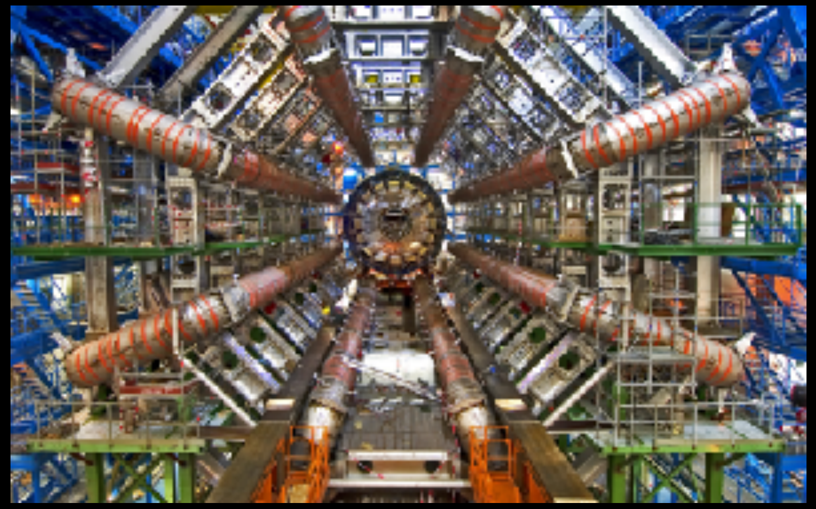
Diffuse gamma-ray Emission

Cosmic-Ray Acceleration, Propagation, and Emission

Tim Linden — Fermi Summer School, 2023

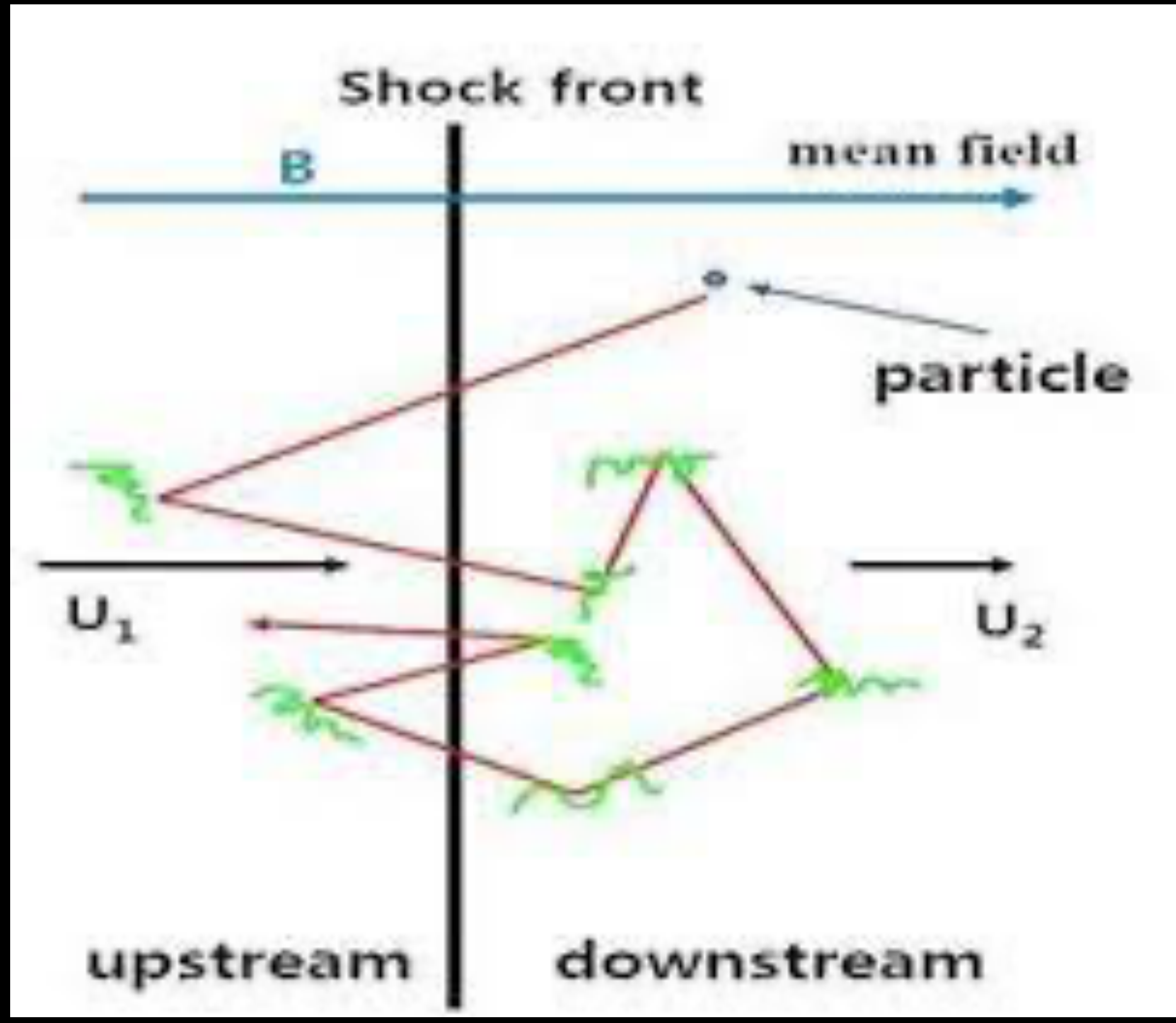
Overview

Cosmic-Ray Acceleration

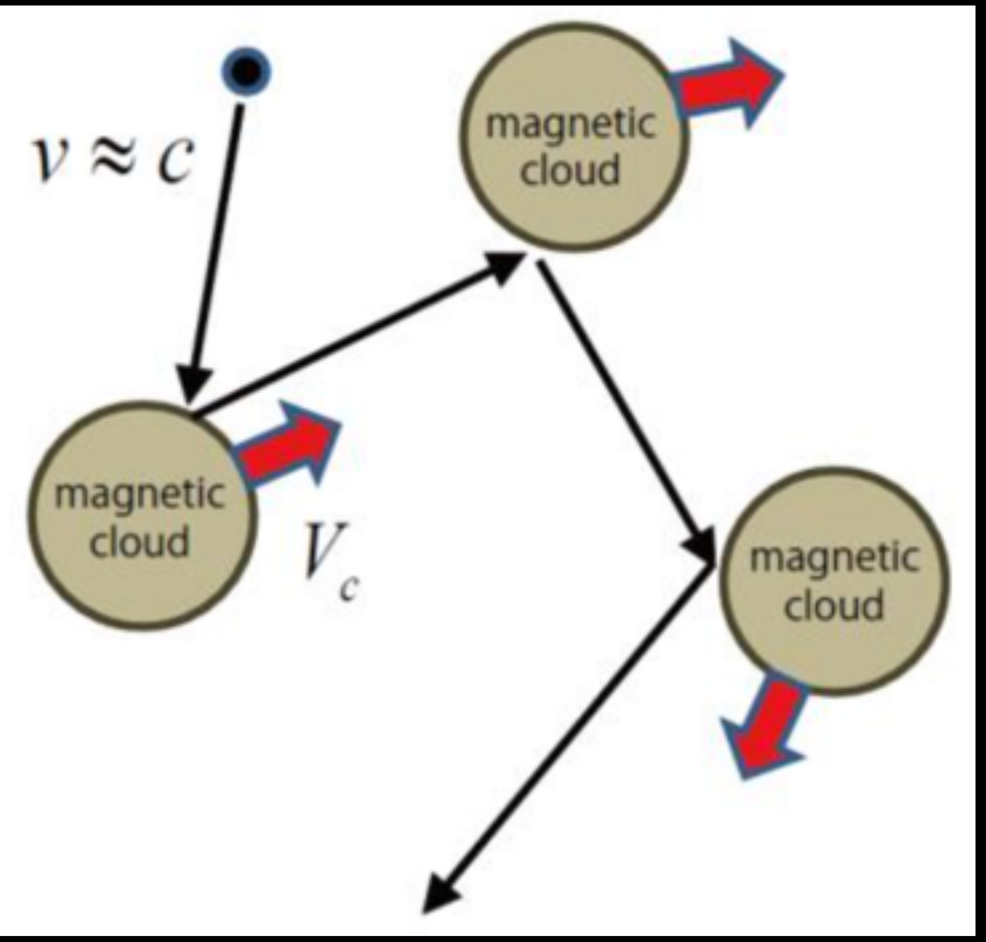


- First Order Fermi Acceleration
  - Charged particles moving in an outgoing shock front
  - Reflected by stationary turbulence in ISM -> energy gain
  - Re-enter shock front and reflect -> more energy gain!

$$\frac{dN(\epsilon)}{d\epsilon} \propto \epsilon^{-p}$$



- Second order Fermi acceleration
  - Similar to 1st Order Fermi acceleration, but particle is in the ISM and bounces off of randomly moving shocks.
  - More bounces with incoming clouds -> net energy gain
  - Second order in energy gain per collision (due to bounces off of retreating clouds)



Cosmic-Ray Acceleration - Not Stars

- The maximum energy of first-order Fermi acceleration depends on the magnetic field strength and the shock velocity:

$$E_{\rm max} \simeq \alpha \left(\frac{n_{\rm ISM}}{\rm cm^{-3}}\right)^{\frac{1}{2}} \left(\frac{v_{\rm sh}}{10^3\ {\rm km\ s^{-1}}}\right)^2 \left(\frac{R_{\rm sh}}{\rm pc}\right)\ {\rm GeV}$$

- With $\alpha \sim 10^3$

- For the Sun (coronal mass ejection)
  - $n_{ISM} = 10^8\ \text{cm}^{-3}$
  - $v_{sh} = 200\ \text{km s}^{-1}$
  - $R_{sh} = 100\ \text{R}_\odot$

Which gives us an energy around 1 GeV:

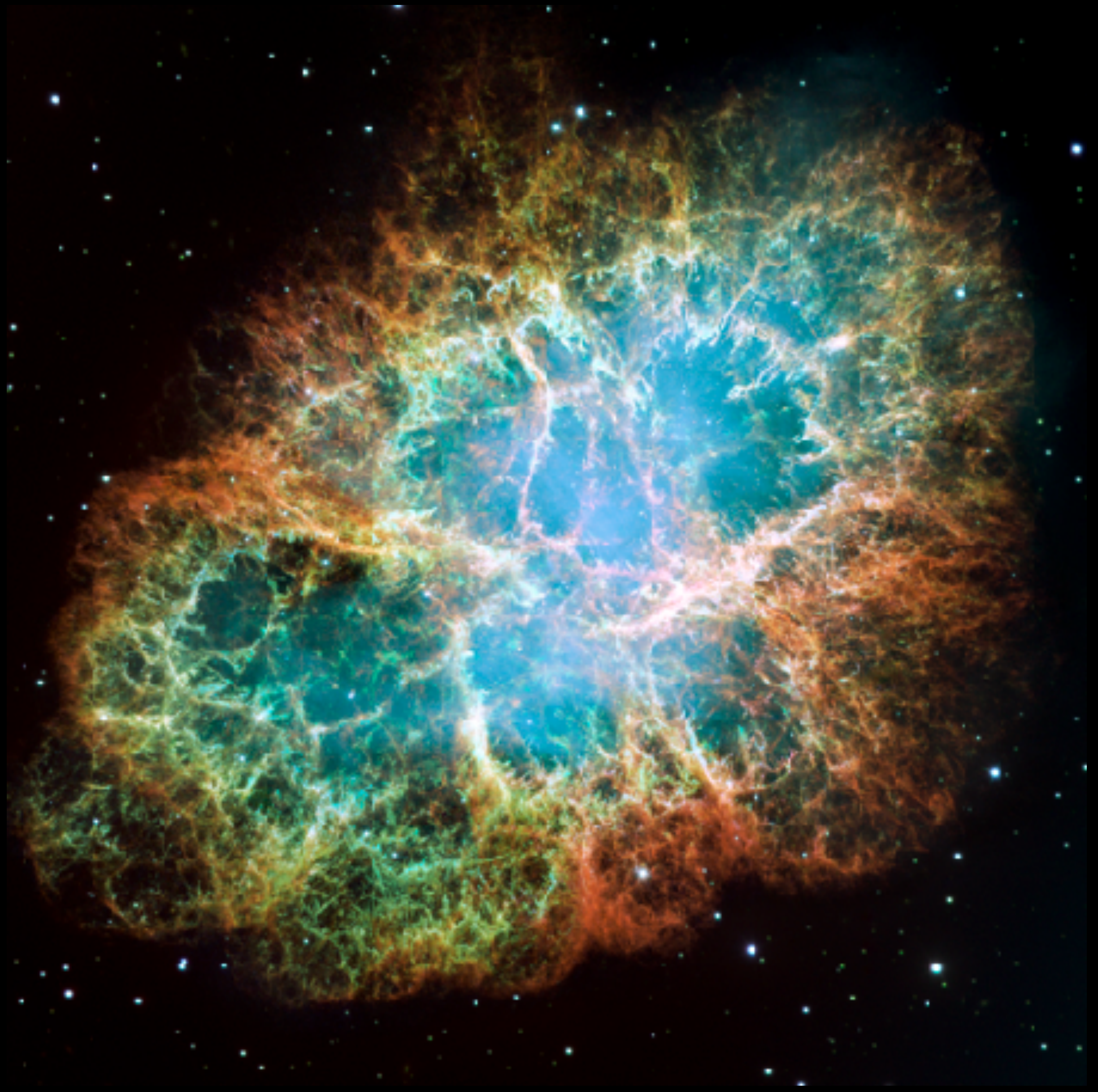
$$E_{max} = 10^3 \times 10^4 \times 0.2^2 \times 2.5 \times 10^{-6} \approx 1\ \text{GeV}$$

Diesling 2023 (2305.07697)

Supernova Remnants

- The maximum energy of first-order Fermi acceleration depends on the magnetic field strength and the shock velocity:

$$E_{\max} \simeq \alpha \left(\frac{n_{\mathrm{ISM}}}{\mathrm{cm}^{-3}}\right)^{\frac{1}{2}} \left(\frac{v_{\mathrm{sh}}}{10^3 \ \mathrm{km \ s}^{-1}}\right)^2 \left(\frac{R_{\mathrm{sh}}}{\mathrm{pc}}\right) \ \mathrm{GeV}$$



- With $\alpha \sim 10^3$

- For a supernova remnant:
  - $n_{ISM} = 10^0 \ \mathrm{cm}^{-3}$
  - $v_{sh} = 10^4 \ \mathrm{km \ s}^{-1}$
  - $R_{sh} = 10 \ \mathrm{pc}$

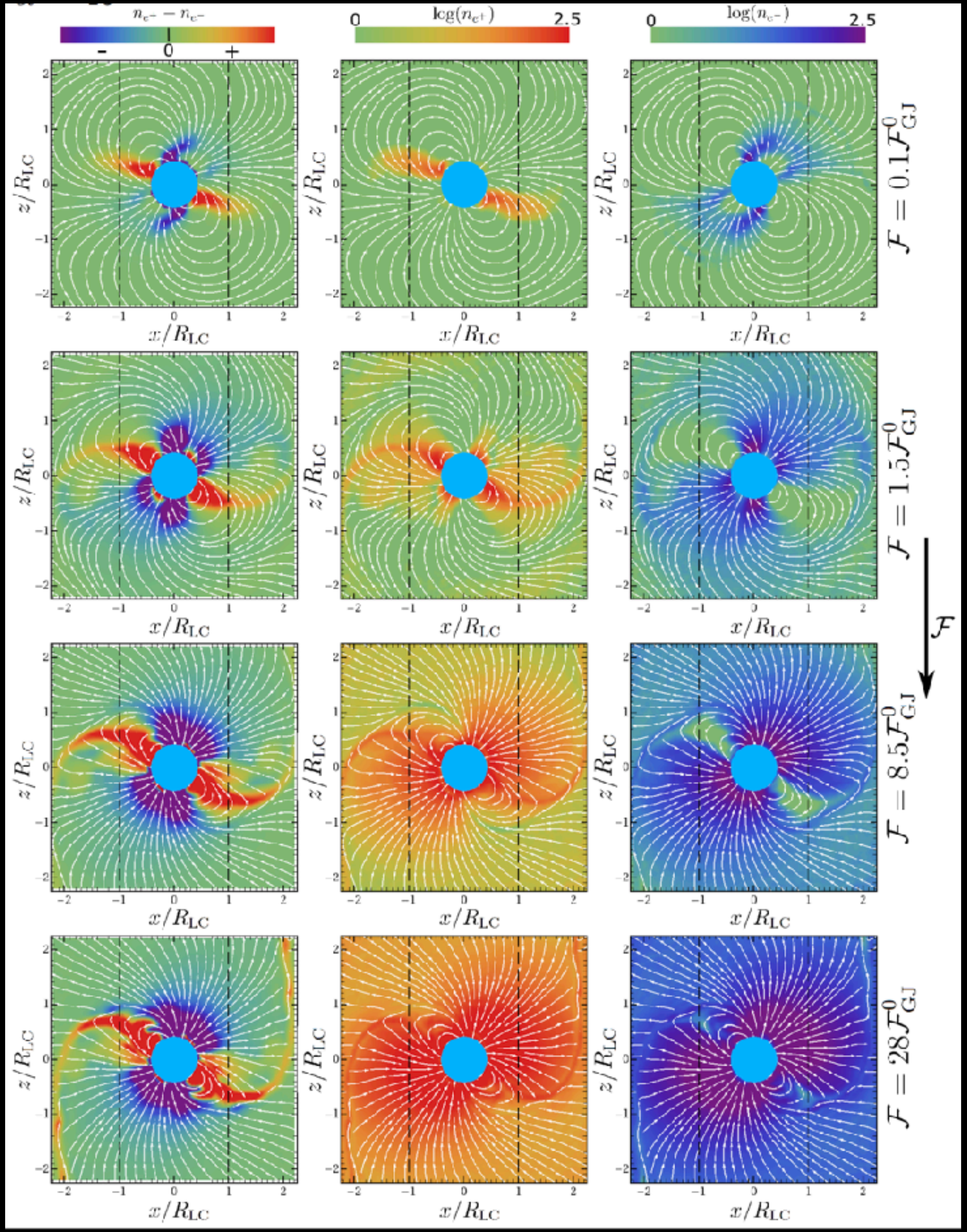
Which gives us an energy around 1 GeV:

$$E_{max} = 10^3 \times 1 \times 10^2 \times 10 = 1 \ \mathrm{PeV}$$

Diesling 2023 (2305.07697)

Pulsars/Pulsar Wind Nebulae

- Critical e^+e^- creation point is the pulsar magnetosphere.
  - 1.) Electrons "boiled" off the pulsar surface, and accelerated to TeV-PeV energies.
  - 2.) Synchrotron emission produces e^+e^- pairs which then cascade to produce a high e^+e^- multiplicity.



