Overview of Dark Matter
with emphasis on Indirect Detection

R. Caputo
UMD/NASA/GSFC

GEMMA Workshop
June 4, 2018

Mystery of Missing Mass

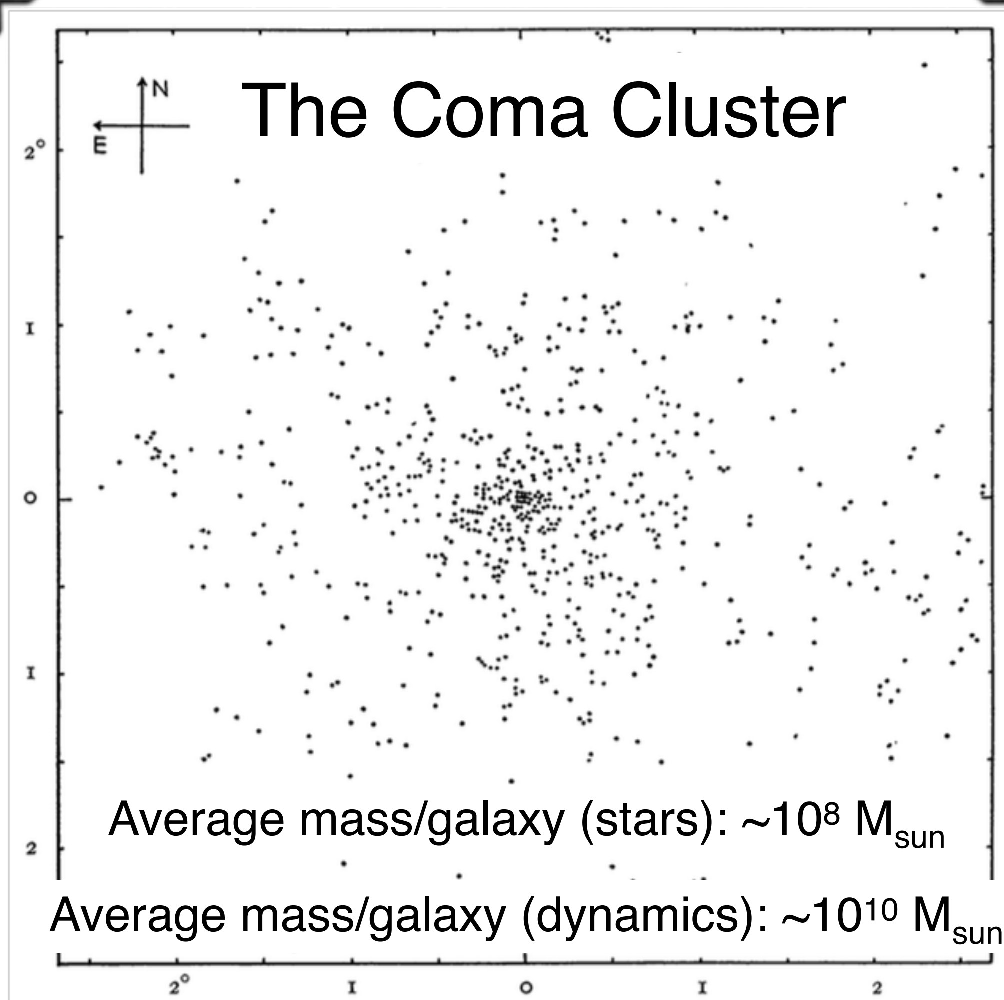


FIG. 3.—The Coma cluster of nebulae

1930s- Zwicky, others

F. Zwicky, Astrophys. J. 86, 217 (1937)

Mystery of Missing Mass

The Coma Cluster

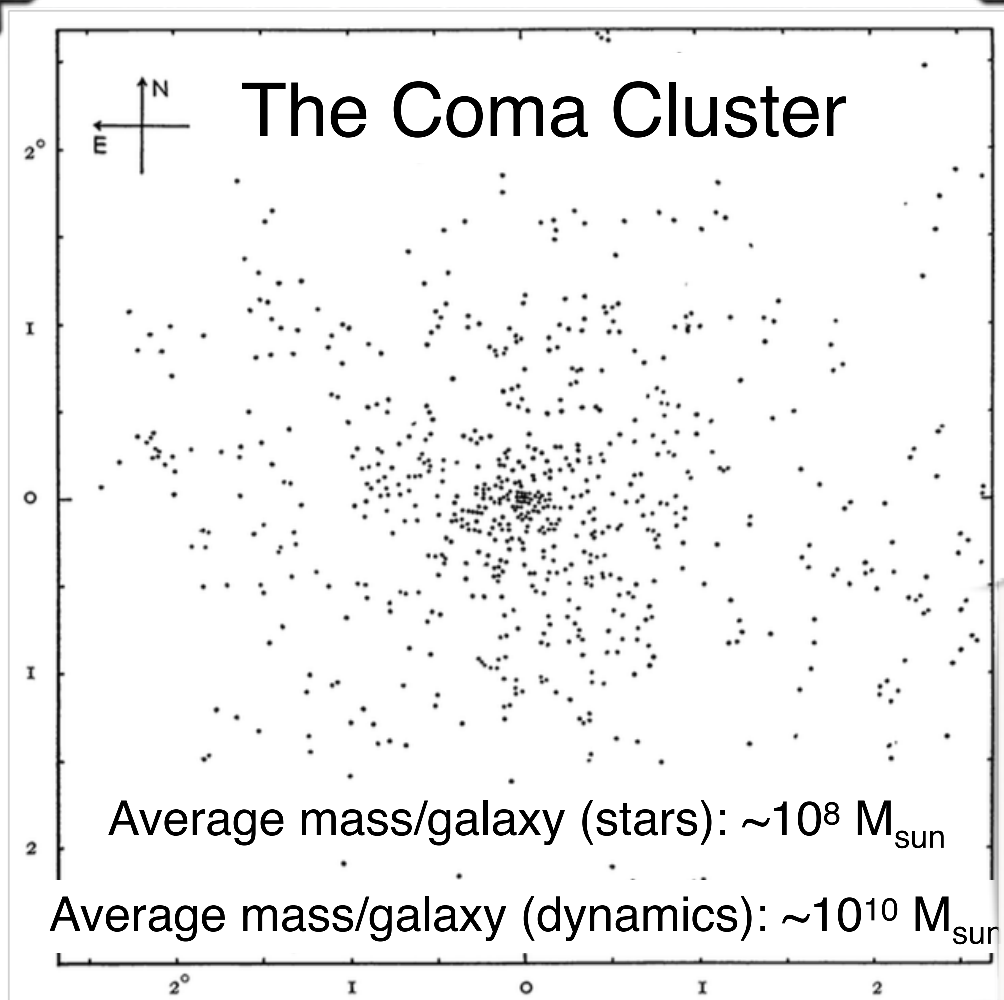


Fig. 3.—The Coma cluster of nebulae

Average mass/galaxy (stars): ~10^8 M_{sun}

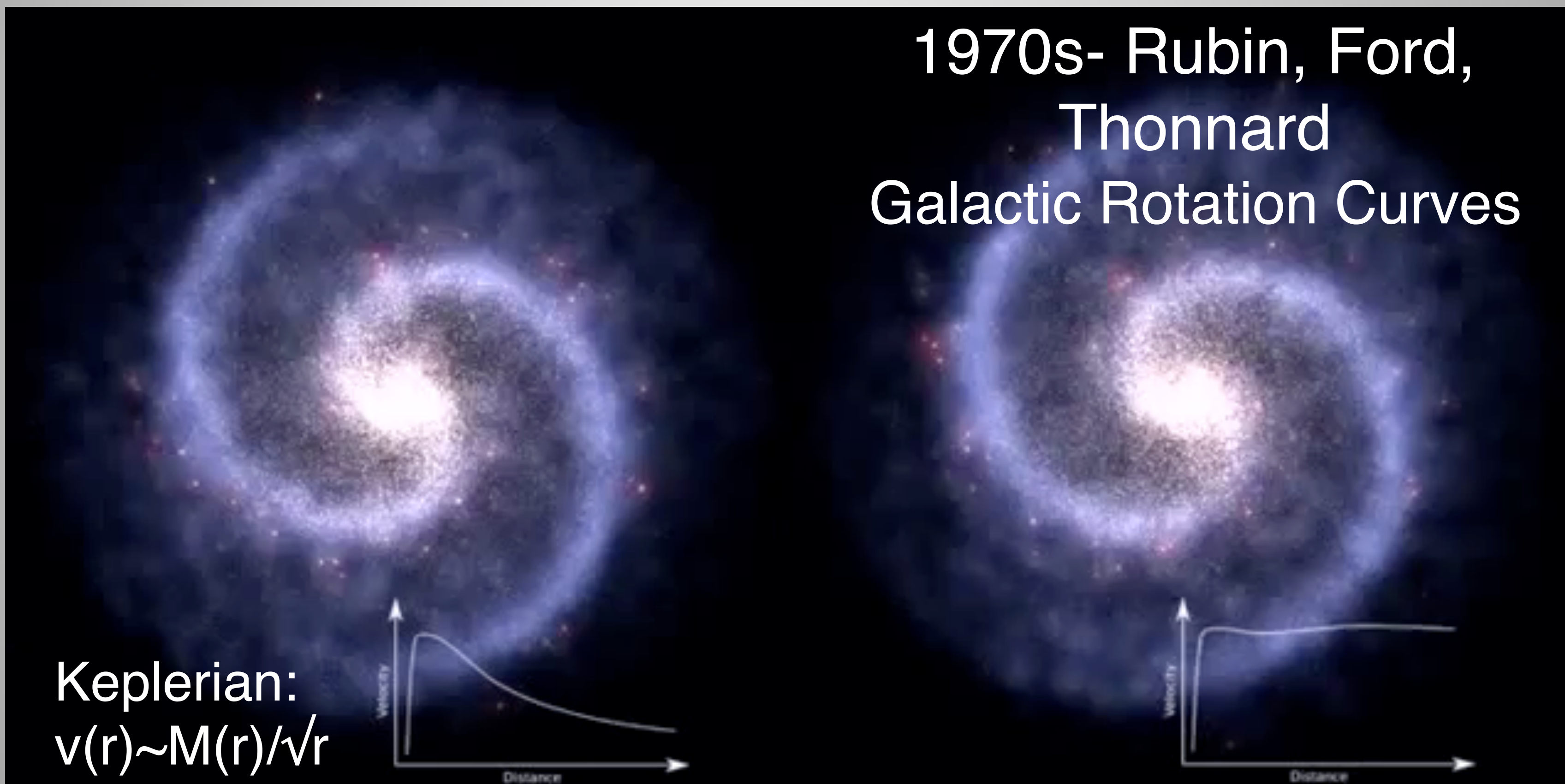
Average mass/galaxy (dynamics): ~10^{10} M_{sun}

1930s- Zwicky, others

Coma cluster of galaxies: only small % mass from luminous matter

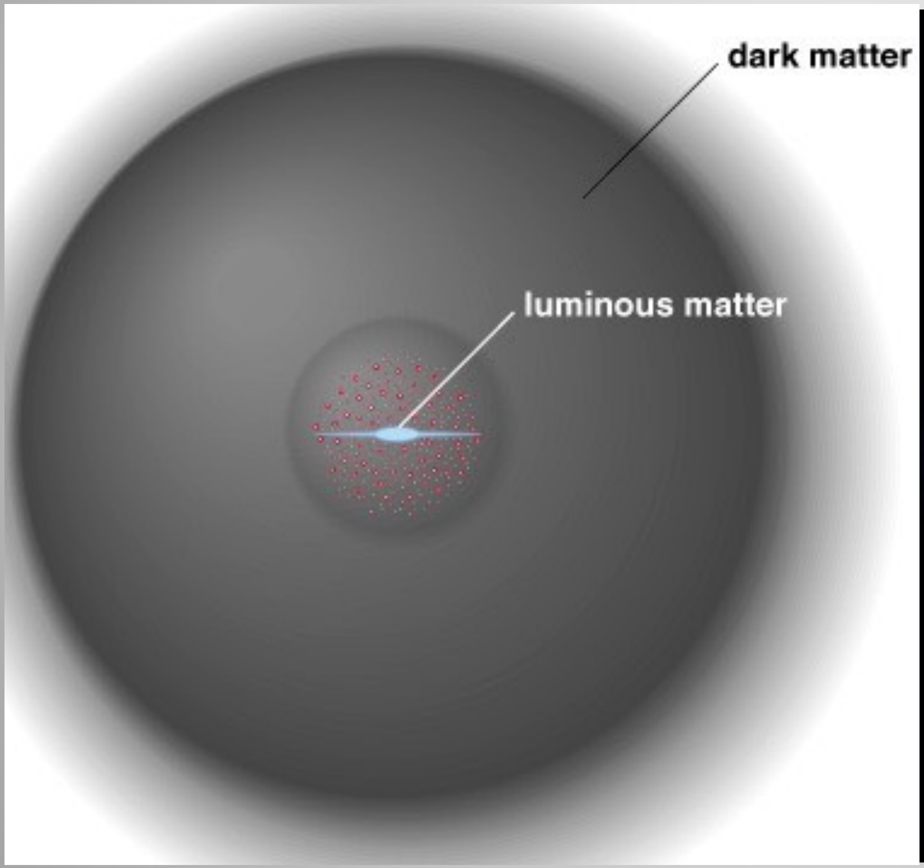
F. Zwicky, Astrophys. J. 86, 217 (1937)

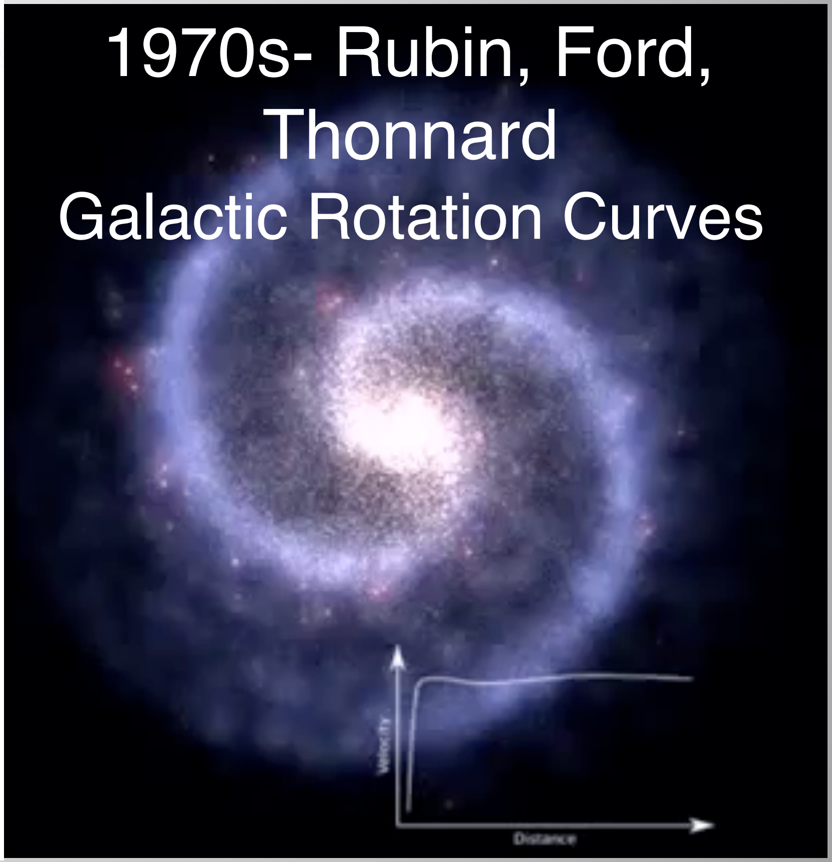
Mystery of Missing Mass



YouTube: https://www.youtube.com/watch?v=Omjx3OKAGDo
http://cse.ssl.berkeley.edu/bmendez/ay10/2002/notes/lec18.html

Mystery of Missing Mass





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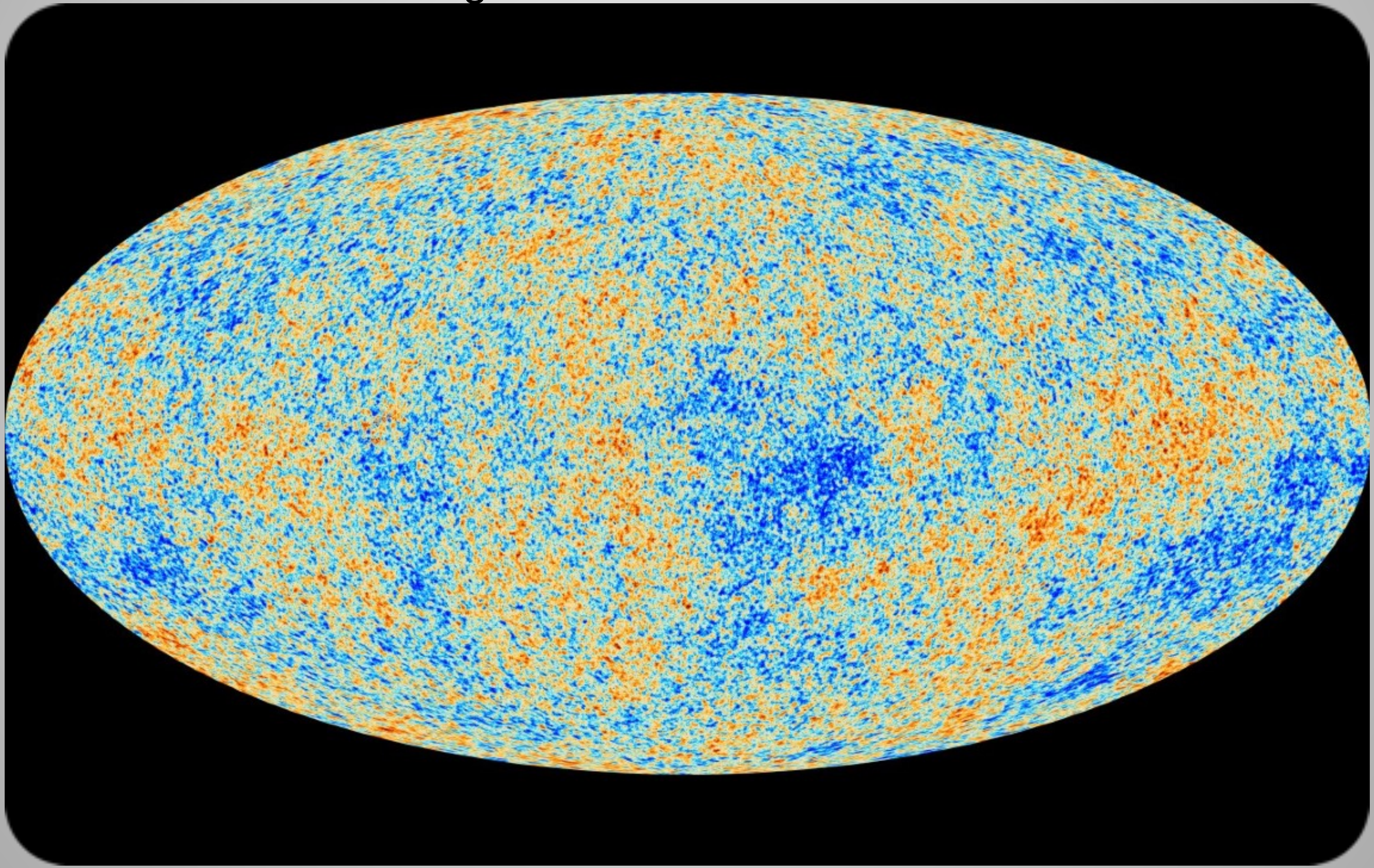
Precision Cosmology

Cosmic Microwave Background



Planck Collaboration, 2013; SubbaRao et al. (2008); J. Primack et al.,2011; NASA, APOD, 2006 August 24, J. A. Tyson et al., Astrophys.J.498:L107,1998

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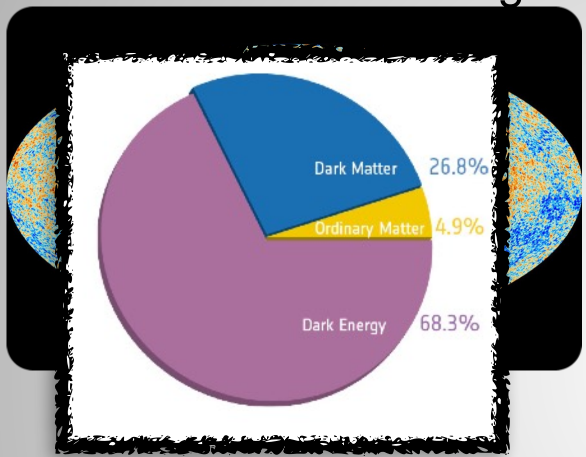

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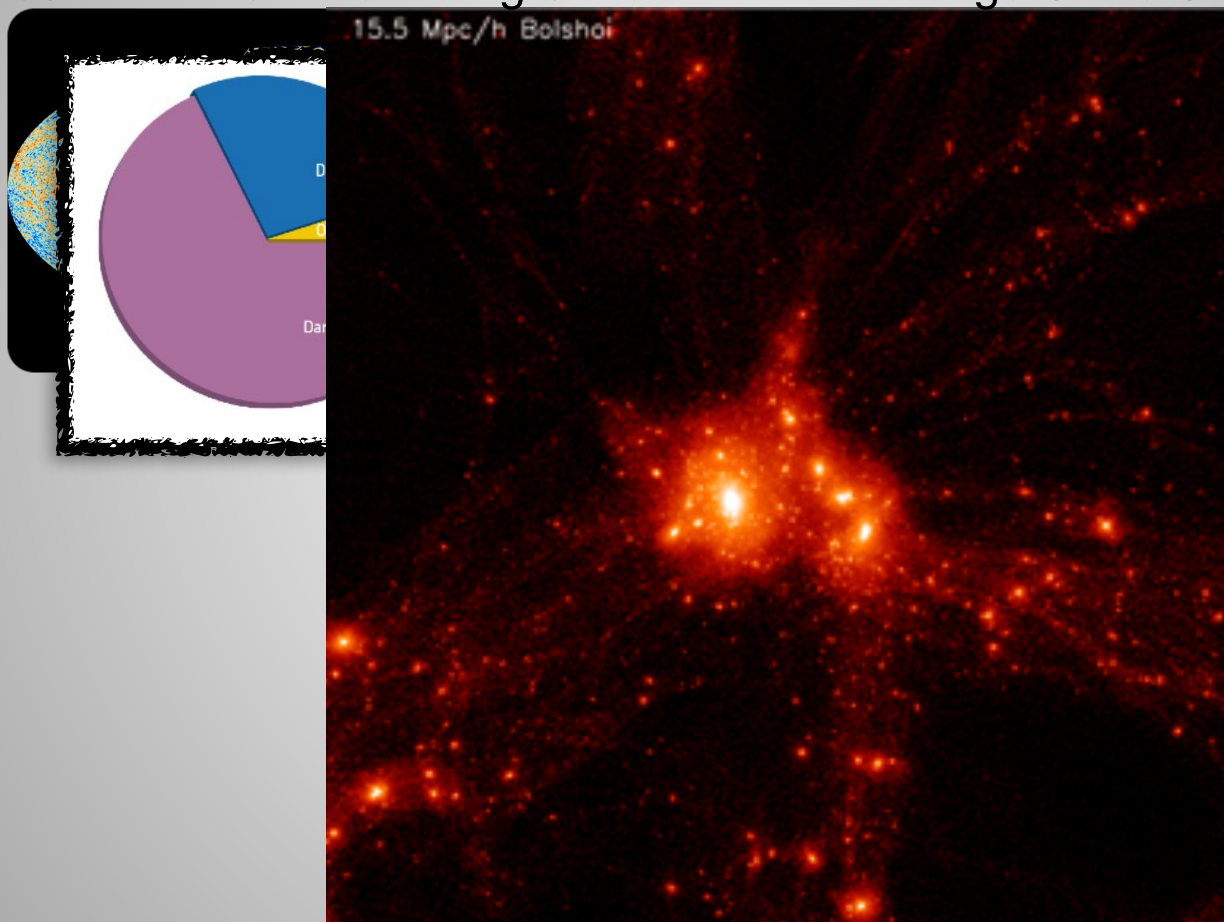
Precision Cosmology

Cosmic Microwave Background

Large Scale Structure



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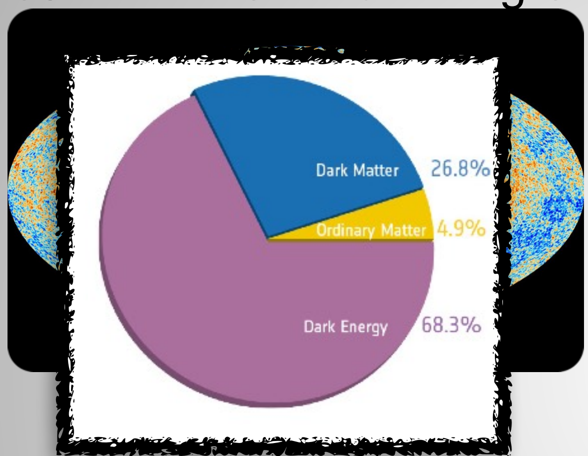

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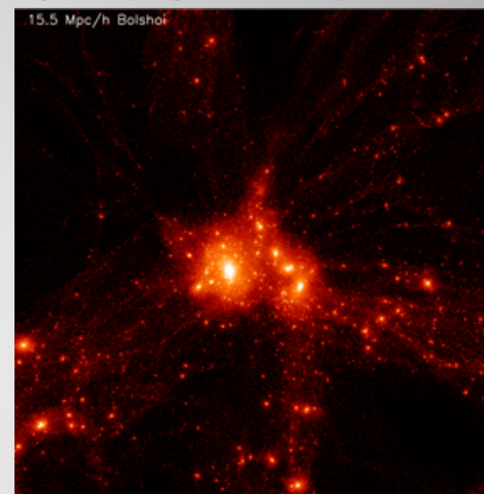

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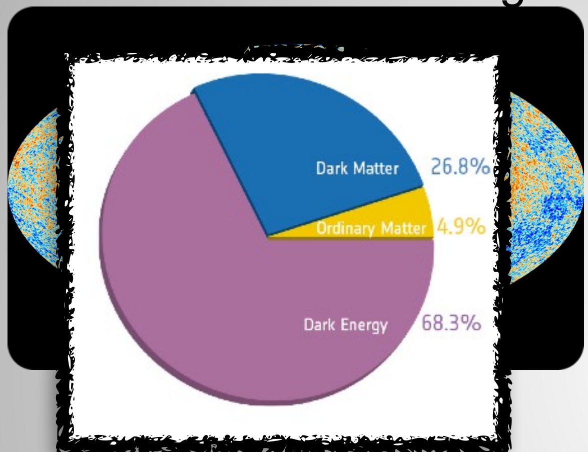

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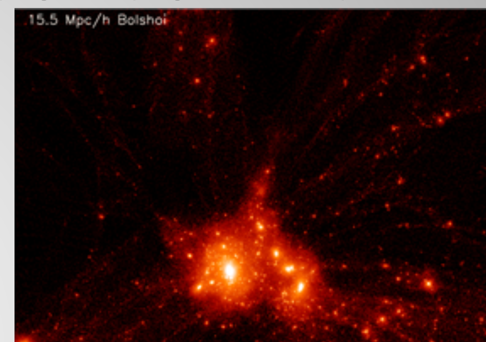

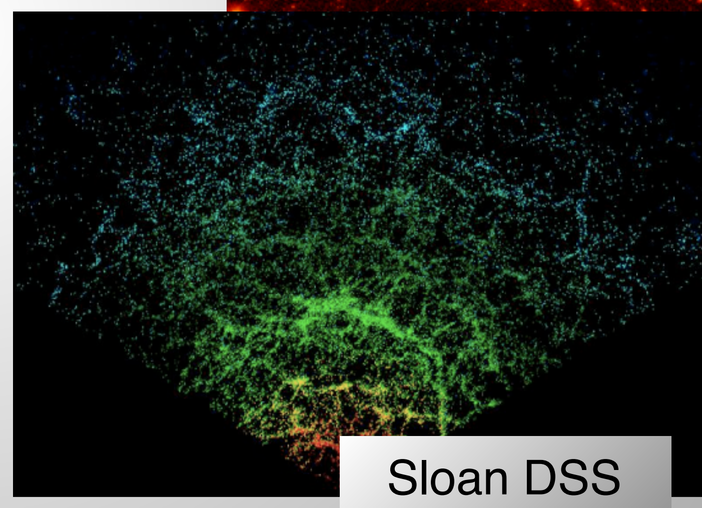

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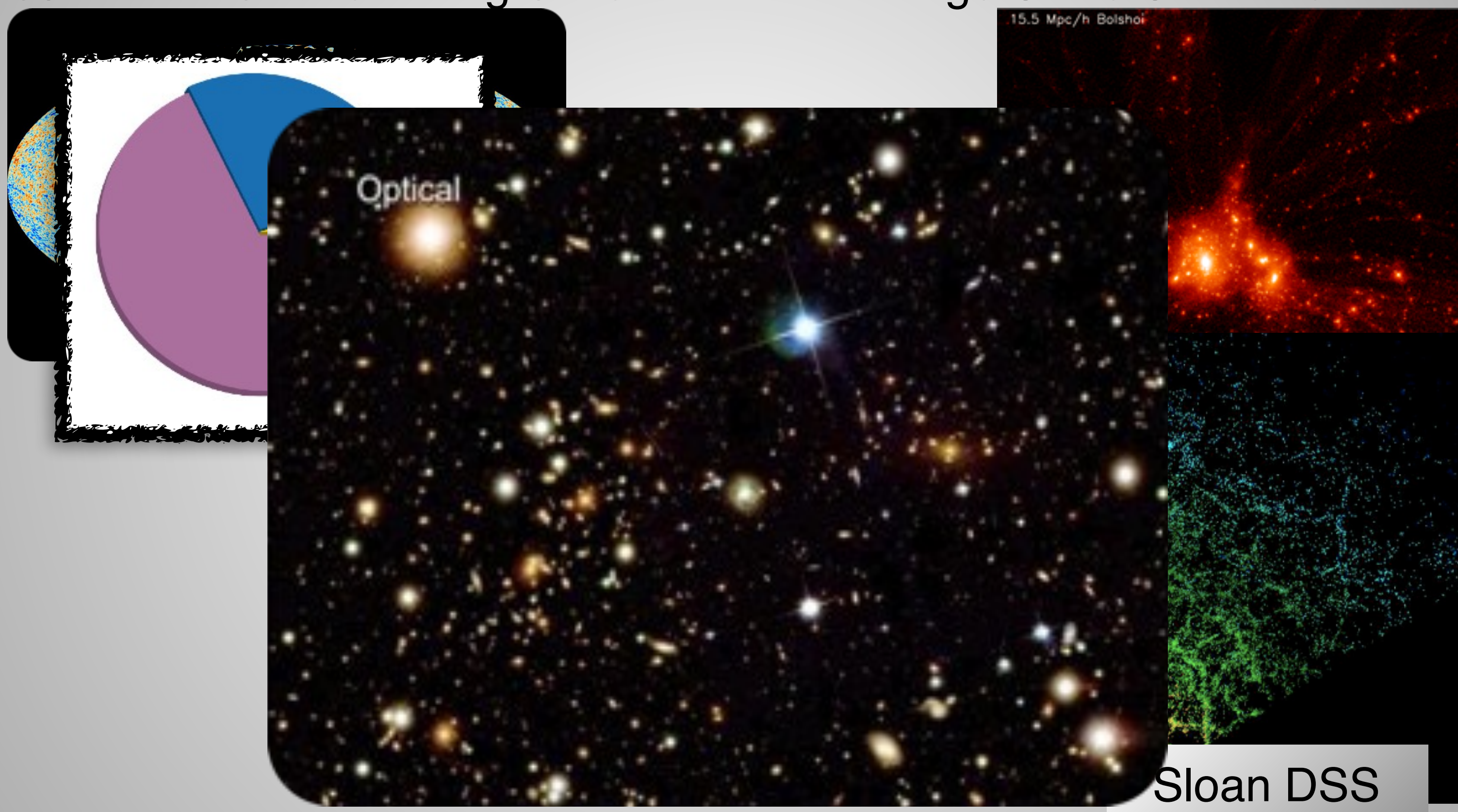

Lensing/The Bullet Cluster

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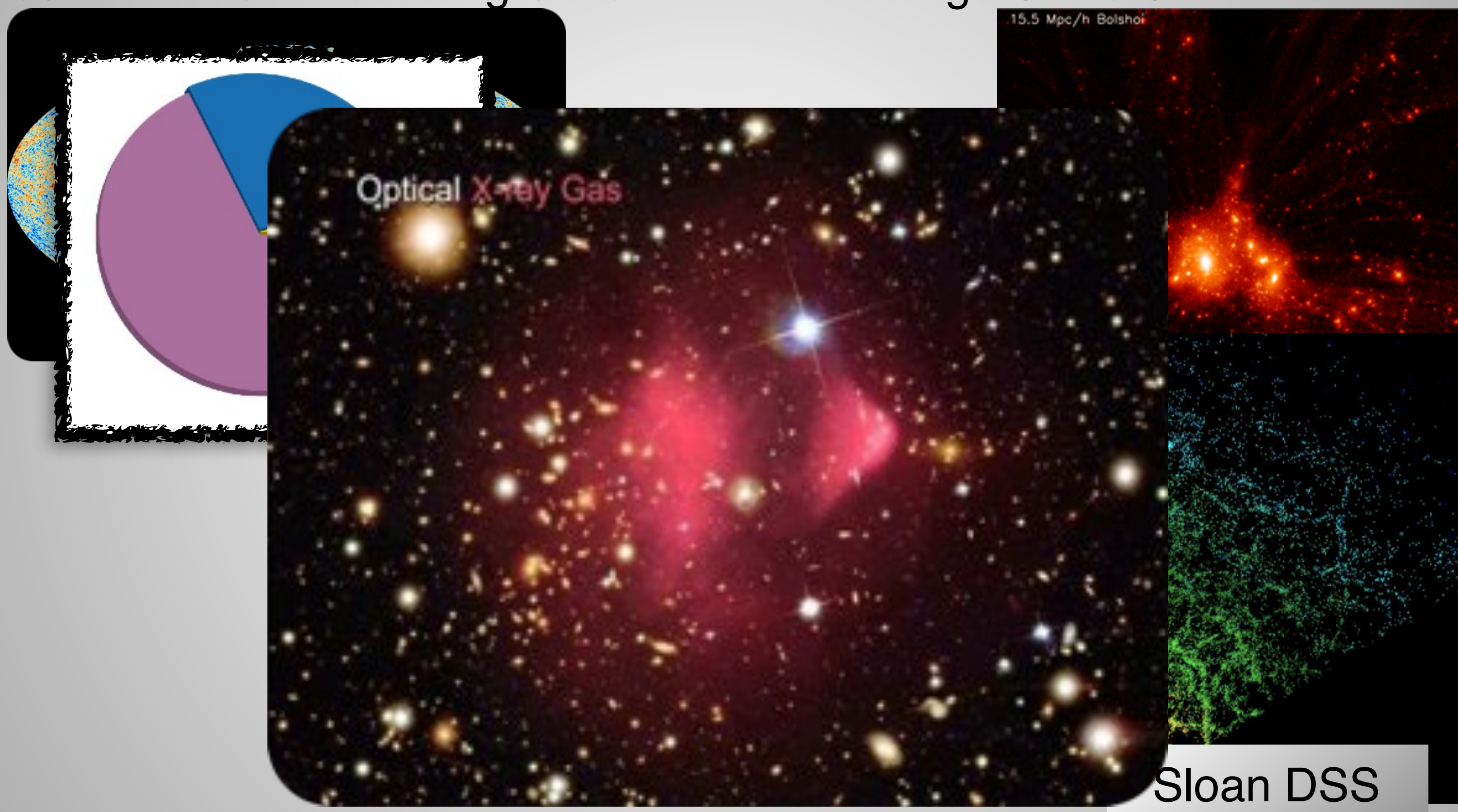

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Precision Cosmology

Cosmic Microwave Background

Large Scale Structure

Sloan DSS

Blue: mass from lensing

Lensing/The Bullet Cluster

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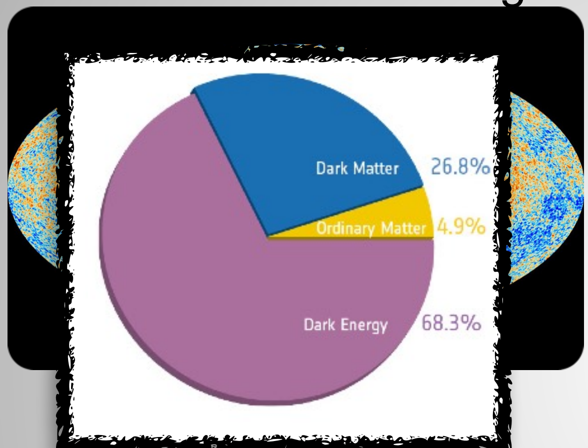

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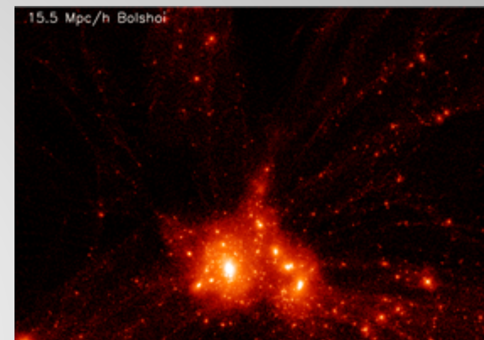

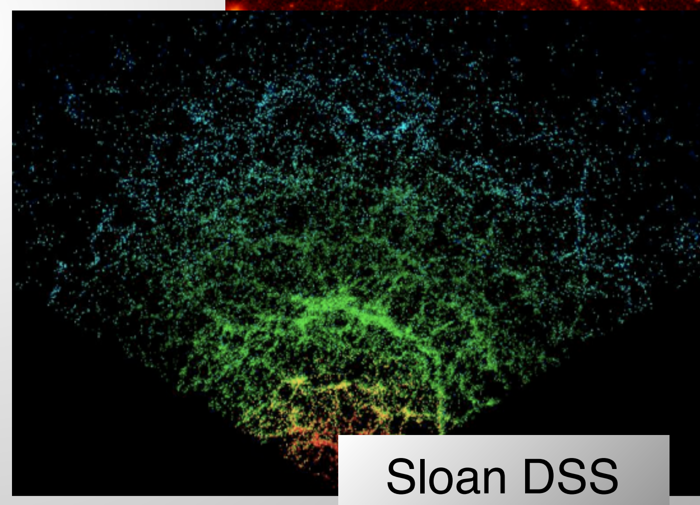

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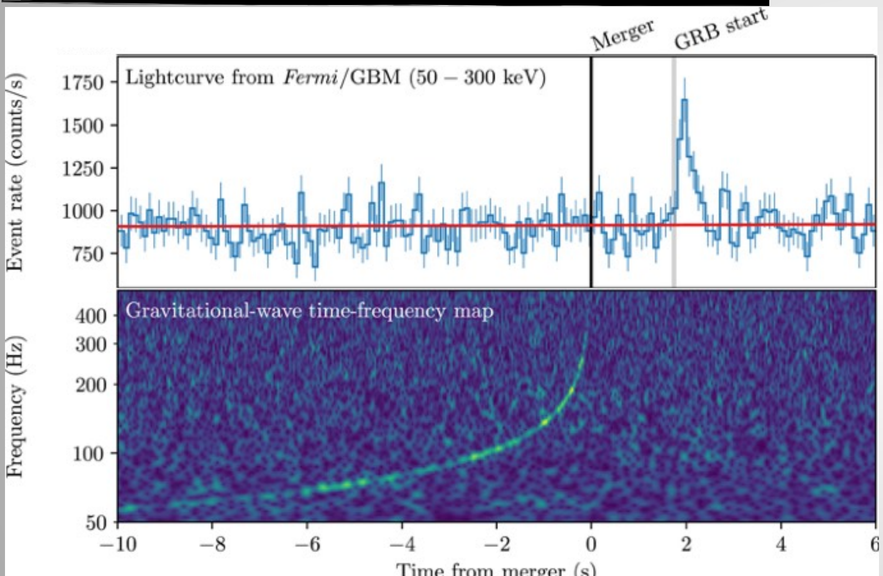
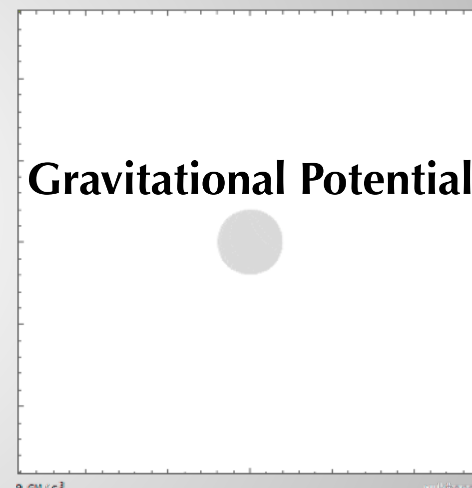
Modified Gravity?

