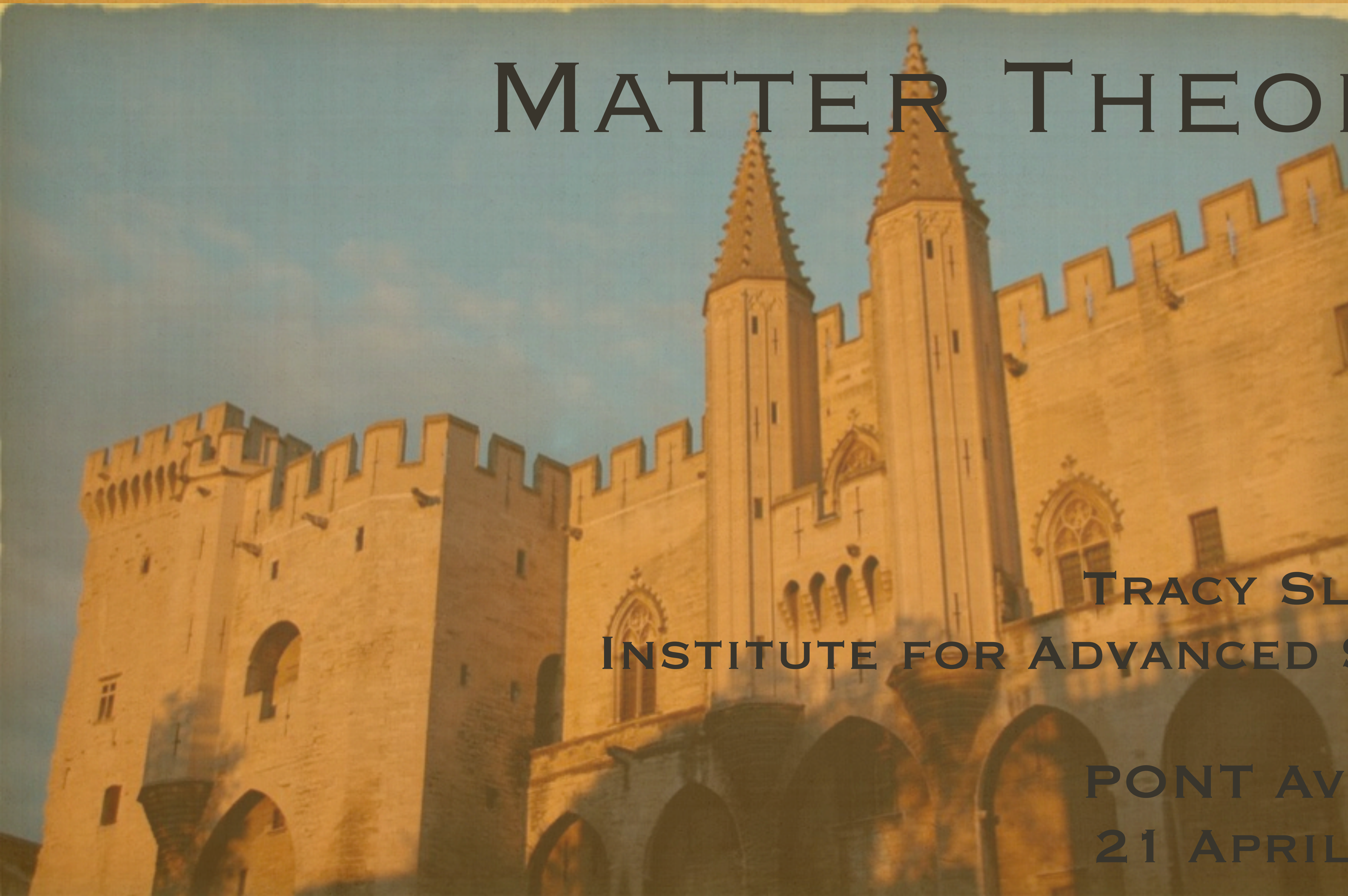
News from the Forefront of Dark Matter Theory



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21 April 2011

Outline

- Status and challenges of dark matter model-building for cosmic ray excesses.
- Status and challenges of dark matter model-building for direct detection anomalies.
- Future outlook and directions:
  - Addressing uncertainties in DM distribution/velocity.
  - Combining data from multiple experiments.

DM & Experimental Anomalies (Disclaimer)

- The past few years have seen several exciting potential signals, in both direct and indirect detection. Much of this talk will focus on models driven by these (usually unexpected!) results.
- Of course, individual anomalies could be coming from:
  - Problems with the experiment / contamination.
  - Known effects that standard background models do not account for. Example: cosmic ray reacceleration in supernova remnants (Blasi 0903.2794).
  - Some new or poorly understood background. Example: pulsar contribution to cosmic rays - they certainly produce high-energy e^+e^-, but no clear prediction for expected spectrum.
- Nonetheless, still interesting and important to ask:
  - Can dark matter explain these “signals”?
  - What kind of dark matter models do they demand?
  - How do we test the DM hypothesis?

A New Source of e^+e^-

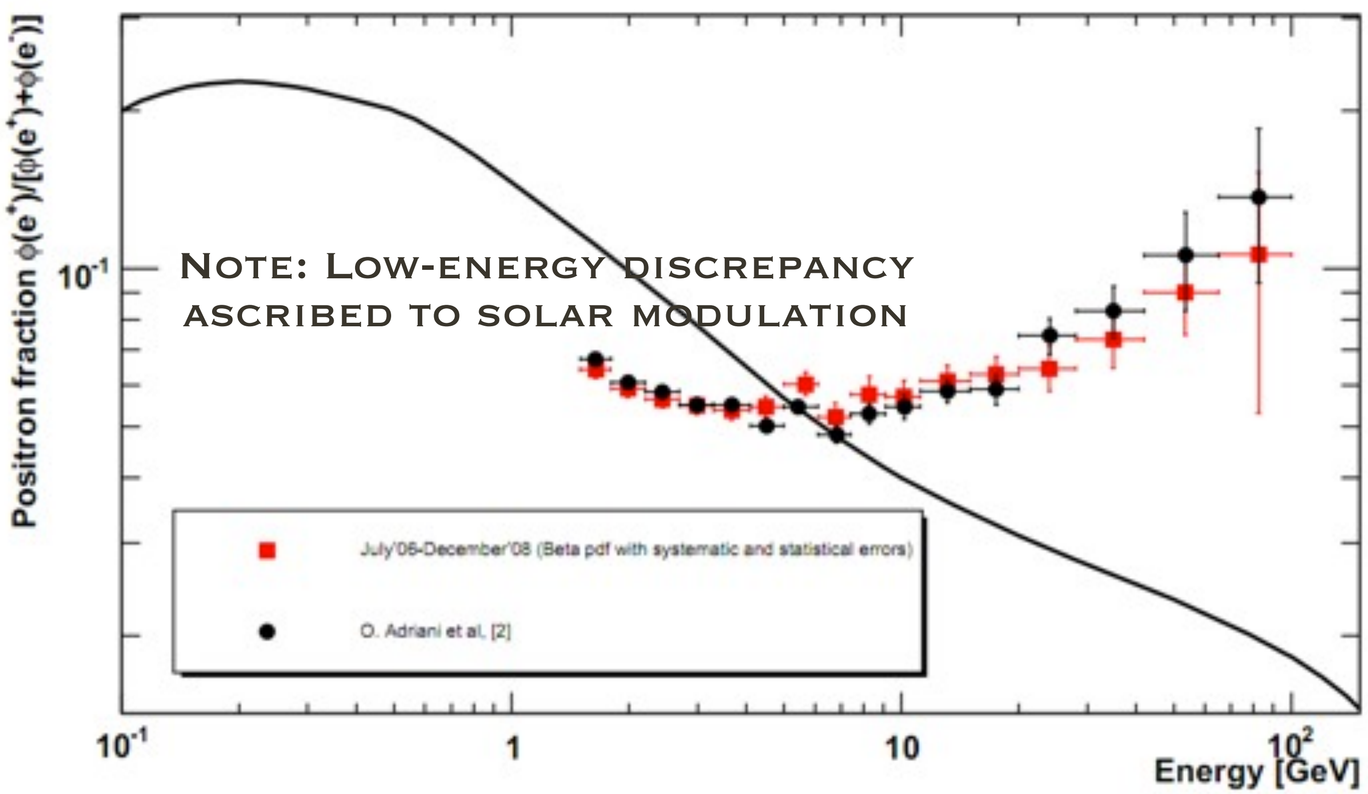
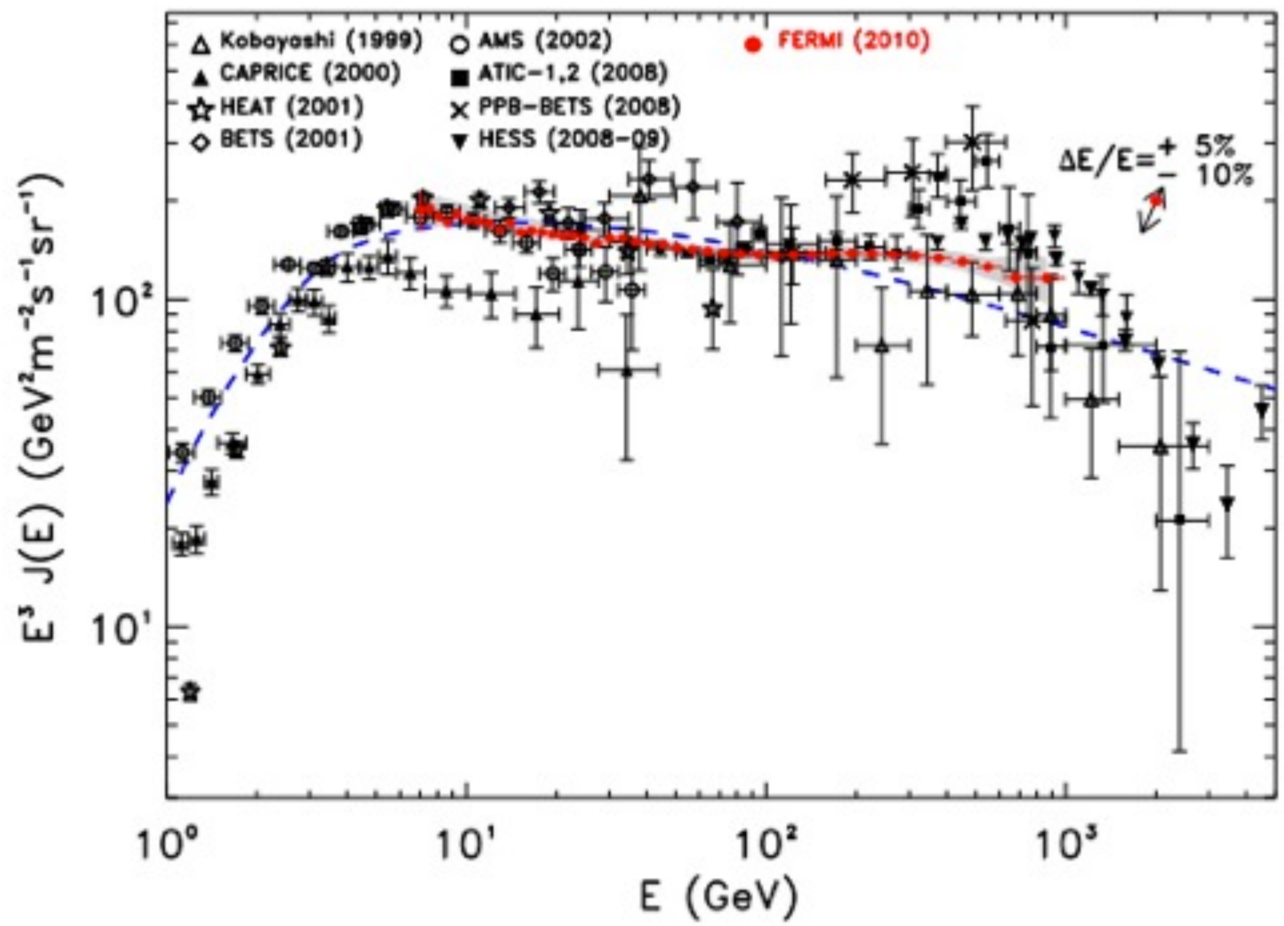


Figure 11: The positron fraction R obtained using a beta-fit with statistical and systematic errors summed in quadrature (red), compared with the positron fraction reported in [2] (black). The solid line shows a calculation by Moskalenko & Strong [40] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy.

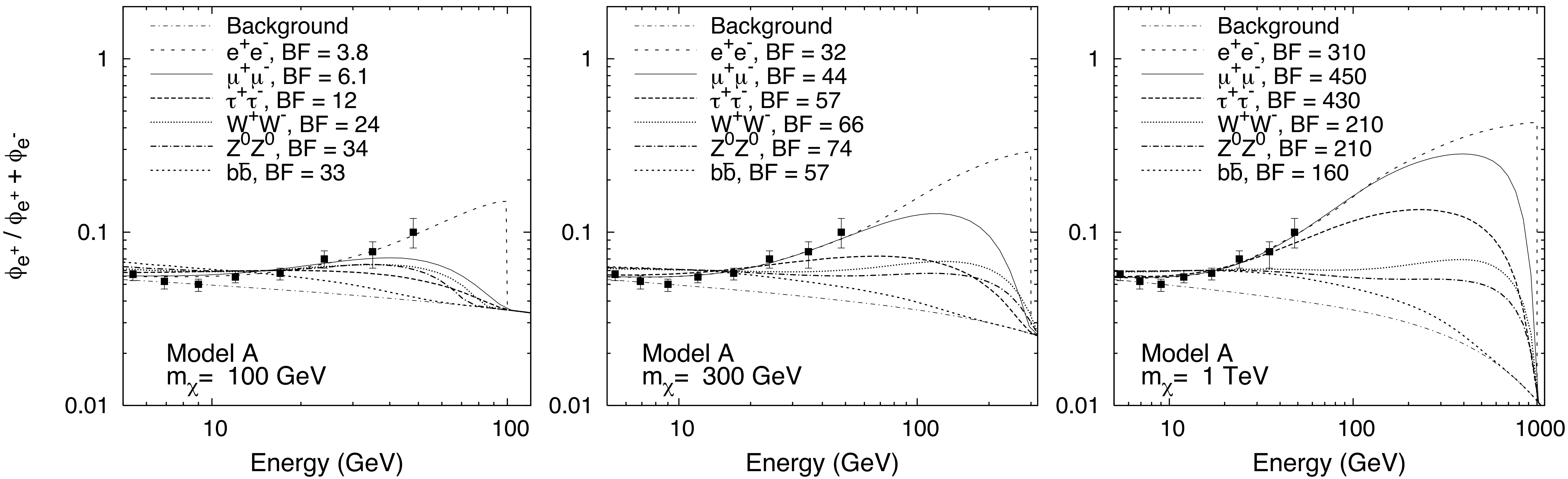
Adriani et al (PAMELA Collaboration) 1001.3522



Ackermann et al (Fermi Collaboration) 1008.3999

- PAMELA: positron fraction **rises** with energy above 10 GeV. Contrary to expectations: expect electrons + protons accelerated in supernova shock, softer **secondary** positrons produced from proton-ISM scattering.
- FERMI: e^++e^- spectrum hardens at higher energies; consistent with PAMELA if there is a new component half e^+, half e^-. Also consistent with slight hardening in PAMELA electron spectrum measurement (1103.2880).
- ATIC: agrees with Fermi on hardening, identifies multi-peak structure in 200-800 GeV range (1104.3452). No good understanding of Fermi/ATIC discrepancy.

WIMPs in Cosmic Rays?



Cholis et al 08 (similar results from Cirelli et al 08)

- Energy scale = electroweak scale: suggestive of WIMP DM?
- Three major challenges:
  - If DM has weak-scale mass, annihilates to kinematically allowed SM final states, generically expect antiprotons as well as positrons - PAMELA sees no excess in antiprotons.
  - If electrons/positrons result from long cascade of decays, spectrum is too soft to explain signal.
  - Expected annihilation rate if DM is a thermal relic is 1-3 orders of magnitude too small.

Models for PAMELA

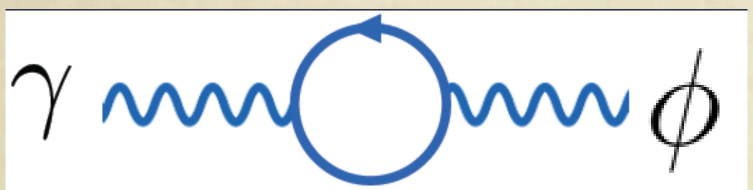
- PAMELA/Fermi/ATIC results triggered enormous theoretical activity (PAMELA positron measurement: 702 citations on SPIRES, 173 published papers citing it in 2009 alone).
- To enhance annihilation rate:
  - Non-thermal dark matter? (e.g. Grajek et al 08, Nagai & Nakayama 08, Murayama & Shu 09, Bi et al 09)
  - Velocity-dependent enhancement to cross section? Sommerfeld enhancement, Breit-Wigner resonant enhancement? (e.g. Hisano et al 04, Cirelli et al 07, March-Russell et al 08, Ibe, Murayama & Yanagida 08, Guo & Wu 09)
- Decaying dark matter, rather than annihilation? (e.g. Arvanitaki et al 09, Okada & Yamada 09, Ibarra, Tran & Weniger 09, Buchmuller et al 09, Ibe et al 09, Mardon, Nomura & Thaler 09) Correct lifetime from dimension-six operator. Evades some constraints more easily than annihilating case.
- To produce hard positron spectrum, no antiproton excess:
  - Kinematics, from annihilation/decay through intermediate light states? (see next slide)
  - Symmetries requiring leptophilic annihilation/decay? (e.g. Baek & Ko 08, Kyae 09, Bi, He & Yuan 09, Goh, Hall & Kumar 09, Dutta, Leblond & Sinha 09, Chen 09, Chun, Park & Scopel 09)
  - Multi-TeV dark matter, to push antiproton bump to higher (un-measured) energies? (e.g. Minimal Dark Matter, Cirelli & Strumia 08)

A New Dark Force

Arkani-Hamed, Finkbeiner, TRS & Weiner 08, Pospelov & Ritz 08

- Suppose DM has weak-scale mass, but is charged under "dark" gauge symmetry broken at the GeV scale. Then naturally solve all three problems!

