Quest for Dark Matter with Cosmic Gamma-ray Observations

Hiroyasu Tajima
Solar-Terrestrial Environment Laboratory
Nagoya University

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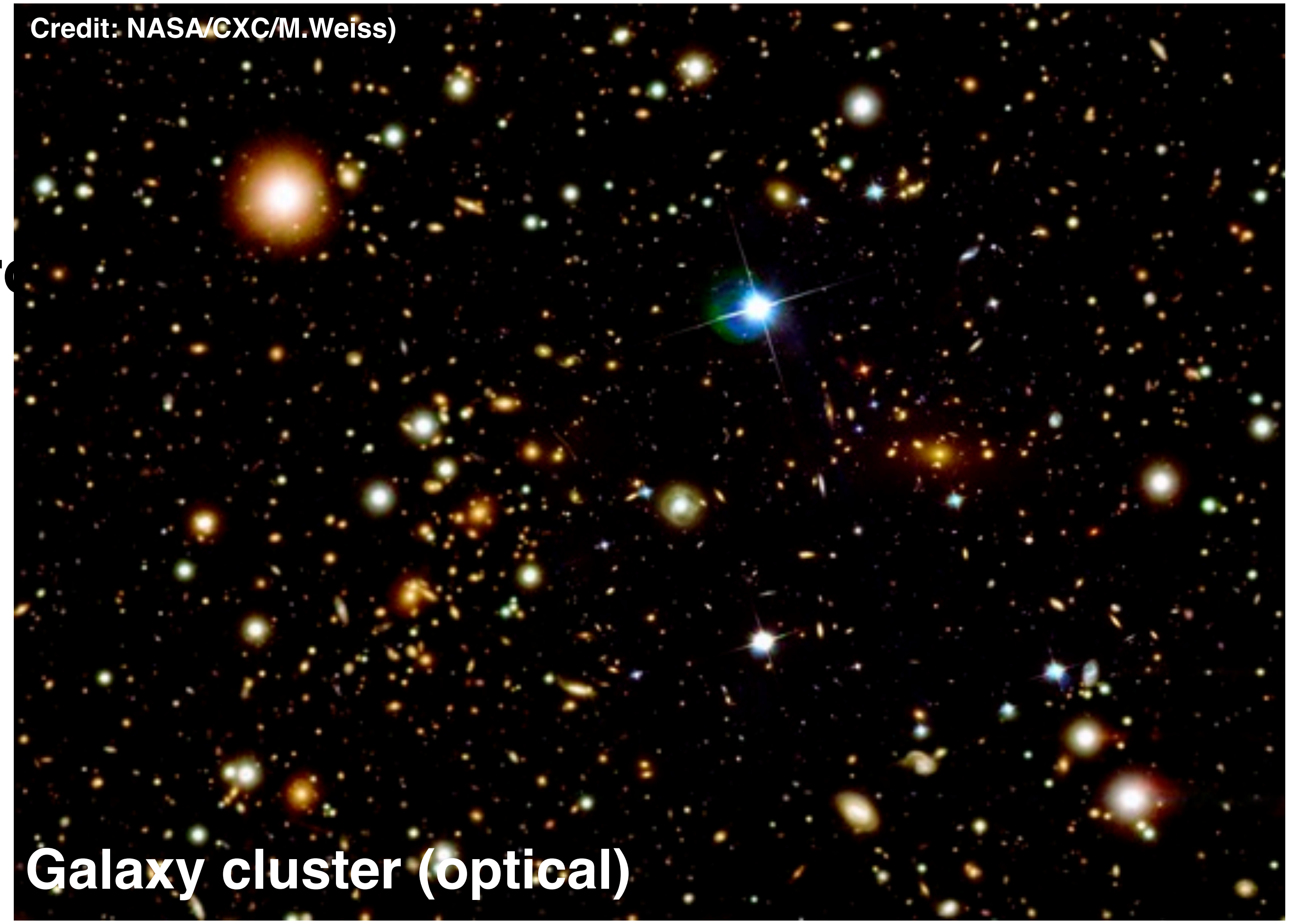
Outline

- Introduction
- Cosmic gamma-ray experiments
  - Fermi Gamma-Ray Space Telescope
  - Imaging atmospheric Cherenkov telescopes (IACTs)
- WIMP searches with Fermi
- WIMP search with IACT
- Future prospects

Dark Matter

- What we know
  - Dark matter exists
    - Orbital velocities of stars in galaxies, velocity dispersions of galaxies in clusters, temperature distribution of hot gas in clusters of galaxies and gravitational lensing
  - Non-relativistic ("cold dark matter")
  - ~6 x ordinary matter
- What we don't know
  - What is dark matter?
    - MACHO: constrained by micr
    - WIMP
      - Weak scale new particles happen to have suitable mass and cross-section

        WIMP miracle
    - Axion



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Mass distribution by gravitational lensing

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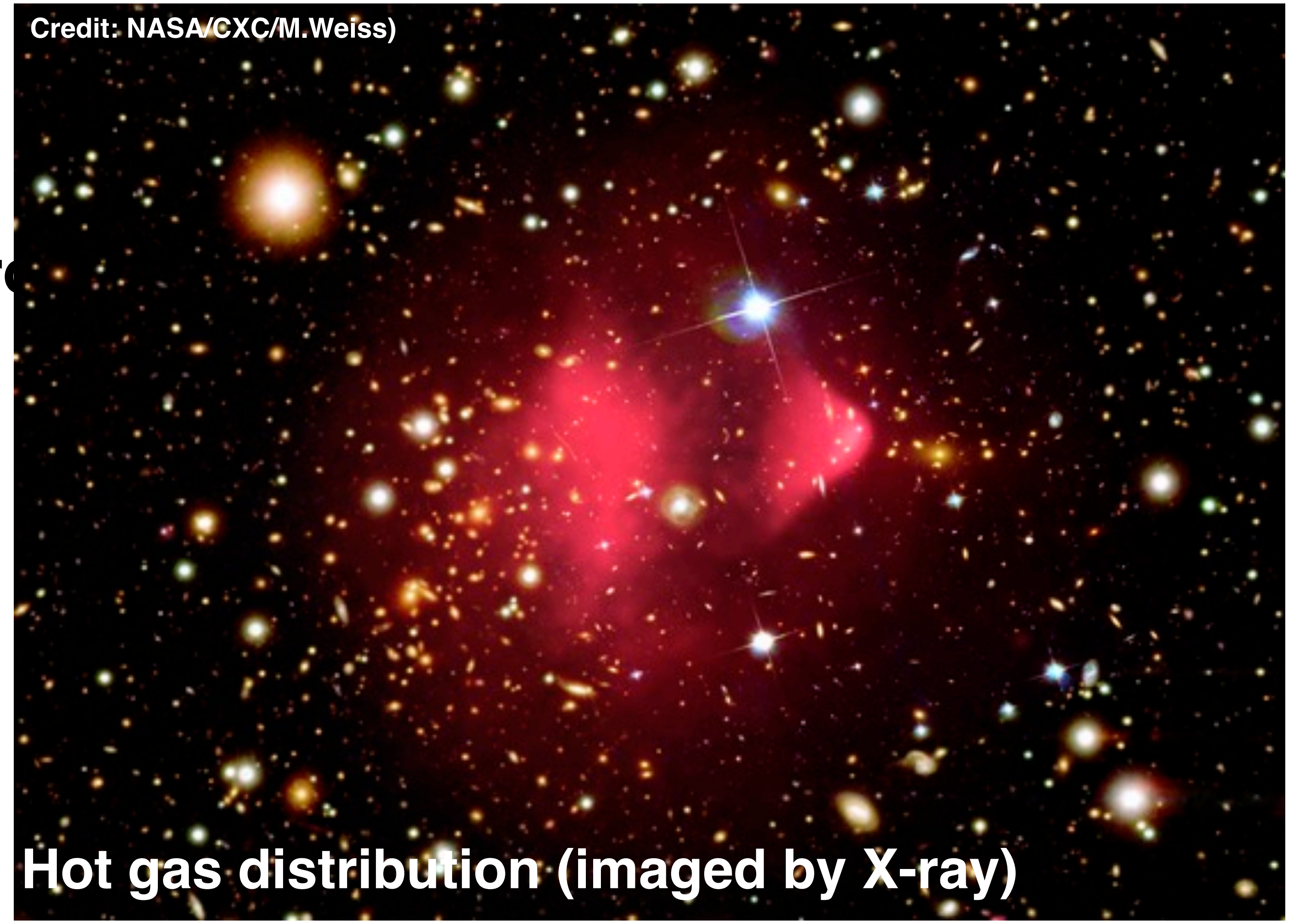

Hot gas distribution (imaged by X-ray)

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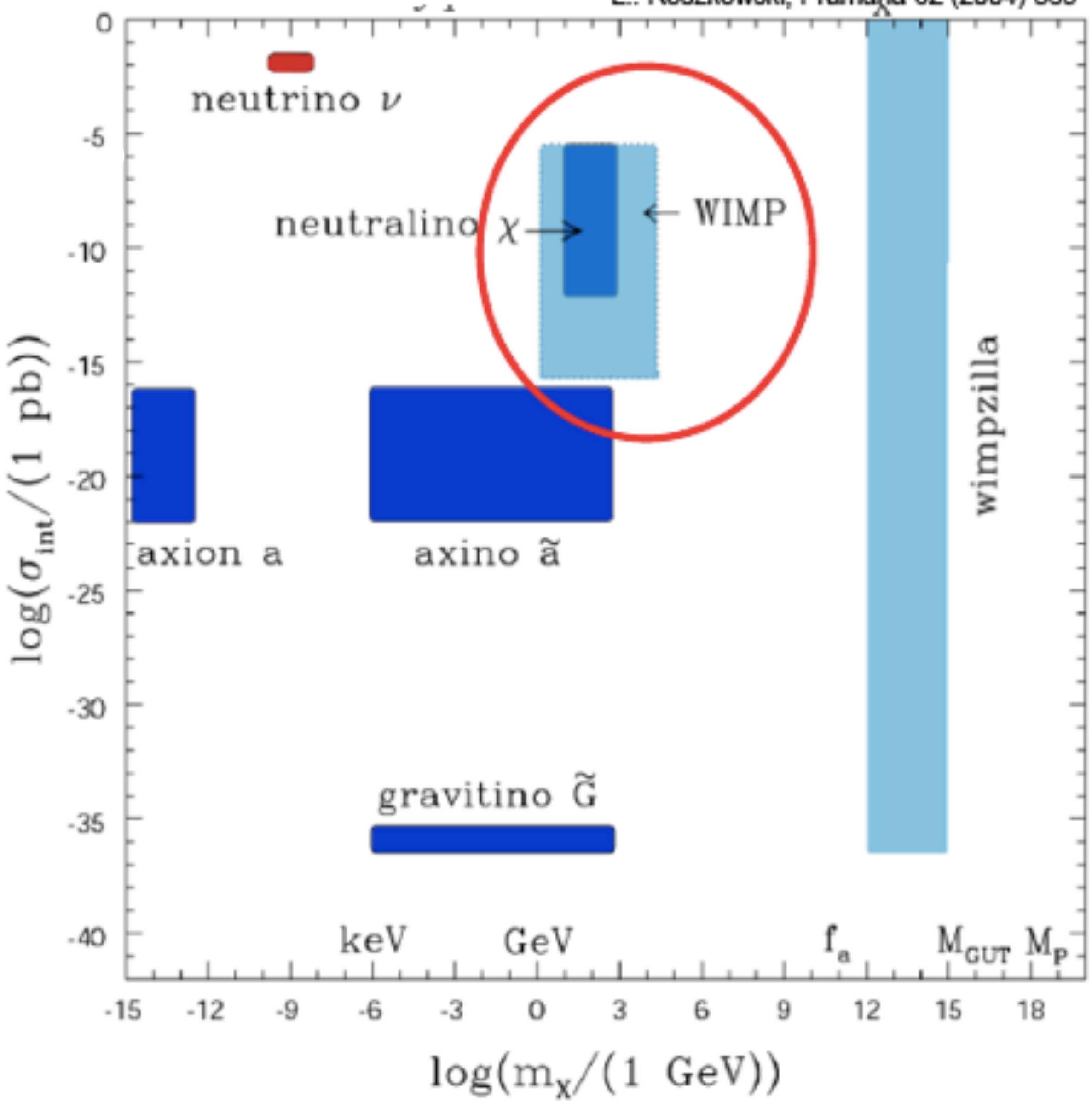
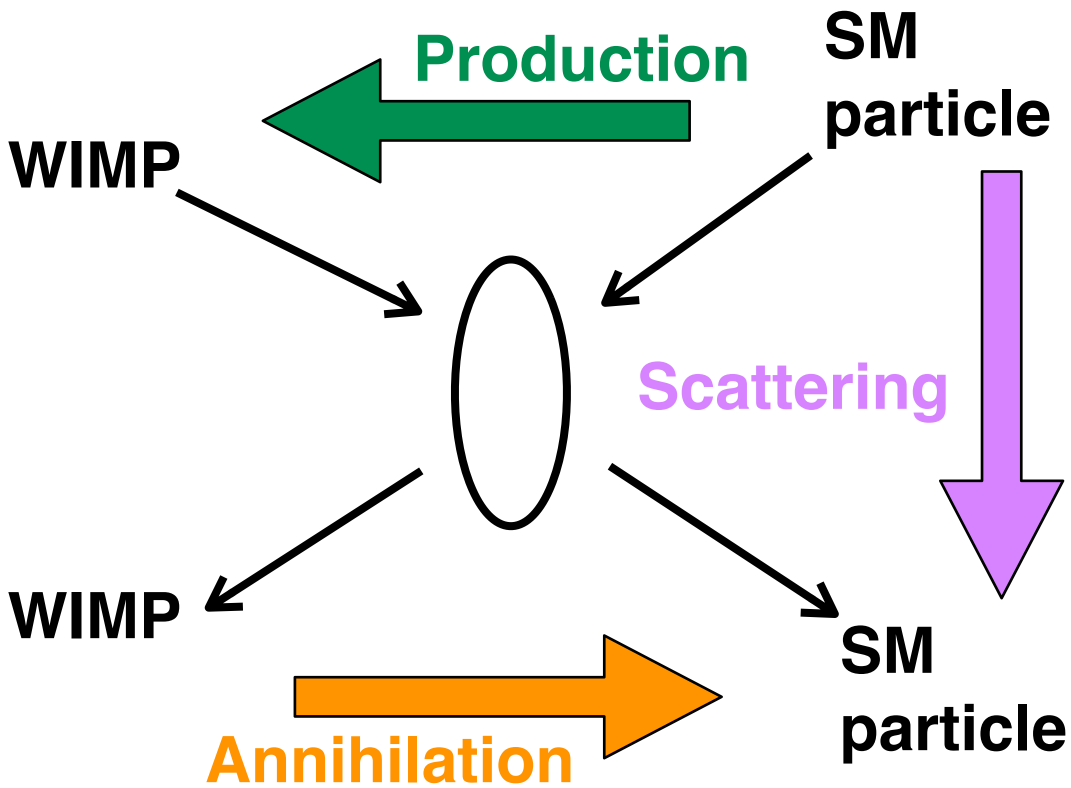


WIMP Search Approaches

- Accelerator production
  - Precise measurements of “DM” properties: mass, cross section
  - UED (KK) vs SUSY
- Direct detection of WIMP scattering
  - Measurement of local WIMP density
- Indirect detection of WIMP annihilation
  - “Direct” constraints on annihilation cross section
  - Distribution of WIMP in the Universe

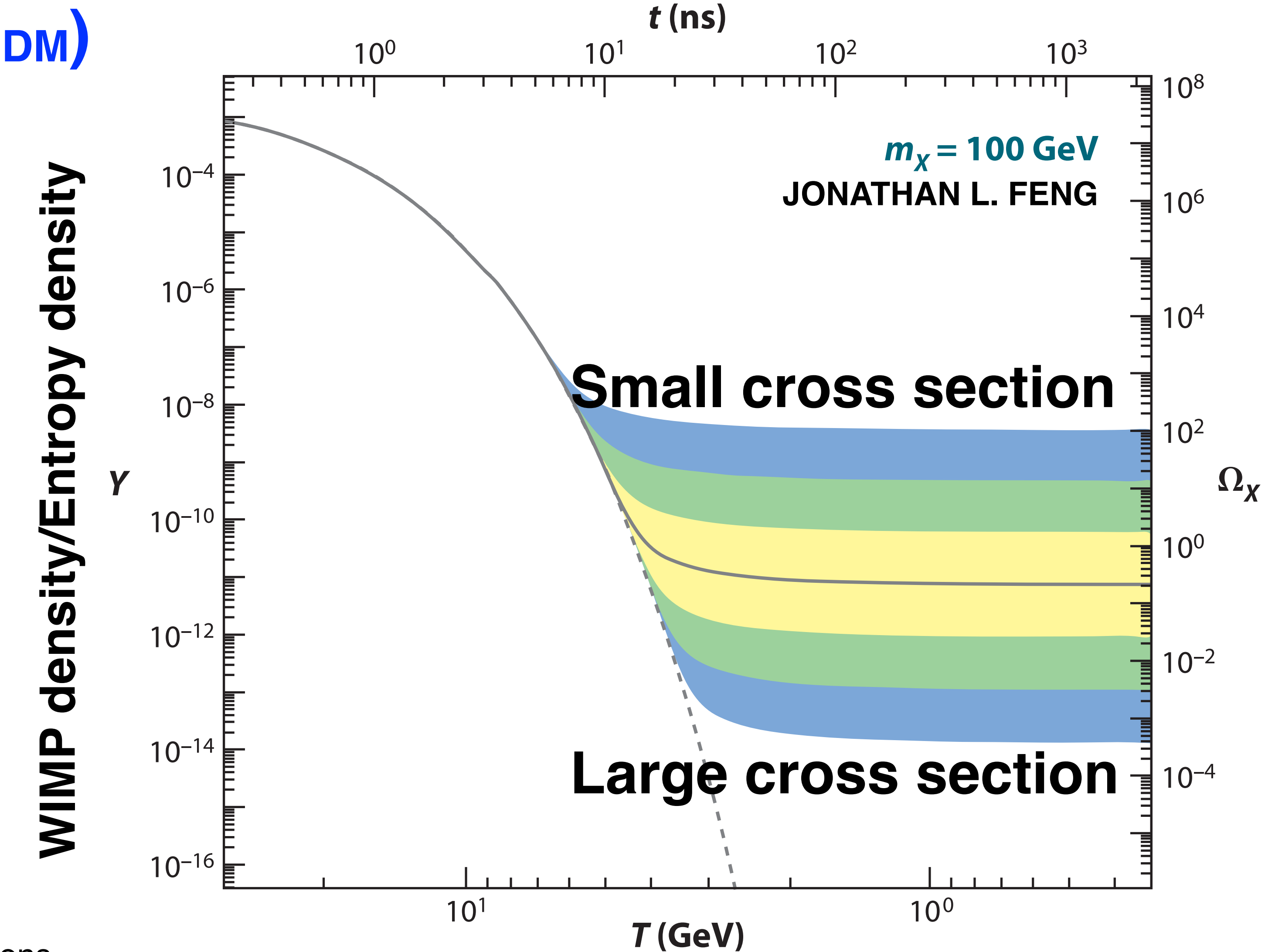
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\varphi,\theta) = \overbrace{\frac{1}{4\pi}\frac{\langle \sigma_{ann} v \rangle}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}^{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega(\varphi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\varphi'))\, dl(r,\varphi')}_{\text{DM distribution}}$$



- Those approaches are complimentary
  - Different model dependences and sensitivity phase space

