Astrophysical Dark Matter Lecture 2

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Summary of Lecture 1

- We actually know quite a bit about dark matter!
- The distribution and gravitational effects of dark matter can be a powerful probe of dark-matter properties and interactions, independent of any interaction with the known particles. We have direct observational tests of:
  - The overall cosmological abundance of dark matter.
  - Any dark matter physics that modifies the low end of the matter power spectrum (e.g. warm dark matter below the ~keV scale, subdominant hot dark matter, very low decoupling temperatures).
  - Any dark matter physics that modifies ~galactic-scale halos, in regions where stellar orbits can be used to probe the DM distribution (from dwarfs to the central regions of clusters). Generally constrains DM-DM interactions with rates > 1/Hubble time.
  - Any dark matter physics that produces a "drag force" or similar effect on dark matter in merging clusters.

From last time: SIDM and mergers

- Bullet cluster (and other similar systems) set constraints on SIDM close to relevant cross sections to affect dwarf galaxies - suggests cluster/galaxy collisions may have sensitivity for detection.
- Simple picture: gas is collisional, stars ~collisionless. Does DM trace gas, stars or something in between? Offset from stars = diagnostic of self-interaction.
- Difficulties:
  - Requires non-equilibrium systems, so the various components have not relaxed into the common gravitational potential. These are rare.
  - Mapping the DM density in detail in colliding systems can be highly non-trivial.
  - What are the systematics and backgrounds? Not yet well explored (some work by Schaller et al '15). For example, it is not always easy to correctly associate the lensed images with the underlying objects.

Nonetheless…

The behaviour of dark matter associated with 4 bright cluster galaxies in the 10 kpc core of Abell 3827

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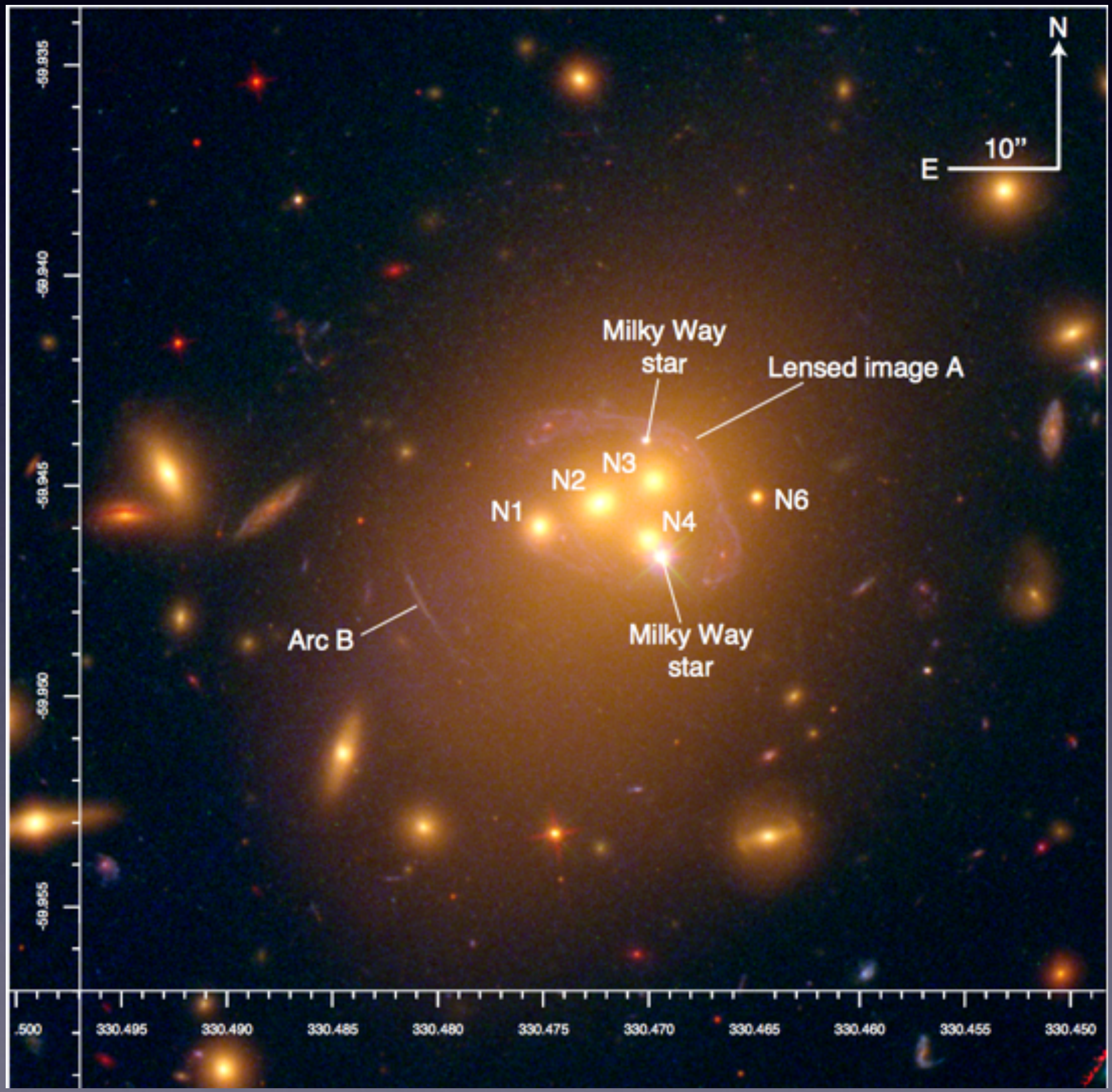
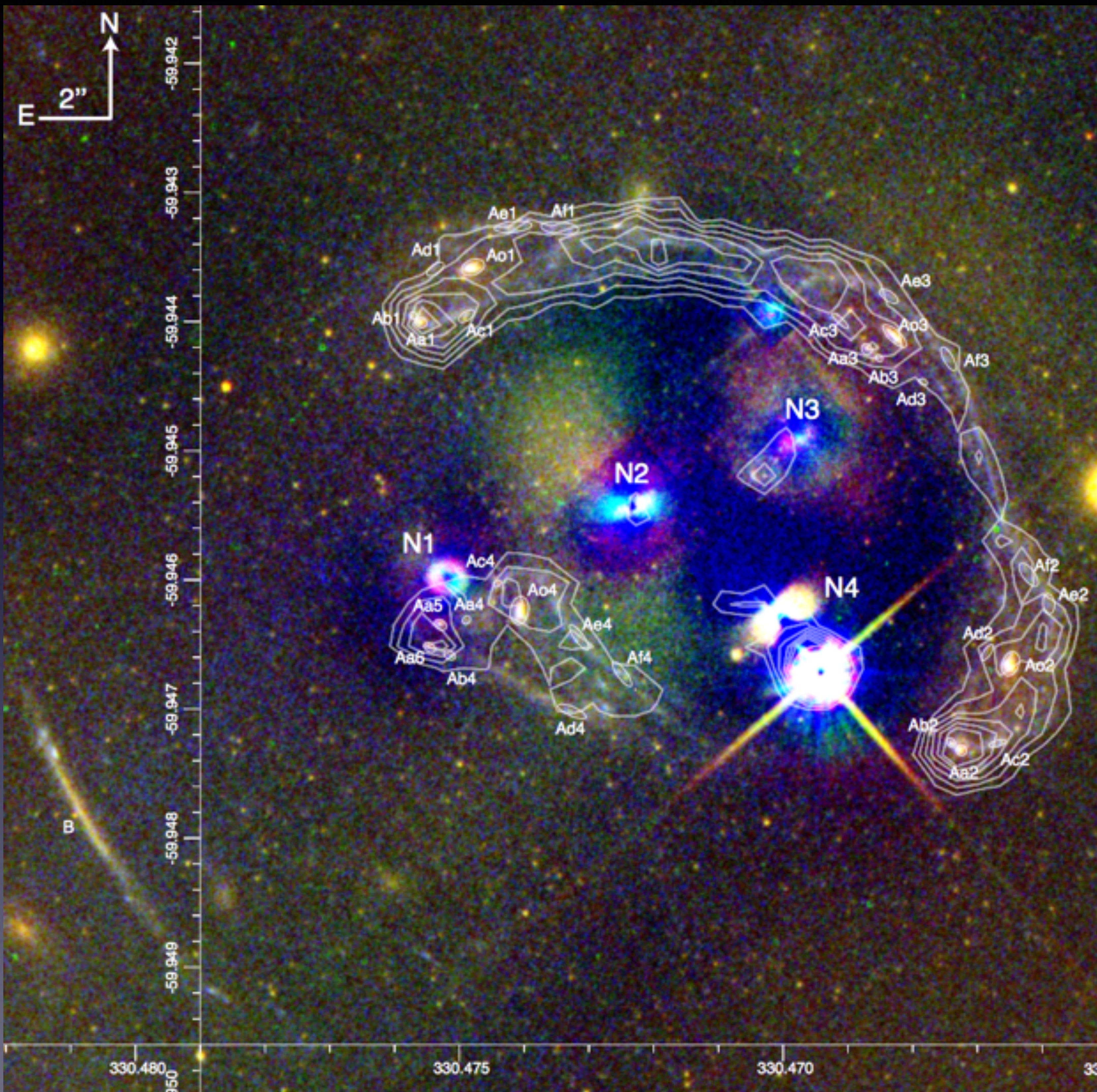
Galaxy cluster Abell 3827 hosts the stellar remnants of four almost equally bright elliptical galaxies within a core of radius 10 kpc. Such corrugation of the stellar distribution is very rare, and suggests recent formation by several simultaneous mergers. We map the distribution of associated dark matter, using new *Hubble Space Telescope* imaging and *VLT/MUSE* integral field spectroscopy of a gravitationally lensed system threaded through the cluster core. We find that each of the central galaxies retains a dark matter halo, but that (at least) one of these is spatially offset from its stars. The best-constrained offset is $1.62^{+0.47}_{-0.49}$ kpc, where the 68% confidence limit includes both statistical error and systematic biases in mass modelling. Such offsets are not seen in field galaxies, but are predicted during the long infall to a cluster, if dark matter self-interactions generate an extra drag force. With such a small physical separation, it is difficult to definitively rule out astrophysical effects operating exclusively in dense cluster core environments – but if interpreted solely as evidence for self-interacting dark matter, this offset implies a cross-section $\sigma_{\rm DM}/m \sim (1.7 \pm 0.7) \times 10^{-4}\,{\rm cm}^2/{\rm g} \times (t_{\rm infall}/10^9\,{\rm yrs})^{-2}$, where $t_{\rm infall}$ is the infall duration.

The case of Abell 3827

- System of four elliptical galaxies in a cluster, presumably formed recently by several simultaneous mergers.
- Map the mass distribution using gravitational lensing. (Used two independent methods to reconstruct the distribution, with good agreement.)
- Find evidence for an offset of 1.6±0.5 kpc between one DM halo and the associated stellar halo.

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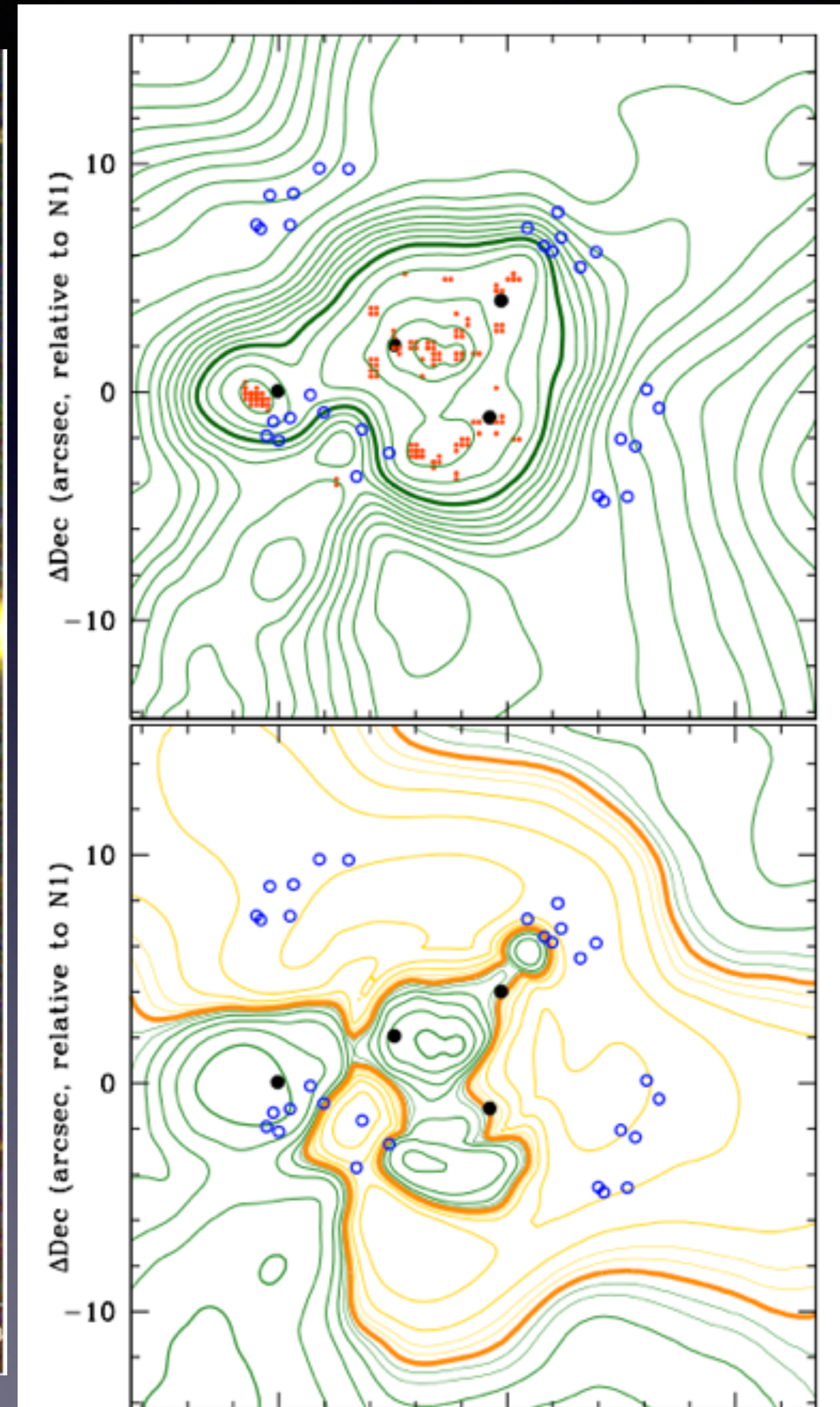
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Converting an offset to a cross section

- Original paper: estimate drag force on DM from self-interactions, slows the subhalo's infall.
- Look at difference in accelerations, assuming same starting point; infer difference in distance traveled after a time t_{infall}.
- Kahlhoefer et al '15 argue one must include the gravitational pull on the stars from the subhalo - drag force must outweigh this restoring force in order for there to be a separation.
- Resulting cross section is much higher, in mild tension with other cluster bounds.

$$F_{st} \sim \frac{G M_{co} M_{st}}{r^2}$$

$$F_{dm} \sim \frac{G M_{co} M_{dm}}{r^2} \times \left[1 - \frac{M_{dm}\,\sigma/m}{\pi s^2}\right]$$

$$d \sim \left(\frac{F_{st}}{M_{st}} - \frac{F_{dm}}{M_{dm}}\right) t^2 = \frac{G M_{co} M_{dm}\,\sigma/m}{\pi r^2 s^2}\, t^2$$

$$\sigma/m \sim (1.7 \pm 0.7) \times 10^{-4} \left(\frac{t_{\rm infall}}{10^9\ {\rm yrs}}\right)^{-2} {\rm cm}^2/{\rm g}.$$

$$\frac{F_{\rm drag}}{m_{\rm DM}} = \frac{1}{4}\frac{\tilde{\sigma}}{m_{\rm DM}} v^2 \rho \qquad \frac{F_{\rm sh}}{m_{\rm star}} = \frac{G_{\rm N}\, M_{\rm sh}(\Delta)}{\Delta^2}$$

$$F_{\rm sh}/m_{\rm star} < F_{\rm drag}/m_{\rm DM}$$

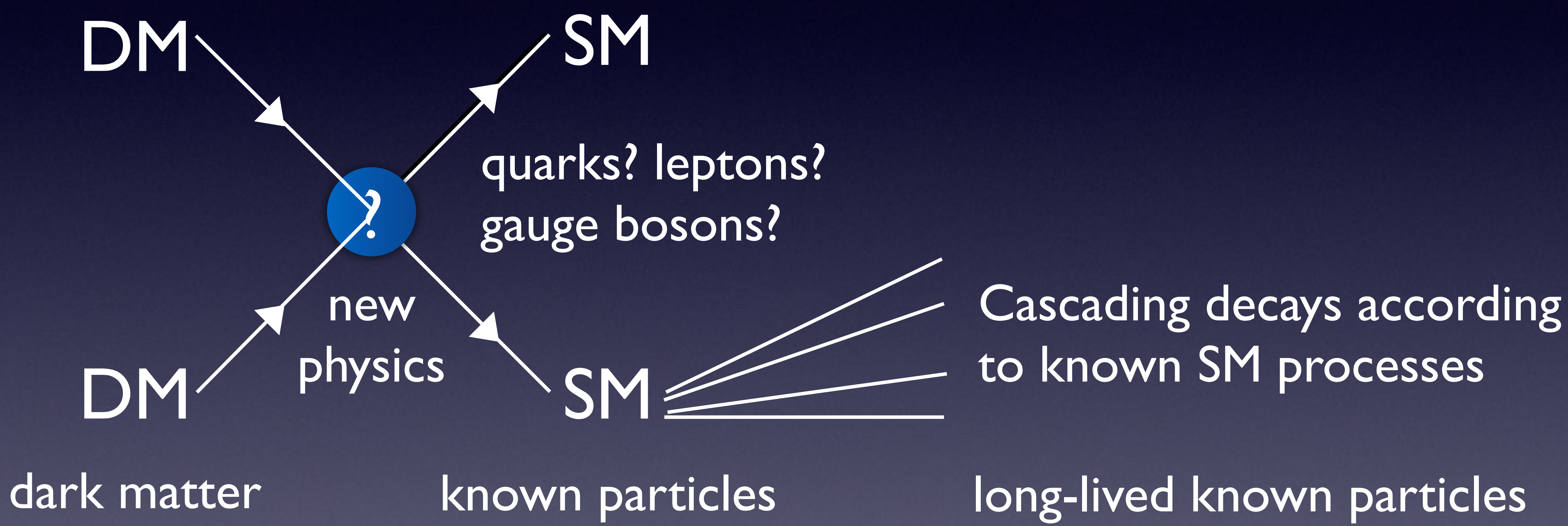
$$\frac{\tilde{\sigma}}{m_{\rm DM}} > \frac{4}{v^2 \rho} \frac{G_{\rm N}\, M_{\rm sh}\, \Delta}{a_{\rm sh}^3} \gtrsim 2\ {\rm cm}^2\, {\rm g}^{-1}$$

Light from dark matter?

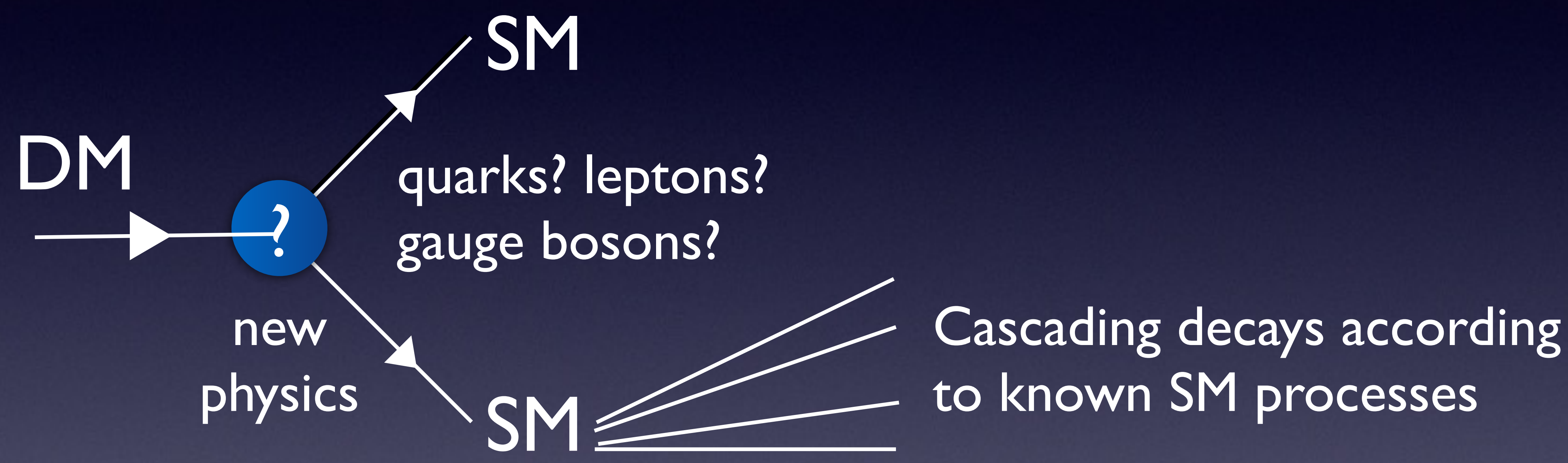
- Last time: probes of dark matter that are largely <u>independent</u> of its interactions with known particles.