- If the dark gauge group has a U(1) factor, the U(1) dark gauge boson naturally kinetically mixes with the Standard Model photon:



$$\mathcal{L}_{\rm kin} = \frac{\epsilon}{4} F^{\mu\nu} F^{D}_{\mu\nu}, \qquad \epsilon \sim 10^{-3} - 10^{-4}$$

IF GENERATED AT ONE-LOOP

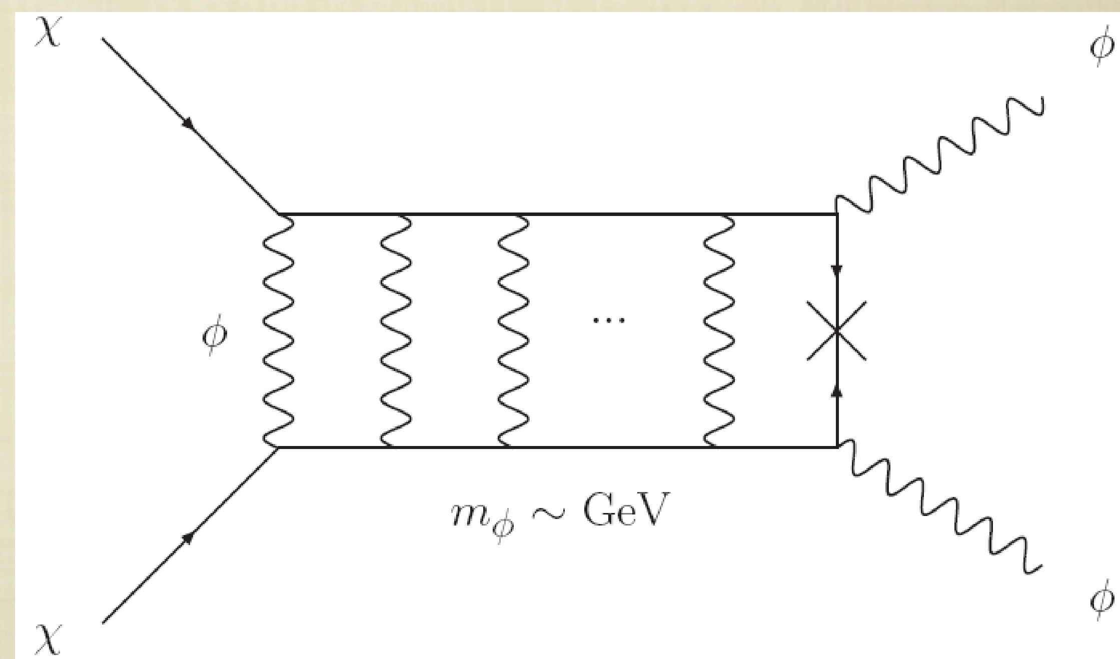
- Dominant annihilation channel is then:

$$\chi\chi \rightarrow \phi\phi$$

- On-shell φ's decay to SM final states:

$$\phi \rightarrow e^+e^-,\ \mu^+\mu^-\ \pi^+\pi^-,\ \ldots$$

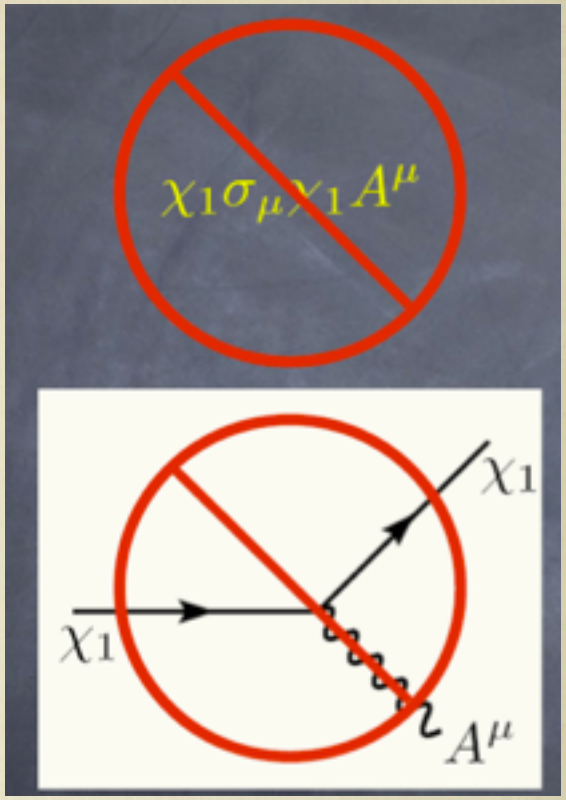
- If m_φ < twice proton mass, no antiprotons light charged SM final states only.

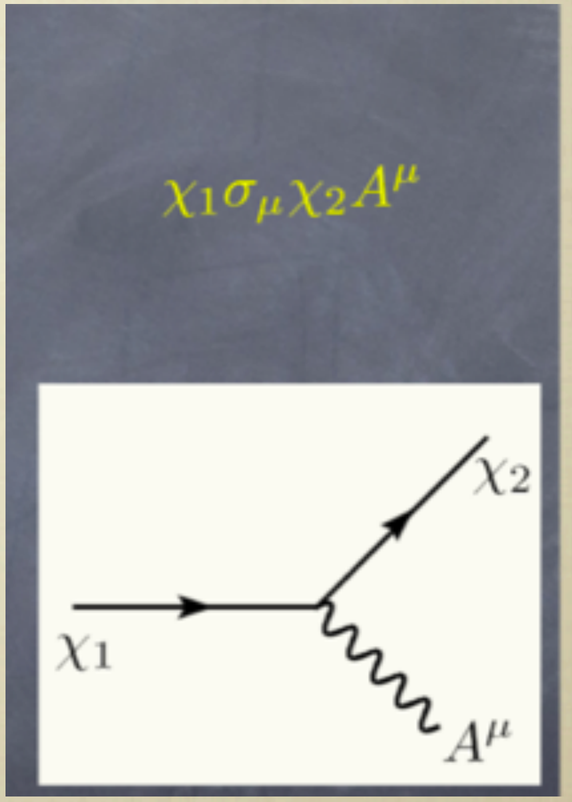


- New interaction => attractive fm-range force between DM particles => ~1/v boost to annihilation (Sommerfeld enhancement). Typically 2-3 orders of magnitude in local halo, O(1) at freezeout.

Multi-State Dark Matter

- We now have a multiplet of dark-charged states: it is **not** generic for these states to be degenerate.
- What is the natural size of the mass splittings δ?
  - Radiative contribution to mass ~ $\alpha_D\, m_\varphi$; if dark gauge group is non-Abelian with different gauge boson masses, radiative splittings naturally generated at $\delta \sim \alpha_D\, \Delta m_\varphi$, so ~ MeV for GeV-scale m_φ.
  - If dark gauge group is U(1), degeneracy is possible, but higher-dimension operators can break it. For example, for dim-5 operator involving new physics at the TeV scale, $\delta \sim \text{GeV}^2/\text{TeV} \sim \text{MeV}$.
- The mass eigenstates are rotated from the gauge eigenstates: interactions between gauge bosons and mass eigenstates are **off-diagonal only**. Important consequences for indirect AND direct detection!
- Direct detection: if no splitting, $\varepsilon < 10^{-6}$-10^{-7}. 100 keV splitting => scattering kinematically suppressed, $\varepsilon \sim 10^{-3}$ okay.
- Also some phenomenological motivations: inelastic dark matter (see later slides), exciting dark matter (Finkbeiner & Weiner 07, Chen, Cline & Frey 09, Finkbeiner, TRS, Weiner & Yavin 09, Chen et al 09).





Model-Building and New Searches

- Models of this type have very different direct/indirect detection signatures to more-studied SUSY neutralinos, despite the theory modification being quite small.
  - Indirect detection: very few gamma-rays produced from annihilation, but potentially large gamma-ray signal from inverse Compton scattering on copious electrons/positrons.
  - Direct detection: can have large cross section from light mediator, but kinematic suppression from inelastic scattering - very different energy spectrum of recoils.
  - Have motivated exploration of new DM searches and approaches to constraints - interesting even if this is not the right explanation for PAMELA/Fermi.
  - In particular, there are now new accelerator searches for light gauge bosons mixed with the photon (e.g. Essig, Schuster & Toro 09, Bjorken et al 09, Batell, Pospelov & Ritz 09, Reece & Wang 09, Essig et al 10, Merkel et al 11).
- I have given a general description: there are many more detailed studies and models in the literature (e.g. Arkani-Hamed & Weiner 08, Baumgart et al 09, Cheung et al 09, Katz & Sundrum 09, Morrissey, Poland & Zurek 09, Chen, Cline & Frey 09, Chen et al 09).
- Of particular note, SUSY extensions give natural explanation for GeV scale of dark symmetry breaking: inherited from weak scale, $m_\varphi^2 \sim \varepsilon\, m_W^2$ (Cheung et al 09, Morrissey, Poland & Zurek 09).

The Status of Sommerfeld Enhancement

- In the last year, there has been some controversy over whether Sommerfeld enhancement is actually large enough to generate PAMELA/Fermi signals.
- Feng et al 10: model Sommerfeld enhancement from Yukawa potential, for single DM state (no excited states), solve for thermal relic abundance including effect of enhancement on freezeout (previously done by Dent, Dutta & Scherrer 09, Zavala, Vogelsberger & White 09).
    - Assume 4-muon final state (φ decays only into muons), 2.4 TeV DM, local DM density 0.3 GeV/cm^3 - find required boost of ~**1500**.
    - Maximal Sommerfeld enhancement for these parameters ~**100** (would be ~200 not taking effect on freezeout into account). **Order of magnitude discrepancy?!**
- Finkbeiner, Goodenough, TRS, Vogelsberger & Weiner 10: **no tension!**
    - Include effect of DM excited states - increases enhancement by at least factor of 2, can be more. Semi-analytic approximation for Sommerfeld enhancement with excited states derived in TRS 09. Maximal enhancement consistent with correct relic density > **500**.
    - Use up-to-date estimate for local DM density, 0.4 GeV/cm^3 (see Catena talk this afternoon).
    - Decays of φ determined by kinetic mixing. Hard electron component lowers preferred DM mass to 1-2 TeV (depending on φ mass). Typical required boost factors O(**100-300**).

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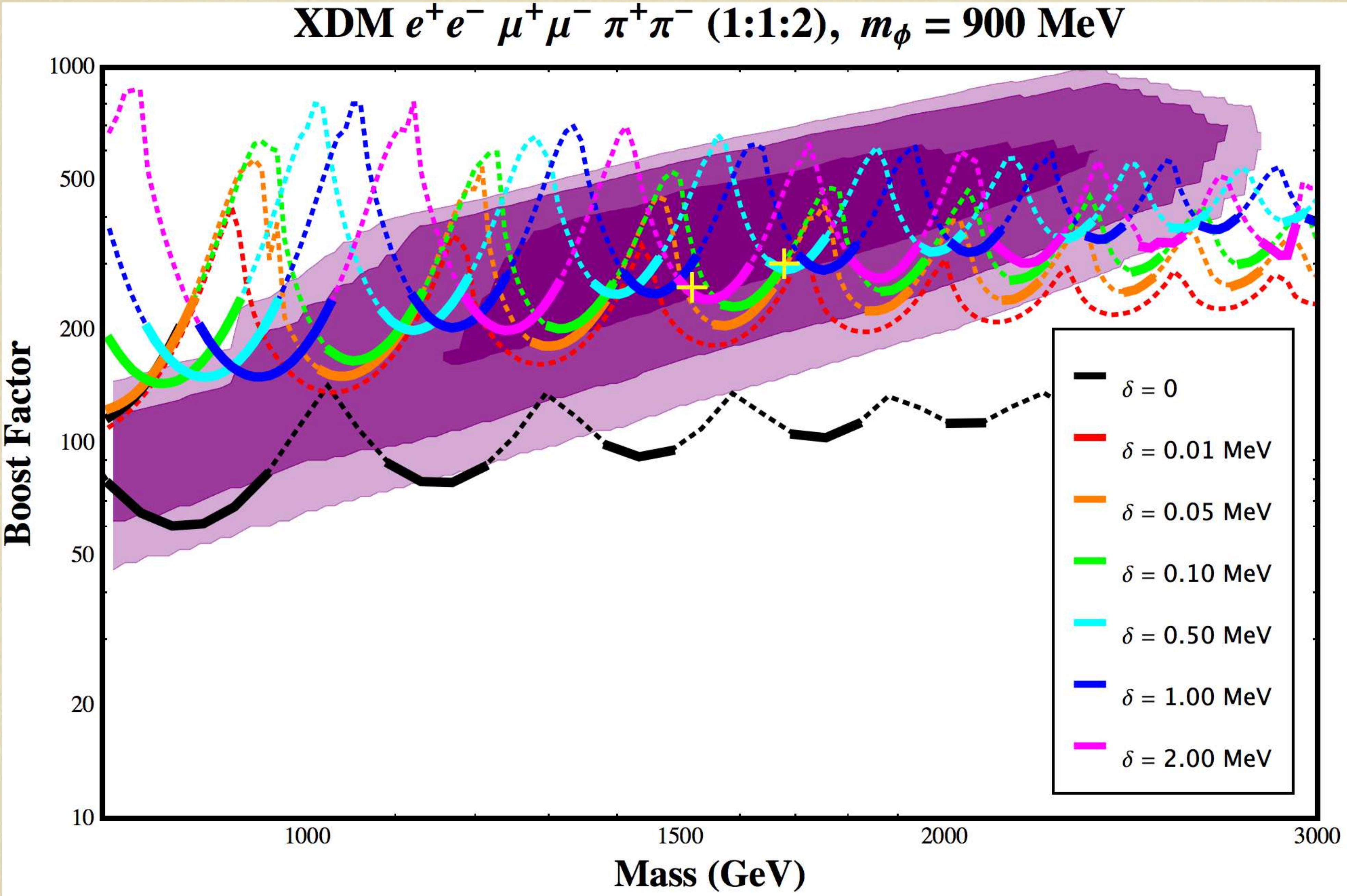
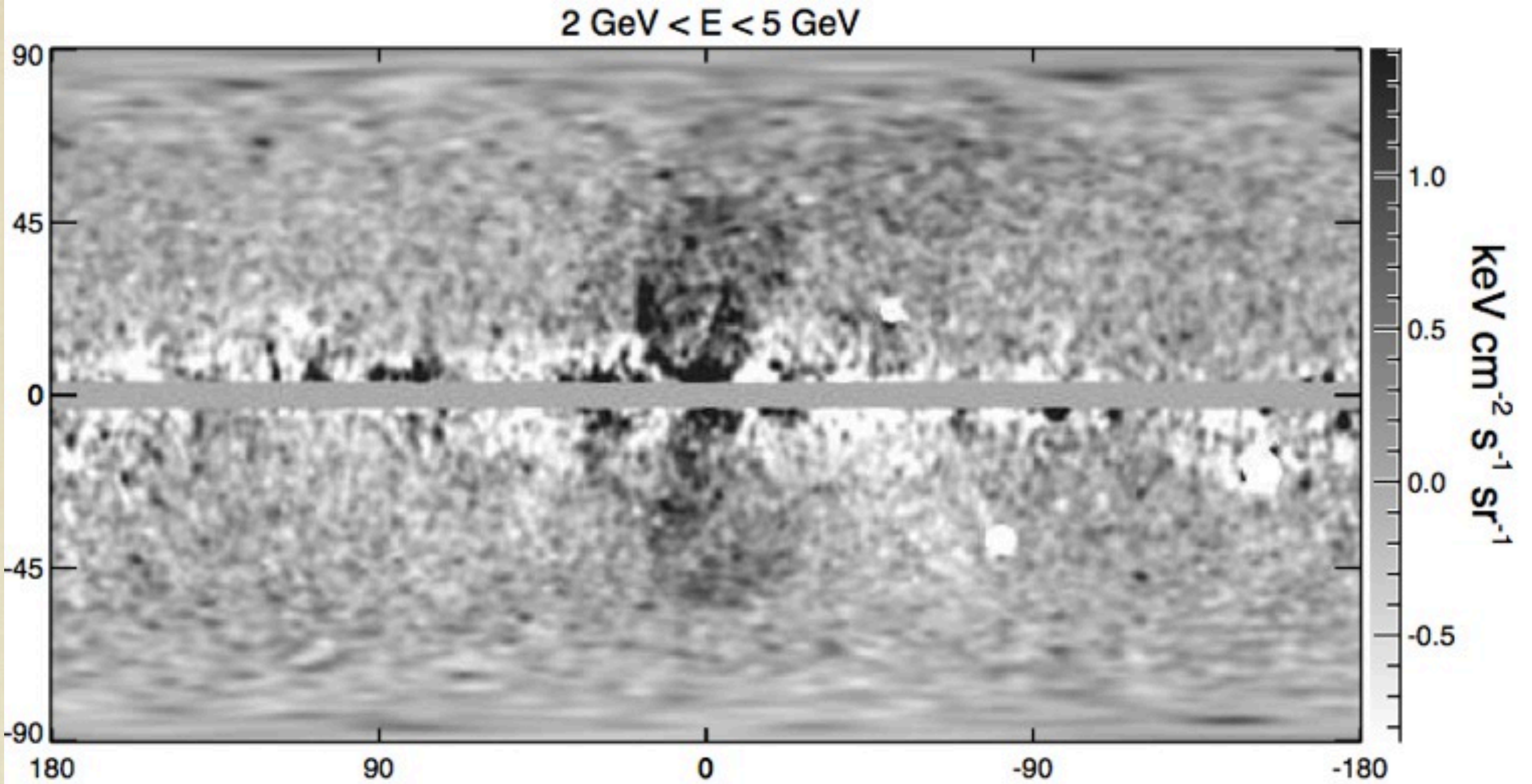


- Example from Finkbeiner, Goodenough, TRS, Vogelsberger & Weiner 10; colored lines = local "boost" to annihilation (over thermal relic value) in simple two-state model with U(1) dark gauge group, for 900 MeV mediator and a range of mass splittings. Purple regions = favored by PAMELA/Fermi.

Other Indirect Constraints

- Previous slide: Sommerfeld enhancement can generate large enough signal with correct relic density (non-thermal production can achieve this too).
- Gamma-rays (Fermi, HESS): **some tension, not ruled out** (but see talk by Zaharijas). Models with 4-lepton final states (e.g. via new light mediator) are generally less constrained.
    - Inner Galaxy bounds seem to prefer a fairly flat/cored DM profile (Bertone et al 08, Bergstrom et al 08, Cirelli & Panci 09, Meade et al 09, Pato, Pieri & Bertone 09, Zaharijas et al 10) - for Sommerfeld-enhanced annihilation, also subject to (large) uncertainties on velocity distribution, and DM substructure may be important.
    - To avoid conflict with diffuse gamma-ray bounds, cannot have very much low-mass dark matter substructure (e.g. Cirelli, Panci & Serpico 09, Papucci & Strumia 09, Hutsi, Hektor & Raidal 10, Zavala, Vogelsberger, TRS, Loeb & Springel 11).
    - Presence of a dark disk or local substructure may alleviate constraints (e.g. Cholis & Goodenough 10, Vincent, Xue & Cline 10).
    - Decaying dark matter constrained by Fermi observations of nearby galaxies and clusters (Dugger, Jeltema & Profumo 10), evades most other constraints.
- Neutrinos (SuperKamiokande, IceCube + DeepCore): **potential for 5σ discovery with 5yr IceCube + DeepCore** if annihilation is to muons (Spolyar et al 09, Mandal et al 09).