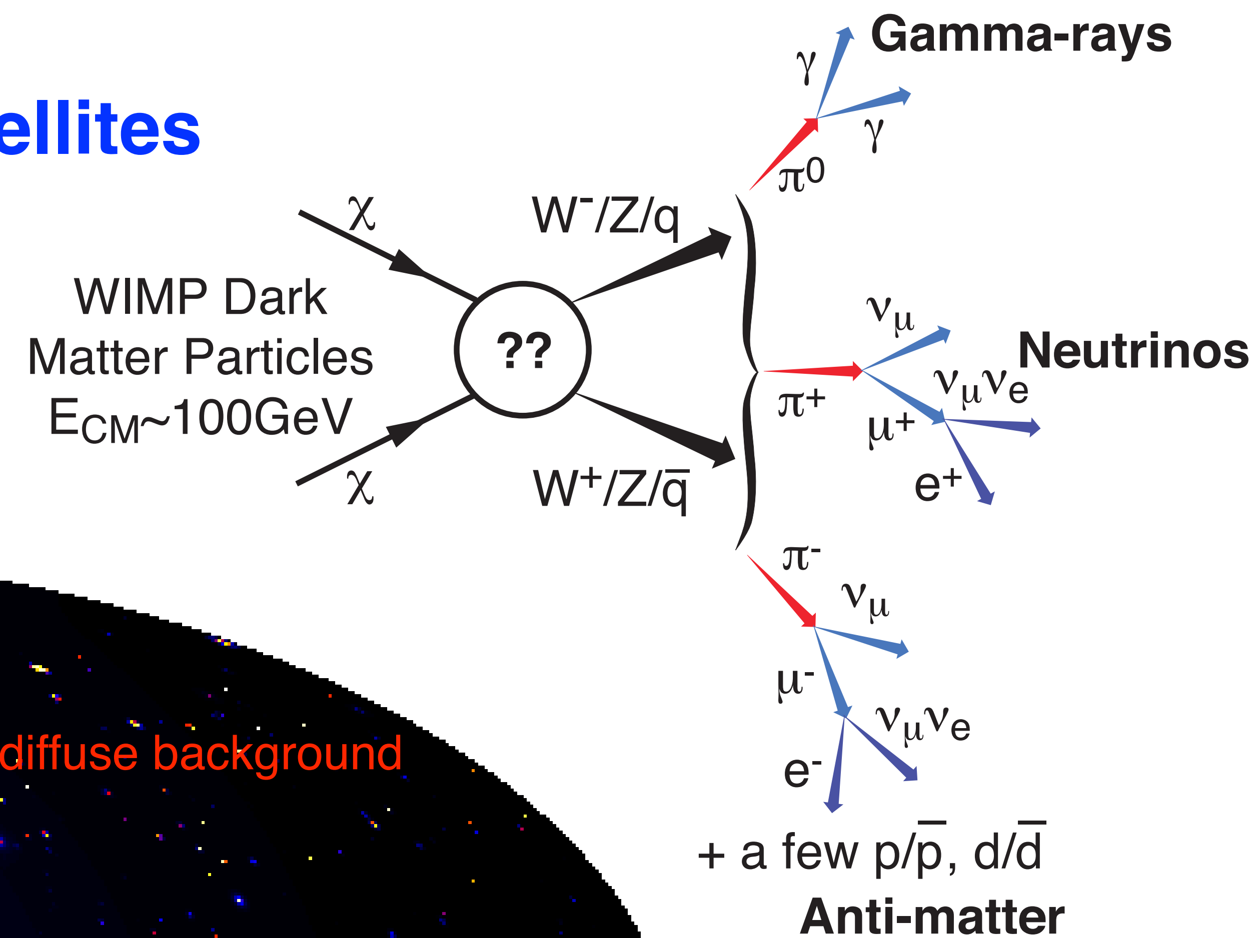
Thermal Relic Dark Matter (WIMP)

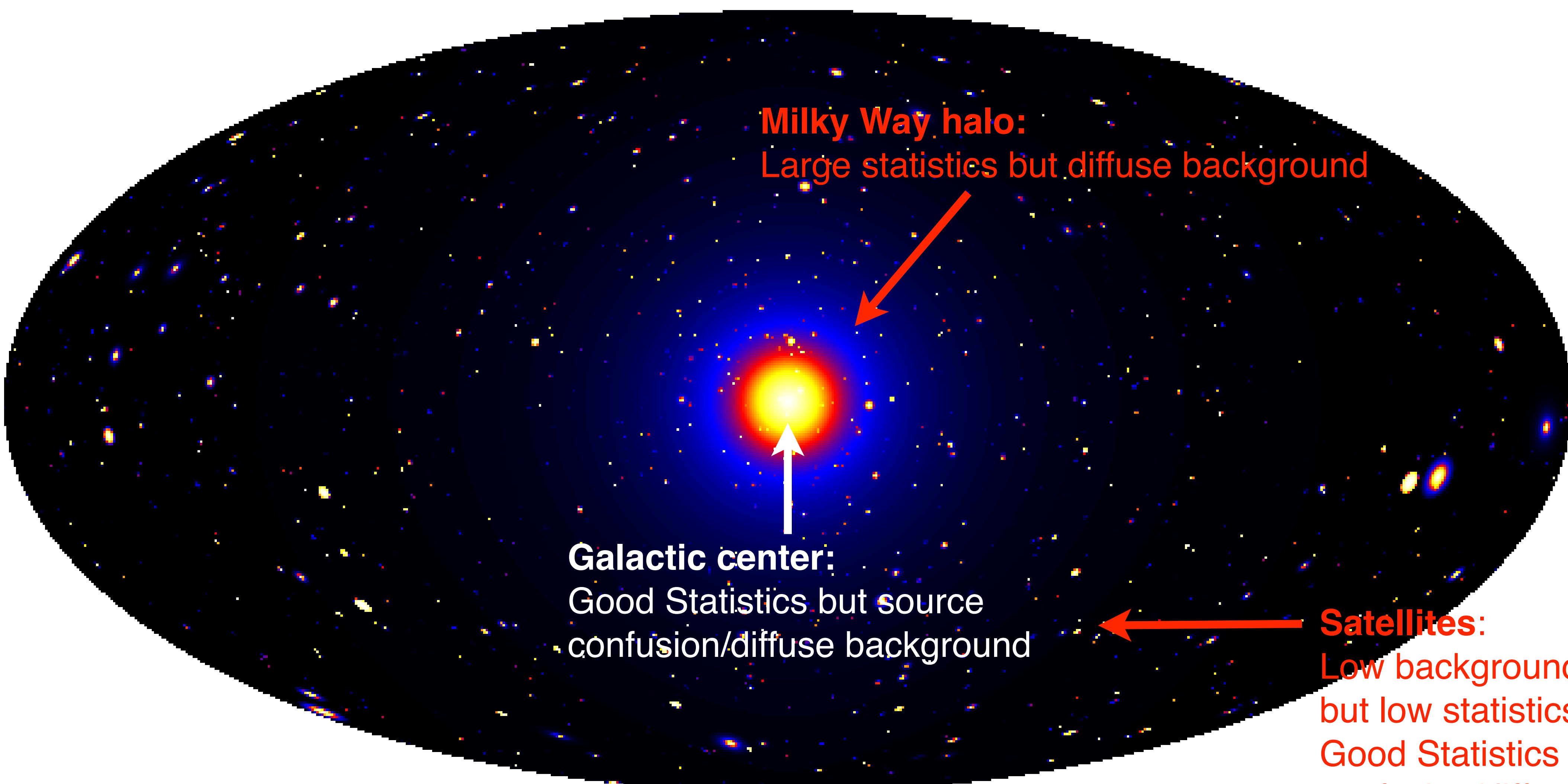
- WIMP is in equilibrium between pair creation and annihilation in early Universe
  - Pair creation stops when thermal energy is not sufficient
  - Annihilation continues and WIMP density become too low compared with annihilation cross section
    - WIMP density and annihilation cross section is anti-correlated
  - Current dark matter density (Ω_{DM}) constrains annihilation cross section to ~3×10^{-26} cm²/s



Search for WIMP with Gamma Rays

- **Multi-pronged approaches**
  - **Galactic center, Milky Way halo, Satellites**
  - **Line emission, Continuum**
  - **CR electrons, Diffuse gamma-ray background**





Satellites:
Low background and good source id,
but low statistics, astrophysical background
Good Statistics but source
confusion/diffuse background

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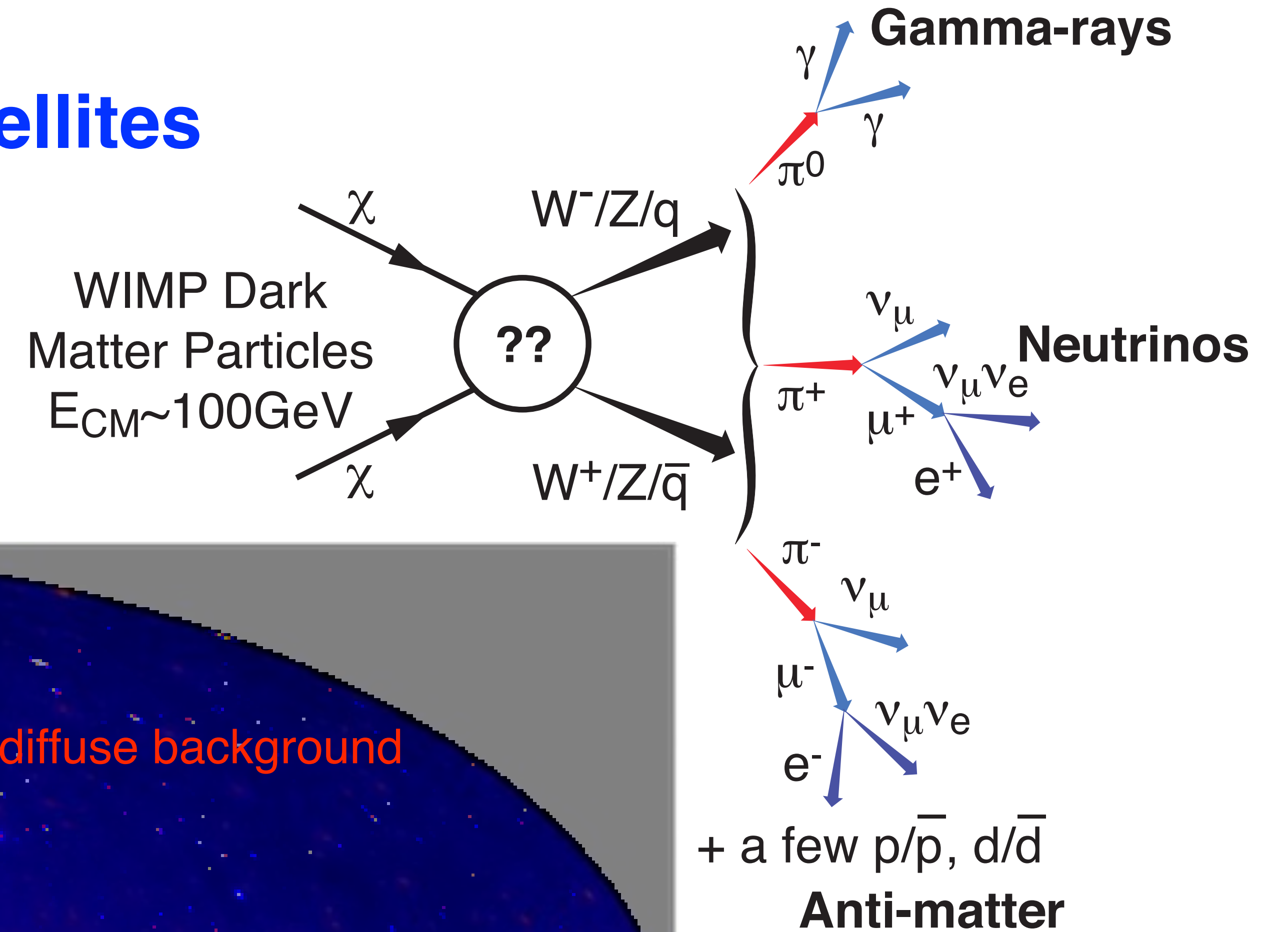
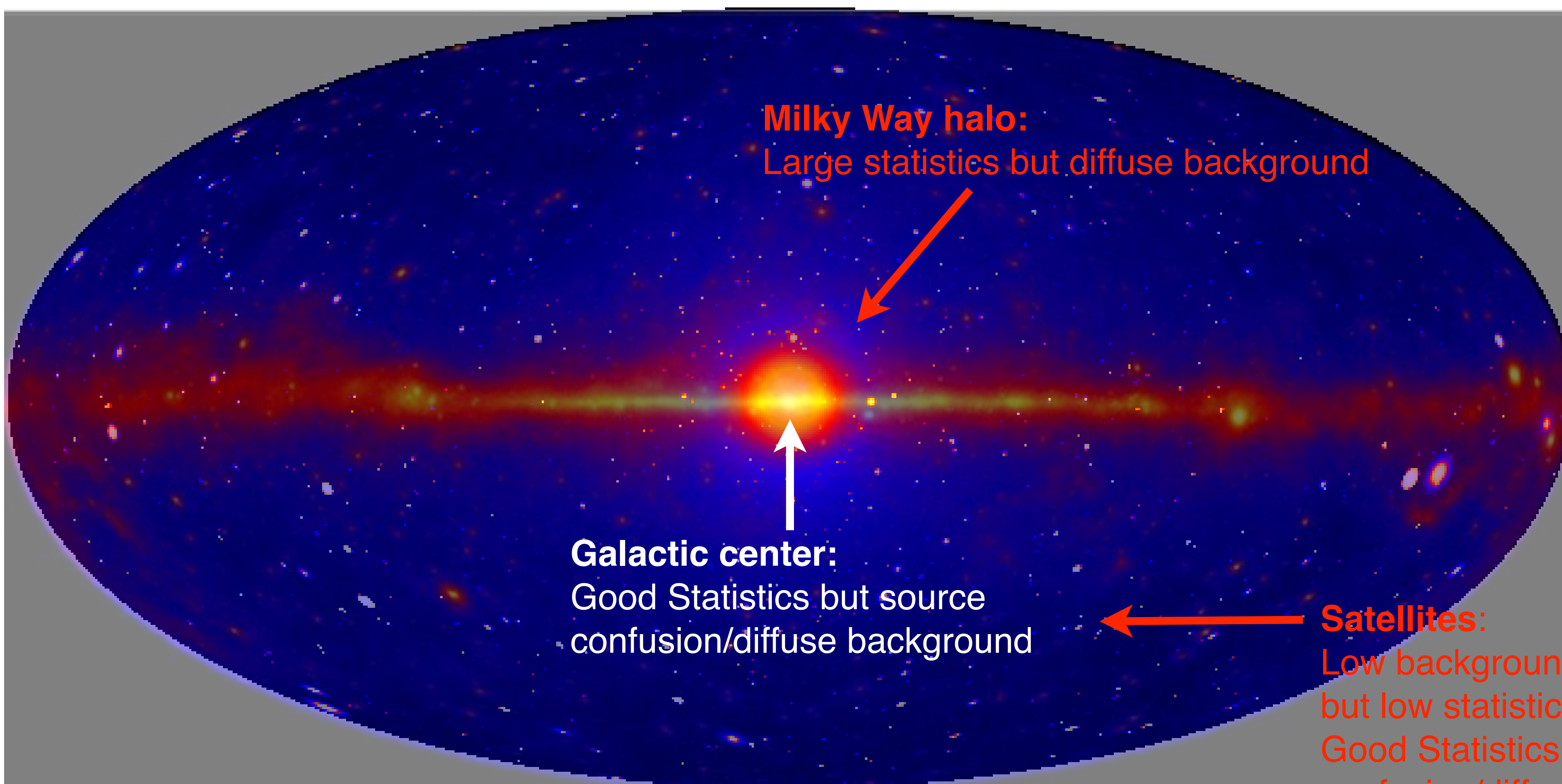


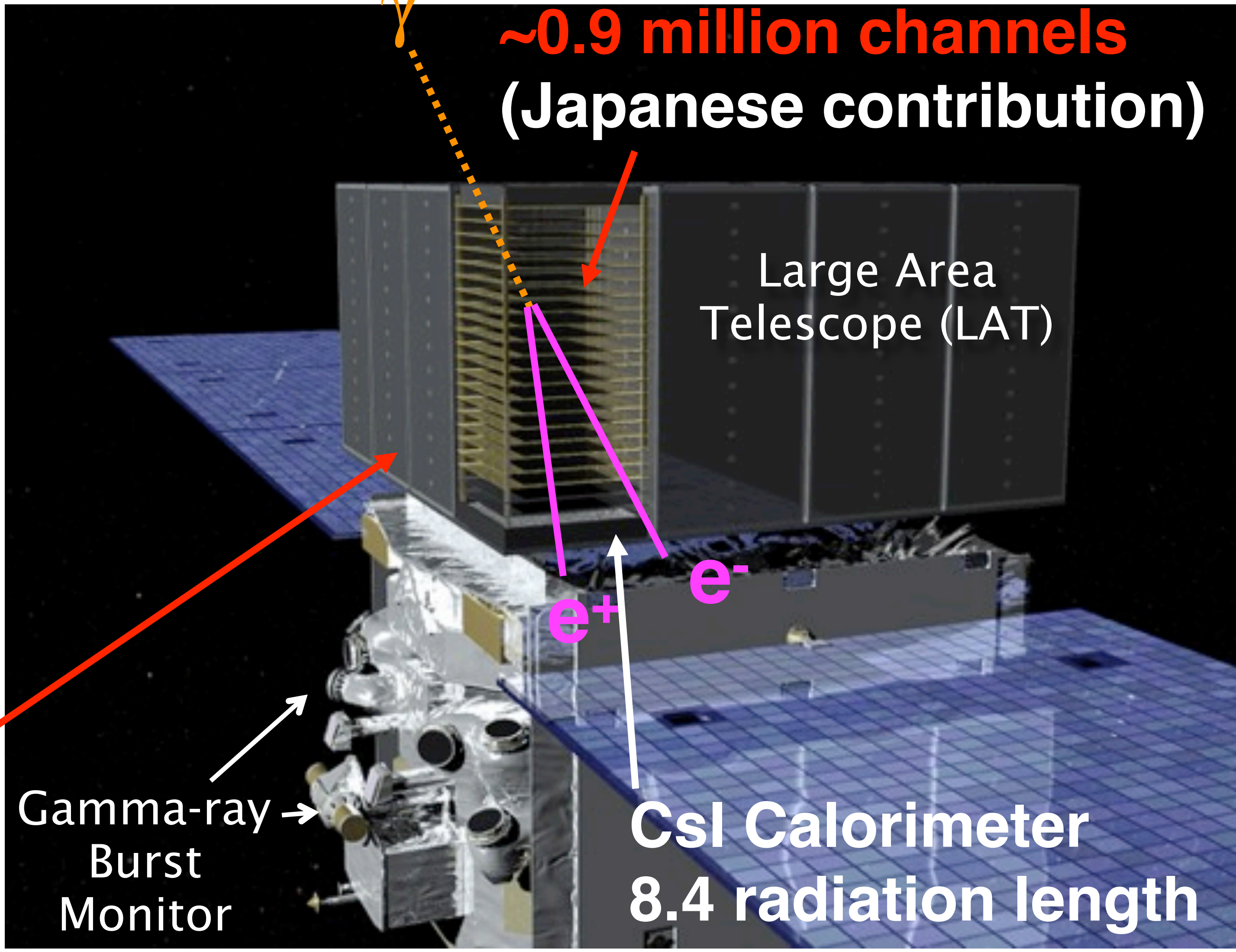


Fermi LAT (Large Area Telescope)

- Pair-conversion telescope
  - Good background rejection due to “clear” gamma-ray signature
- Tracker (TKR): pair conversion, tracking
  - Angular resolution is dominated by scattering below ~GeV
- Calorimeter: energy measurement
  - 8.4 radiation length
  - Use shower development to compensate for the leakage
- Anti-coincidence detector:
  - Efficiency > 99.97%

Energy band: 20 MeV to >300 GeV
Effective area: > 8000 cm2 (~6xEGRET)
Field of view: > 2.4 sr (~5xEGRET)
Angular resolution: 0.04 – 10°
Energy resolution: 5 – 10%

Si Tracker
70 m^2 , 228 μm pitch



Anti-coincidence Detector
Segmented scintillator tiles
99.97% efficiency

Fermi/LAT Collaboration

Stanford University & SLAC
NASA Goddard Space Flight Center
Naval Research Laboratory
University of California at Santa Cruz
Sonoma State University
University of Washington
Purdue Univeristy-Calumet
Ohio State University
University of Denver

~400 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

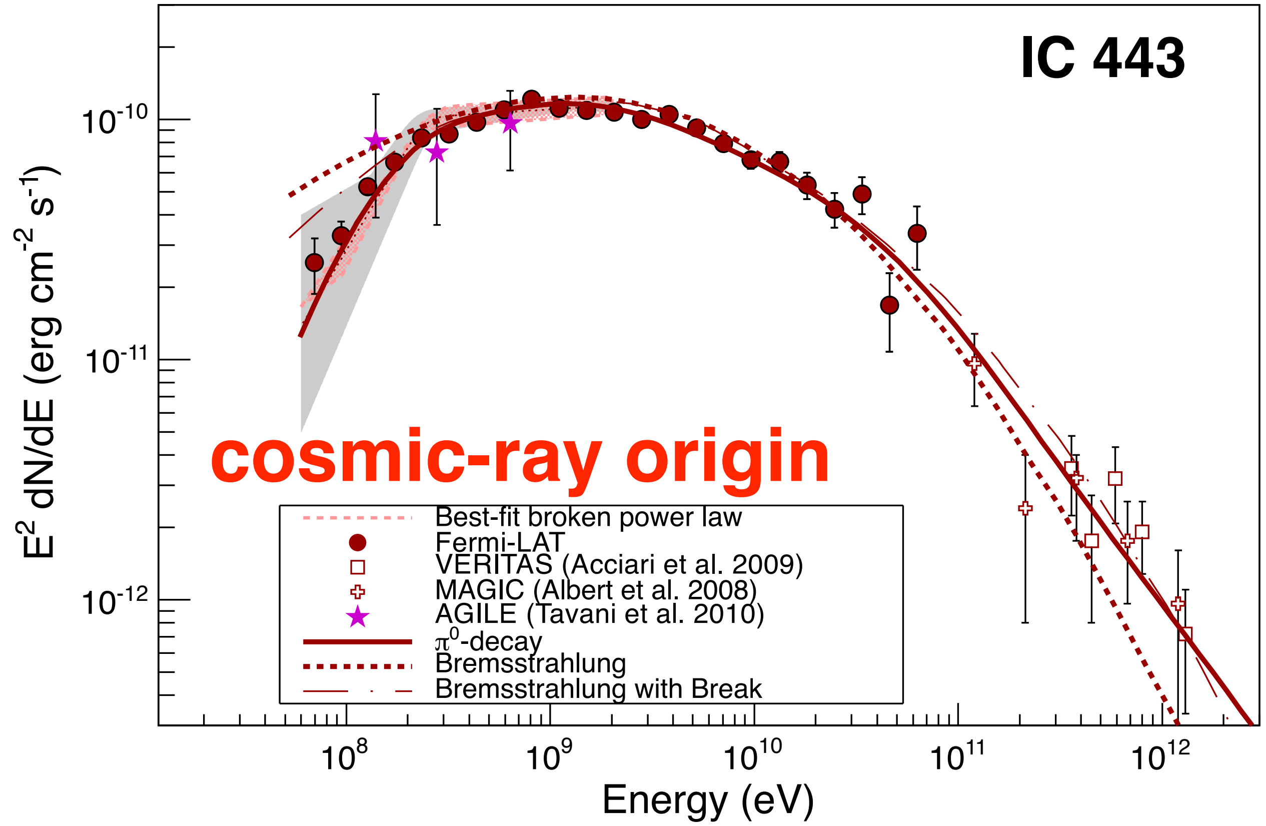
Commissariat a l'Energie Atomique, Saclay
CNRS/IN2P3 (CENBG-Bordeaux, LLR-Ecole polytechnique, LPTA-Montpellier)