- This time: searching for the visible byproducts of dark matter interactions with itself or the SM.

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

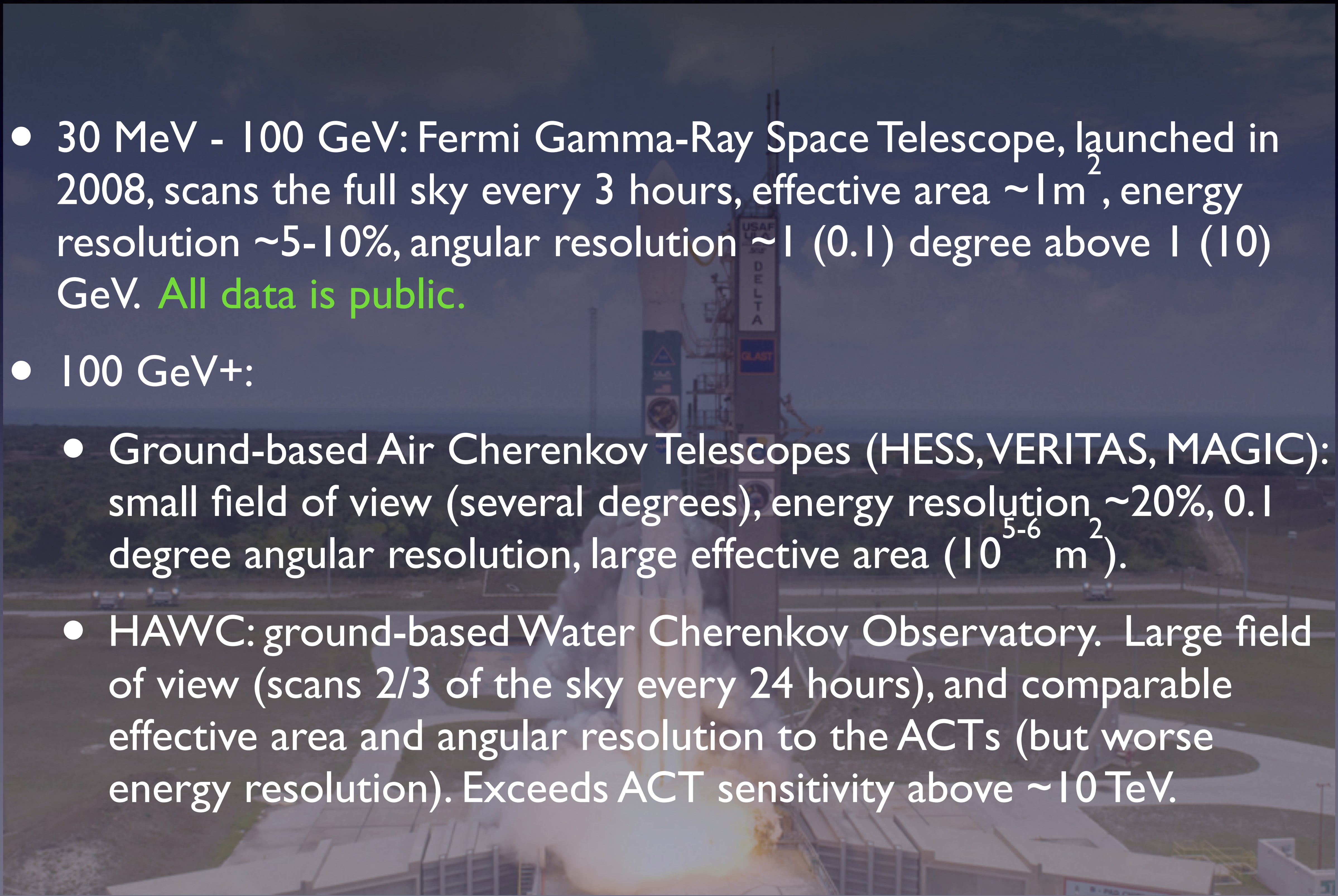
- Model the effects of Standard Model particles produced/absorbed by dark matter interactions. Many examples, here are just a handful:
  - Changes to nucleosynthesis due to injection of energetic particles (e.g. Jedamzik & Pospelov 0906.2087)
  - Distortions to the energy spectrum of the cosmic microwave 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 possible gamma-ray signal 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):

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

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

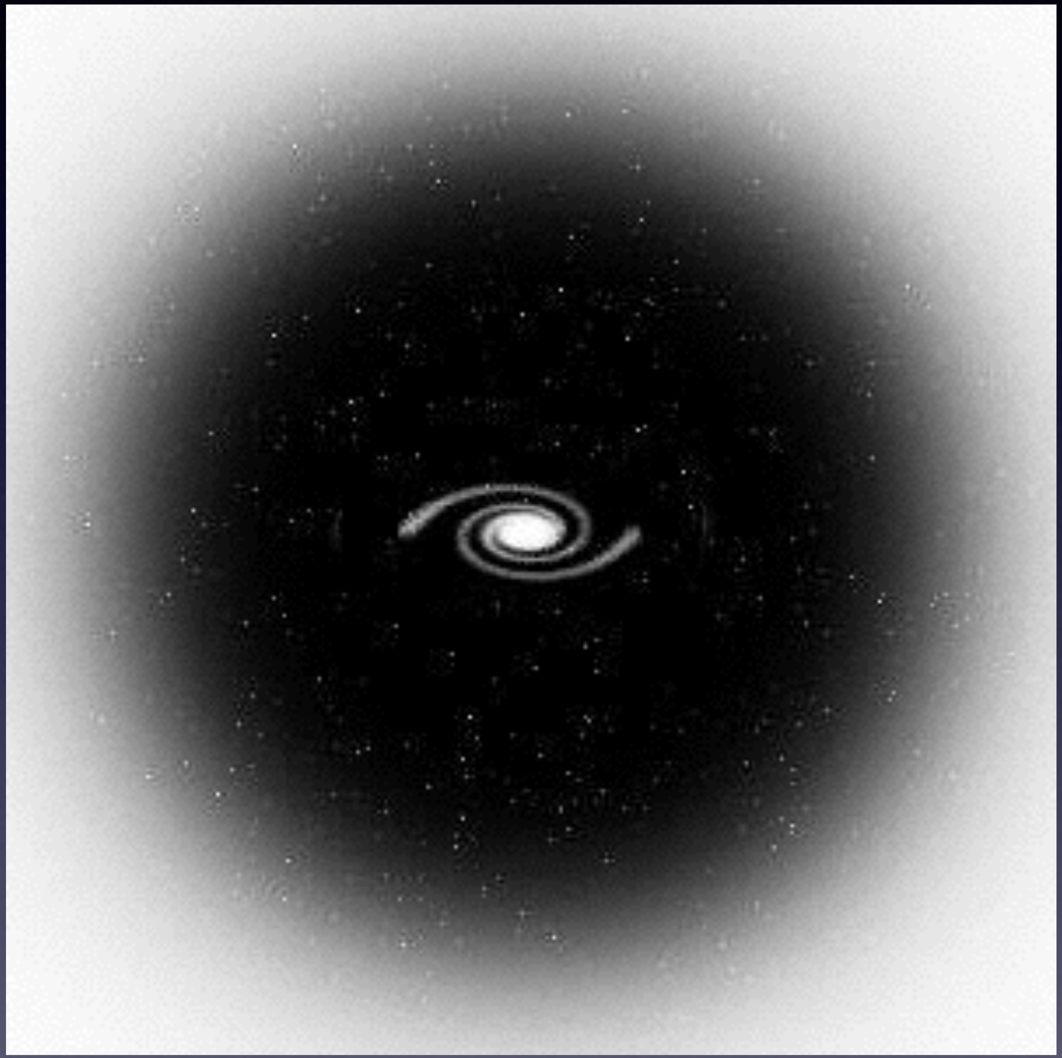
- For region within 10 degree x 10 degree box around Galactic Center, with classic NFW cusp, J ~ 10^{22} GeV^2/cm^5.
- For the closest/biggest of the dwarf galaxies, J ~ $10^{19\text{-}20}$ GeV^2/cm^5.

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.



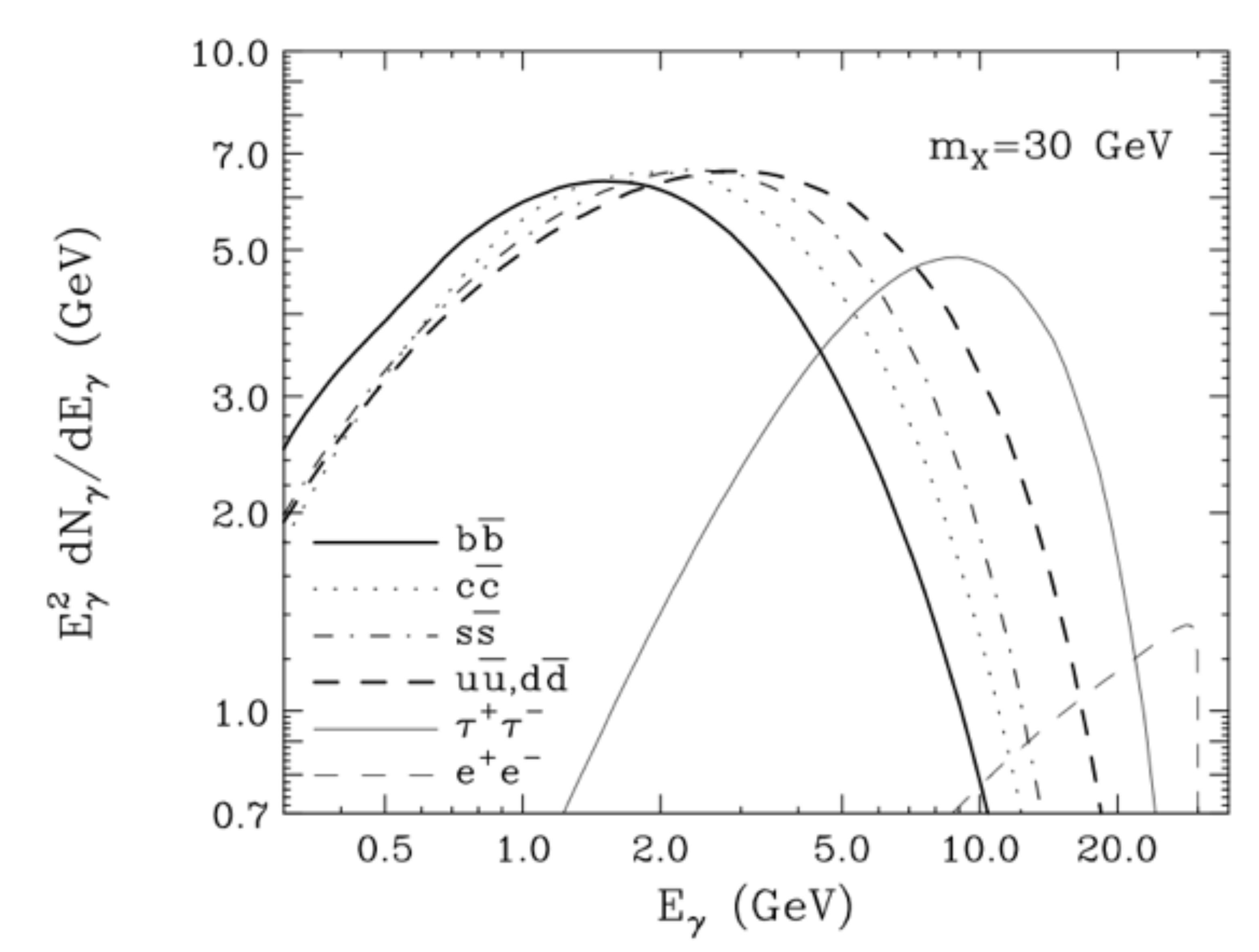
$$\rho \propto \frac{r^{-\gamma}}{\left(1 + \frac{r}{R_s}\right)^{3-\gamma}}$$

$\gamma = 1$ 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

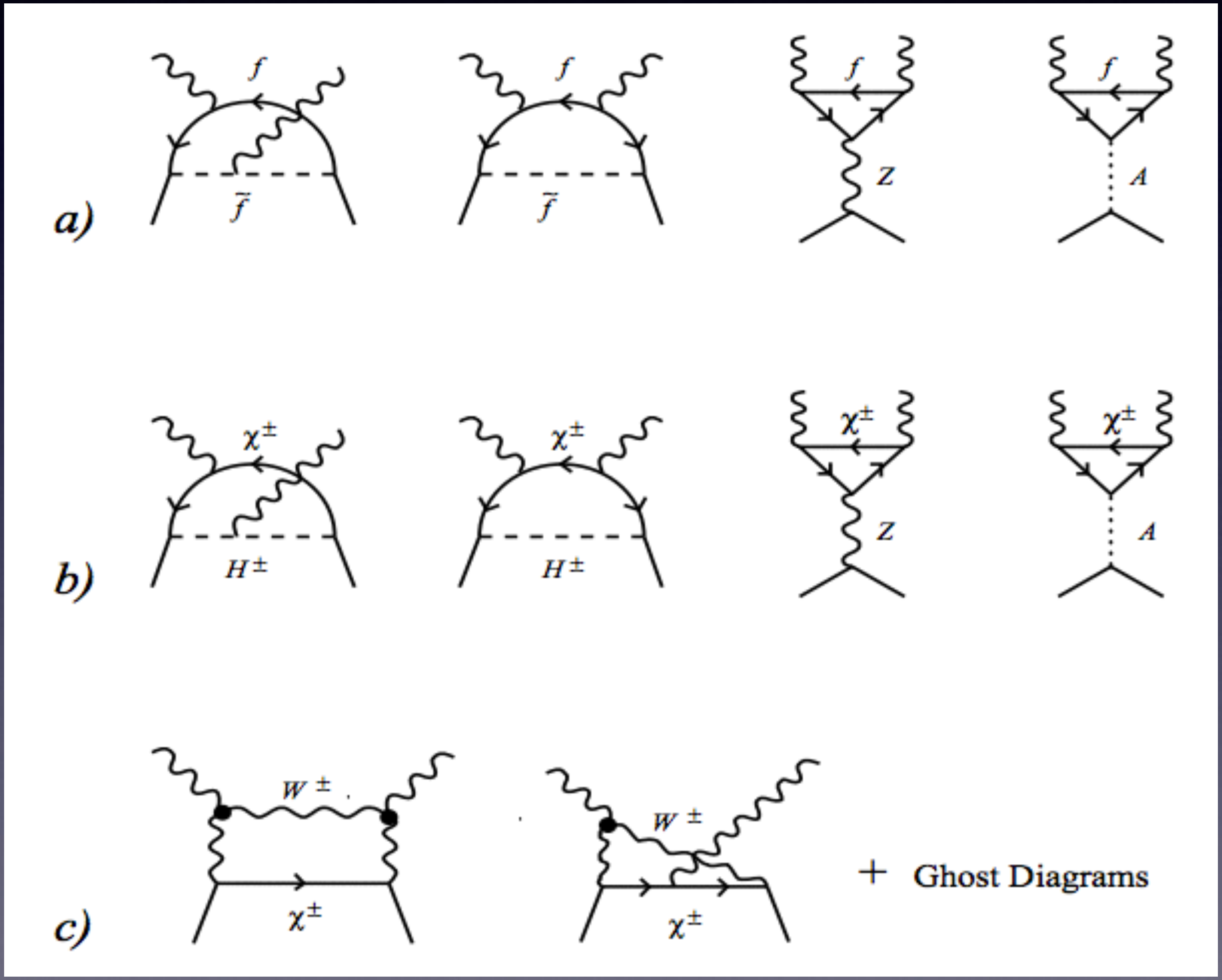
Spectral shape of a signal

- 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.

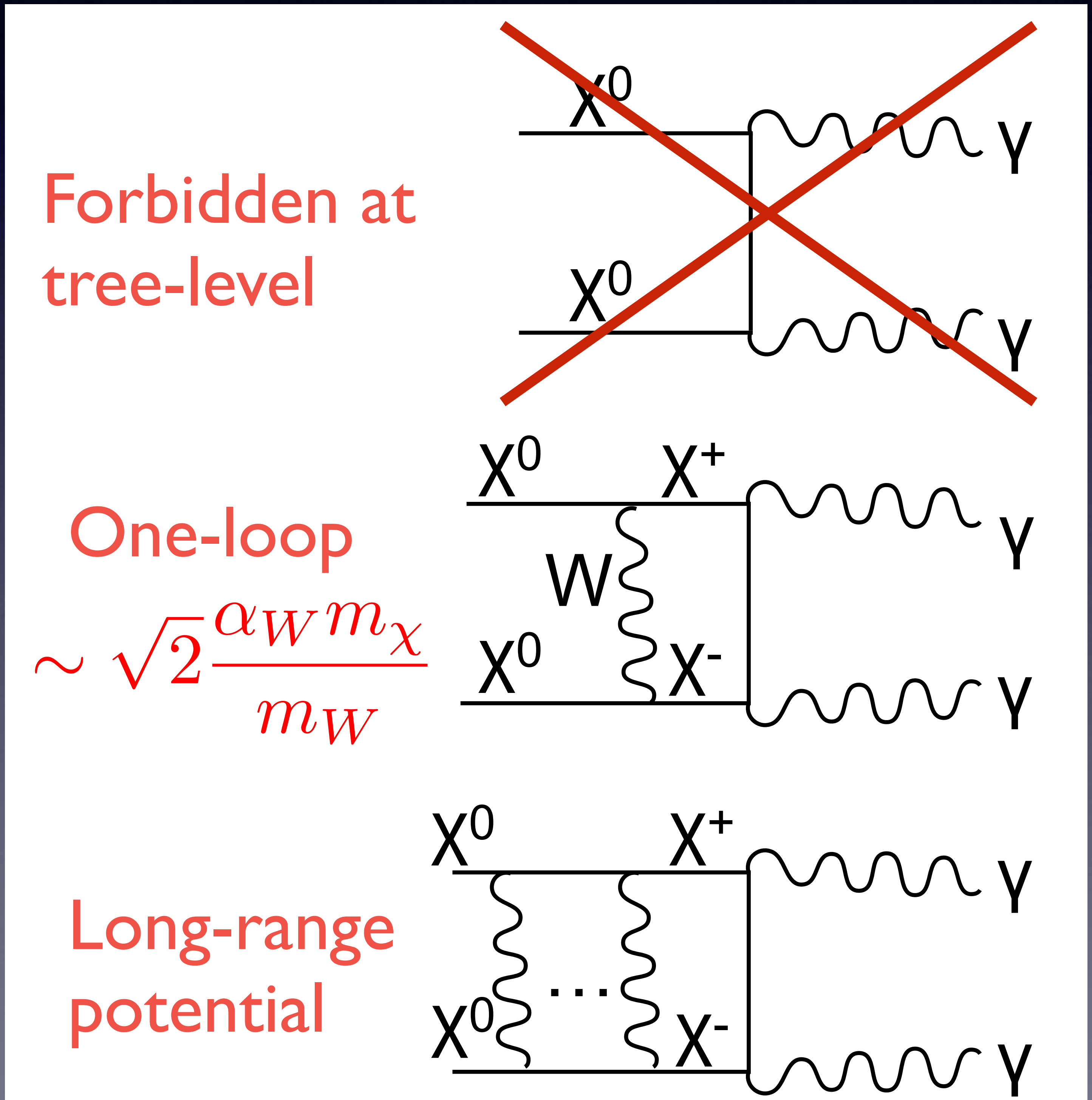


Jungman and Kamionkowski, hep-ph/9501365

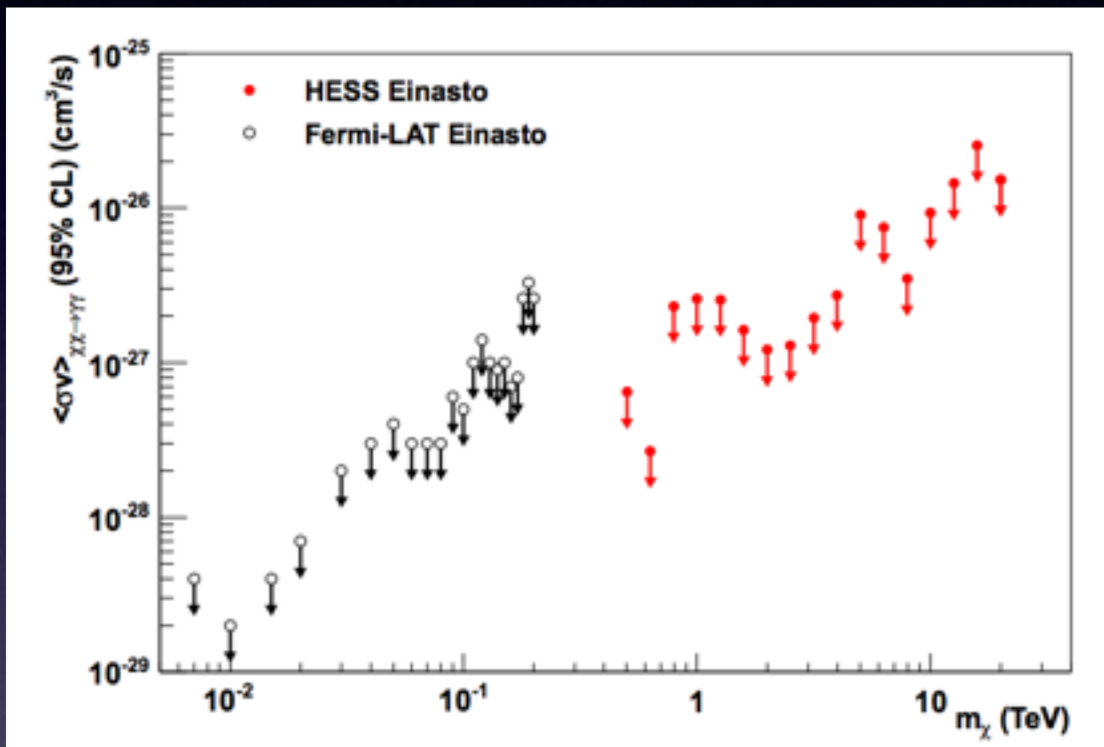
Line searches and heavy DM

- 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.

