Dark Matter
Lecture 3: Astrophysical and Cosmological Indirect Searches

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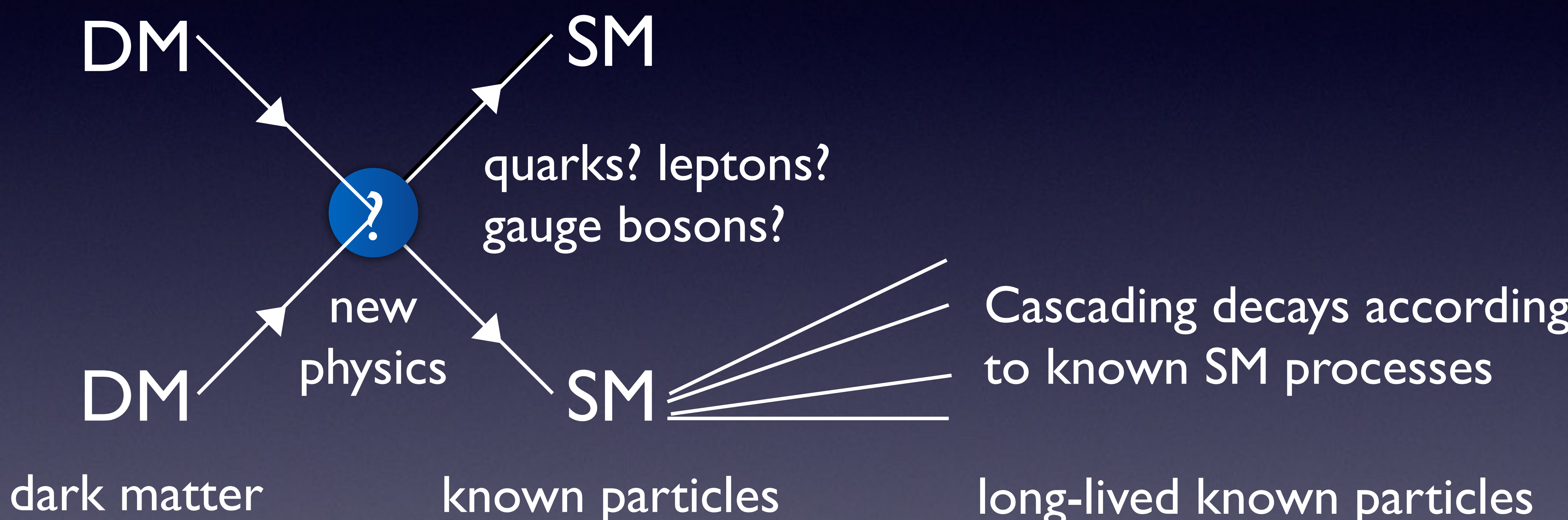
Summary of Lectures 1-2

- Dark matter is constrained to be fairly <u>cold</u> and (almost?) <u>collisionless</u>.
- There are many ideas for its properties - we talked about WIMPs and axions:
  - WIMPs - heavy, weakly interacting particles.
    - Relic abundance from thermal production and freezeout, controlled by annihilation to Standard Model.
    - Well-motivated in scenarios like SUSY.
  - Axions - very light particles that form a low-momentum condensate.
    - Motivated by the strong CP problem of the Standard Model.
    - Abundance controlled by "misalignment angle" and axion mass.

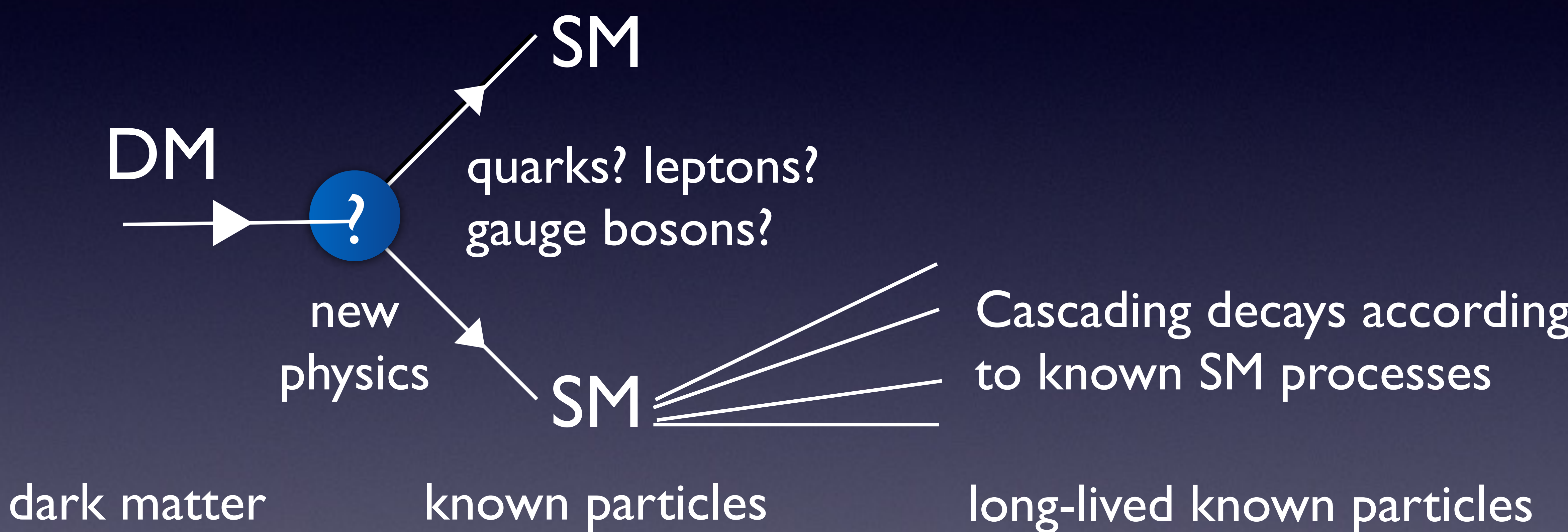
Light from dark matter?

- So far:
  - probes of dark matter that are largely <u>independent</u> of its interactions with known particles.
  - theoretical frameworks for dark matter models
- This time: searching for the visible byproducts of cosmological dark matter interacting with other DM particles or the SM ("indirect detection")
- Next time: using Earth-based experiments to observe the interactions of DM particles and SM particles directly.

Annihilation



Decay



- From a model-building perspective, quite different from annihilation
- But from a phenomenological perspective, major difference is how the signal varies with changing dark matter density

Categorizing indirect searches

- By origin:

annihilation, decay, de-excitation, 3+-body processes, processes that produce “dark” particles in addition to visible ones…

- By signature:

photons, neutrinos, positrons, antiprotons, antideuterons, secondary effects (wide category - effects on stellar structure, cosmic ionization history, etc)…

- By target region (primarily relevant for photons/neutrinos):

dwarf galaxies? clusters? the Galactic Center? the halo of the Milky Way? the ~isotropic background radiation?

Phenomenology

- From an observational perspective we care about:
  - Spectra (and species) of visible products
  - How the rate changes with dark matter density (decay with a long lifetime scales like density, annihilation like density^2, etc)
  - If the rate has any other non-trivial dependences, e.g. on velocity, temperature, cosmic time, environment.
    - p-wave annihilation: $\langle \sigma v \rangle \propto v^2$
    - decay of a metastable species: decay rate $\propto e^{-t/\tau}$
    - collisions with another species: depends strongly on abundance of other species

Direct indirect detection

- Searches for the actual particles produced by DM interactions. One major subdivision is between charged and neutral particles.

CHARGED

diffuse in Galactic magnetic fields

hard to recover source locations, measure only local spectrum

- Hadrons have long cooling times; can diffuse throughout the Galaxy. Local measurements probe volume of Milky Way.
- Electrons and positrons cool quickly, by synchrotron radiation and scattering on ambient photons. Local measurements probe a volume ~1kpc around the Earth, for few-GeV electrons - less at higher energies.

NEUTRAL

propagate directly to Earth (modulo absorption, lensing)

recover at least 2D spatial information on sources (projected along line of sight)

in some cases can recover 3D information (e.g. due to redshifting of spectral line)

Indirect indirect detection

- Model the effects of Standard Model particles produced/absorbed by dark matter interactions. Many examples, here are just a handful:
  - Changes to nucleosynthesis due to injection of energetic particles (e.g. Jedamzik & Pospelov 0906.2087)
  - Distortions to the energy spectrum of the cosmic microwave background (e.g. Chluba & Jeong 1306.5751, Ali-Haimoud et al 1506.04745)
  - Modifications of stellar structure/evolution (e.g. Iocco et al 0805.4016, see also Vincent et al 1504.04378)
  - Ionization and heating of the intergalactic medium in the early universe (to be discussed later)

Case studies

- A "direct" indirect search: photon searches in three energy bands
  - A gamma-ray excess in the Galactic Center
  - Gamma-ray line searches and the 3.5 keV X-ray line
  - Along the way: best current indirect bounds on weak-scale thermal relic dark matter
- An "indirect" indirect search: constraining early DM annihilation with Planck.
  - Along the way: the PAMELA/Fermi/AMS-02 positron excess
- Other searches I would like to discuss, but will avoid due to time limits (not a complete list):
  - Antideuterons - near-background-free cosmic ray search (see GAPS experiment page, http://gamma0.astro.ucla.edu/gaps/)
  - IceCube neutrinos (see IceCube collaboration papers)
  - Photon anisotropy searches, the extragalactic background light, searches for photon signals from the Milky Way halo, searches for subhalos shining due to annihilation (a very tentative hint may already exist here), etc…

(some) photon searches

Gamma-ray telescopes

- 30 MeV - 100 GeV: Fermi Gamma-Ray Space Telescope, launched in 2008, scans the full sky every 3 hours, effective area ~$1 m^2$, energy resolution ~5-10%, angular resolution ~1 (0.1) degree above 1 (10) GeV. All data is public.
- 100 GeV+:
    - Ground-based Air Cherenkov Telescopes (HESS, VERITAS, MAGIC): small field of view (several degrees), energy resolution ~20%, 0.1 degree angular resolution, large effective area (10^{5-6} m^2).
    - HAWC: ground-based Water Cherenkov Observatory. Large field of view (scans 2/3 of the sky every 24 hours), and comparable effective area and angular resolution to the ACTs (but worse energy resolution). Exceeds ACT sensitivity above ~10 TeV.

Dwarfs vs the Galactic Center

- Dwarf galaxies are dark-matter-dominated and should have low background.
- But if the Milky Way has a cusp, Galactic Center should be much brighter.
- Summarize expected brightness by "J-factor", integrated density^2 along line of sight (or integrated density for decay):

$$J(l,b) = \int_0^\infty ds \rho^2 \left(\sqrt{s^2 + r_\odot^2 - 2 r_\odot s cos(l) cos(b)} \right)$$

$$J = \int d\sin(b) dl J(l,b)$$

l, b describe angles from the line-of-sight to center of (here assumed spherical) object
Galactic "longitude" and "latitude" for GC searches

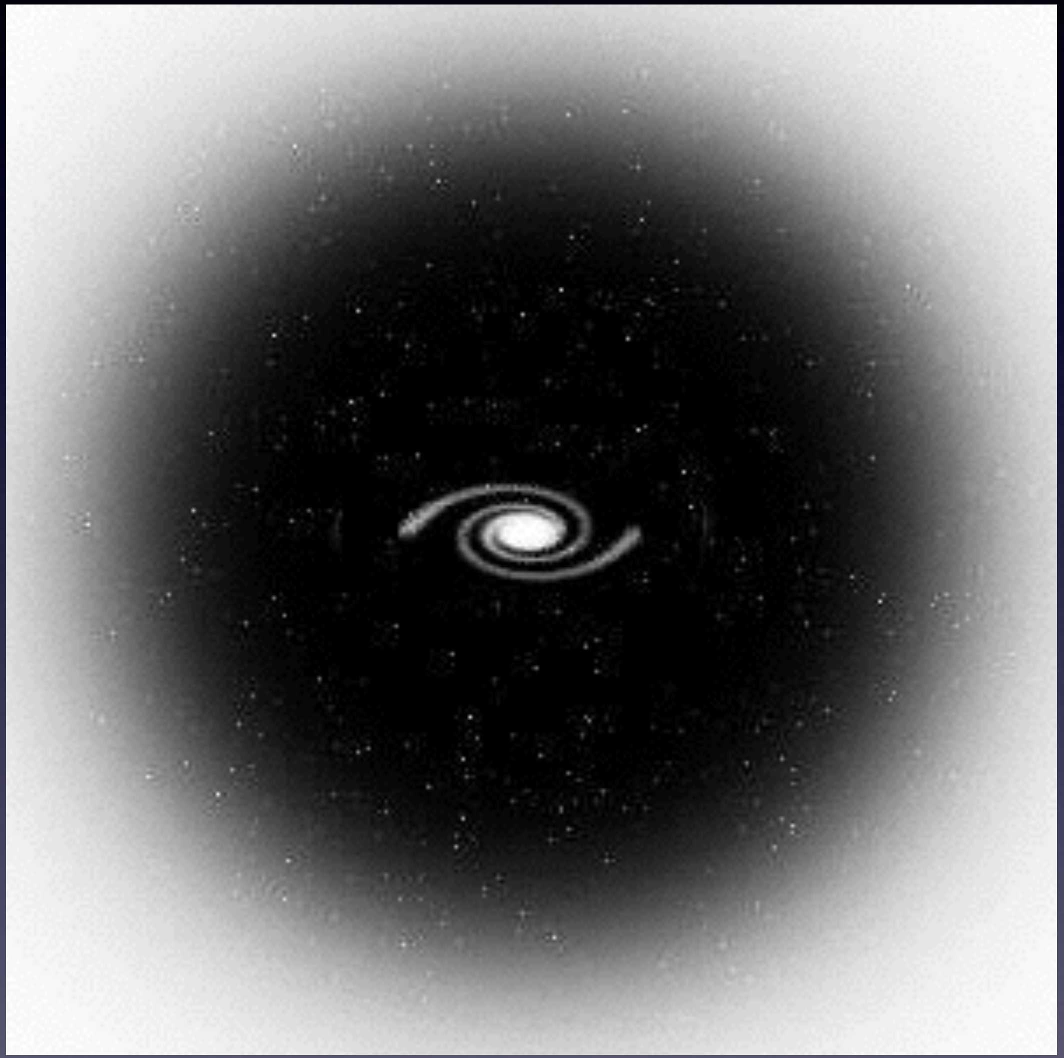
- For region within 10 degree x 10 degree box around Galactic Center, with classic NFW cusp, J ~ 10^{22} GeV^2/cm^5.
- For the closest/biggest of the dwarf galaxies, J ~ $10^{19\text{-}20}$ GeV^2/cm^5.

Bright signal, or low background?

- Galactic center:
  - High sensitivity - if there is any kind of cusp, expect to see a signal here first.
  - High statistics $\Rightarrow$ more detailed study of properties of any signal.
  - High background - critical to use spectral and/or spatial information to disentangle signal from background.
- Dwarfs:
  - Low background $\Rightarrow$ detection of a DM-like signal would be more convincing, all else being equal.
  - J-factor for whole dwarf doesn't depend strongly on cusp vs core - more robust limits.
  - Can use multiple dwarfs to cross-check results.

Spatial shape of a signal

- Rotation curves: DM should have a roughly spherical distribution, not following the Galactic plane.
- The signal scales as DM density squared since annihilation is a two-particle process.
- As yesterday we use a simulation-motivated NFW profile for the Galactic Center.
- In dwarf galaxies, angular resolution of Fermi = dwarfs are nearly pointlike in gamma rays, profile not important.



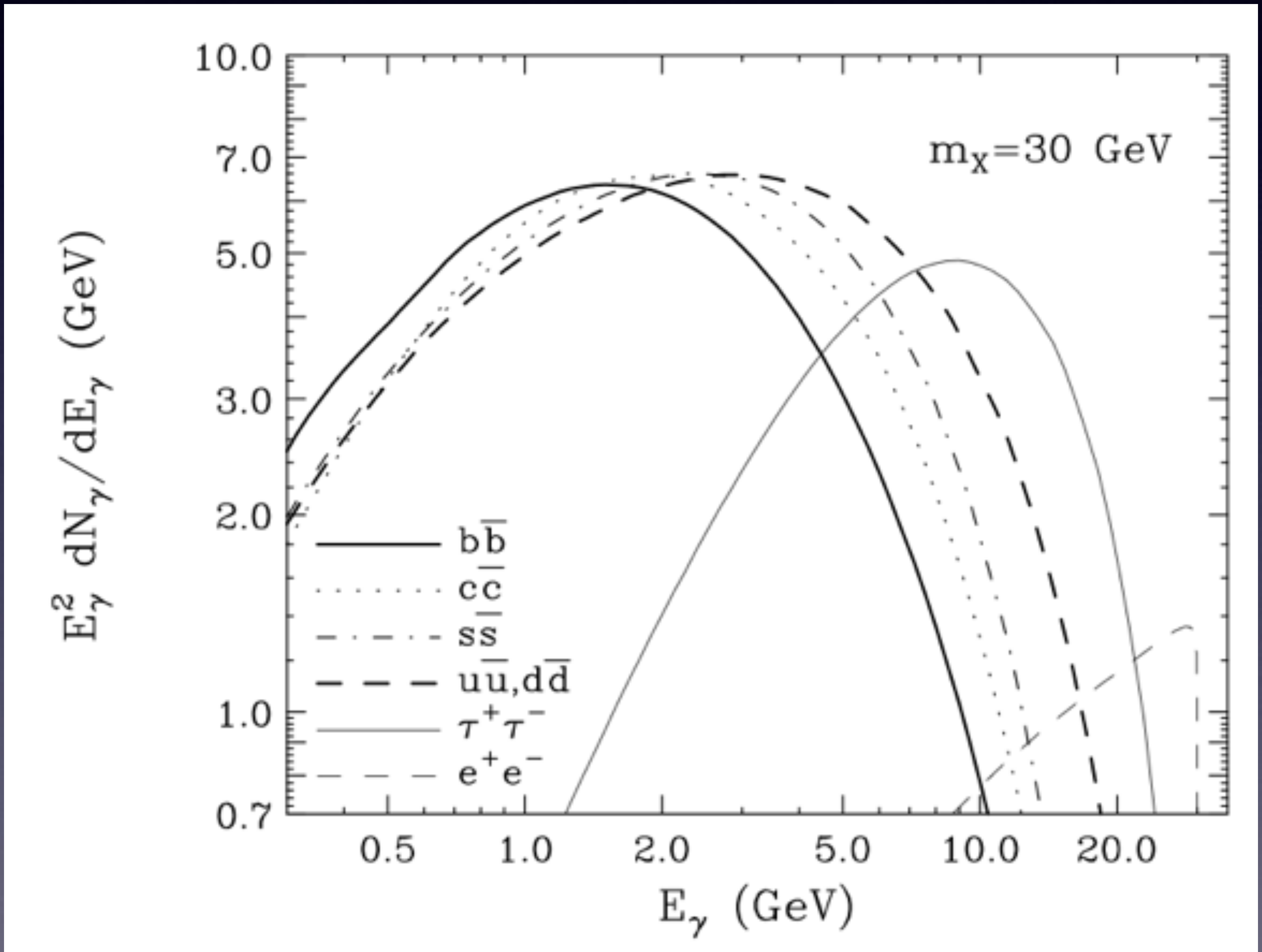
$$\boxed{\rho \propto \frac{r^{-\gamma}}{\left(1+\frac{r}{R_s}\right)^{3-\gamma}}}$$

$\gamma = 1$ for classic NFW, but allow it to float as small-r DM density profile is uncertain - core/cusp!