Hiroshima University
Nagoya University
Institute of Space and Astronautical Science
Tokyo Institute of Technology
RIKEN

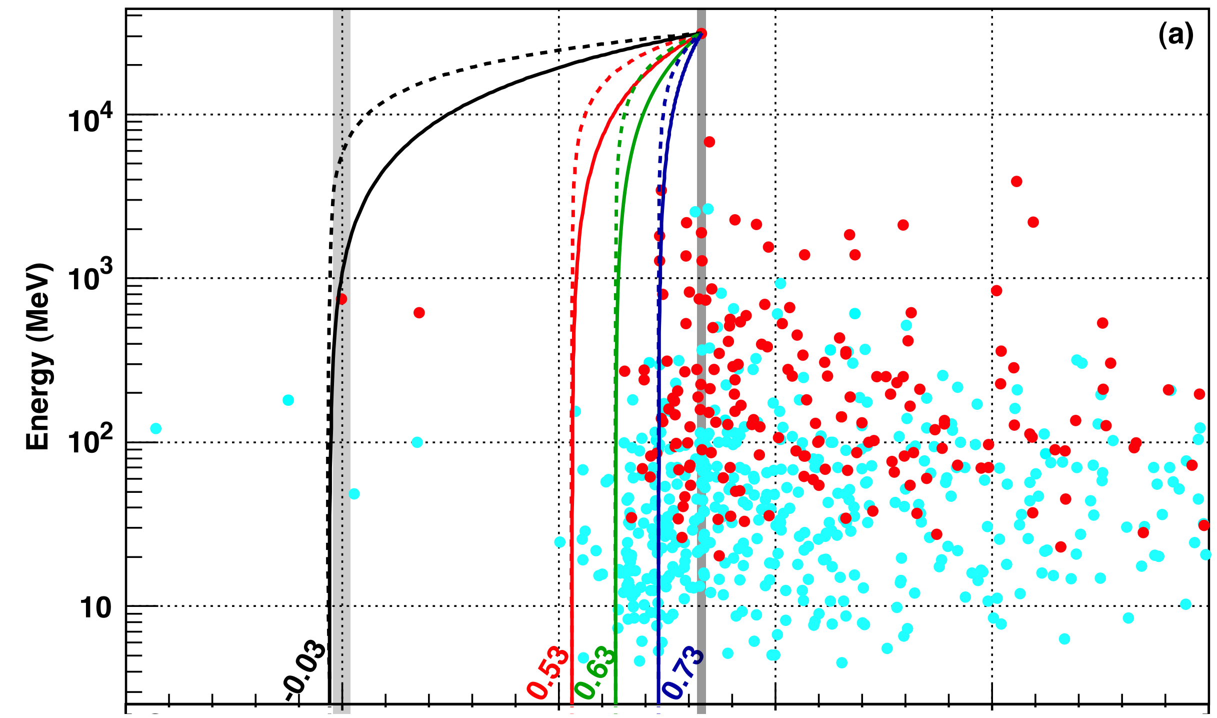
Instituto Nazionale di Fisica Nucleare
Agenzia Spaziale Italiana
Istituto di Astrofisica Spaziale e Fisica Cosmica

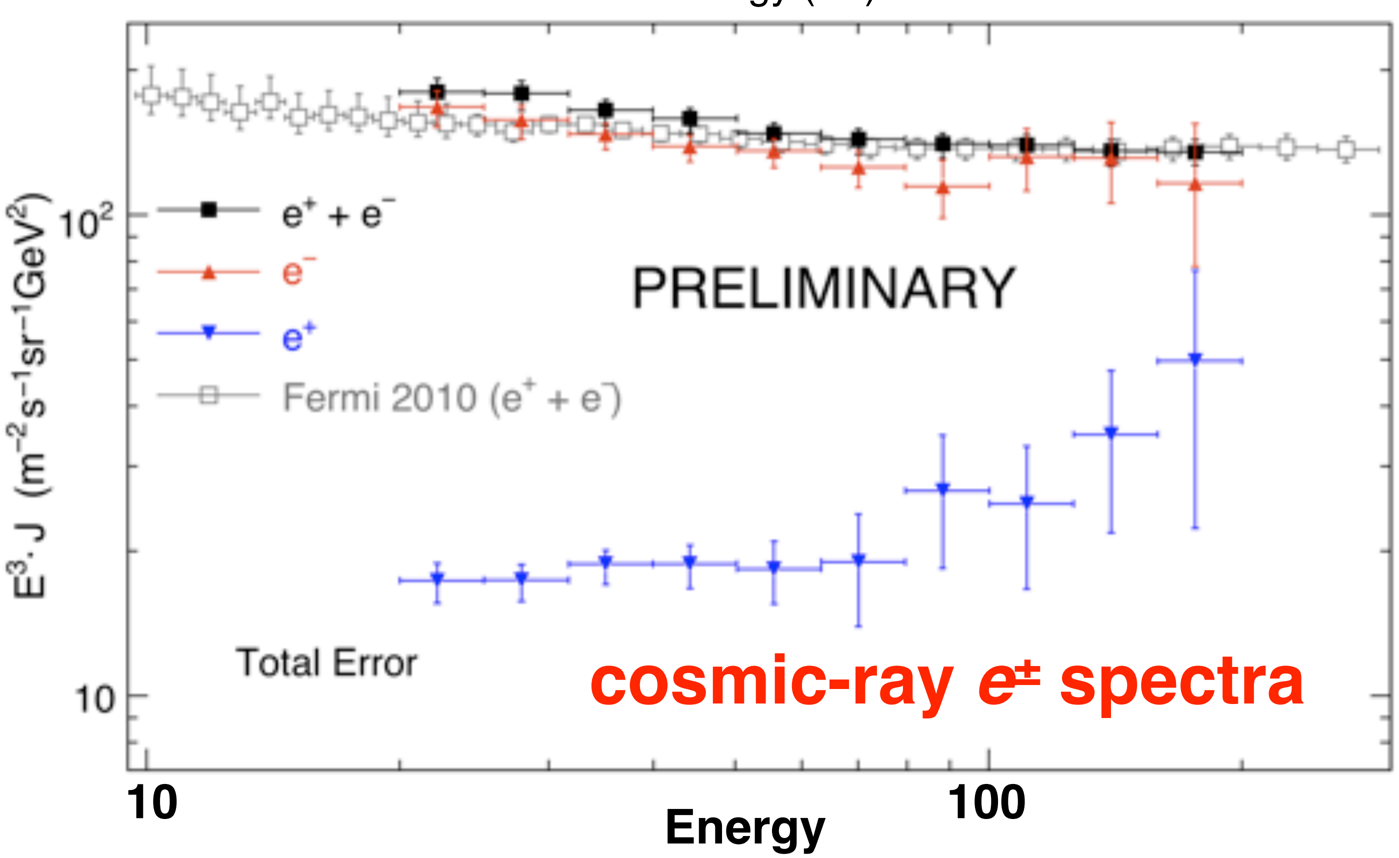
Royal Institute of Technology, Stockholm
Stockholms Universitet

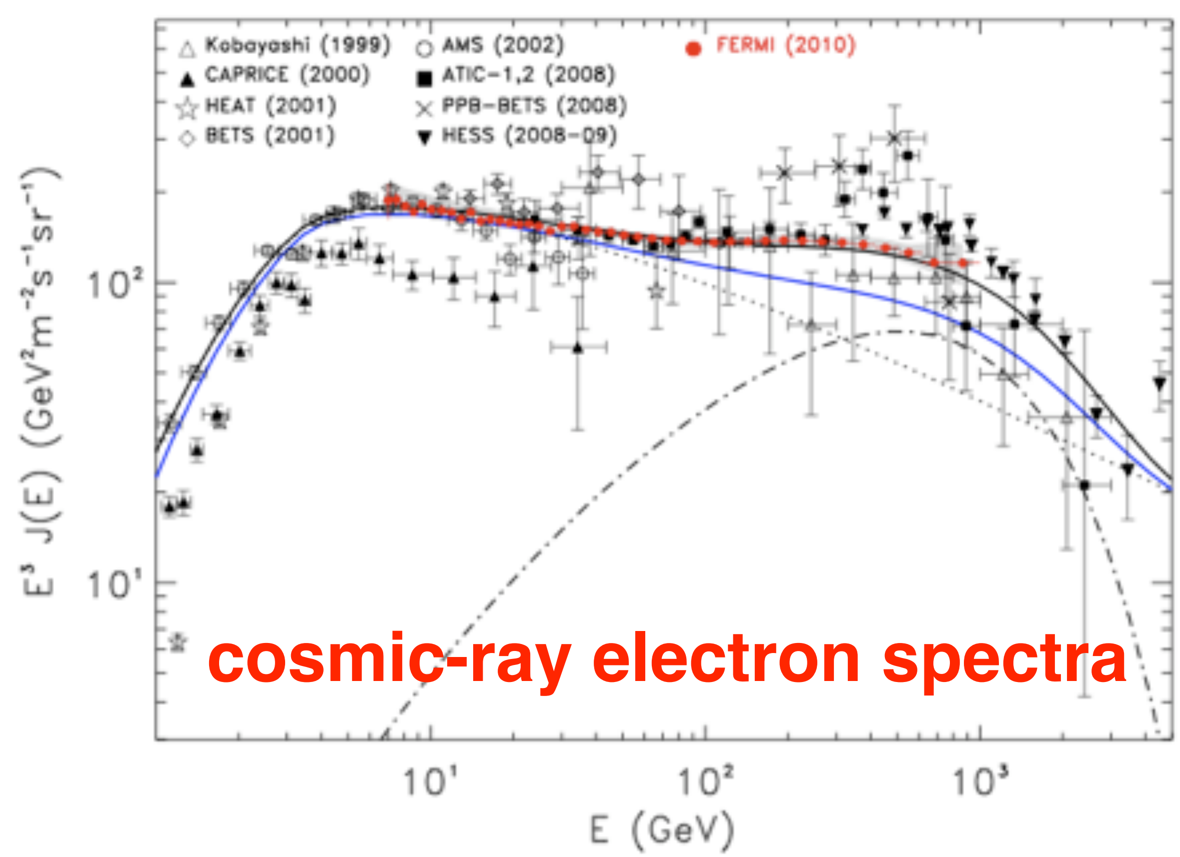
Highlights of Fermi Science



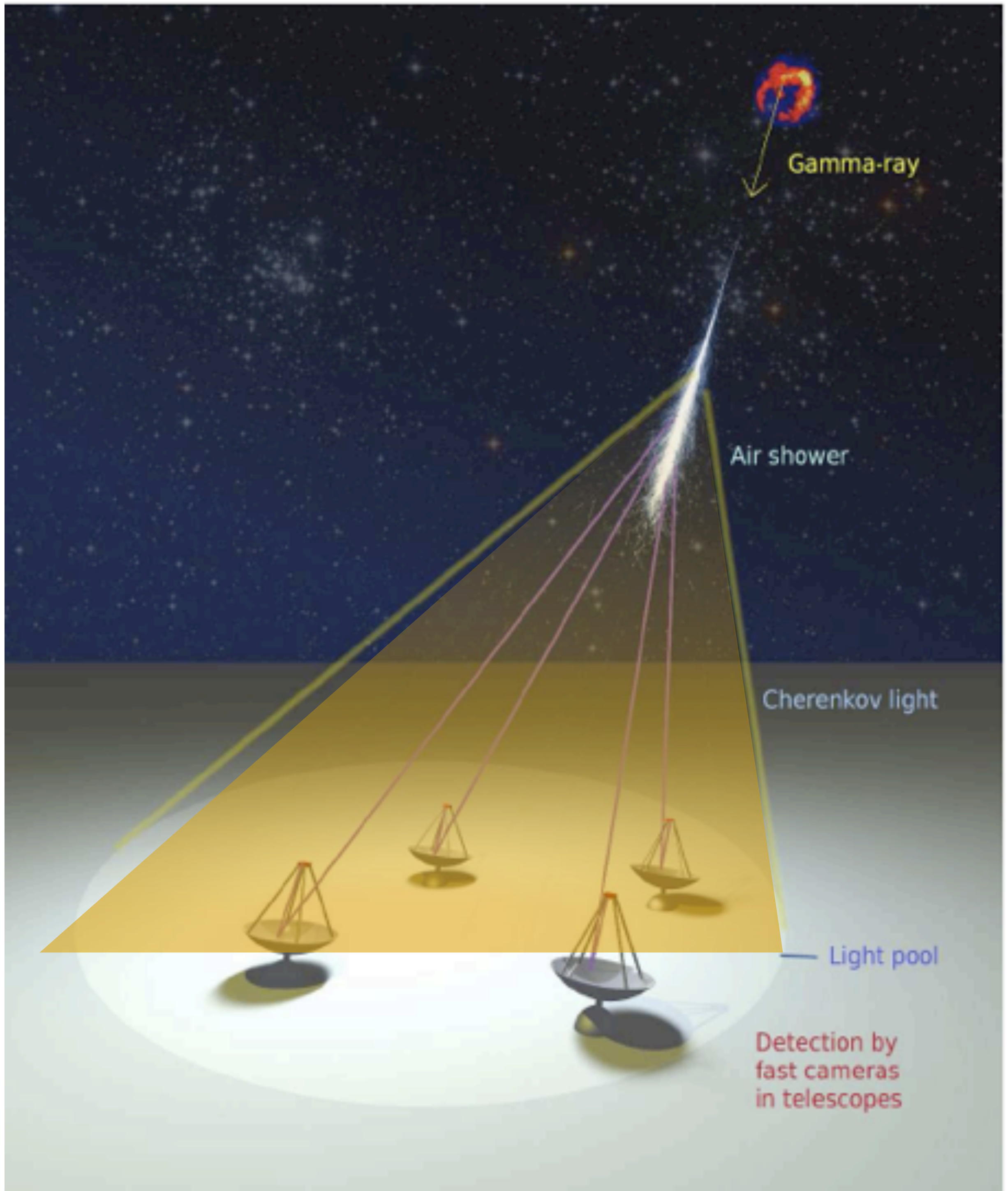
Test of Lorentz Invariance Violation



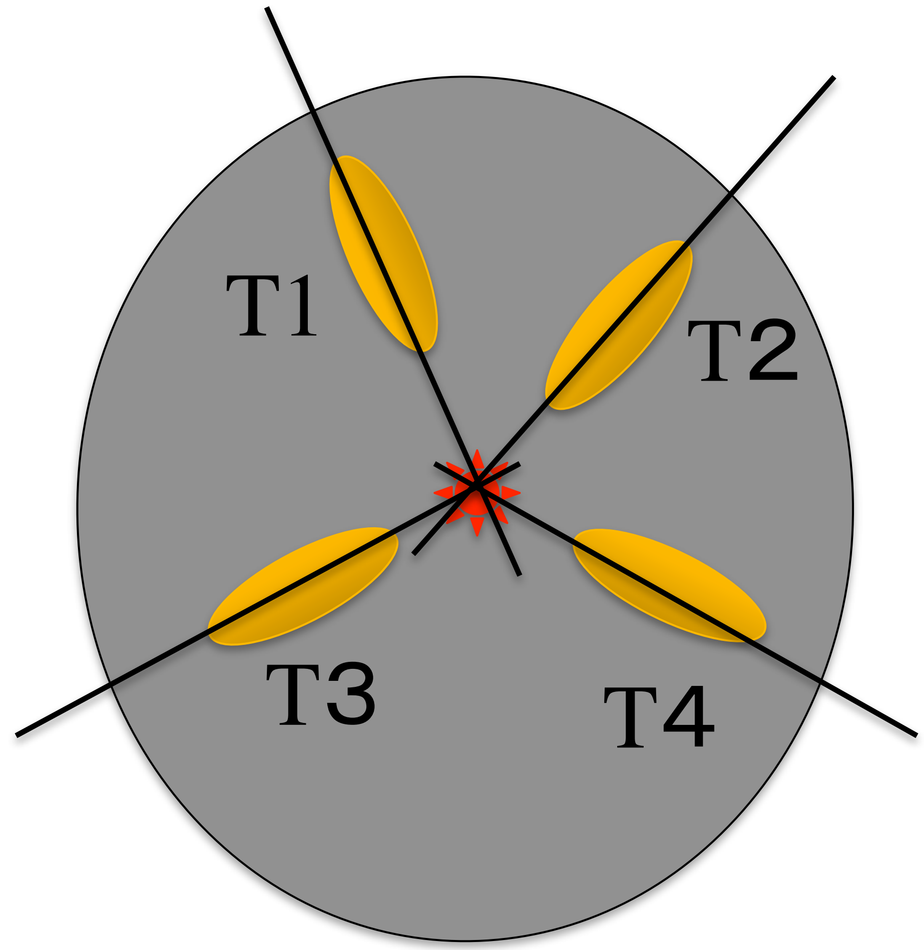




Imaging Atmospheric Cherenkov Telescope



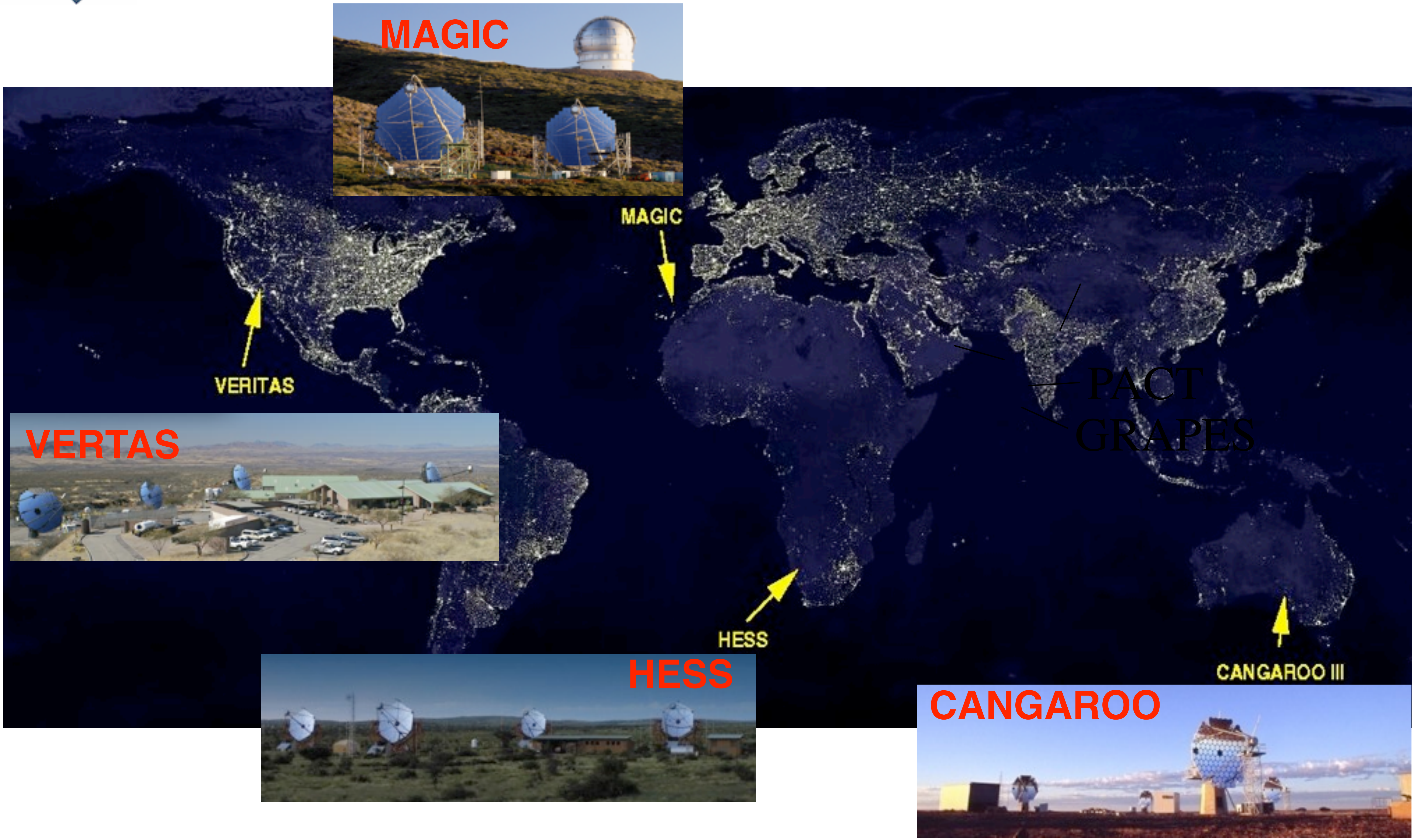
Cherenkov Light
50 photons/m² (5 pe/m²) at 1TeV



