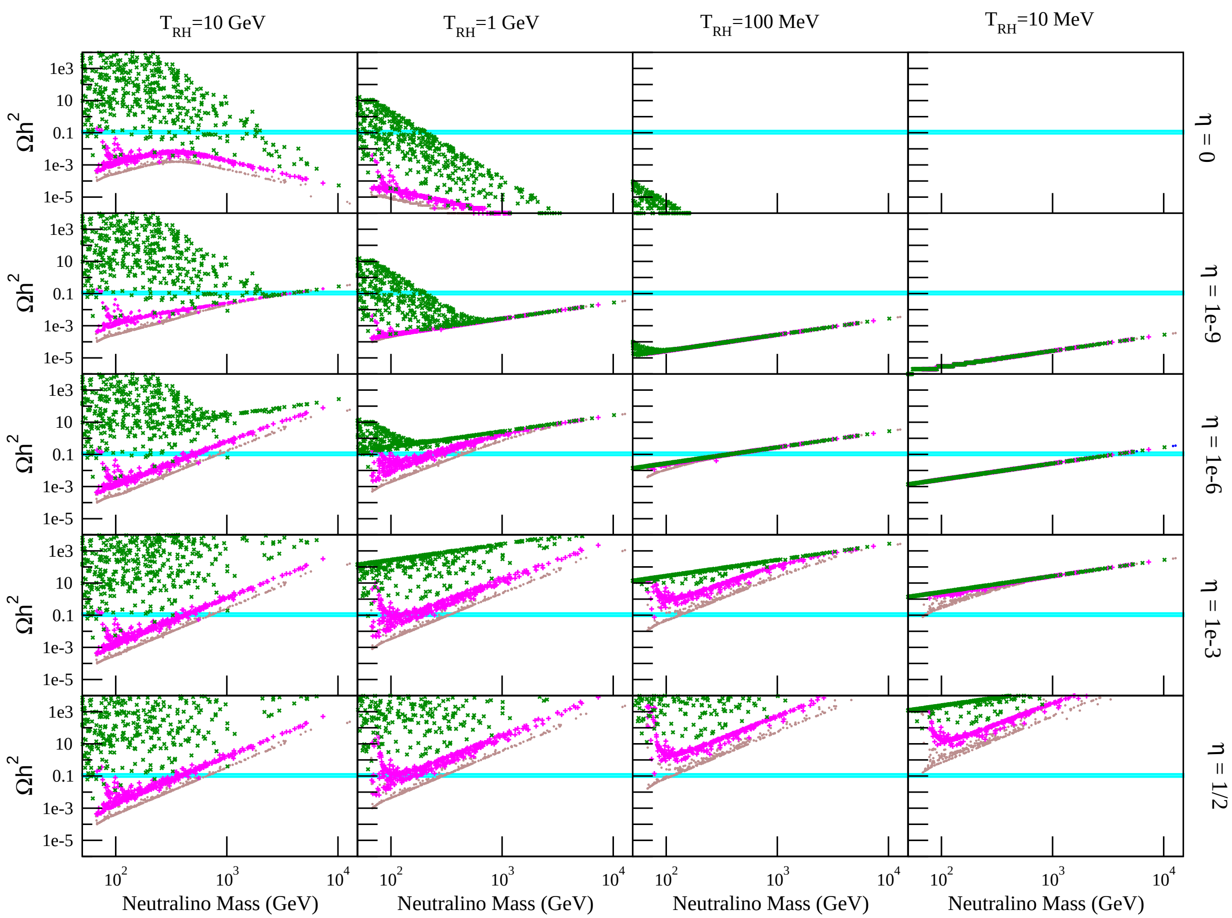
G.G. etal PRD 74: 083514, 2006

All points can be brought to cross the DM cyan line with suited T_{RH}, η !

bino-like

higgsino-like

wino-like



Asymmetric DM (ADM)

For Baryons: if usual decoupling, $\sigma_{\rm strong} \sim 1/m_\pi^2$ emplies $T_{f.o.} \simeq m_N/45$.
Predicted: $\Omega_B \simeq 10^{-10}$ and equal numbers of baryons and antibaryons
Observed: $\Omega_B \simeq 0.05$ and only baryons. Thus an early Baryon Asymmetry must exist
$A_B = n_B - n_{\bar{B}}/n_\gamma \simeq 10^{-9}$, and annihilation ceases when no $\bar{B}$ left.

