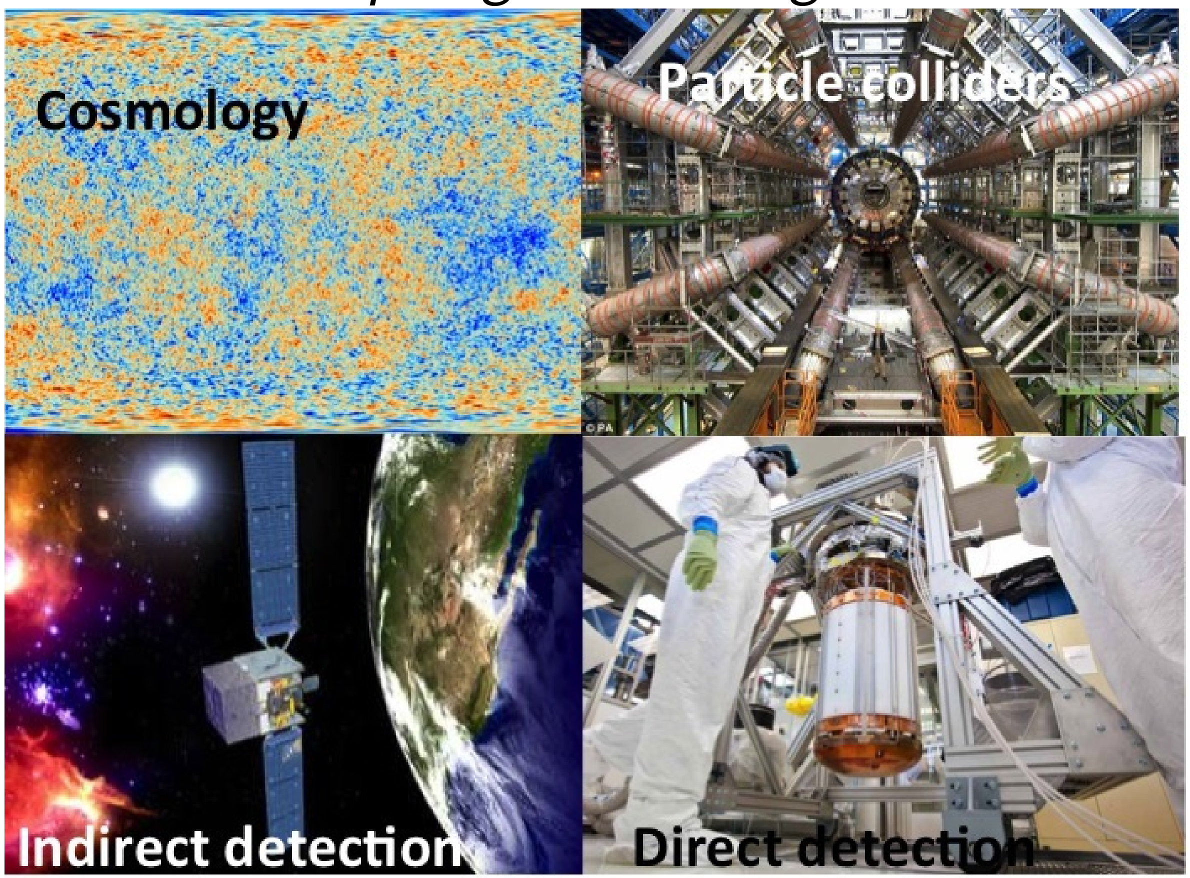
The

for the Dark Matter

Graciela Gelmini - UCLA

Invisibles 2016, Padova, September 15, 2016

The Quest for the Dark Matter, the most abundant form of matter in the Universe is multi-pronged involving ...



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What we are looking for

The DARK MATTER problem has been with us since 1930's,

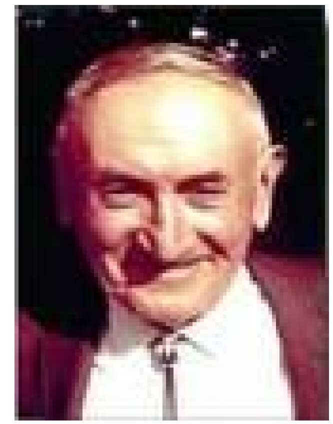
name used by Fritz Zwicky in Helvetica Physica Acta Vol6 p.110-127, 1933

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.



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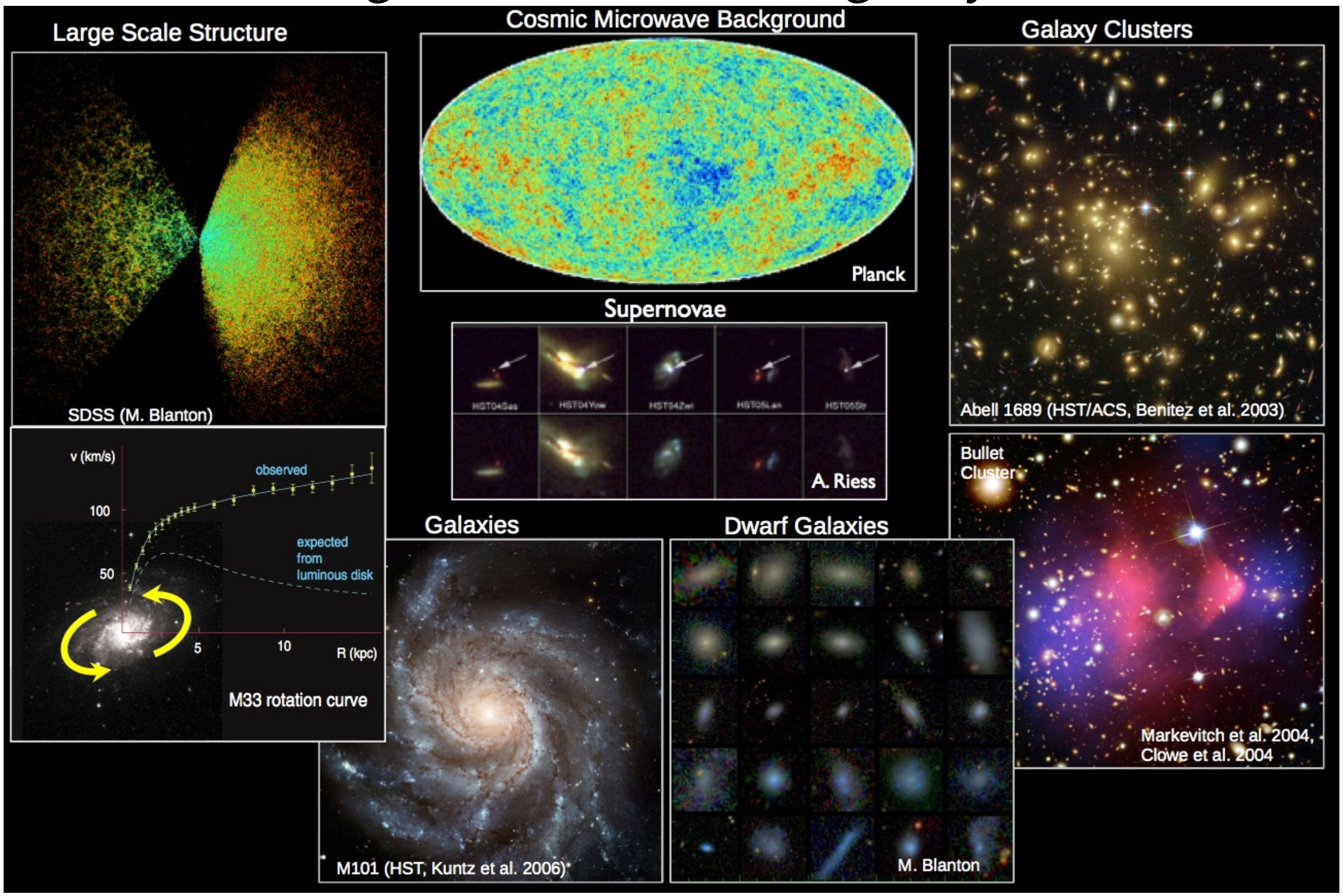
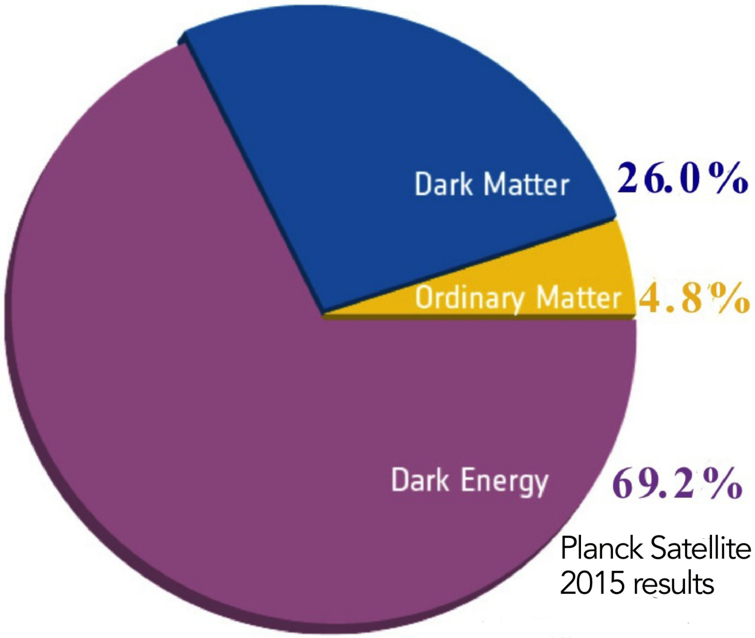
gr/cm³. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\varrho \sim 10^{-28}$ gr/cm³ erscheint daher nicht

