Dark Matter discussion session

Piero Ullio
SISSA & INFN (Trieste)

"Higgs and BSM physics at the LHC", Trieste, June 26, 2013

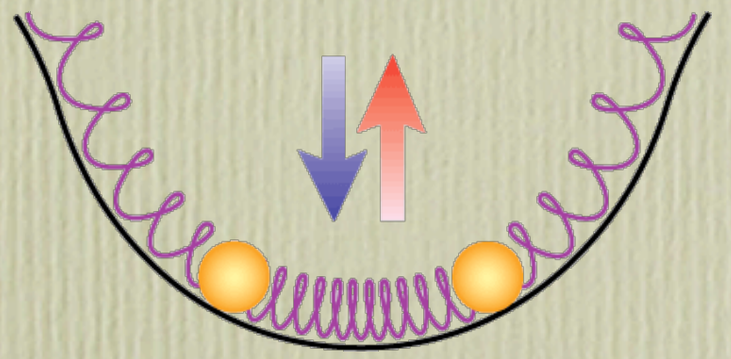
A few proposals for topics we may discuss:

- Learning properties of dark matter particles from cosmological and astrophysical observations
- Are WIMP natural dark matter candidates?
- Chasing dark matter ambulances
- Clean dark matter signatures (... and being unhappy about them)
- ... add your own ...

Dark matter (indirectly) detected!

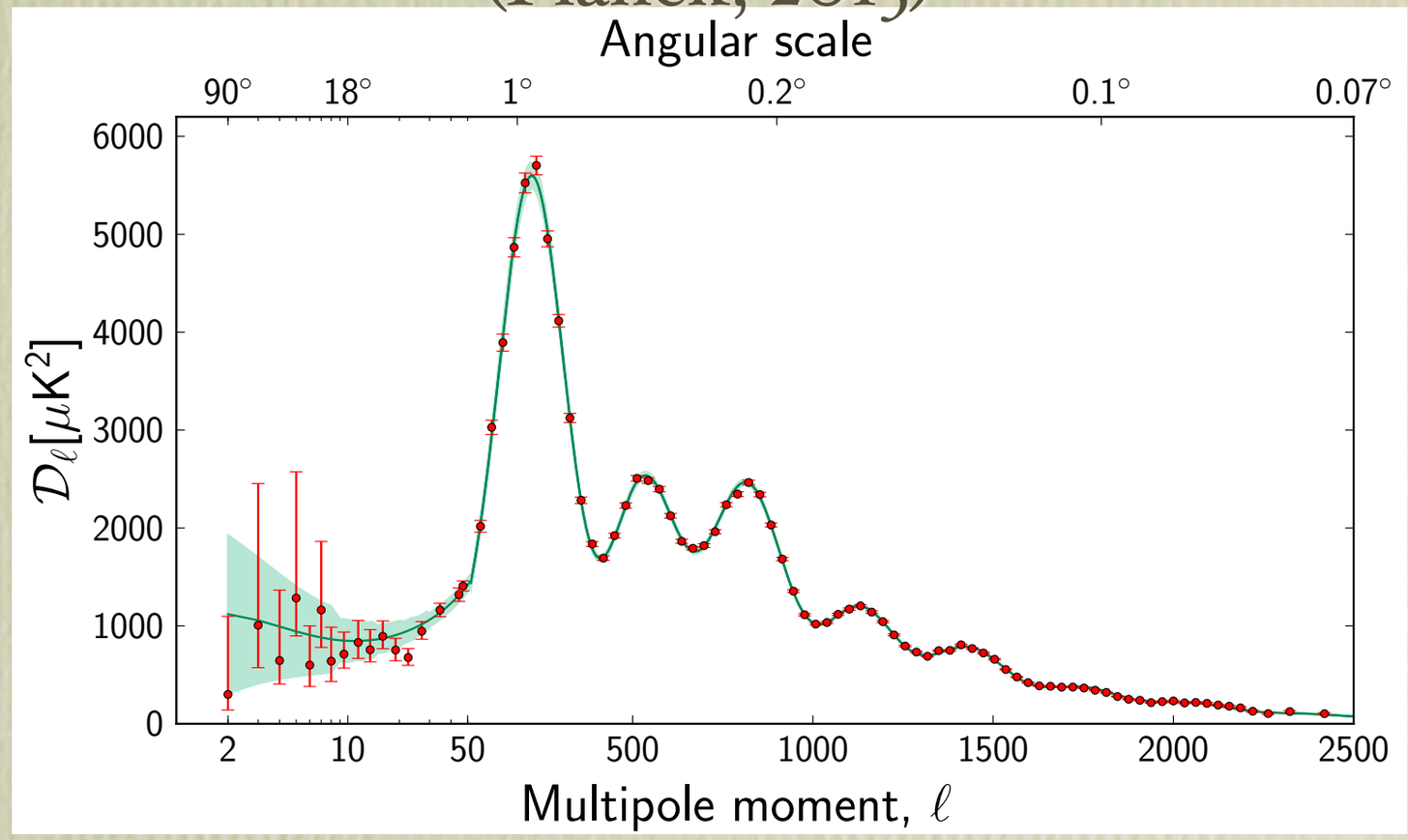
Plenty of (gravitational) evidence for non-baryonic cold (or coldish - as opposed to hot) DM being the building block of all structures in the Universe. E.g.:

it accounts for the gravitational potential wells in which CMB acoustic oscillations take place:



Credit: W. Hu website

(Planck, 2013)



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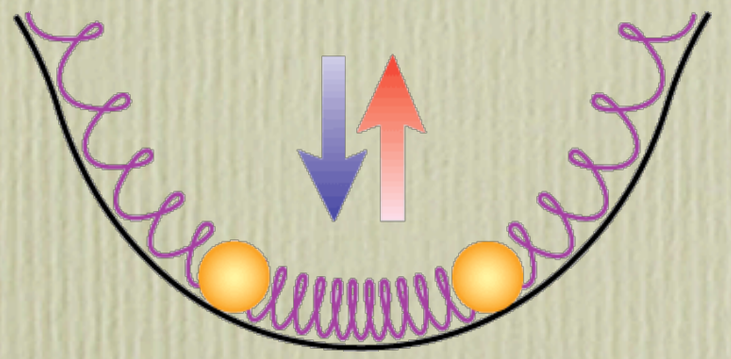

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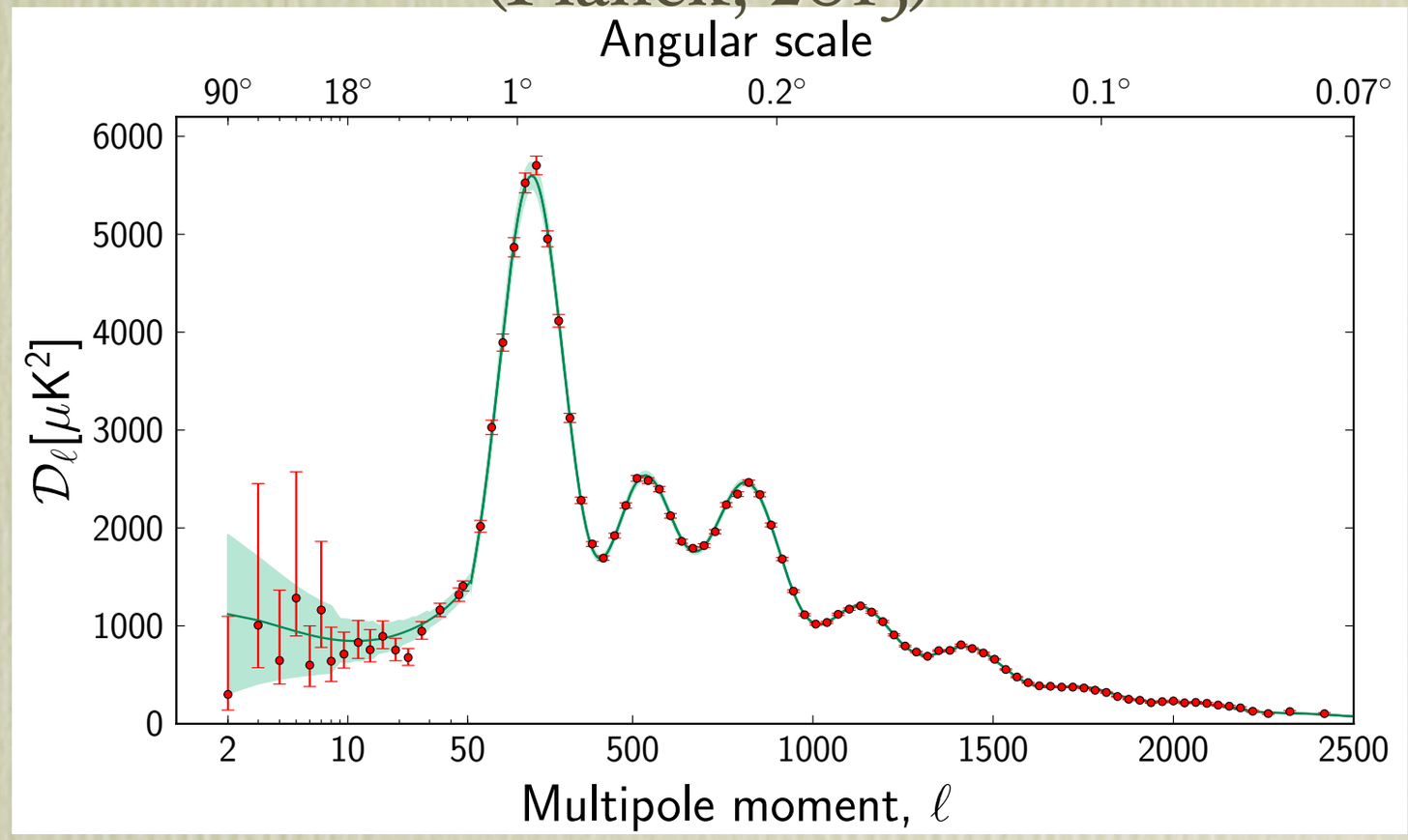

Relying on the assumption that GR is the theory of gravity; still, it is very problematic to explain, e.g., the prominence of the third peak in an alternative theory of gravity and matter consisting of baryons only

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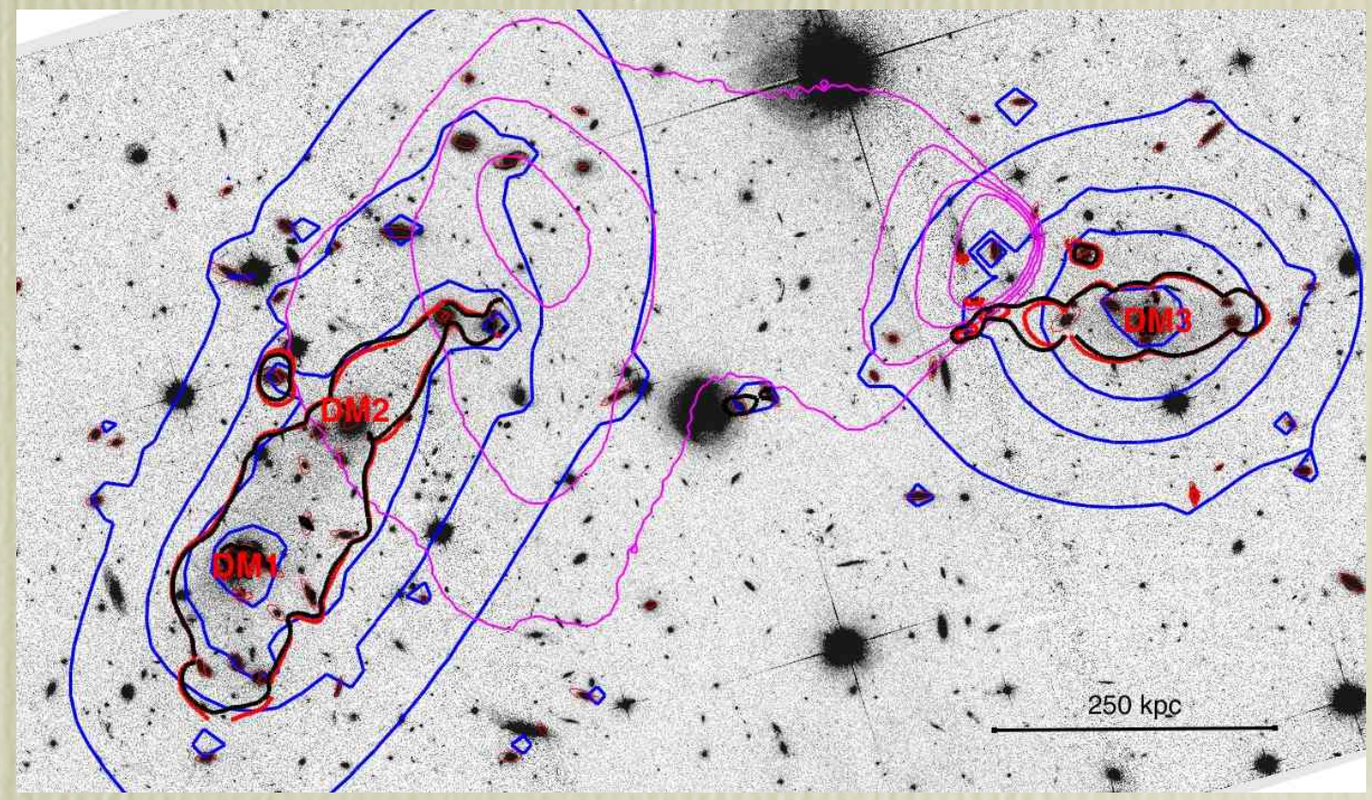
Bullet cluster:

offset between DM, mapped via gravitational lensing, and hot gas - the bulk of the baryonic in the system, traced via its X-ray emissivity, in the 1E0657-558 cluster

magenta contours: Chandra X-ray image; blue contours: strong lensing map

Paraficz et al., arXiv: 1209.0384



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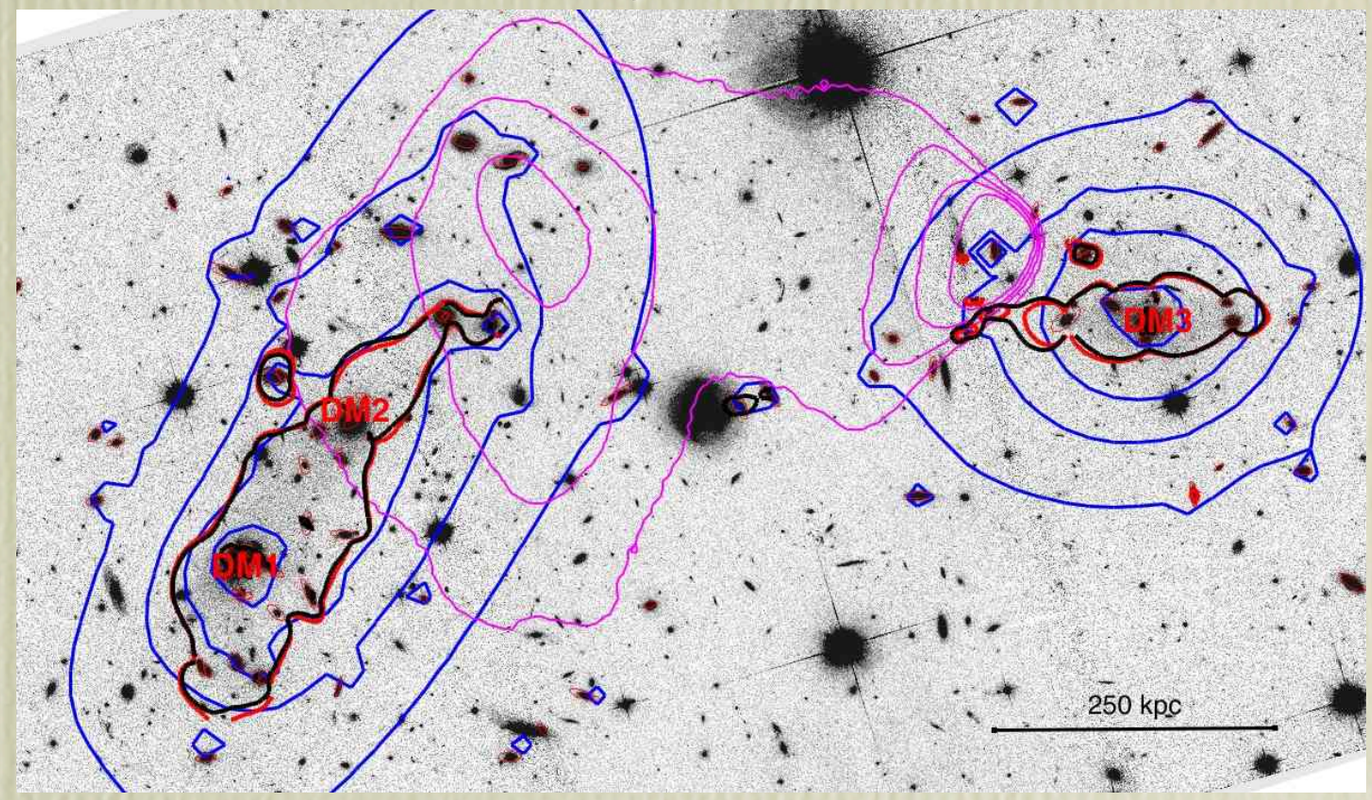

Relying again on GR as a theory of gravity; again it is very problematic to introduce an alternative theory and explain the component segregation within a model without DM but having baryons only

(Indirect) detection of dark matter particles?

Jump from this indirect evidence to a specific particle DM candidate?

(review: Bertone, (ed.) e al., 2010)

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On one hand: ΛCDM cosmology with extraordinarily accurate measurement of the mean density of DM particles:

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$

(Planck, 2013 + WMAP 7 yr pol.)