For Dark Matter particles: assume A_{DM} and A_B generated by similar physics,
$A_{DM} \simeq A_B$ so $n_{DM} \simeq n_B$

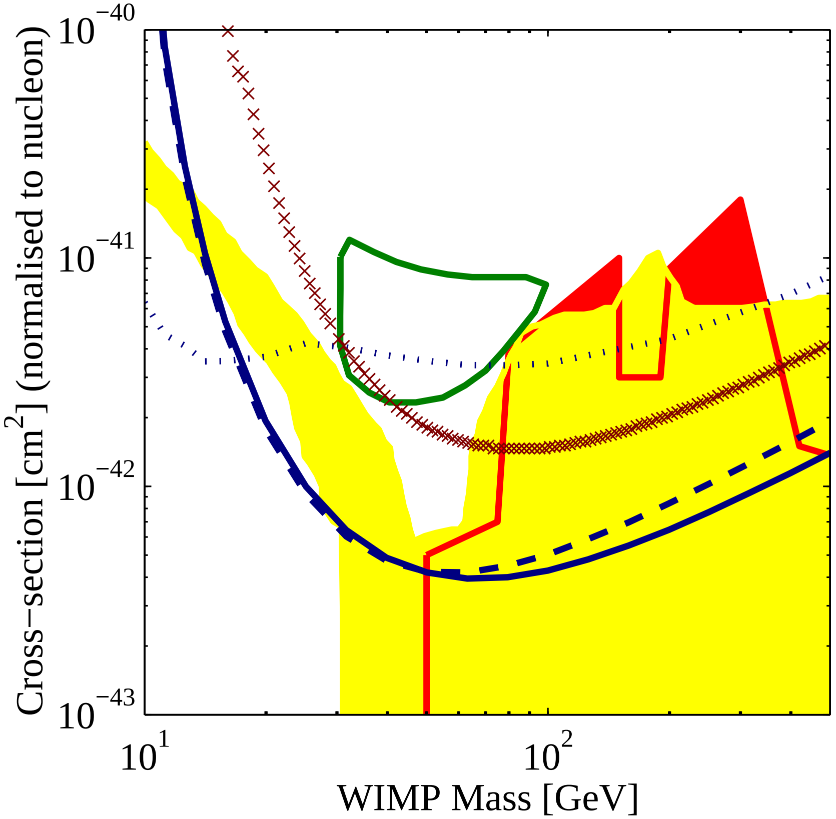
$$\frac{\Omega_{DM}}{\Omega_B} \simeq \frac{n_{DM} m_{DM}}{n_B m_N} \simeq \frac{m_{DM}}{m_N}$$

$\Omega_{DM}/\Omega_B \simeq 5$ if $m_{DM} \simeq 5$ GeV. So ADM explains why $\Omega_{DM}/\Omega_B \simeq O(1)$

GeV scale ADM in hidden/mirror sector, or pNGB in Technicolor or low scale strong interactions.... Also possible TeV scale ADM in Technicolor: $A_{DM} \simeq A_B \exp\left(-m_{DM}/T_{\rm weak}\right)$ (Nussinov 85; Gelmini, Hall, Lin 87; Kaplan 92; Barr, Chivukula, Fahri 90; Enkvist, MacDonald 98; Gudnason, Kouvaris , Sannino 05; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)

