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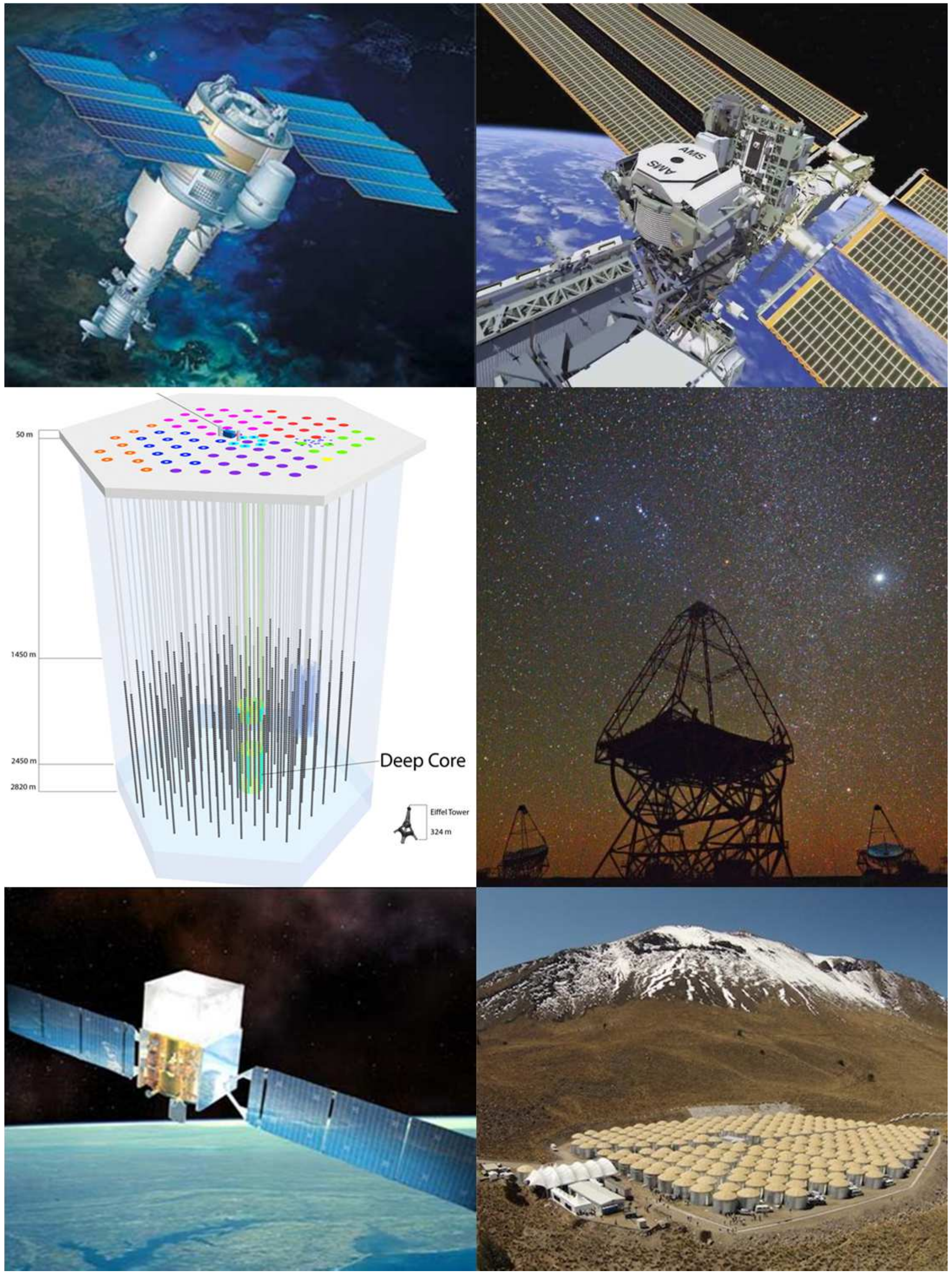


Probing Dark Matter with Cosmic Messengers

Andrea Albert
Los Alamos National Lab

3rd KMI International Symposium
January 6, 2017

Outline

- **Indirect Detection Overview**
  - **evidence for dark matter**
  - **dark matter candidates**
  - **indirect detection messengers**

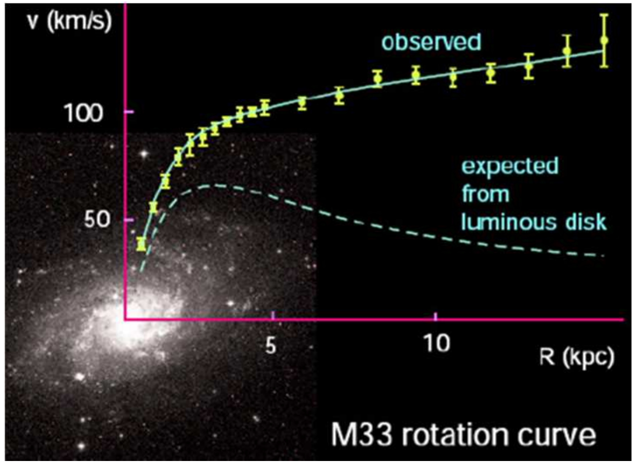
- **Recent Dark Matter Results**
  - **unexplained anomalies**
  - **current constraints**

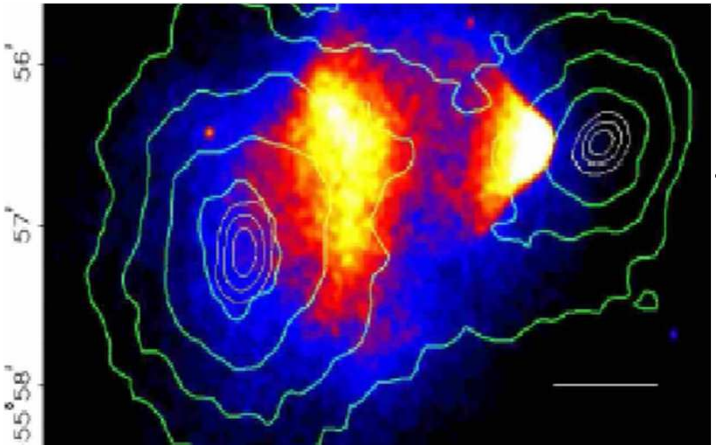
- **Future Gamma Ray Prospects**

Dark Matter and Dark Matter Particle Candidates

Dark Matter Primer

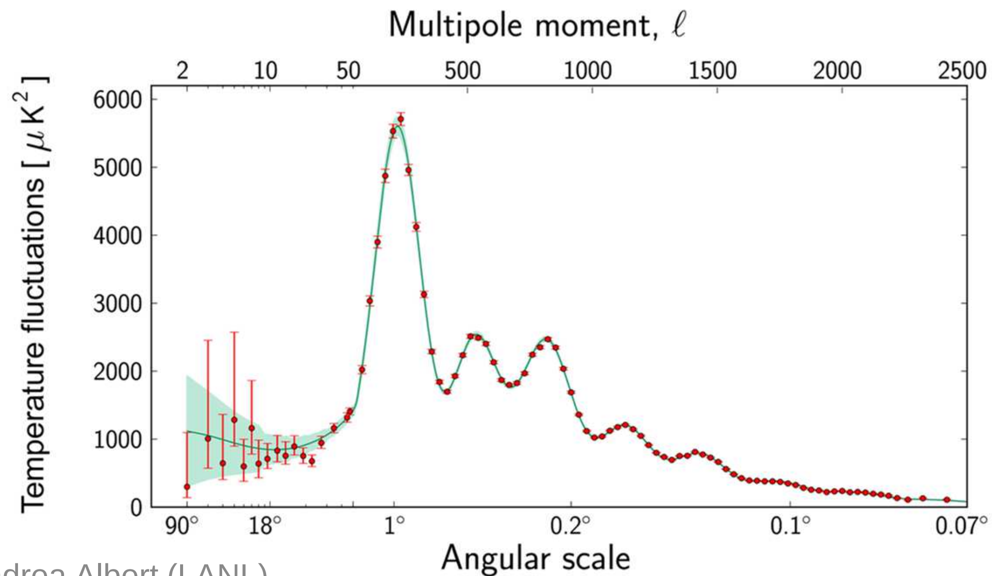
- **Galaxies form in large Dark Matter *halos*, which make up most of their *mass***
  - **Coma Cluster + Virial, F. Zwicky (1937)**
  - **Rotation Curves, V. Rubin et al 1980)**





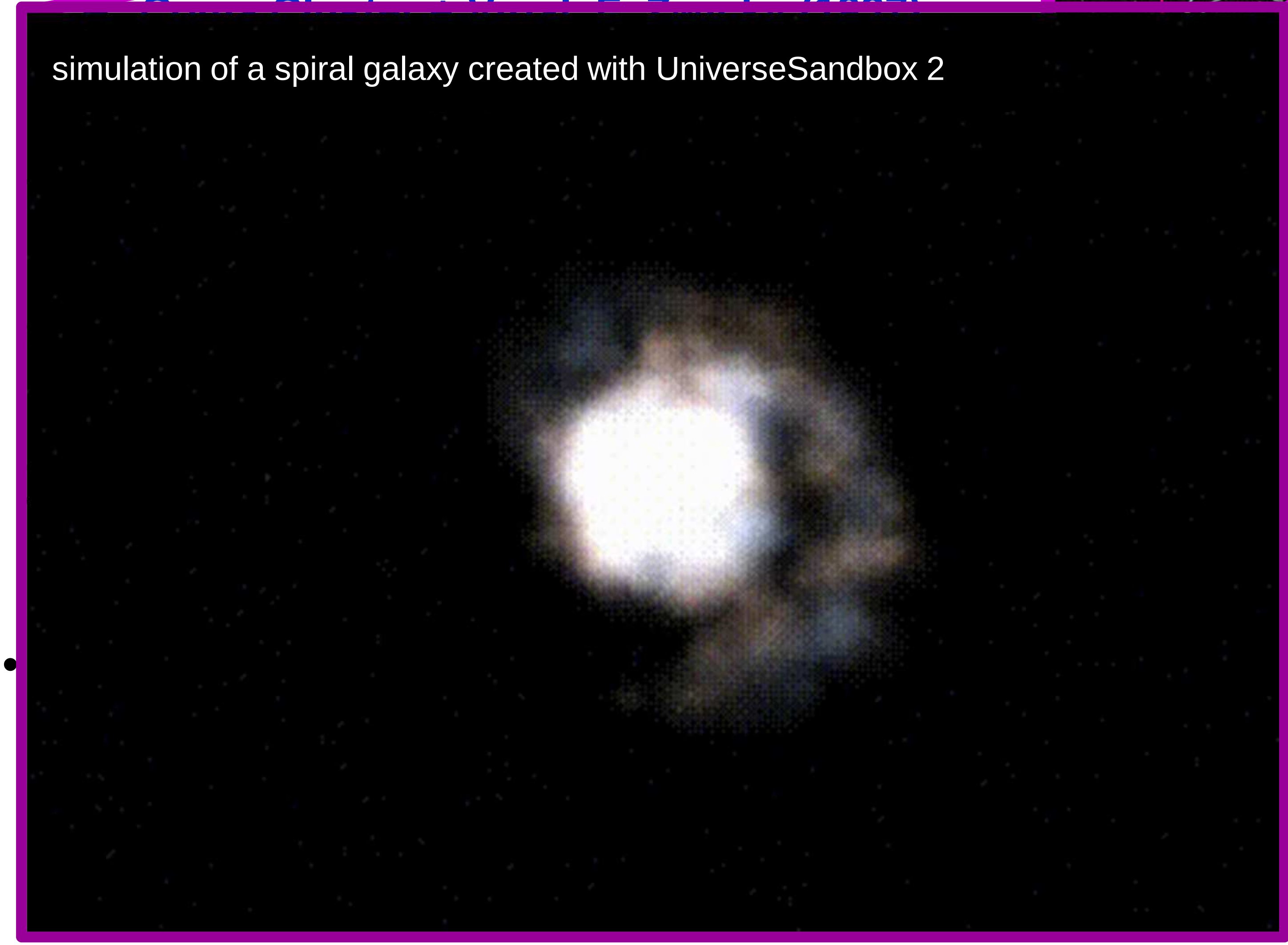
- **Dark Matter is virtually *collisionless***
  - **The Bullet Cluster, D. Clowe et al (2006)**

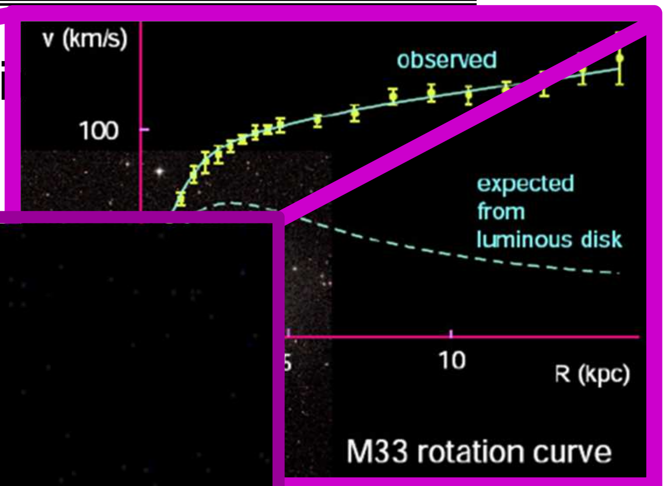
- **Dark Matter is *non-baryonic***
  - **CMB acoustic oscillations**
  - **Big Bang nucleosynthesis**



Dark Matter Primer

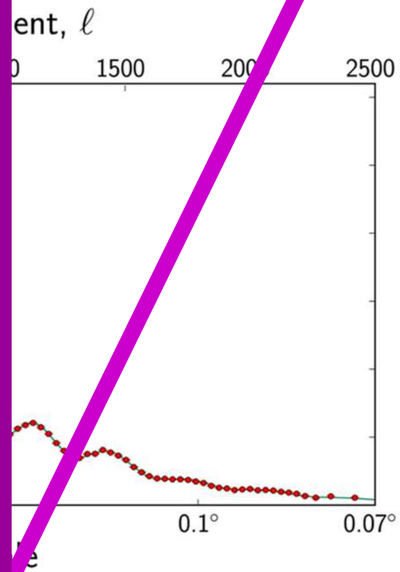
- Galaxies for in large Dark Matter *halos*, whi… make up most of their *mass*





…*llisionless*

…owe et al (2006)



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Dark Matter Primer

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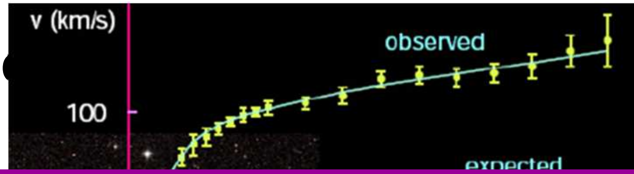

