COMPLEMENTARITY OF INDIRECT DARK MATTER DETECTION

AMS Days at CERN

Jonathan Feng, UC Irvine

15 April 2015

CONGRATULATIONS TO AMS

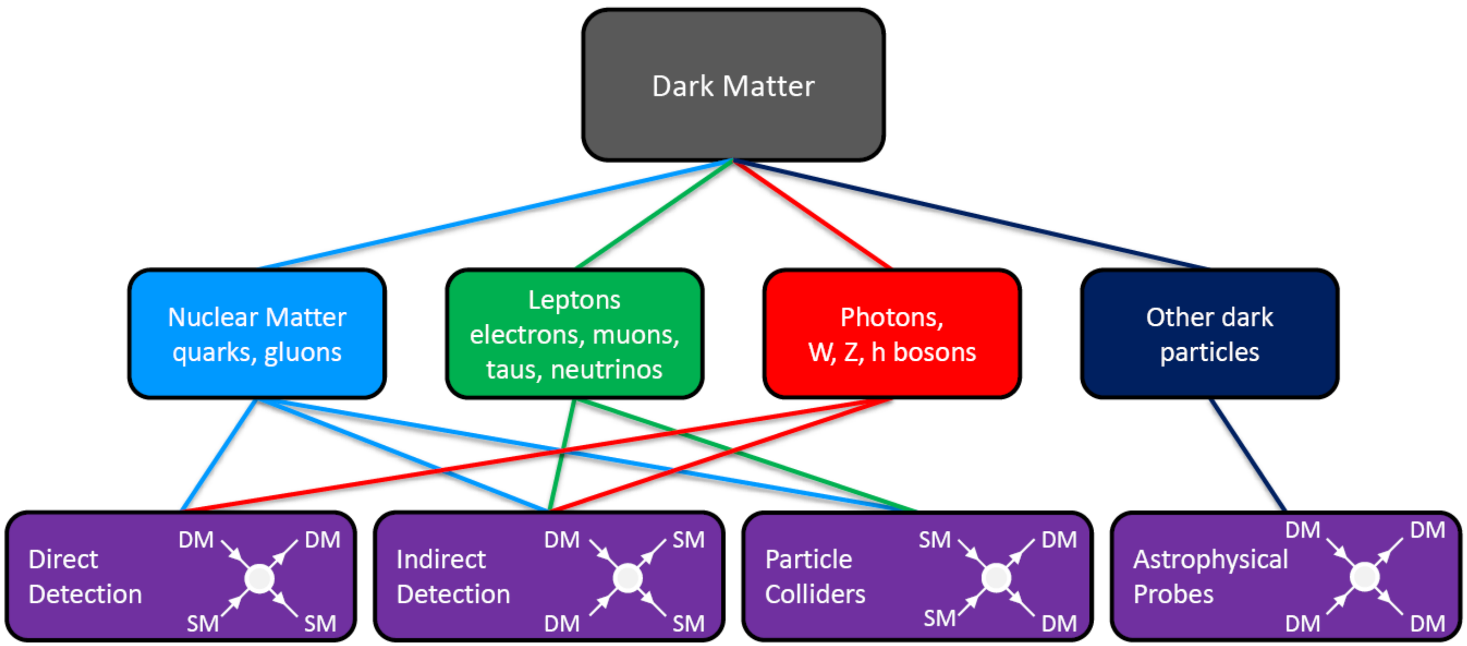
RECENT PROGRESS
IN SUPERSYMMETRY
AND
IMPLICATIONS FOR
DARK MATTER

Jonathan Feng
IAS, Princeton

AMS Workshop, Erice
9 May 2000

DARK MATTER COMPLEMENTARITY

Complementarity permeates dark matter: diverse approaches are required to search for different candidates, probe various regions of parameter space for a given candidate, confirm and study a signal, find the particle properties of dark matter, and determine if there's more than one kind of dark matter

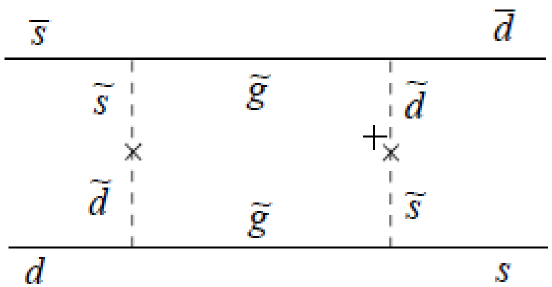


DARK MATTER AT THE WEAK SCALE

- The weak scale ~10 GeV – 1 TeV remains an excellent place to look for dark matter
- This case has not been diminished much by null results from the LHC
- Consider supersymmetry

EXCERPTS FROM 2000 AMS ERICE TALK

Flavor Problem



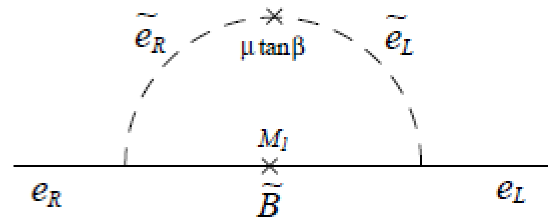
$$\Delta m_K \Rightarrow \left[\frac{10\ \text{TeV}}{m_{\tilde{q}}}\right]^2 \left[\frac{\Delta m^2_{\tilde{q}_{12}}/m^2_{\tilde{q}}}{0.1}\right]^2 < 1$$

Contini, Scimemi, etc.

Requires squark degeneracy (superGIM mechanism) or extremely heavy squarks.

Also $\mu \to e\gamma$.

CP Problem



$$\text{EDM}_e \Rightarrow \left[\frac{2\ \text{TeV}}{m_{\tilde{e}}}\right]^2 \left[\frac{\mu M_1}{m^2_{\tilde{e}}}\right] \tan\beta \sin\phi_{CP} < 1$$

Moroi, etc.

Requires heavy selectrons or $\phi_{CP} \ll 1$.

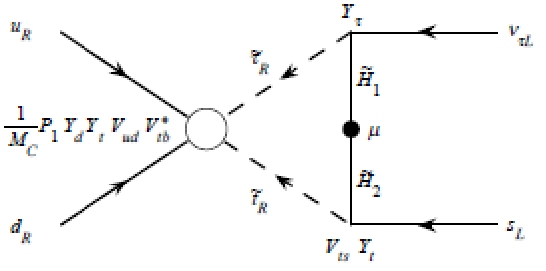
Note: flavor-conserving, so cannot be suppressed by degeneracy.

Also EDM_n.

EXCERPTS FROM 2000 AMS ERICE TALK

Proton Decay

Gauge coupling unification $\Rightarrow$ proton unstable



"New" $\tan^2\beta$-enhanced operator.

Goto, Nihei

Proton decay in minimal SU(5) is generally too fast:

$$\left[\frac{\tau(p\to K^+\bar\nu)}{5.5\times 10^{32}\text{ years}}\right] \lesssim \left[\frac{m_{\tilde q}^4}{1\text{ TeV}^2\,\mu^2}\right]\left[\frac{5}{\tan\beta}\right]^4 \times\left[\frac{M_C}{10^{17}\text{ GeV}}\right]^2$$

Requires heavy superpartners (or no GUT).

FOCUS POINT SUSY

JF, Matchev, Moroi, 1999

Experiment suggests $m_{\tilde f} \gtrsim 2$ TeV.

The only possible objection is naturalness.

Supersymmetric theories are natural if the weak scale is not unusually sensitive to small variations in the fundamental parameters.

't Hooft

Susskind/Wilson

How do we implement this, quantify fine-tuning? Several proposals in the literature. Adopt the following prescription:

BOTTOM LINE

- Those who were optimistic about SUSY before the LHC began should remain optimistic about SUSY

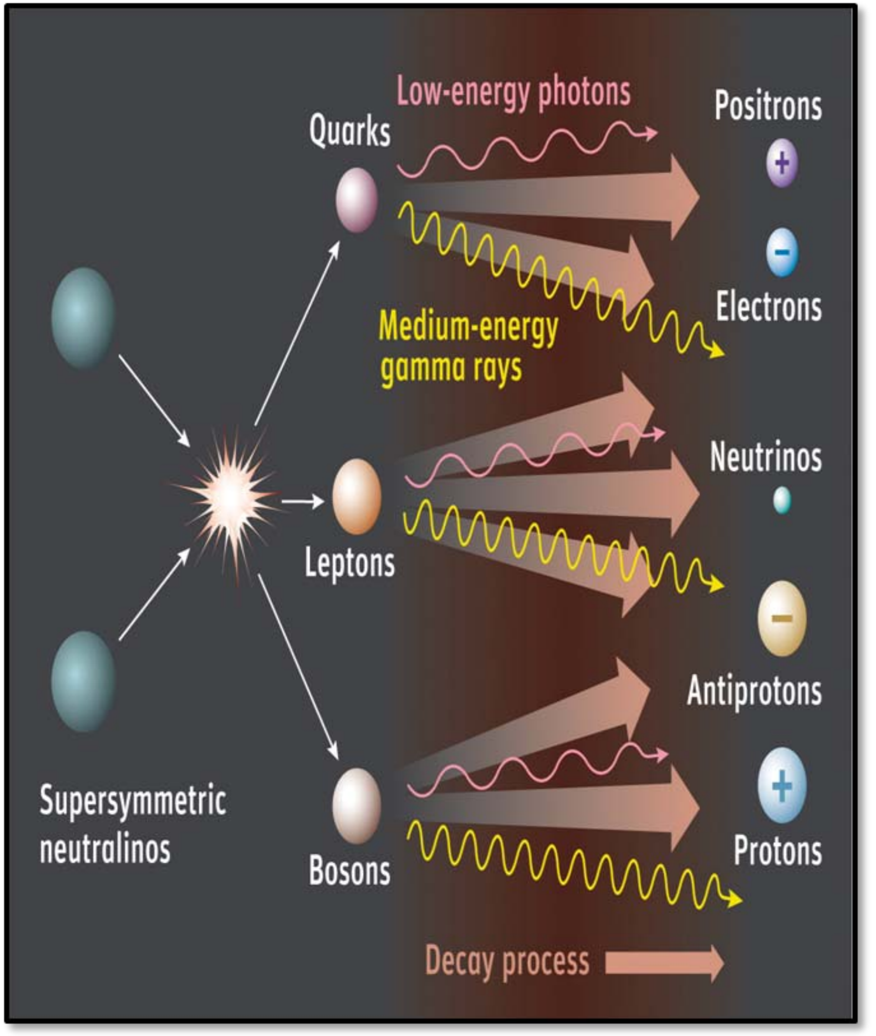
- Those who were pessimistic about SUSY before the LHC began should remain pessimistic about SUSY