GW170817/GRB170817A



ApJ, 848:L13, 2017

Test of Weak Equivalence principle



Boran et al., PRD 97, 041501 (2018),

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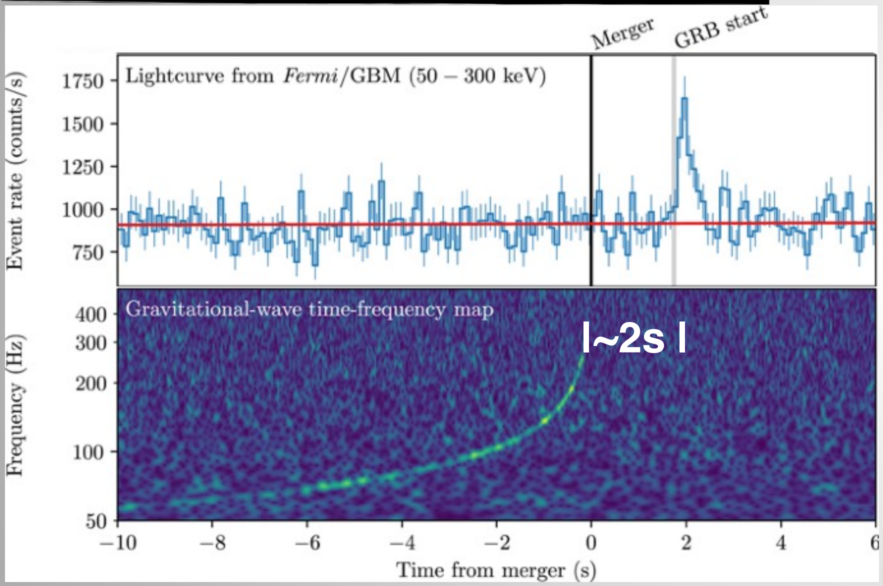


ApJ, 848:L13, 2017

Test of Weak Equivalence principle

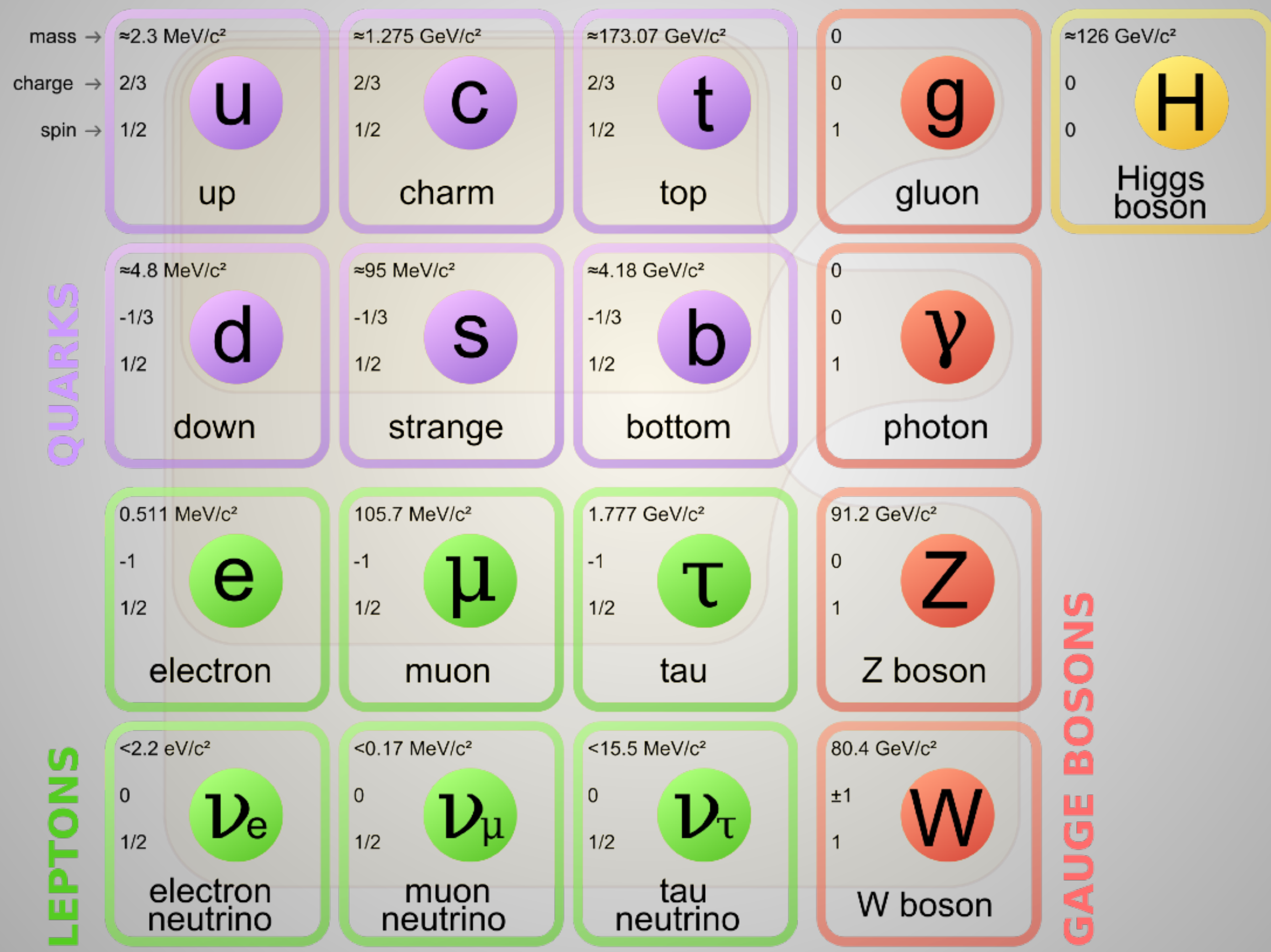
Gravitational Potential

Boran et al., PRD 97, 041501 (2018),

Gravitons and photons travel in space-time in the same way

***SN1987a found the same thing for neutrinos and photons**

Potential Candidates



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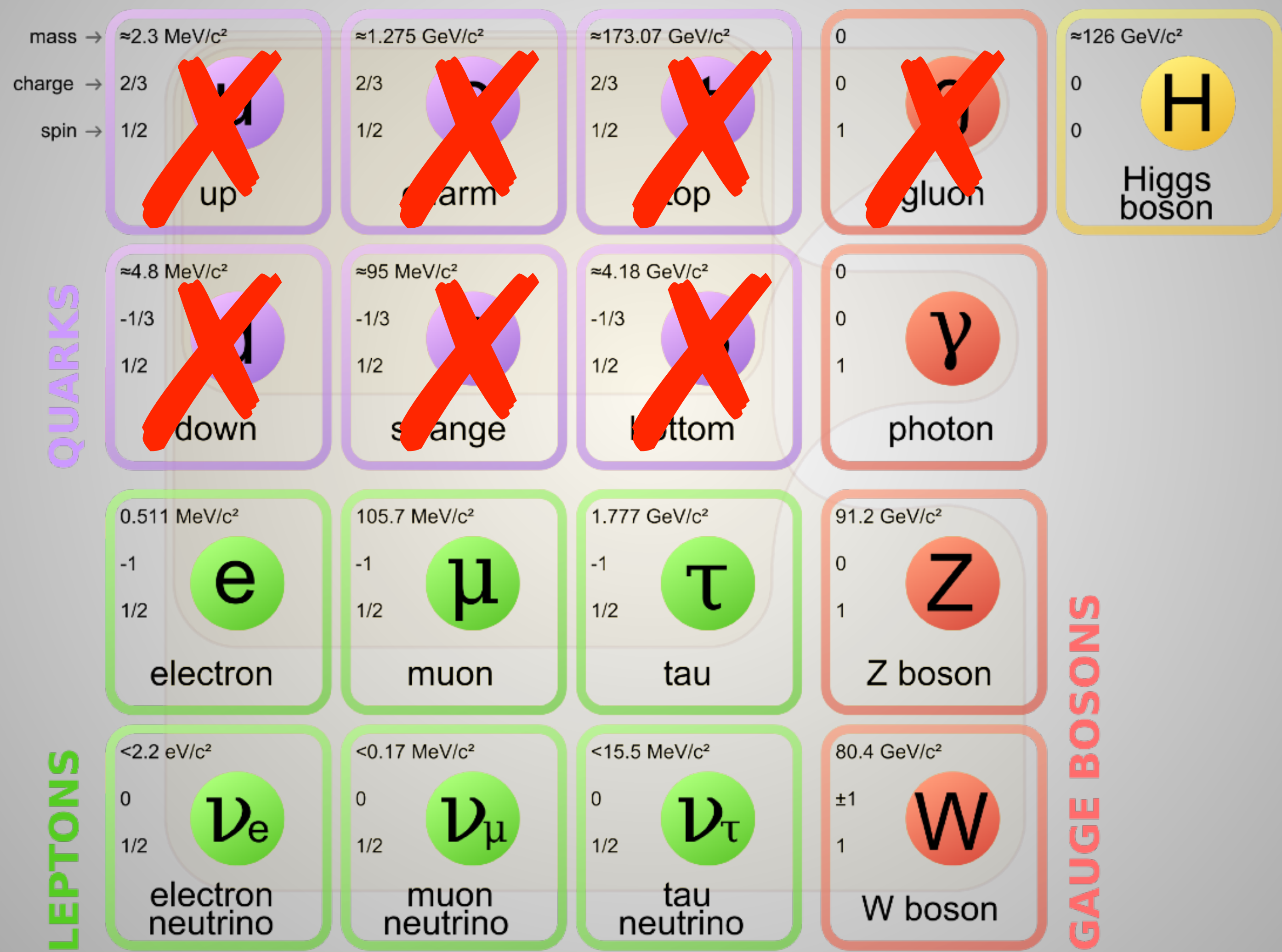

Potential Candidates

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Weak Scale

m~ 100 GeV
100× proton

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~0.5 Caffeine molecule

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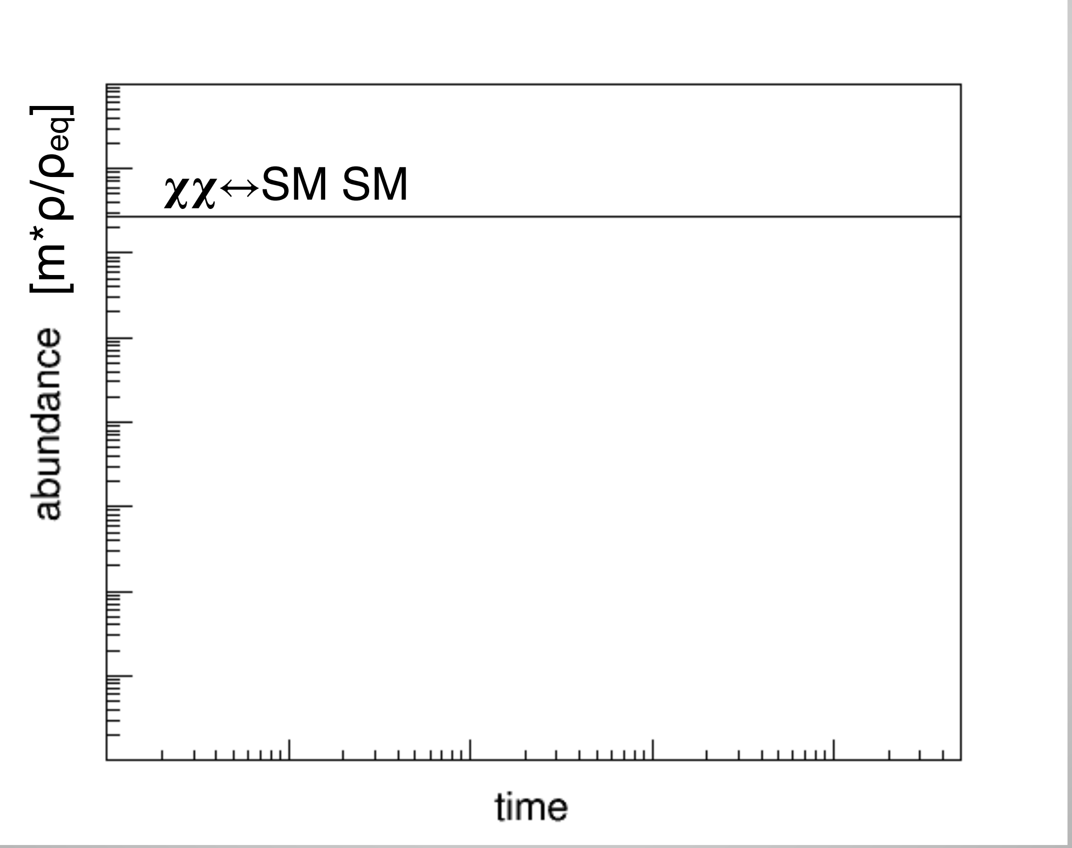
Portrait of a Candidate

Cosmology and Thermodynamics

DM = χ



G. Steigman, et al., Phys.Rev. D86 (2012) 023506

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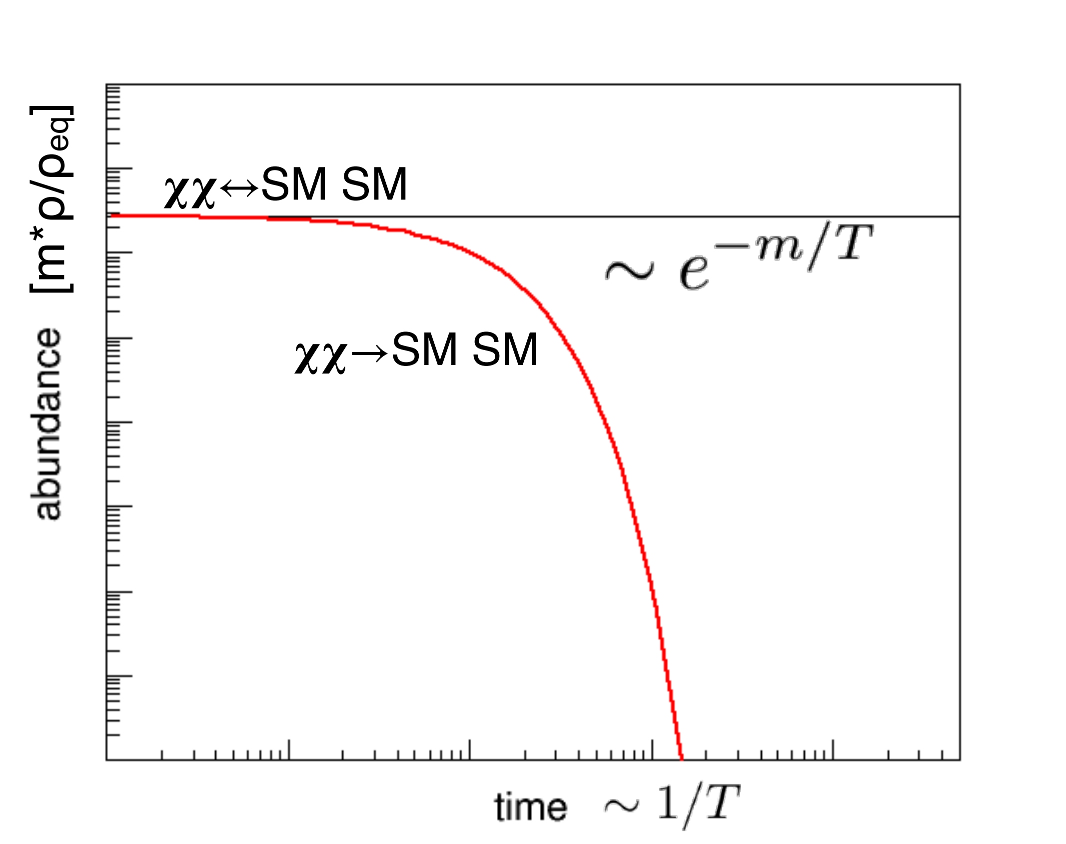

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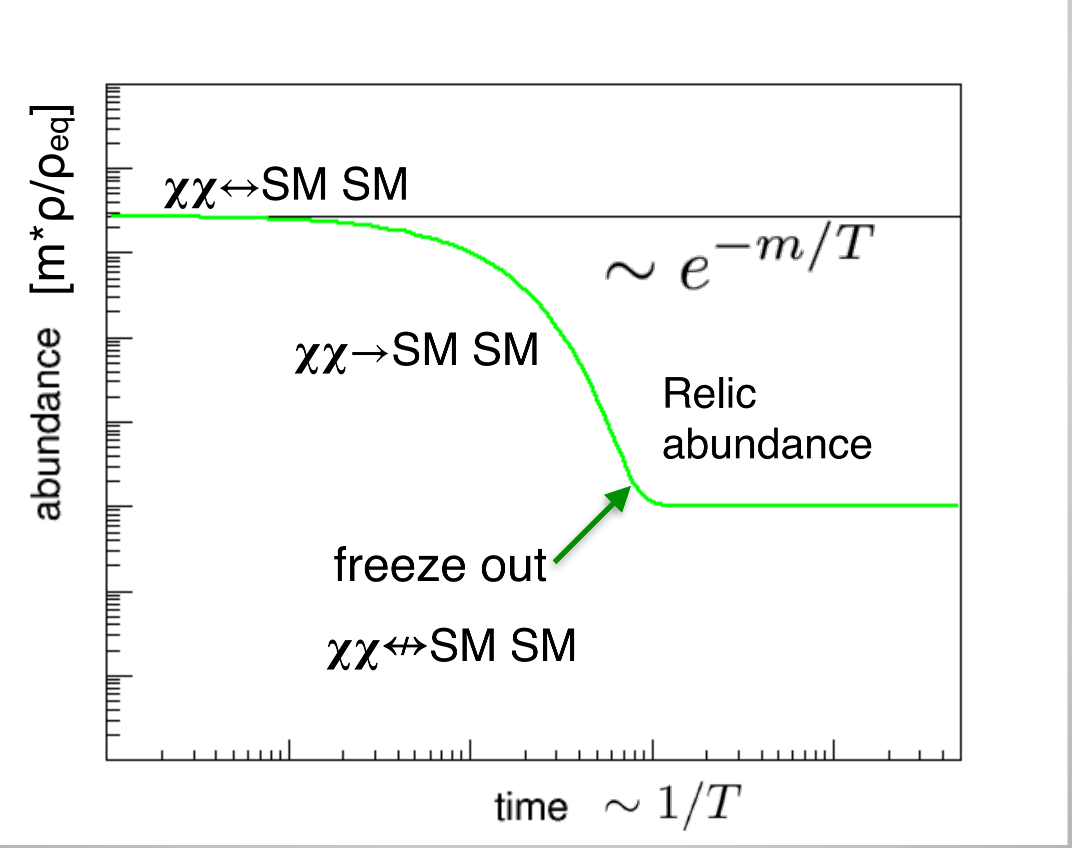

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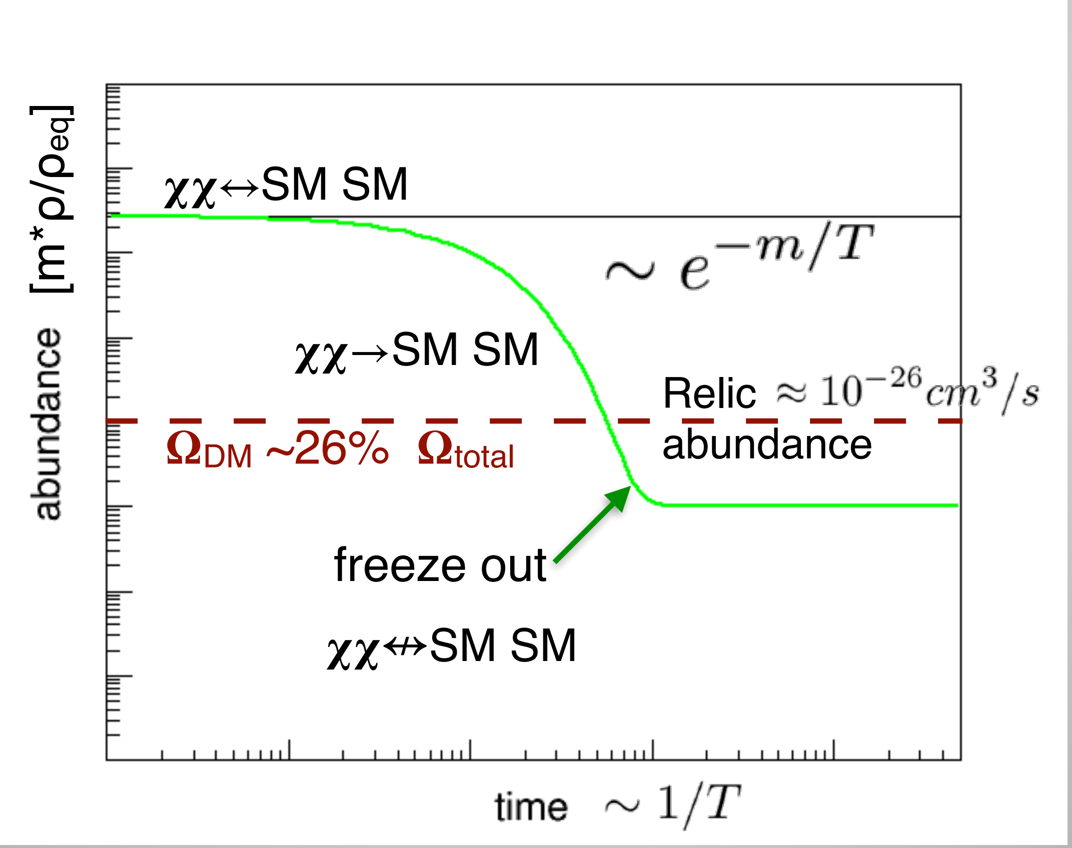


Abundance

$\langle \sigma v \rangle n_{eq} \sim H$

$\langle \sigma v \rangle \sim 10^{-26}\ cm^3/s$

G. Steigman, et al., Phys.Rev. D86 (2012) 023506

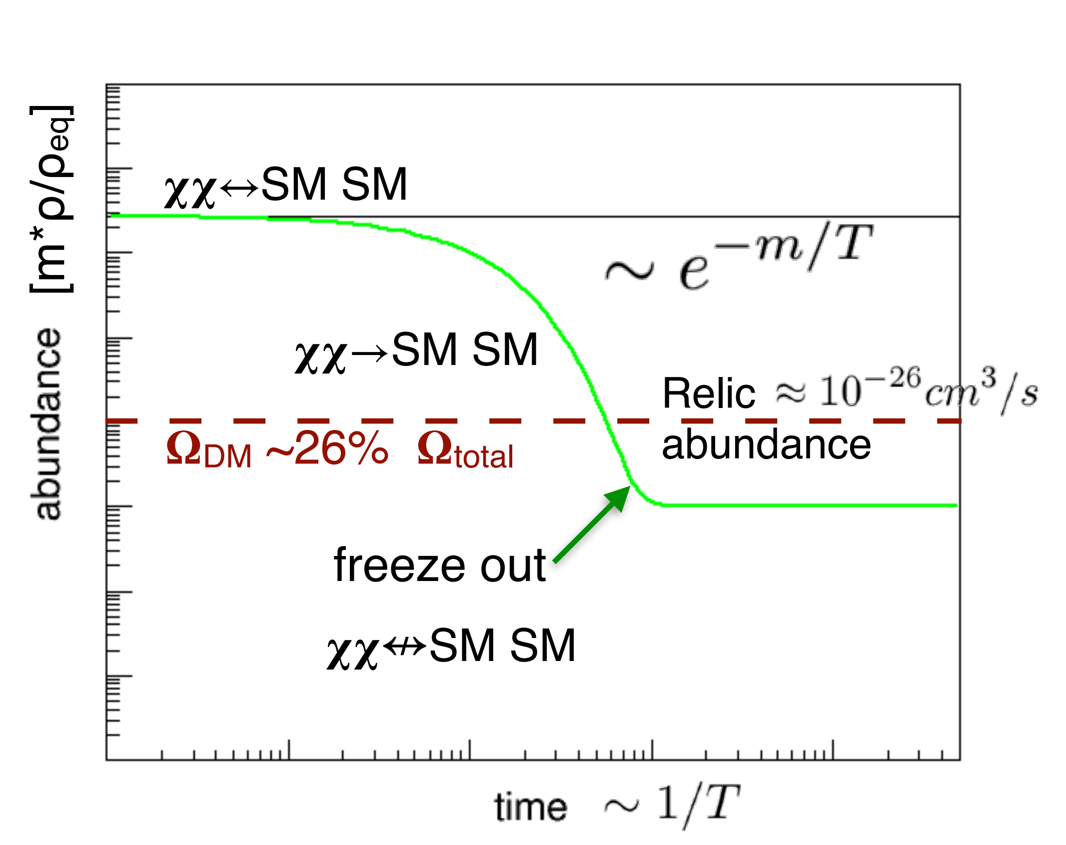
Portrait of a Candidate

Particle Physics

DM = χ

Weak (σ): 10^{-36} cm^2

velocity (v) @ freeze out: 10^5 km/s



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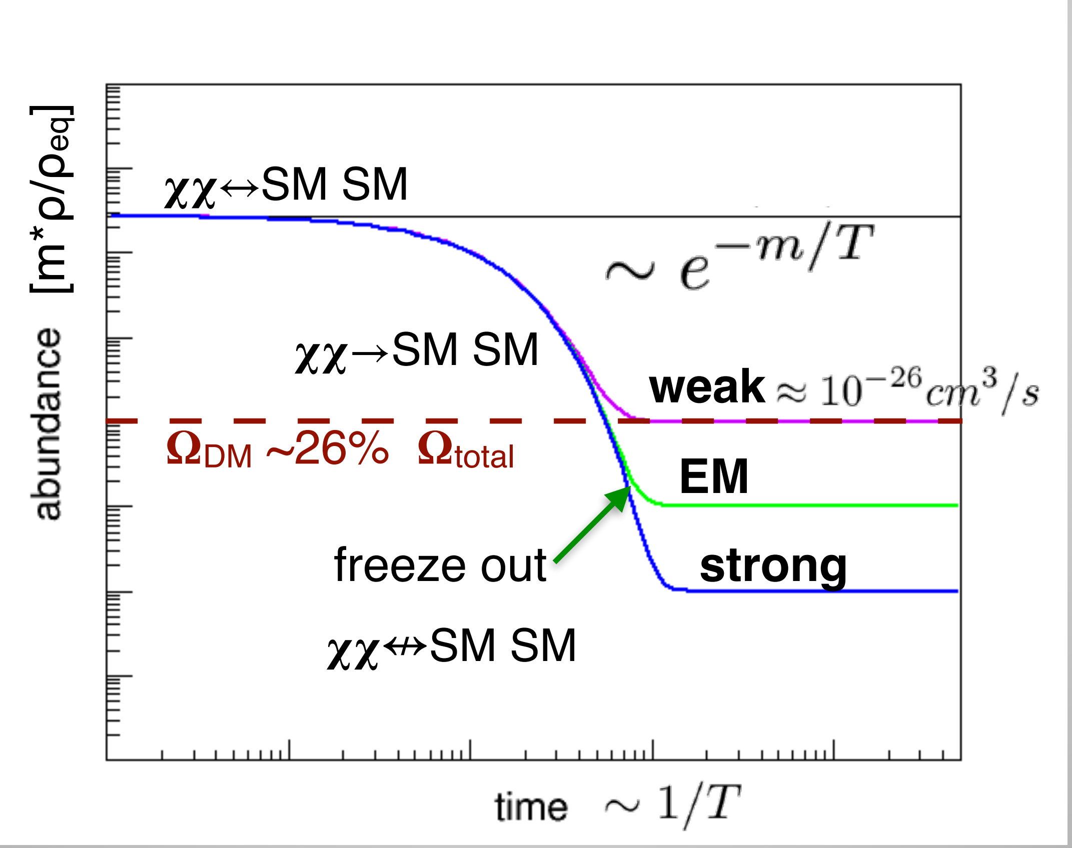

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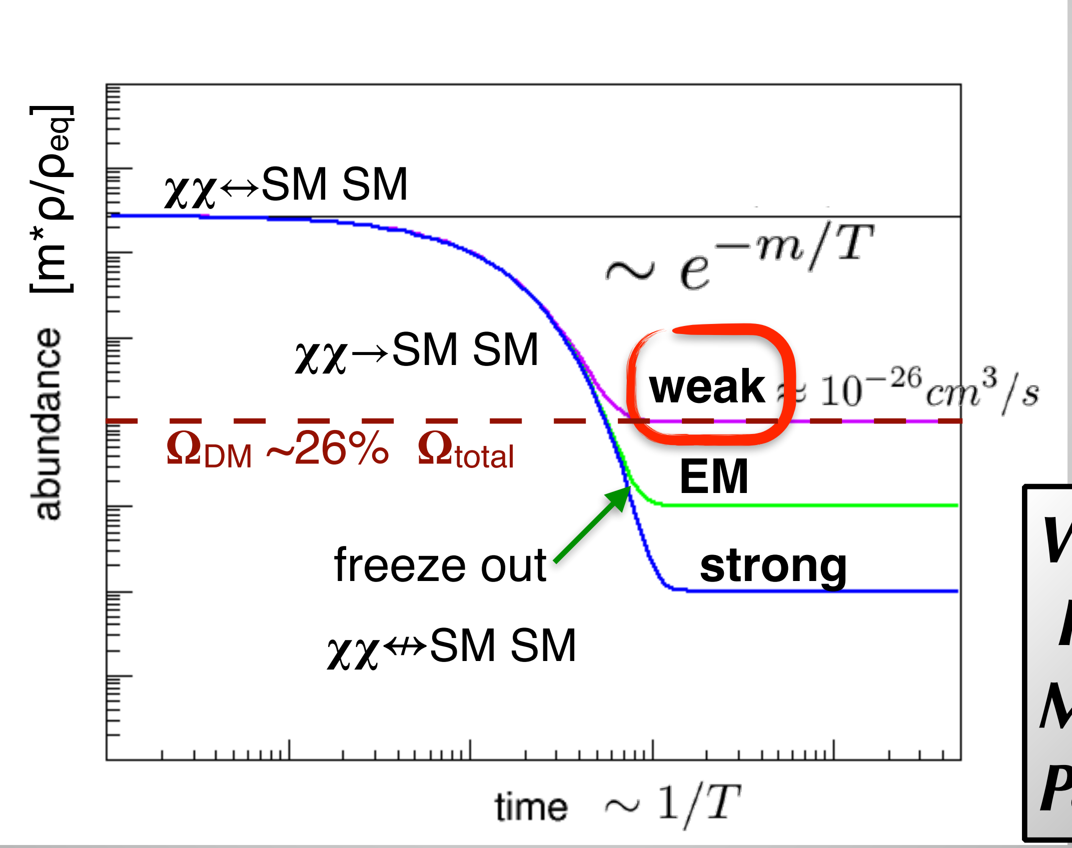

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Weakly Interacting Massive Particles

G. Steigman, et al., Phys.Rev. D86 (2012) 023506

Portrait of a Candidate

The WIMP Miracle…

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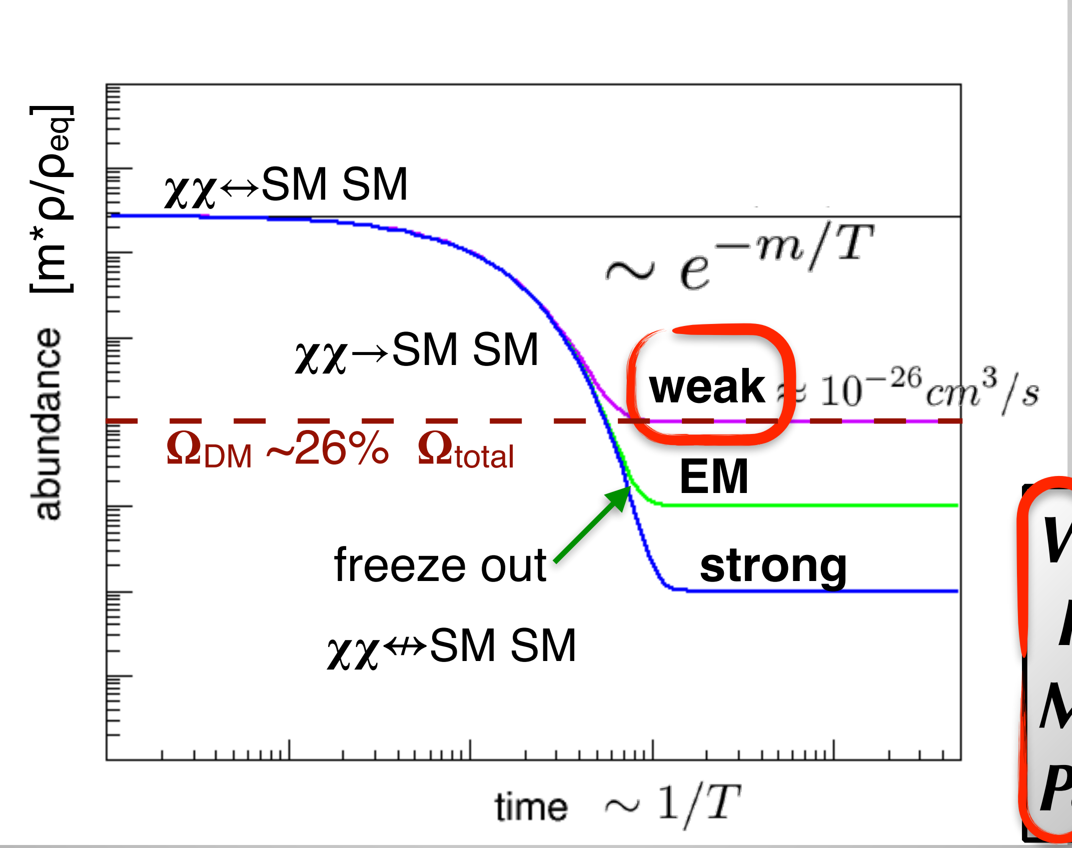

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Weakly
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Portrait of a Candidate

The WIMP Coincidence

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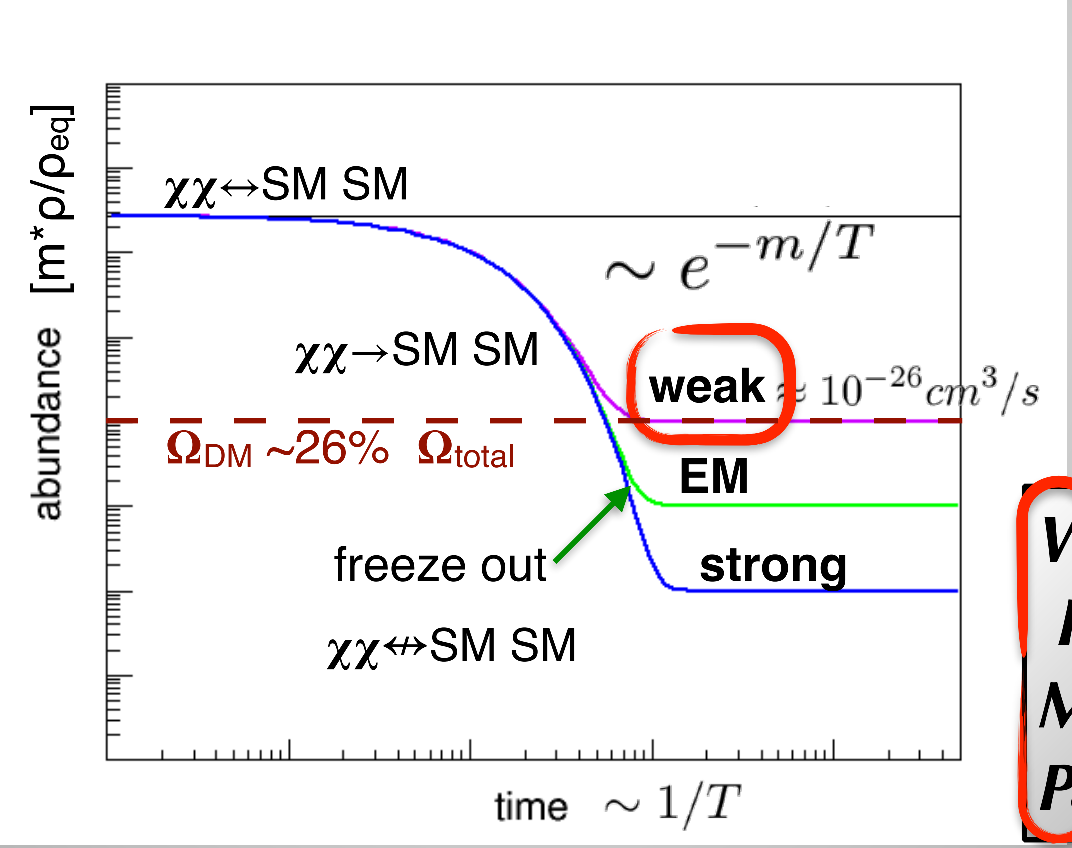

Abundance

$\langle\sigma v\rangle n_{eq} \sim H$

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***W**eakly*
***I**nteracting*
***M**assive*
***P**articles*

G. Steigman, et al., Phys.Rev. D86 (2012) 023506

Portrait of a Candidate

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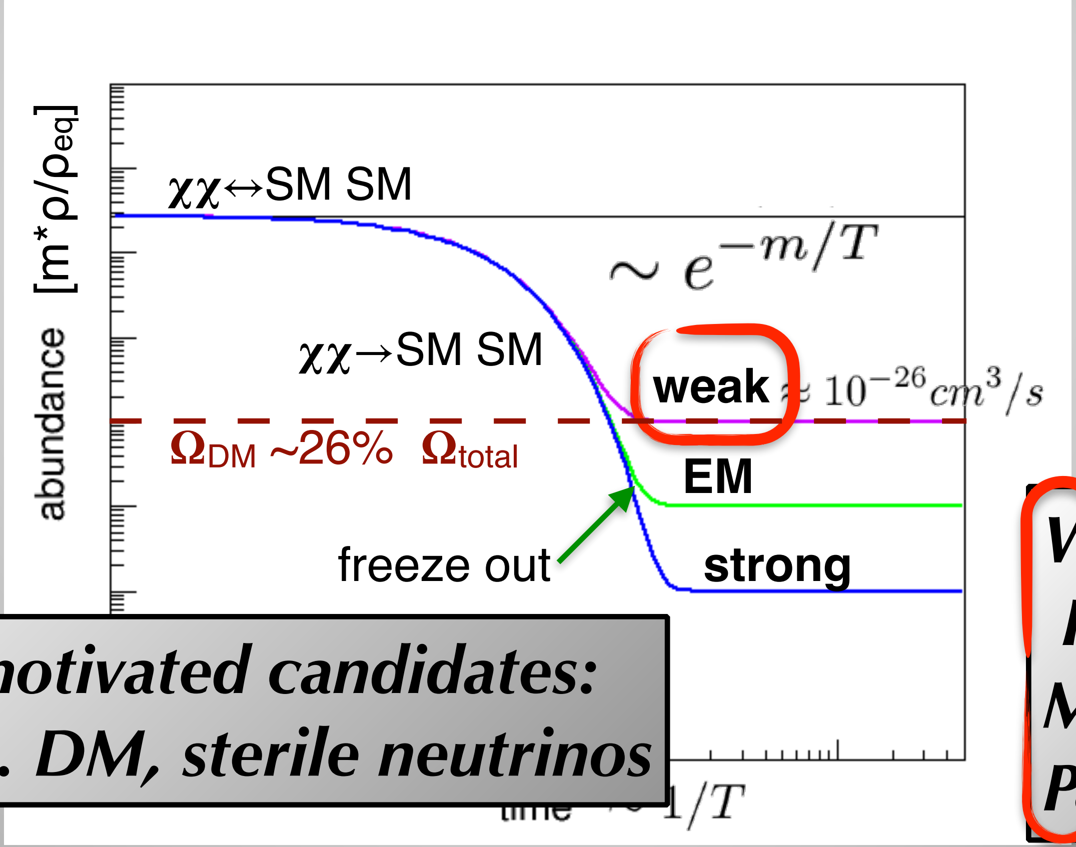