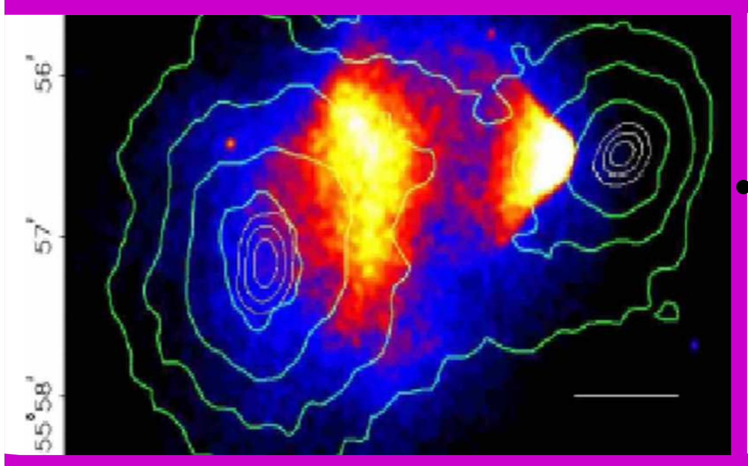

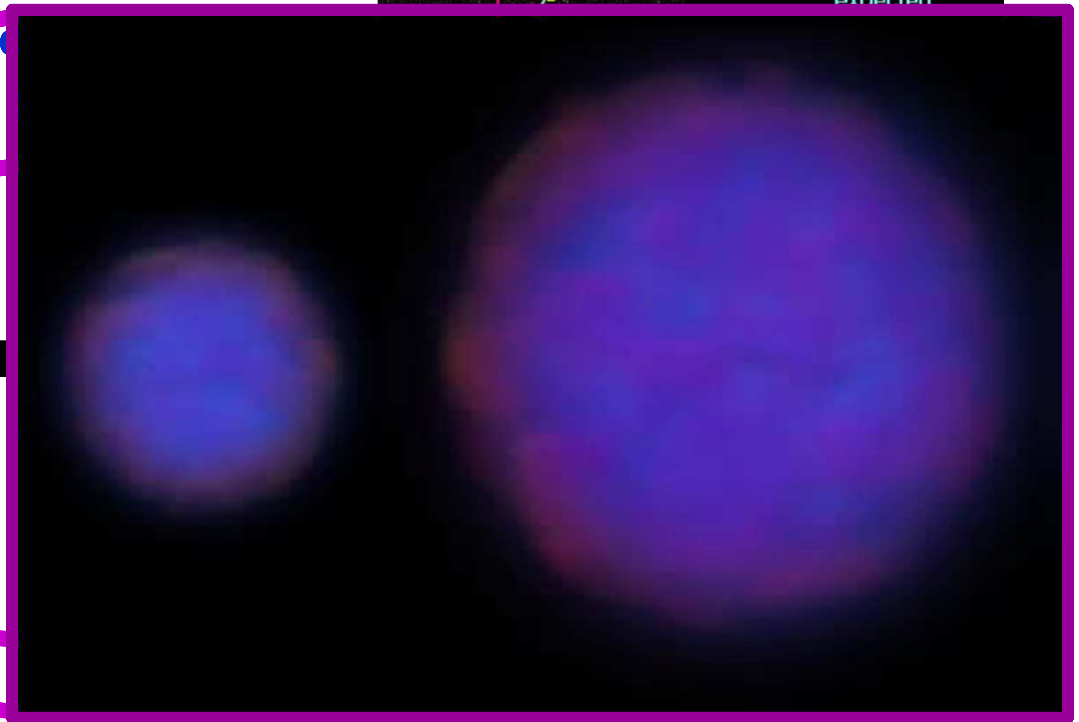

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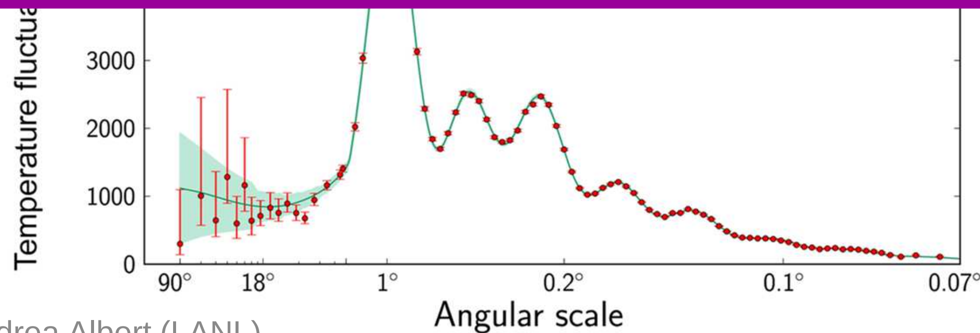
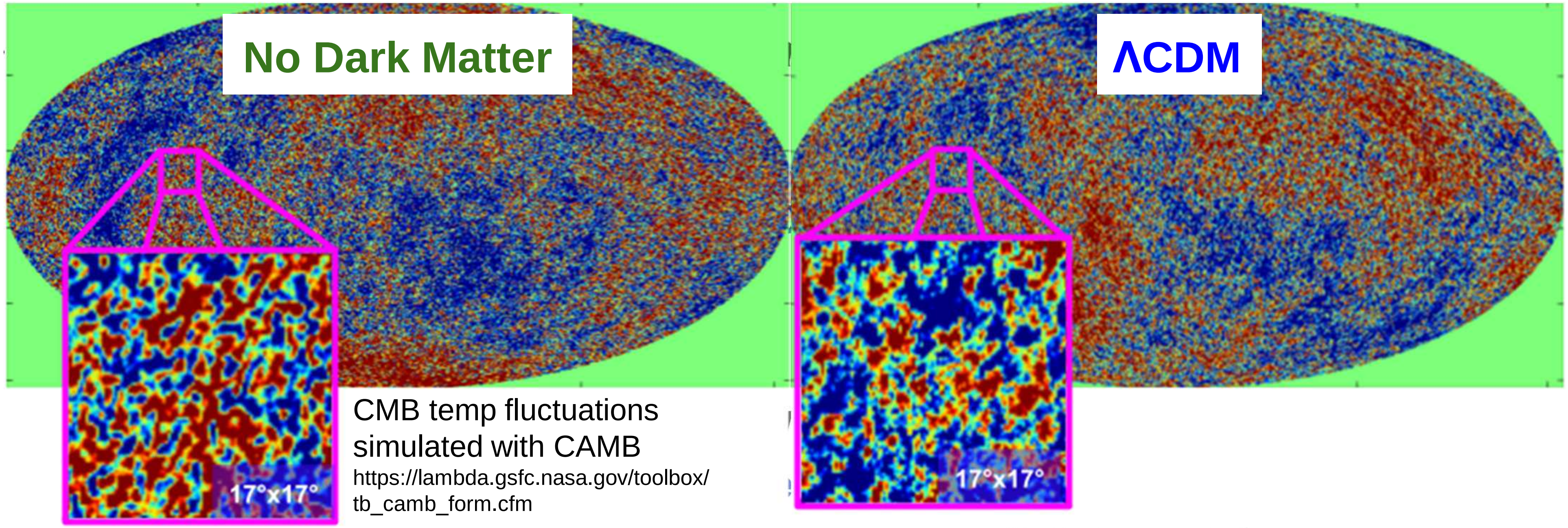
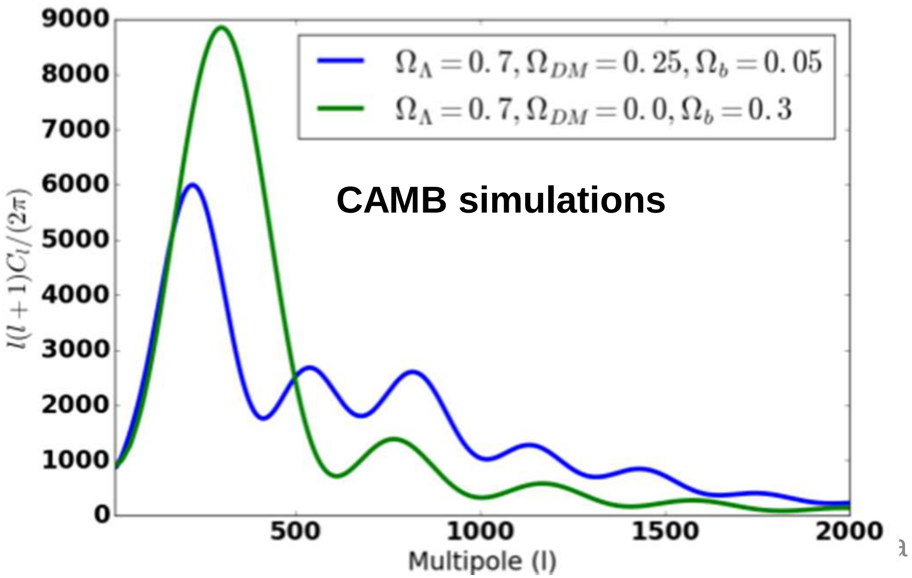
  - CMB acoustic oscillations
  - Big Bang nucleosynthesis

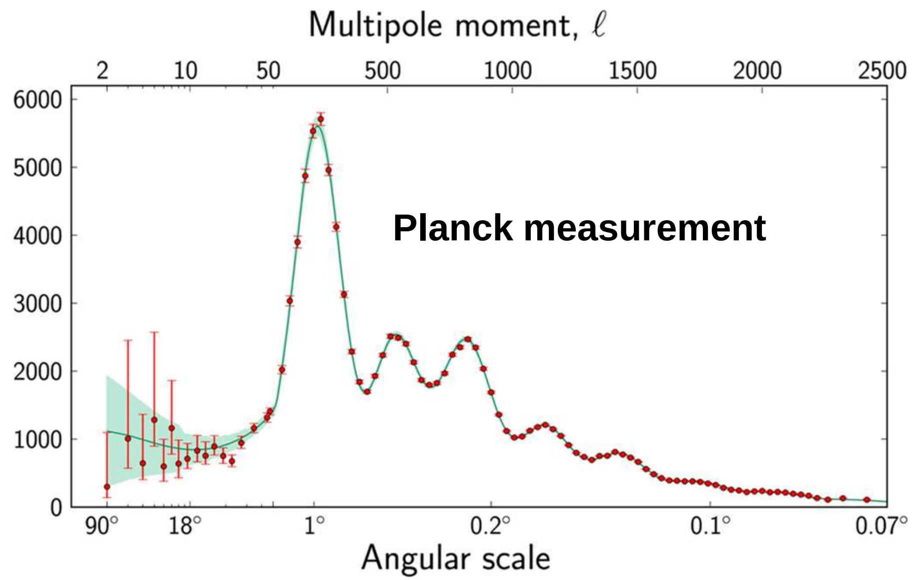


Dark Matter Primer



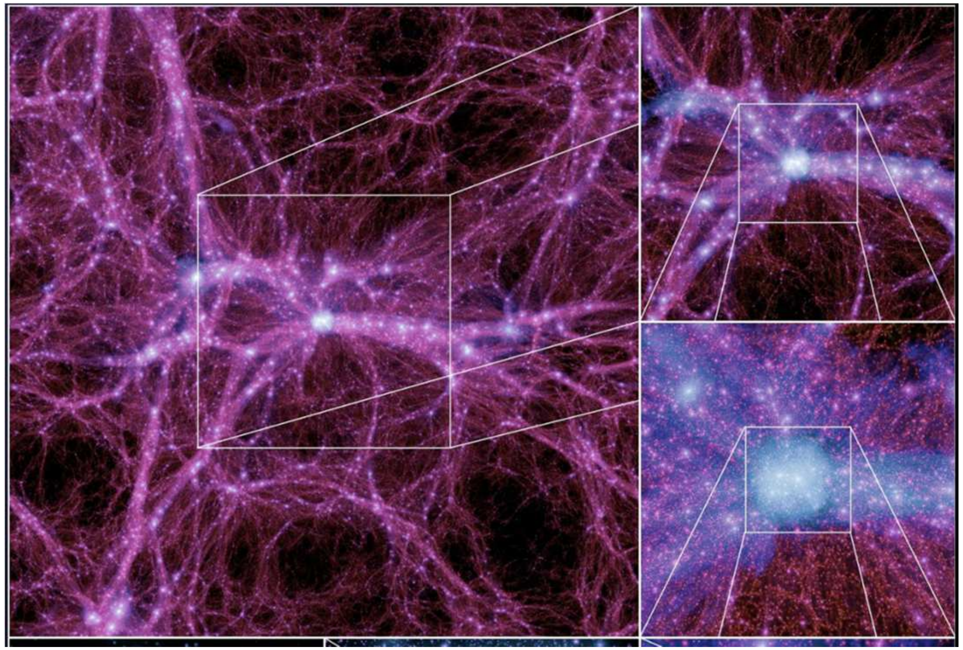
CMB temp fluctuations simulated with CAMB
https://lambda.gsfc.nasa.gov/toolbox/tb_camb_form.cfm



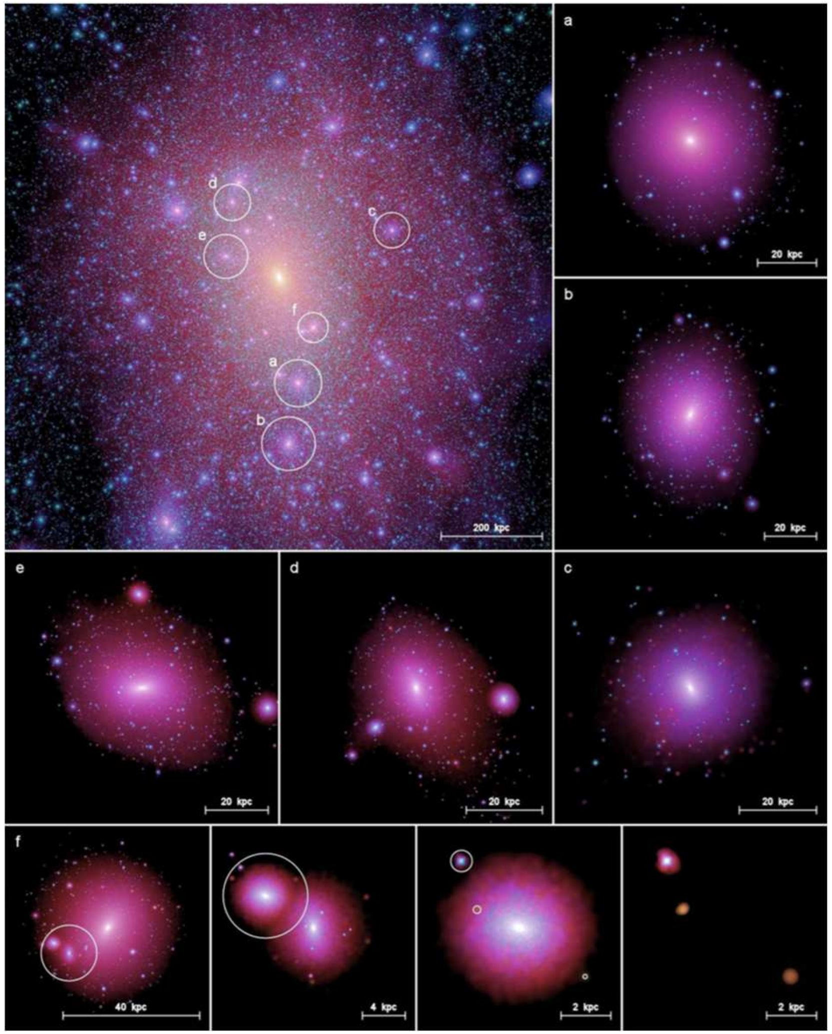


DM Structures are Present on Many Scales

Zoom Sequence of DM Structure on 100 Mpc Scales



Milky Way-like Halo and Several Sub-Halos



- **DM clumps :**
  - **On cosmological scales (left)**
  - **In the Milky Way virial radius (~300 kpc = ~1 MLY, right)**

    (Visible size of MW = ~ 20 kpc)

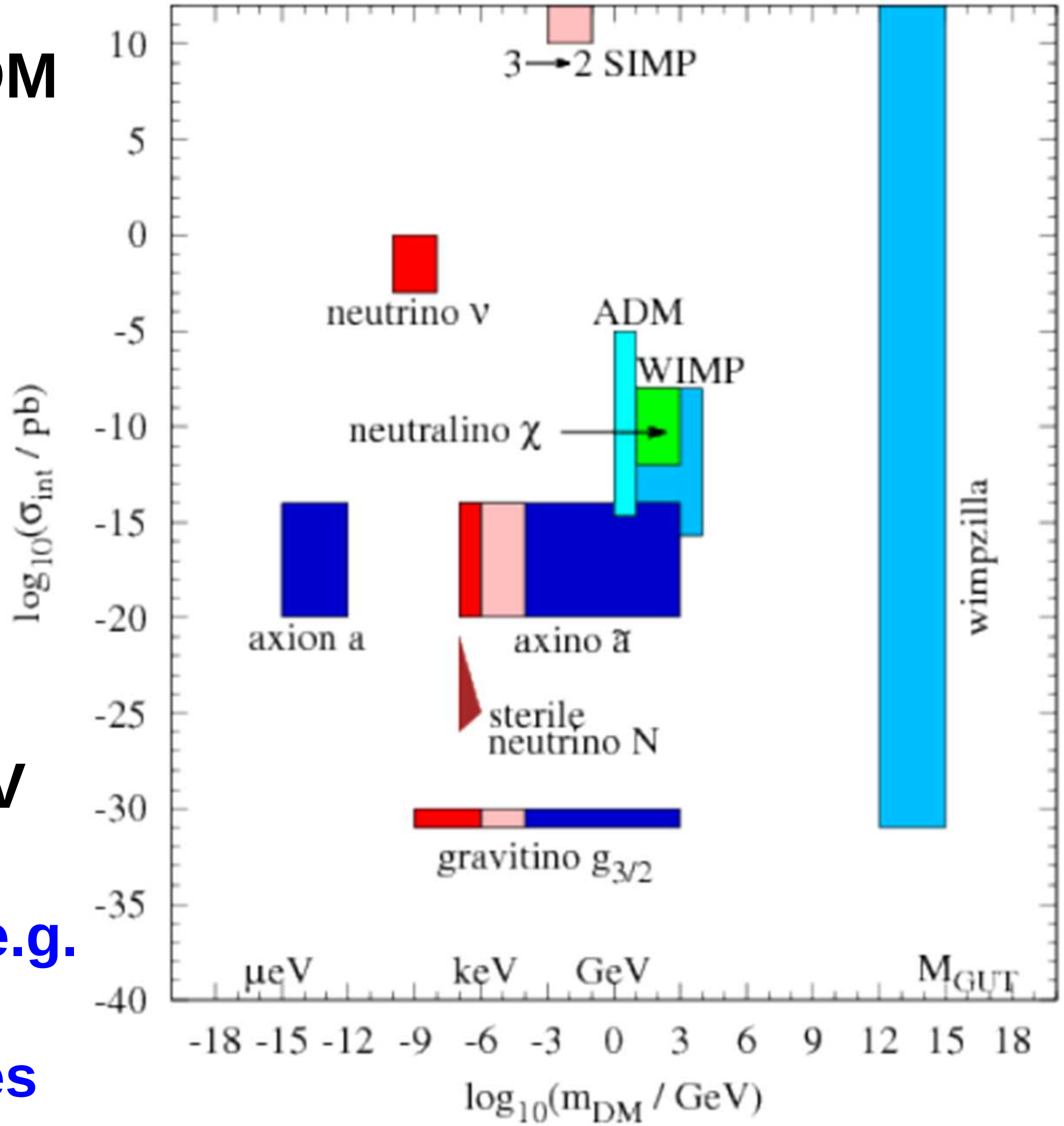
    (M31 is ~800 kpc away)