The Fermi Bubbles (/Lobes/Haze)



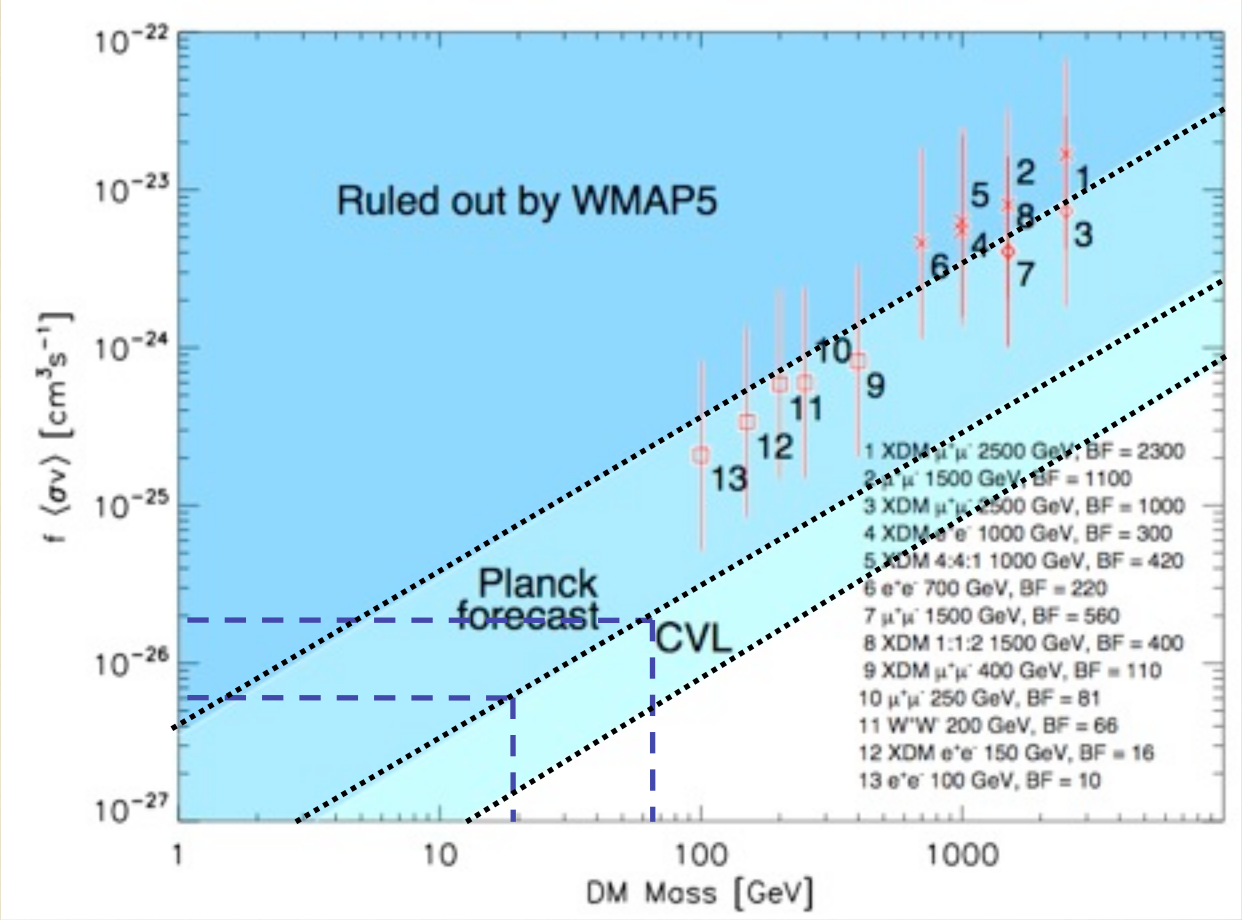
- Large (~10kpc high), hard-spectrum, sharp-edged "bubble"-shaped 1-100 GeV gamma-ray features above and below Galactic plane, apparently centered on Galactic center.
- Possible coincident signals in ~2 keV X-rays and ~20-90 GHz microwave.
- Could they be from DM? (Cholis, Dobler & Weiner 11) Sharp edges are challenging.
- Possible astrophysical models: jet or wind outflow from GC. Modified CR propagation relevant for DM signals?

Bounds from the Early Universe

- Gamma-rays provide excellent **detection** channel, but difficult to get completely robust constraints: tend to depend strongly on poorly known quantities,
  - DM halo density and (for some models) velocity profiles,
  - Amount of unresolved substructure,
  - Modeling of astrophysical backgrounds,
  - (for constraints from inverse Compton scattering) Propagation of injected electrons, Galactic magnetic field.
- Uniquely clean constraints from the era of recombination:
  - High smooth DM density, no dependence on details of structure formation,
  - Low DM velocity (important for models with Sommerfeld-enhanced annihilation),
  - Very sensitive probe of extra ionizing energy, from measurements of the CMB.

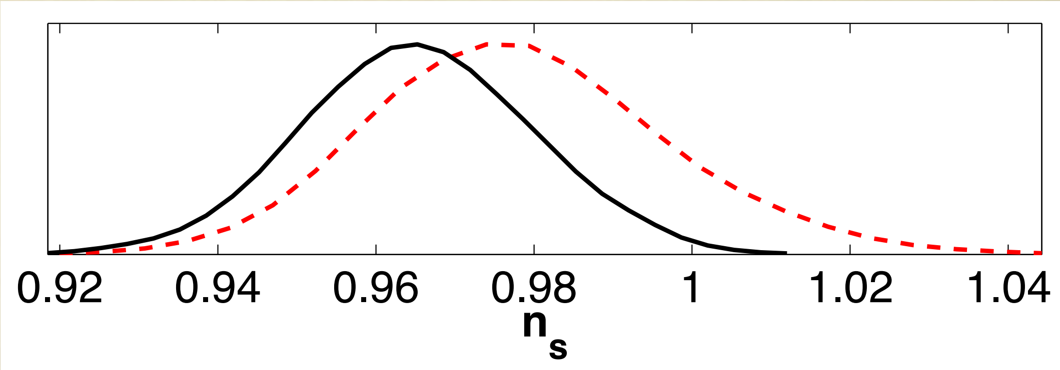
Bounds from the Cosmic Microwave Background

- Injecting electrons/photons around recombination (z~1000 and later) leads to (Finkbeiner & Padmanabhan 05):
  - Extra residual ionization and heating, as the high-energy electrons/photons cool and partition their energy into many low-energy ionizing photons,
  - Consequently, a broader last scattering surface: extra cancellation damping of the temperature anisotropies, and modifications to the polarization anisotropies.
- WMAP comes within a factor of 2-3 of PAMELA/Fermi xsec for O(TeV) DM - Planck should be an order of magnitude better!
  - Already strong limits on light dark matter (few GeV) and Sommerfeld-enhanced models (Galli et al 09, TRS, Padmanabhan & Finkbeiner 09, Hutsi et al 11).
  - Degeneracies with cosmological parameters lead to substantial bias to n_s, if DM annihilation is present and not included.

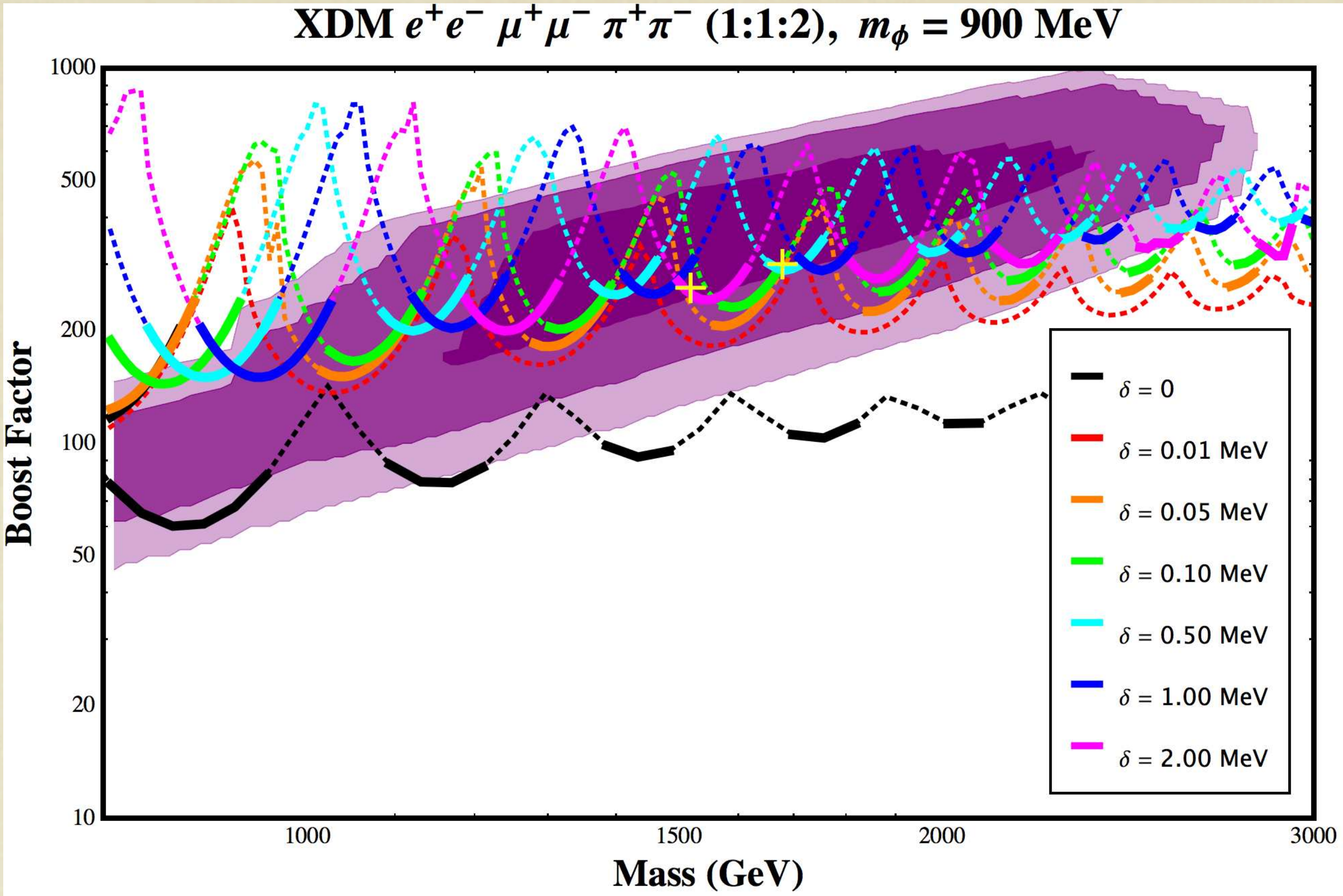


TRS, Padmanabhan & Finkbeiner 09

Galli et al 09



The Status of Sommerfeld Enhancement (II)



Simple Inelastic Sommerfeld-Enhanced Models, Chosen for Correct Relic Density

Thick lines = Allowed by CMB Constraints

- Sommerfeld enhancement does not scale as 1/v to arbitrarily low velocities: saturates at a value proportional to $\alpha_D\ m_\chi/m_\varphi$.
- CMB constrains saturated enhancement: can be used to put a bound on the range of the interaction, if α_D, m_χ are fixed from relic density + fitting PAMELA/Fermi. m_φ > 200 MeV in class of simple models we studied. Bounds from gamma rays from dwarf galaxies constrain m_φ > 100 MeV in similar models (Essig et al 10).
- Also interesting bounds on range of the interaction from non-sphericity of dwarf galaxies, ellipsoidal DM haloes, etc (Buckley & Fox 09, Feng, Kaplinghat & Yu 09), generally constrain m_φ > 10-30 MeV.

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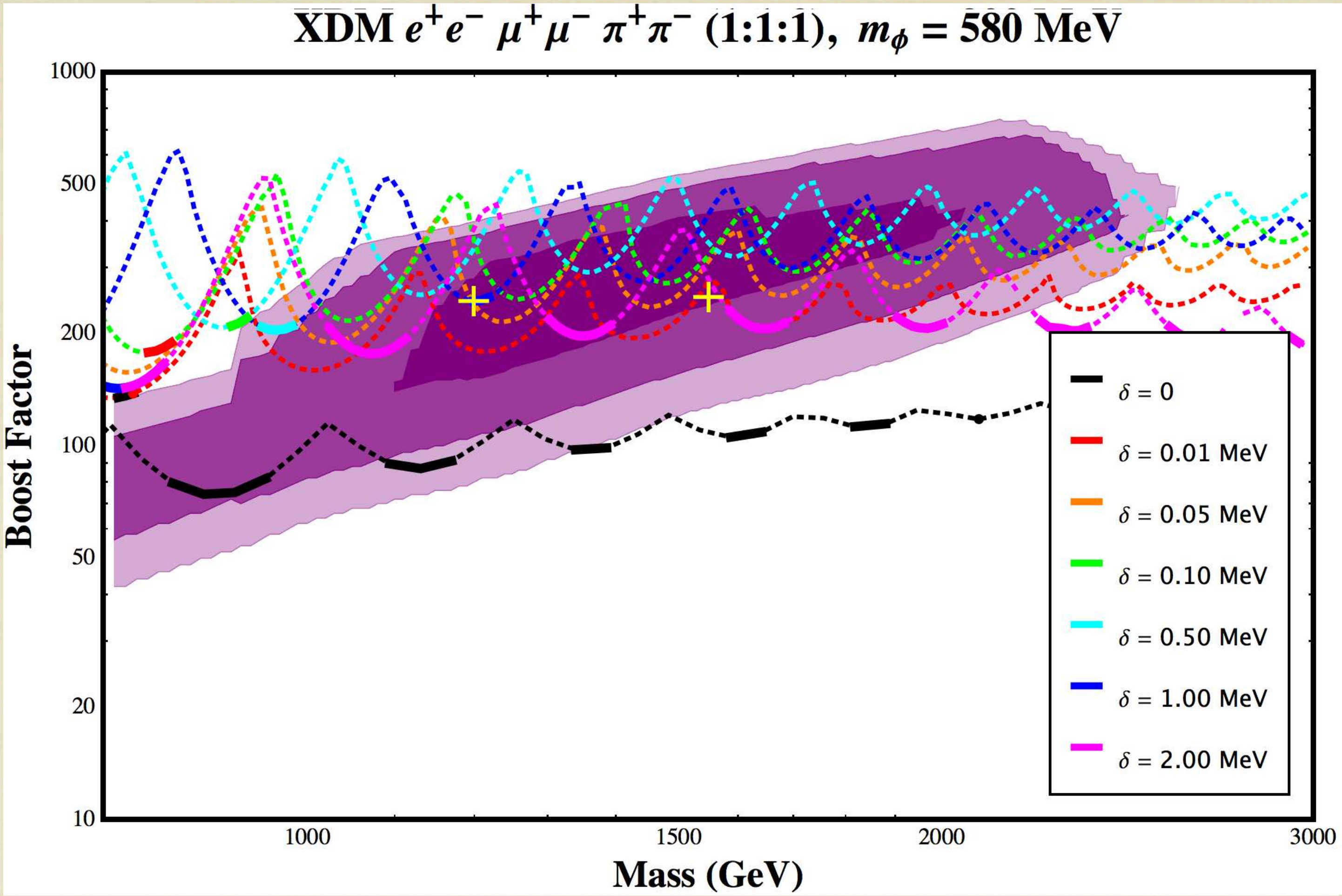

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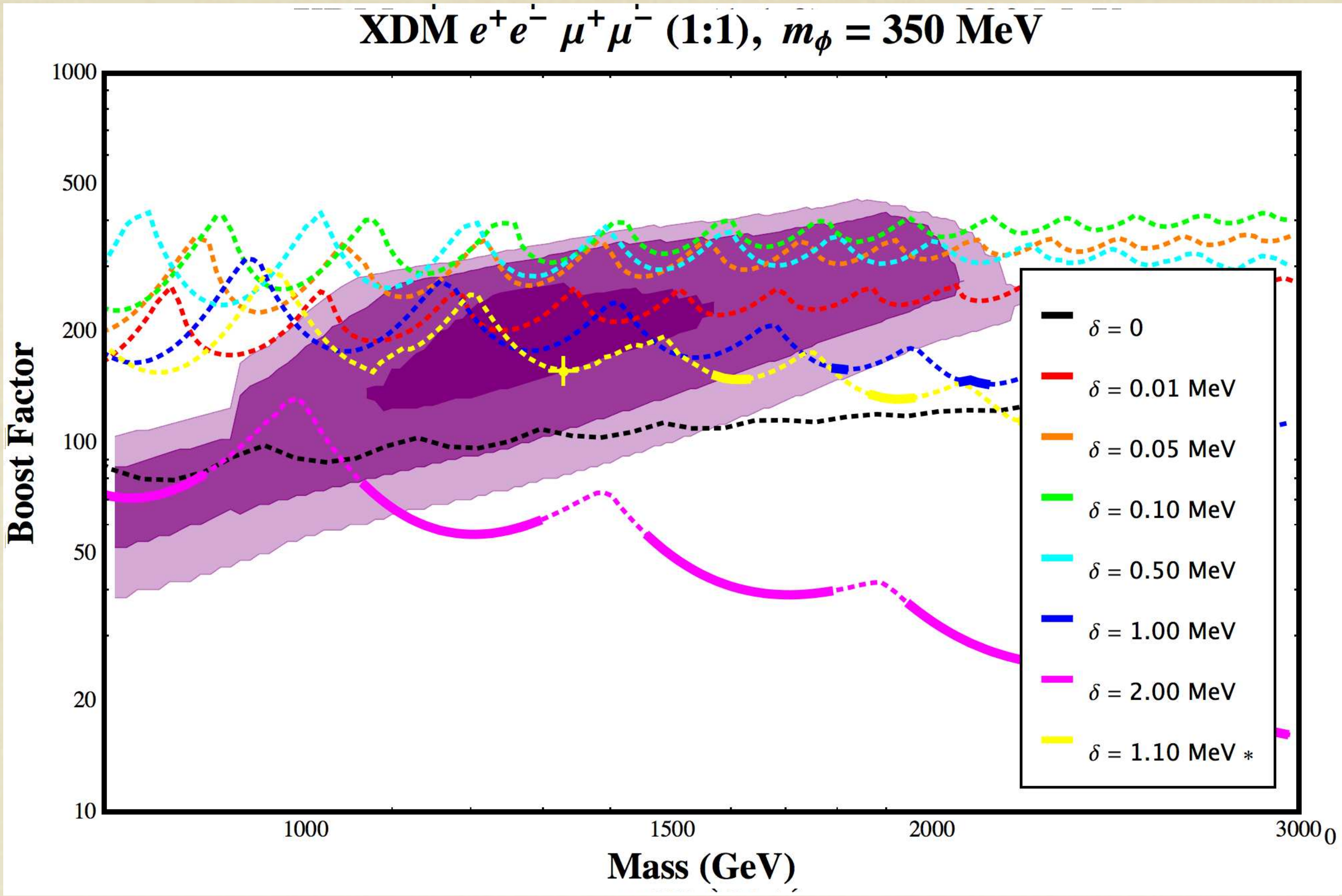

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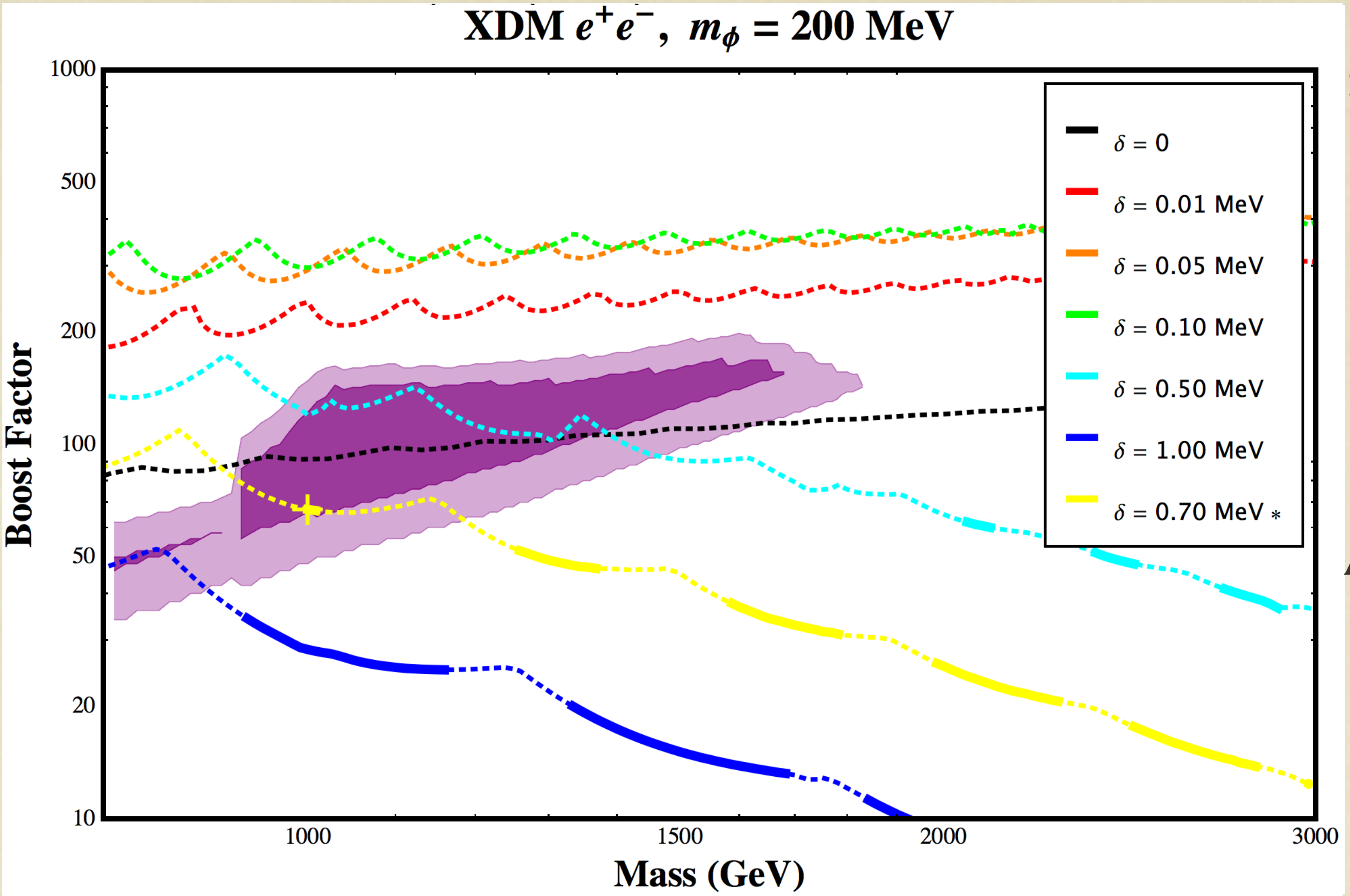