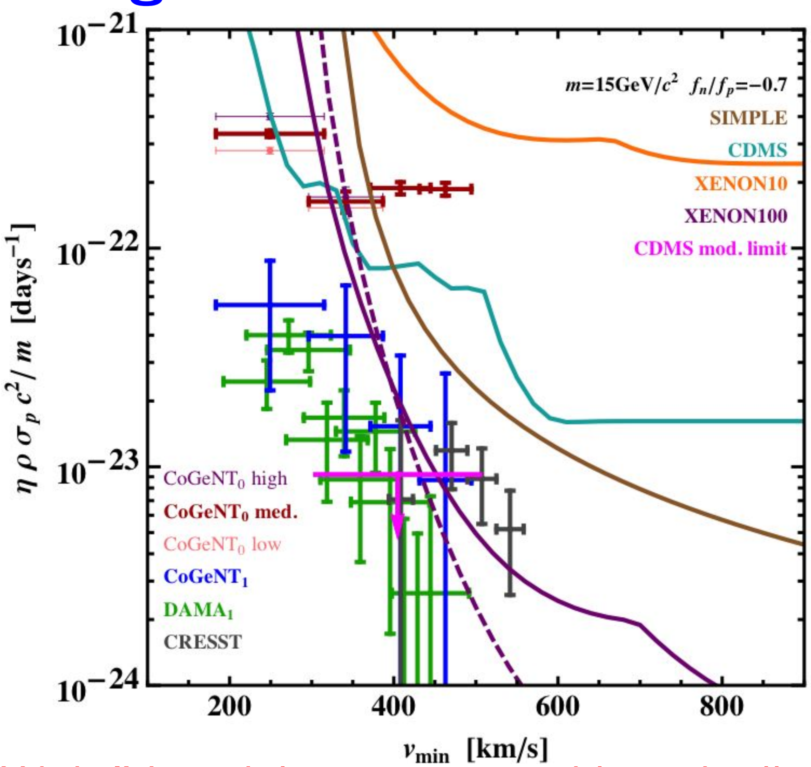
Old DAMA/NaI SI WIMPs?

Theoretical prejudice in early DAMA analysis: DAMA region for SI WIMPs in the SHM was cut at 25GeV (from 1997 until 2003) which was excluded in 2002 by Edelweiss (brown crosses) and in 2004 by CDMS-Soudan (blue).



Bottino et al. light neutralinos m >6 GeV
Baltz et al.

IV light WIMPs "halo independent analysis" Fox, Liu, Weiner 1011.1915



$m = 15$ GeV Gondolo Gelmini 1202.6359
CoGeNT rates and CRESST rate
CoGeNT modulation compatible with DAMA but $>$ 25 % of rate!
DAMA modulation
and CDMS mod. limit
mapped into v_{min}-space

We plot weighted average η_{i0}, η_{im}

$\eta_i = \eta_{i0} + \eta_{im}\cos(\omega t - t_0)$

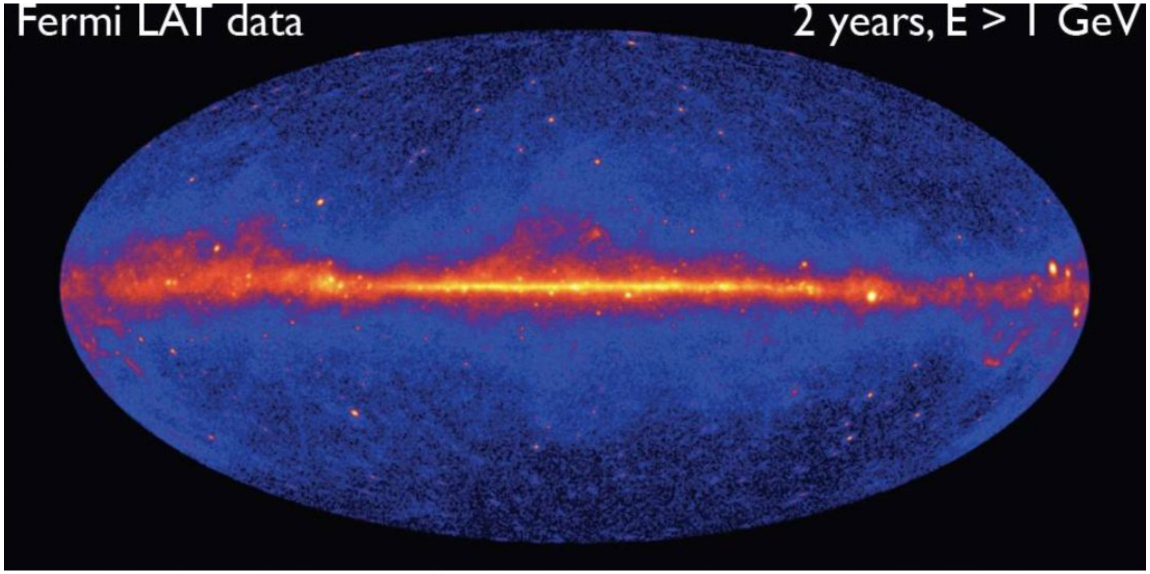
Bins extended by E-resolution ΔE on both sides