Left: Boylan-Kolchin+ 2009MNRAS.398.1150B
Right: Springel+ 2008MNRAS.391.1685S

slide credit: Eric Charles (SLAC)

Dark Matter Candidates

- **Wide variety of particle DM candidates in beyond SM theories**
- **Large scale structure and galactic formation seem to require cold (non-relativistic) DM**
- **Tend to focus on 100 GeV WIMPs**
  - **but lack of detection at e.g. LHC and LUX motivates need for other candidates with m_{DM} >10 TeV**

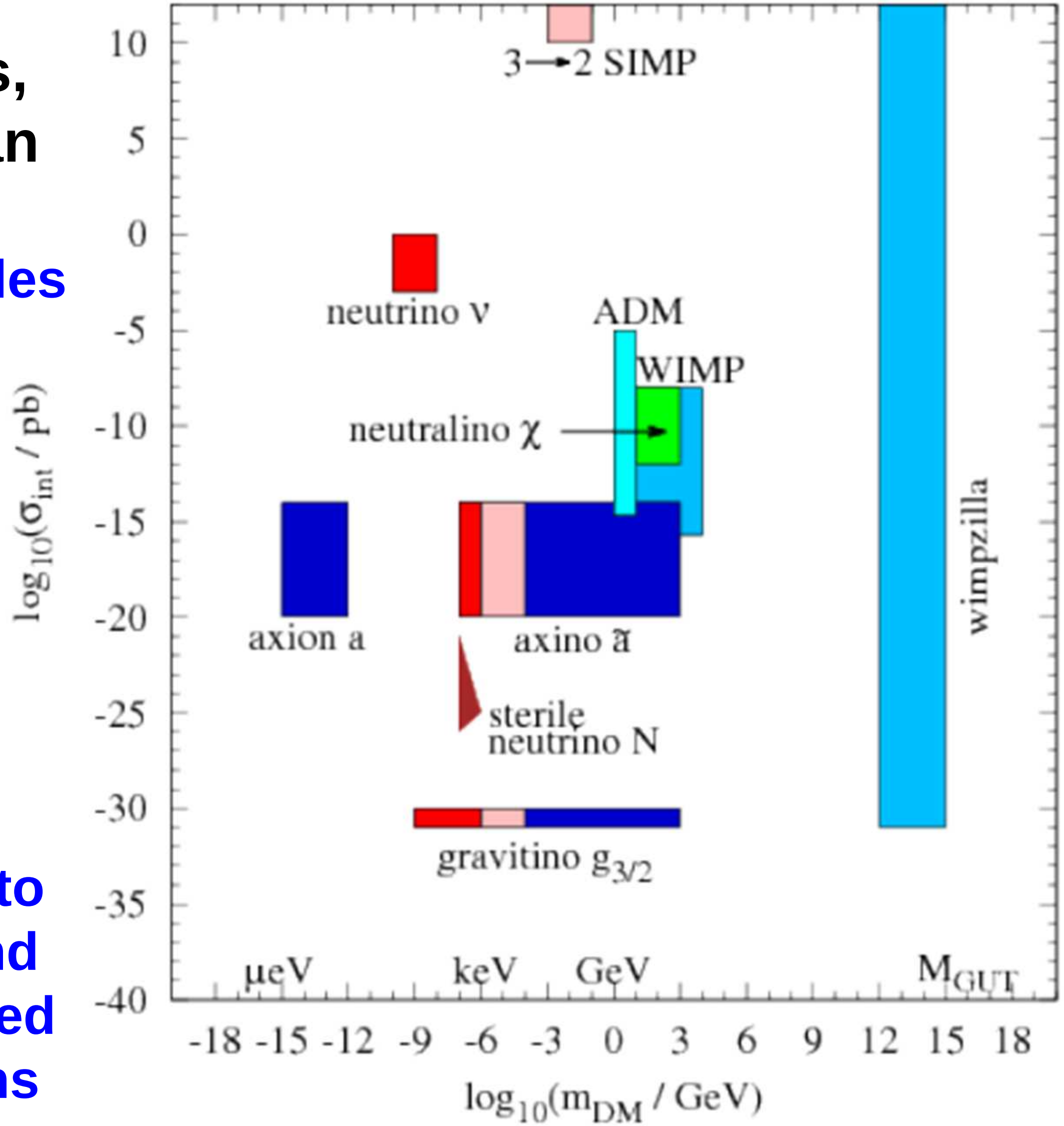


Baer+ PR 555 (2015)

Dark Matter Candidates

- **I will focus on WIMP results, but other DM candidates can leave cosmic signatures**
  - axion and axion-like-particles couple to γ rays in B fields
  - x-ray lines from sterile ν
  - γ-ray lines from gravitinos

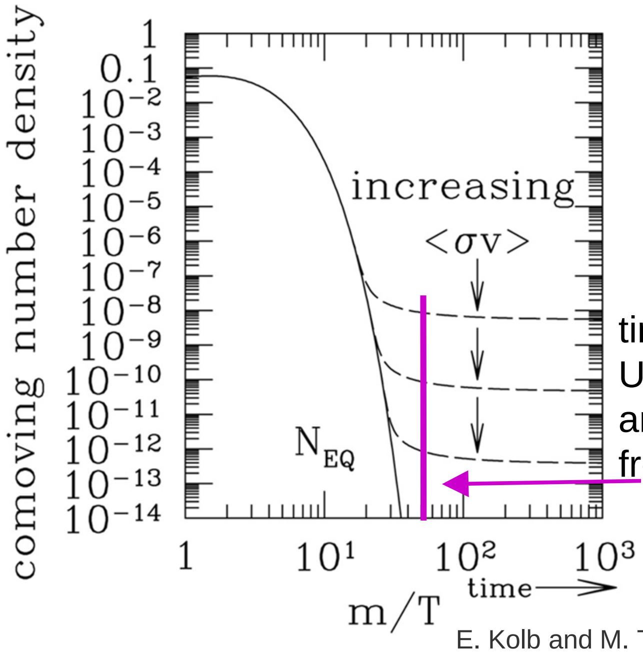
- **Recall all DM results are derived from firm measurements**
  - DM limits from flux limits
  - Important for experiments to publish measured limits and fluxes that are not convolved with DM model assumptions



Baer+ PR 555 (2015)

WIMP Dark Matter

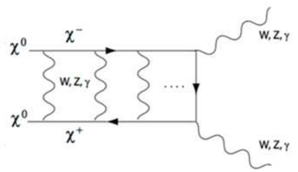
- **Weakly Interacting Massive Particle (WIMP, χ)**
  - **GeV - TeV mass scale**
  - **WIMPs may be thermal relics**
  - **e.g. neutralino (SUSY, electrically neutral, stable)**
- **Assuming a weak scale σ_{ann} at freeze yields observed relic abundance**
  - **$\langle\sigma v\rangle_{ann}$ ~ 3×10^{-26} cm³/s**

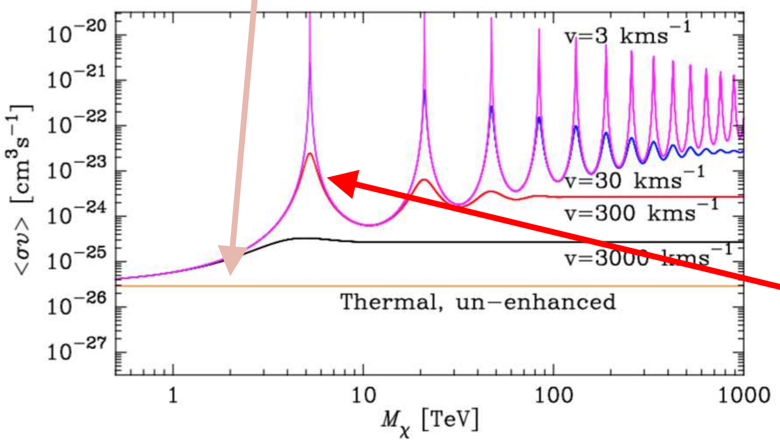


time in early Universe when amount of DM freezes out

E. Kolb and M. Turner, *The Early Universe*, Westview Press (1994)

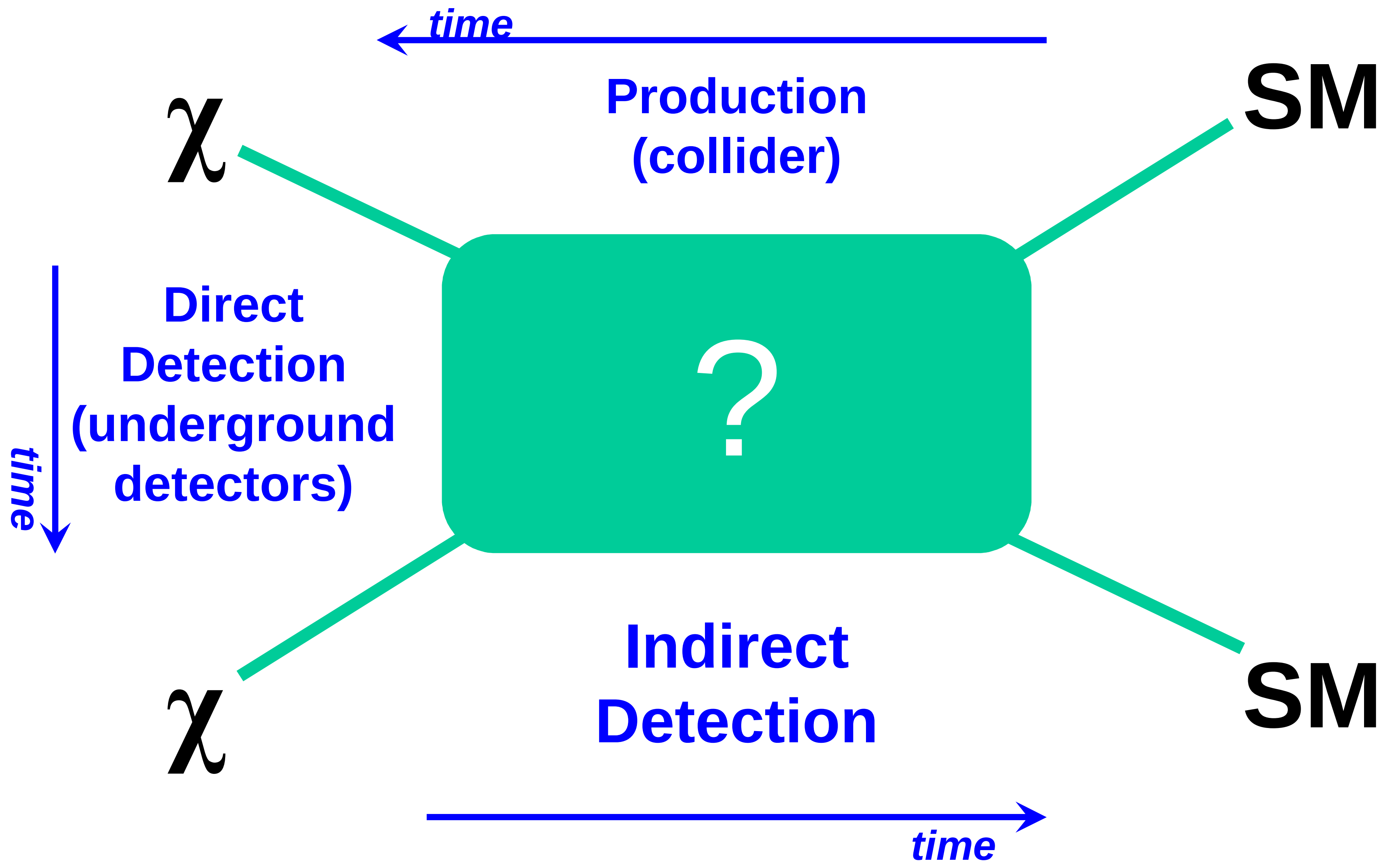
arXiv:1202.1170
arXiv:1405.1730





- **Sommerfeld enhancement**
  - **relevant for high DM masses (>~1 TeV)**
  - **enhanced at low WIMP velocities**
    - **this effect was suppressed at time of freeze out**
  - **high mass thermal relics have present $\langle\sigma v\rangle_{ann}$ larger than 3×10^{-26} cm³/s in some models**