"Scale radius" r_s ~ 20 kpc for Milky Way, large-r behavior matches rotation curves

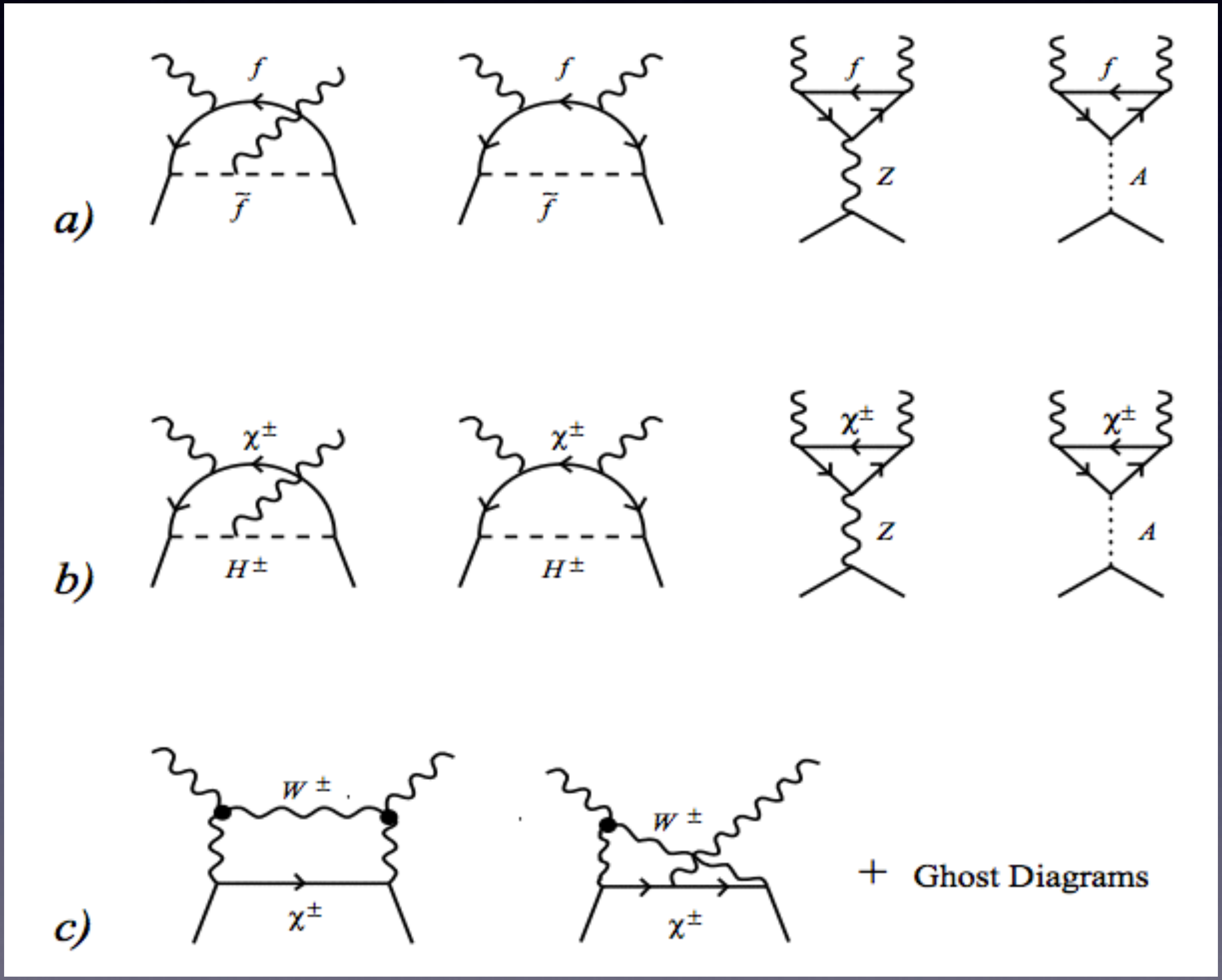
Spectral shape of a signal

- Can be predicted in any given DM model, but in general can vary widely.
- Typically has a “bump” with scale set by the DM mass.
- Astrophysical backgrounds are usually power-law-like.
- However, some classes of astrophysical point sources have bump-like features or cutoffs.



Spectral lines as smoking guns

- A gamma-ray spectral line at the dark matter mass is very hard to mimic with astrophysical backgrounds.
- However, DM cannot couple directly to photons.
- Generally suppressed by ~3+ orders of magnitude relative to tree-level annihilation.

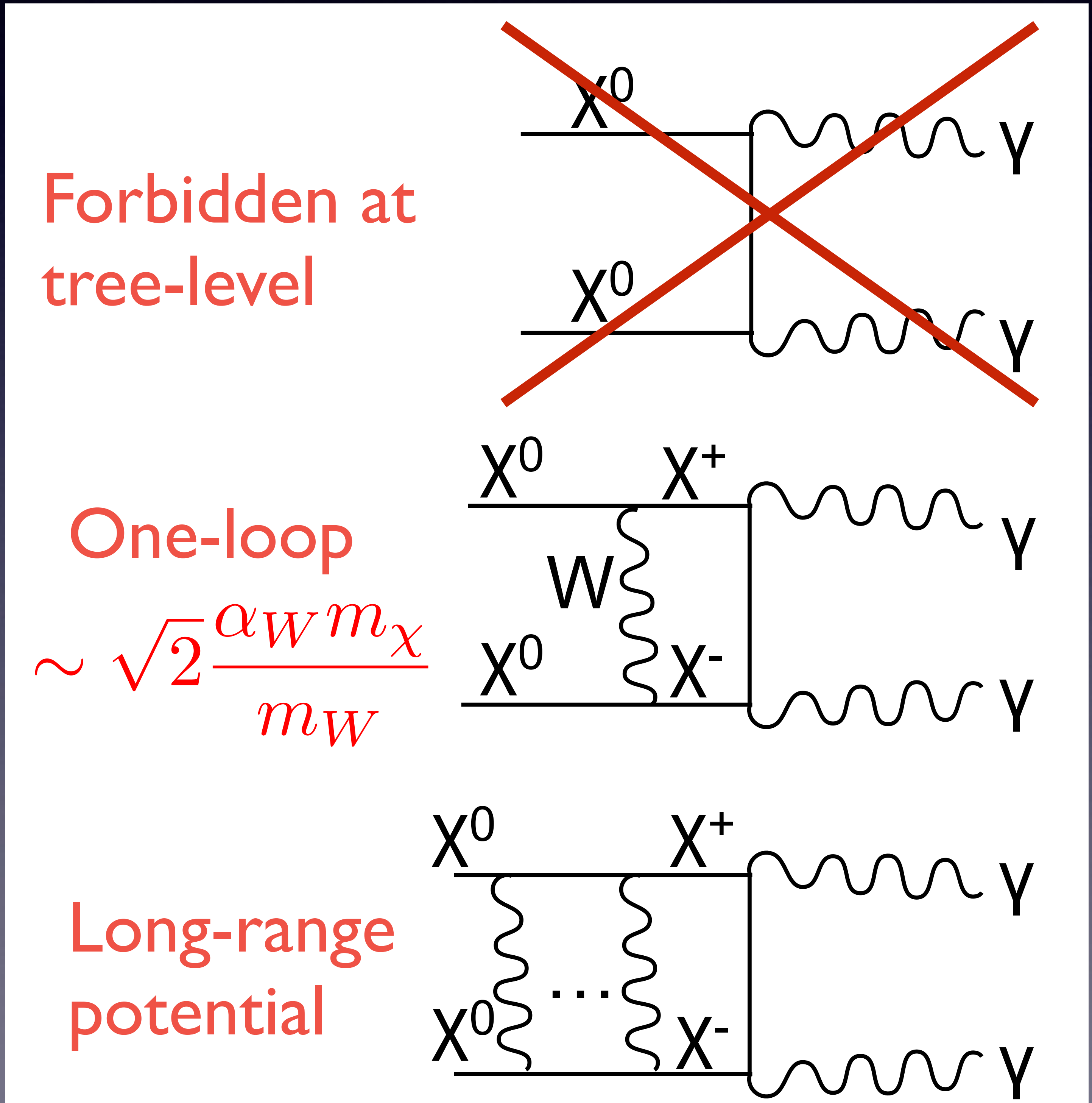


Jungman and Kamionkowski, hep-ph/9501365

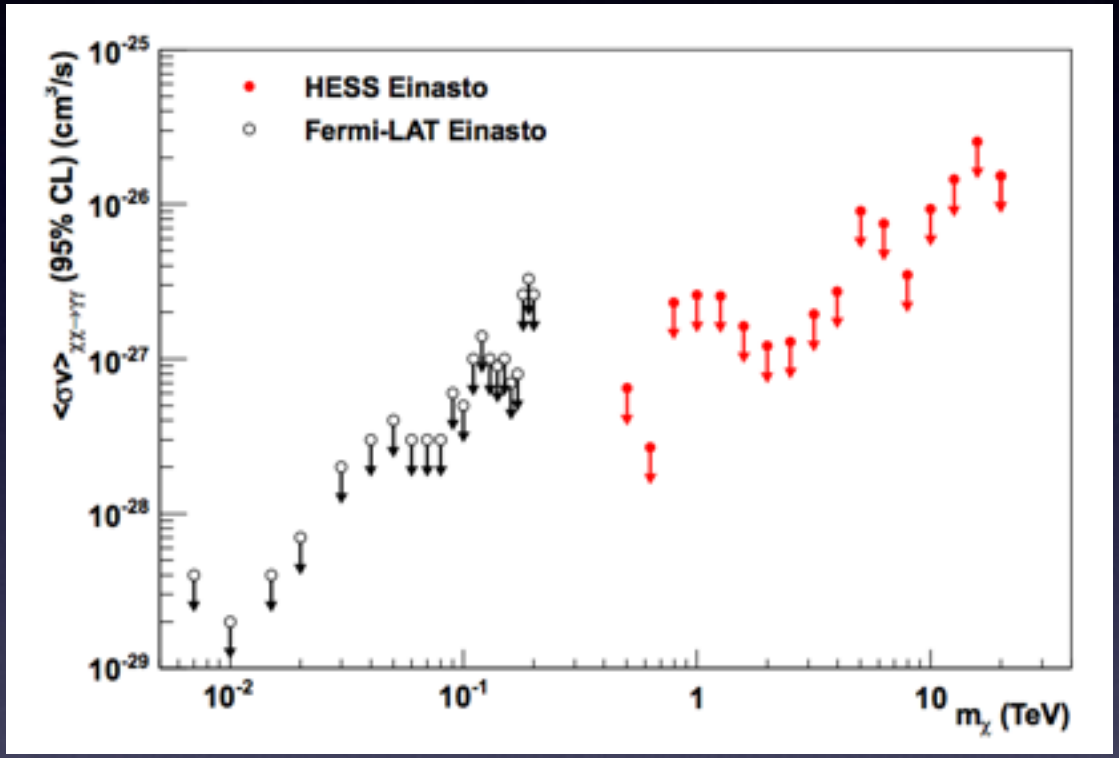
Line searches and heavy DM

- For heavy dark matter, can benefit from “Sommerfeld enhancement” of annihilation signal.
- Coupling to a lighter particle can mediate a long-range attractive force, enhancing annihilation.
- Cross section can become close to (enhanced) tree-level in some circumstances.

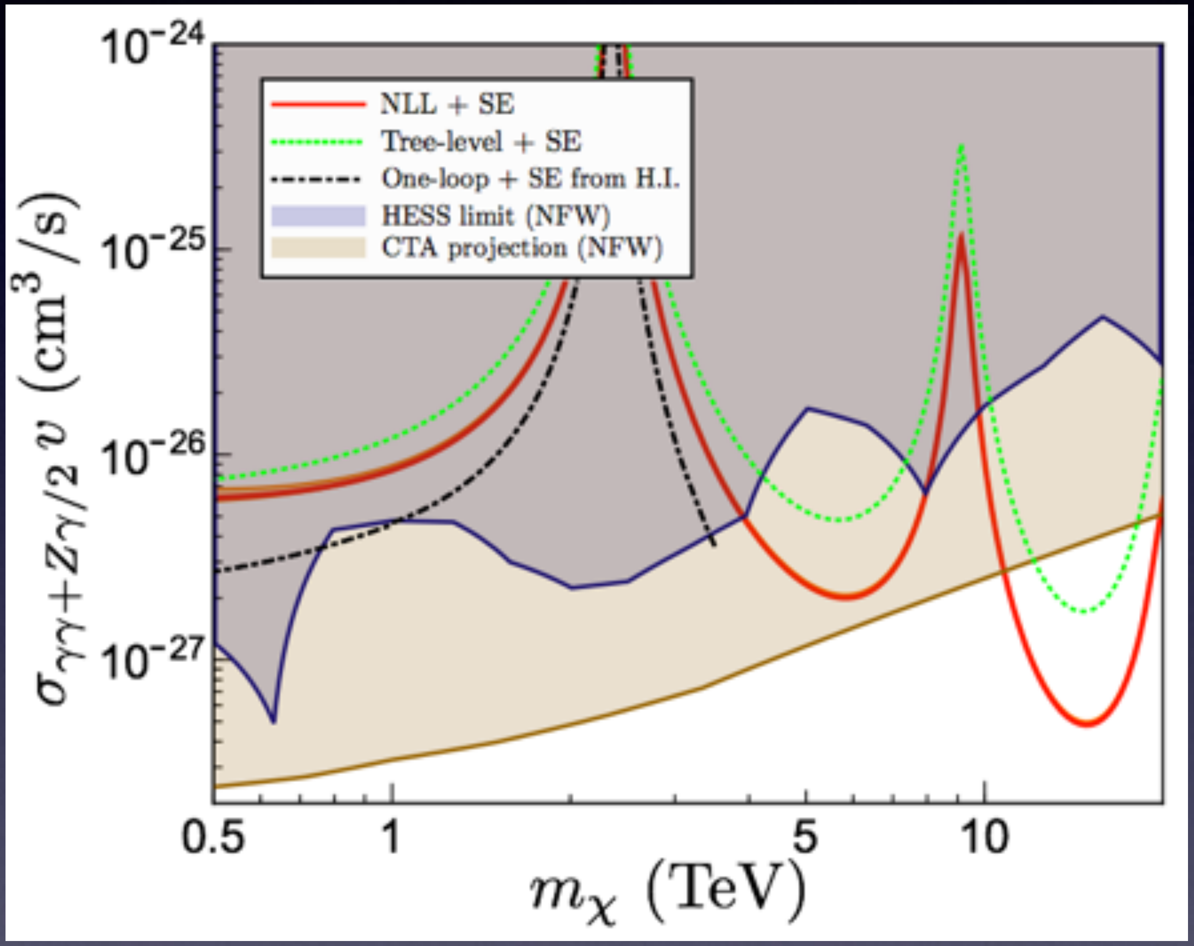
Example: wino-like dark matter



Example of line constraints for wino DM



HESS Collaboration '13 (1301.1173)

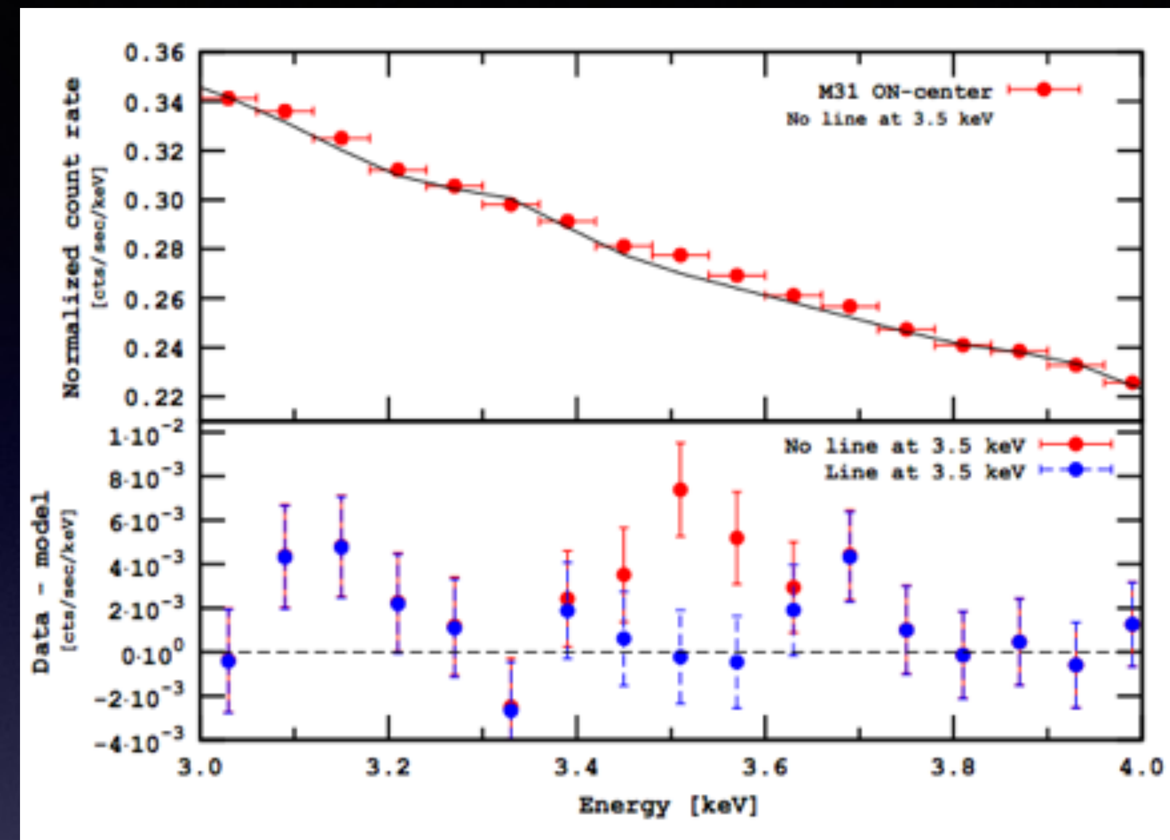


Ovanesyan et al '14

- Example of line cross section limits from Galactic Center (left), compared to theoretical prediction from pure wino dark matter (right, red line).
- Brown region in right plot is projected limit from upcoming CTA experiment (~2020).

