Fantastic Dark Matter and Where to Find Them: Indirect Detection

Ruihao Li

CERCA Friday Seminar

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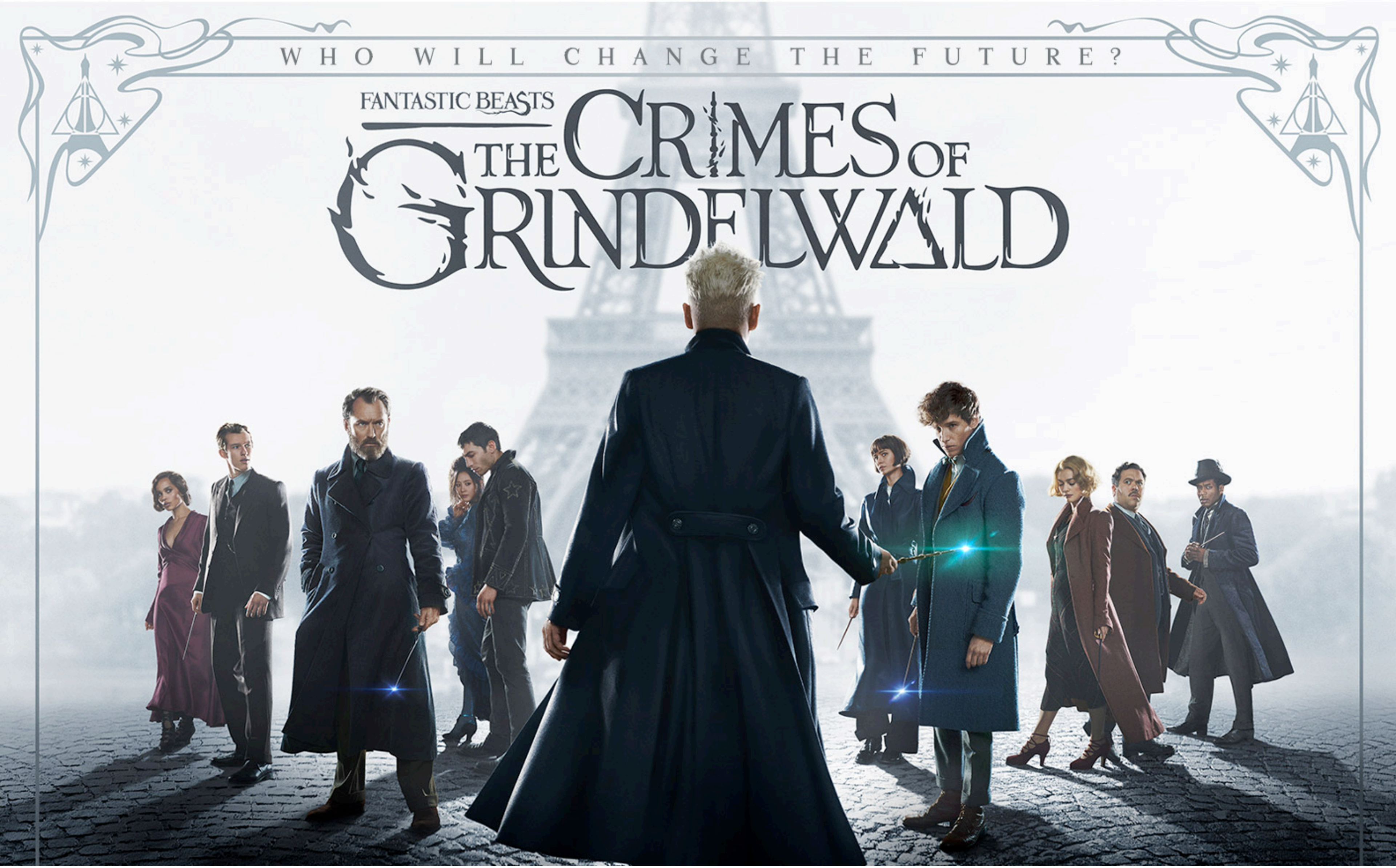
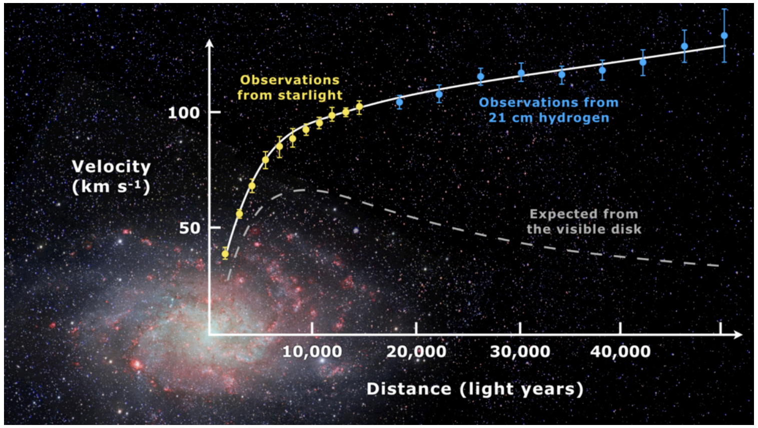
Fantastic Beasts and Where to Find Them (2016)

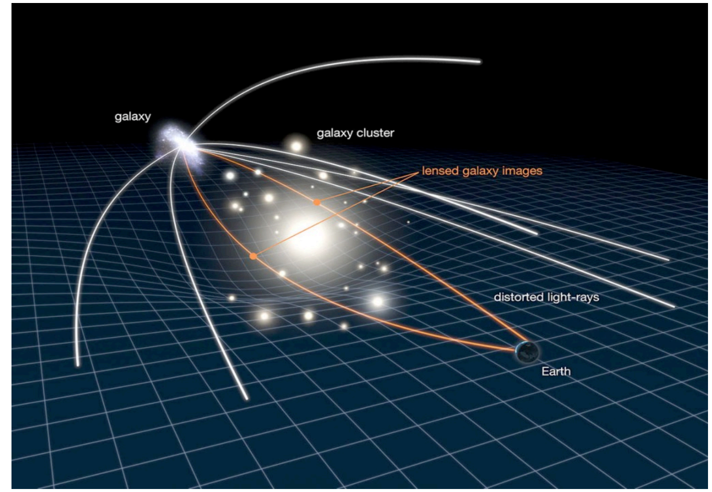


Fantastic Beasts: Crimes of Grindelwald (2018)