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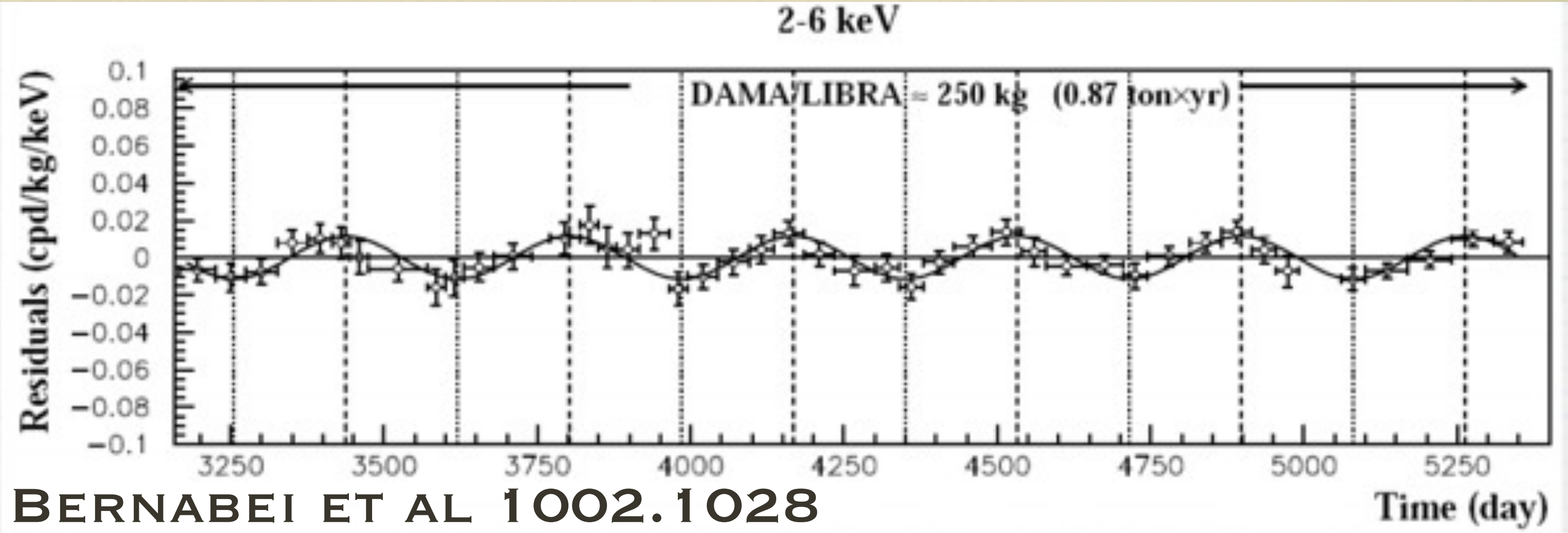
Anomalies in Direct Detection

- Two clear potential signals:
  - DAMA/Libra annual modulation (Bernabei et al 10).
  - CoGeNT low-energy excess (Aalseth et al 10).
  - Also preliminary unpublished results from CRESST show excess events from scattering on oxygen (low-mass target).
- Challenges:
  - Inferred scattering xsec exceeds (at least naively) limits from other experiments.
  - Favored regions apparently not consistent.



Bernabei et al 1002.1028

Kelso & Hooper 1011.3076

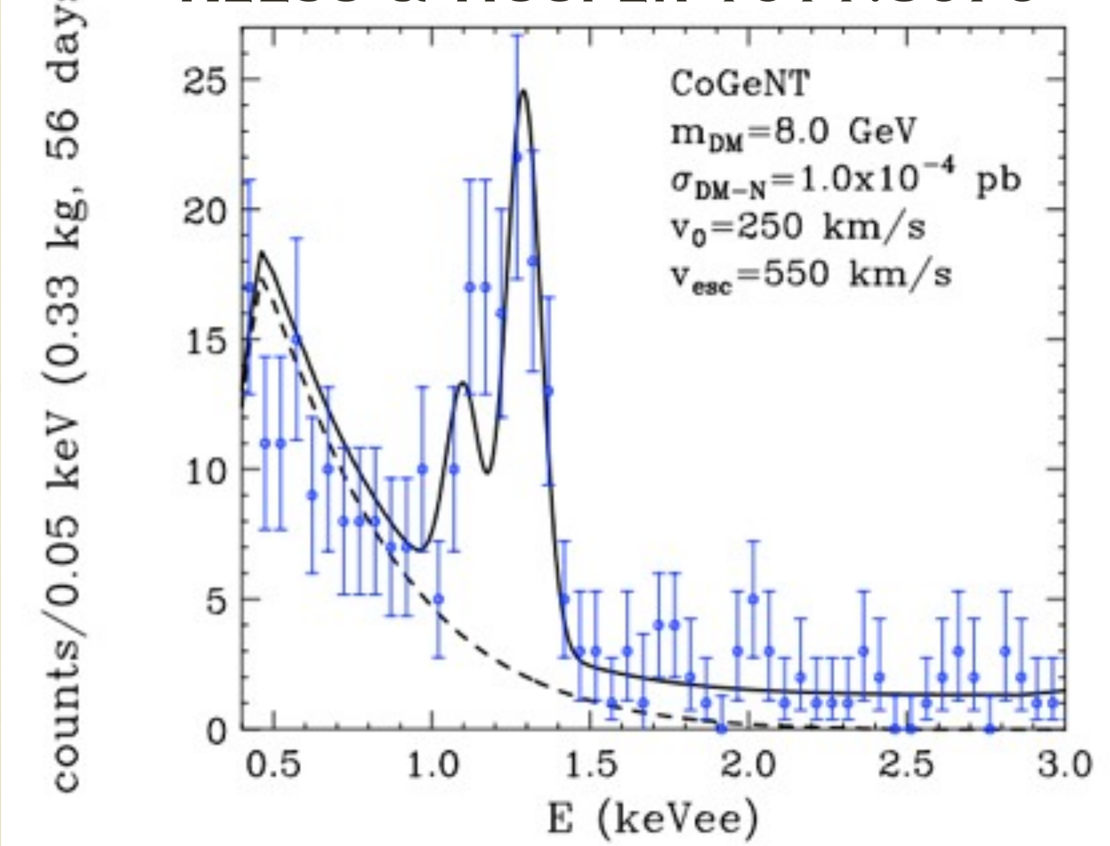
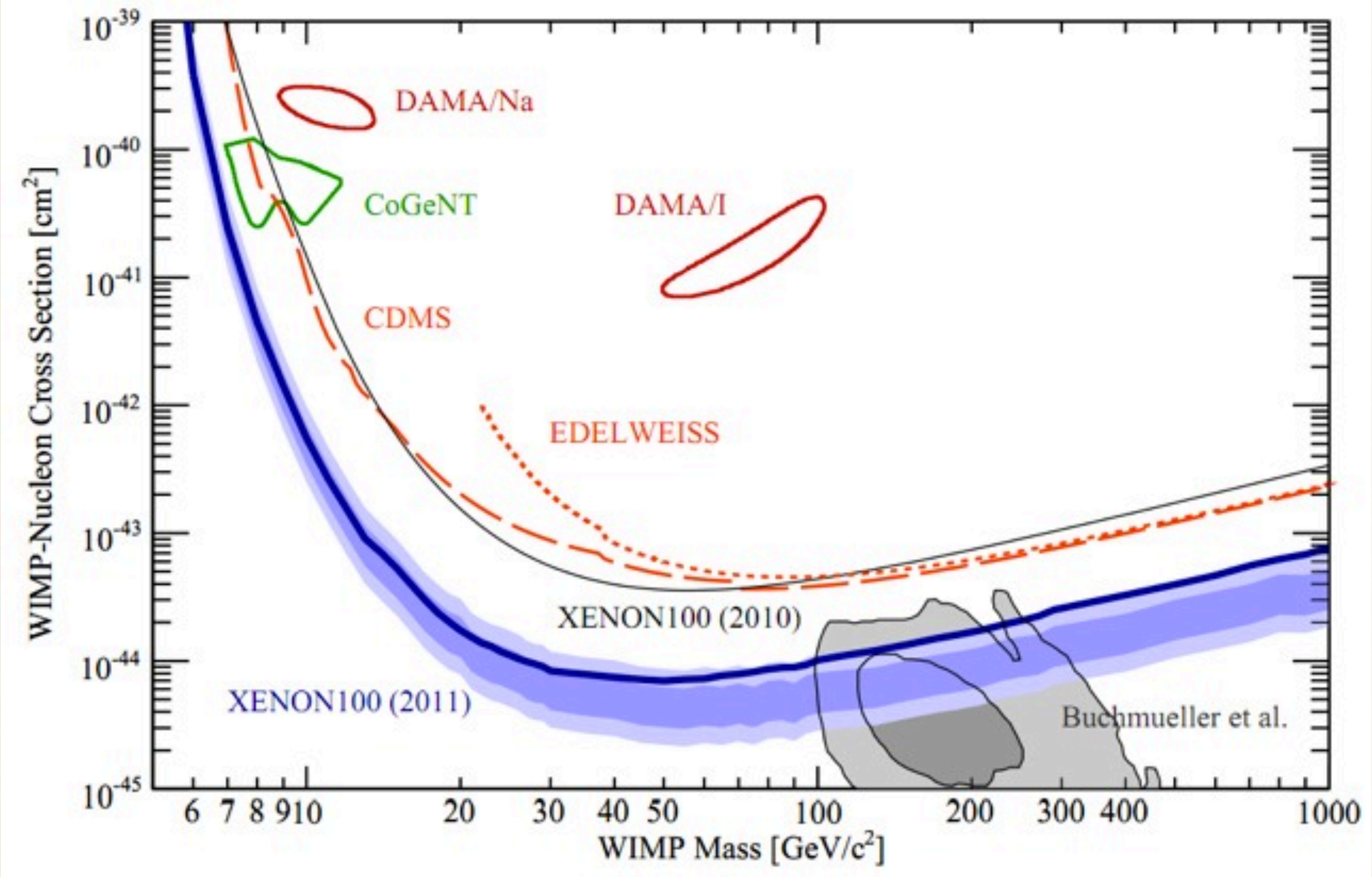


FIG. 1: The current spectrum of events reported by CoGeNT compared to the spectrum predicted for an elastically scattering dark matter particle. The dashed line denotes the spectrum of dark matter events alone, while the solid line is the dark matter spectrum plus backgrounds.

Elastic Spin-Independent Scattering



Aprile et al
1104.2549

- DAMA and CoGenT excesses both have interpretations in terms of light (~10 GeV) elastically scattering DM, but preferred mass / xsec are not identical. How model-dependent is this statement?

- Apparently ruled out by XENON100, XENON10, CDMS (CDMS Collaboration 1011.2482, Aprile et al 1104.2549, Angle et al 1104.3088) - can this be evaded?

Status of "Channeling"

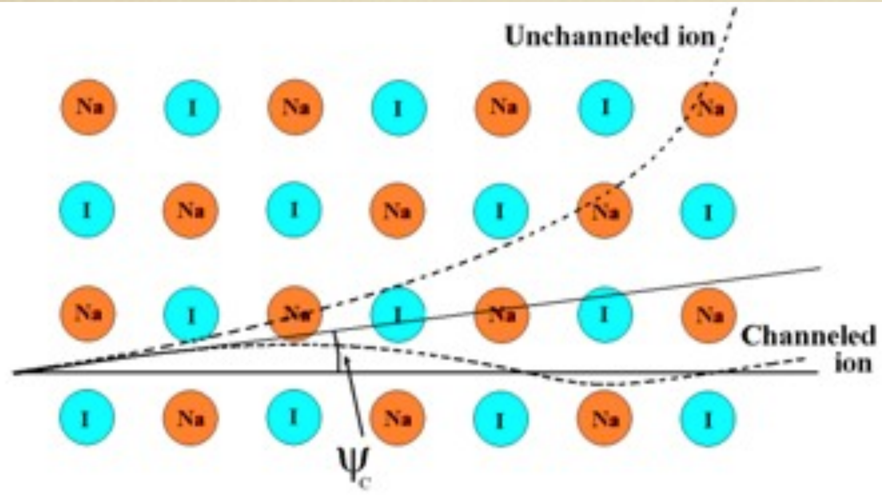
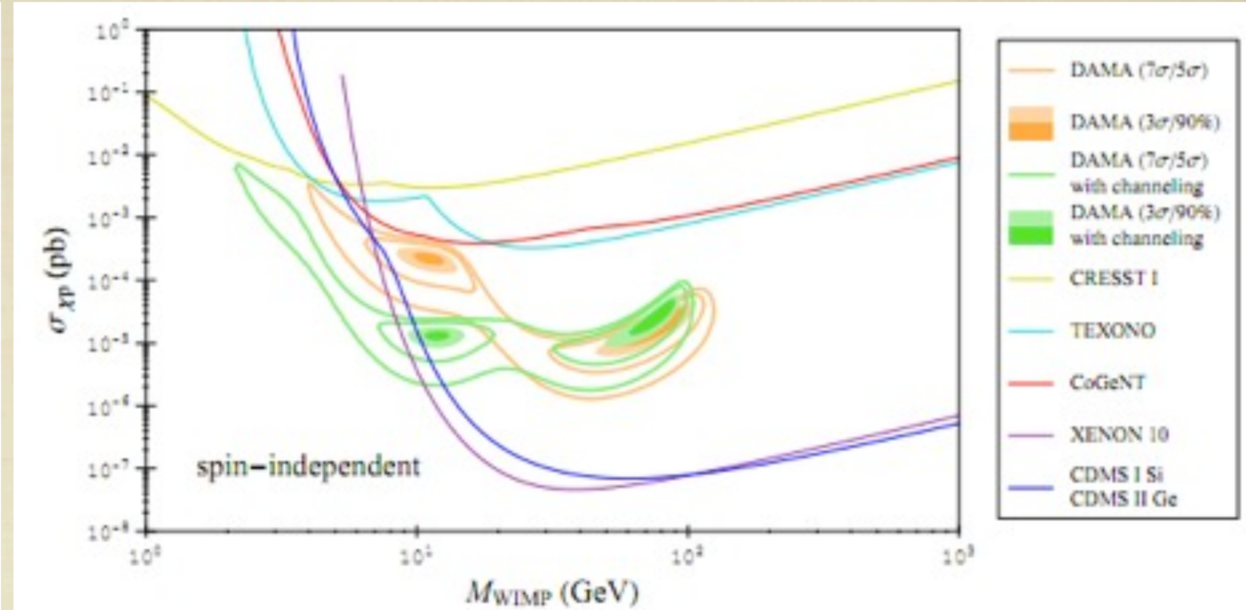


Figure 1: Simplified schema of the channeling effect in the NaI(Tl) lattice. The axial channeling occurs when the angle of the motion direction of an ion with the respect to the crystallographic axis is less than a characteristic angle, Ψ_c, depicted there (see for details Sec. 2). Two examples for channeled and unchanneled ions are also shown (dashed lines).



Savage et al 0808.3607

- Nuclear recoils along symmetry plane/axis of crystal lattice can be "channeled": most energy goes into electrons, not nuclear recoils (Drobyshevski 07, Bernabei et al 07). Increases scintillation signal in DAMA/Libra, reduces required scattering cross section. Consequently, can improve consistency with CoGeNT, especially in models with exothermic scattering (Graham et al 10, Essig et al 10).

- Series of papers by Bozorgnia, Gelmini & Gondolo 2010-2011, using analytic model for channeling. Key insight: previous calculation was correct for ions injected **into** crystal, nuclei recoiling from lattice sites are almost never channeled (only finite-temperature corrections allow channeling).

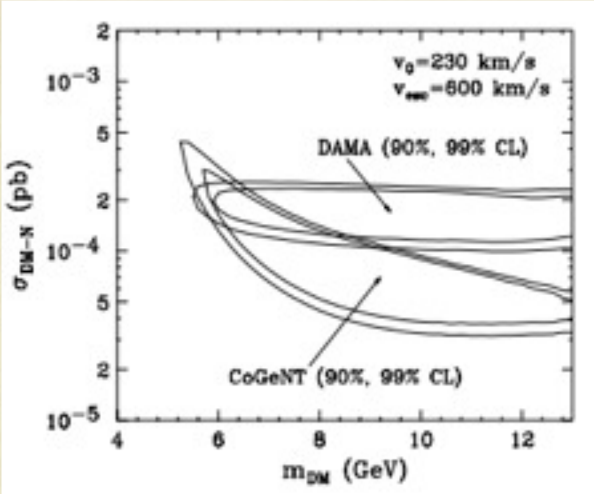
- Current status: **channeling probably cannot be used to resolve the discrepancy**.

DAMA-CoGeNT Consistency

- Systematic uncertainties in "quenching factors" - ratio of measured ionization energy to inferred nuclear recoil energy. Can broaden preferred regions for CoGeNT & DAMA, leading to overlap (Hooper et al 1007.1005). However, this region remains in tension with bounds from other experiments. Some controversy on true uncertainties.

- Momentum-suppressed scattering operators allow better consistency, since CoGeNT corresponds to lower momentum transfer = larger underlying cross section than in usual case (Chang et al 10, Fitzpatrick & Zurek 10).

