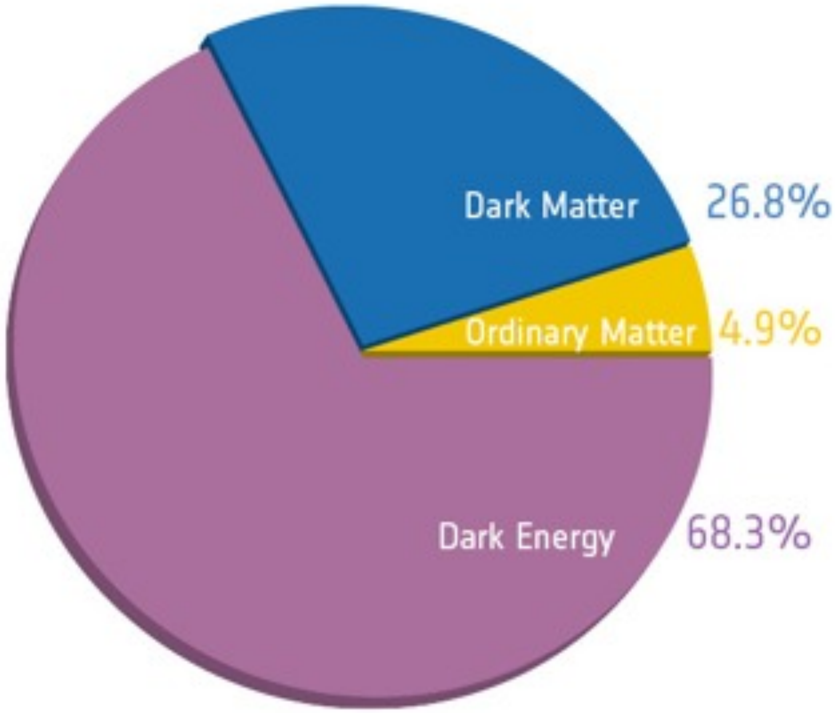
Indirect dark matter searches with gamma rays and cosmic rays

Jennifer Siegal-Gaskins
Caltech

The nature of dark matter

Observational evidence indicates:

- non-baryonic
- neutral
- virtually collisionless



Credit: Planck Collaboration

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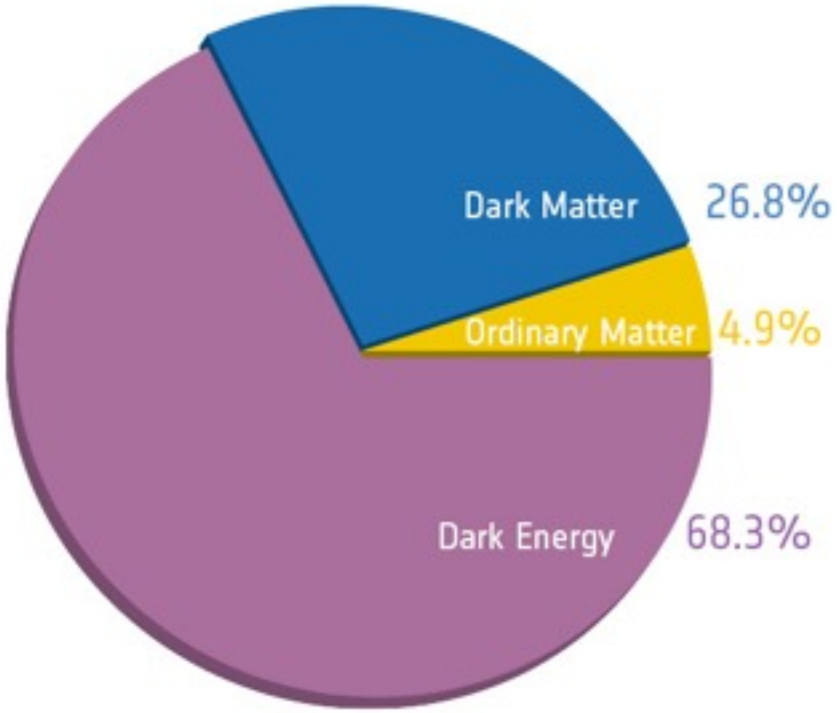
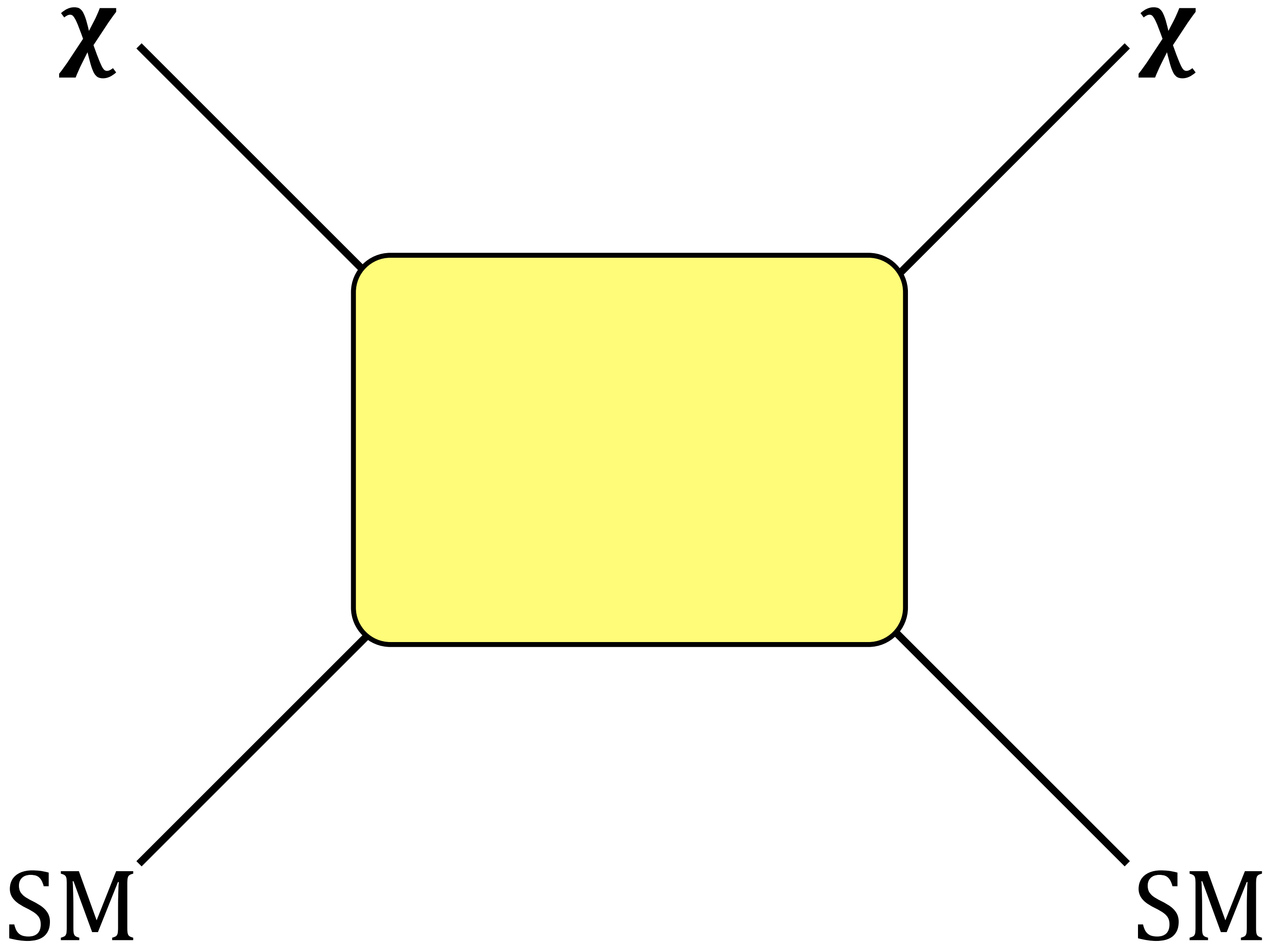


Credit: Planck Collaboration

Additional assumptions for this talk:

- dark matter is a weakly-interacting massive particle (WIMP)
- GeV - TeV mass scale
- can pair annihilate or decay to produce standard model particles

How to detect particle dark matter?



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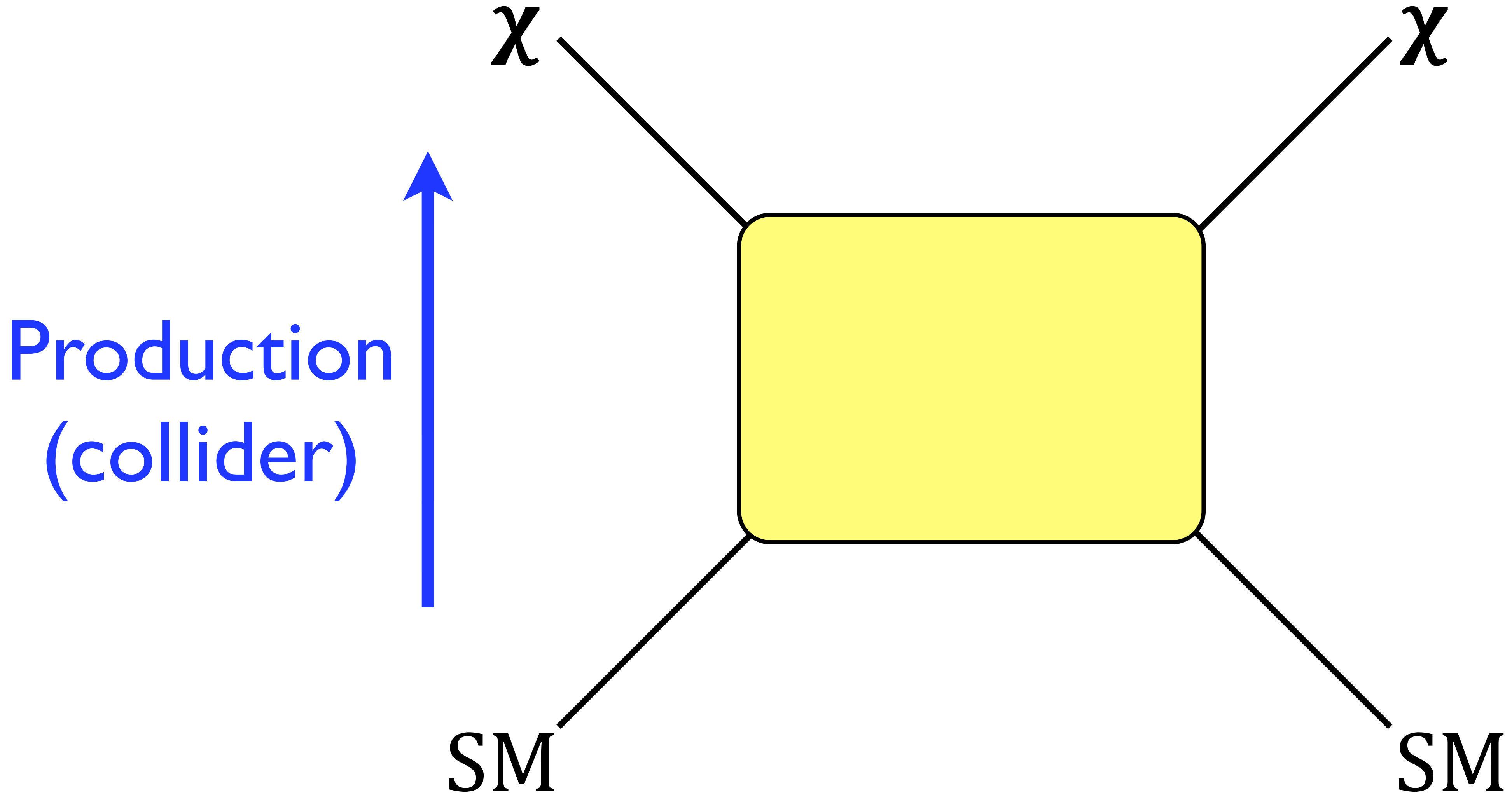