Evidence for DM



Flat rotation curves



Gravitational lensing

Optical image from Magellan and Hubble

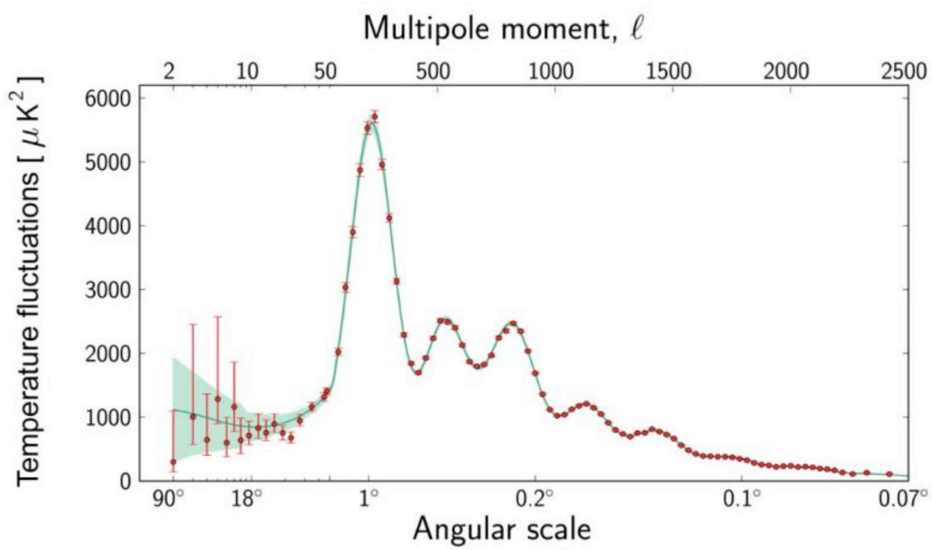
Optical +X-ray

hot gas detected by Chandra, containing most of normal matter

Optical + gravitational lensing

Most of the mass in the cluster, measured by gravitational lensing, shown in blue

Bullet Cluster

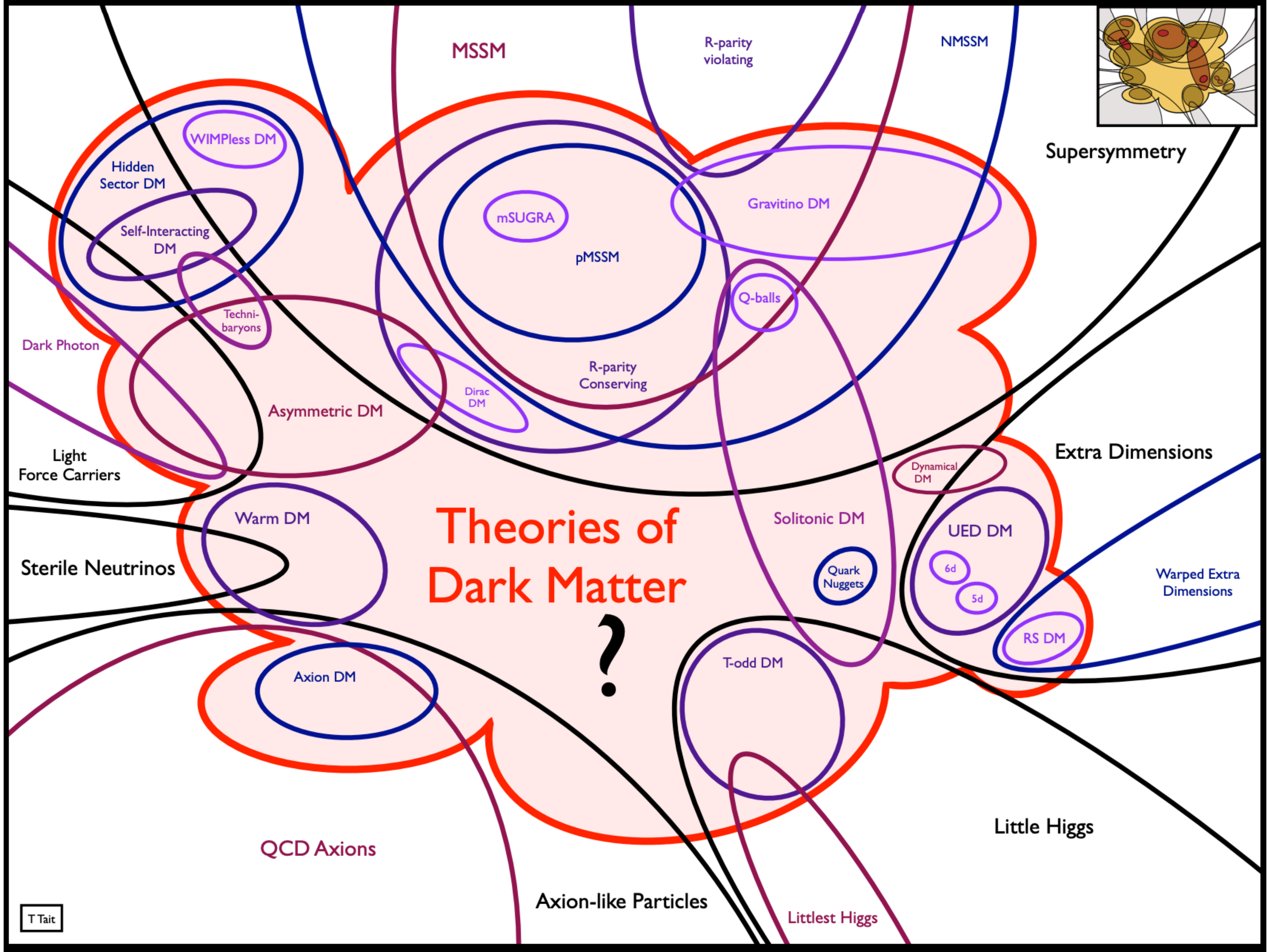


Cosmic Microwave Background (CMB)