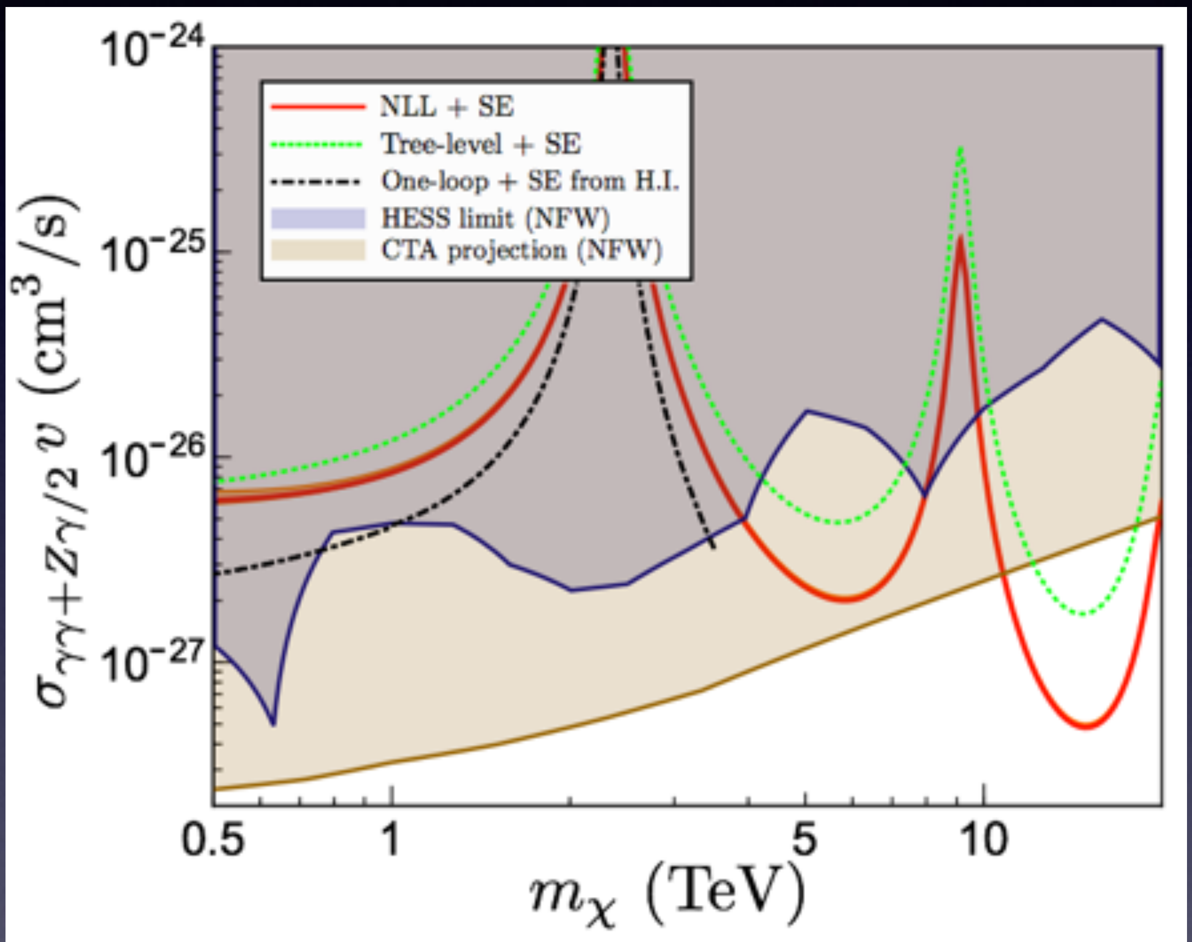
Example: wino-like dark matter



Example of line constraints for wino DM



HESS Collaboration '13 (1301.1173)

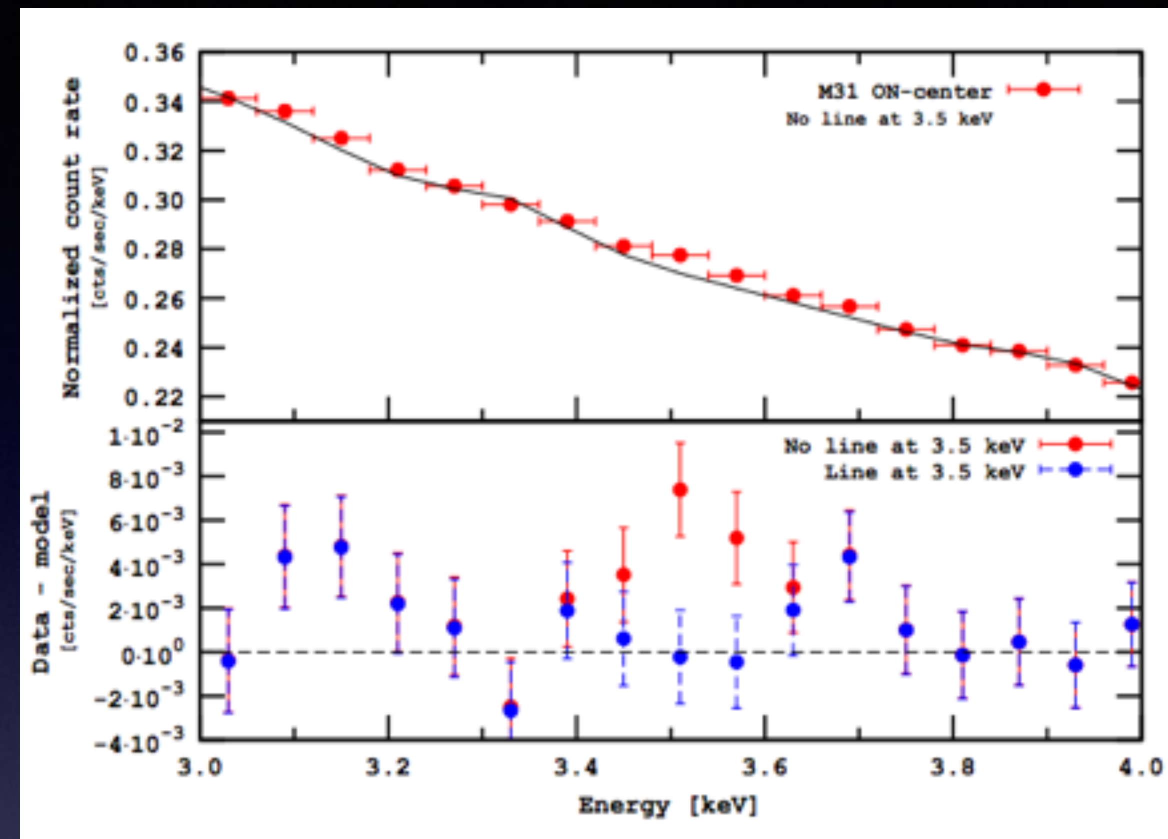


Ovanesyan et al '14

- 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)

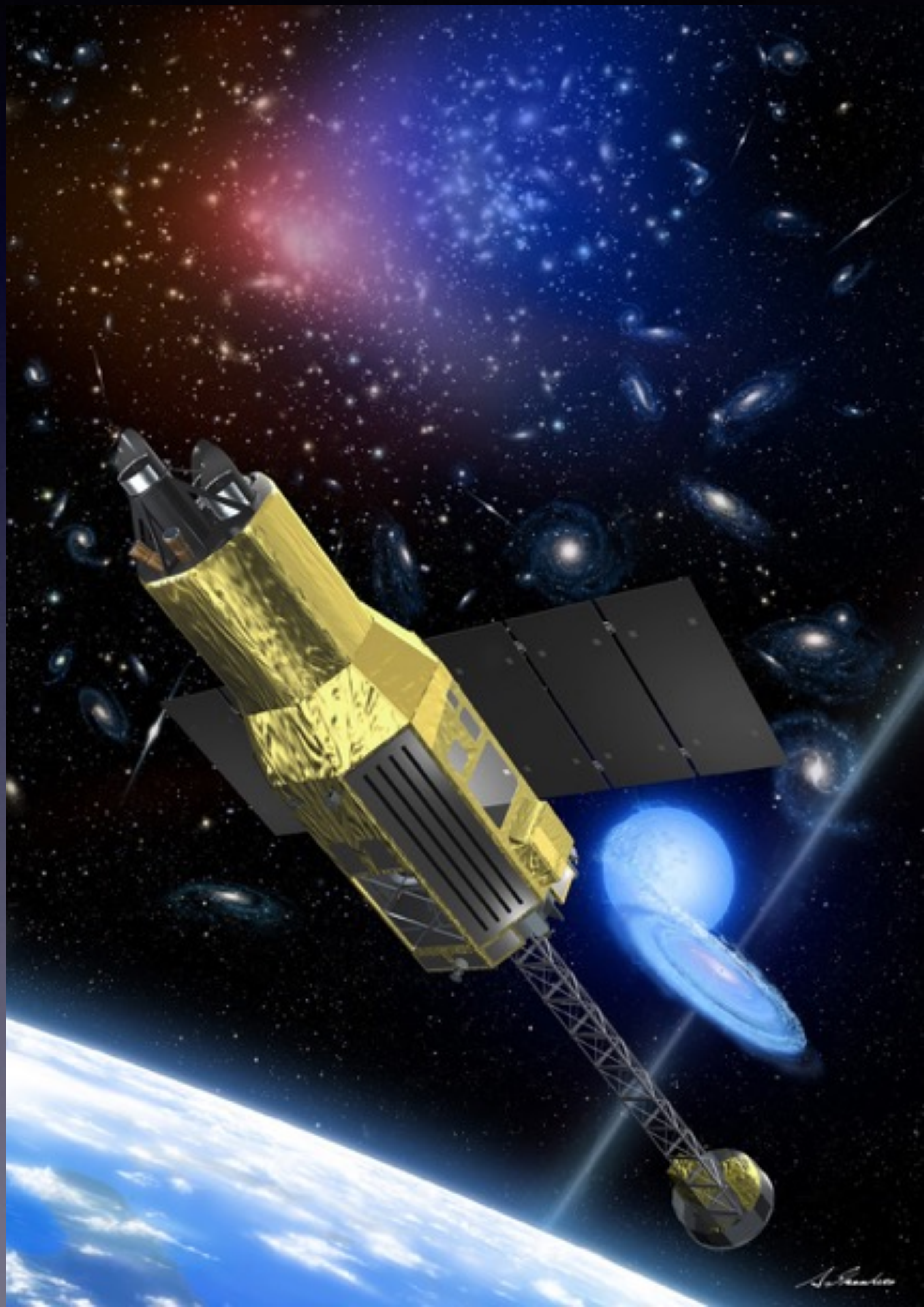
	XMM-Newton	Chandra	Suzaku
Milky Way center	✓	✗	
Andromeda galaxy	?		
Perseus cluster	✓	✓	?
Coma, Virgo, Ophiuchus	✓	✗ studied Virgo only	✗
Stacked clusters	✓		
Stacked galaxies	✗	✗	
Milky Way dwarfs	✗		

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 morphology is 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.
- Astro-H experiment hopes to launch in 2016.
- Soft X-ray Spectrometer System will cover energy range 0.3-12 keV with energy resolution ~7 eV.



Continuum gamma-rays in the Galactic Center

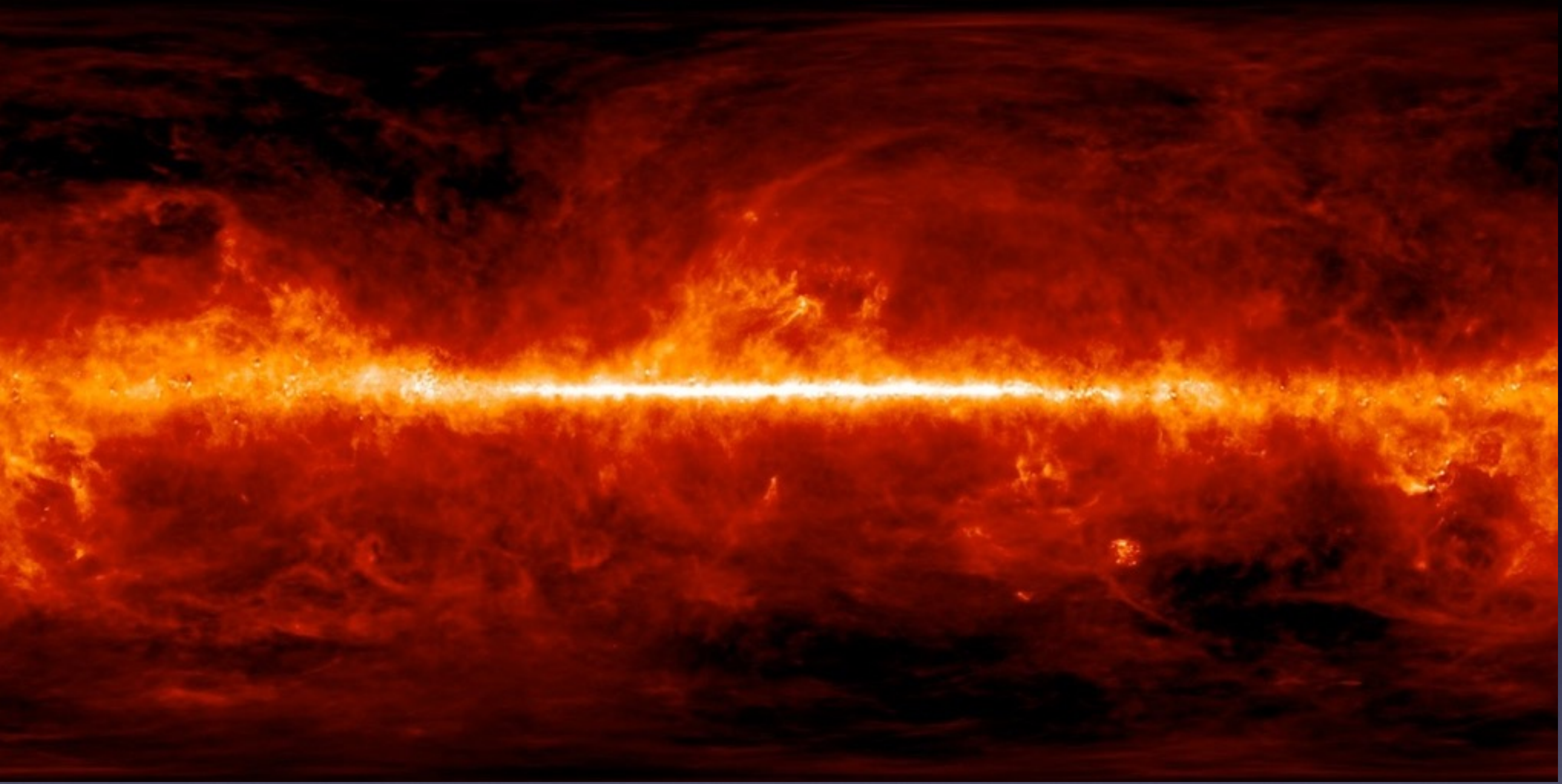
- In absence of line signal, need a way to estimate or parameterize backgrounds in the Galactic Center.
- At weak-scale energies, dominant backgrounds come from:
  - Cosmic ray protons striking the gas, producing neutral pions which decay to gammas.
  - Cosmic ray electrons upscattering starlight photons 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