Abundance

$\langle\sigma v\rangle n_{eq} \sim H$

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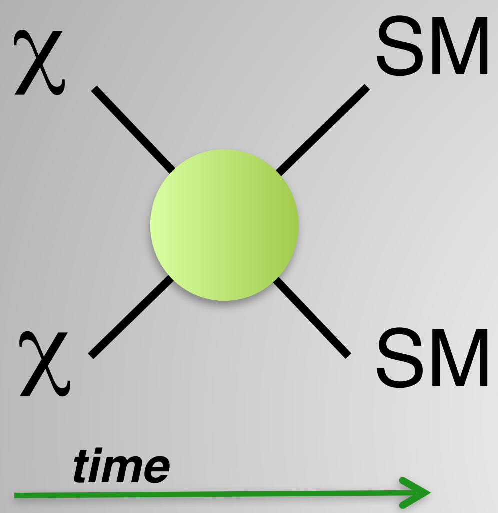
Other well motivated candidates: axions, asym. DM, sterile neutrinos

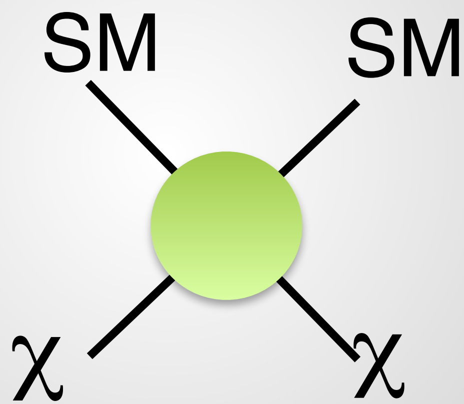
Weakly Interacting Massive Particles

G. Steigman, et al., Phys.Rev. D86 (2012) 023506

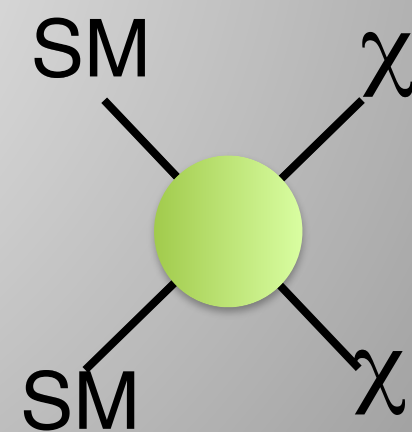
Detecting Particle Dark Matter



Indirect Detection



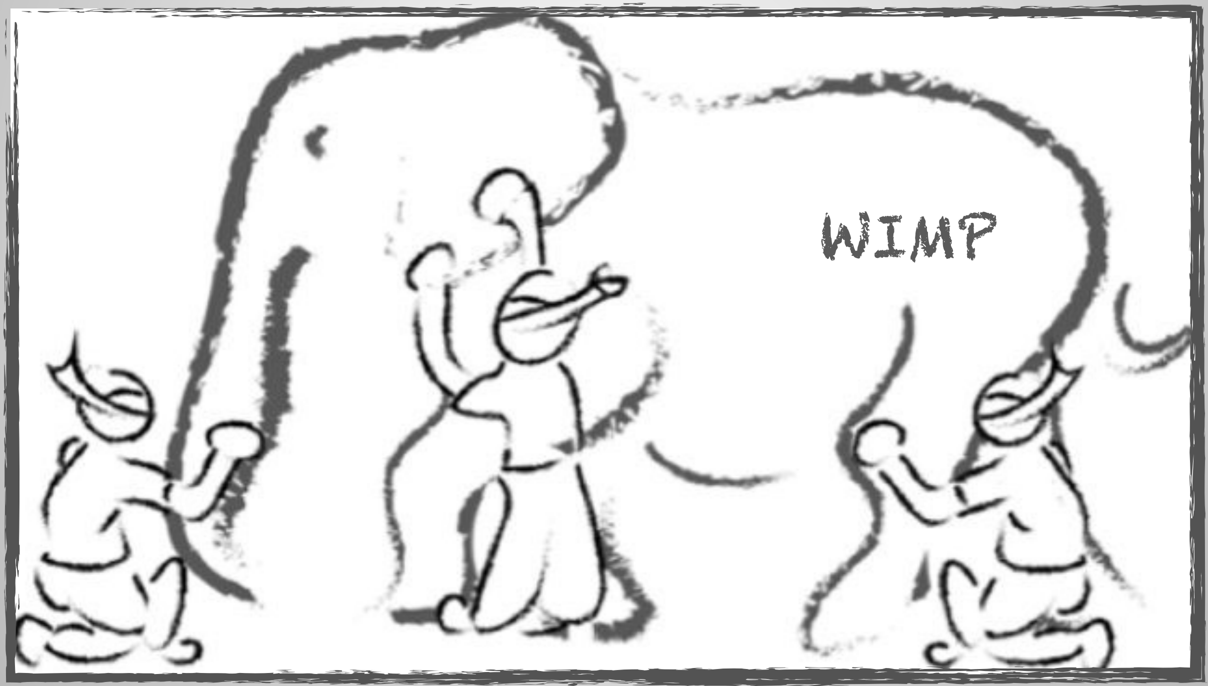
Direct Detection



Collider

Detecting the Elephant in the Universe

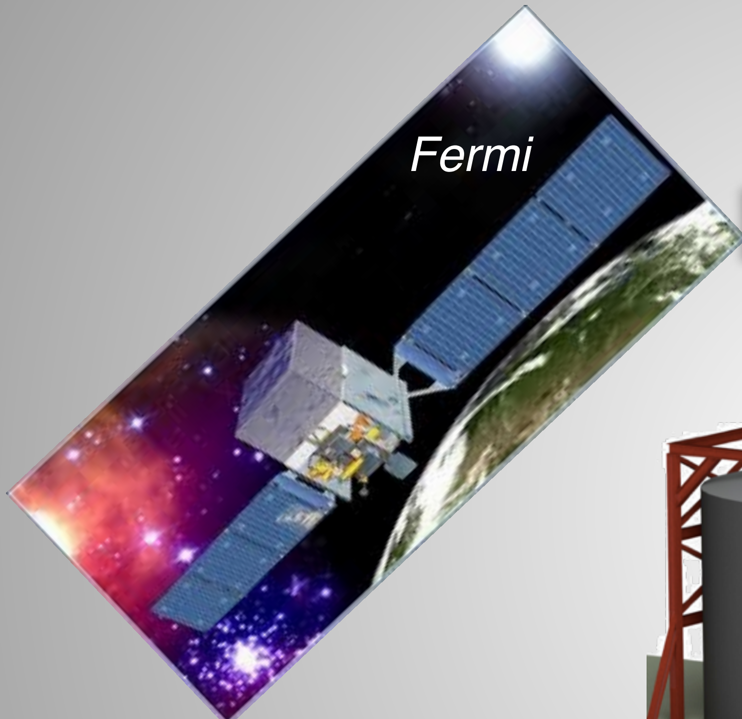
Indirect Detection



Direct Detection

Collider

Dark Matter Searches



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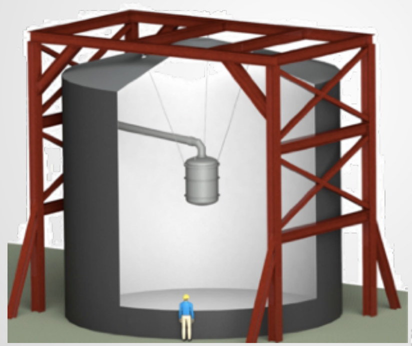

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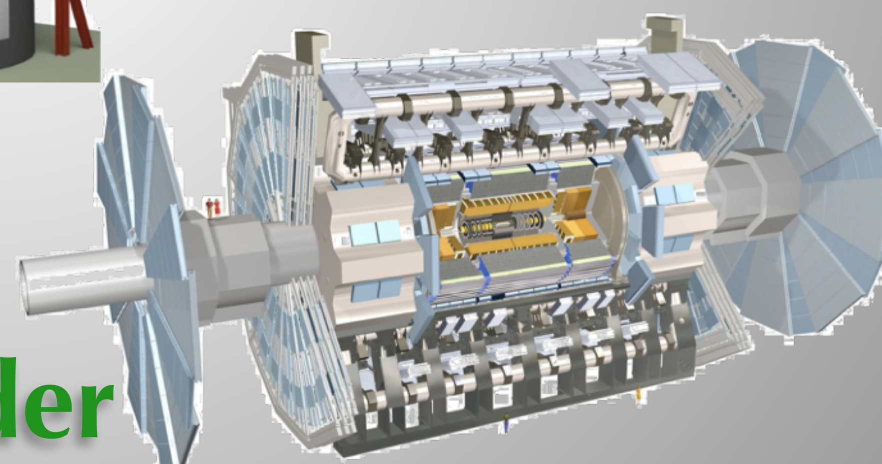

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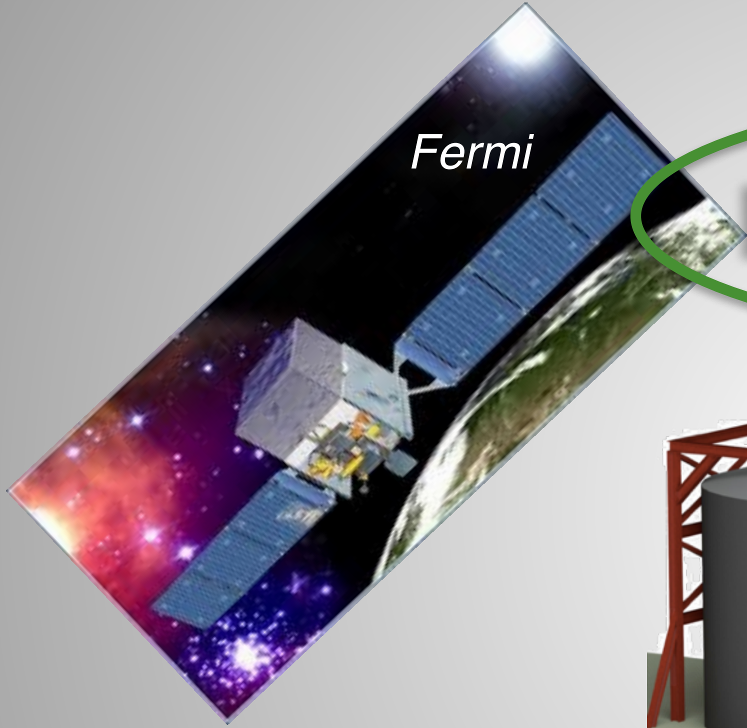

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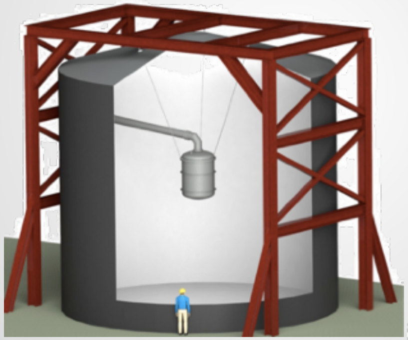

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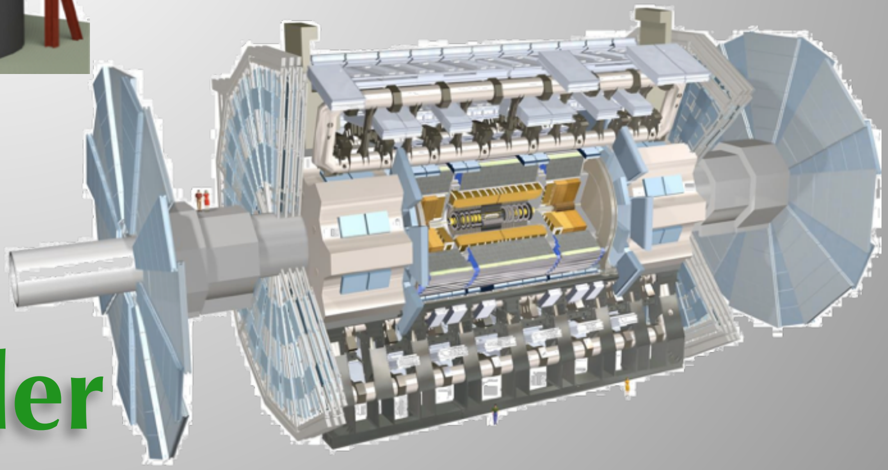
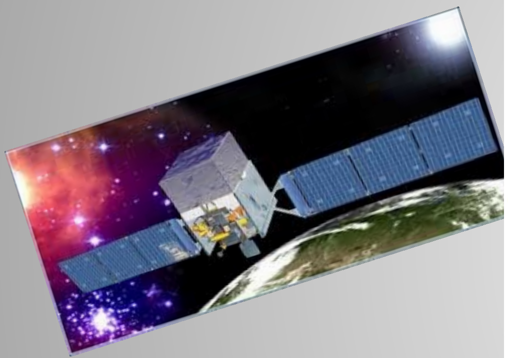
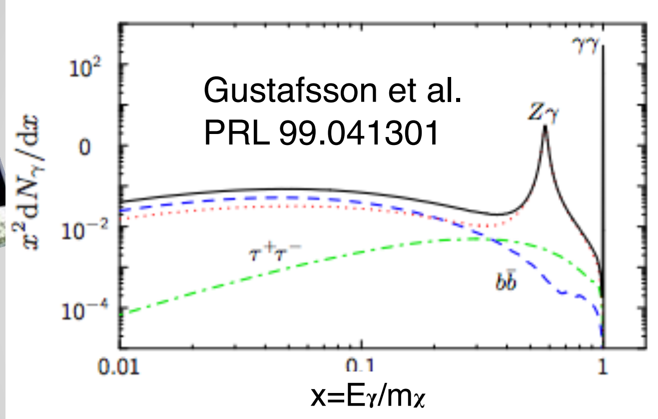


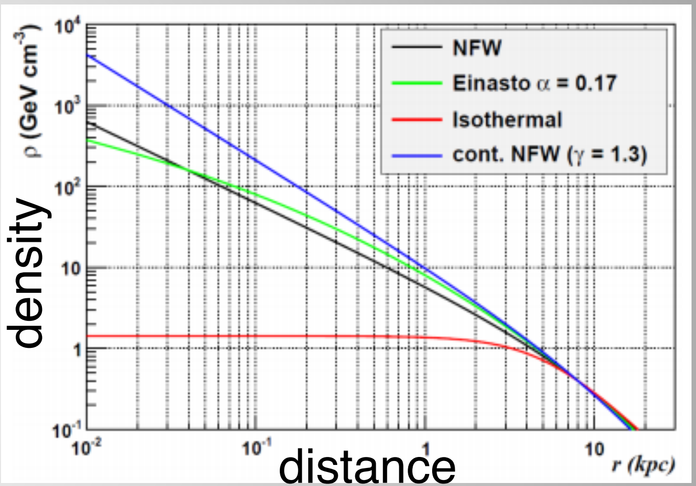
Collider

Indirect Searches: γ-rays

Observed = Particle Properties x Astrophysics Properties







$$\Phi_\gamma(E,\psi) = \frac{1}{4\pi}\frac{\langle\sigma_\chi v\rangle}{2m_\chi^2}N_\gamma(E) \times J(\psi)$$

cross section

mass

photons

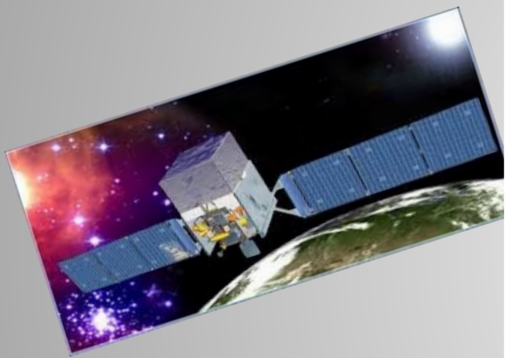
J-Factor: ~ ∫ρ²

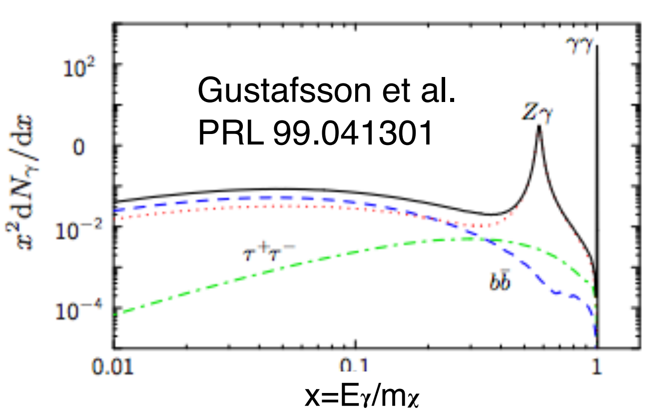
(solid angle, line of sight)

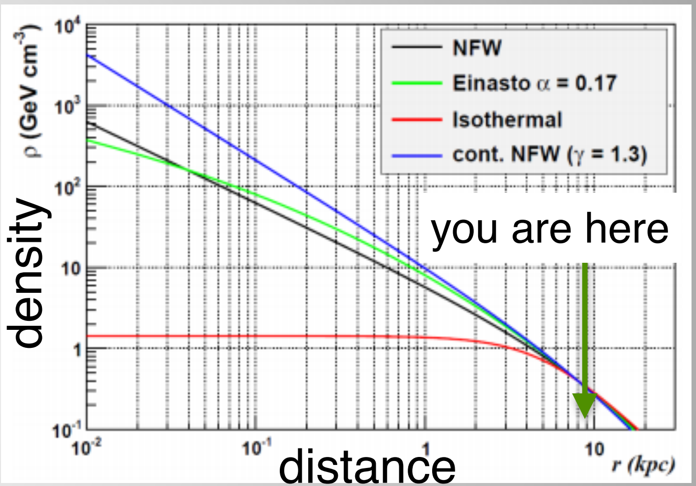
L. Bergstrom et al., ApJ. 9:137-162,1998

Indirect Searches: γ-rays

Observed* = *Particle Properties* x *Astrophysics Properties







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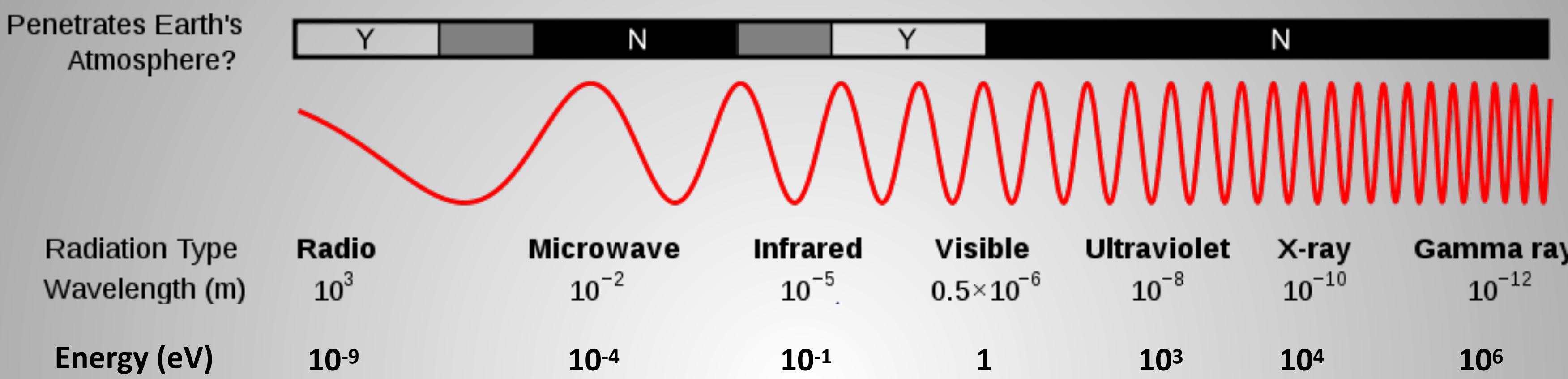
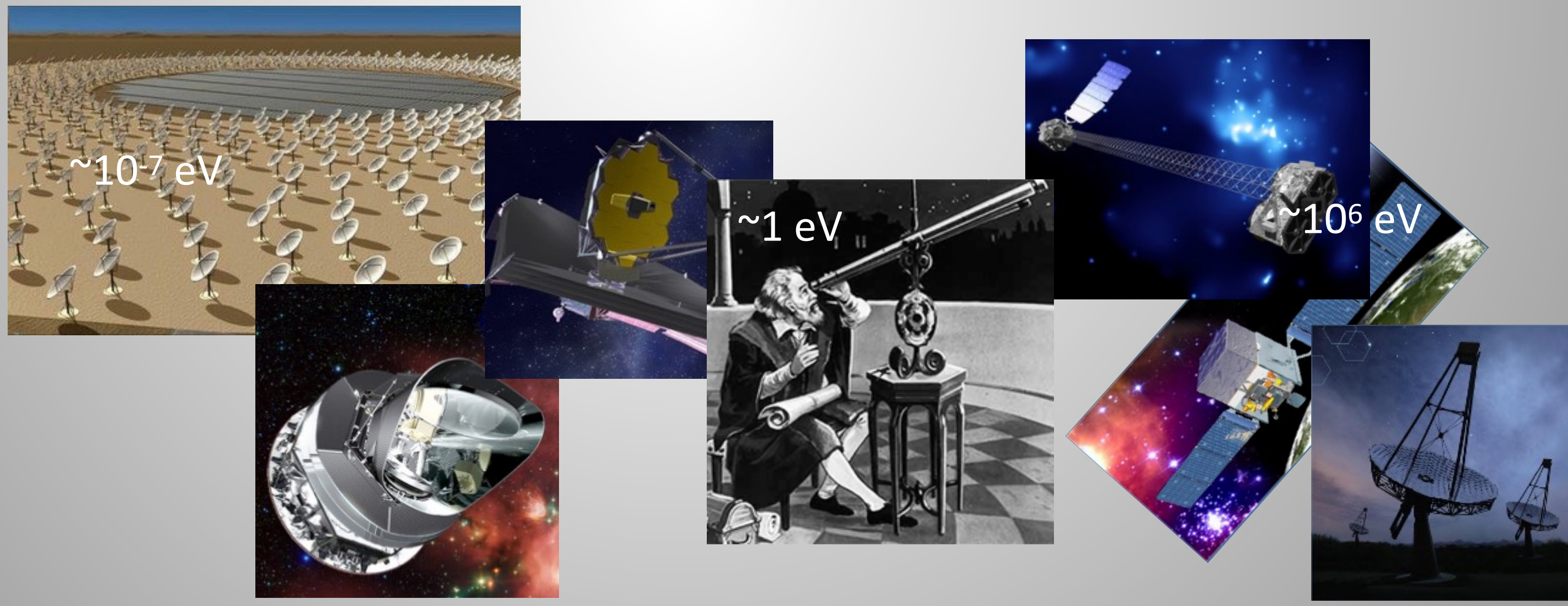
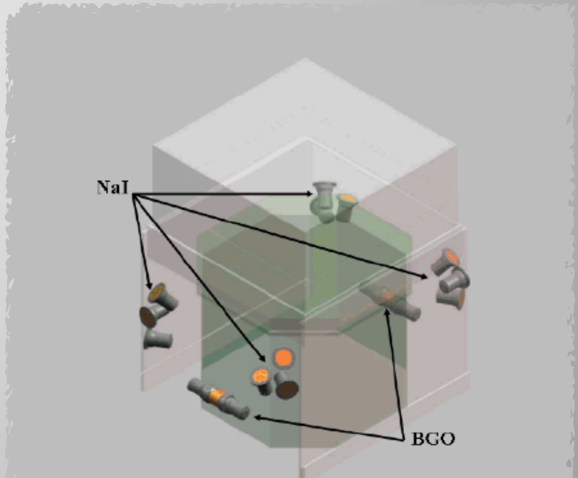




http://earthsky.org/space/what-is-the-electromagnetic-spectrum

Fermi Gamma-Ray Space Telescope

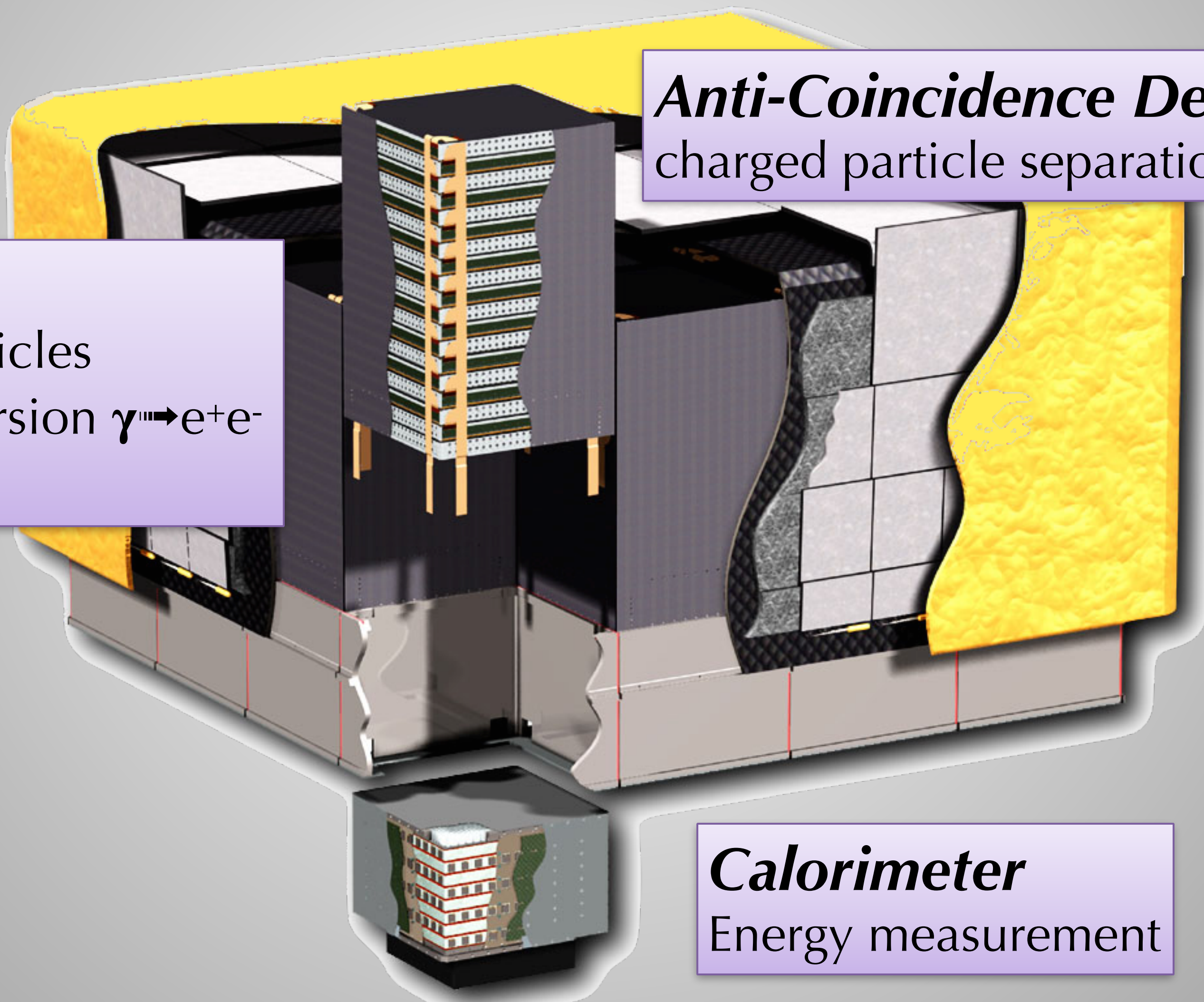
20% sky at once
Scans full sky
20 MeV to >300 GeV



Gamma-ray Burst Monitor

full sky continuous
8 keV to 40 MeV

Fermi Large Area Telescope

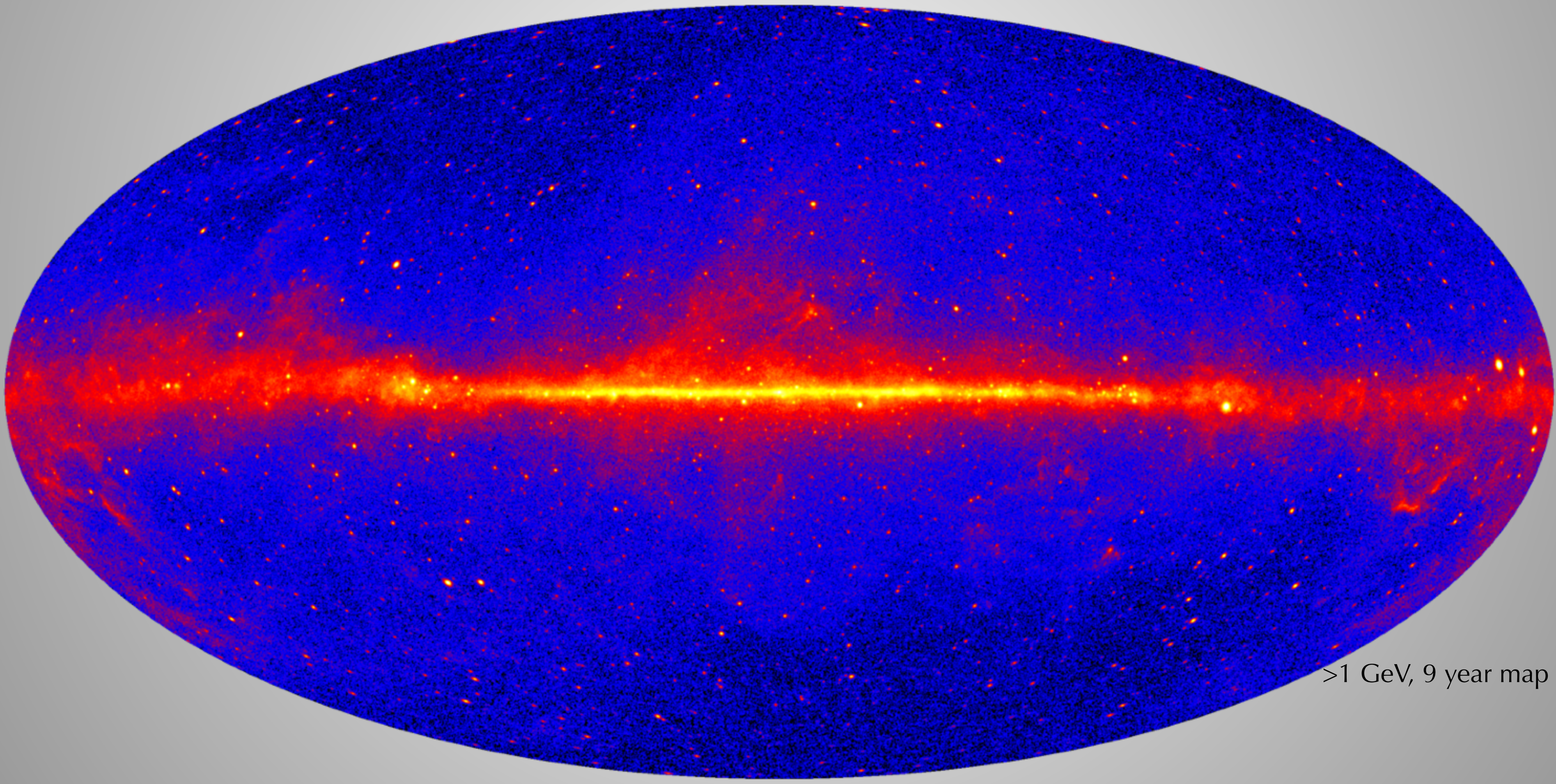


Anti-Coincidence Detector
charged particle separation

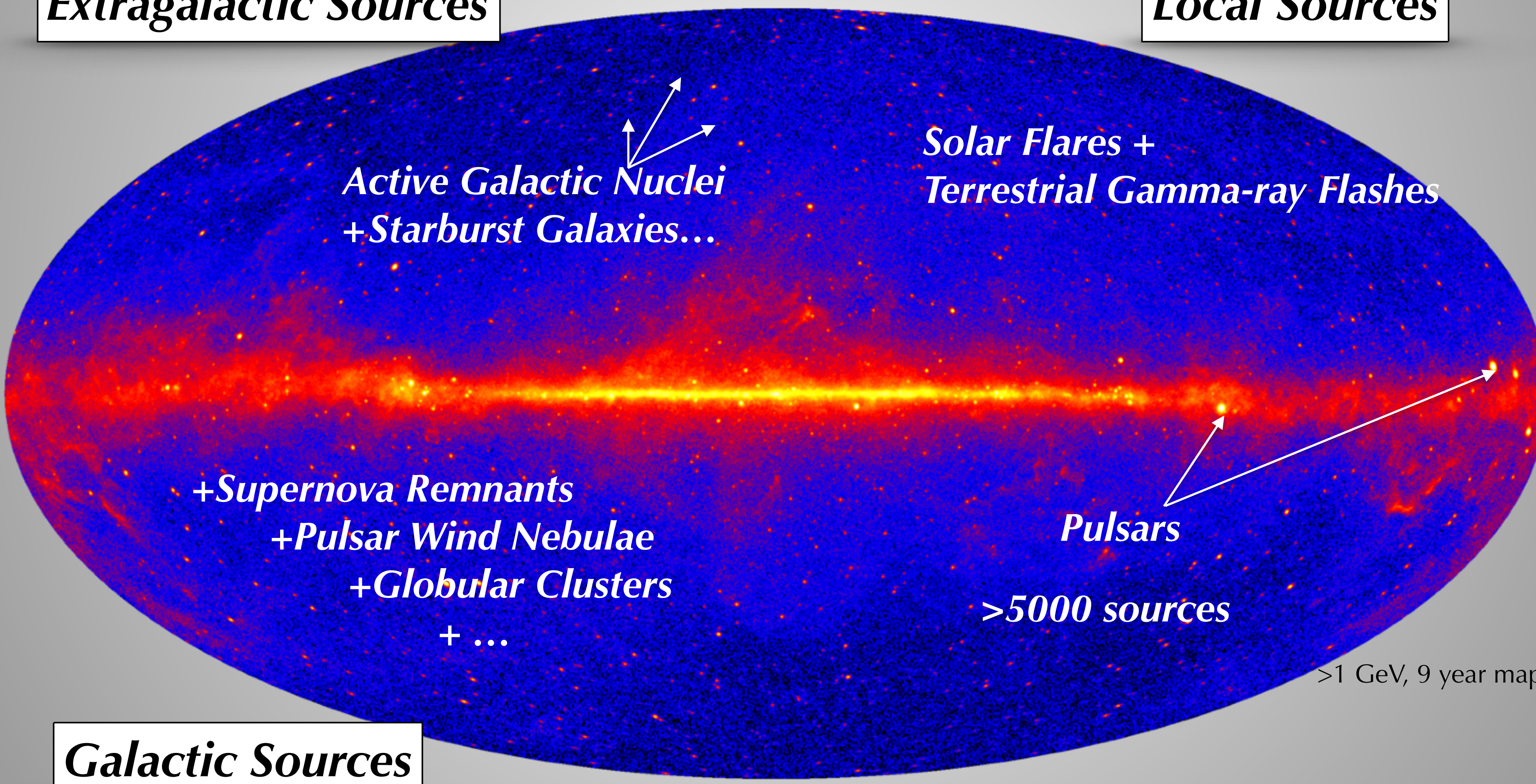
Tracker
charged particles
cause conversion $\gamma \rightarrow e^+e^-$
direction