- Those who were optimistic about SUSY before the LHC began and are now pessimistic: why?

- LHC Run 2 and dark matter searches for SUSY and other new weak-scale physics are as promising as ever

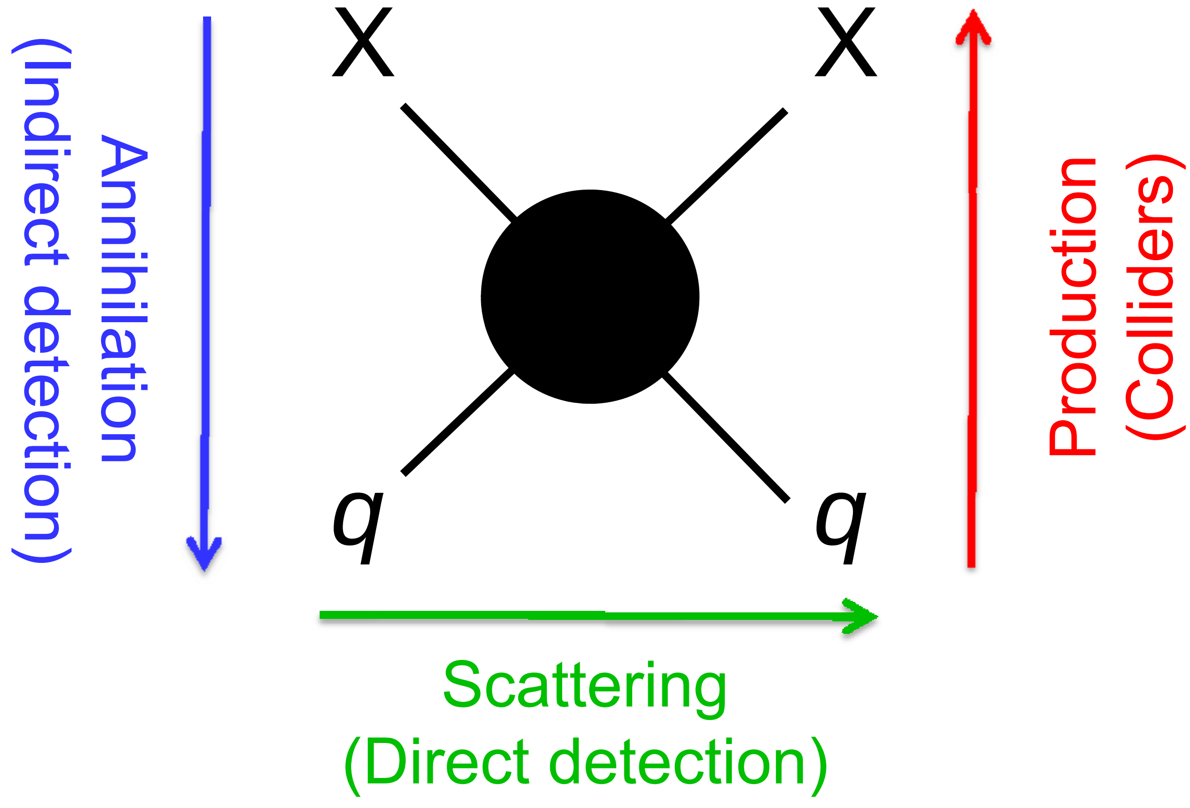
INDIRECT DETECTION

- Dark matter may pair annihilate or decay in our galactic neighborhood to
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Antideuterons
  - …



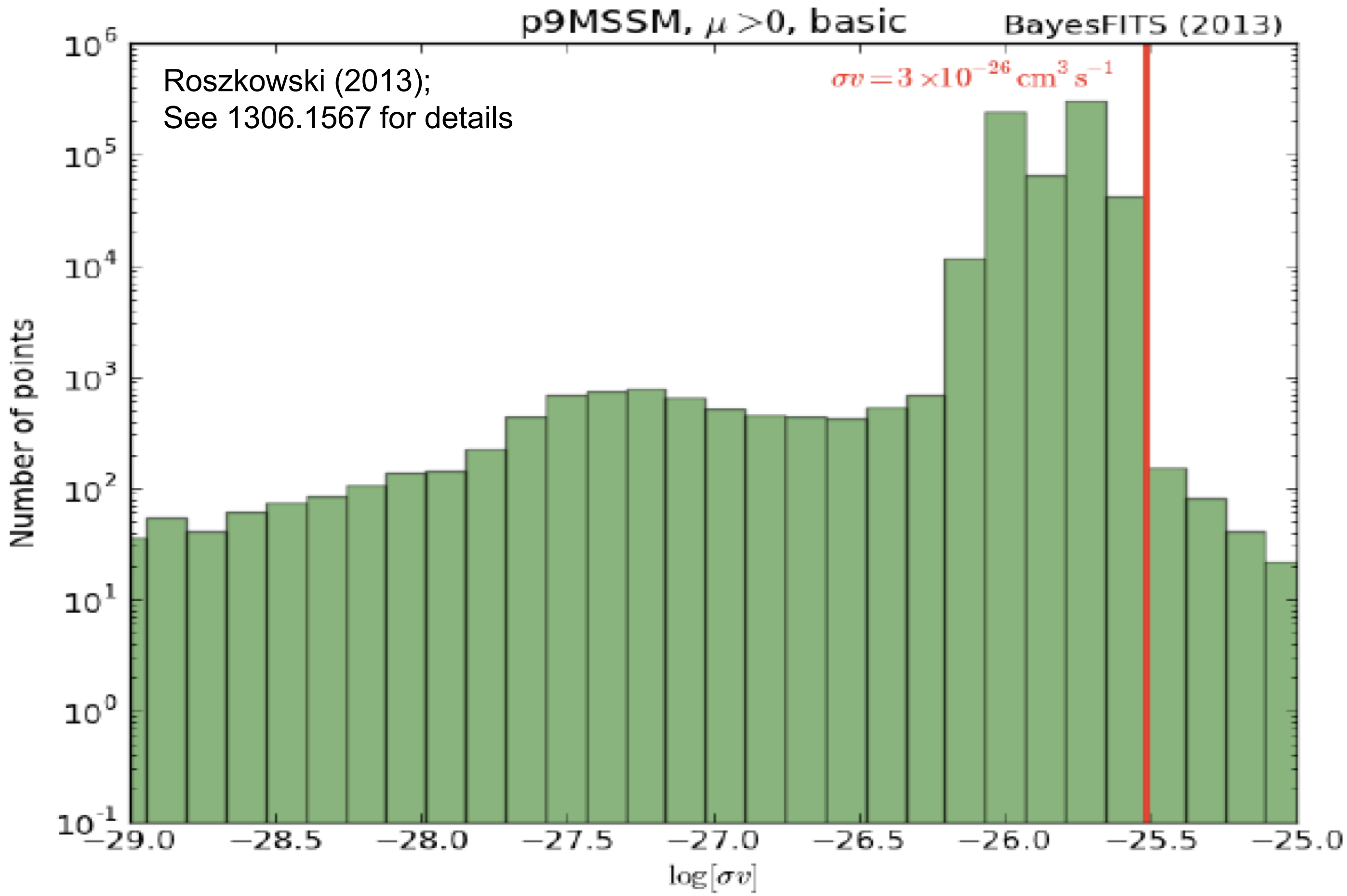
INDIRECT DETECTION BASIC FEATURES

- Energy: high, provided by the Big Bang (or reheating)
- Rate: relic density provides a target $\langle \sigma_A v \rangle \sim 3 \times 10^{-26}$ cm^3/s