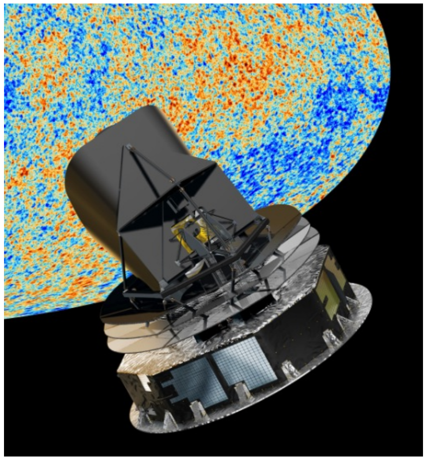
Used the Virial theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only. J. Ostriker: in the first 40y his seminal 1937 paper had 10 citations!

Evidence for "missing mass" from dwarf galaxy scales on



At the largest scales: the "Double-Dark" model





"DARK ENERGY" 69% (with repulsive gravitational interactions)
"MATTER" 31% (with usual attractive gravitational interactions- forms gravitationally bound objects) and most of it is **"DARK MATTER" 26%**

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What we know about dark matter

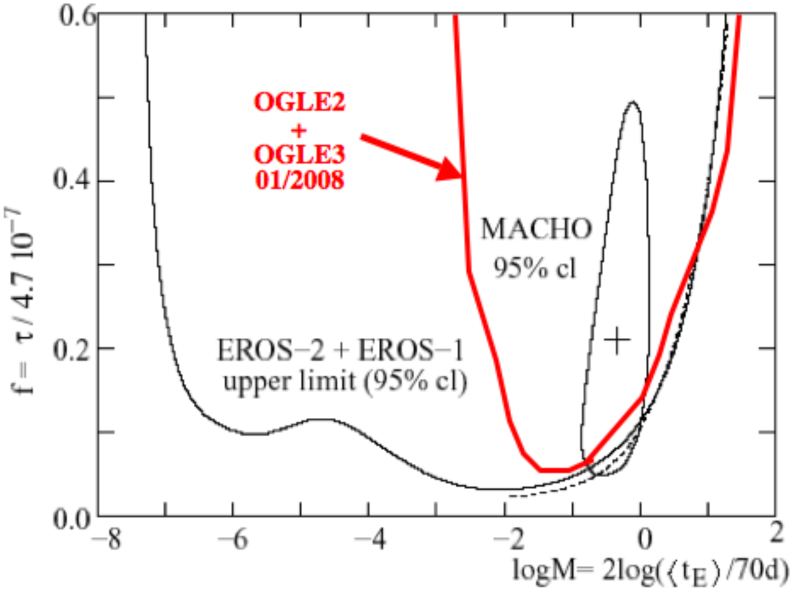
After 80 years, what we know about DM:

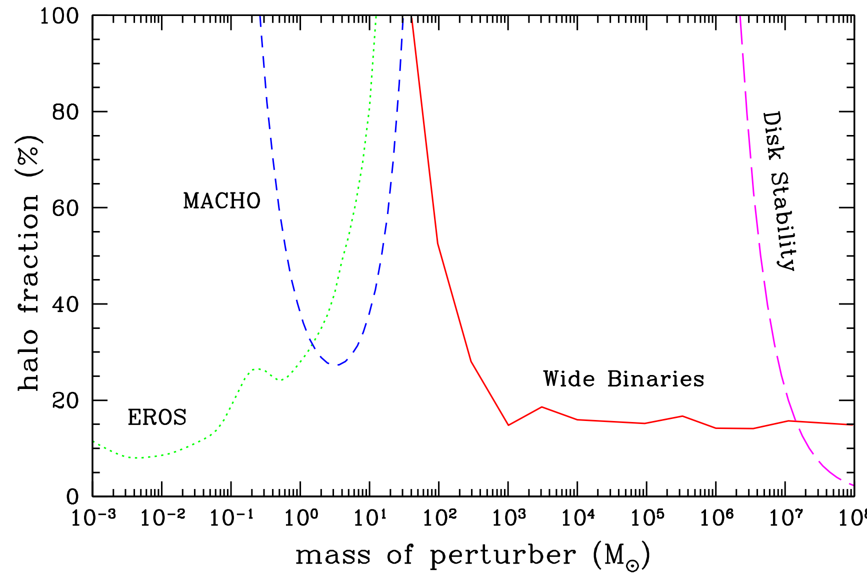
- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- DM and not [MOND + only visible matter]**
- **3- DM is not observed to interact with light** "milli-charge" "dipole" or "anapole DM"
- **4- The bulk of the DM must be nearly dissipationless, but ≤10% of it could be dissipative.** Fan, Katz, Randall & Reece 1303.1521-1303.3271
- **5- The mass of the major component of the DM has only been constrained within some 80 orders of magnitude!**

  10^{-31} GeV ≤ **mass** ≤ $2{\times}10^{-9}M_{\odot}$ =2 $\times 10^{48}$GeV

Dark Matter: not MACHOS

M. Moniez arXiv:0901.0985 [astro-ph.GA] Combined with older results for larger masses: Yoo, Chaname, Gould, ApJ**601**, 311, 2004 Griest, Cieplak and Lehner 1307.5798





2009 limit: $m > 10^{-7}$ M$_\odot$ cannot be the bulk of the DM (M$_\odot = 10^{57}$GeV)

2013 limit: (using Kepler satellite data) $m >2\ 10^{-9}$ M$_\odot$ cannot either.

Notice, possible window 20 M$_\odot < m <$100 M$_\odot$? (LIGO $M_{BH} \simeq 30 M_\odot$)

Problem with MACHOS: how would they form? Could be Primordial Black Holes but limits constrain them to be only a fraction of the DM for almost any mass.

Dark Matter: could be Primordial Black Holes (PBH)?

PBH are hypothetical type of black hole not formed by the gravitational collapse of a large star but in an early phase transition Carr and Hawking, 1974

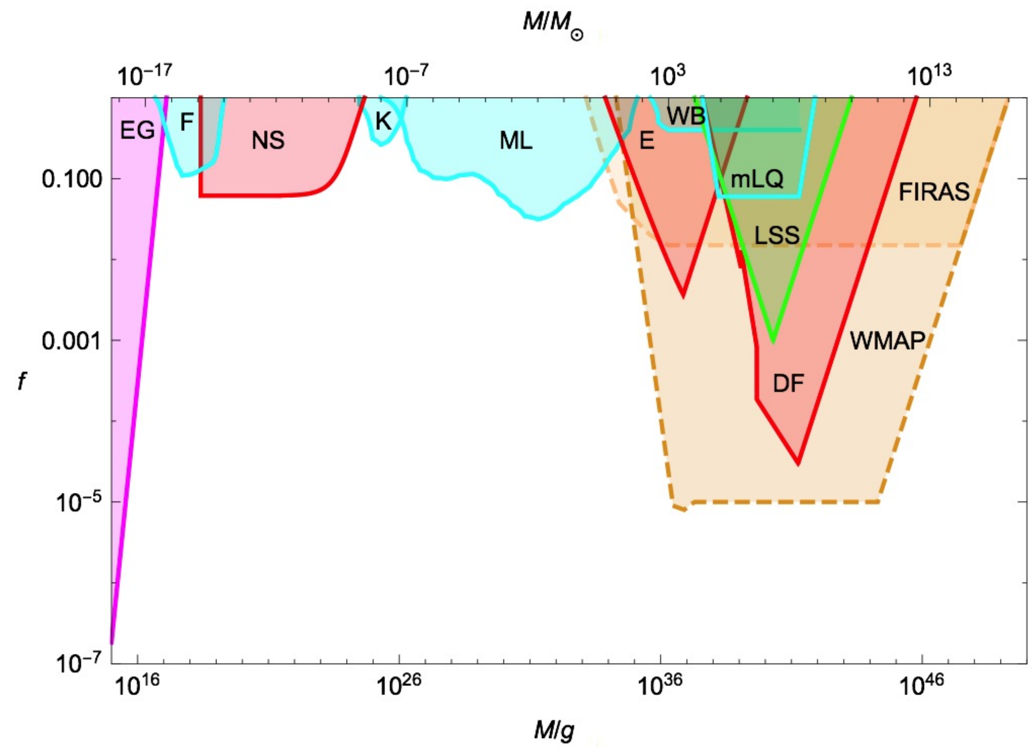
Many limits exclusively applying to BH:

- $m_{PHB} > 10^{15}$g $= 6 \times 10^{38}$ GeV lighter would have evaporated by now
- $m_{PHB} > 10^{17}$g or evaporating BH would have been observed (by EGRET and Fermi)
- 5 10^{17}g$< m_{PHB} < 10^{20}$g excluded by non-observation of "femtolensing" of GRB 1204.2056
- 10^{16}g$< m_{PHB} < 10^{22}$g excluded- its accretion in stars would destroy compact remanent 1209.6021
- 3 10^{18}g$<m_{PHB}<$ 5 10^{24}g excluded- its accretion in n stars in GC would destroy them 1301.4984
- $m >$ $M_{\odot}$= 2 10^{33}g excluded by absence of CMB spectral distortions 0709.0524

Dark Matter: could be Primordial Black Holes (PBH)?

compilation of bounds on density fraction f

Carr, Kuhnel and Sandstad 1607.06077



Only narrow windows might remain for PBH weakening some constraints, e.g.

just below the MACHO microlensing limit 4 10^{24}g=2 10^{-9}M$_\odot$

or in MACHO "window" 20 M$_\odot$-100 M$_\odot$ between microlensing and wide binaries disruption limits

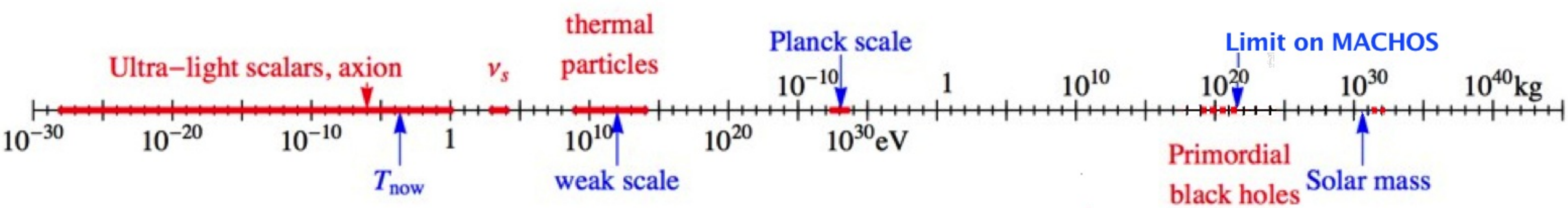
(e.g. if PBH are small at CMB emission and merge very efficiently) Clesse&Garcia-Bellido 1501.07565

Could LIGO BH $\sim$ 30M$_\odot$ be most of the DM? Bird etal. 1603.00464, Clesse&Garcia-Bellido 1603.05234

- **5- The mass of the major component of the DM has only been constrained within some 80 orders of magnitude.**

$$10^{-31}\ \text{GeV} \leq \textbf{mass} \leq 2\times10^{-9} M_{\odot} = 2\ 10^{48}\text{GeV} = 4\ 10^{21}\text{kg}$$

Lower limit: "Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000 or $0.2\text{-}0.7\ \times10^{-6}$ GeV $\leq$ **mass** for particles which reached equilibrium - depending on boson-fermion and d.o.f. Tremaine-Gunn 1979; Madsen, astro-ph/0006074



The limits just presented, and the fact that particle candidates can have the right relic abundance to be the DM, constitute the only observational arguments we have in favor of DM elementary particles candidates.

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- **3- DM is not observed to interact with light**
- **4- The bulk of the DM must be nearly dissipationless, but $\leq$10% of it could be dissipative.**
- **5- Mass within some 80 orders of magnitude.**
- **6- DM has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is huge**

  Bullet cluster + non-sphericity of galaxy and cluster halos
  $\boldsymbol{\sigma_{self}/m} \leq 1$ cm^2/g = 2 barn/GeV = 2×10^{-24} cm^2/ GeV
  by comparison e.g. ^{235}U-neutron capture cross section is a few barns!
  Self Interacting DM (SIDM) just below limit

  (Limit on σ_{self}/m ratio comes from requiring self-interaction mean free path $\lambda_{mfp} \simeq 1/n\sigma_{self} = m/\rho\sigma_{self}$ be long enough, $n = \rho/m$ is the DM number density)

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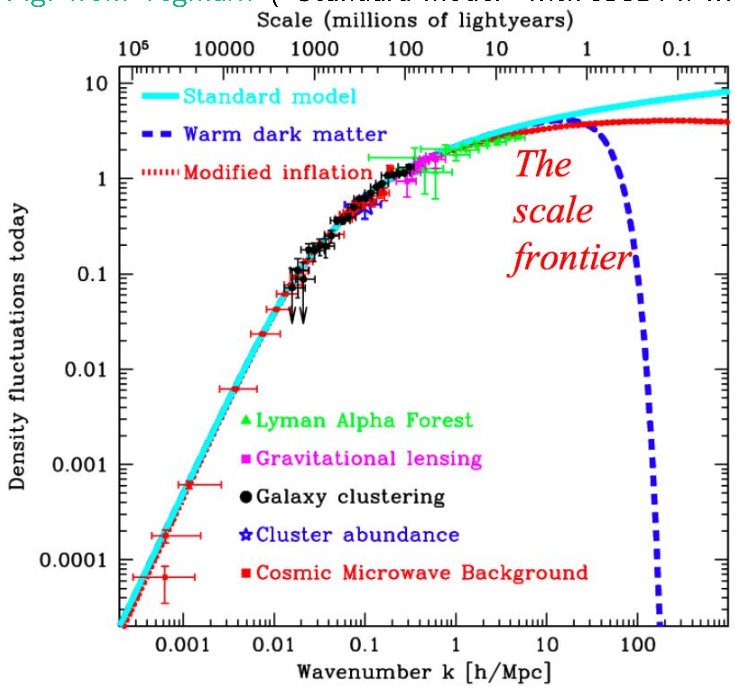
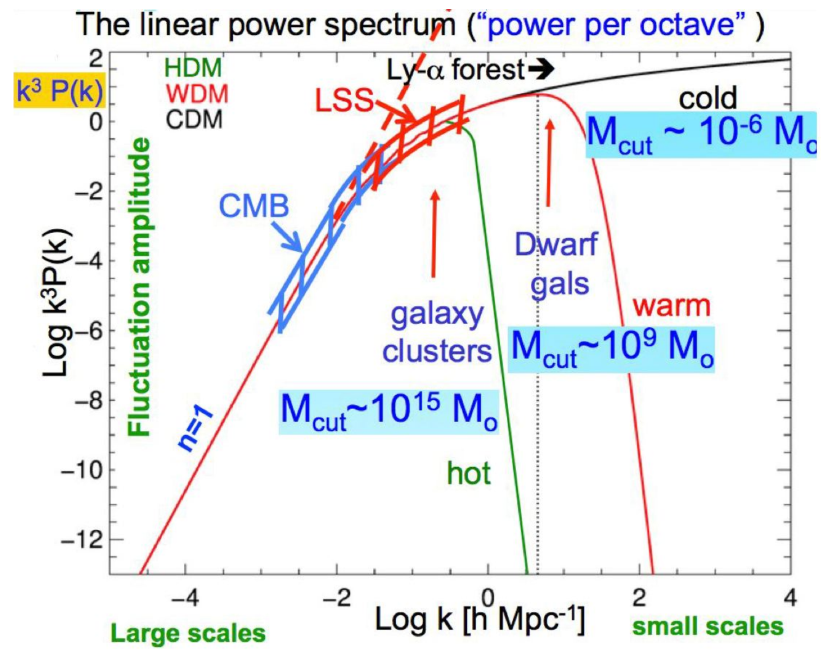
- **6- DM has been mostly assumed to be collisionless, but huge self interaction upper limit $\sigma_{\rm self}/{\rm m} \leq$ 2 barn/GeV**
- **7- The bulk of the DM is Cold or Warm, thus particle DM requires BSM physics**

"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





Distinguishing CDM-WDM-SIDM-mixed DM and baryonic effects at sub-galactic scales is where most of the structure formation simulations and observational efforts are directed at present.

No CDM or WDM particle candidate in the SM!

In the SM only **neutrinos** are part of the DM- the are light m< 10^{-1} eV and in equilibrium until BBN, $T \simeq 1$ MeV thus they are **Hot DM (HDM)**

But many in extensions of the SM!

Instead of “The Fifty Shades of Gray” we have here “The 500 shades of dark”...

Particle DM requires new physics beyond the SM!

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- **6- DM has been mostly assumed to be collisionless, but huge self interaction upper limit** $\sigma_{\rm self}/{\rm m} \leq 2$ **barn/GeV**
- **7- The bulk of the DM is Cold or Warm, thus particle DM requires physics beyond the SM**
- **8- Most DM candidates are relics from the pre-BBN era, from which we have no data.** The computation of the relic abundance and velocity distribution of particle DM candidates produced before $T \simeq 4$ MeV depends on assumptions made regarding the thermal history of the Universe.

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Dark matter hints

Sterile neutrinos? WIMPs?

Sterile Neutrino DM?

If ν_s are the DM, $\nu_s \to \nu\gamma$ would produce a monochromatic X-ray line in galaxies and galaxy clusters. This line may have been seen at 3.5 keV!

Or "Fluorescent" DM?