Pulsars/Pulsar Wind Nebulae

- PWN termination shock:
  - Voltage Drop > 30 PV
  - e^+e^- energy > 1 PeV (known from synchrotron)
- Resets e^+e^- spectrum.
- Many Possible Models:
  - 1st Order Fermi-Acceleration
  - Magnetic Reconnection
  - Shock-Driven Reconnection

Cosmic-Ray Transport

Latex by Isabelle John

$$\overbrace{\frac{\partial \psi\left(\vec{r},p,t\right)}{\partial t}}^{\text{flux}} = \overbrace{Q\left(\vec{r},p,t\right)}^{\text{source}} + \vec{\nabla} \times (\overbrace{D_{xx} \vec{\nabla} \psi}^{\text{diffusion}} - \overbrace{\vec{V} \psi}^{\text{convection}}) + \overbrace{\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p^2} \psi}^{\text{re-acceleration}}$$

$$- \underbrace{\frac{\partial}{\partial p}\left(\dot{p}\psi - \frac{p}{3}\left(\vec{\nabla} \times \vec{V}\right)\psi\right)}_{\text{energy loss}} - \frac{\psi}{\underbrace{\tau_f}_{\text{fragmentation}}} - \frac{\psi}{\underbrace{\tau_r}_{\text{radioactive decay}}}$$

- **Source term - inhomogeneous term of PDE**
- **Diffusion:**
  - **Kolmogorov:** $D \propto E^{-1/3}$
  - **Kraichnan:** $D \propto E^{-1/2}$
- **Reacceleration: Diffusion in momentum space**

Cosmic-Ray Transport

Latex by Isabelle John

$$\overbrace{\frac{\partial\psi\left(\vec{r},p,t\right)}{\partial t}}^{\text{flux}} = \overbrace{Q\left(\vec{r},p,t\right)}^{\text{source}} + \vec{\nabla}\times\Big(\overbrace{D_{xx}\vec{\nabla}\psi}^{\text{diffusion}} - \overbrace{\vec{V}\psi}^{\text{convection}}\Big) + \overbrace{\frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p^2}\psi}^{\text{re-acceleration}}$$

$$\underbrace{-\frac{\partial}{\partial p}\left(\dot{p}\psi - \frac{p}{3}\left(\vec{\nabla}\times\vec{V}\right)\psi\right)}_{\text{energy loss}} - \frac{\psi}{\underbrace{\tau_f}_{\text{fragmentation}}} - \frac{\psi}{\underbrace{\tau_r}_{\text{radioactive decay}}}$$

- **Convection: Winds driven by injection of cosmic-rays and relativistic gas from the Milky Way**
- **Energy Losses: (Next Section)**
- **Fragmentation: Nuclei can be split by interactions**
- **Radioactive Decay: For radioactive nuclei**

Note About Scales

- **Gyroradius of particles in a magnetic field is small:**

$$r_g/\text{meter} = 3.3 \times \frac{(\gamma m c^2/\text{GeV})(v_\perp/c)}{(|q|/e)(B/\text{Tesla})}$$

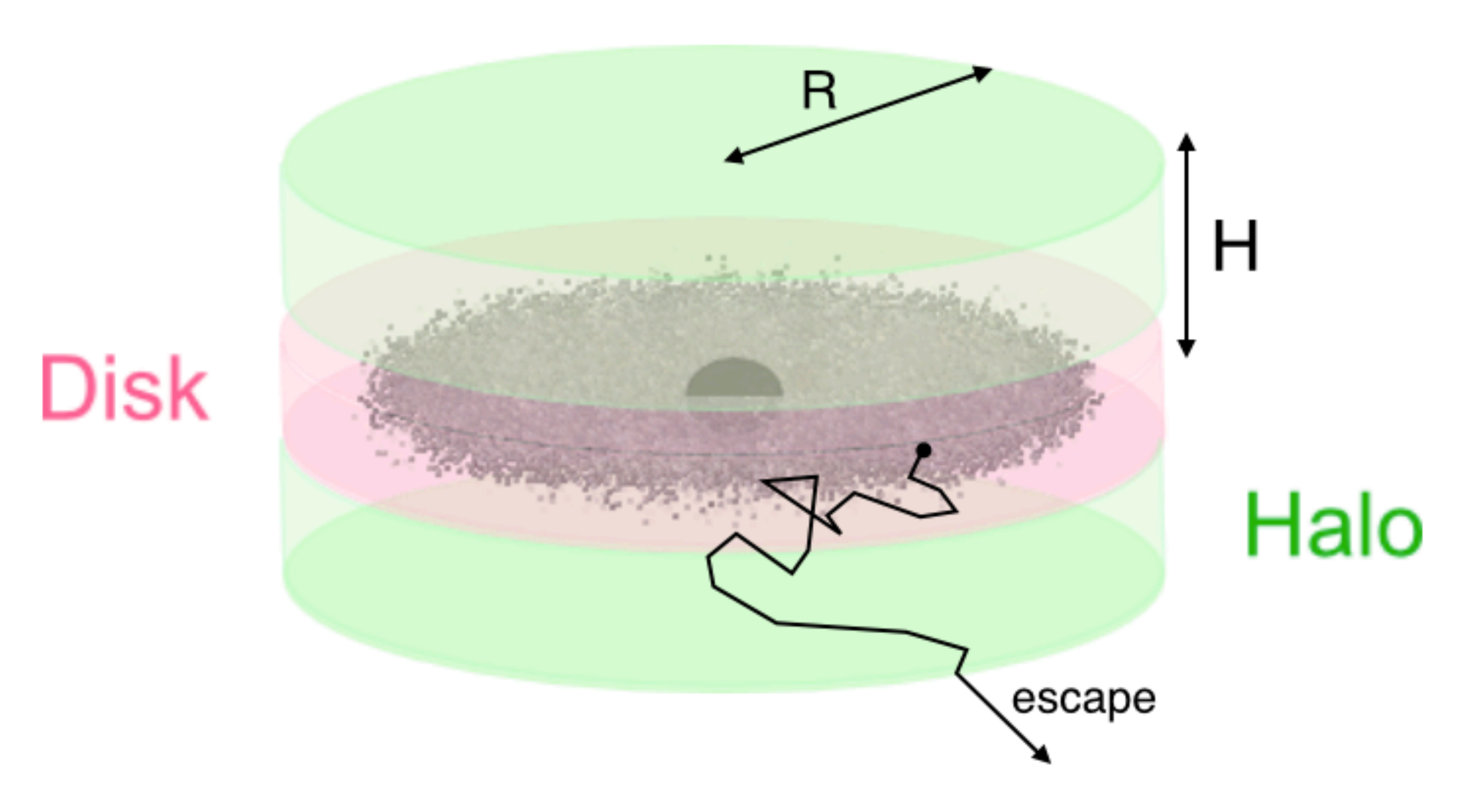
- **"Stepsize" of particles diffusing through the Milky Way is large:**

- $D \approx 3 \times 10^{28}\ \frac{\text{cm}^2}{\text{s}} \rightarrow l = \frac{D}{c} = \frac{D}{3 \times 10^{10}\ \text{cm s}^{-1}} = 10^{18}\ \text{cm} = 0.3\ \text{pc}$

- **On small scales - particles are locked into the preferential direction of the local field.**

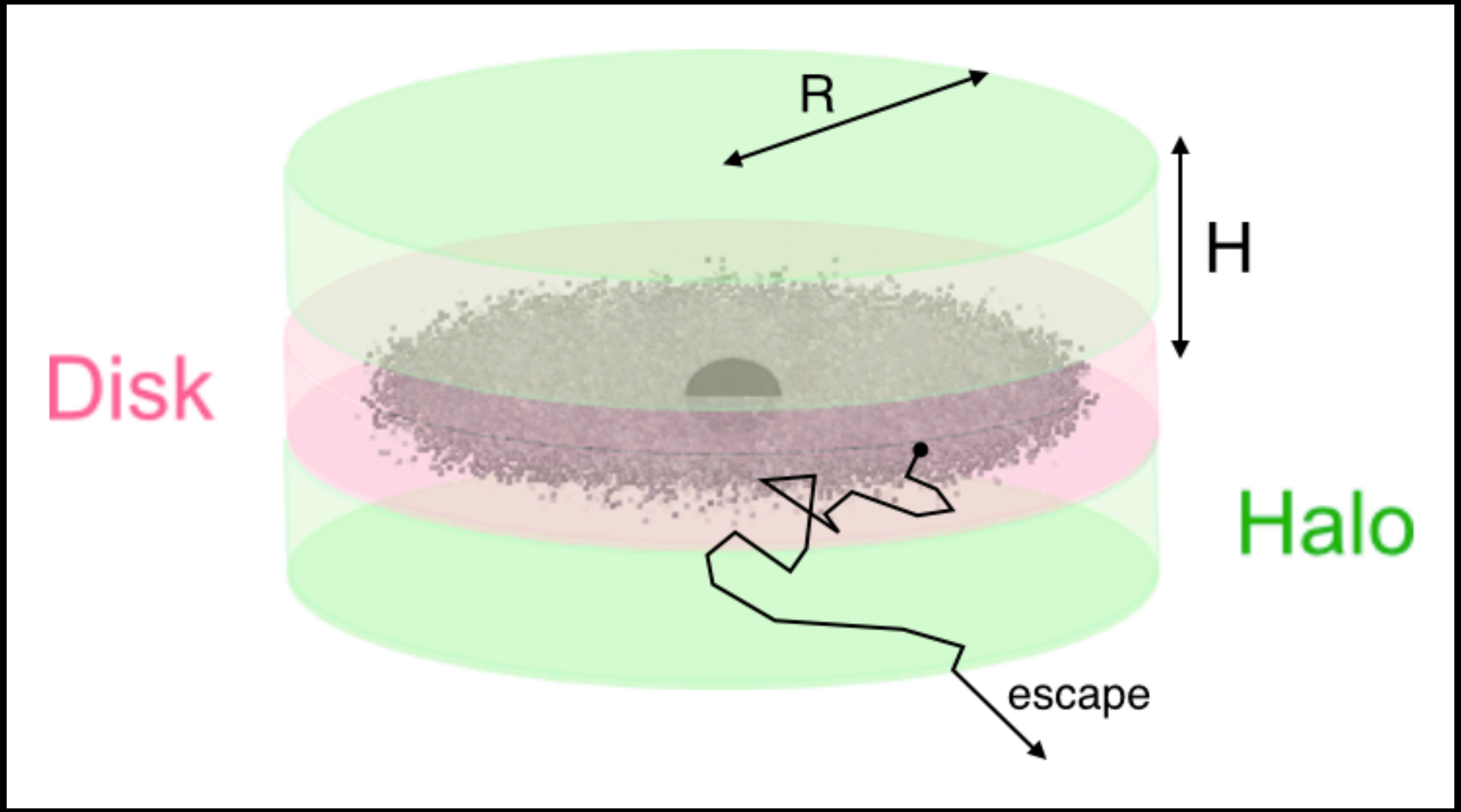
Leaky Box Model

- Cosmic-Rays produced in the thin disk, and diffuse until they leave the thick disk (halo)



- Thin Disk is ~100 pc
- Thick disk is ~5 kpc
- Radius of Milky Way is ~20 kpc

Leaky Box Model



- Cosmic-Rays produced in the thin disk, and diffuse until they leave the thick disk (halo)

- Residence time: $\sim 10\ \mathrm{Myr} \left(\frac{E}{1\mathrm{GeV}}\right)^{-1/3}$

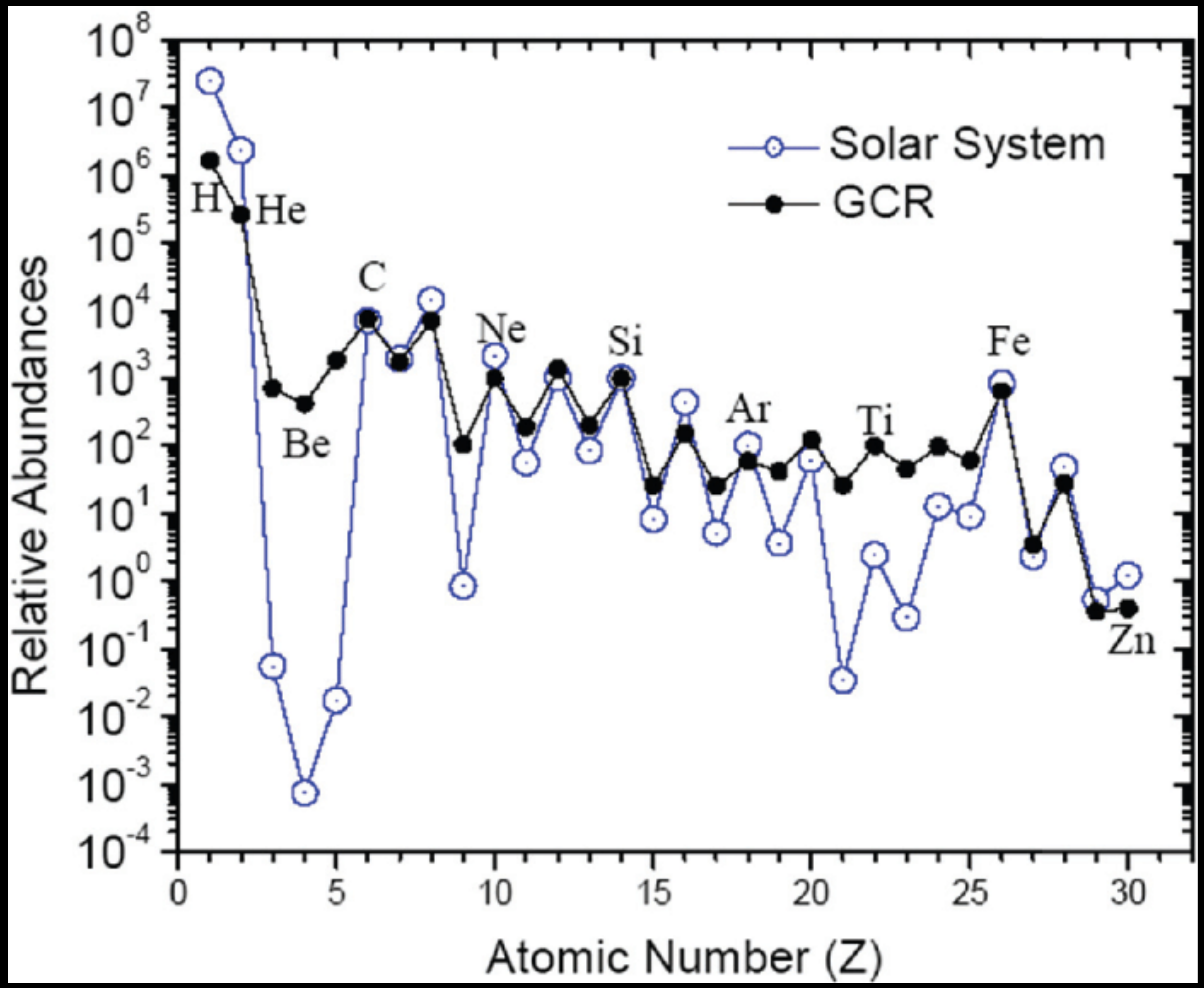
- Interaction probability: $\sim 10\ \mathrm{Myr}\ \sigma_{pp} \left(\frac{V_{disk}}{V_{halo}}\right) \left(\frac{E}{1\mathrm{GeV}}\right)^{-1/3}$

Calorimetry

- Fraction of cosmic-rays that have an interaction before leaving the medium.
- Calorimetric fraction of 1 means that cosmic-rays undergo one e-fold of interactions.
- Milky Way - Average cosmic ray proton has calorimetric fraction of 0.1
- Star-forming Galaxy (e.g., NGC 253) calorimetric fraction >1.

Primary Cosmic Rays

- Primary cosmic rays are those that are produced in the final stages of stellar evolution, and thus efficiently accelerated in supernova explosions/ SNR

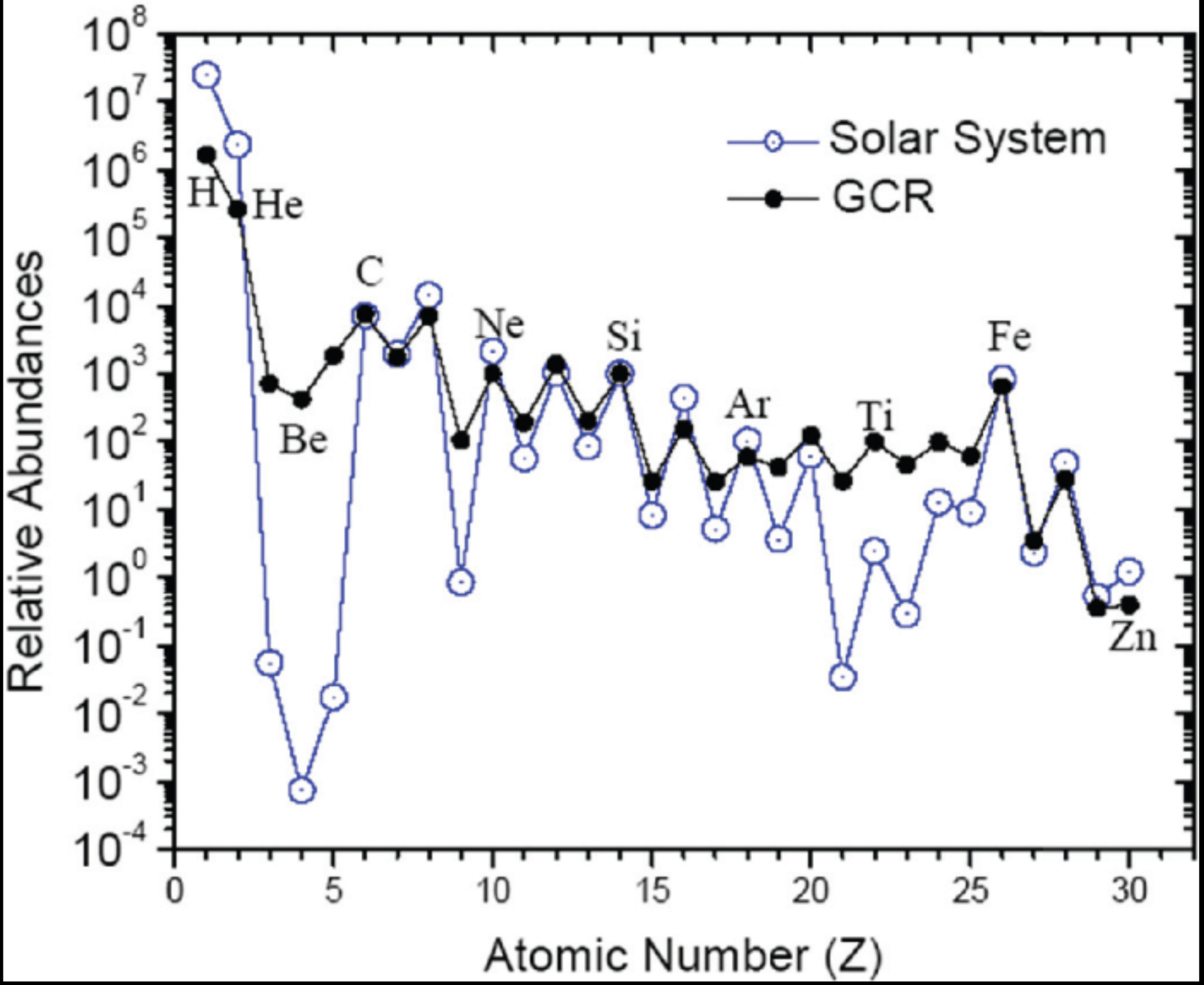


- H/He/C/O/Ne/Si/Fe

- Models of stellar nuclear synthesis provide these elements (e.g., CNO cycle)

- Local Spectrum: $E^{-p-\delta} = E^{-2.X-0.Y} = E^{-2.7}$

Secondary Cosmic Rays



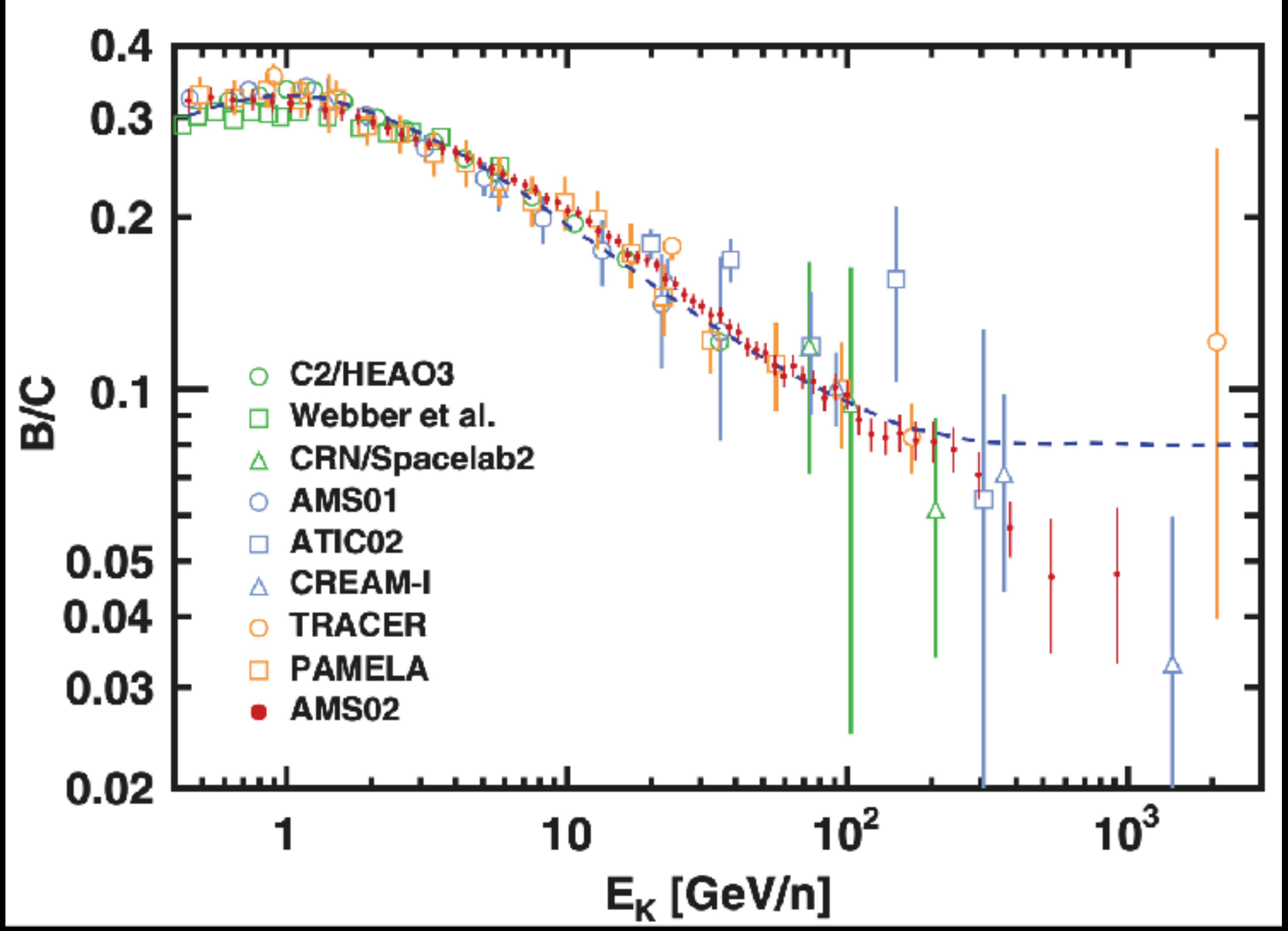
- Secondary cosmic rays are not directly produced in supernovae, but are instead produced via the spallation of heavier cosmic-rays.

- e.g., C + H -> B + ?