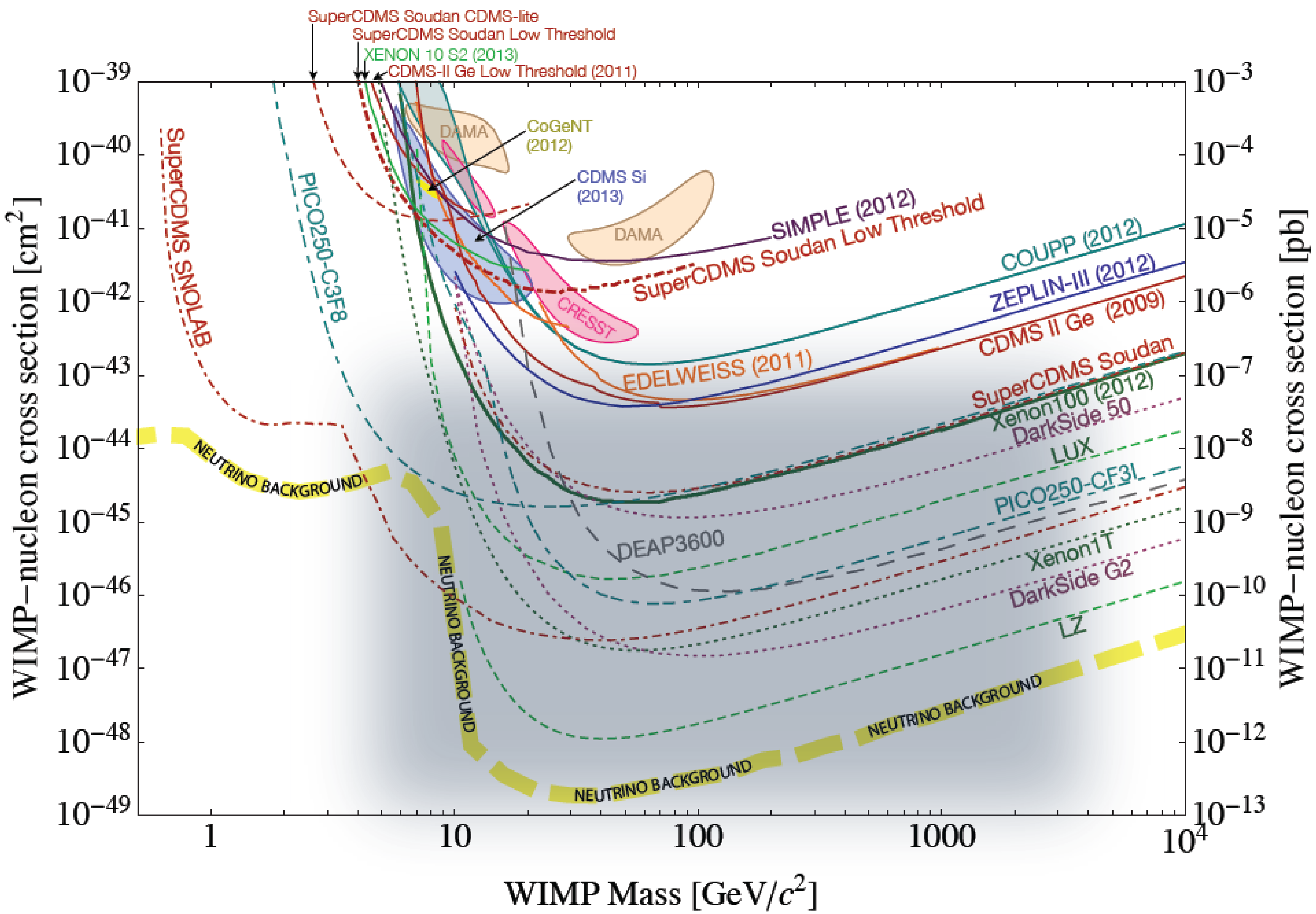


ROBUSTNESS OF TARGET CROSS SECTION

Relative to direct, indirect rates typically have smaller particle physics uncertainties (but larger astrophysical uncertainties)



CONTRAST WITH DIRECT DETECTION



PHOTONS

Dark Matter annihilates in __the GC / dwarf galaxies__ to
a place

__photons__ , which are detected by __Fermi, HESS, …__ .
some particles — an experiment

The flux factorizes:

$$\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE} \sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Astro-Physics}}$$

Particle physics: two kinds of signals

- Lines from XX → γγ, γZ: loop-suppressed rates, but distinctive signal
- Continuum from XX → ff → γ: tree-level rates, but a broad signal

Astrophysics: two kinds of sources

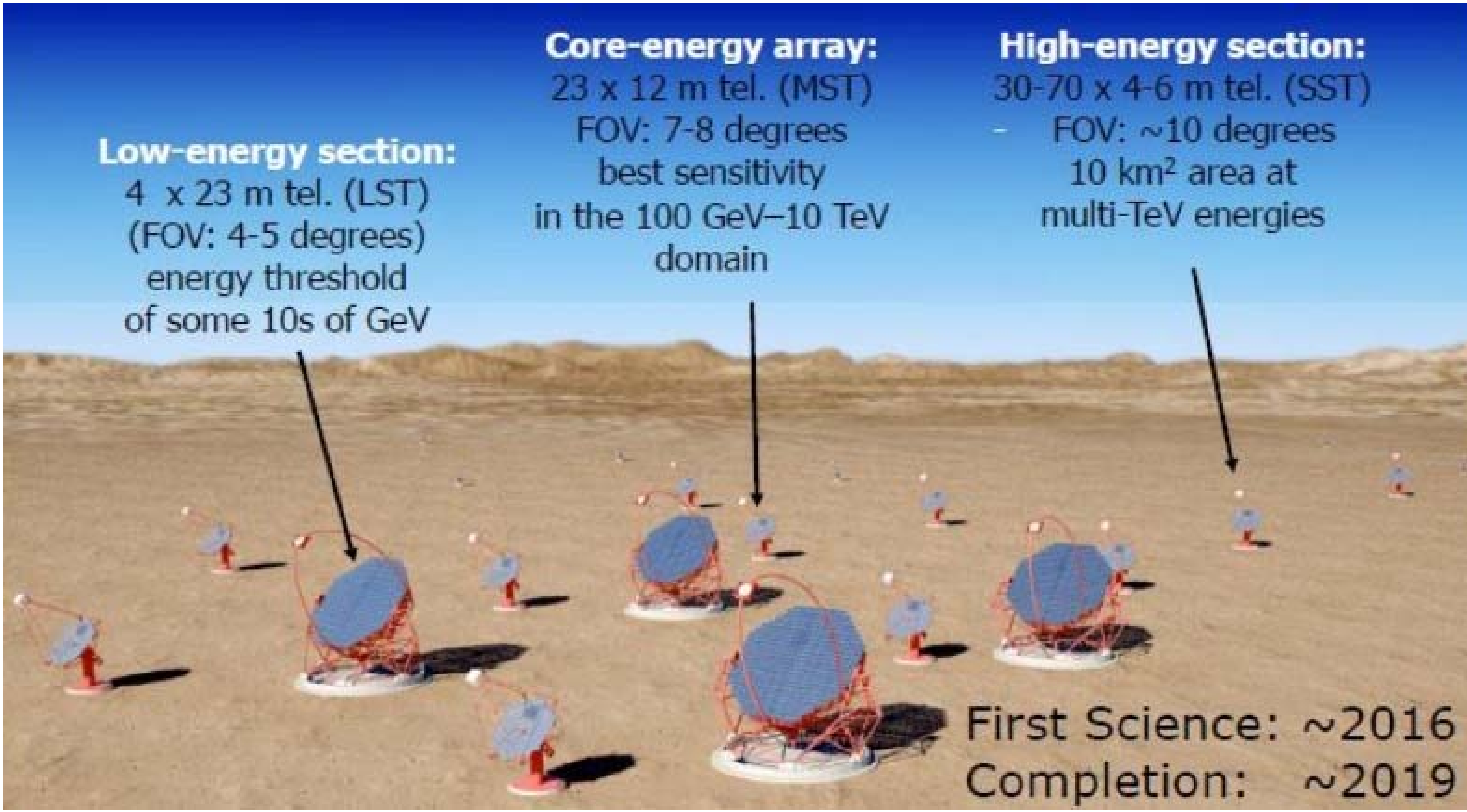
- Galactic Center: close and large signal, but high backgrounds
- Dwarf galaxies: farther and smaller, but low backgrounds