With IV modulations compatible with all rate bounds! - Problems:
- CoGeNT rate could be lowered but then modulation too high;
-CRESST unmodulated is on top of CoGeNT modulation! so they are incompatible

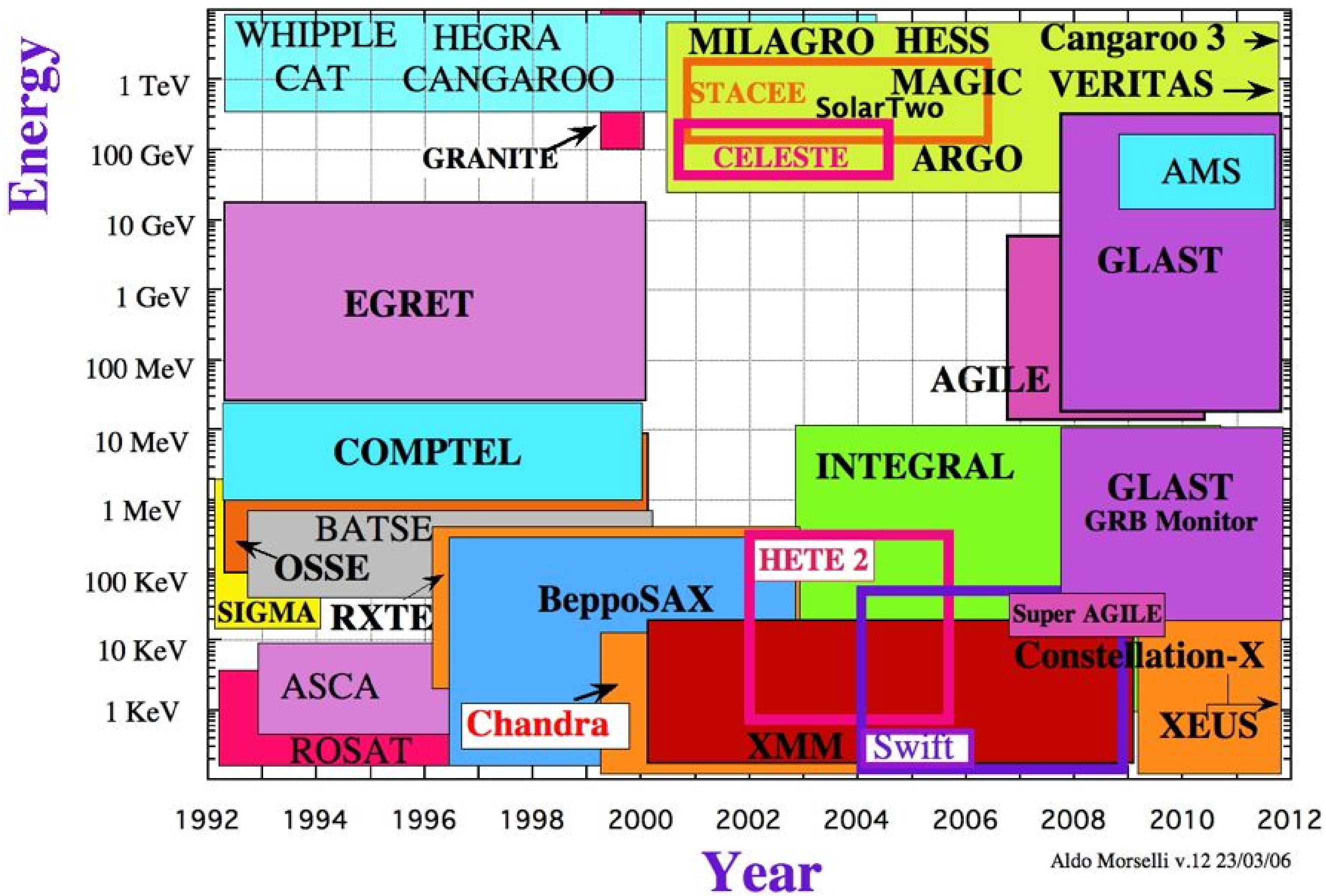
Fermi Space Telescope (FST)