Hooper et al
1007.1005



Fitzpatrick & Zurek
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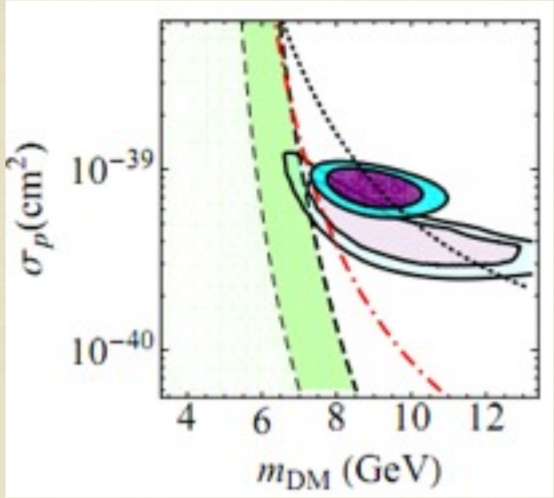

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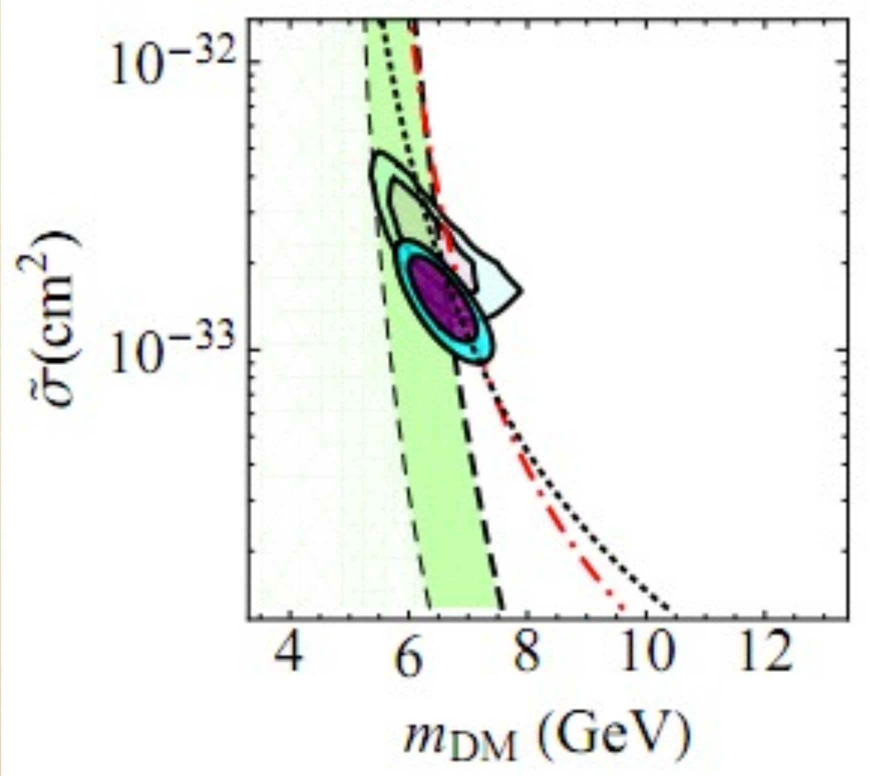


DAMA-CoGeNT Consistency (II)

- Isospin-dependent couplings: dark matter couples differently to protons and neutrons (Chang et al 10, Feng et al 11).
- Feng et al 11: best fit for f_n/f_p = -0.63 to -0.74, tension with XENON (but not CDMS) also alleviated. Can be achieved with WIMPless DM model.

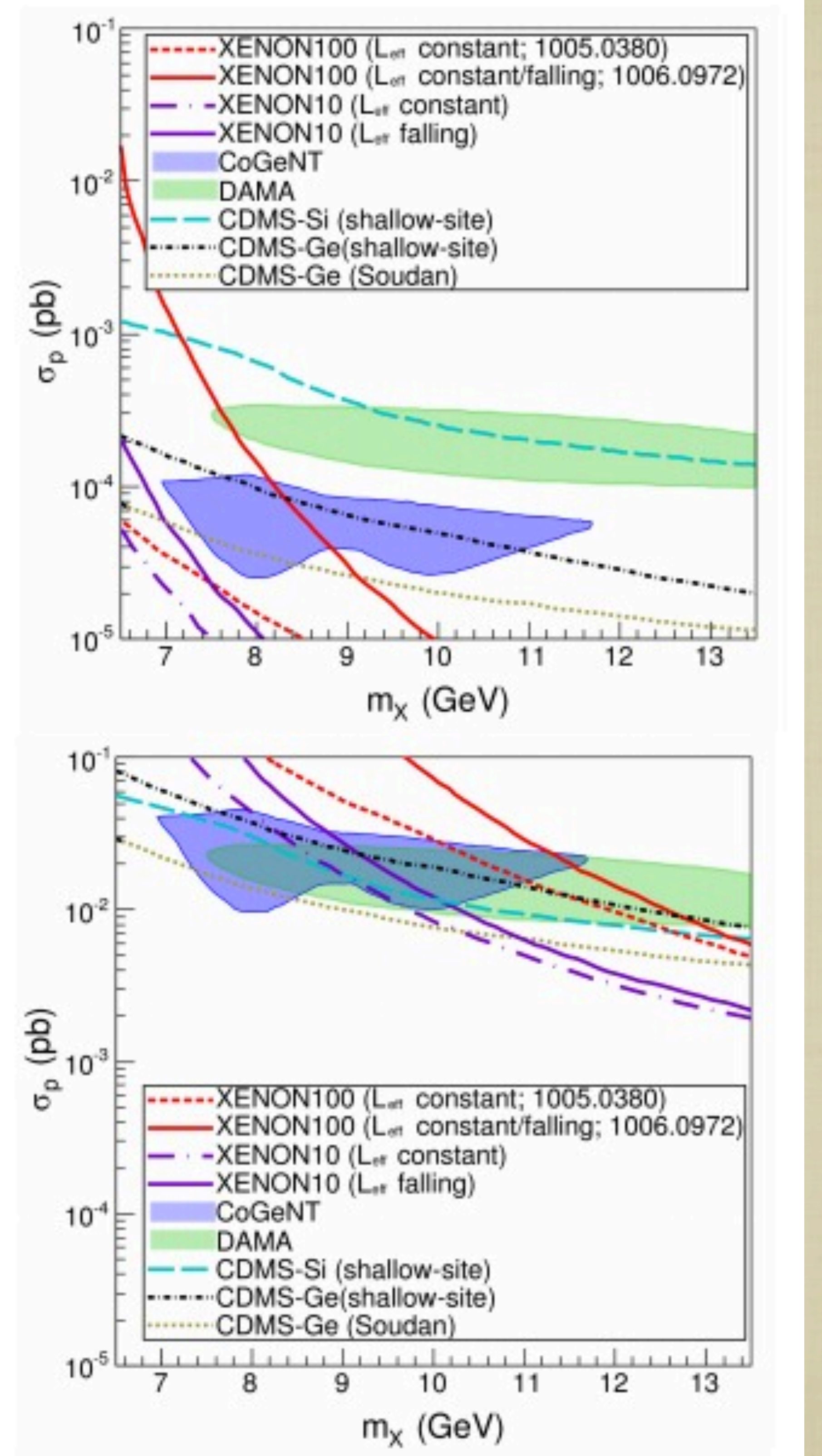


FIG. 1. Favored regions and exclusion contours in the (m_X, σ_p) plane for (top) the standard isospin-conserving case $f_n/f_p = 1$ and (bottom) IVDM with $f_n/f_p = -0.7$.

DAMA/CoGeNT as Light Dark Matter?

- The fairly large scattering cross section inferred from CoGeNT/DAMA means that the particle mediating the scattering must either (a) be relatively light, or (b) have relatively large couplings to quarks (Fitzpatrick, Hooper & Zurek 10, Buckley, Hooper & Tait 10).

- Cannot be achieved in the MSSM while maintaining the correct relic density and not violating other constraints (Fitzpatrick, Hooper & Zurek 10, Gunion, Belikov & Hooper 10, Gunion 10), but several examples of non-minimal SUSY neutralino models have been put forward:

  - An extended NMSSM with generalized superpotential and soft-SUSY-breaking potential, where the LSP is singlino-like and the scattering is through a mostly-singlet h_1 (Gunion 10).

  - Limit of NMSSM with light singlino-like DM, scattering mediated by a very light (GeV-scale) singlet-like h_1 (Draper et al 2010).

  - Extension of MSSM where scattering is mediated by 30-70 GeV singlet scalar Higgs (Belikov 10).

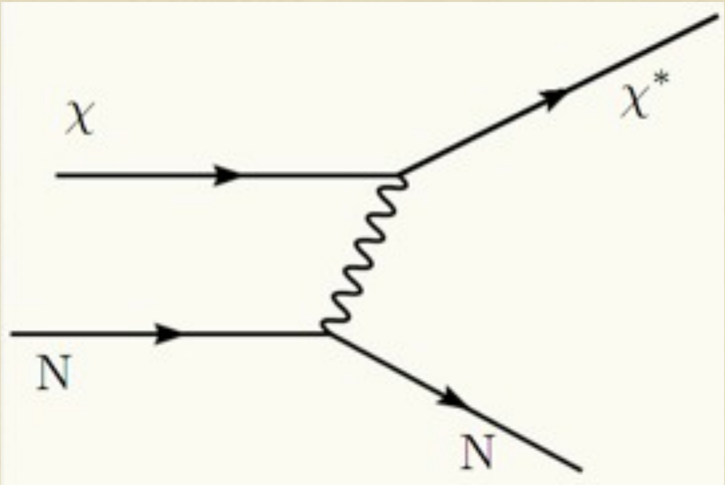
- In asymmetric DM models, the DM is naturally light, and the relic density is not tied to its annihilation rate; again, though, the high scattering cross section requires a mediator that is relatively light or has large couplings (Fitzpatrick, Hooper & Zurek 1003.0014).

- Scenarios of the type discussed with regard to PAMELA/Fermi, with a light mediator coupled to the photon through kinetic mixing, can easily achieve the right scattering cross section and relic density (Essig et al 10, Mambrini 10).

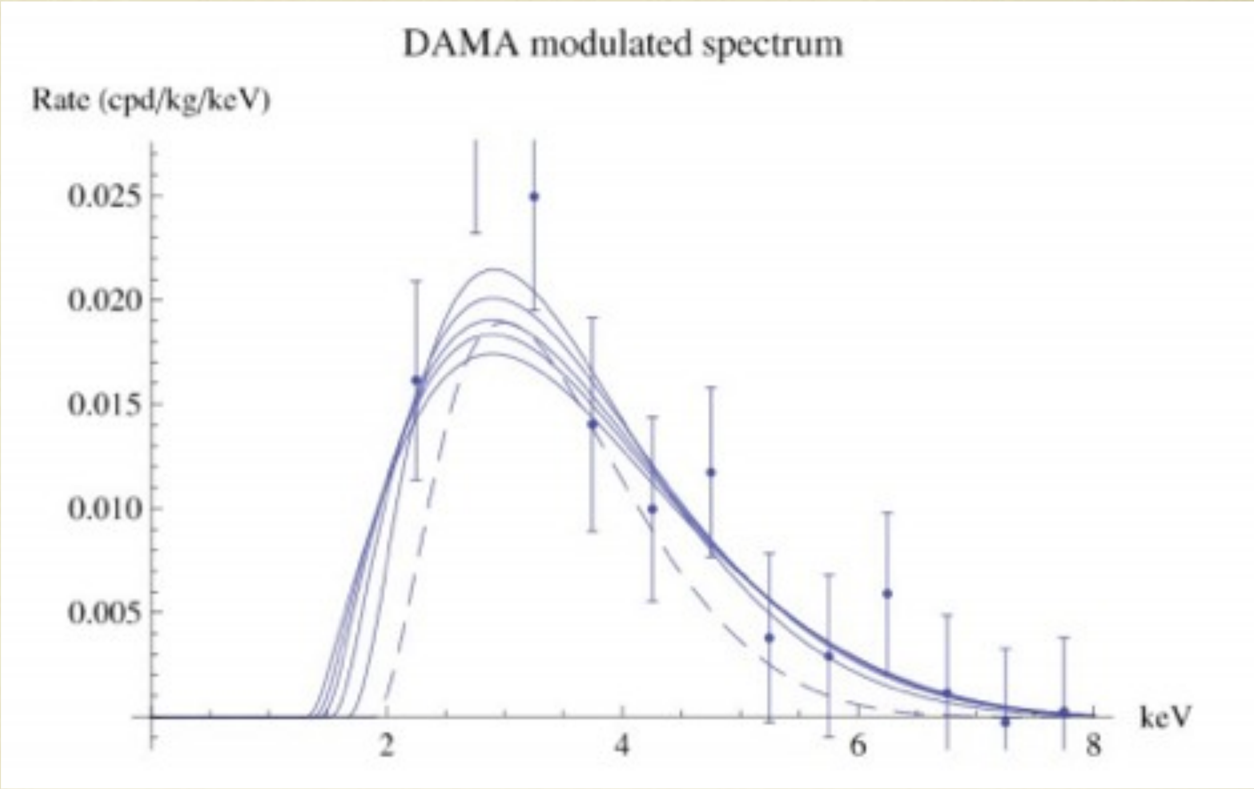
Inelastic Dark Matter

Smith & Weiner 01, Chang et al 08

- Proposed in 2001 to explain DAMA annual modulation.
- The idea: O(100) GeV DM has a nearly-degenerate excited state (~100 keV splitting): modifies kinematics of nuclear scattering.
    - Low-energy cutoff in spectrum.
    - Enhanced modulation (scattering samples high-velocity tail of DM distribution).
    - Strong dependence on mass of target nucleus (heavier = better: DAMA/LIBRA modulation ascribed to iodine).
- Correctly predicts apparent peak in DAMA modulated spectrum, unlike light DM explanation.



$$\beta^2 \geq \frac{2\delta}{\mu}$$



- Many detailed models proposed, including composite dark matter & models suited to PAMELA/Fermi excesses (e.g. Kaplan et al 09, Arina, Ling & Tytgat 09, Alves et al 09, Cui et al 09, Arkani-Hamed et al 08...)

XENON100 Results

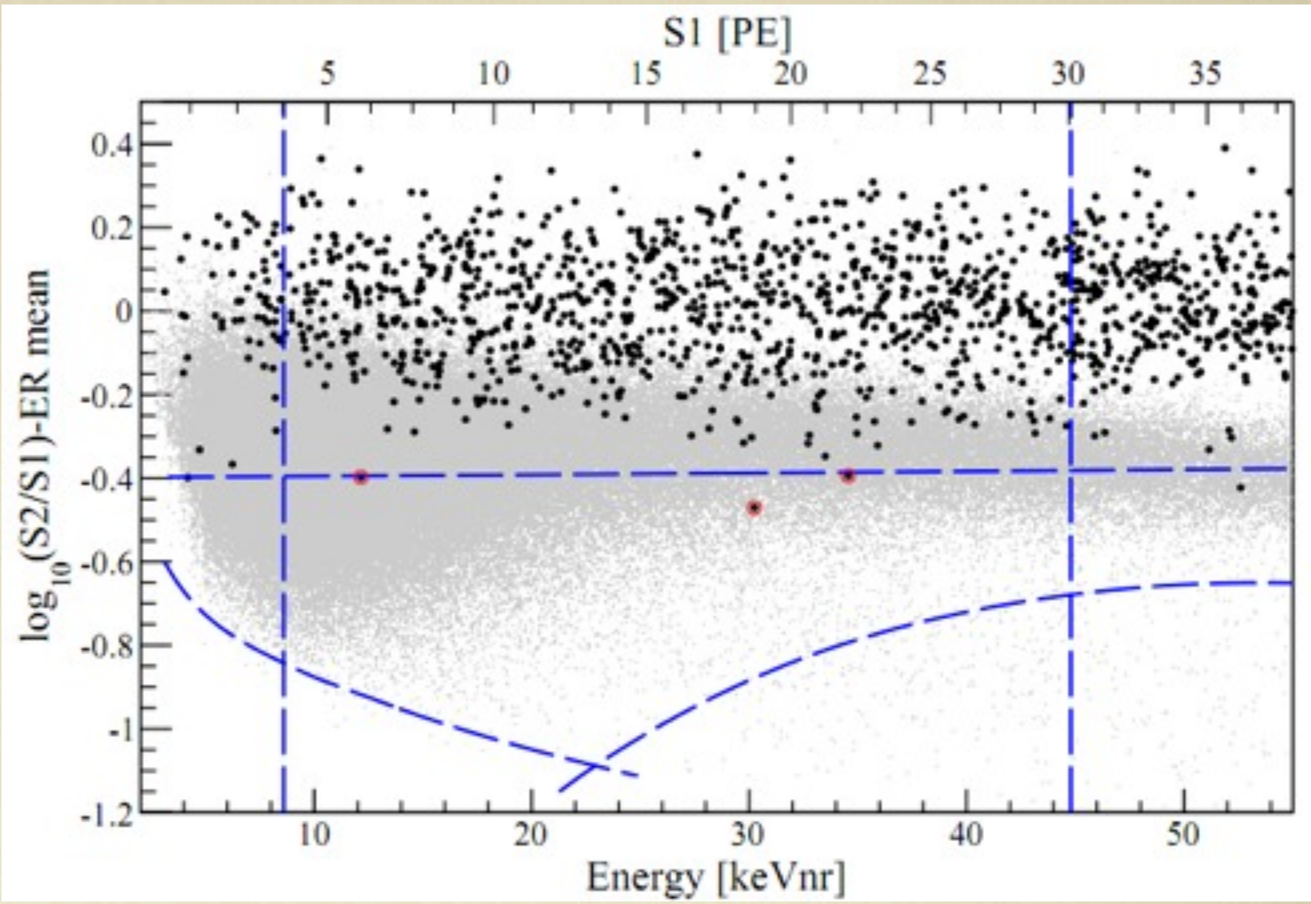
Aprile et al 1104.2549

- Pre-release prediction in 10-100 keV_{NR} window: with respect to inelastic dark matter "there is an order of magnitude uncertainty, with the predictions ranging from 20-200 counts per 1000 kg-days" - Alves, Lisanti & Wacker 10.

- Actual events observed: 4 in 10-55 keV_{NR} window (in 1471 kg-days).

- Not looking at all good for traditional iDM, although would like to see higher energy events to be sure.

- XENON100 presented constraints on iDM, but did not do an analysis independent of DM velocity distribution uncertainties - iDM signal very dependent on high-velocity tail.



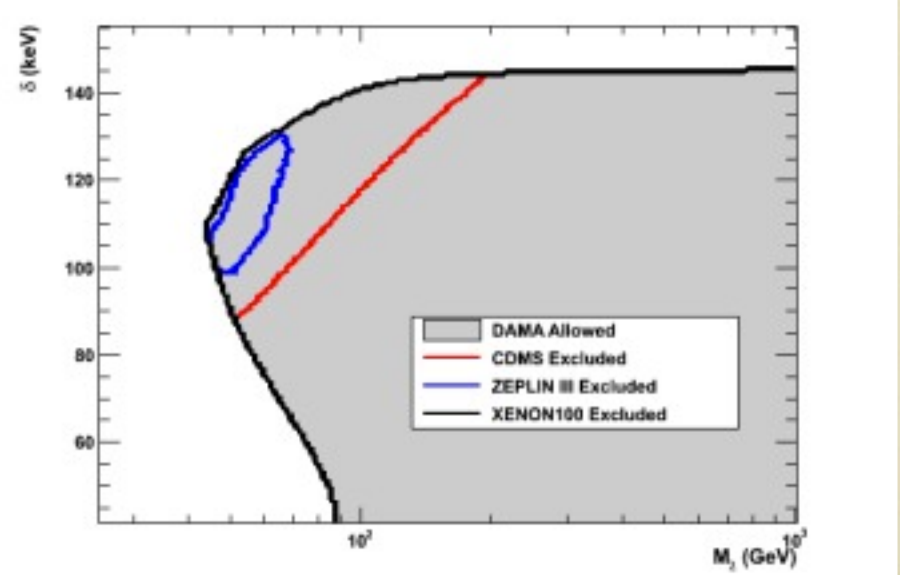


FIG. 4: Parameter space to explain the DAMA annual modulation with iDM (bounded area), and parameter space excluded by different experiments. The black line corresponding to XENON100 excludes the whole DAMA allowed region. v_0 = 220 km/s and v_{esc} = 544 km/s have been used. CDMS [14] (red) and ZEPLIN-III [15] (blue) exclusion curves are also shown.

Aprile et al 1104.3121

Magnetic Inelastic Dark Matter

- General question: what distinguishes the DAMA target from other experiments?
- One possible answer: iodine has a large magnetic dipole. What if DM couples to magnetic dipole moment? (Chang, Weiner & Yavin 10)
- DM can have a conventional magnetic dipole moment, or alternatively a "dark" magnetic dipole (where the "dark photon" kinetically mixes with the normal photon).
- Excited DM state decays, producing photon - typical length scale O(1 m), can decay inside detector! Potentially interesting signature (Lin & Finkbeiner 10).