What Might DM Be

Properties of Dark Matter

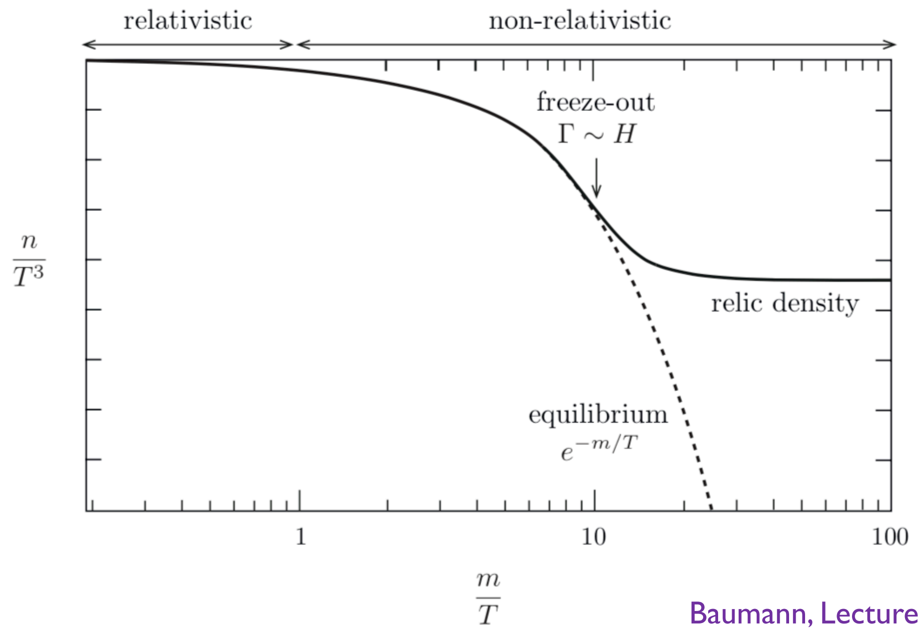
- Non-relativistic (cold, or warm)
- Stable or long lived
- Interact gravitationally but weakly with ordinary matter
- Have no or little electric charge



Theories of Dark Matter
?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
Light Force Carriers
Asymmetric DM
mSUGRA
pMSSM
R-parity Conserving
Dirac DM
Gravitino DM
Q-balls
Extra Dimensions
Dynamical DM
Solitonic DM
UED DM
6d
5d
Quark Nuggets
Warped Extra Dimensions
RS DM
Warm DM
Sterile Neutrinos
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

WIMP Paradigm

- I will focus on the weakly interacting massive particles (WIMPs).



Baumann, Lecture notes on Cosmology

- Thermal production in the early Universe: freeze-out mechanism by annihilation or decay, leaving a relic density:

$$\Omega_X h^2 \approx 0.12 \left(\frac{2.2 \times 10^{-26} \, \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \right) \left(\frac{80}{g_\star} \right)^{1/2} \left(\frac{m_X/T_\mathrm{F}}{23} \right)$$

Thermally averaged cross section

Velocity Dependence

- Can DM annihilate with a different cross section in the Universe today than the benchmark cross section?

- Velocity expansion: $\langle \sigma v \rangle = a + bv^2 + \mathcal{O}(v^4)$

s-wave p-wave

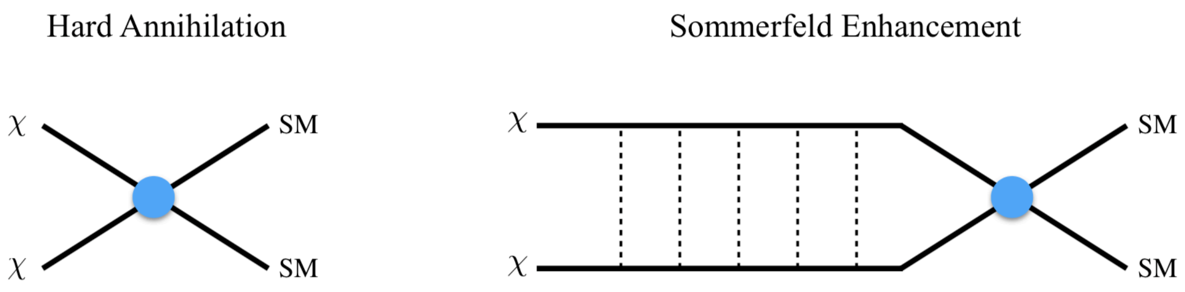
- Cases with s-wave suppression
  - Majorana fermion DM annihilated to SM Higgs
  - Majorana fermion DM annihilate through an s-channel Z boson to SM fermions

	Fermion Bilinear			
Fermionic DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{X}X$	$\sigma v \sim v^2$	$\sigma v \sim v^2$	$-$	$-$
$\bar{X}\gamma^5 X$	$\sigma v \sim 1$	$\sigma v \sim 1$	$-$	$-$
$\bar{X}\gamma^\mu X$	$-$	$-$	$\sigma v \sim 1$	$\sigma v \sim 1$
$\bar{X}\gamma^\mu\gamma^5 X$	$-$	$-$	$\sigma v \sim v^2$	$\sigma v \sim 1$
Scalar DM				
$\phi^\dagger\phi$	$\sigma v \sim 1$	$\sigma v \sim 1$	$-$	$-$
$\phi^\dagger \overleftrightarrow{\partial_\mu} \phi$	$-$	$-$	$\sigma v \sim v^2$	$\sigma v \sim v^2$
Vector DM				
$X^\mu X^\dagger_\mu$	$\sigma v \sim 1$	$\sigma v \sim 1$	$-$	$-$
$X^\nu \partial_\nu X^\dagger_\mu$	$-$	$-$	$\sigma v \sim v^2$	$\sigma v \sim v^2$

Berlin, Hooper, McDermott 2014

Velocity Dependence

- In the other direction: Sommerfeld enhancement



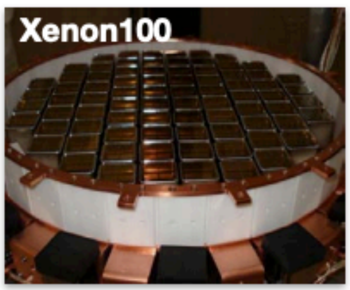
- In the non-relativistic limit: DM scattering off a potential

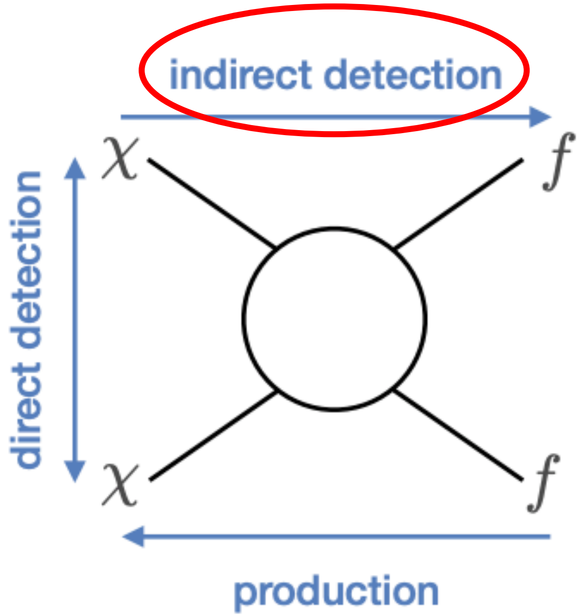
$$V(r) = \frac{\alpha}{r} e^{-m_\phi r}$$