- Local Spectrum: $E^{-p-2\delta} = E^{-2.X-2\ 0.Y} = E^{-3.1}$

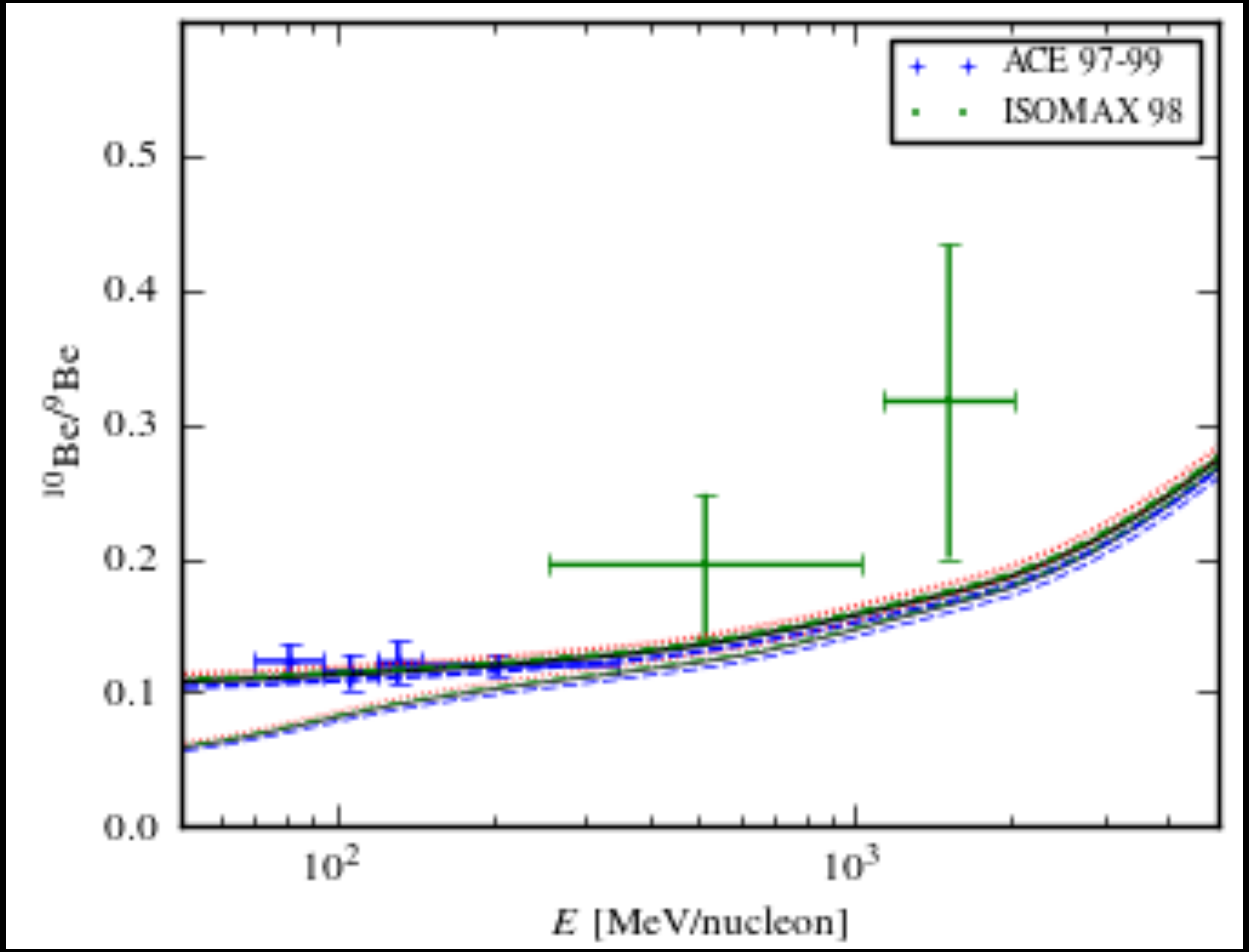
Primary-to-Secondary Ratios

- Measurements of the cosmic-ray secondary to primary ratios isolate the value of δ.
- Amplitude of the ratios tests a combination of the residence time and the gas density (or a preference for particles staying in the thin disk).
- Verifies the main features of diffusion model.



Primary-to-Secondary Ratios

- Can use radioactively decaying nuclei to isolate the dependence on the residence time.
- Does not depend on gas density (independent information).
- Isotopic ratios very hard to measure with things like AMS-02



Cosmic-Ray Electron Propagation

- Different cooling mechanisms than protons (inverse Compton scattering, synchrotron (does not produce gammas), bremsstrahlung
- Which produces the following energy loss rate:

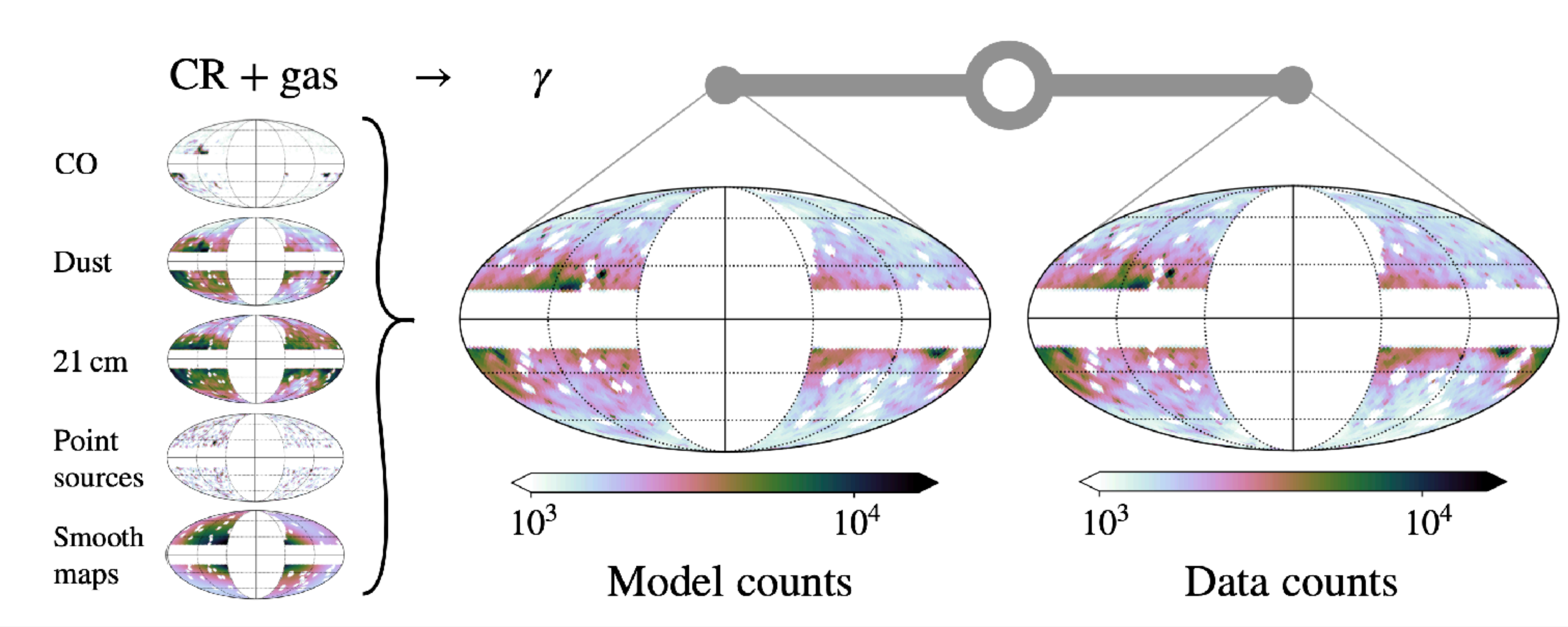
$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T c \left(\frac{E}{m_e}\right)^2 \left[\rho_B + \sum_i \rho_i(\nu_i) S(E, \nu_i)\right]$$

$$t_{loss} \approx 320 \text{ kyr} \left(\frac{E}{1 \text{ TeV}}\right)^{-1} \left(\frac{\rho_{\text{tot}} \, S_{\text{eff}}(E)}{1 \text{ eV cm}^{-3}}\right)$$

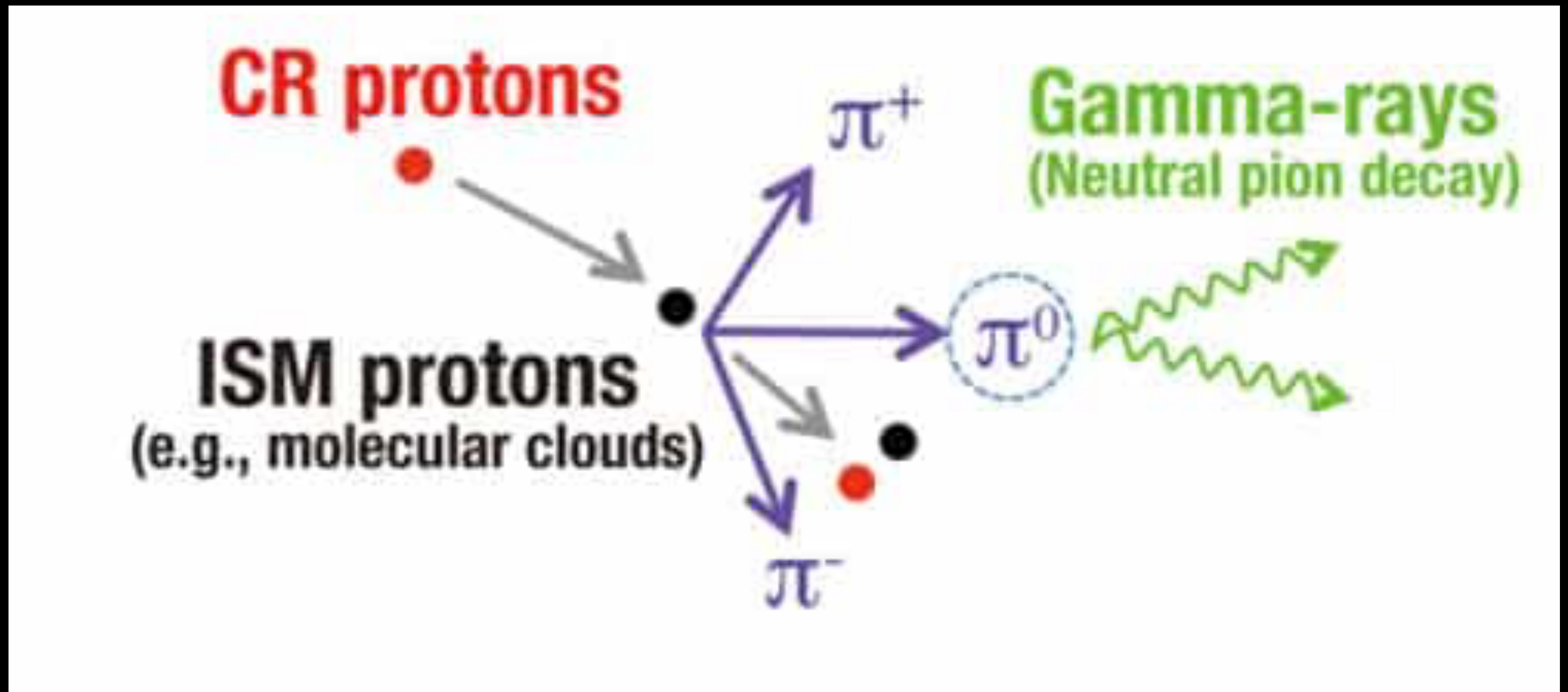
- Calorimetric at high energies! (But not at low energies).

Diffuse Emission

- Calculated by multiplying the steady state cosmic-ray density (fit by Galprop to local observations) by the observed gas density.



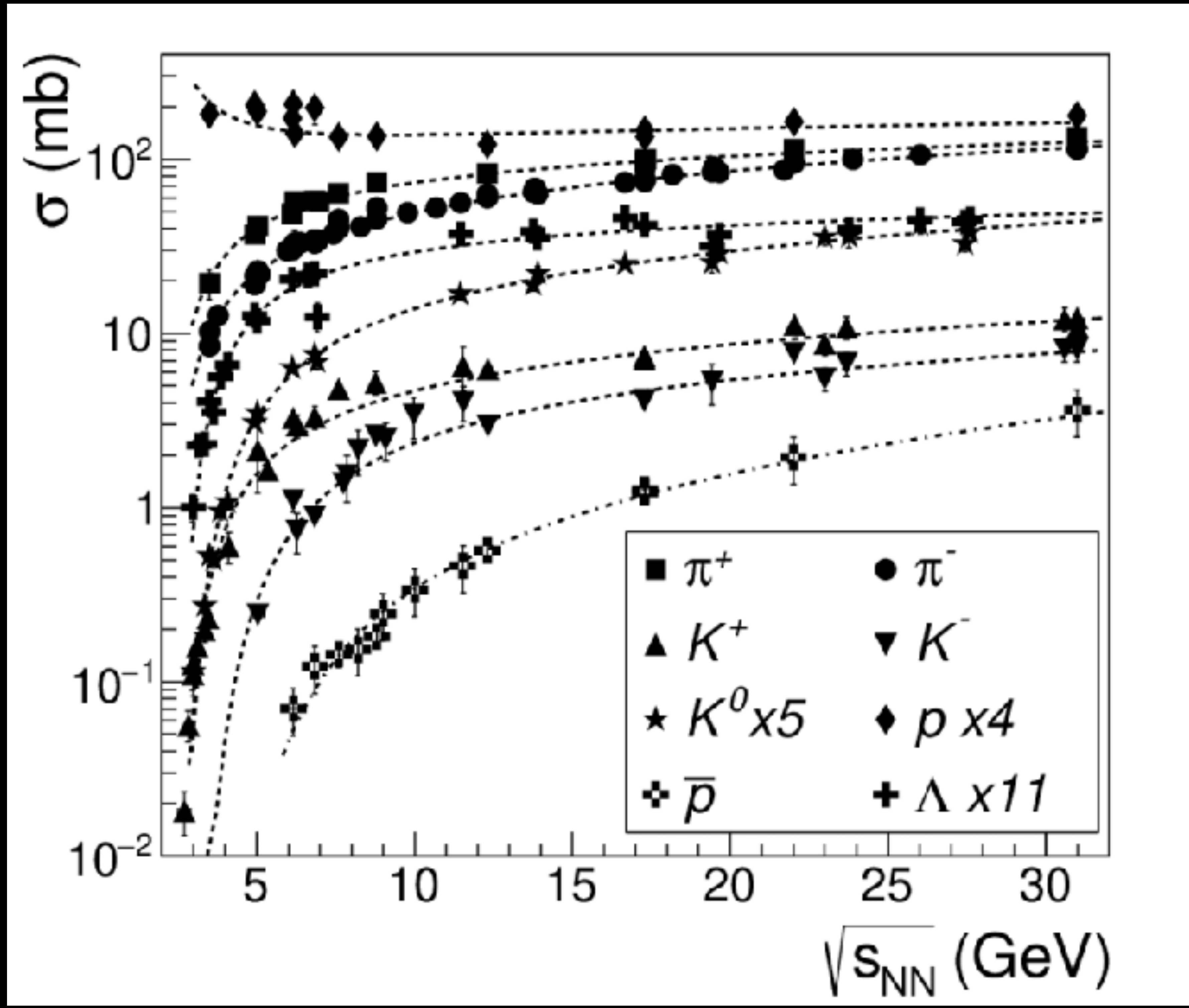
Pion-Decay (Hadronic)



- Cosmic ray protons strike ambient gas in the Milky Way
- Produce both charged and neutral pions
  - Ratio between neutrino and gamma-ray flux

- Gamma-Ray energy is ~1/20 of proton energy
- Cross-section is roughly energy independent

- Gamma-Ray spectrum mirrors proton spectrum

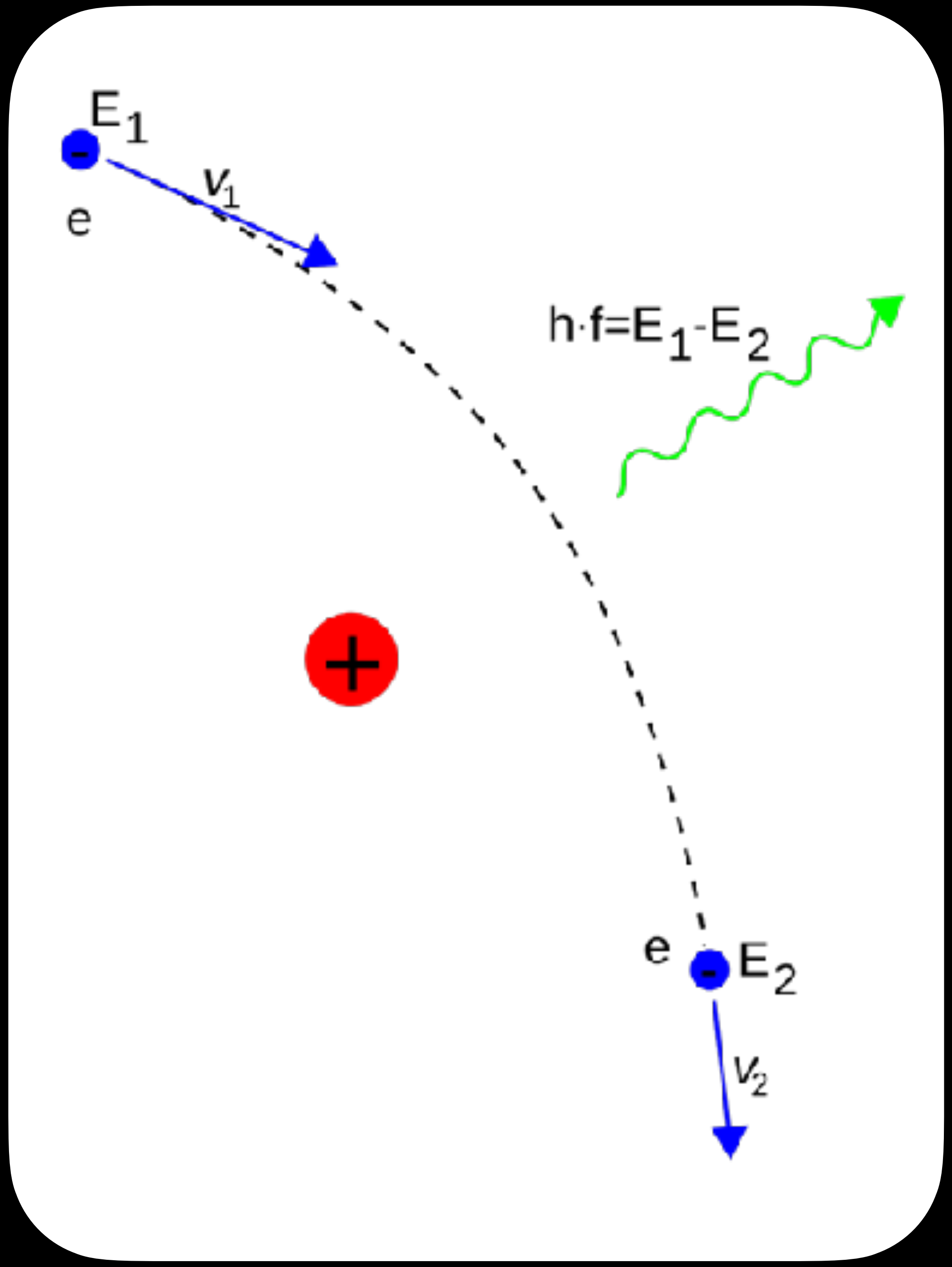


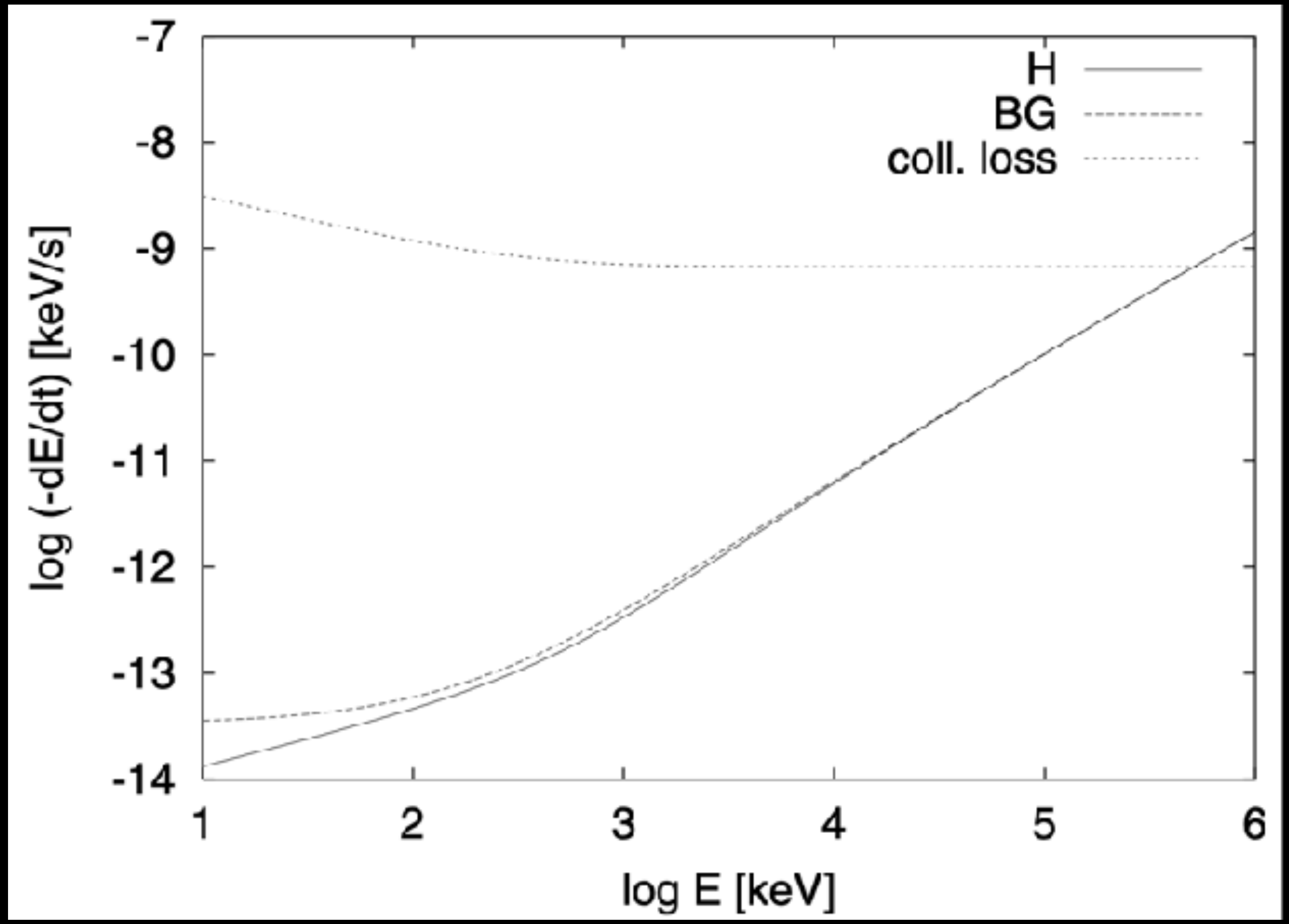
Bremsstrahlung

- Cosmic-ray electrons are deflected when moving near plasma
- Lose energy via these interactions, which release MeV and GeV scale photons

$$P = \frac{q^2\gamma^4}{6\pi\varepsilon_0 c}\left(\dot{\beta}^2 + \frac{\left(\boldsymbol{\beta}\cdot\dot{\boldsymbol{\beta}}\right)^2}{1-\beta^2}\right)$$

- Energy loss rate is linear, meaning the timescale for particle energy loss is energy independent.