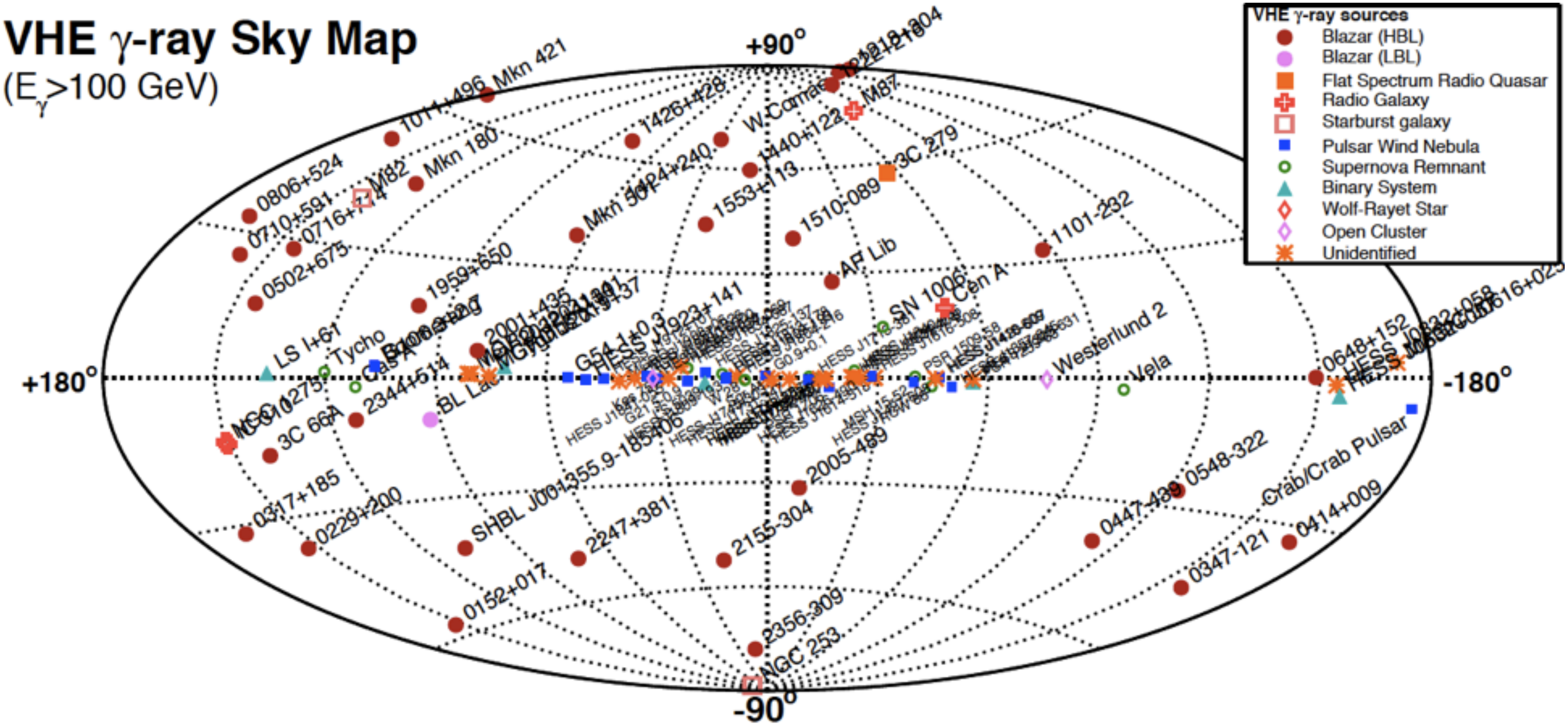
Typical parameters

Energy range	**50GeV ~ 10TeV**
Angular resolution	**~0.1 degrees**
Energy resolution	**~20%**
Detection area	**~10^5m²**
Field of view	**~4° (~10^{-2} sr)**

IACTs on Earth



VHE Skymap

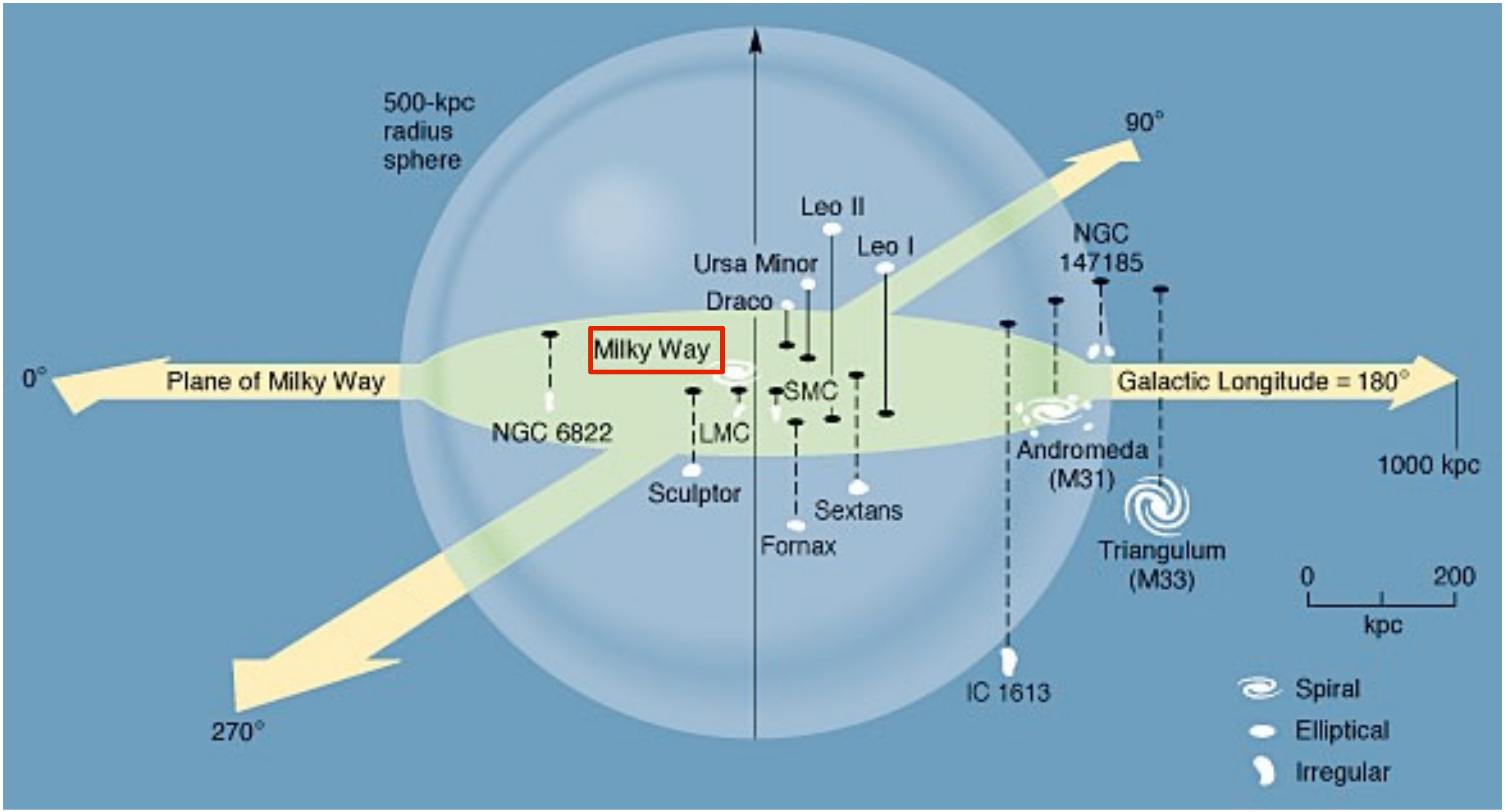


2010-11-11 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/

106 sources (45 Extragalactics + 61 Galactics) in Nov 2010
Blazars, FSRQs, FR-I, Starburst galaxies
SNRs, PWNe, Pulsar, Binaries, un-IDs

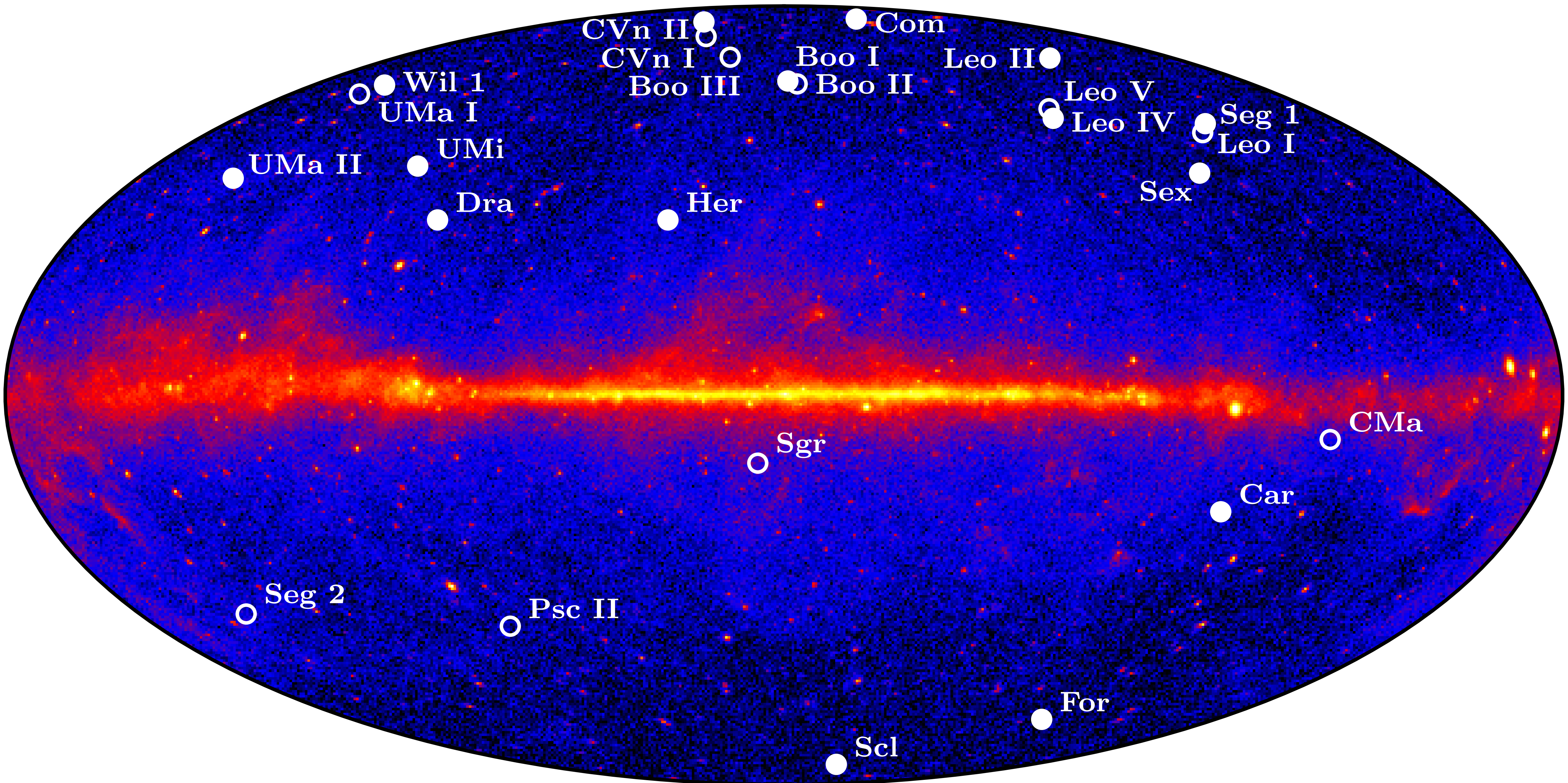
Dwarf Spheroidal Galaxies

- Many dwarf spheroidal galaxies (dSph) around our Galaxy
  - dSphs are known to have large dark matter fraction (~100%)
  - Negligible gamma-ray backgrounds from ordinary matter (few stars)



Fermi WIMP Search in Dwarf Galaxies

- 15 most promising dSph (dwarf spheroidal) based on distance, Matter/Light (M/L)
  - New DM-dominated dSph is being discovered recently



arXiv:1310.0828v1

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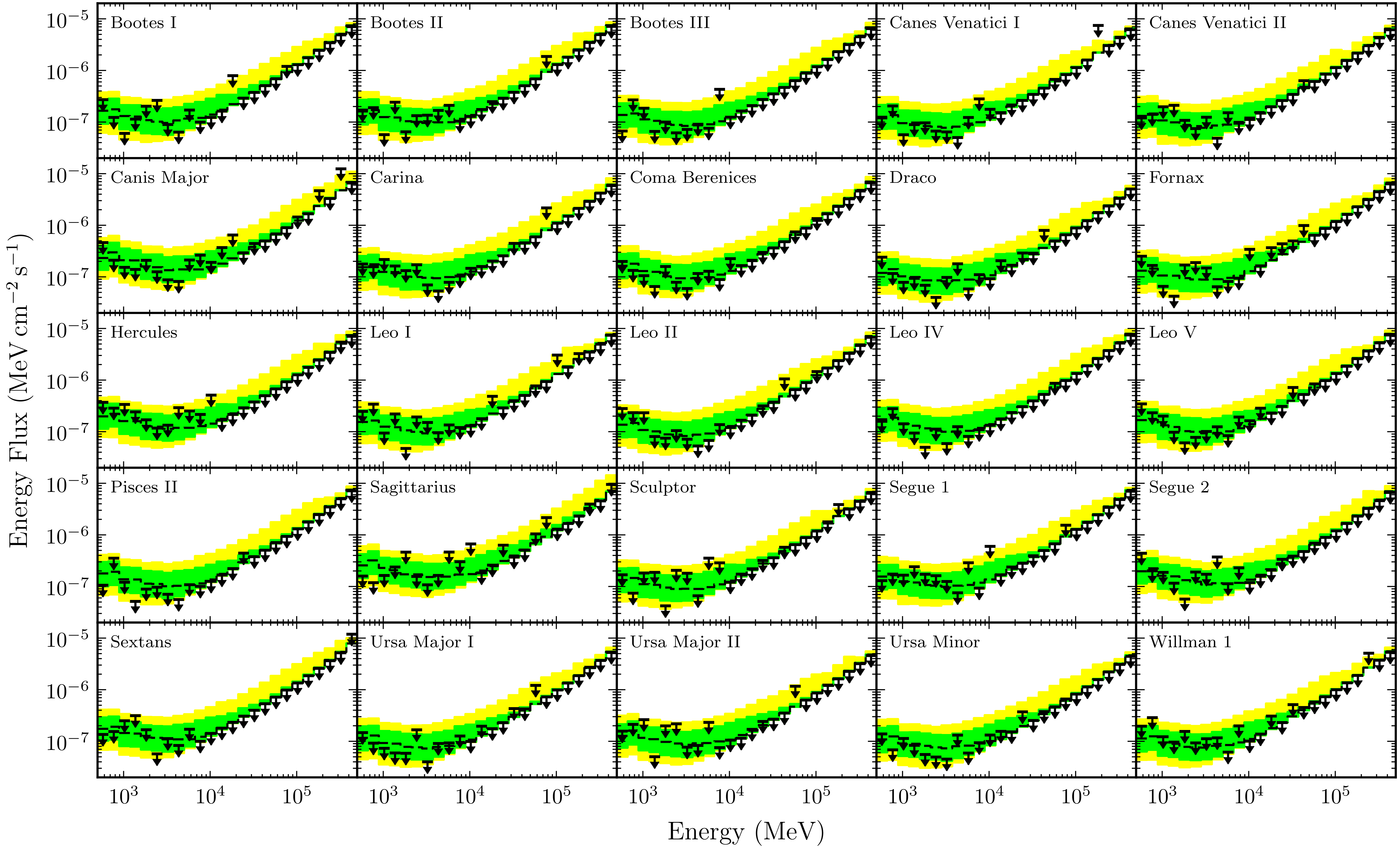

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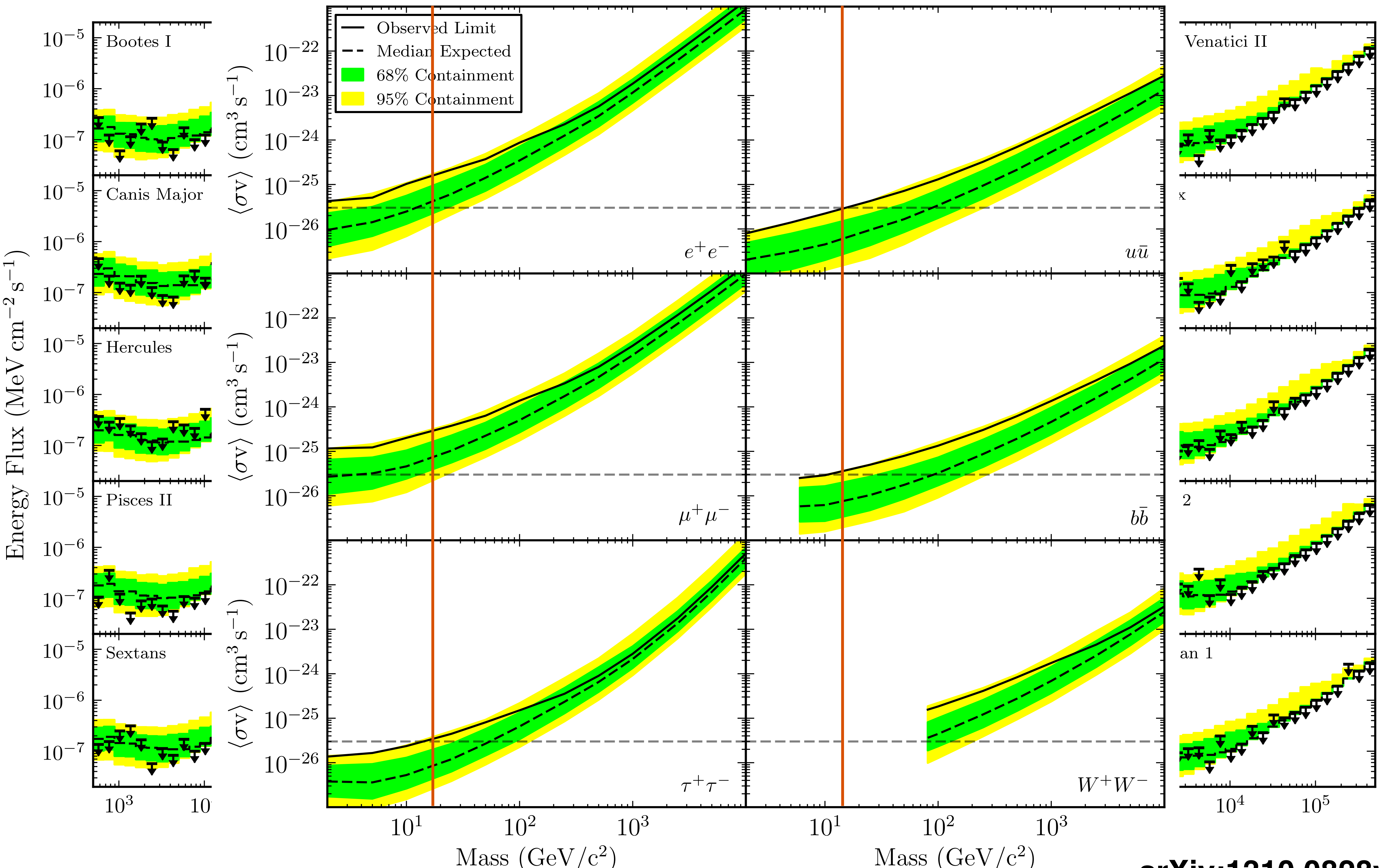