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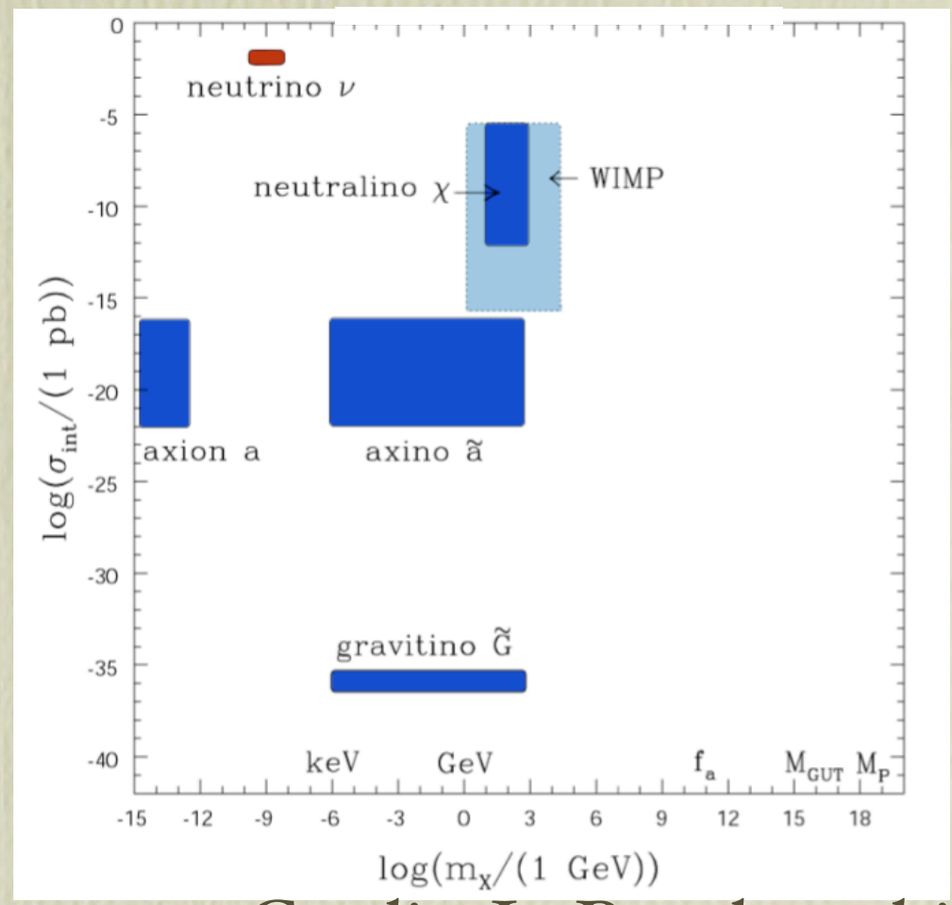

Credit: L. Roszkowski

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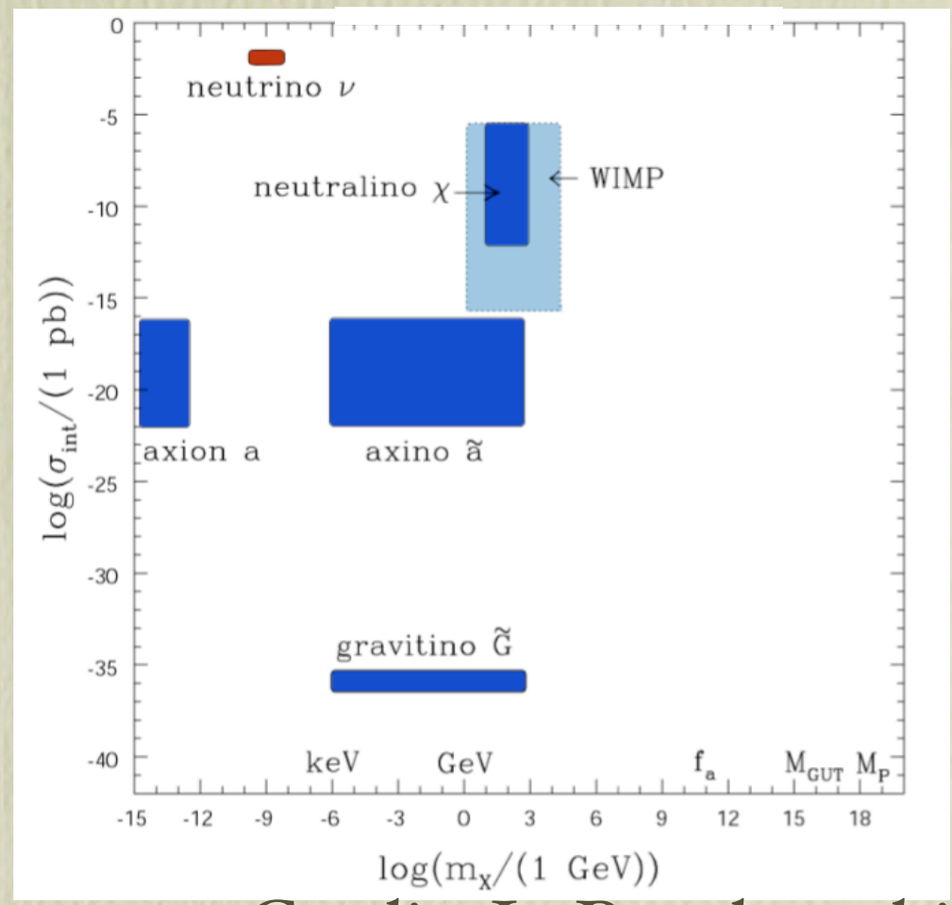
E.g.: from the CMB, limits on eventual DM electromagnetic couplings and on the DM heating of the plasma at (moderately) recent times, and, from the Bullet cluster, limits on the self-interaction of DM particles



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Learning more on DM particles from cosmology?

In the SM for cosmology and structure formation, the ΛCDM model, DM is treated as a collisionless, cold fluid, coupled to ordinary (baryonic) matter only gravitationally: spectacular agreement between predictions from this model and data, especially on large scales!

Shortcomings of the model on small scales, in the (very) non-linear regime, usually addressed via numerical N-body simulations?

- the missing satellite "problem", Moore et al., Klypin et al. 1999

- the too-big-to-fail Milky Way problem, Boylan-Kolchin et al. 2012

- the CDM profiles too cuspy when looking at low mass objects, like dwarf or LSB galaxies, see, e.g., Salucci et al. 2011, Kuzio de Naray et al. 2008

- ...

All of these loosely targeted as an excess of power on small scales? Introduce a dissipation of power on small scales as an imprint from DM particles? or just blame the fact the it is really hard to include a realistic model for baryonic components in the DM numerical simulations?

Learning more on DM particles from cosmology?

Improving on ΛCDM with some extra ingredient from particle physics:

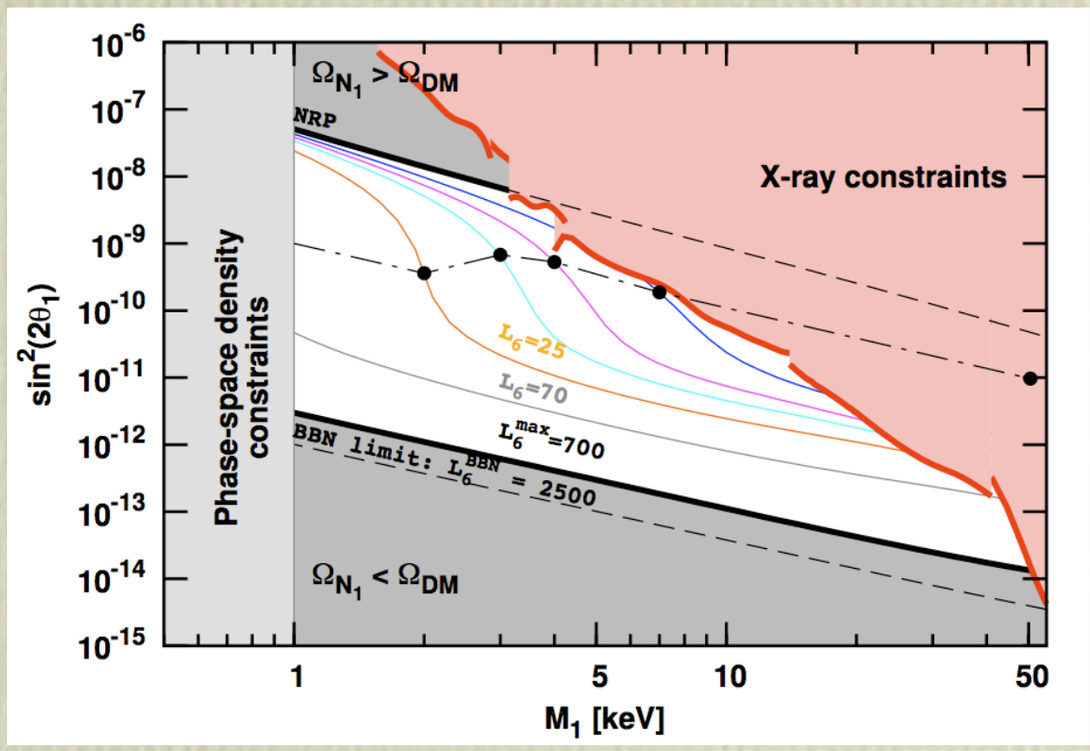
Warm DM: imprint on the sky of the DM particle free streaming scale, approximately:

$$\lambda_{FS} \simeq 0.4\,\mathrm{Mpc}\,(M_p/\mathrm{keV})^{-1}(T_p/T)$$

DM mass scale in, say, the keV - 100 keV range depending on the DM temperature T_p. Popular candidates: sterile neutrinos and gravitinos.

Their detection depends on features in the specific model; e.g. for sterile neutrinos:

- search for the decay into 1 photon & 1 neutrino
- + constraints from production + constraints from being a fermion



Boyarsky et al., arXiv:0901.0011

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Improving on ΛCDM with some extra ingredient from particle physics:

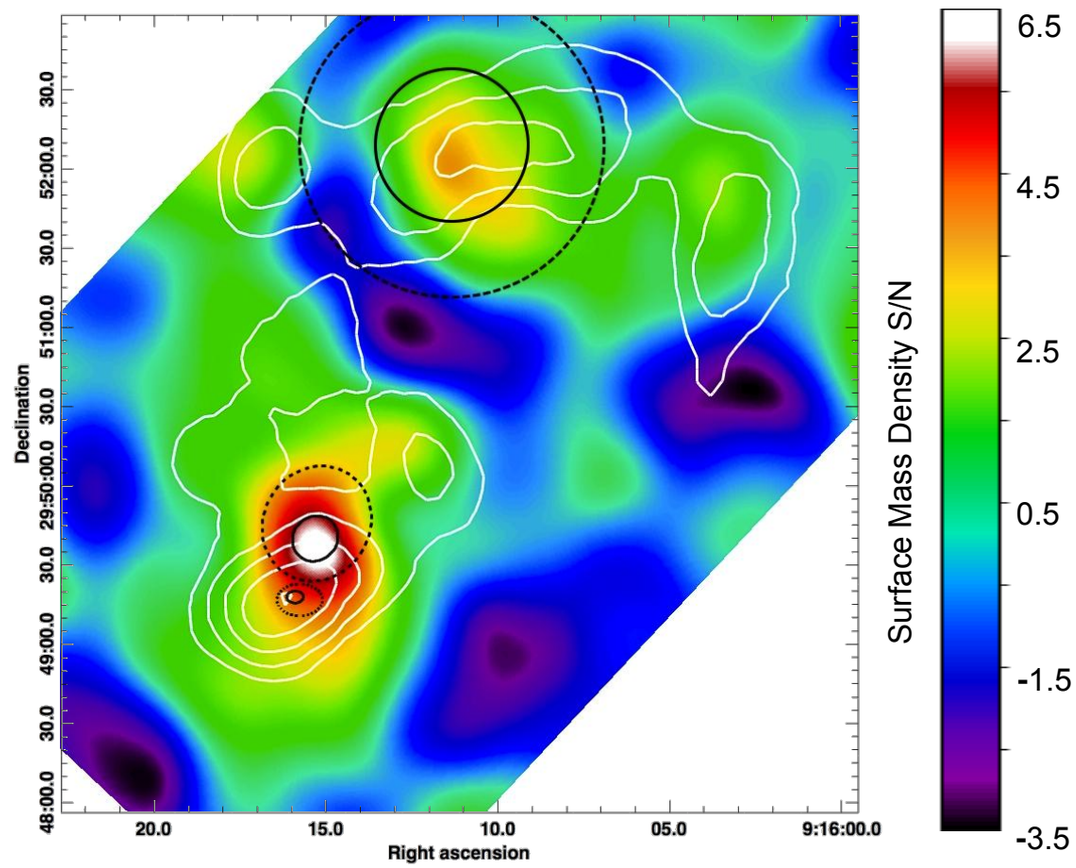
Self interacting DM: a "hint of detection" from the Musket Ball cluster?

Dawson et al. 2013

Surface mass density S/N map

Galaxy density (white contours)

Centroid errors; 68%, 95% Confidence (black contours)



another merging event, although at much smaller impact speed than for the Bullet cluster

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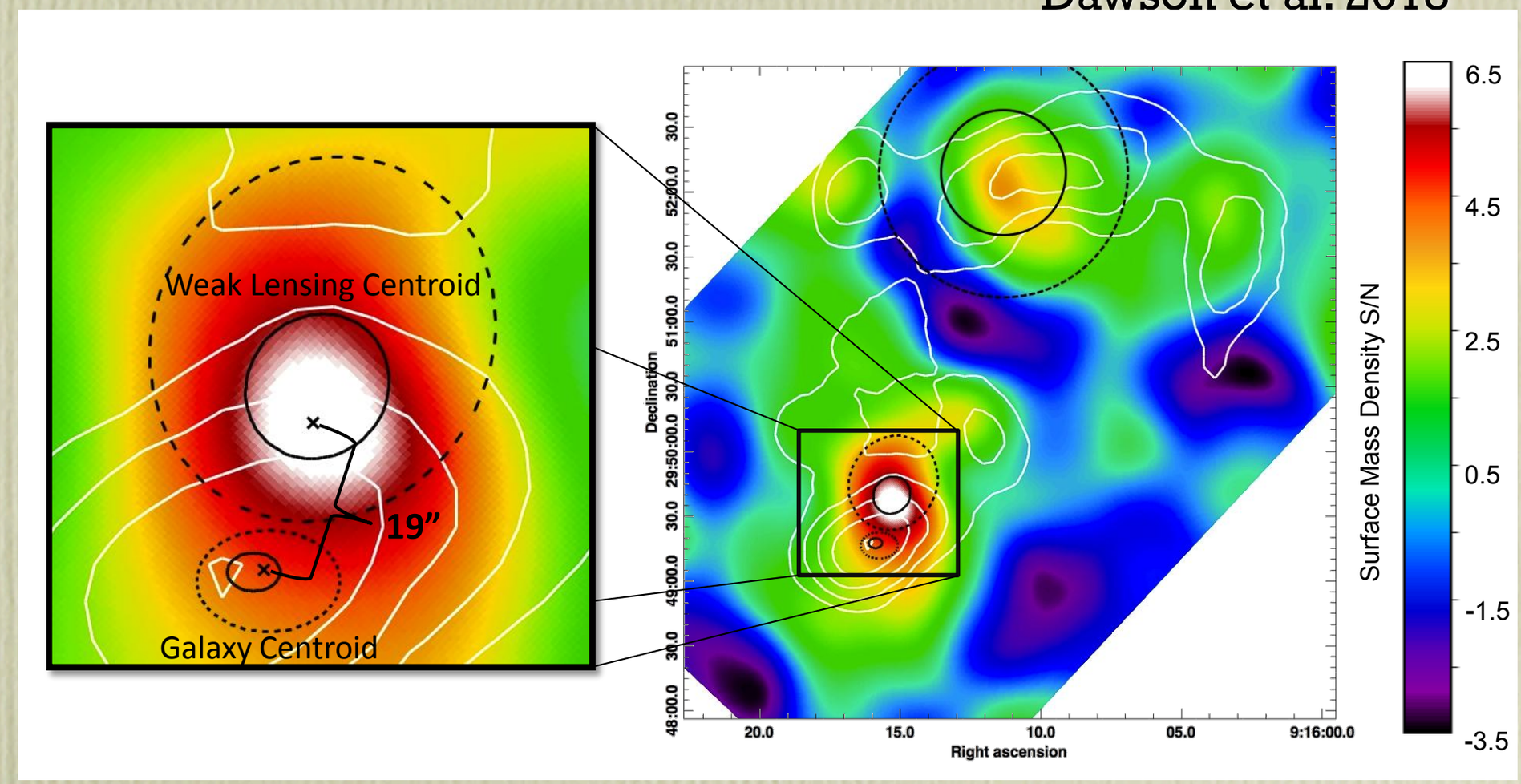


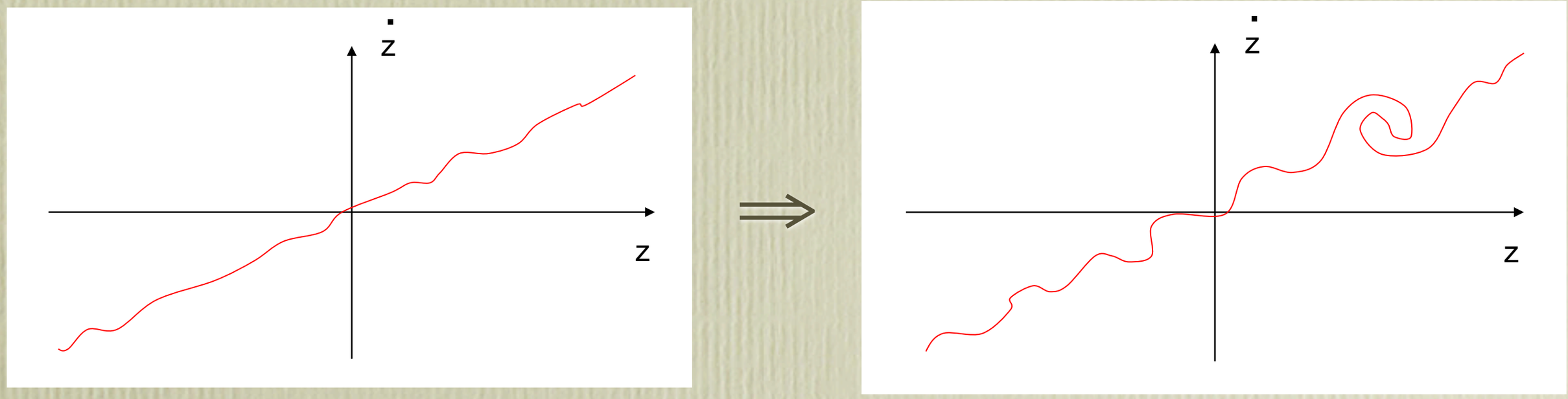
displacement consistent with: $\sigma_{DM}/M_{DM} \sim 0.8\,\mathrm{cm}^2\,\mathrm{g}^{-1}$, rather large effect! Pointing towards, e.g., a dark sector with a light mediator generating a fifth force? Feng et al. 2009, Tulin et al. 2013

Learning more on DM particles from cosmology?

Improving on ΛCDM with some extra ingredient from particle physics:

DM as a BEC: identical bosonic particles highly condensed in phase space, going to the lowest energy available state when thermalizing.