PHOTONS: CURRENT EXPERIMENTS

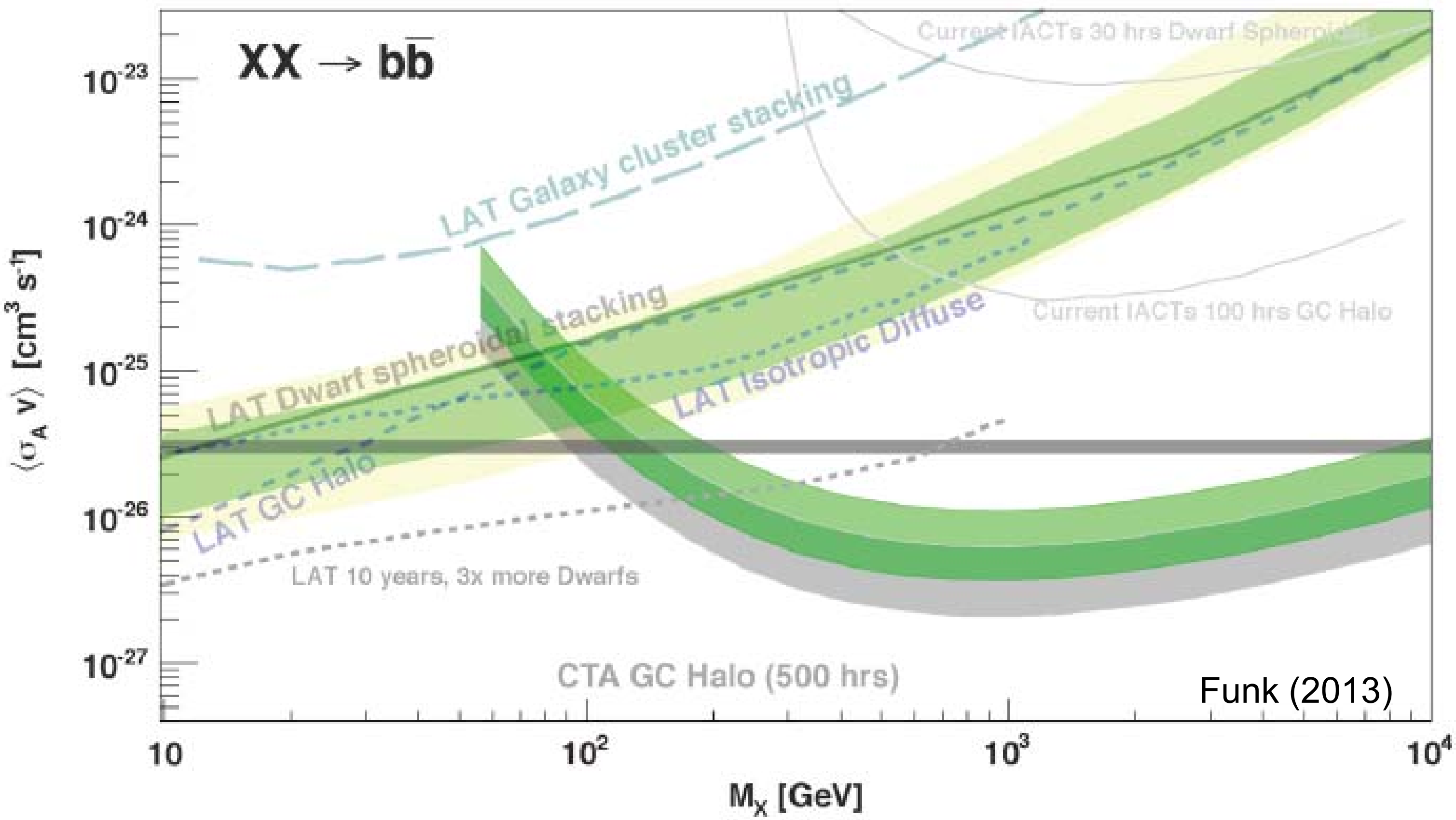
Veritas, HESS, Fermi-LAT, HAWC, many others

PHOTONS: FUTURE EXPERIMENTS

Cerenkov Telescope Array



PHOTONS: STATUS AND PROSPECTS

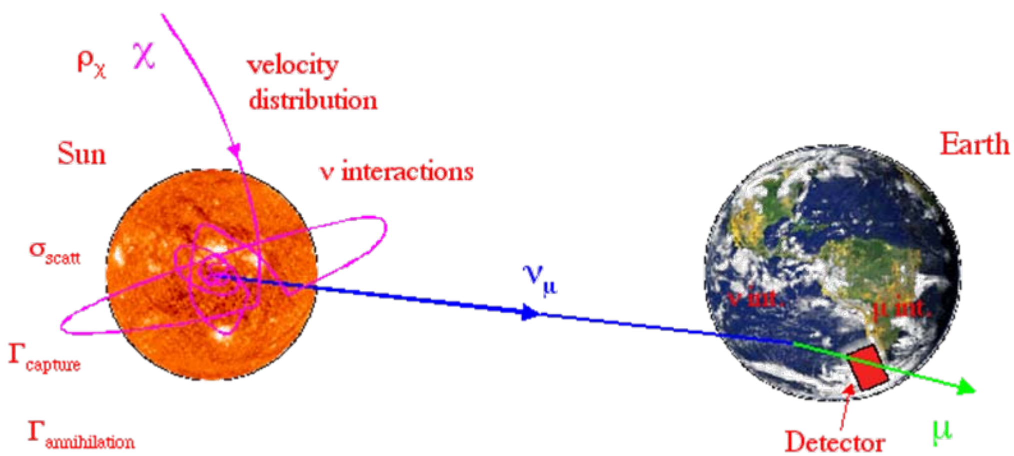


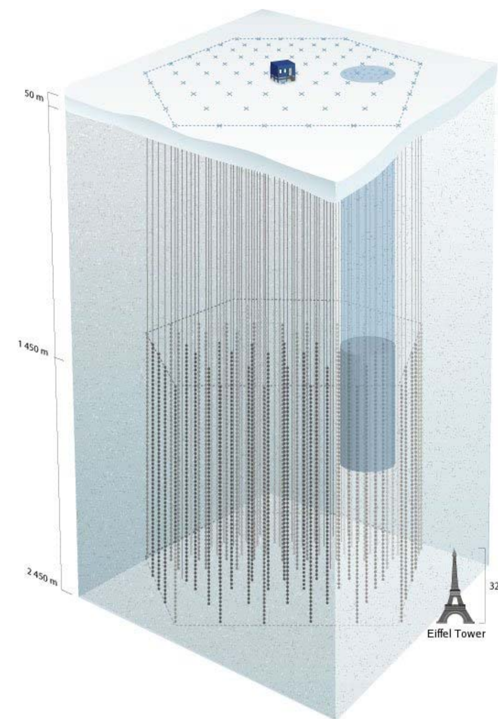
- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA will extend the reach to masses ~ 10 TeV