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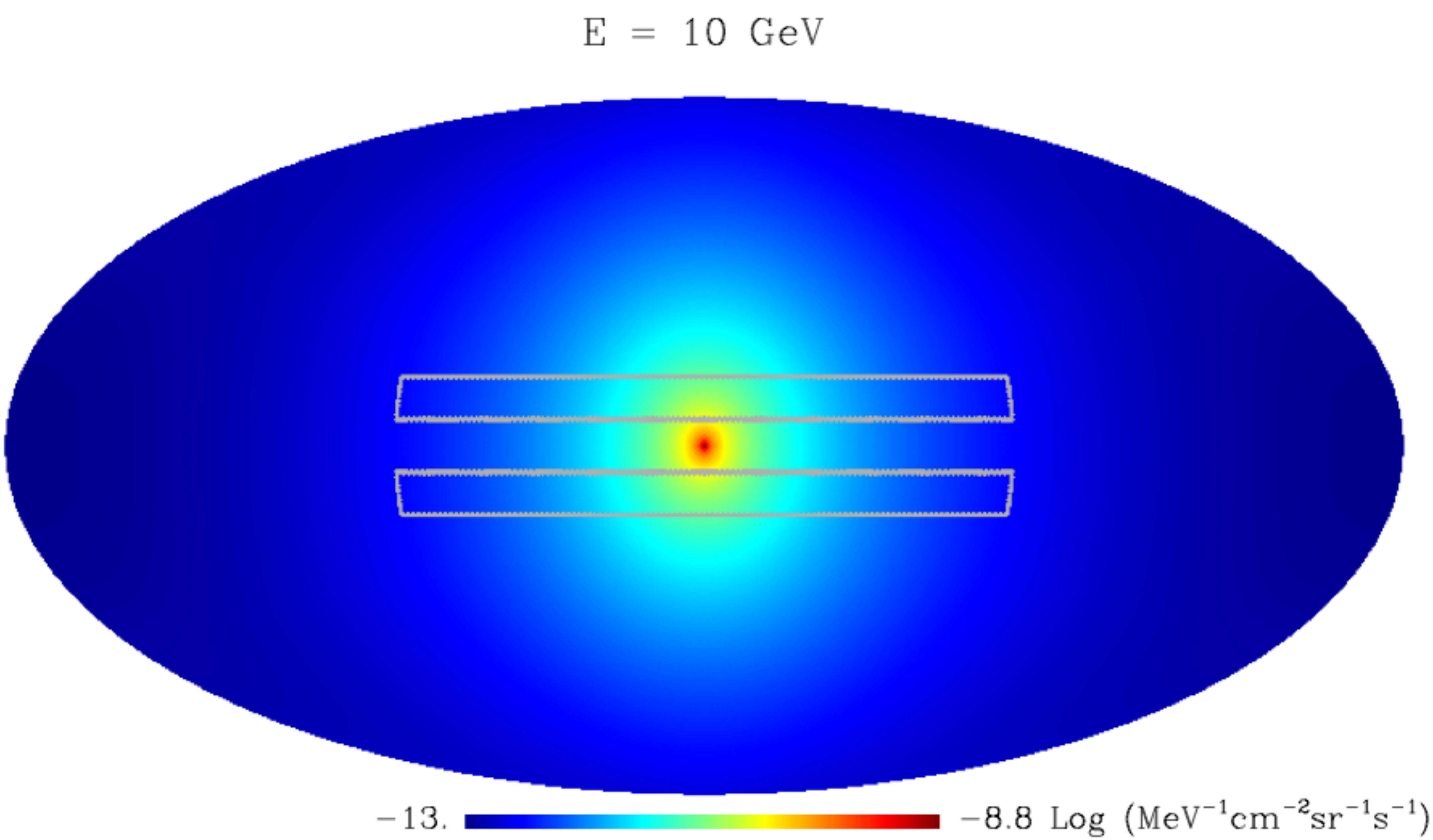
Fermi WIMP Search in Galactic Halo

- Galactic halo region except Galactic disk
  - Avoid very large Galactic diffuse background in the disk region



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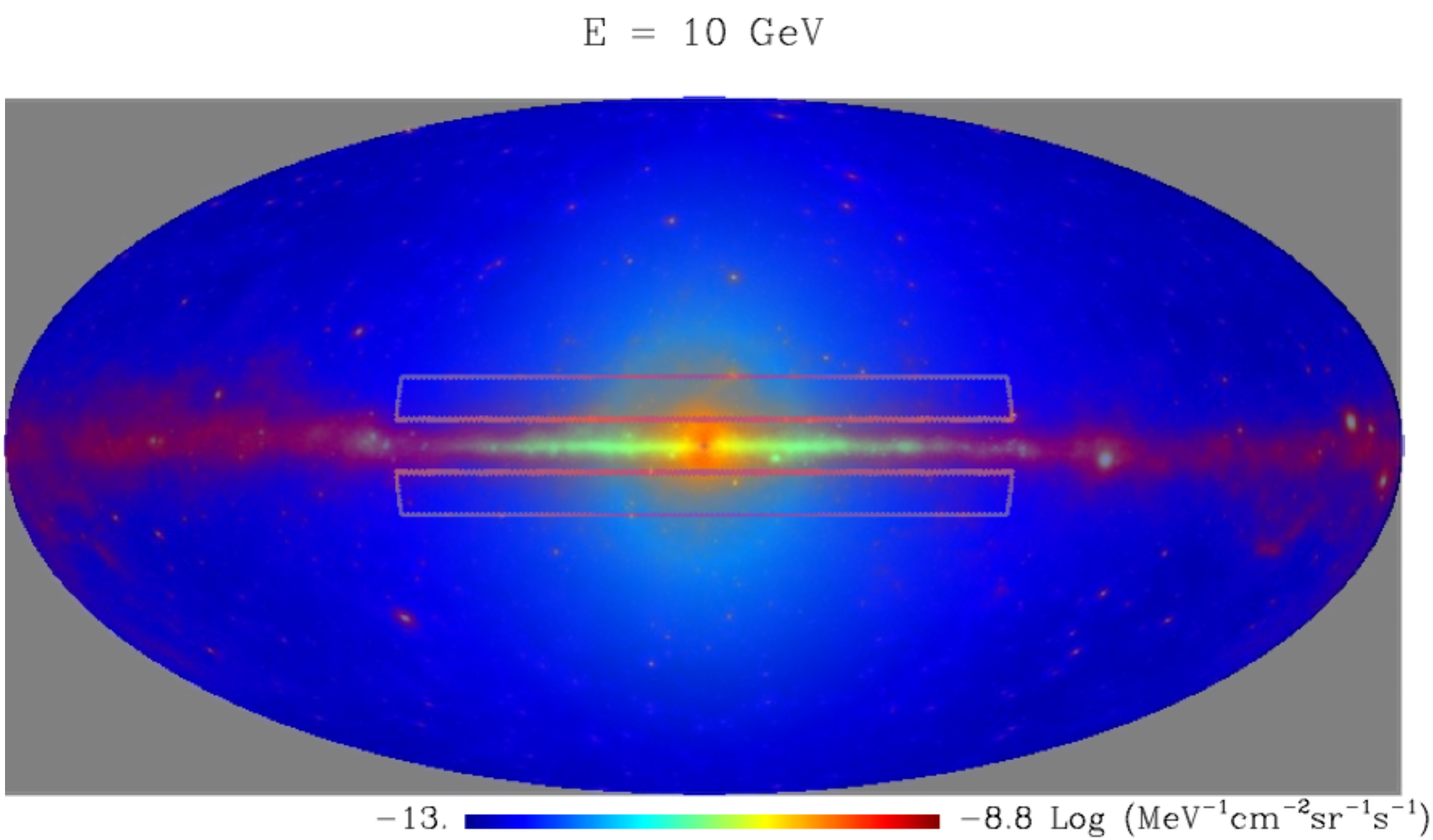

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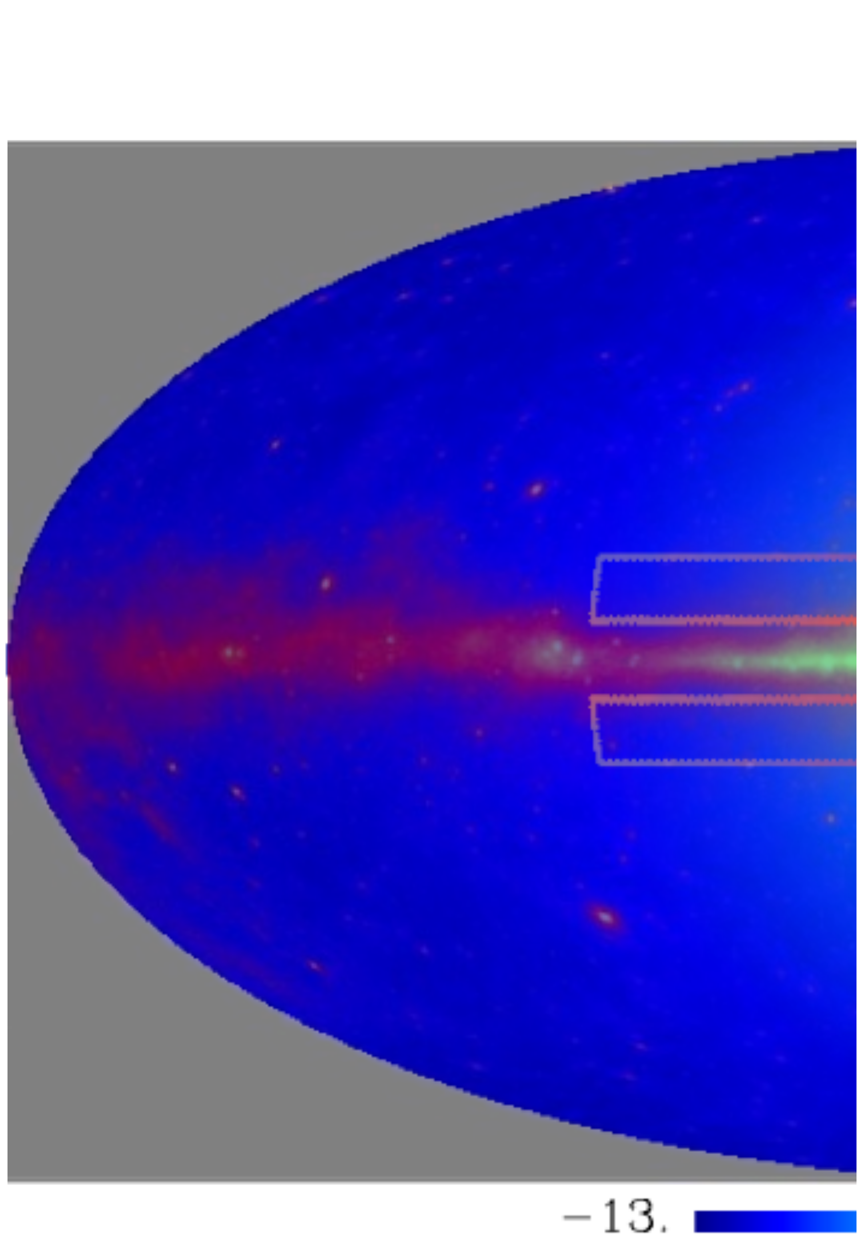

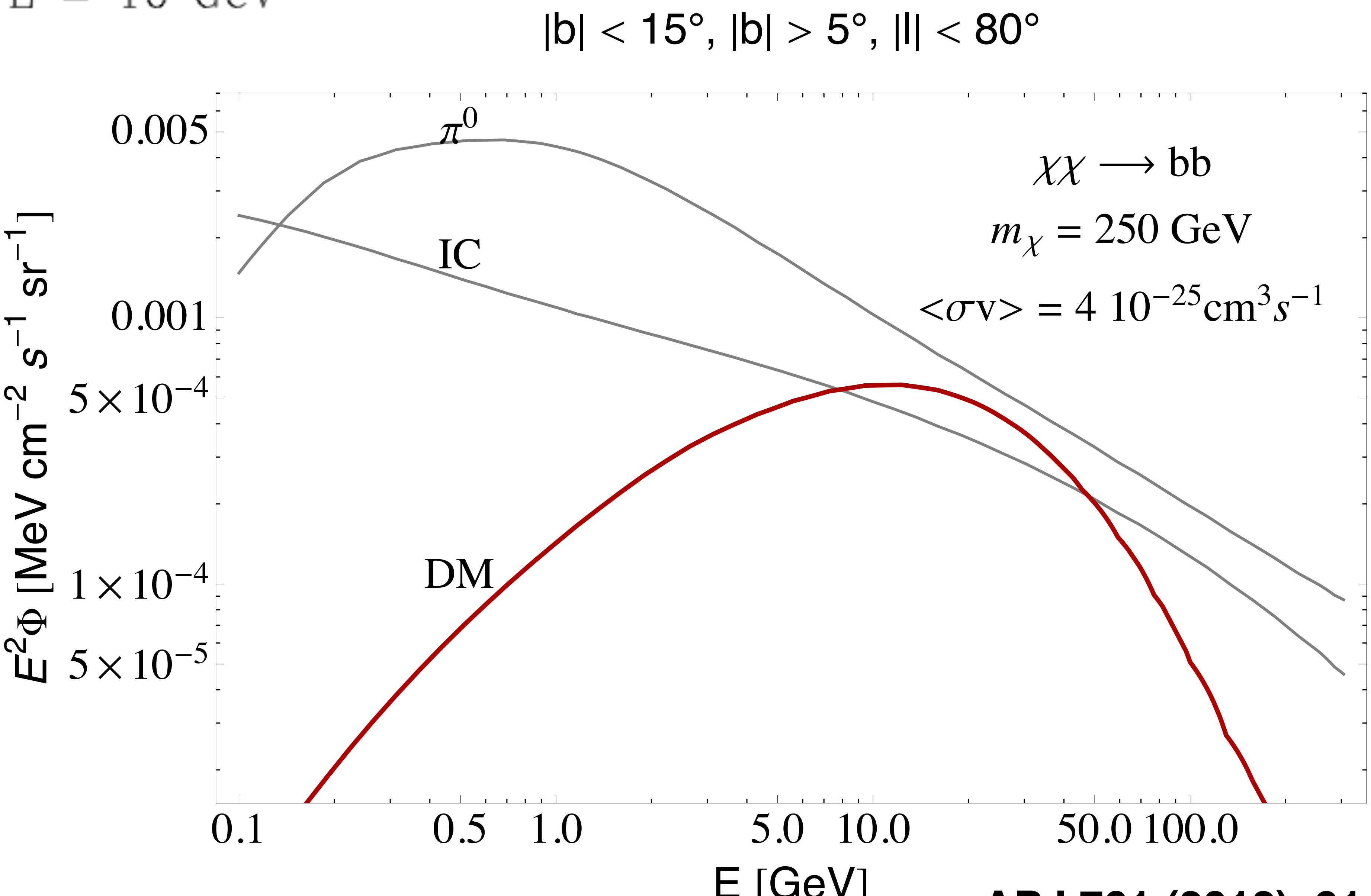

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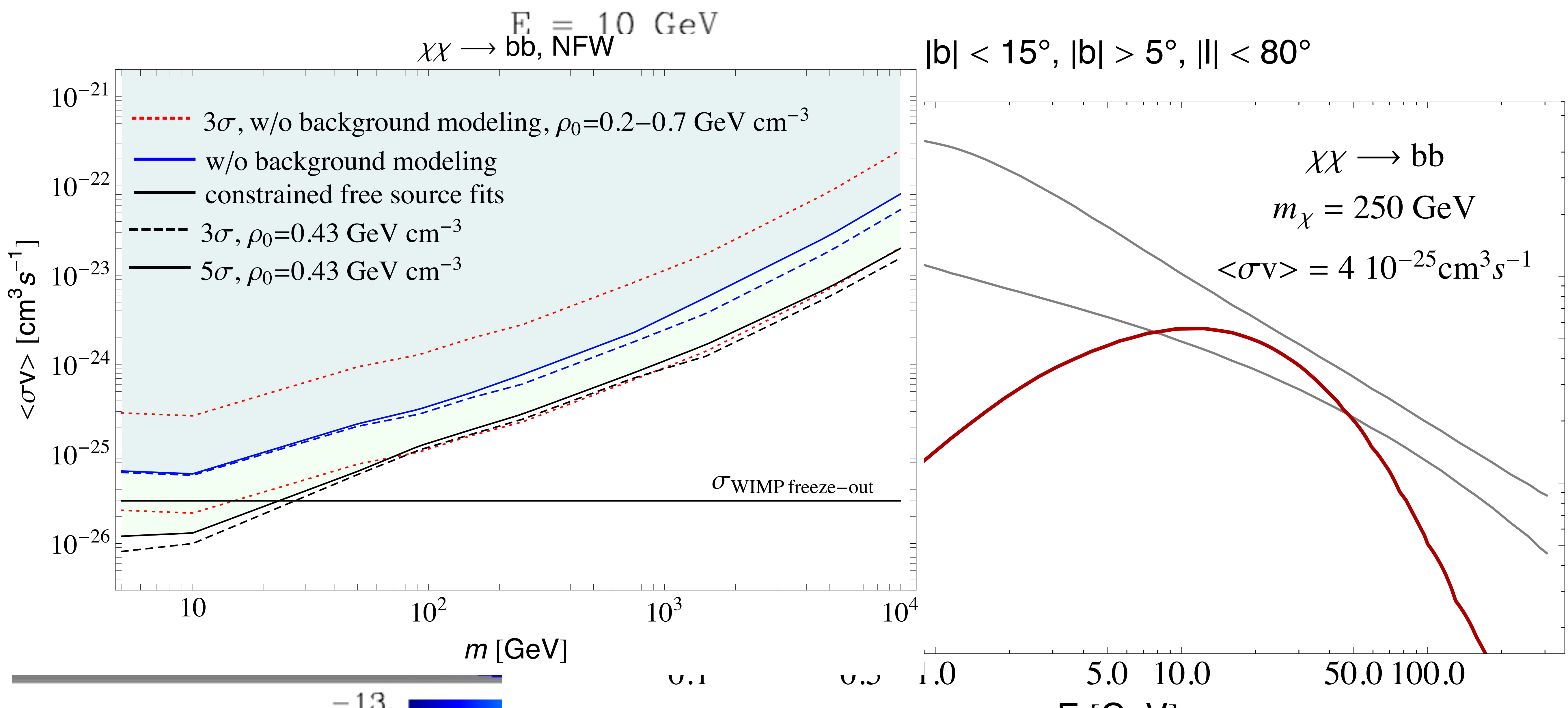

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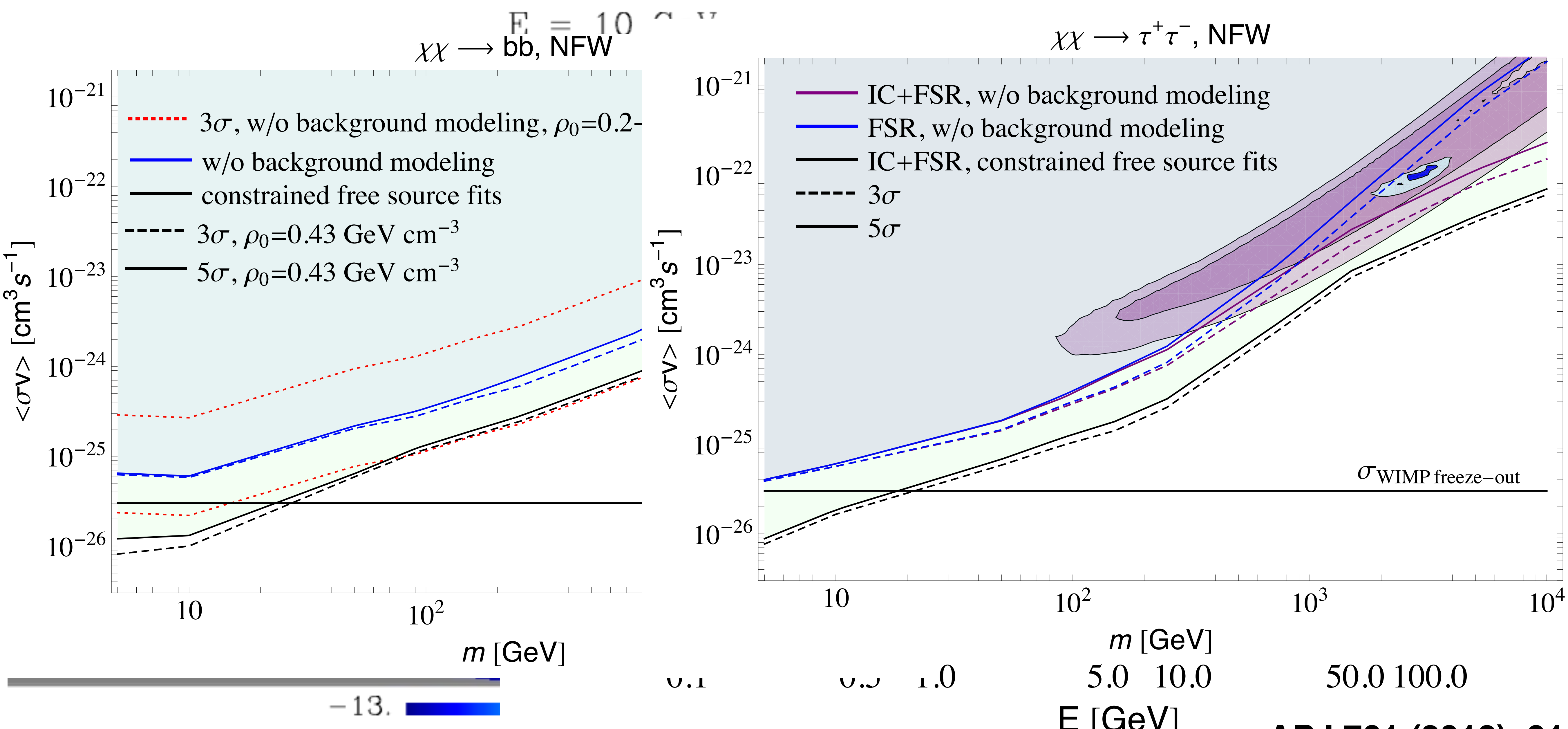