Various Dark Matter Search Techniques



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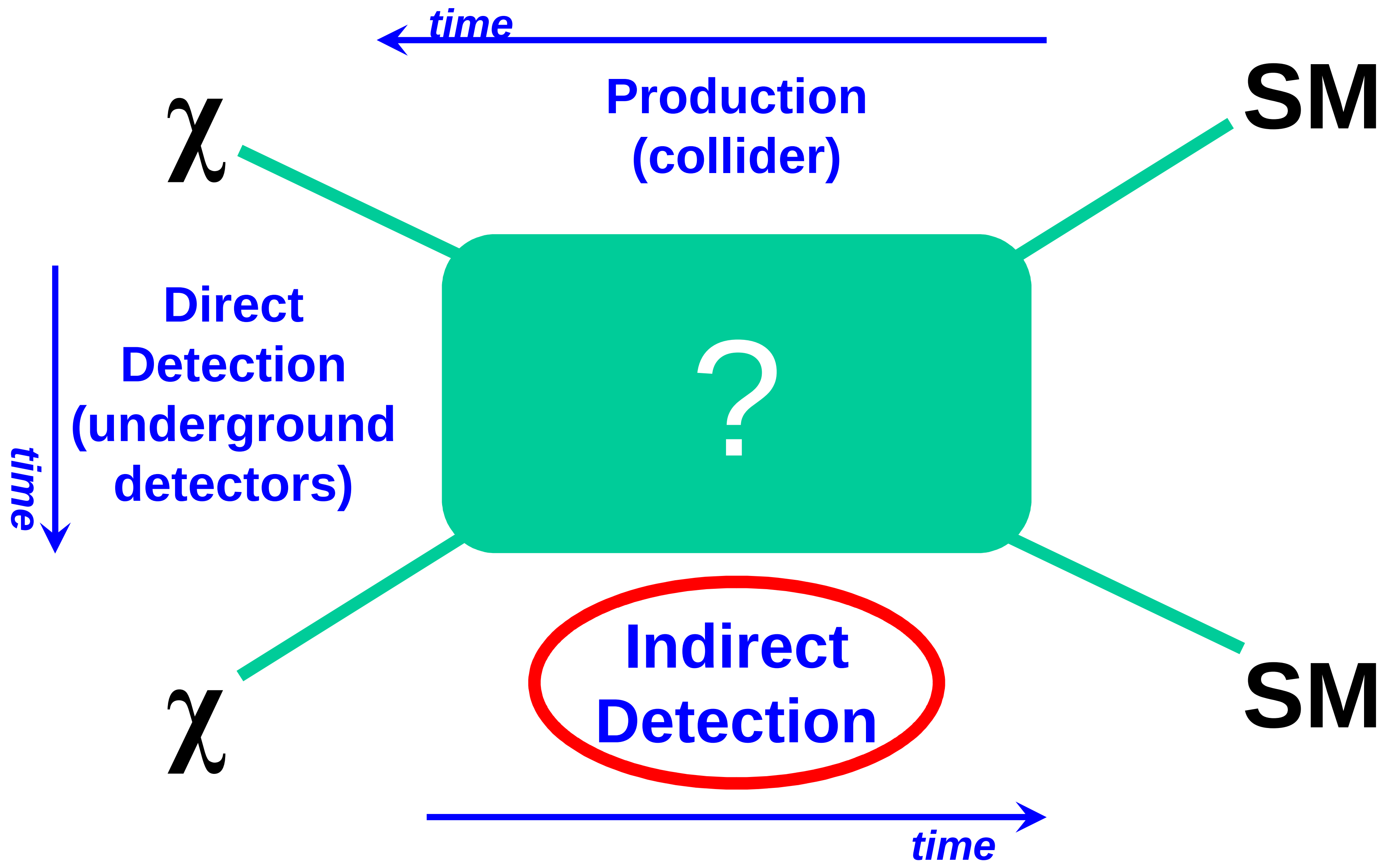
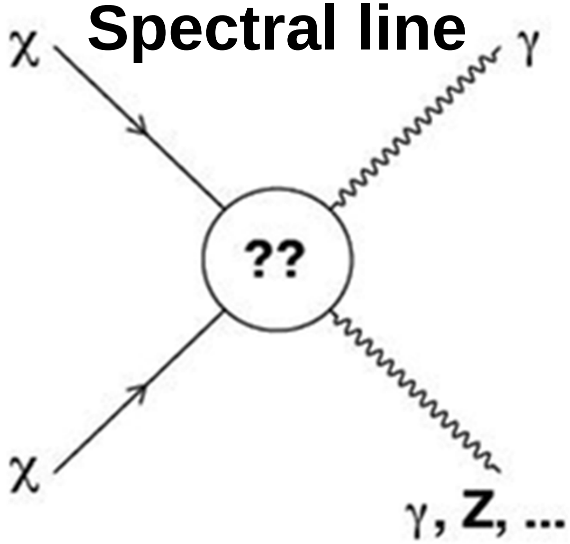
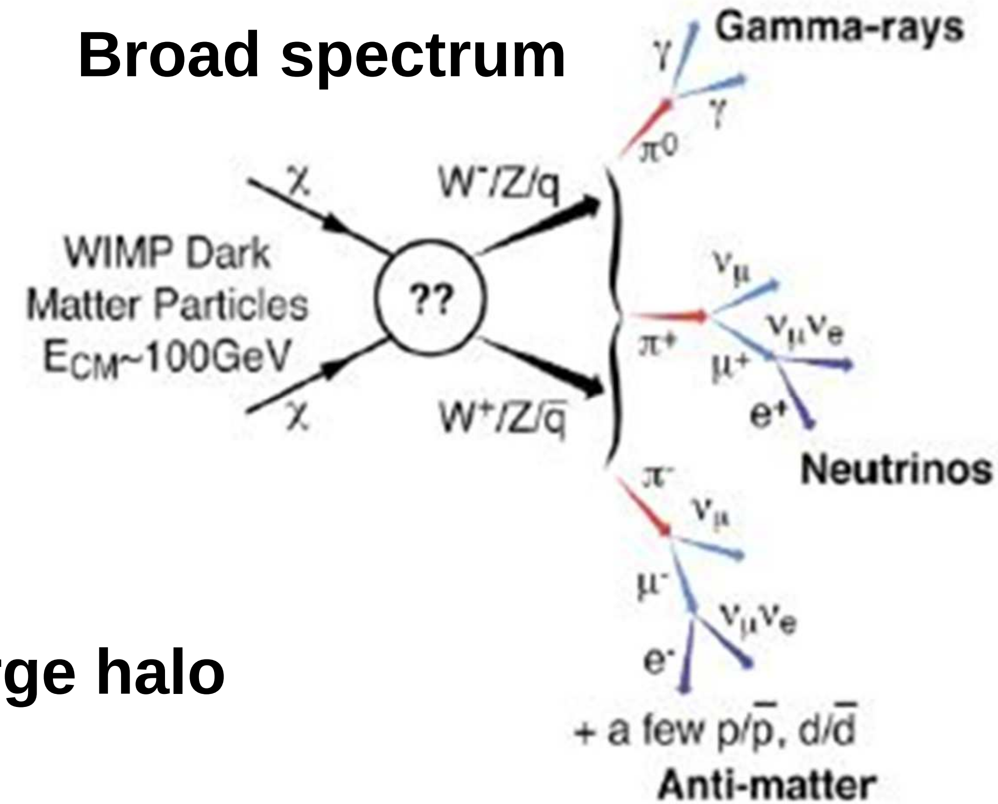


Indirect Dark Matter Detection

Spectral line



Broad spectrum



- **The Milky Way sits in a large halo of cold DM (v_{DM} << c)**
  - **Expect additional DM overdensities (halos / subhalos)**
    - **e.g. Milky Way dwarf galaxies**
    - **e.g. Galaxy Clusters**
- **WIMP annihilations (decays) may produce gamma rays**

Indirect Dark Matter Detection

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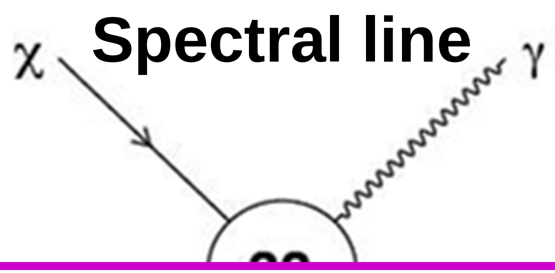

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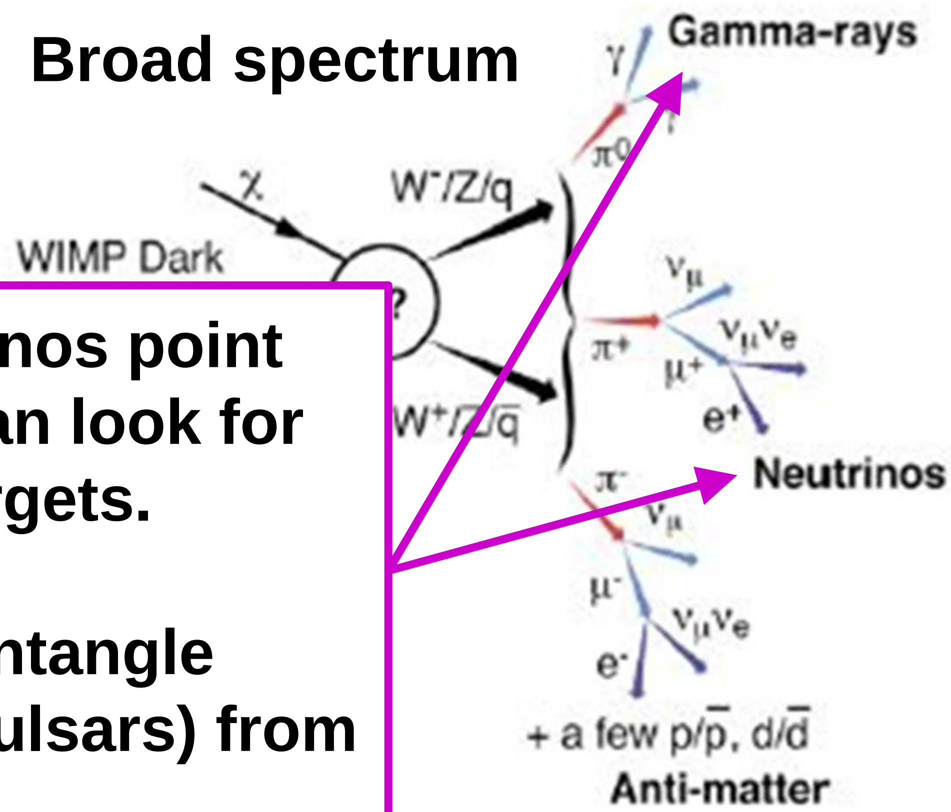

Pro: Gamma rays and neutrinos point back to their source so we can look for excesses from known DM targets.

Con: Can be difficult to disentangle from non-DM sources (e.g. pulsars) from those targets

- Expect additional DM overdensities (halos / subhalos)
  - e.g. Milky Way dwarf galaxies
  - e.g. Galaxy Clusters

- WIMP annihilations (decays) may produce gamma rays

Indirect Dark Matter Detection

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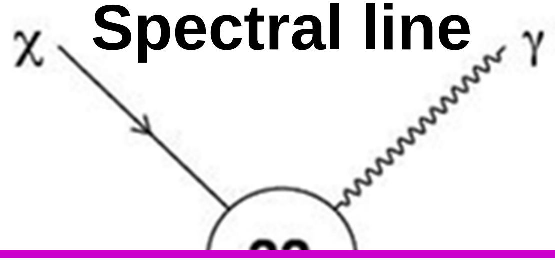

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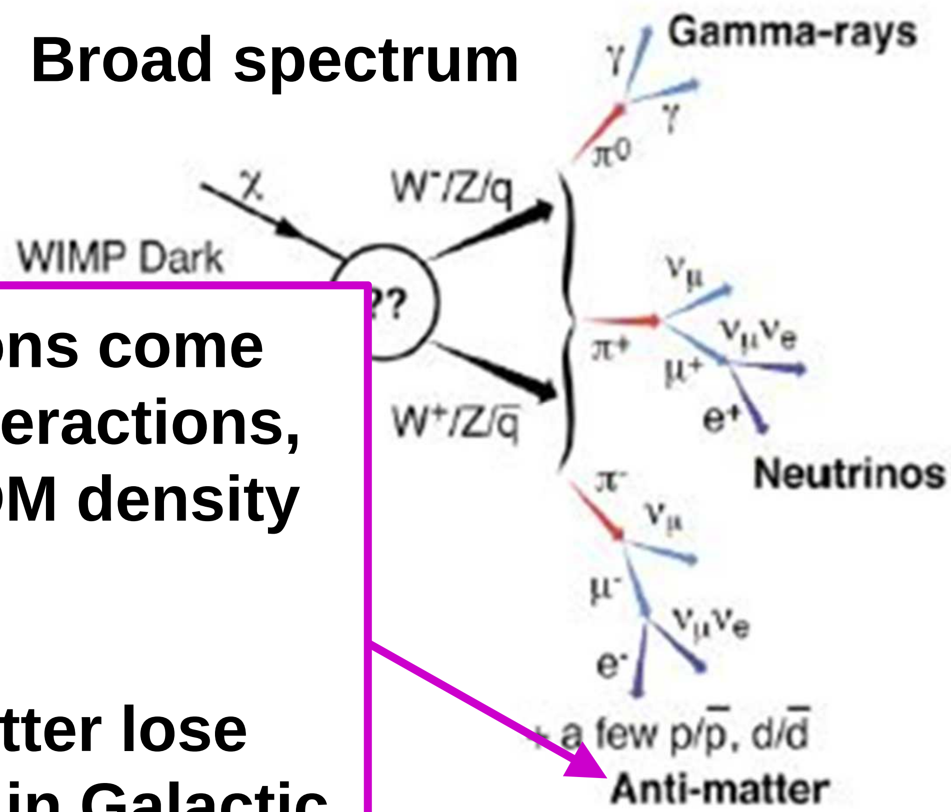


Pro: Positrons and antiprotons come from relatively nearby DM interactions, so are only subject to local DM density uncertainties

Con: Charged matter/antimatter lose source direction information in Galactic magnetic field. Difficult to disentangle from non-DM sources

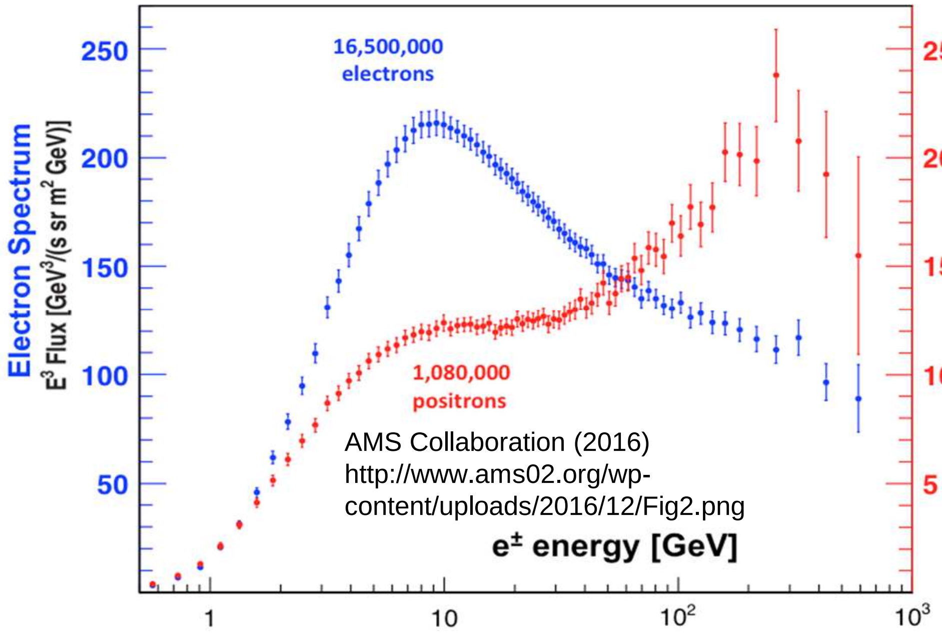
•

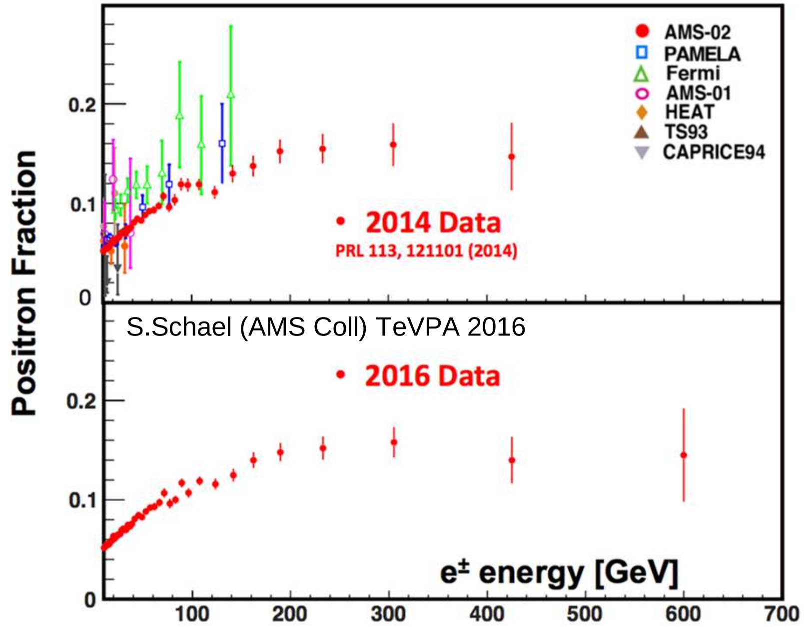
os / subhalos)

- **WIMP annihilations (decays) may produce gamma rays**

Overview of Recent Results

Local Positron Fraction





- **AMS-02 on board the International Space Station observes local cosmic rays since 2011**
  - **excellent charge resolution and particle species discrimination**
- **TeV e^-e^+ lose energy quickly and therefore must be produced locally (d < ~100 pc)**
  - ***secondaries* produced by cosmic ray interactions with ISM (spallation)**
  - ***primaries* produced by local source**
    - **local cosmic accelerator (e.g. Geminga)? local dark matter interactions?**
- **Larger positron flux observed above ~10 GeV than expected from secondaries**
  - **First observed by Pamela in 2009, since confirmed by Fermi LAT and AMS-02**
  - **Are they from a local cosmic accelerator or dark matter?**
    - **If they are from dark matter, other annihilation products should be produced**

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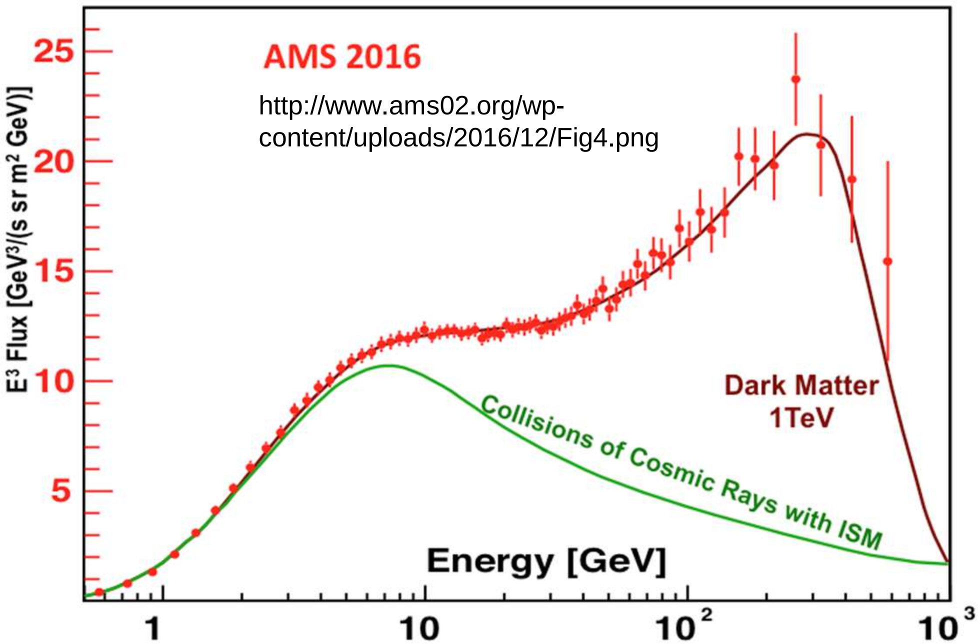