Very "thin" phase space sheets wrapping themselves into and generating caustics when structures form:

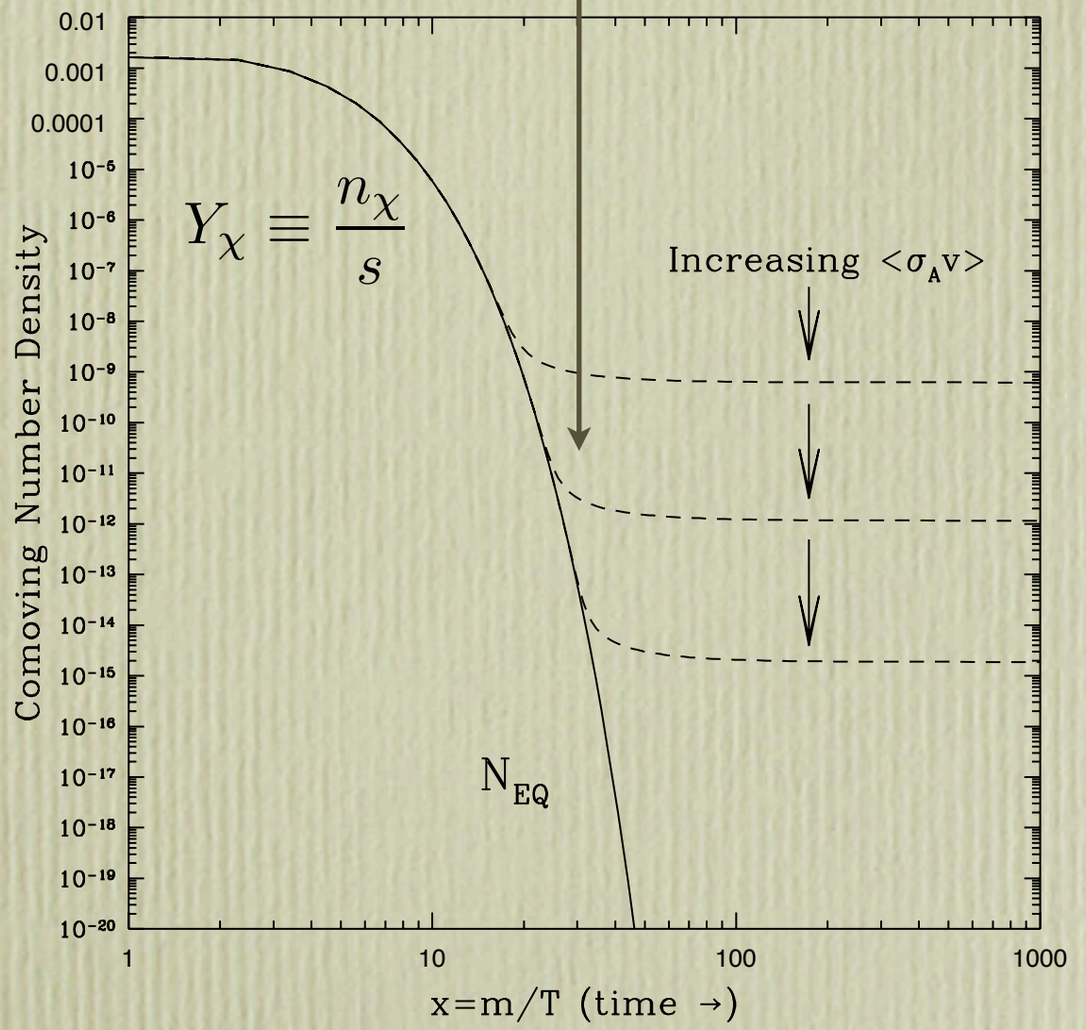


Look for their imprint in today's galaxy halos; axion would give rise to such features Sikivie et al. 1998-2012

WIMPs as natural DM candidates (?)

Thermal generation of DM:

$$\Gamma(T_f) = n_\chi^{eq}(T_f)\langle\sigma_A v\rangle_{T=T_f} \simeq H(T_f)$$



$$\Omega_\chi h^2 \simeq \frac{M_\chi\, s_0\, Y_\chi^{eq}(T_f)}{\rho_c/h^2}$$

(freeze-out + entropy conservation)

$$\simeq \frac{M_\chi\, s_0}{\rho_c/h^2}\,\frac{H(T_f)}{s(T_f)\langle\sigma_A v\rangle_{T_f}}$$

(standard rad. dominated cosmology)

$$\simeq \frac{M_\chi}{T_f}\,\frac{g_\chi^\star}{g_{\rm eff}}\,\frac{1\cdot 10^{-27}{\rm cm}^{-3}{\rm s}^{-1}}{\langle\sigma_A v\rangle_{T=T_f}}$$

with: $M_\chi/T_f \sim 20$

$$\Omega_\chi h^2 \simeq \frac{3\cdot 10^{-27}{\rm cm}^{-3}{\rm s}^{-1}}{\langle\sigma_A v\rangle_{T=T_f}}$$

→ WIMP "miracle"

Plenty of WIMPs in BSM setups! DM as a byproduct of some other property of the theory which urged you to go beyond the SM!

WIMPs as natural DM candidates (?)

Great idea, except that "vanilla" models usually fail. E.g.:

MSSM with R-parity: the lightest neutralino as a DM candidate from the superposition of 4 interaction eigenstates:

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

"Bino" "Wino" "Higgsinos"

- Binos annihilate into fermions via sfermions (helicity suppressed) and their relic abundance matching the cosmological DM density only for "light" masses, about 100-150 GeV, and fairly light sfermions (squarks) → excluded.
- Higgsinos (SU(2) doublet) mainly annihilate into gauge bosons (process not helicity suppressed); compensate the larger cross section lifting the mass scale up to about 1.1 TeV
- Winos (SU(2) triplet) also annihilate into gauge bosons and even more efficiently than for Higgsinos, with the mass for thermal relic as large as about 2.8 TeV

In the last two cases clearly very little connection to naturalness as a motivation for SUSY

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MSSM with R-parity: loopholes (pessimists would say epicycles)

• Consider compressed spectra: the thermal relic density of a "lazy" Bino driven by a state (a slepton? a squark?) much more tightly coupled to the thermal bath (coannihilation process), decaying into the LSP after decoupling

• Tune the mixing: at a given mass scale find out the right balancing between Bino component and Higgsino or Wino component in the LSP, essentially decreasing the Higgsino or Wino annihilation efficiency

• Boost the Bino annihilation via S-channel resonance (a Higgs with mass being about twice the Bino mass) → harder in light of LHC Higgs discovery

NOTE 1: Except for the last case, the picture of thermal relic DM in the MSSM has not changed dramatically entering the LHC era; it did when focussing on simplified scenarios, as the CMSSM

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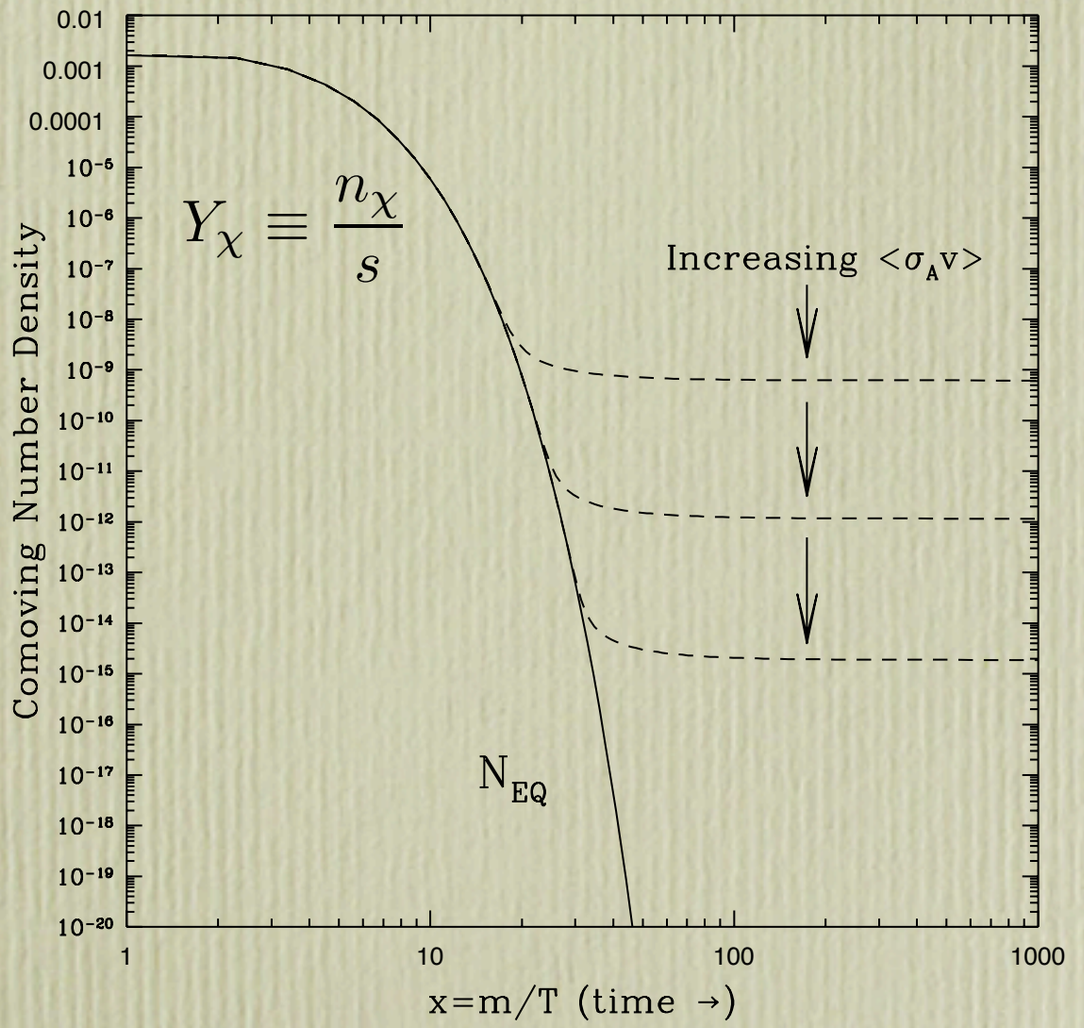
NOTE 2: stop buying the perspective of DM as a byproduct in a deeply motivated setup; DM becomes (one of) the strong motivation(s) for the scenario; on the other hand there are way more minimal setups one can consider motivated by the presence of a DM candidate (SM + 1 extra scalar field is good enough)

WIMPs as natural DM candidates (?)

Give up on thermal generation (???):



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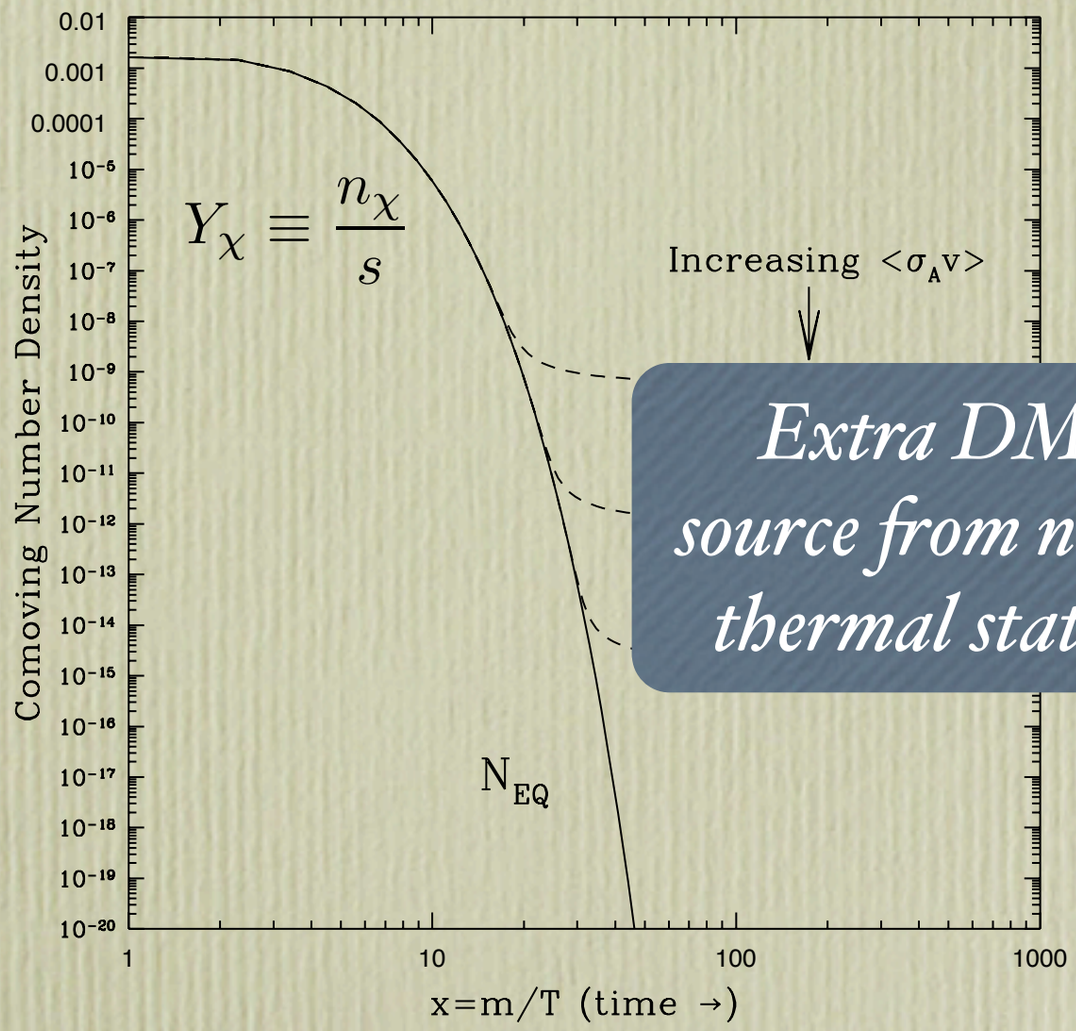

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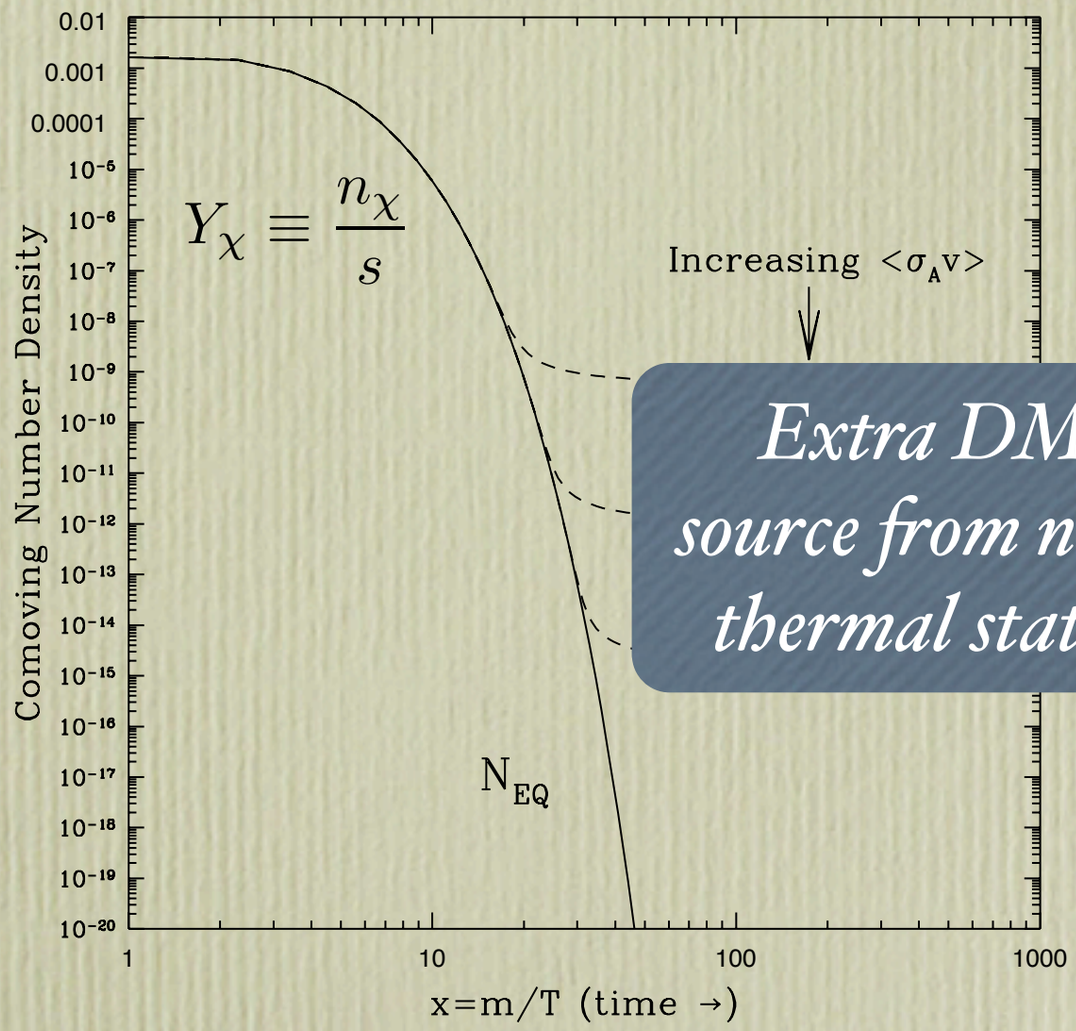

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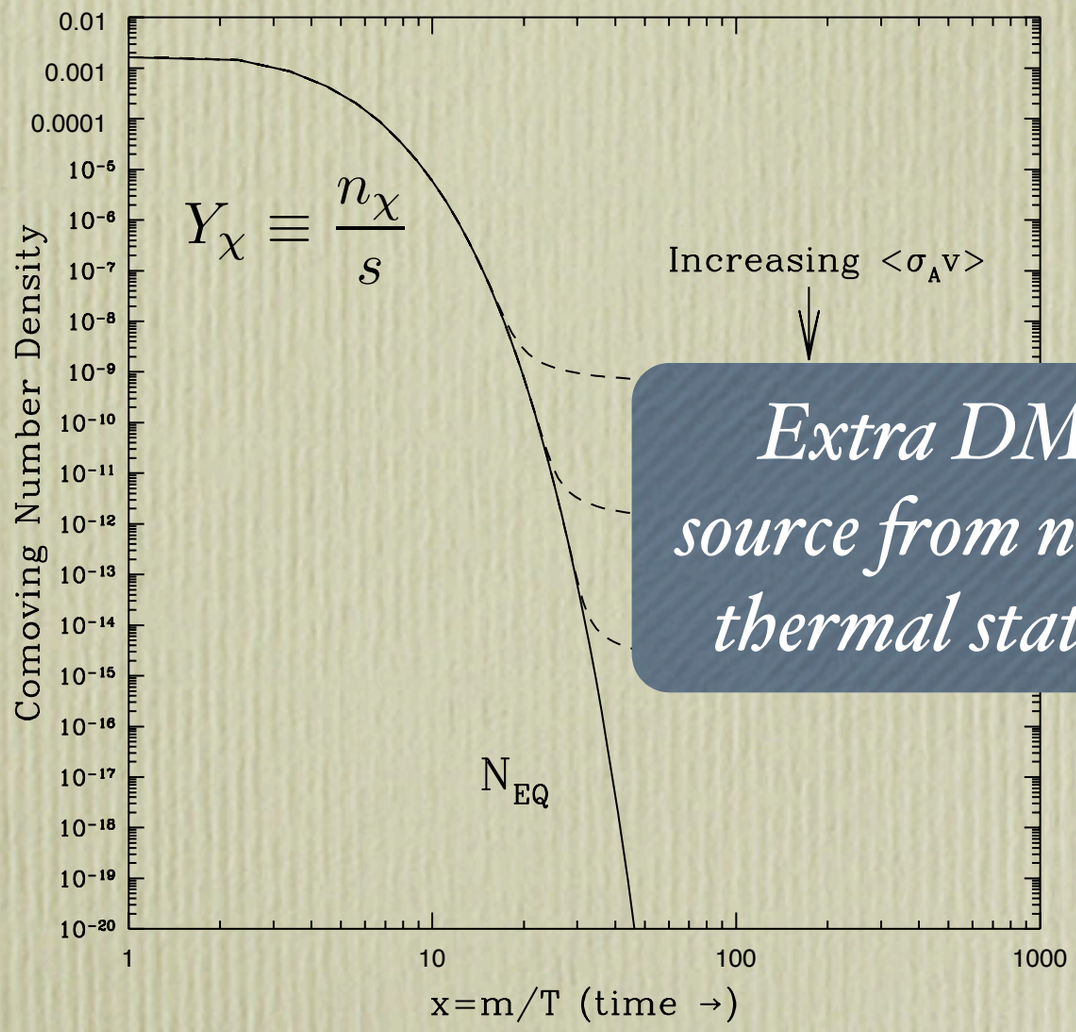