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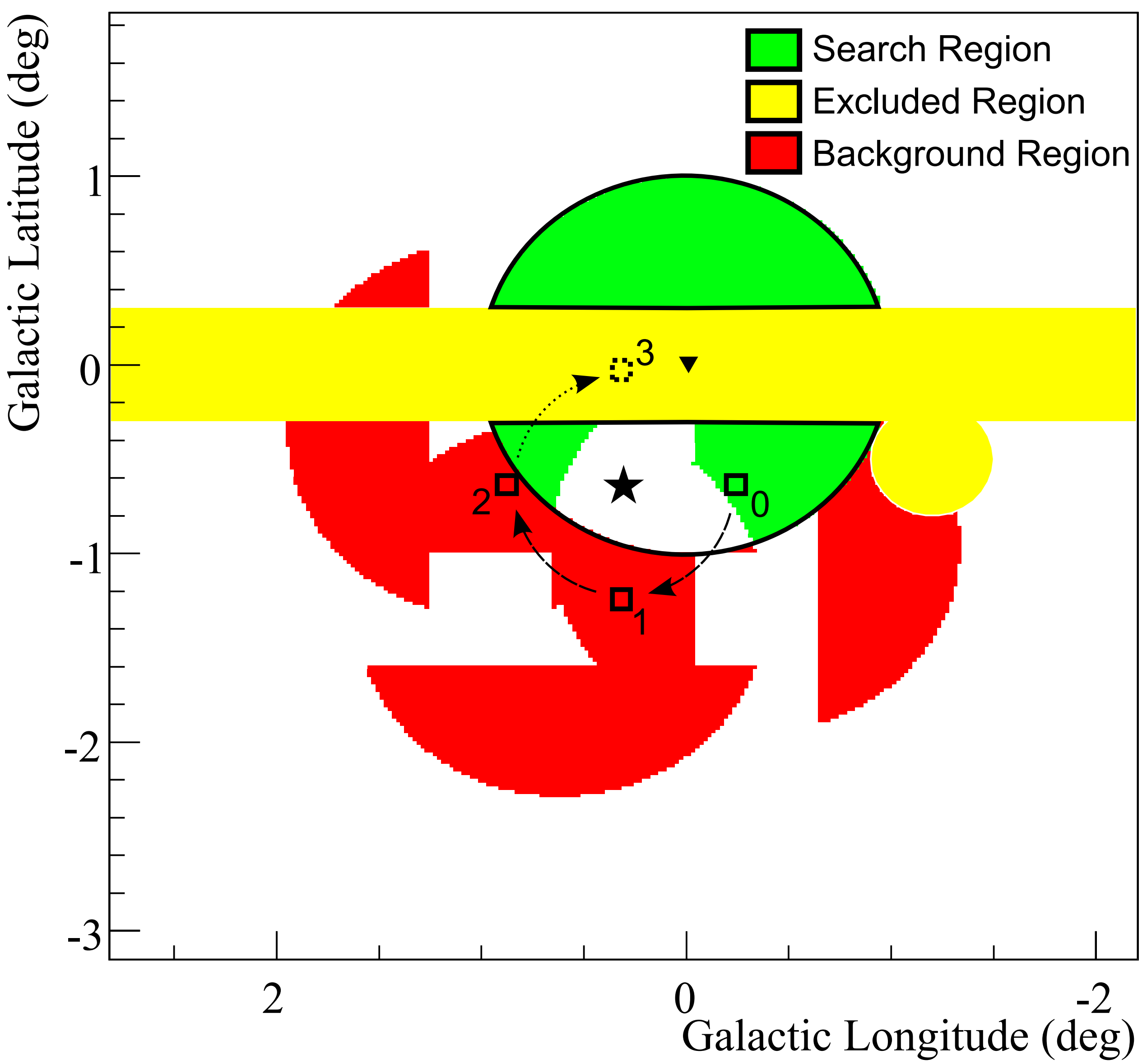
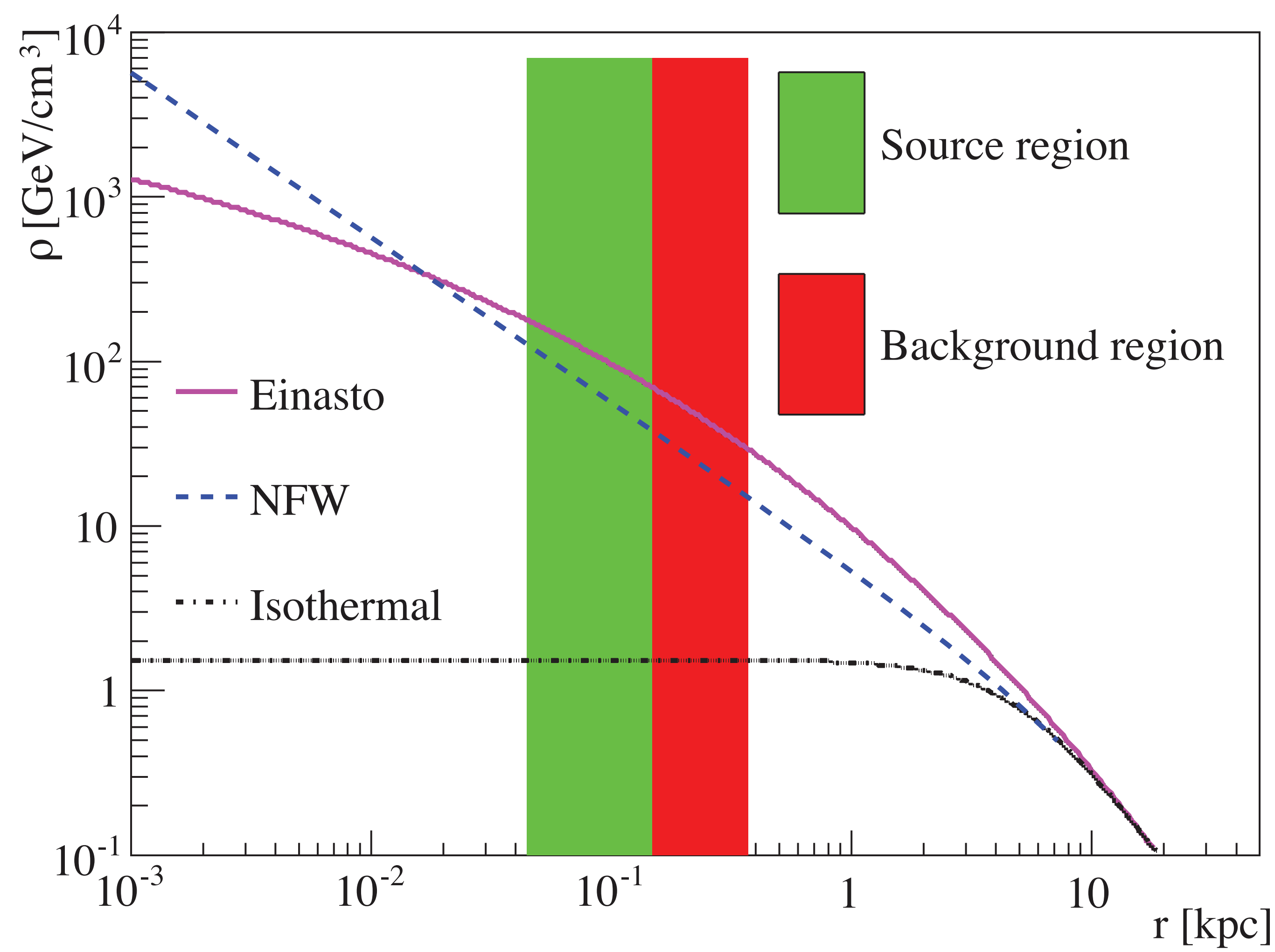
HESS WIMP Search in Galactic Center

- Galactic center is expected to have enormous amount of WIMPs
  - BG in TeV band is relatively low compared with GeV band due to steep Galactic diffuse BG spectrum
  - BG is dominated by cosmic-ray electrons

Phys.Rev.Lett.106:161301,2011





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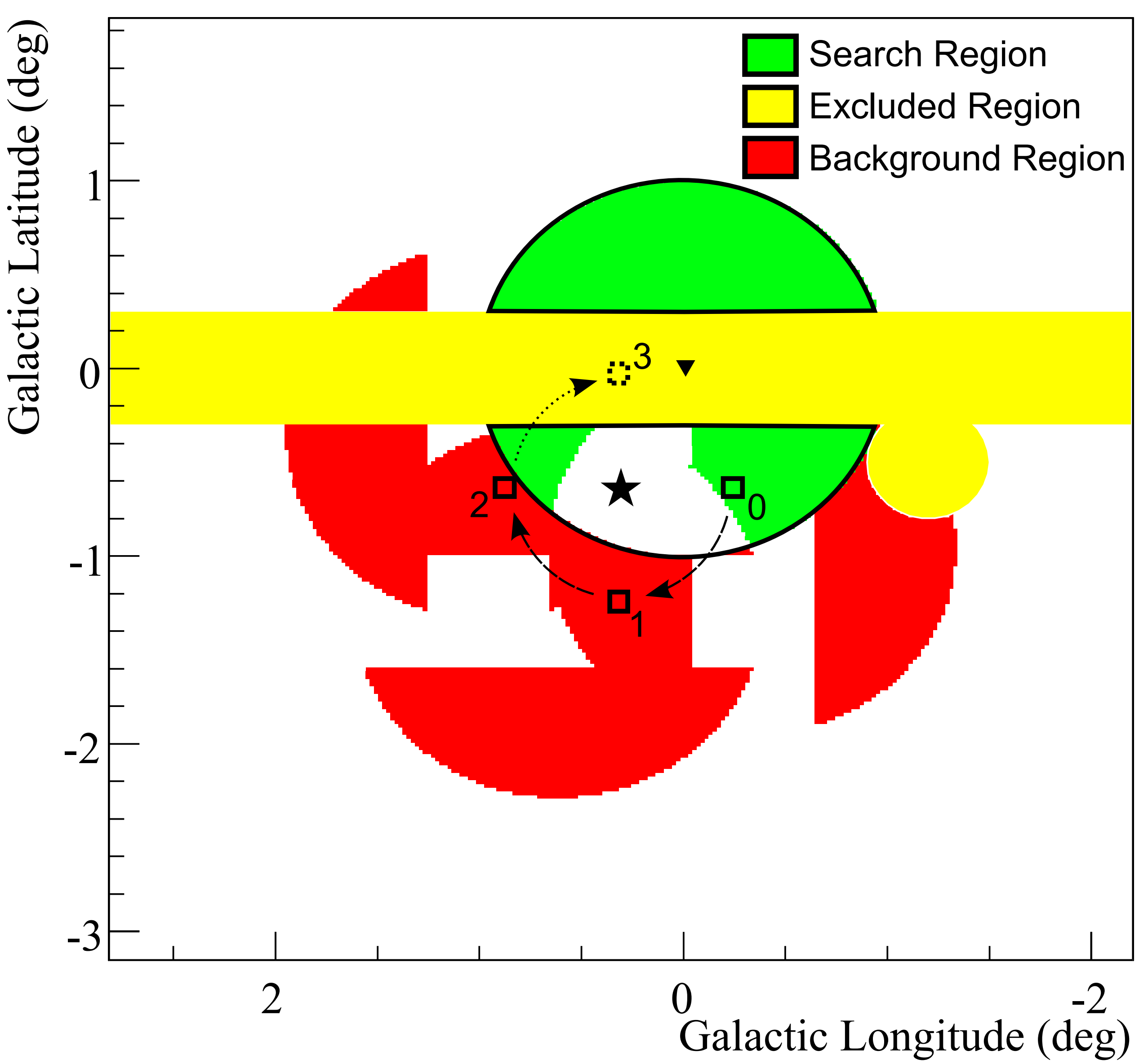