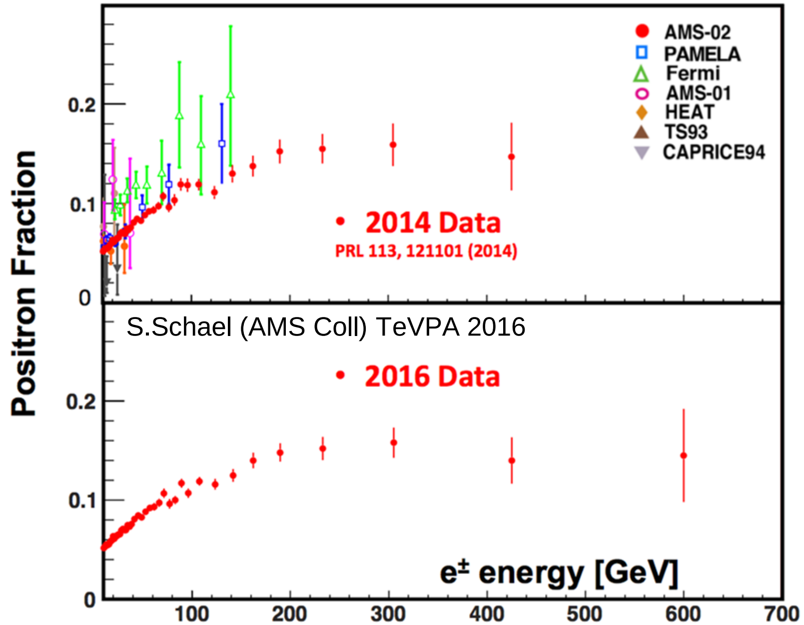

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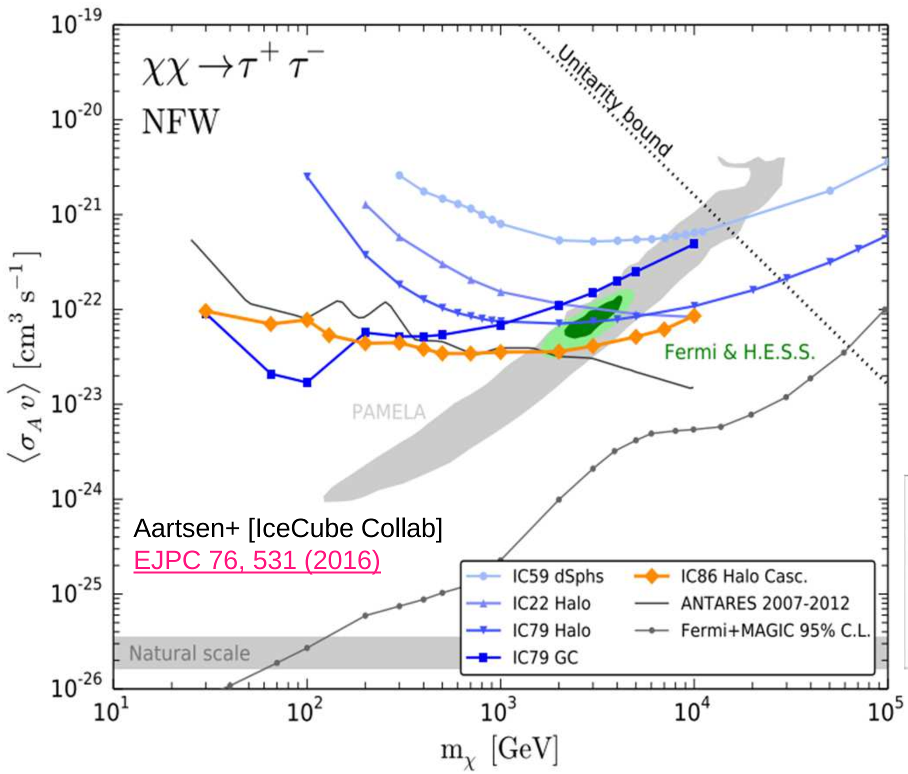
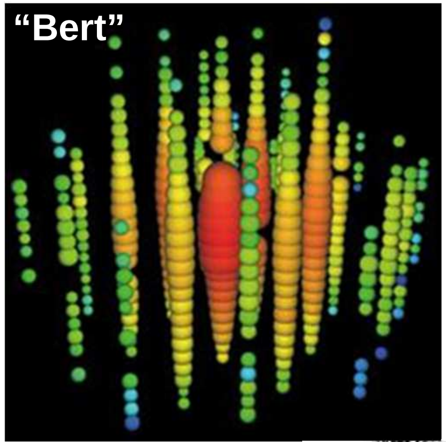
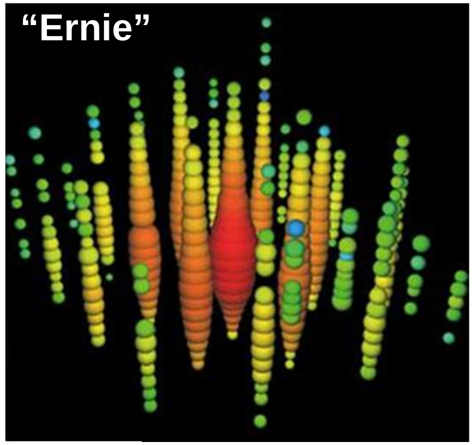
Cosmic Neutrinos

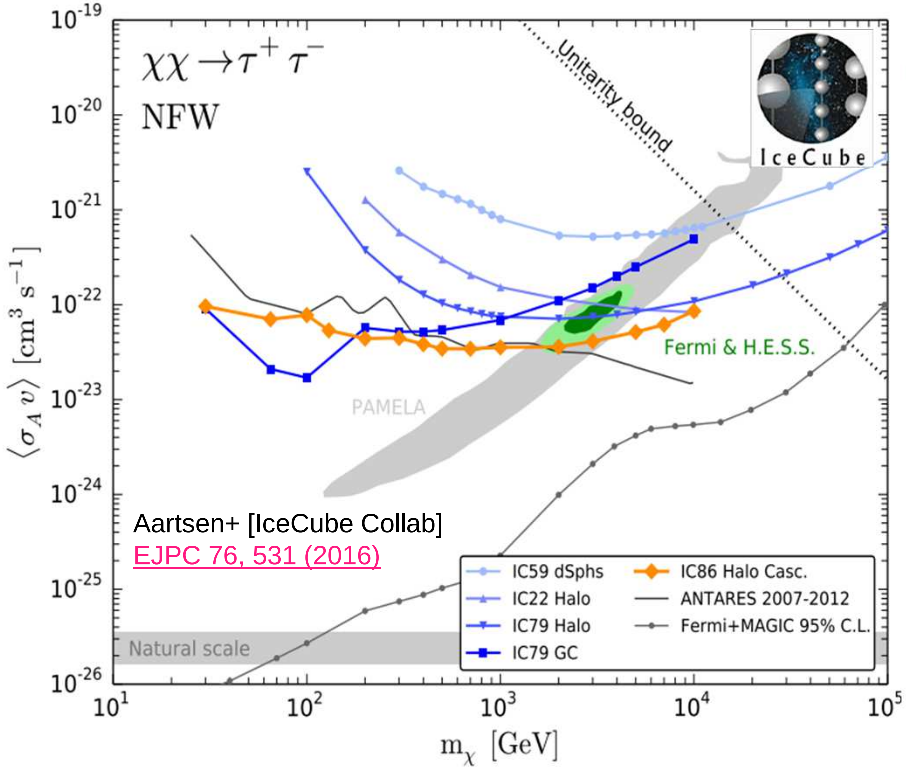


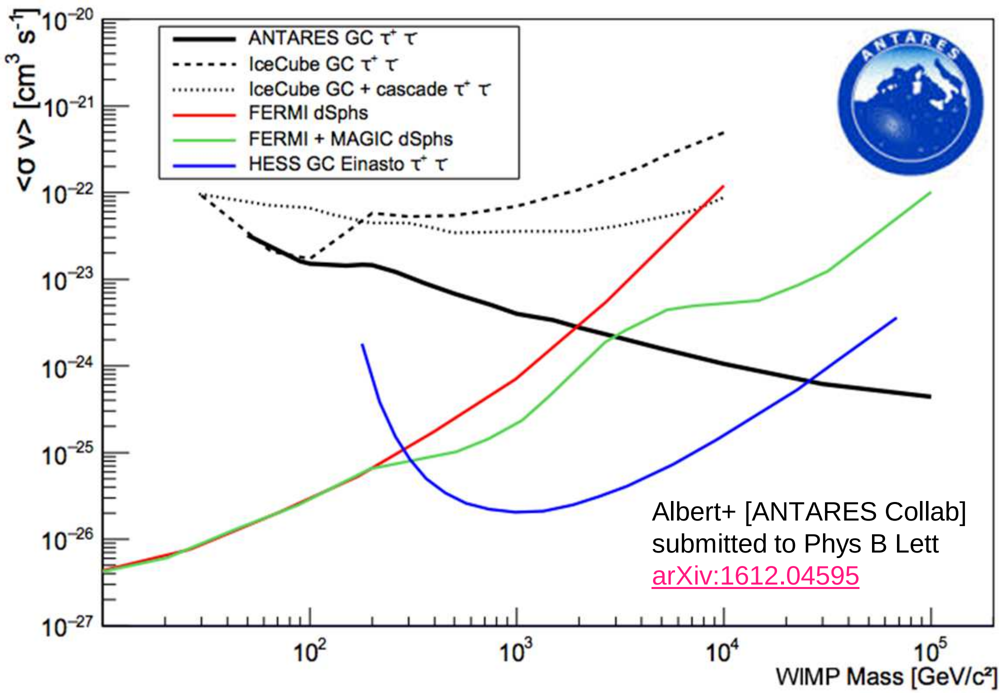




- **With the detection of Bert and Ernie by IceCube in 2014, we entered the era of cosmic neutrino astronomy**
  - **before the only extra-solar neutrinos came from SN1987a**
- **Expect brightest neutrino signal from DM annihilations from the Galactic Center**
  - **no neutrino excess observed towards the GC**
- **Recent limits from IceCube constrain DM models proposed to explain local positrons**
  - **gamma ray limits from dwarf galaxies (more later) are more constraining, but it's important to have multi-messenger constraints from various targets**

Cosmic Neutrinos





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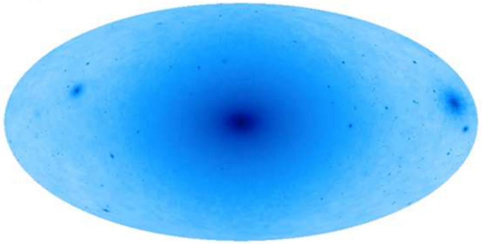
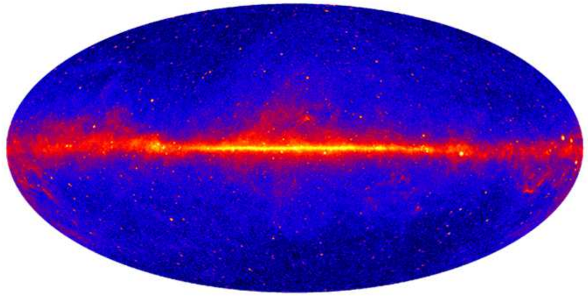
"GeV Excess" in the Galactic Center



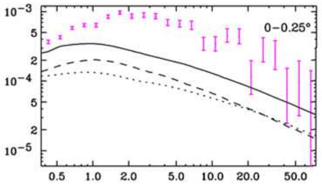
Via Lactea II, Kuhlen et al.,
Science 325:970-973,2009

?

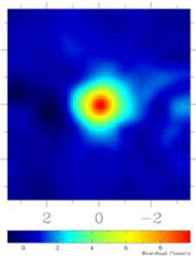


Fermi LAT >1 GeV, 6 years, Pass 8 data

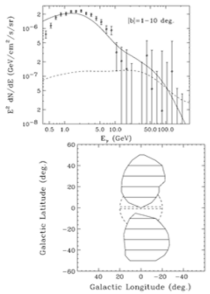
Excess emission spectrum peaks around 3 GeV



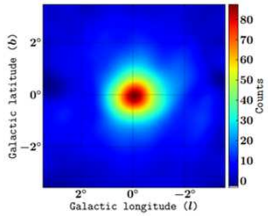
Goodenough & Hooper
Phys.Lett. B697 (2011)



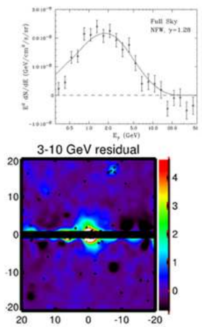
Abazajian & Kaplinghat
PRD 87 129902 (2012)



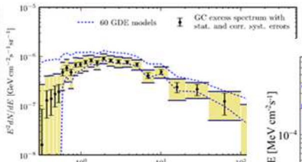
Hooper & Slatyer
Phys.Dark Univ. 2 (2013)



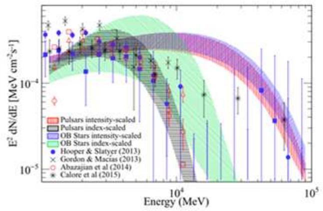
Gordon & Macias
PRD 88, 083521 (2013)



Daylan et al.
Phys. Dark Univ. 12 (2016)



Calore et al.
JCAP 1503 (2015)

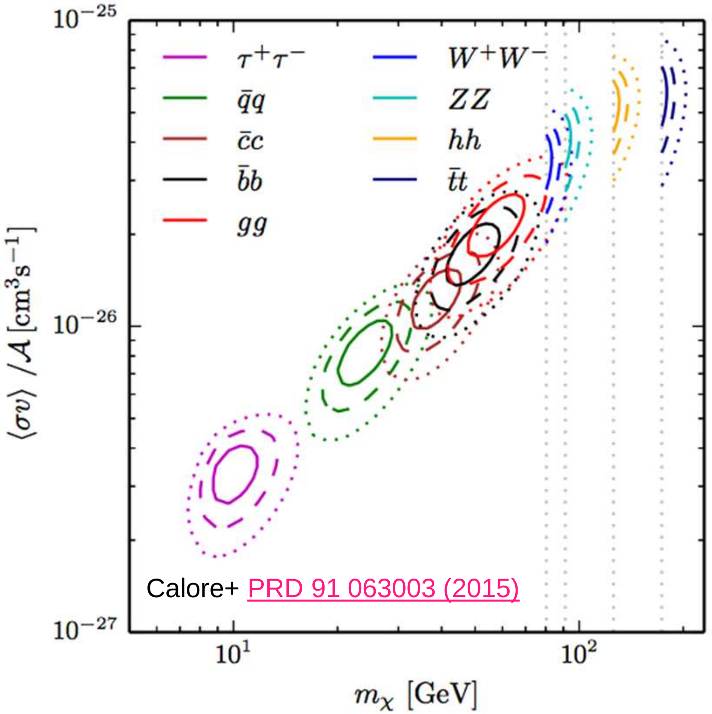


Ajello et al.
(The Fermi-LAT Collaboration)
ApJ 819 1 44 (2016)

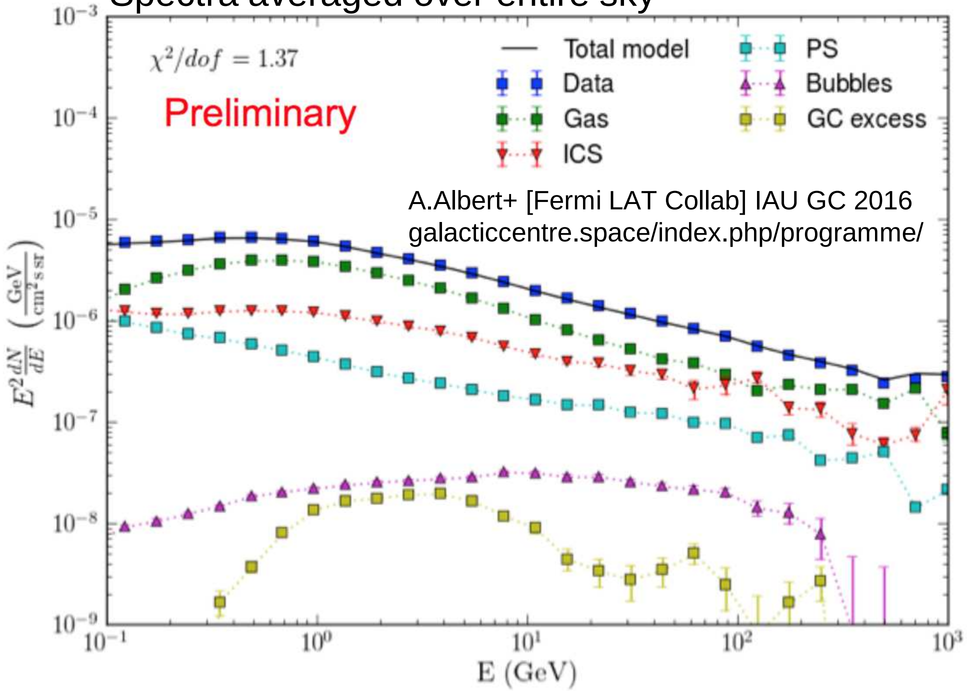
Dark matter annihilation, unresolved sources, CR electrons?