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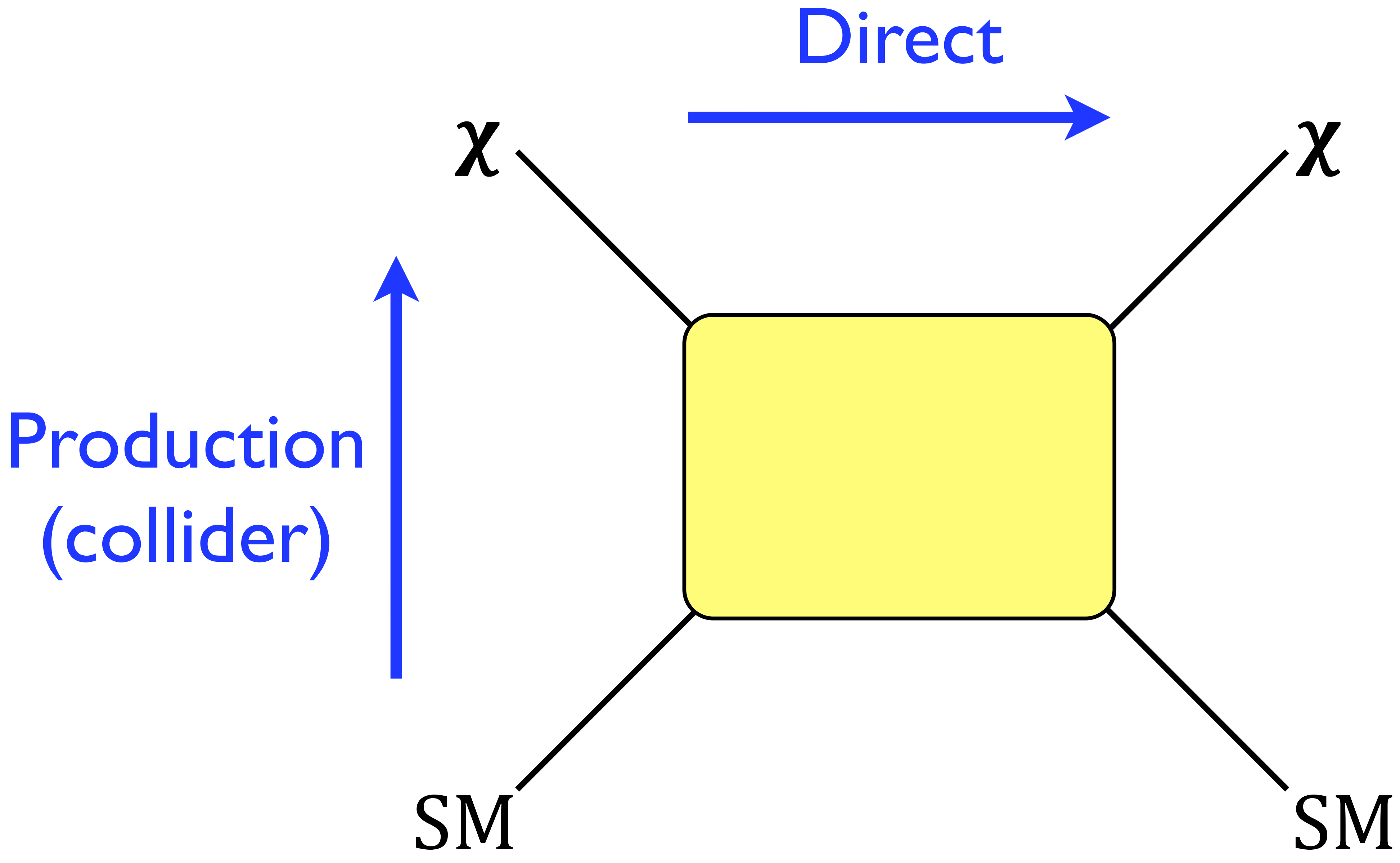

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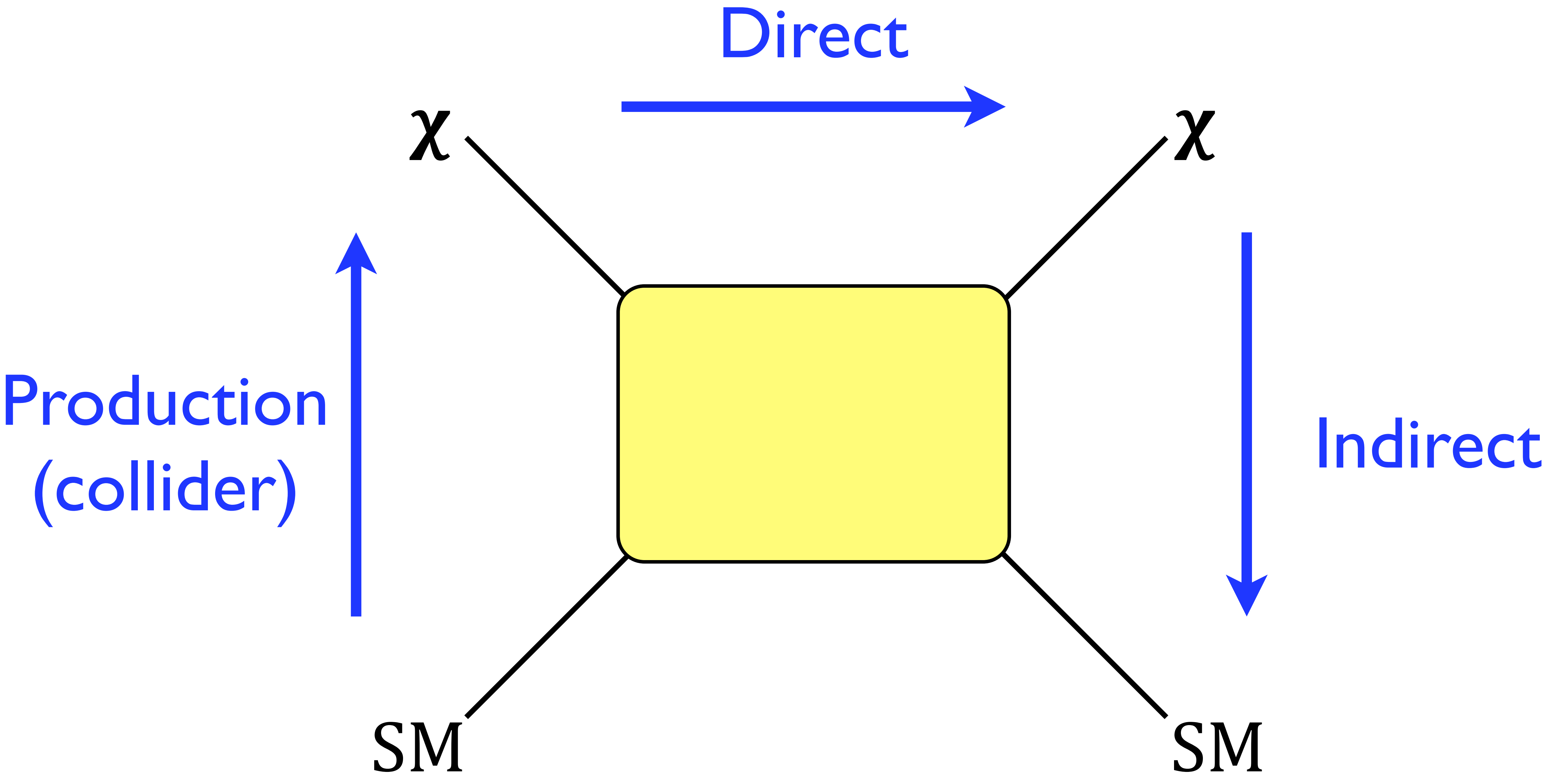


Direct

χ

χ

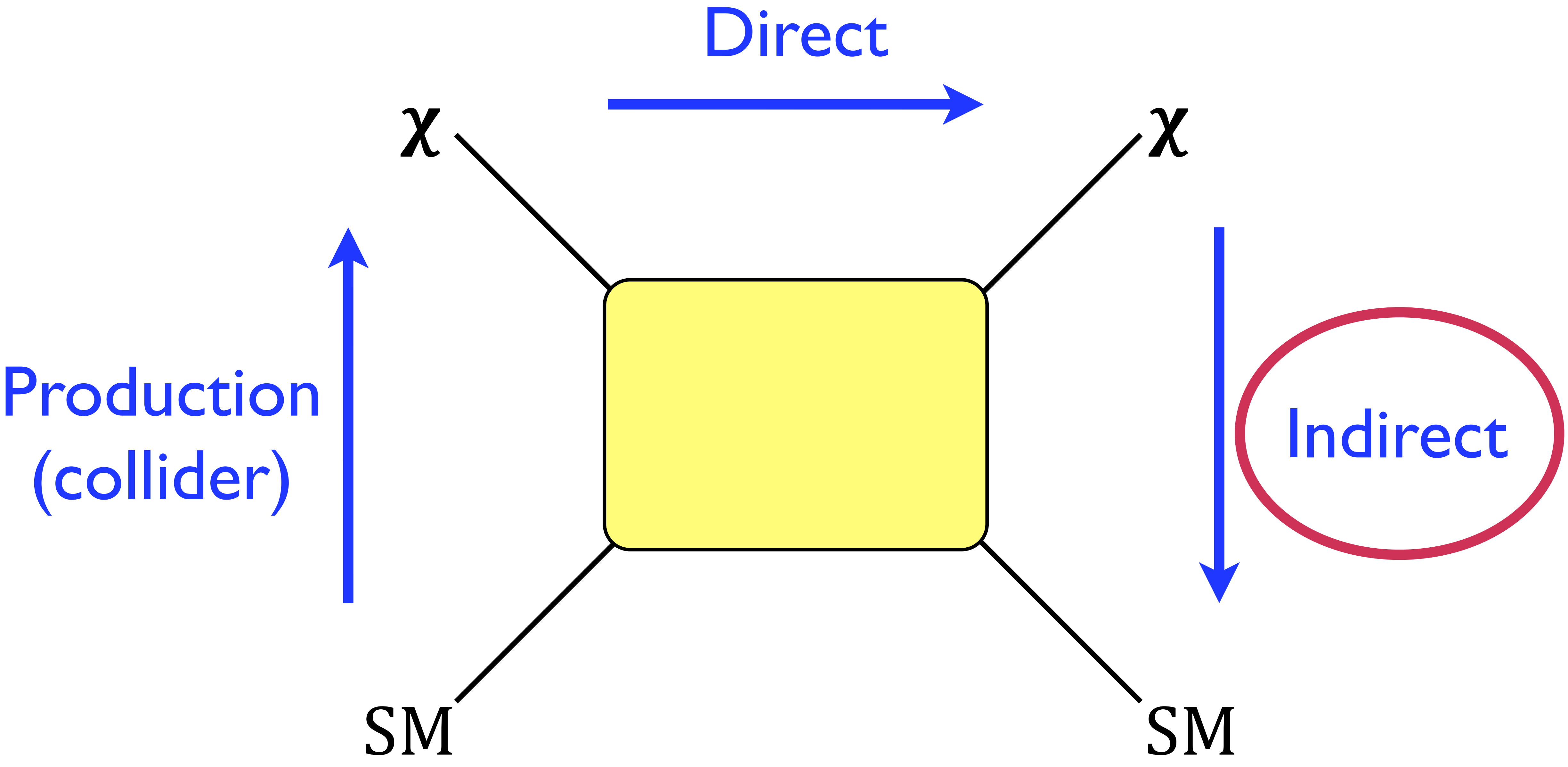
Production (collider)