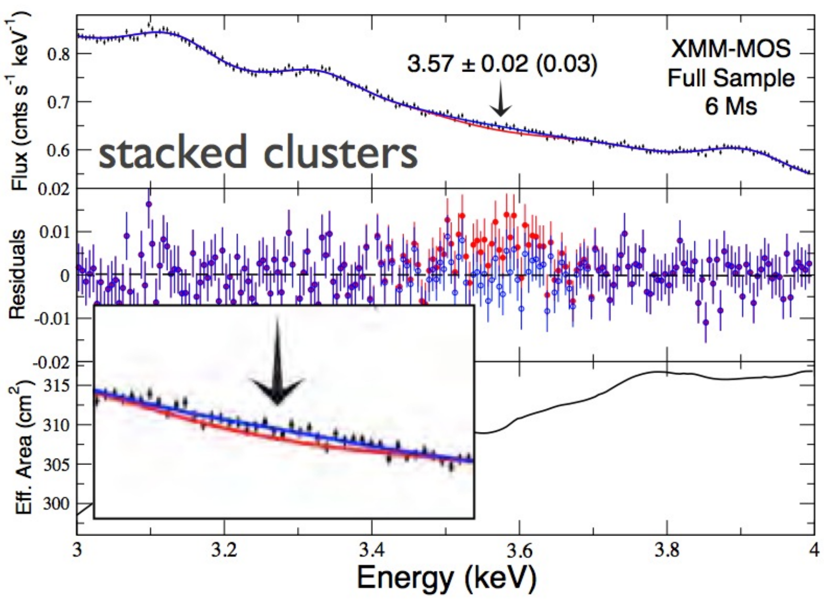
Alternative explanation of line: DM particle χ with mass m_χ can be excited to a state $\chi^{'}$ with $m^{'}_\chi = m_\chi + \delta$ which subsequently deexcites emitting a photon, $\chi^{'} \to \chi\gamma$, with $E_\gamma \simeq \delta$ (for $\delta << m_\chi$ or in general at the resonance energy for γ absorption E^{res}_γ)

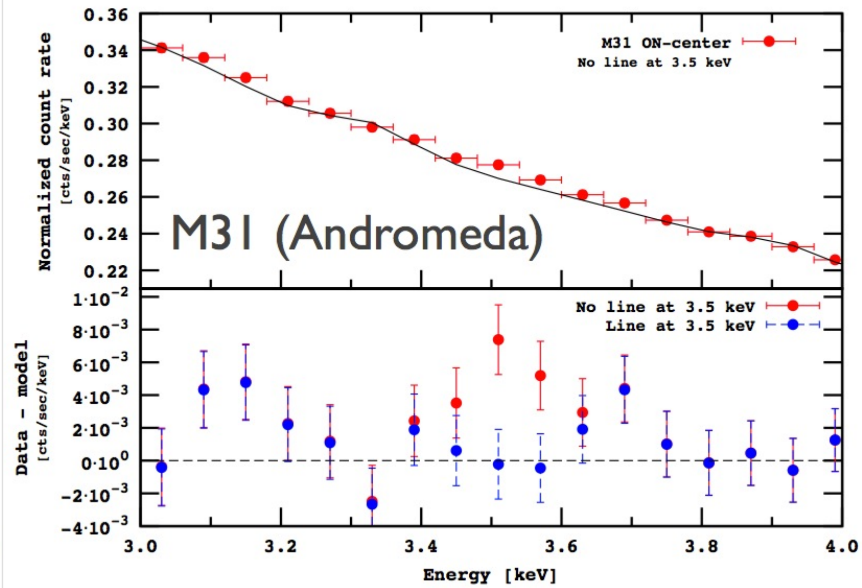
"Fluorescent" DM, such that $\chi\gamma \to \chi^{'} \to \chi\gamma$,named by Conlon etal 1608.01684; studied first by Profumo& Sigurdson 0611129, see also D'Eramo etal 1603.04859, similar but different from "eXciting DM (XDM)" Finkbeiner& Weiner 1402.6671, originally 0702587

A 3.5 keV X ray line found in X-rays from 74 stacked Galaxy Clusters E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Lowenstein, S. Randall, 1402.2301 and from the Andromeda galaxy and Perseus cluster A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse, 1402.4119.

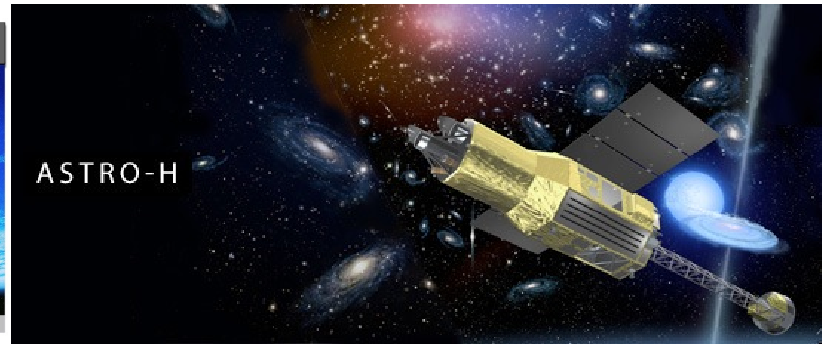
Could correspond to a 7 keV mass sterile neutrino ($E_\gamma = m_s/2$)

or to "Fluorescent" DM with a resonant γ absorption at $E_\gamma^{res} = 3.5$ keV !





ESA's XMM-Newton & NASA's Chandra do not provide enough energy resolution of the line.



JAXA's ASTRO-H (Hitomi after "first light"), launched on Feb. 17 2016 expected to measure the profile of the line and prove/disprove that it is due to DM in 1 year! was destroyed on March 26. Collected 1 month of extraordinary data on Perseus cluster.

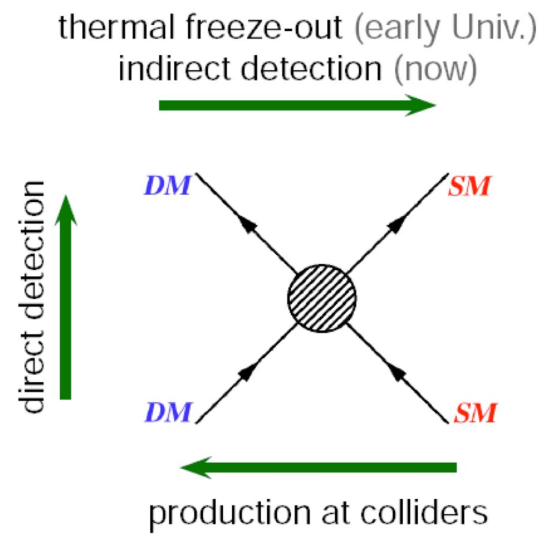
Hitomi coll. 1607.07420: Saw no 3.5 keV line, but signal expected from DM decay scenario too faint to be detected in data Previously reported Perseus core signal was anomalously bright, is rejected at $> 3\sigma$ for broad (DM) line). Inconsistent for ν_s but not conclusive...
Conlon et al 1608.01684 claim results could be consistent with "Fluorescent" DM (N. Jennings)

(Next planned X-ray astronomy satellite is ESA's ATHENA, scheduled for 2028)

WIMP DM searches:

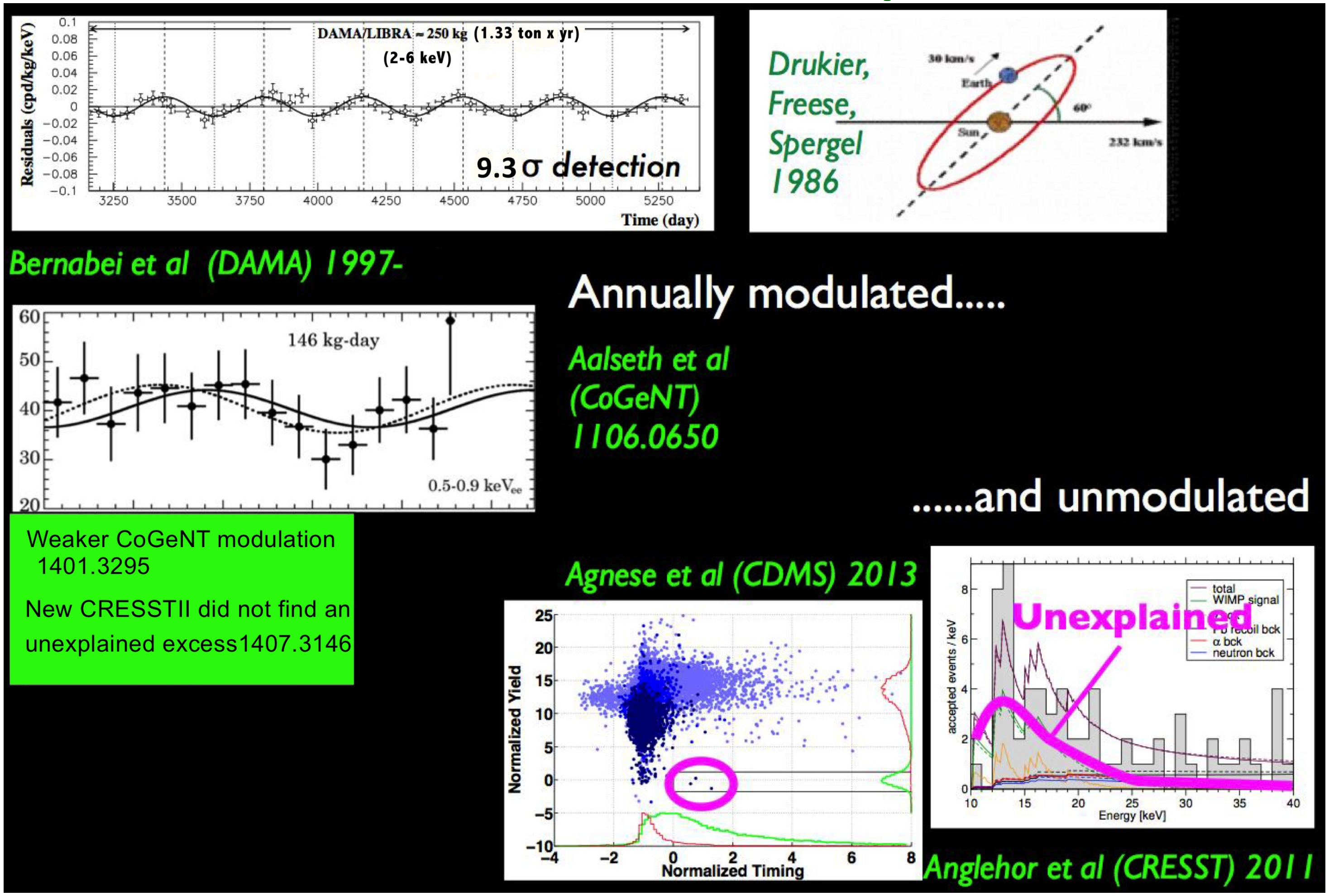
- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way.