– **Mirabal** (MNRAS 436 (2013) 2461)**, Petrovic et al.** (JCAP 1502 (2015) 02,023)**, Cholis et al.** (JCAP 1512 (2015) 12, 005), **Lee et al.** (PRL 116 051103 (2016)), **Bartels et al.** (PRL 116 051102 (2016))**, Brandt & Kocsis** (ApJ 812 (2015) 1, 15), **Carlson et al. (**arXiv:1510.04698) **etc.**

“GeV Excess” in the Galactic Center

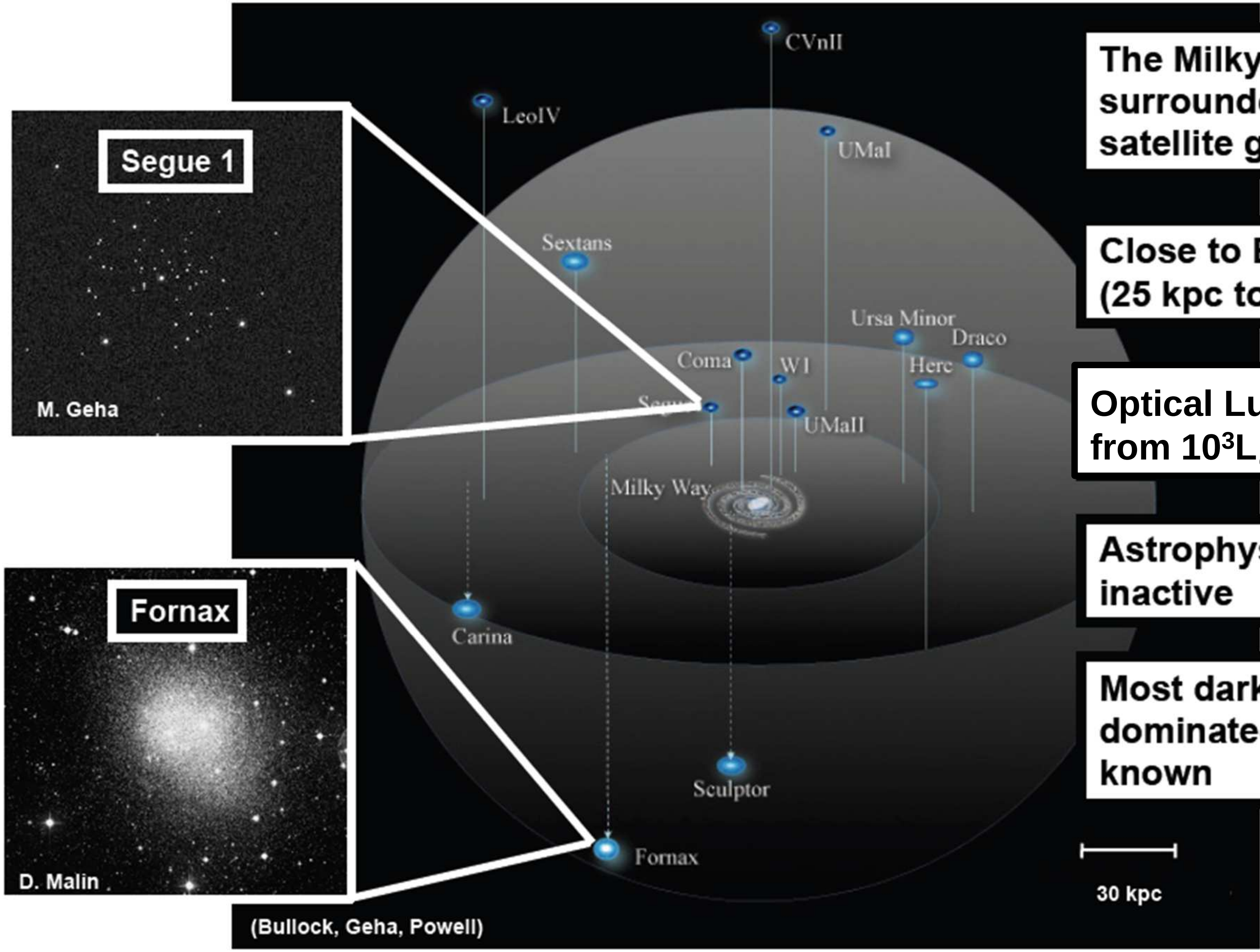


Spectra averaged over entire sky



- **Excess of GeV gamma rays from the GC above standard models first detected by Goodenough & Hooper in 2009 in the Fermi Large Area Telescope data**
  - **If interpreted as DM annihilation, m_{DM} ~ 50 GeV with ‘WIMP miracle’ cross section value**
- **Currently not clear if it is from DM or non-DM sources**
  - **Complicated region of the sky and the community is working hard to disentangle a potential DM component**
    - **~85% of the gamma rays at 1 GeV are from fore/backgrounds**
  - **DM is a small component of the gamma-ray sky, so precision modeling of the non-DM components is necessary to tease out DM component in the Galactic Center**

Milky Way Dwarf Spheroidal Galaxies

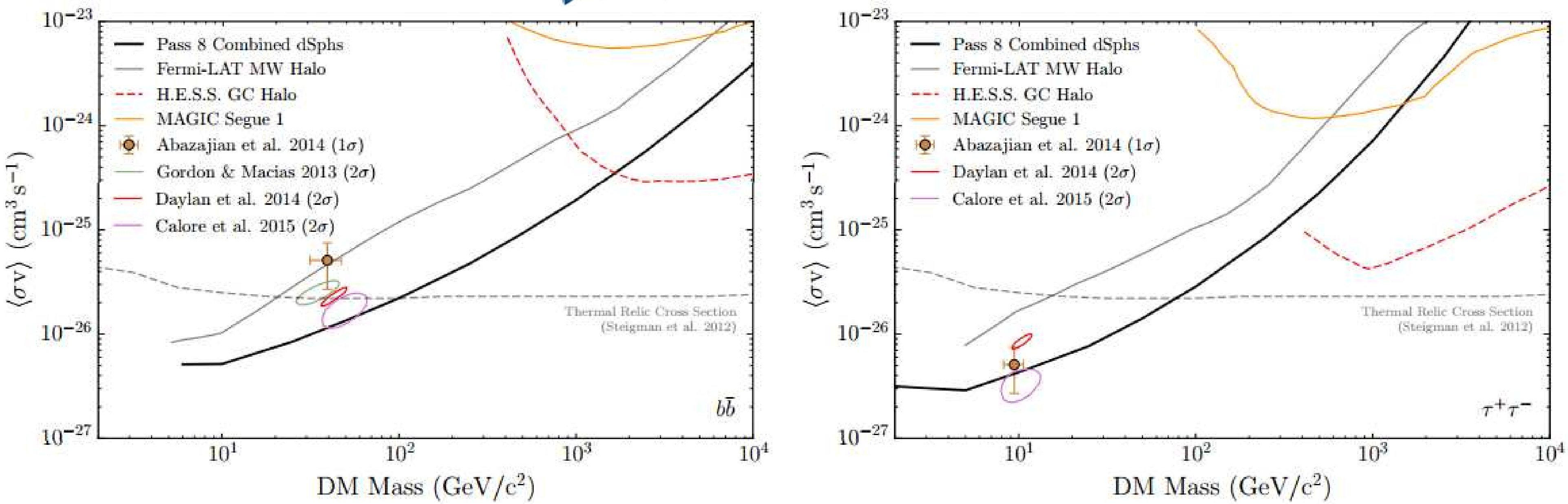


- The Milky Way is surrounded by small satellite galaxies
- Close to Earth (25 kpc to 250 kpc)
- Optical Luminosities from $10^3 L_\odot$ to $10^7 L_\odot$
- Astrophysically inactive
- Most dark matter dominated objects known

A.Drlica-Wagner
DPF 2013

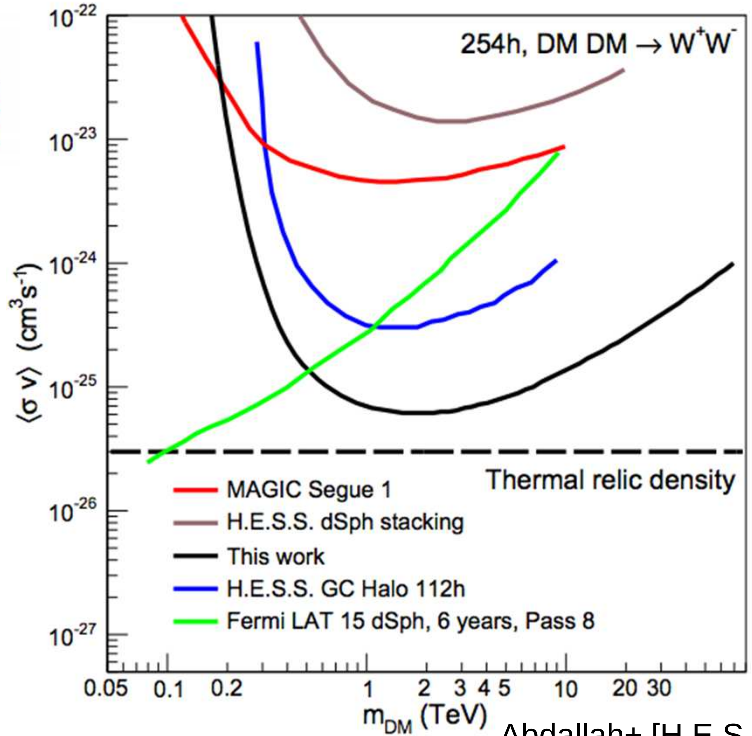
6 year Fermi LAT dSphs Results

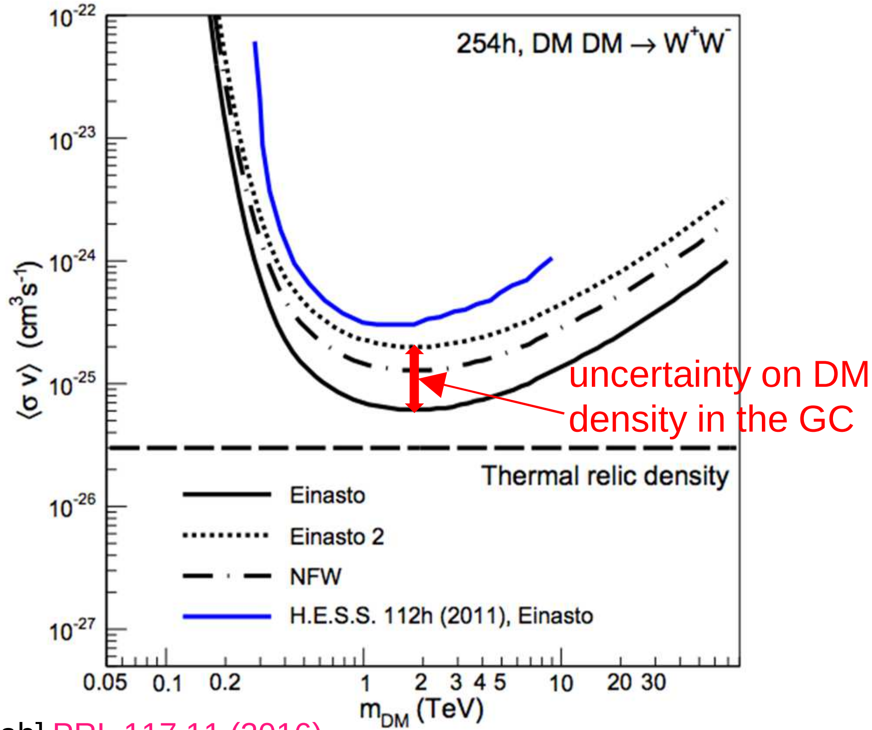
The Fermi LAT Collab
PRL 115, 23 (2015)



- **Joint likelihood analysis of 15 well characterized dwarf galaxies**
- **Limits exclude thermal relic $<\sigma v>_{ann}$ in $b\bar{b}$ channel for 5 GeV $< m_\chi <$ 100 GeV**

TeV Gamma-ray DM Constraints





Abdallah+ [H.E.S.S. Collab] PRL 117 11 (2016)

- **For gamma-rays from 500 GeV to 5 TeV, best sensitivity comes from Air Cherenkov Telescopes (ACTs, e.g. H.E.S.S.)**
- **H.E.S.S. located in the southern hemisphere can observe the Galactic Center**
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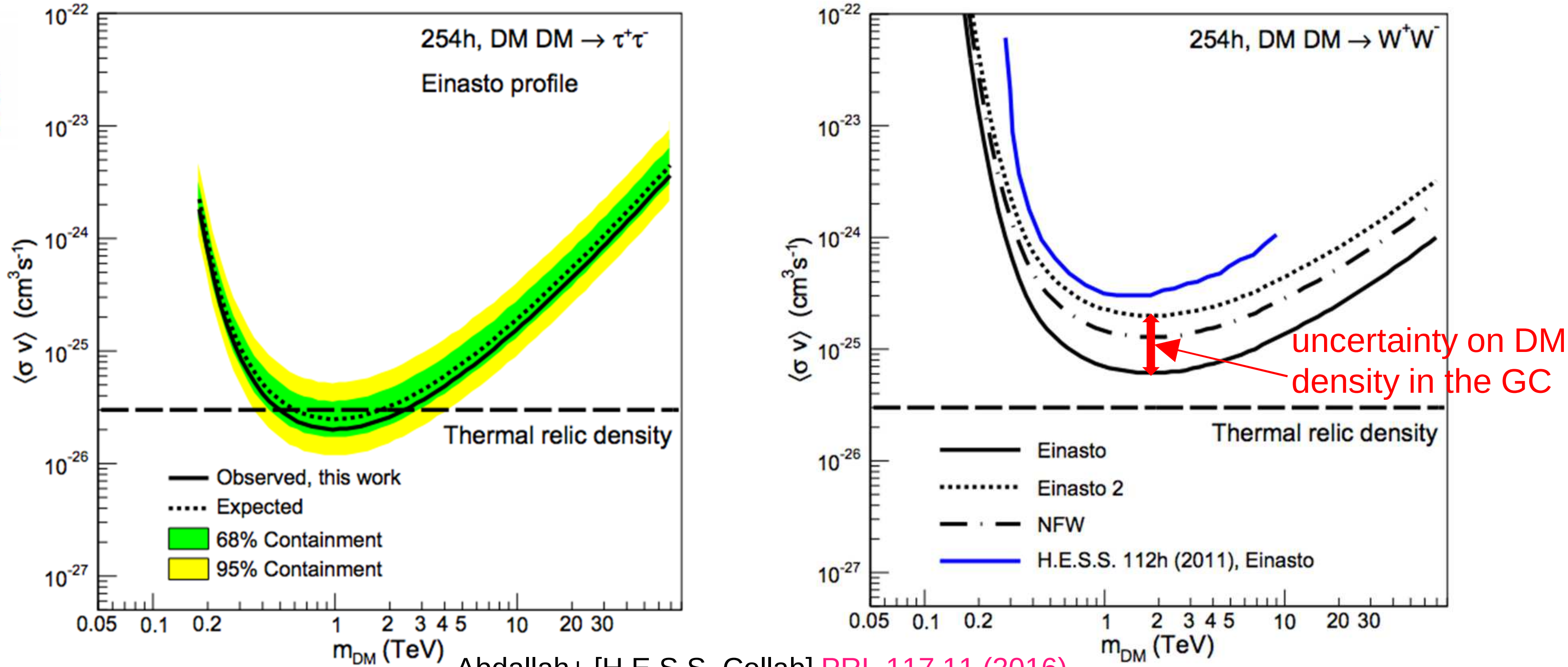