A line at a different scale

- 3.5 keV X-ray spectral line: initial discovery in XMM-Newton data by Bulbul et al (1402.2301) and Boyarsky et al (1402.4119), at ~4σ significance.



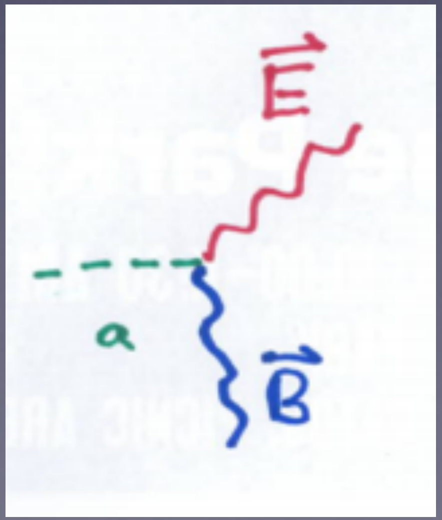
- Follow-up observational studies by:

Riemer-Sorenson (1405.7943, MW with Chandra data)
Jeltema & Profumo (1408.1699, MW)
Boyarsky et al (1408.2503, MW center)
Malyshev et al (1408.3531, dwarf spheroidal galaxies)
Anderson et al (1408.4115, stacked galaxies with Chandra and XMM-Newton)
Urban et al (1411.0050, Suzaku)
Tamura et al (1412.1869, Suzaku)

	XMM-Newton	Chandra	Suzaku
Milky Way center	✓	×	
Andromeda galaxy	?		
Perseus cluster	✓	✓	?
Coma, Virgo, Ophiuchus	✓	× studied Virgo only	×
Stacked clusters	✓		
Stacked galaxies	×	×	
Milky Way dwarfs	×		

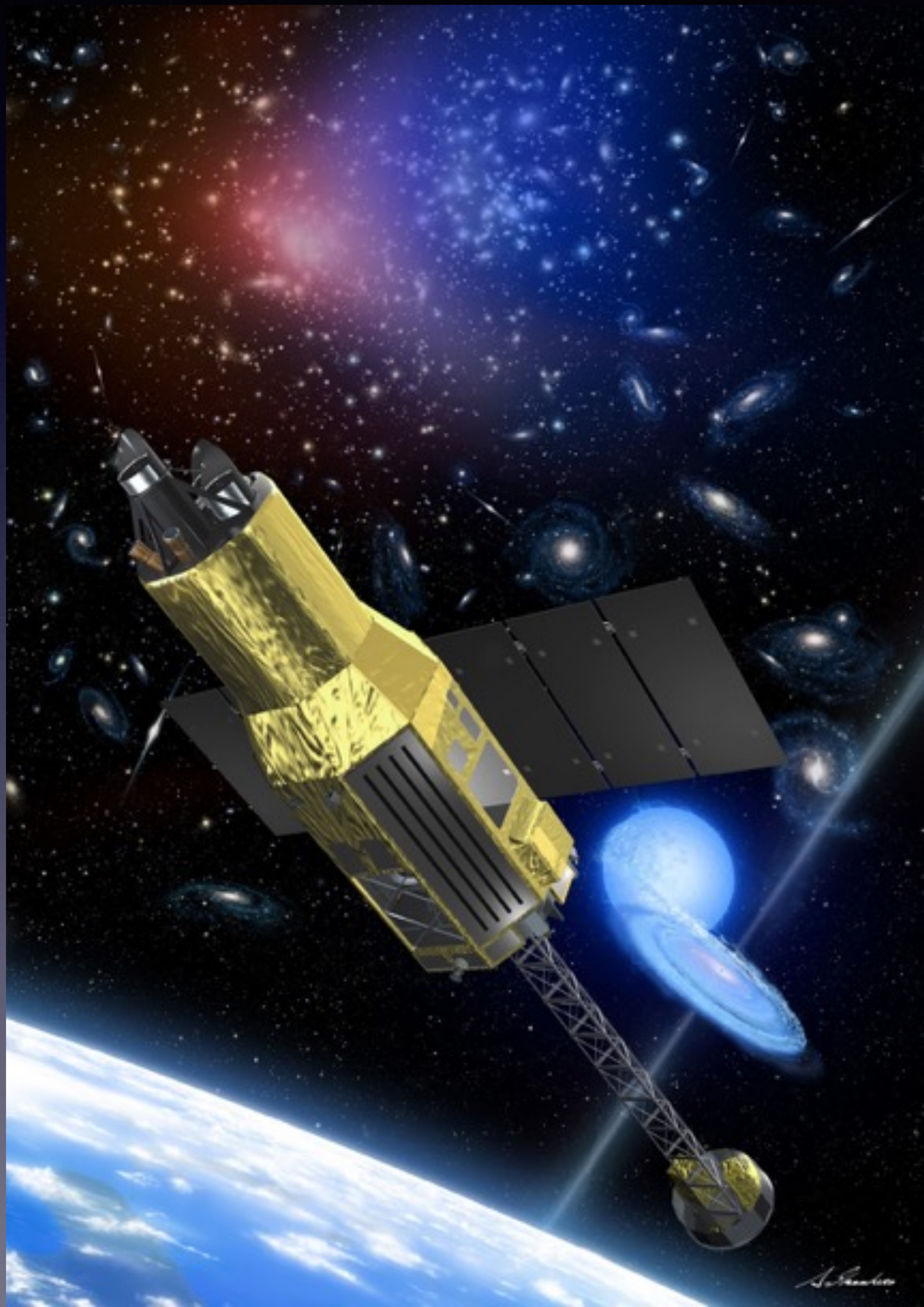
DM interpretations

- Simplest DM explanation is decaying sterile neutrino at a mass around 7 keV - long-standing DM candidate.
- However, simple DM decay models appear ruled out (at 12σ) by non-detection in dwarfs and stacked galaxies (1411.1758 also claims Perseus and Galactic Center morphologies are incompatible with DM decay).
- DM alternatives include exciting dark matter (Finkbeiner & Weiner 1402.6671, Cline & Frey 1410.7766)
  - DM has a metastable excited state 3.5 keV above the ground state.
  - This state is excited by DM-DM collisions, and subsequently decays producing a photon.
  - Rate of excitation scales as density^2 x velocity dependence - much less constrained than just DM density, seems to allow compatibility with data.
- Another possibility is conversion of an axion-like particle to an X-ray photon in the presence of magnetic fields (e.g. 1404.7741) - can lead to widely varying signals from different systems (e.g. 1410.1867).



Possible backgrounds

- Ongoing controversy over possible contamination from potassium and chlorine plasma lines - a spectral line at a few keV is much easier to mimic than a gamma-ray line (see e.g. 1408.1699, 1408.4388, 1409.4143, 1411.1759)
- There are several known X-ray lines close to 3.5 keV and their strength can depend sensitively on the plasma temperature.
- Hope was that Astro-H experiment (launched earlier this year) would resolve this issue - but it broke up in orbit.
- Micro-X sounding rocket may be able to provide a test (Figueroa-Feliciano et al 1506.05519).



Continuum gamma-rays in the Galactic Center

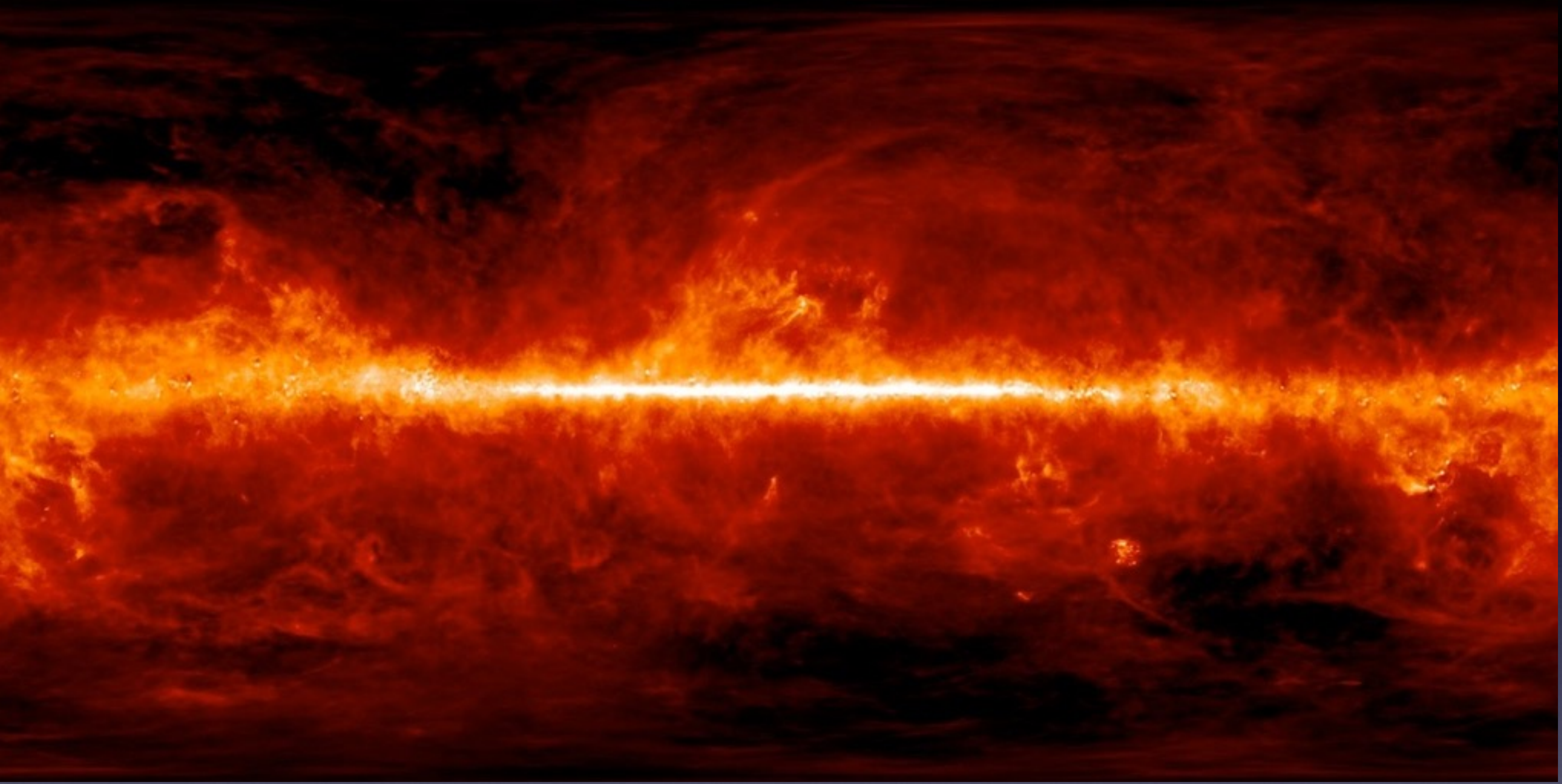
- In absence of line signal, need a way to estimate or parameterize backgrounds in the Galactic Center.
- At weak-scale energies, dominant backgrounds come from:
  - Cosmic ray protons striking the gas, producing neutral pions which decay to gammas.
  - Cosmic ray electrons upscattering starlight photons to gamma-ray energies.
  - Compact sources producing gamma-rays - pulsars, supernova remnants, etc.
- Backgrounds should roughly trace gas, starlight, star formation, supernovae, etc - all more common in the disk of the Milky Way.
- Physical processes are fairly well understood, but 3D distribution of gas/starlight/etc is not well measured.