Indirect

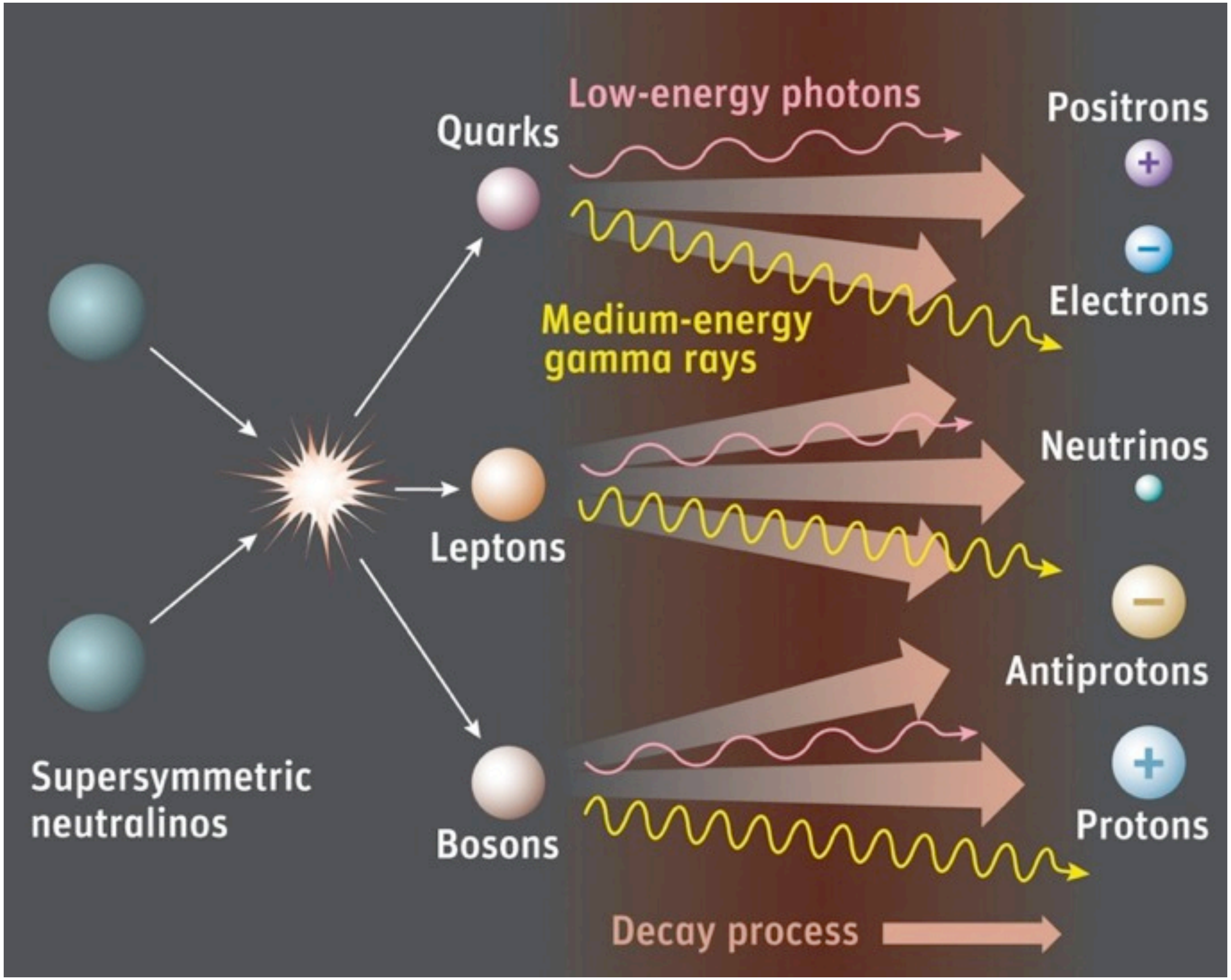
SM

SM

How to detect particle dark matter?

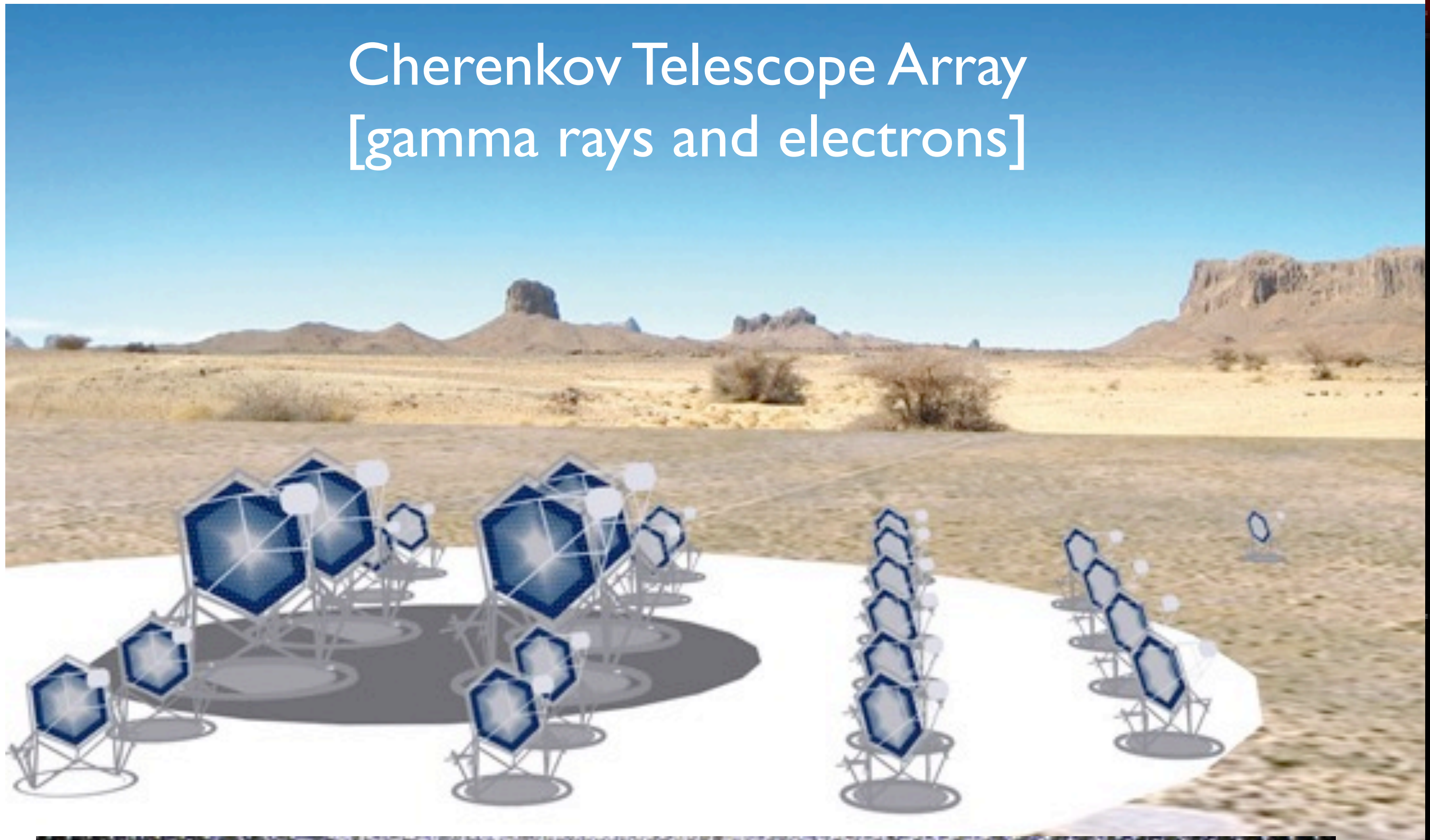


Indirect dark matter signals



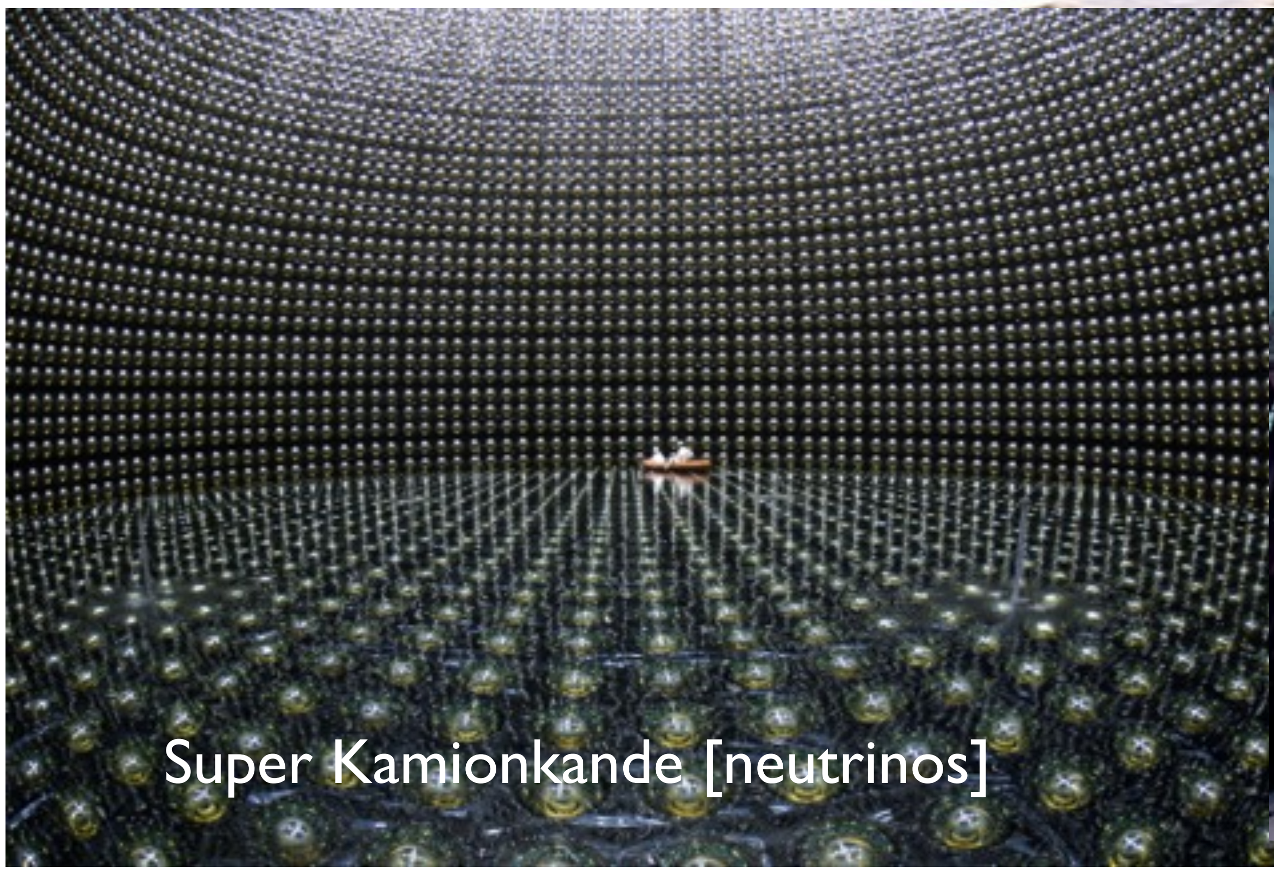
Credit: Sky & Telescope / Gregg Dinderman

Indirect detection experiments



Cherenkov Telescope Array
[gamma rays and electrons]

Fermi Gamma-ray Space Telescope
[gamma rays and electrons]



Super Kamionkande [neutrinos]

AMS-02 [cosmic rays]

Indirect messengers

	Instruments	Advantages	Challenges
Gamma-ray photons	Fermi, ACTs (HESS, VERITAS, MAGIC, CTA)	point back to source, spectral signatures	backgrounds, attenuation
Neutrinos	IceCube/DeepCore/PINGU, ANTARES, KM3NET, Super-K, Hyper-K	point back to source, spectral signatures	low statistics, backgrounds
Charged particles	PAMELA, AMS(-02), ATIC, ACTs, Fermi, CTA, CALET	antimatter hard to produce astrophysically	diffusion, propagation uncertainties, don't point back to sources

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Gamma-ray and neutrino indirect signals

(particles that propagate directly to the observer without deflection,
attenuation, or secondary production)

differential intensity = particle physics term "K" • astrophysics term "J"

[differential intensity] = $\dfrac{\text{particles}}{\text{time} \cdot \text{area} \cdot \text{solid angle} \cdot \text{energy}}$

Caution: definition of "J" is not standardized! Watch for factors of 2, 4π, r⊙, ρ⊙, and integration over solid angles!