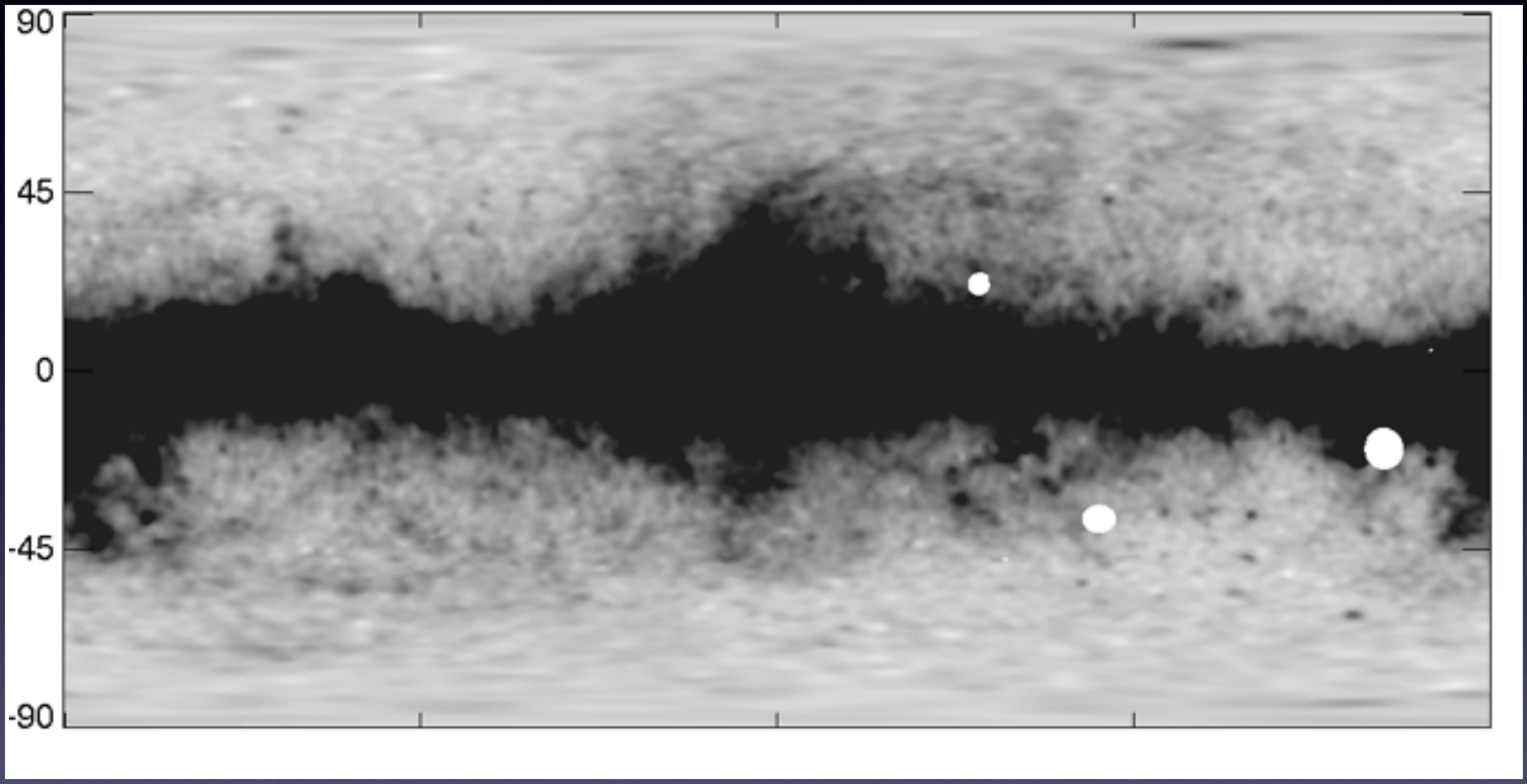
The gas-correlated background

Video credit: NASA



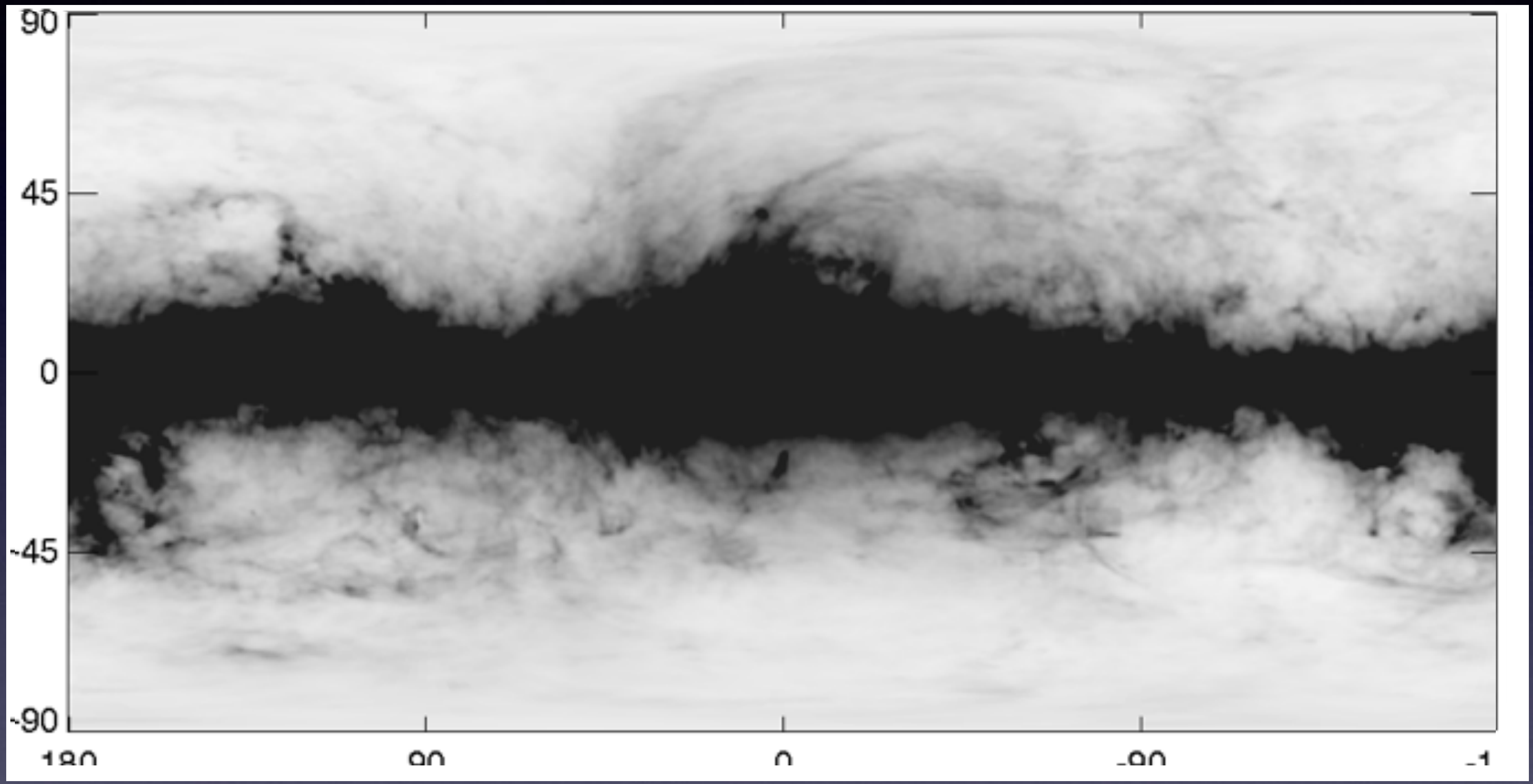
- Dominant background emission roughly traces the distribution of gas in the galaxy, other components depend on starlight distribution, sources of cosmic rays, etc.
- Very “disk-like” - brightest along the plane of the Galaxy.

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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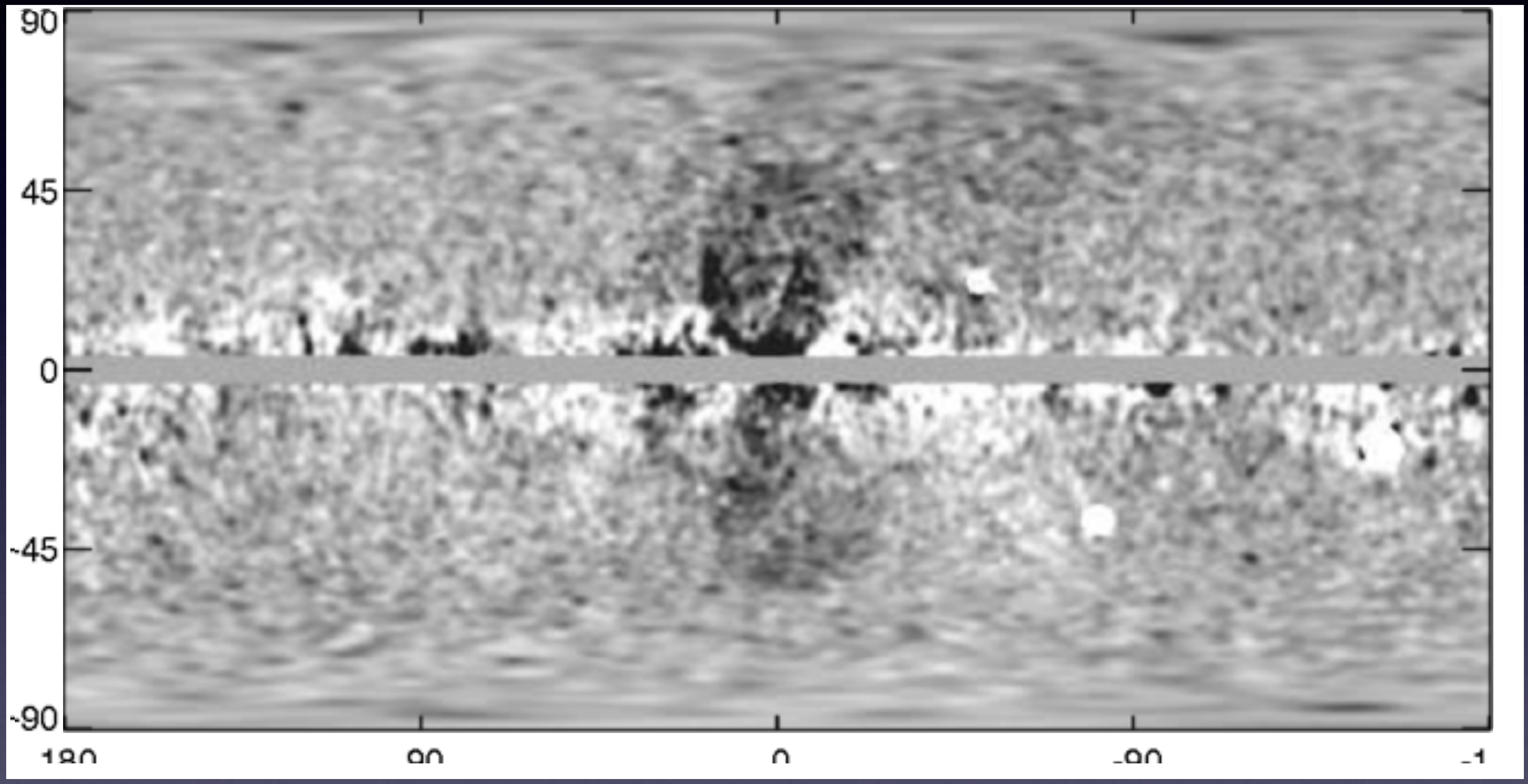

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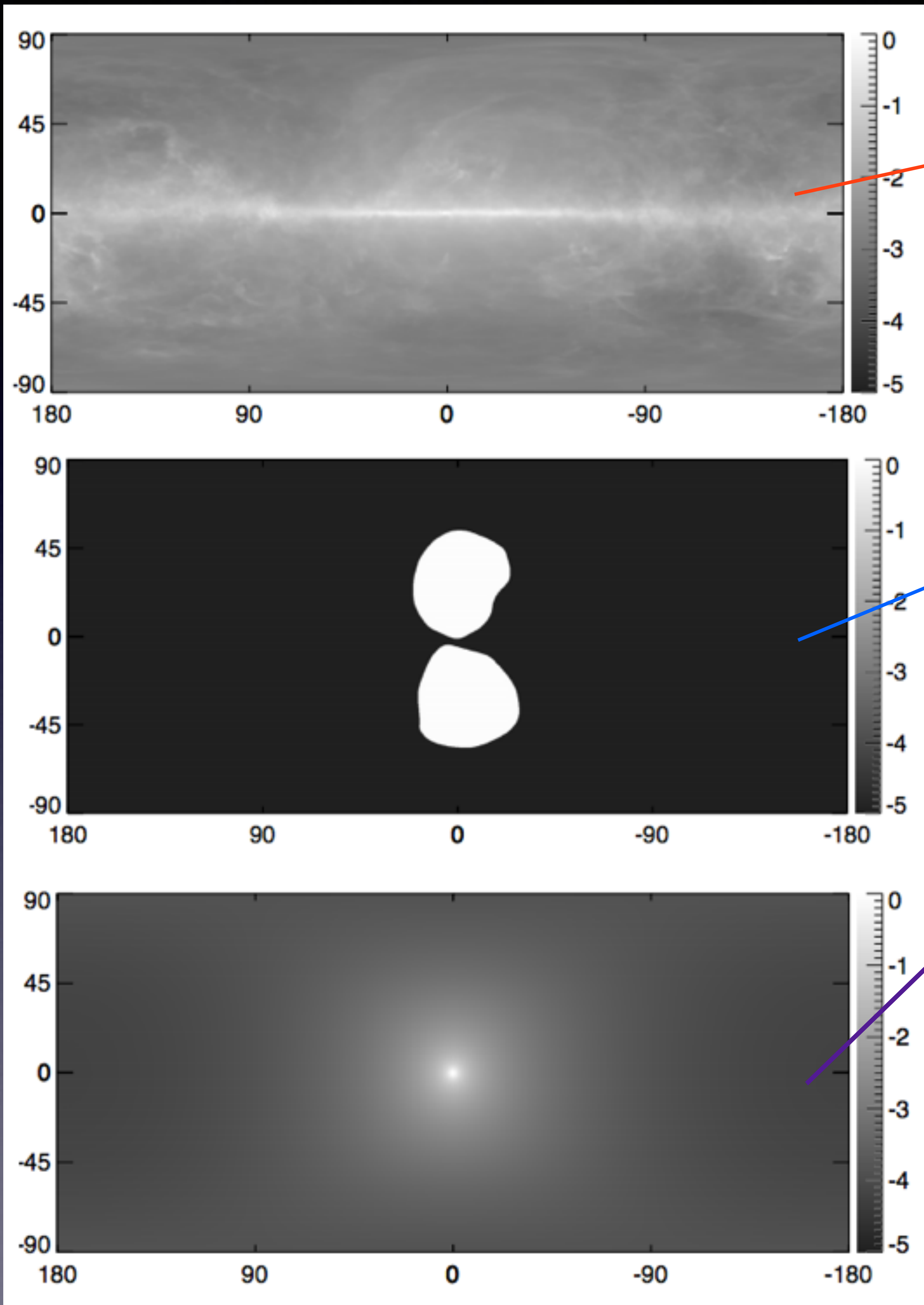
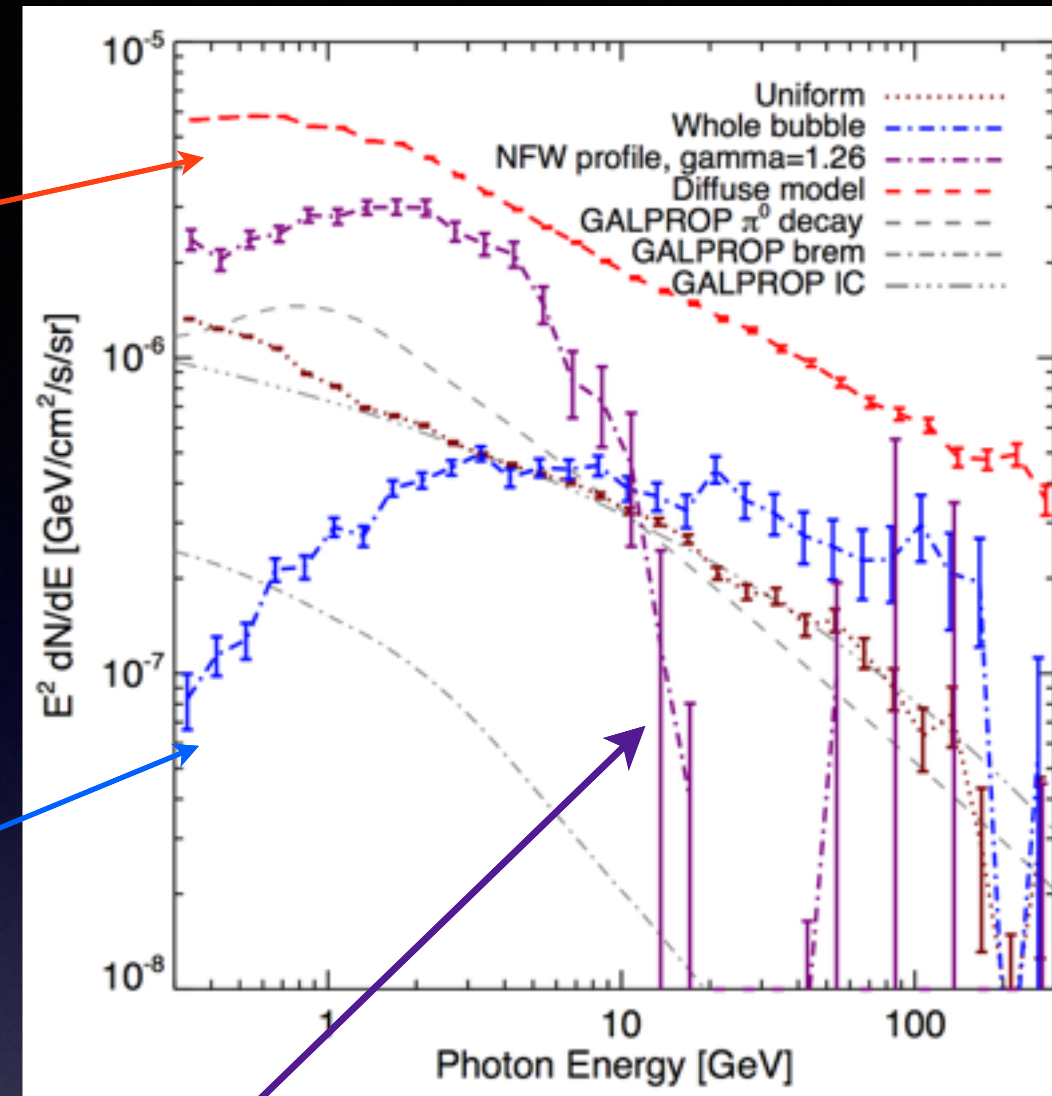
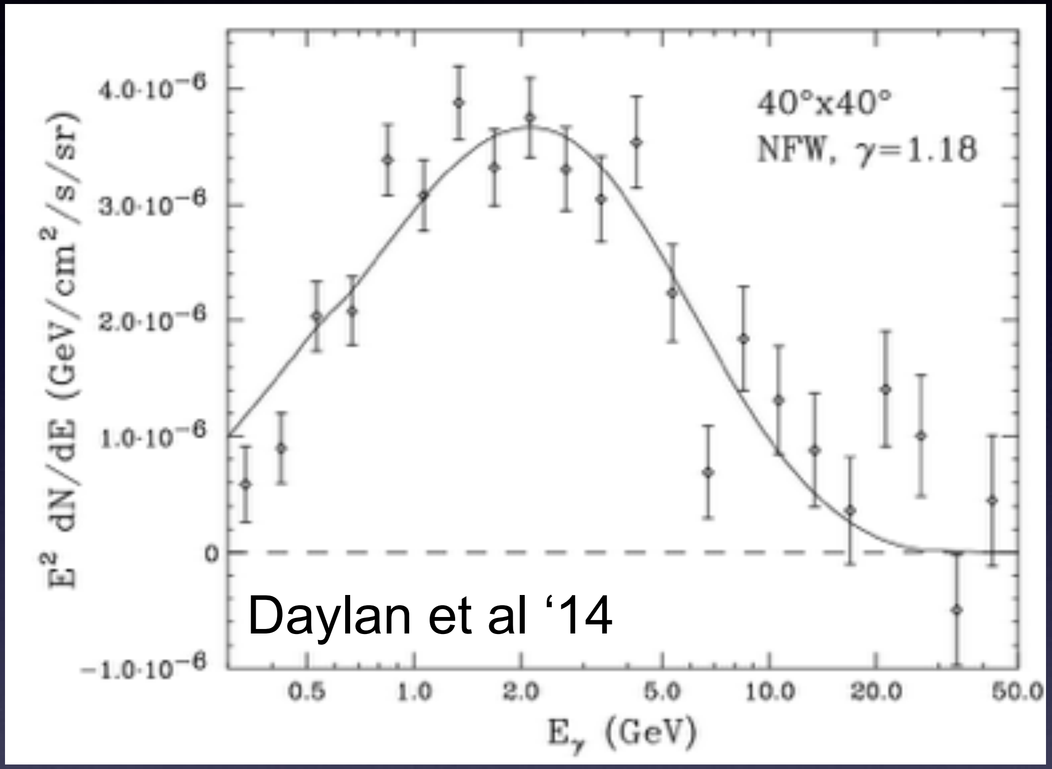


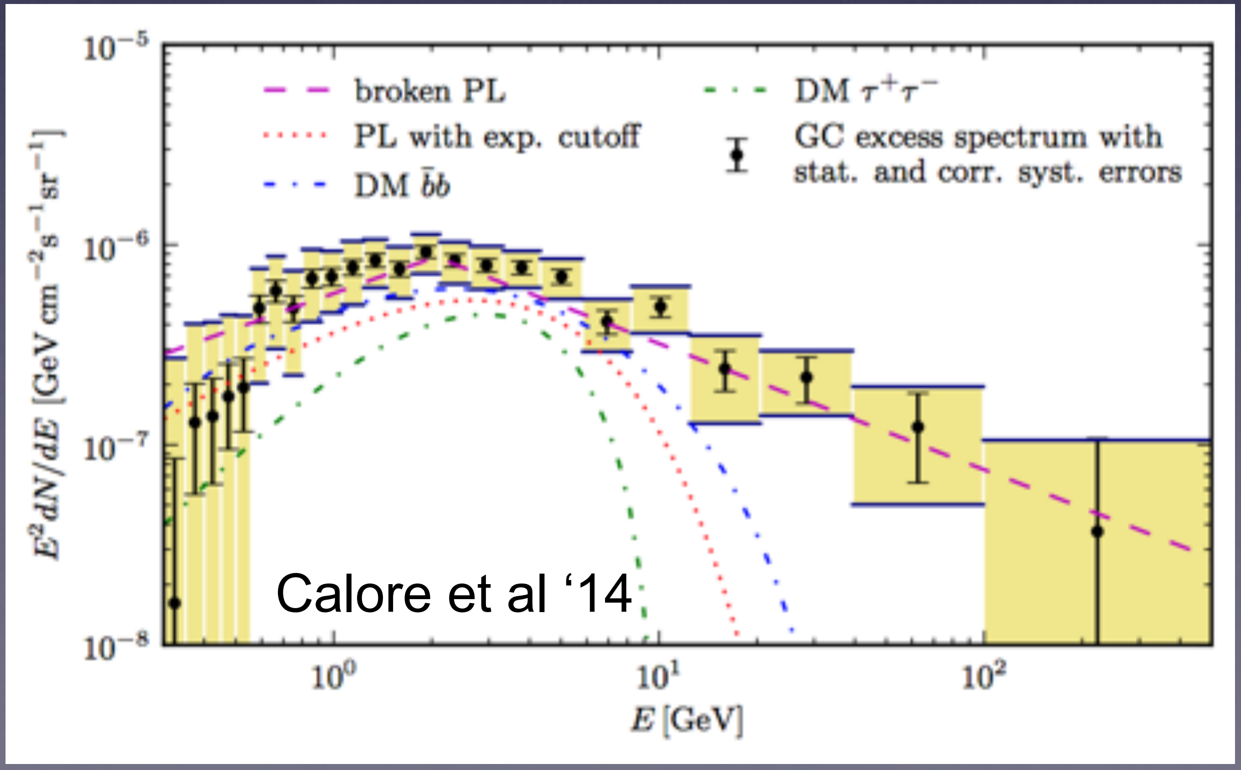


- Can add a model for a DM signal motivated by N-body simulations (or your favorite cored model) - generalized NFW profile, squared and projected along the line of sight.
- Fit the data as a linear combination of background(s) + signal, extract best-fit coefficient and error bars for each.
- Repeat at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