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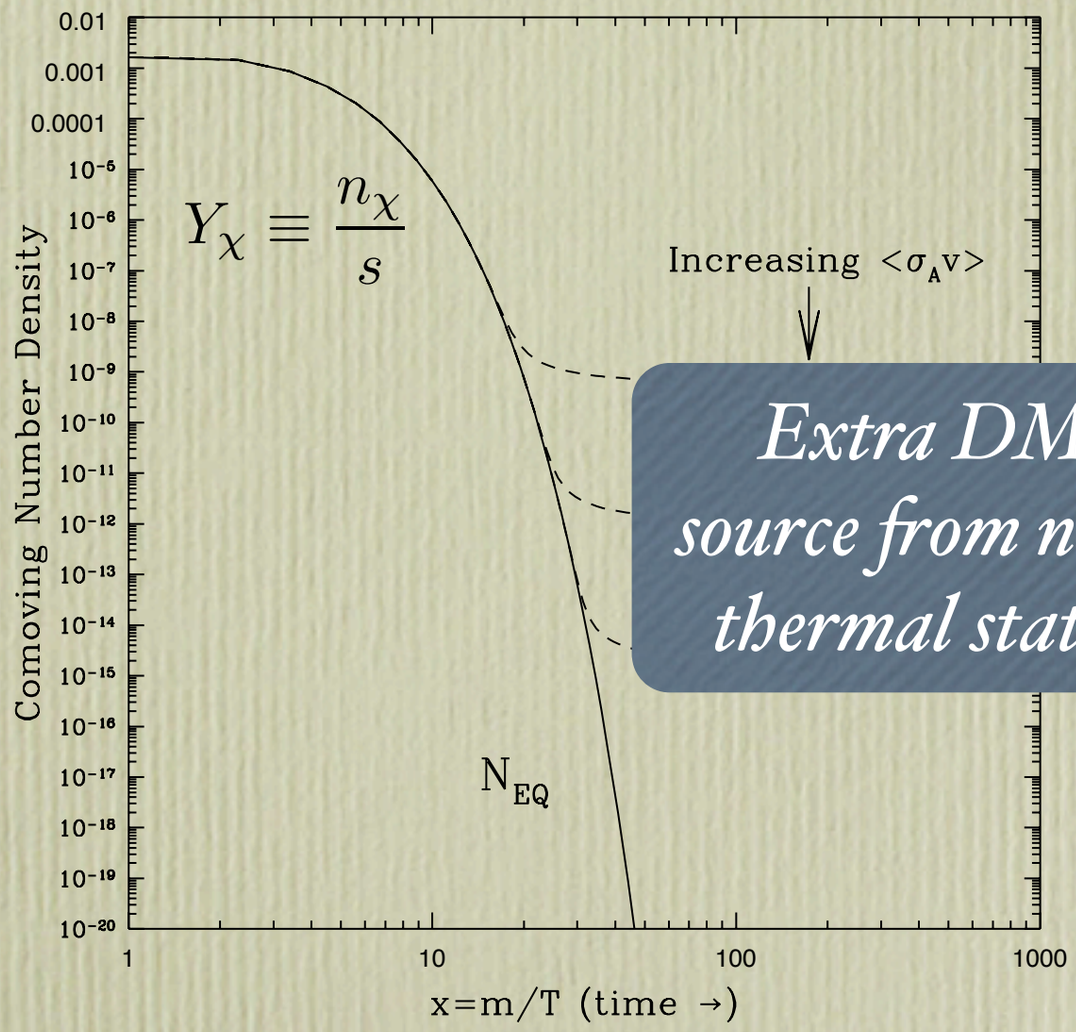

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relation reshuffled by even a few orders of magnitude

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Change the Universe expansion rate

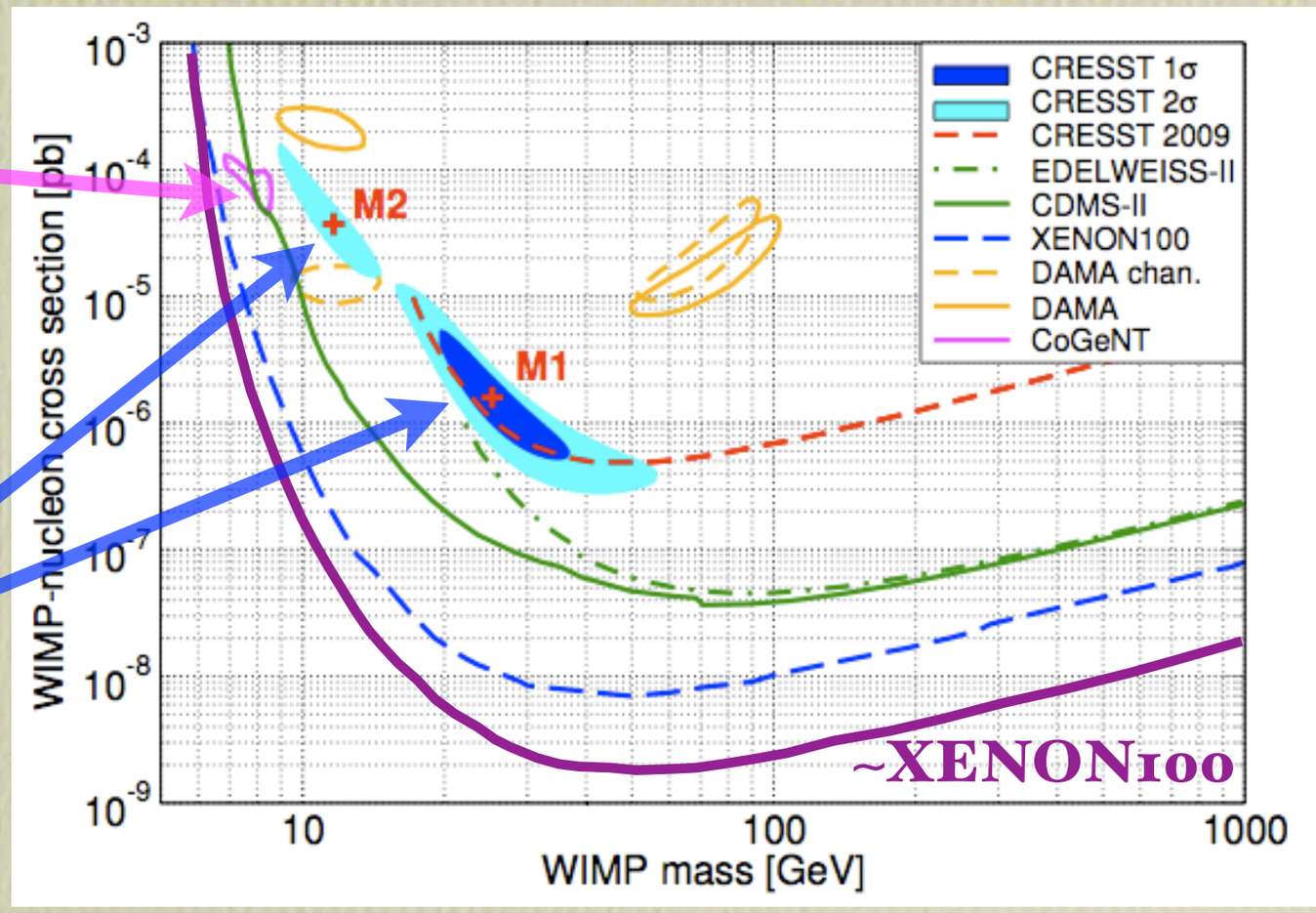
Chasing DM ambulances

Several "hints" of detection in cases in which "backgrounds" are not under control and the DM signal is not supported by a clean DM signature. E.g.:

Light WIMPs and Direct detection signals:

CoGeNT
(excess + ann. mod.)
Aalseth et al.,
arXiv:1106.0650

CRESST
(excess)
Angloher et al.,
arXiv:1109.0702



Xenon 100, Aprile et al., arXiv:1207.5988

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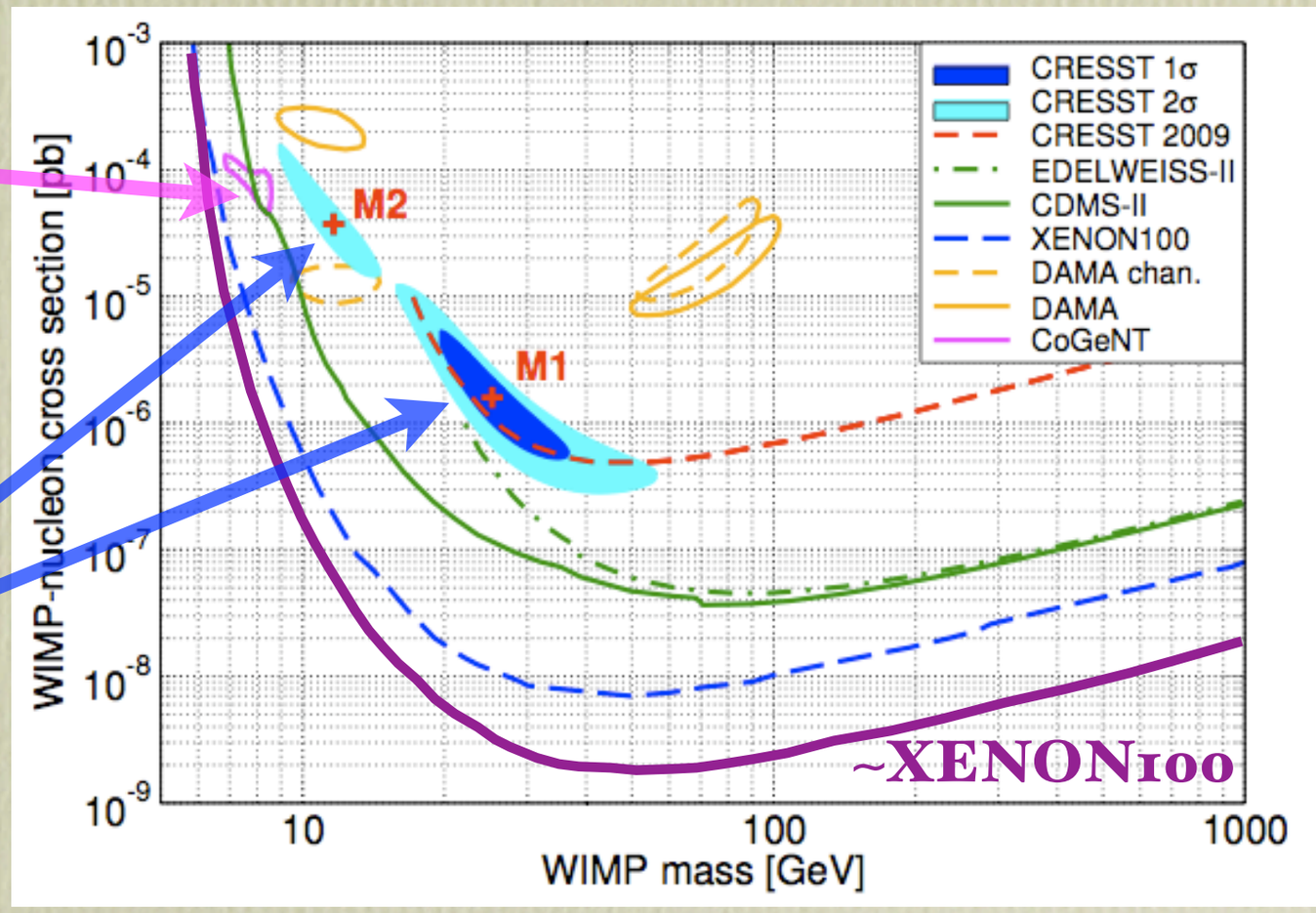

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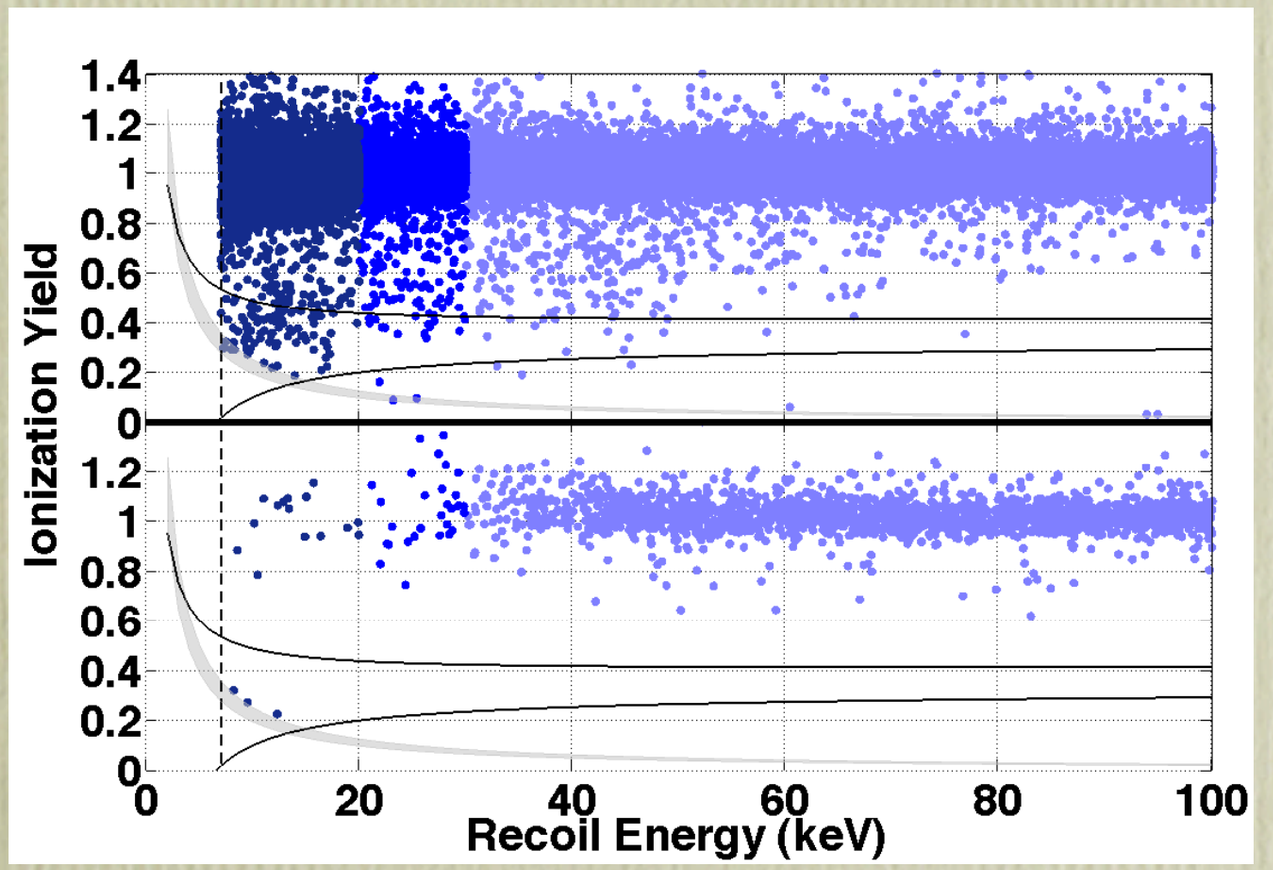
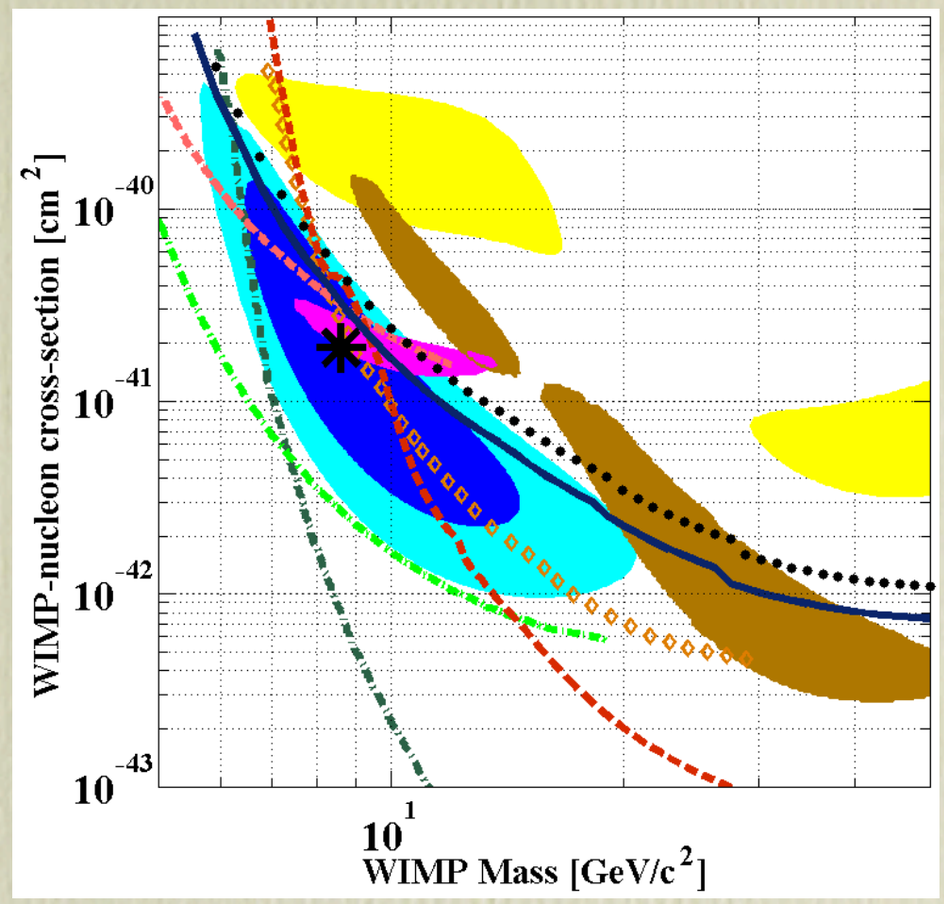