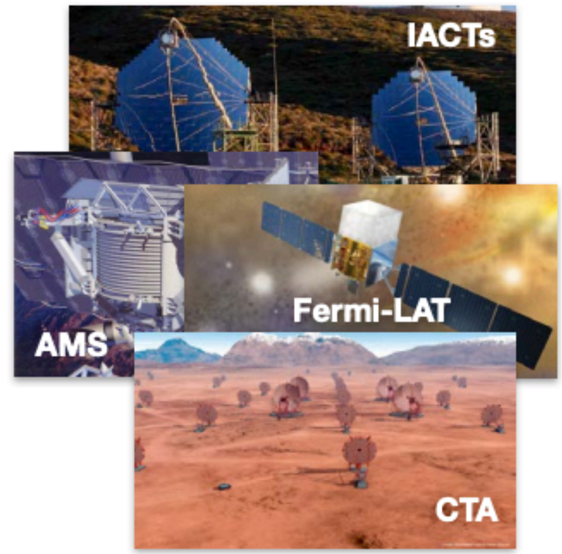
- Quantum mechanical analysis → s-wave enhancement ($m_\phi = 0$)

$$S = \left| \frac{\psi(0)}{\psi_0(0)} \right|^2 = \left| \frac{\alpha}{v} \right| \frac{2\pi}{1 - e^{-2\pi|\alpha|/v}} \approx \begin{cases} \frac{2\pi\alpha}{v}, & v \to 0 \\ 1, & v \to \infty \end{cases}$$

How Might We Find Them



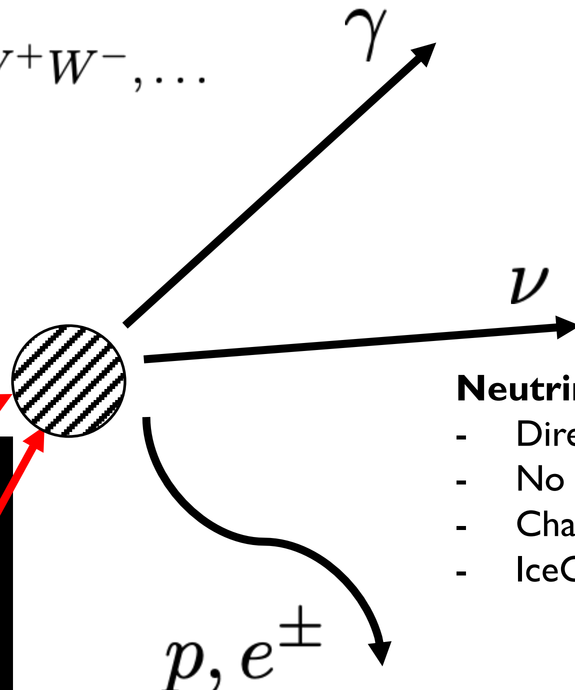




Indirect Detection

- SM final states:

$$\chi\chi \rightarrow q\bar{q}, \ell\bar{\ell}, \gamma\gamma, ZZ, W^+W^-, \ldots$$



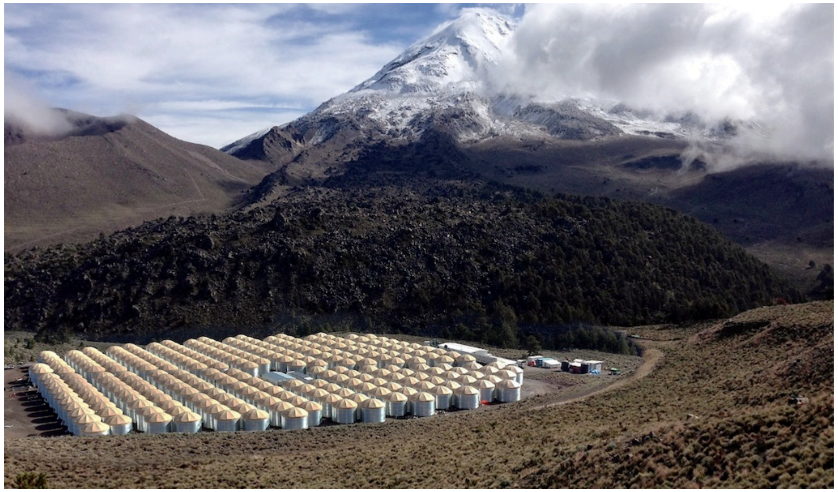
Gamma rays
- Not affected by B-fields; directly point to their origin
- Negligible absorption in galaxy
- Distinct spectral shape
- Fermi-LAT, H.E.S.S., HAWC, CTA, GAMMA-400

Neutrinos
- Direct propagation
- No absorption
- Challenges from backgrounds, low statistics
- IceCube, Super-Kamiokande, Hyper-Kamiokande

Charged cosmic rays
- Low backgrounds for antimatter
- Deflected by B-fields; hard to trace the origin
- Sizable energy losses
- PAMELA, AMS-02, Auger, GAPS

Gamma-Ray Telescopes

Fermi Large Area Telescope



High Altitude Water Cherenkov (HAWC)

Imaging Atmospheric Cherenkov Telescopes (e.g. H.E.S.S.)