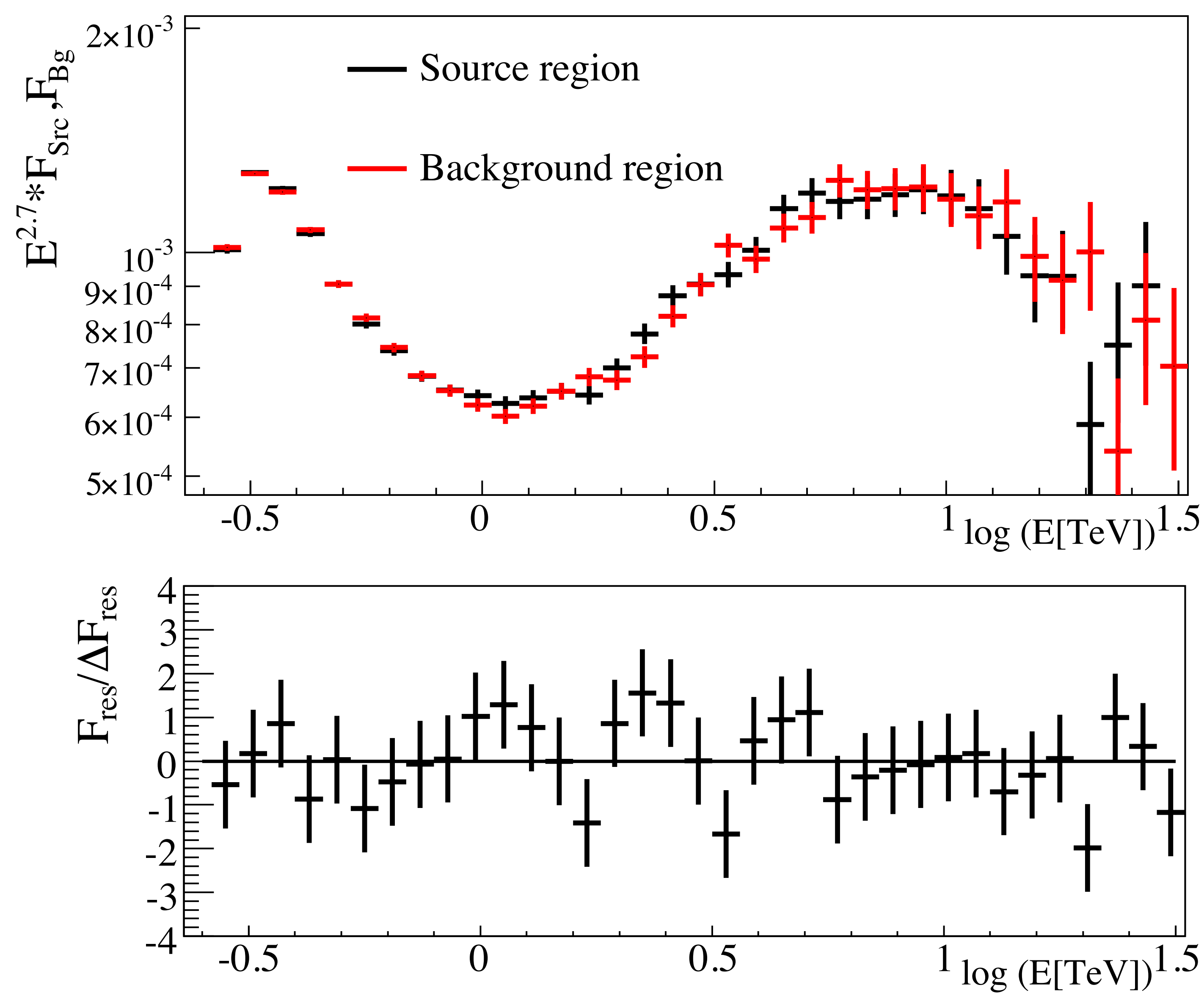

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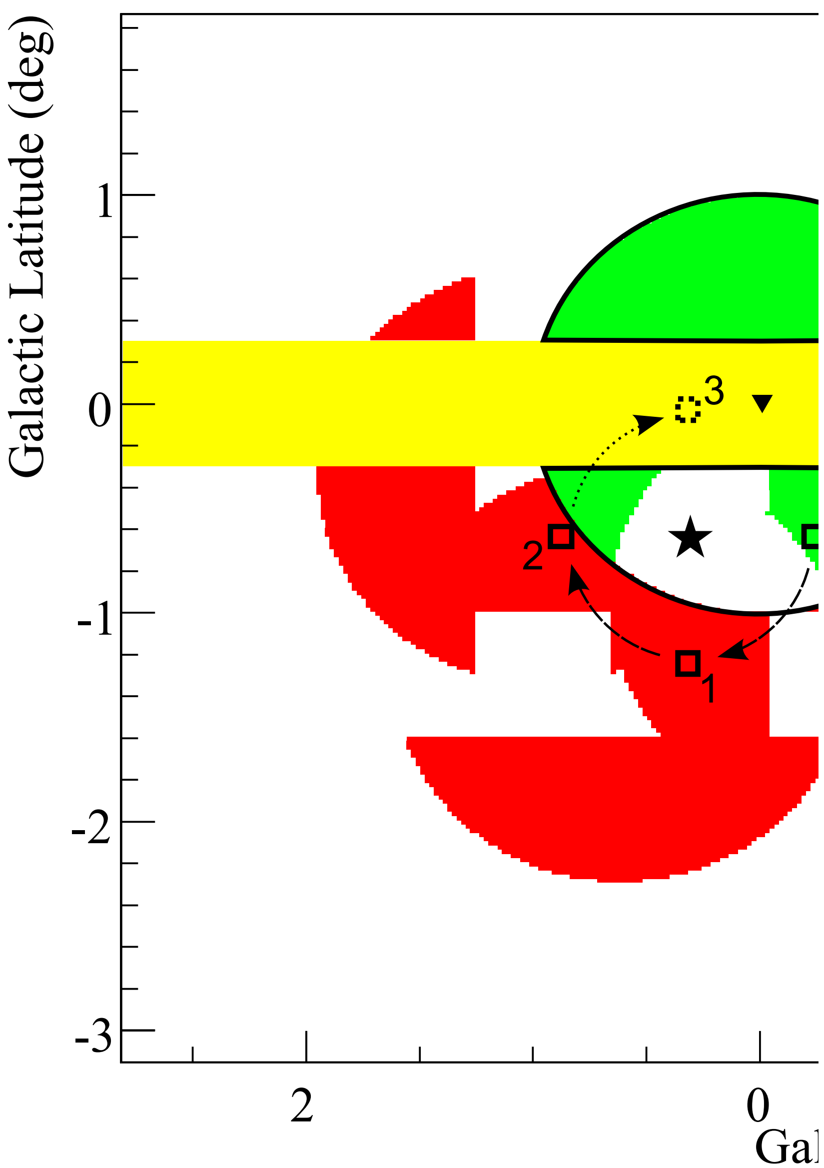
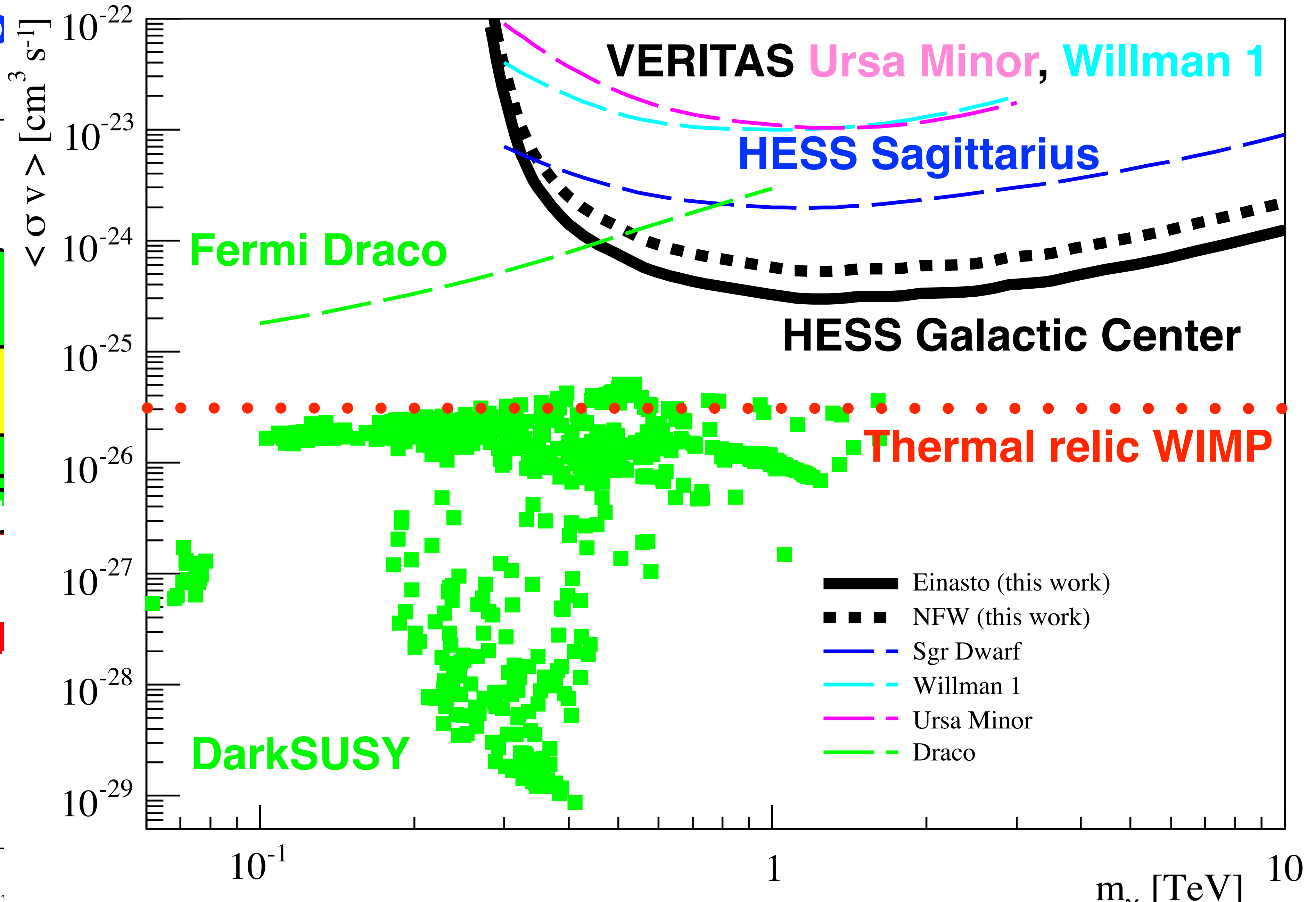
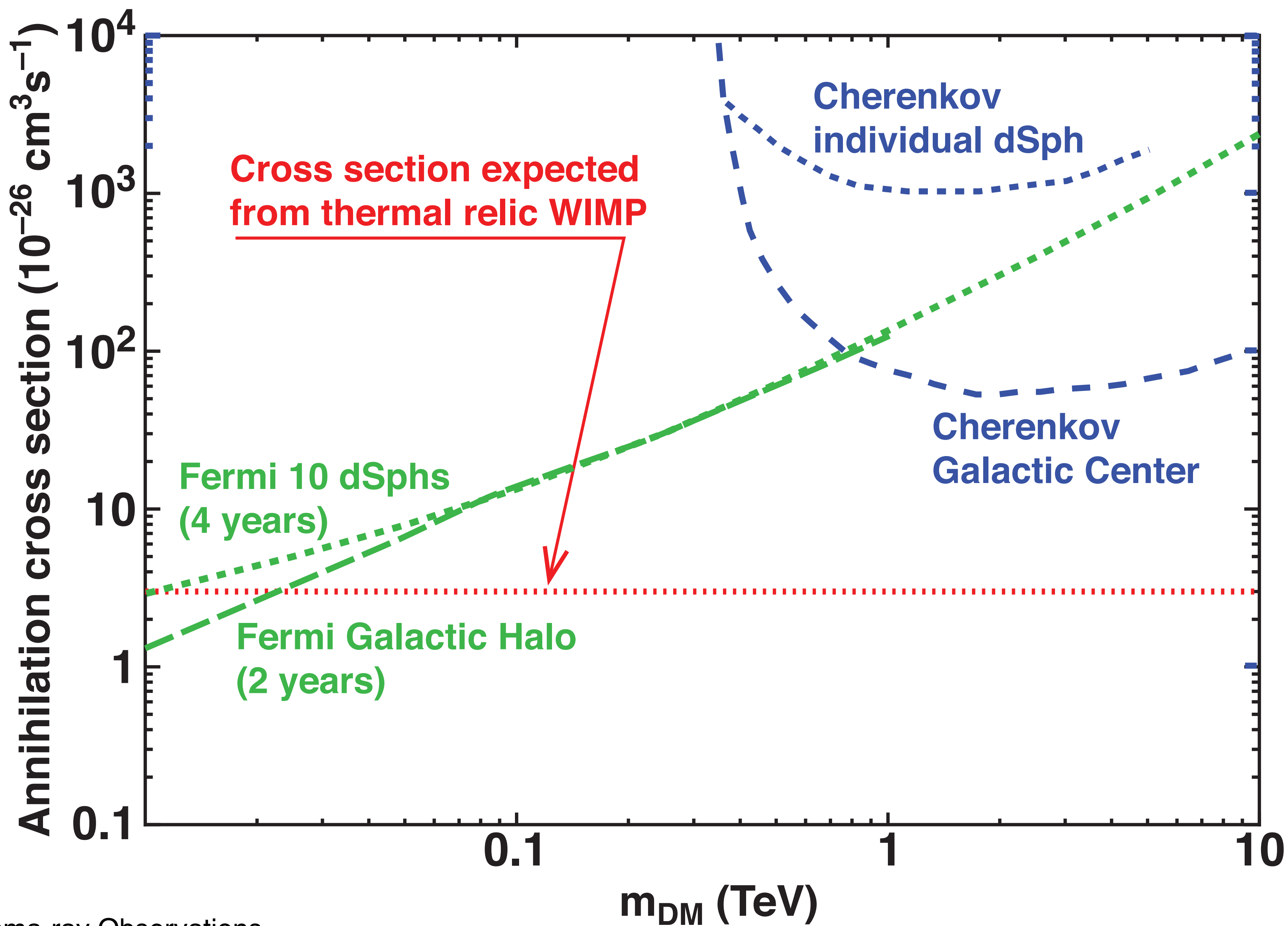




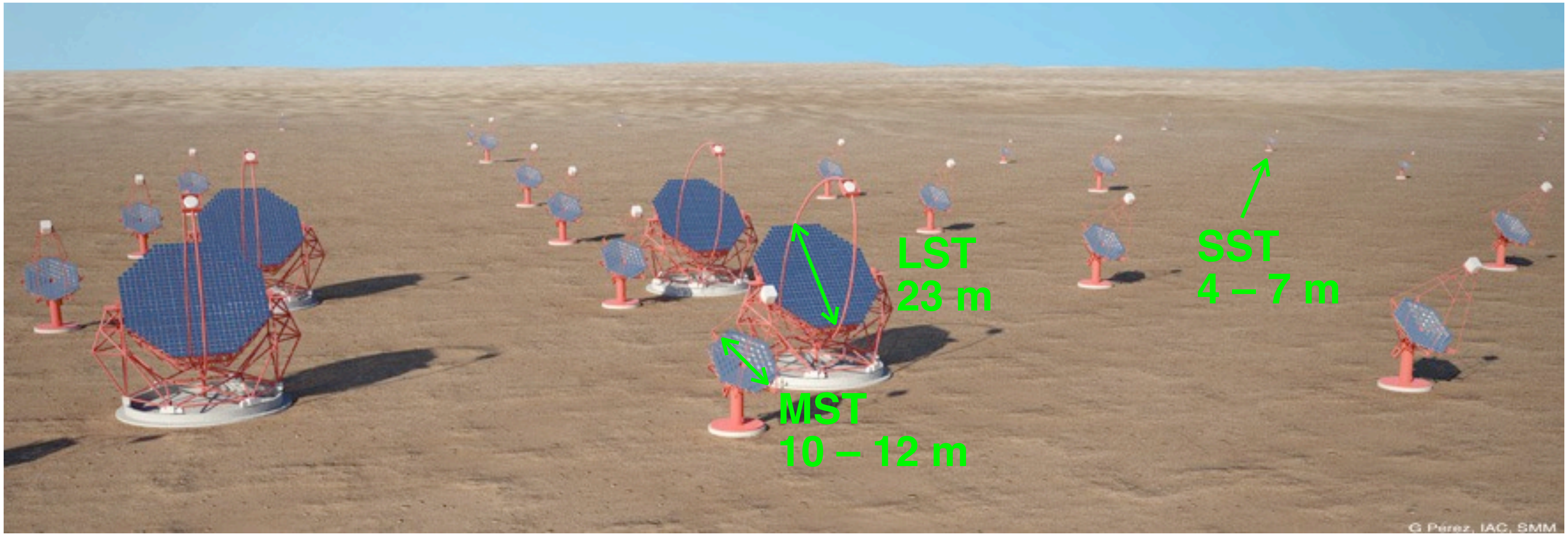
Current Status of Indirect DM Search

- Fermi/LAT limit on WIMP annihilation cross section now cuts into expected value for thermal relic WIMP for the mass below 15~20 GeV/c^2
- Cherenkov telescope is not currently very competitive



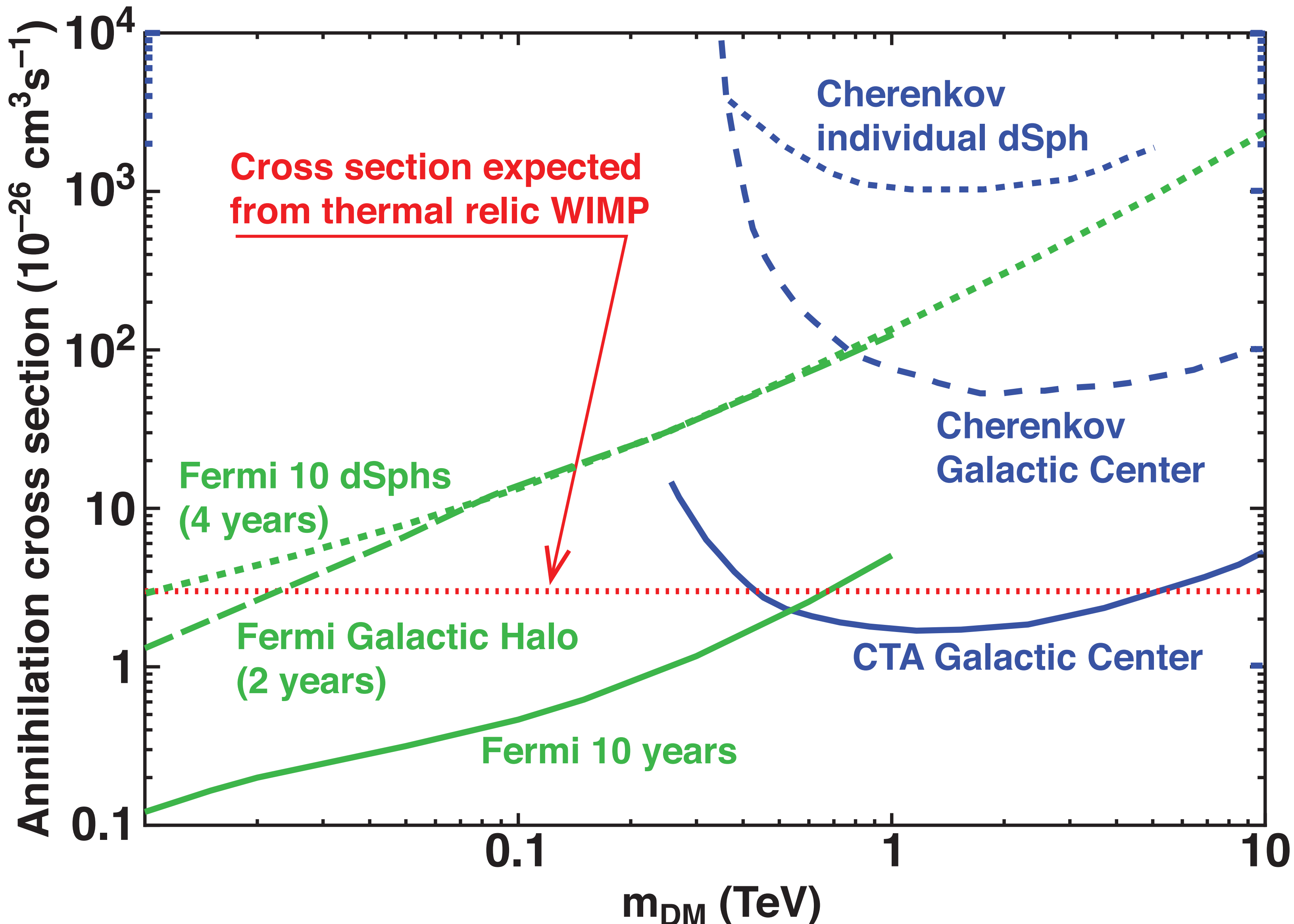
Cherenkov Telescope Array

- Observations of gamma rays in 20 GeV – 100 TeV band
  - Cherenkov light from electromagnetic shower produced by interaction of gamma rays with atmosphere
- Large collection area by placing many telescopes
  - x10 better sensitivity
- Wide energy band coverage by three different size of telescopes
  - Large-size telescope (LST): Φ = 23 m, 20 GeV – 1 TeV, 4 telescopes
  - Medium-size telescope (MST): Φ = 10 – 12 m, 0.1 – 10 TeV, ~20 telescopes
  - Small-size telescope (SST): Φ = 4 – 7 m, 1 – 100 TeV, 30 – 70 telescopes



Future Prospects for Indirect Searches

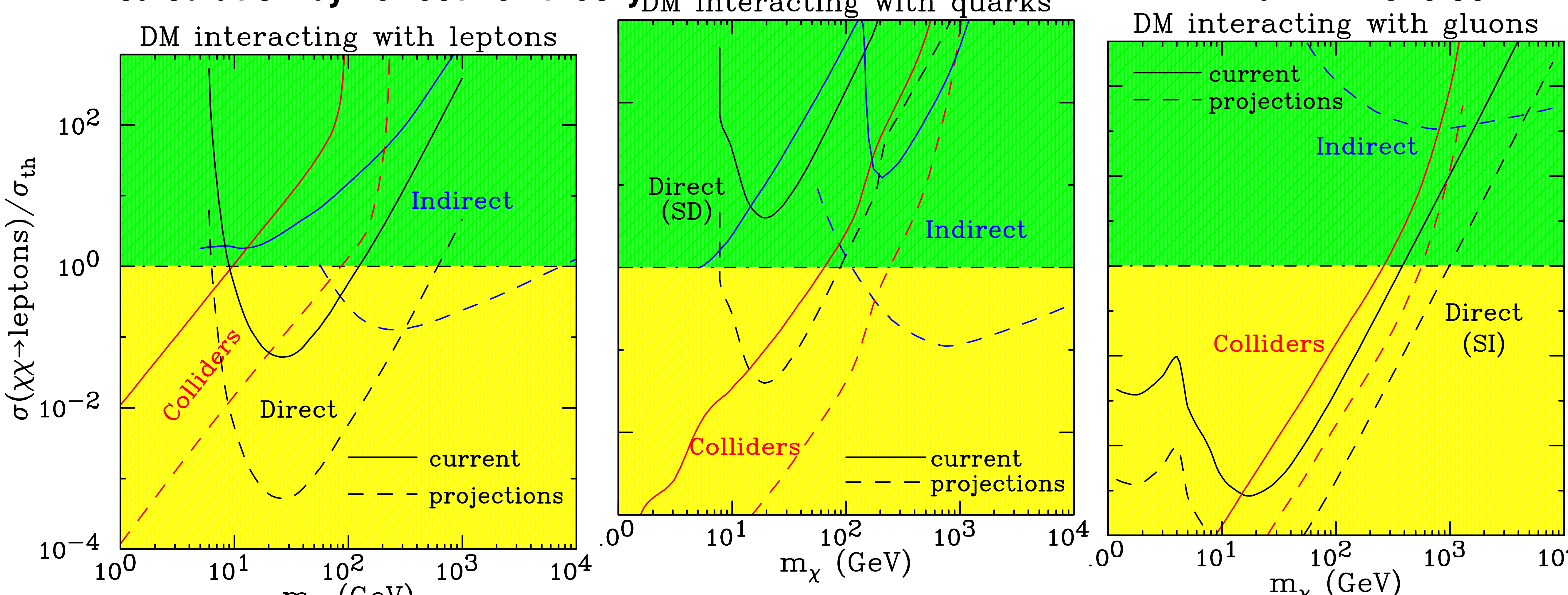
- ~ an order of magnitude improvements expected
  - Fermi: increased statistics and more dwarf spheroids
    - New dwarf spheroids have been discovered due to improved detection techniques
  - Cherenkov telescope: better sensitivities with CTA



Complimentarily of Different Approaches

- **Collider, direct and indirect WIMP searches are complimentary**
  - **Collider: best for gluon and quark (m_{DM} < 200 GeV) interactions**
  - **Direct: best for lepton (m_{DM} < 200 GeV) and gluon interactions**
  - **Indirect: best for lepton and quark interactions (m_{DM} > 200 GeV)**

calculation by "effective" theory **arXiv: 1310.8621v1**



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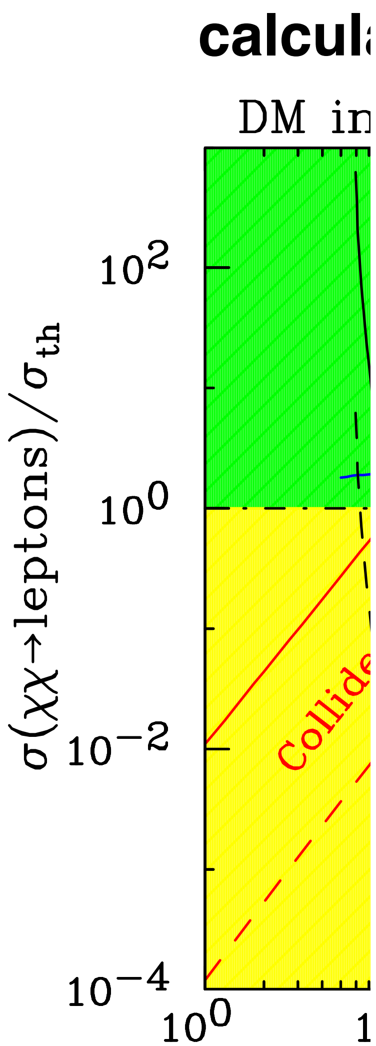