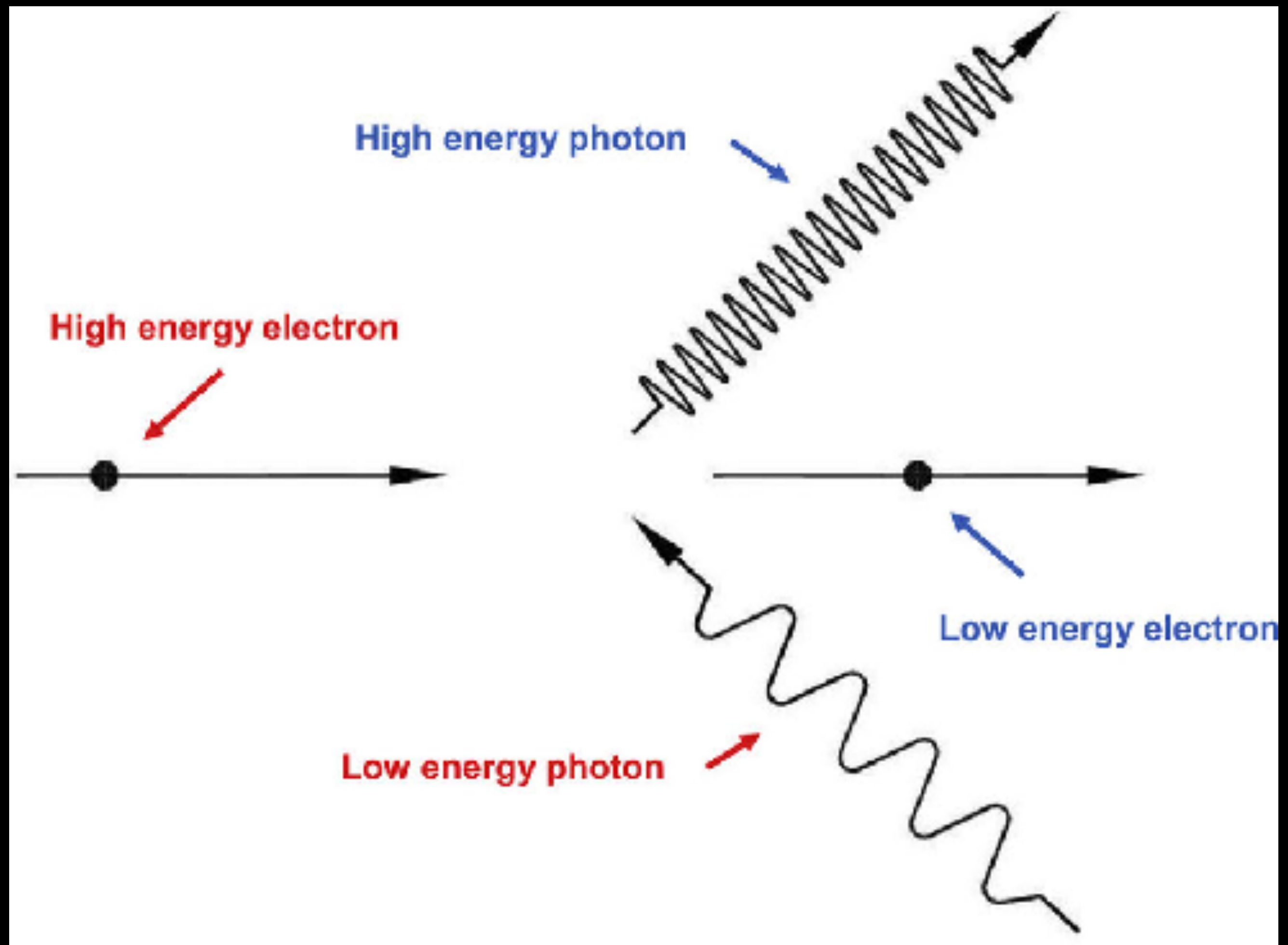




inverse-Compton Scattering

- inverse-Compton scattering based on the following cross-section

$$\frac{d^2\sigma(E_\gamma,\theta)}{d\Omega dE_\gamma} = \frac{r_0^2}{2\nu_i E^2} \times \left[1+\frac{z^2}{2(1-z)}-\frac{2z}{b_\theta(1-z)}+\frac{2z^2}{b_\theta^2(1-z)^2}\right]$$

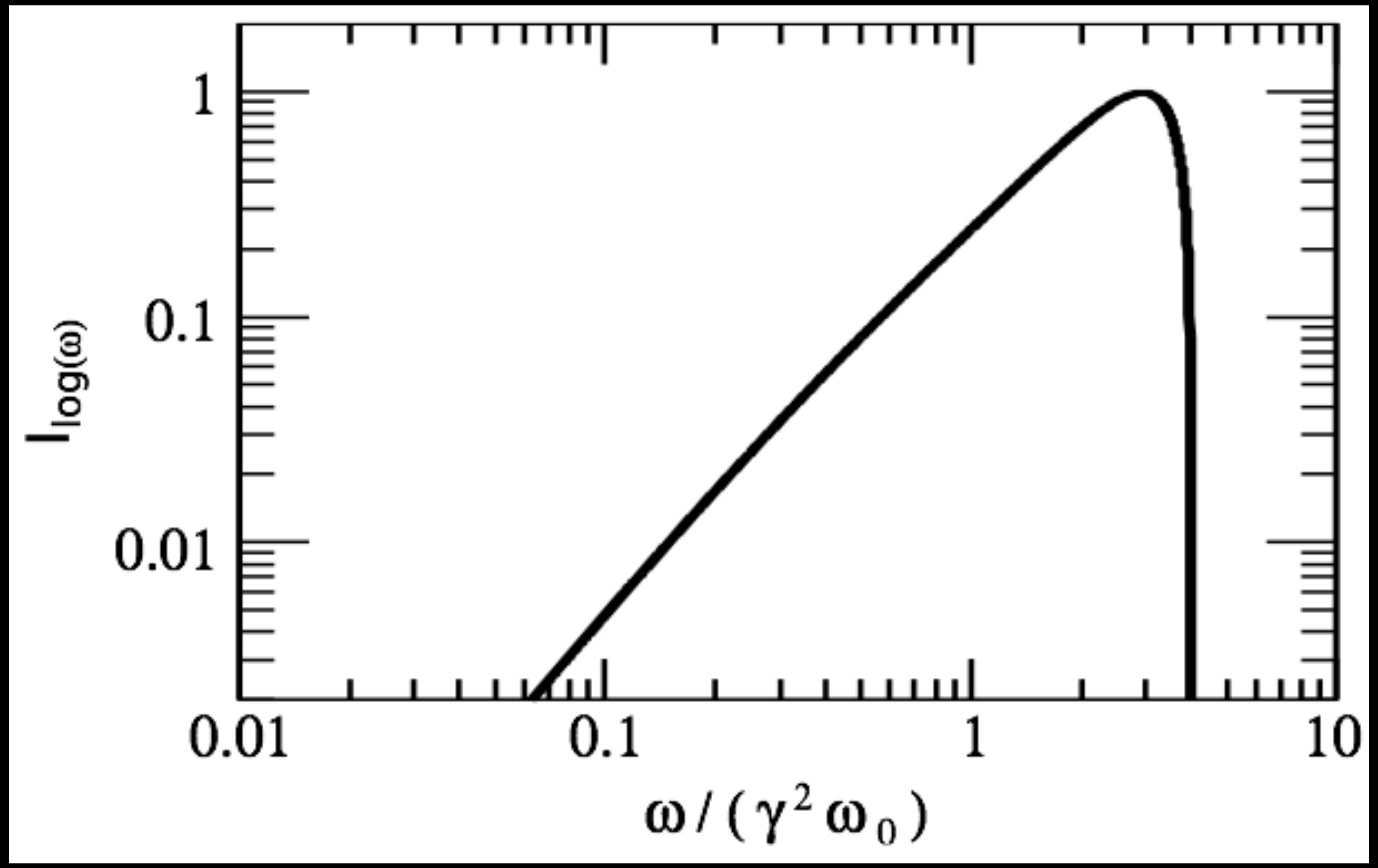


- Which produces the following energy loss rate:

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T c \left(\frac{E}{m_e}\right)^2 \left[\rho_B + \sum_i \rho_i(\nu_i) S(E,\nu_i)\right]$$

$$t_{loss} \approx 320 \text{ kyr} \left(\frac{E}{1 \text{ TeV}}\right)^{-1} \left(\frac{\rho_{\text{tot}}\, S_{\text{eff}}(E)}{1 \text{ eV cm}^{-3}}\right)$$

$$E_{\gamma,c} = \frac{4}{3}\gamma^2 \nu_i$$



Energy Loss Timescales (Overview)

Wild at Heart:-
The Particle Astrophysics of the Galactic Centre

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Accepted XXX. Received XXX; in original form XXX

ABSTRACT

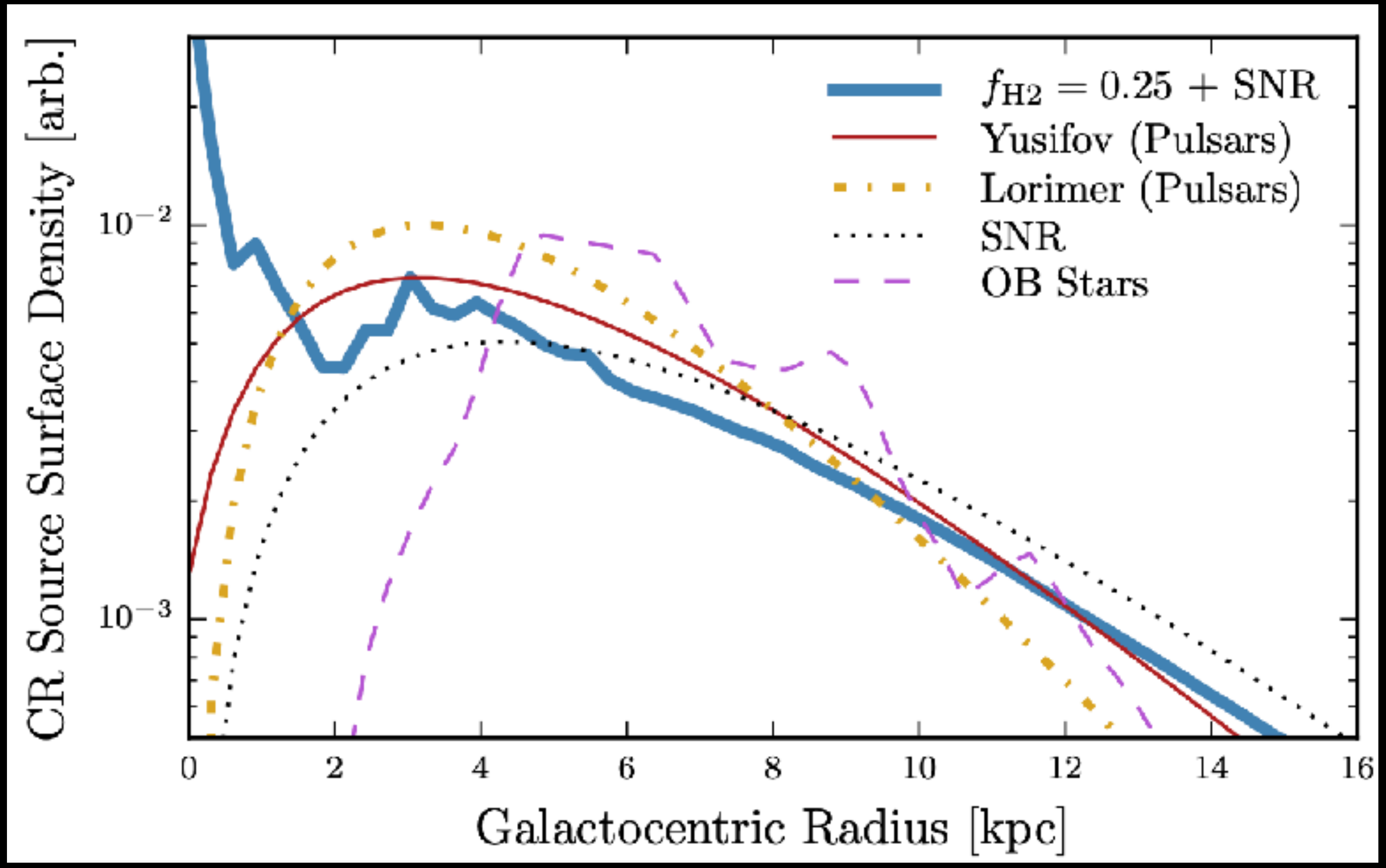
We treat of the high-energy astrophysics of the inner ∼200 pc of the Galaxy. Our modelling of this region shows that the supernovae exploding here every few thousand years inject enough power to i) sustain the steady-state, in situ population of cosmic rays (CRs) required to generate the region's non-thermal radio and TeV γ-ray emission; ii) drive a powerful wind that advects non-thermal particles out of the inner GC; iii) supply the low-energy CRs whose Coulombic collisions sustain the temperature and ionization rate of the anomalously warm, envelope H_2 detected throughout the Central Molecular Zone; iv) accelerate the primary electrons which provide the extended, non-thermal radio emission seen over ∼150 pc scales above and below the plane (the Galactic centre lobe); and v) accelerate the primary protons and heavier ions which, advected to very large scales (up to ∼10 kpc), generate the recently-identified WMAP haze and corresponding Fermi haze/bubbles. Our modelling bounds the average magnetic field amplitude in the inner few degrees of the Galaxy to the range $60 < B/\mu$G < 400 (at 2σ confidence) and shows that even TeV CRs likely do not have time to penetrate into the *cores* of the region's dense molecular clouds before the wind removes them from the region. This latter finding apparently disfavours scenarios in which CRs – in this star-burst-like environment – act to substantially modify the conditions of star-formation. We speculate that the wind we identify plays a crucial role in advecting low-energy positrons from the Galactic nucleus into the bulge, thereby explaining the extended morphology of the 511 keV line emission. We present extensive appendices reviewing the environmental conditions in the GC, deriving the star-formation and supernova rates there, and setting out the extensive prior evidence that exists

$$
\begin{aligned}
t_{\rm SN} &\simeq 2.5\times10^{3}\ {\rm yr}\left(\frac{\nu_{\rm SN}}{0.04\ (100\ \ {\rm yr})^{-1}}\right)^{-1}, \\
t_{\rm wind} &\simeq 4.1\times10^{5}\ {\rm yr}\left(\frac{v_{\rm wind}}{100\ {\rm km/s}}\right)^{-1}, \\
t^{p}_{\rm pp} &\simeq 3.1\times10^{5}\ {\rm yr}\left(\frac{n_H}{120\ {\rm cm}^{-3}}\right)^{-1}, \\
t^{e}_{\rm inztn} &\simeq 6.7\times10^{5}\ {\rm yr}\left(\frac{E}{\rm GeV}\right)\left(\frac{n_H}{120\ {\rm cm}^{-3}}\right)^{-1}, \\
t^{e}_{\rm brems} &\simeq 2.4\times10^{5}\ {\rm yr}\left(\frac{n_H}{120\ {\rm cm}^{-3}}\right)^{-1}, \\
t^{e}_{\rm synch} &\simeq 1.3\times10^{6}\ {\rm yr}\left(\frac{E}{\rm GeV}\right)^{-1}\left(\frac{B}{100\ \mu{\rm G}}\right)^{-2}, \\
t^{e}_{\rm IC} &\simeq 1.7\times10^{7}\ {\rm yr}\left(\frac{E}{\rm GeV}\right)^{-1}.
\end{aligned}
\qquad (1)
$$

Topic: Galprop/Dragon

- Codes that solve cosmic-ray propagation numerically.
- Grid galaxy in r, z, and p
- Take a cosmic ray injection profile from models
- Calculate diffusion, secondary production and gamma-ray generation

- <u>Step 1:</u>
  - Start with a model for the energy spectrum and morphology of cosmic-ray injection



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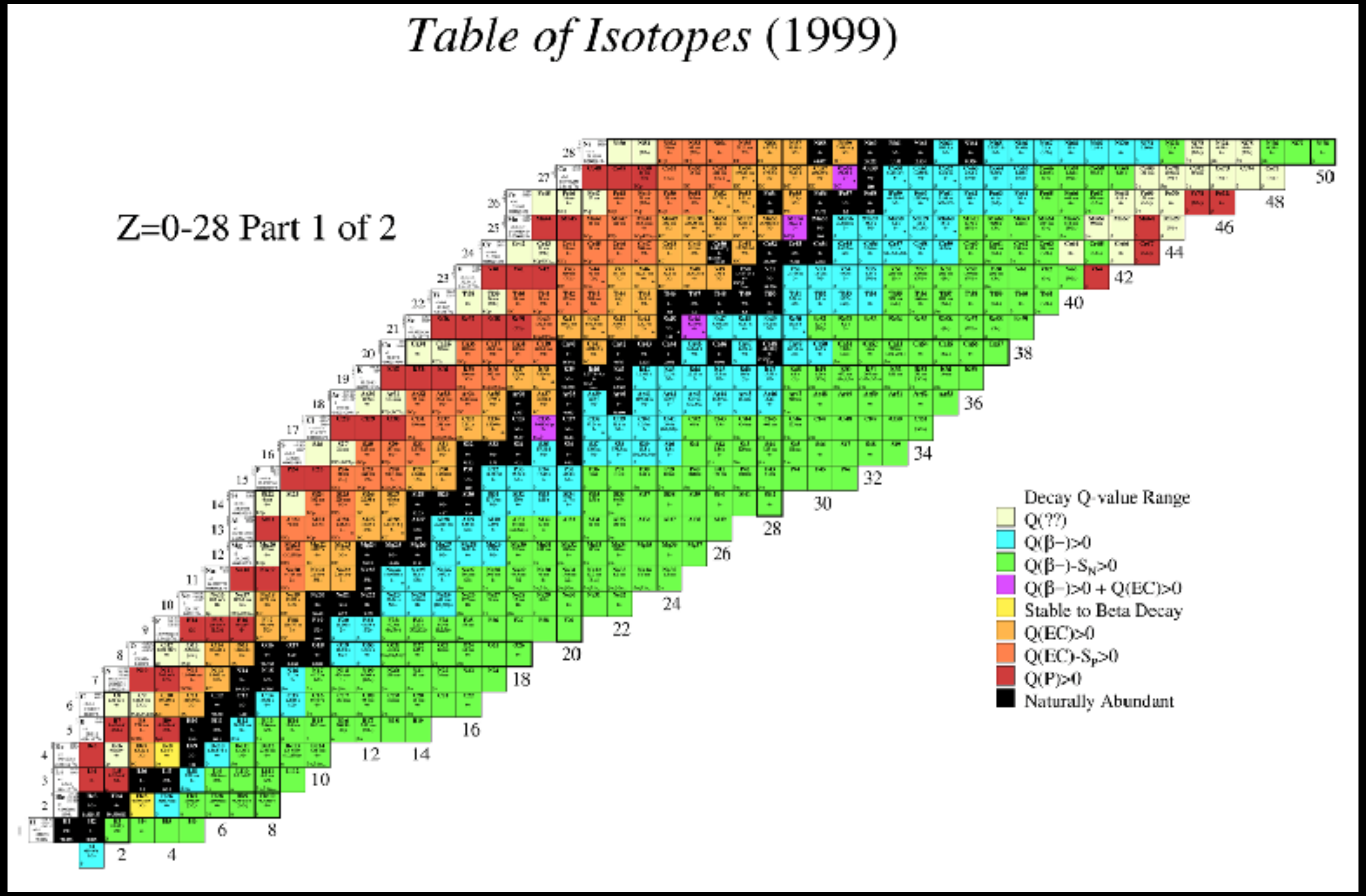
- <u>Step 2:</u>
  - Solve the PDE numerically on a grid



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- Calculate diffusion, secondary production and gamma-ray generation

- <u>Step 3:</u>
  - Combine with gas density to produce a diffuse emission model.