Calorimeter
Energy measurement

Fermi-LAT γ-ray sky



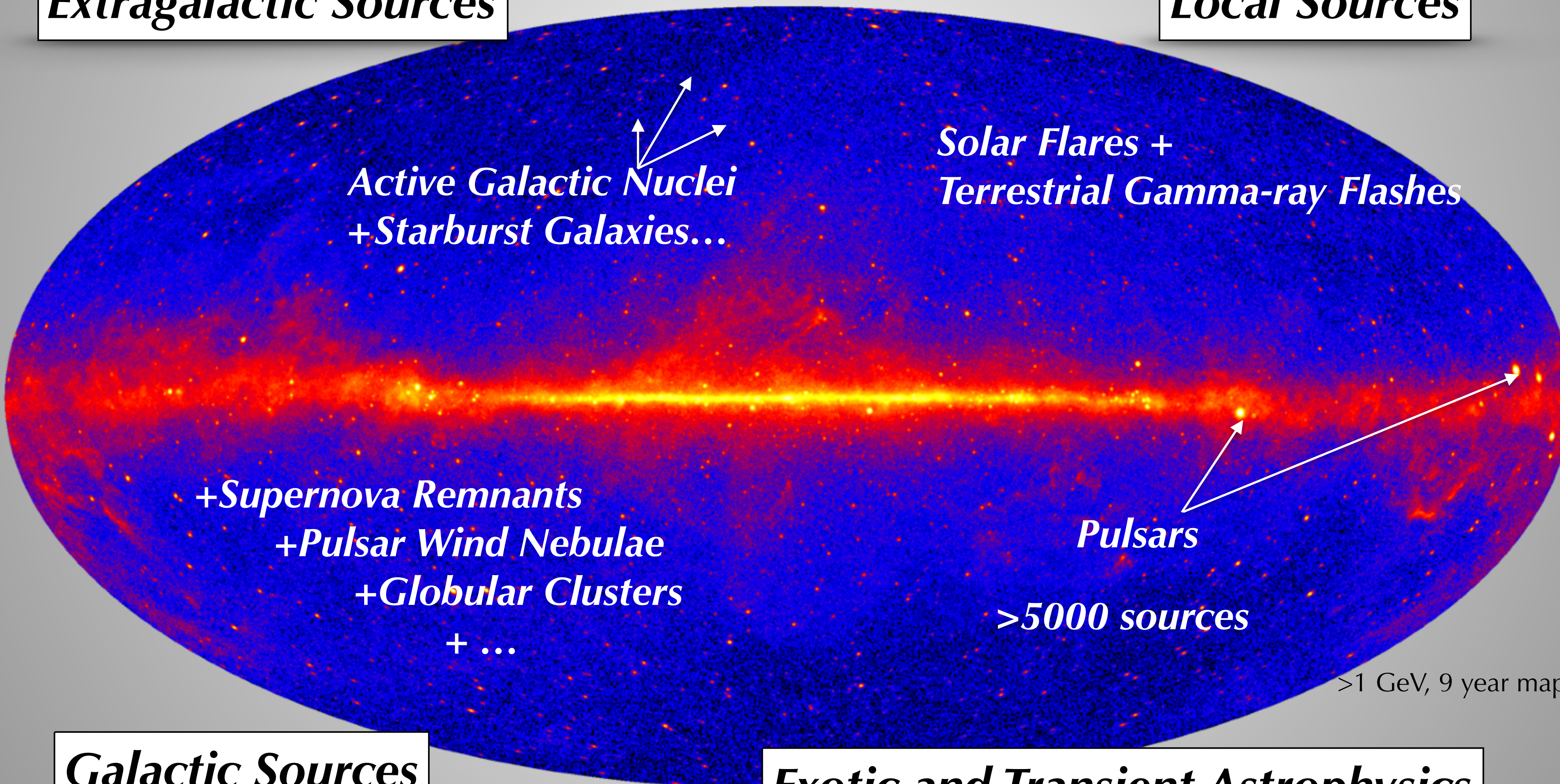
Fermi-LAT γ-ray sky



Fermi-LAT γ-ray sky

Extragalactic Sources

Local Sources

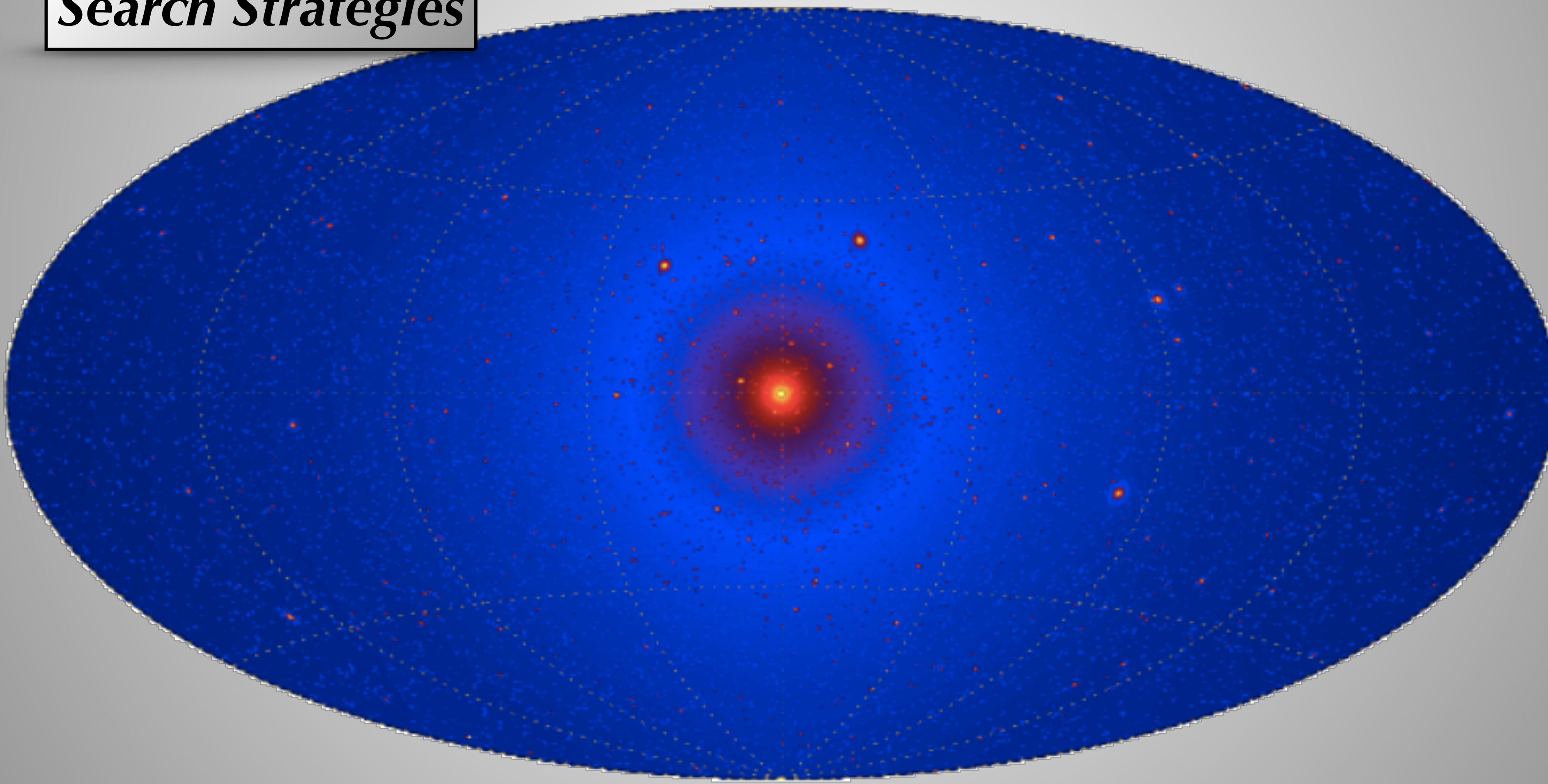


Galactic Sources

Exotic and Transient Astrophysics

Model of Dark Matter Distribution

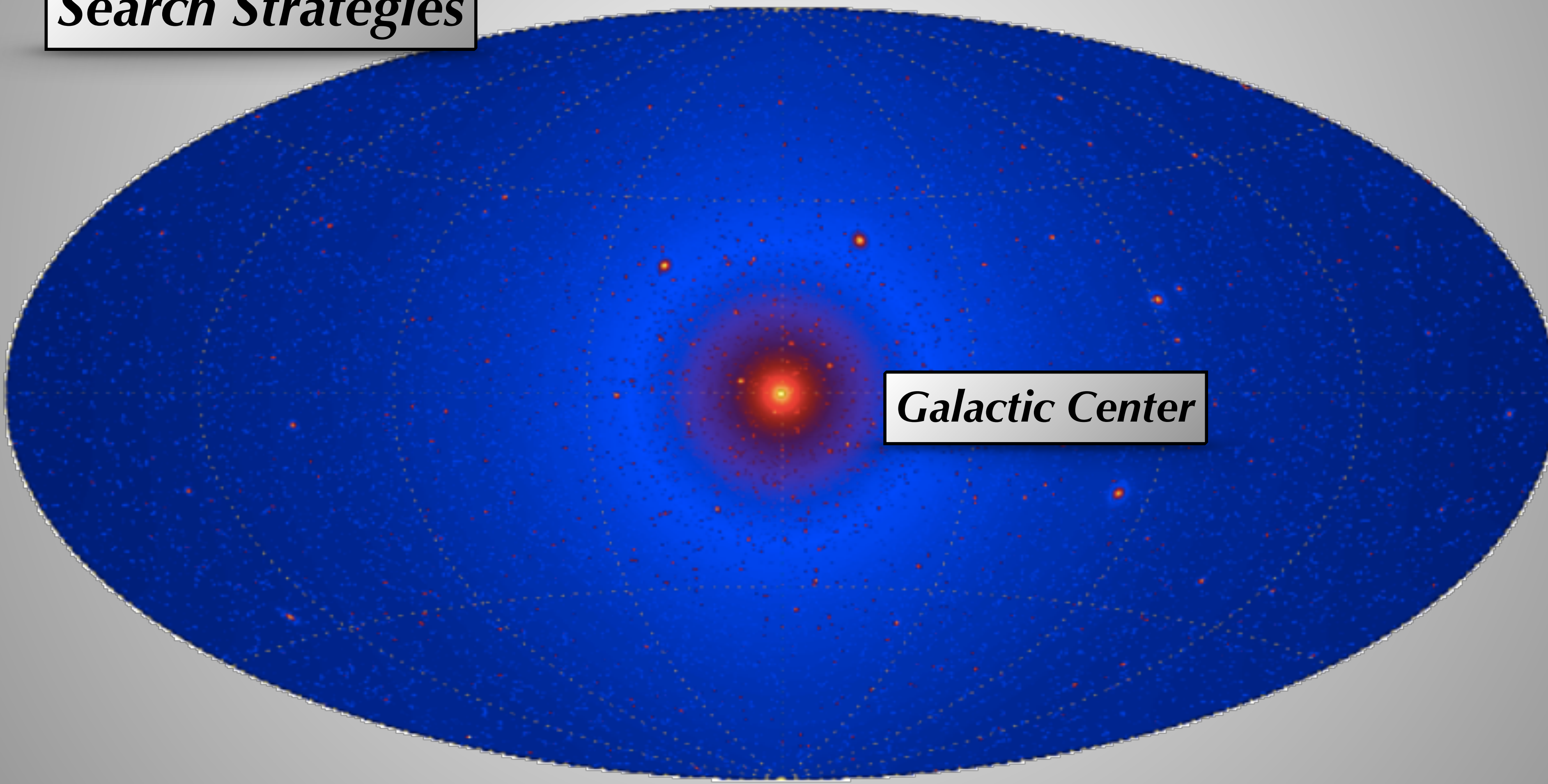
Search Strategies



L. Pieri et al., PRD83:023518,2011

Model of Dark Matter Distribution

Search Strategies



L. Pieri et al., PRD83:023518,2011

Galaxies shine in γ rays

Active Galactic Nucleus

accretion onto supermassive black hole

Population of particle accelerators

pulsars, supernova remnants, …

Interstellar Medium

cosmic rays interacting with gas and photons

Dark matter

particle annihilation/decay into gamma rays

Galaxies shine in γ rays

~~Active Galactic Nucleus~~

accretion onto supermassive black hole

Population of particle accelerators ✔

pulsars, supernova remnants, …

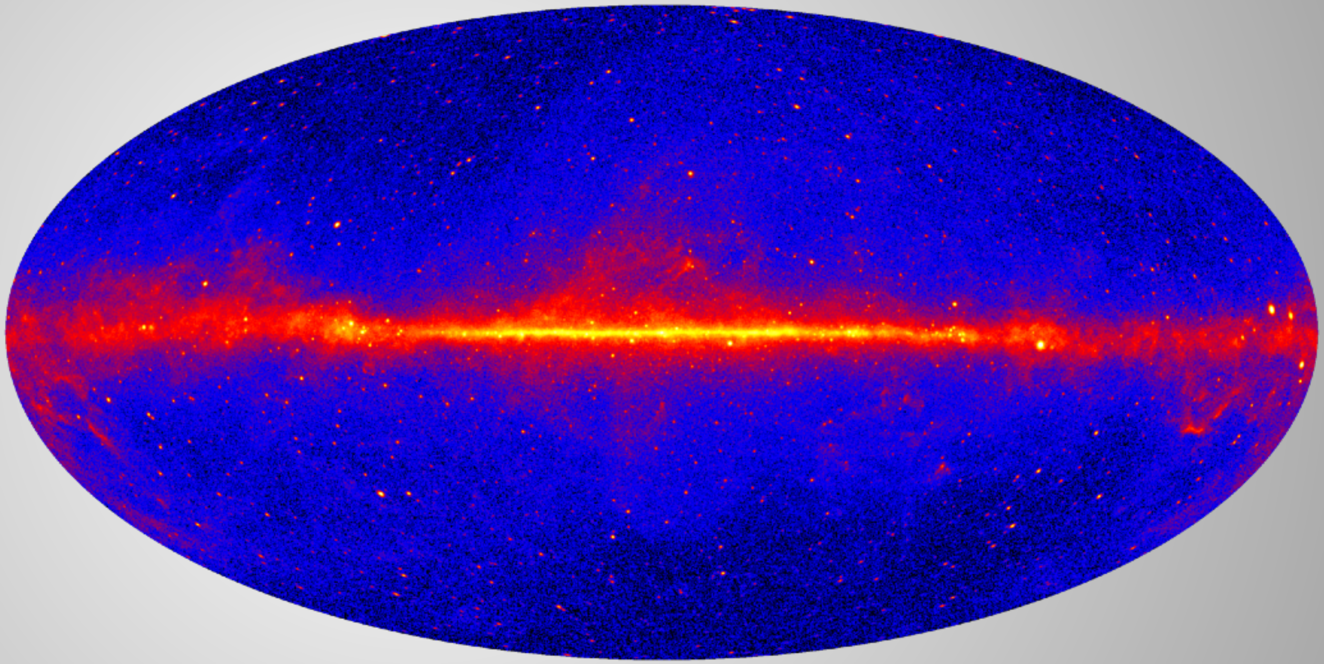
Interstellar Medium ✔

cosmic rays interacting with gas and photons

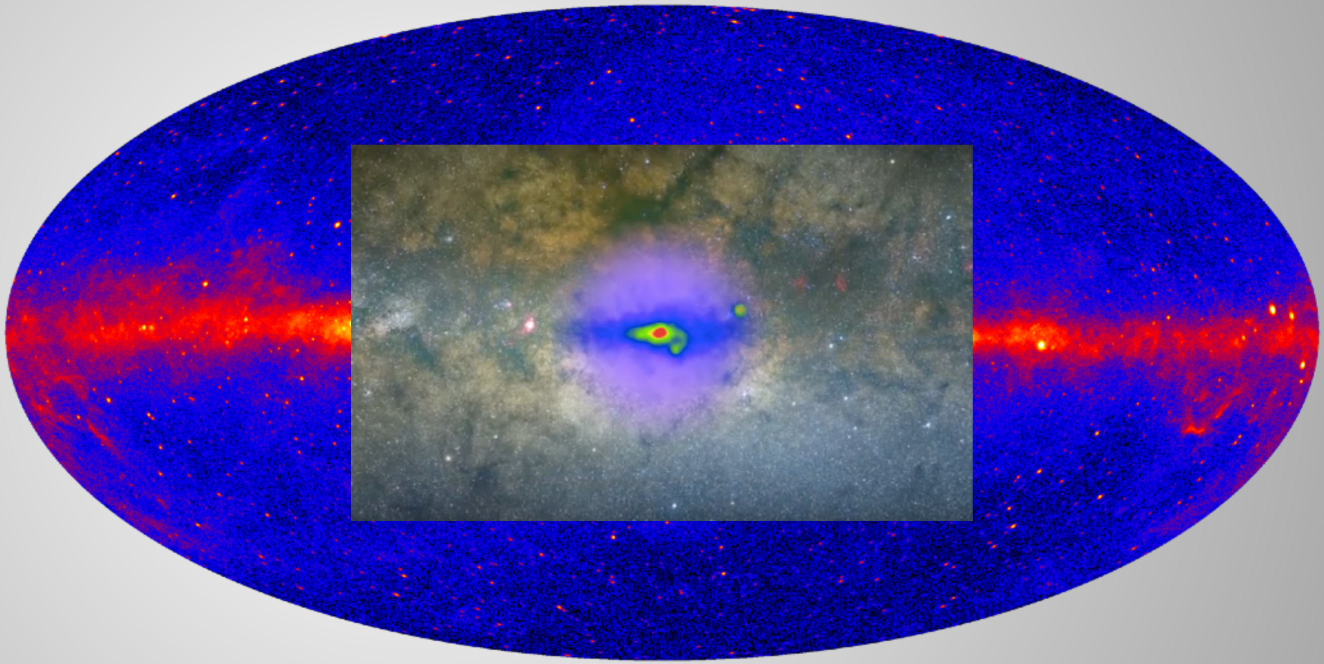
Dark matter ???

particle annihilation/decay into gamma rays

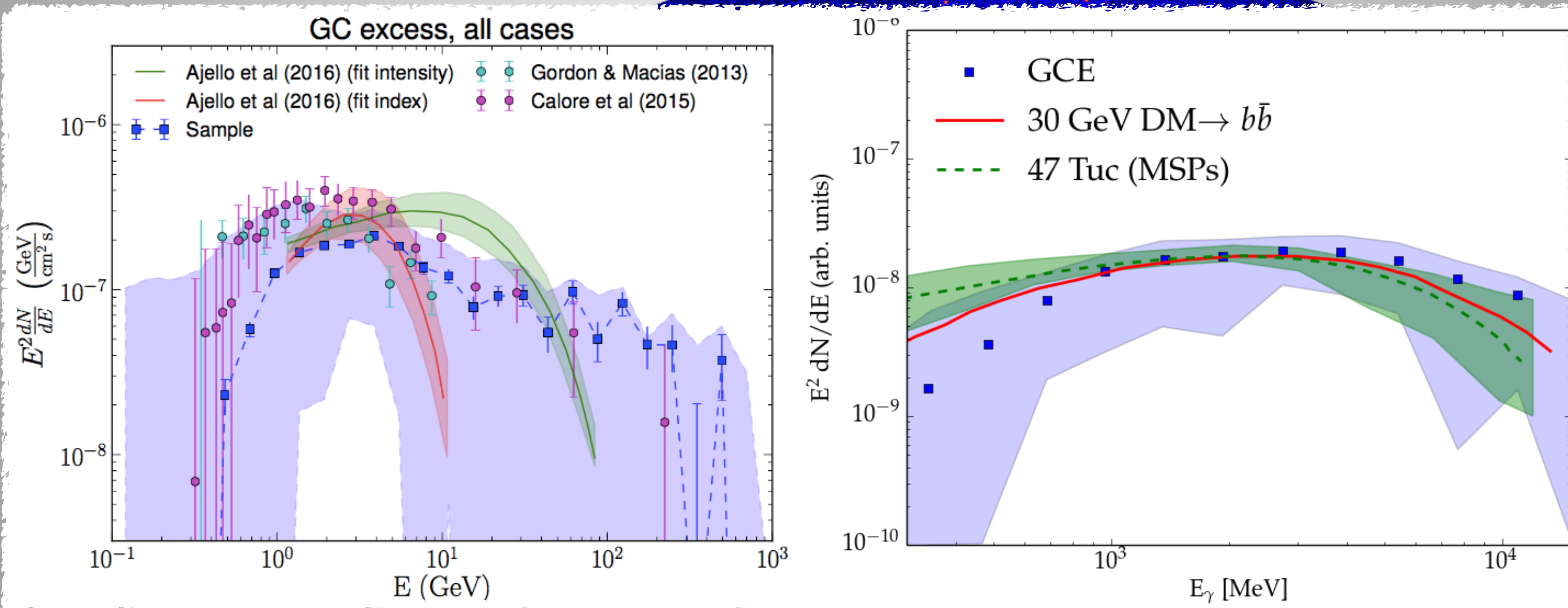
γ rays @ Galactic Center



γ rays @ Galactic Center



γ rays @ Galactic Center

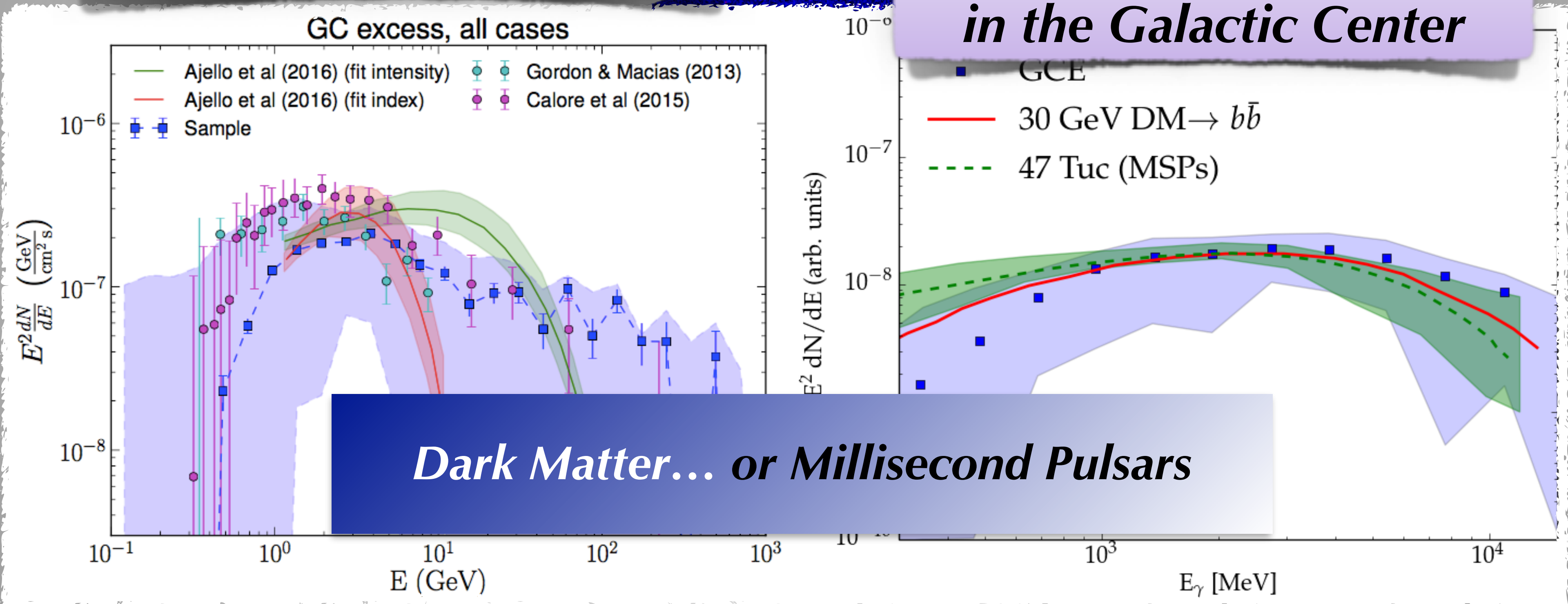


Ackermann et al., ApJ 2017

γ rays @ Galactic Center

Consistent with Thermal Relic cross sections

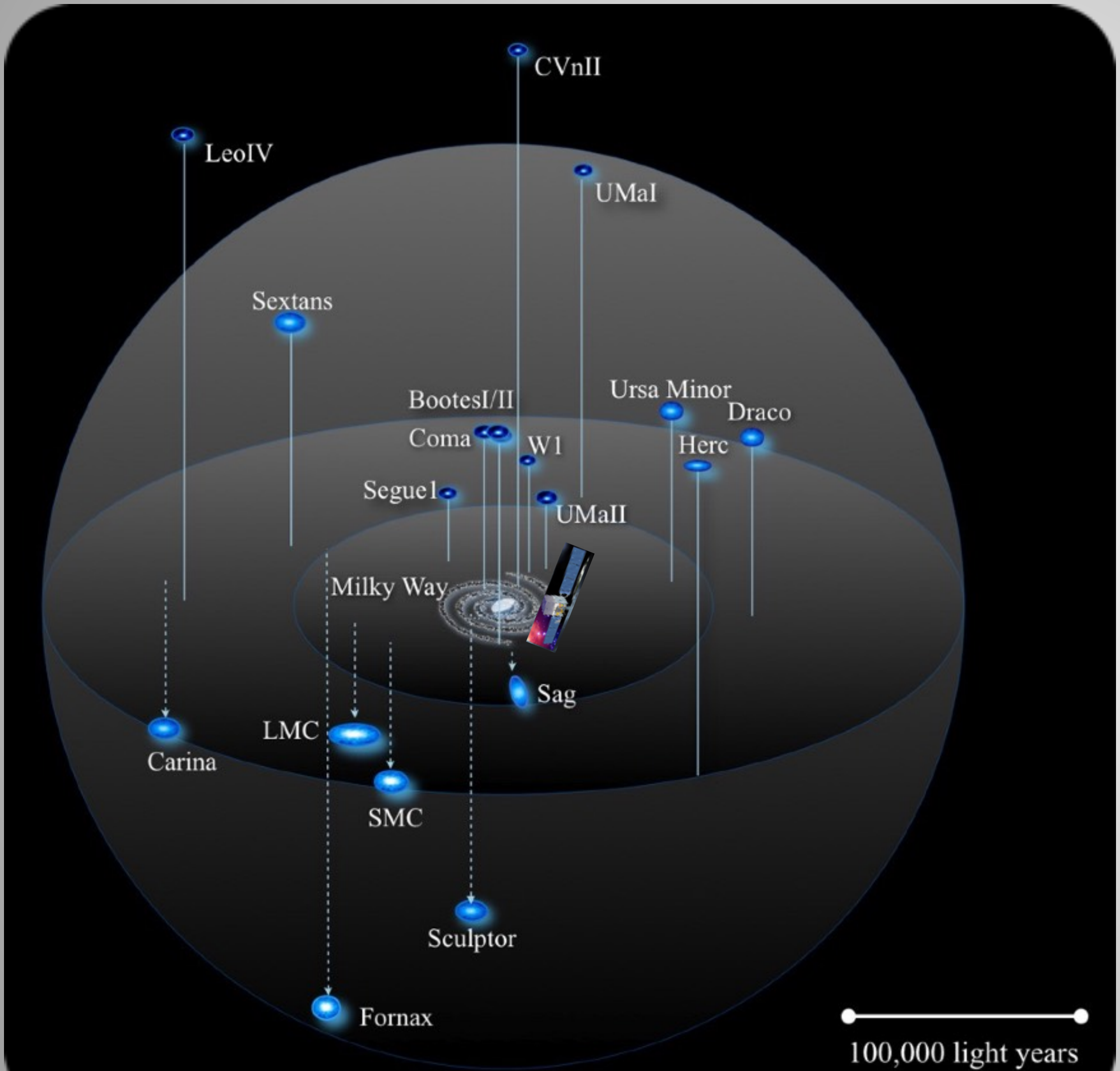
Current radio campaigns to identify pulsars in the Galactic Center



Dark Matter… or Millisecond Pulsars

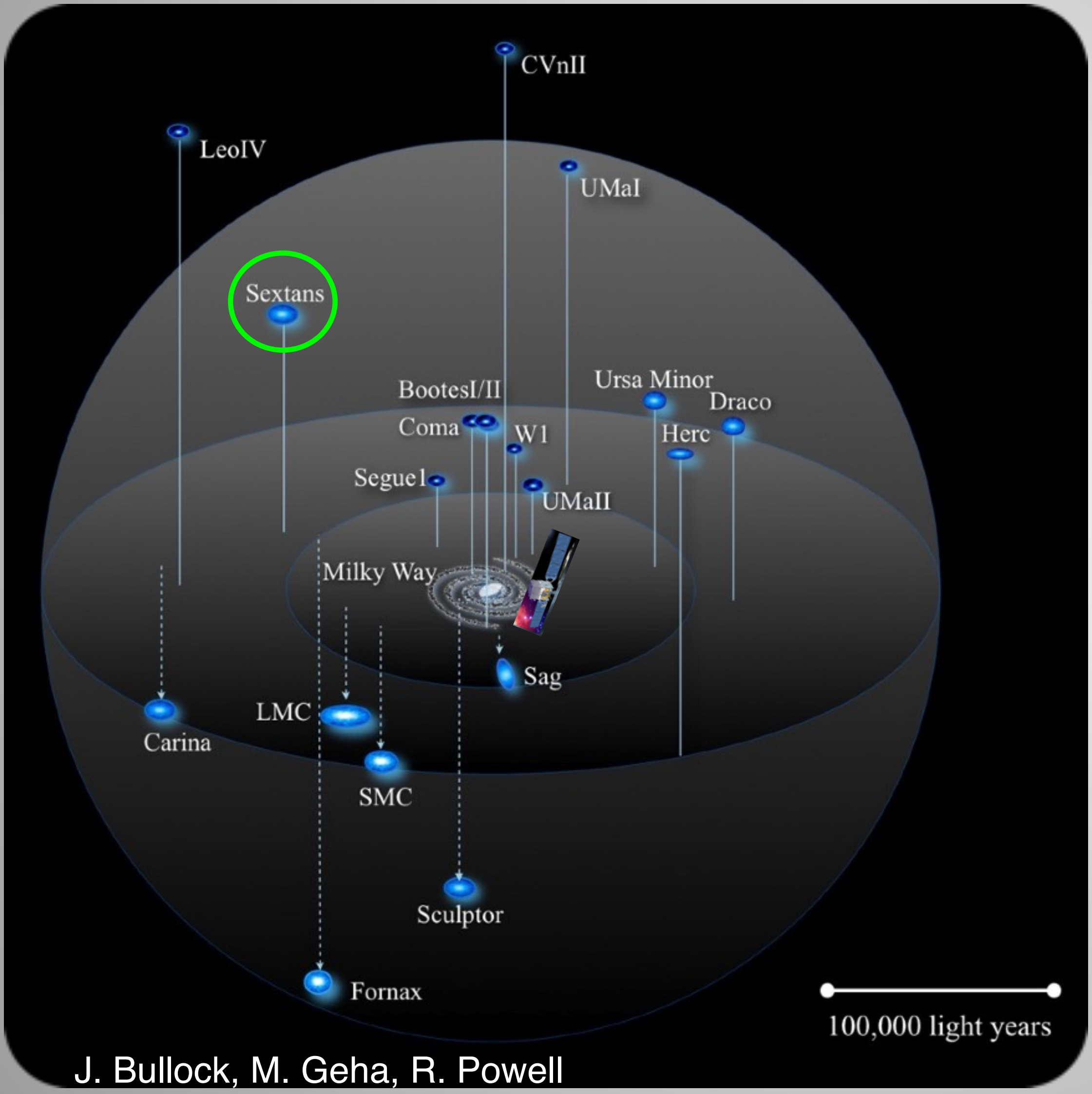
Ackermann et al., ApJ 2017

Dwarf Spheroidal Galaxies



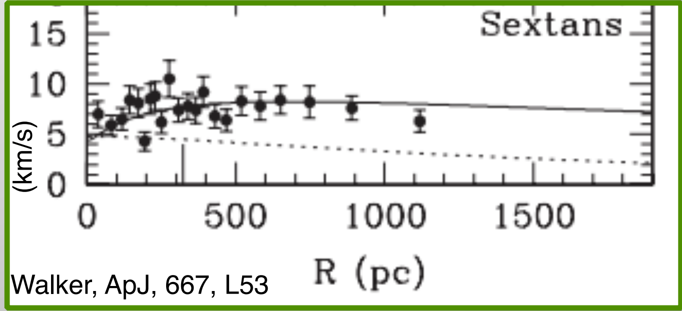
J. Bullock, M. Geha, R. Powell

Dwarf Spheroidal Galaxies

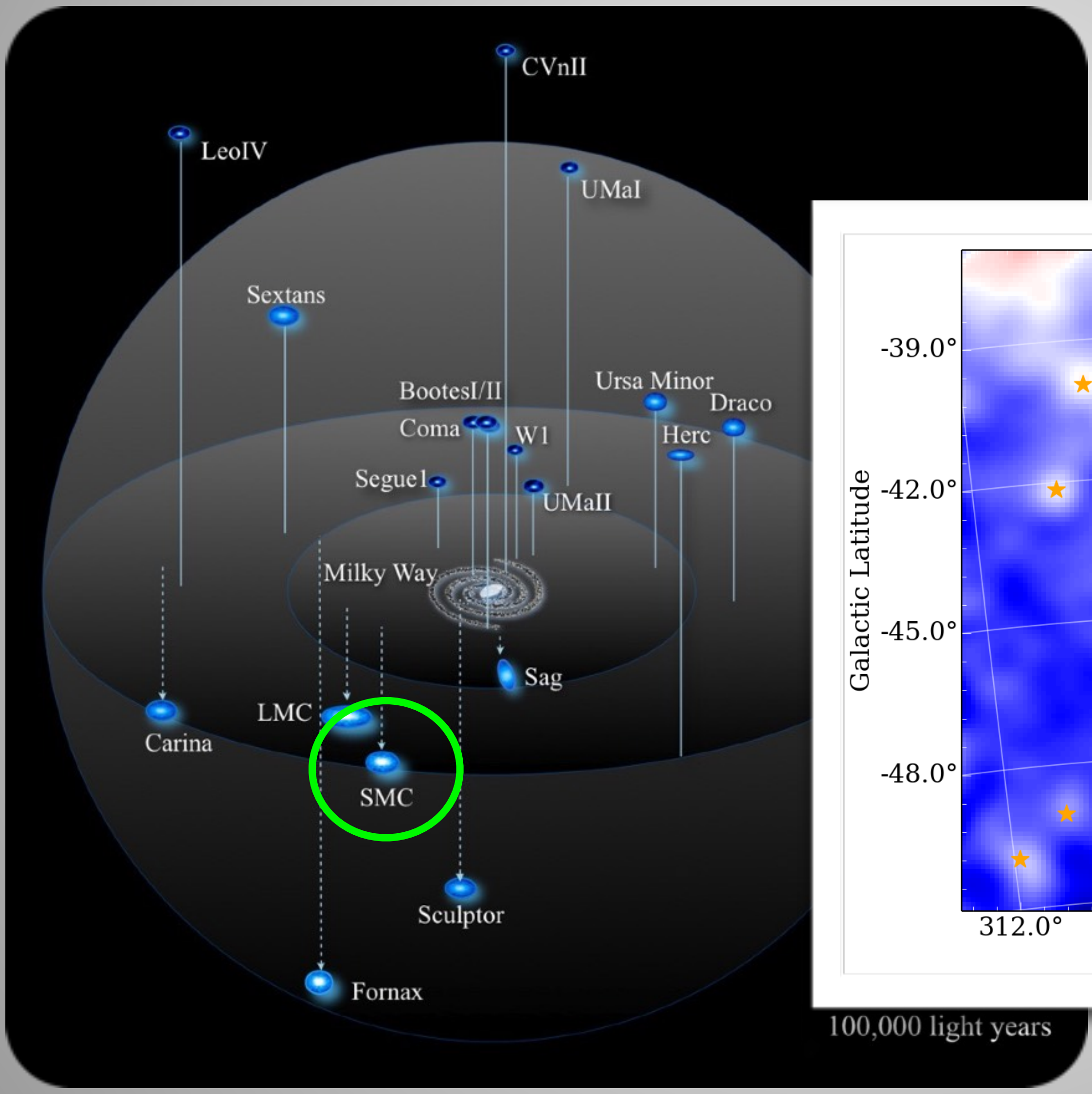


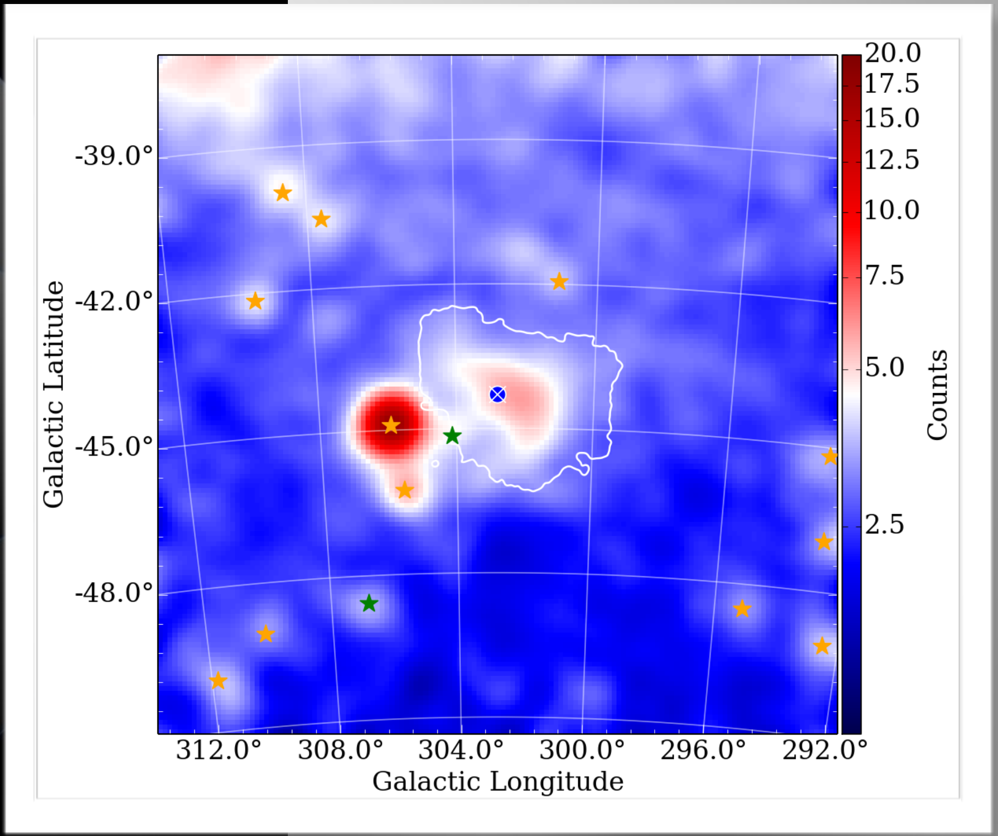
lower backgrounds but…
lower signal

High Dark Matter to Baryonic Matter Ratio



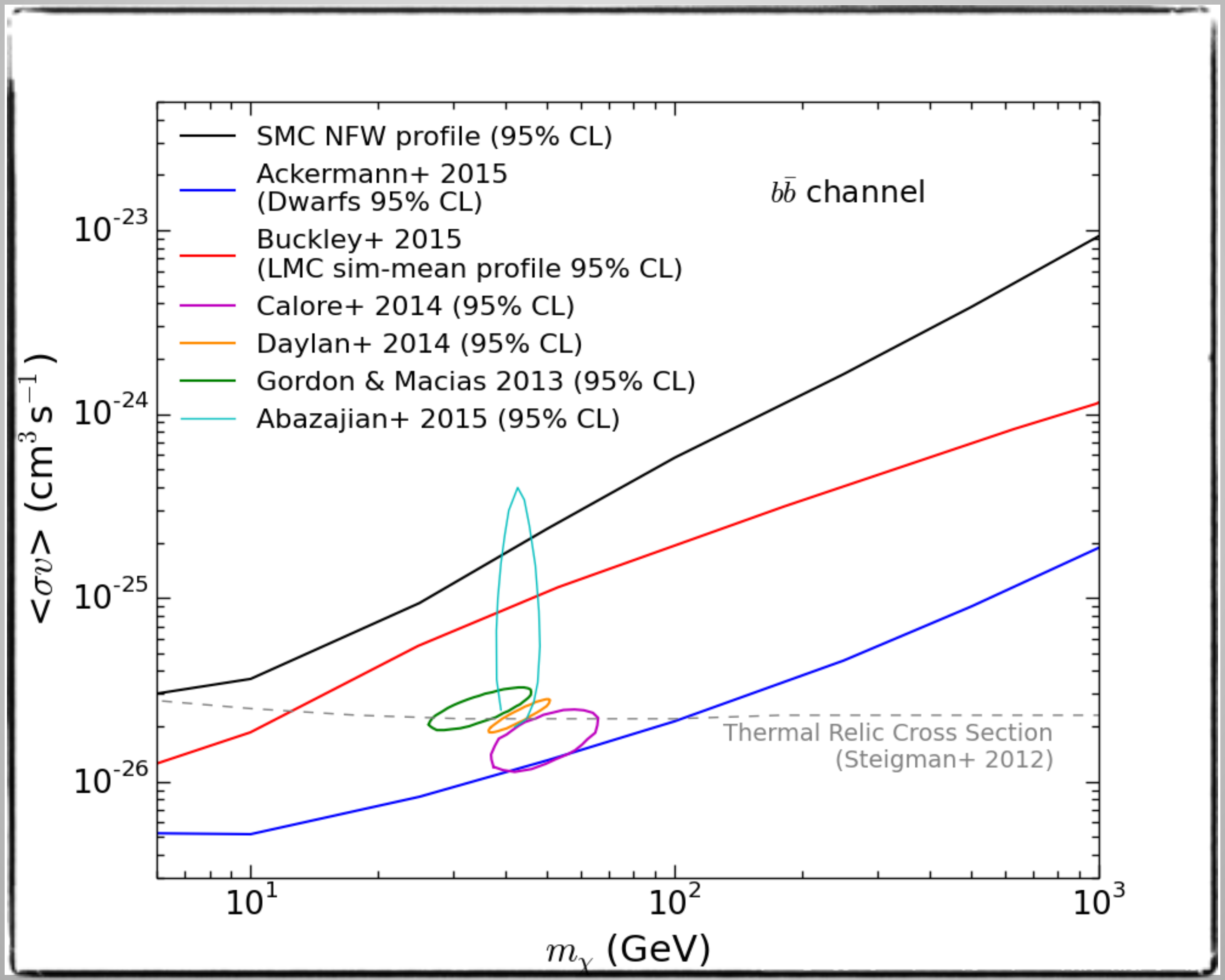
Star Forming Galaxies





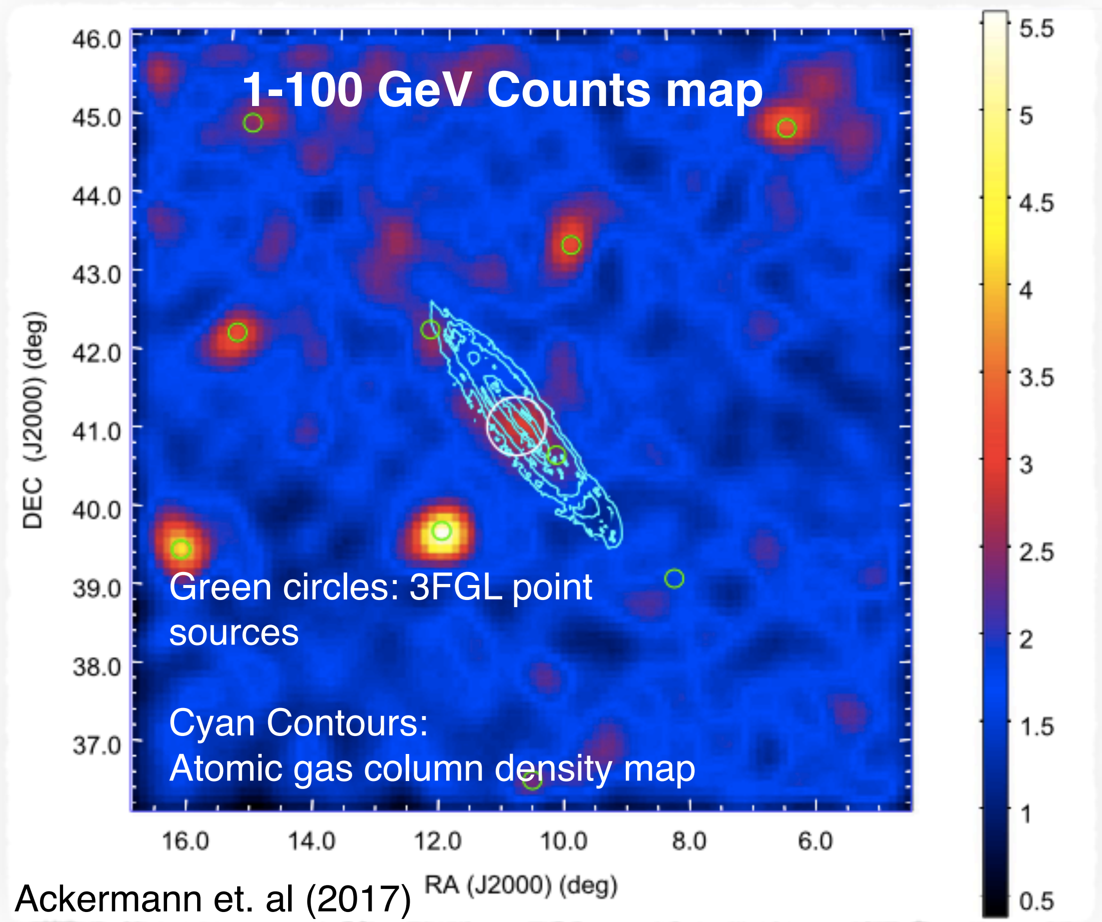
RC et al., PRD 2016

Searching in Dwarf Galaxies



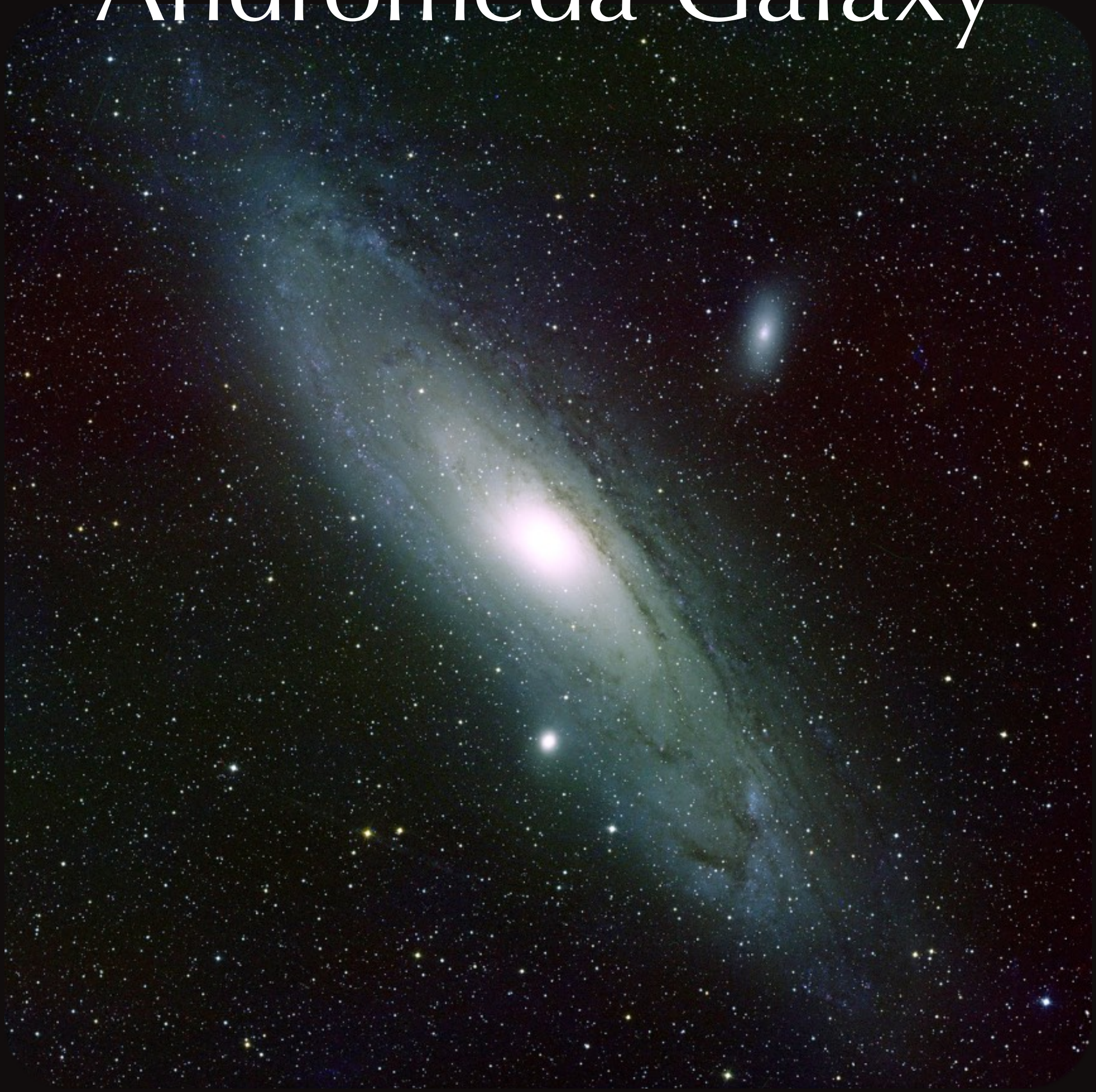
RC et al., PRD 2016

γ-ray emission in the Andromeda Galaxy



Ackermann et. al (2017)