- Indirect Detection- looks for WIMP annihilation (or decay) products.



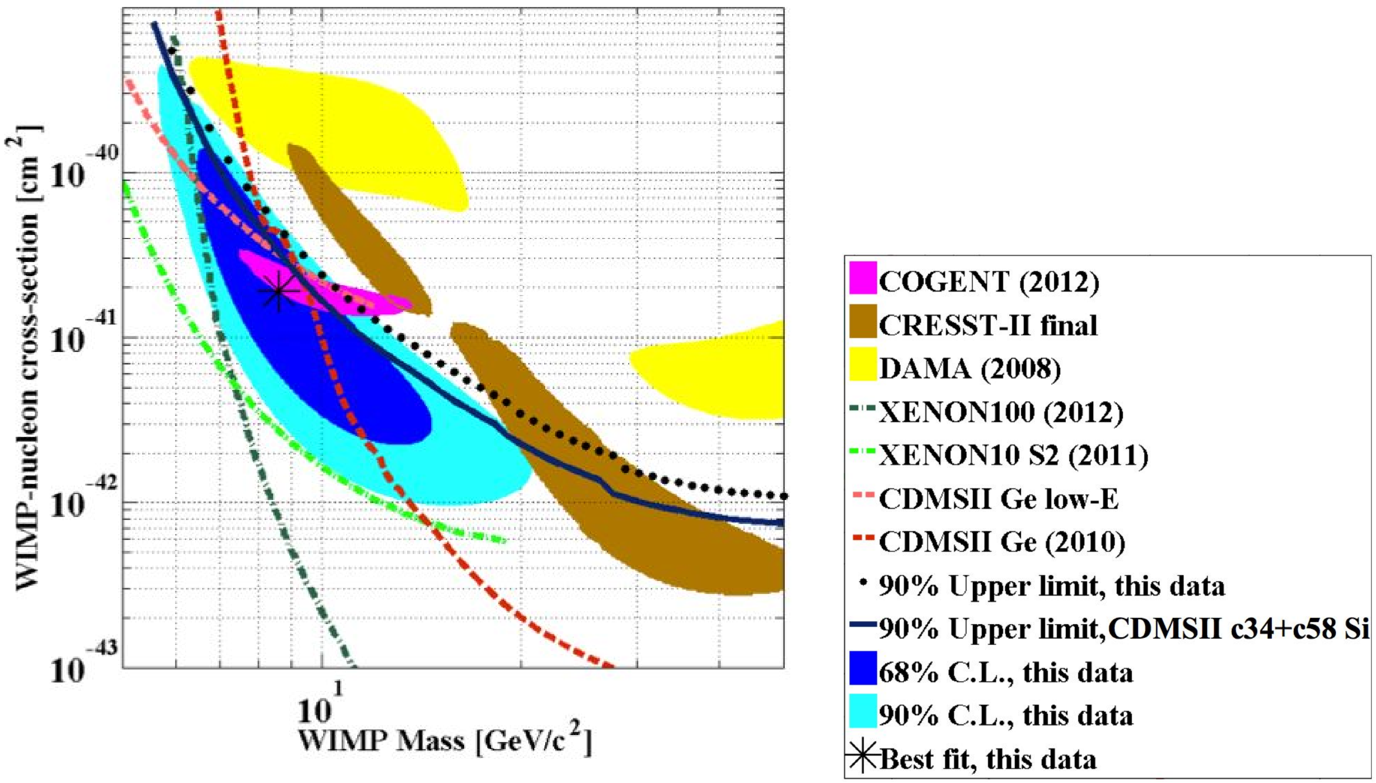
Recent DM hints in both

DM hints in four direct detection experiments (Fig. from P. Gondolo)



All point to “Light WIMP’s” with mass of few to 10 GeV?

As of 2013- for a particular particle candidate and the Standard Halo Model



All point to "Light WIMP's" with mass of few to 10 GeV?

However:

- some data were not confirmed by the further data of the same collaboration (CRESST)

- some lost significance with more data (CoGeNT)

- no particle candidate of many tried seems to make compatible any two hints with all upper limits of direct searches with negative results. One can make one hint at a time compatible with all negative results, but this is not enough.

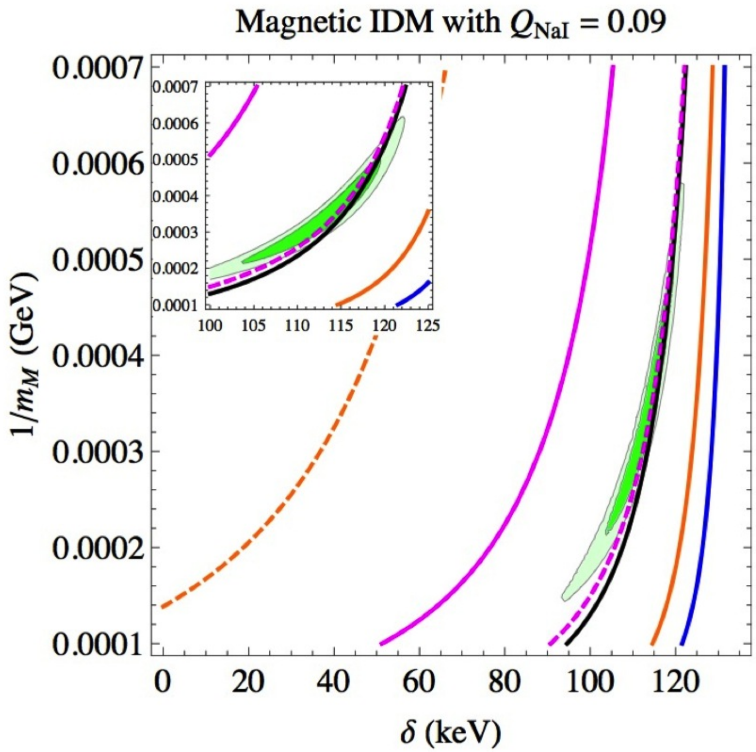
Extraordinary claims require extraordinary evidence! So several experiments must find the same DM candidate to believe it is there.

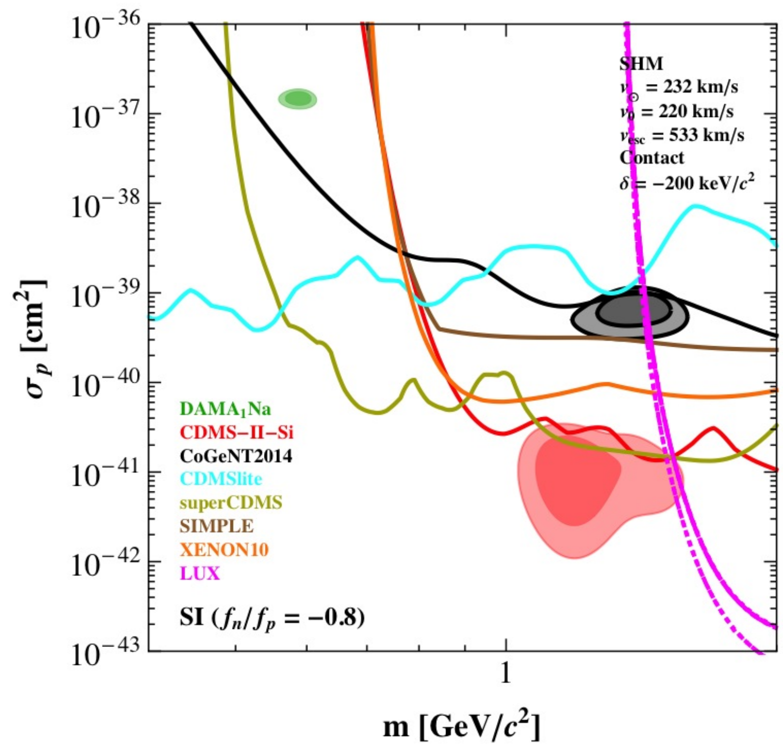
Either DAMA or CDMS-Si compatible with all limits?