ANNIHILATION:

$$K_{\mathrm{ann}} = \frac{\mathrm{d}N}{\mathrm{d}E}\frac{\langle\sigma v\rangle}{2m_\chi^2}$$

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spectrum of particles produced

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dark matter particle mass

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pair annihilation cross section
times average relative velocity

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dark matter particle lifetime

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dark matter density

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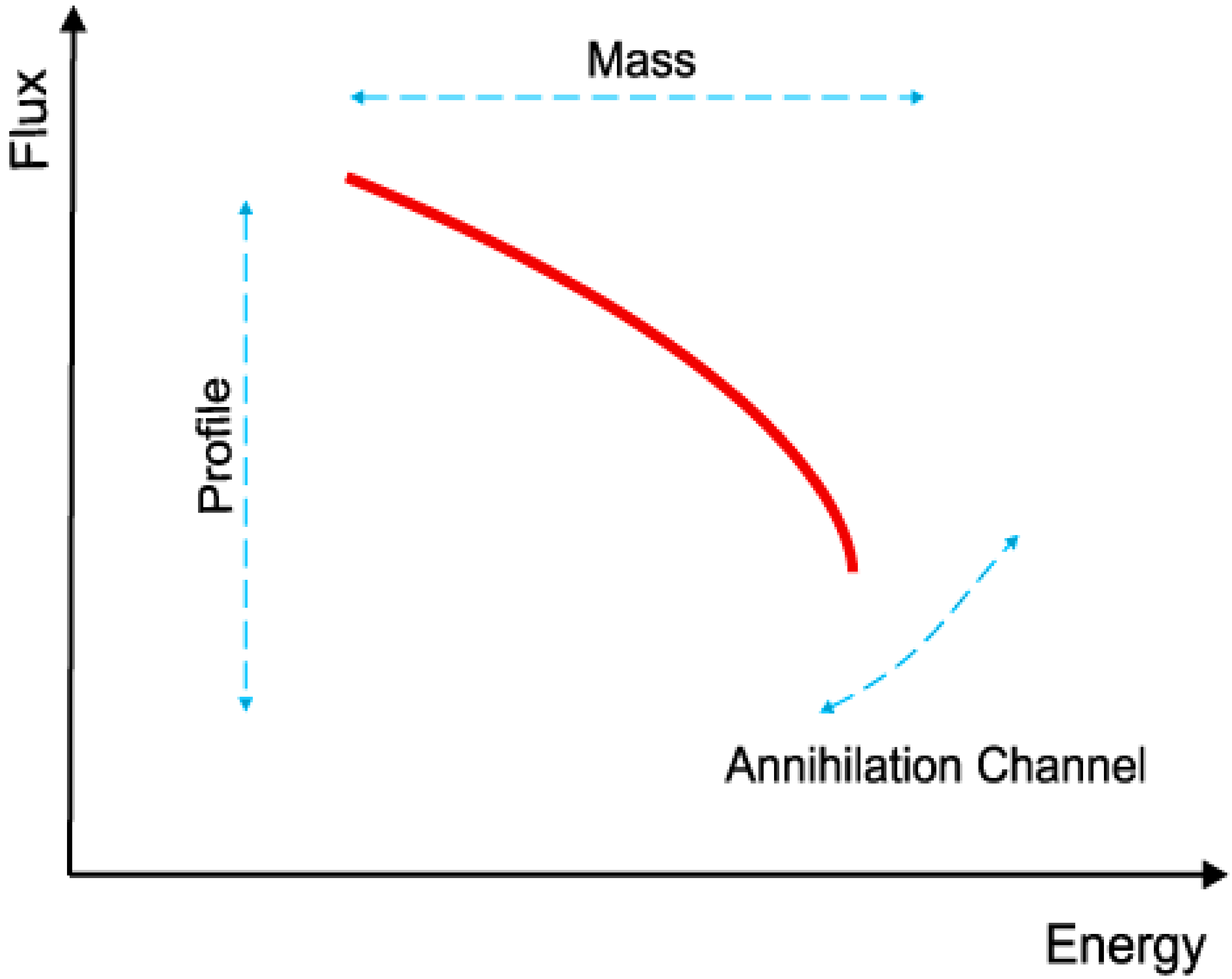
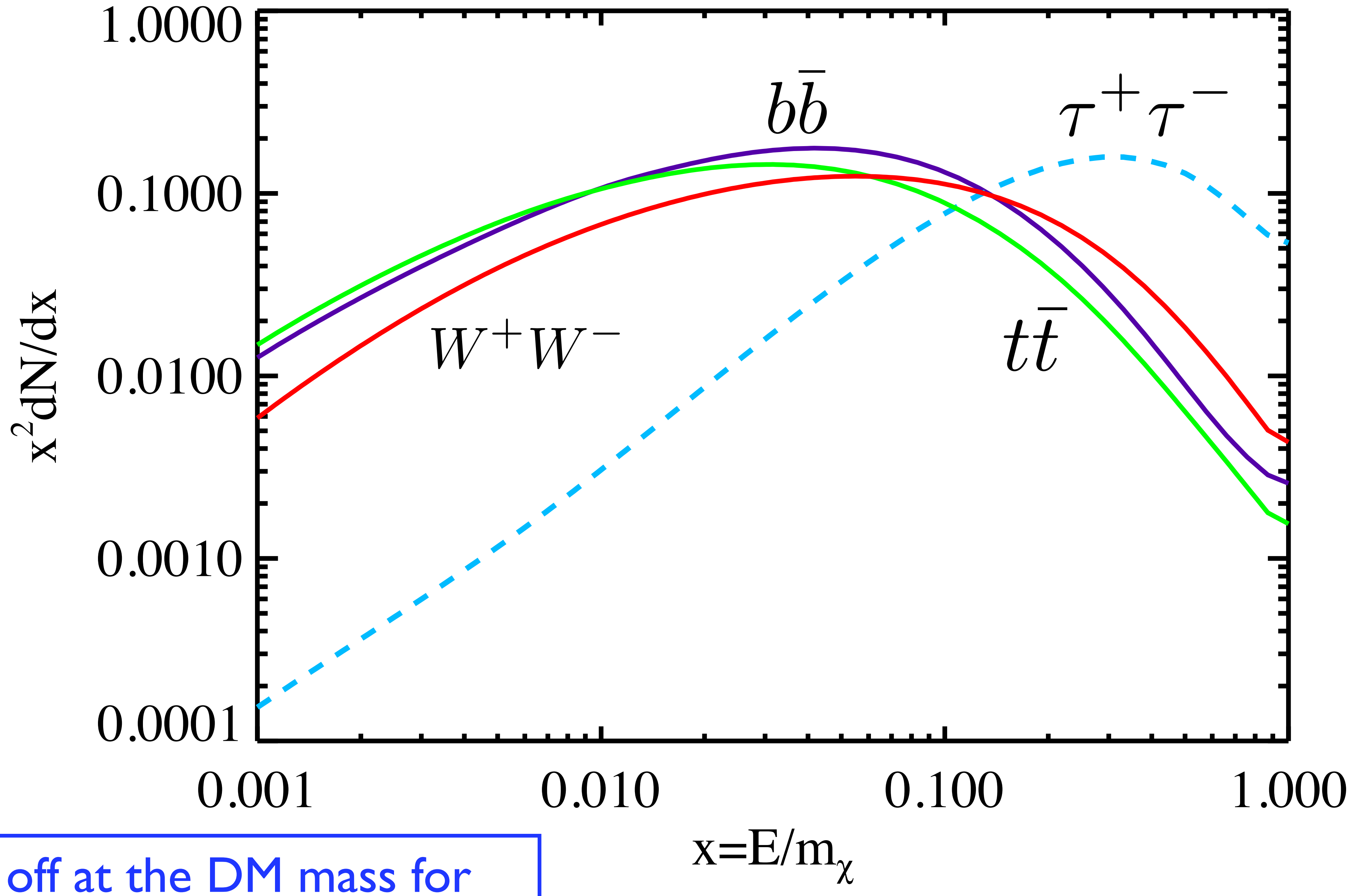


Bertone 2007

Dark matter photon spectra

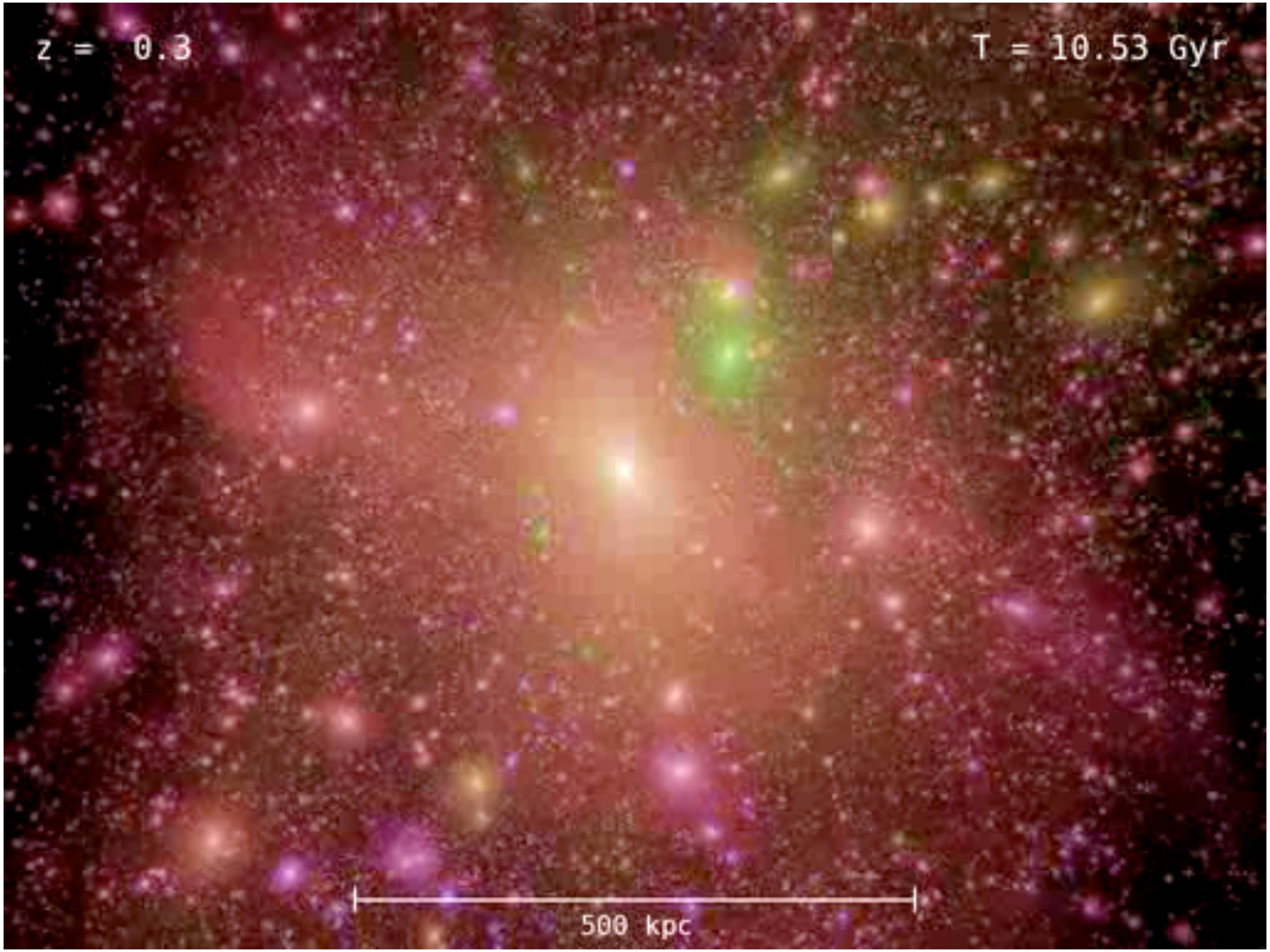
- "soft" channels: produce a continuum gamma-ray spectrum primarily from decay of neutral pions
- "hard channels": include final state radiation (FSR) associated with charged leptons in the final states
- direct annihilation to photons = line emission (γγ, Zγ)



energy spectrum cuts off at the DM mass for annihilation, half the DM mass for decay

Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

The dark matter spatial distribution



Credit: Springel et al. (Virgo Consortium)