3 events after phonon timing criteria

CDMS II Si, Agnese et al., arXiv:1304.4279

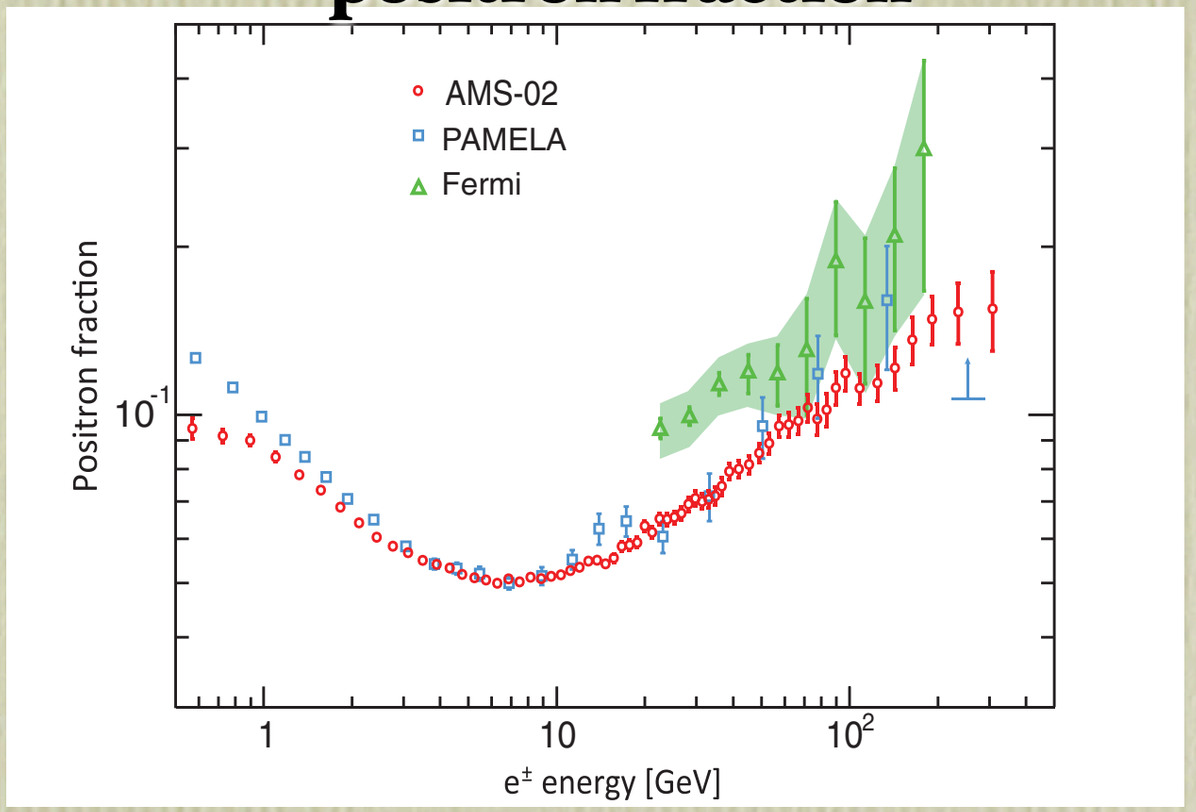


blue and cyan are 68% and 90% C.L. contours; 5.8% probability of fluctuation of estimated background

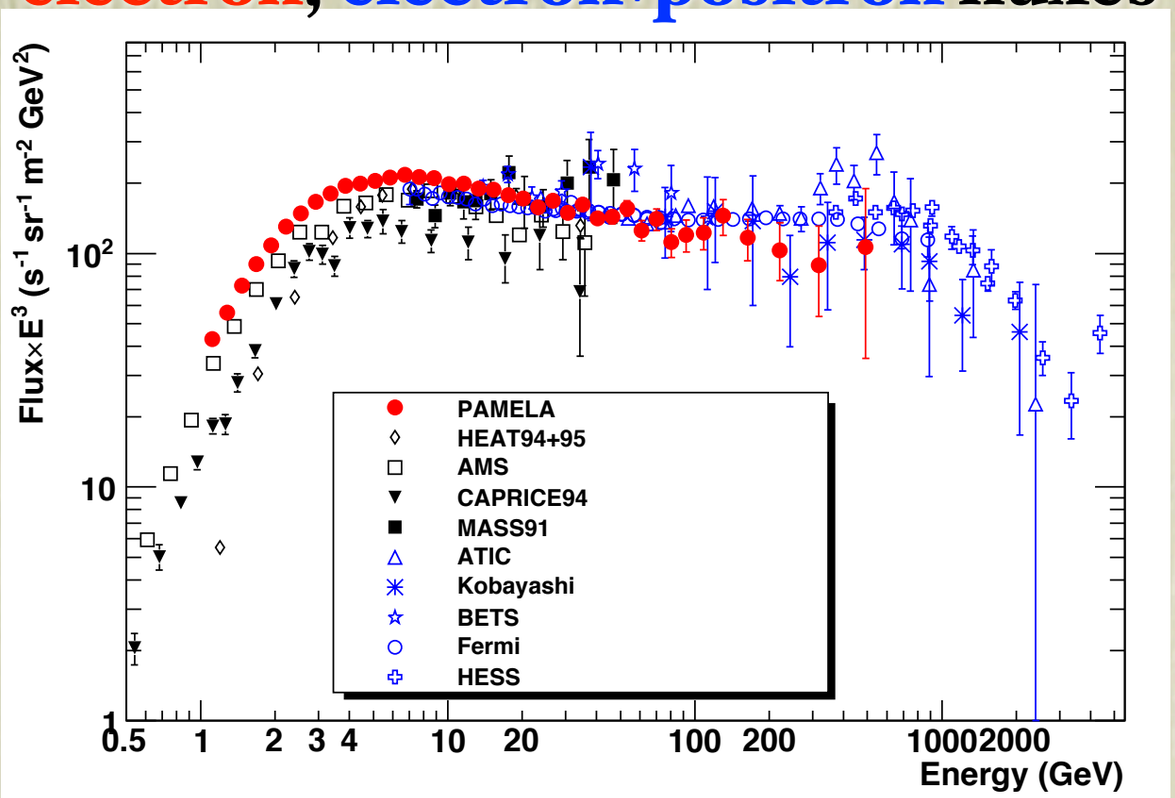
Chasing DM ambulances

The cosmic ray lepton puzzle and leptophilic WIMPs:

positron fraction



electron, electron+positron fluxes



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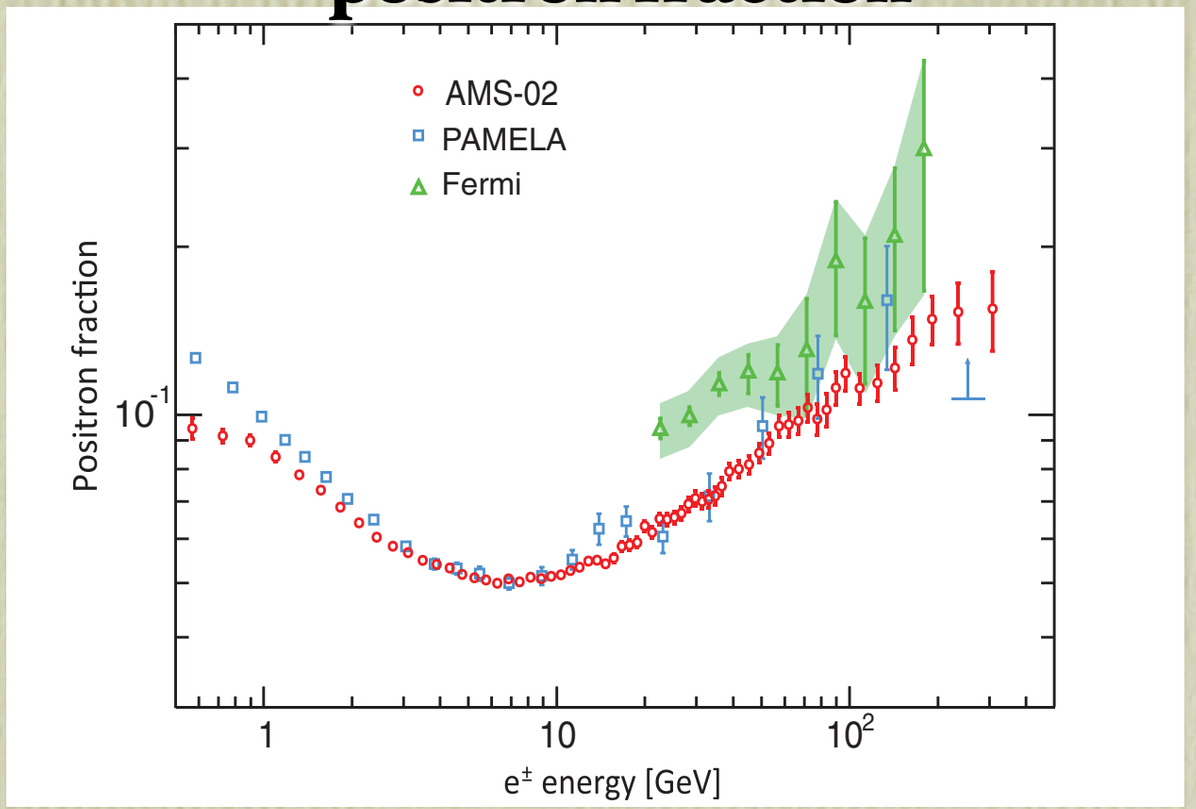
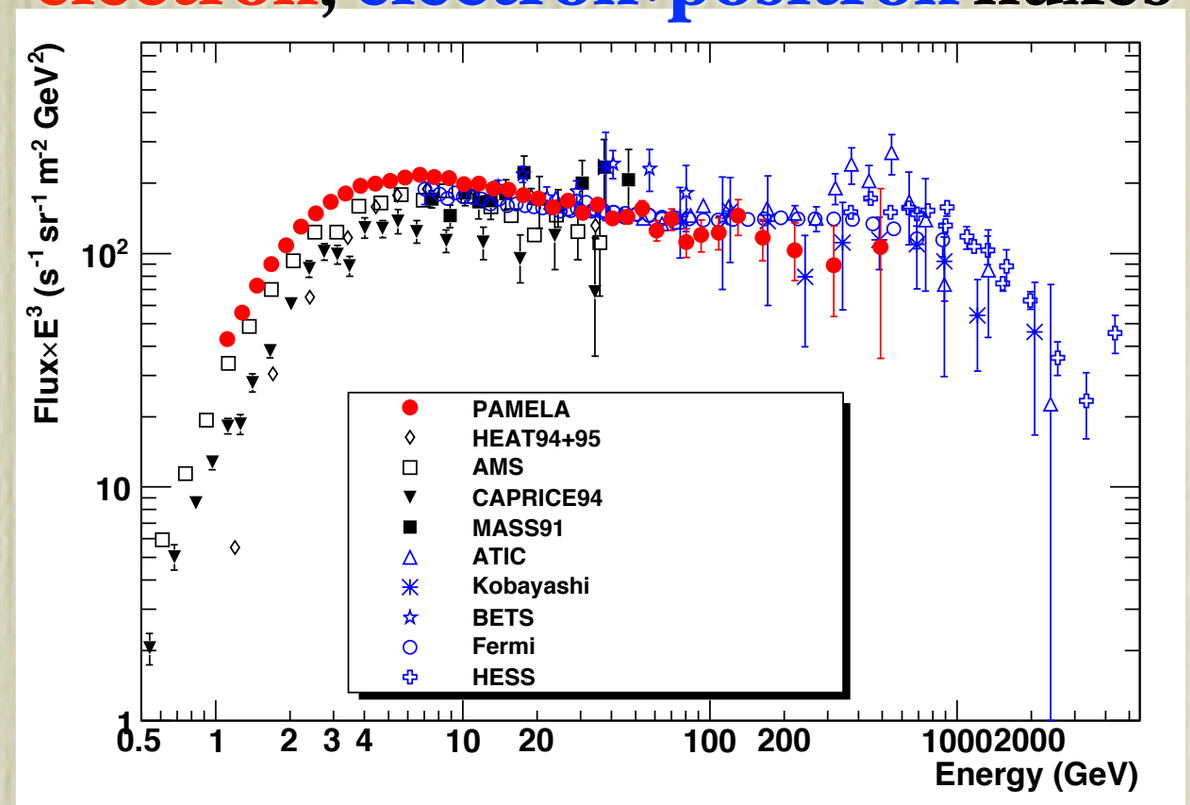


electron, electron+positron fluxes



We learned that the picture with electrons as primaries from SNRs and positrons as secondaries from the interaction of CRs on the ISM is wrong!

Chasing DM ambulances

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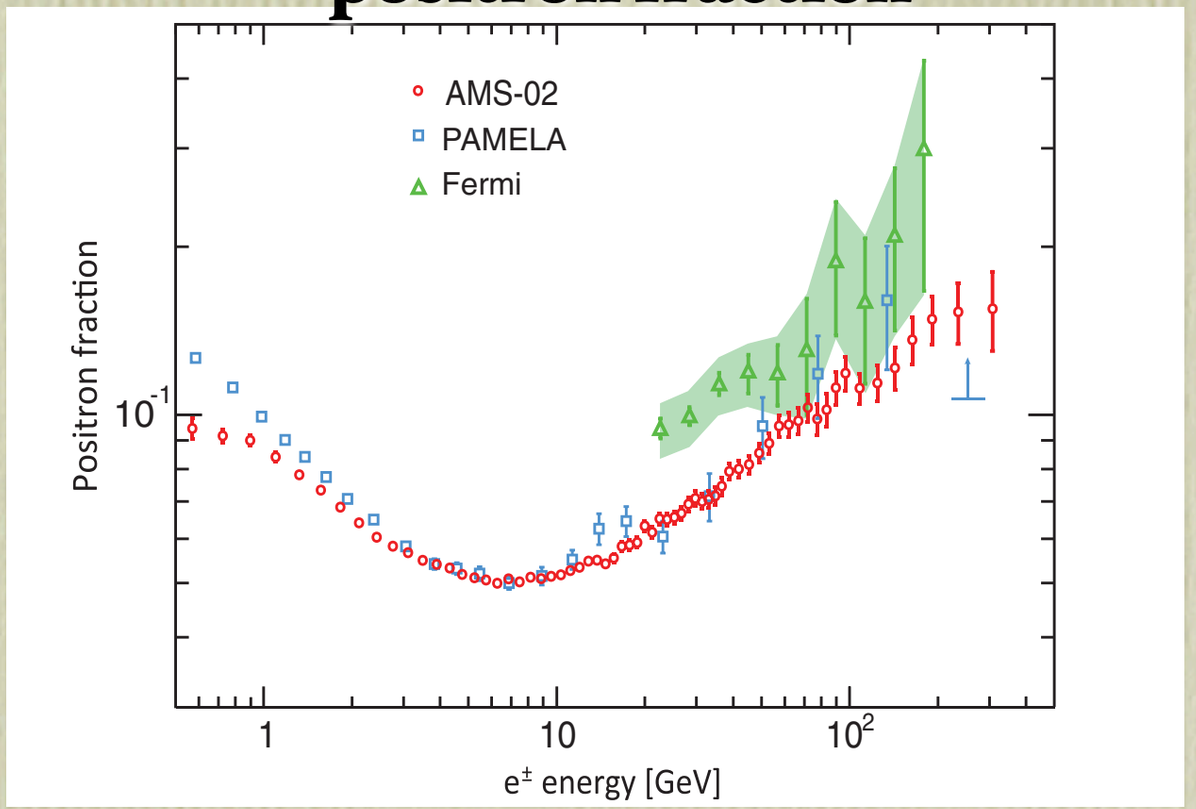

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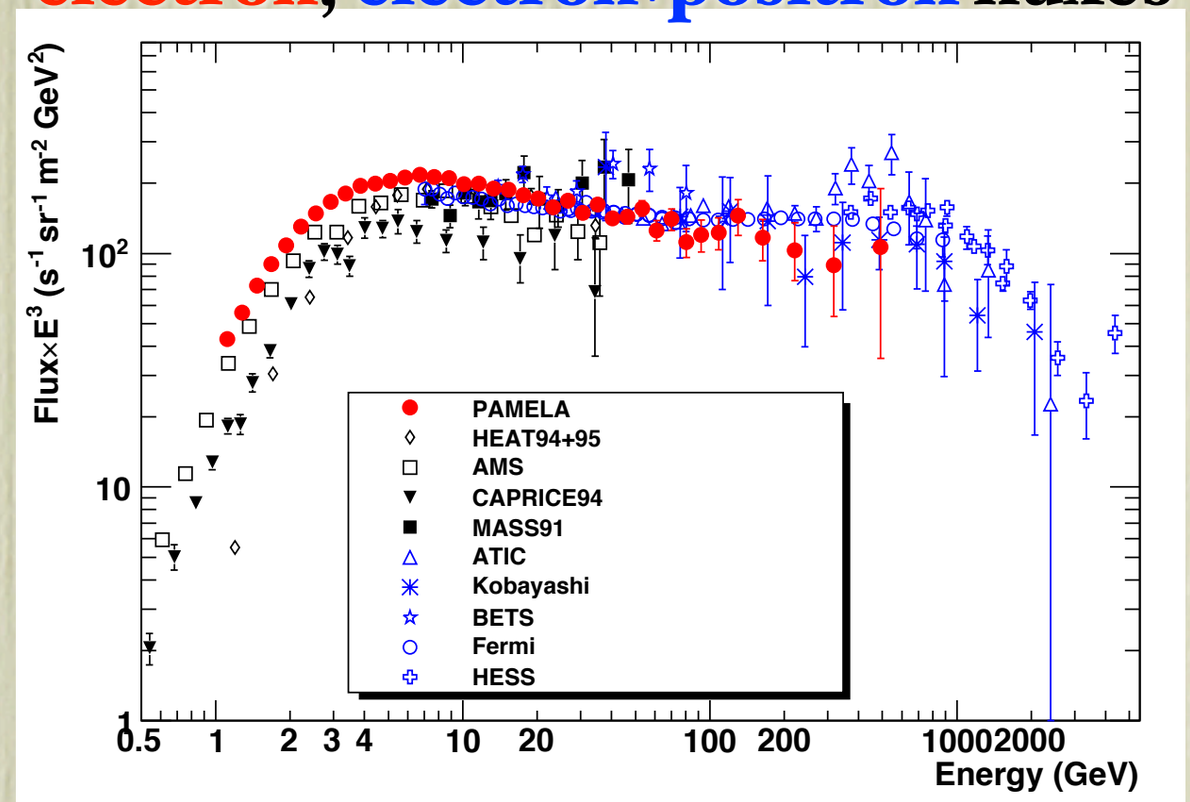


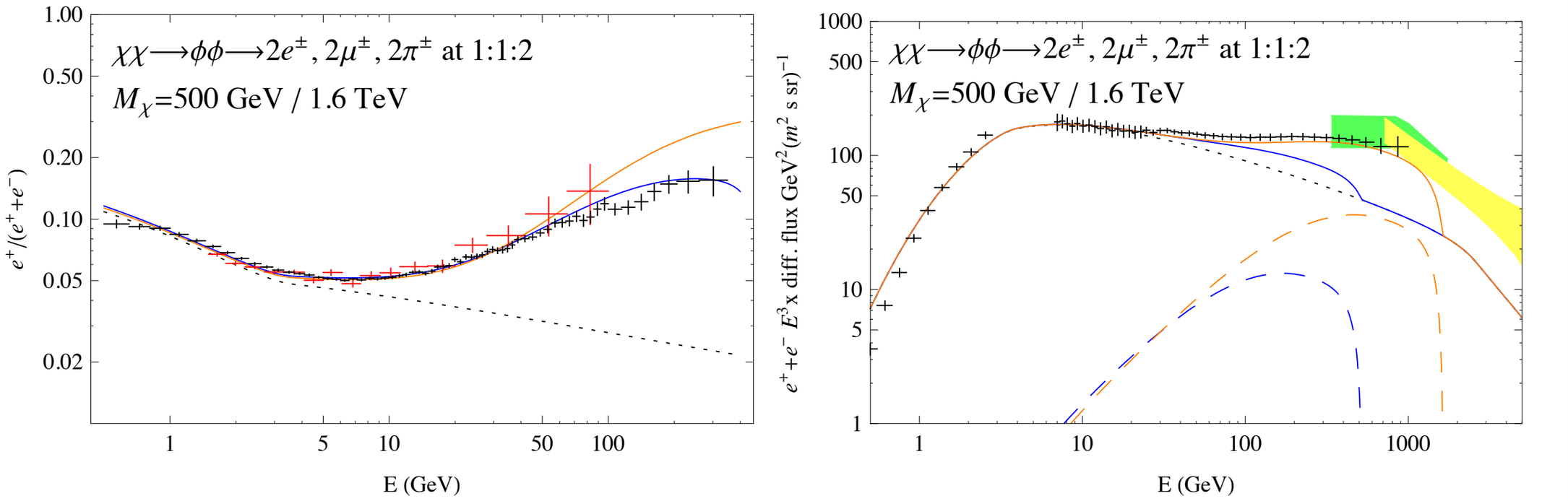
We learned that the picture with electrons as primaries from SNRs and positrons as secondaries from the interaction of CRs on the ISM is wrong!