Inelastic DM scatters to another state with a mass-difference $\delta = m_{final} - m_{initial}$

Left:DAMA, Magnetic IDM $m_{initial} = 58$GeV, $1/m_M = e\mu$ Barello, Chang, Newby 1409.0536

Right: CDMS-Si, $\delta = -200$keV Spin-Independent DM with $f_n/f_p = -0.8$ GG, Georgescu, Huh 1404.7484





Elements of the Event Rate in Direct DM detection

each with its own uncertainties

[Event Rate] = [Detector Response] x [Cross Section] x [Halo Model]

It says how many DM particles are passing through the detector and with which velocity distribution

Usually assumed Standard Halo Model is a good first approximation but not expected to be correct. Uncertainty in measurements of key parameters, and Earth could be within a DM clump, or stream, and maybe a Dark Disk and there are debris flows ....

Given all these uncertainties, could we avoid using a halo model when comparing Direct DM detection data?

Halo-Independent Direct DM detection data comparison

Event rate: events/(unit mass of detector)/(keV of recoil energy)/day

$$\frac{dR}{dE_R} = \sum_T \int \frac{C_T}{M_T} \times \frac{d\sigma_T}{dE_R} \times n v f(\vec{v}, t) d^3 v$$

$$\frac{d\sigma_T}{dE_R} = \frac{\sigma_T(E_R)\ M_T}{2\mu_T^2 v^2} \qquad \sigma_T(E_R) \sim \sigma_{ref}$$

$$\frac{dR}{dE_R} = \sum_T \frac{\sigma_T(E_R)}{2m\mu_T^2} \rho\eta(v_{min}, t) \quad where \qquad \eta(v_{min}, t) = \int_{v>v_{min}} \frac{f(\vec{v}, t)}{v} d^3 v$$

-$\rho = nm$, $f(\vec{v}, t)$: local DM density and $\vec{v}$ distribution depend on halo model.
Given $\rho\eta(v_{min})$ the plots are in the m, σ_{ref} plane: usual "Halo-Dependent"

NOTICE: $\tilde{\eta}(v_{min}) = \sigma_{ref}\rho\eta(v_{min})/m$ contains all the dependence of the rate on the halo and is common to all experiments! Fox, Liu, Weiner 1011.1915

Given m the plots are in the $v_{min}, \tilde{\eta}(v_{min})$ plane: "Halo-Independent"

“Halo Independent” data comparison

Fox, Liu, Weiner 1011.1915; Frandsen et al 1111.0292

Early versions of the method used the recoil spectrum dR/dE_R which is not directly accessible to experiments.

Halo Independent analysis for ANY interaction

Gondolo-Gelmini 1202.6359; Del Nobile, Gelmini, Gondolo and Huh, 1306.5273

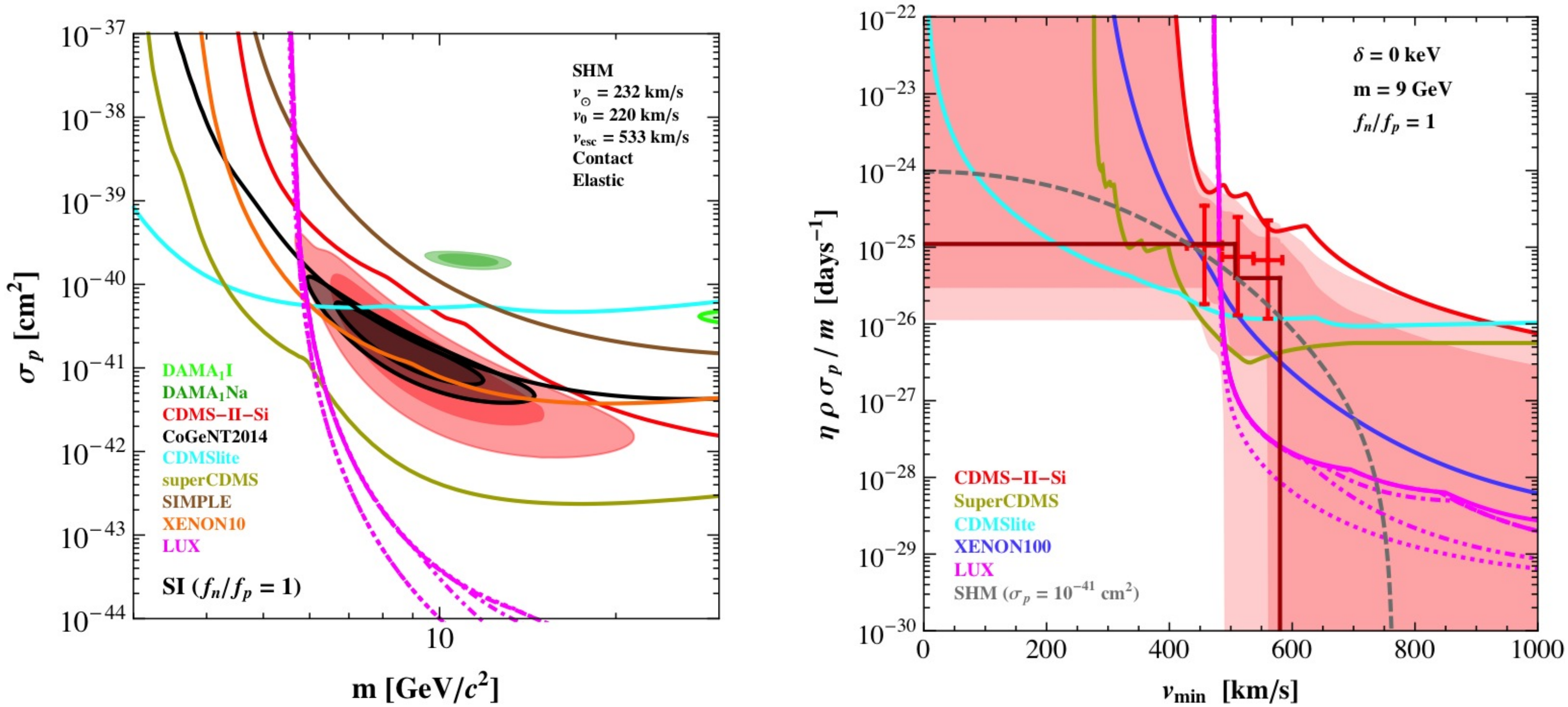
Using instead experimentally accessible quantities, including isotopic composition and energy resolution and efficiency with arbitrary energy dependence, we write the expected rate over a detected energy interval $[E_1^{'}, E_2^{'}]$ for any cross section as

$$R_{[E_1^{'},E_2^{'}]} = \int_0^\infty dv_{min}\, \mathscr{R}_{[E_1^{'},E_2^{'}]}(v_{min})\, \tilde{\eta}(v_{min})$$

where $\mathscr{R}_{[E_1^{'},E_2^{'}]}$ is an EXPERIMENT AND INTERACTION DEPENDENT response function

EHI- Extendent likelihood Halo Independent method Fox, Kahn and McCullough 1403.6830; Gelmini, Georgescu, Gondolo and Huh, 1507.03902

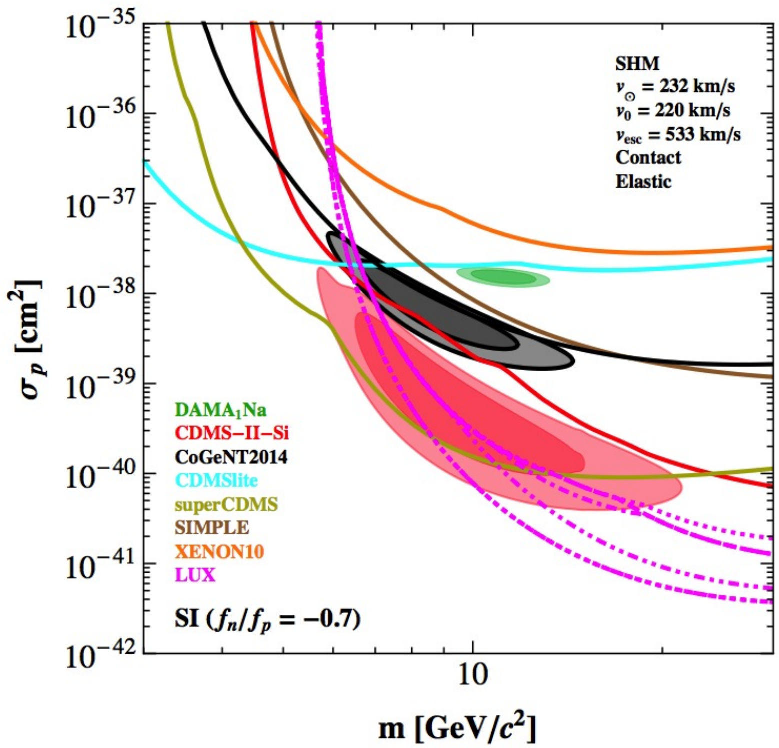
LEFT: halo dependent Figs. from Del Nobile, Gelmini, Gondolo, Huh 1405.5582 RIGHT: halo independent