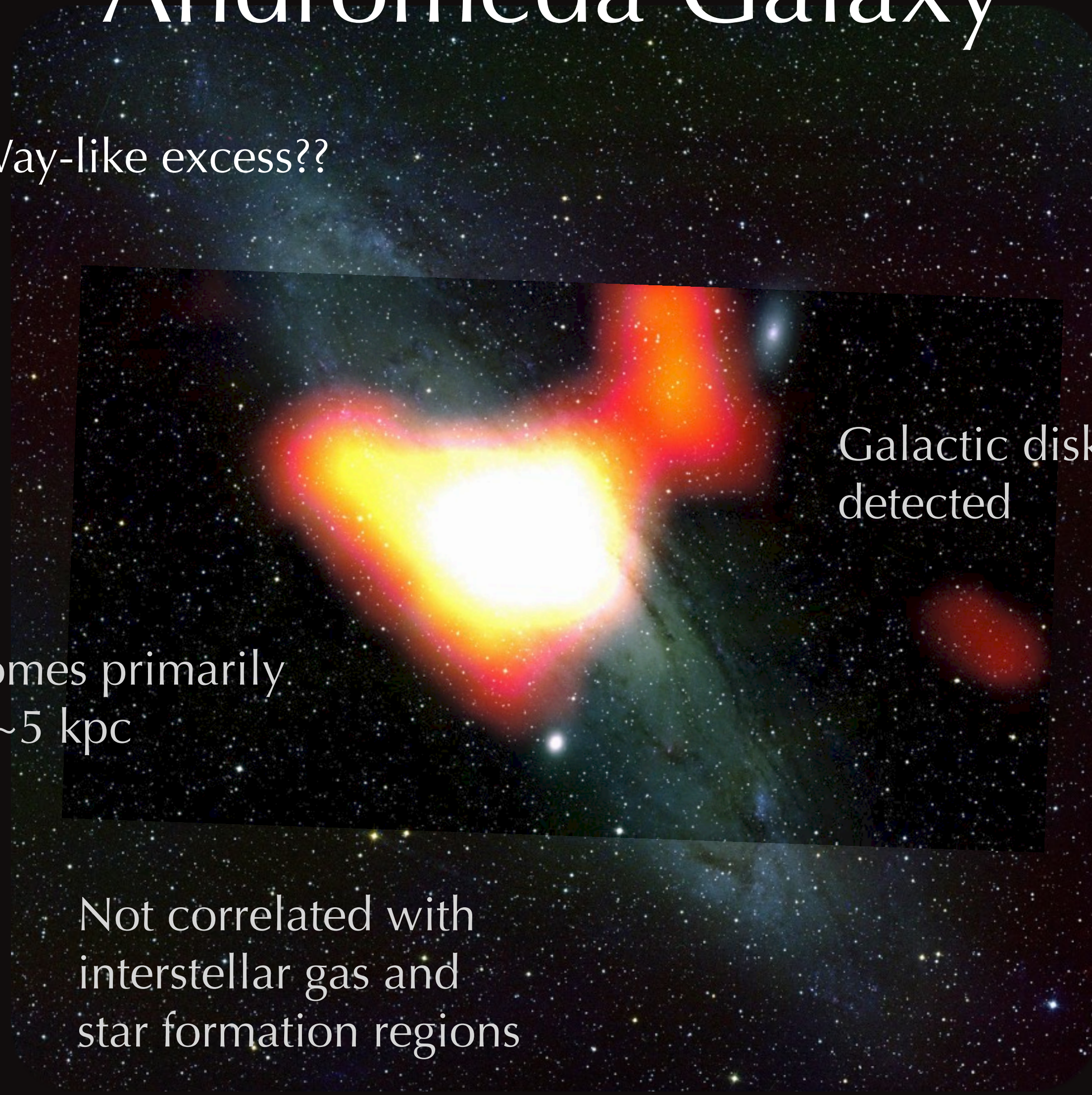
γ-ray emission in the Andromeda Galaxy



Credit: NASA/GSFC

γ-ray emission in the Andromeda Galaxy

Another Milky Way-like excess??



Galactic disk not detected

Emission comes primarily from inner ~5 kpc

Not correlated with interstellar gas and star formation regions

Credit: NASA/GSFC

γ-ray emission in the Andromeda Galaxy

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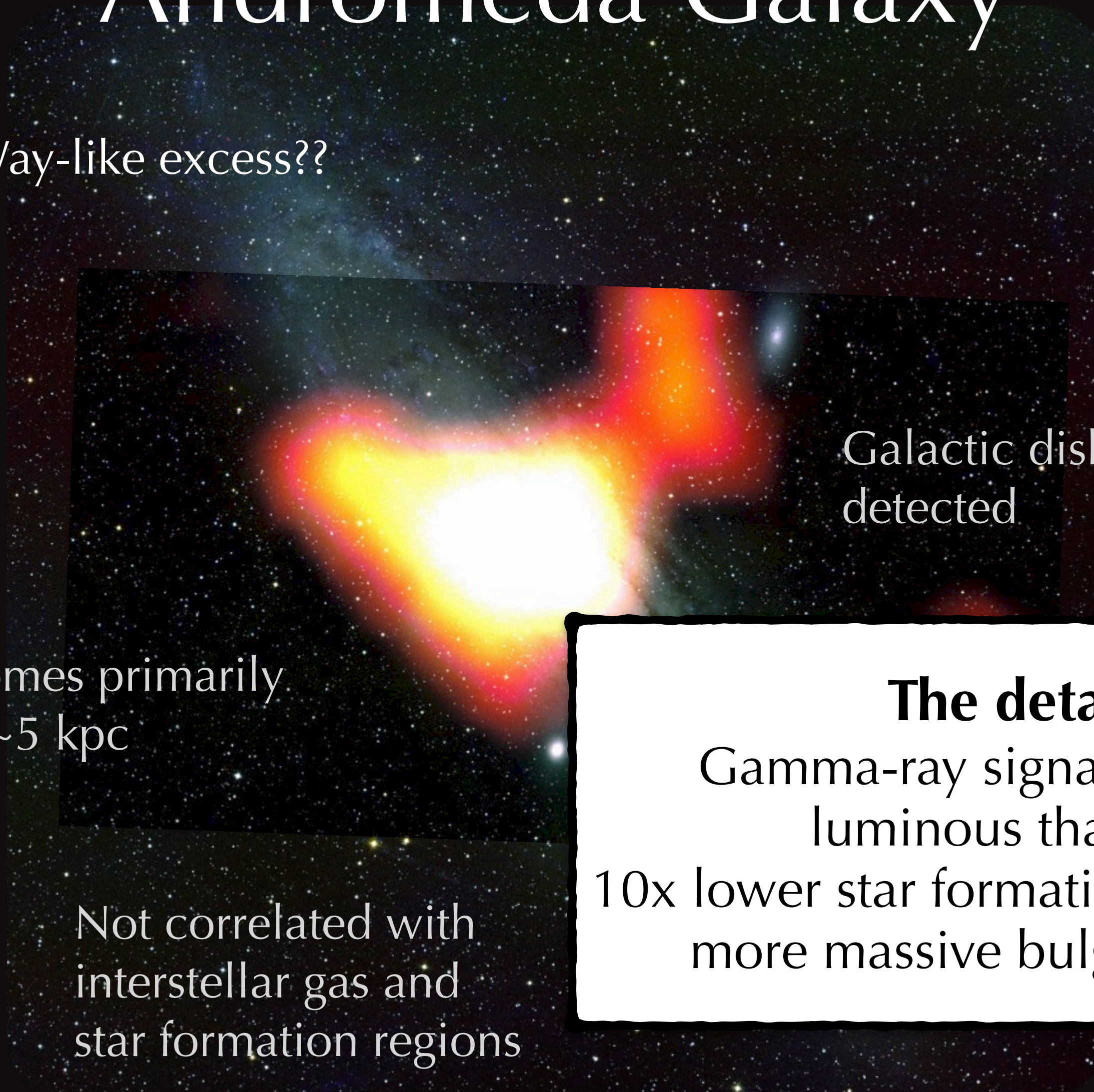


Galactic disk not detected

Emission comes primarily from inner ~5 kpc

Not correlated with interstellar gas and star formation regions

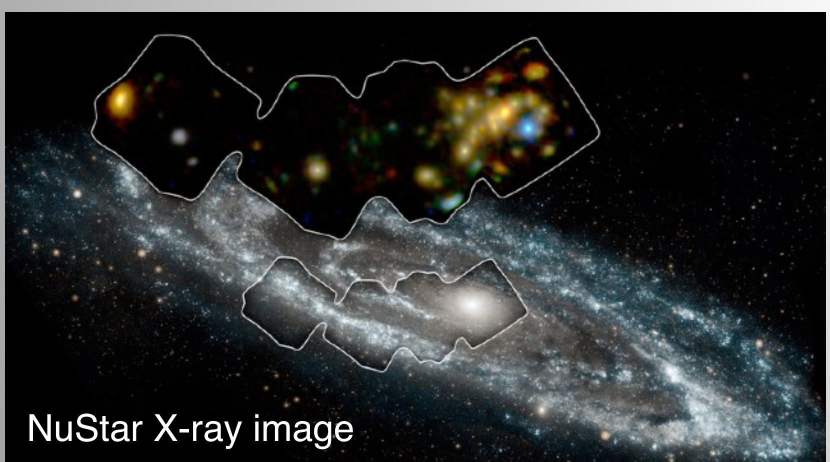
The details:
Gamma-ray signal 4-5x more luminous than GCE
10x lower star formation rate and 5-6x more massive bulge than MW

Credit: NASA/GSFC

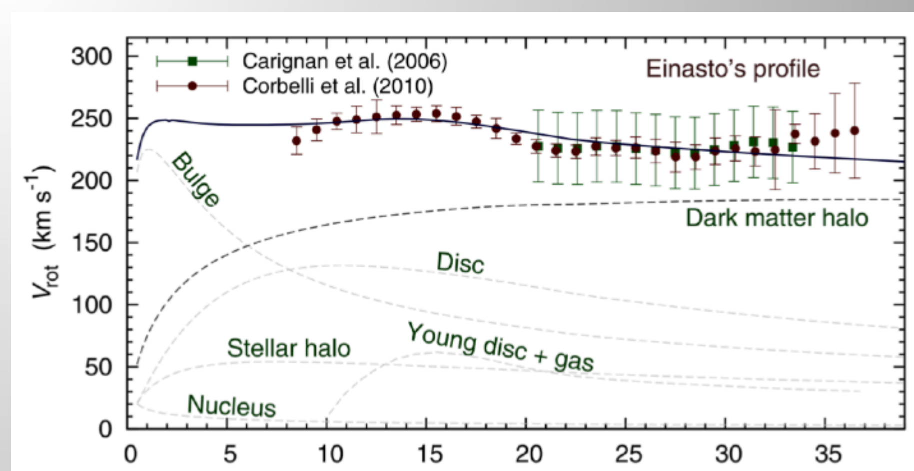
γ rays@M31: Interpretations

Old stellar populations: Low-mass X-ray binaries and MSPs… found in the inner regions of M31 *(reminiscent of the GCE)*

Consistent with DM from GCE?



https://www.jpl.nasa.gov/news/news.php?feature=4811

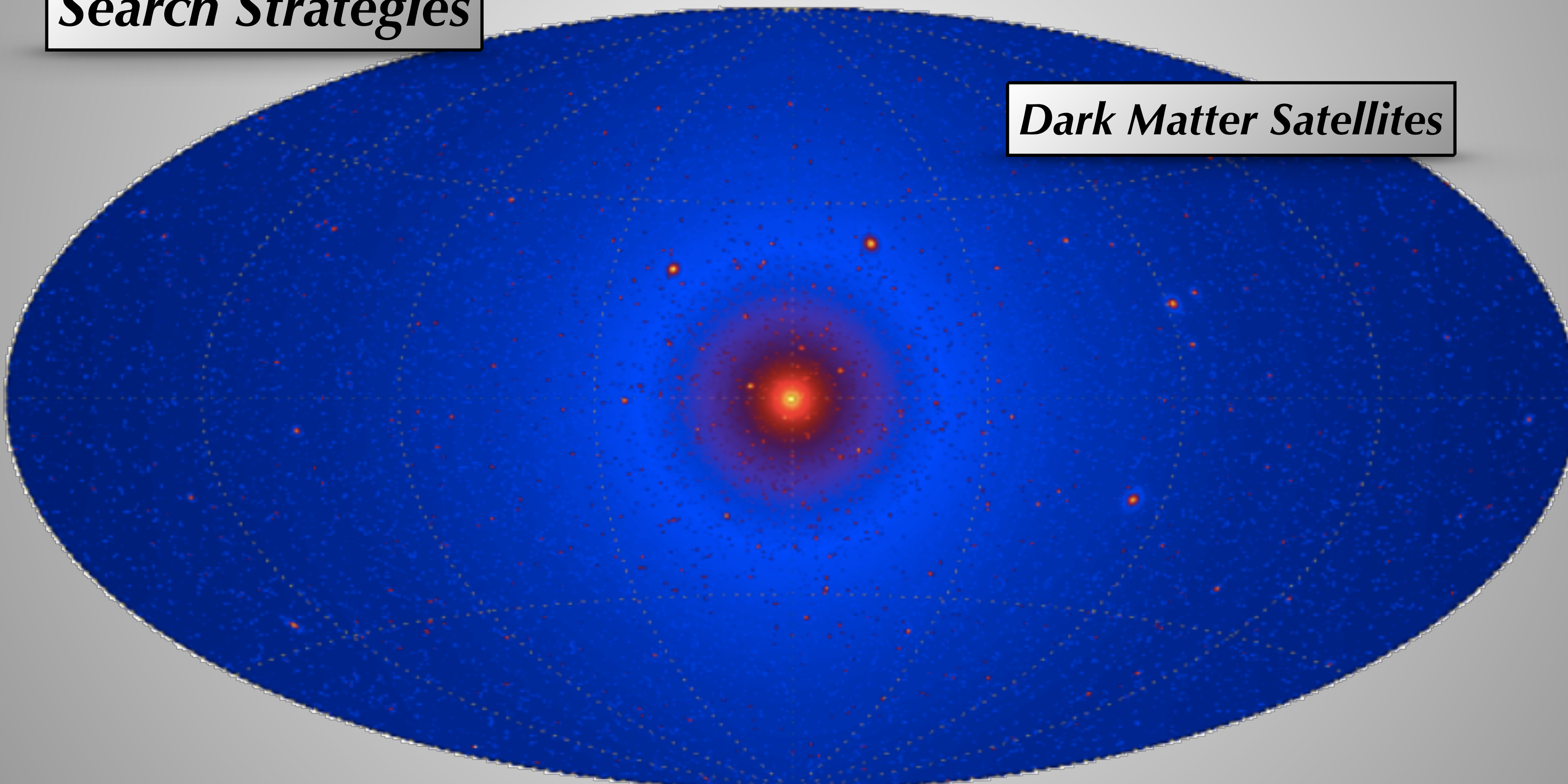


Tamm et al. (2012)

J-factors:
Milky Way: 2×10^{22} GeV^2/cm^5
M31: 8×10^{18} GeV^2/cm^5

Model of Dark Matter Distribution

Search Strategies

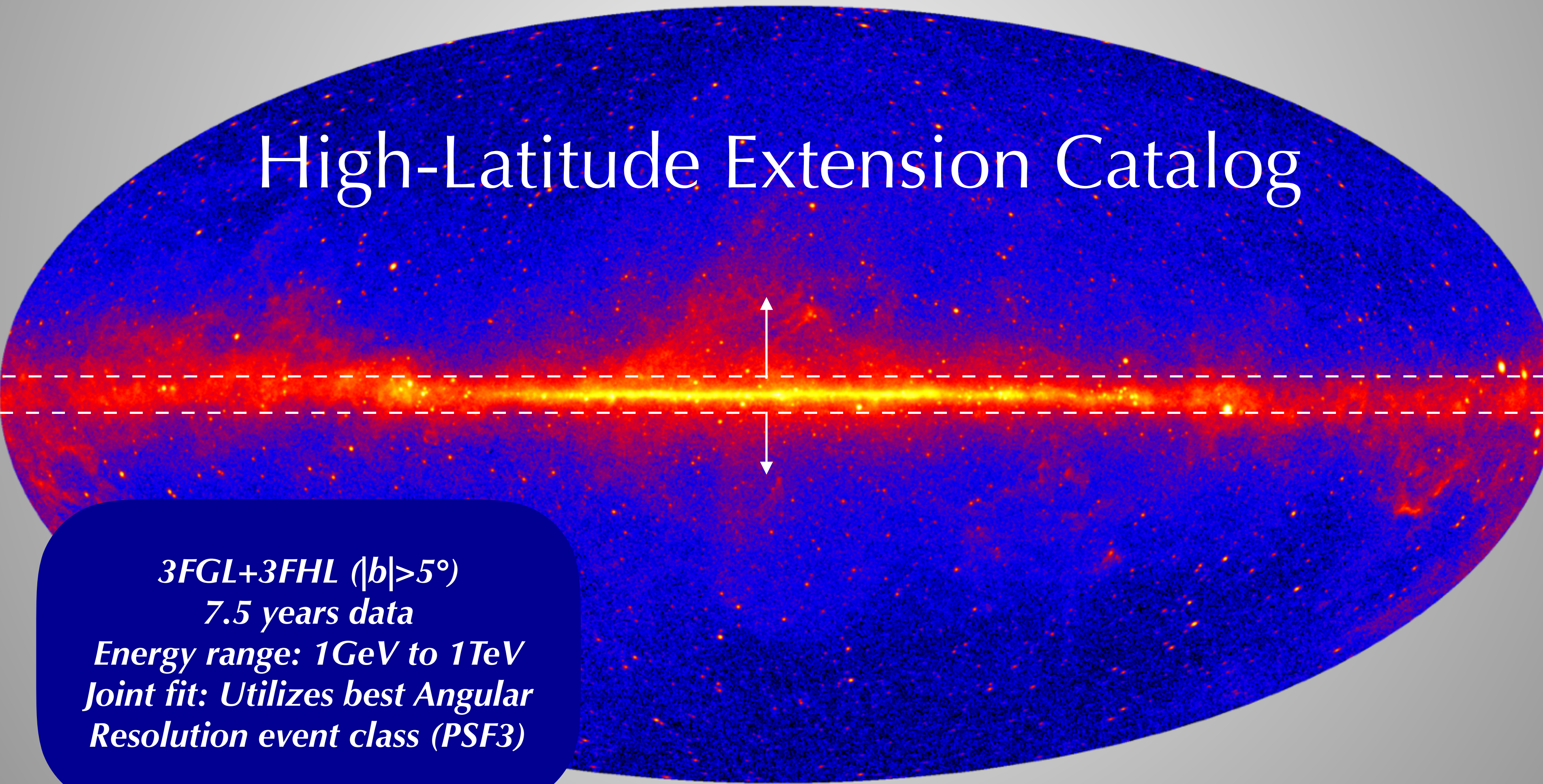


Dark Matter Satellites

L. Pieri et al., PRD83:023518,2011

Unassociated Extended Sources

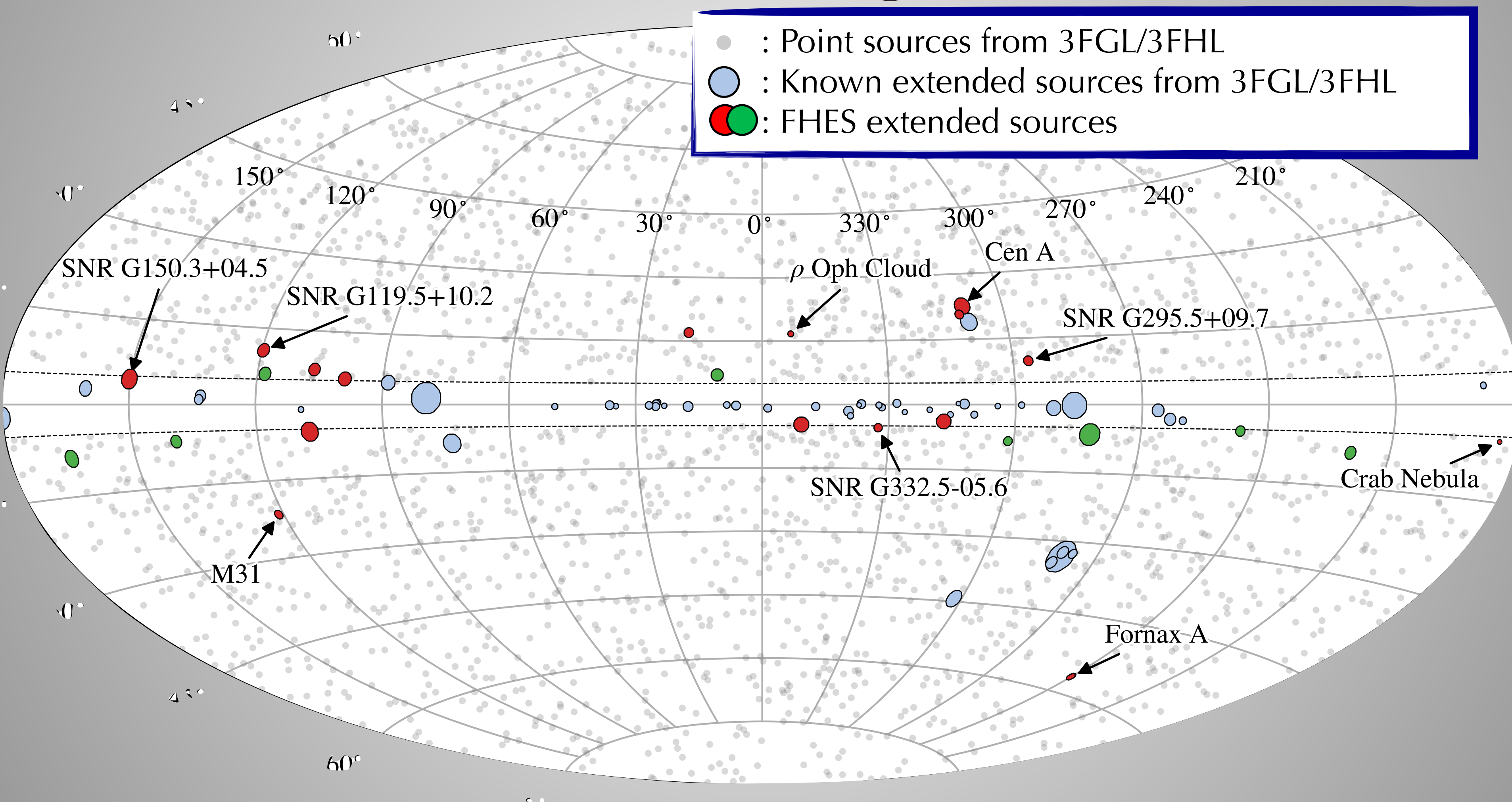
High-Latitude Extension Catalog



3FGL+3FHL (|b|>5°)
7.5 years data
Energy range: 1GeV to 1TeV
Joint fit: Utilizes best Angular Resolution event class (PSF3)

Ackermann, RC, et al., arXiv: 1804.08035

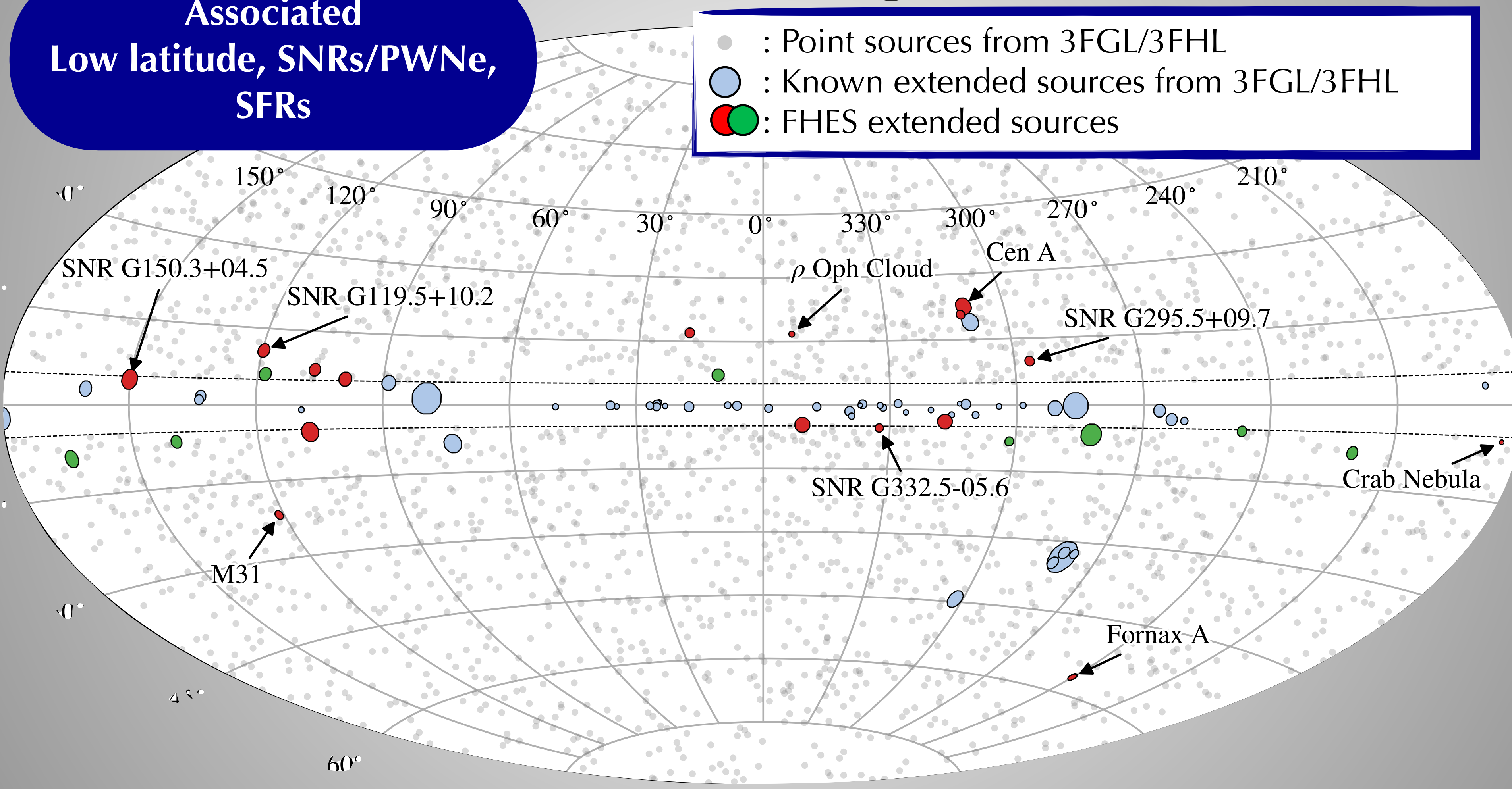
High-Latitude Extension Catalog



Ackermann, RC, et al., arXiv: 1804.08035

High-Latitude Extension Catalog

Associated
Low latitude, SNRs/PWNe, SFRs



Ackermann, RC, et al., arXiv: 1804.08035

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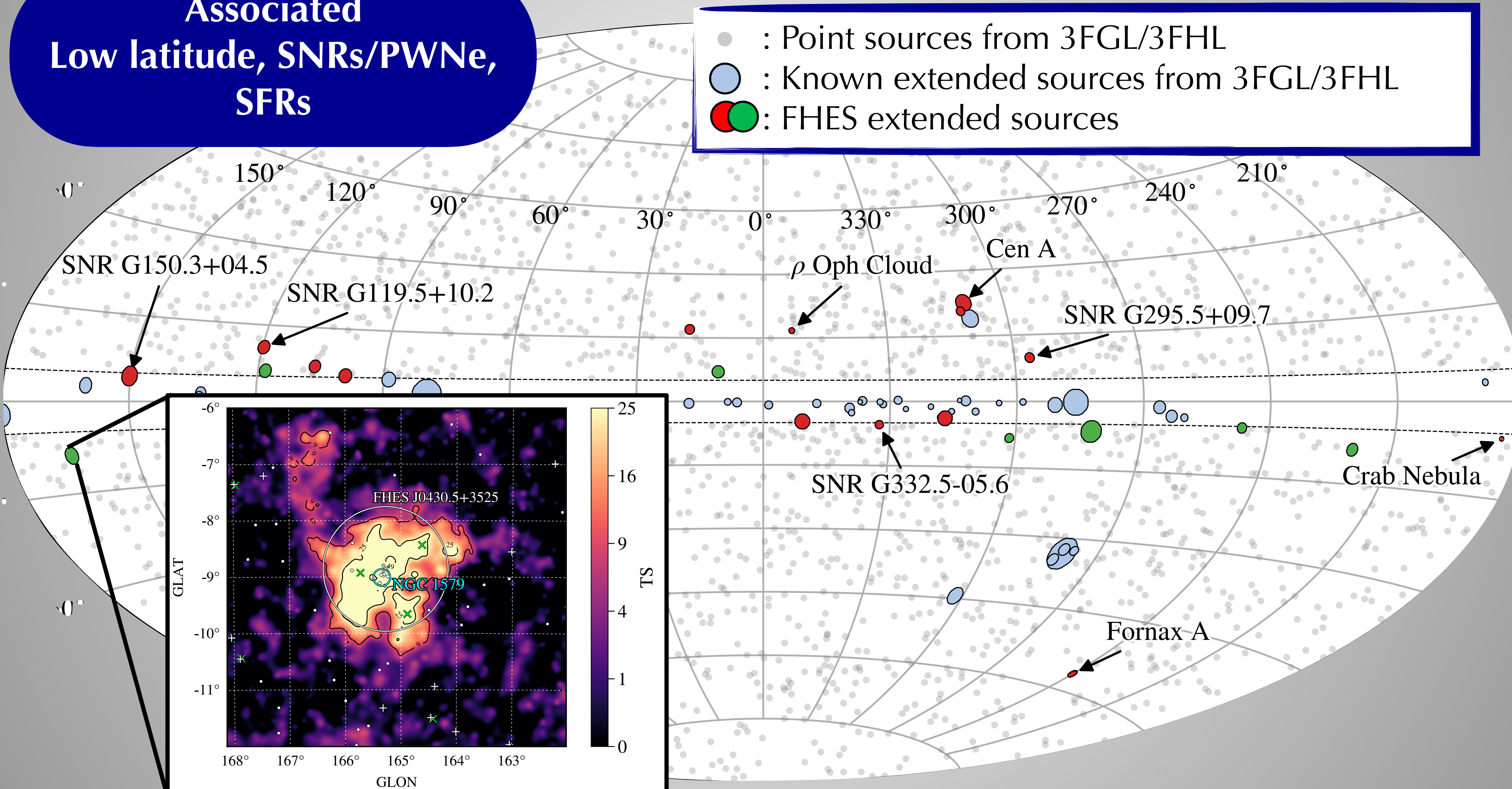

Ackermann, RC, et al., arXiv: 1804.08035

High-Latitude Extension Catalog

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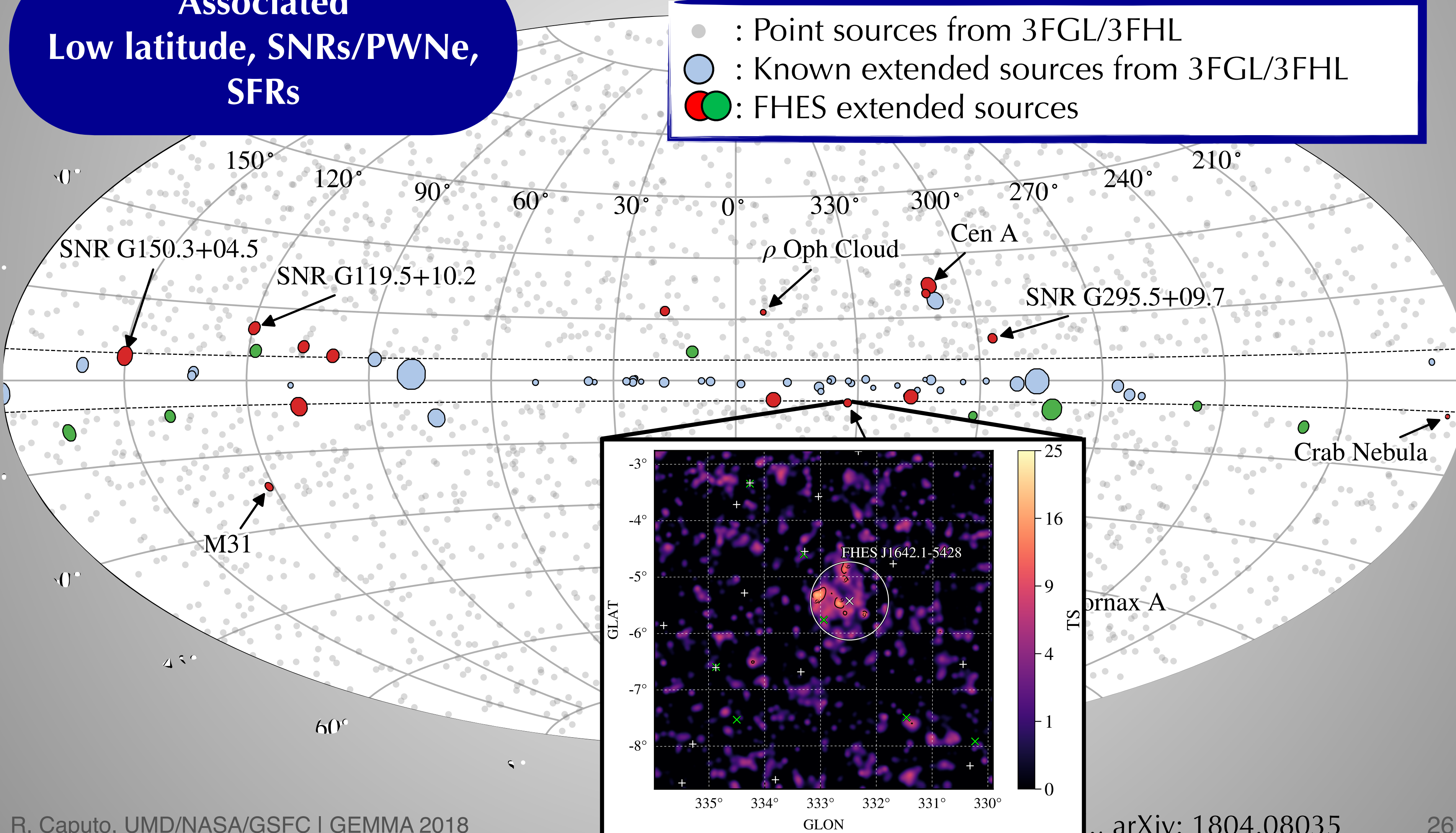

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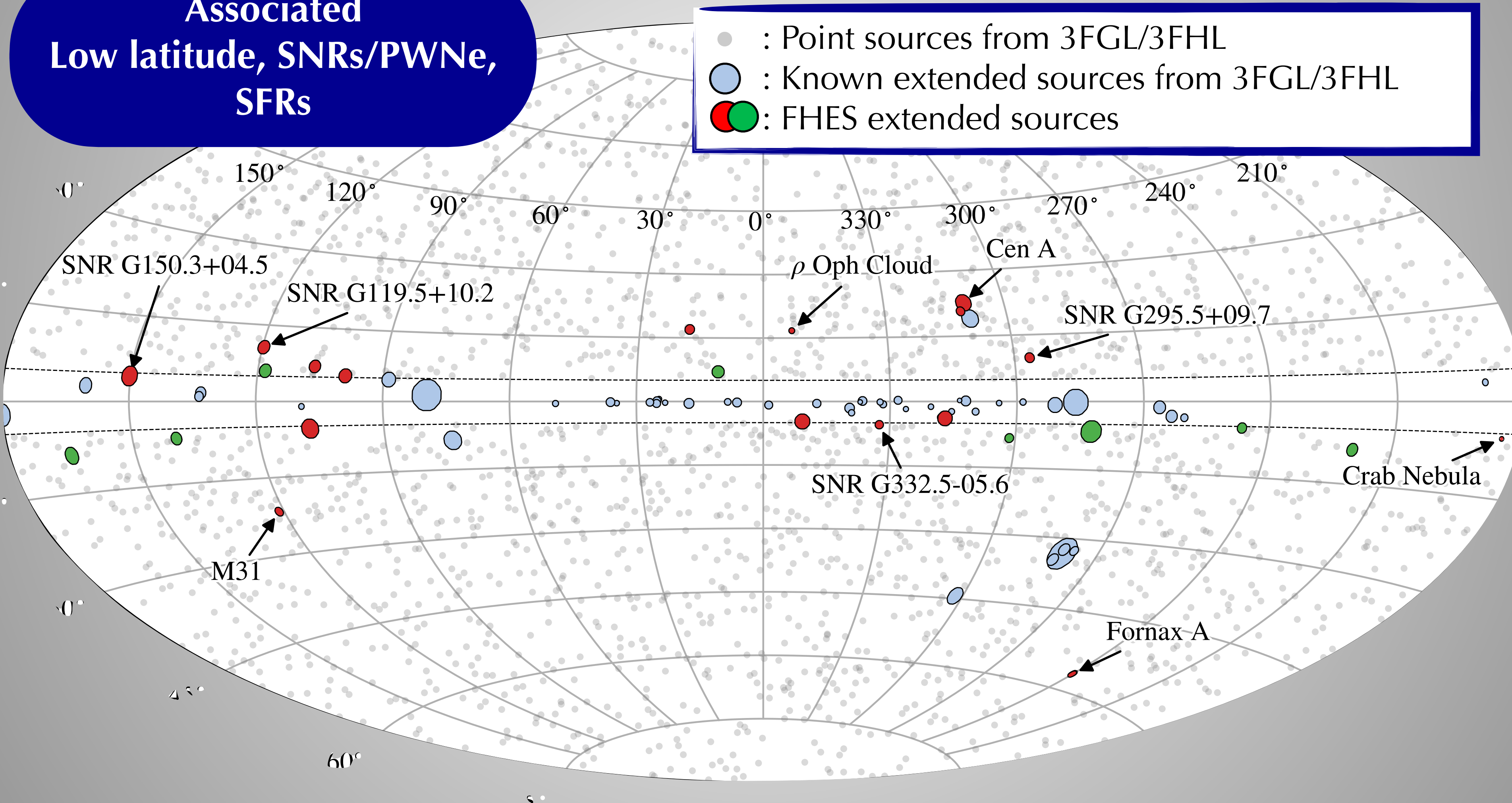