Photon Flux

- Consider multiple DM annihilation channels to produce photons.
- Annihilation rate per particle

$$\sum_i n_\chi \times \langle \sigma_i v \rangle = \sum_i \frac{\rho[r(l,\psi)]}{m_\chi} \langle \sigma_i v \rangle$$

- Total annihilation rate in a volume $\mathrm{d}V = l^2 \mathrm{d}l \mathrm{d}\Omega$

$$\left(\sum_i \frac{\rho[r(l,\psi)]}{m_\chi} \right) \times \left(\frac{\rho[r(l,\psi)]}{2m_\chi} \mathrm{d}V \right)$$

- Differential photon flux in the observational volume oriented in the direction ψ

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma}(E_\gamma, \psi) = \boxed{\sum_i \frac{\langle \sigma_i v \rangle}{2m_\chi^2} \frac{\mathrm{d}N_i}{\mathrm{d}E_\gamma}} \boxed{\frac{1}{4\pi} \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \mathrm{d}l\, \rho^2[r(l,\psi)]}$$

Particle physics | Astrophysics (J-factor)

DM Density Profile

$$J_{\rm ann} = \frac{1}{4\pi}\int_{\Delta\Omega} {\rm d}\Omega \int_{\rm l.o.s.} {\rm d}l\, \rho^2[r(l,\psi)]$$

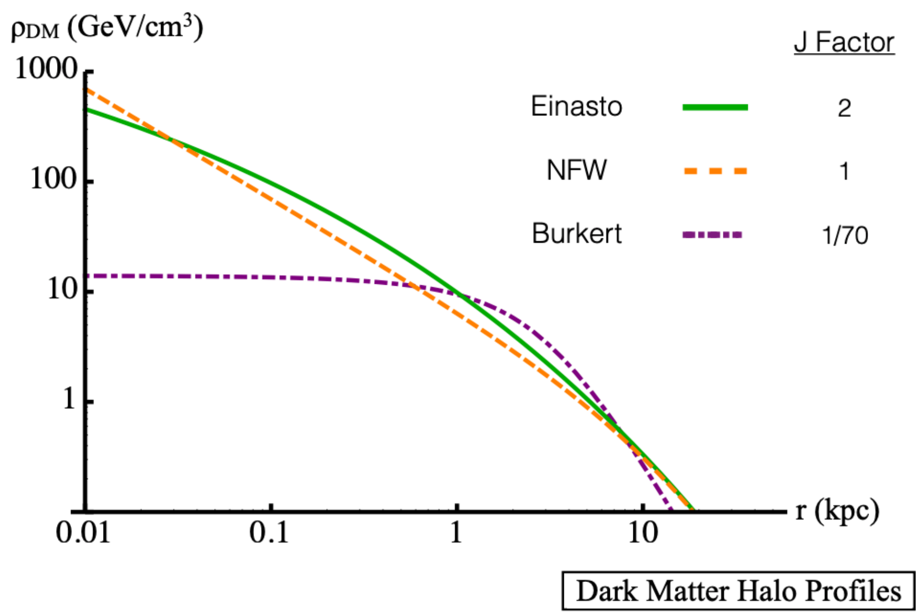
- We cannot measure the DM distribution directly. It is a prediction of numerical DM simulations with associated error bars.

- There exists 3 standard profiles:

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{\frac{r}{R}\left(1+\frac{r}{R}\right)^2}$$

$$\rho_{\rm Einasto}(r) = \rho_0 \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{R}\right)^\alpha - 1\right)\right]$$

$$\rho_{\rm Burkert}(r) = \frac{\rho_0}{\left(1+\frac{r}{R}\right)\left(1+\frac{r^2}{R^2}\right)}$$



Bramante, Desai, Fox, Martin, Ostdiek, Plehn 2016

Where to Look

- DM particles annihilating in a spherical dwarf galaxy:

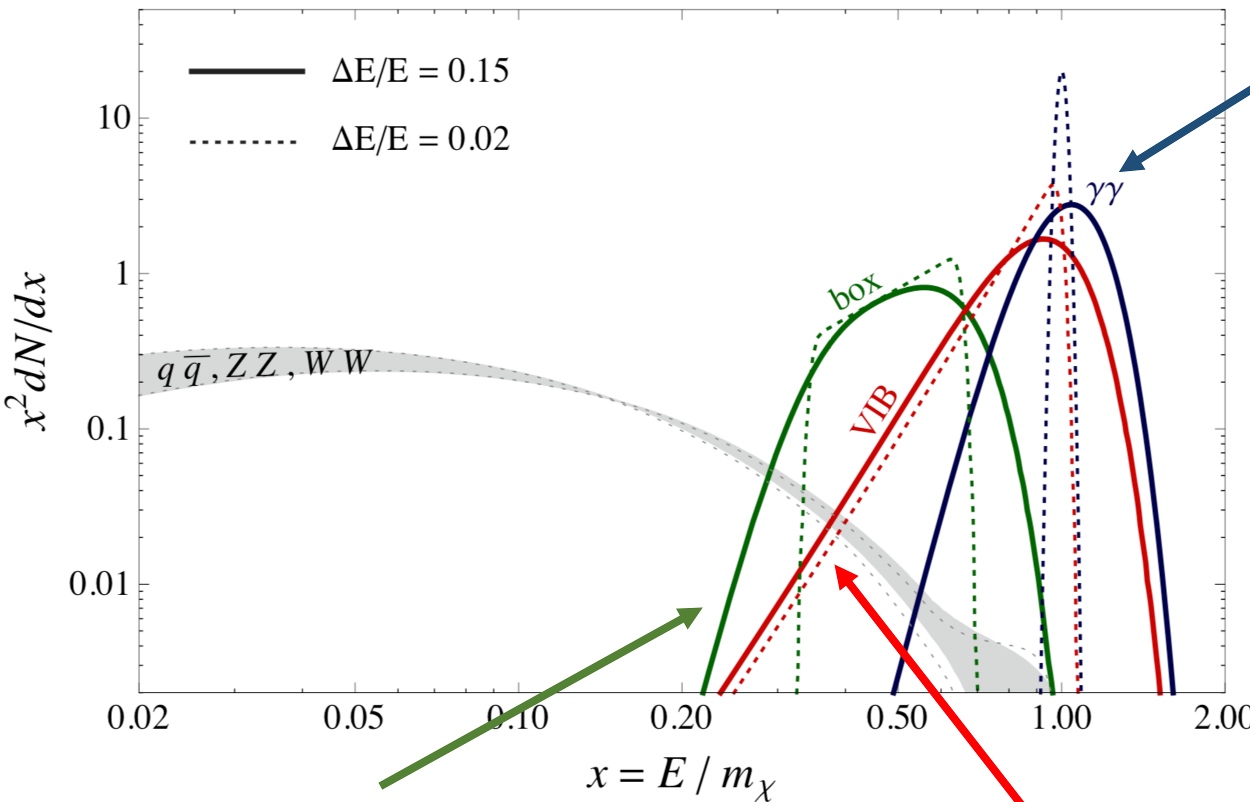
$$d \gg r : J = \frac{1}{4\pi} \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \mathrm{d}l \, \rho^2[r(l,\psi)] \simeq \frac{\rho^2 r^3}{3d^2}$$