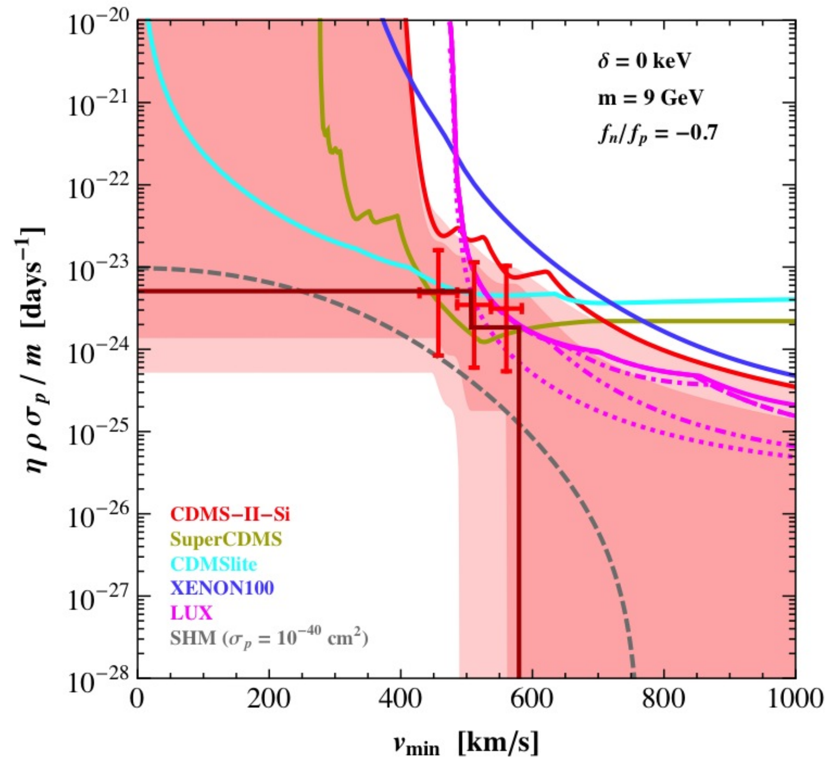


90%CL bounds and the 68% and 90%CL regions (Left) and confidence confidence bands (Right) for CDMS-II-Si, $m = 9$ GeV elastic SI and $f_n/f_p = 1$. No continuous part of the bands allowed

EHI- Extendent likelihood Halo Independent method Fox, Kahn and McCullough 1403.6830; Gelmini, Georgescu, Gondolo and Huh, 1507.03902

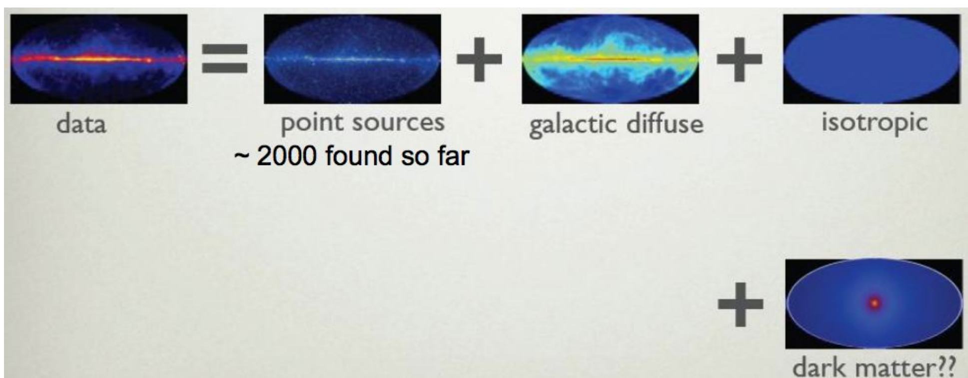
LEFT: halo dependent Figs. from Gelmini, Georgescu, Huh 1404.7484 RIGHT: halo independent

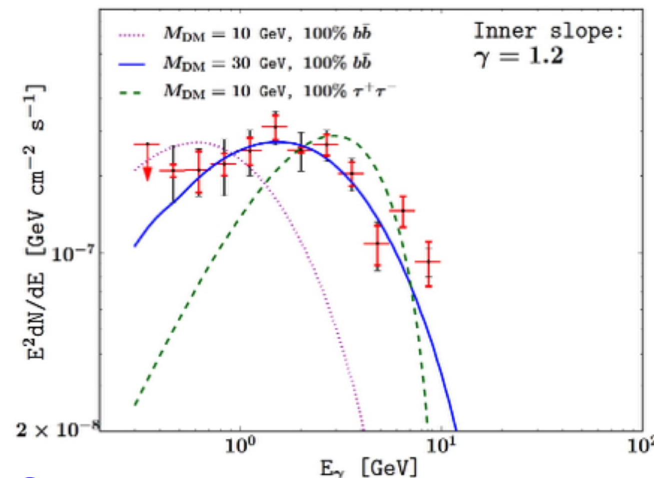




90%CL bounds and the 68% and 90%CL regions and confidence bands for CDMS-II-Si, $m = 9$ GeV elastic SI f_n/f_p=-0.7. A continuous part of the bands (so any $\tilde{\eta}$ contained in it) is allowed

Light WIMPs in the sky too? GeV γ's from extended region at the Galactic Center and Inner Galaxy from annihilation of DM with m =7-10GeV (into $\tau^+\tau^-$) or 30-45GeV (into $q\bar{q}$)? Goodenough& Hooper 0910.2998, Hooper& Goodenough 1010.2752, Hooper& Linden 1110.0006; Hooper 1201.1303; Abazajian& Kaplinghat 1207.6047, Hooper etal 1305.0830, Macias& Gordon, 1306.5725, Abazajian et al. 1402.4090, Dayland et al. 1402.6703, Cholis, Hooper& Linden 1407.5625, Calore, Cholis& Weniger 1409.0042, Fermi-LAT 1511.02938, Bartels, Krishnamurthy& Weniger 1506.05104, Lee et al. 1506.05124, Hooper& Mohlabeng 1512.04966...





DM annihilation or millisecond pulsars? Still not clear.

But for DM GC excess is in considerable tension with combined dwarf galaxy Fermi-LAT analyses.

Abazajian&Keeley 1512.04966, Fermi LAT 1503.0264

To conclude

There is no compelling observational or experimental evidence in favor of any of our DM candidates: avoid oversimplifications!

DM searches are advancing fast in all fronts, direct and indirect detection, the LHC, astrophysical observations and modeling. Lots of data necessarily lead to many hints.

No hint has been confirmed but we have opened up to consider all possible interactions of DM and SM particles and have developed better ways to compare data from different experiments.

Present DM hints to follow: 3.5 keV line for sterile neutrinos or exciting DM,
for WIMPs direct DM detection potential signals (soon new DAMA threshold 1keVee- Xenon 1T...) and GeV extended signal from the GC,
LIGO data for PBH.

Hopefully at some point one of the hints will be confirmed as a DM signal!

EXTRA SLIDES

Note about annual modulation of direct detection rates

An annual modulation due to Earth's rotation around the Sun is the main DM signature in non-directional experiments. But the annual modulation could be different in different experiments even as function of v_{min}. Usual cross section $\sim 1/v^2$ imply the rate in any experiment as function of v_{min} has the same time dependence!
$dR_T/dE_R \sim \rho\eta(v_{min}, t)$.