Ackermann, RC, et al., arXiv: 1804.08035

Searching for extended populations

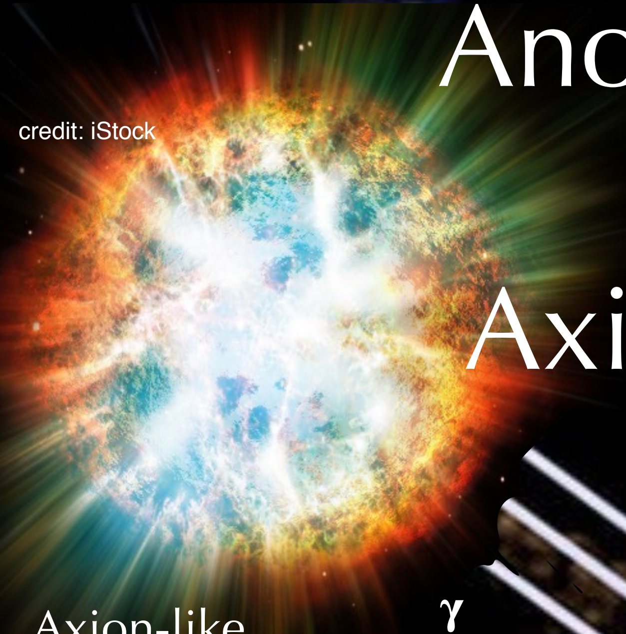
Method	Stacking
Control	Pulsars: 89
Control	Low-synchrotron peaked AGN: 246
Tested Sample	High-synchrotron peaked AGN (sub groups within) ~300
Tested Sample	Chen et al. (2015): 24 sources TeV detected AGN: 38 sources

Searching for extended populations

Method	Stacking
Control	Pulsars: 89
Control	…n peaked AGN: 246
Tes… …ample	High-synchrotron peaked AGN (sub groups within) ~300
Tested Sample	Chen et al. (2015): 24 sources TeV detected AGN: 38 sources

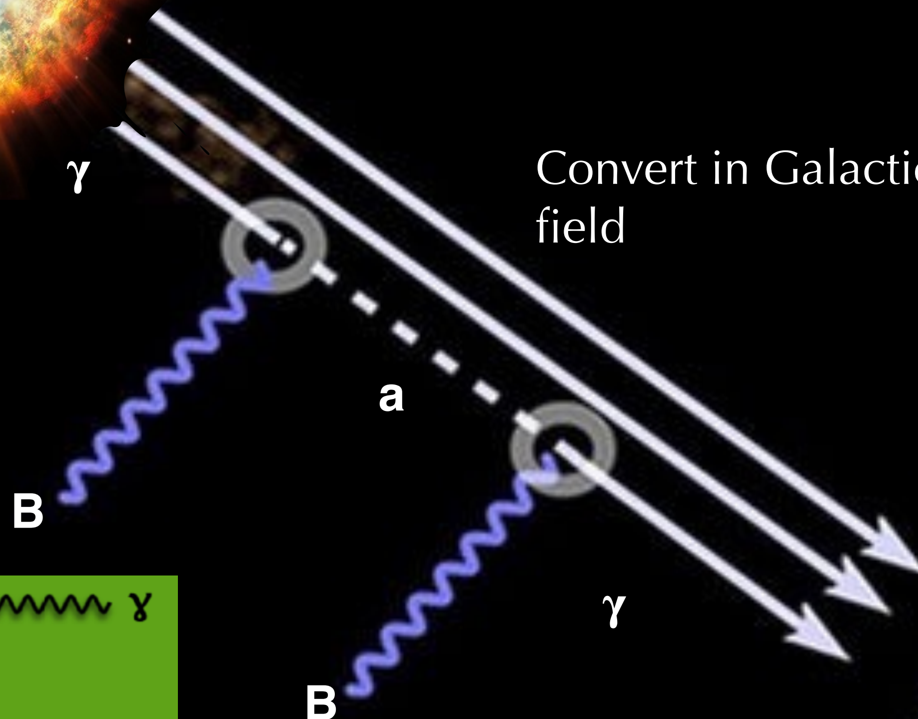
No Significant Extension Found

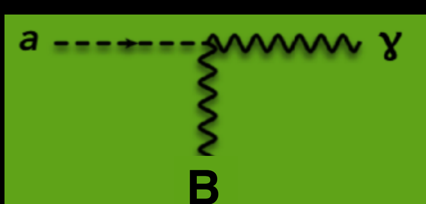
Another Dark Matter Candidate: Axion-Like Particles



Axion-like particles produced in a core-collapse supernova

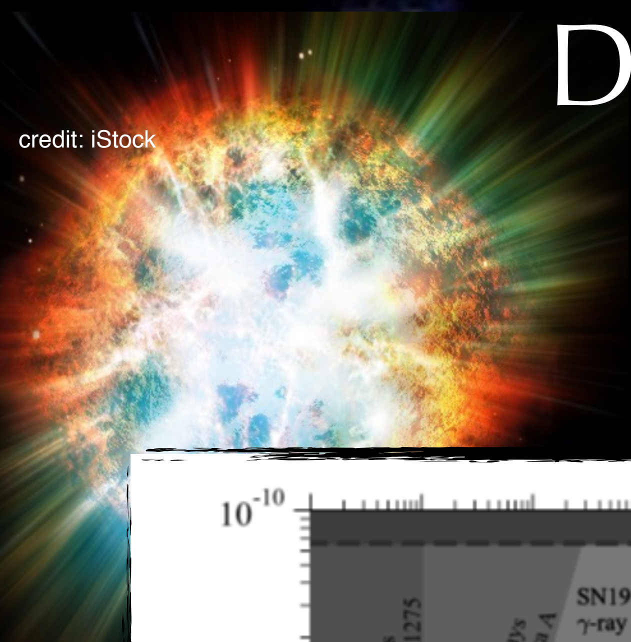
Convert in Galactic magnetic field

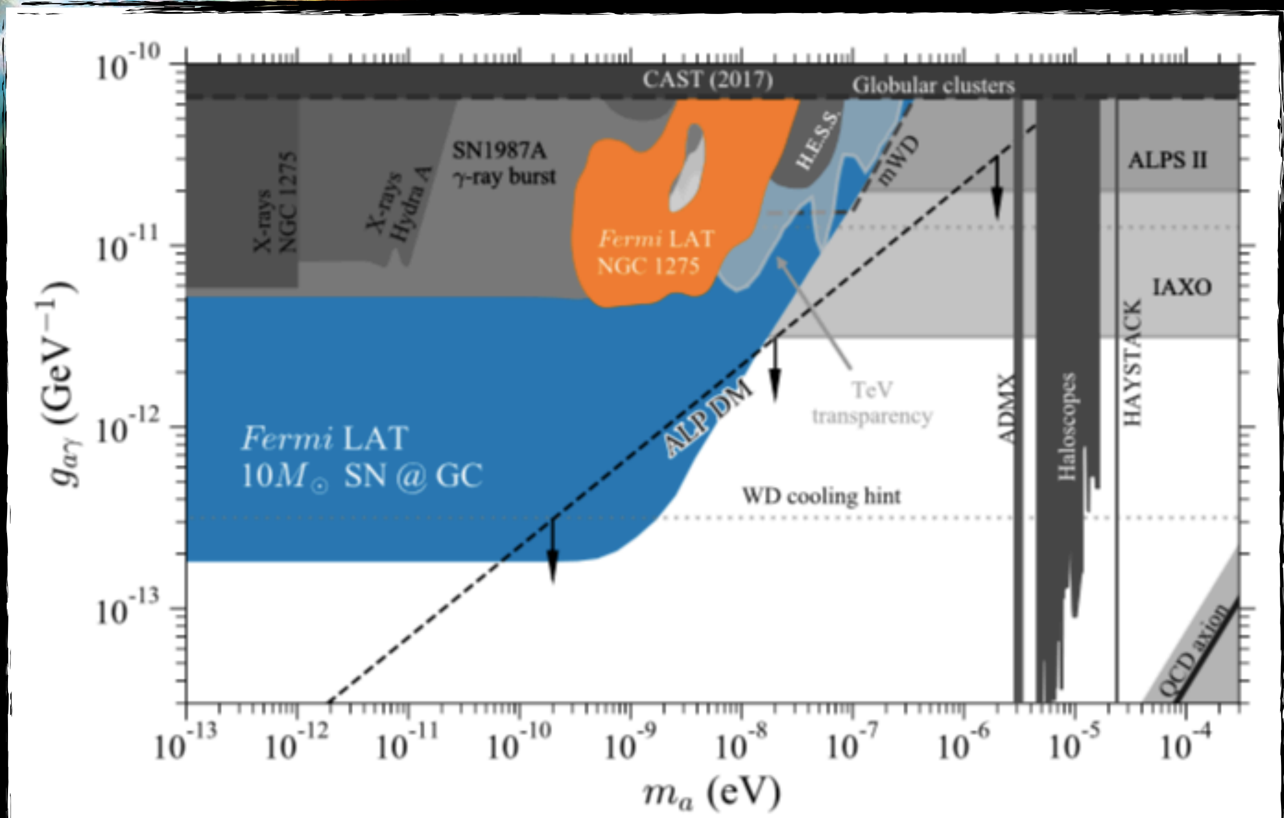




Raffelt & Stodoslky 1988

Dark Matter and Supernovae

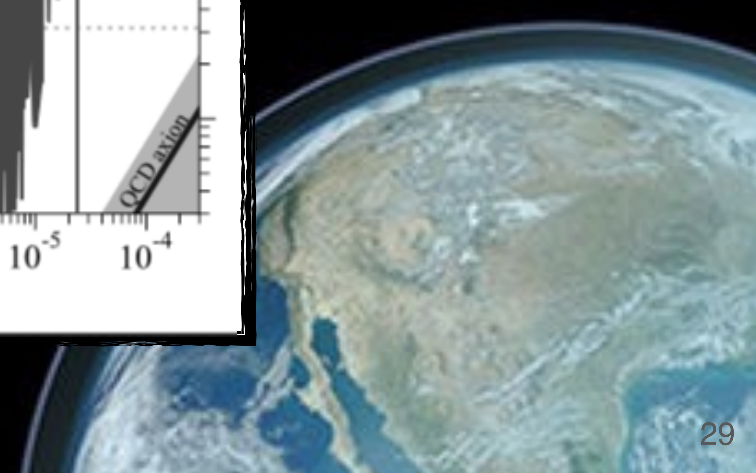




Produced ~10s with neutrinos

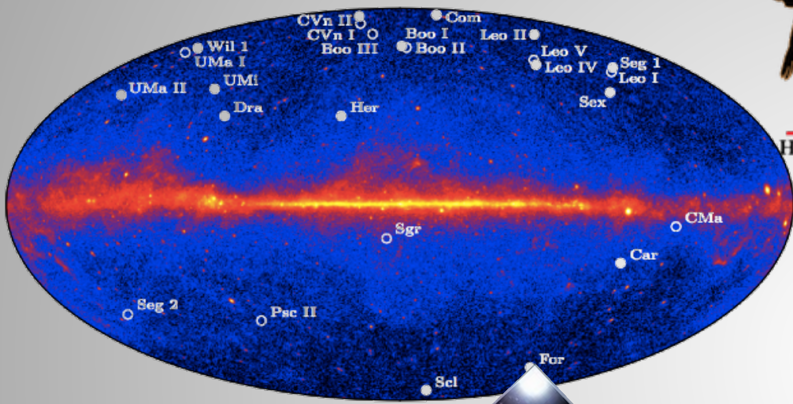
Peak ~60 MeV

Flux ∝ $g_{a\gamma}^4$



Meyer et al., 2017

The Next Generation…



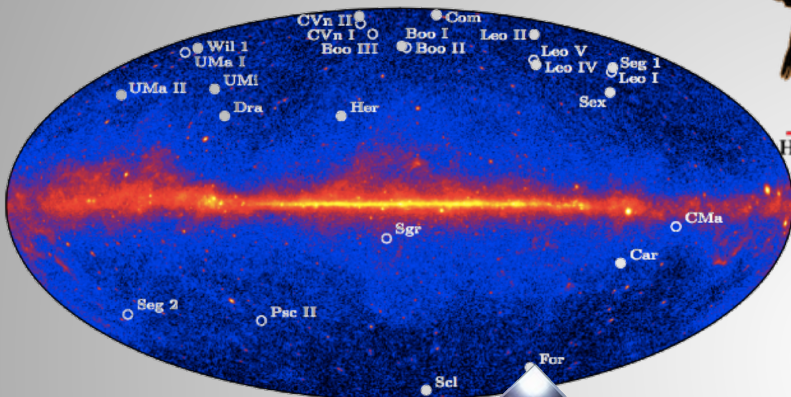
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

DARK ENERGY
SURVEY

Fermi DES/IACTs/HAWC

Today 2018 2020 2023 2020s

The Next Generation…



HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

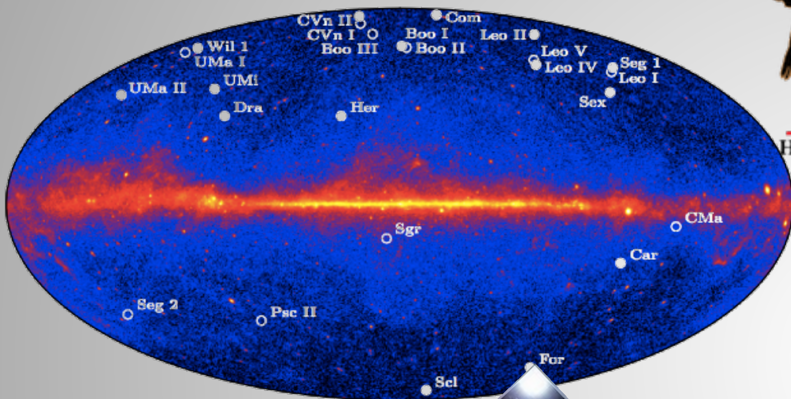
DARK ENERGY SURVEY

LSST

Fermi DES/IACTs/HAWC LSST

Today 2018 2020 2023 2020s

The Next Generation…



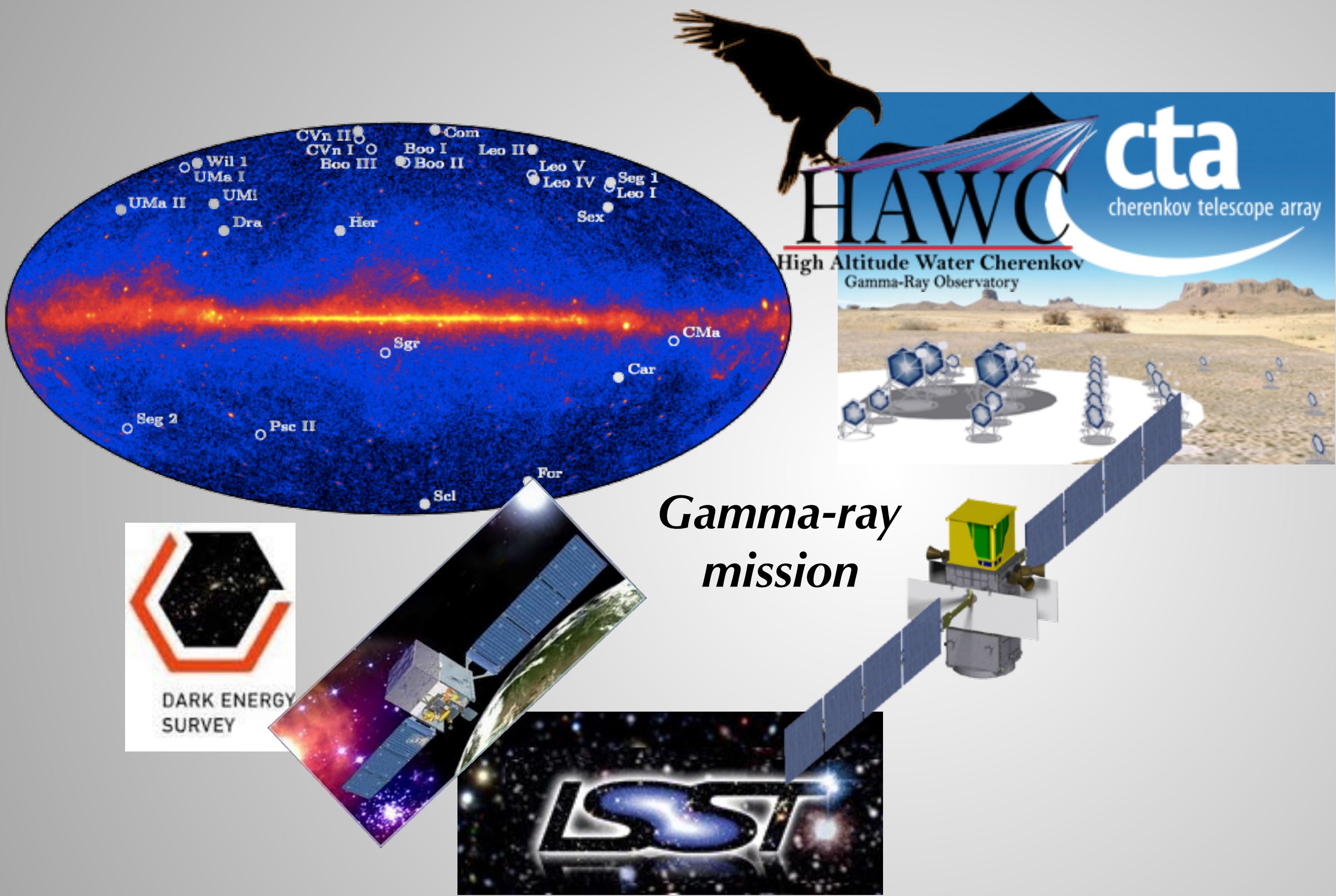
DARK ENERGY SURVEY

LSST

Fermi DES/IACTs/HAWC LSST CTA

Today 2018 2020 2023 2020s

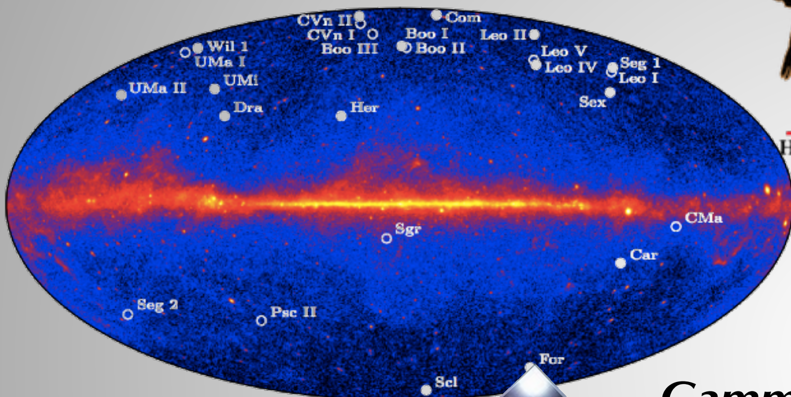
The Next Generation…



Gamma-ray mission

Fermi	DES/IACTs/HAWC	LSST	CTA	MeV Mission
Today 2018		2020	2023	2020s

The Next Generation…



DARK ENERGY SURVEY

Gamma-ray mission

Gamma rays are the key player

New space-based gamma-ray missions are Essential and Urgent to understand anomalies in the current data and to complement upcoming facilities

Fermi DES/IACTs/HAWC LSST CTA MeV Mission

Today 2018 2020 2023 2020s

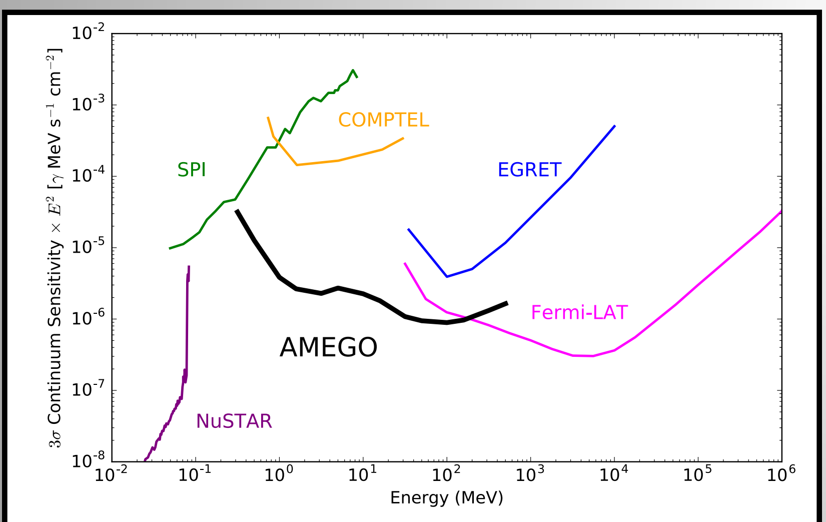
The Next Generation…

Proposed new gamma-ray missions…

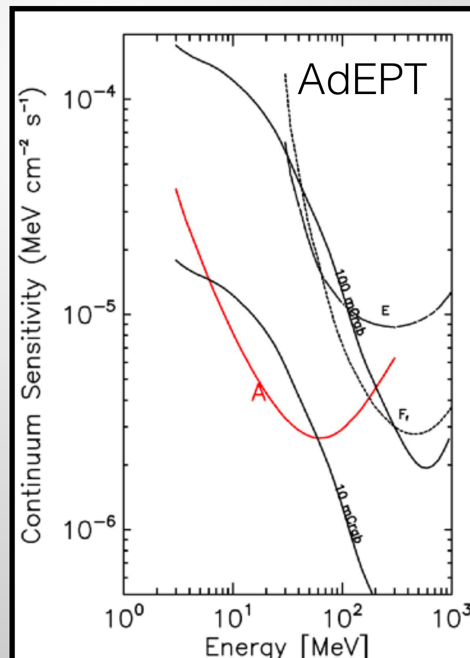
All-sky Medium Energy Gamma-ray Observatory: ***AMEGO***

Advanced Energetic Pair Telescope: ***AdEPT***

- incomplete list -

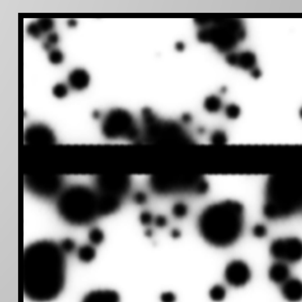


RC, et al., PoS (ICRC2017) 783



Astropart. Phys 59 (2014) 18-28

View of the Galactic Plane



ComPair arXiv:1508.07349

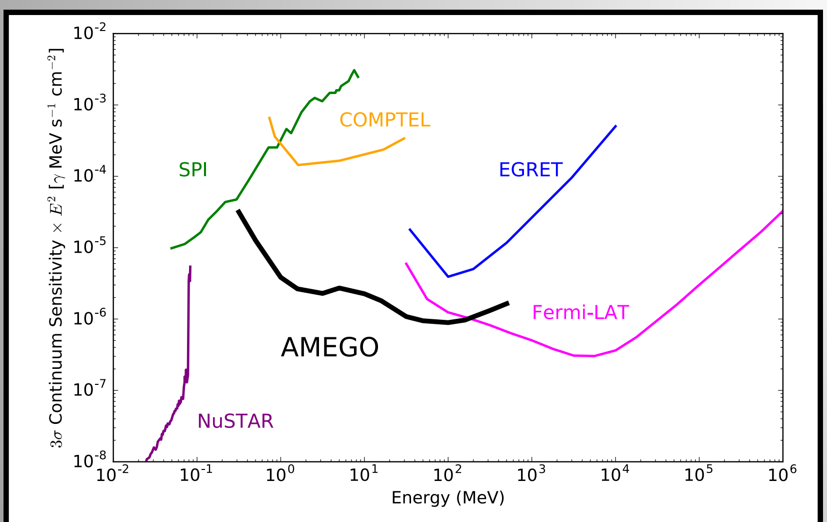
The Next Generation…

Proposed new gamma-ray missions…

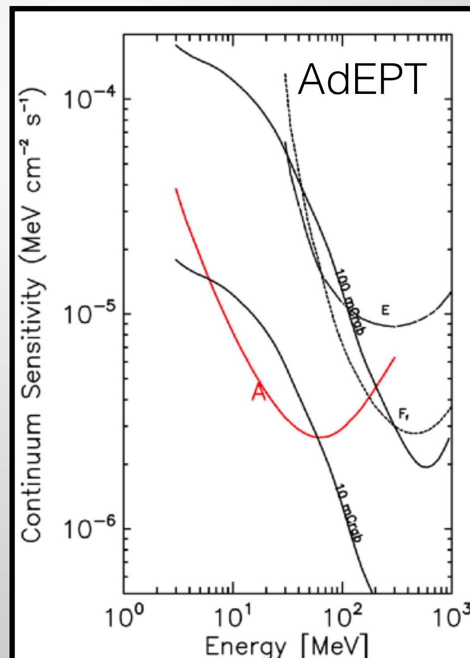
All-sky Medium Energy Gamma-ray Observatory: ***AMEGO***

Advanced Energetic Pair Telescope: ***AdEPT***

- incomplete list -



RC, et al., PoS (ICRC2017) 783



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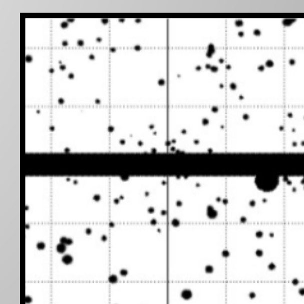
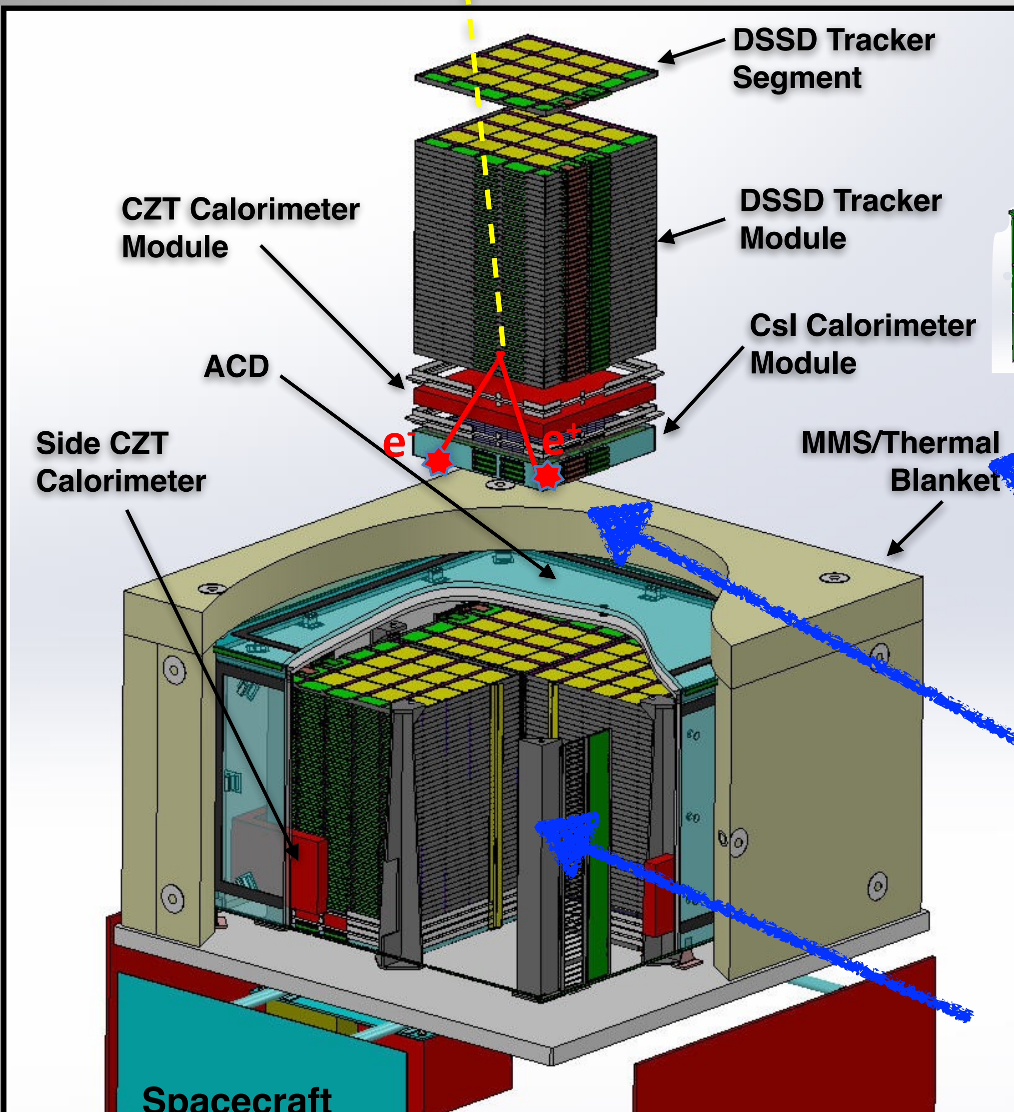


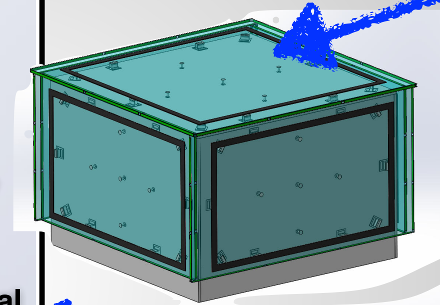
Next-Gen MeV

ComPair arXiv:1508.07349

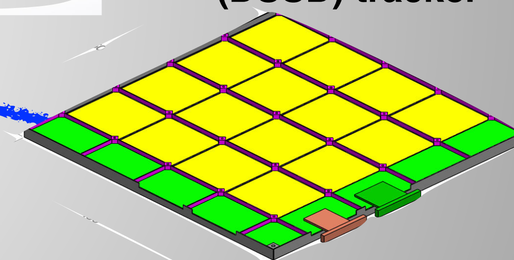
AMEGO Instrument

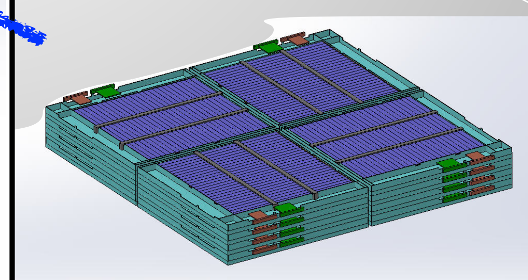


Anti-Coincidence Detector plastic scintillator



Segment of Double Sided Silicon Detector (DSSD) tracker

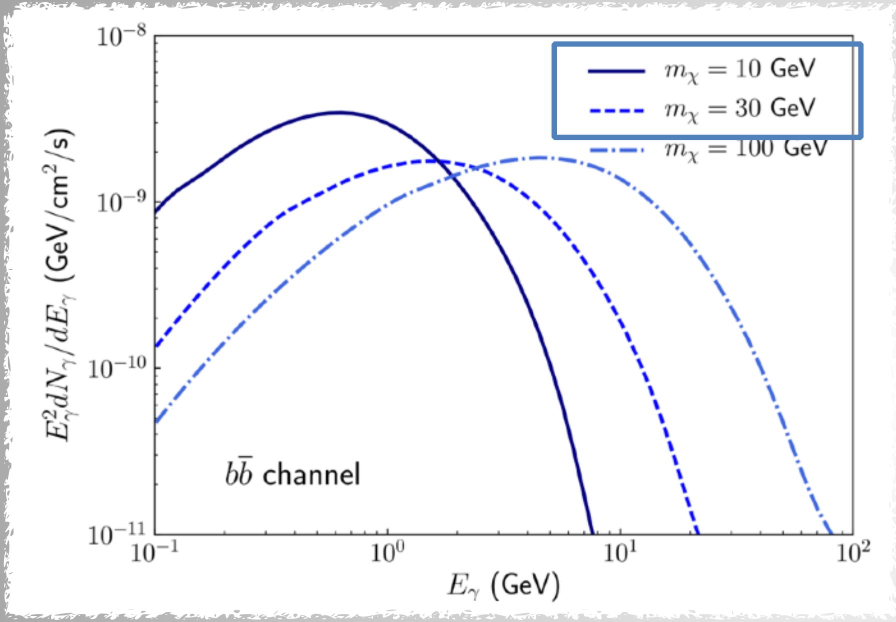




Calorimeter:
4 layers/tower
16 total

Tracker and Calorimeter Towers

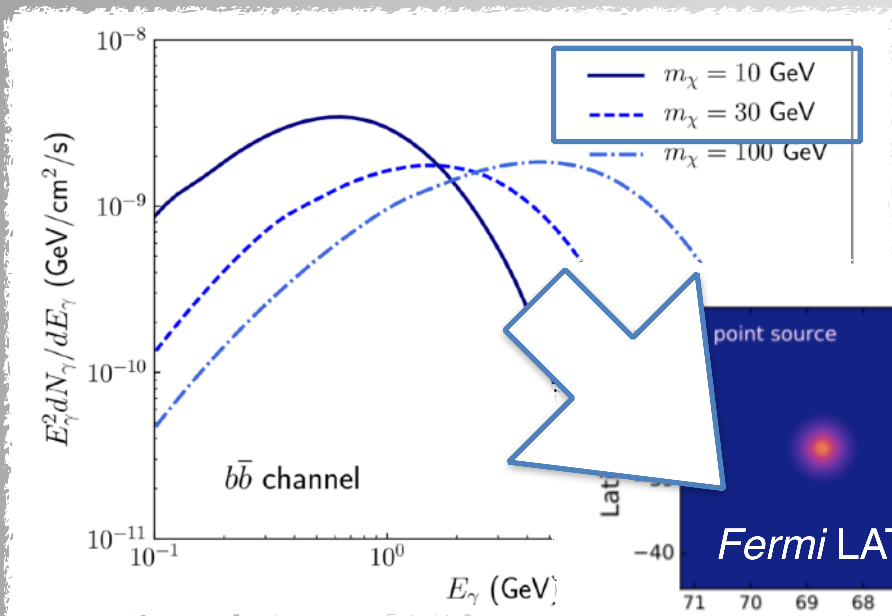
Complementarity in the γ-ray Sky



Relevant for extended sources and Galactic Center

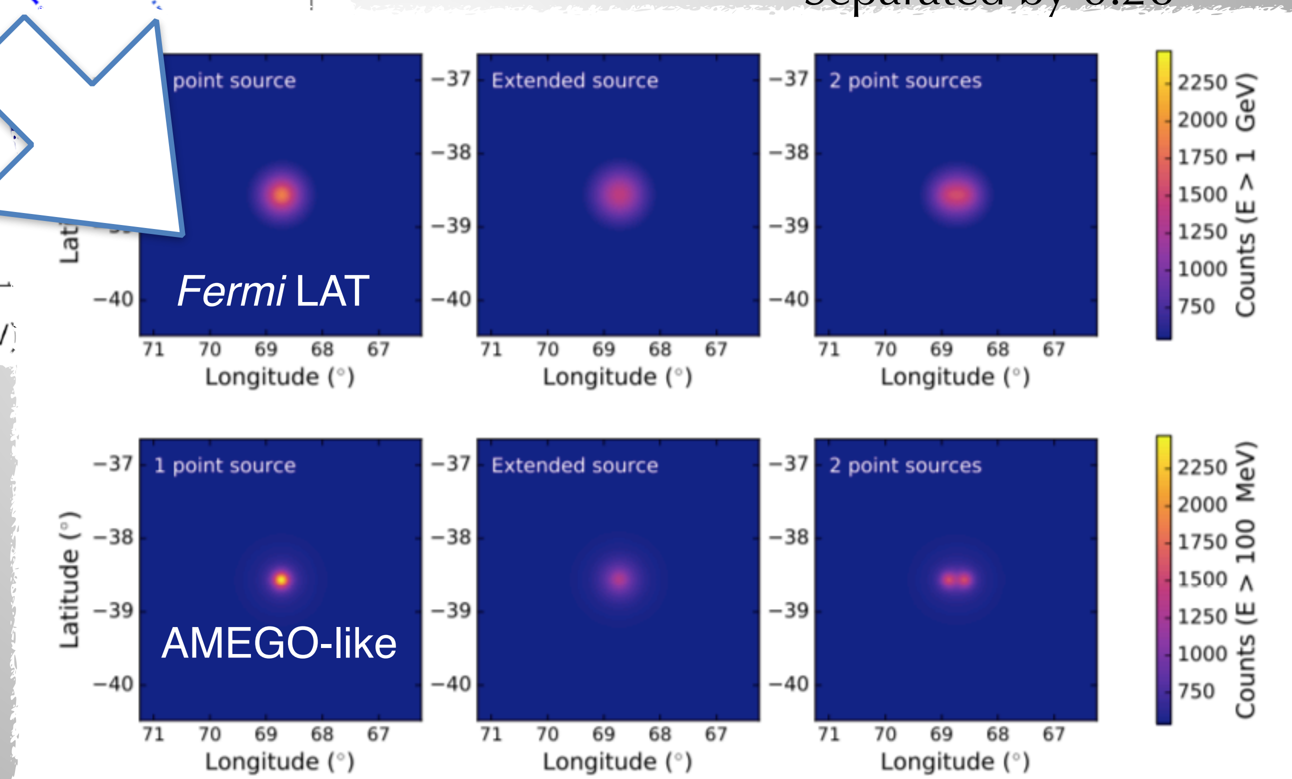
Chou et al. arXiv: 1709.08562

Complementarity in the γ-ray Sky



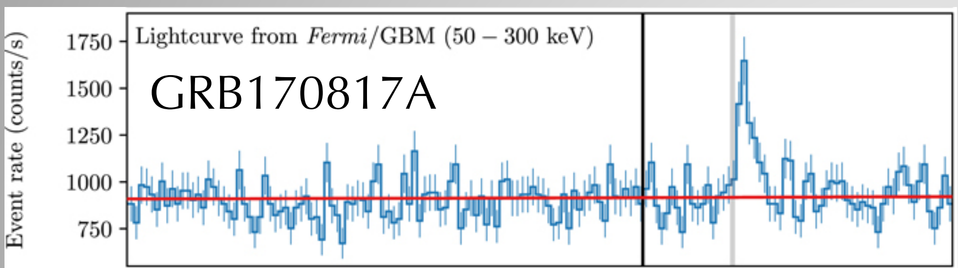
Relevant for extended sources and Galactic Center