The gas-correlated background

Video credit: NASA

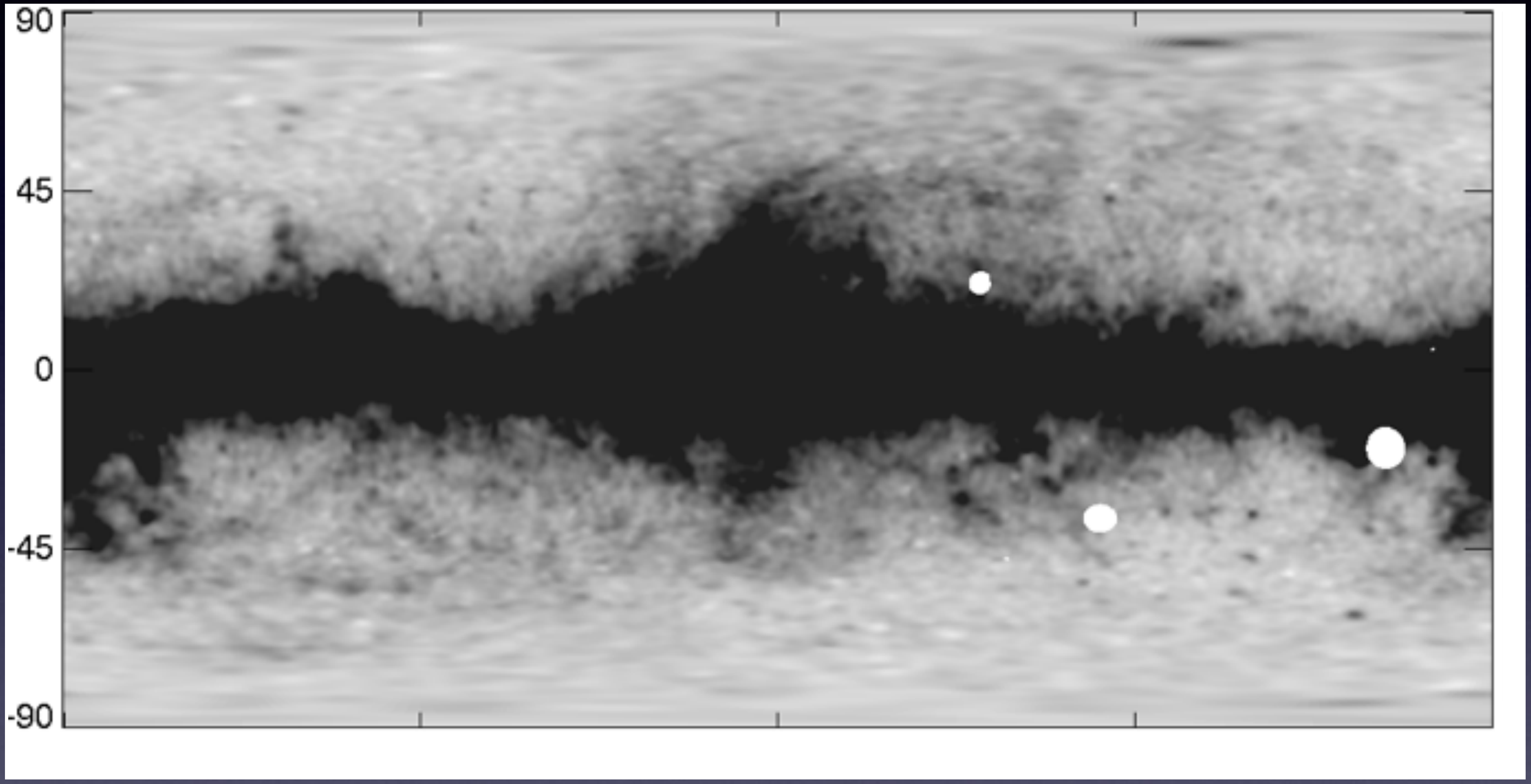
The gas-correlated background

Video credit: NASA



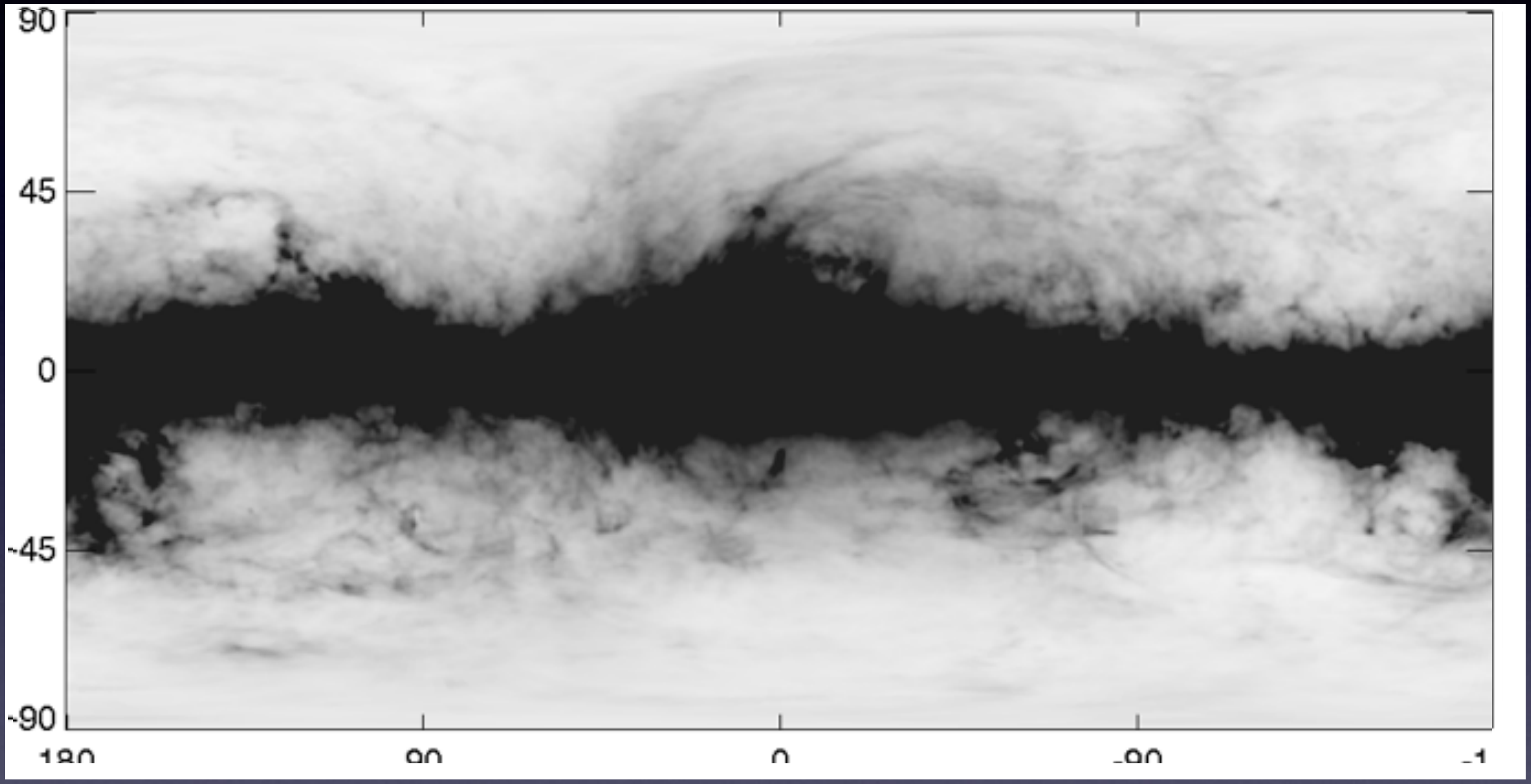
- Dominant background emission roughly traces the distribution of gas in the galaxy, other components depend on starlight distribution, sources of cosmic rays, etc.
- Very “disk-like” - brightest along the plane of the Galaxy.

Modeling the background



- Can build a model for the background incorporating maps of the gas + models for the cosmic-ray and radiation distributions, the latter e.g. based on the public GALPROP code.
- Some public models made available by the Fermi Collaboration; later models include ad hoc spatial templates to absorb large-scale discrepancies between data and model.
- Not restricted to gamma-rays; similar template methods have been used in the microwave sky to extract the CMB and probe possible DM signals.

Modeling the background



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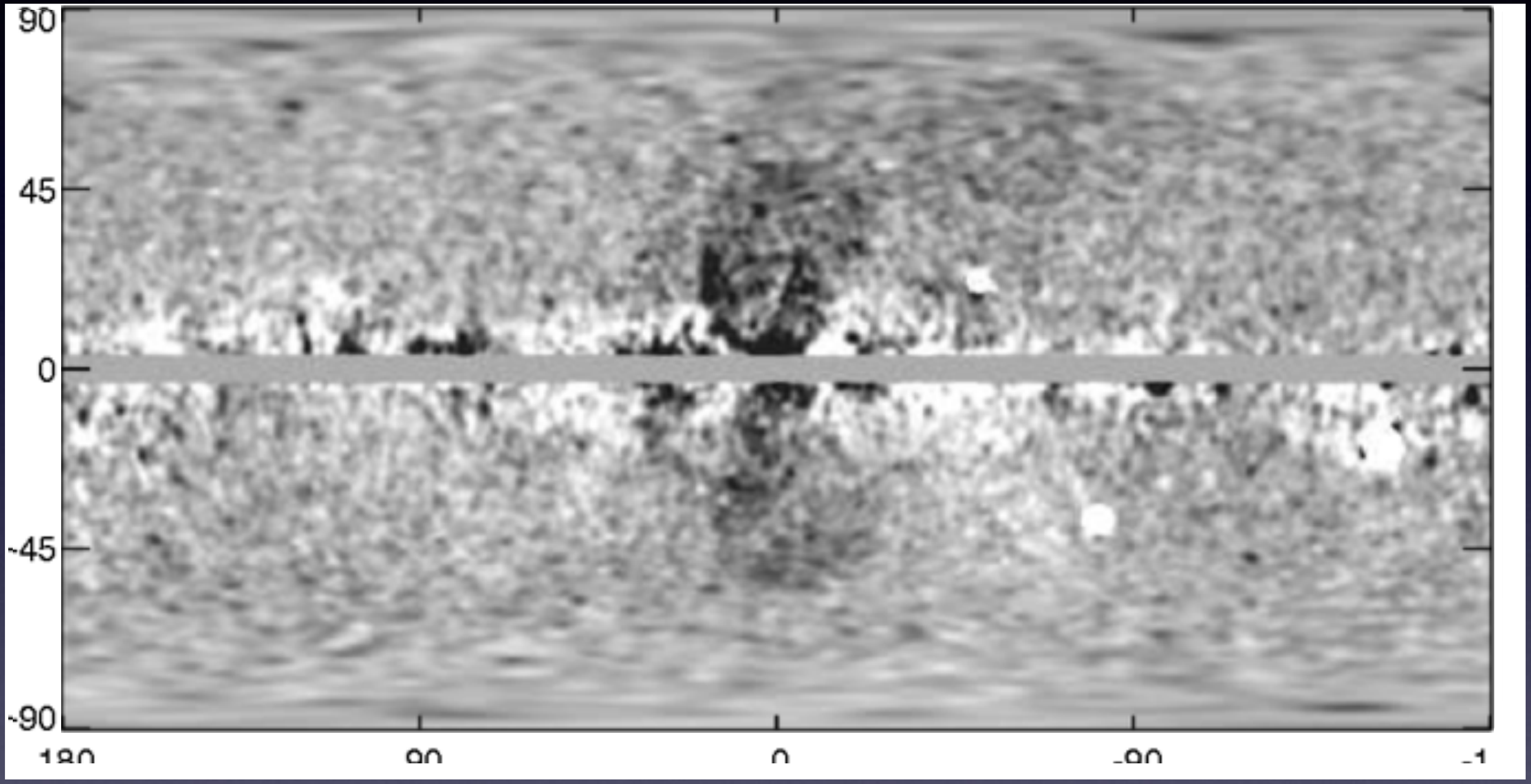

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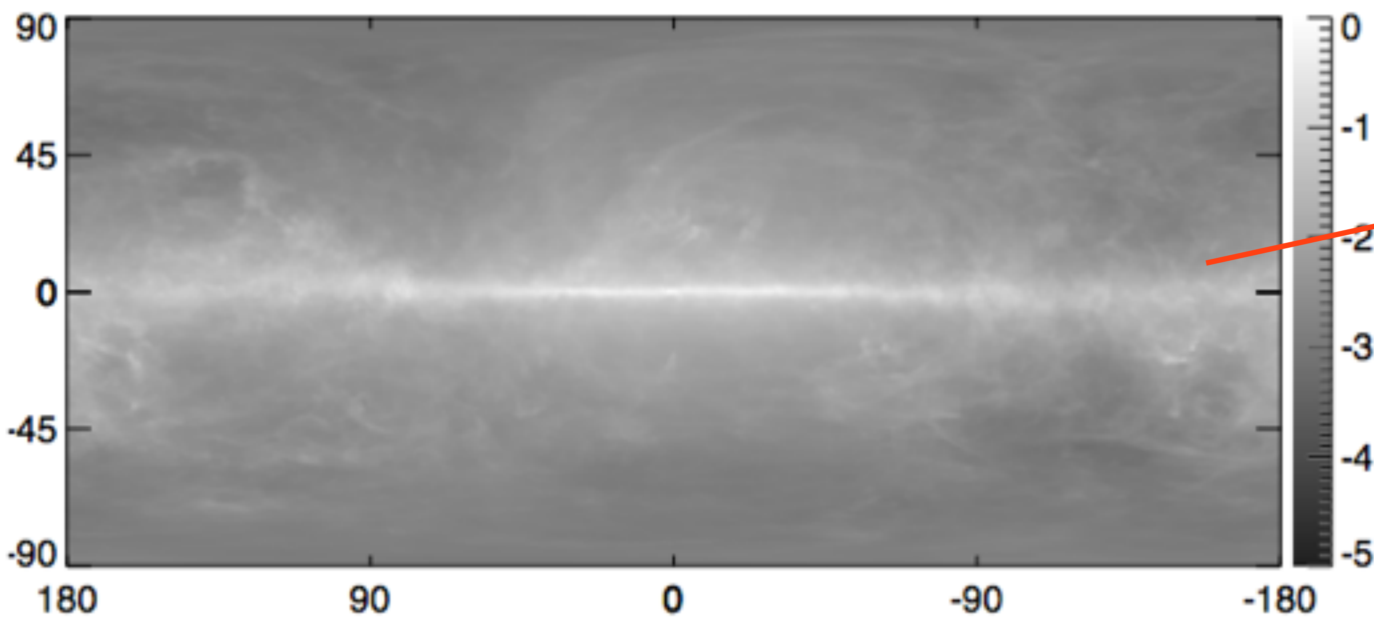
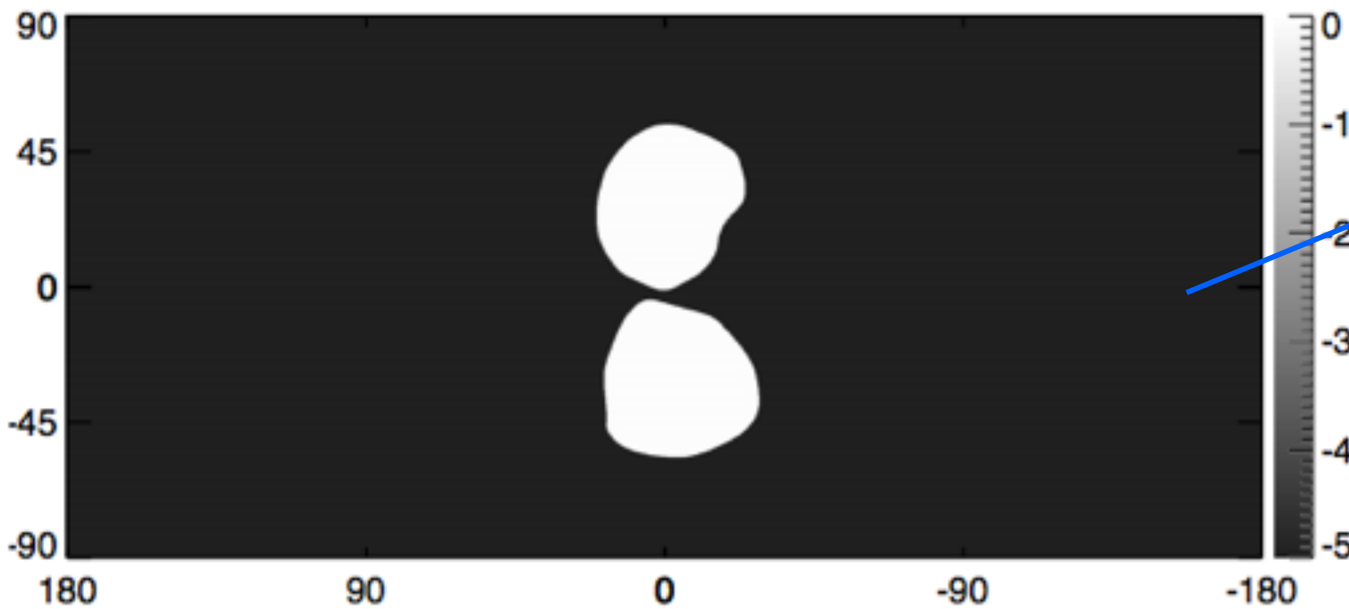
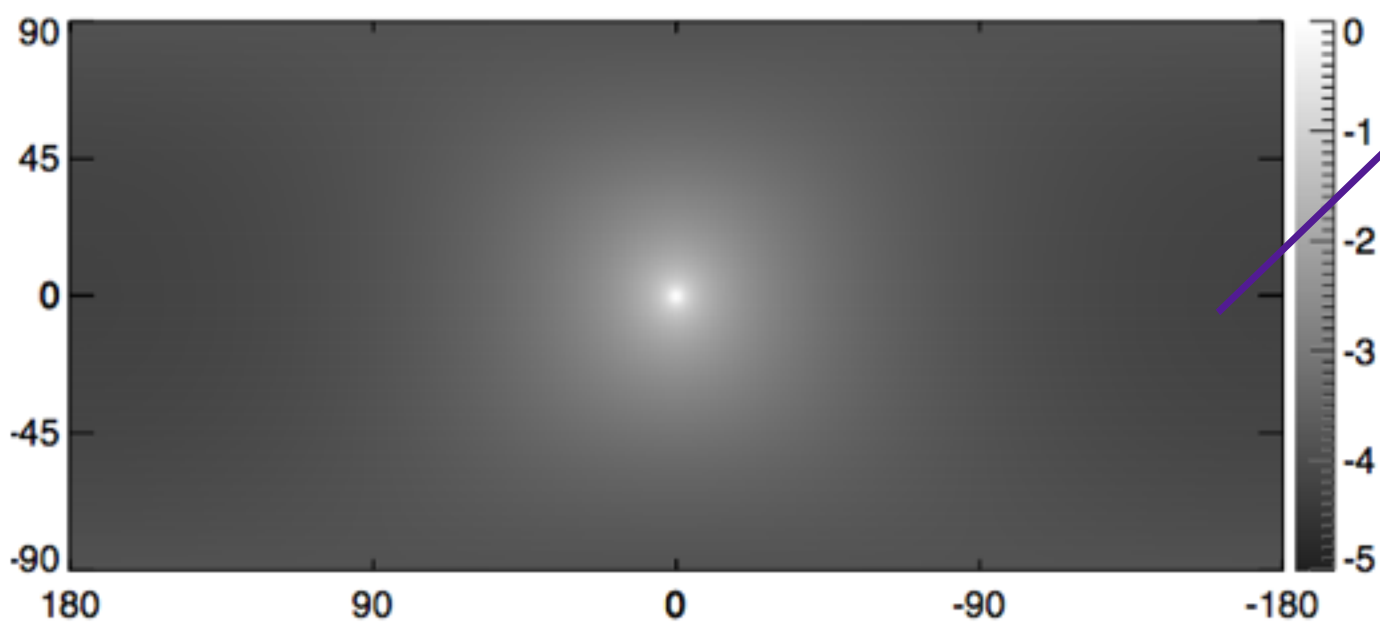
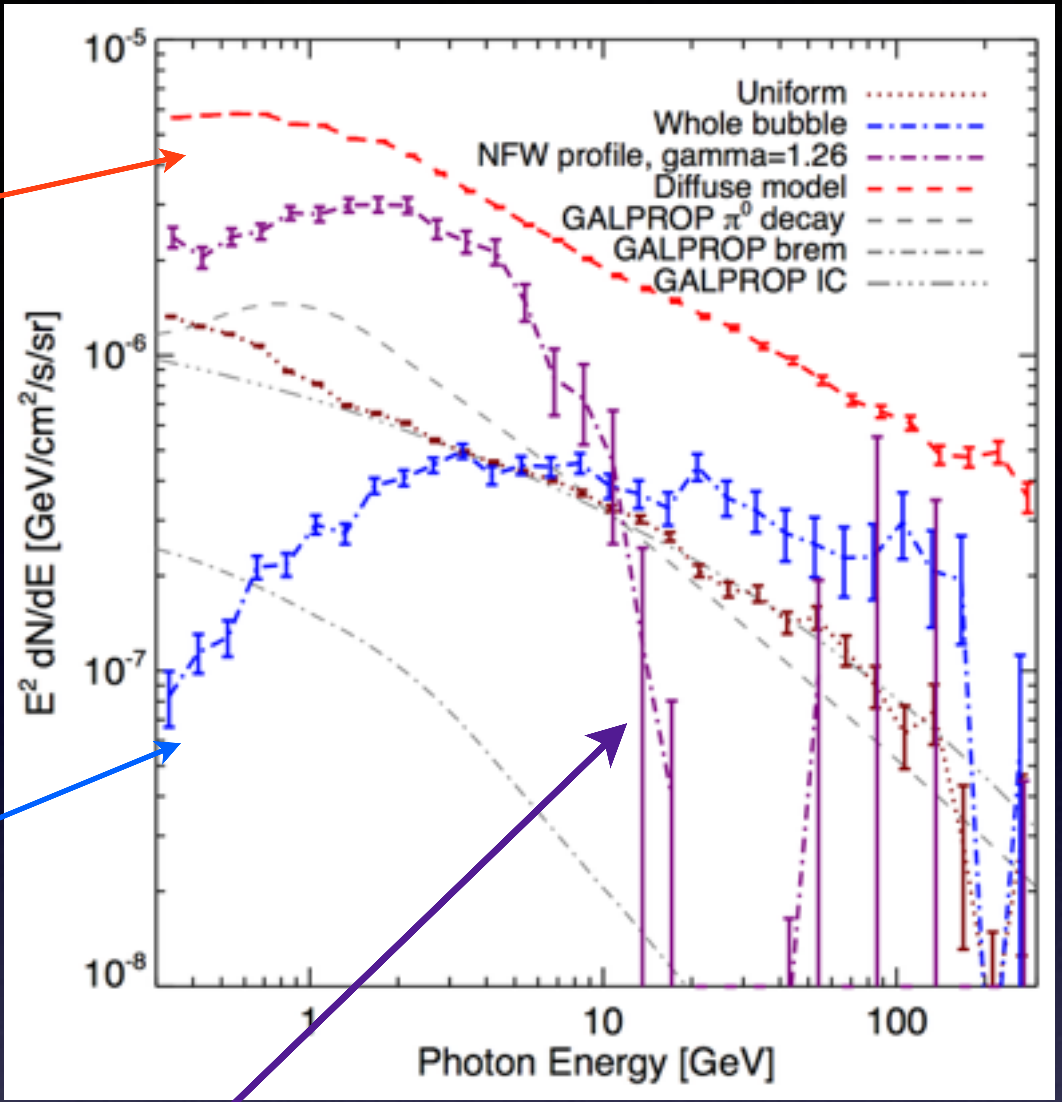