- Ideal targets
  - Have high density of DM
  - Are nearby
  - Are extended across a large volume
  - Are accompanied by low and/or well-understood astrophysical backgrounds
- Choices
  - Galactic center: large signal, large backgrounds
  - Dwarf galaxies: low statistics, low backgrounds
  - Galactic halo: moderate signal, complex backgrounds
  - Other galaxies and clusters: large DM content, sensitive to amount of substructures

Gamma-Ray Spectral Signatures

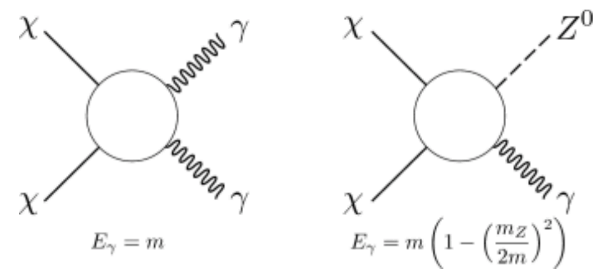
- Hadronic continuum: $\chi\chi \to \tau^+\tau^-, q\bar{q}, W^+W^-, ZZ \to \pi^0 \to \gamma\gamma$
  - Large number of neutral pions form from the decays of these particles
  - Neutral pions decay to a photon pair with a 99% branching ratio
  - A broad spectrum of photons produced
- Leptonic: $\chi\chi \to e^+e^-, \mu^+\mu^- \to \gamma\gamma$
  - Photons produced by final state radiation (FSR) or virtual internal bremsstrahlung (VIB)
  - Rate for photon production is suppressed
  - Typically hard photon spectrum, peaked toward the DM mass
- Lines: $\chi\chi \to \gamma\gamma$
  - Monoenergetic peak in the photon spectrum $E_\gamma \simeq m_\chi$
  - DM do not couple to photon directly; loop suppressed
  - Difficult to see

Gamma-Ray Spectral Signatures



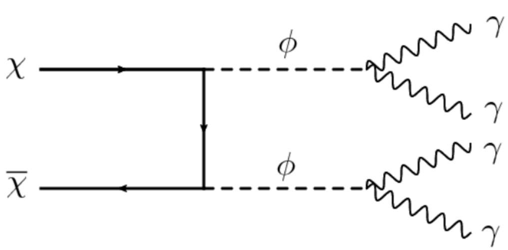
Gamma-ray lines

$$\chi\chi \to \gamma\gamma, \gamma Z$$



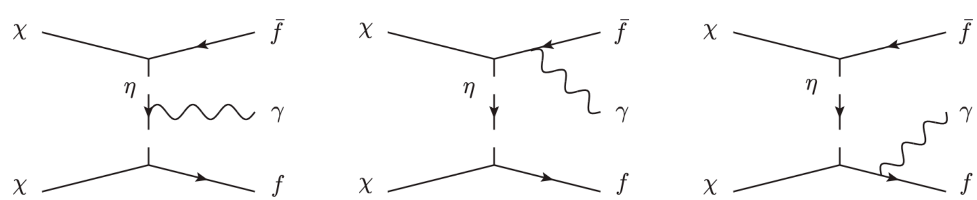
Bergstrom, Snellman 1988

Cascade decays $\chi\chi \to \phi\phi \to \gamma\gamma\gamma\gamma$



Ibarra, Lopez Gehler, Pato 2012

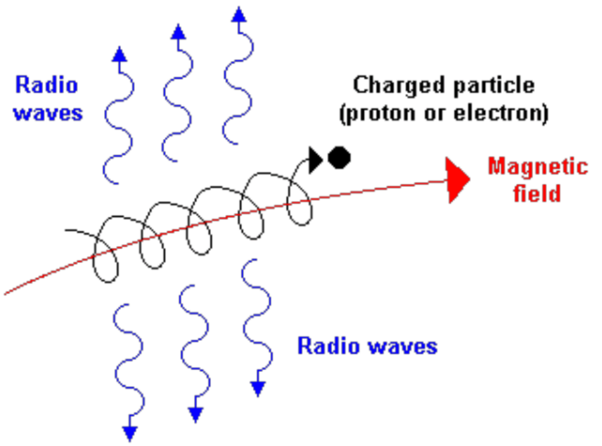
VIB $\chi\chi \to \bar{f} f \gamma$



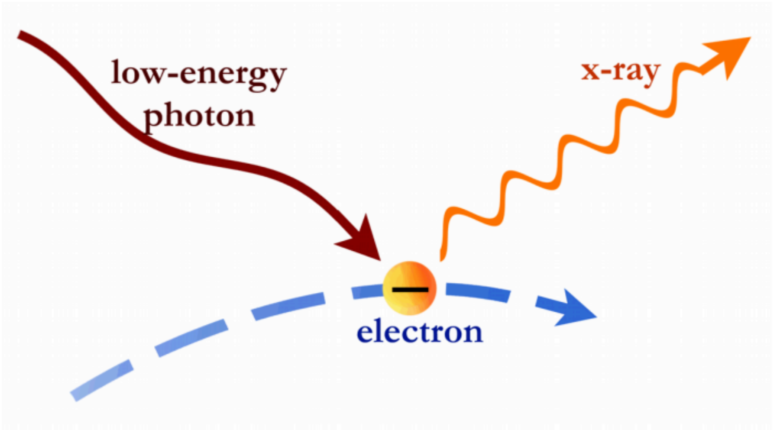
Bringmann, Huang, Ibarra, Vogl, Weniger 2012

Secondary Photons

- Photon signals from highly energetic electrons and positrons
  - Synchrotron radiation