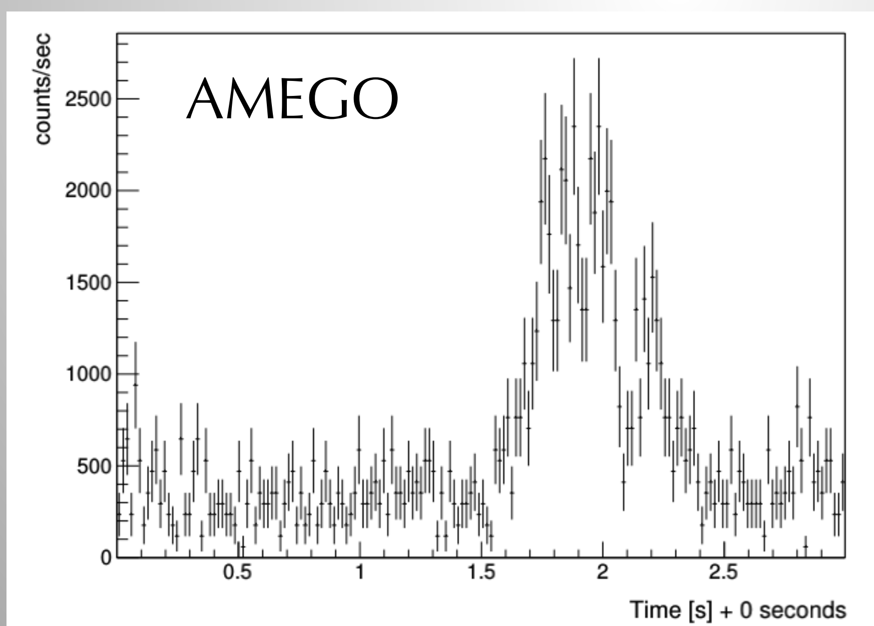
Separated by 0.28°



Chou et al. arXiv: 1709.08562

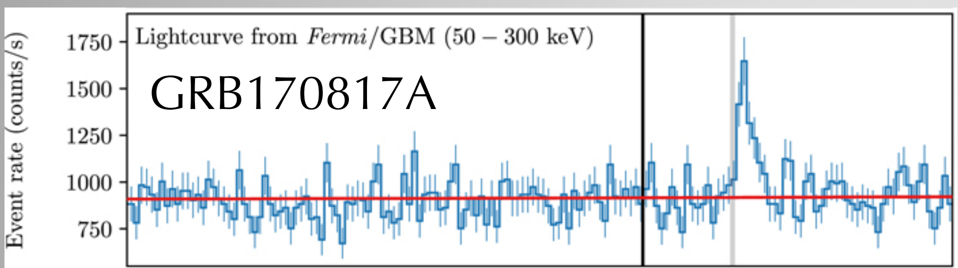
Gamma-ray Bursts with AMEGO



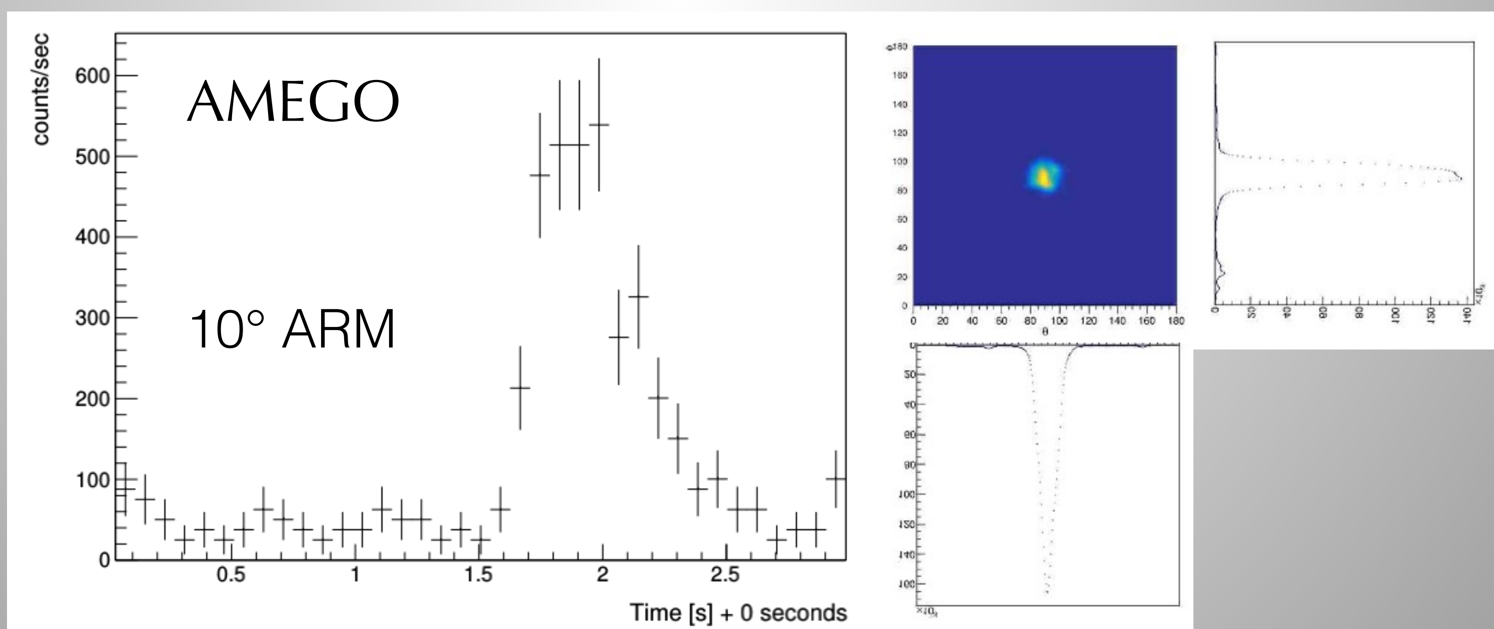


AMEGO Simulations: RC & J. Racusin

Gamma-ray Bursts with AMEGO

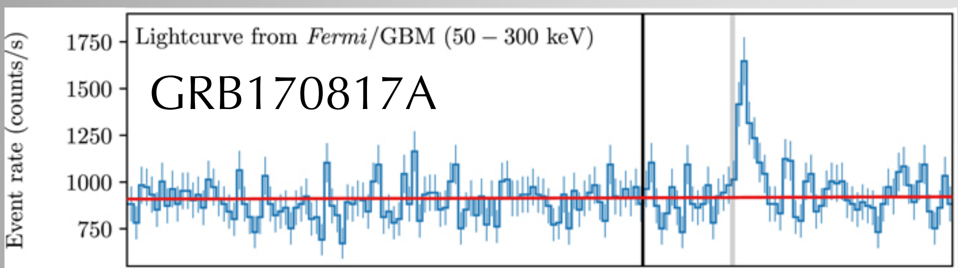


GRB170817A is no longer a faint GRB
⇒Greatly expanded detection horizon

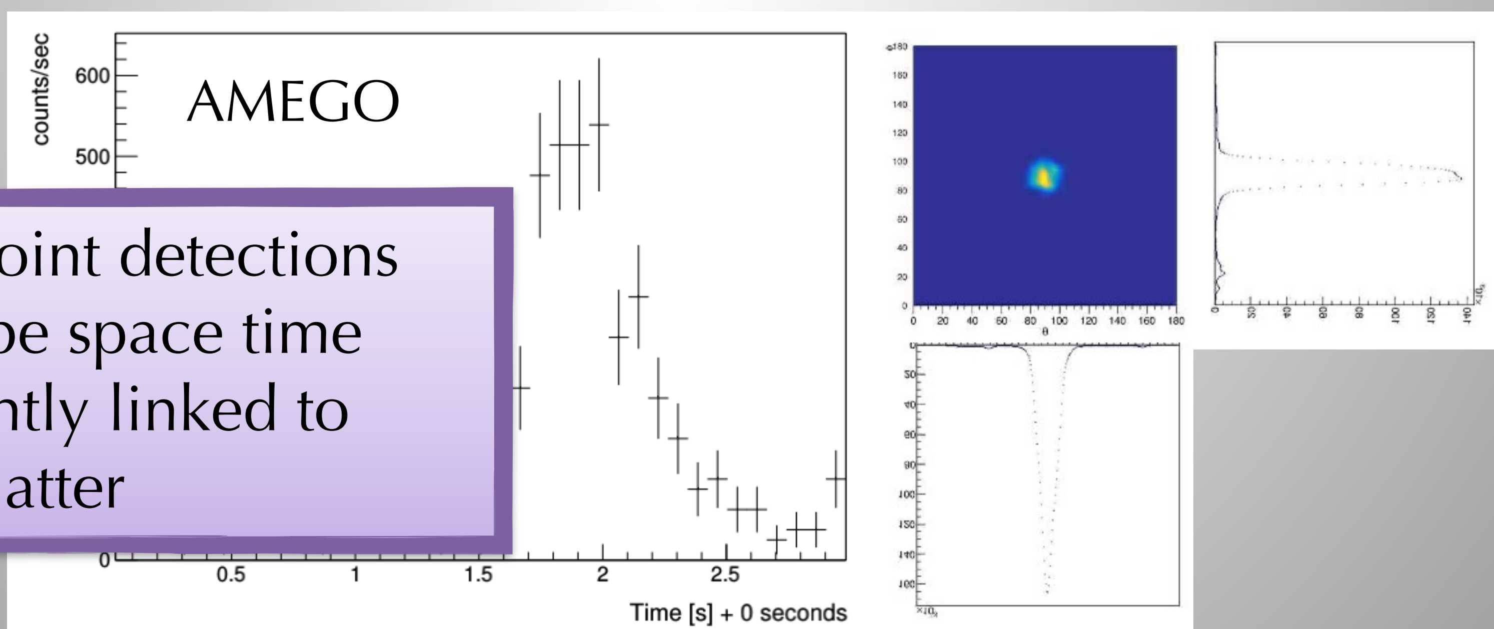


AMEGO Simulations: RC & J. Racusin

Gamma-ray Bursts with AMEGO



GRB170817A is no longer a faint GRB
⇒Greatly expanded detection horizon



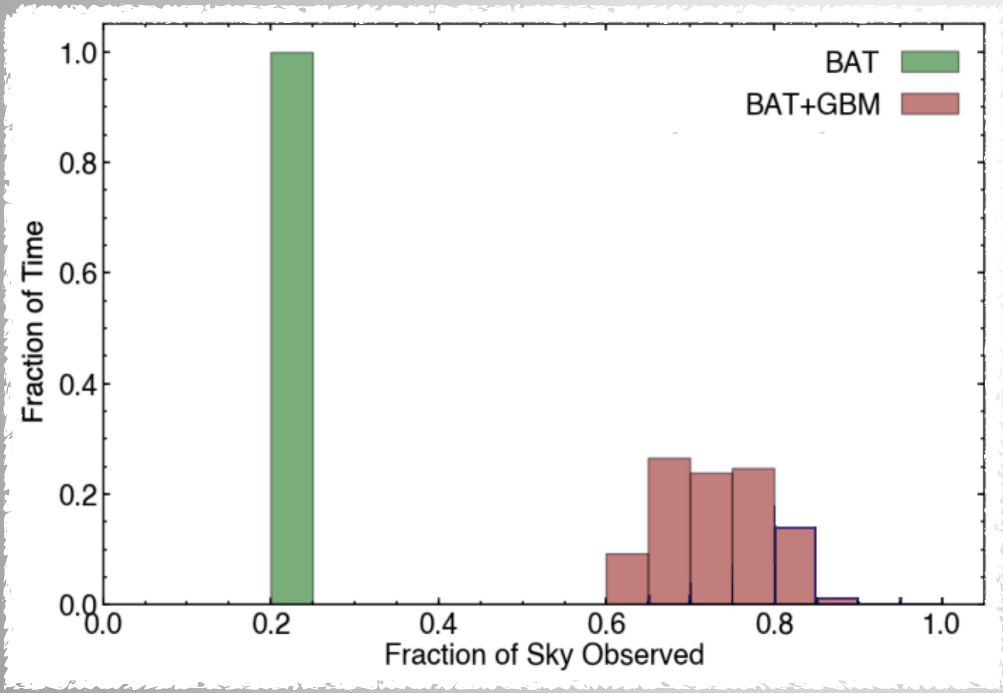
More joint detections ➜ probe space time inherently linked to dark matter

AMEGO Simulations: RC & J. Racusin

The Next Generation…

Funded new gamma-ray missions…

Targeted small satellites looking only for GRBs: Launch in 2021



J.S. Perkins… RC, et al., PoS(ICRC2017)760

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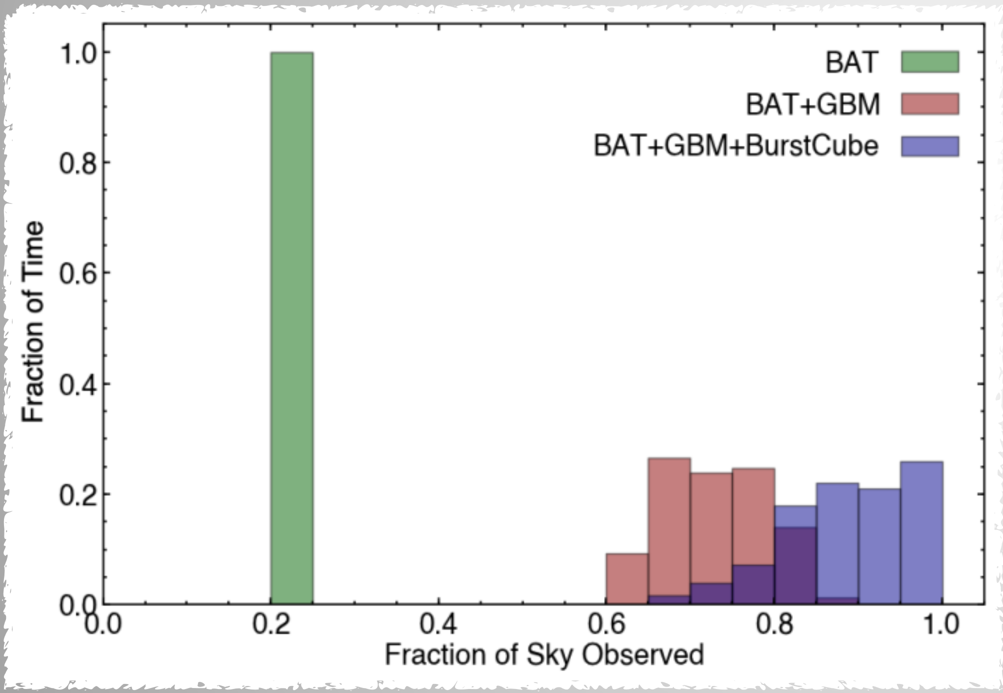

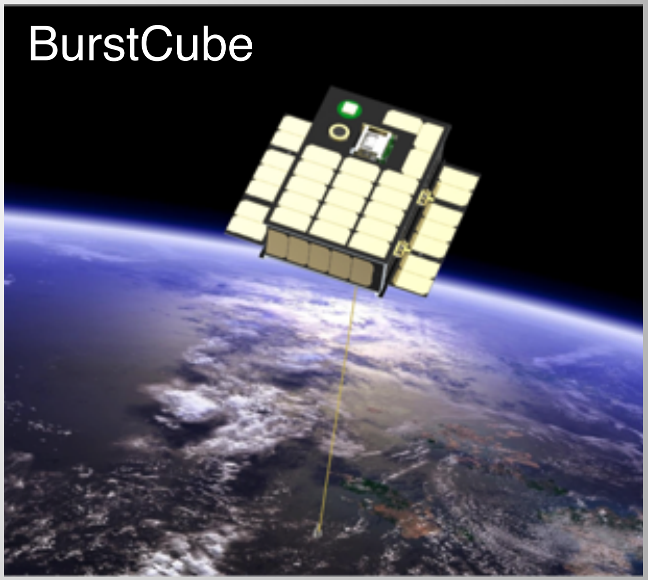

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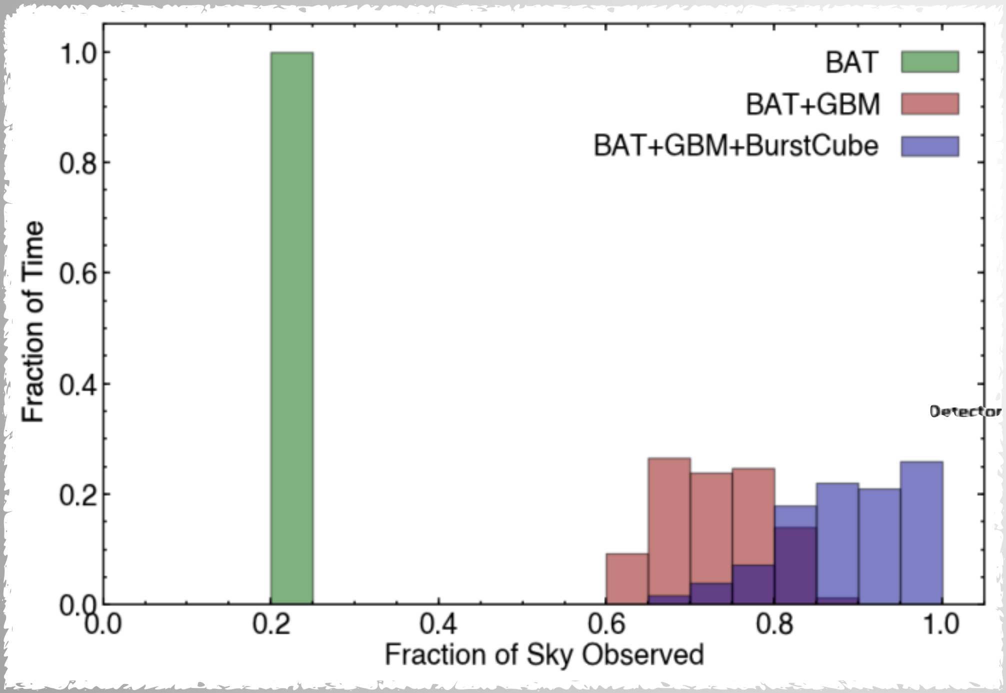

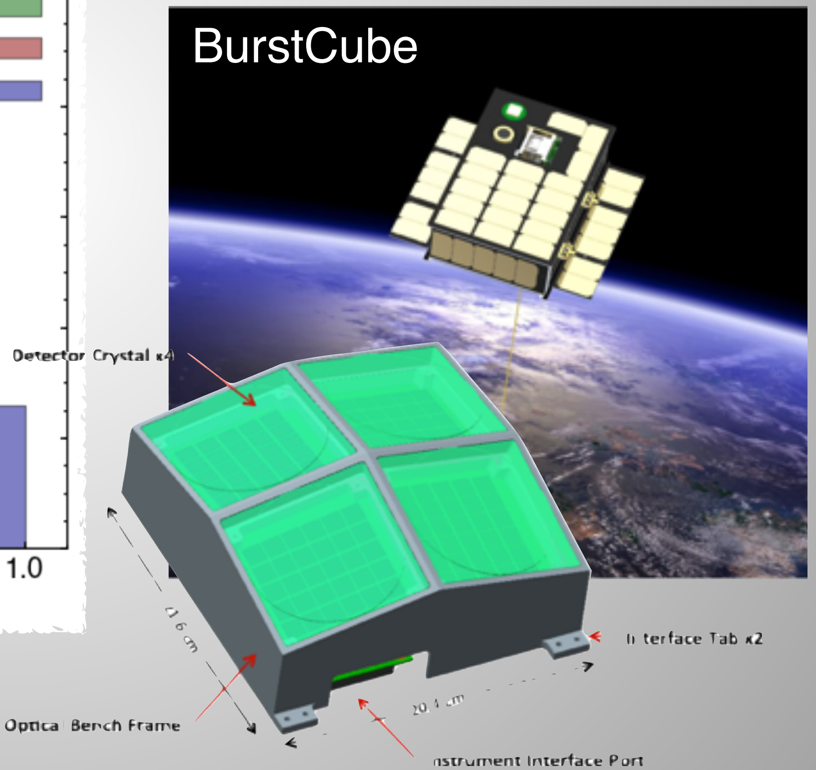

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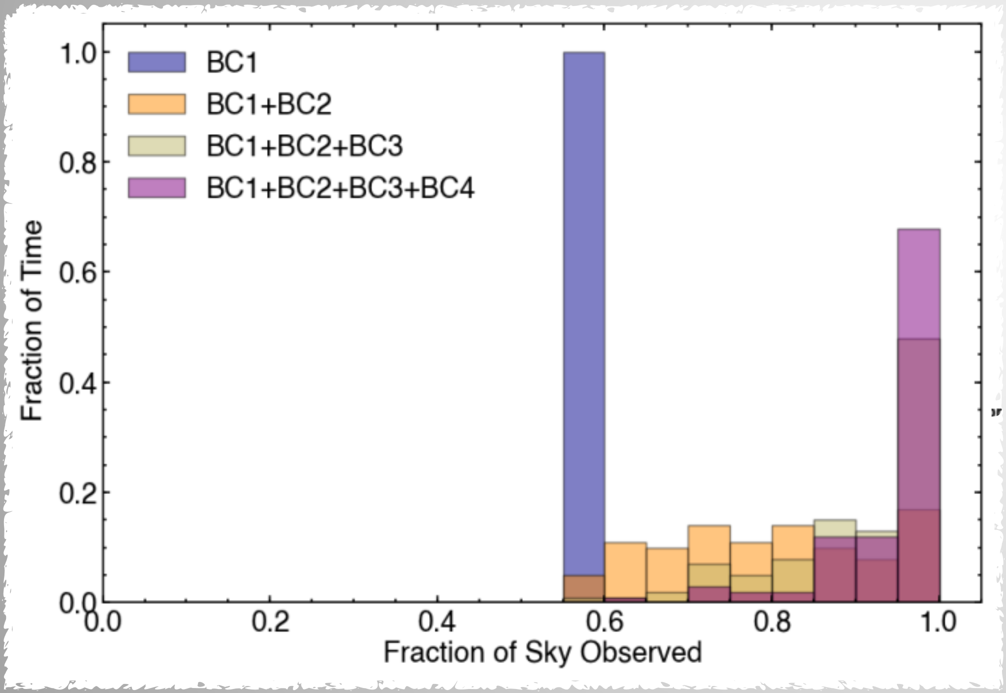

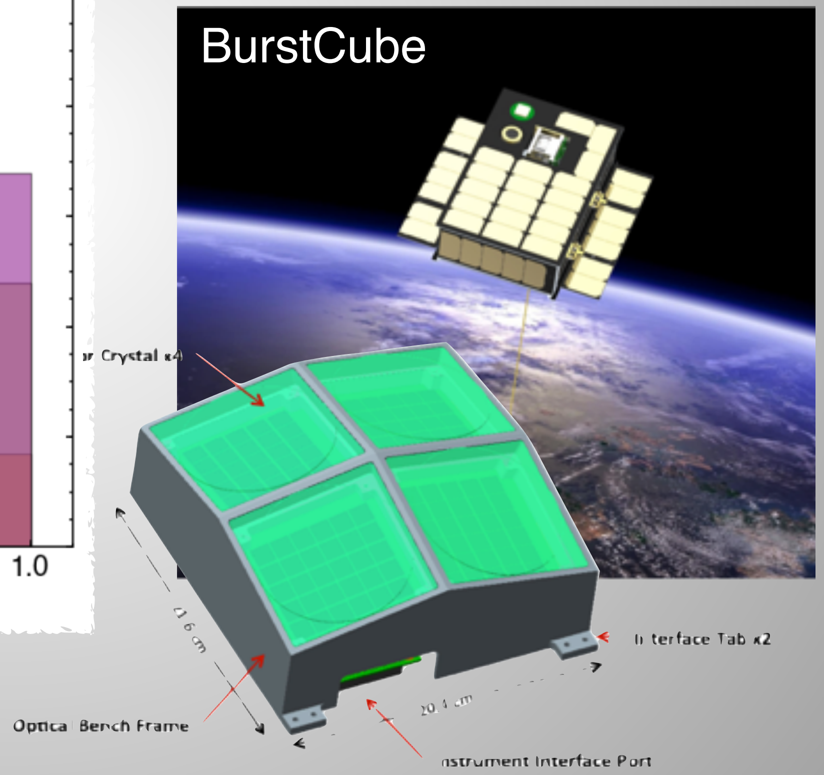

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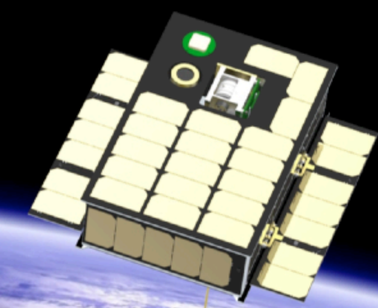
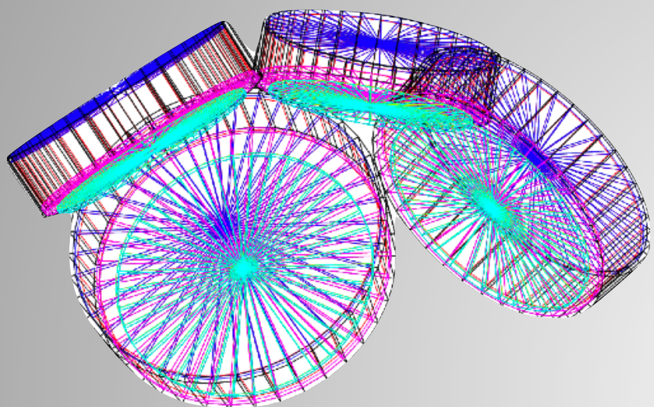
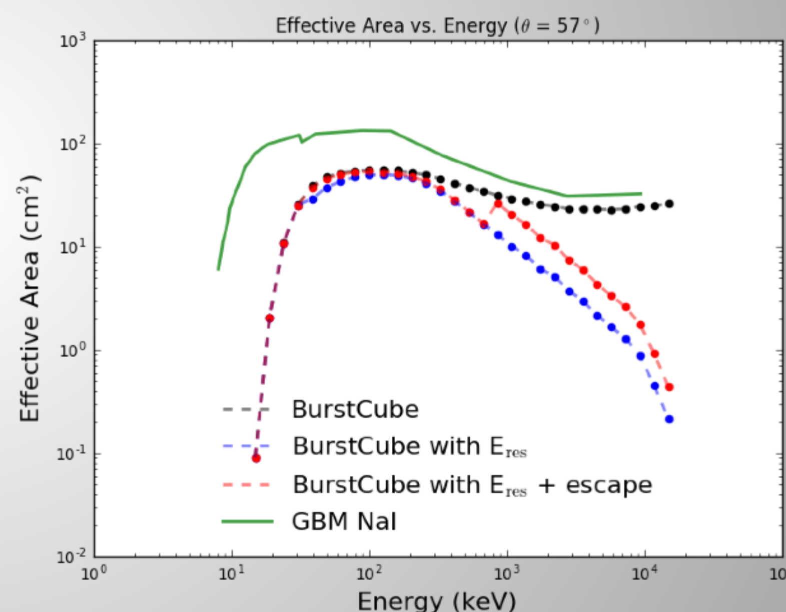
BurstCube



Performance

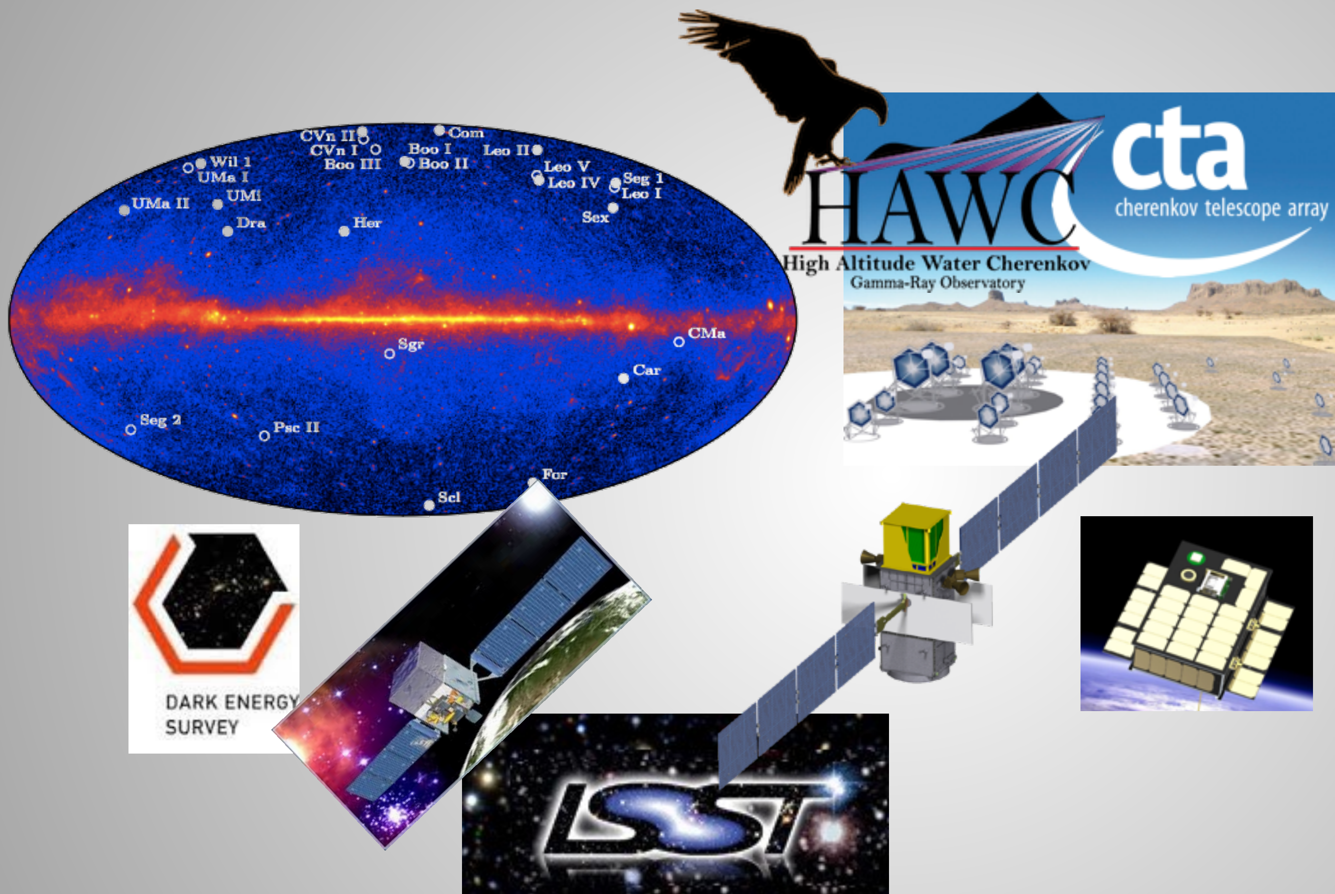


- Spacecraft based on NASA/GSFCs Dellingr platform
- Observes the full un-occulted sky and triggers on significant rate fluctuations
- Complement existing facilities (i.e.: Neil Gehrels Swift Observatory, Fermi Gamma-ray Burst Monitor)



Effective area is 67% that of the GBM NaI detectors at 100 keV
(Simulated using Geant4/MEGAlib)

The Next Generation…



Fermi DES/IACTs/HAWC LSST CTA BurstCube/T.B.S…

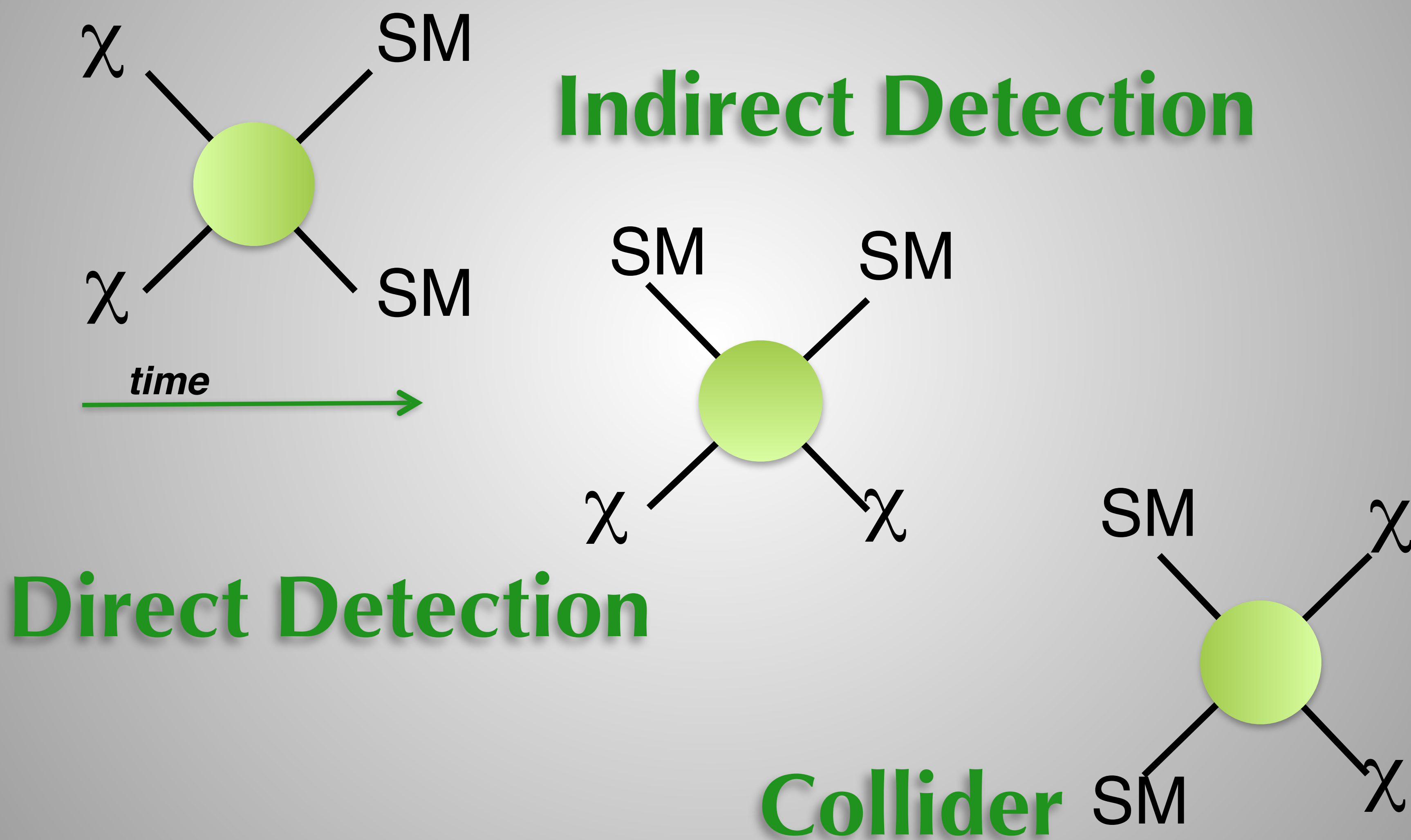
Today 2018 2020 2023 2020s

The Next Generation…

Fermi DES/IACTs/HAWC LSST CTA BurstCube/T.B.S…

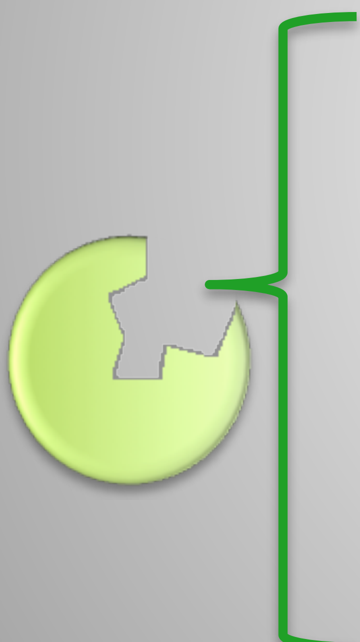
Today 2018 2020 2023 2020s

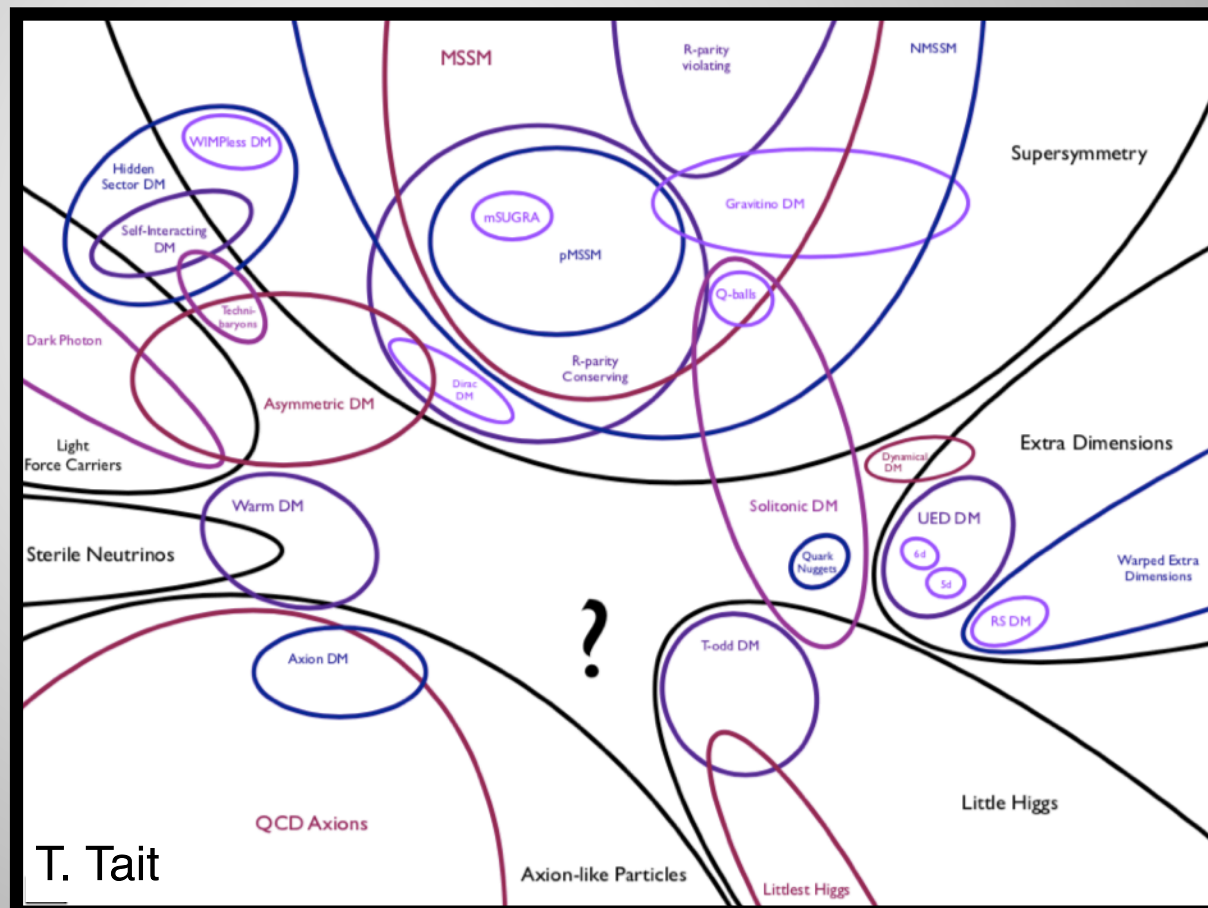
Detecting Particle Dark Matter



Connecting the Pieces

Need a theory to connect the measurements…





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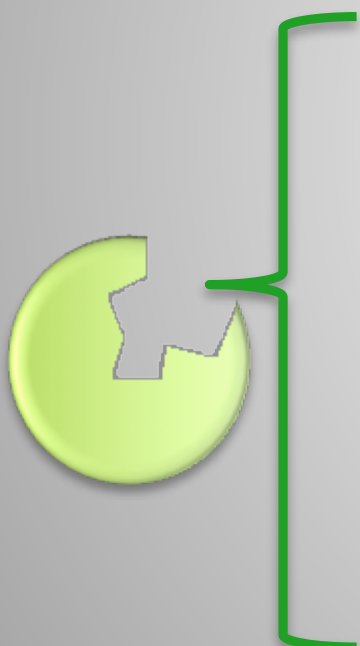
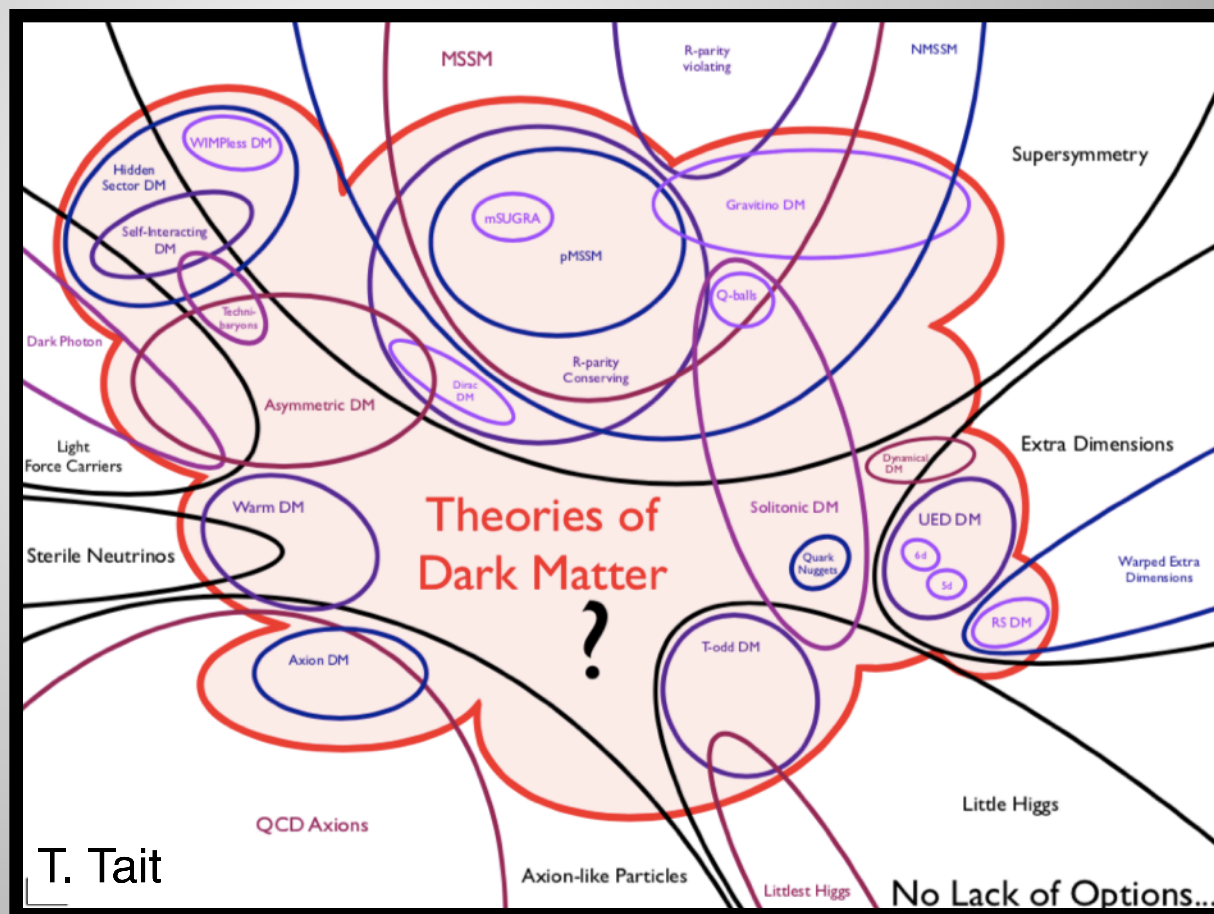
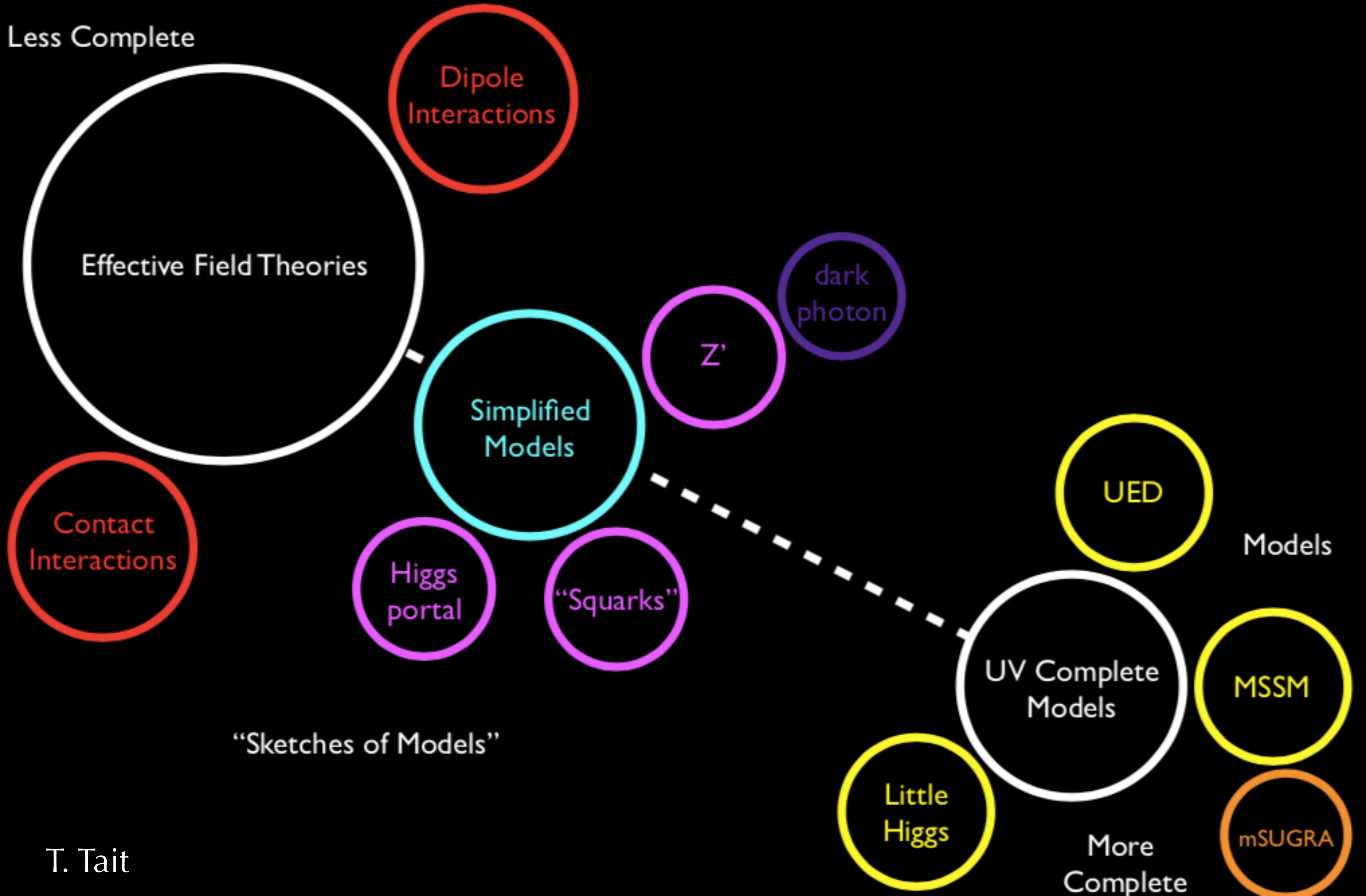