INDIRECT DETECTION: NEUTRINOS

Dark Matter annihilates in __the center of the Sun__ to
a place

__neutrinos__ , which are detected by __IceCube, ANTARES,…__
some particles an experiment

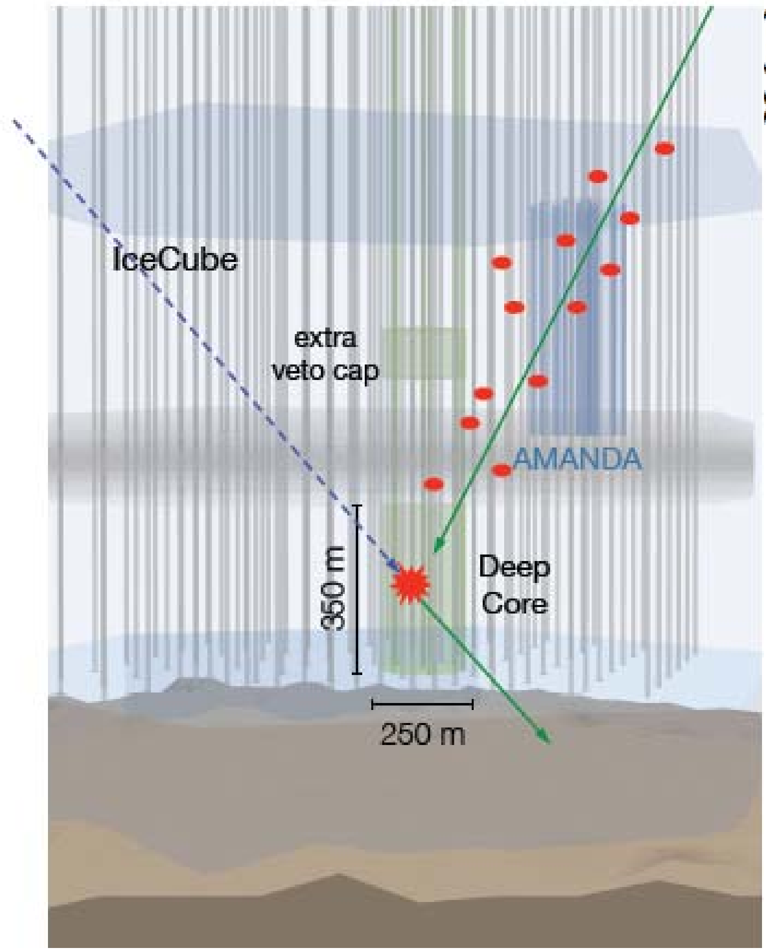


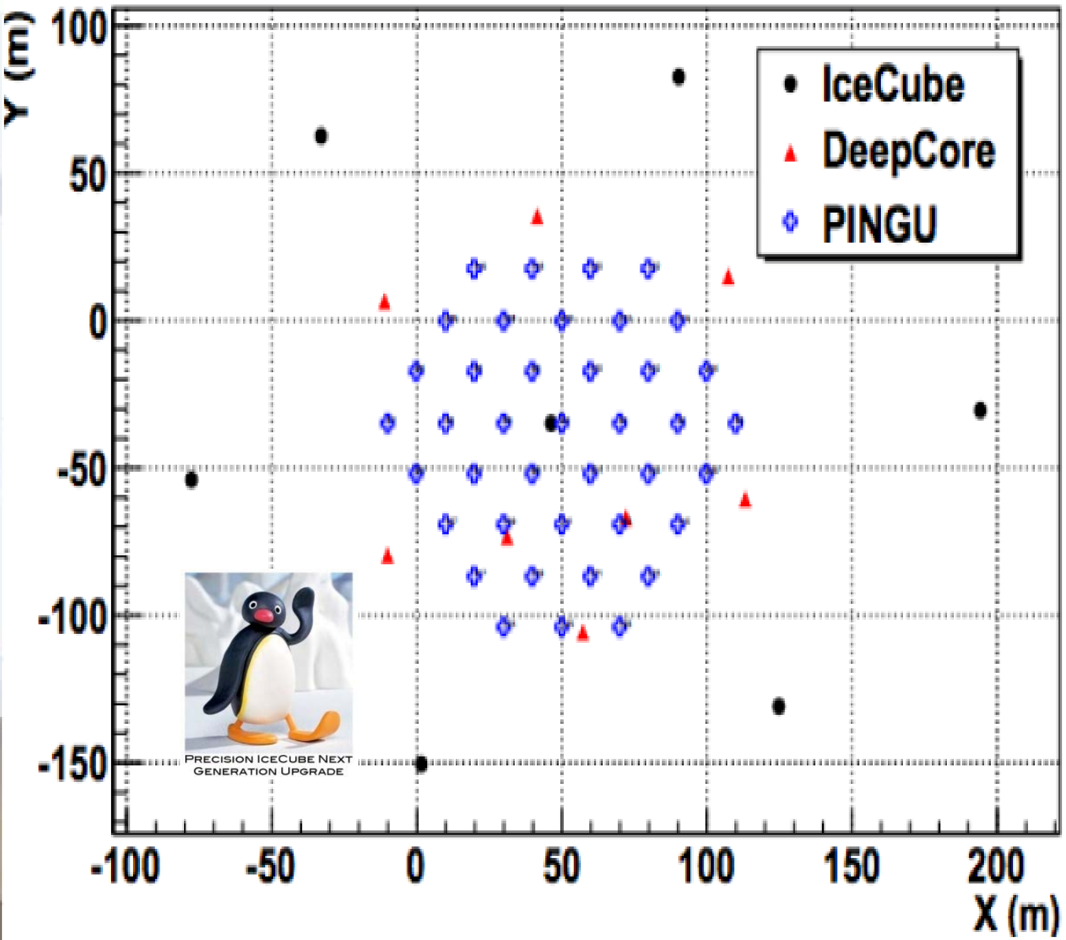


NEUTRINOS: EXPERIMENTS

Current: IceCube/DeepCore, superK, ANTARES

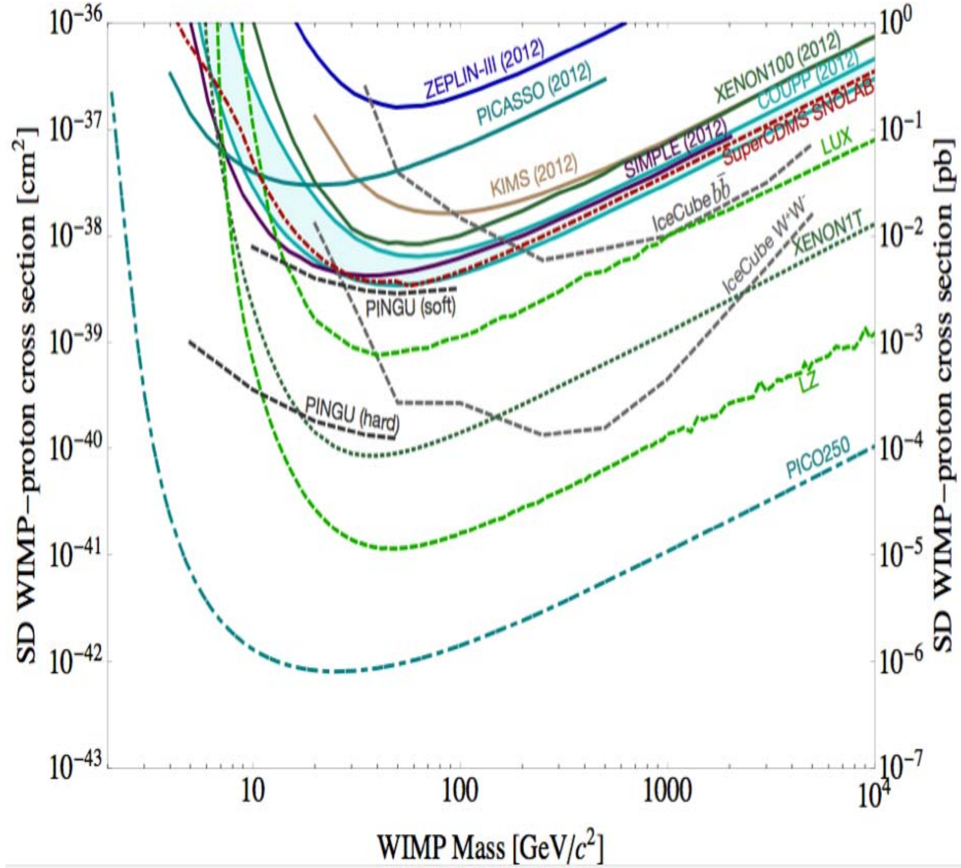
Future: KM3NeT, PINGU





NEUTRINOS: STATUS AND PROSPECTS

- The Sun is typically in equilibrium
- Spin-dependent scattering off hydrogen → capture rate → annihilation rate
- Results are typically plotted in the (m_X, σ_{SD}) plane and compared with spin-dependent direct detection experiments



Future experiments may discover the smoking-gun signal of HE neutrinos from the Sun, or set stringent σ_{SD} limits

INDIRECT DETECTION: ANTI-MATTER

Dark Matter annihilates in the halo (a place) to positrons (some particles), which are detected by AMS, PAMELA,… (an experiment).

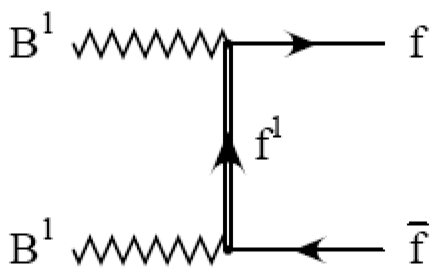
In contrast to photons and neutrinos, anti-matter does not travel in straight lines

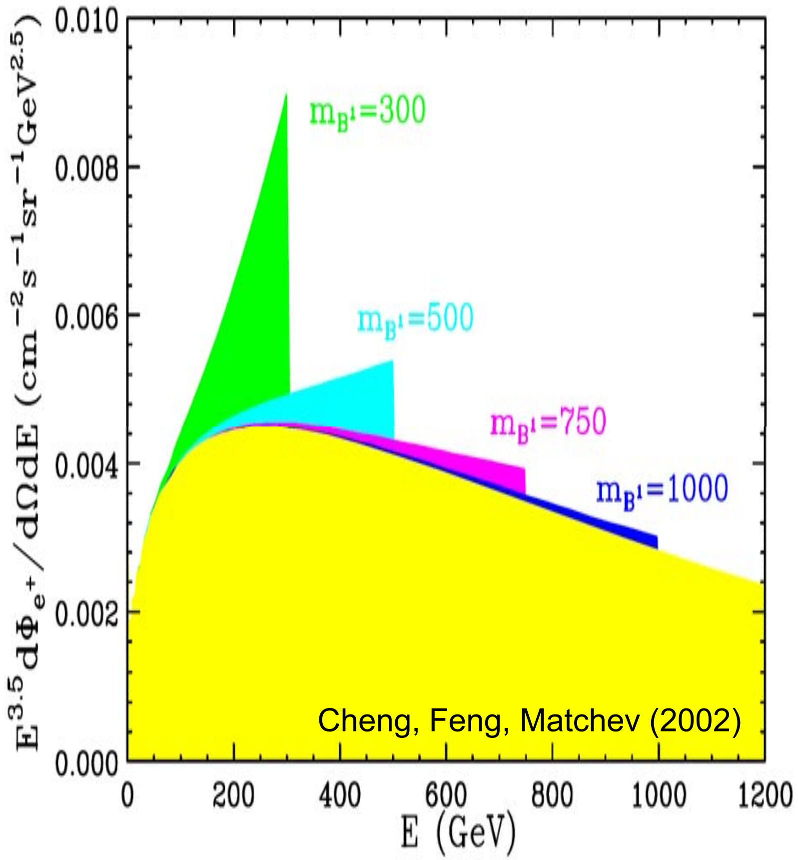
- bumps around the local halo before arriving in our detectors
- for example, positrons, created with energy E_0, detected with energy E

$$\frac{d\Phi_{e^+}}{d\Omega dE} = \frac{\rho_\chi^2}{m_\chi^2} \sum_i \sigma_i v B_{e^+}^i \int dE_0 \, f_i(E_0) \, G(E_0, E)$$