We learned that there are primary (hard) positrons sources (or eventually secondaries from the interaction of CRs in source environments) & possibly extra electron sources. Since this extra components are measured at 100 GeV - few TeV they need to be from local source (because of energy losses).

Chasing DM ambulances

The cosmic ray lepton puzzle and leptophilic WIMPs:

A hard positron component (from AMS data possibly slightly softer than from Pamela data) in fair agreement with measurements, can be obtained from toy models of annihilating WIMPs, e.g.: **Cholis & Hooper, arXiv:1304.1840**



Not really a "vanilla" WIMP. You need: i) a large boost factor in the cross section compared the level at thermal freeze out ($1.5 \cdot 10^{-24}/1.3 \cdot 10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}$ in the example above) or in local density of WIMP pairs (substructures???); ii) a (combination of) leptophilic annihilation channel (hard from the model building point of view, possibly enforced via kinematics, see e.g.: **Arkani-Hamed et al., arXiv:0810.0713; Nomura & Thaler, arXiv:0810.5397**)

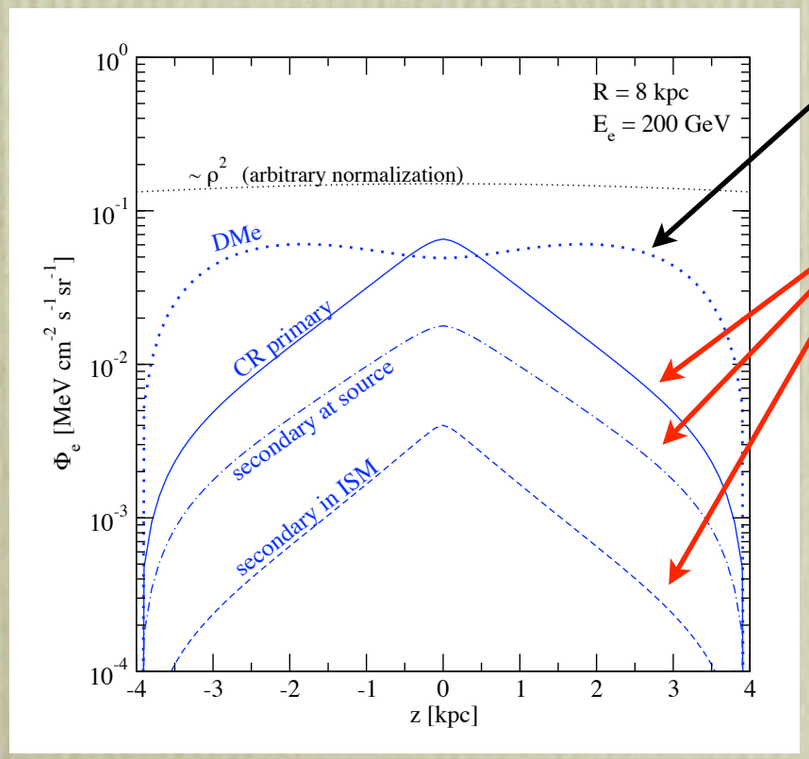
Chasing DM ambulances

The cosmic ray lepton puzzle and leptophilic WIMPs:

Testing the DM hypothesis against other possibilities?

• Very hard from CR lepton data alone; possible falsification of the DM hypothesis from the detection of angular anisotropies in the flux (still one should be confident about modeling propagation in the local environment).

• In principle possible by looking at the radiative emissions associated to the extra lepton components. Sources confined to the disc (as in case of pulsars) or spread out in the whole diffusive halo (as for DM annihilations) produce very different vertical lepton density profiles:



versus a DM term extending to much larger z

Primary/secondary astrophysical components mostly localized at z≅0

Regis & P.U., arXiv: 0904.4645

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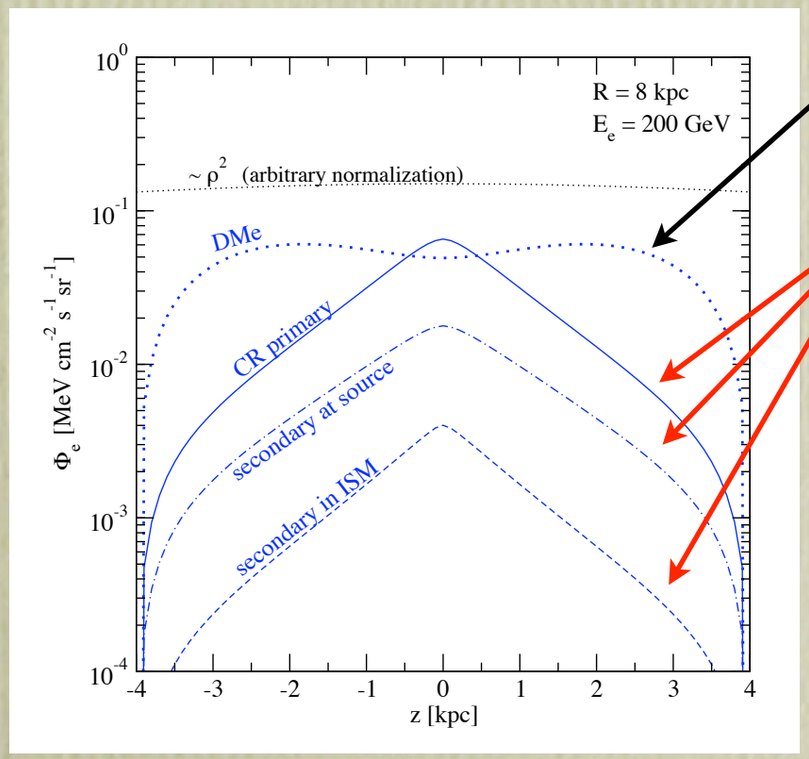

versus a DM term extending to much larger z

Primary/secondary astrophysical components mostly localized at z≅0

High-latitude inverse Compton and synchrotron profiles are sensibly different in the two cases and should be distinguishable

Chasing DM ambulances

The cosmic ray lepton puzzle and leptophilic WIMPs:

• Consistency checks are also possible looking at radiative emissions from the central region of the Galaxy, however these are much more model dependent. In particular they heavily rely on what extrapolation one takes for the dark matter distribution; in case of NFW profile, there is a severe tension with currently available radio data

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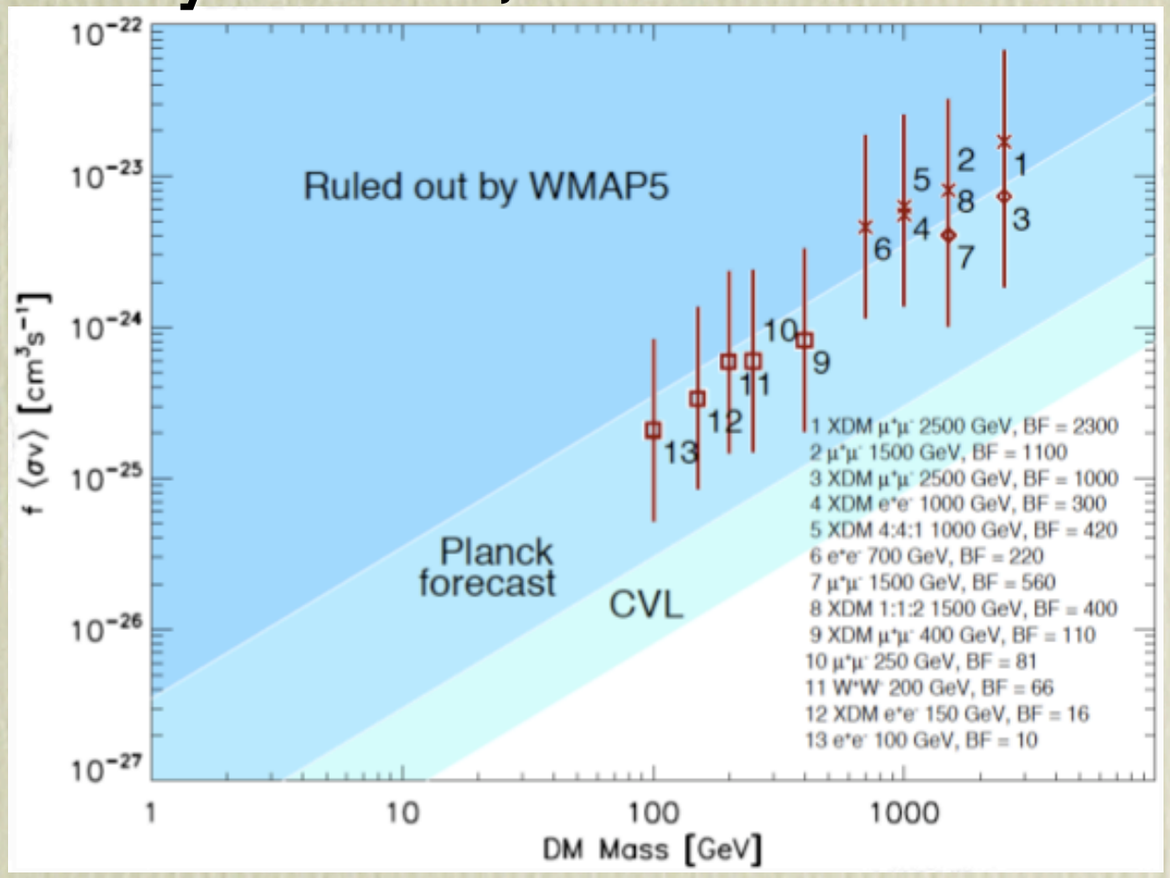
• Limits from "polluting" the early Universe with DM yields:

CMB limits: mainly from ionization of the thermal bath, Ly-α excitation of Hydrogen and heating of the plasma

Slatyer et al., arXiv: 0906.1197



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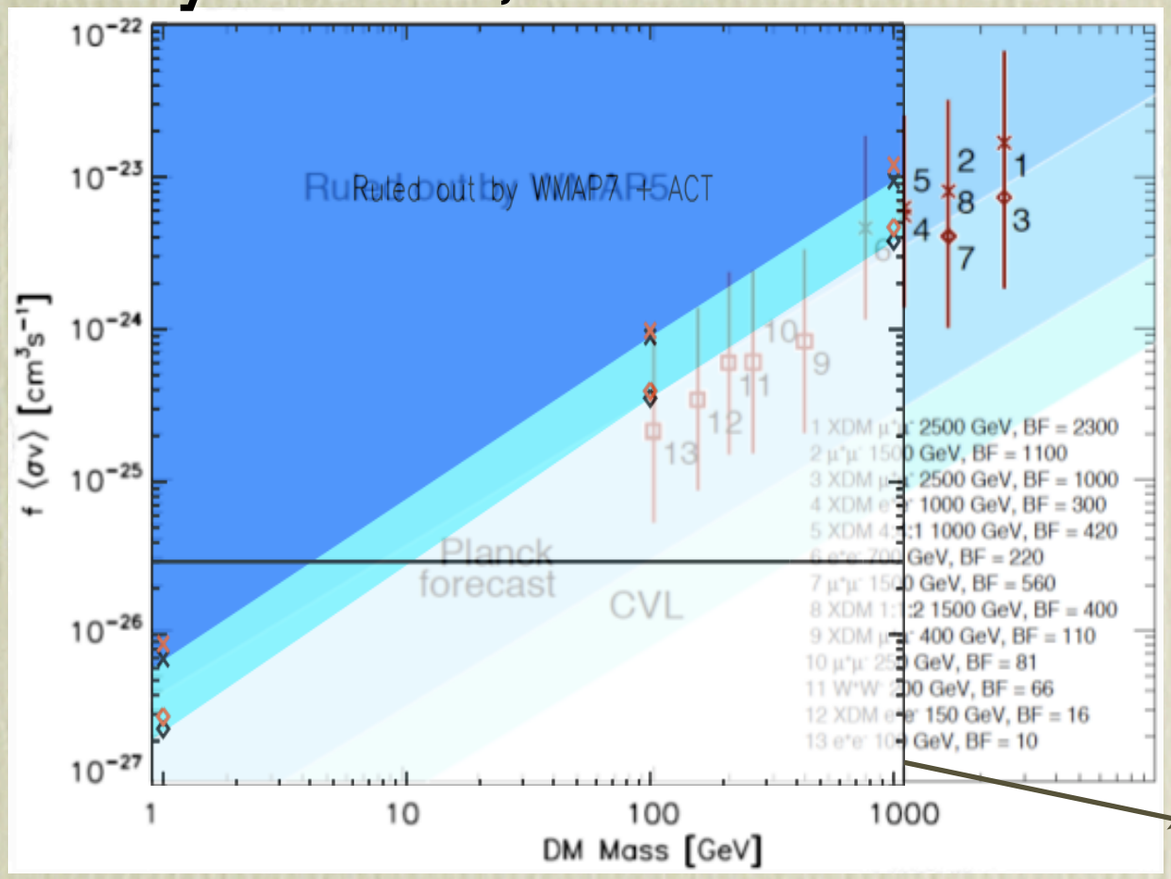


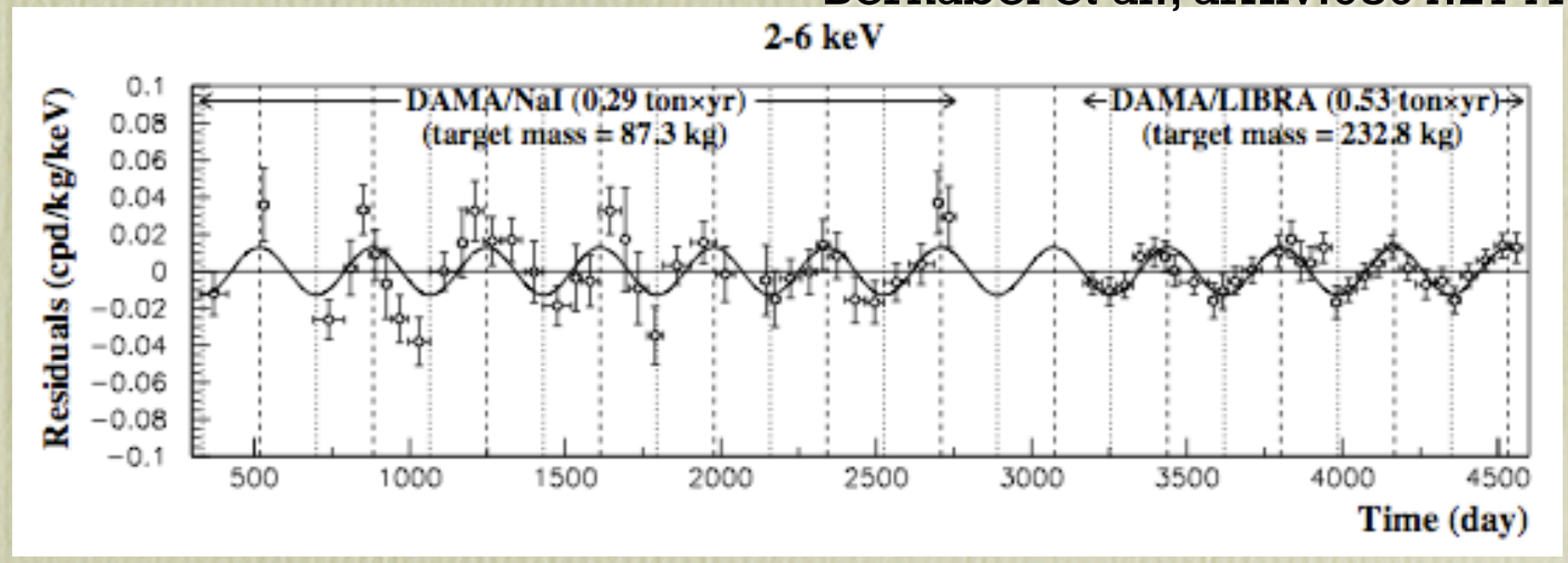
Galli et al., arXiv: 1106.1528

A clean signature (… and being unhappy about it)

About smoking guns and guns that quitted smoking… E.g.:

Annual modulation in direct detection signals:

Bernabei et al., arXiv:0804.2741



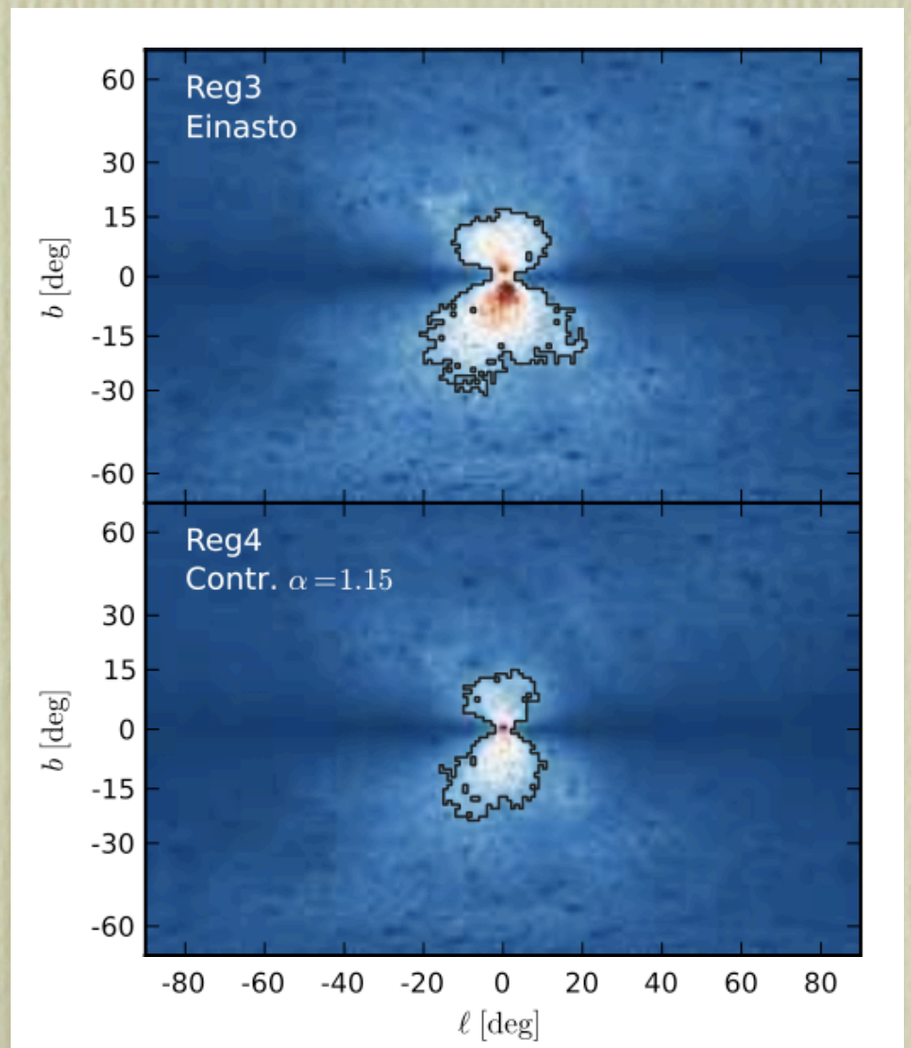
An effect solidly detected over 10 annual cycles with huge statistics. For its interpretation, the phase of the modulation and its amplitude are compatible and suggestive of WIMP DM scatterings; however converting the effect into a WIMP event rate, there is tension with other direct detection experiments.