Topic: Galprop/Dragon

GALPROP version: 54
click to change
WebRun Help
Configure & Submit
Help: Configure & Submit
First-time User Mode
Advanced User Mode
Batch Runs
Monitor Queue
Download Results
Heliospheric modulation with HelMod
Exchange Runs

Enter the desired GALPROP v. 54 parameters and click 'Submit' at **the bottom of the form** ⇓

Common | Grids | Propagation | Gas | Sources | Emission | Abundances

Import configuration from: | you can use an example or retrieve your old run

Common Parameters

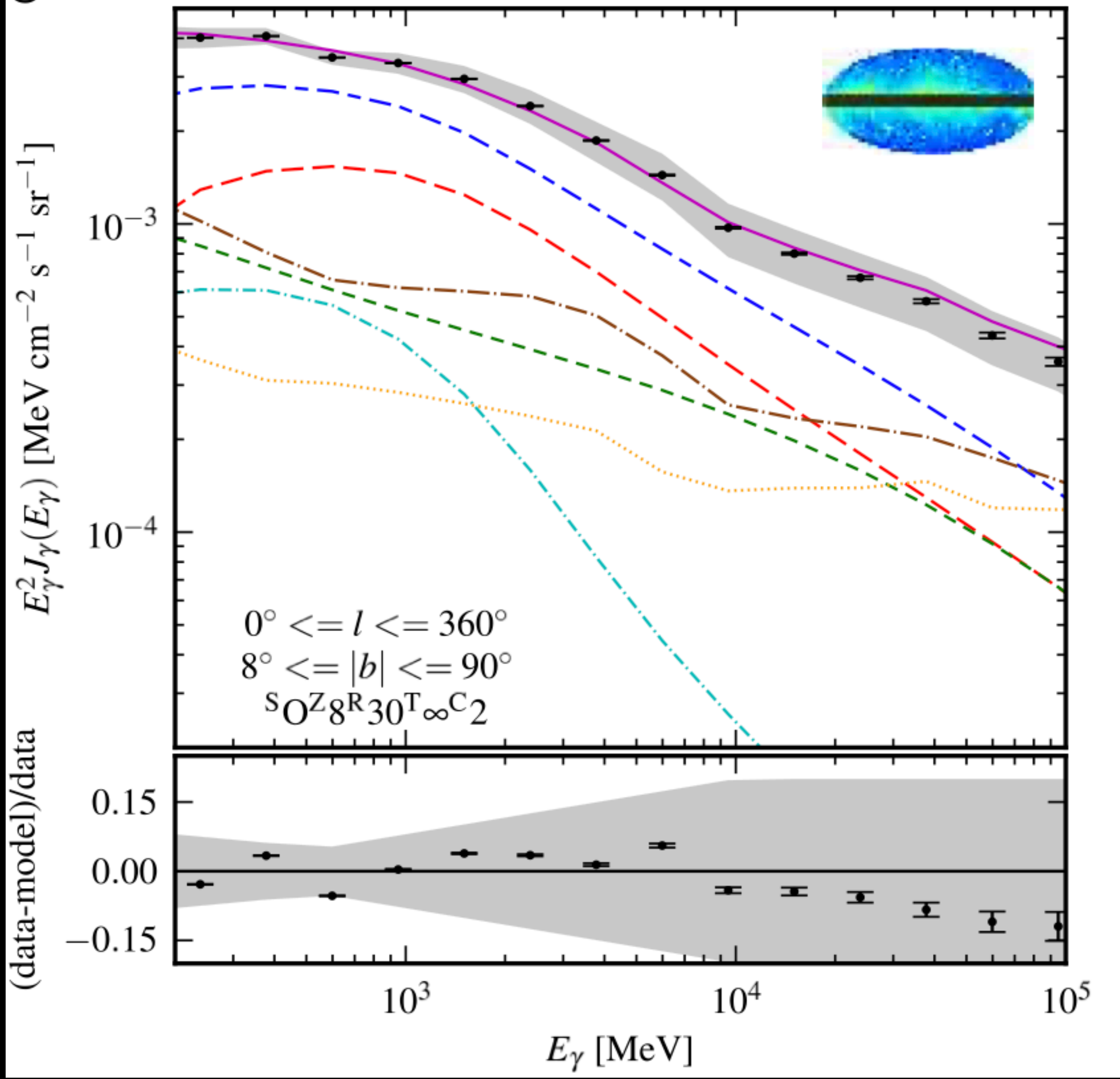
Name	Value	Description
Title	Untitled WebRun cal	Descriptive title used to identify the run.
n_spatial_dimensions	2	Specifies whether 2 or 3 spatial dimensions.

Energetic and Spatial Grids

Name	Value	Description
r_min	0.0	Minimum galactocentric radius (R) for 2D case, in kpc. Ignored for 3D.
r_max	25.0	Maximum galactocentric radius (R) for 2D case, in kpc. Ignored for 3D.
dr	0.2	Cell size in galactocentric radius (R) for 2D case, in kpc.
z_min	-04.0	Minimum height for 2D and 3D case, in kpc.
z_max	+04.0	Maximum height for 2D and 3D case, in kpc.
dz	0.1	Cell size in z for 2D and 3D case, in kpc

CR Propagation

Name	Value	Description
D0_xx	6.10e28	The value of the spatial diffusion coefficient D for a particle of rigidity rho is determined via the formula: D=beta D0_xx (rho / D_rigid_br)^D_g, where beta=v/c, rho=cp/(Ze), D_rigid_br is a reference rigidity (see parameter D_rigid_br), and the power law index D_g=D_g_1 for rho<D_rigid_br, and D_g=D_g_2 for rho>D_rigid_br. The units of D0_xx are cm^2 s^{-1}, and c, e, Z, v and p have their usual meanings.
D_rigid_br	4.0e3	Rigidity for D0_xx formula, in MV, and also break point in case D_g_1 != D_g_2.
D_g_1	0.33	Diffusion coefficient index below reference rigidity. See formula for D0_xx. Kolmogorov turbulence corresponds to a value 1/3.
D_g_2	0.33	Diffusion coefficient index above reference rigidity. See formula for D0_xx. Kolmogorov turbulence corresponds to a value 1/3.
diff_reacc	1	Indicates whether diffusive reacceleration is to be included in propagation (0=no, >=1 yes). **Recommended 0, 1 or 2 for first time users.** 1 and 11=Kolmogorov turbulence, 2 and 12=Kraichnan turbulence. 1 and 2=no damping, 11 and 12=with wave-damping (additional parameters describe the regime of damping).
v_Alfven	30.0	Alfven speed for computation of reacceleration momentum diffusion coefficient. This parameter is in fact Alfven speed/sqrt(w), where w is the ratio of MHD wave energy density to magnetic field energy density, see Strong & Moskalenko (1998).
convection	0	Set to 1 to indicate if convection is to be included in propagation.
cross_section_option	012	Options for determining isotopic production cross sections. Experimental data (table or fit) are used whenever available. Otherwise, for cross_section_options=012, the code of Webber et al. 93 is used (re-normalized if data exist), and for cross_section_option=022, the code of TS'00 is used (re-normalized if data exist).
primary_electrons	1	Indicates whether to propagate primary electrons (0: no, 1: yes). Set to 1 if inverse Compton and/or synchrotron skymaps are to be computed.
secondary_electrons	0	Indicate whether to propagate secondary electrons (0: no, 1: yes).



- Red: Pion decay
- ICS: green dashed
- Brem: Cyan dot-dashed
- Total: Blue dashed

- Orange: All Sources
- Brown: Isotropic background (assumed extragalactic)

- Note Residuals are ~10%

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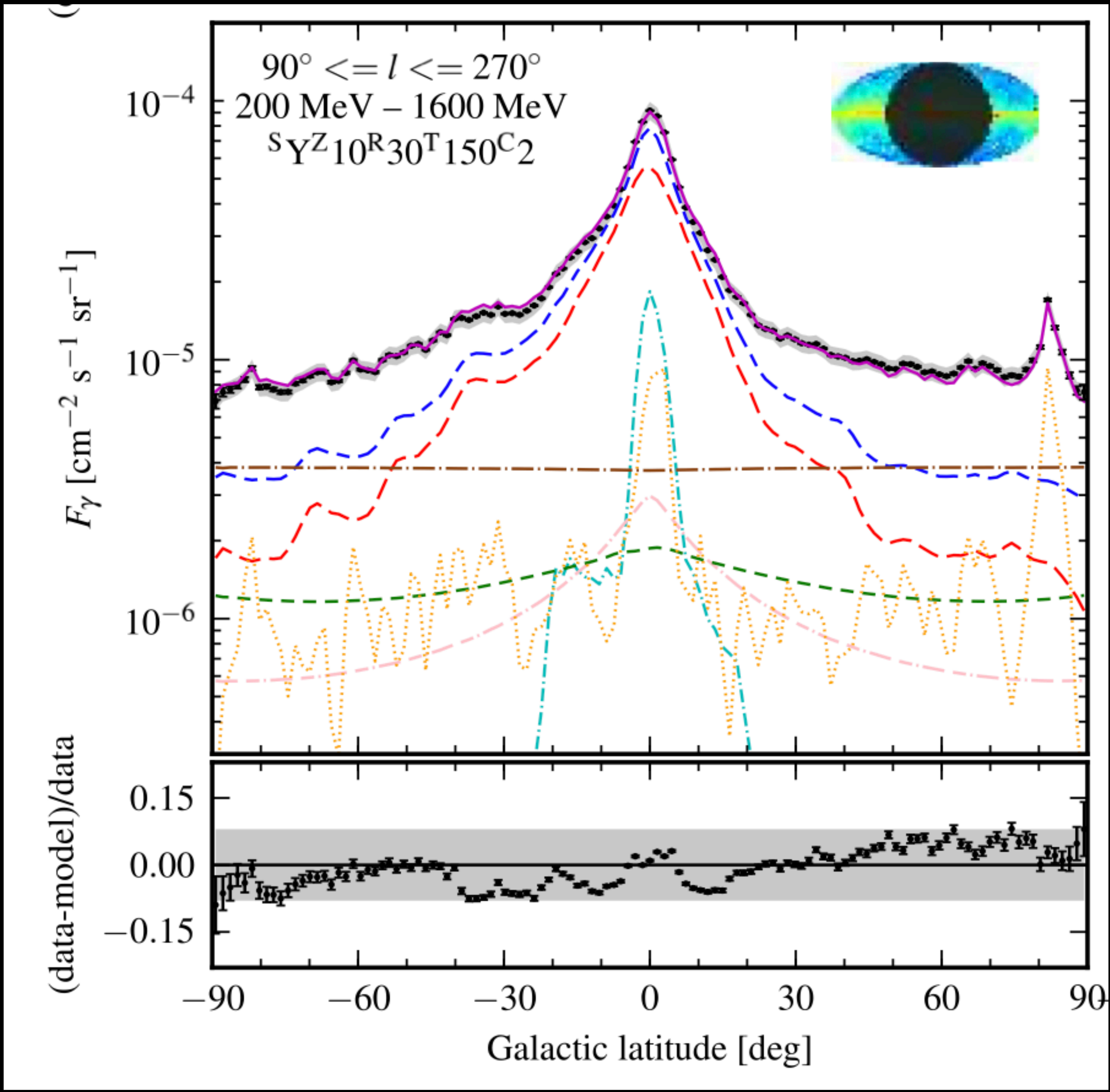
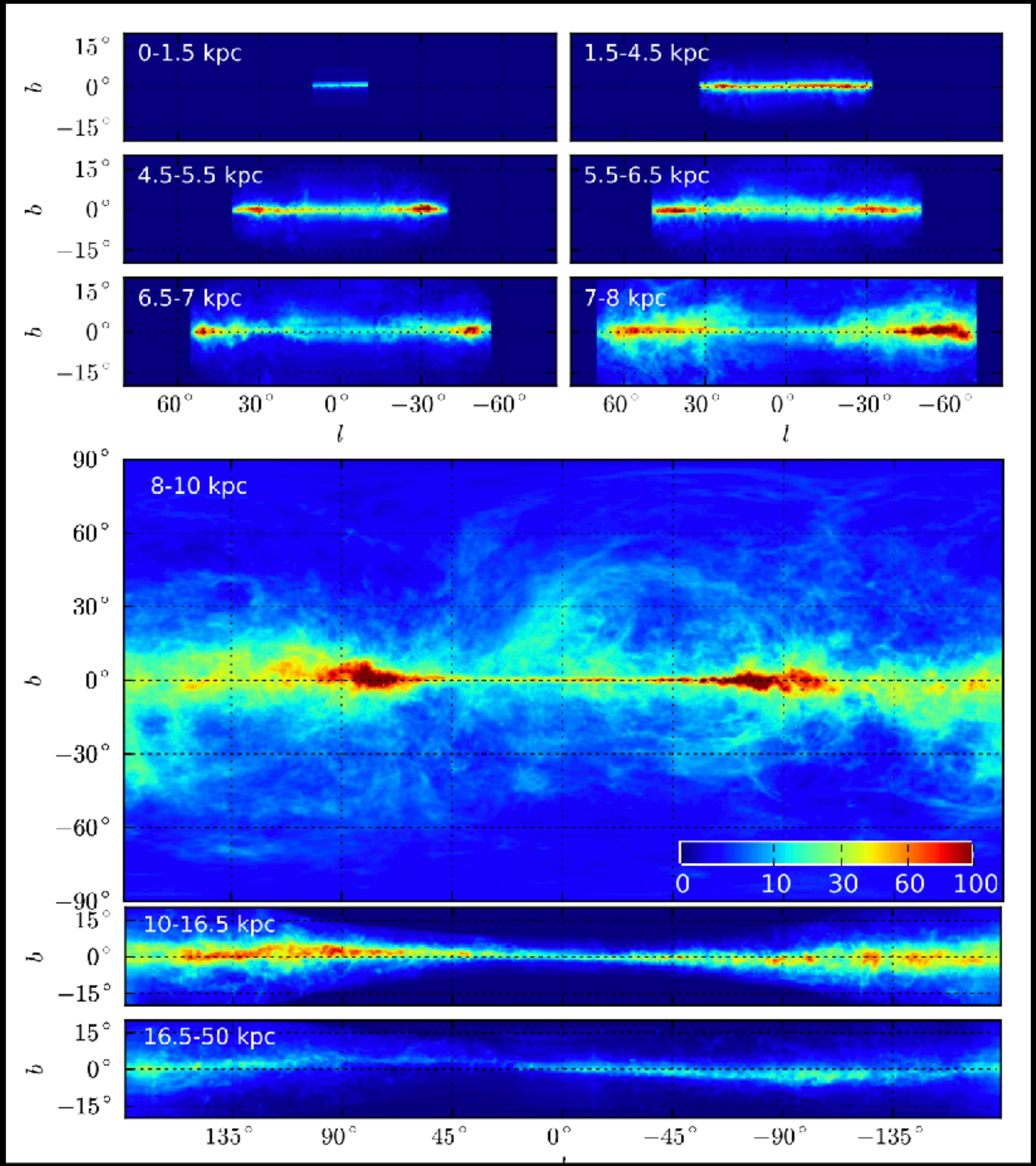


Results: Fermi Diffuse Emission Model

- Ring based model developed for point source analyses
- Break down gas densities into galactocentric rings
- Additional post-processing fits to large scale residuals (since p7v6)
- Additional included templates for the Fermi bubbles, Loop I.



Development of the Model of Galactic Interstellar Emission for Standard Point-Source Analysis of *Fermi* Large Area Telescope Data

F. Acero[1], M. Ackermann[2], M. Ajello[3], A. Albert[4], L. Baldini[5,4], J. Ballet[1], G. Barbiellini[6,7], D. Bastieri[8,9], R. Bellazzini[10], E. Bissaldi[11], E. D. Bloom[4], R. Bonino[12,13], E. Bottacini[4], T. J. Brandt[14], J. Bregeon[15], P. Bruel[16], R. Buehler[2], S. Buson[14,17,18], G. A. Caliandro[4,19], R. A. Cameron[4], M. Caragiulo[11], P. A. Caraveo[20], J. M. Casandjian[1,21], E. Cavazzuti[22], C. Cecchi[23,24], E. Charles[4], A. Chekhtman[25], J. Chiang[4], G. Chiaro[9], S. Ciprini[22,23,26], R. Claus[4], J. Cohen-Tanugi[15], J. Conrad[27,28,29], A. Cuoco[12,13], S. Cutini[22,26,23], F. D'Ammando[30,31],

Implications

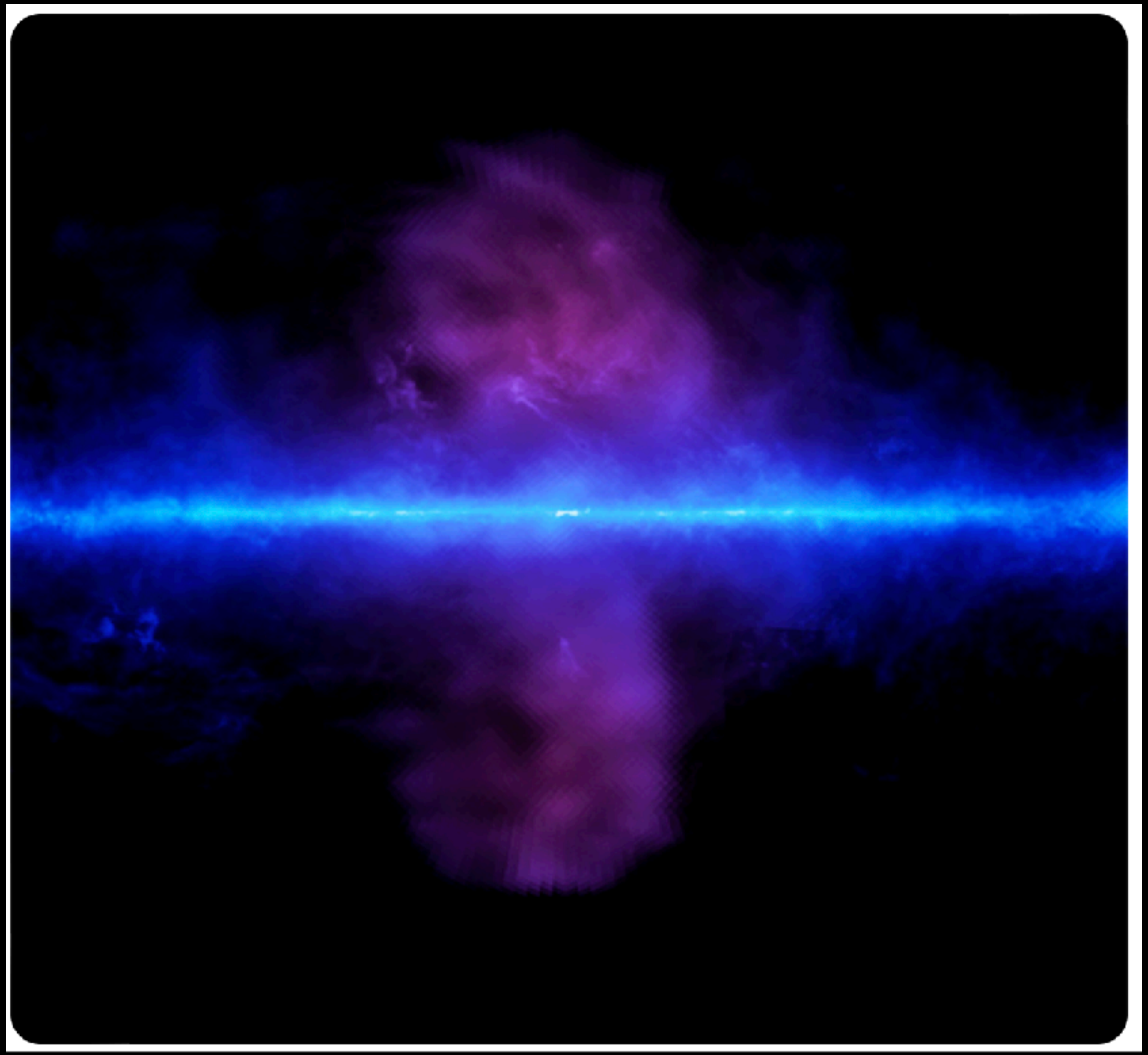
- Need a diffuse model to do any Fermi science on point sources.

- Diffuse Emission Interesting on its Own!
  - Cosmic-ray driven feedback
  - Regulation of star formation
  - Information about pulsar, supernova sources
  - Understanding of interstellar turbulence, magnetic fields throughout the universe.
  - Particle physics properties - studies of the highest energy particles, and new constraints on particle cross-sections.

Fermi Bubbles

- Gigantic lobes of gamma-ray emission from cosmic-rays launched out of the Milky Way Core.

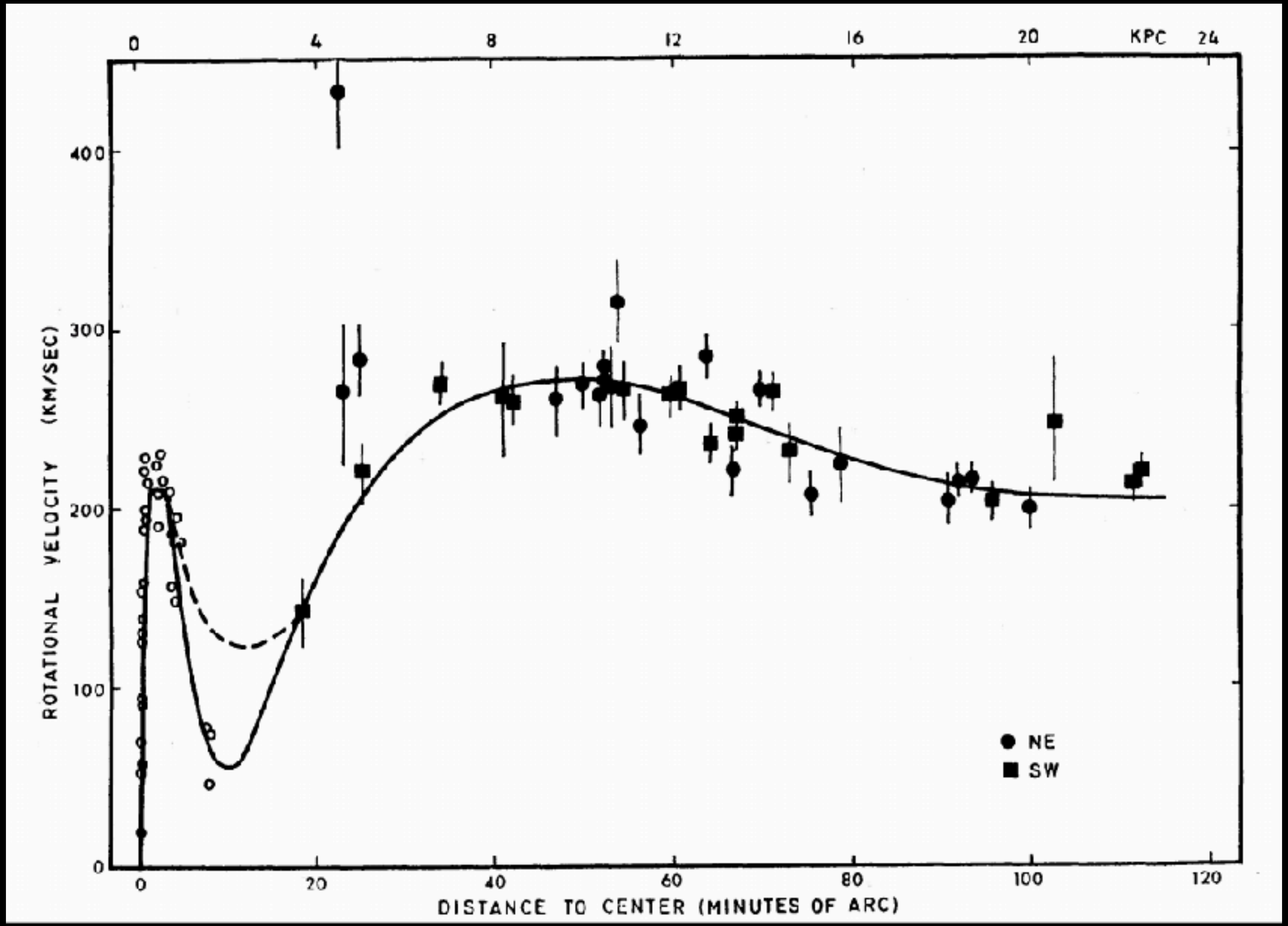
- 10 kpc in height above the galactic plane
- Unknown origins?
  - Prior AGN activity in the Milky Way?!
  - Winds launched from supernova explosions in Milky Way Galactic Center
- Has been subsequently detected in WMAP and ROSAT data.