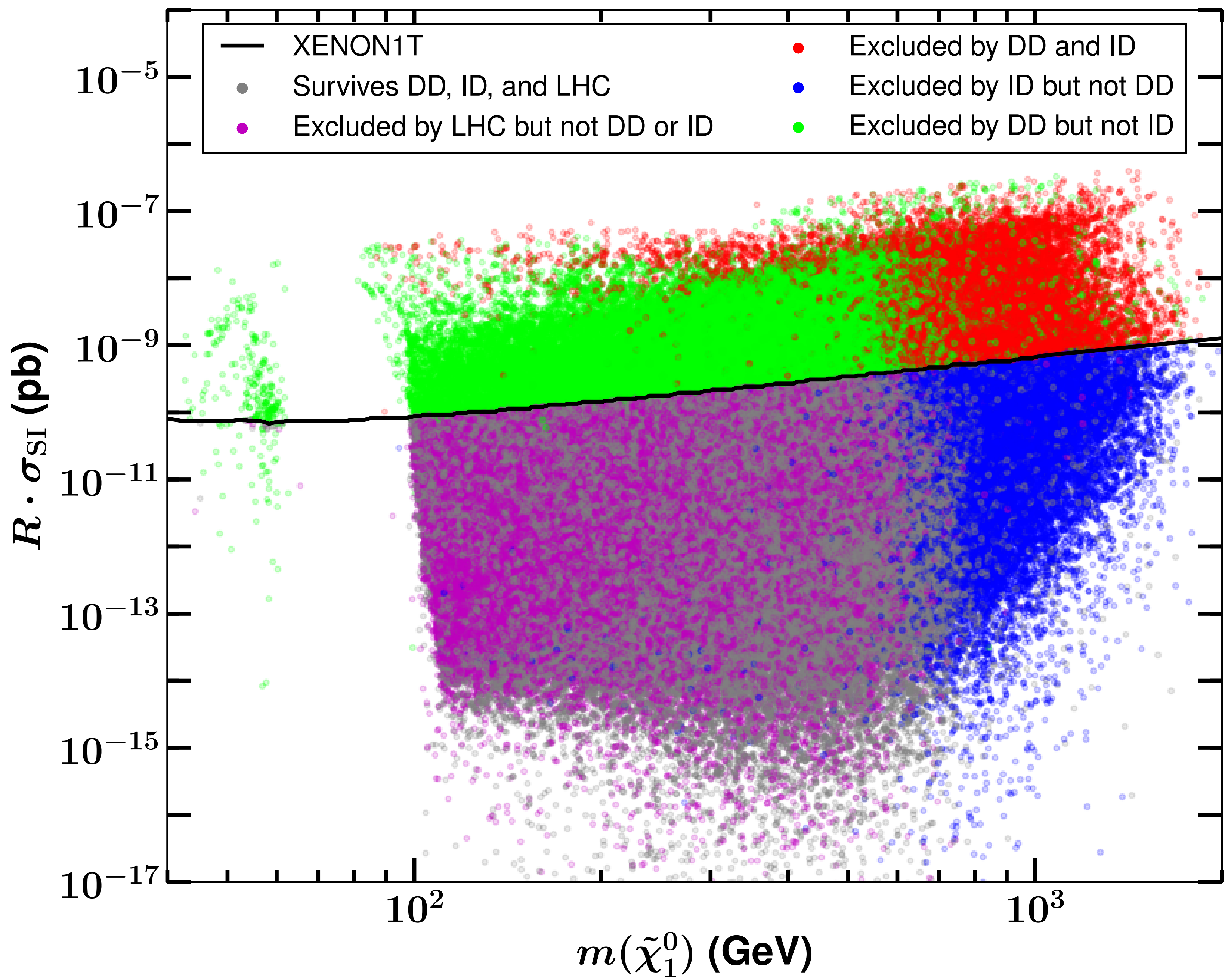

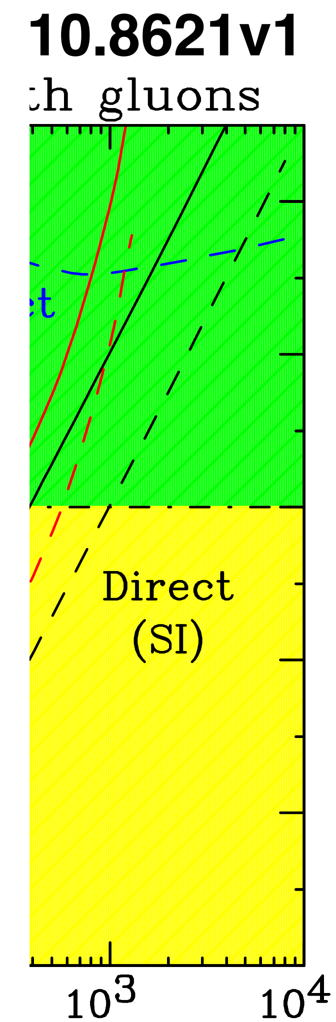

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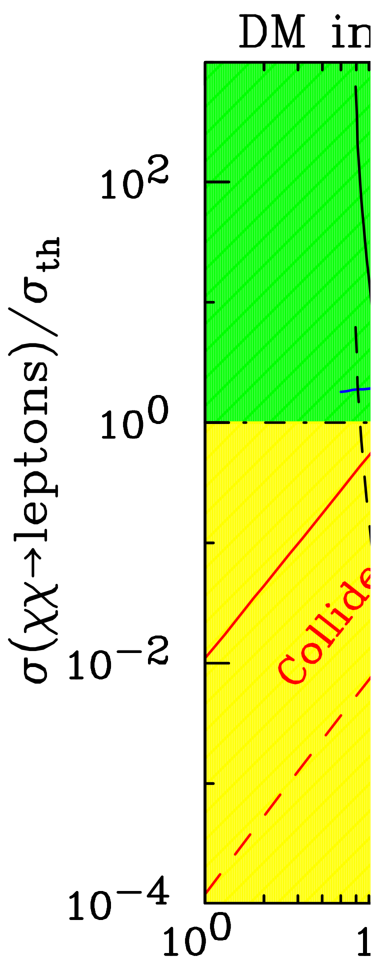

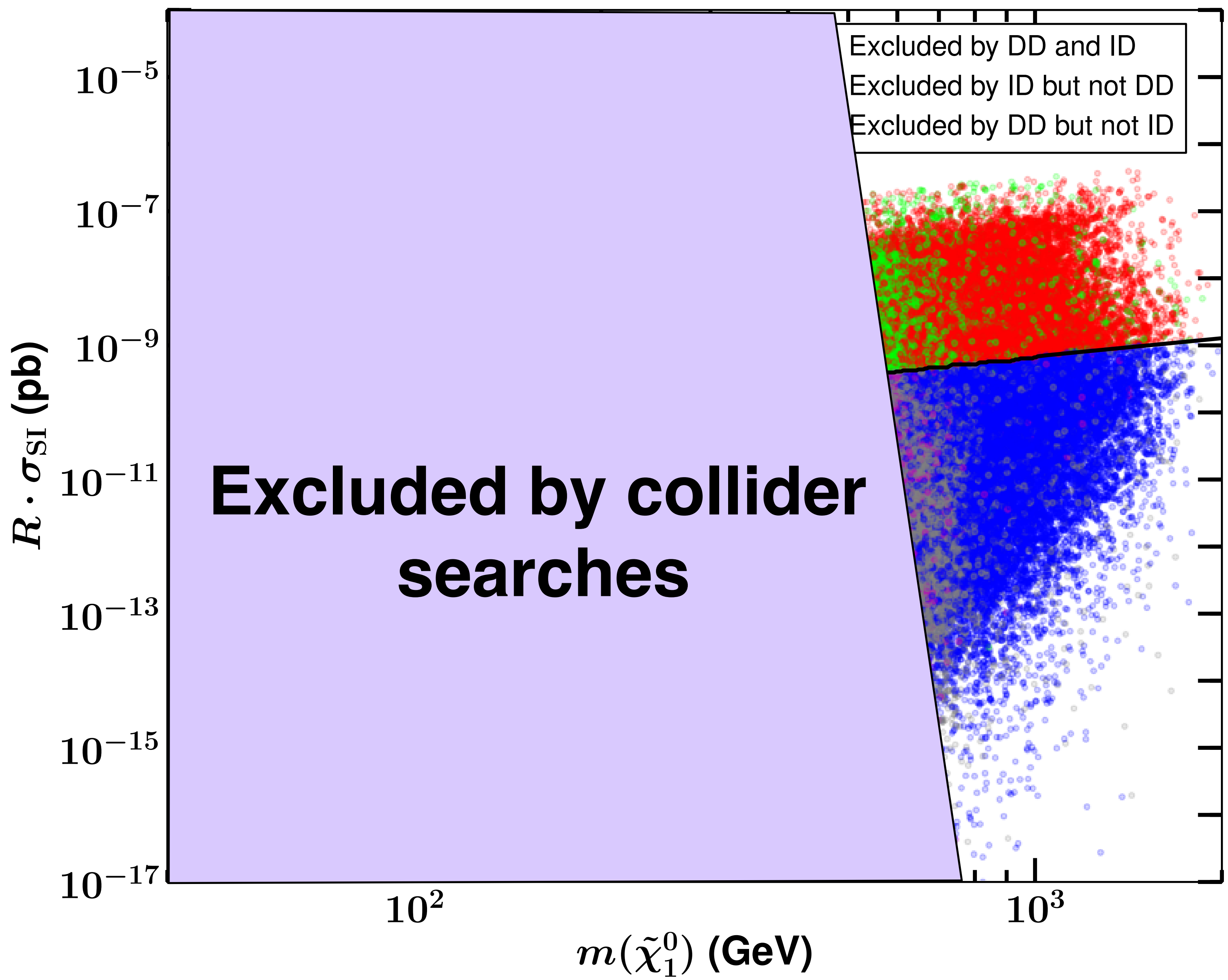

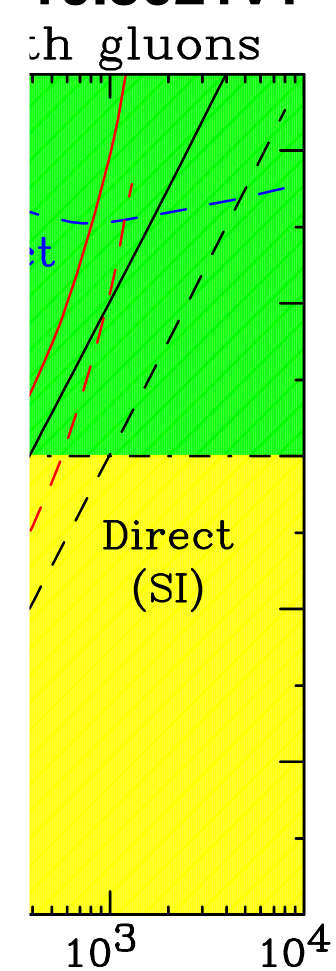

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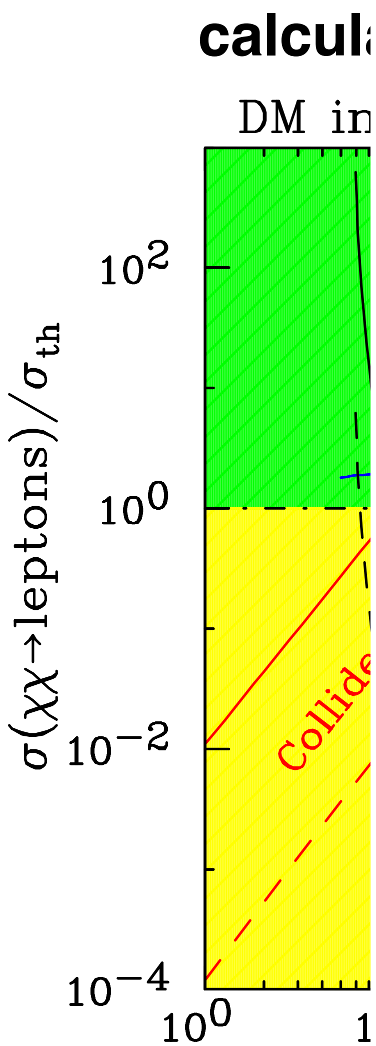

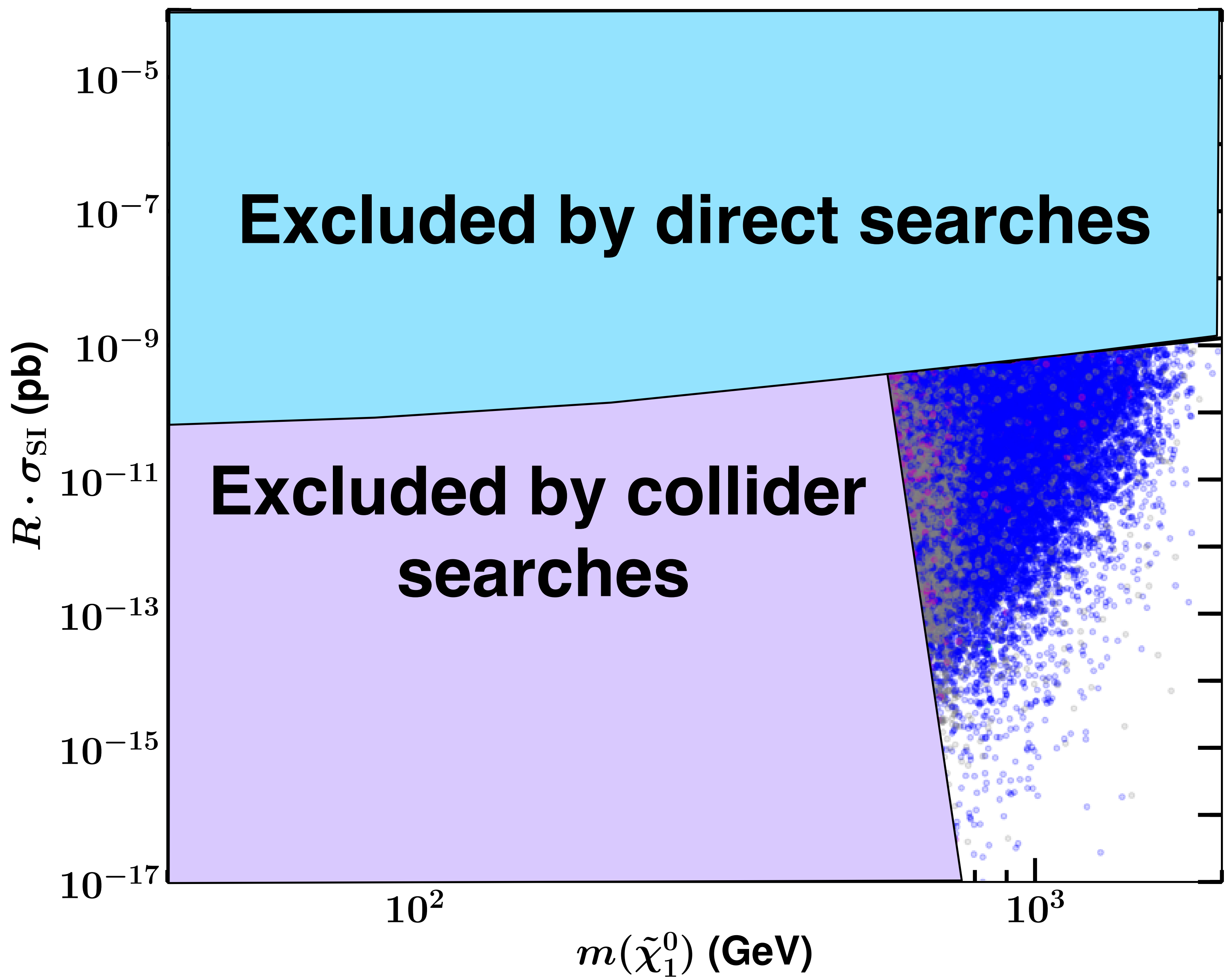

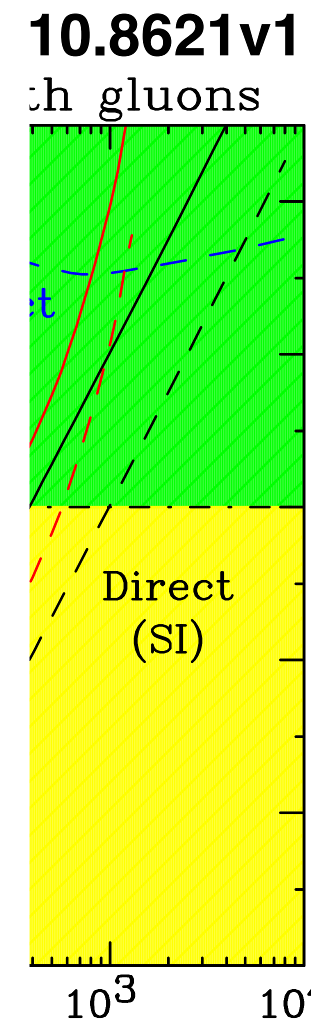

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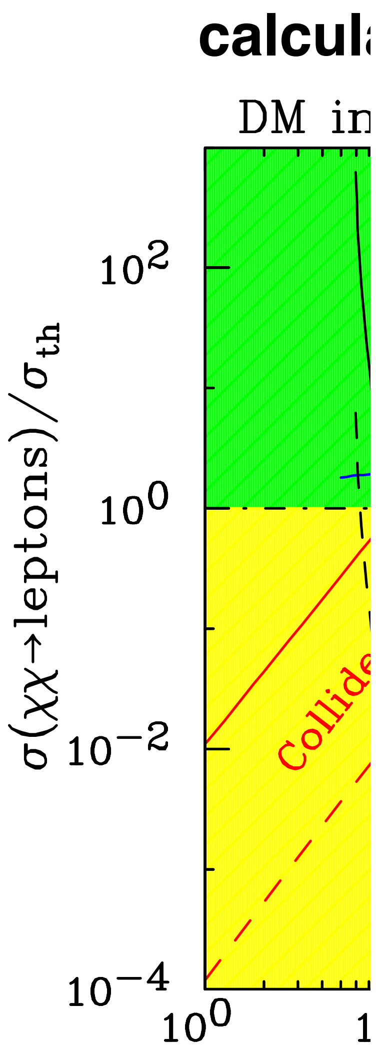
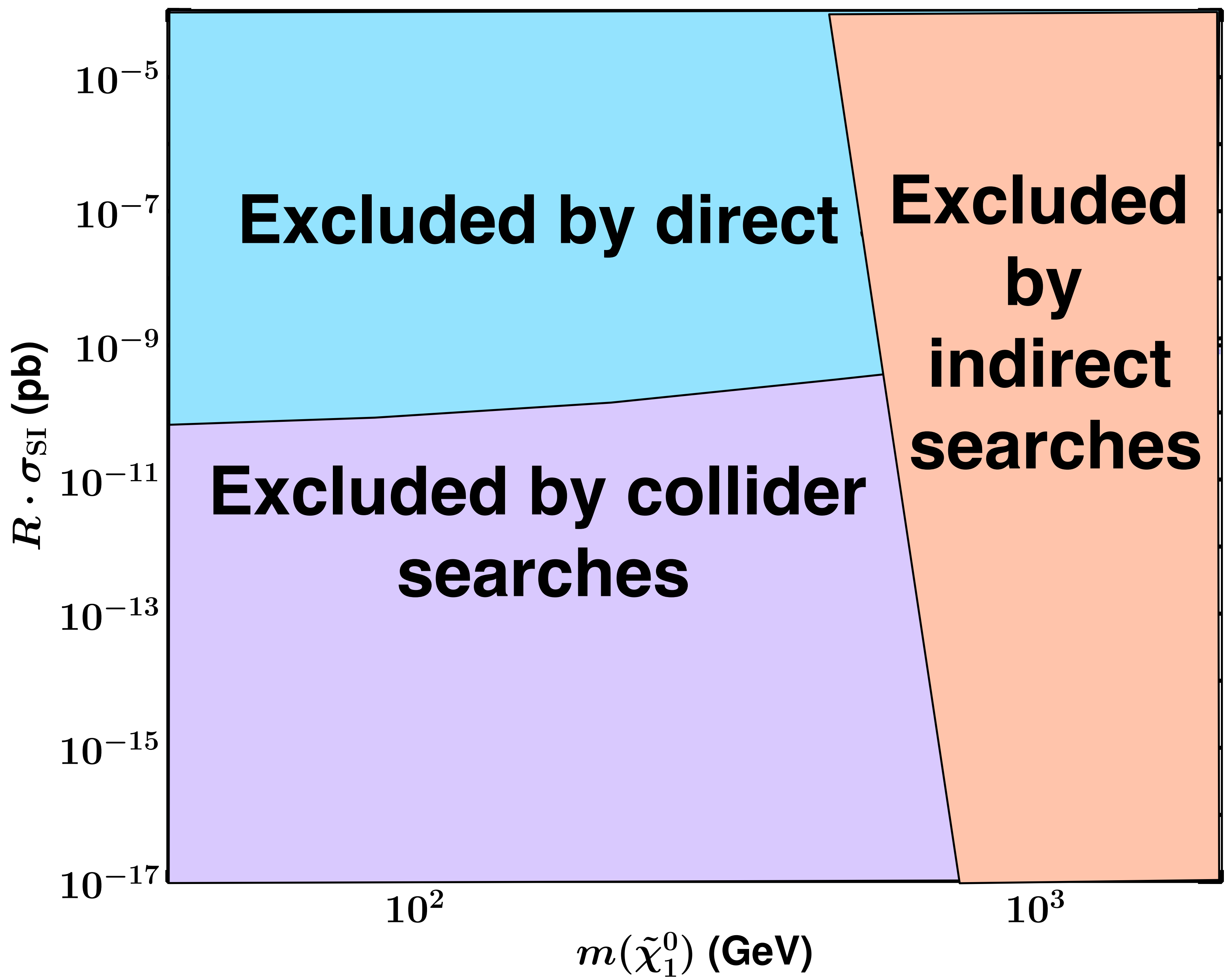
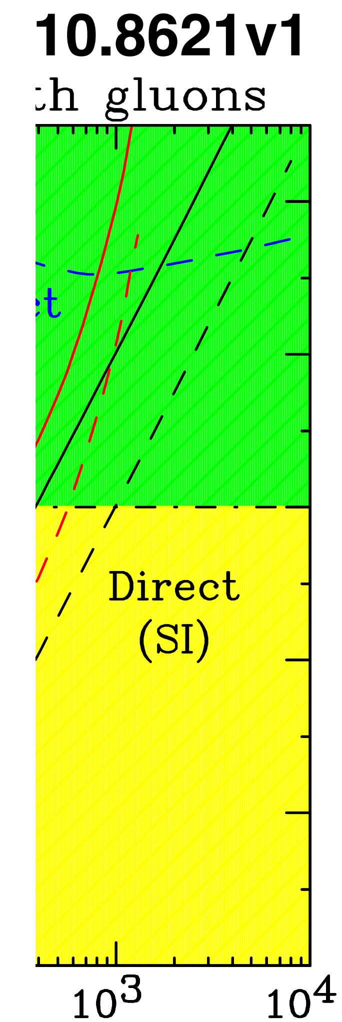
  - Indire)







Summary and Future Prospects

- Weakly Interacting Massive Particle is a extremely promising candidate for dark matter
- Indirect search is one of complimentary approaches in WIMP dark matter studies
- Fermi/LAT limit on WIMP annihilation cross section is now cutting into expected value from thermal relic WIMP for the mass below 15~20 GeV/c^2
  - Excluded mass range would extend to multi-100 GeV/c^2 in the future with longer observations with more targets
- CTA is a promising project to search for WIMP in TeV energy band
  - Excluded mass range would overlap with Fermi at lower energies
  - Excluded mass range would extend to multi-TeV/c^2
    - Region beyond collider and direct searches