The GeV excess

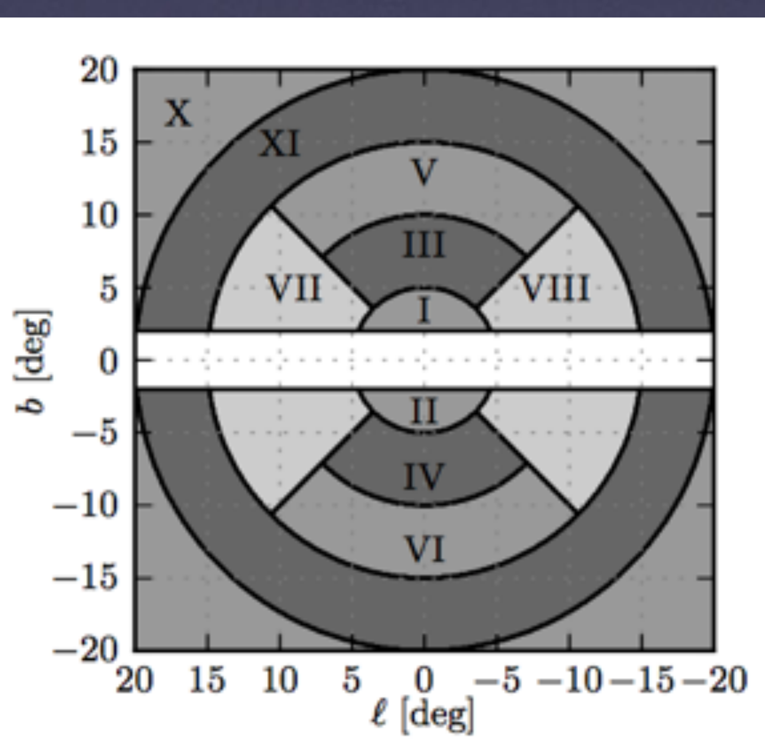
- There appears to be evidence for a new component in the Galactic Center (Goodenough & Hooper '09) and inner Galaxy (Hooper & TRS '13).
- Spectrum peaked at ~1-3 GeV.
- Rate consistent with simple thermal relic scenario, for ~50 GeV DM annihilating to quarks.
- Spatially, resembles a slightly steepened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



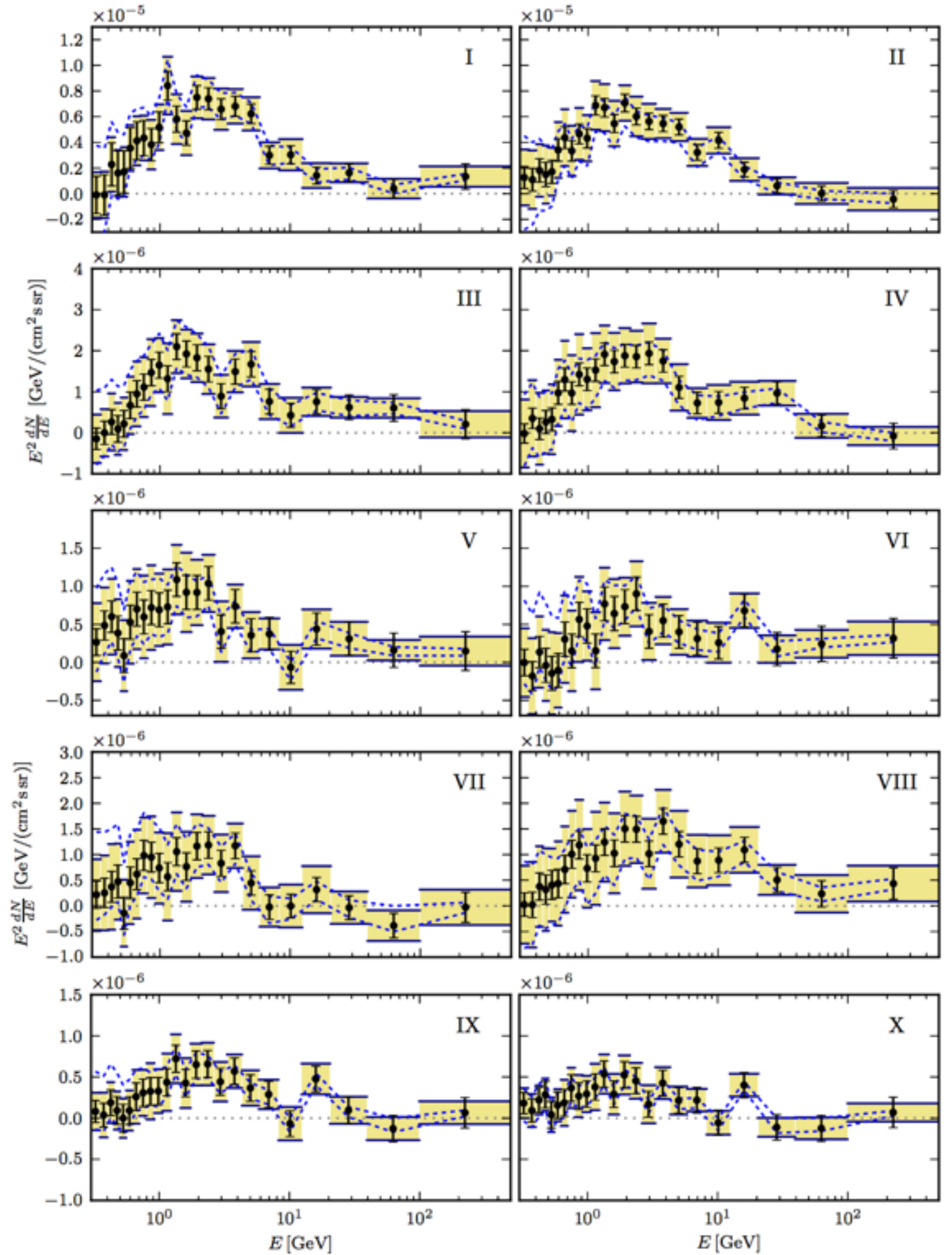


Morphology

- 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).



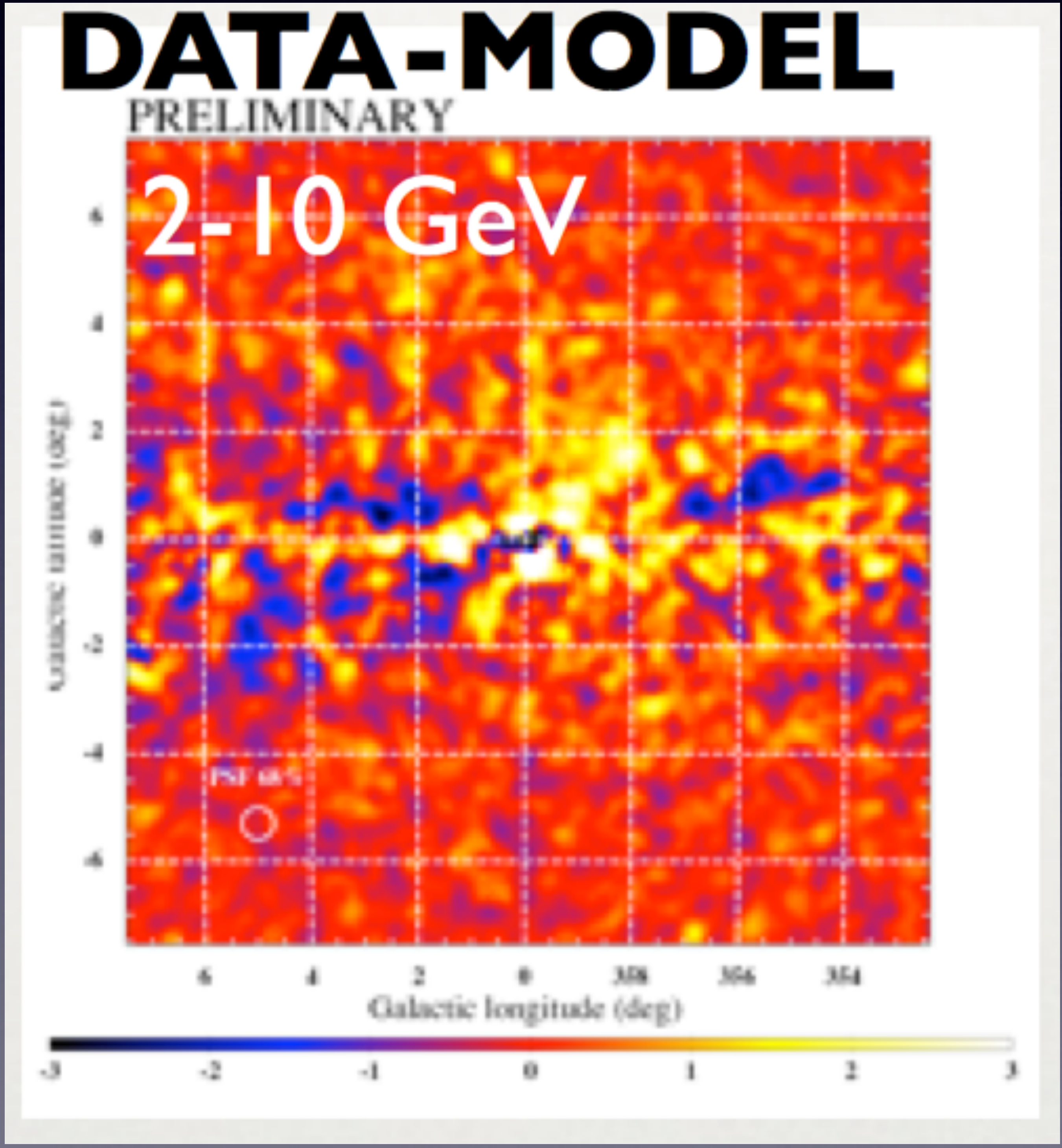
Plots taken from Calore, Cholis & Weniger '14



What does the Fermi Collaboration say?

conference proceeding Porter & Murgia 1507.04688

- Collaboration has developed new diffuse model + point source model for the inner Galaxy region.
- Talk by Simona Murgia given at Fermi Symposium 20-24 October ’14:
    - “We find an enhancement approximately centered on the Galactic center with a spectrum that peaks in the GeV range, that persists across the models we have employed”
    - “Peaked profiles with long tails (NFW, NFW contracted) yield the most significant improvements in the data-model agreement”
- Spectrum depends on background modeling (esp. at low+high energies) but for best models seems ~consistent with other groups.

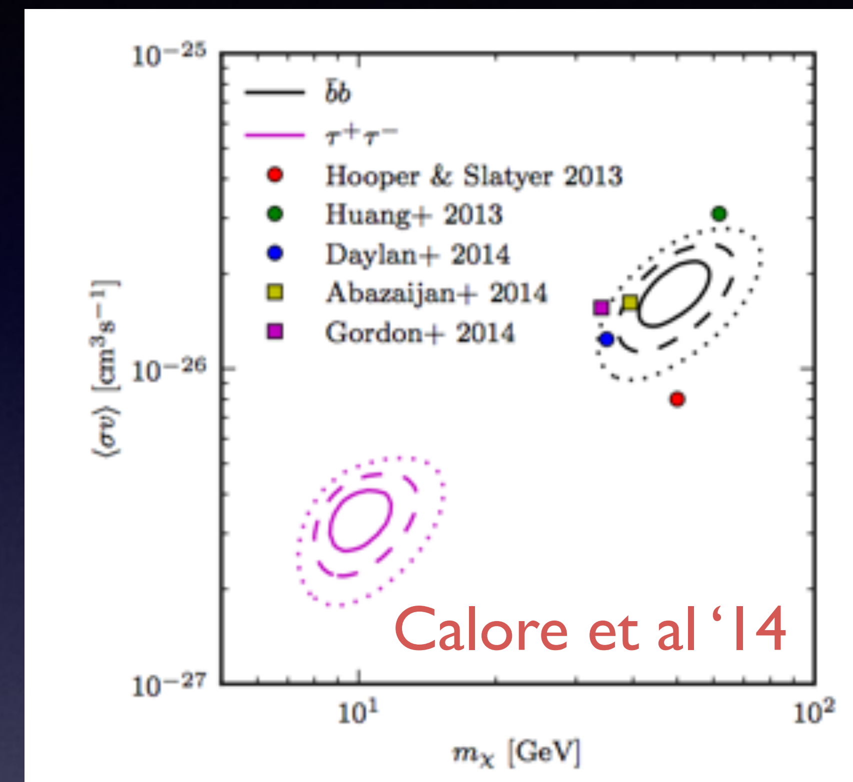


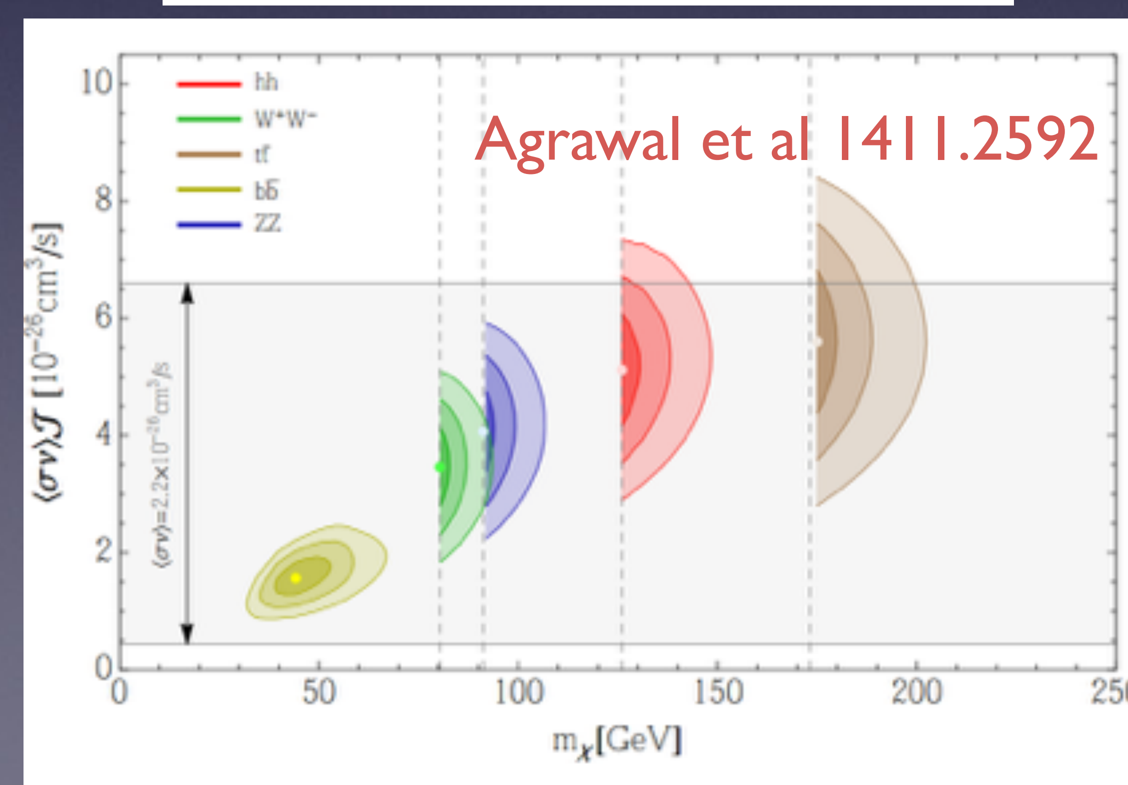
Possible pitfalls

- Stability to background modeling - tested by Calore et al '14. General features appear robust (but risk is that tests have not spanned a sufficient range of possibilities).
- Sphericity of excess + consistent spectrum seems hard to explain by simple failure of background modeling.
- May also reflect a physical new background, not accounted for in model - e.g. new population of compact sources, or transient outflow of cosmic rays from Galactic Center.
  - Recent work by Lee et al and Weniger et al suggests a strong statistical preference for a point source population.

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.

Effective field theory…

(a) Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A

(b) Operators for Complex scalar DM

Name	Operator	Dimension	SI/SD
C1	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	6	SI
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$	6	N/A
C3	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu q$	6	SI
C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	6	N/A
C5	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	6	SI
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

Study couplings to
hadronic states only

Alves et al
1403.5027

Effective field theory…

(a) Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
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D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	6	N/A
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A

(b) Operators for Complex scalar DM

Name	Operator	Dimension	SI/SD
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$	6	N/A
C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	6	N/A
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

ruled out by DD

Study couplings to hadronic states only

Alves et al
1403.5027

Effective field theory…

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C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

ruled out by DD

cannot fit signal

Study couplings to hadronic states only

Alves et al 1403.5027

Effective field theory…

(a) Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
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Name	Operator	Dimension	SI/SD
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ruled out by DD

cannot fit signal

ruled out by LHC

Study couplings to hadronic states only

Alves et al 1403.5027

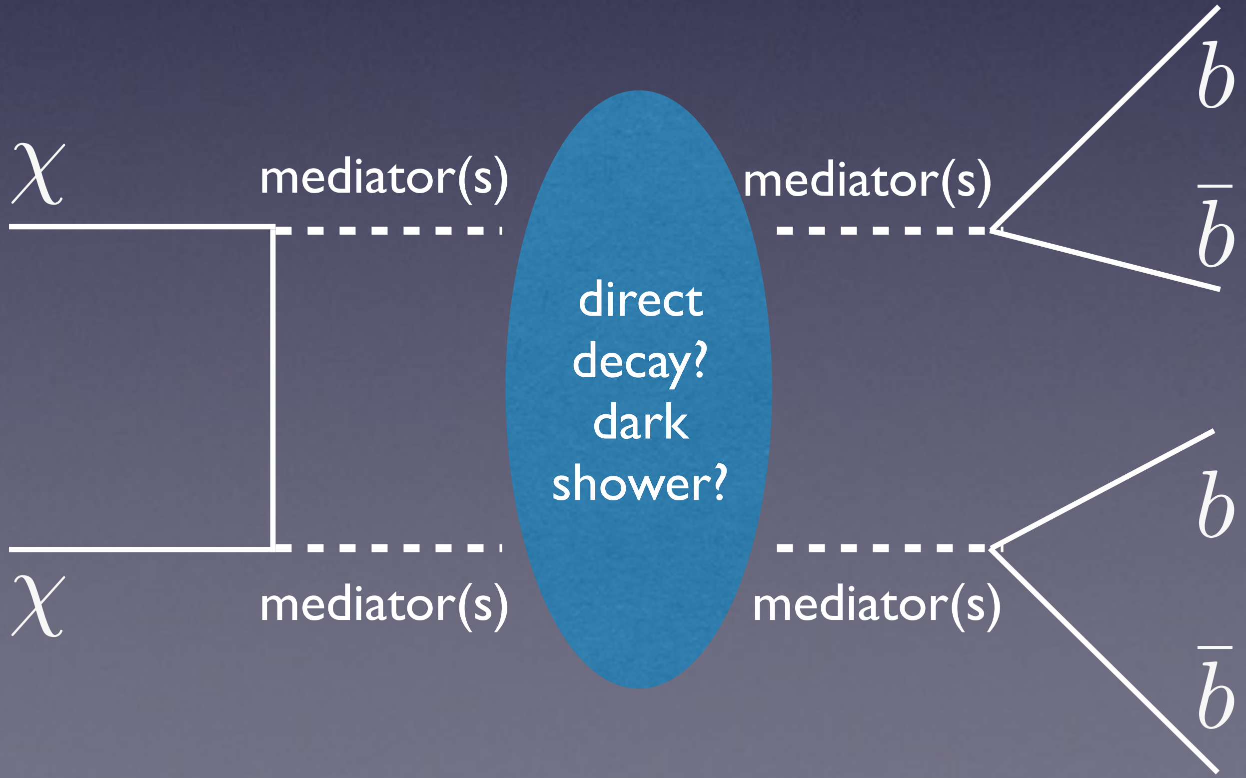
… and beyond

Berlin et al 1404.0022 (simplified models)

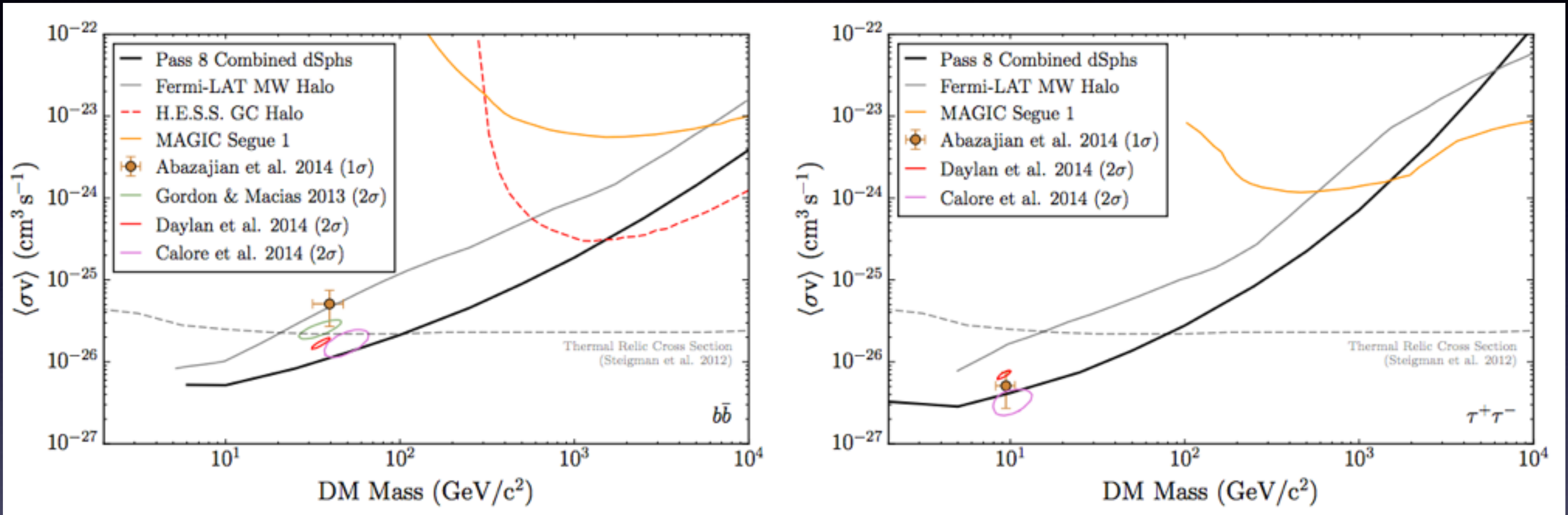
Model Number	DM	Mediator	Interactions	Elastic Scattering	Near Future Reach? Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

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).