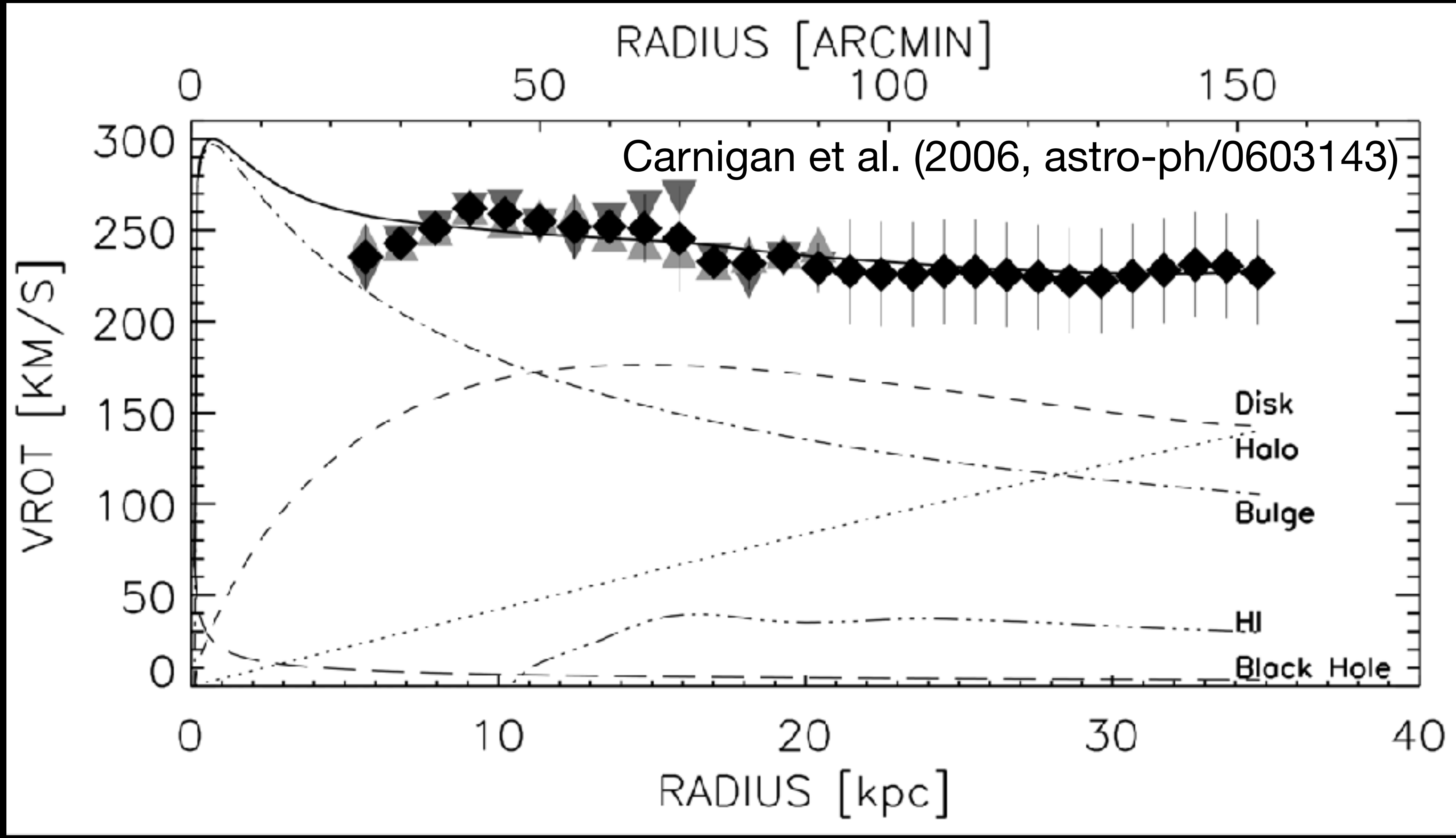


Indirect Detection of Dark Matter

Tim Linden — Fermi Summer School, 2023

Historical Observations of Dark Matter



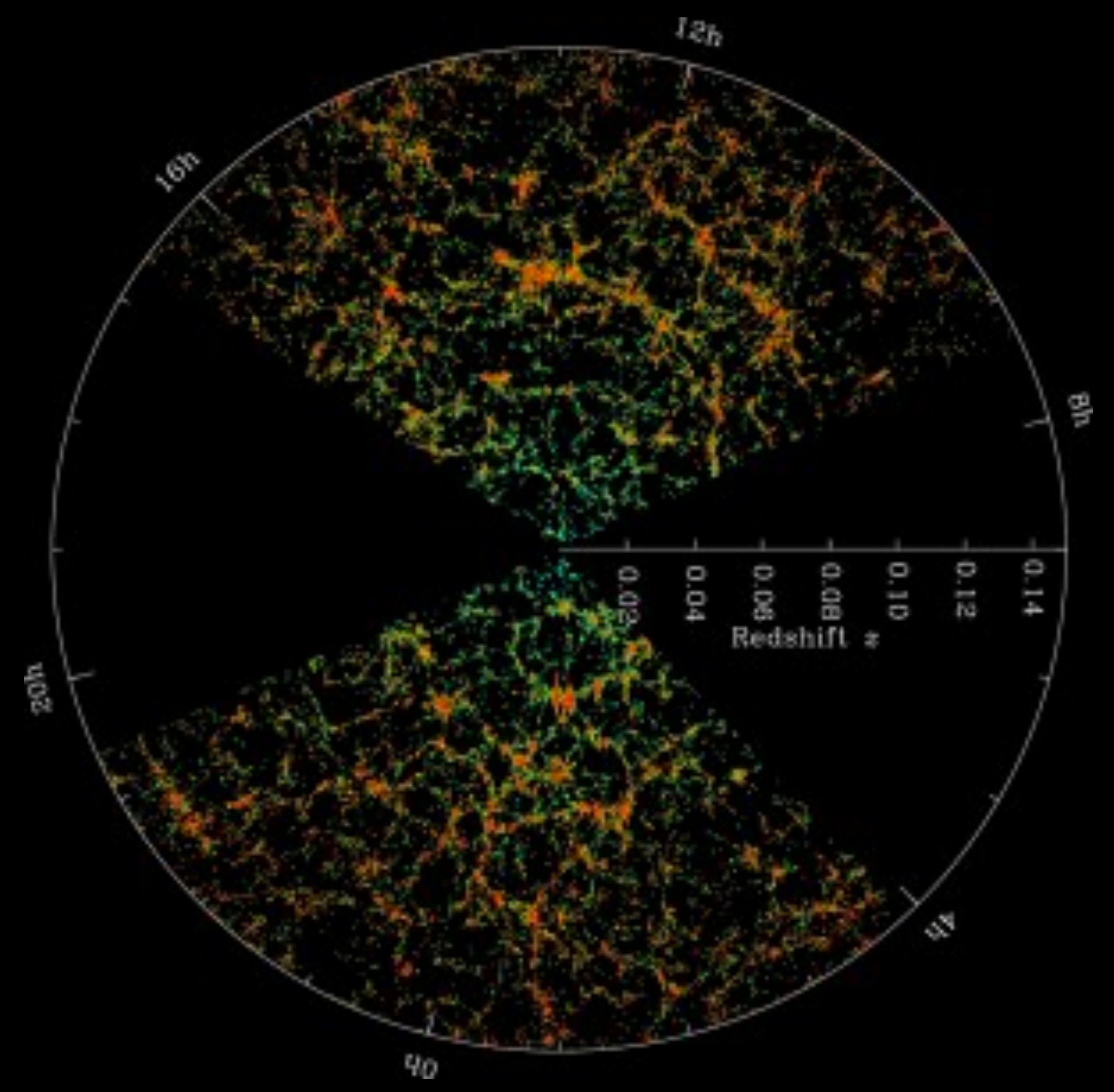


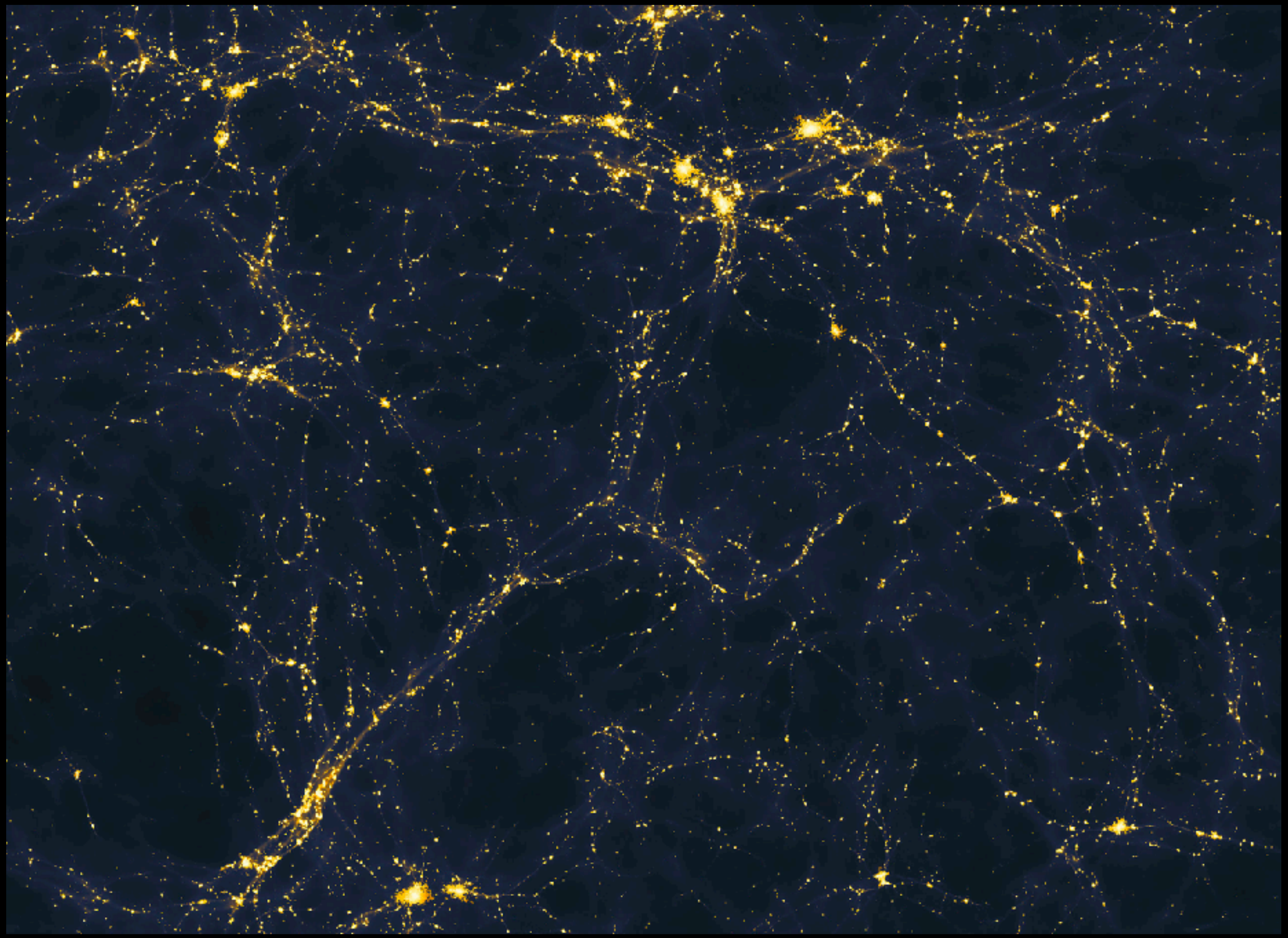
$$M_*(r < 35\text{kpc}) \approx 10^{11} M_\odot$$
$$M_{\text{DM}}(r < 35\text{kpc}) \approx 2 \times 10^{11} M_\odot$$
$$M_{\text{DM}}(r < 300\text{kpc}) \approx 2 \times 10^{12} M_\odot$$

See reviews:
Bertone & Hooper (1605.04909)
Faber & Gallahger (1979)

Historical Observations of Dark Matter

Historical Observations of Dark Matter





Dark Matter Velocity

$$M_{\mathrm{tot}}(r < 35\mathrm{kpc}) \approx 3 \times 10^{11} M_\odot$$

$$v_{\mathrm{esc}} = \frac{2GM}{r}$$

$$= 260 \frac{\mathrm{km}}{\mathrm{s}} = 10^{-3}\ \mathrm{c}$$

Cold Dark Matter

See reviews:
Bertone & Hooper (1605.04909)
Faber & Gallahger (1979)

Limits on Dark Matter Particle Properties

Pauli-Exclusionary Principle

$$f(\vec{x}, \vec{p}) = \mu$$

$$n_x \leq \int_0^{p_{\max}} \frac{d^3p}{(2\pi)^3} f(\vec{x}, \vec{p}) = \mu p_{\max}^3$$

$$m_x^3 v_{\rm esc}^3 \geq n_\chi = \frac{2 \times 10^{11} M_\odot}{4\pi (35 {\rm kpc})^3 m_\chi}$$

$$m_\chi > 100 \text{ eV}$$

If dark matter is a Fermion

Limits on Dark Matter Particle Properties

Limits on Dark Matter Particle Properties

$$M_{\rm DM} \leq M_{\rm dSph} = 2 \times 10^5 M_\odot = 10^{71}\ \rm GeV$$

$$R_{\rm DM} \leq R_{\rm dSph}$$

$$\lambda = \frac{h}{p}$$

$$30\ \rm pc \approx 10^{26} \mu m$$

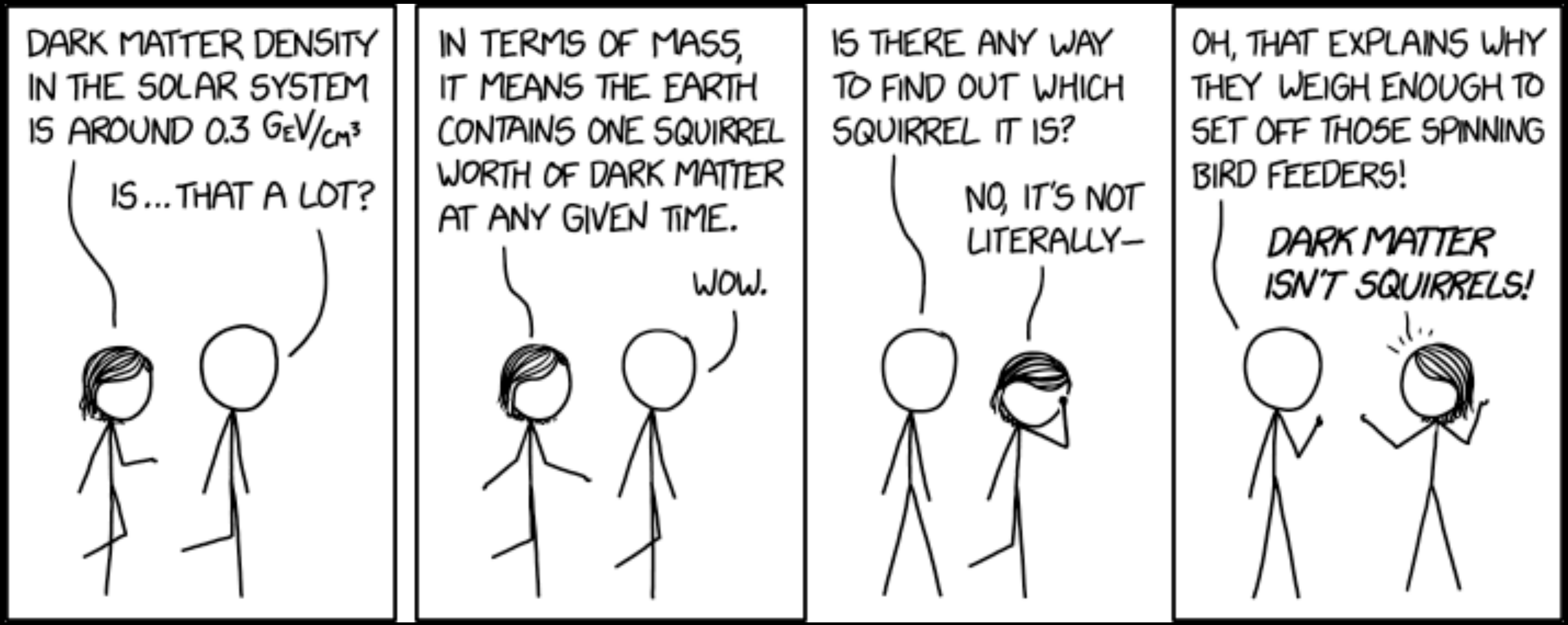
$$R_{\rm DM} = \frac{1.2\rm eV\ \mu m}{p}$$

$$p = m_\chi (10\ \rm km\ s^{-1})$$

$$m_{\rm min} \approx 3 \times 10^{-22}\ \rm eV$$

Limits on Dark Matter Particle Properties

Local Observations of Dark Matter

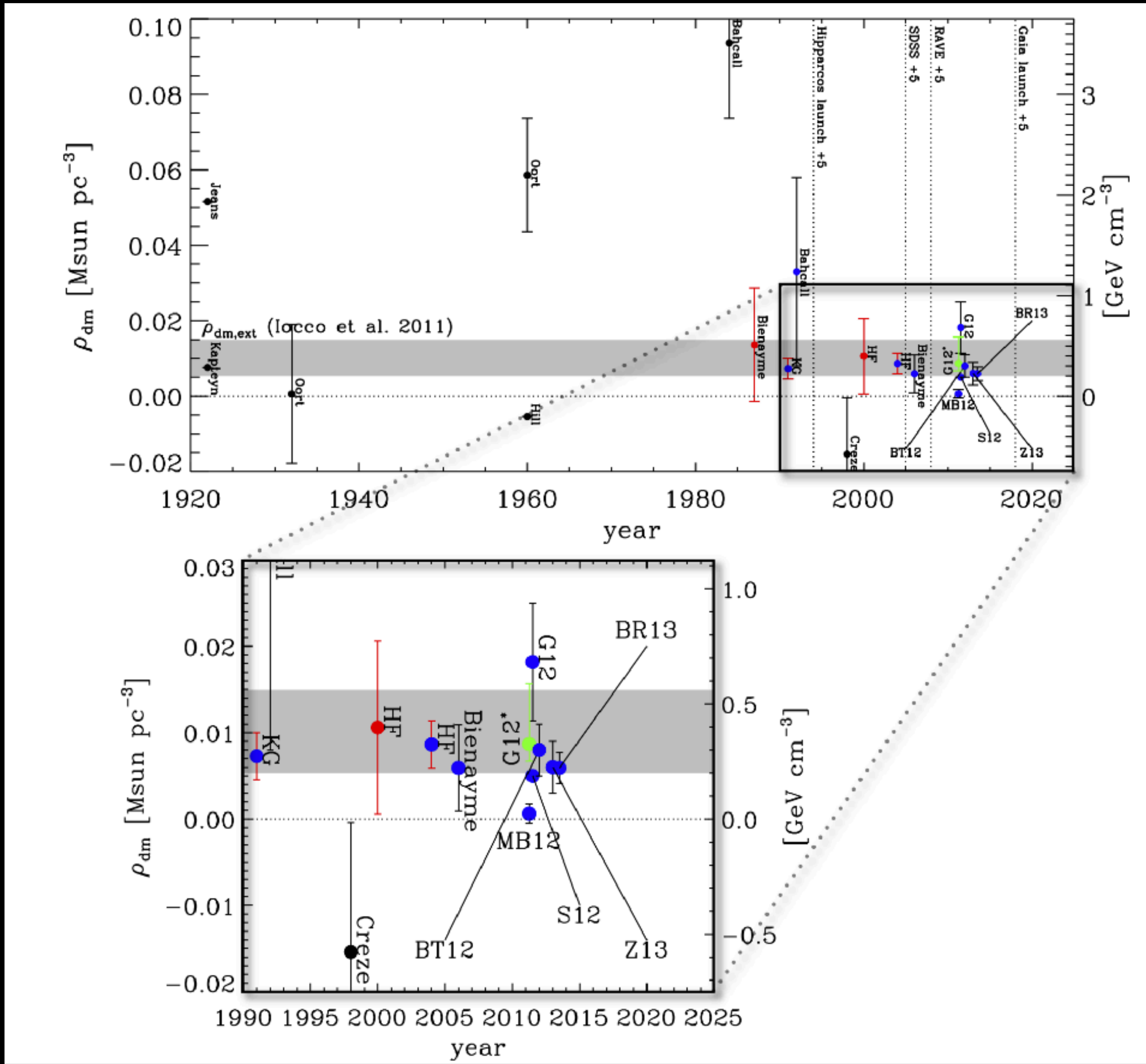


Local Observations of Dark Matter

- Many observations of local density

- Stellar rotation curves, height distributions, GAIA data

- Still 50% uncertainties.