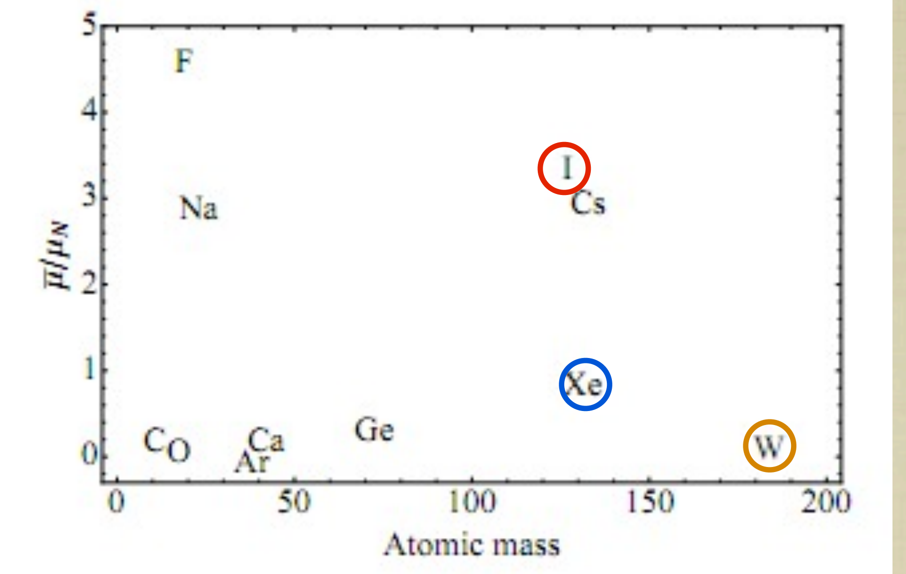
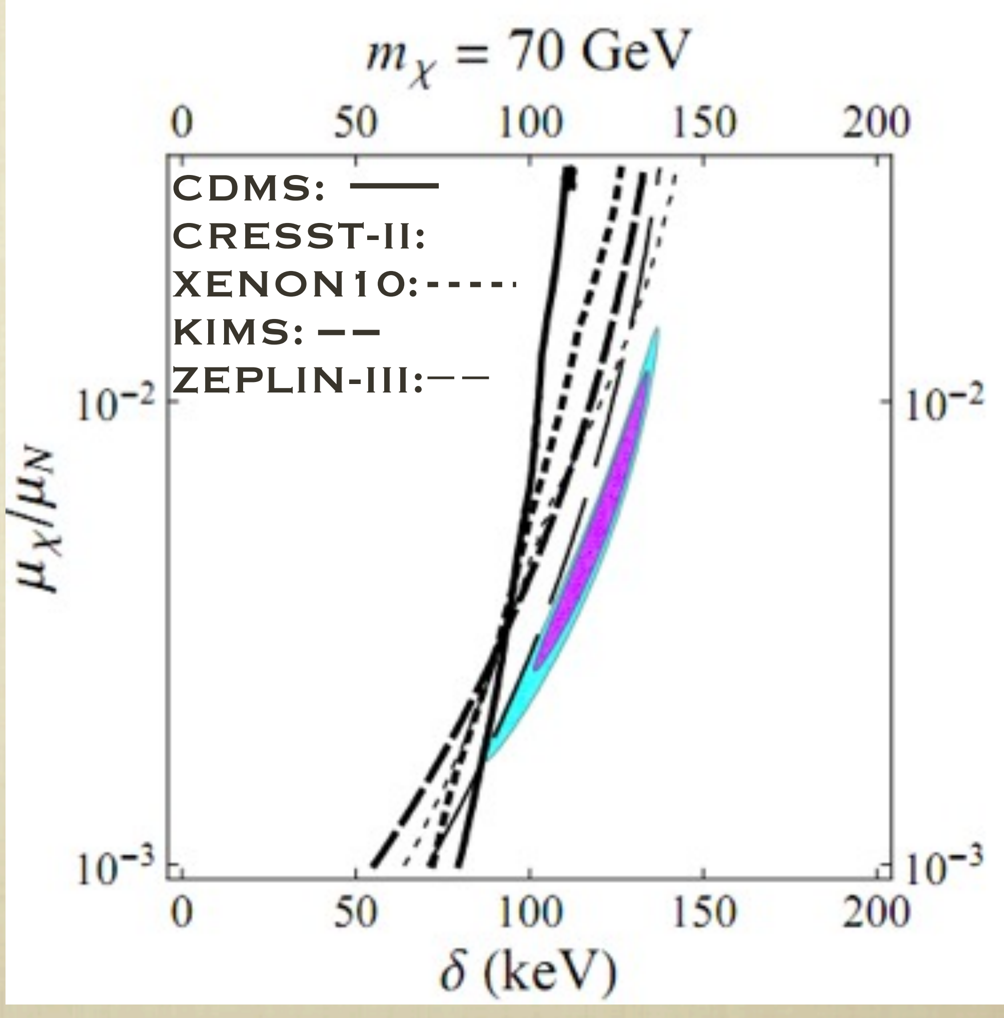


FIG. 1: The weighted-atomic mass and weighted-magnetic dipole moment (Eq. (2) in units of the nuclear magneton μ_N of various dark matter search targets. (C,O and Ca,Ar have been shifted slightly so as not to overlay each other.)



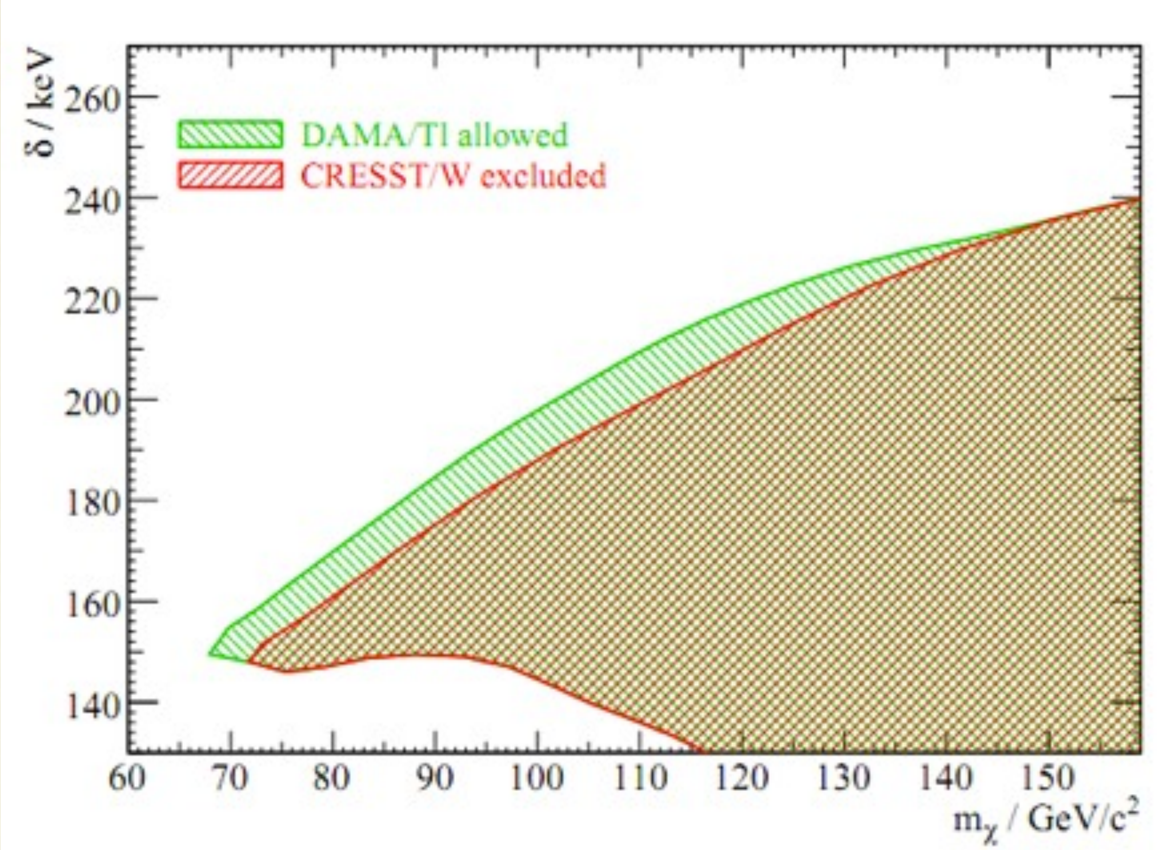
Impure Inelastic Dark Matter

- Or maybe it's not sodium OR iodine... (Chang, Lang & Weiner 10)

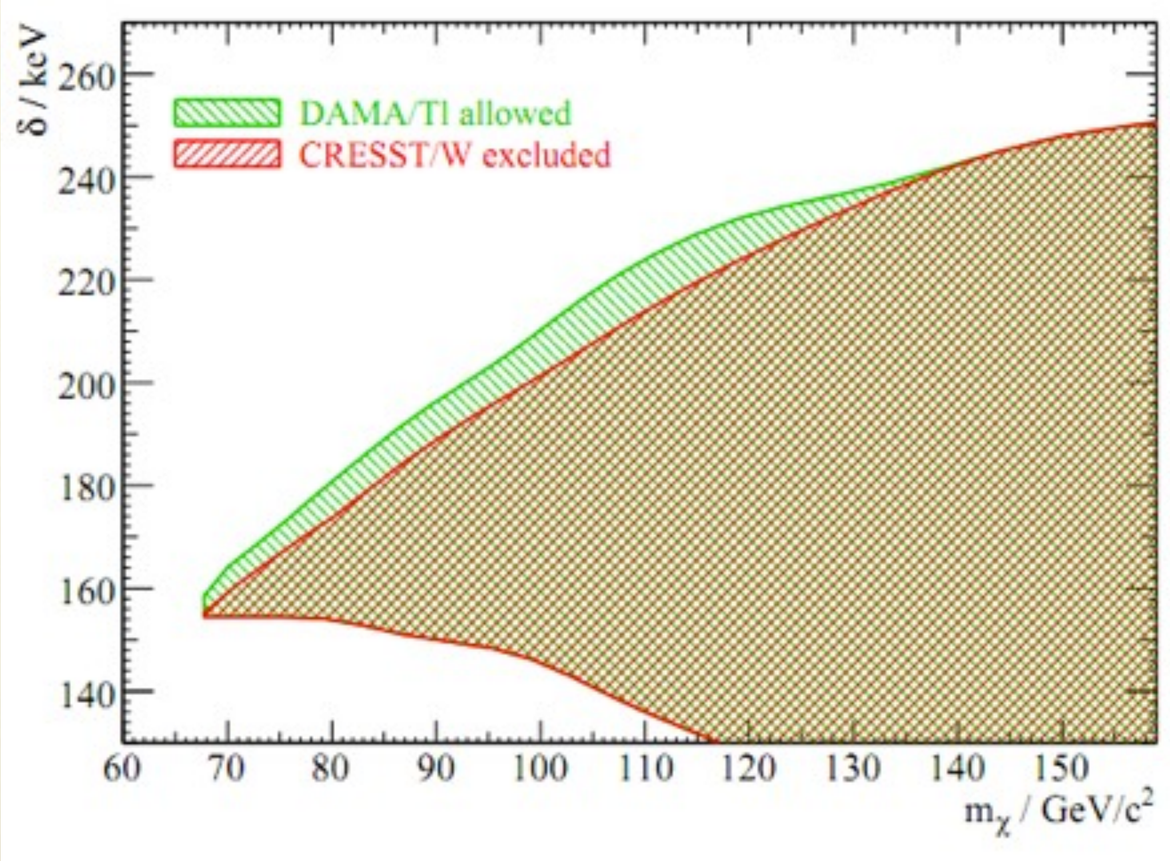
- DAMA NaI crystals are doped with thallium: very heavy, so relevant for iDM. Atomic number 81, atomic mass ~ 204 (compared to 54/131 for Xe, 53/127 for I).

- Only definitely excludable by KIMS (or other NaI(Tl) experiment).

Maxwellian velocity distribution



Based on Via Lactea Simulation



Or Something Else Entirely...

- Resonant dark matter (Bai & Fox 09): scattering takes place through the production of a resonance, DM forms a short-lived bound state with target nucleus.
    - Can only occur for a narrow range of DM velocities.
    - Highly modulated - can be 100% modulation, can also be negative modulation, with more events in winter than in summer! (if the required velocity is below the peak of the Maxwell-Boltzmann distribution)
    - Highly dependent on target (can tune so only iodine can form the bound state).
- Luminous dark matter (Feldstein, Graham & Rajendran 11): DM has a nearly-degenerate excited state, upscatters in the Earth. Decays to ground state emitting a photon; when these decays occur inside the DAMA detector, the photon registers as a scattering event (DAMA does not veto electronic events).
    - Element of detector is irrelevant, only volume matters.
    - Would show up as low-energy electronic recoil events (background) in CDMS and XENON100.
    - Spectrum is a monoenergetic line: can fit DAMA modulated spectrum well.

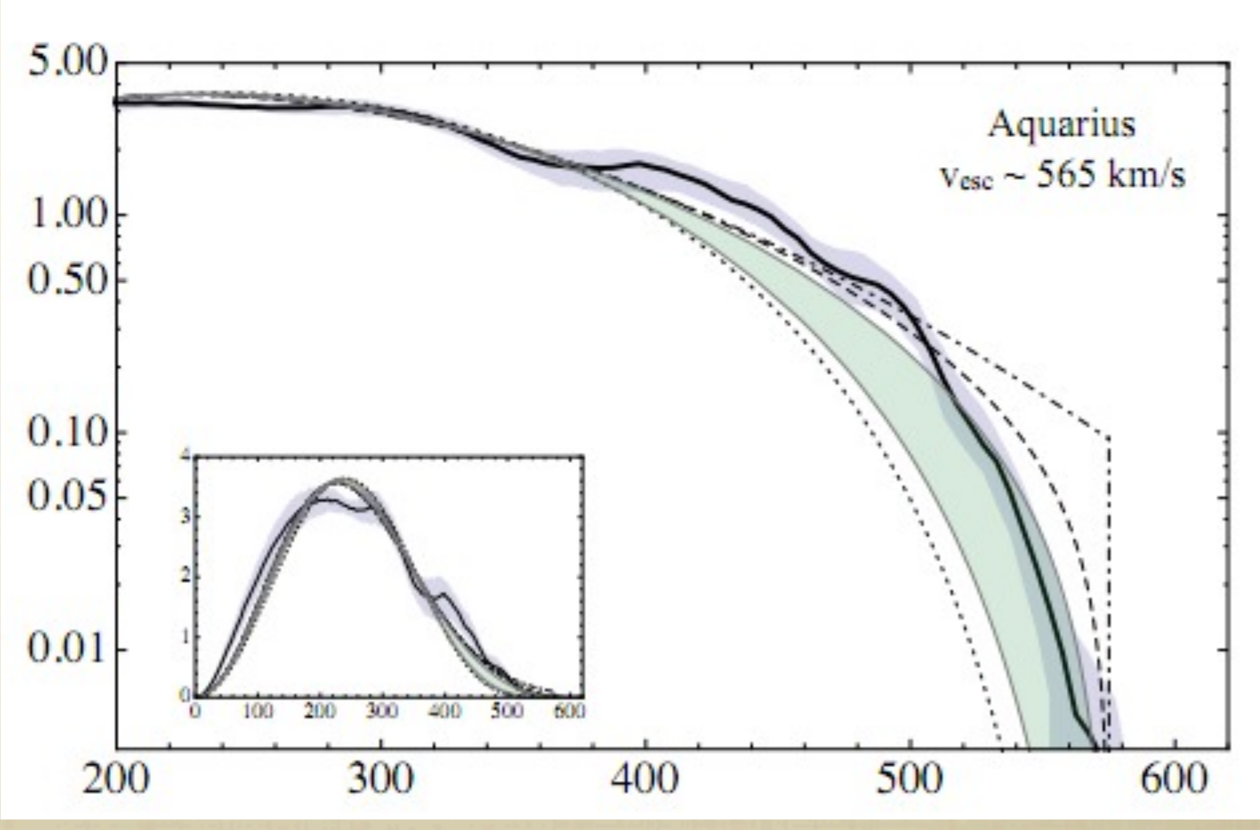
Lessons from Anomalies

- LARGE unresolved uncertainties in:
    - DM density and velocity distribution (locally, in Milky Way halo, in other galaxies/clusters, etc),
    - (direct detection) properties of target materials,
    - (indirect detection) astrophysical backgrounds, cosmic ray propagation.
- Even when multiple apparent signals are observed, whether they are consistent or not can be a highly non-trivial and model-dependent question.
- If we do see a potential signal, how do we (a) convince ourselves that it's dark matter, or (b) falsify the DM interpretation robustly? Further, how much information can we extract about the DM properties?

Improved Models for DM Density and Velocity

- Much recent theoretical progress in estimating the local DM density and velocity distributions - critical for direct detection.
  - Ullio & Catena 09: Bayesian approach to parameter estimation using wide class of dynamical observables, estimate local DM density 0.389 ± 0.025 GeV/cm^3 (see talk by Riccardo Catena later today).
  - Salucci et al 10: estimate local DM density without modeling the entire halo, by use of centrifugal equilibrium equation at solar radius, find 0.43 ± 0.11 GeV/cm^3.
  - Pato et al 10: use simulation with baryons to study effect of stellar disk, find density on the disk is higher than average around spherical shell (inferred from dynamical measurements) by factor 1-1.4.
- Non-Maxwellian velocity distributions especially important for scattering with unusual kinematics, velocity-dependent annihilation (e.g. Sommerfeld enhancement).
  - High-density "dark disc"? (e.g. Read et al 08, Bruch et al 08, Ling et al 09) Effects on direct detection discussed by Green 10.
  - Dark matter streams and substructure, studied with N-body simulations (e.g. Vogelsberger et al 08, Kuhlen et al 09).
  - Lisanti et al 10: analytic ansatz for velocity distribution function, to fit tail of distribution from N-body simulations.