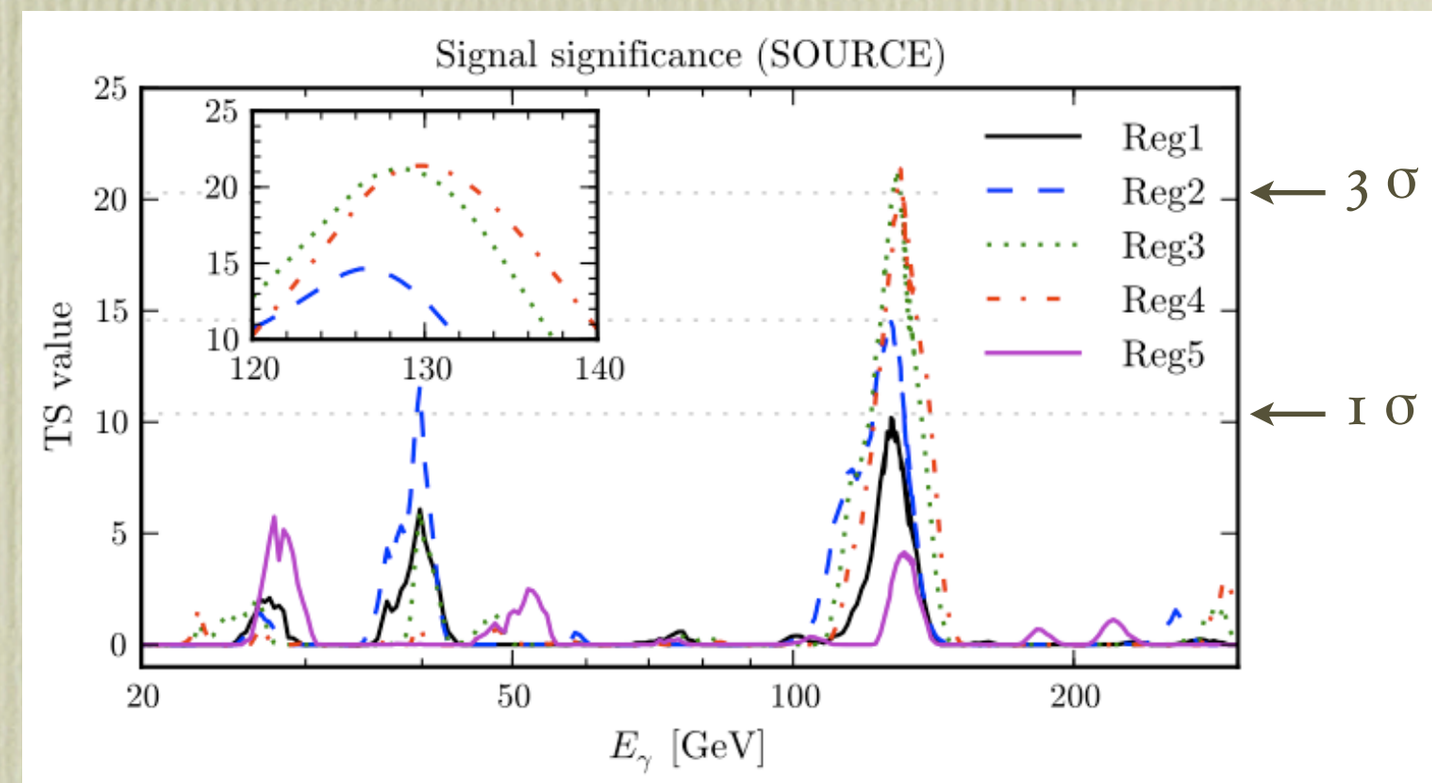
New run at lower threshold, expecting results next year (?). Competitors are not targeting annual modulation. Directional detectors are at R&D phase.

A clean signature (… and being unhappy about it)

A γ-ray line detected by FERMI towards the GC?

Weniger, arXiv:1204.2797 optimized the search region (assuming a simple power-law background and find a 3.2σ statistical significance (if "look elsewhere" effect included) for a line signal at about 130 GeV!





Compatible with line limits from the whole sky: Fermi-LAT coll., arXiv:1205.2739, as well as from dwarfs: Geringer-Sameth & Koushiappas, arXiv:1206.0796

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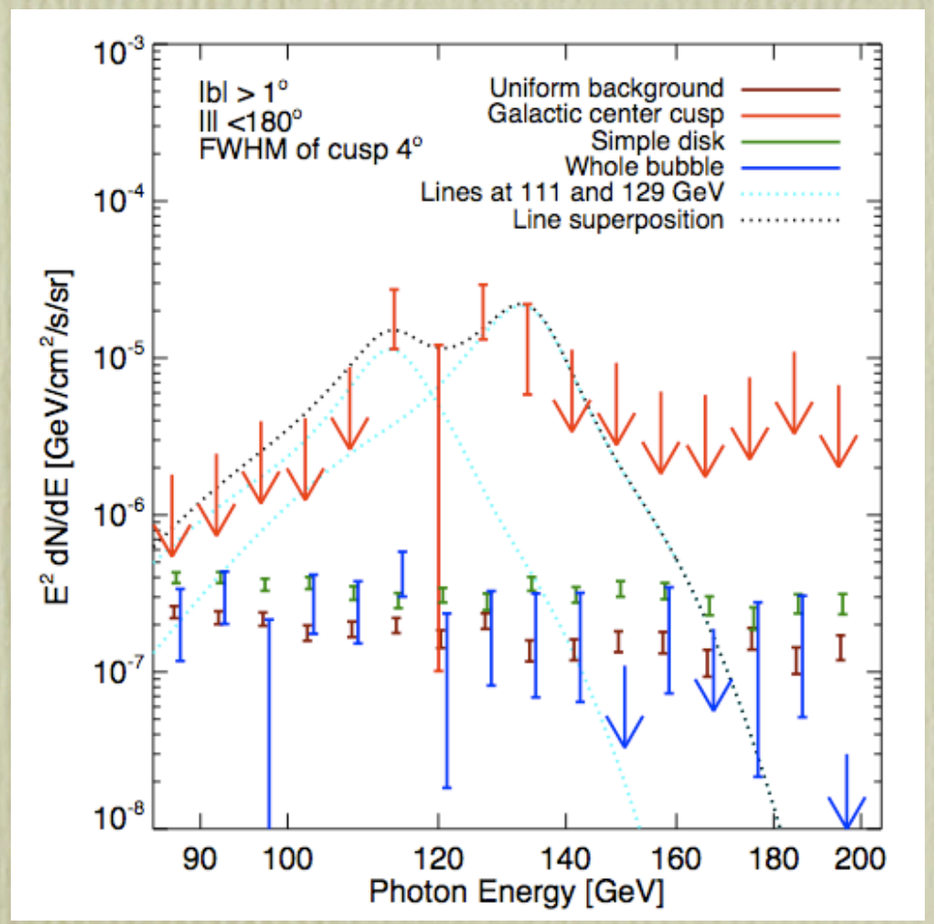
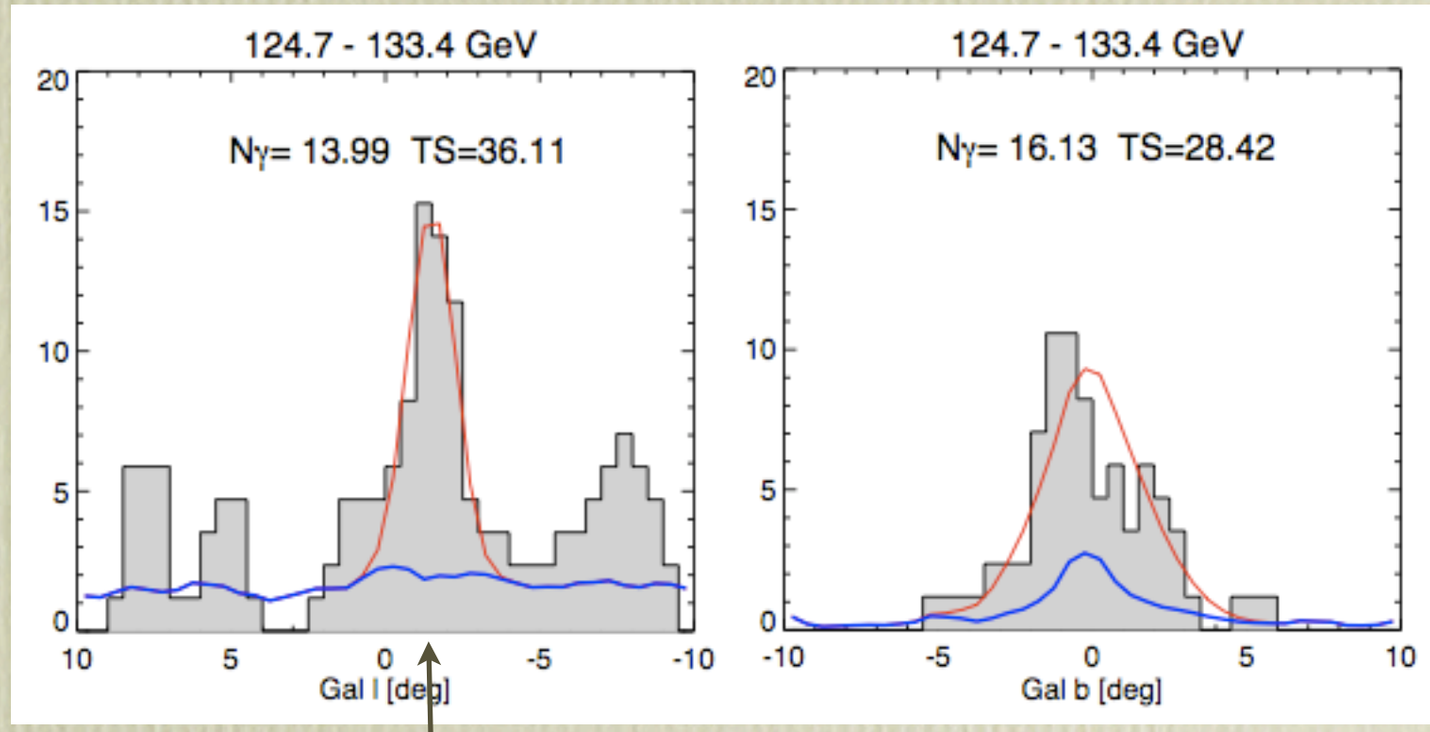
Su & Finkbeiner, arXiv:1206.1616 use a template fitting method and claim "strong evidence", with *local significance* of 5 o 6 σ for 2 lines at 111 & 129 GeV!





Template for the DM cusp off-centered by 1.5° (200 pc)

Off-center due to a density wave excitation by the stellar components? Matching a hydrodynamical N-body result Kuhlen et al., arXiv:1208.4844

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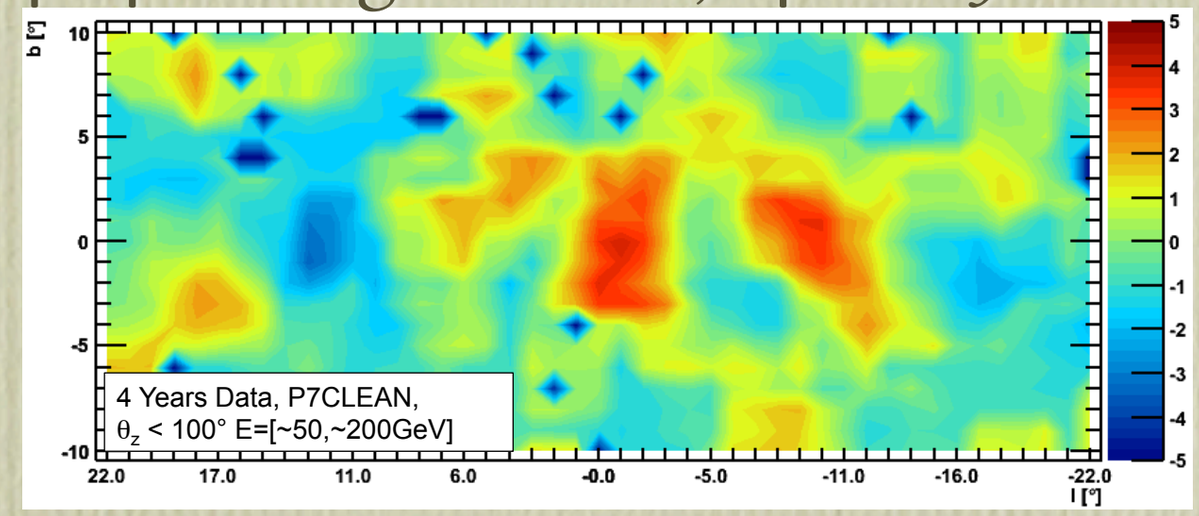
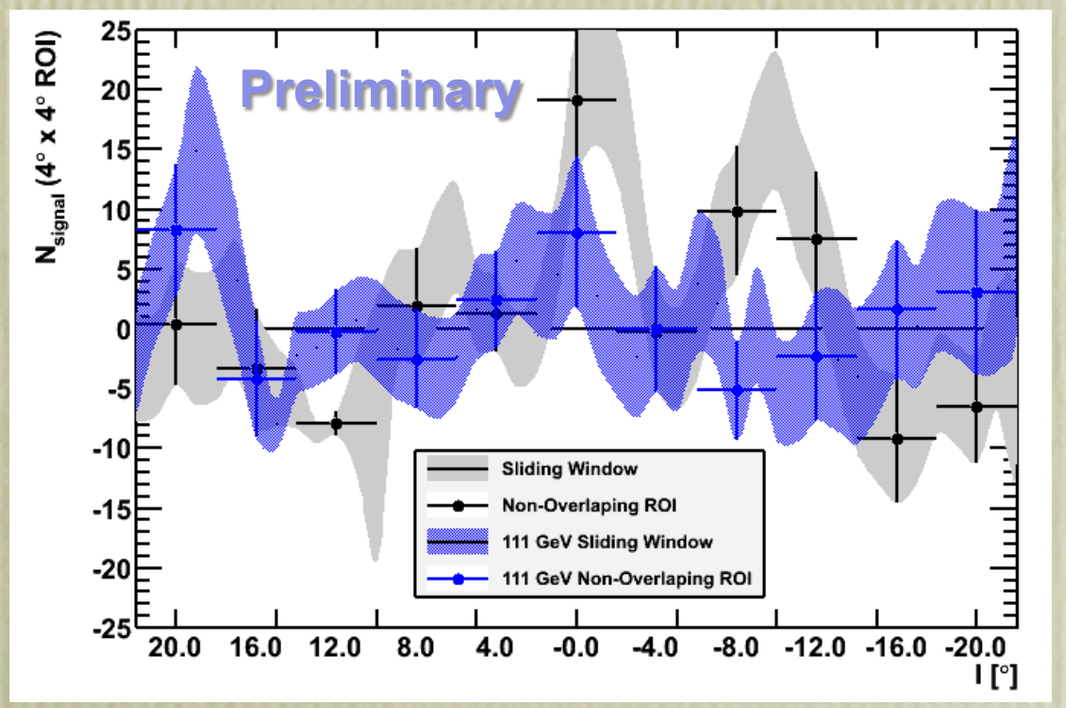
The preliminary statements from the FERMI collaborations:

4°x4° sliding windows, ~4σ at 130 GeV





E. Charles, Fermi Symposium 2012

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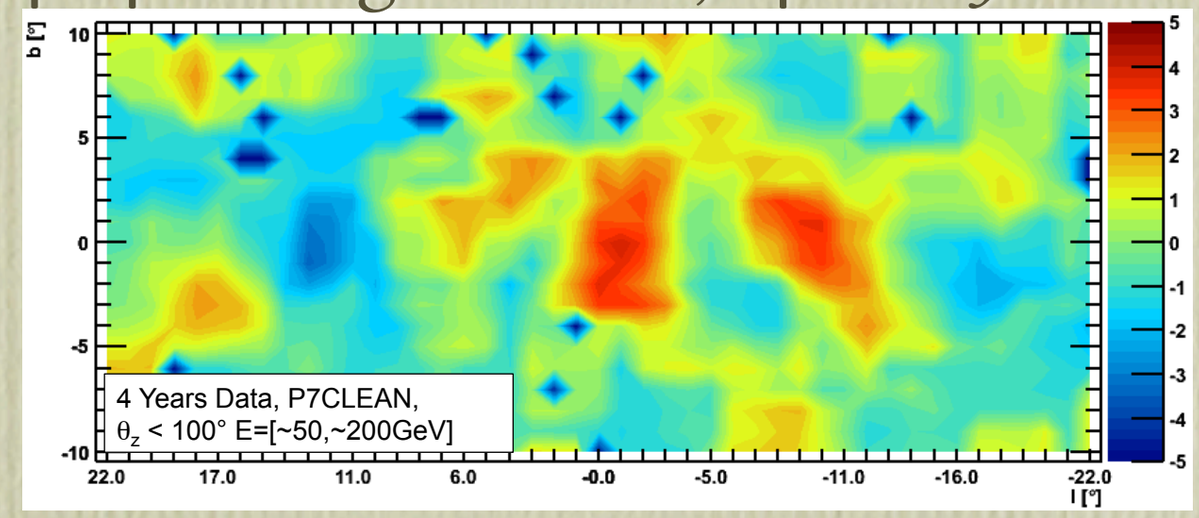