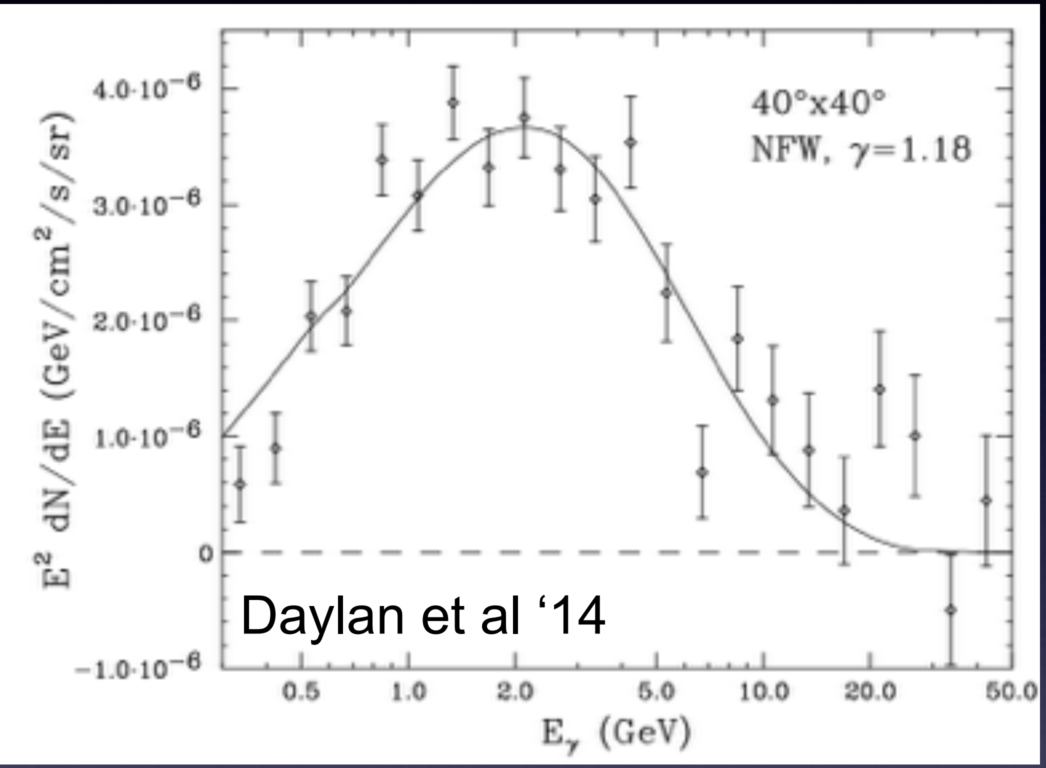


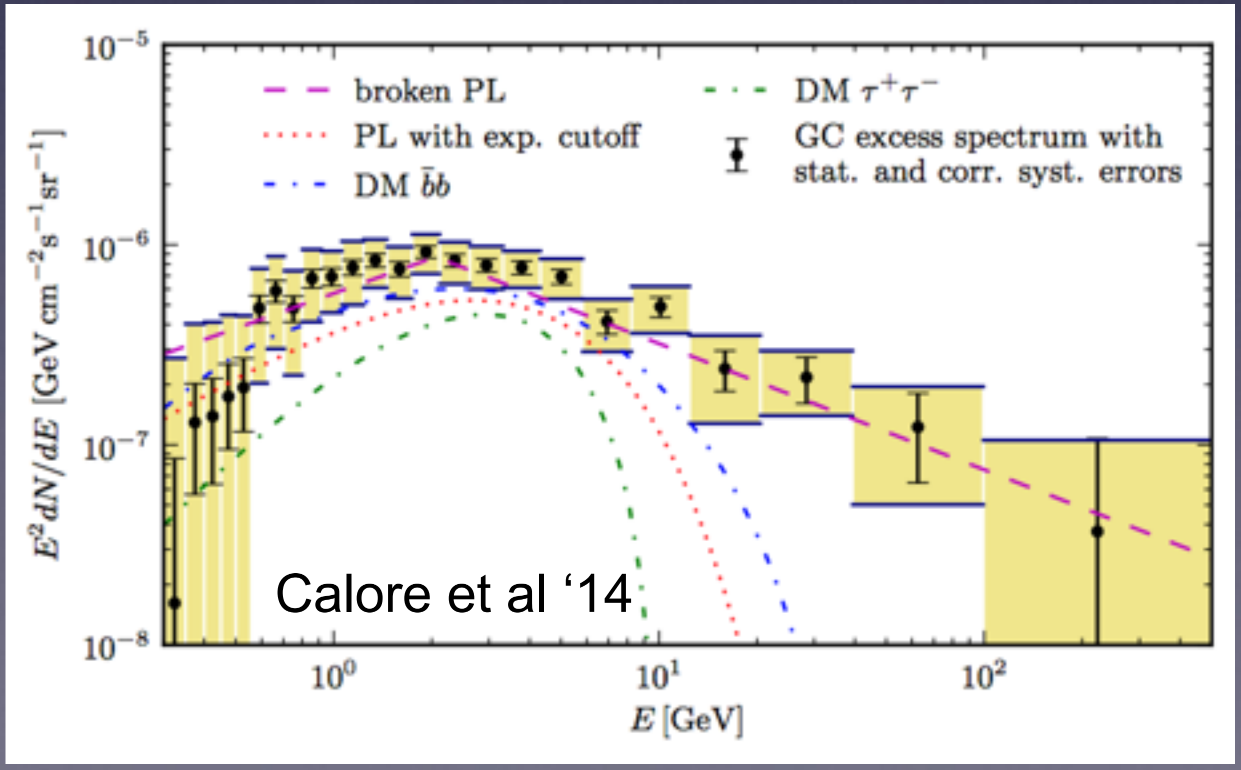


- Can add a model for a DM signal motivated by N-body simulations (or your favorite cored model) - generalized NFW profile, squared and projected along the line of sight.
- Fit the data as a linear combination of background(s) + signal, extract best-fit coefficient and error bars for each - “template fitting”.
- Repeat at each energy to find a spectrum for each component.

The GeV excess

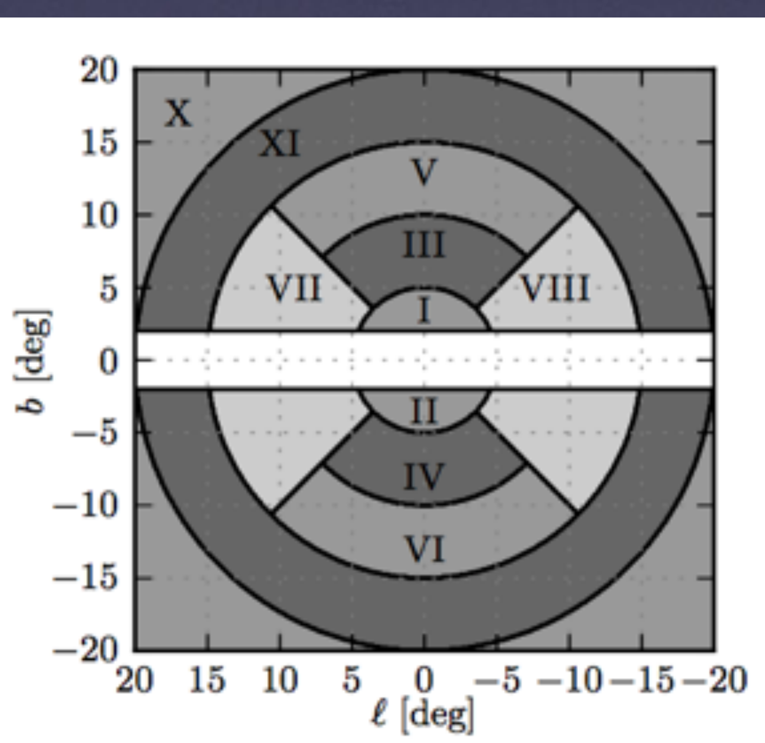
- There appears to be evidence for a new component in the Galactic Center (Goodenough & Hooper '09) and inner Galaxy (Hooper & TRS '13).
- Spectrum peaked at ~1-3 GeV.
- Rate consistent with simple thermal relic scenario, for ~50 GeV DM annihilating to quarks.
- Spatially, resembles a slightly steepened NFW profile (no core).



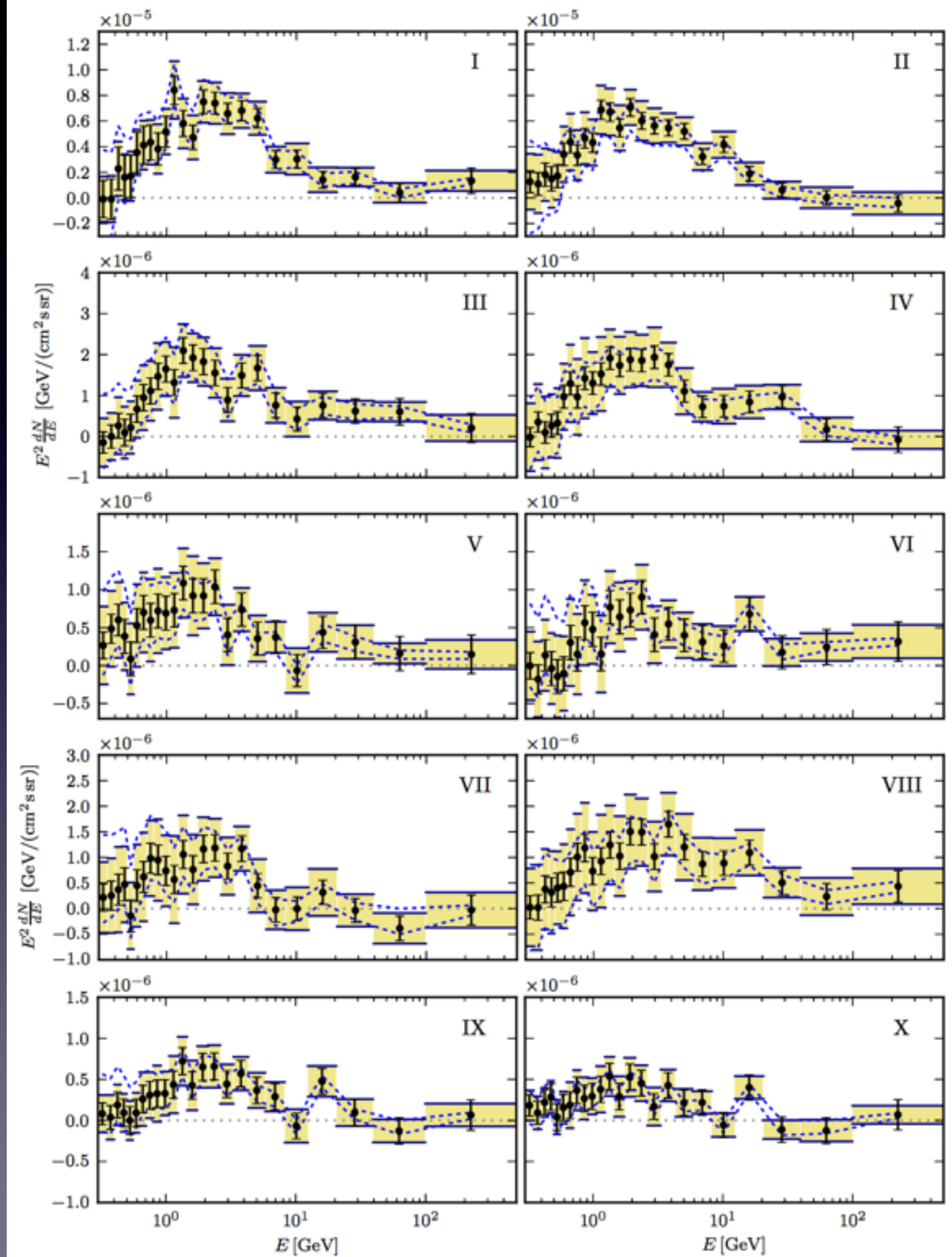


Morphology

- Highly spatially symmetric about the GC, not elongated along plane (showed in Daylan et al '14, studied further by Calore et al).
- Also appears centered on GC (Daylan et al '14).

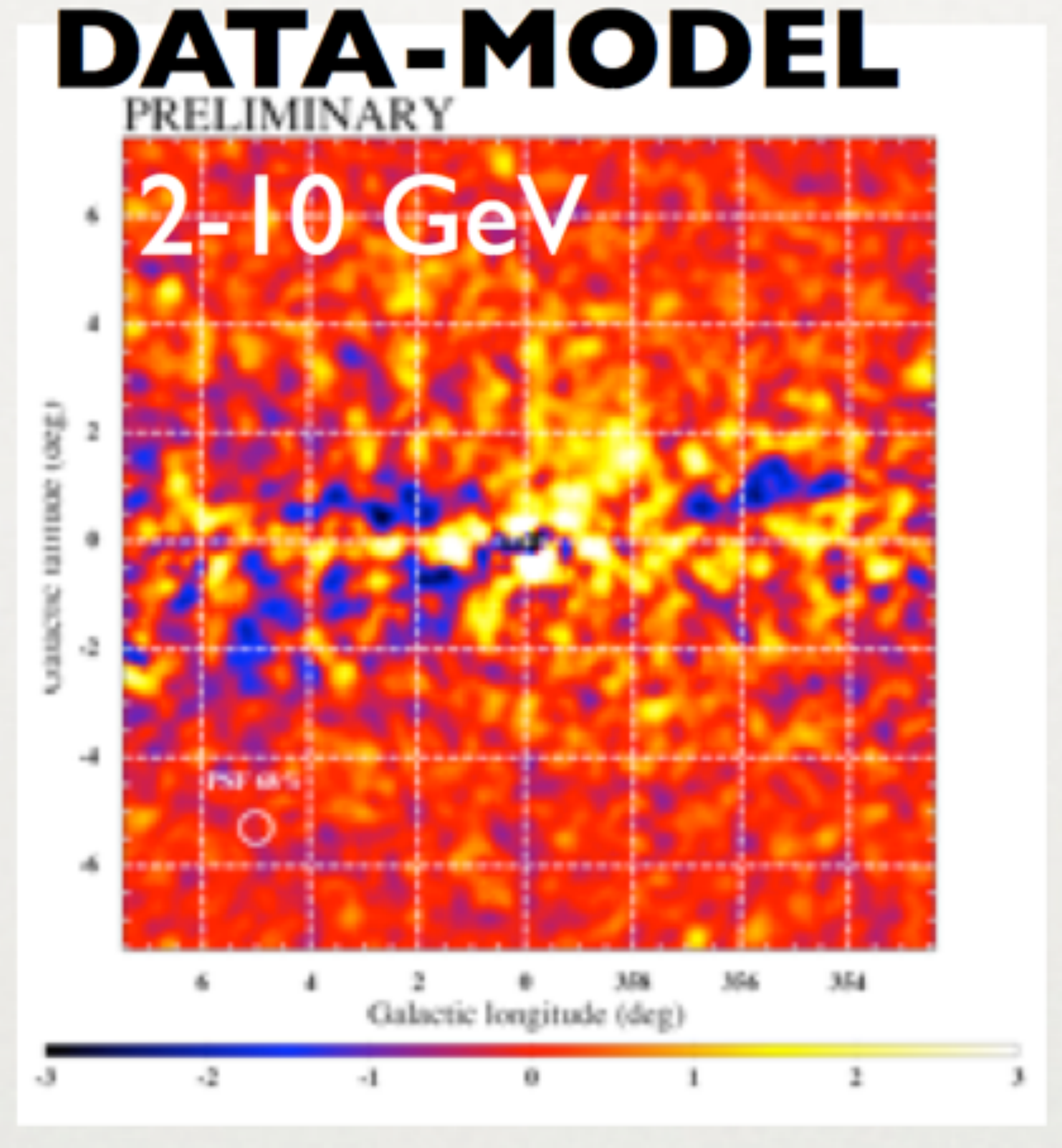


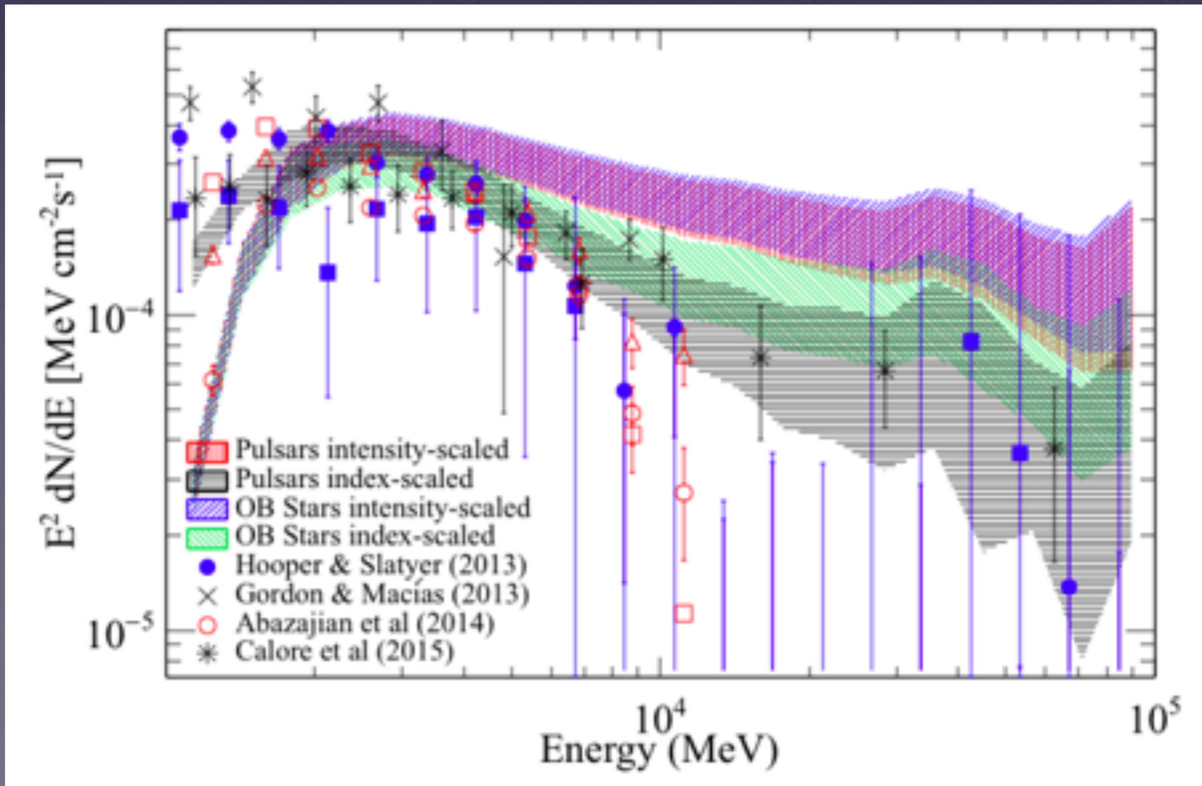
Plots taken from Calore, Cholis & Weniger '14