Dark matter annihilation signal

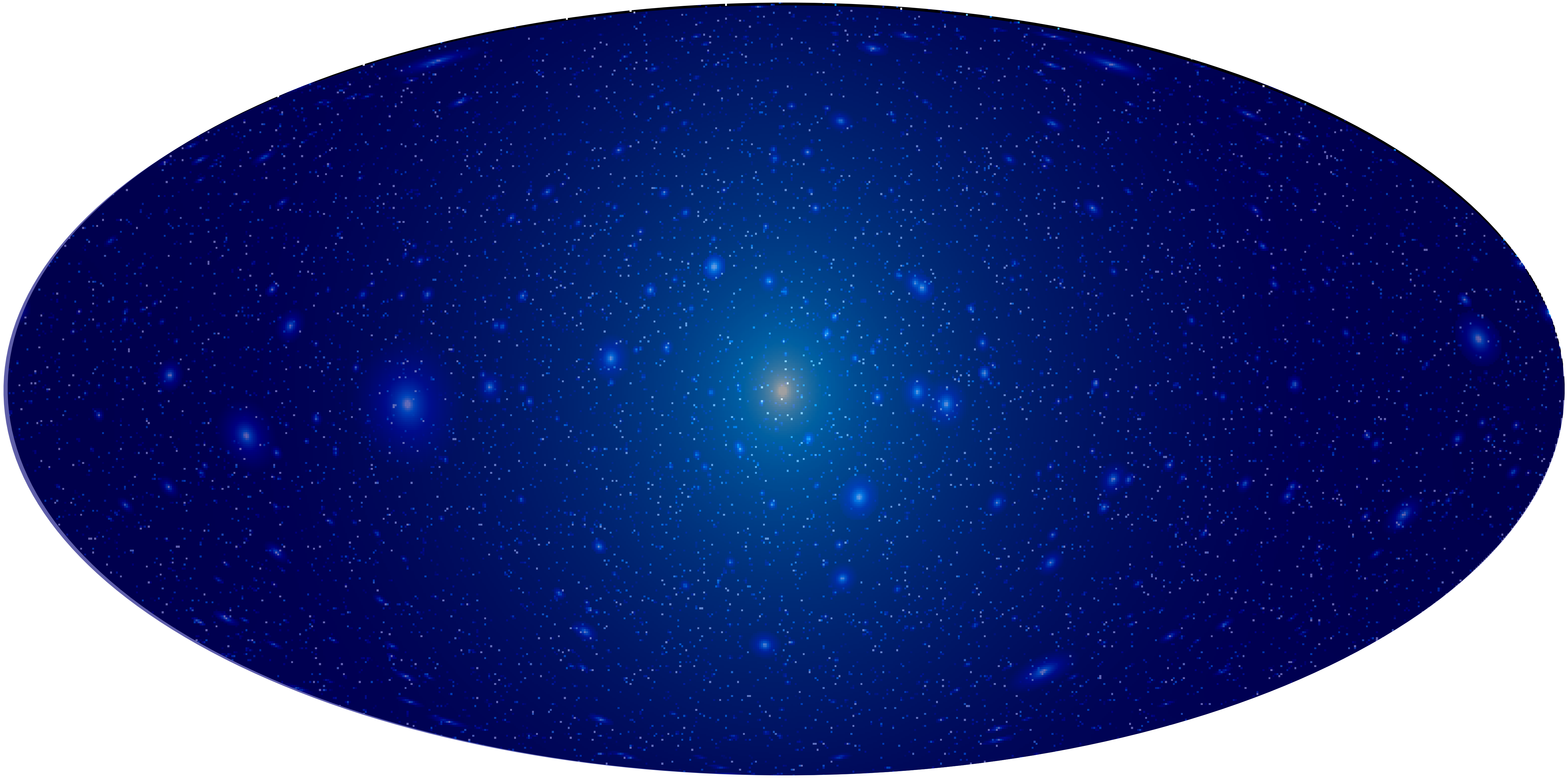


Image credit: JSG 2008

Instruments and analyses:
Fermi Gamma-ray Space Telescope

The Fermi Gamma-ray Space Telescope

the Large Area Telescope (LAT)

- 20 MeV to > 300 GeV
- large FOV ~ 2.4 sr

the Gamma-ray Burst Monitor (GBM)

- 12 sodium iodide (NaI) detectors: 8 keV to 1 MeV
- 2 bismuth germanate (BGO) detectors (200 keV to 40 MeV)
- observes entire unocculted sky

Fermi data and analysis tools are public!

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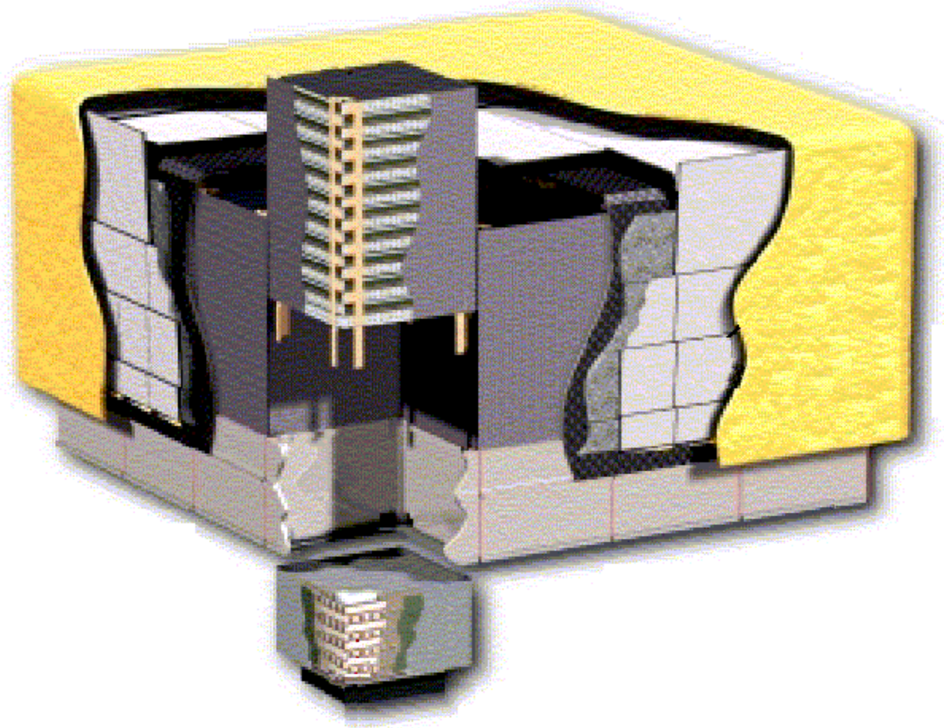
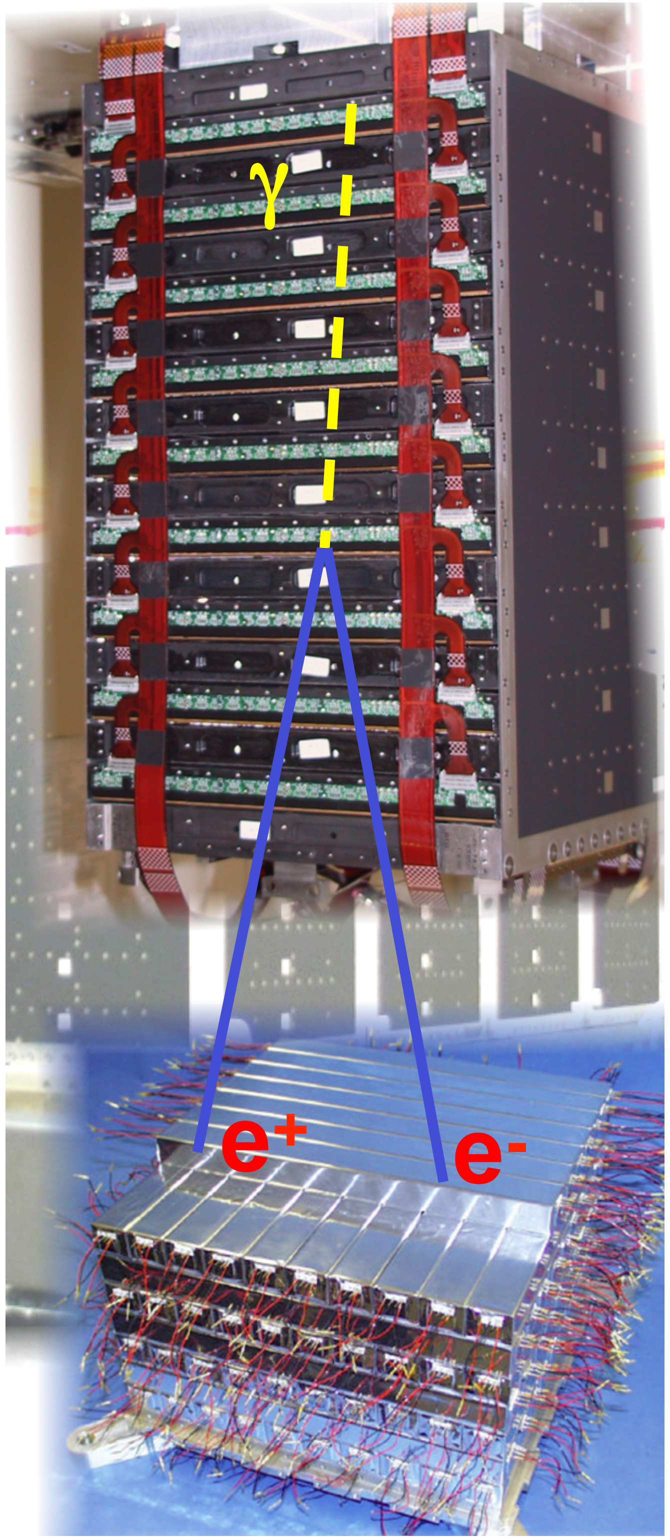
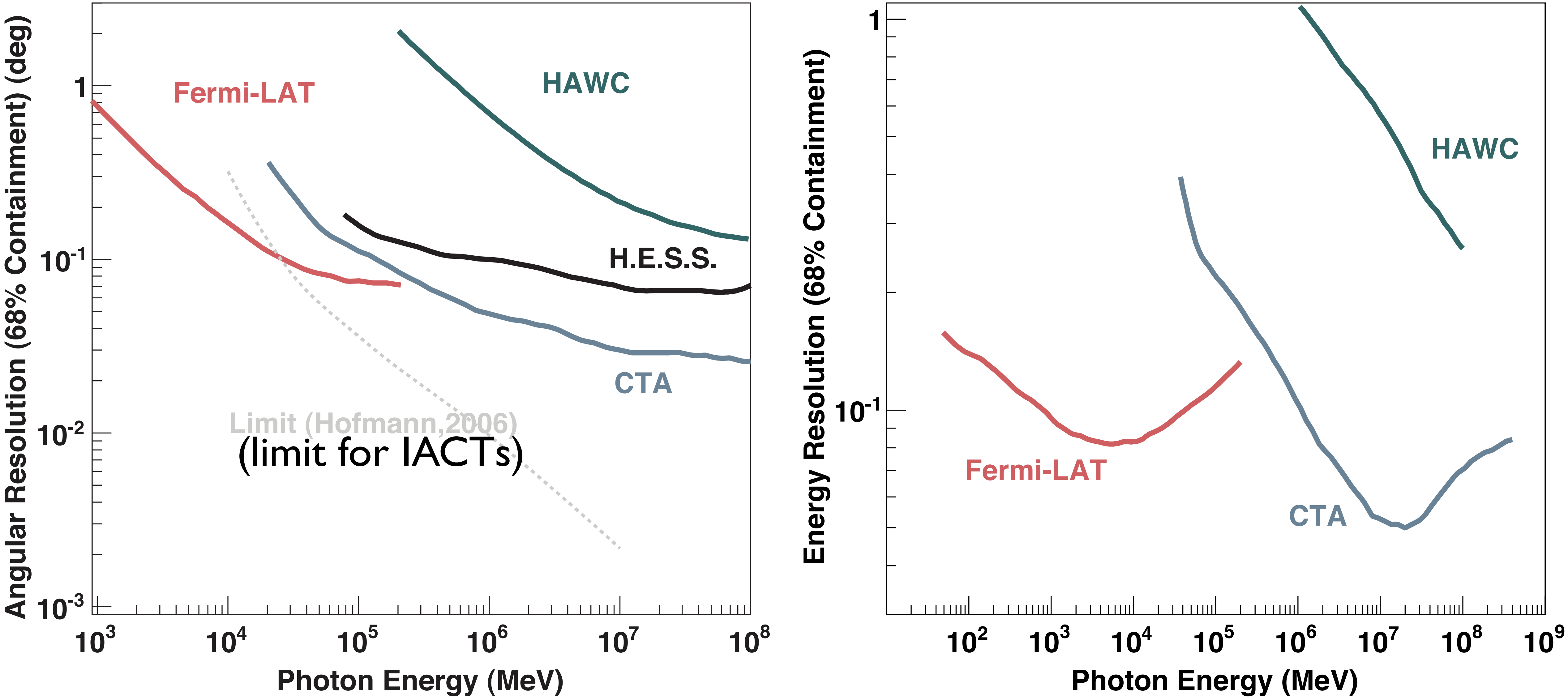