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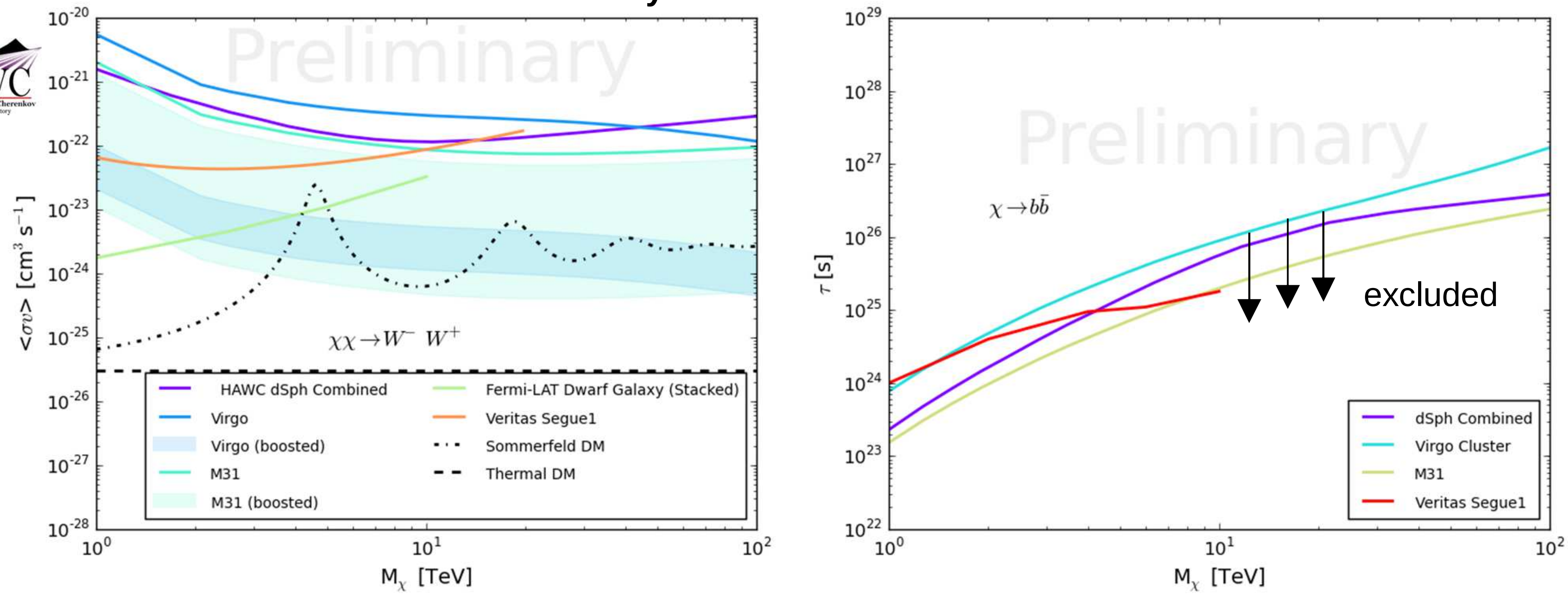
>TeV Gamma-ray Constraints

1 year HAWC limits



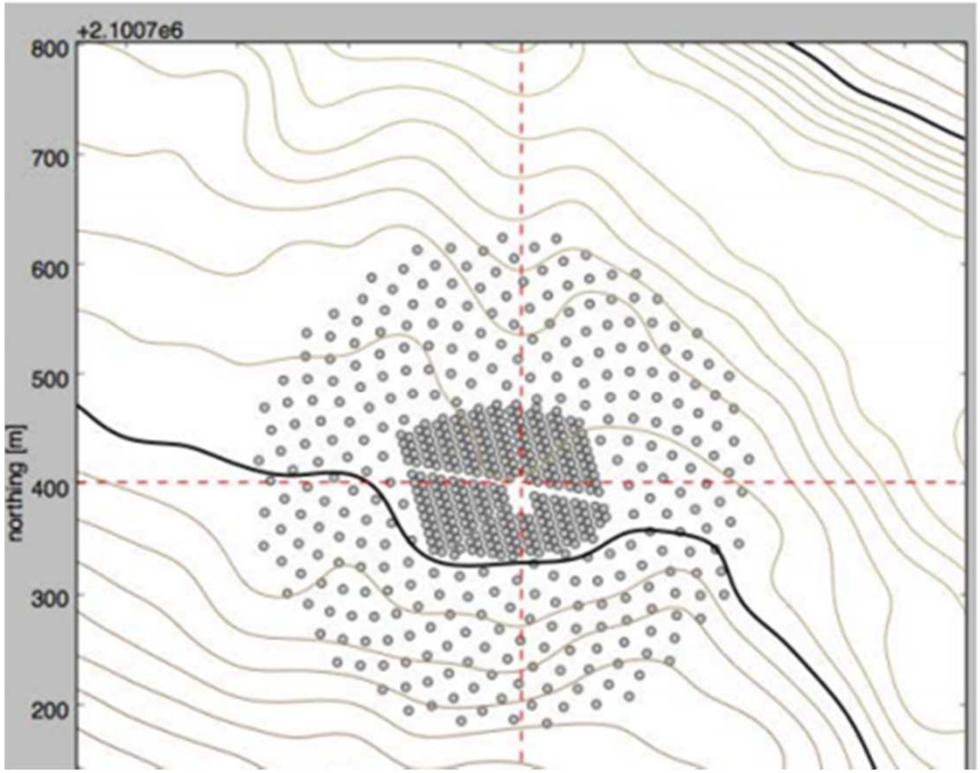
- **For gamma-rays >5 TeV, best sensitivity comes from the High Altitude Water Cherenkov Observatory (HAWC)**
  - **HAWC has a wide field of view making it sensitive to extended objects**
  - **HAWC surveys ⅔ of the sky every day, including several DM targets**
- **No excesses observed, limits extend out to the highest DM masses**
  - **will be able to test DM decay models proposed to explain the IceCube neutrinos**
    - **Typically PeV mass DM with lifetime ~ 1e27 s**

      e.g. A. Esmaili+ (2013) arXiv:1308.1105, K. Murase+ (2015) 1503.04663v2

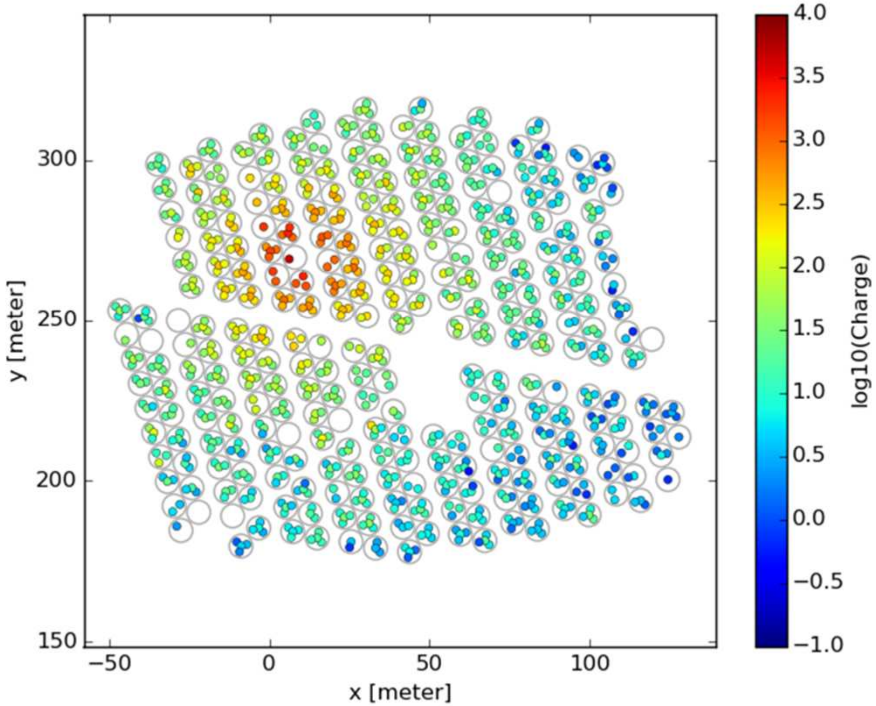
Future Gamma Ray Prospects

Upgrade to HAWC Observatory

A. Sandolval arXiv:1509.04269

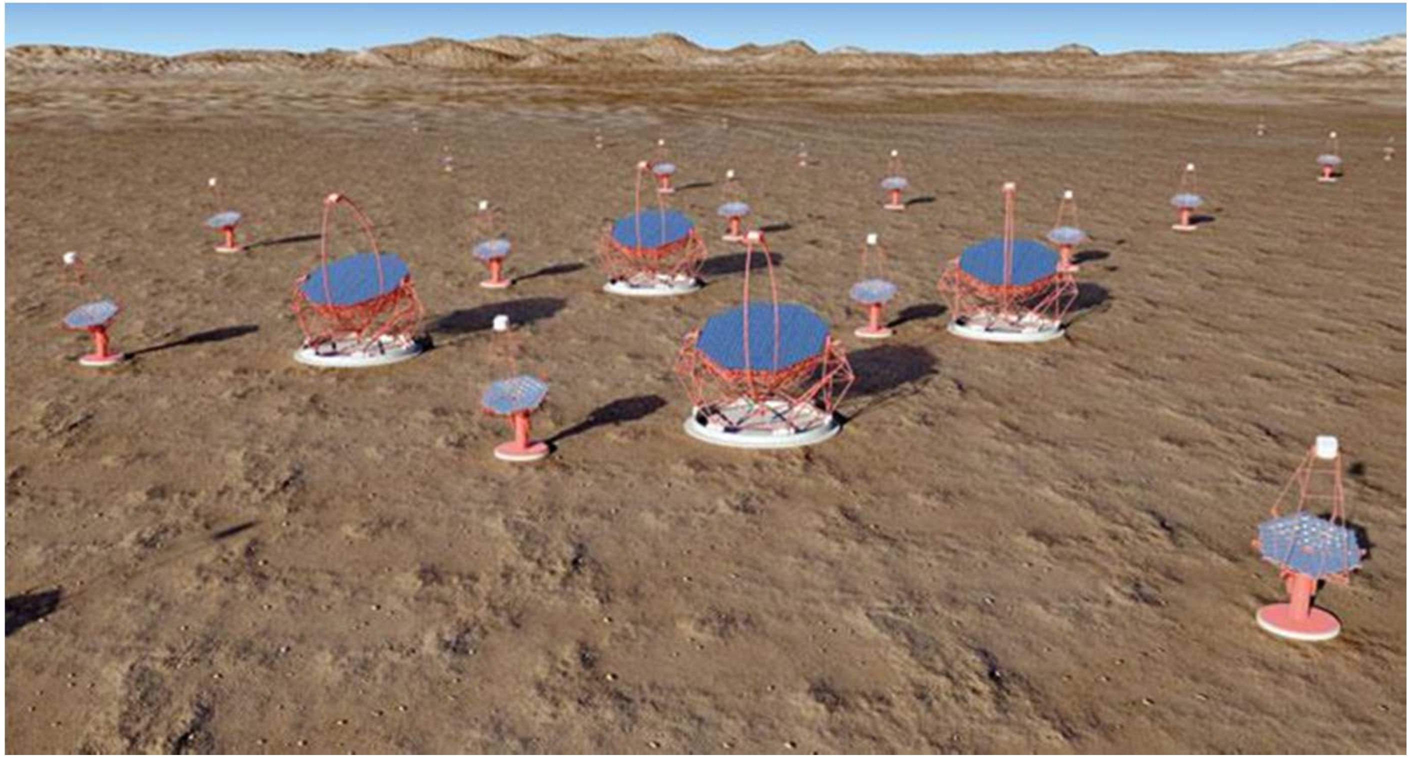


~60 TeV gamma ray event
from the Crab Nebula



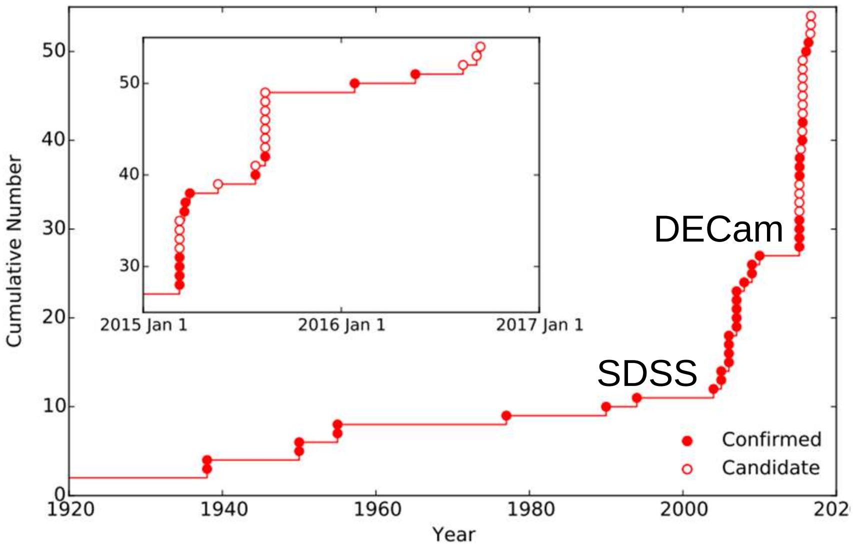
- **Upgrade to HAWC array is underway**
  - **–increase collection area with sparse array of small tanks**
- **Provide better measure of highest energy air showers**
  - **–expected gain in sensitivity above 10 TeV of 3-4**
  - **–will allow HAWC to search for the highest energy gamma-ray ever observed**

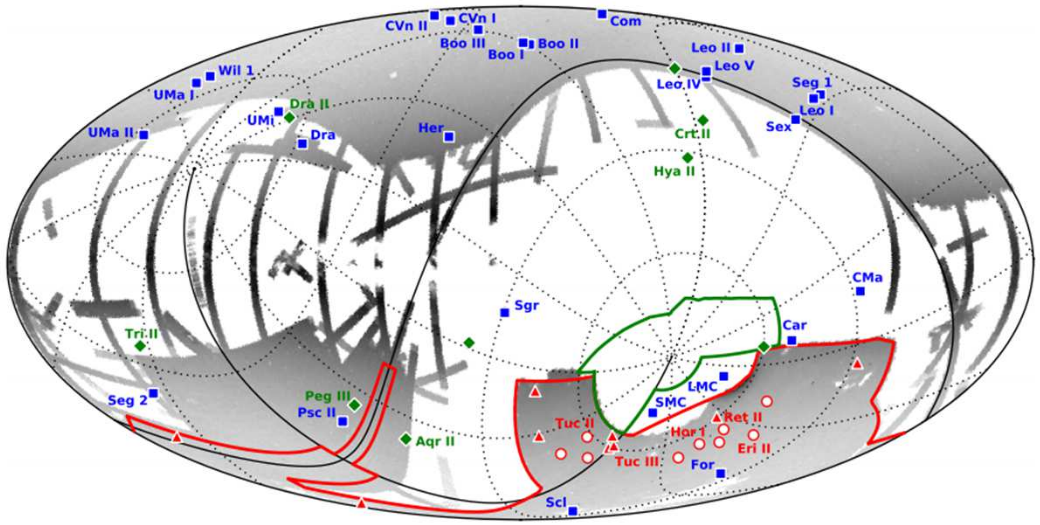
The Cherenkov Telescope Array



- CTA is a next-generation gamma-ray observatory
- International Consortium combines existing ACT expertise
- Plan for Northern and Southern array -> full sky coverage
  - sites will be La Palma, Spain and Paranal, Chile
- Will increase TeV point source sensitivity by ~10x relative to current instruments