  - Inverse Compton scattering



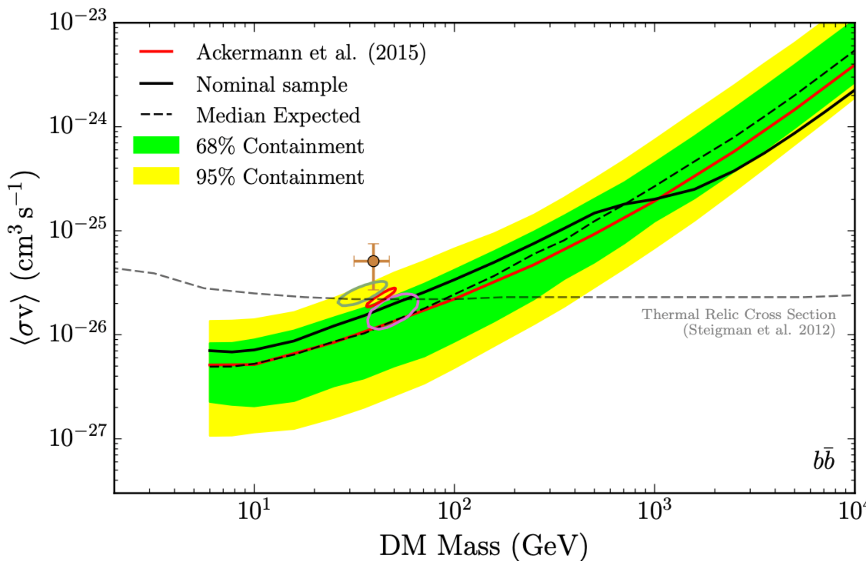
Continuum Limits From Dwarfs

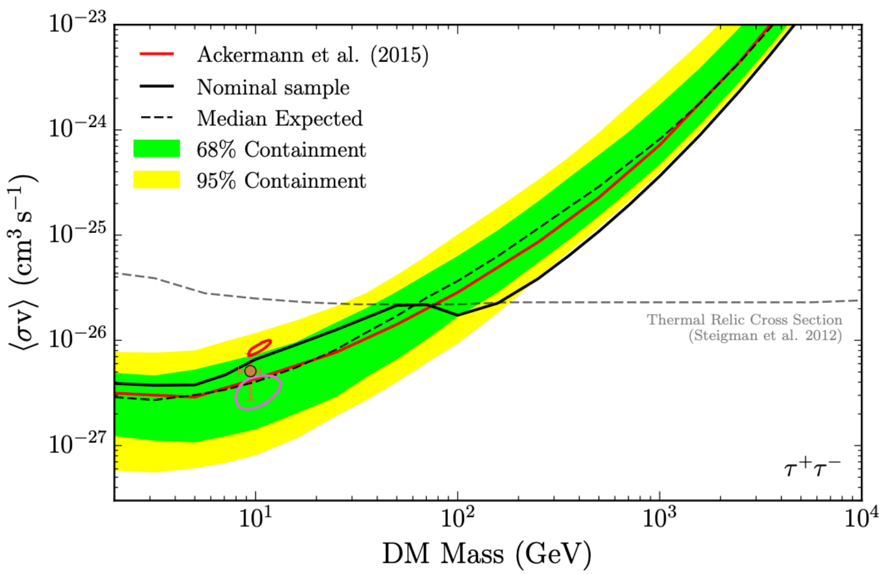
- Dwarf spheroidal galaxies (dSphs)
  - Large M/L ratio → highly DM dominated
  - DM density inferred from stellar data
  - Astrophysically inactive → expected to be free from other gamma-ray sources and have low dust/gas content, very few stars

- No significant emission in stacked analysis of dSphs with Fermi-LAT 6 yrs of data

- Provide the strongest bounds on sub-TeV DM annihilating to photon-rich channels (continuum)