- pair-production detector: detects charged particles as well as gamma rays
- excellent charged particle event identification and background rejection
- 20 MeV to > 300 GeV
- angular resolution ~ 0.1 deg above 10 GeV

Current and future capabilities



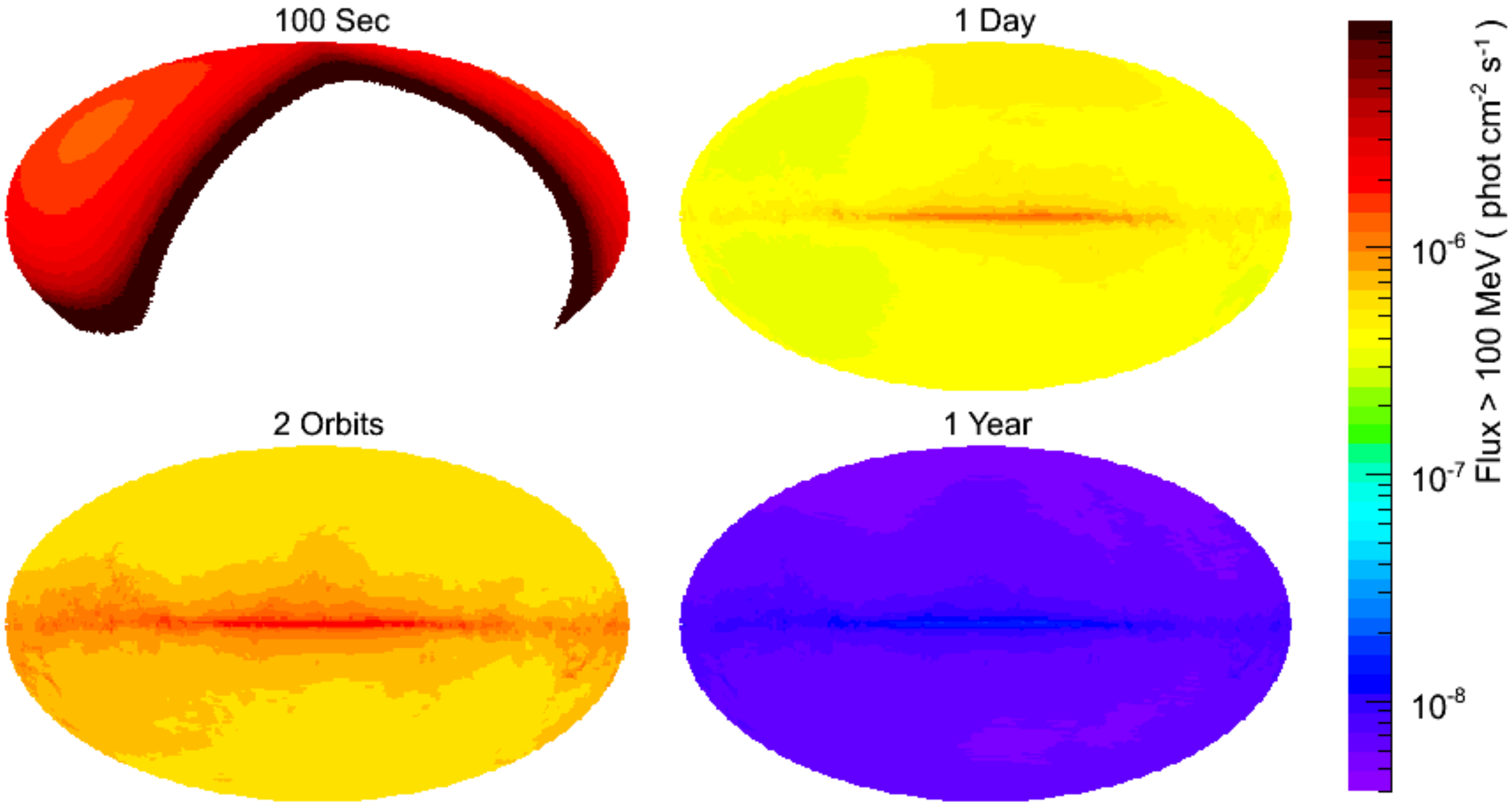
(limit for IACTs)

Funk et al. 2012

NB: Fermi LAT effective area ~ 0.8 m^2 vs ~ 10^6 m^2 for CTA

The Fermi Large Area Telescope (LAT)

Fermi LAT sensitivity maps



- standard observing strategy = sky survey
- each orbit takes ~ 90 minutes
- rocks to point North or South, changes each orbit
- uniform sky exposure of ~ 30 mins every 3 hrs

The Fermi LAT gamma-ray sky

3-year all-sky map, E > 1 GeV

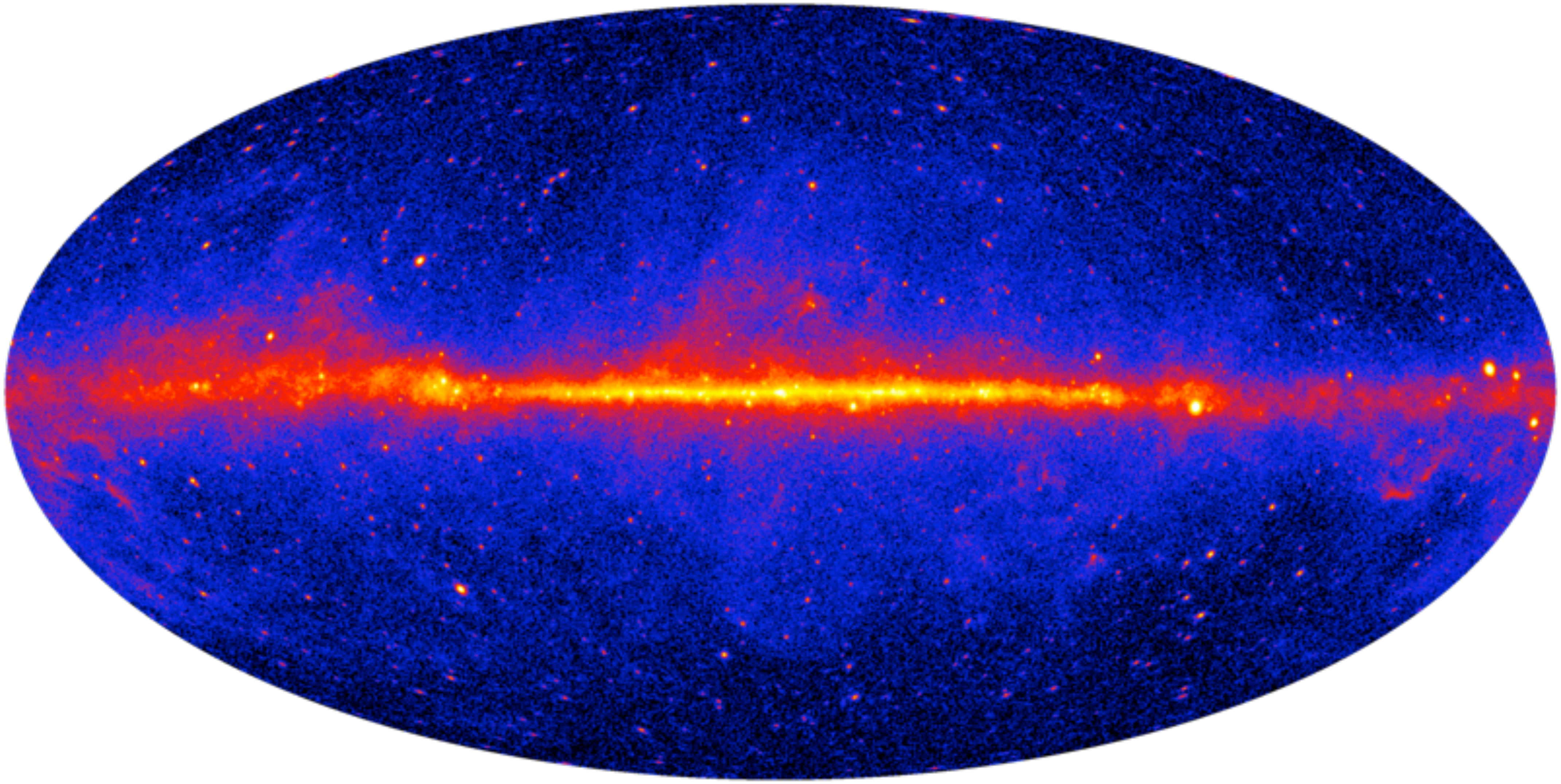
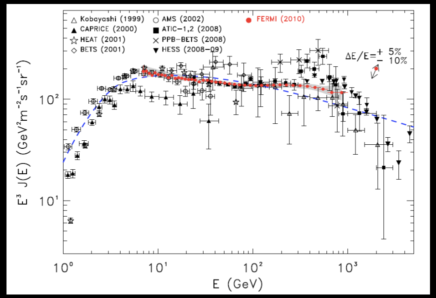
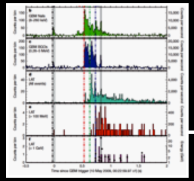


Image Credit: NASA/DOE/International LAT Team

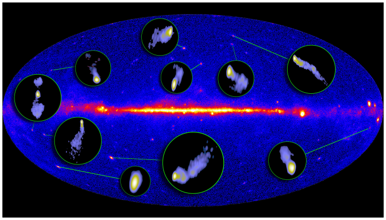
Increasing Classes of Fermi-LAT Sources



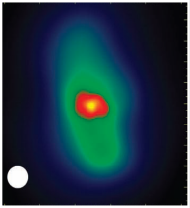
e^+e^- spectrum



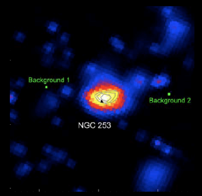
GRBs



Blazars (782)

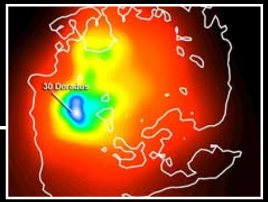


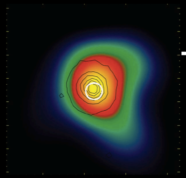
Radio Galaxies (12)



Starburst Galaxies (4)

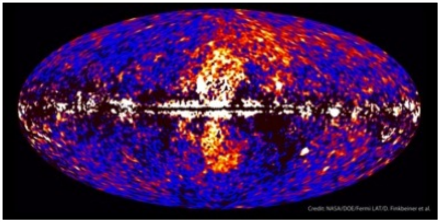
LMC & SMC

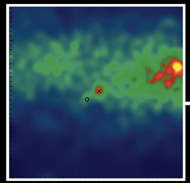




Globular Clusters (11)

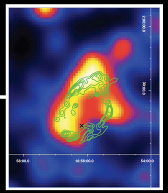
Fermi Bubbles



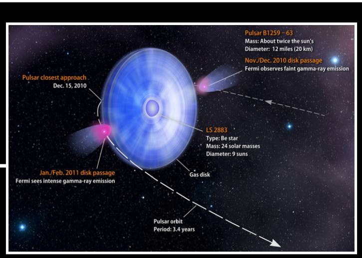


Nova (1)

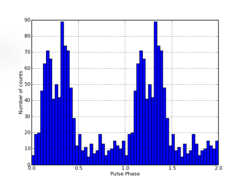
SNR & PWN (68)



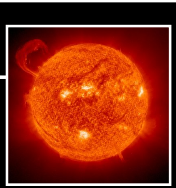
γ-ray binaries (6)



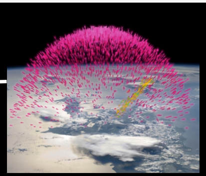
Pulsars: young & millisecond (MSP) (117+)