Growing Number of Known Dwarf Galaxies

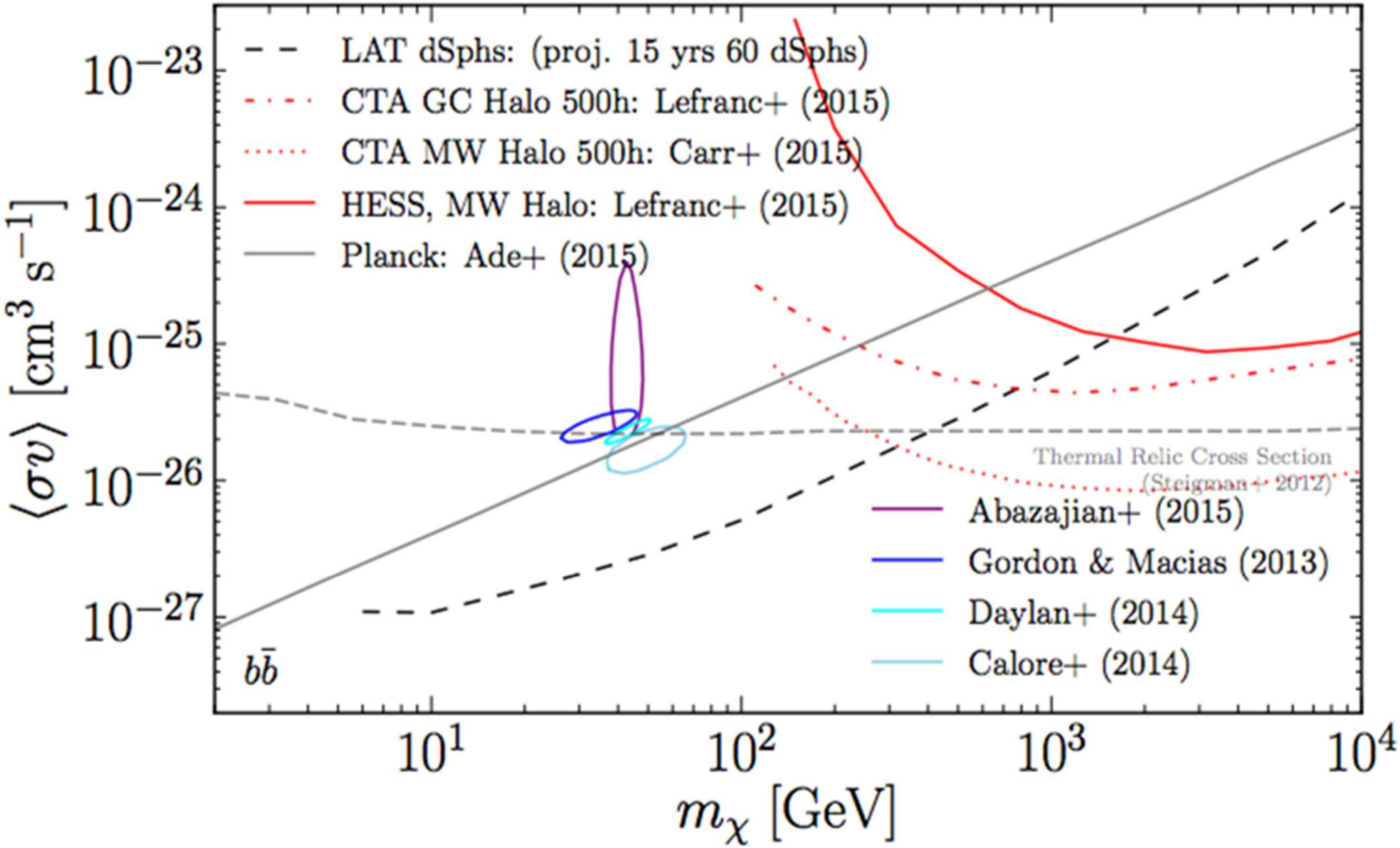




Dark Energy Survey Year 2 Data: Drlica-Wagner+, 2015ApJ...813..109D
Dark Energy Survey Year 1 Data: Bechtol+, 2015ApJ...807...50B
Koposov+,
2015ApJ...805..130K

- **Deep photometric surveys in optical astronomy have led to the discovery of numerous new Milky Way-satellites**
  - **Spectroscopic follow up necessary to determine if they are DM-dominated dwarf galaxies. Many new dwarf galaxies have already been spectroscopically confirmed**
- **LSST & other surveys will continue to find new dwarf galaxies**
  - **Wide field of view survey instruments (e.g. Fermi LAT, HAWC) will have already observed these new DM targets**

Expected Future Sensitivity



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Summary

- Evidence for DM exists on all cosmic scales
  - all observational evidence for dark matter comes from space; we must continue investigating dark matter in its cosmic setting
- Dark matter annihilations (decay) are predicted to produce a cascade of secondary standard model particles
  - We can search for these cosmic messengers with a network of ground-based and space-based observatories
- Some intriguing anomalies exist that require extensive follow up work from all experiments to complete the picture
  - The fundamental particle properties of DM (e.g. mass) must be the same from all messengers and targets
- The future is bright and full of exciting questions!
  - We need to continue our multimessenger indirect detection quest to complement terrestrial experiments and gain a complete picture of the DM puzzle

Extra Slides

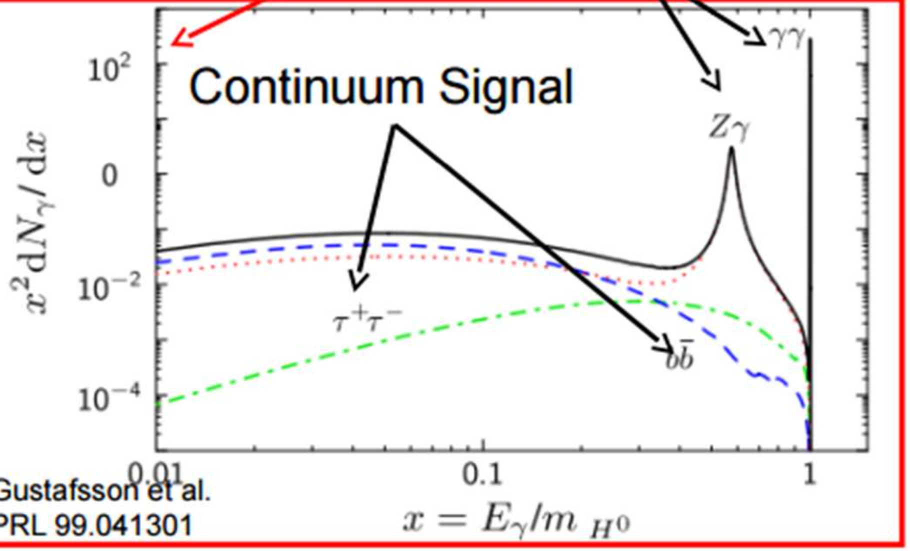
Gamma rays from DM Annihilation

What we observe | Intrinsic Particle Properties | Astrophysics

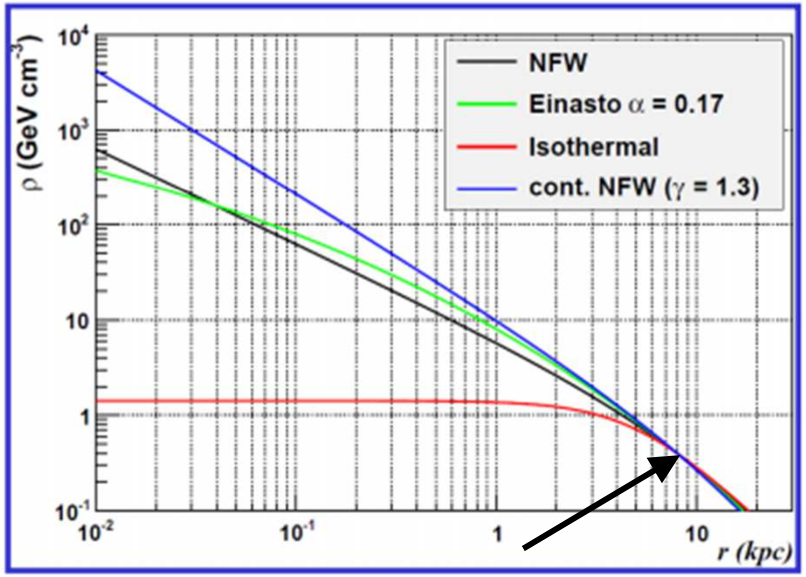
$$\Phi_\chi(E,\Psi) = \frac{\langle \sigma_\chi v \rangle}{2} \sum \frac{dN_f}{dE} B_f \int_{LOS} dl(\Psi) \frac{1}{4\pi} \frac{\rho(l)^2}{m_\chi^2}$$

J-factor – Line of sight integral over a ROI

Monochromatic Signal



Gustafsson et al.
PRL 99.041301



r_{sun} = 8.5 kpc

Gamma rays from DM Annihilation

What we observe | **Intrinsic Particle Properties** | **Astrophysics**

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J-factor – Line of sight

Target	Distance (kpc)	J factor ($\mathrm{GeV}^2\,\mathrm{cm}^{-5}$)	Angular Extent (°)
Galactic center / halo (§4.4)	8.5	3×10^{22} to 5×10^{23}	>10
Known Milky Way satellites (§4.5)	25 to 300	3×10^{17} to 3×10^{19}	<0.5
Dark satellites (§4.6)	25 to 300	up to 3×10^{19}	<0.5
Galaxy Clusters (§4.7)	$>5\times10^4$	up to 1×10^{18}	up to ~3
Cosmological DM (§4.8)	$>10^6$	-	Isotropic

Table 1: Summary table of DM search targets discussed in this paper.

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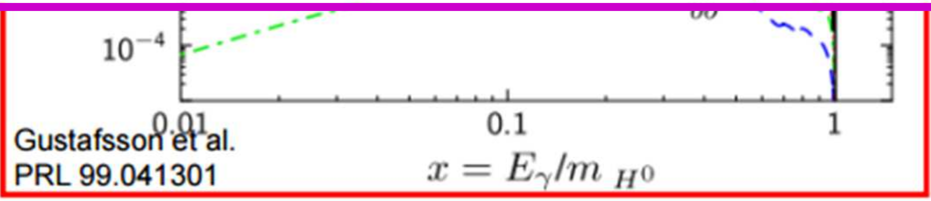

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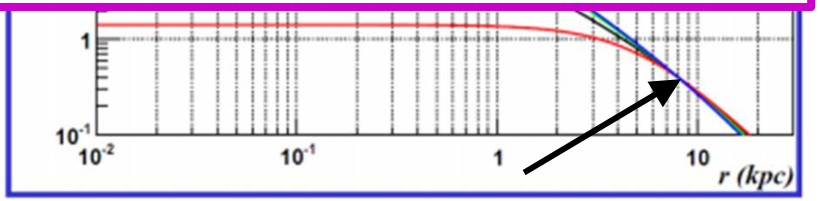

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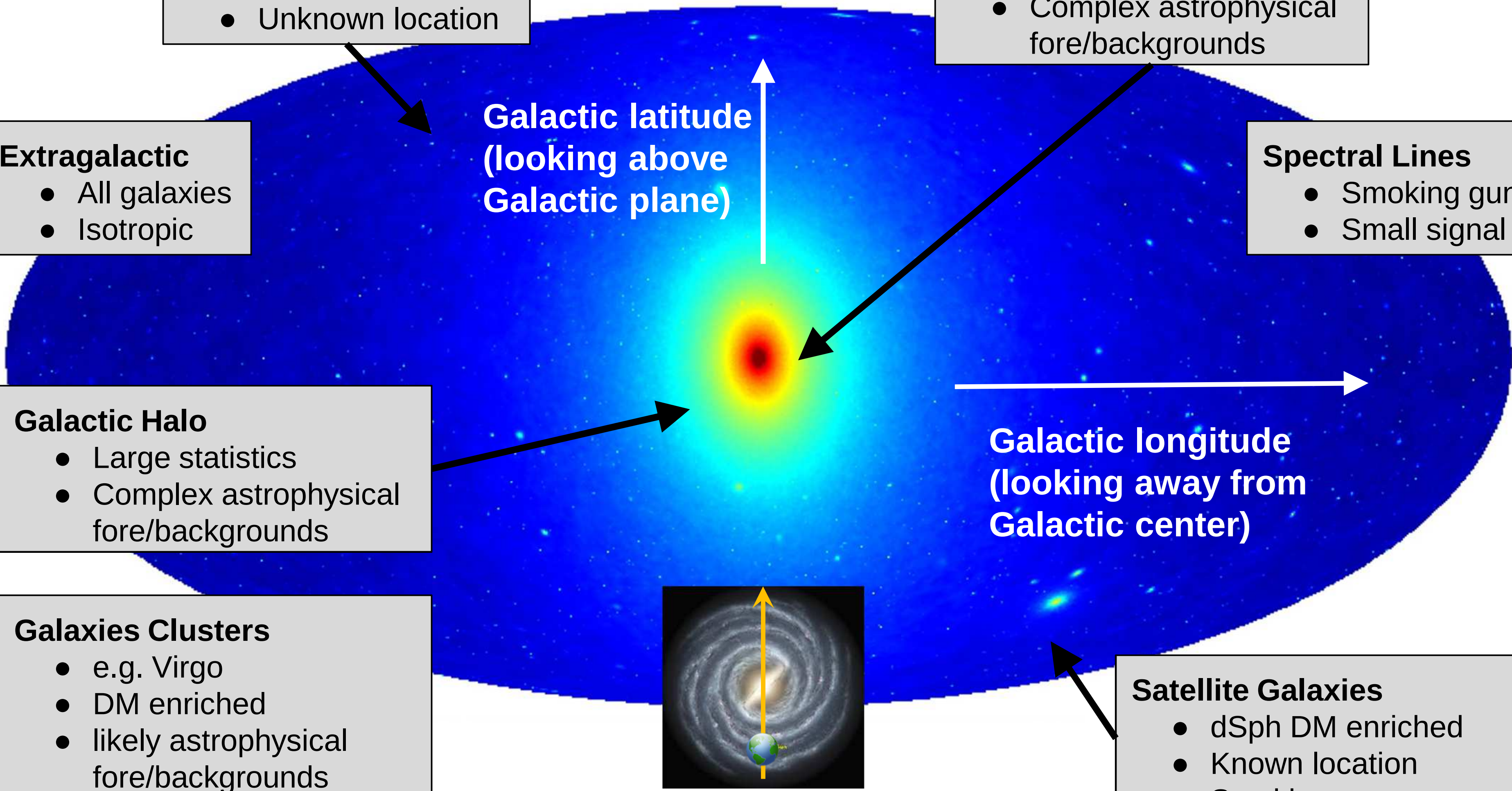
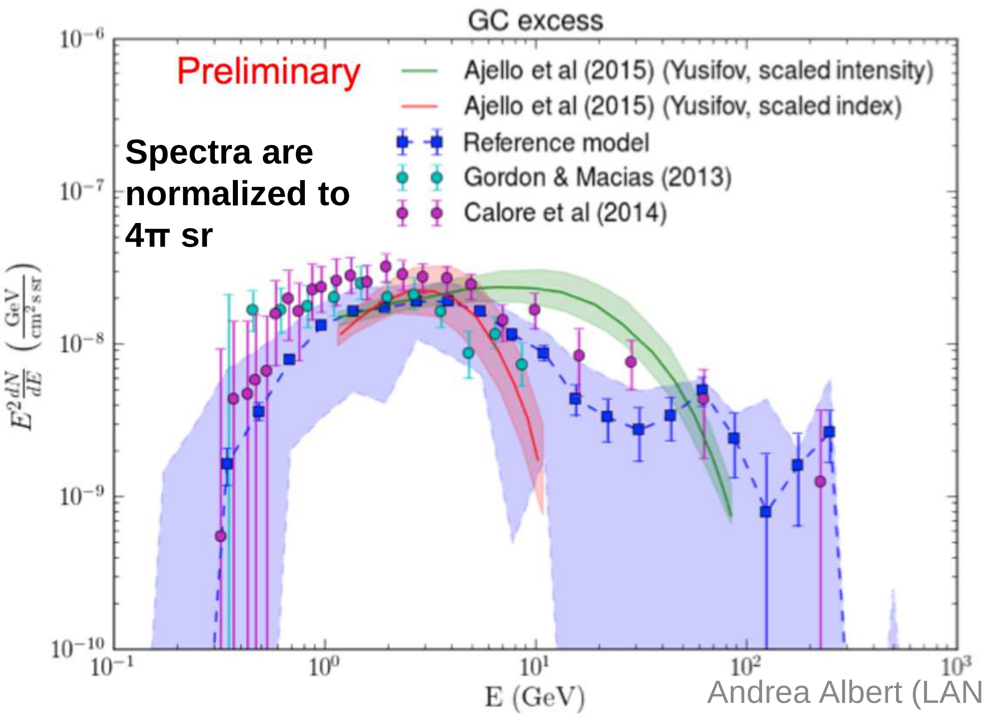
Expected Gamma rays from Dark Matter



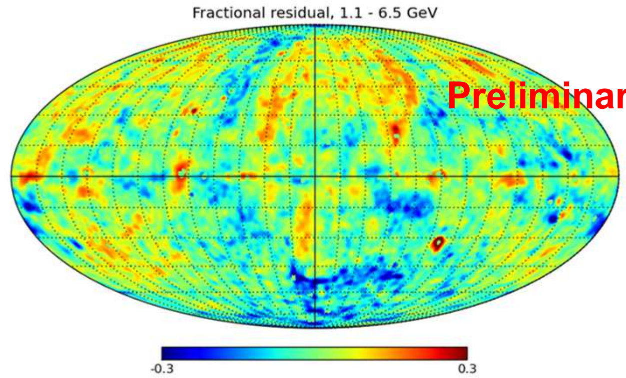
Aquarius (A1) simulation

Characterization of the GeV Excess

- **Preliminary results from new Fermi GC analysis have been shown**
  - **A. Albert, D. Malyshev, A. Franckowiak, L. Tibaldo, E. Charles, et al**
- **Goal: study the effects of varying diffuse emission modeling on the GeV excess**
  - **see backup slides for modeling details**
- **Results: Excess persists, large spectral uncertainties at low and high energies**



Fractional residual, 1.1 – 6.5 GeV



Fractional residual, 1.1 -- 6.5 GeV
no excess template included in fit