(ex GLAST, γ-ray Large Area Space Telescope):

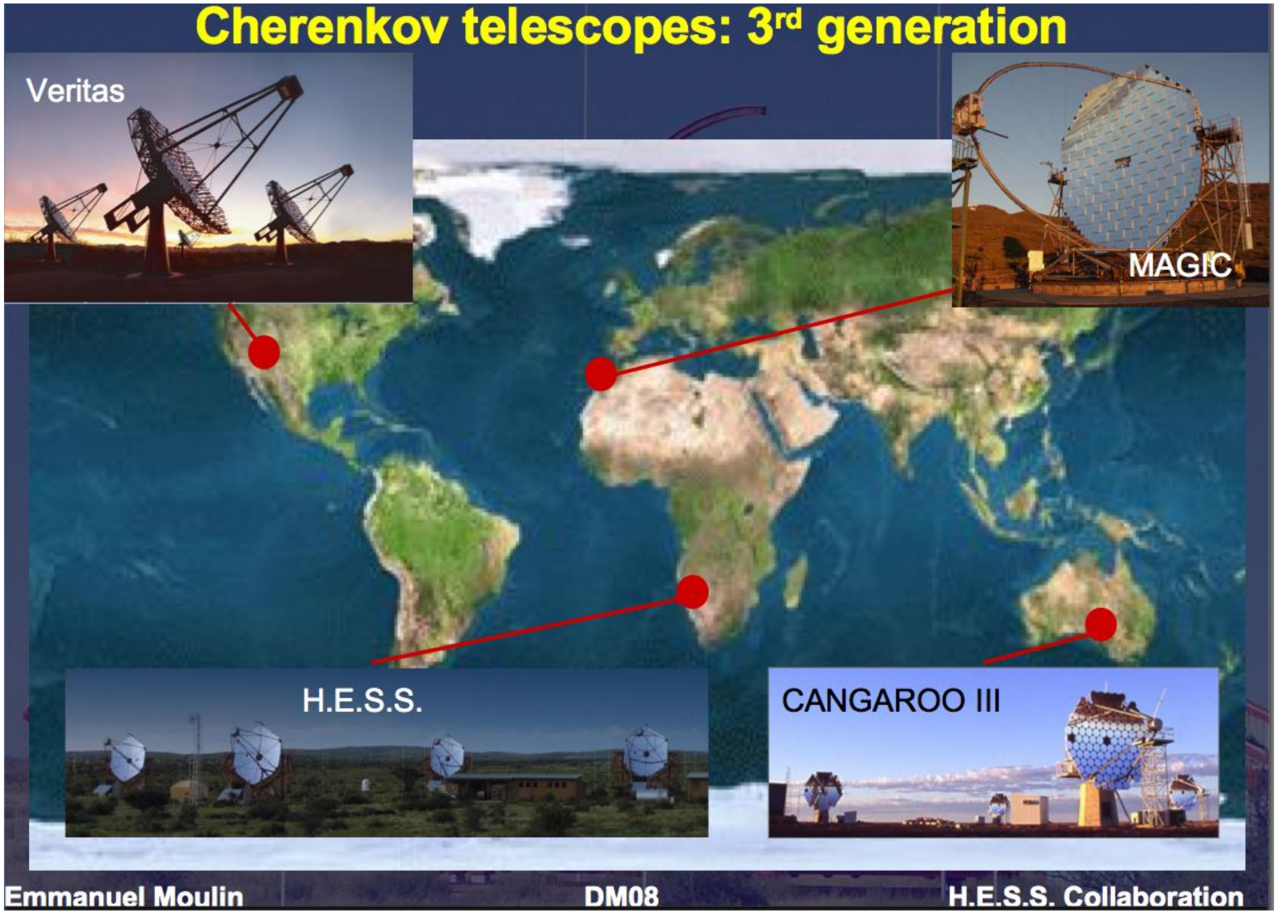
launched Jun 11,08 is providing γ ray spectroscopic data of unprecedented quality