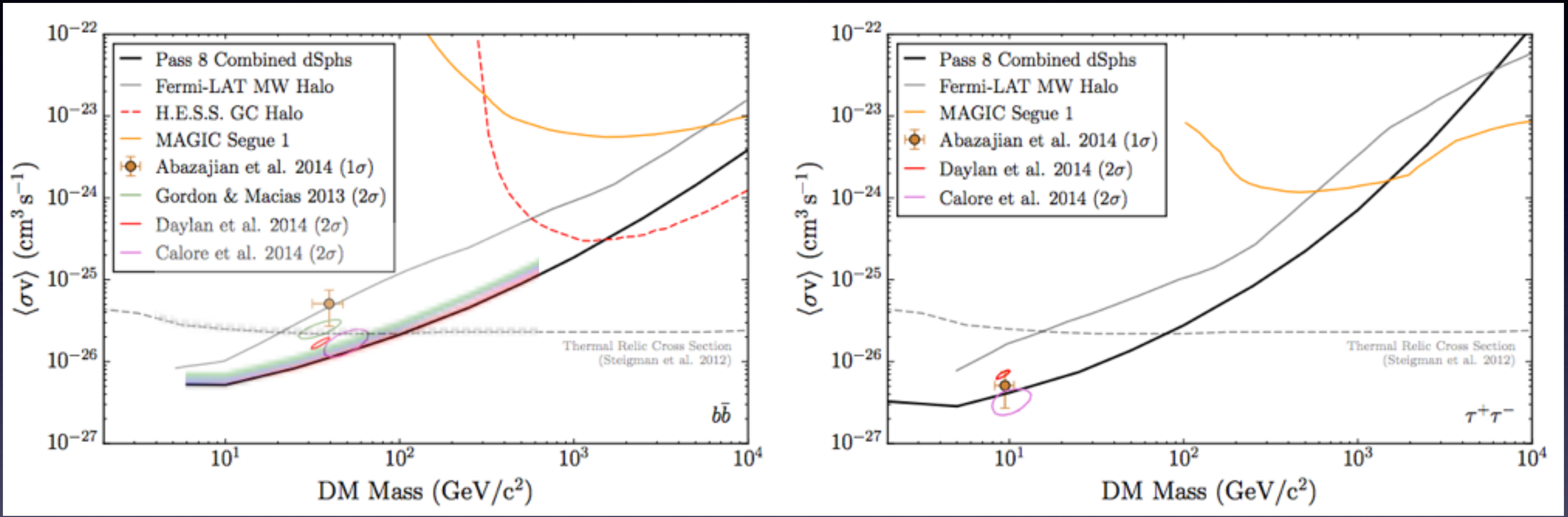


Dwarf galaxies



- Fermi study of stacked dwarfs with Pass 8 (1503.02641) can constrain preferred cross section for some channels.
- But no uncertainties on density profile for inner Galaxy study included in this analysis; also includes statistical but not systematic uncertainties for the dwarf dark matter content (not a strong effect, but can be relevant at the borderline).
- Hope for a possible confirmation?

Dwarf galaxies



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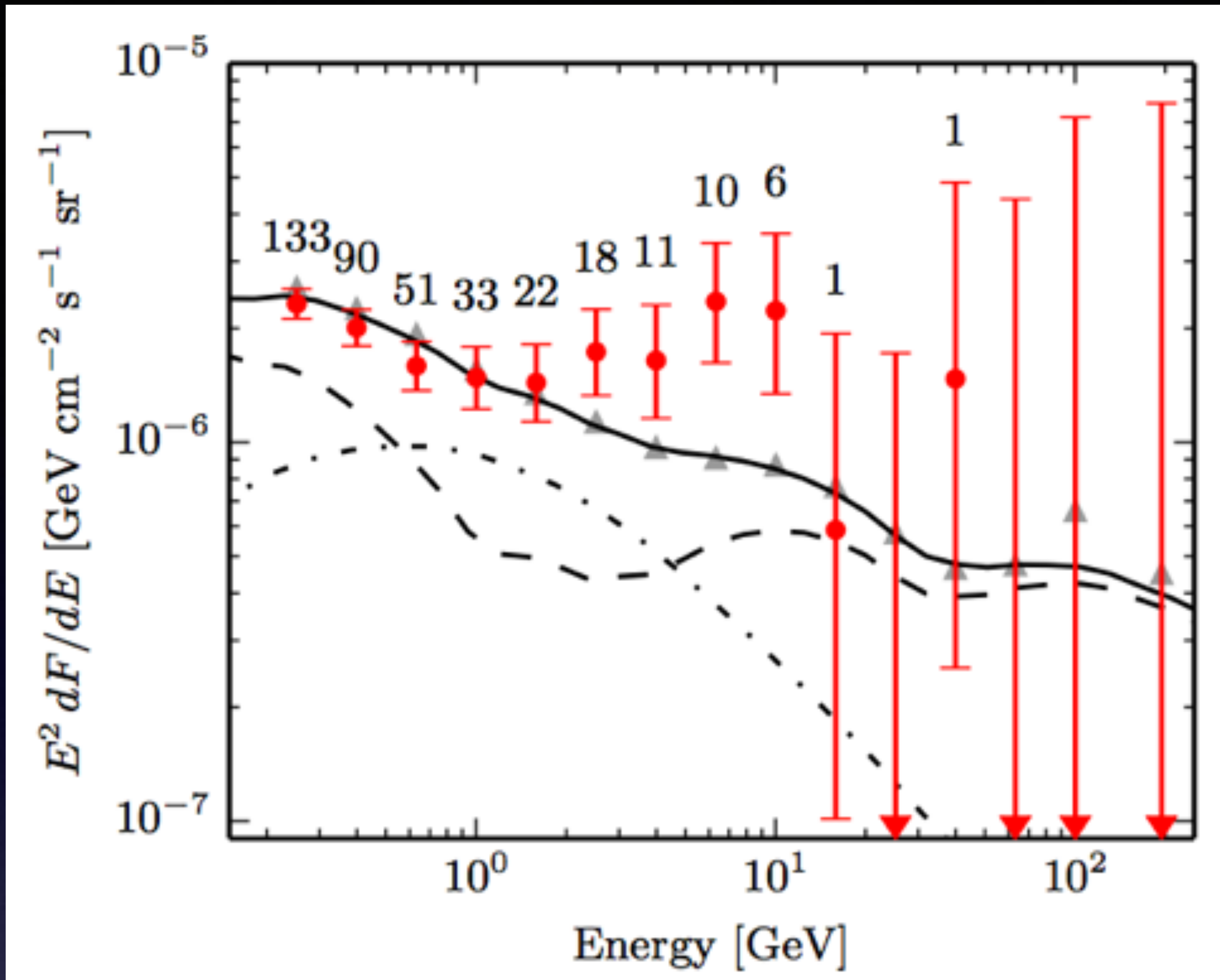
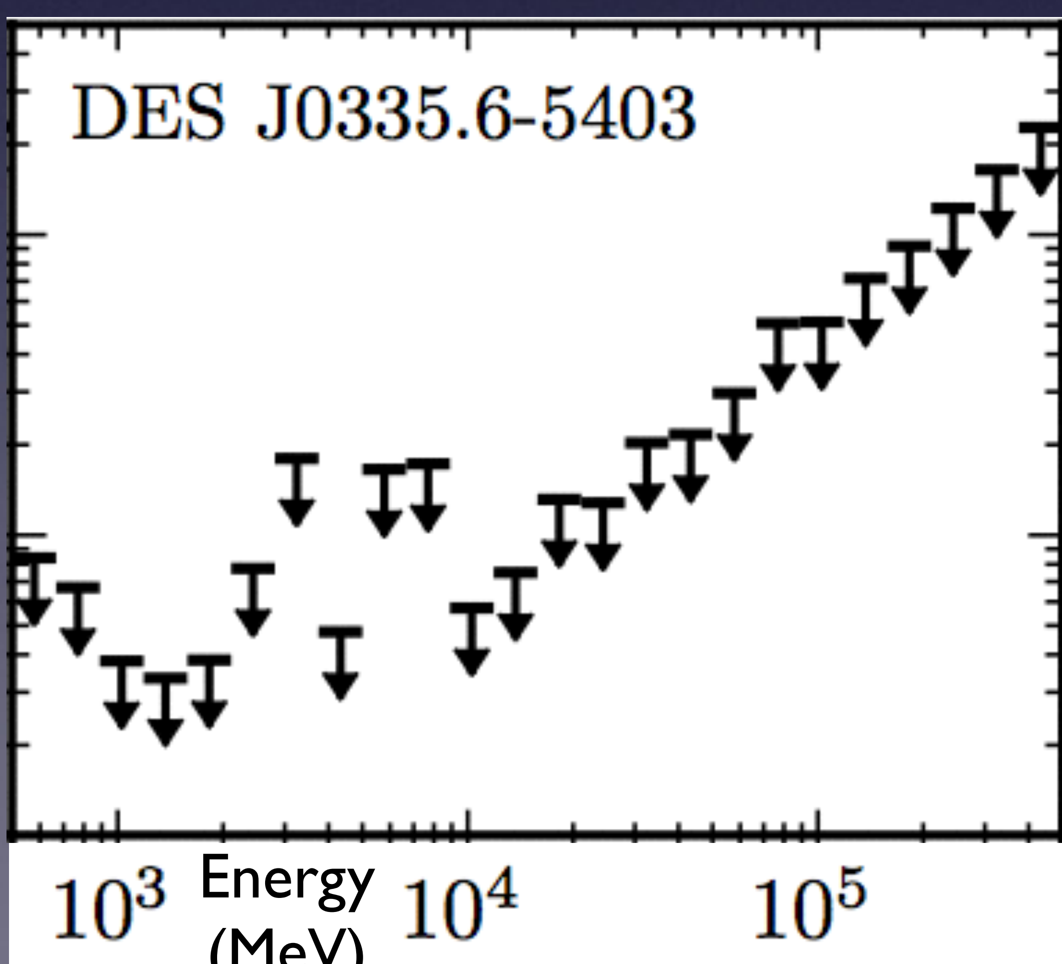
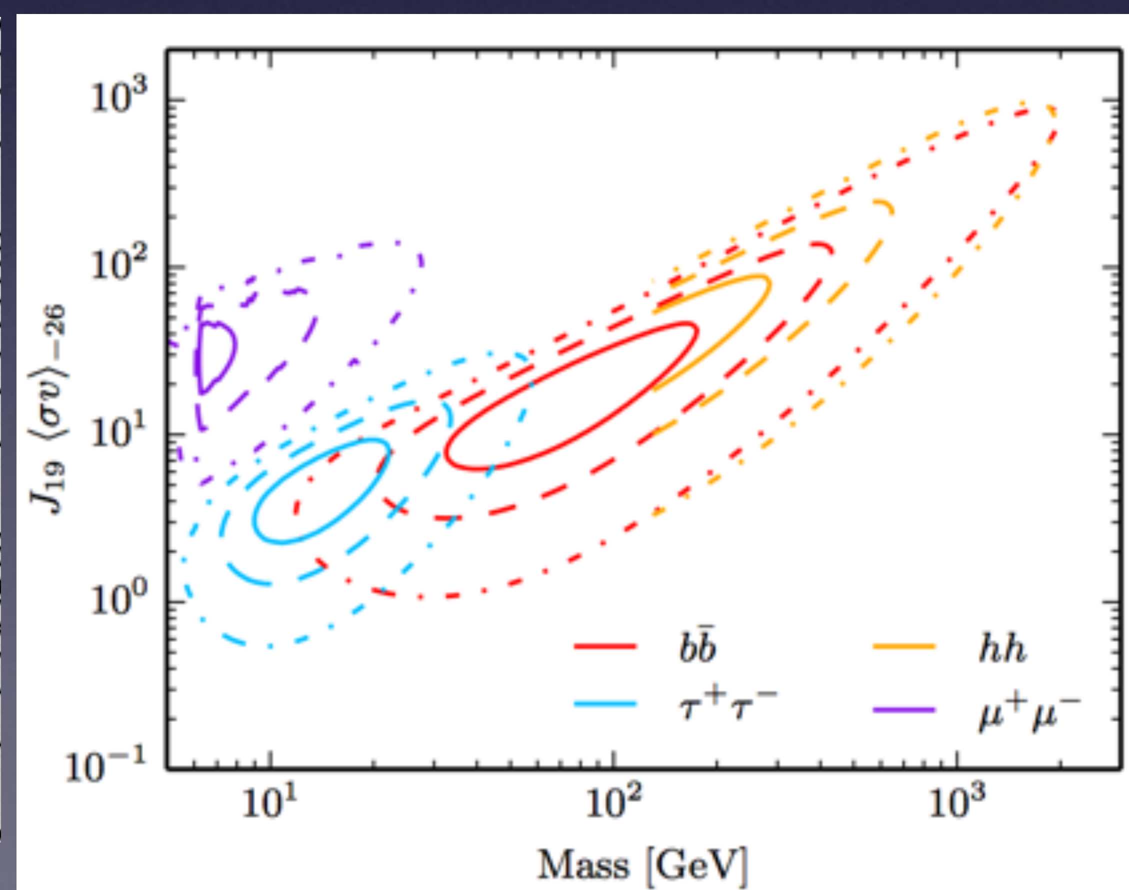
- Hope for a possible confirmation?

Reticulum II

- Small excess of 2-10 GeV gamma rays found from newly discovered dwarf candidate Reticulum II by three independent groups.
- Claimed significance of 2.3-3.7σ (Geringer-Sameth et al, 1503.02320, upper left); 2.2σ local significance or 1.65σ after trials for DM models (Fermi Collaboration, 1503.02632, lower left); 3.2σ (Hooper & Linden, 1503.06209)

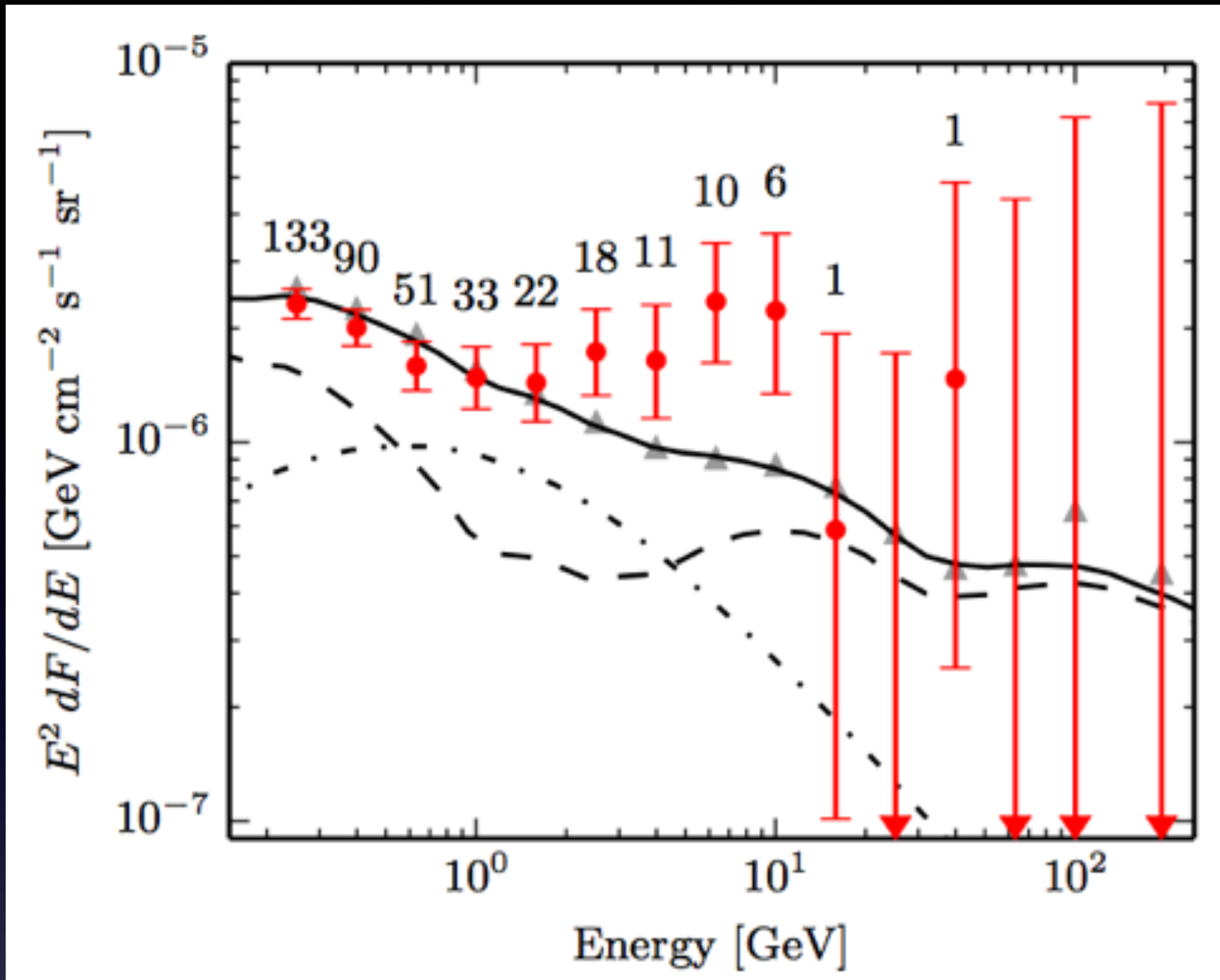






If we take a J-factor of $10^{19.5}$ GeV^2/cm^5 within 0.5 deg as found by 1504.03309*, favored region compatible with inner Galaxy excess.

*Note that this value has a 1-order-of-magnitude error bar. 1504.02889 finds $10^{18.8(9)\pm0.6}$ GeV^2/cm^5 in an 0.2 (0.5) deg radius.