Fermi-LAT bounds

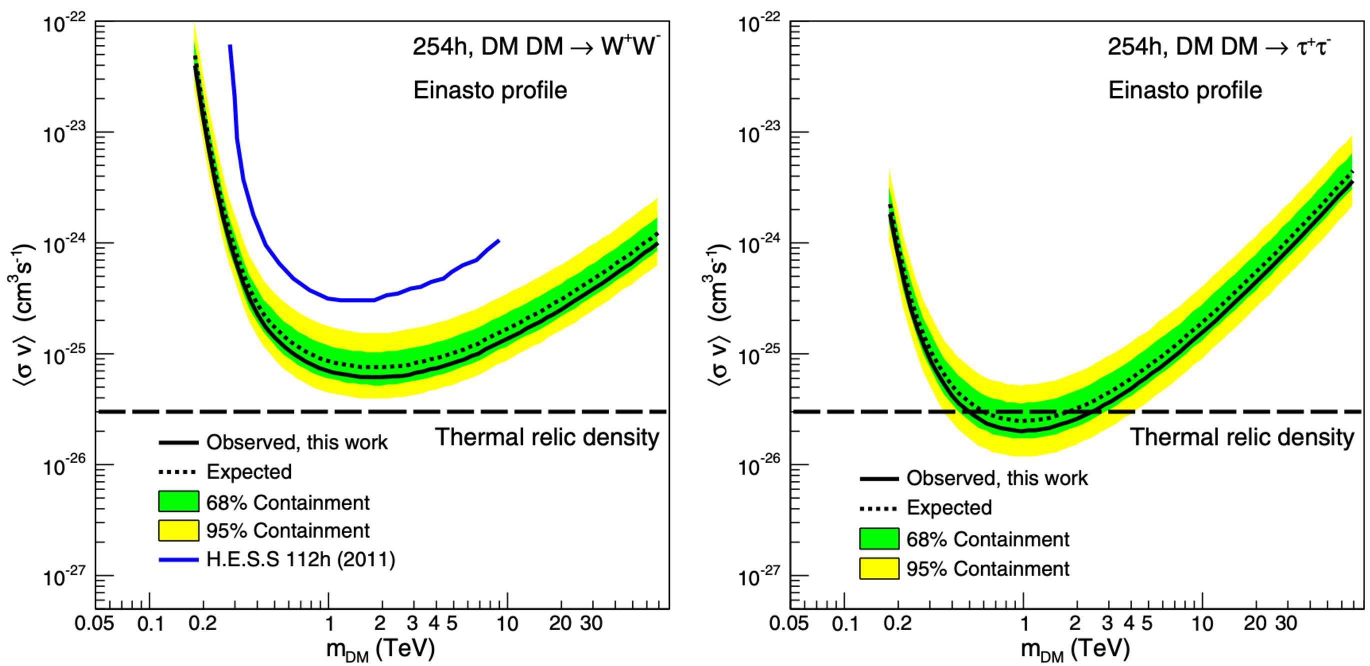




Albert et al., Fermi-LAT and DES Collaborations 2017

Continuum Limits from GC

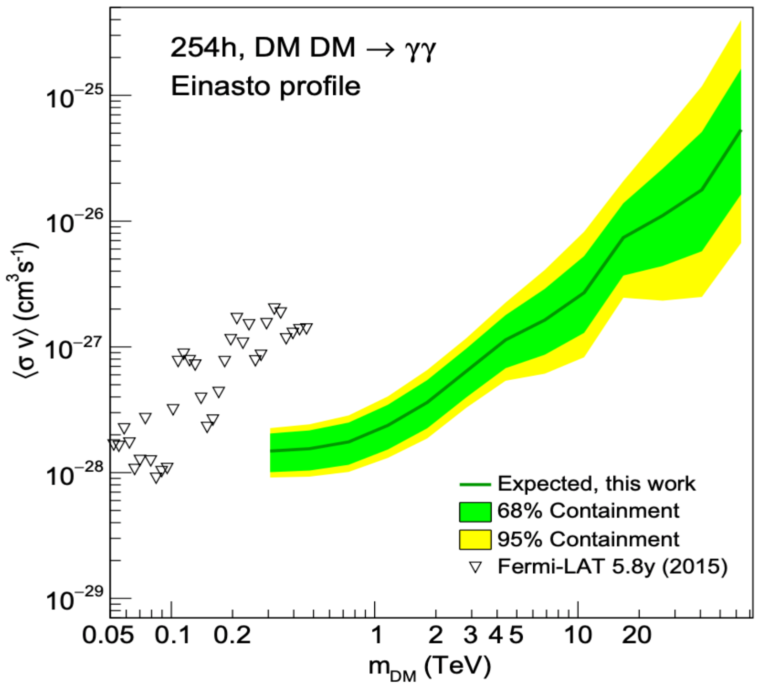
- Cherenkov telescopes: greatest sensitivity at higher energies
  - Nominally strongest limits above 1 TeV DM mass come from H.E.S.S. observations of a small region of the inner Milky Way
  - Constraint more sensitive to uncertainties in the DM density profile



Abdallah et al., H.E.S.S. Collaboration 2016

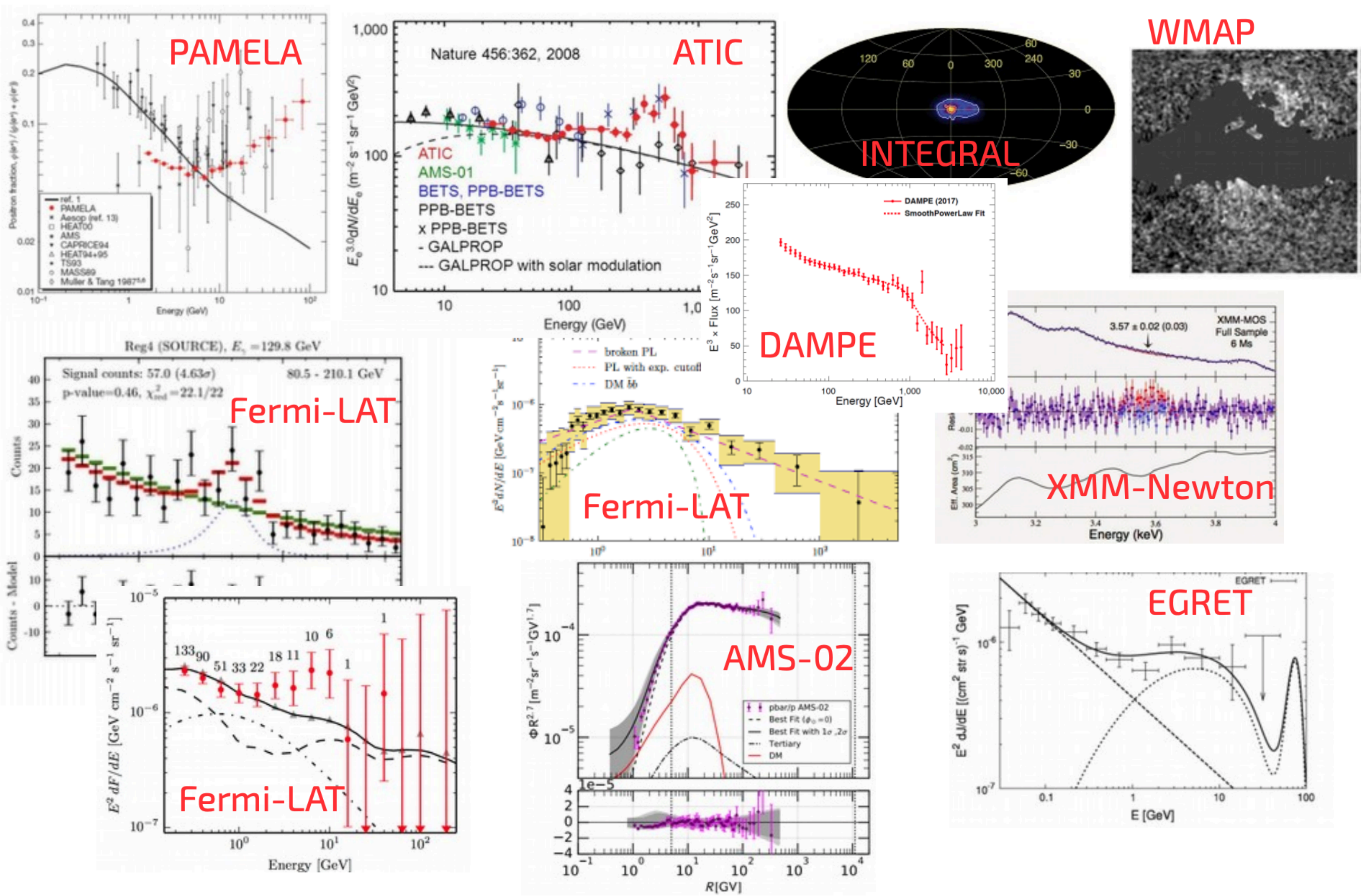
Line Limits from GC

- For gamma-ray lines, astrophysical backgrounds are low
- Need to optimize statistics - motivates search toward inner Galaxy
- Both Fermi-LAT and H.E.S.S. have presented limits on the possible gamma-ray line strength



Rinchiuso et al. 2016

Beyond Constraints: Hints of Signals?



Summary

- Indirect DM searches for gamma rays such as Fermi-LAT and H.E.S.S. set strong constraints on the nature of DM; Future experiments will continue to improve these constraints

- Other indirect detection constraints by probing neutrinos and cosmic rays, as well as early universe bounds, can shed more light on our understanding of DM

- There are several tentative signals that might originate from DM physics, but could also come from astrophysical sources

- Crucial to cross-correlate indirect searches with direct detection and collider searches; a consistent signal from other DM searches would provide the most compelling confirmation of a DM origin

“Keep buggering on!”

Winston Churchill (1874 - 1965)

Back-up Slides

Probing Lower energies: CMB

- Impacts of DM annihilation on the CMB

- Energy injection from DM annihilation/decay at $z \sim 600$
  - Would change ionization balance via photon and e+e- interaction with electrons and hydrogen atoms
  - Would change timing + extent of recombination
  - Distortion of CMB angular power spectrum