Sun: flares & CR interactions



Terrestrial Gamma-ray Flashes



Local

Galactic

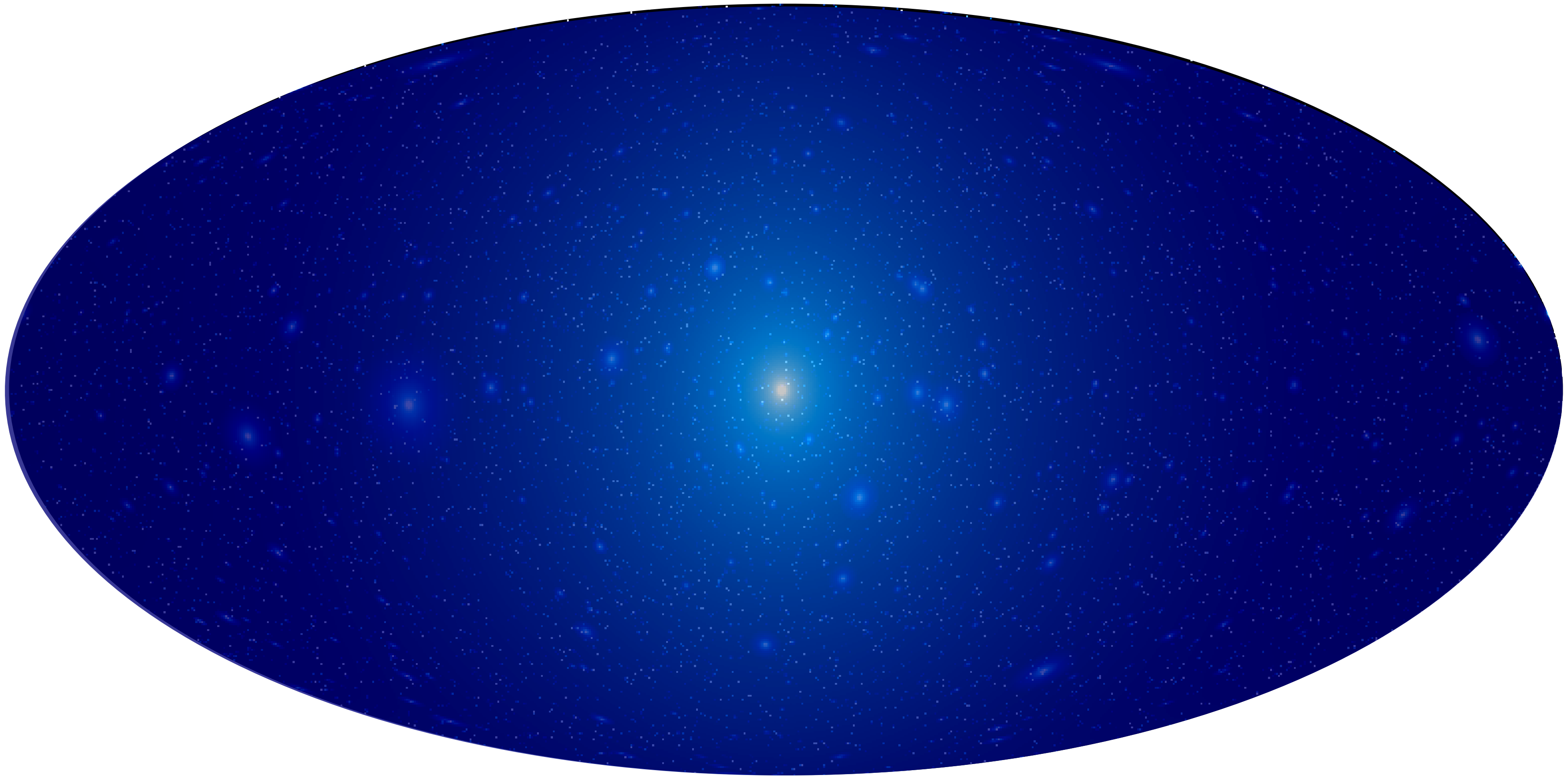
Extragalactic

Ackermann+ (LAT)
[arXiv:1108.1202]

Unidentified Sources (~600)

slide credit: Matthew Wood

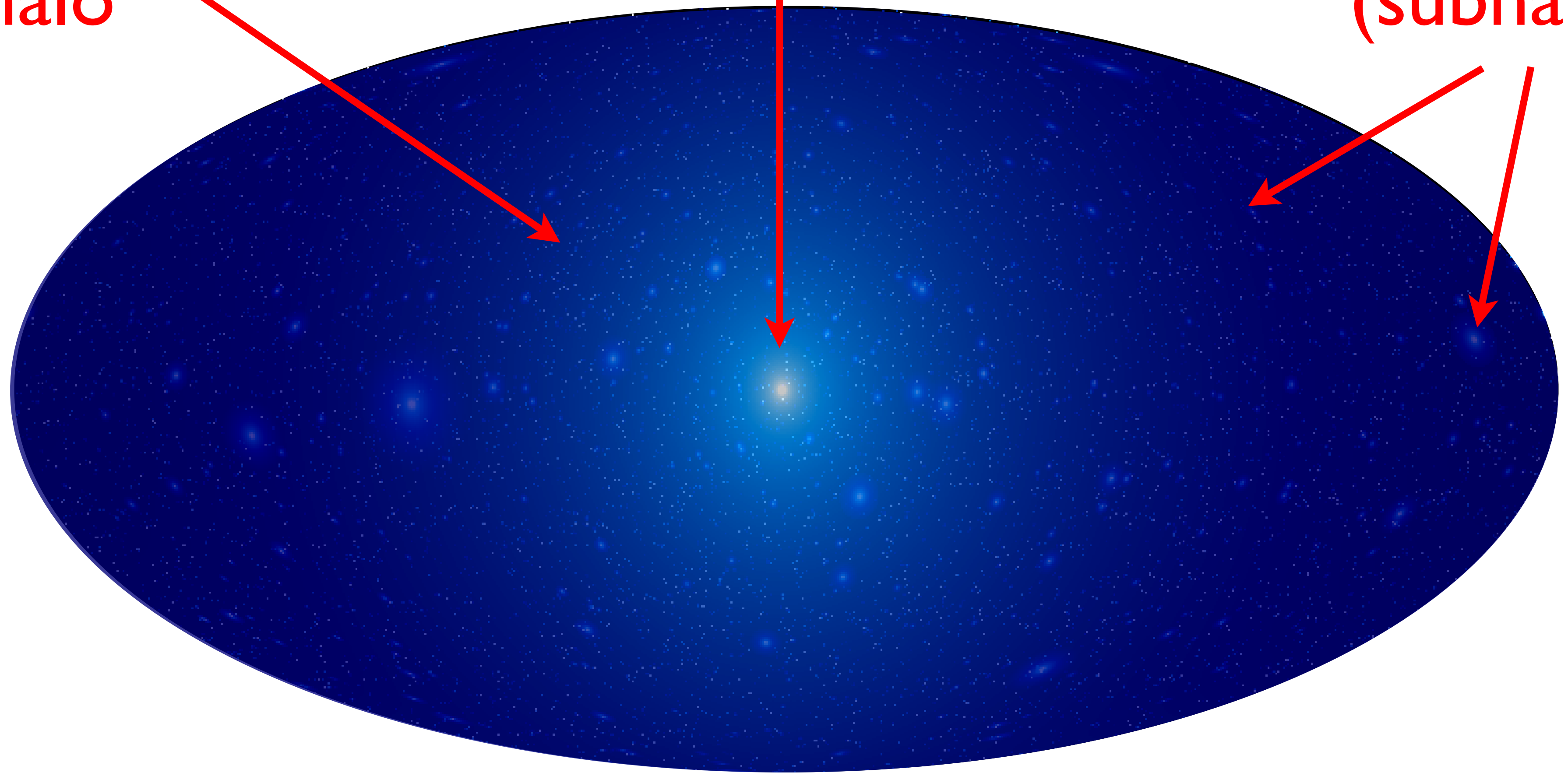
Fermi LAT dark matter search targets



Gamma rays from dark matter annihilation

Image credit: JSG 2008

Fermi LAT dark matter search targets



The Milky Way halo

The inner galaxy

Unassociated sources (subhalos?)