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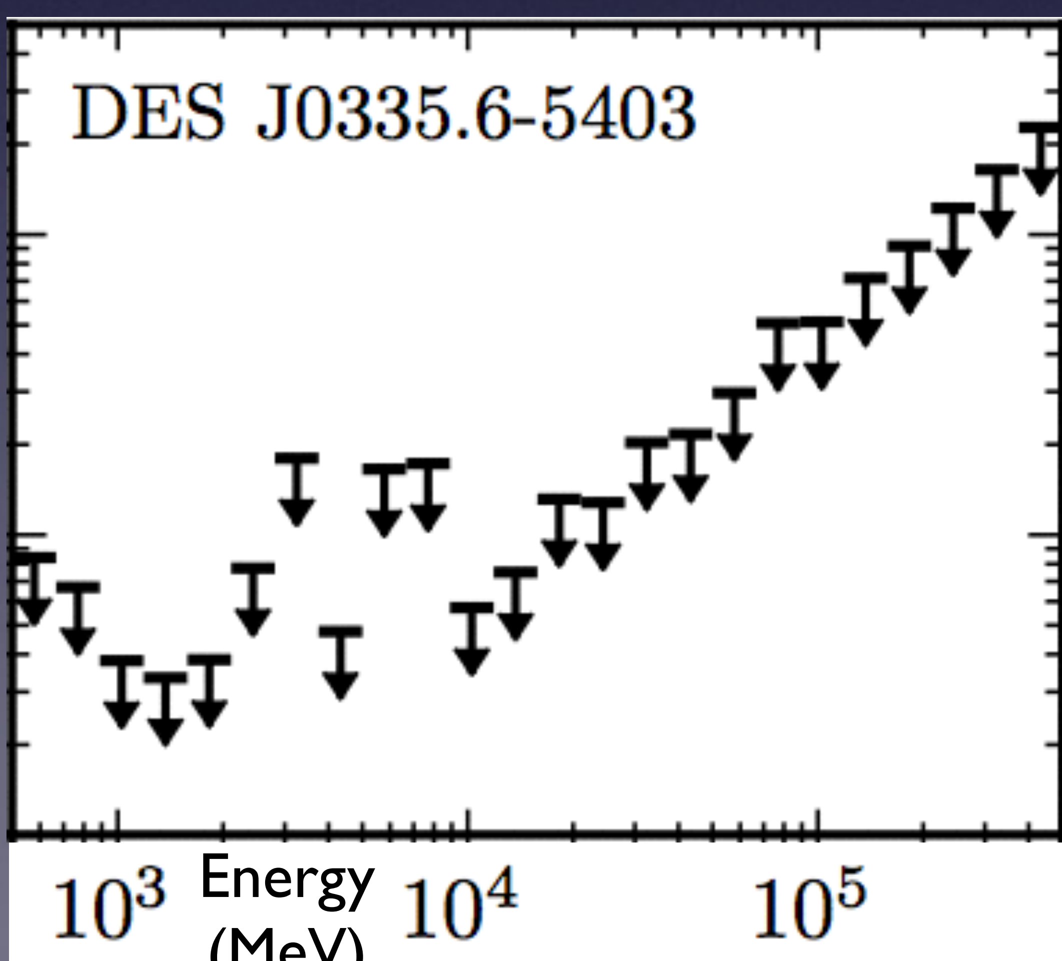

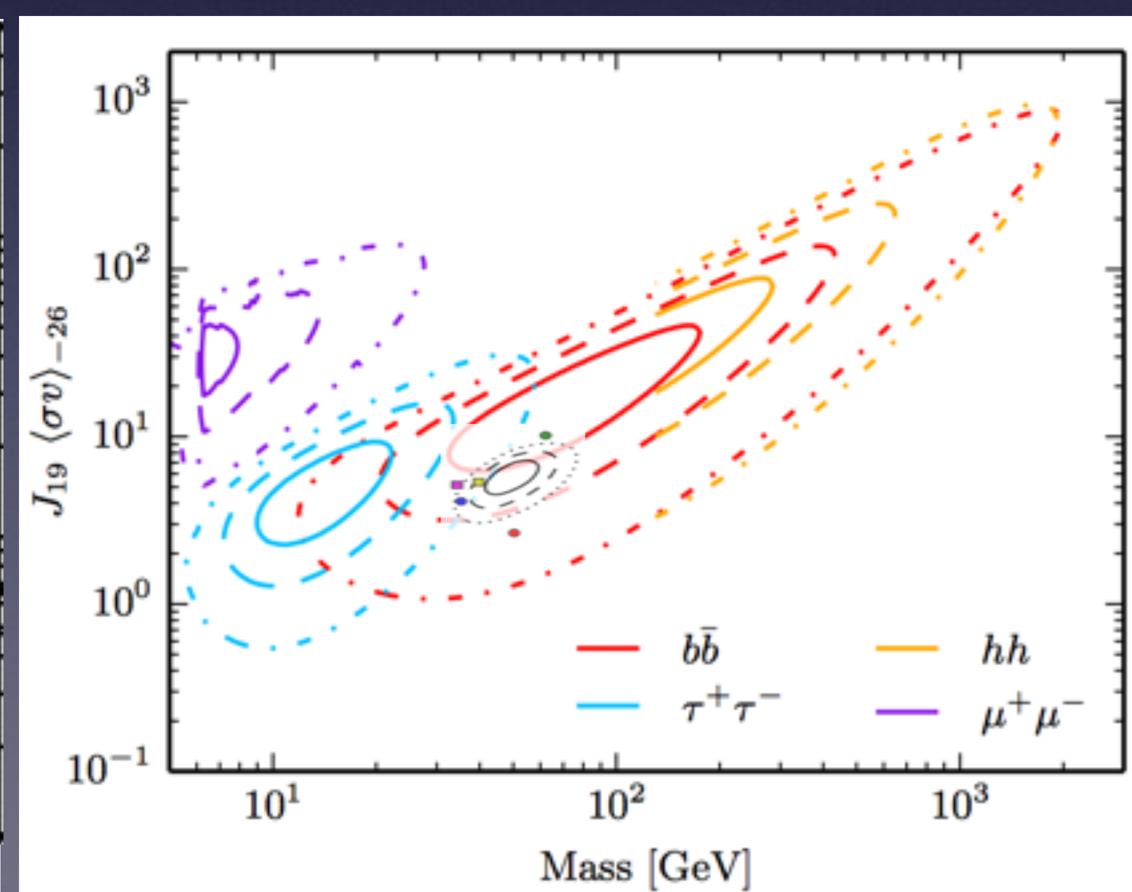

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an example of “indirect” annihilation probes

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

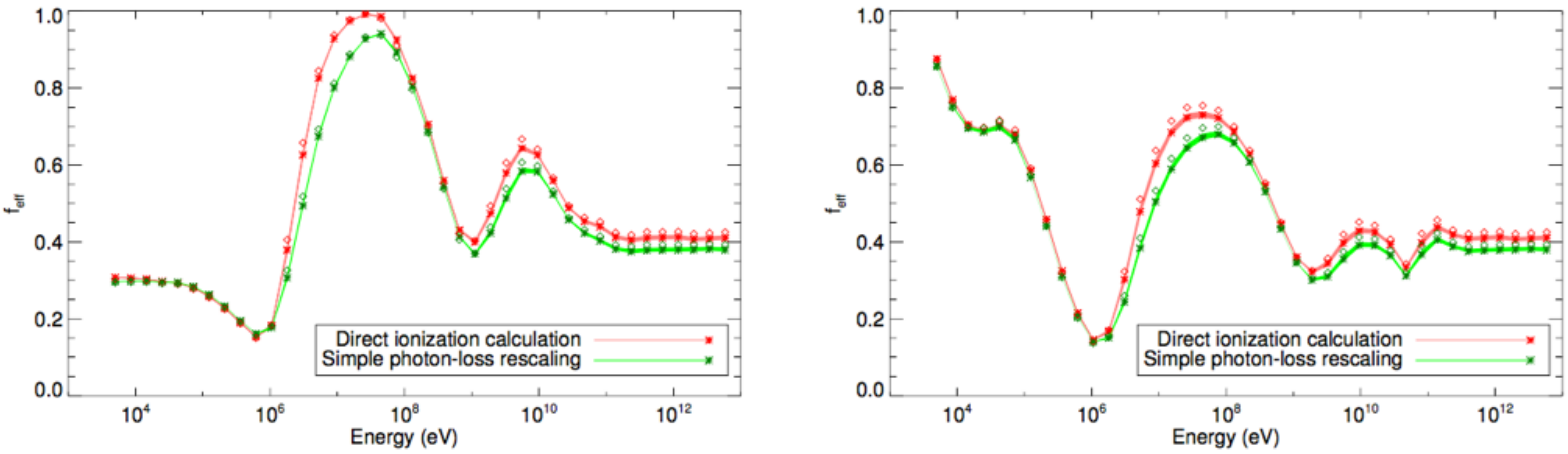
DM annihilation → photons, electrons, positrons → ionization → scale-dependent perturbation to CMB anisotropies

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).

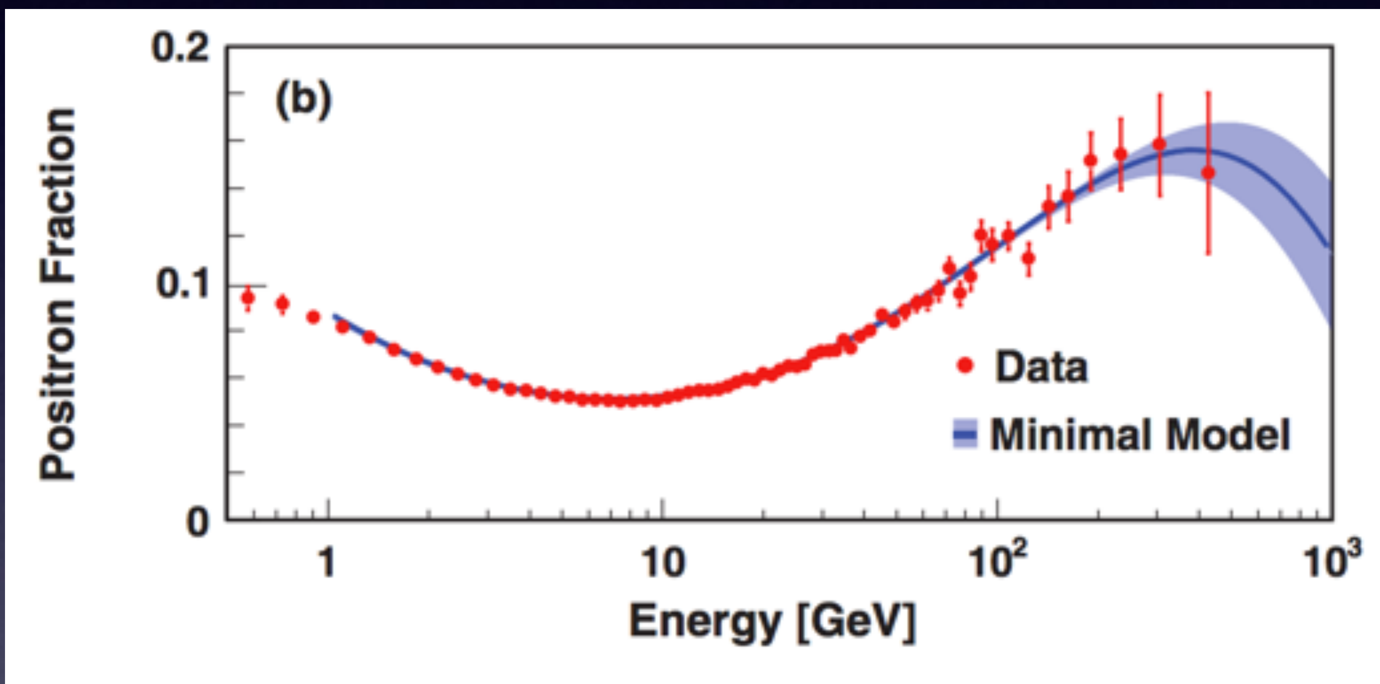
Energy-dependent efficiency factor



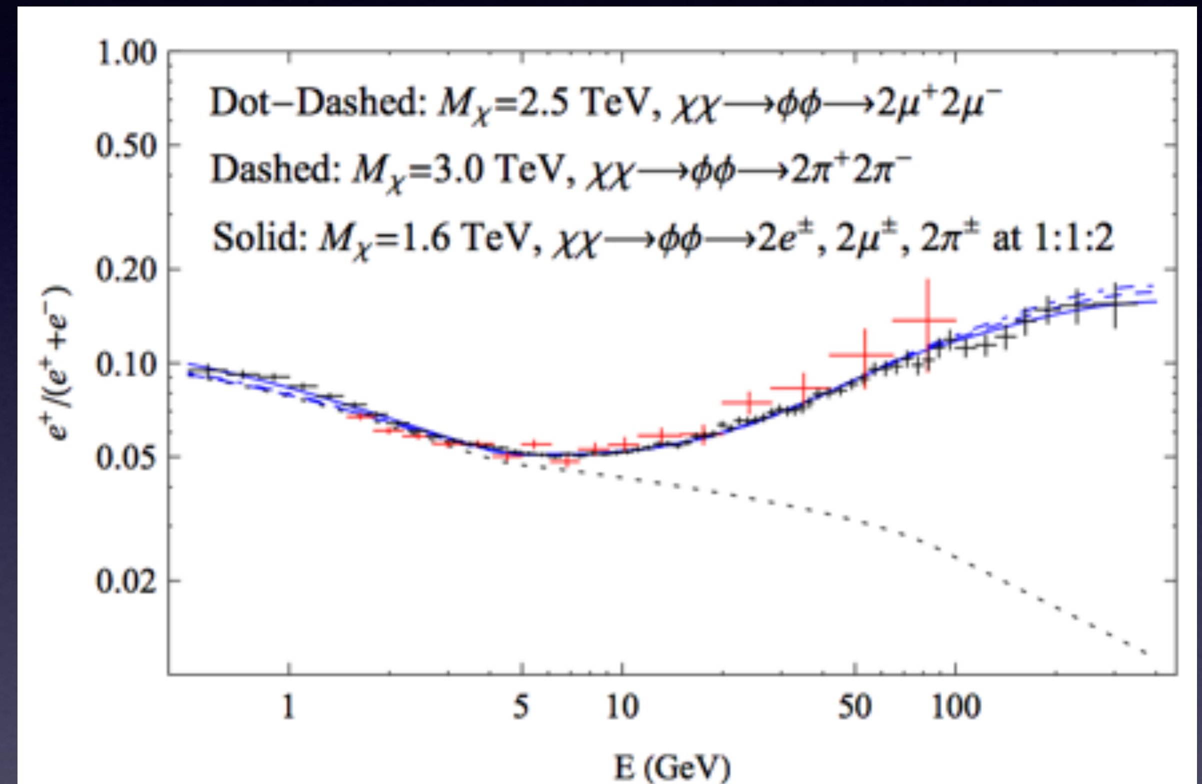
- Results for e^+e^- pairs (left) and photons (right).
- Results for arbitrary spectra can be determined by taking linear combinations of these results.
- Computed by tracking the cooling of electrons, positrons and photons from high to low energies, in the environment of the early universe.

The PAMELA/Fermi/AMS-02 positron excess

AMS-02 Collaboration '14



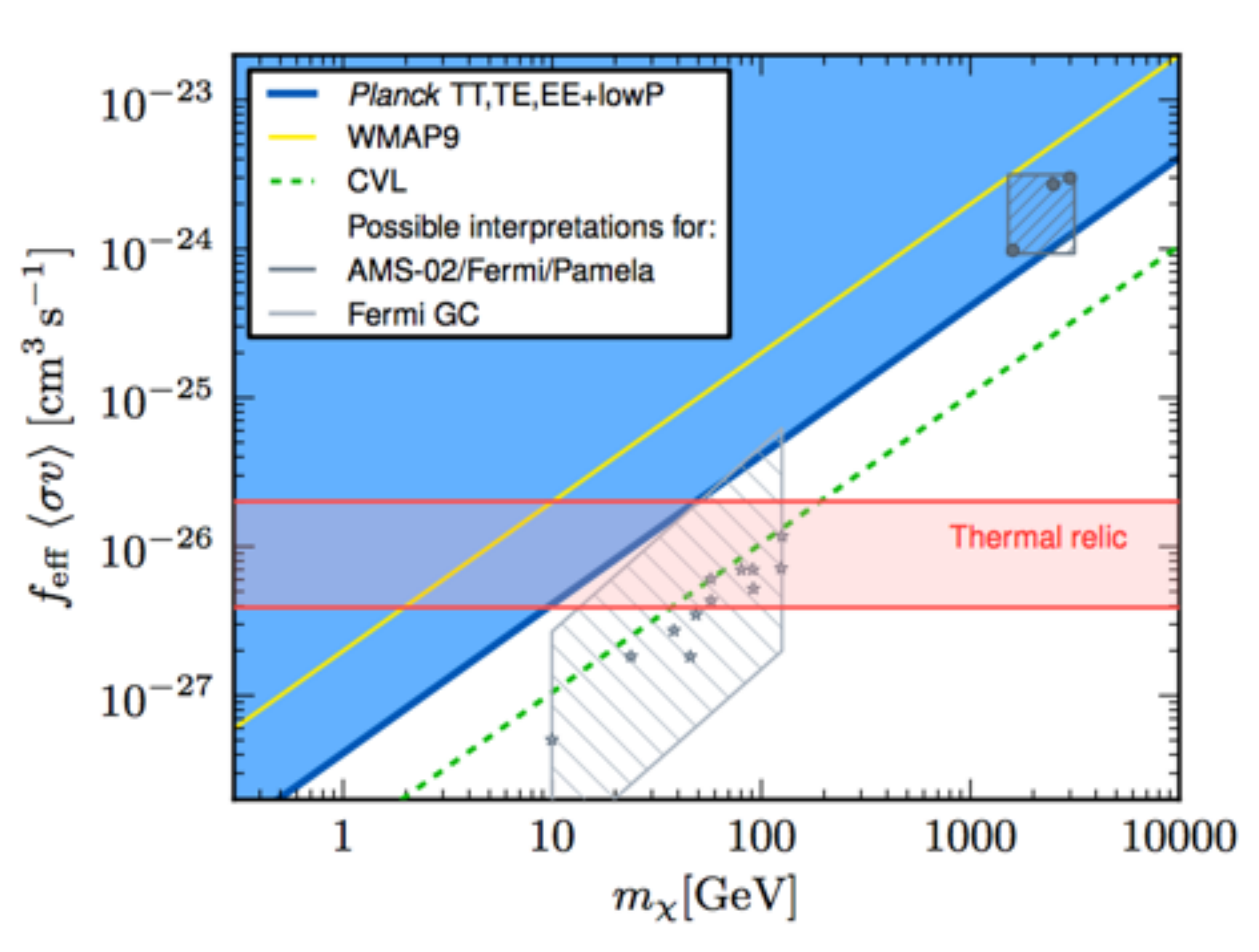
Cholis & Hooper '13

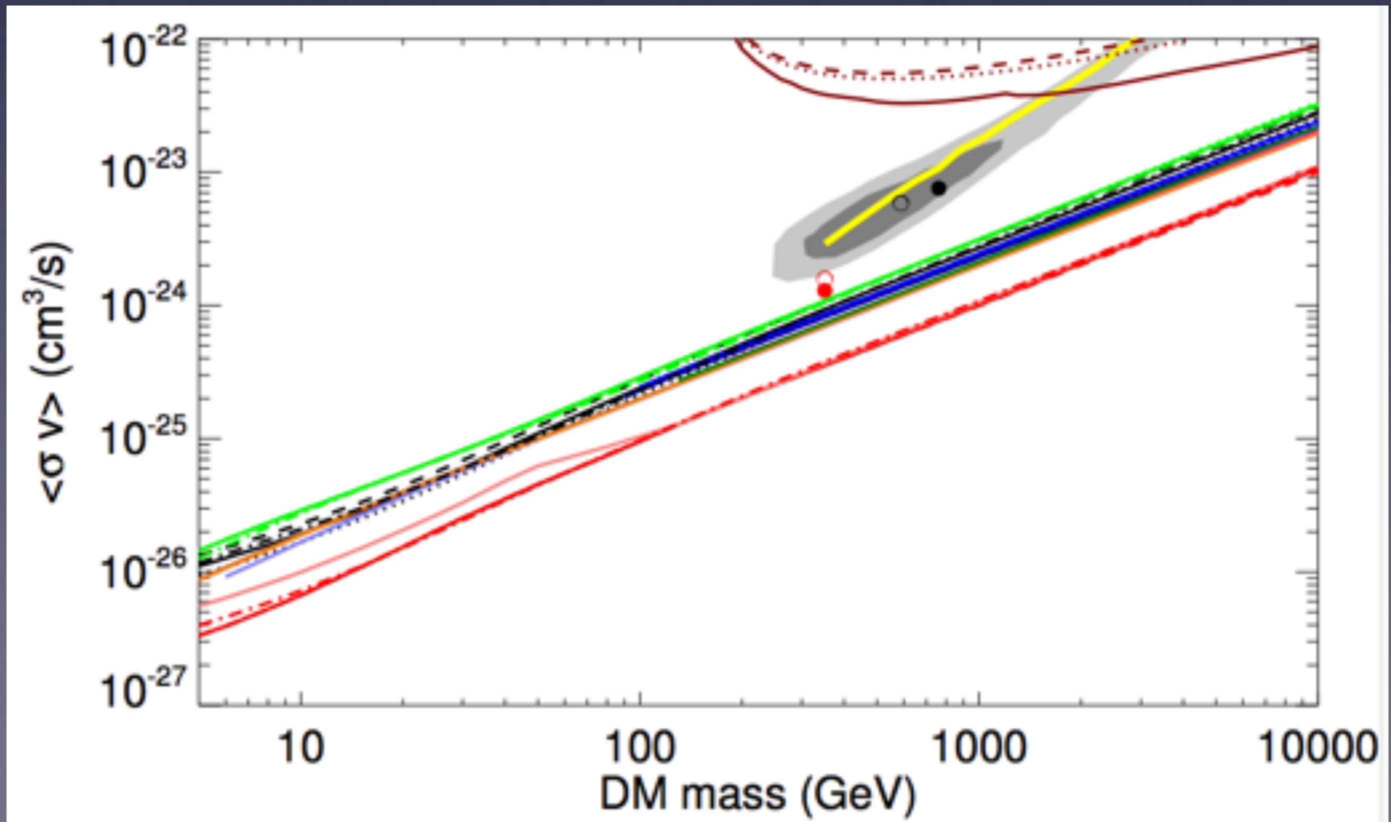


- Rise in positron fraction above 10 GeV observed by PAMELA experiment in 2008, later confirmed by Fermi, now confirmed to extend up to at least 500 GeV by AMS-02.
- Possible signal of DM annihilation, producing additional primary positrons. (Other possibilities: pulsars, supernova remnants, modified 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.