BUT SHARP FEATURES ARE PRESERVED

- For example, KKDM with large $B^1B^1 \rightarrow e^+e^-$



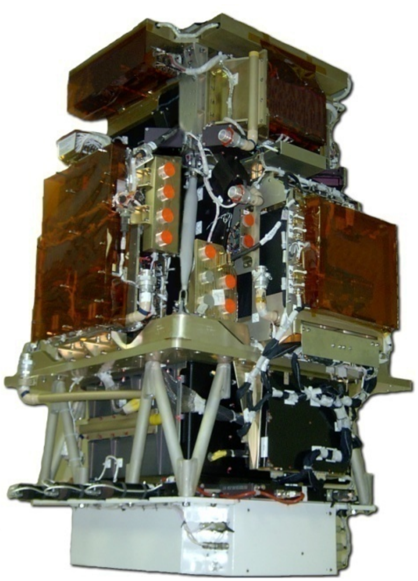


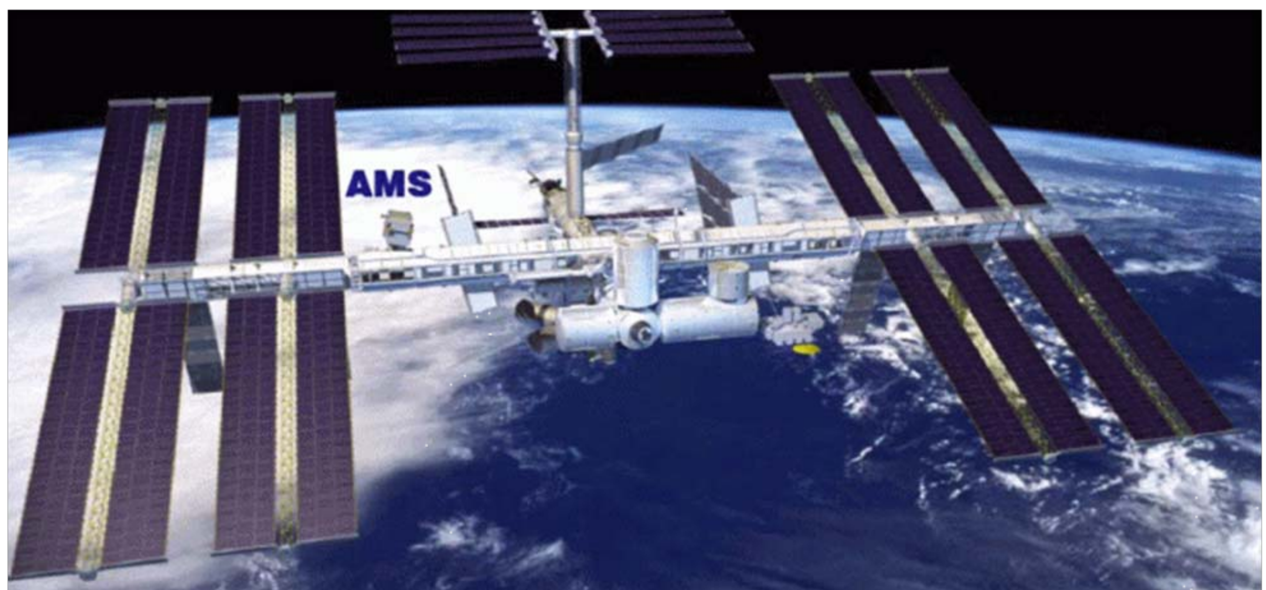
- Note: In SUSY, $\chi\chi \rightarrow e^+e^-$ is suppressed because neutralinos are Majorana fermions, and so the feature is not as sharp (but still prominent)

- Precise measurements can provide evidence for DM, distinguish SUSY and extra dims, measure DM mass

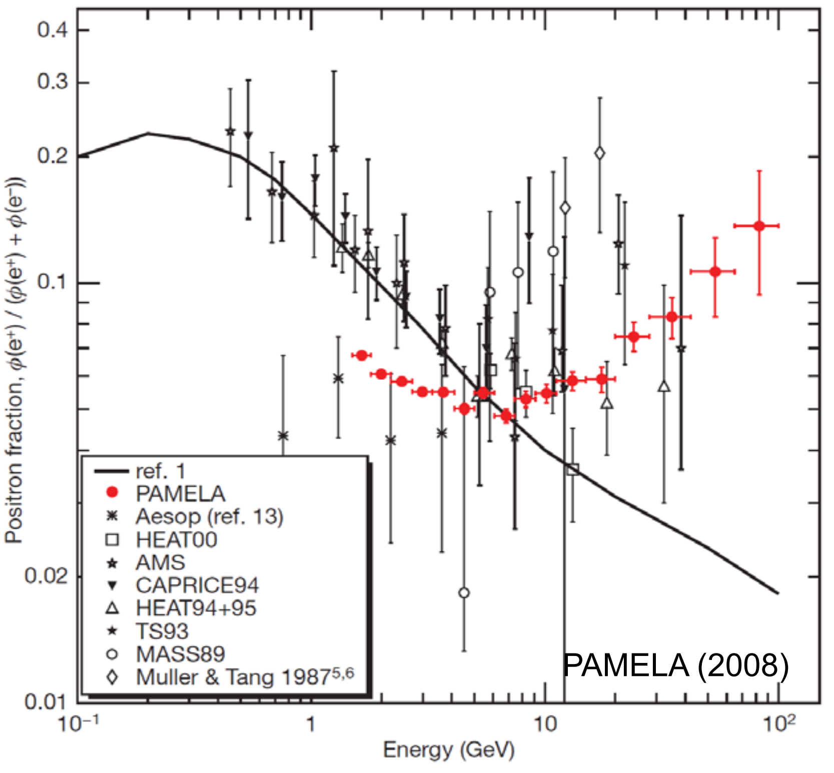
ANTI-MATTER: EXPERIMETS

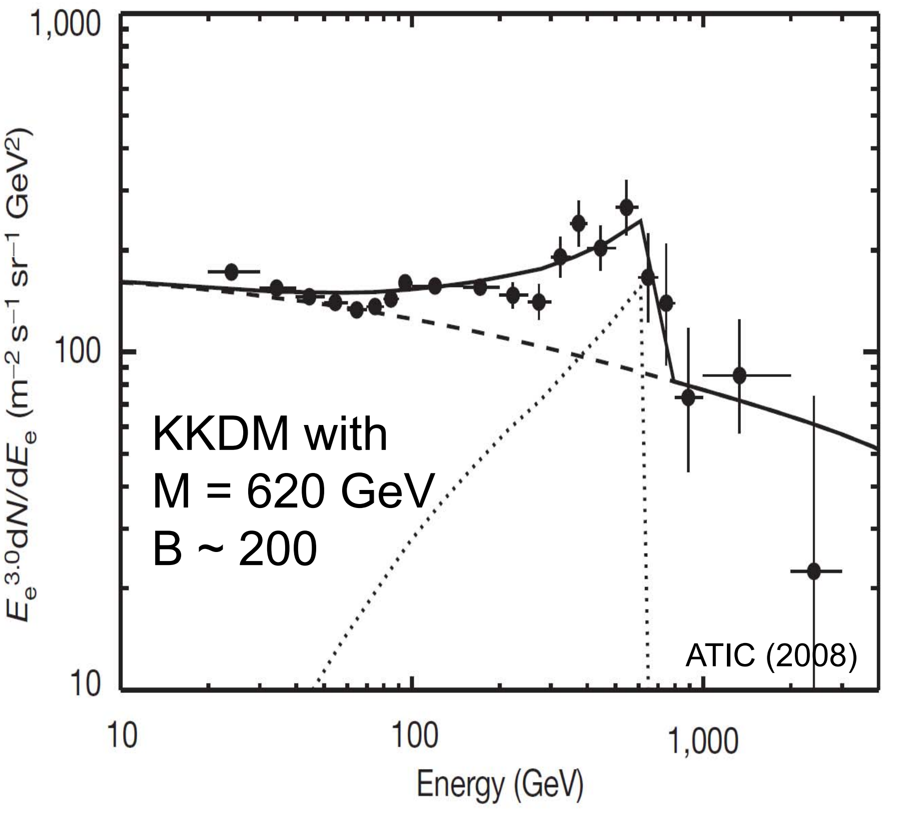
- Positrons (PAMELA, Fermi-LAT, AMS, CALET, …)
- Anti-Protons (PAMELA, AMS, …)
- Anti-Deuterons (AMS, GAPS, …)