Example Velocity Distribution Models; Lisanti et al 2010



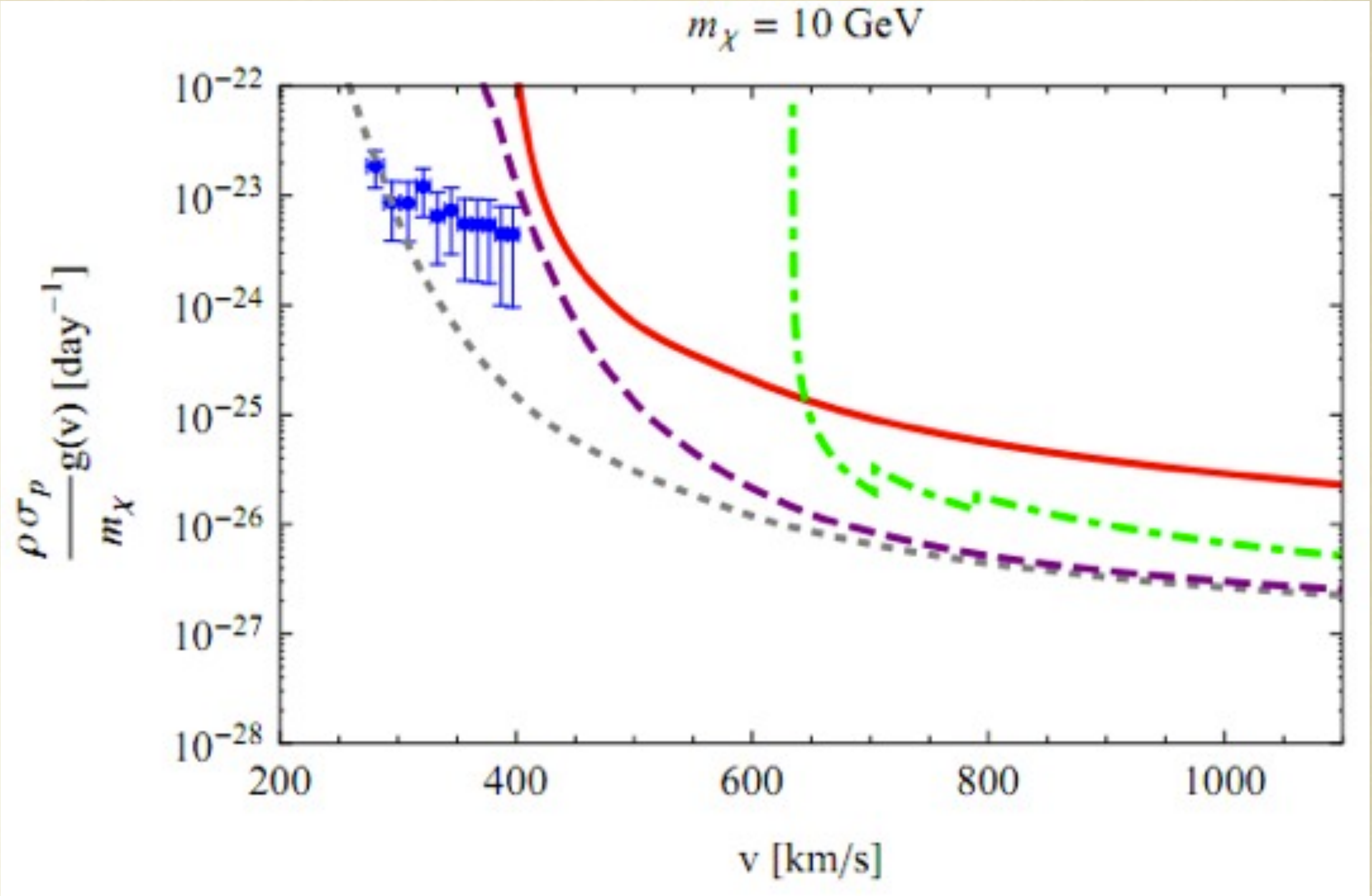
Factoring out the velocity distribution

Fox, Kribs & Tait 10

- Suppose a signal is observed: what particle physics properties can be extracted from DD experiments making no assumptions about the local velocity distribution?
- Assume cross section (after deconvolving nuclear form factor) has factorizable form, $\sigma_0(v) F_\chi^2(E_R)$.
- Recoils at a given energy depend only on DM particles above a minimum velocity. If a deconvoluted scattering rate $\mathcal{R}$ is observed, then by differentiating this rate with respect to energy, we can solve **uniquely** for the value of the (solid-angle integrated) velocity distribution at the minimum recoil velocity.
- Simple properties of the velocity distribution can then be applied to make very general statements:
    - The mere fact that the velocity distribution is always non-negative places constraints on the shape of the scattering cross section.
    - For standard elastic scattering, $\mathcal{R}$ must be a monotonically falling function of E_R: non-monotonicity indicates an inelastic threshold for scattering or a dark matter form factor.
    - The CoGeNT excess can be fitted by a dark matter candidate of any mass, by changing the maximum value of the DM velocity distribution.
    - A dark matter form factor can always "fake" inelastic scattering, with a different velocity distribution.

Model-Independent Experiment Comparisons

Fox, Liu & Weiner 10



Example g(v) vs v plot for 10 GeV elastically scattering DM. Blue points = CoGeNT, Red = CDMS-Si, Green = CDMS-Ge, Purple/Grey = Xenon10 with two Leff values.

- Continuing on, we can make model-independent comparisons between experiments, if we compare event rates at recoil energies that correspond to the **same v_{min}** at different experiments. Such rates probe exactly the same part of the velocity distribution, so are independent of the details of its shape.
- Express the velocity distribution in terms of integrated quantities, e.g.

$$g(v_{\min}) = \int_{v_{\min}} dv f(v)/v$$

- Now can express constraints on g-v plot, independent of astrophysics.
- Current treatment only for elastic scattering, but similar principles hold for inelastic case (but mapping from E_R to v_{min} is not 1:1 anymore).

Combining Multiple Experiments: Outlook

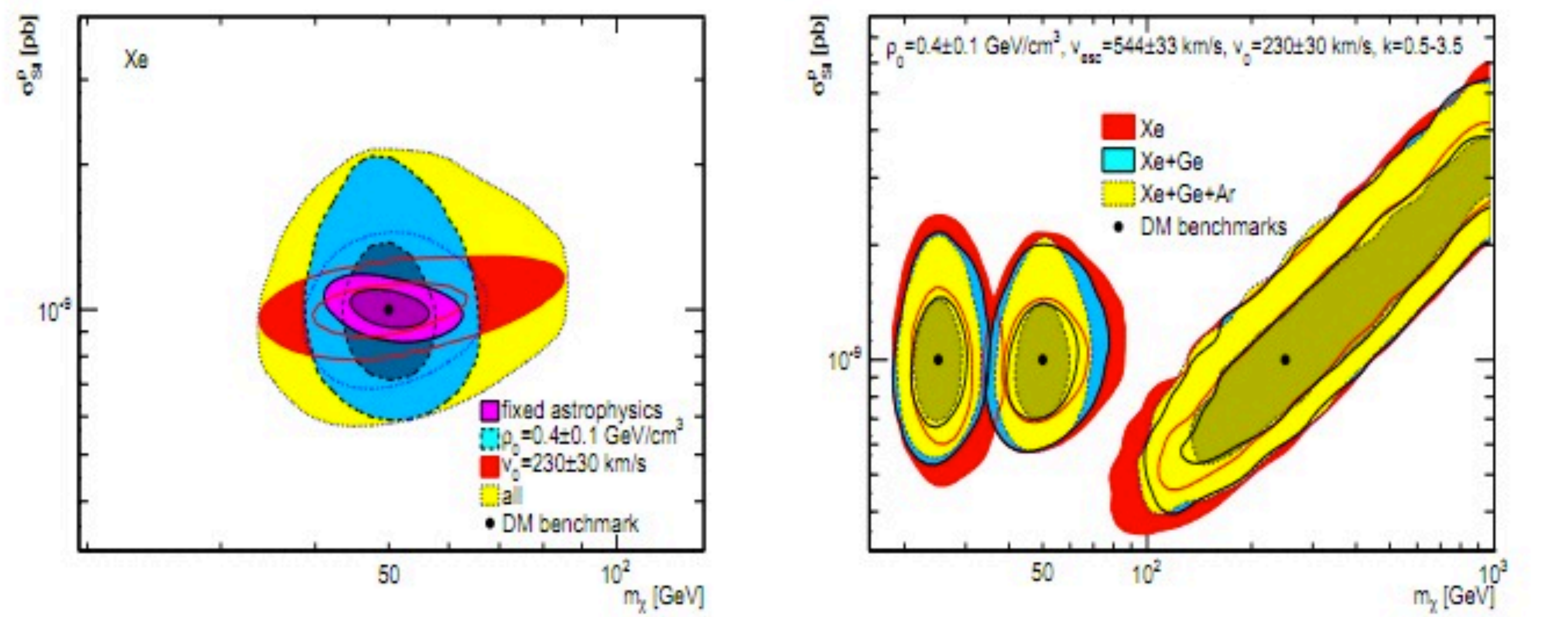


FIG. 2: The joint 68% and 95% posterior probability contours in the $m_\chi - \sigma^p_{SI}$ plane for the case in which astrophysical uncertainties are taken into account. In the left frame, the effect of marginalising over ρ_0, v_0 and all four (ρ_0, v_0, v_{esc}, k) astrophysical parameters is displayed for a Xe detector and the 50 GeV benchmark WIMP. In the right frame, the combined data sets Xe+Ge and Xe+Ge+Ar are used for the three DM benchmarks ($m_\chi = 25, 50, 250$ GeV).

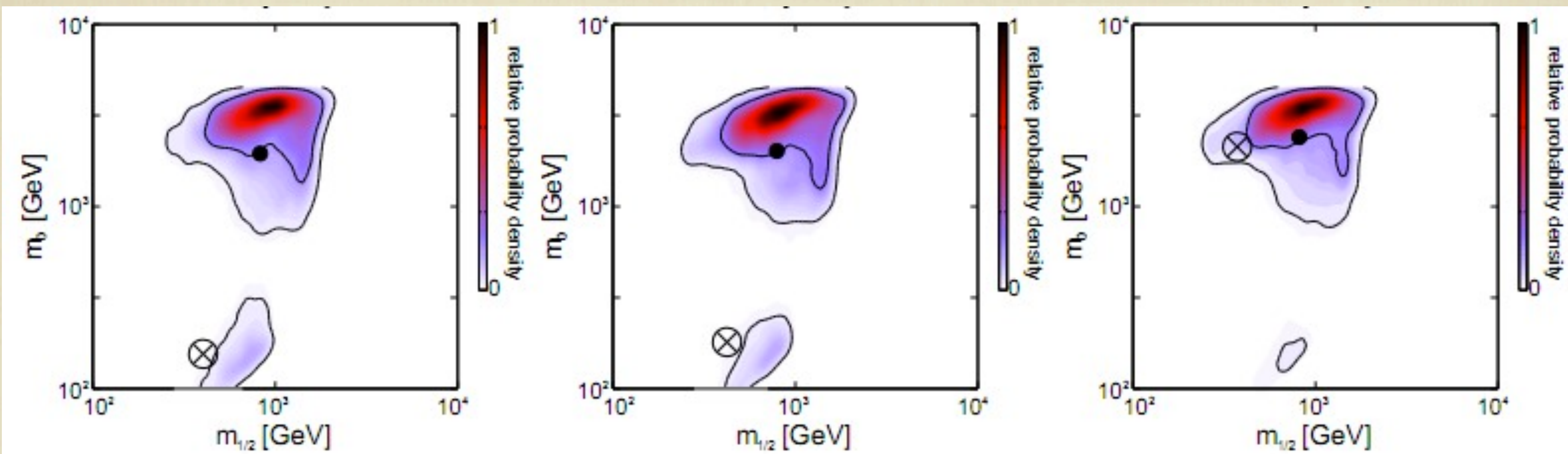
	Percent 1σ accuracy	
	$m_\chi = 25$ GeV	$m_\chi = 50$ GeV
Xe	6.5% (14.3%)	8.1% (20.4%)
Ge	5.5% (16.0%)	7.0% (29.6%)
Ar	12.3% (23.4%)	14.7% (86.5%)
Xe+Ge	3.9% (10.9%)	5.2% (15.2%)
Xe+Ge+Ar	3.6% (9.0%)	4.5% (10.7%)

TABLE III: Marginalised percent 1σ accuracy of the DM mass reconstruction for the benchmarks $m_\chi = 25, 50$ GeV. Figures between brackets refer to scans where the astrophysical parameters were marginalised over (with priors as in Table II), while the other figures refer to scans with the fiducial astrophysical setup.

- Pato et al 10, Peter 10: effect of using multiple DD experiments with different target masses to counter uncertainties in the DM density and velocity profile.
- Possibility for “WIMP astronomy”: study DM distribution simultaneously with mass/xsec.

Parameter Scans with Complementary Bounds (I)

- Several examples already using current data:
  - Effect on CMSSM parameter space of including H.E.S.S. data from Sagittarius dwarf galaxy (Ripken, Conrad & Scott 10).



  - Effect on CMSSM parameter space from XENON100 data (Farina et al 1104.3572). (Unfortunately, these two scans disfavor opposite regions of the CMSSM parameter space - H.E.S.S. disfavors coannihilation region, XENON100 disfavors focus point region.)

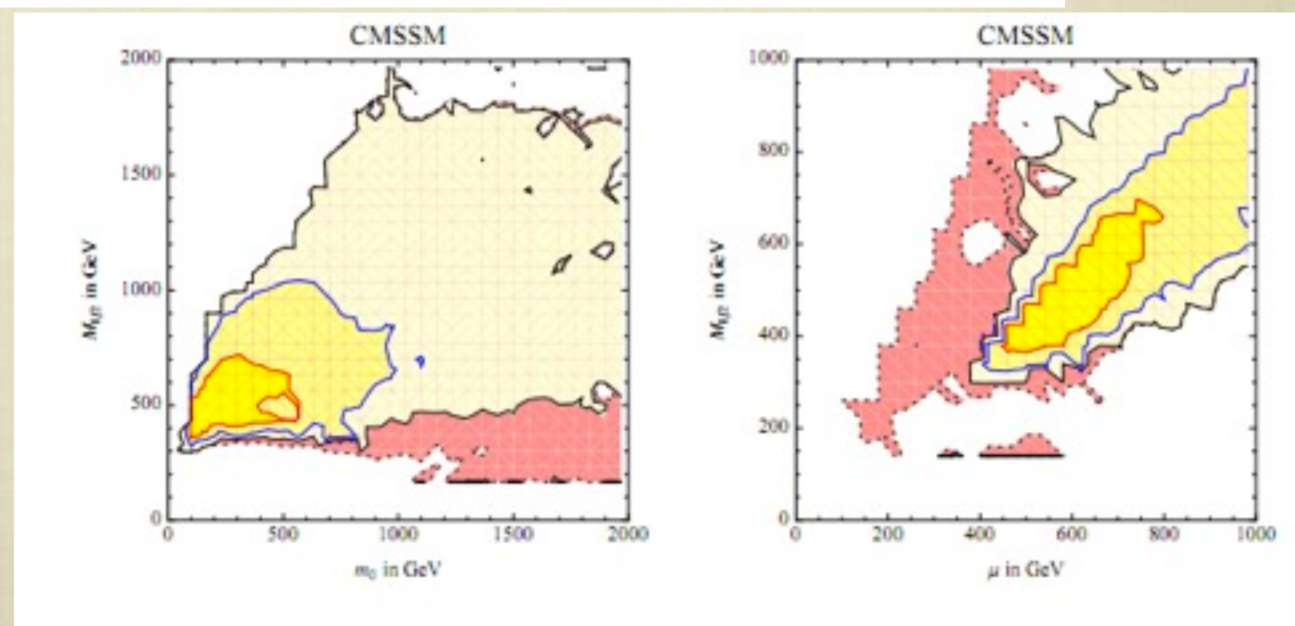


Figure 5: *Global CMSSM fits in $(m_0, M_{1/2})$ (left) and in $(\mu, M_{1/2})$ (right) planes. The red contours are excluded by Xenon100, other details are as in Fig. 4a.*

Parameter Scans with Complementary Bounds (II)

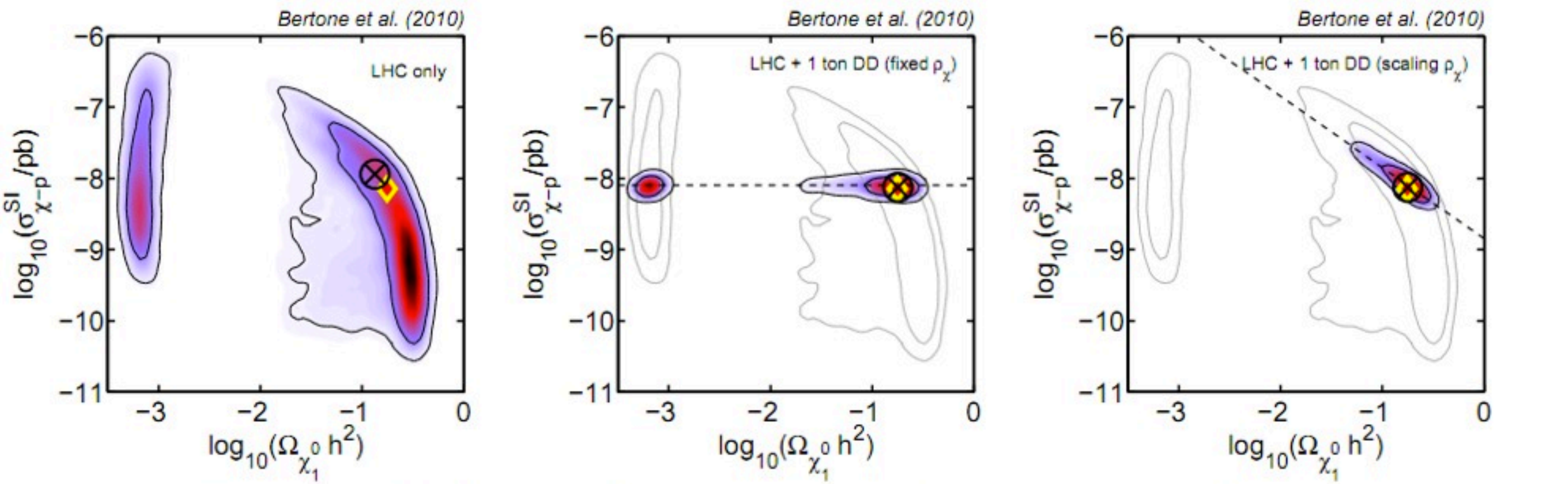


FIG. 2: As in Fig. 1, but in the $\sigma^{SI}_{\chi-p}$ vs $\Omega_{\tilde{\chi}^0_1} h^2$ plane. From left to right: constraints using LHC data alone, adding direct detection data assuming a fixed local DM density, and with our scaling Ansatz for the local density. The inner and outer contours enclose 68% and 95% probability regions, respectively. The probability distributions have been smoothed with a Gaussian kernel for display purposes. The best fit point is shown by the encircled black cross, while the true value is given by the yellow/red diamond. In the center and right panels we show for reference the LHC-only contours of the left panel (light grey), along with the directions along which the different Ansätze break the degeneracy (dashed lines).

- Bertone et al 10: reconstruction of DM parameters in a 24-parameter SUSY model, showing benefit of combining anticipated LHC measurements and ton-scale DD experiments.
- Akrami et al 10: example of Bayesian and frequentist scans over CMSSM parameter space using future ton-scale DD experiments.

Conclusions

- Indirect detection (ID) experiments: many constraints, potential signal from cosmic ray experiments. Have motivated models of leptophilic DM and expanded dark sectors with GeV-scale interactions.
  - DM explanations of CR excesses are in some tension with gamma-ray data; seem to prefer flat/cored DM density profiles and low unresolved substructure.
  - Sommerfeld-enhanced models can produce the signal with the correct relic density, but can conflict with CMB and self-interaction bounds if the force carrier is too light. Will soon be tested robustly by Planck.
- Direct detection (DD) experiments: possible signals at DAMA and CoGeNT, best-ever constraints just released from XENON100. Have motivated light DM models and models with unusual scattering kinematics.
  - DAMA and CoGeNT can have a common light DM origin if systematic uncertainties on quenching factors are pushed to their limits, or DM has isospin-dependent or momentum-suppressed interactions. Also requires mediator to be light or have large couplings to quarks: can be accommodated in NMSSM, or in models with new light force carriers.
  - Inelastic DM explanation for DAMA seems in trouble with new XENON100 results (but need velocity-distribution-independent analysis). Modified iDM explanations for DAMA modulation include scattering on thallium impurity & magnetic dipole scattering.
- Looking forward: recent progress on estimating local density/velocity distribution, and new analysis tools to extract information from DD data independent of the velocity distribution. In future years, combining data from collider, DD and ID experiments should allow better constraints on both particle physics and astrophysics of DM.

BONUS SLIDES

CR "Excesses"?

- Could it just be proton mis-identification by PAMELA?
    - Their estimated proton rejection would have to be off by a factor of 30.
    - Measurements of the **electron** spectrum also show a hardening, consistent with the positron fraction rise if there is a new component that is half positrons, half electrons.
- There are large uncertainties in CR propagation - can't that absorb this "signal"?
    - Not unless we're missing a key ingredient: the exact spectrum is uncertain, but the statement that (secondary) positrons should have a softer spectrum than (primary) electrons is fairly robust in the standard picture.
- But positrons are secondaries from protons, which have a much longer path length than electrons. At some energy, electron path length < distance to nearest source. What if the rising positron fraction is just due to the lack of electrons above this energy?
    - This was a reasonable idea, but the electron spectrum has been measured. It gets harder above 10 GeV (more high-energy electrons than expected), not softer.