See:
Read (2014; 1404.1938)

Density Profiles

- Navarro-Frenk White (NFW) Profile

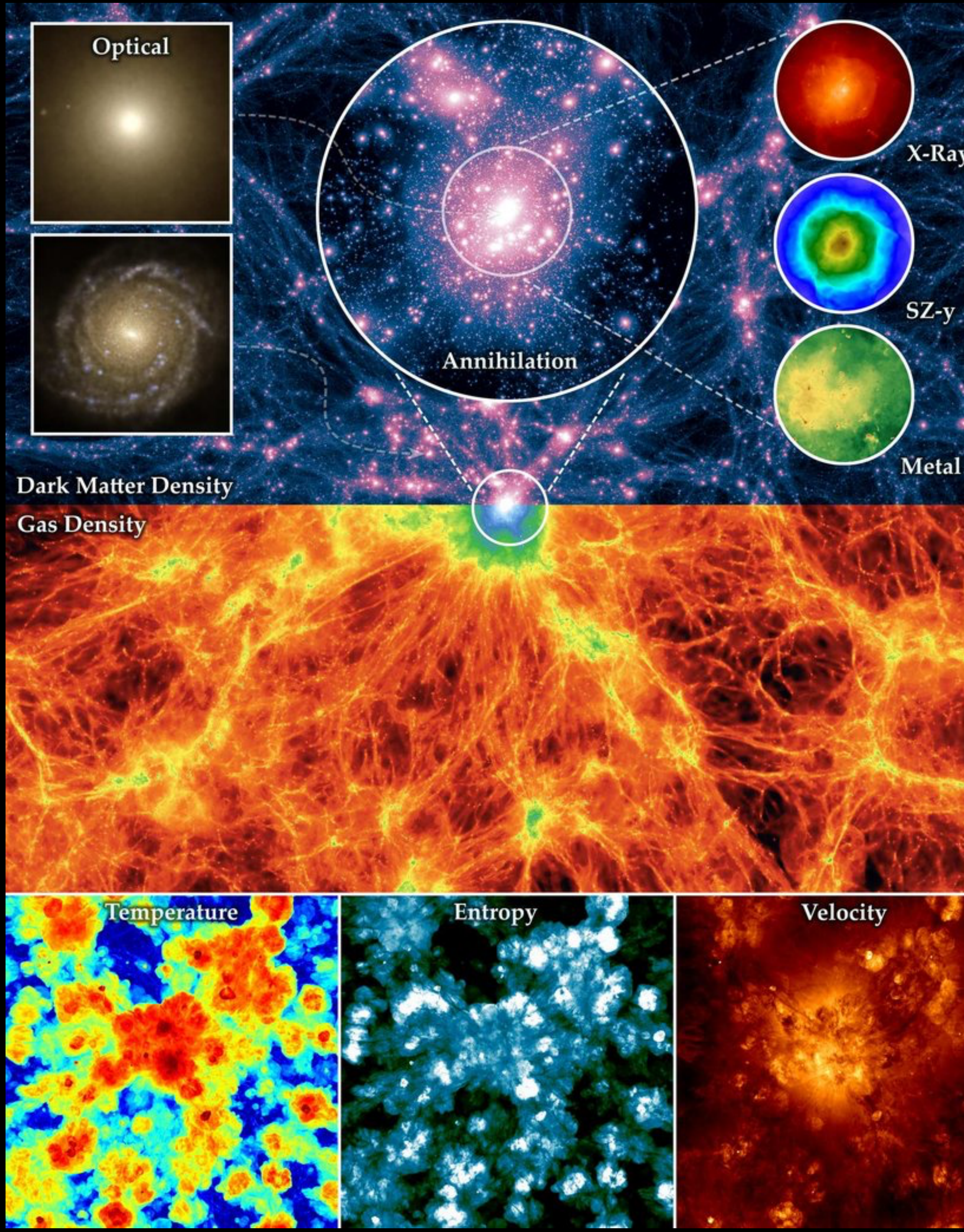
$$\rho_\chi = \rho_0 \left(\frac{r}{r_s}\right)^{-1} \left(1 + \frac{r}{r_s}\right)^{-2}$$

-Generalized NFW Profile

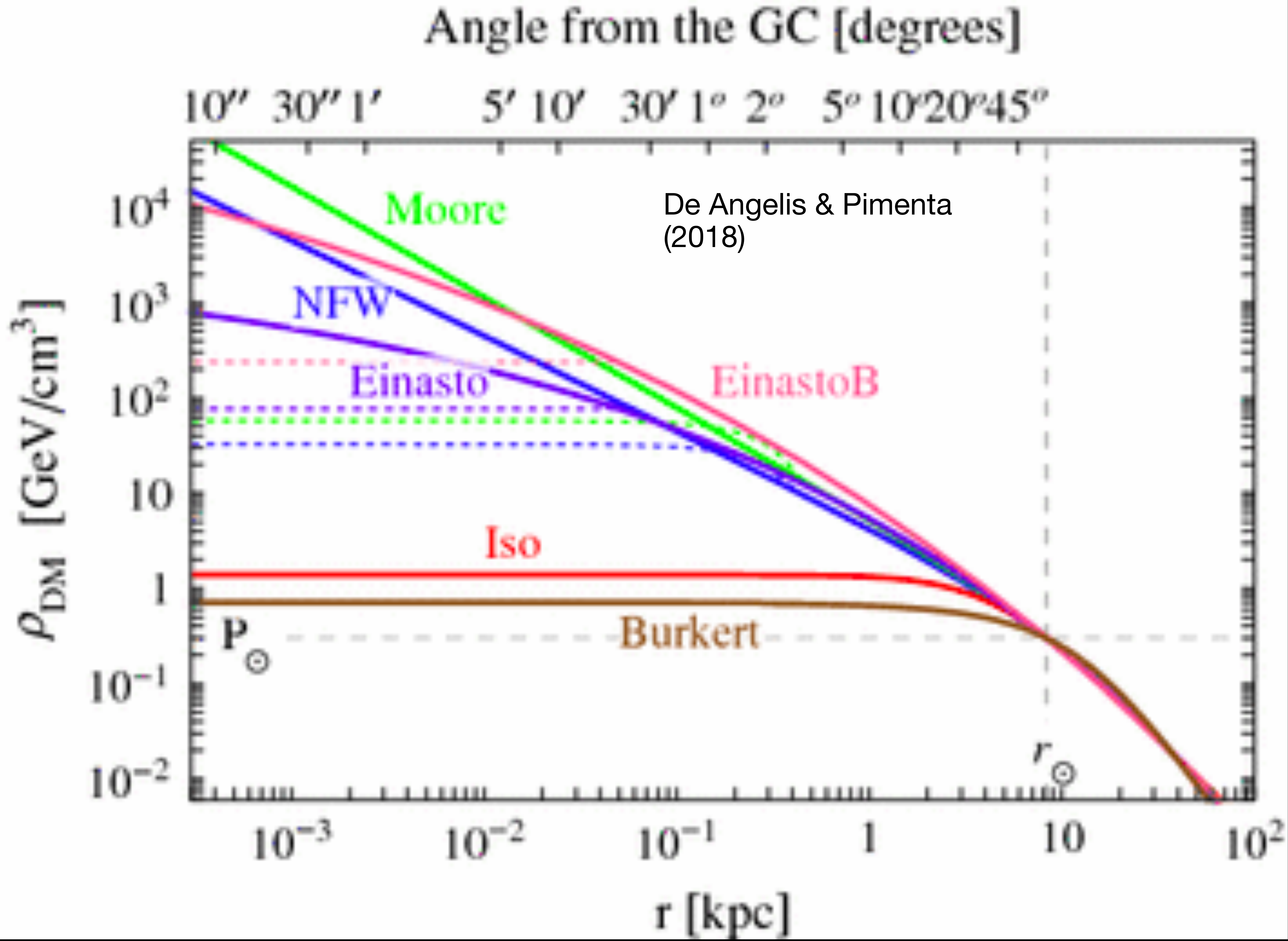
$$\rho_\chi = \rho_0 \left(\frac{r}{r_s}\right)^{-\alpha} \left(1 + \frac{r}{r_s}\right)^{-3+\alpha}$$

-Einasto Profile

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



Density Profiles



De Angelis & Pimenta (2018)

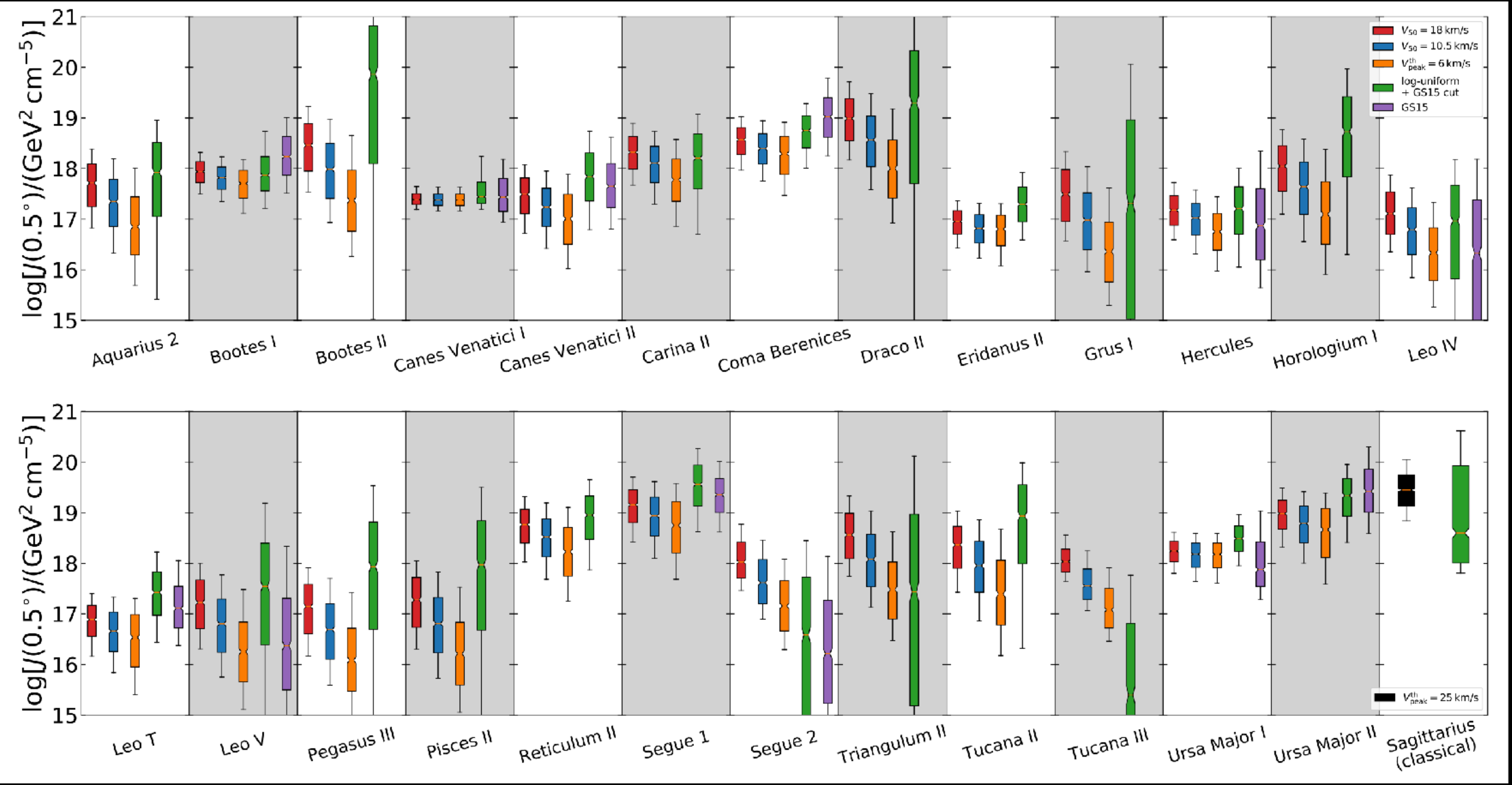
J-Factors

-Remember, we cannot constrain distances astrophysically.

$$\underbrace{\int_{\Delta\Omega}\int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}^2(\boldsymbol{r})\mathrm{d}l\mathrm{d}\Omega'}_{\mathrm{J-factor}}$$

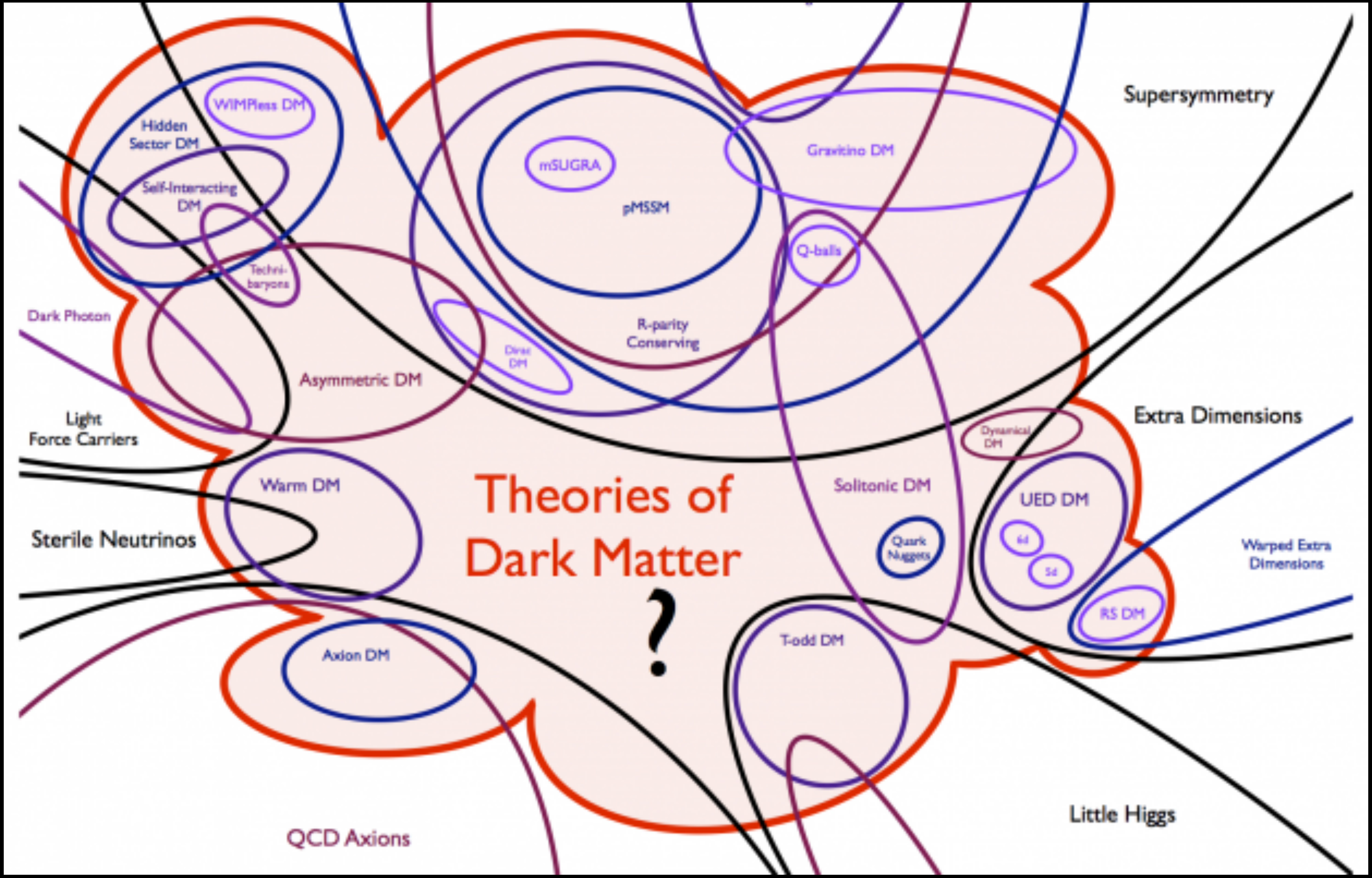
-For decaying dark matter, this will depend on ρ and not ρ^2

J-Factors



log[J(0.5°)/(GeV² cm⁻⁵)]
$V_{50} = 18$ km/s
$V_{50} = 10.5$ km/s
$V^{th}_{peak} = 6$ km/s
log-uniform + GS15 cut
GS15
$V^{th}_{peak} = 25$ km/s
Aquarius 2
Bootes I
Bootes II
Canes Venatici I
Canes Venatici II
Carina II
Coma Berenices
Draco II
Eridanus II
Grus I
Hercules
Horologium I
Leo IV
Leo T
Leo V
Pegasus III
Pisces II
Reticulum II
Segue 1
Segue 2
Triangulum II
Tucana II
Tucana III
Ursa Major I
Ursa Major II
Sagittarius (classical)

Dark Matter Models



WIMP Dark Matter

- Three Key Particle Properties of Dark Matter
  - Does not Interact with Light (Dark)
  - Does not move relativistically throughout the Universe (Cold)

  - Stable

- What about the lightest supersymmetric particle?
  - Can't decay if it has a supersymmetric quantum number that prevents decay into standard model particles (R-parity)
  - Likely Heavy (cold)
  - Would not interact with light if it is neutral (Weak/Gravitational interactions only)

Thermal Freeze-Out/WIMP Miracle

- Three periods:
  - Thermal equilibrium with baryons
  - Annihilating away
  - Hubble expansion wins

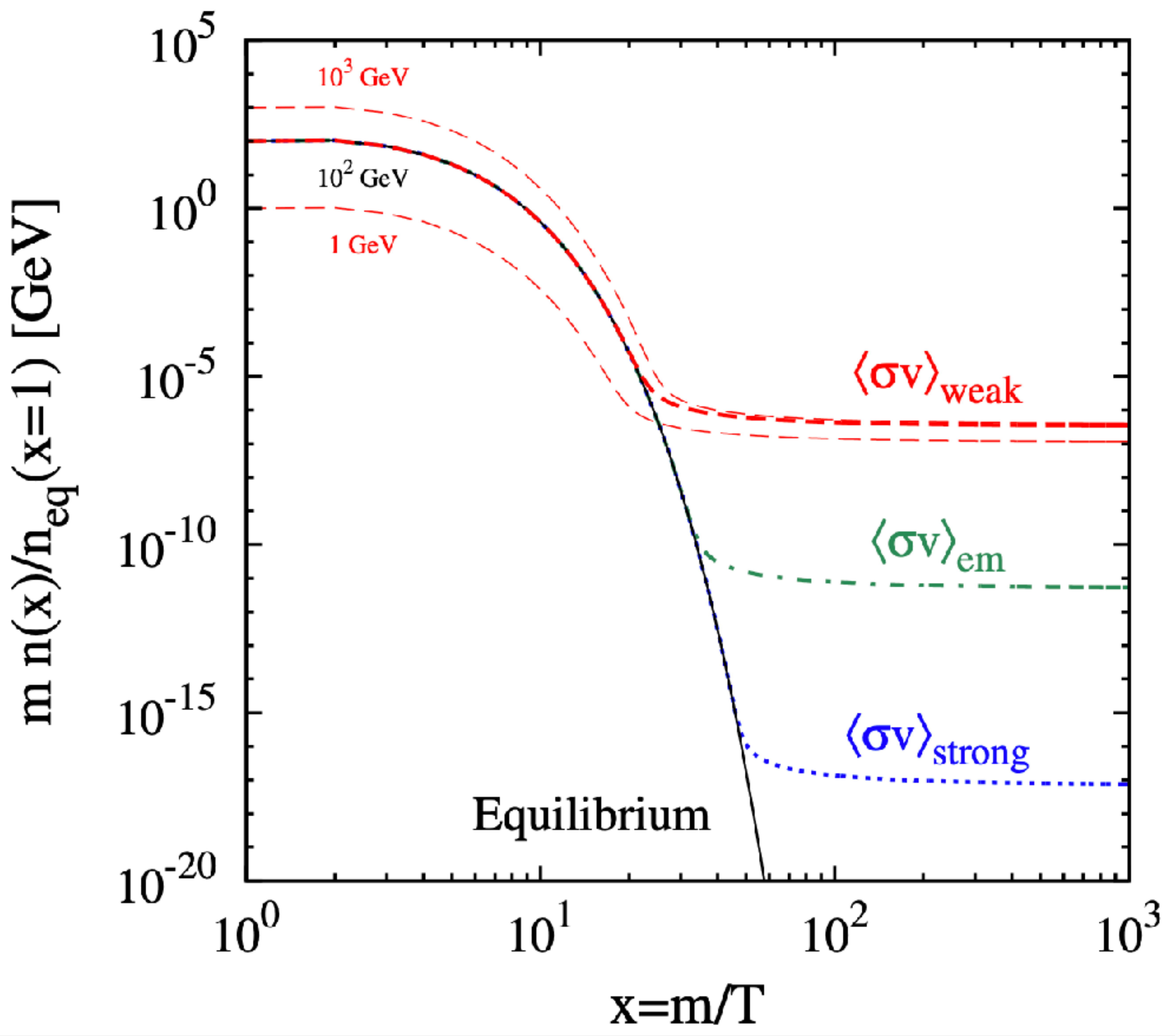
$$\frac{dn}{dt} + 3Hn = -\frac{n^2}{2}\langle\sigma v_{\rm rel}\rangle \times 2$$

$$\frac{dn}{dt} + 3Hn = (n_{\rm eq}^2 - n^2)\langle\sigma v_{\rm rel}\rangle$$

- For a cold particle during freeze out

$$n \sim (m_\chi T)^{3/2} \exp\left(-\frac{m_\chi}{T}\right)$$

- If interaction has weak force strength - current DM density = Present Density!