POSITRONS: PAST

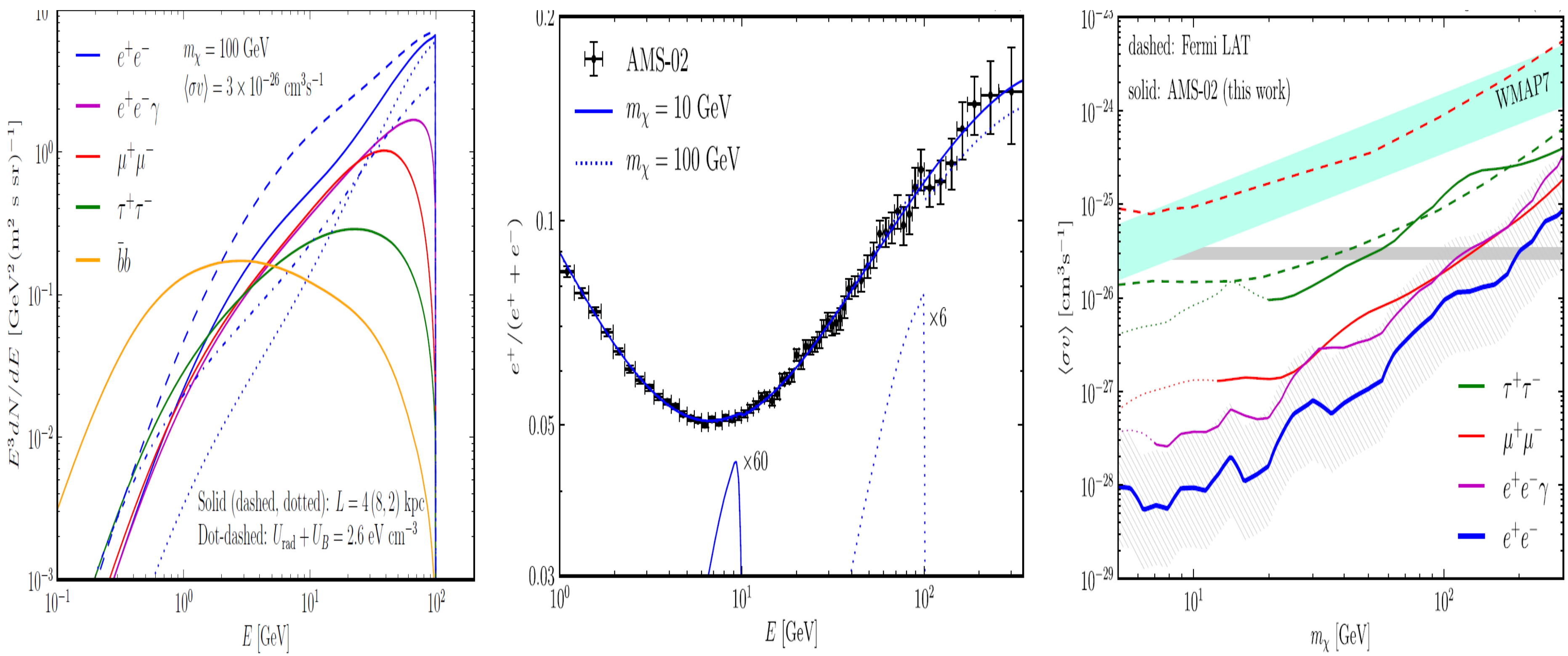




- Large excesses were reported previously, but required DM signals with boost factors of B ~ 100-1000 over target cross sections

POSITRONS: PRESENT AND FUTURE

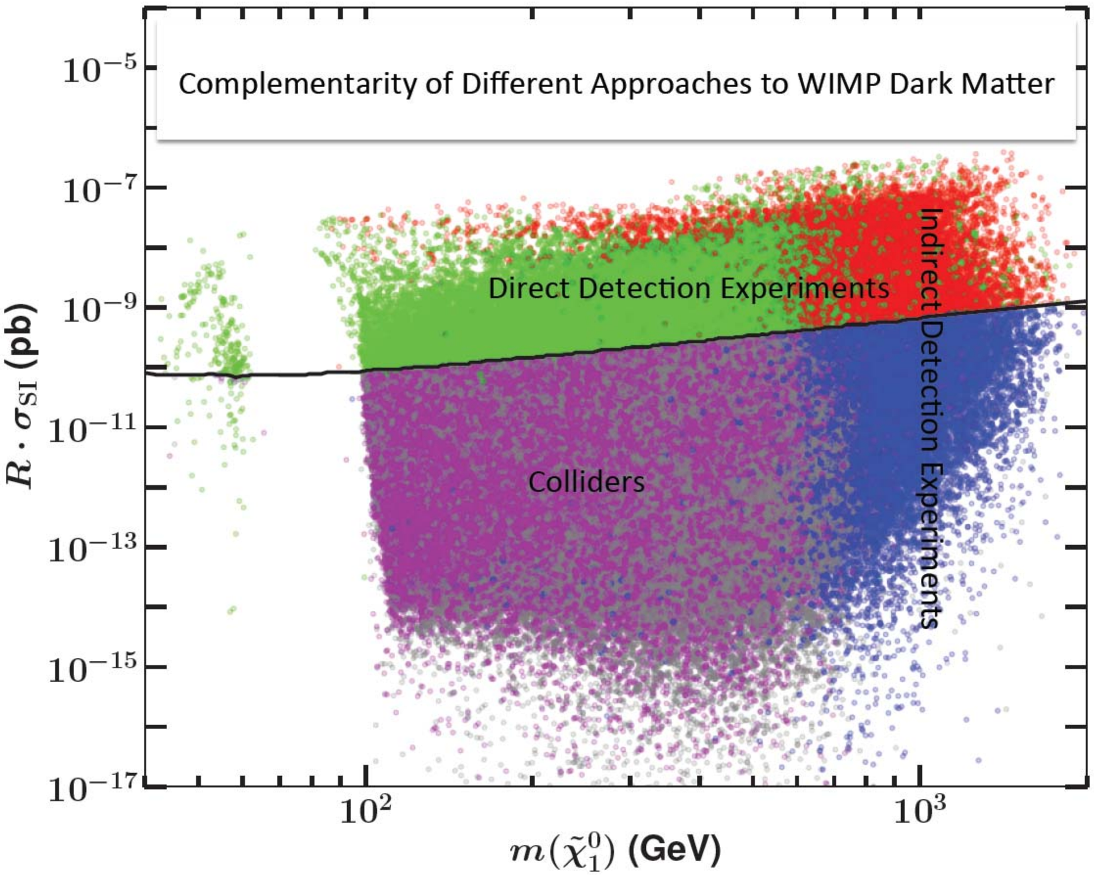
- With the new, precise AMS-02 data, we have entered a new era of looking for signals based not on fluxes, but on spectral features



Bergstrom, Bringmann, Cholis, Hooper, Weniger (2013)

COMPLEMENTARITY: FULL MODELS

pMSSM 19-parameter scan of SUSY parameter space



Cahill-Rowley et al. (2013)

- Complementarity for SUSY models; also for DM effective theories
- Many promising approaches to dark matter, and any compelling signal will have far-reaching implications

INDIRECT DETECTION OF DARK SECTORS

- All evidence for dark matter is gravitational. Perhaps it's in a hidden sector, composed of particles without EM, weak, strong interactions

- *A priori* this seems pretty unmotivated
  - No WIMP miracle
  - No connection to known problems

THE WIMPLESS MIRACLE

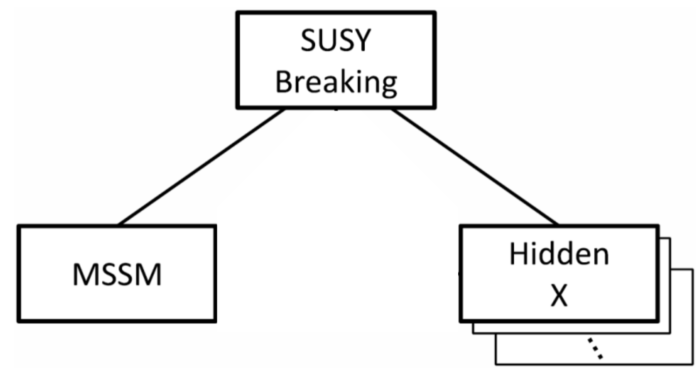
Feng, Kumar (2008)

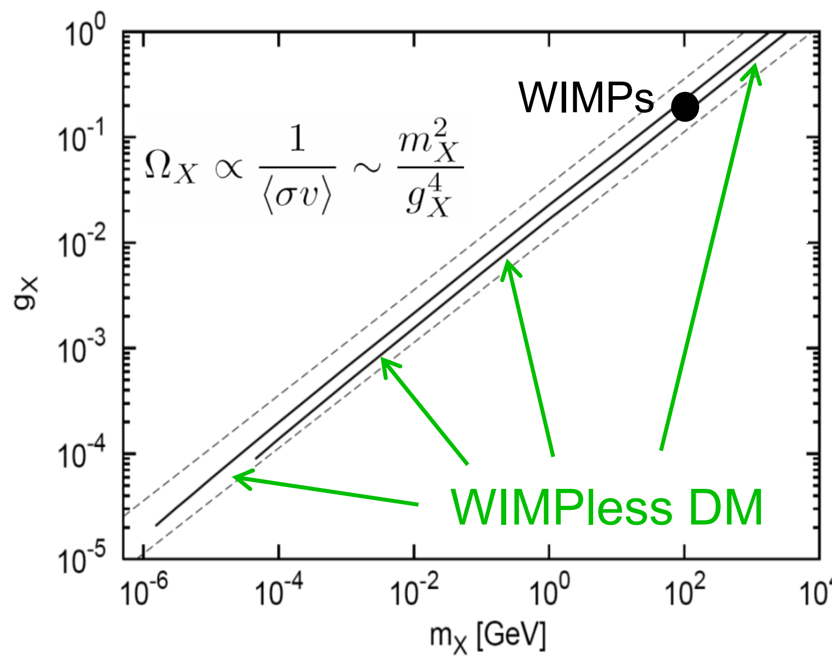
- Can we recover the WIMP miracle in a hidden sector?