Galaxy clusters

Dwarf galaxies

The Sun

Spectral lines

Cosmic-ray electrons and positrons

Gamma rays from dark matter annihilation

Anisotropies

The isotropic gamma-ray background

Image credit: JSG 2008

The Fermi LAT gamma-ray sky

3-year all-sky map, E > 1 GeV

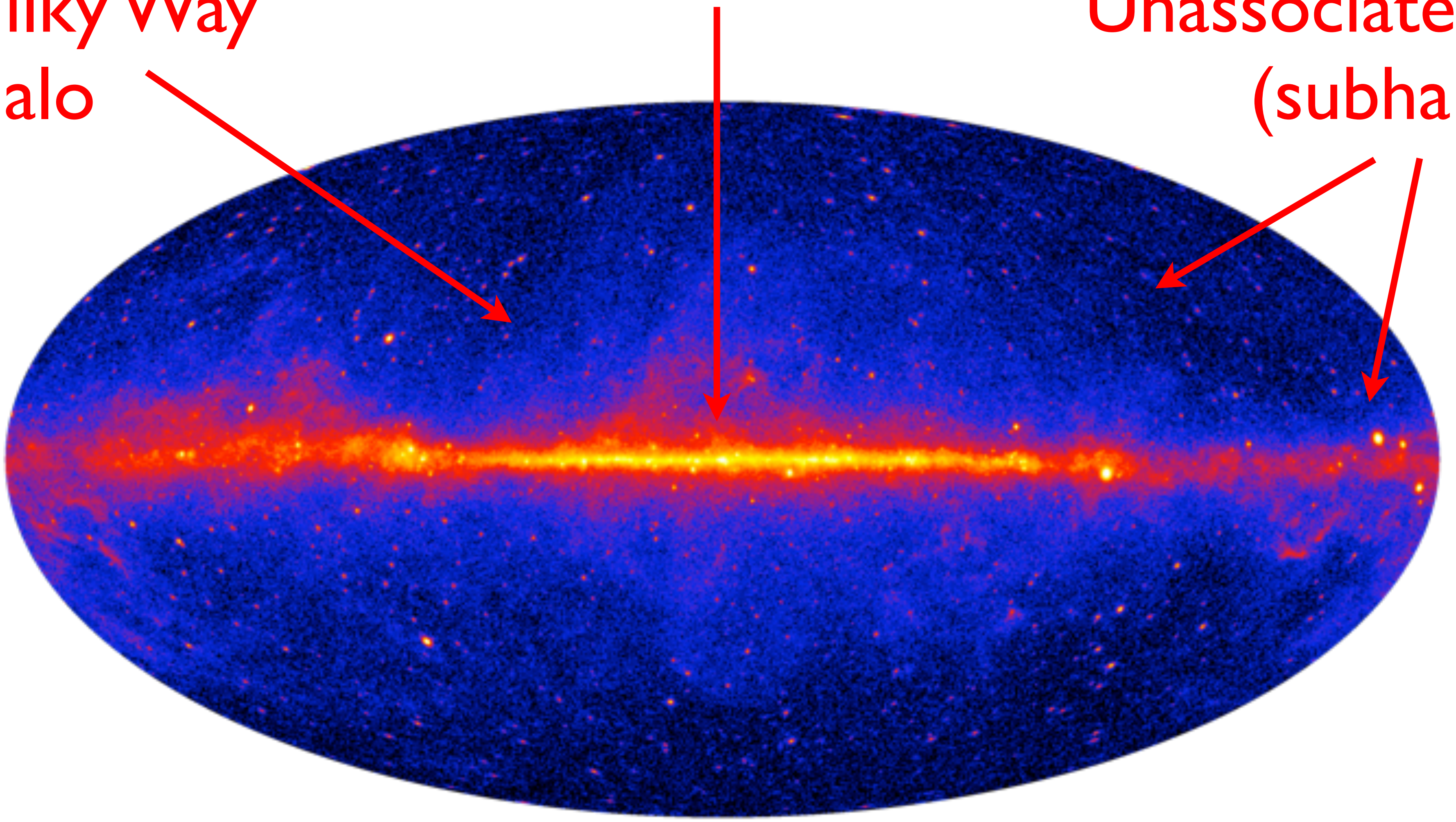


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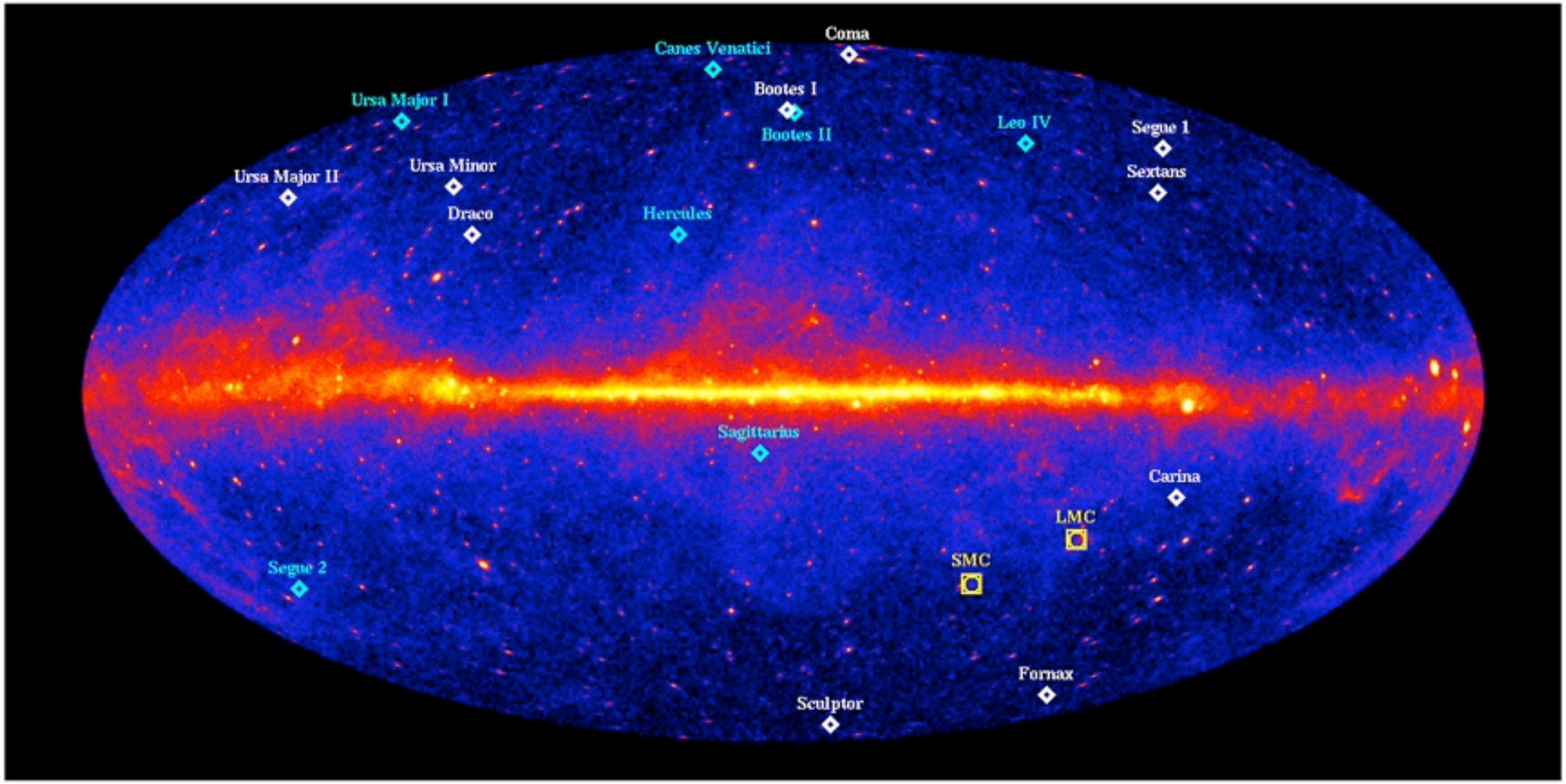
Image Credit: NASA/DOE/International LAT Team

Anisotropies

The isotropic gamma-ray background

Search for gamma rays from dwarf galaxies



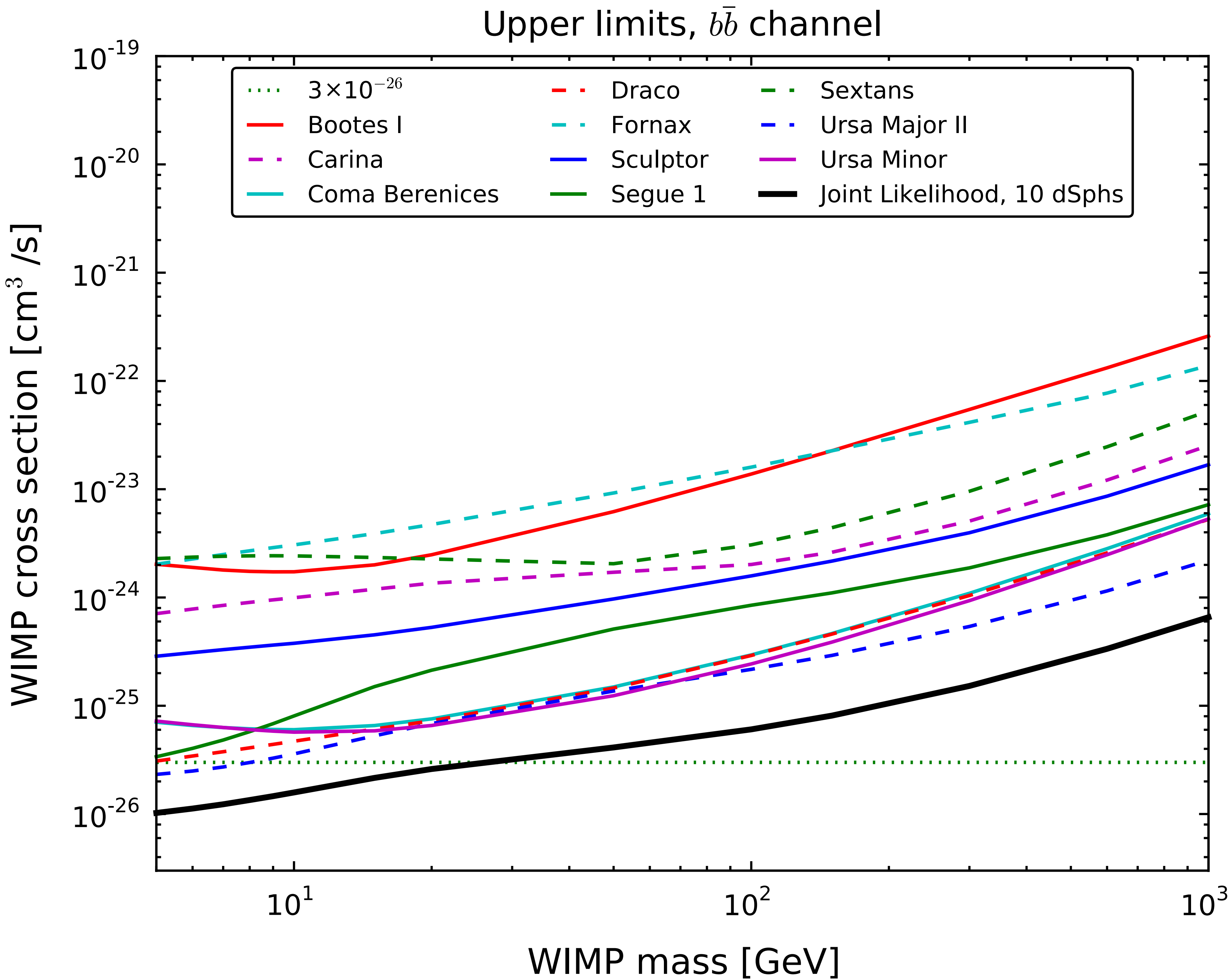
- there are roughly two dozen known dwarf spheroidal galaxies (dSphs) of the Milky Way
- some of the most dark-matter--dominated objects in the Universe
- no non-DM astrophysical gamma-ray production expected

DM limits from combined analysis of dSphs

Joint likelihood analysis of Fermi LAT data:

- 10 dwarf galaxy targets
- 2 years data, energy range: 200 MeV - 100 GeV, P6_V3_diffuse
- 4 annihilation channels
- incorporates statistical uncertainties in the solid-angle-integrated "J-factor"

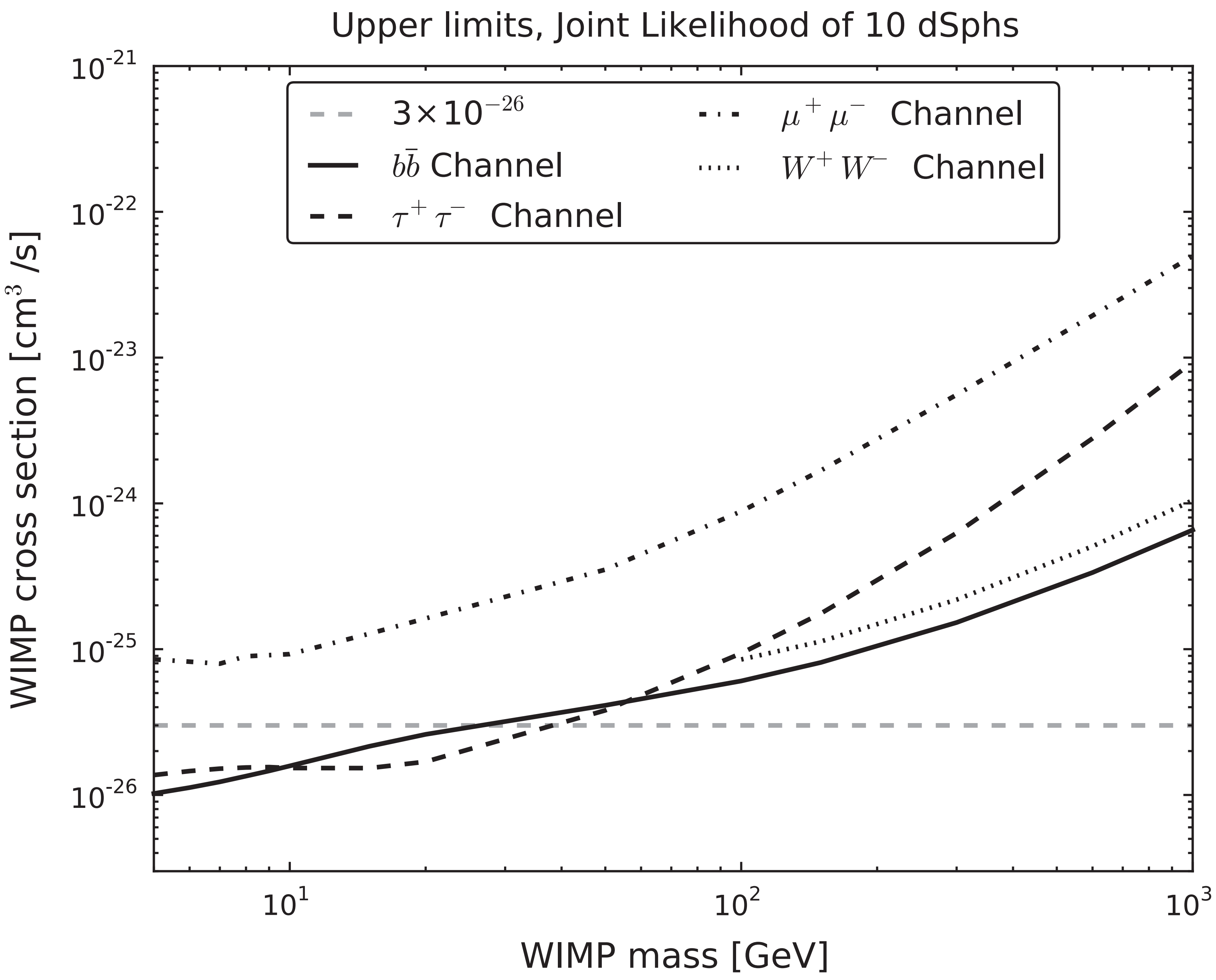
  (= "astrophysical factor" in the predicted signal, set by the dark matter distribution)



see also: Geringer-Sameth & Koushiappas, PRL 107, 241303 (2011); Cholis & Salucci, arXiv:1203.2954

M. Ackermann et al. [Fermi LAT Collaboration], PRL 107, 241302 (2011)

DM limits from combined analysis of dSphs



M. Ackermann et al. [Fermi LAT Collaboration], PRL 107, 241302 (2011)

results exclude the canonical WIMP thermal relic cross-section for annihilation to $b\bar{b}$ or $\tau^+\tau^-$ for masses below ~ 30 GeV

Future prospects for dwarf spheroidals

future DM limits from dSph projected to improve due to:

- increased observation time
- discovery of new dwarfs