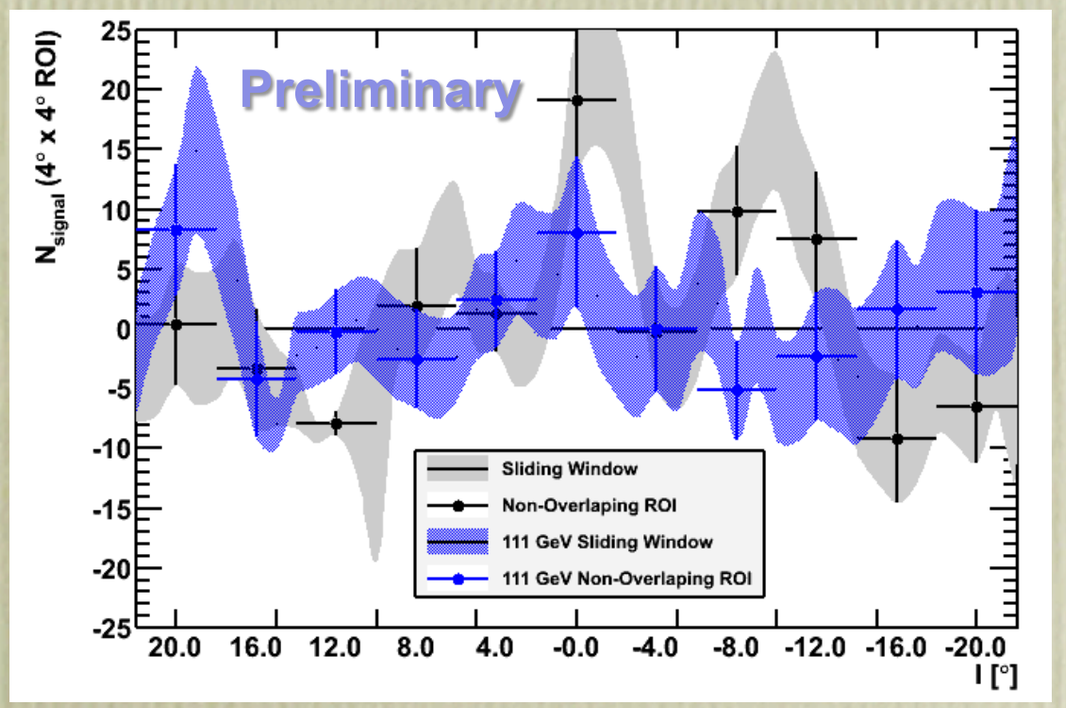

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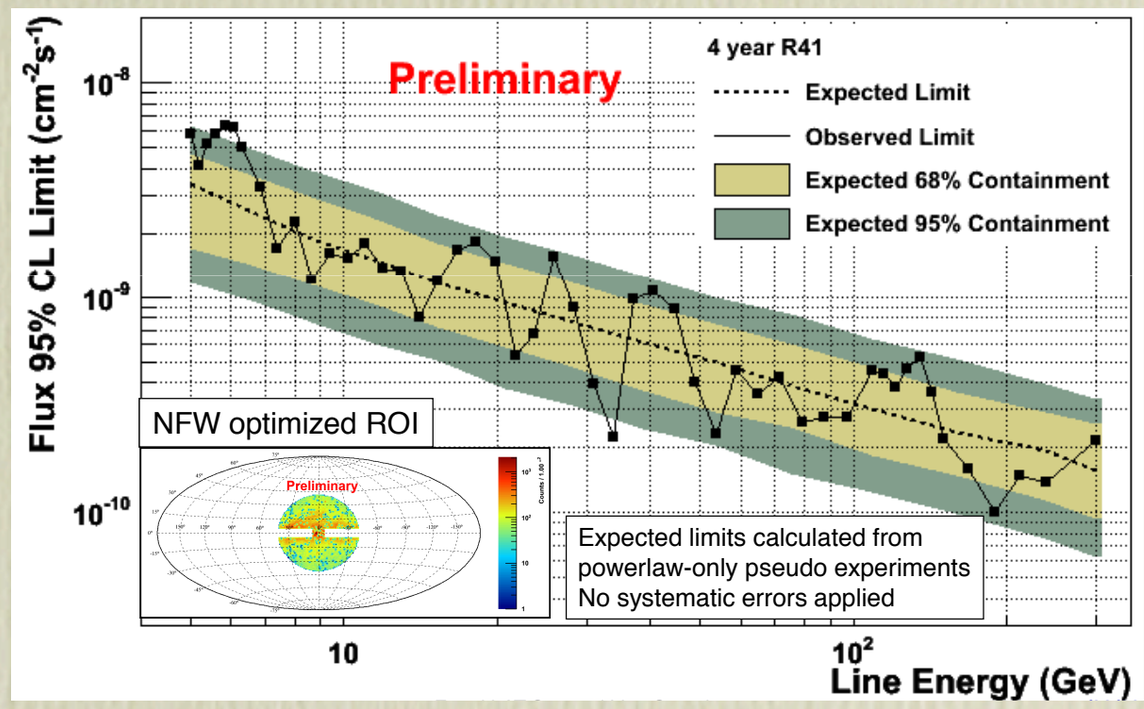

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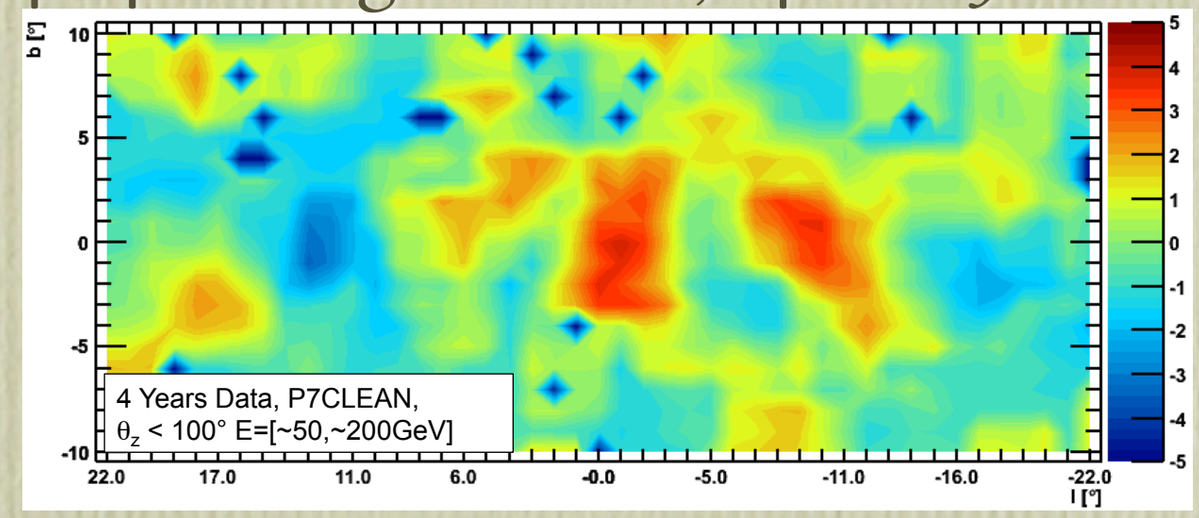

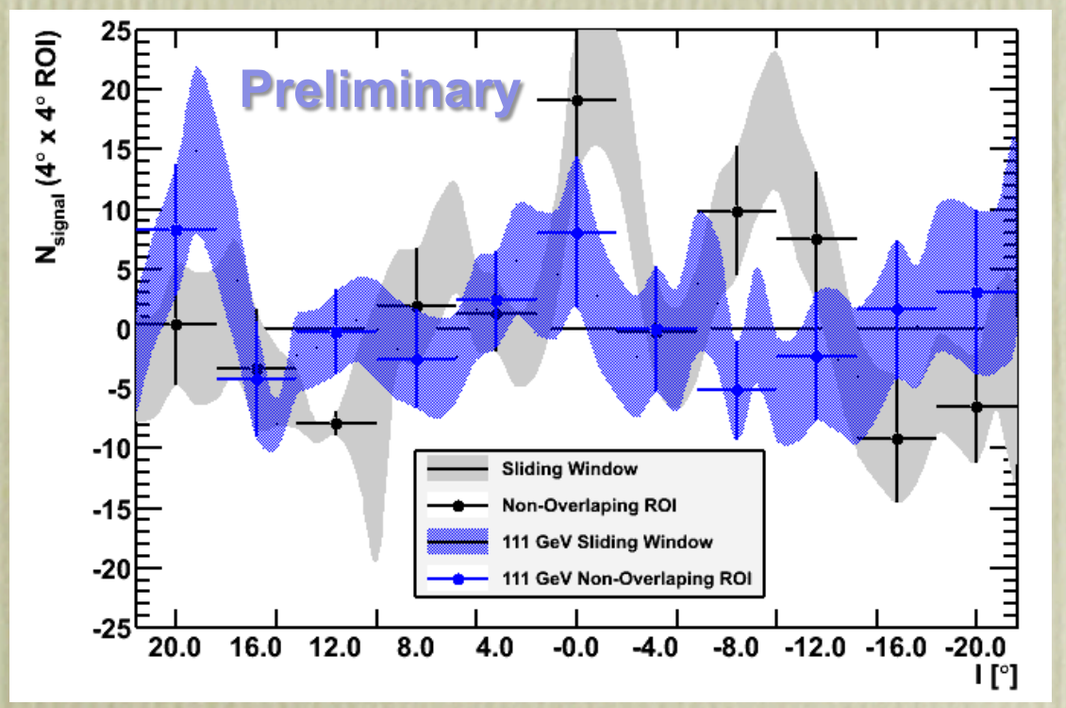

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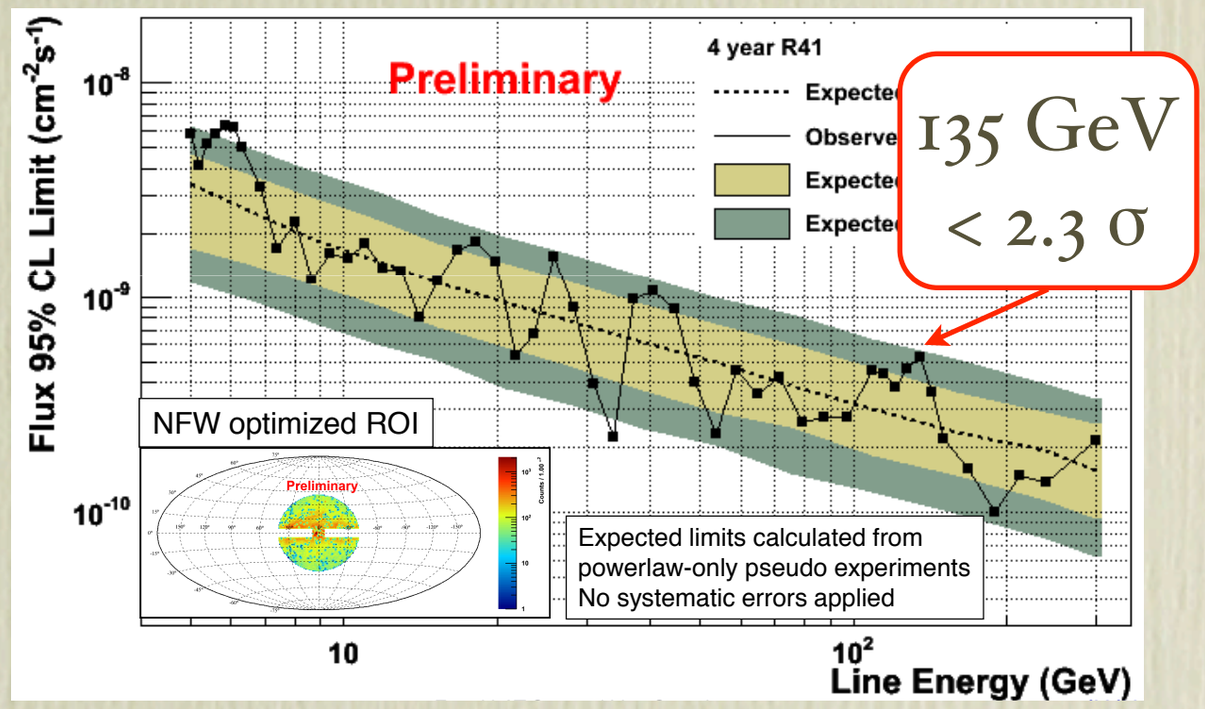
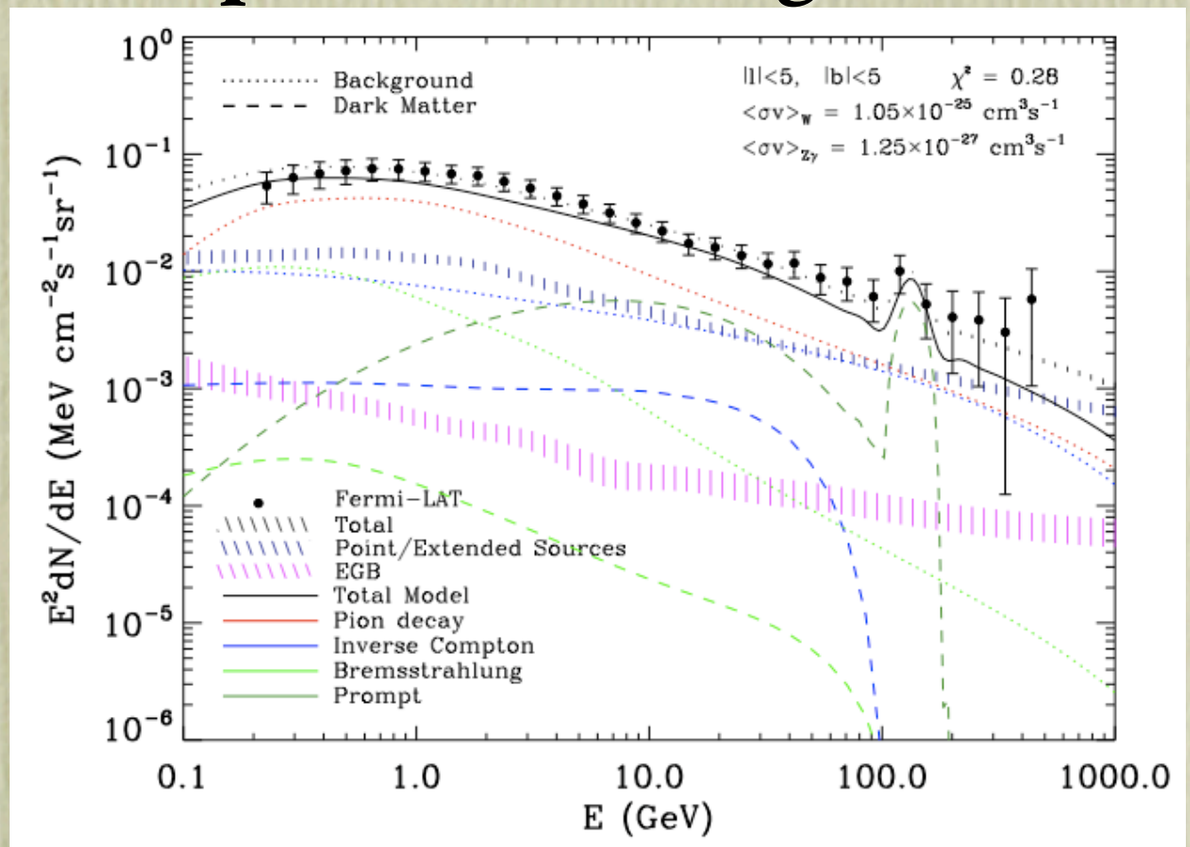


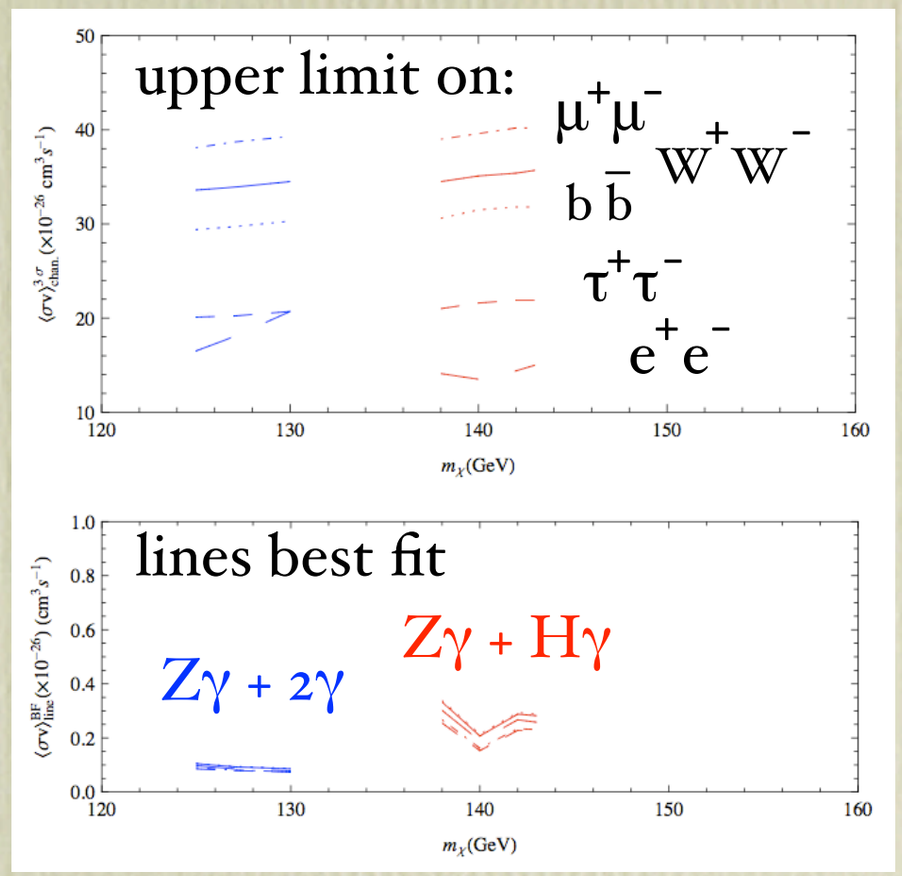
A. Albert, Fermi Symposium 2012

A clean signature (… and being unhappy about it)

A **monochromatic signal** + **continuum counterpart** in a model with physical background: Cholis, Tavakoli & P.U., arXiv:1207.1468

Sample model fitting the data:





A fit with several degeneracies, given the many components in the fit: Diffuse emission + point sources + DM component

Significantly away from the typical 1-loop over tree-level ratio: definite guideline for the DM model?