Fermi Collaboration analysis

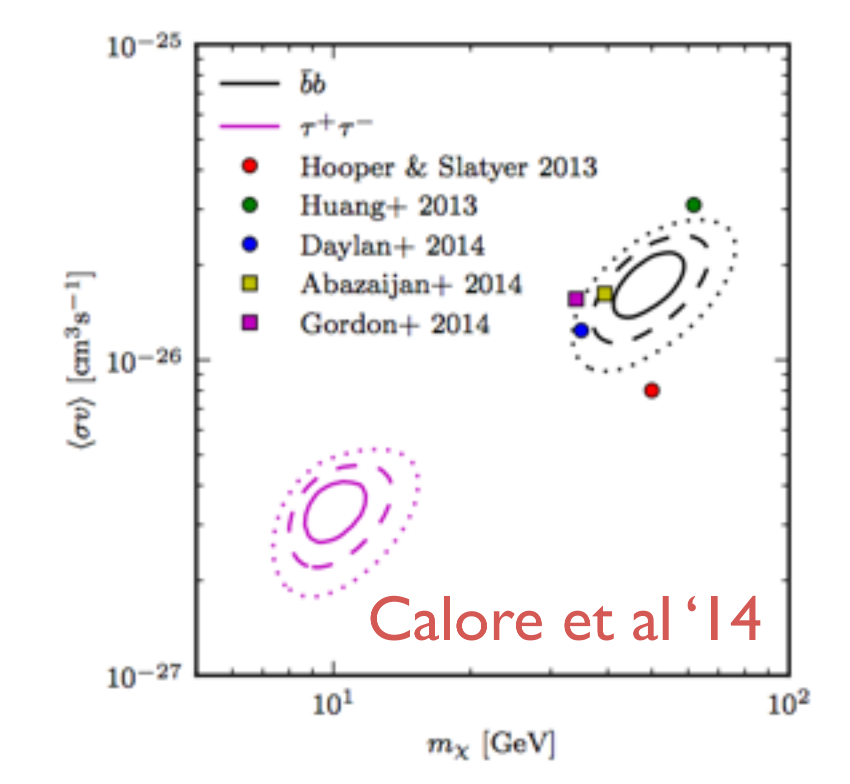
- Recent work by the Fermi LAT Collaboration (Nov '15) seems to identify the same excess.
  - Careful alternate approach to background/foreground modeling
  - Spectrum depends on diffuse model, but peak around a few GeV seems consistent
  - Greatest improvements in the fit provided by spatial models peaked steeply toward the GC

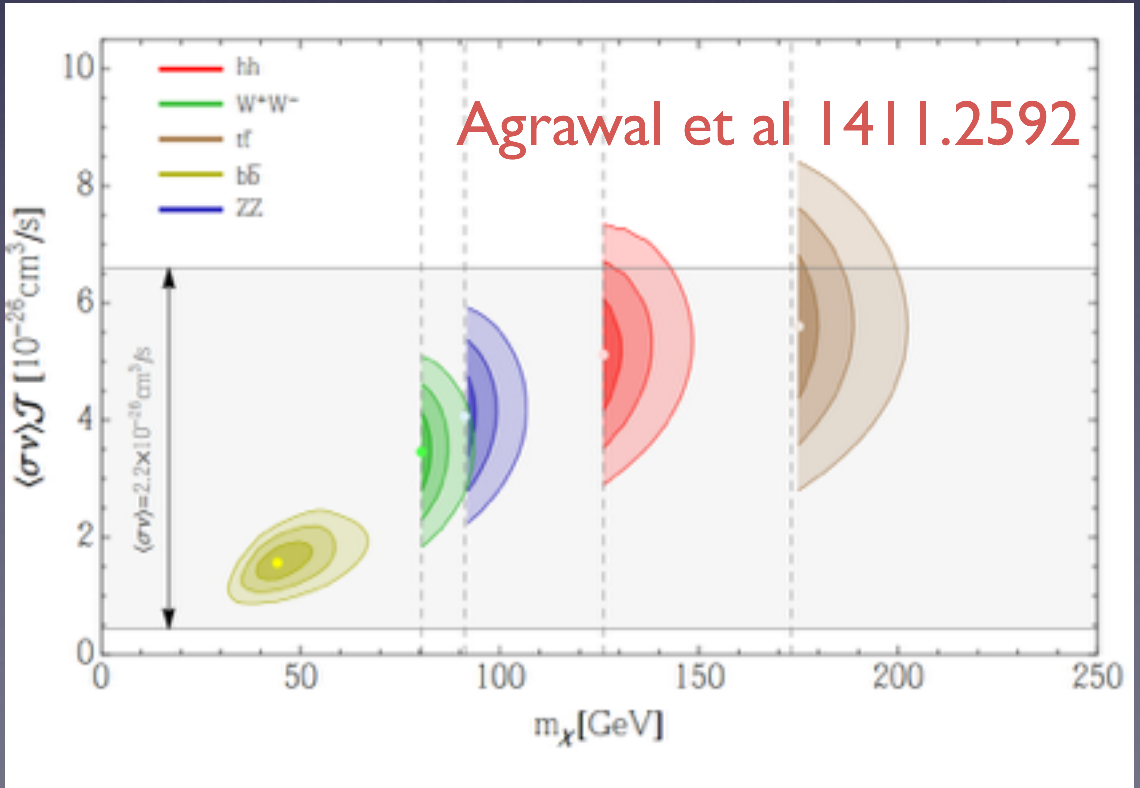




If it is dark matter…

- Our best fits are for DM masses around 10-50 GeV depending on channel, ~35-45 GeV for b's. Cross section is ~thermal, i.e. ~weak-scale.
- Heavier DM annihilating to hh can also provide a good fit to CCW results (1411.2592; Calore et al 1411.4647). Preferred DM mass is right at the threshold.
- Annihilation to W's, Z's and tops provides a worse fit.



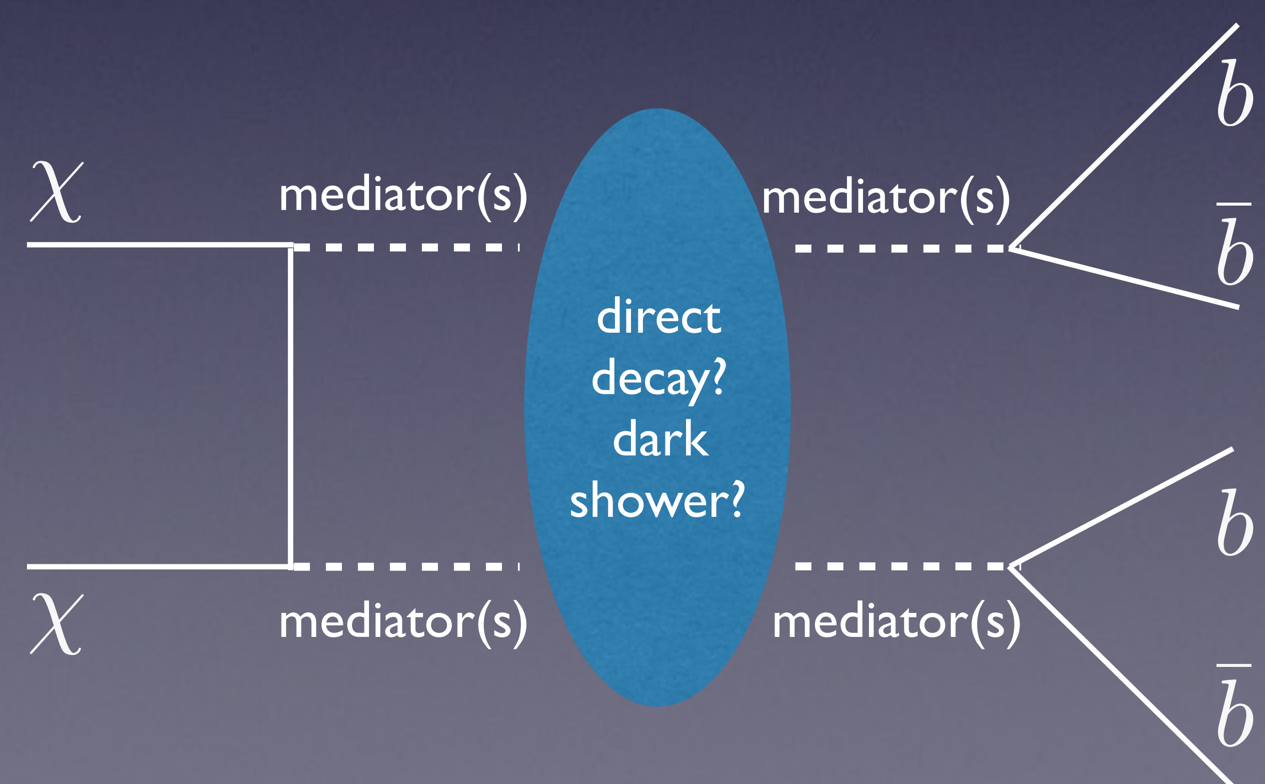


Model-building challenges

- Direct detection is very sensitive in this mass range, why haven't we seen it?
  - Annihilation may be resonant
  - Direct detection may be dominantly spin-dependent or otherwise suppressed (although in many models, upcoming direct detection experiments have sensitivity anyway)
  - Annihilation may be $2 \to 4$ and the intermediate particles may have small couplings to the SM
- What about bounds from colliders?
  - Sensitivity is reduced in the presence of light mediators, which may be needed to raise the cross section to thermal relic values
  - Nonetheless, substantial classes of simplified models can be ruled out.
- There are existence proofs of UV-complete models that satisfy all constraints.

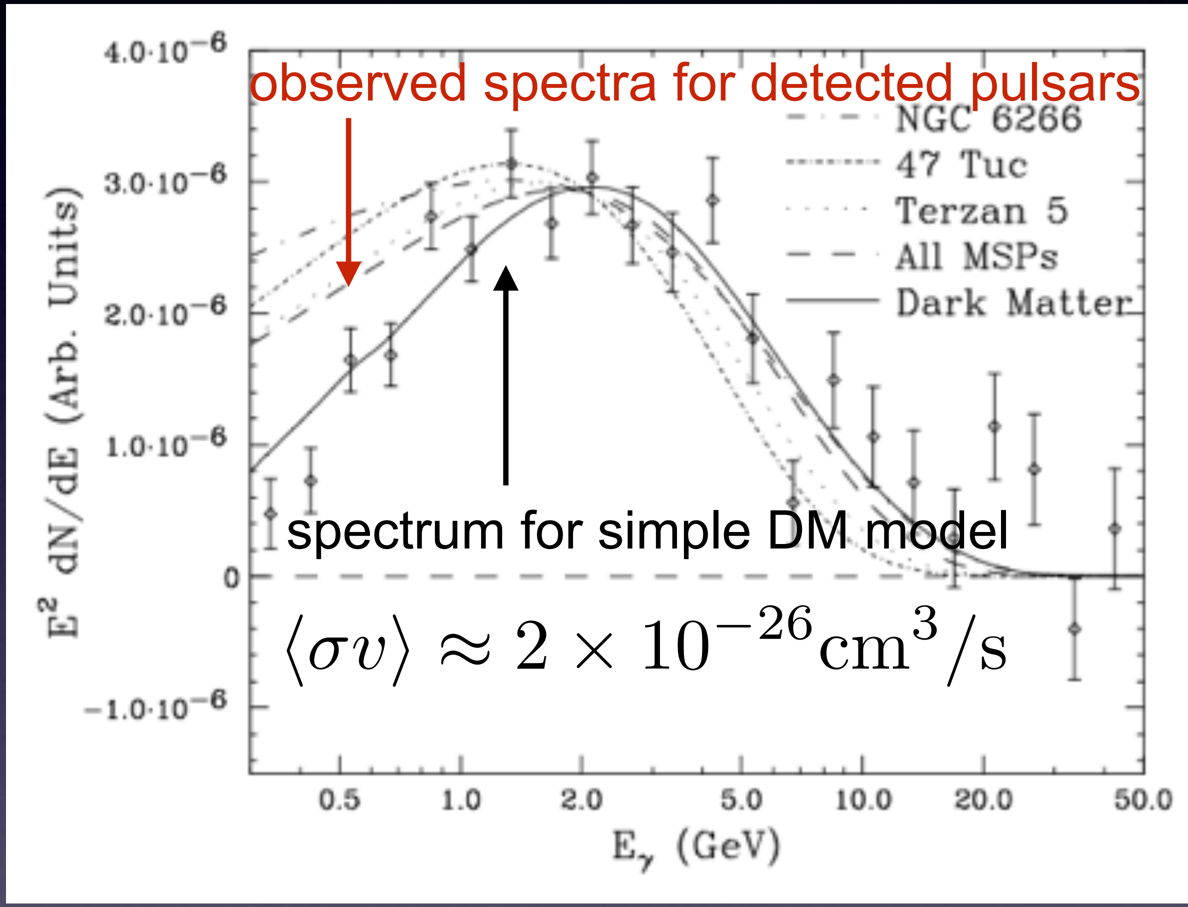
Examples

- Annihilation through a pseudoscalar to b's (e.g. "coy DM" of 1401.6458)
  - Renormalizable model presented in 1404.3716, pseudoscalar mixes with CP-odd component of 2HDM
  - Z_3 NMSSM implementation in 1406.6372, bino/higgsino DM annihilates through light MSSM-like pseudoscalar. General NMSSM study in 1409.1573.
- 2→4 models - DM annihilates to an on-shell mediator, subsequently decays to SM particles (e.g. 1404.5257, 1404.6528, 1405.0272, dark photon and NMSSM implementations in 1405.5204, dark-sector showering in 1410.3818).



But is it dark matter?

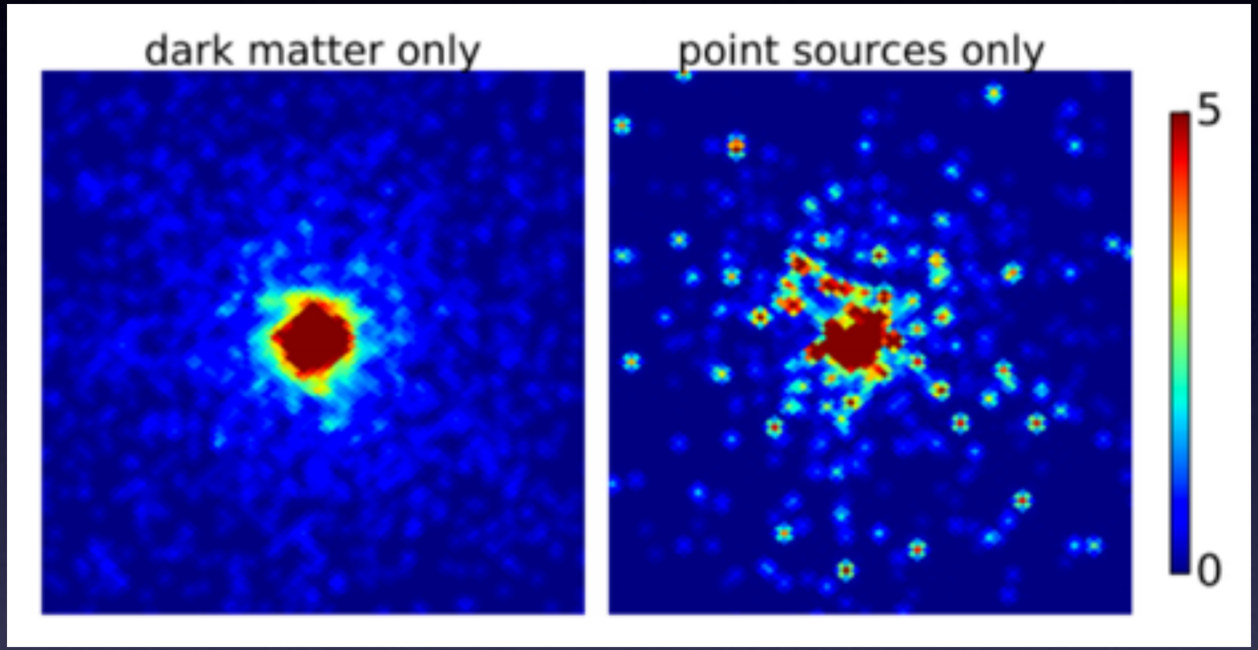
- Pulsars (spinning neutron stars) are known to emit gamma rays with a similar spectrum
  - No reason to expect this spatial distribution
  - That doesn't mean it's impossible
- Outflows of high-energy cosmic rays from the Galactic Center could also produce gamma rays
  - Protons striking gas - although signal doesn't look gas-correlated
  - Electrons upscattering photons - although not easy to accommodate constant spectrum



Daylan et al '14

A brief and not exhaustive list of references:
1405.7685, 1405.7928, 1506.05119, 1507.06129

Photon statistics



- We may be able to distinguish between hypotheses by looking at <u>clumpiness</u> of the photons.
- If we are looking at dark matter or an outflow, we expect a fairly <u>smooth</u> distribution.
- In the pulsar case, we might instead see many "hot spots" scattered over a fainter background.
- Can be made quantitative by considering the differing photon statistics in these two cases - variance larger for same mean when point sources are present, modifies likelihood.
- Related analysis by Bartels et al '15, using wavelet approach - finds consistent results.