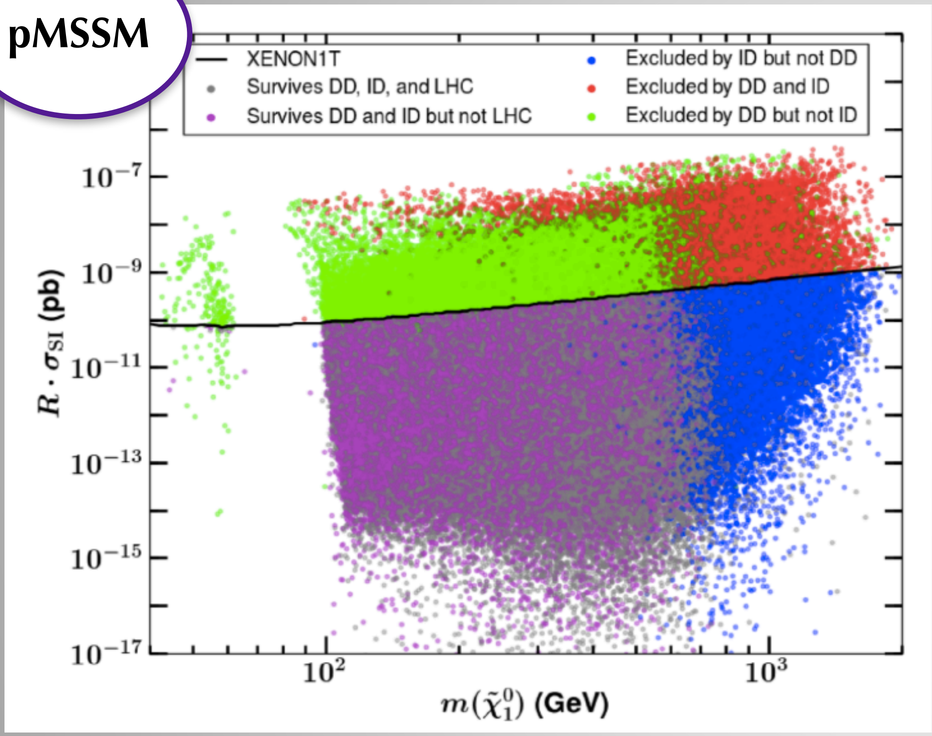
Spectrum of Theory Space



T. Tait

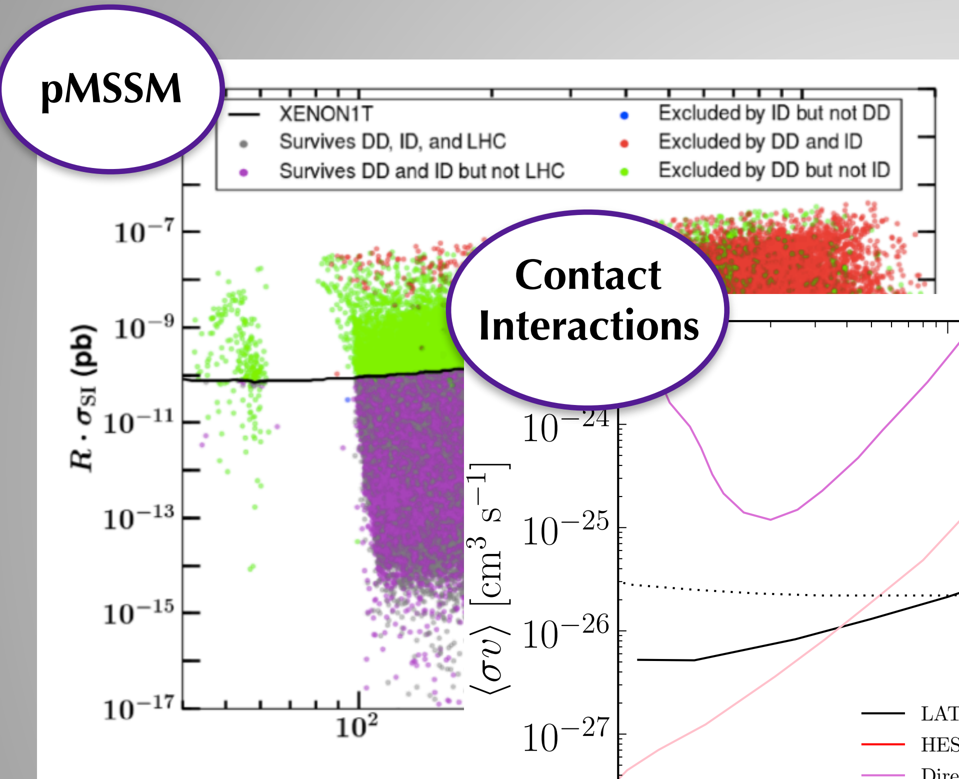
Scanning Parameter Space

pMSSM

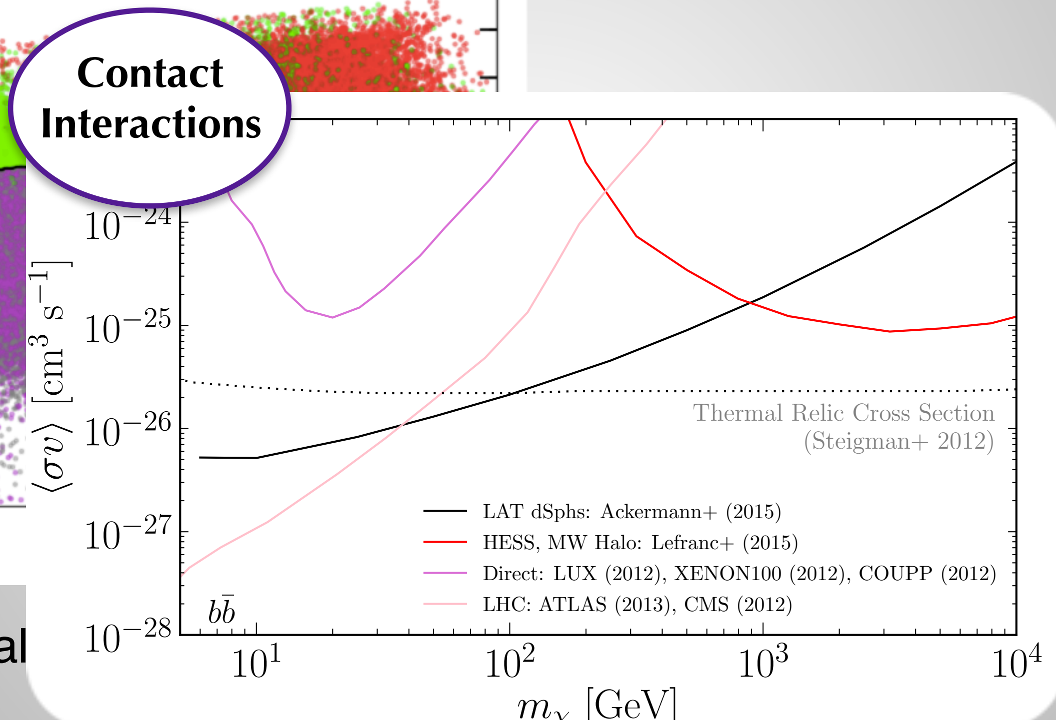


Cahill-Rowley et al., arXiv:1305.6921

Scanning Parameter Space

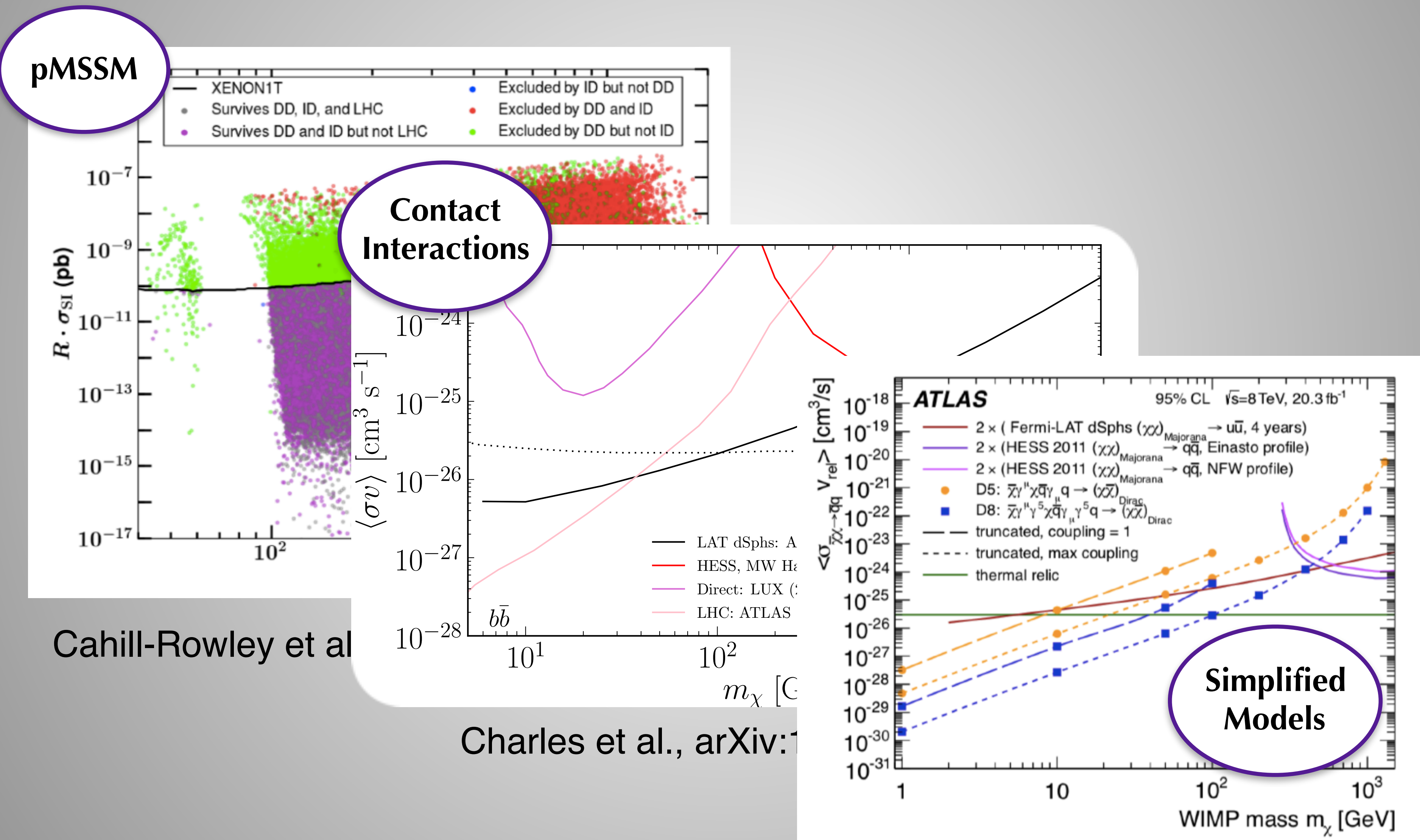


Cahill-Rowley et al



Charles et al., arXiv:1605.02016

Scanning Parameter Space



Cahill-Rowley et al

Charles et al., arXiv:1

ATLAS arXiv:1502.01518

Dark Mater: An Overview

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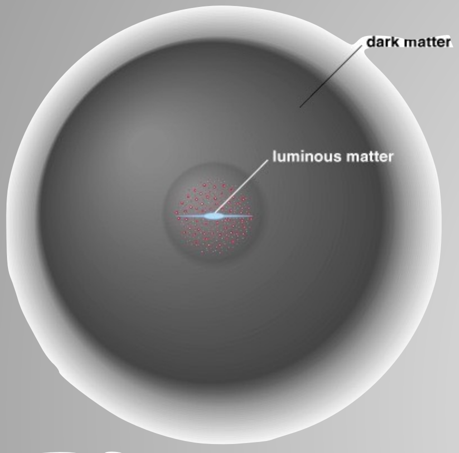

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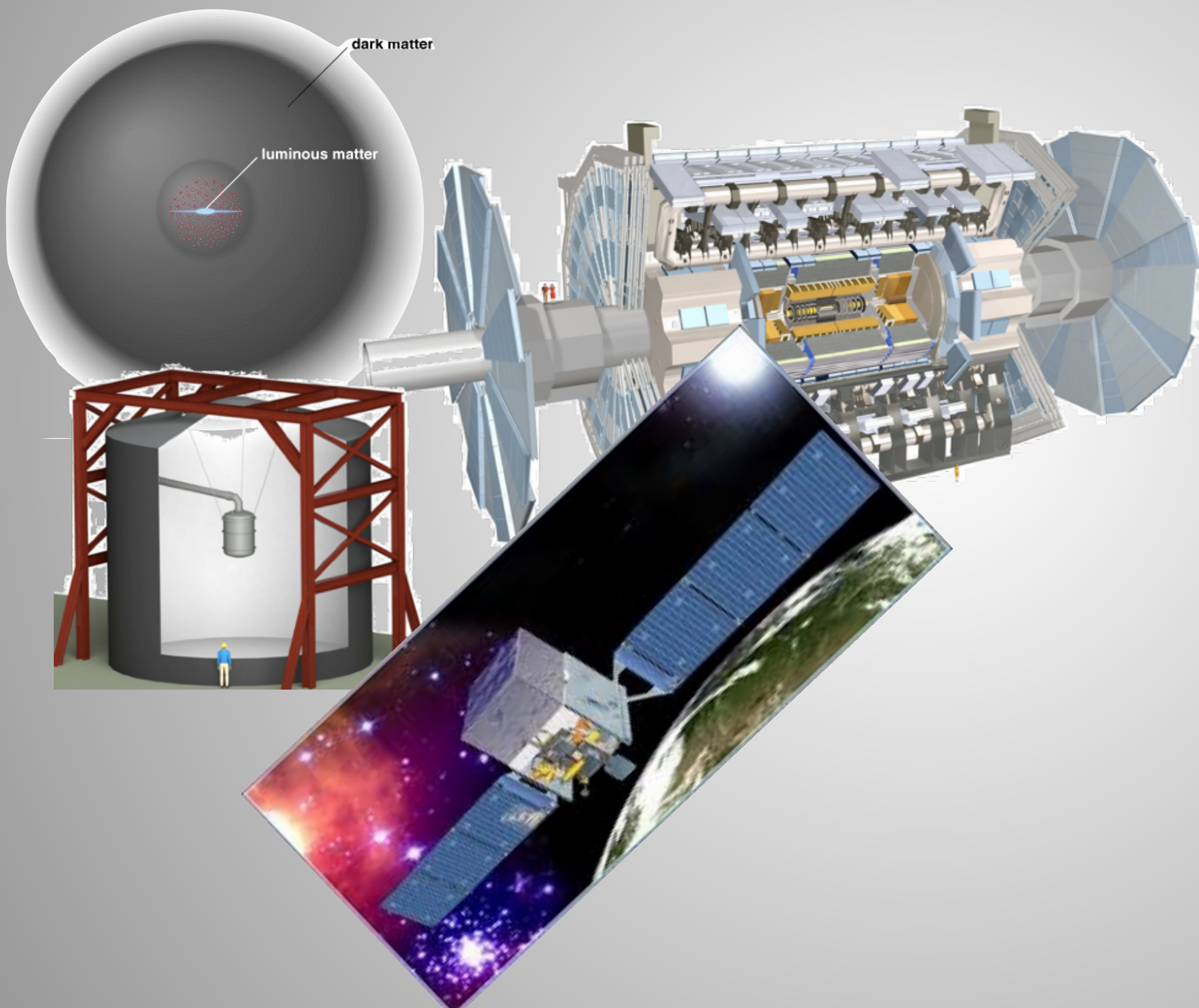

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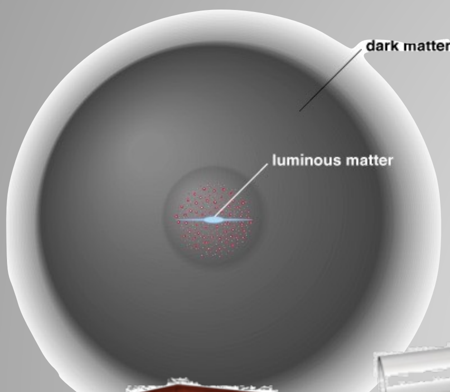

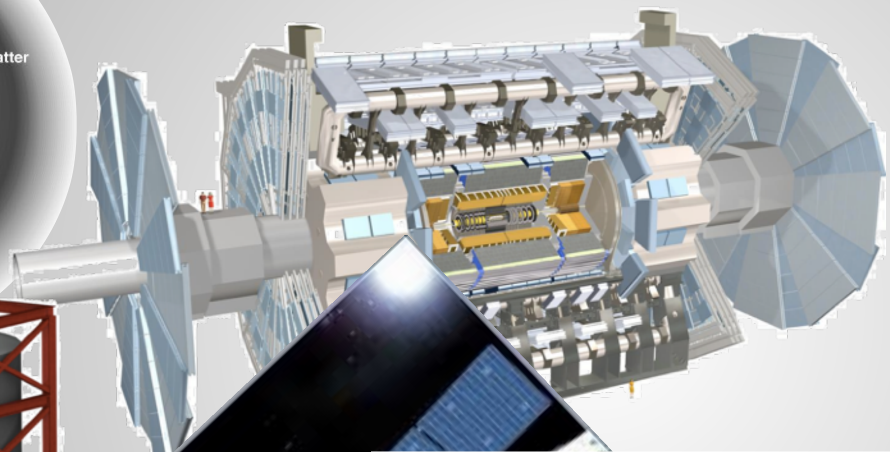

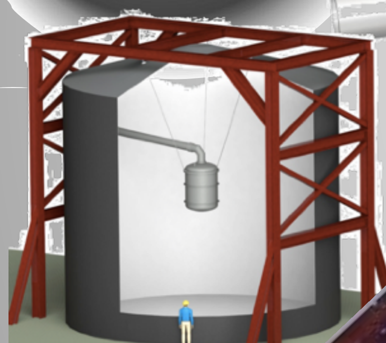

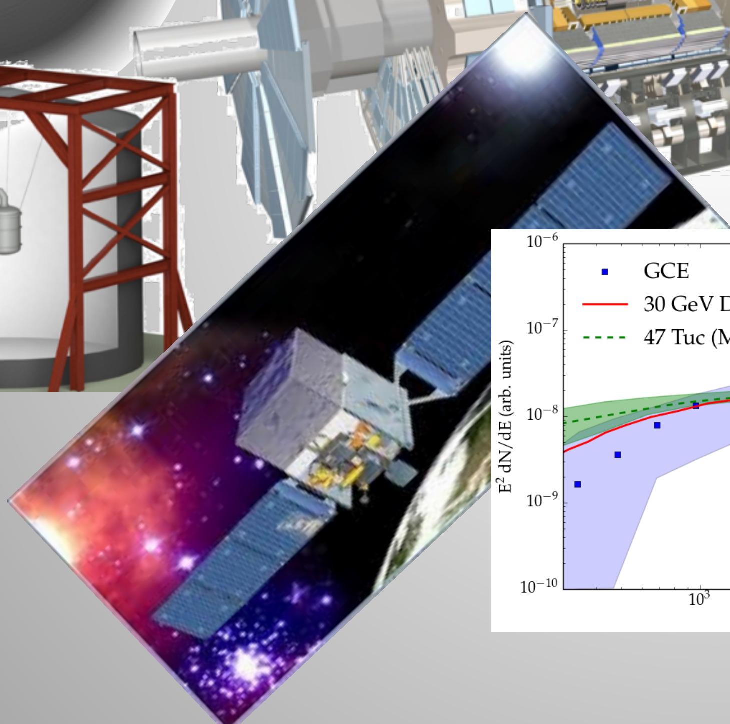

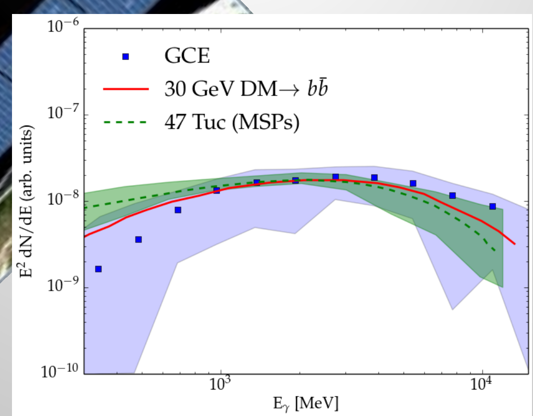

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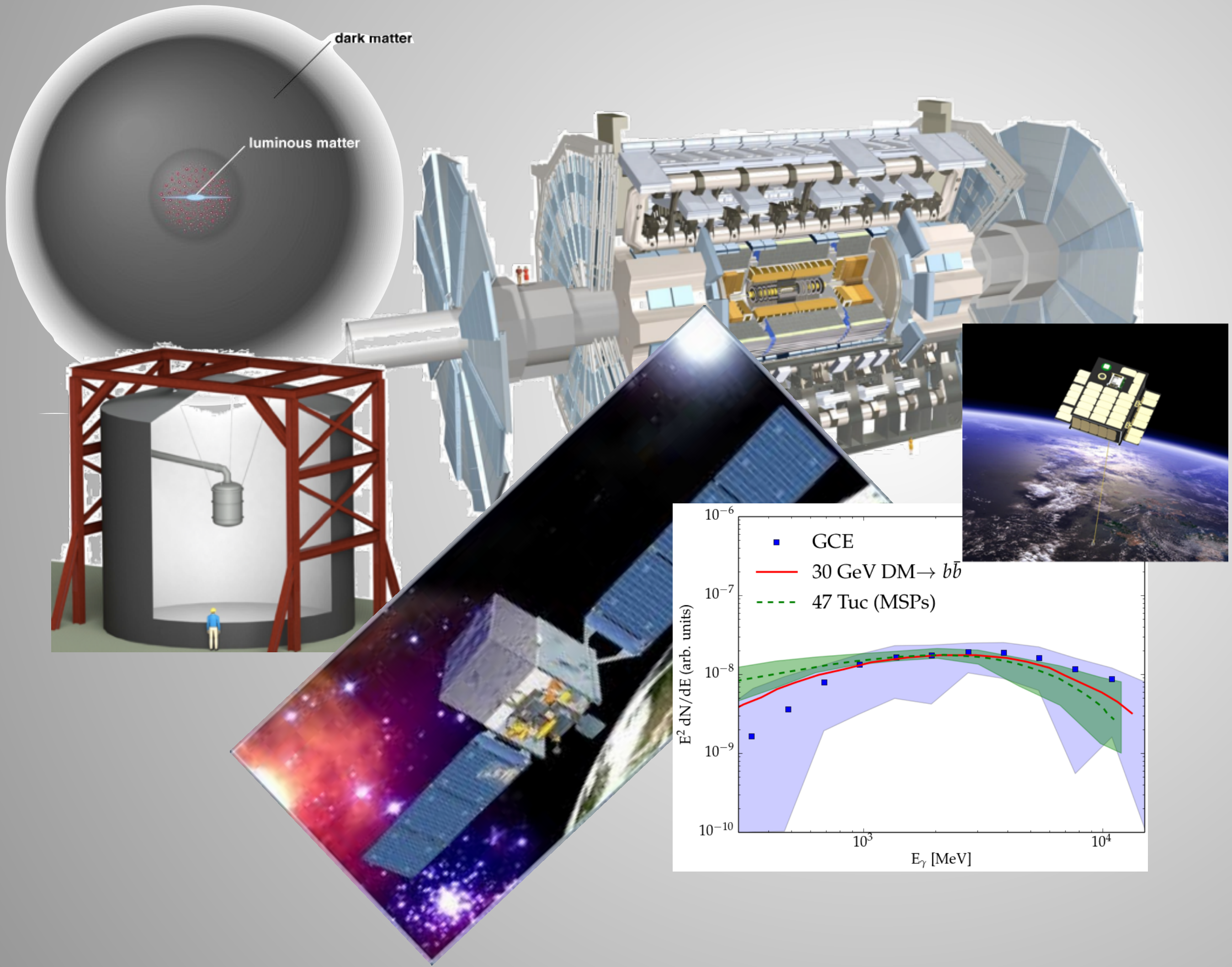

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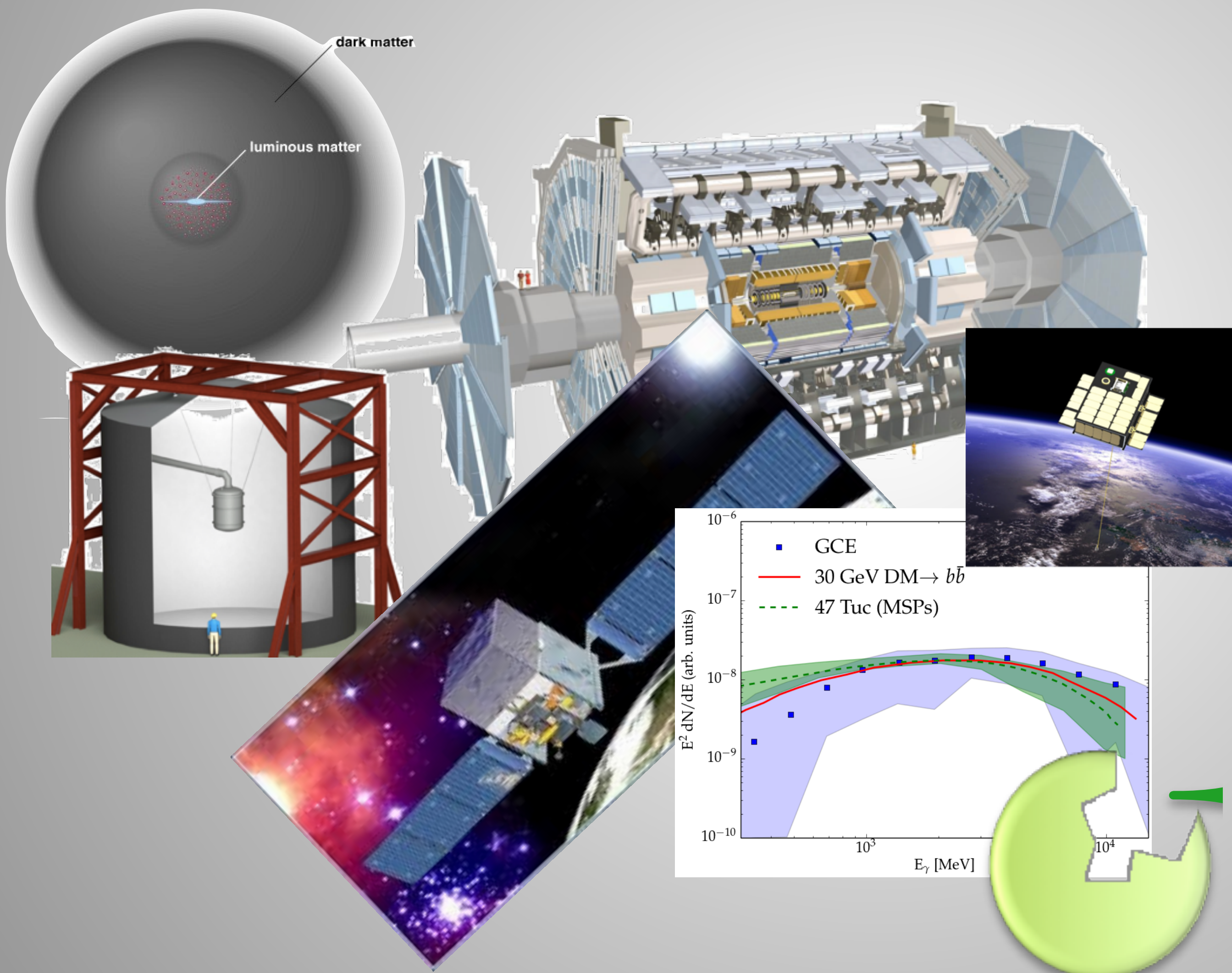

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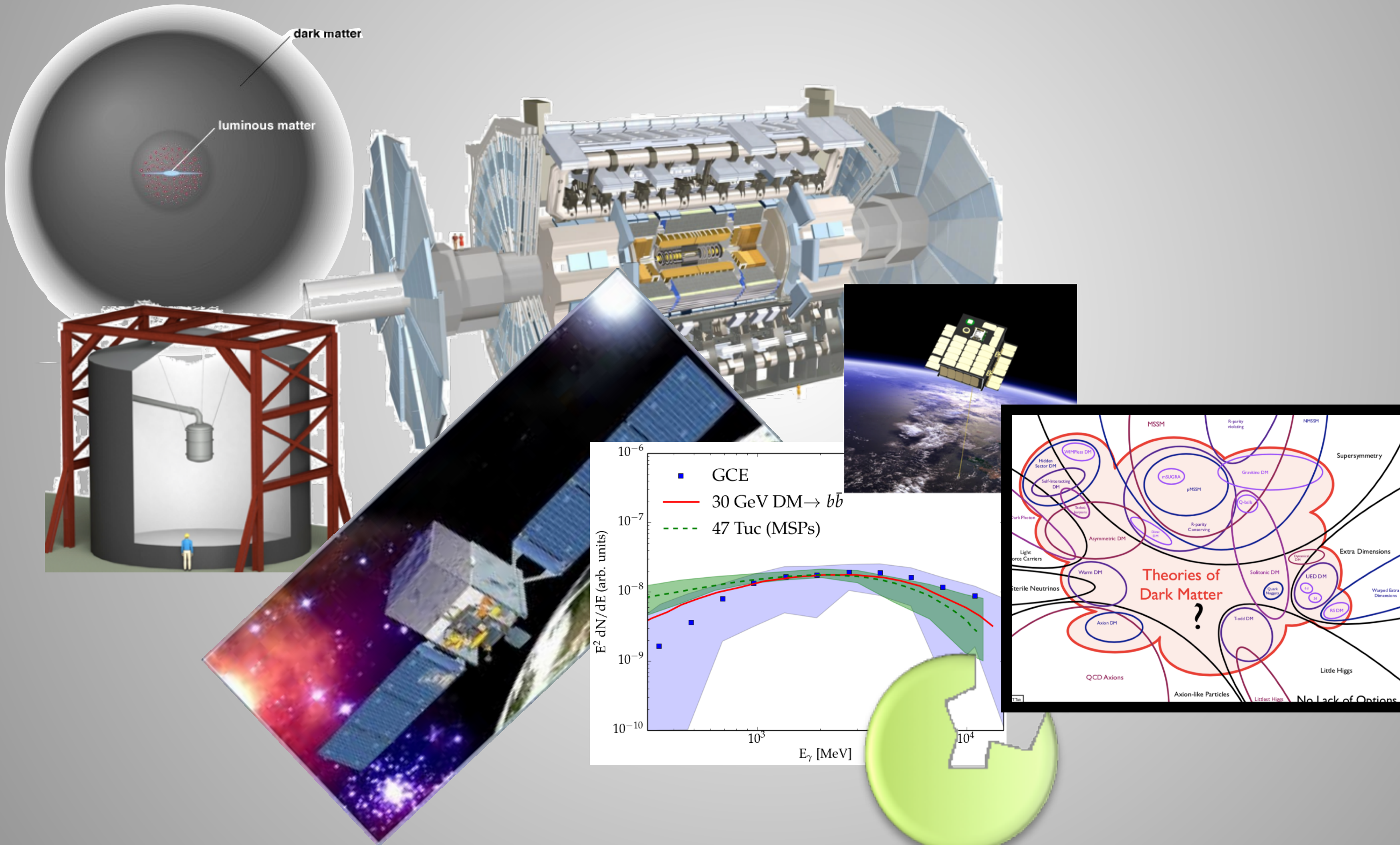

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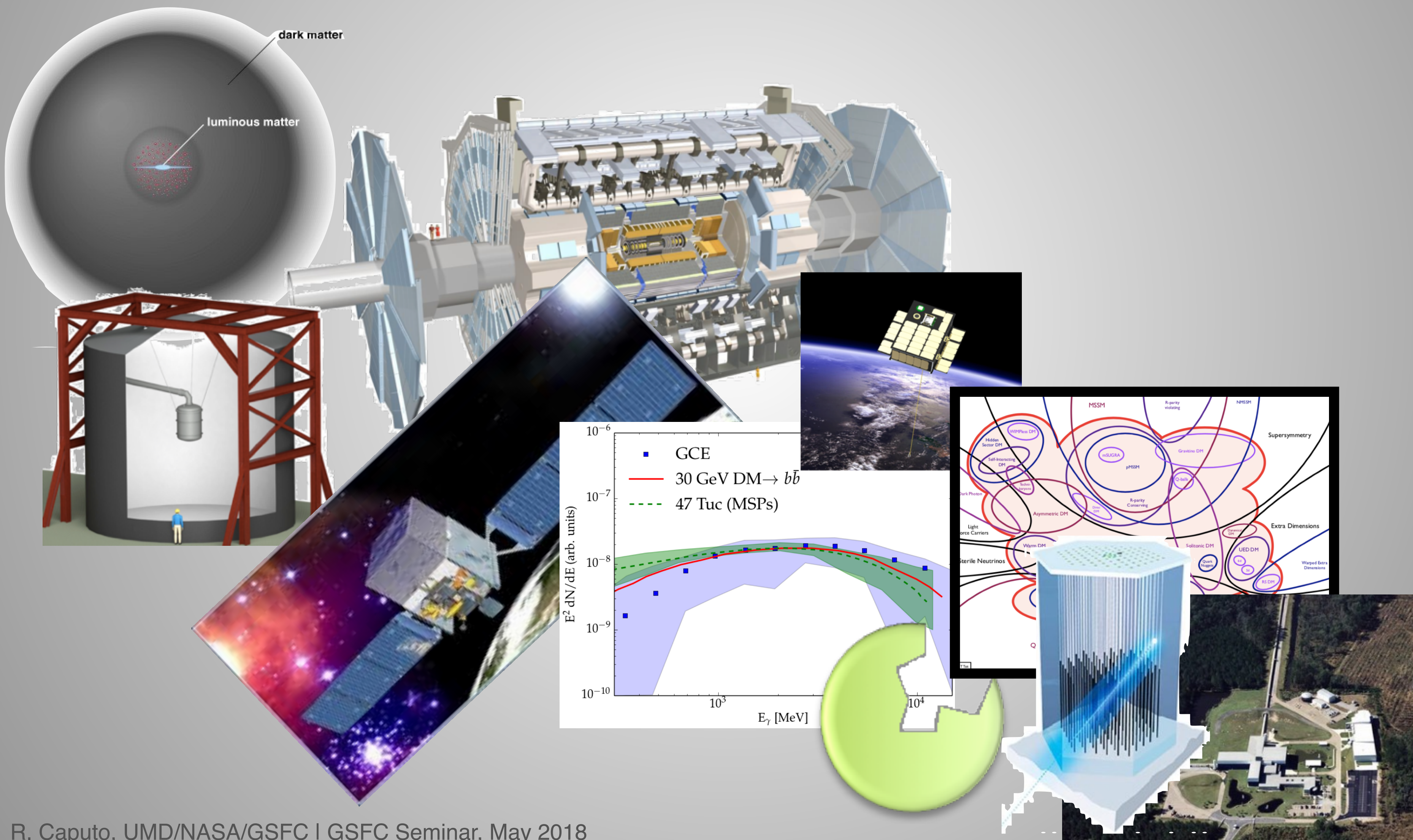

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Thank you