- In many SUSY models (GMSB, AMSB), to avoid unseen flavor effects, superpartner masses satisfy

$$m_X \sim g_X^2$$

- If this holds in a hidden sector, we have a "WIMPless Miracle": hidden sectors of these theories automatically have DM with the right Ω (but they aren't WIMPs)

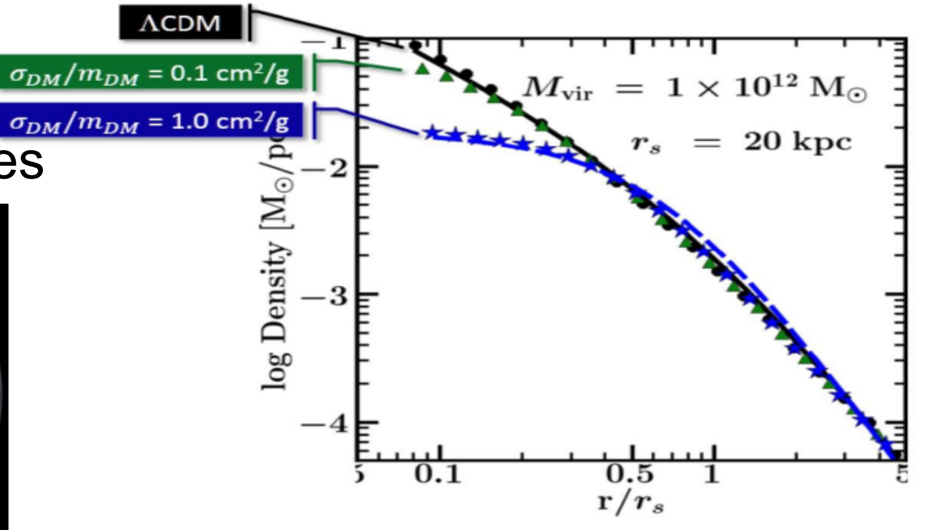




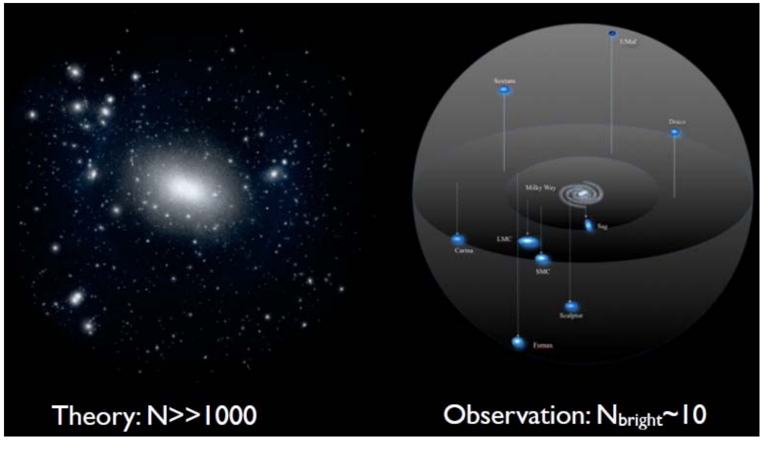
SELF-INTERACTING DARK MATTER

- The Bullet Cluster provided evidence for DM. Since it passed through unperturbed → $\sigma_T/m < 1\ cm^2/g$ (~ 1 barn/GeV)

- But there are indications that the self-interactions may be near this limit
  - Cusps vs. cores
  - Number of visible dwarf galaxies



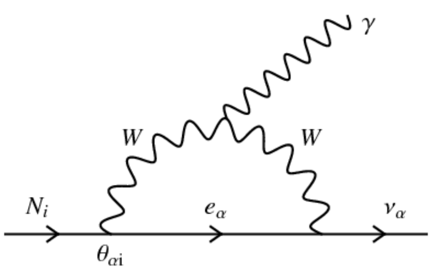
Rocha et al. (2012), Peter et al. (2012)
Vogelsberger et al. (2012); Zavala et al. (2012)

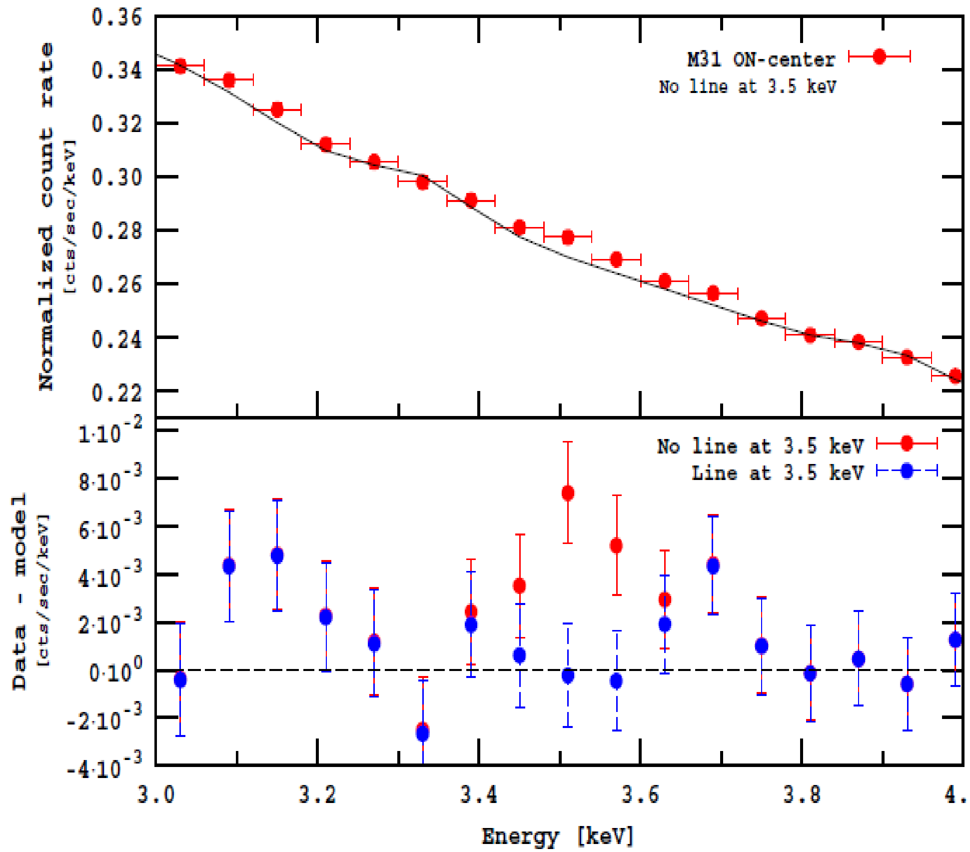


3.5 KEV LINE

- There is evidence of a 3.5 keV X-ray line being emitted from galaxies and galaxy clusters

- The default DM explanation is sterile neutrino decay: N → νγ





Boyarsky, Ruchayskiy, Iakubovskyi, Franse (2014)
Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall (2014)
but see also Riemer-Sorensen (2014), others

MODELS

- None of the indications for exotic DM is completely compelling on its own. But can we find a simple model where dark matter:

  Has the right relic density through the WIMPless miracle?

  Self-interacts with the right cross section?

  Explains the 3.5 keV line?

SIMPle DARK MATTER

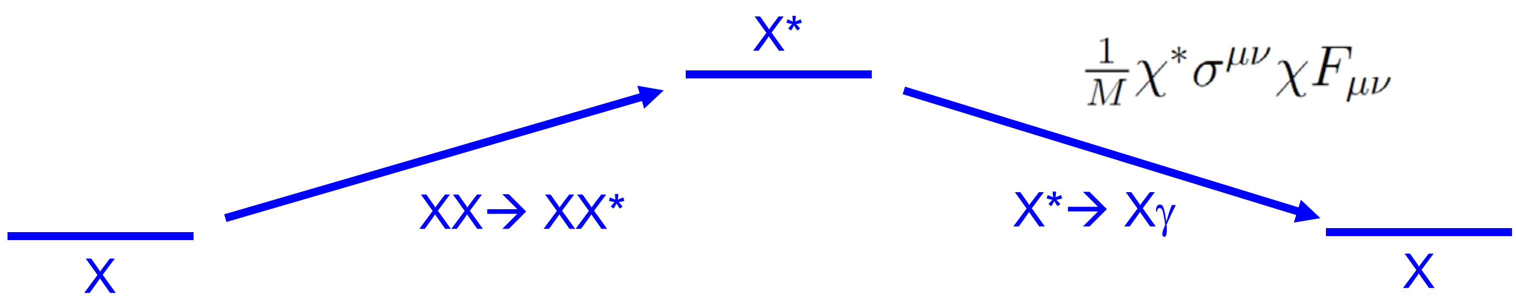
Boddy, Feng, Kaplinghat, Shadmi, Tait (2014)

- In fact, we can put all of these together in a simple theory: a pure SU(N) SUSY hidden sector with only hidden gluons g and gluinos $\tilde{g}$
- At early times, the interaction is weak, the gluinos with m ~ TeV freeze out with correct Ω, in accord with the WIMPless miracle
- Then the Universe cools, the theory confines at Λ ~ 100 MeV, forming glueballs (gg) and glueballinos ($g\tilde{g}$)
- The glueballinos self-interact through glueball exchange with $\sigma_T/m \sim 1\ cm^2/g$

SIMPle DARK MATTER

- Such a system has a glueballino spectrum with hyperfine splitting $\Lambda^2/m \sim 10$ keV (cf. $\alpha^4\, m_e^2/m_p$ for Hydrogen)

- X* created in collisions with $m_X v^2 > \Delta m$



Finkbeiner, Weiner (2007, 2014)

- Adding a dipole operator, the excited state can decay to the ground state and a 3.5 keV photon; the 3.5 keV line is the "21 cm line" for DM

Cline, Farzan, Liu, Moore, Xue (2014)

CONCLUSIONS

- WIMPs remain interesting and there has also been a recent proliferation of other dark matter ideas
- Indirect detection plays an essential role in probing these dark matter candidates
- With AMS, other indirect searches, direct detection, and cosmological probes improving rapidly, and the LHC coming back on-line, these are exciting times for dark matter