Re-acceleration?,

Blasi 0903.2794, Mertsch & Sarkar 0905.3152

- Perhaps secondary positrons themselves get re-accelerated in the supernova shocks that accelerate the primaries.
- Effect is certainly present at some level, magnitude controlled by one free parameter.
- Fit this parameter to PAMELA data: robust predictions for secondary-to-primary ratios for heavier nuclei. Very predictive model!
- Current data on boron-to-carbon ratio from CREAM seems to disfavor this scenario, but for e.g. titanium-to-iron ratio there is disagreement between experimental results, with ATIC hinting at upturn: hope for more clarity from PAMELA, AMS.

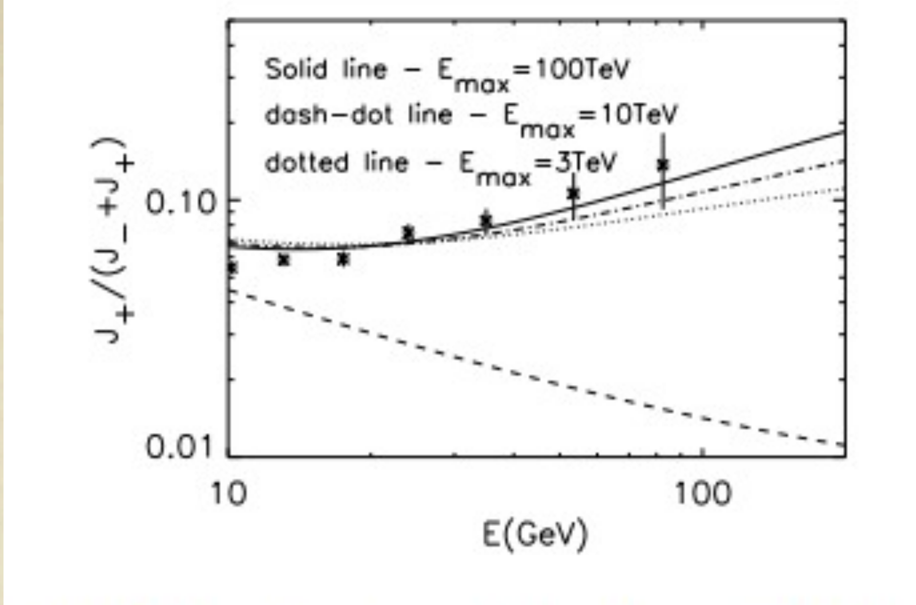
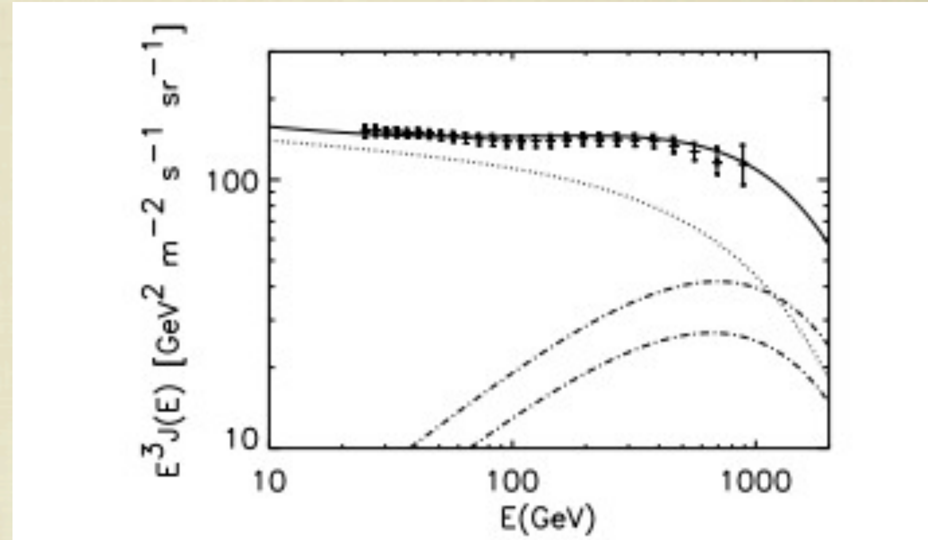
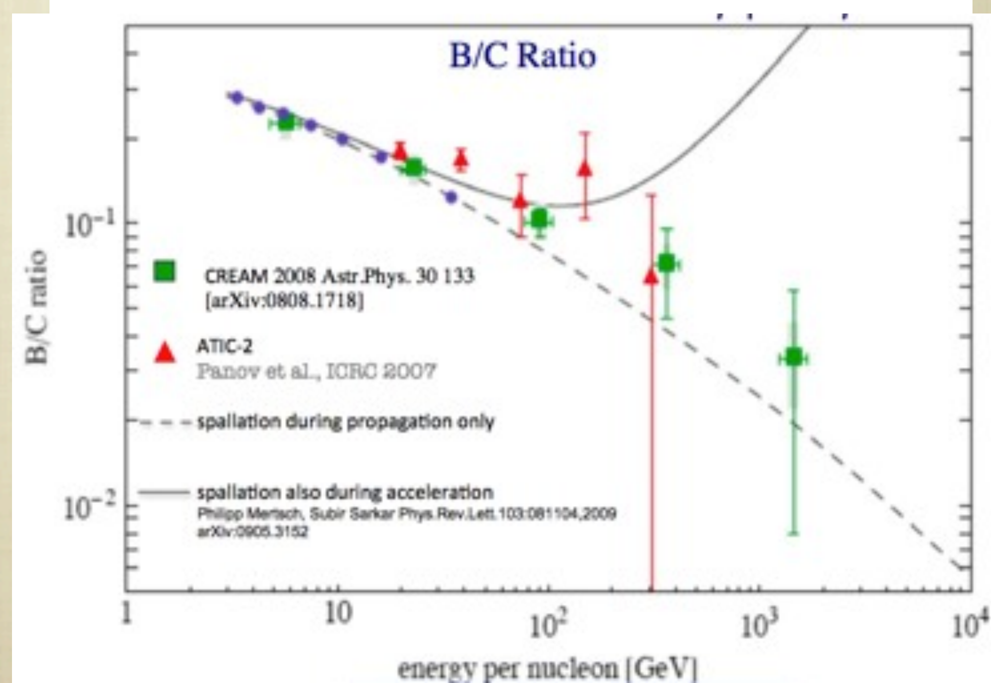


FIG. 1: Positron fraction as a function of energy. The data points are the results of the PAMELA measurement.





Sommerfeld Enhancement

(First studied in DM context by Hisano et al 03-04)

- First approximation: assume only one relevant DM state, interaction described by the Yukawa potential.

- Behavior described by two parameters:

$$\epsilon_v = \frac{v/c}{\alpha}, \quad \epsilon_\phi = \frac{m_\phi/m_\chi}{\alpha}$$

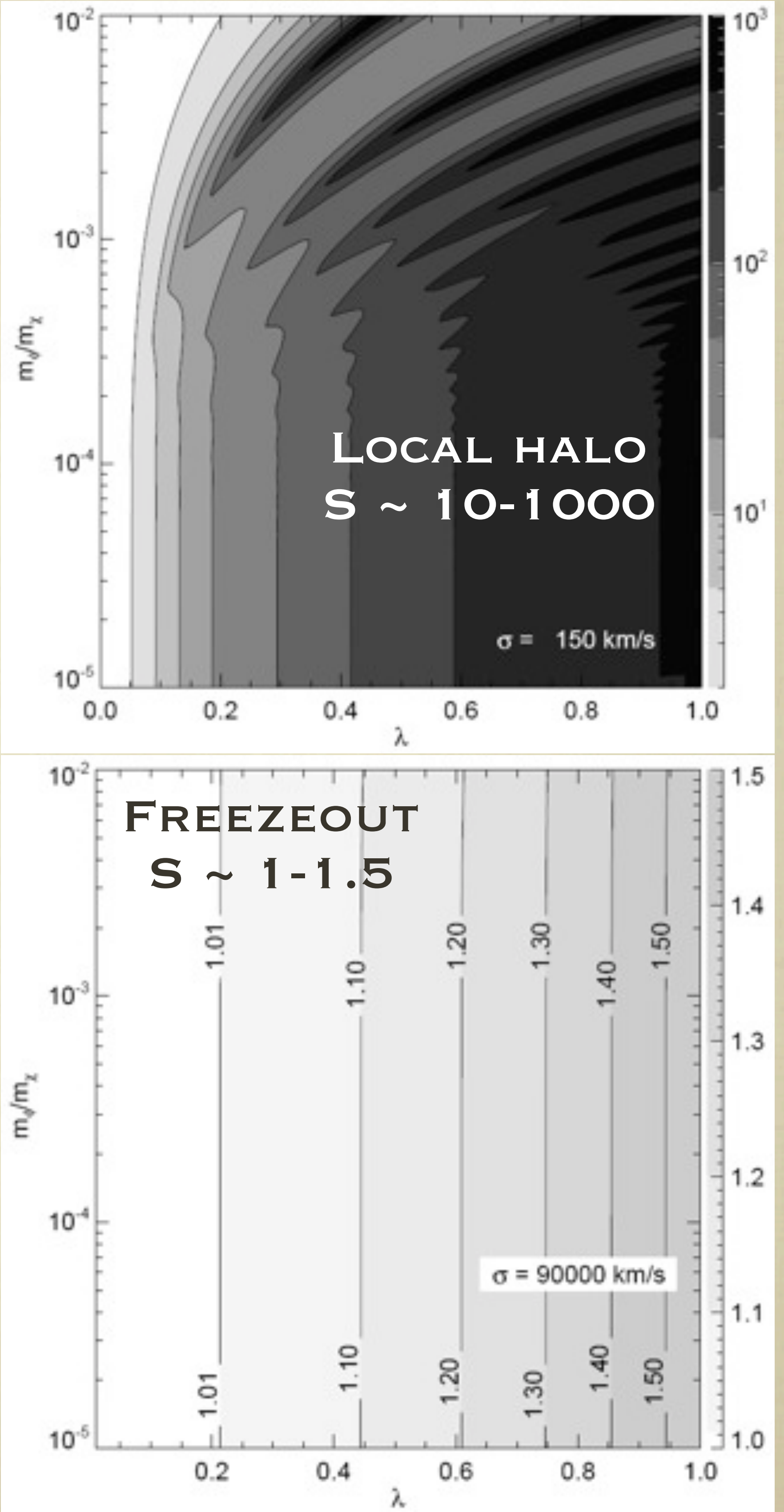
- When the mediator mass can be neglected,

$$S = \frac{\pi}{\epsilon_v}, \quad \epsilon_\phi \ll \epsilon_v \ll 1$$

- Certain values of give rise to zero-energy bound states in the spectrum, leading to large resonances where $S \propto 1/v^2$.

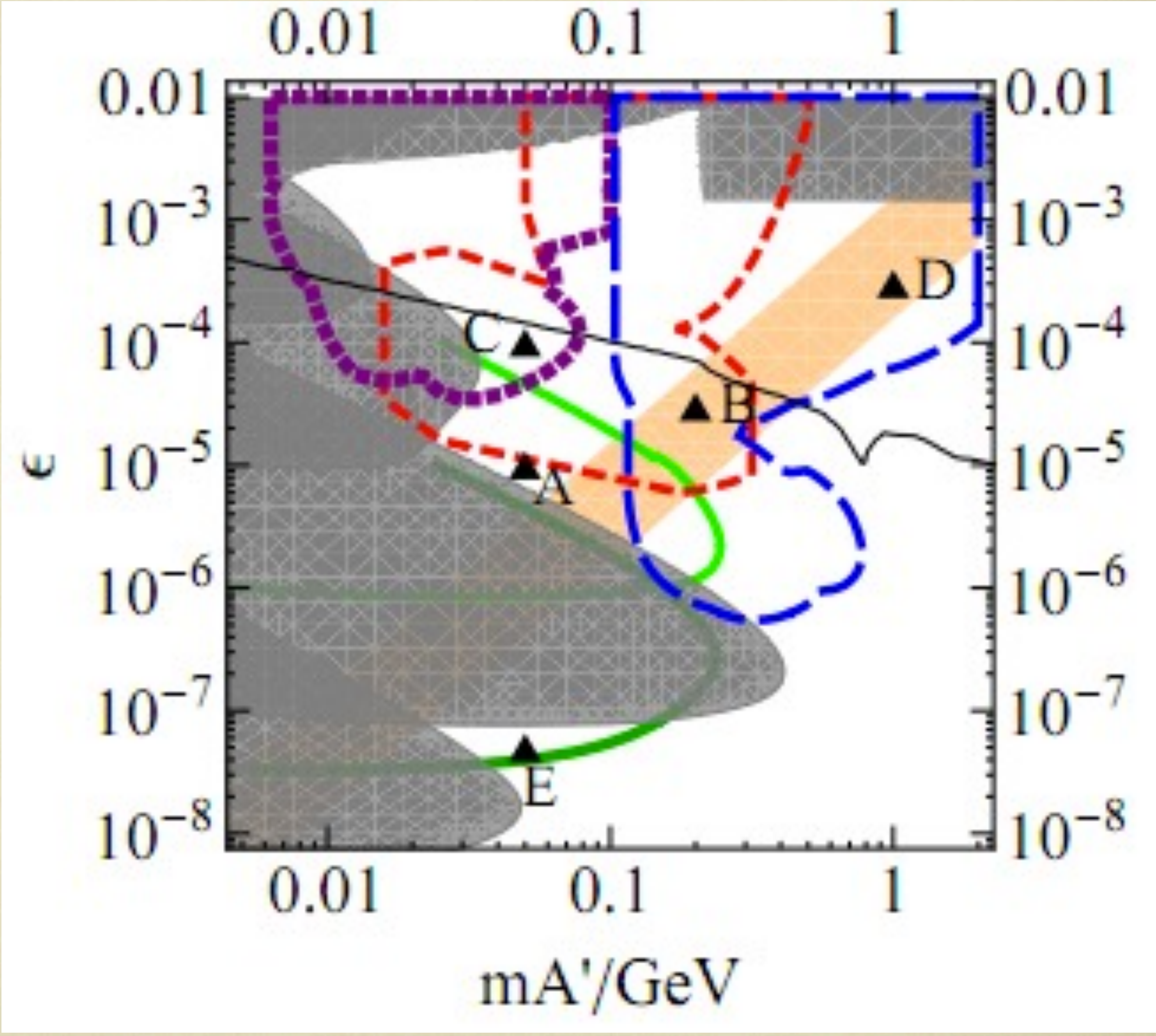
- Away from resonances, the enhancement saturates at,

$$S \approx \frac{12}{\epsilon_\phi}, \epsilon_v \ll \epsilon_\phi \ll 1$$



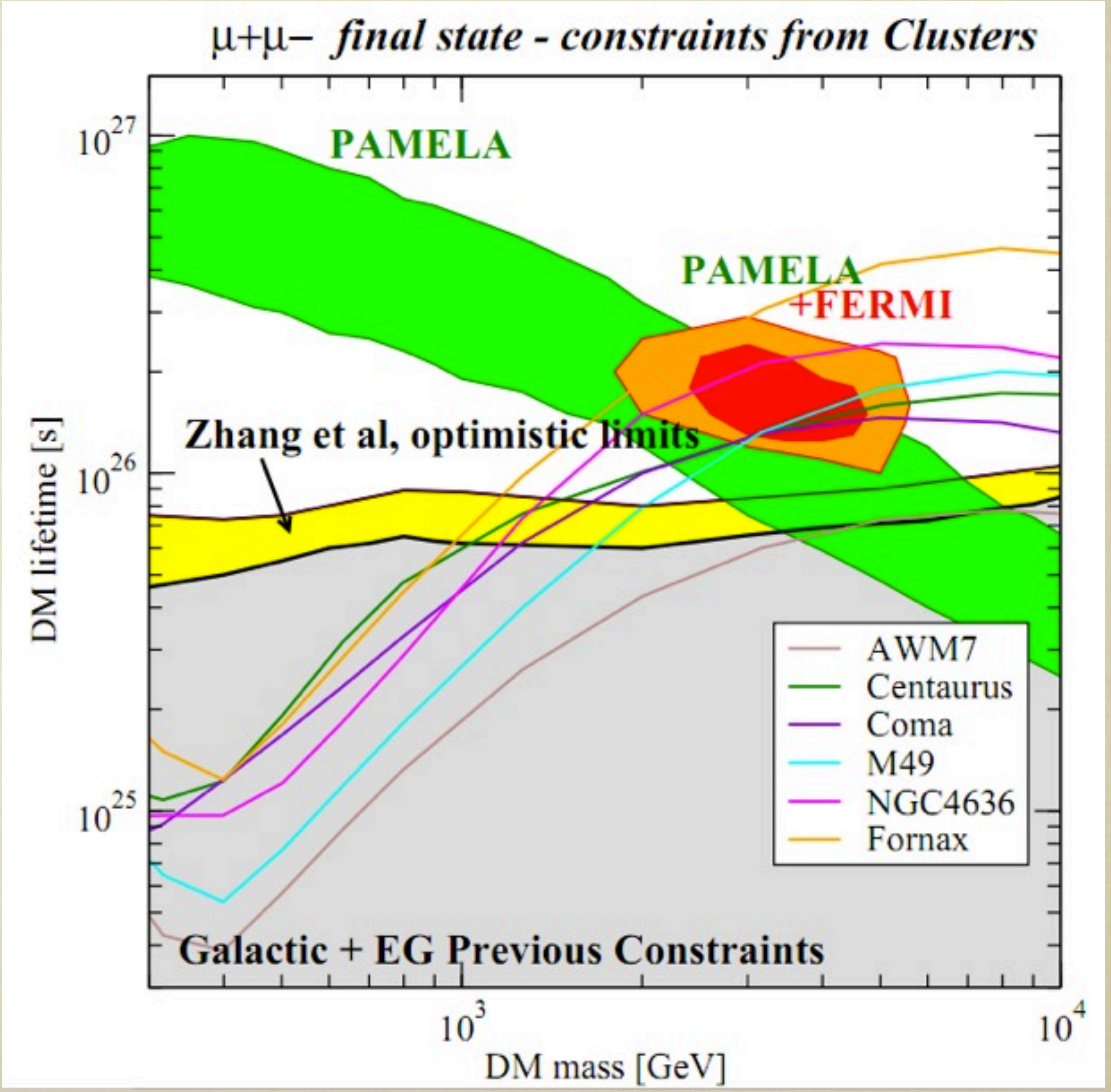
Dark Photon Searches

- Bounds from precision electroweak constraints
- Beam dump experiments
- Supernovae



Galaxy Cluster Constraints - Decaying DM

- Dugger, Jeltema & Profumo, 1009.5988.



Gamma-ray Bounds on DM Models for PAMELA/Fermi

- Previous slide: Sommerfeld enhancement can generate large enough signal with correct relic density (non-thermal production can achieve this too). But what about other constraints?

- Gamma rays - HESS Galactic Center + Ridge, Fermi inner galaxy + dwarf galaxies + line search + diffuse gamma-ray background. Models with 4-lepton final states (e.g. via new light mediator) are generally less constrained, due to softer gamma-ray spectra from internal bremsstrahlung.
  Current status: some tension, not ruled out.

  - To avoid conflict with inner Galaxy bounds, need a fairly flat/cored dark matter density profile.

  - To avoid conflict with diffuse gamma-ray bounds, cannot have very much low-mass dark matter substructure.

  - Sommerfeld enhanced models = more constrained by dwarfs and diffuse background, since lower typical velocity in dwarfs and substructure => higher expected signal. Constraints from inner Galaxy are more uncertain due to lack of information on velocity distribution.