However, in some cross sections v dependence does not factorize, e.g. Magnetic Dipole DM

$$\frac{d\sigma_T}{dE_R} = \frac{\alpha d_m^2}{v^2}\left\{ Z_T^2 \frac{M}{2\mu_T^2}\left[\frac{v^2}{v_{min}^2} - \left(1 - \frac{\mu_T^2}{m^2}\right)\right] F_{SI,T}^2(E_R) + \frac{d_{mT}^2}{\mu_N^2}\frac{M}{m_p^2}\left(\frac{S_T + 1}{3S_T}\right) F_{M,T}^2(E_R)\right\}$$

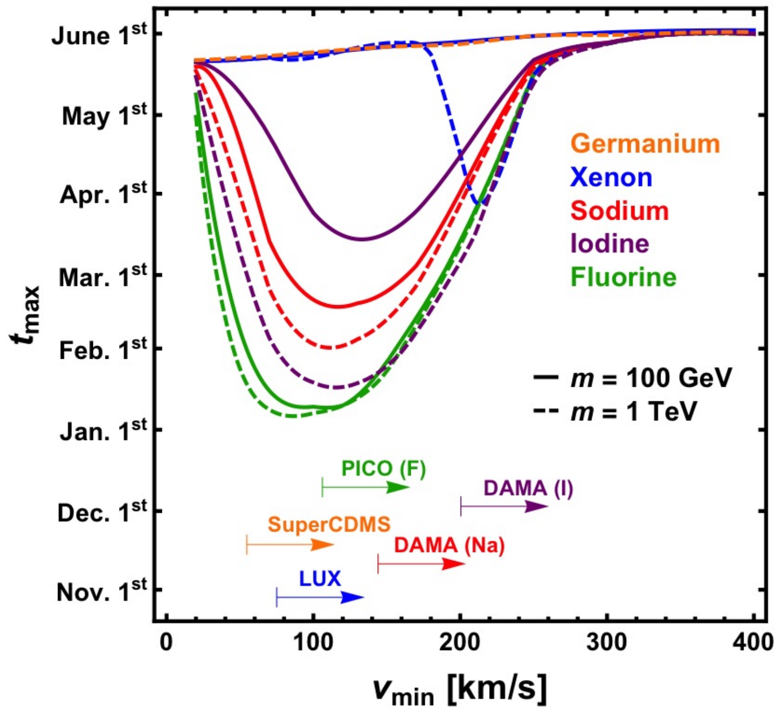
one term $\sim v^{-2}$ another $\sim v^0$ so just integrating over v yields two different functions of v_{min}, with different detector dependent coefficients

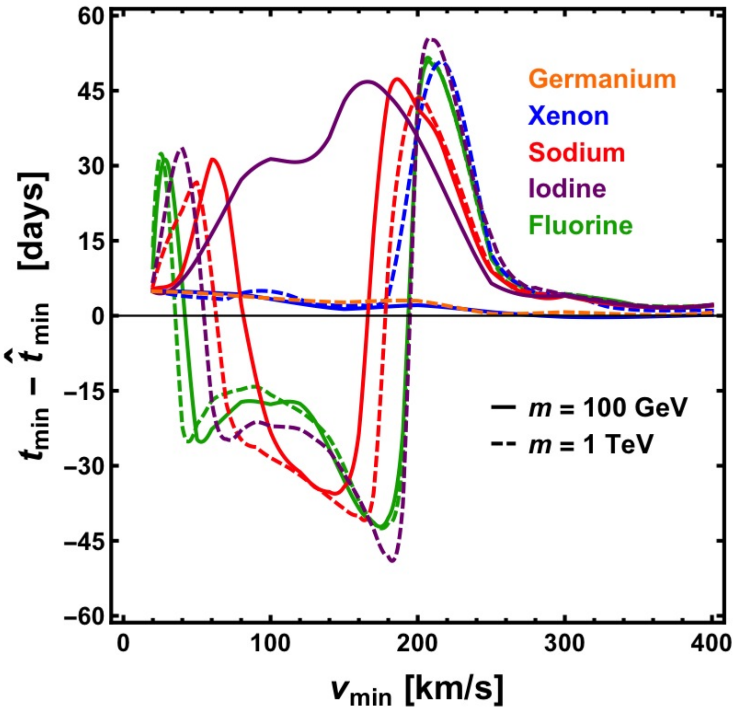
$$\eta(v_{min}, t) \equiv \int_{v \geq v_{min}} \frac{f(\vec{v}, t)}{v} d^3v, \qquad \tilde{\eta}(v_{min}, t) \equiv \int_{v \geq v_{min}} v f(\vec{v}, t) d^3v$$

and $dR_T/dE_R = C_1^T \eta(v_{min}, t) + C_2^T \tilde{\eta}(v_{min}, t)$
with C_1^T, C_2^T target nucleus T dependent coefficients. Thus, the annual modulation is target material dependent!

Time of max. and (min.−1/2 year from max.) of the rate

Del Nobile, Gelmini, Witte 1504.06772 and 1512.03961





Solid (dashed) lines for $m = 100$ GeV (1 TeV) for magnetic dipole DM scattering elastically E.g.
-t_{max} of Xe and F close present LUX-PICO thresholds could differ by 4 months
-modulation in Xe be better described by a sinusoidal t-dependence than in F

EHI- Extendent likelihood Halo Independent method Fox, Kahn and McCullough 1403.6830; Gelmini, Georgescu, Gondolo and Huh, 1507.03902

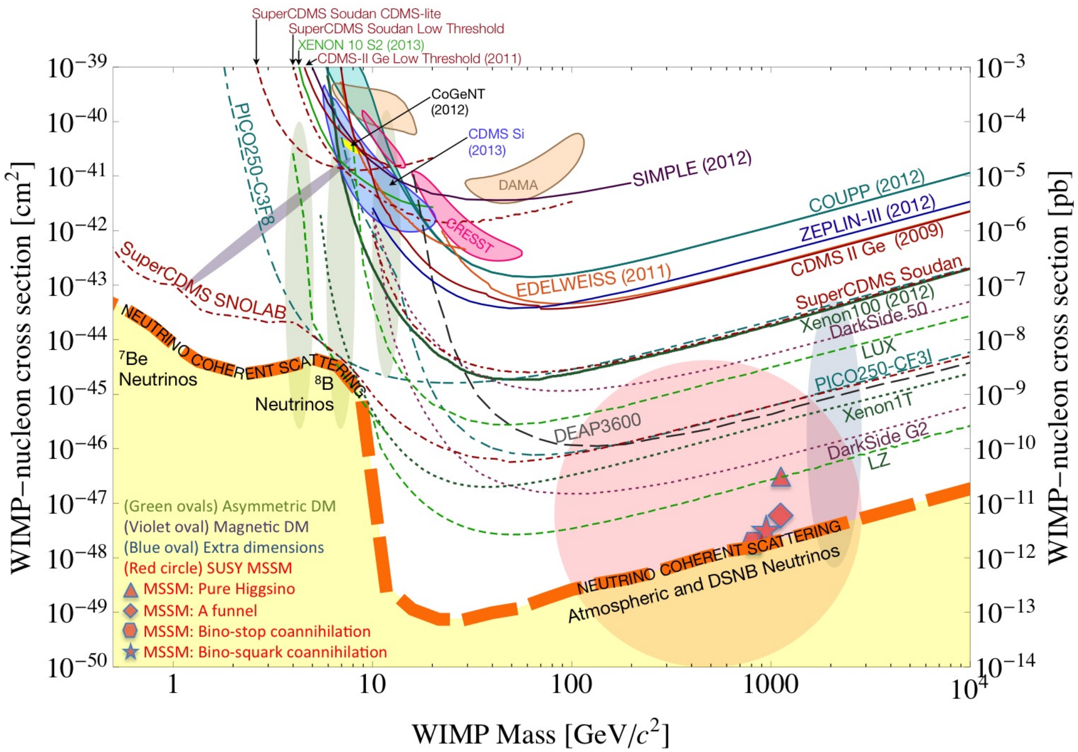
Comparing average $\tilde{\eta}(v_{min})$ values with upper bounds does not have a clear statistic meaning. With unbinned data (as in CDMS-II-Si) a statistically meaningful analysis can be made.

Starting with an extended likelihood for unbinned data

$$\mathscr{L}^{EHI}[\tilde{\eta}(v_{min})] \equiv e^{-N_E[\tilde{\eta}]} \prod_{a=1}^{N_O} MT \left.\frac{dR_{tot}}{dE^{'}}\right|_{E^{'}=E^{'}_a}$$

one can find
- a best fit $\tilde{\eta}(v_{min})$, by extending to functionals the Karush-Kuhn-Tucker (KKT) maximization conditions,(Fox, Kahn and McCullough 1403.6830)
- a statistically meaningful two-sided point-wise band at a chosen CL.
(Gelmini, Georgescu, Gondolo and Huh, 1507.03902)

The future of Direct DM detection several ton-scale detectors will reach the irreducible background ("neutrino floor") others extend to low masses



Future experiments

In the future: new direct detection data. DAMA clearly sees a modulation but is it DM or instrumental?

- DAMA/LIBRA changed its phototubes, so threshold from 2keVee to 1 keVee - results in 2017.
- "Global NaI(Tl) Collaborative Effort": DM-Ice (55 kg-Yangyang), ANAIS (112kg, Canfranc), KIMS NaI (52 kg, Yangyang)) combined are comparable to DAMA $\sim$ 220 kg. Start 2016

And many others... PICO 60 (60litters running, later PICO-250?), Xenon1T (about to start, later Xenon-nT), LUX (360kg running, later LZ, 7T, 2019?), EDELWEISS III (30kg), CRESST III (late 2016?), PandaX (still not competitive PandaX II, 0.5T, in 2017?), XMASS 1.5T (2017, later XMASS-7T 2019), DarkSide50 (50kg now- later to nT?), SuperCDMS-SNOLAB (up to 400kg, 2019?, was at Soudan, maybe later merge with Eureka), distant future Darwin? (30-50 tons)... still others, and directional detectors too

More indirect detection data: Fermi will continue for several years, but it is unclear if GC excess will be confidently rejected or confirmed to be due to DM, because of astrophysical uncertainties, and Athena for X-rays in 2018, LIGO etc