An example

I expect 10 photons per pixel, in some region of the sky. What is my probability of finding 0 photons? 12 photons? 100 photons?

Case 1: diffuse emission, Poissonian statistics

$P(12 \text{ photons}) = 10^{12}\, e^{-10}/12! \sim 0.1$

Likewise $P(0 \text{ photons}) \sim 5 \times 10^{-5}$, $P(100 \text{ photons}) \sim 5 \times 10^{-63}$

Case 2: population of rare sources.

Expect 100 photons/source, 0.1 sources/pixel - same expected mean # of photons

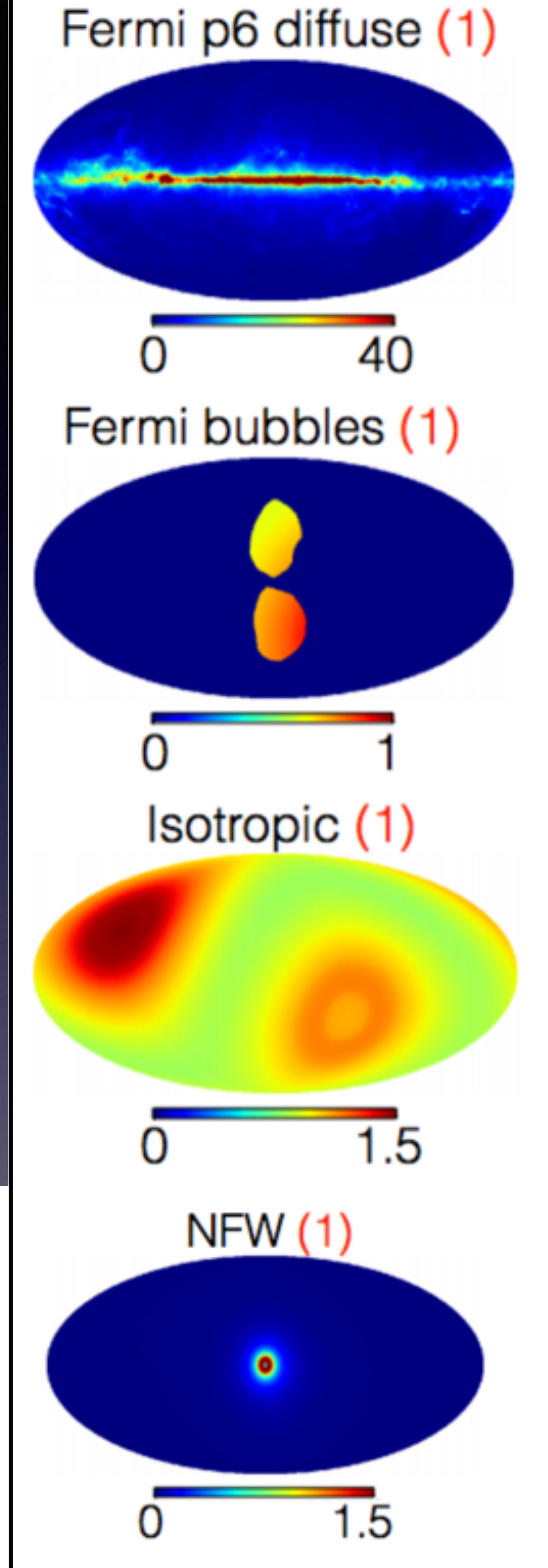
$P(0 \text{ photons}) \sim 0.9$, $P(12 \text{ photons}) \sim 0.1 \times 100^{12}\, e^{-100}/12! \sim 10^{-29}$,

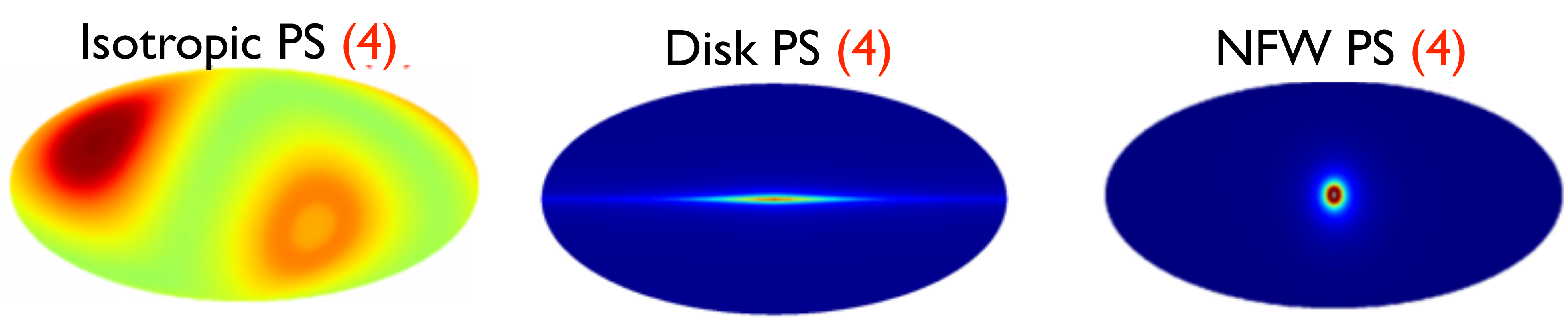
$P(100 \text{ photons}) \sim 4 \times 10^{-3}$

(plus terms from multiple sources/pixel, which I am not including in this quick illustration)

Template fitting II

- Model sky (within some energy bin) as linear combination of spatial templates
- Templates may either have
  - Poissonian statistics
  - Point-source-like statistics - extra degrees of freedom describing number of sources as a function of brightness

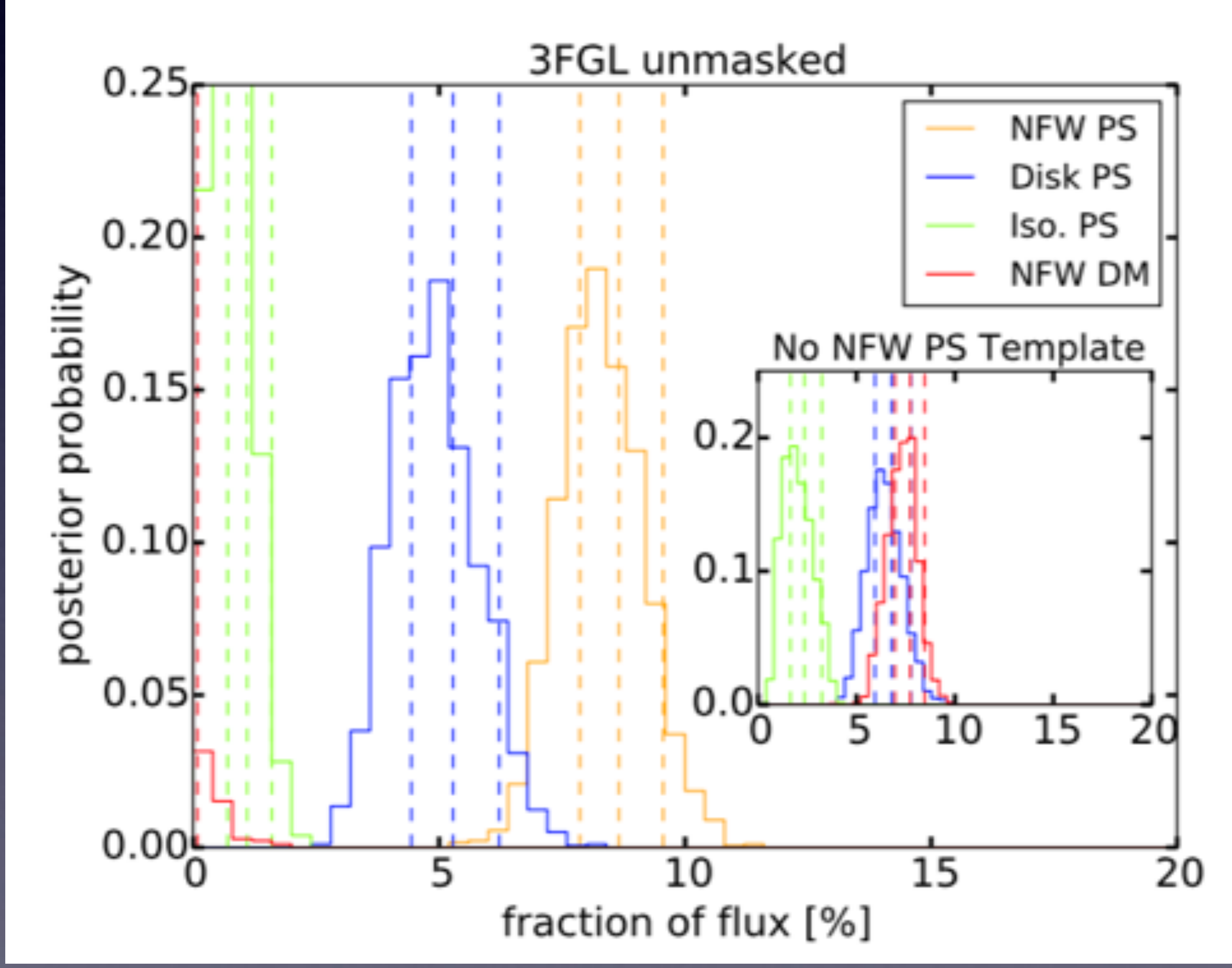




Point source templates

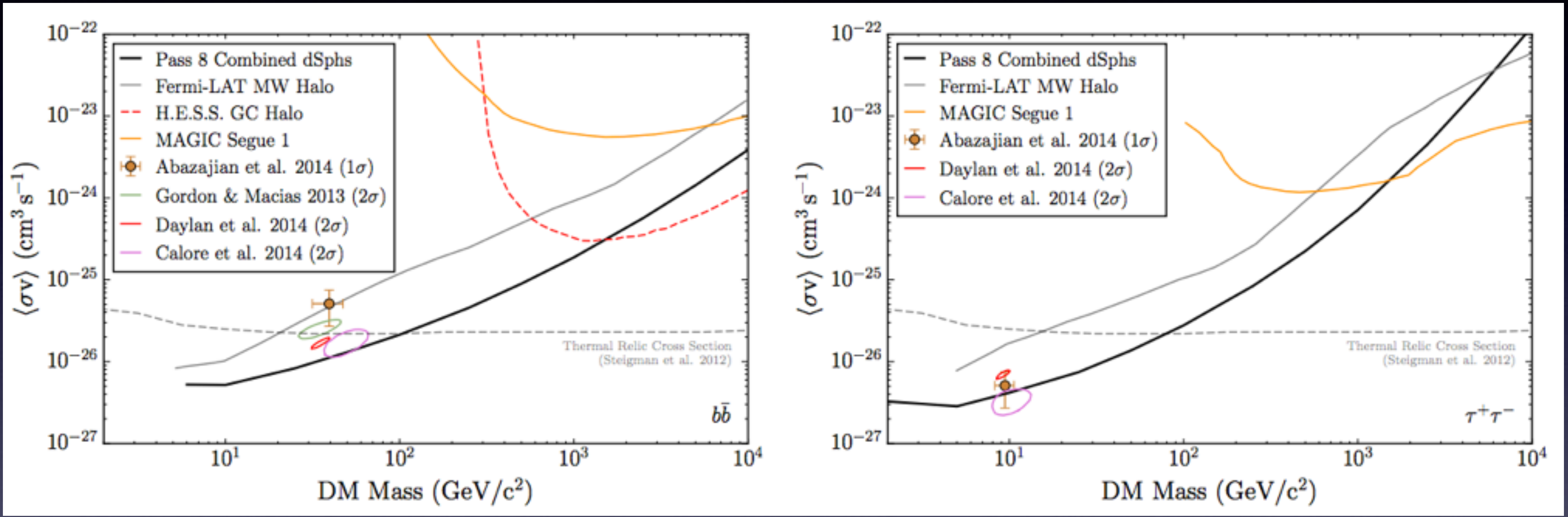
A preference for point sources

- Compare fit with and without point-source template peaked toward GC, "NFW PS".
- In both cases there is a smooth "DM" template peaked toward GC, "NFW DM".
- If "NFW PS" is absent, "NFW DM" template absorbs excess. If "NFW PS" is present, "NFW PS" absorbs full excess, drives "NFW DM" to zero.



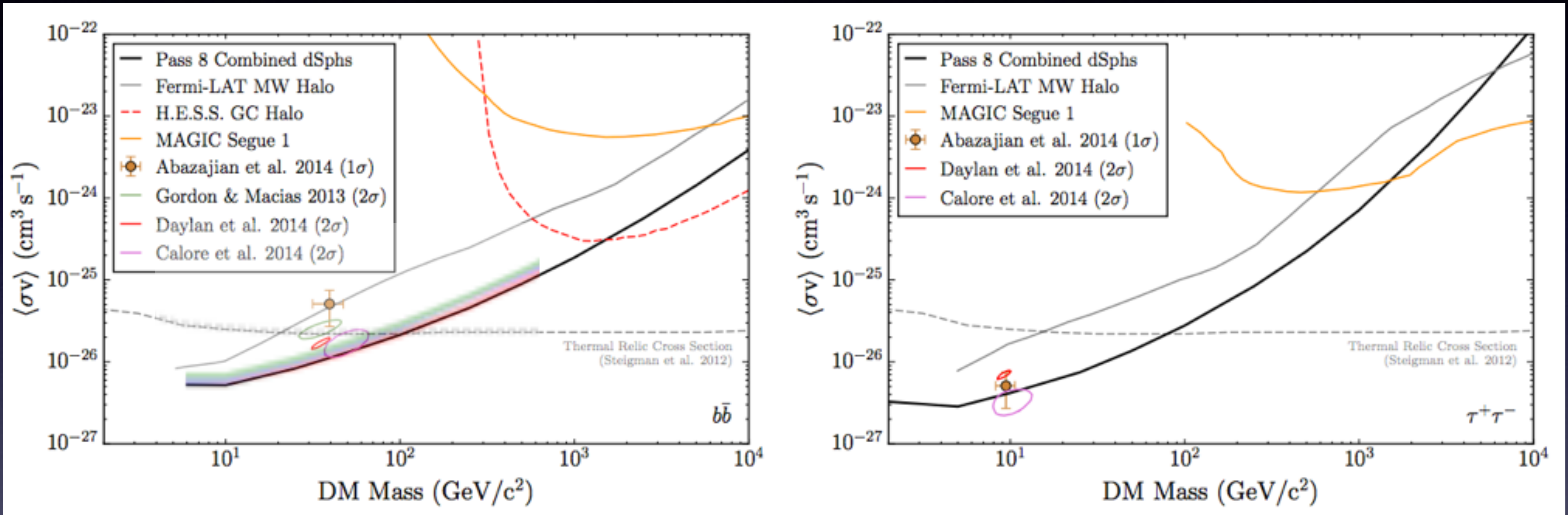
Lee, Lisanti, Safdi, Xue & TRS '15

Dwarf galaxies



- How to avoid backgrounds? Can look at dwarf galaxies, as we discussed earlier.
- Fermi study of stacked dwarfs with Pass 8 (1503.02641) sets strong limits on DM annihilation.
- Some systematic uncertainties in the dwarf dark matter content, but relatively minor compared to Galactic Center.