γ ray detectors

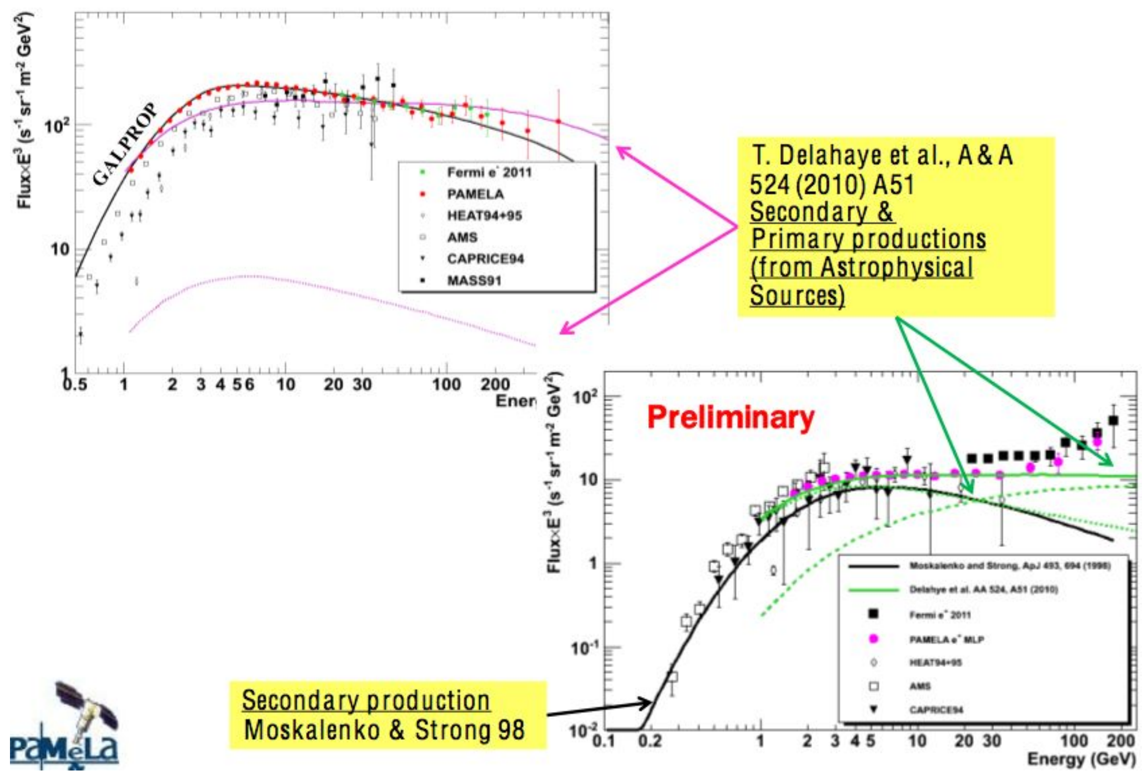


Air Cherenkov Telescopes (ACT's)



PAMELA, FERMI e^+ excess M. Boezio, UCLA DM conf. Feb.2012

PAMELA e⁻ and e⁺ Spectra



Need extra sources of e^+ near Earth (but not $\bar{p}$). Pulsars?