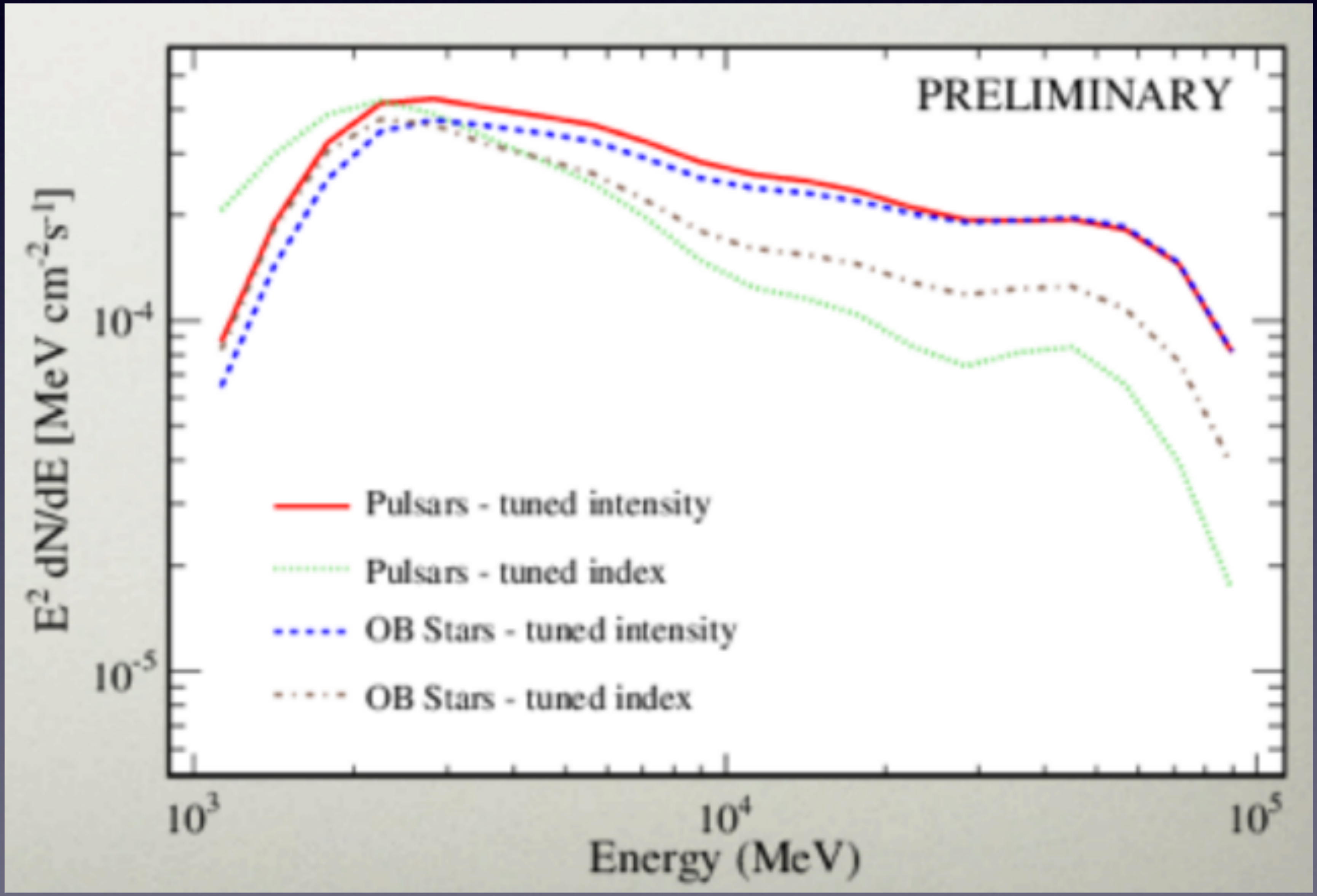
Conclusions

- 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 potential signals that have caused excitement:
  - The GeV excess in the Galactic Center - backgrounds 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.

Bonus Slides

The spectrum

- Two sets of source distributions ("pulsars" and "OB stars"). "Tuned index" models allow spectral indices of background to vary (rather than just intensity), provide better agreement with data.
- Spectrum of excess seems broadly consistent with other results (lower at ~1 GeV); tuned-intensity models lead to higher "signal" tails at large E, but are known to generically undersubtract data at high energies.



Talk presented by Simona Murgia at Fermi Symposium

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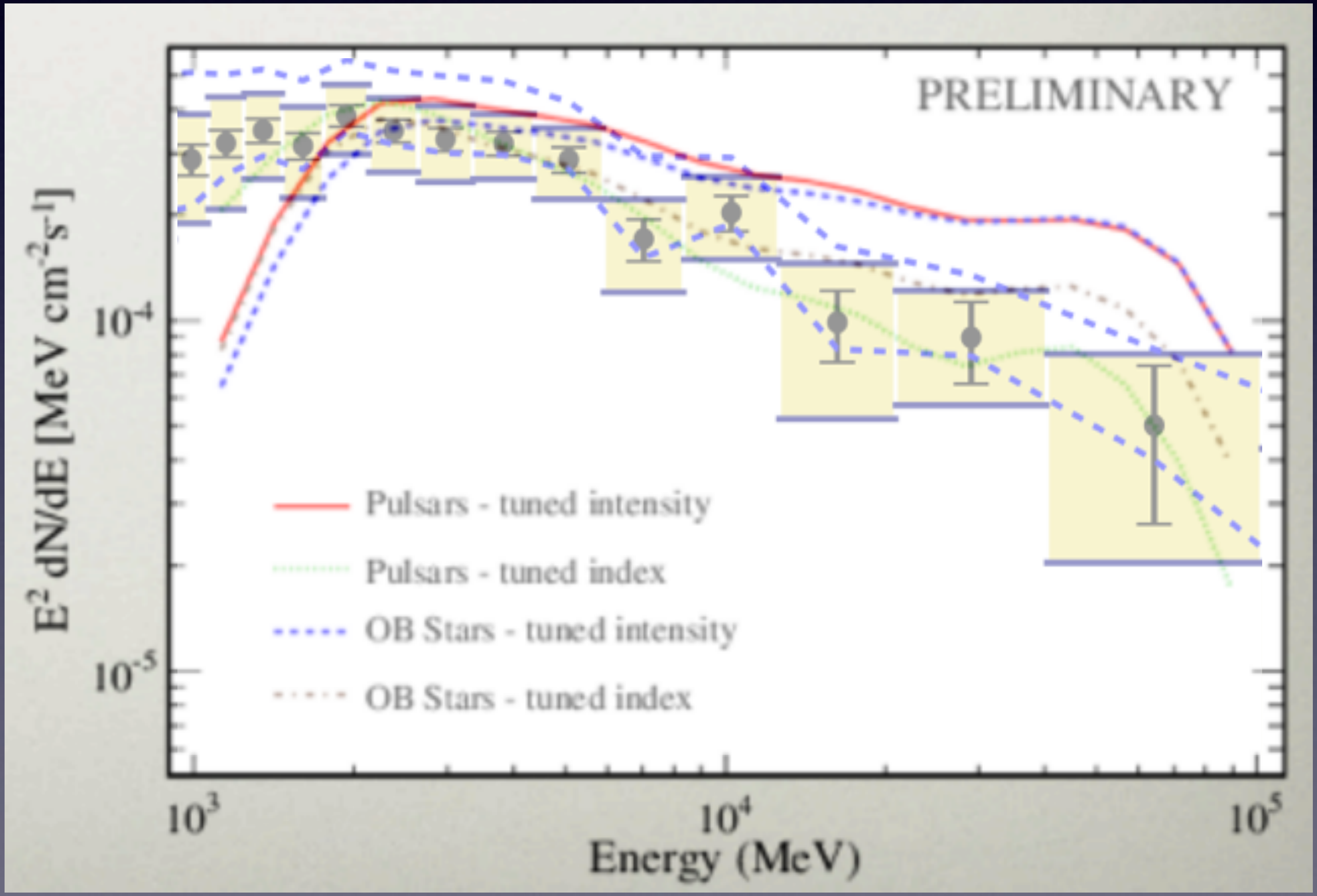
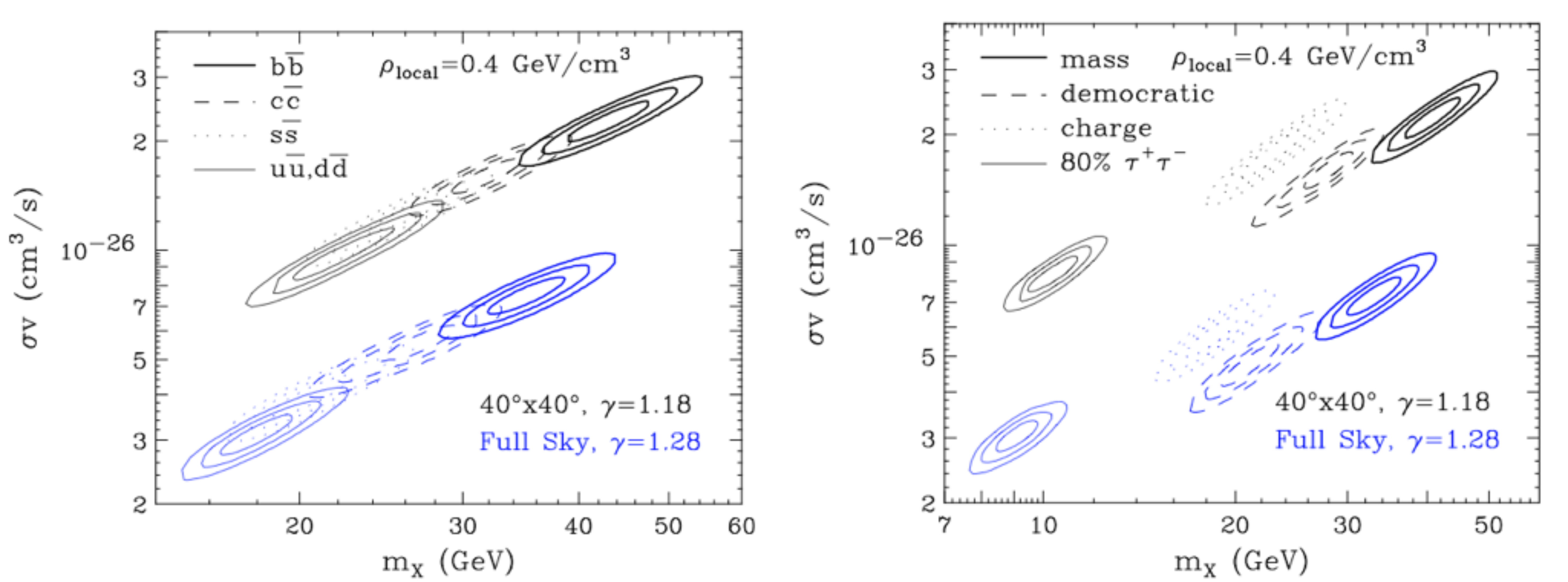


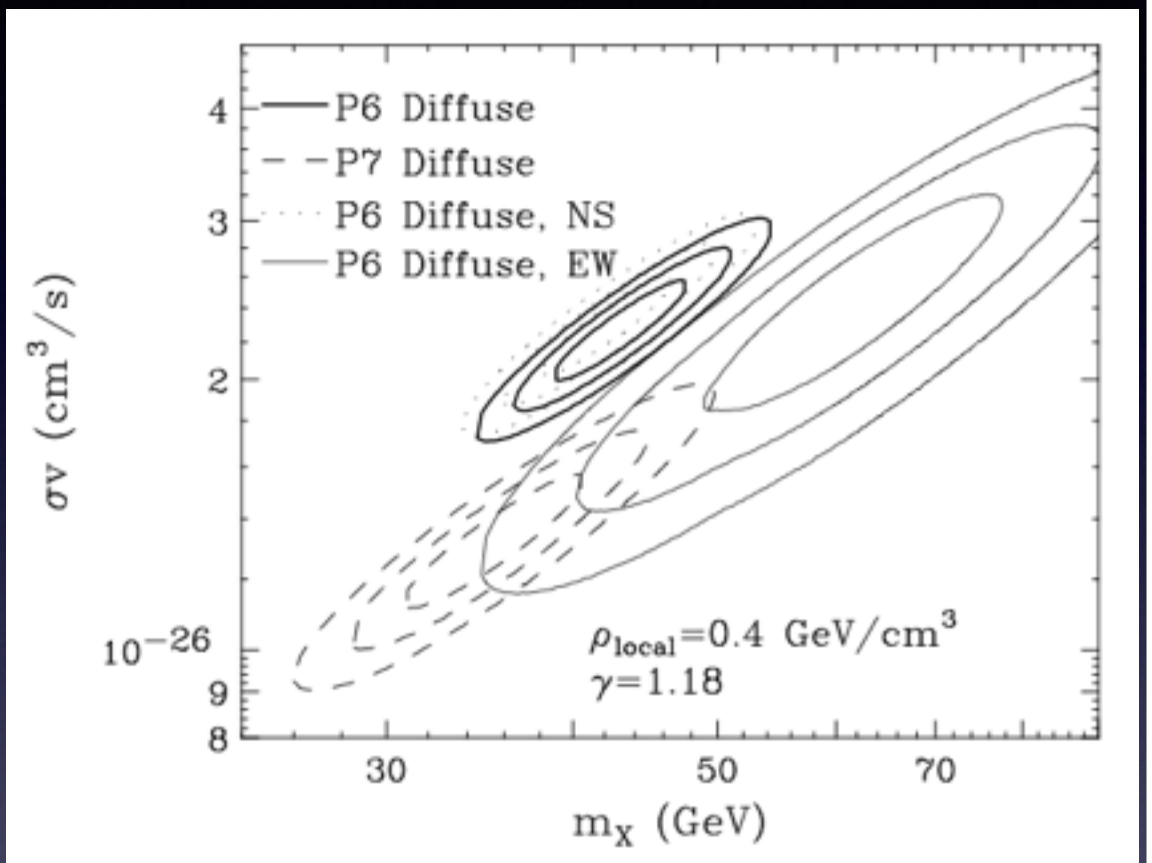
Talk presented by Simona Murgia at Fermi Symposium

The dark matter interpretation



- Our best fits are for DM masses around 10-50 GeV depending on channel, ~35-45 GeV for b's. Cross section is ~thermal.

Systematic uncertainties



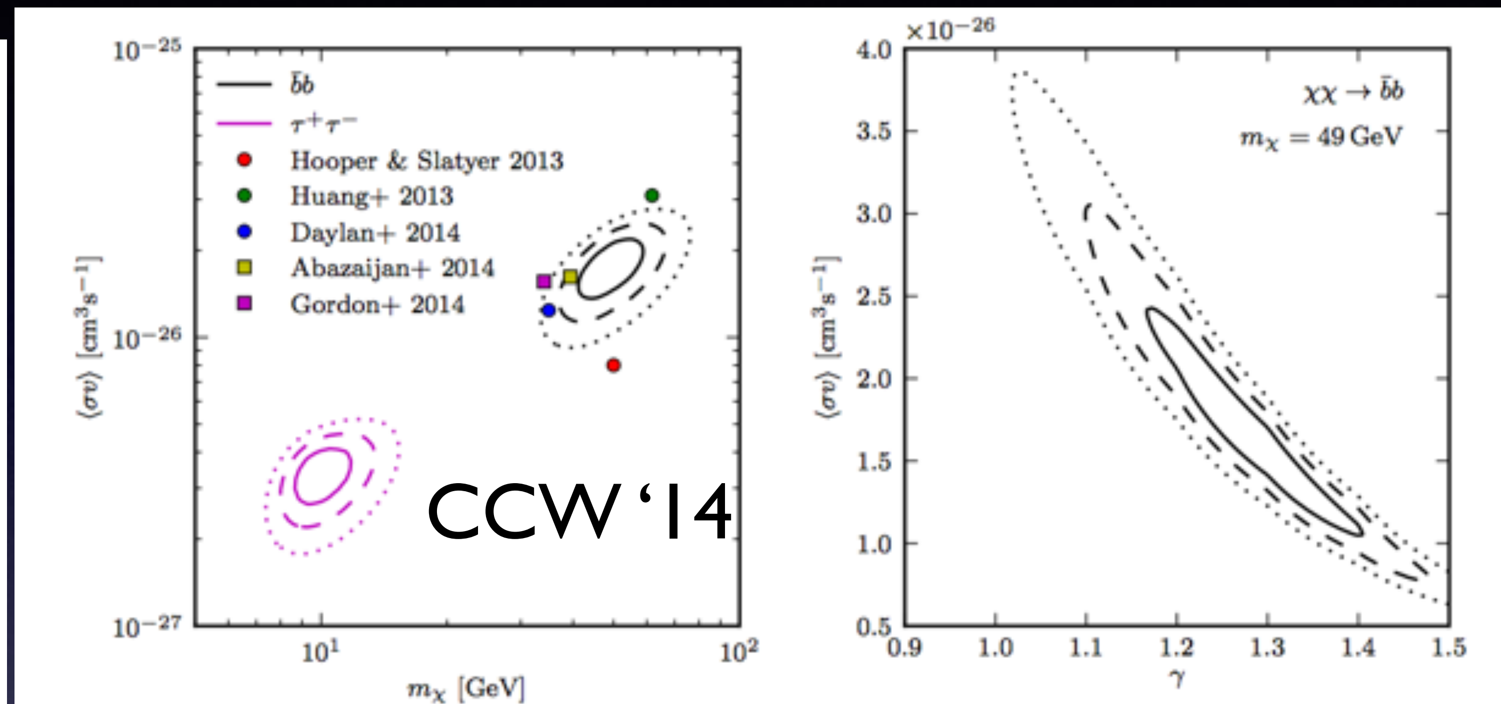


Figure 18. *Left panel:* Constraints on the $\langle\sigma v\rangle$-vs-m_χ plane for three different DM annihilation channels, from a fit to the spectrum shown in figure 14 (cf. table 4). *Colored points (squares)* refer to best-fit values from previous Inner Galaxy (Galactic center) analyses (see discussion in section 6.2). *Right panel:* Constraints on the $\langle\sigma v\rangle$-vs-γ plane, based on the fits with the ten GCE segments.

- Our first estimates of systematic uncertainties from varying the diffuse model and ROI are larger than the statistical errors; shown in left plot.
- CCW prefers a somewhat higher DM mass (closer to 50 GeV). Possible that models we use are absorbing signal emission (since they were fitted to the data assuming no signal).
- We find similar results to CCW when fitting over the same ROI.