Dwarf galaxies



- How to avoid backgrounds? Can look at dwarf galaxies, as we discussed earlier.
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an example of “indirect” annihilation probes

The cosmic dark ages

- Roughly z~30-1000, age of the universe ~400 000 years - 100 million years.
- For most of this period, matter fluctuations are small and perturbative; non-linear structure formation does not begin until $z < 100$.
- Residual ionization fraction ~ few x 10^{-4}.
- Any ionization acts as a screen to the cosmic microwave background radiation - can be sensitively measured.
- Consider the power from a single annihilation of 5 GeV DM - how many hydrogen ionizations?
  - 10 GeV / 13.6 eV ~ 10^{9}
  - For every hydrogen atom there is ~1 DM particle (so DM mass density is ~5x baryonic).
  - If one in a billion DM particles annihilates, enough power to ionize all the hydrogen in the universe…

Understanding the CMB bounds

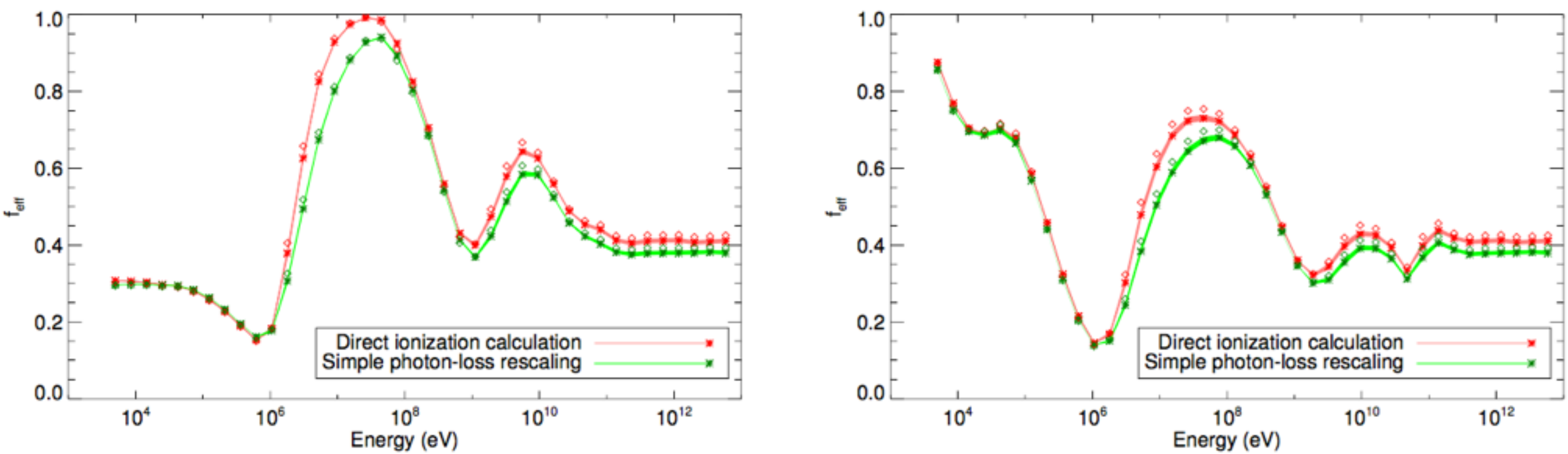
DM annihilation $\longrightarrow$ photons, electrons, positrons $\longrightarrow$ ionization $\longrightarrow$ scale-dependent perturbation to CMB anisotropies

must understand efficiency of this process

Adams, Sarkar & Sciama 1998; Chen & Kamionkowski 2003; Finkbeiner & Padmanabhan 2005

- There is a limit on (s-wave) annihilating DM from the CMB - turns out to depend on essentially one number: excess ionization at z~600 (Galli, Lin, TRS & Finkbeiner '11, Slatyer '15).
- Parameterized by efficiency parameter f_{eff}: first computed in TRS, Padmanabhan & Finkbeiner '09, significant updates to calculation described in Galli, TRS, Valdes & Iocco '13.
- f_{eff}, and hence the constraint on a given (s-wave annihilating) DM model, depends on:
  - PRIMARILY, how much power goes into photons/electrons/positrons vs neutrinos and other channels.
  - SECONDARILY, the spectrum of photons/electrons/positrons produced (but most variation is for particles below the GeV scale).

Energy-dependent efficiency factor

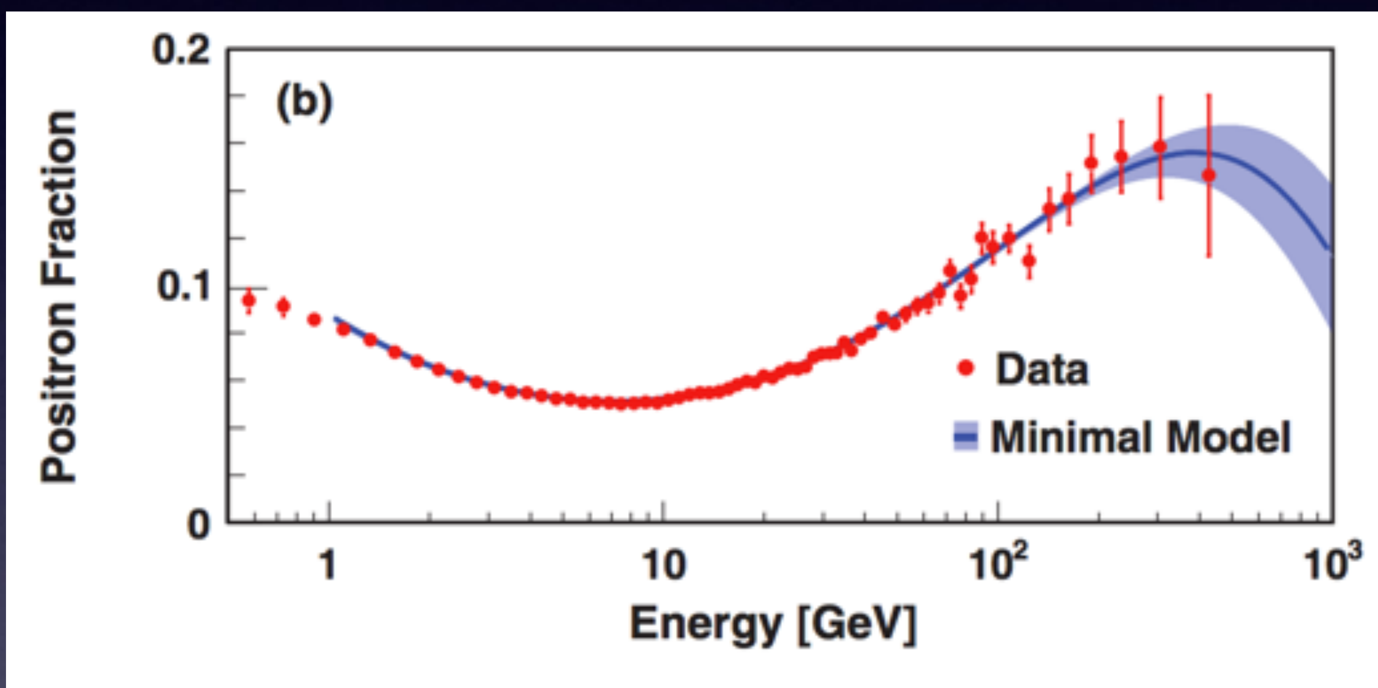


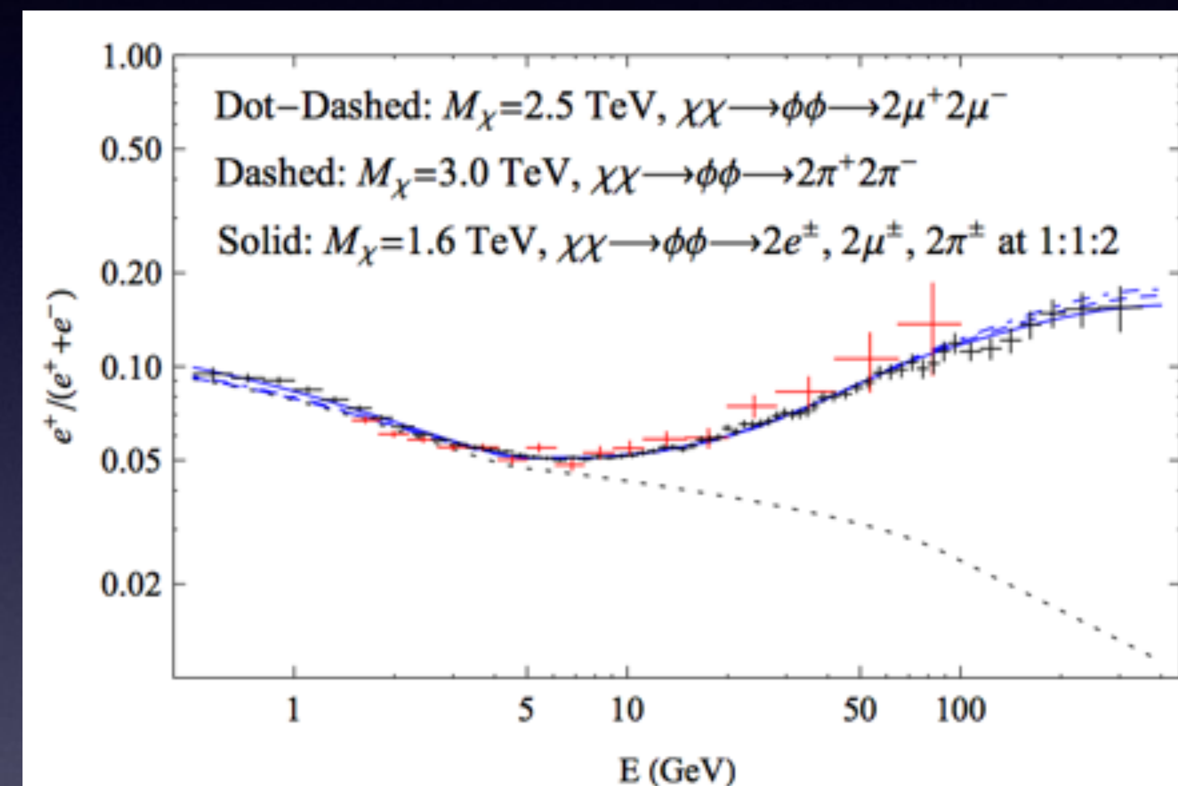
- Results for e^+e^- pairs (left) and photons (right).
- Results for arbitrary spectra can be determined by taking linear combinations of these results.
- Computed by tracking the cooling of electrons, positrons and photons from high to low energies, in the environment of the early universe.

The PAMELA/Fermi/AMS-02 positron excess

Cholis & Hooper '13

AMS-02 Collaboration '14

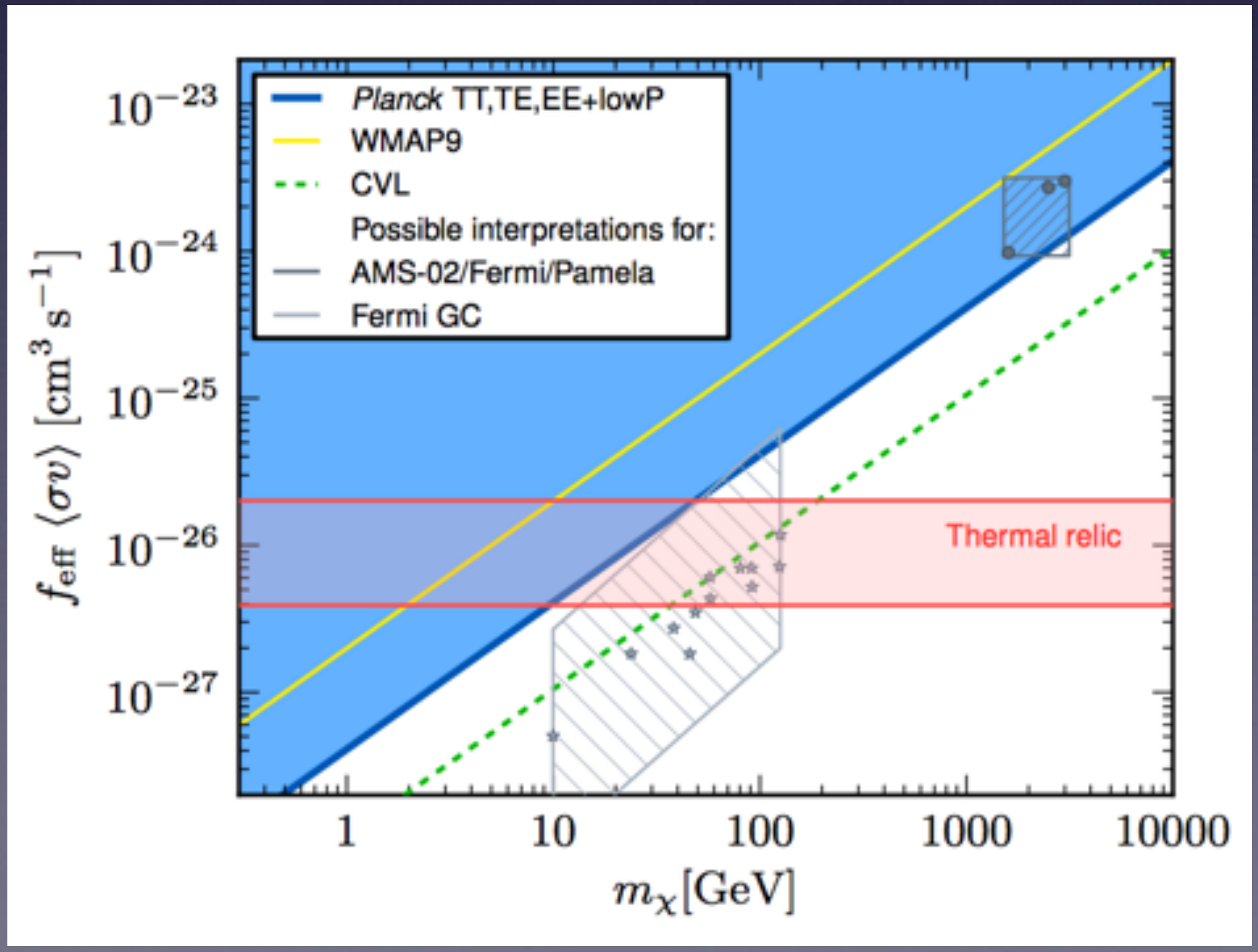


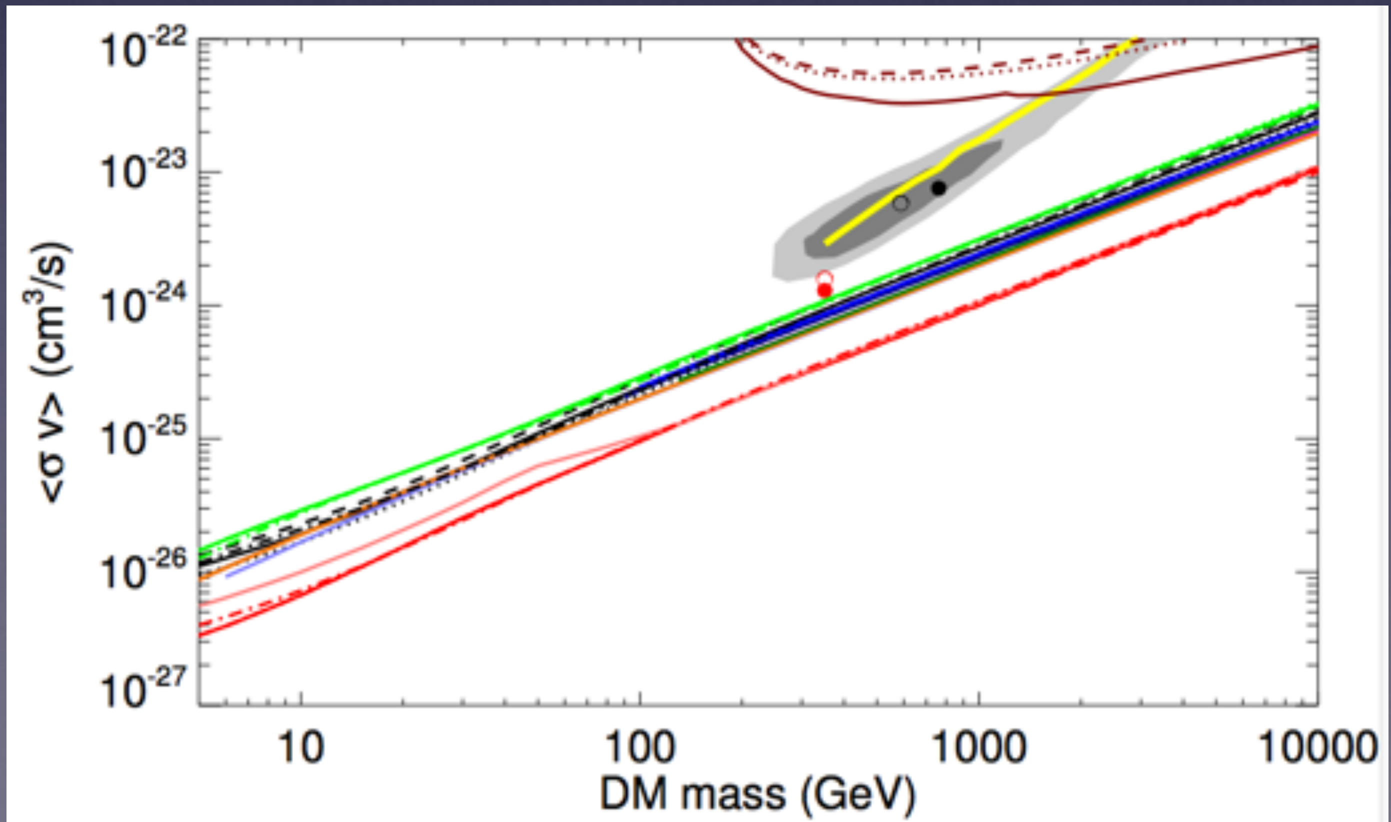


- Rise in positron fraction above 10 GeV observed by PAMELA experiment in 2008, later confirmed by Fermi, now confirmed to extend up to at least 500 GeV by AMS-02.
- Possible signal of DM annihilation, producing additional primary positrons. (Other possibilities: pulsars, supernova remnants, modified cosmic-ray production and/or propagation.)
- DM models generally require large masses and cross-sections, and annihilation to mostly leptonic channels. Can be naturally explained if DM couples to a ~GeV mediator.

Limits from Planck

- Early this year, Planck Collaboration released polarization results.
- 1502.01589 presented bounds on DM annihilation; consistent with sensitivity predictions from TRS et al, Galli et al 2009.
- Left plot shows Planck bound, right plot shows resulting cross-section limits for a range of channels from Slatyer '15.
- These limits appear to rule out the DM annihilation interpretation of the excess positrons observed by PAMELA, Fermi and AMS-02.





Summary (Lecture 3)

- Standard Model particles produced by dark matter interactions could:
    - produce a wide range of potentially observable particles
    - influence the history of the cosmos in subtle ways
- Two current possible signals that have caused excitement:
    - The GeV excess in the Galactic Center - backgrounds for DM signals include bright diffuse emission, new point source populations
    - The 3.5 keV line in X-ray observations of galaxies+clusters - backgrounds include neighboring atomic lines
- Bounds from indirect detection can reach thermal relic cross section for DM masses below ~100 GeV (annihilating to b quarks or similar channels), using gamma-ray observations from Fermi dwarfs.
- Higher-mass thermal DM may be constrained in some cases by the non-observation of gamma-ray lines from the Galactic Center - but depends strongly on density profile.