Thermal Freeze-Out/WIMP Miracle

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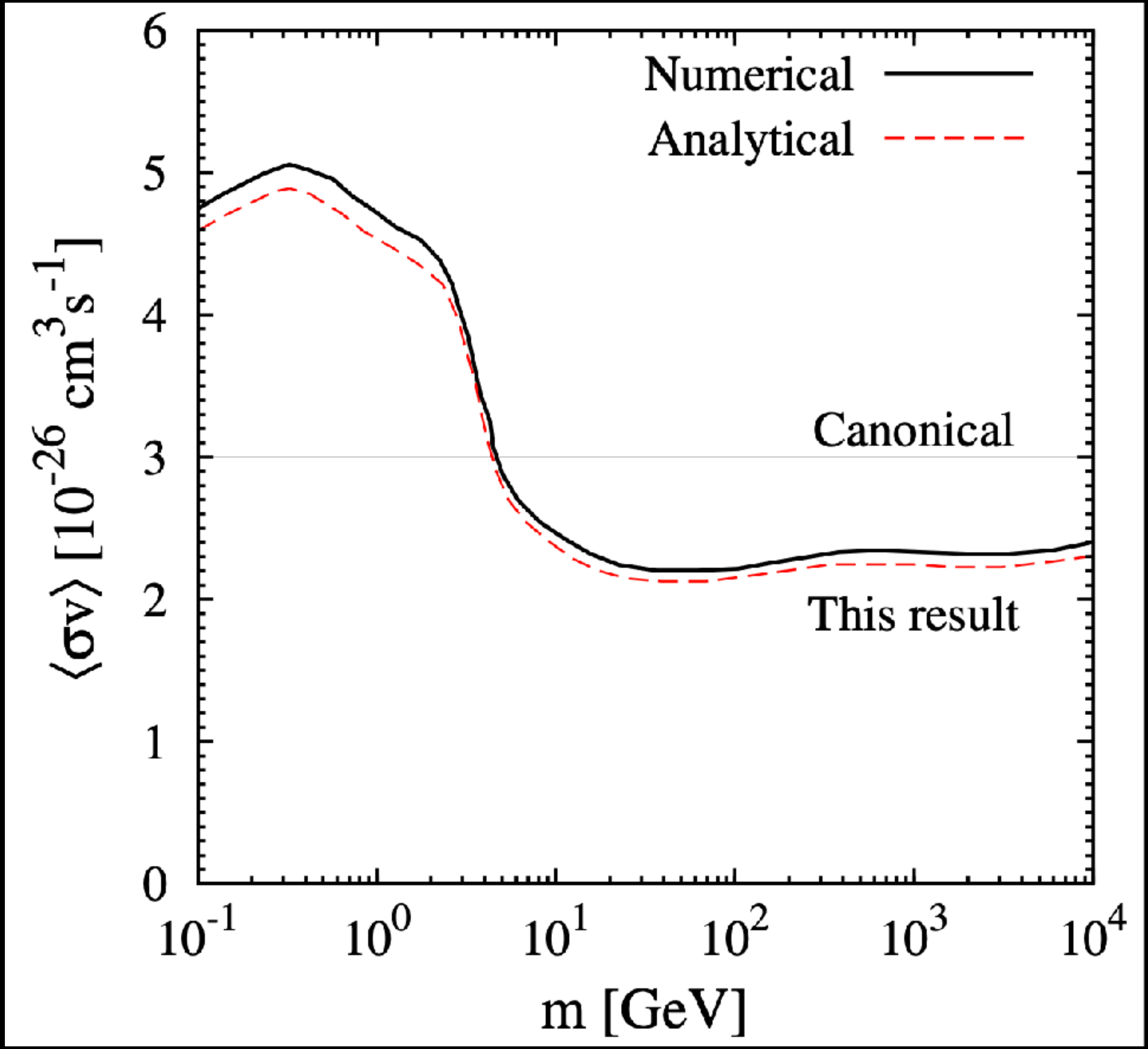
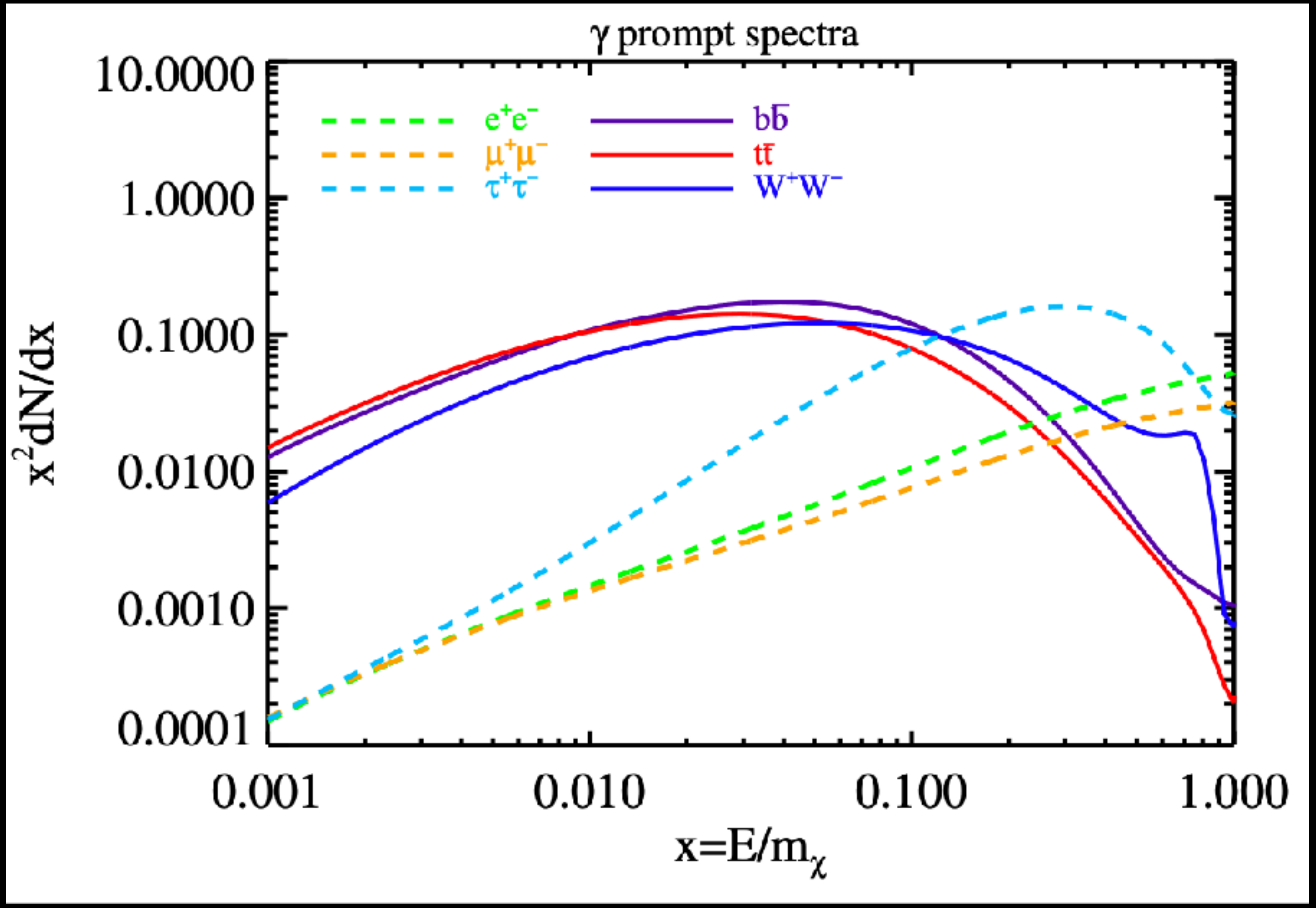


Thermal Freeze-Out/WIMP Miracle

- What does the dark matter annihilate into?

Gaskins (1604.00014)



- Any final states are possible:
  - Higgs-motivated
    - To heaviest quarks, bottom/top pairs
  - Leptophilic
    - Tau/muon/electron pairs
  - Bosons
    - W/Z or combinations

- After fist baryonic particles are created, shower is formed following standard model physics to create gamma-rays, electrons/positrons/protons/neutrons

Calculation of Expected Flux

-Now we have all of the ingredients
- J-factor
- Annihilation Rate
- Annihilation Final State/Spectrum

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\mathrm{DM}}^2}\int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\mathrm{l.o.s.}}\rho_{\mathrm{DM}}^2(\boldsymbol{r})\mathrm{d}l\mathrm{d}\Omega'}_{\mathrm{J-factor}}$$

Practice in Calculating Luminosity of Milky Way

$$< \sigma v > \approx 2 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$$

$$\rho_0 = \frac{2 \times 10^{11} M_\odot}{\frac{4}{3}\pi \left(35\ \mathrm{kpc}\right)^3} = \frac{2 \times 10^{68}\ \mathrm{GeV}}{3 \times 10^{69}\ \mathrm{cm^3}} \sim 0.1\ \mathrm{GeVcm^{-3}}$$

-Pick:

$$m_\chi = 100\ \mathrm{GeV} \qquad \frac{E}{\mathrm{ann}} = 200\ \mathrm{GeV}$$

$$\Phi = \frac{E}{\mathrm{ann}} \frac{\rho^2}{2m_\chi} < \sigma v > V$$

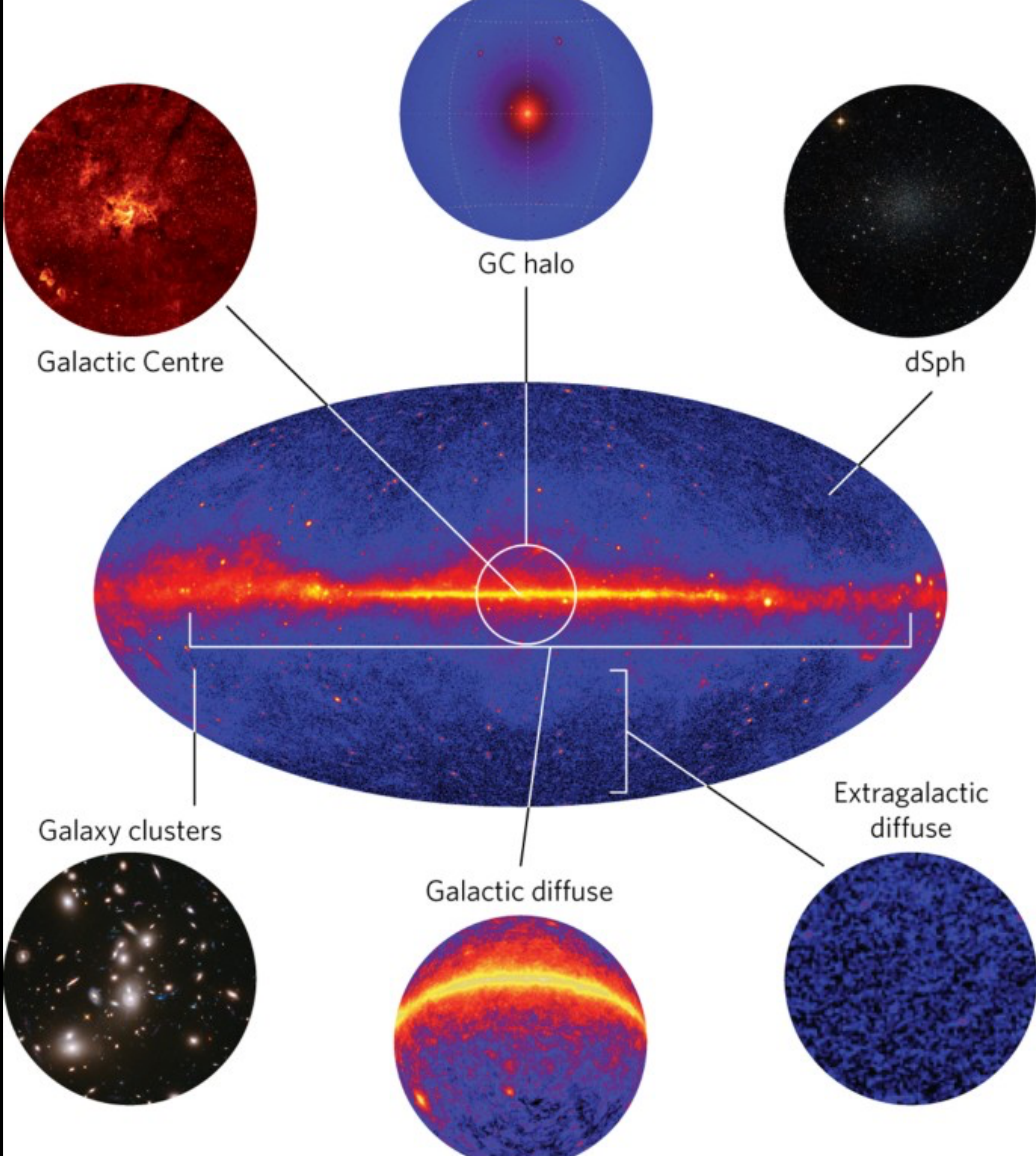
$$= 200\ \mathrm{GeV} \frac{0.1\ \mathrm{GeV\ cm^{-3}}}{200\ \mathrm{GeV}} \left(10^{-26}\ \mathrm{cm^3 s^{-1}}\right) 3 \times 10^{69}\ \mathrm{cm^3} = 3 \times 10^{39}\ \mathrm{GeV\ s^{-1}}$$

10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
$<\sigma v>$ (cm^{3}s^{-1})
Thermal Cross-Section
1 Observed Photon Within 10° of Galactic Center
10
100
1000
10^4
10^5
Dark Matter Mass (GeV)

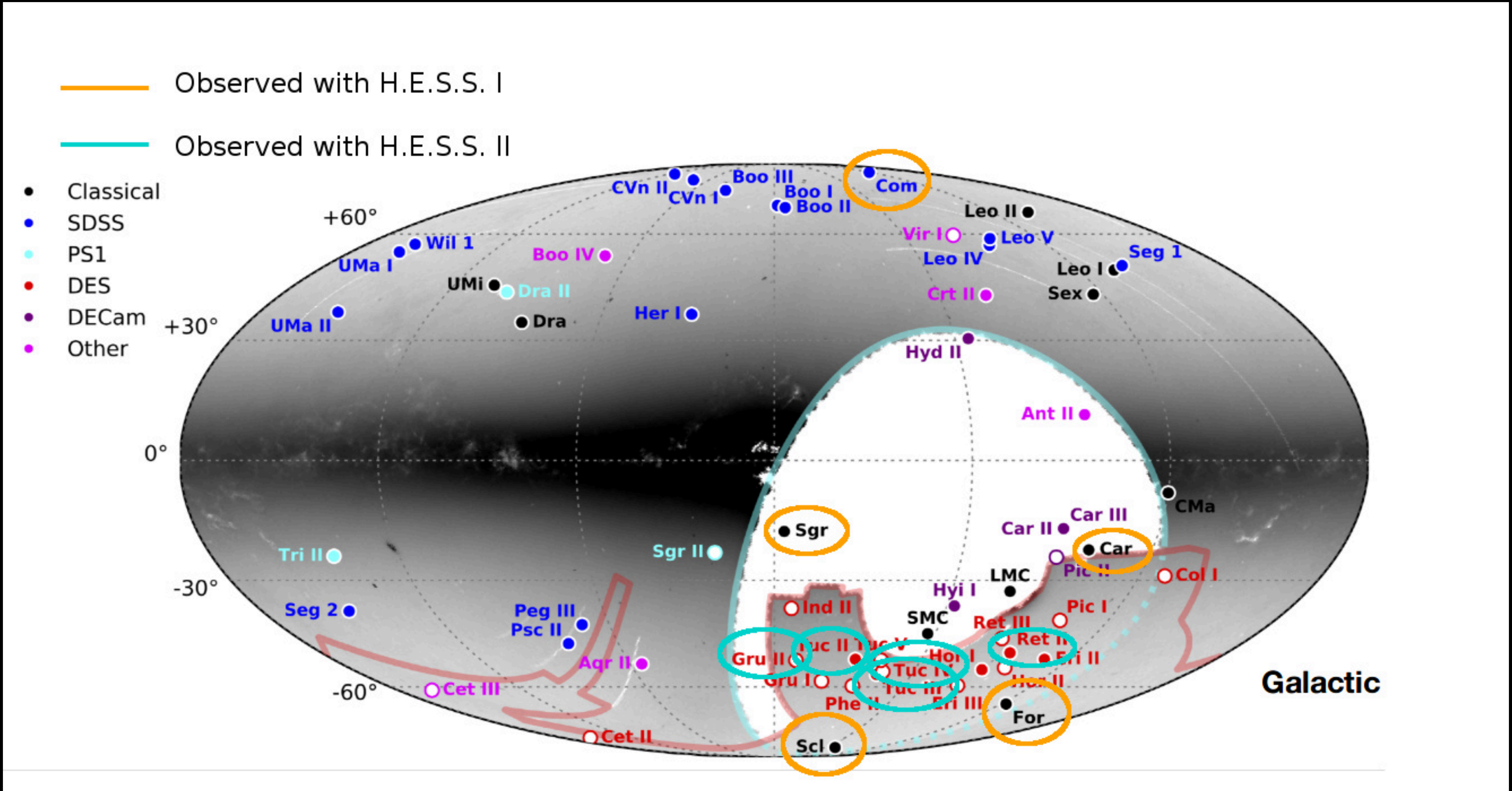
Targets

- 2008: Very uncertain which dark matter targets would be most sensitive

- 2023: Some consensus that most interesting targets are Galactic center and dSphs (though surprises always possible)



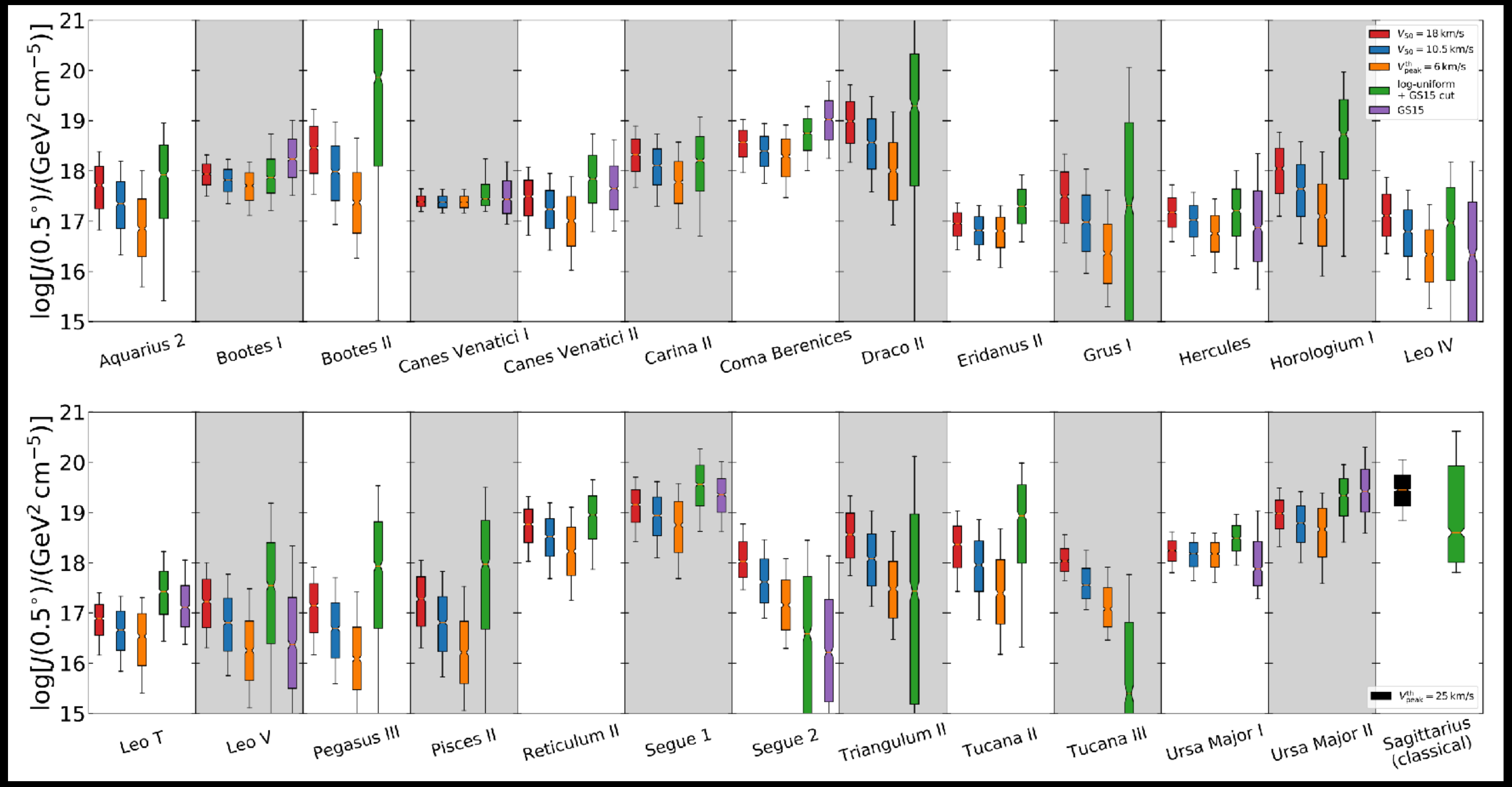
dSphs



Observed with H.E.S.S. I
Observed with H.E.S.S. II
Classical
SDSS
PS1
DES
DECam
Other
+60°
+30°
0°
-30°
-60°
Galactic
CVn II
CVn I
Boo III
Boo I
Boo II
Com
Leo II
Vir I
Leo V
Leo IV
Seg 1
Leo I
Sex
Crt II
Wil 1
UMa I
Boo IV
UMi
Dra II
Dra
Her I
UMa II
Hyd II
Ant II
CMa
Car III
Car II
Car
Sgr
Tri II
Sgr II
LMC
Col I
Hyi I
Pic I
Ind II
SMC
Ret III
Ret II
Seg 2
Peg III
Psc II
Gru II
Hor I
Eri II
Aqr II
Tuc IV
Cet III
Phe II
Eri III
For
Cet II
Scl

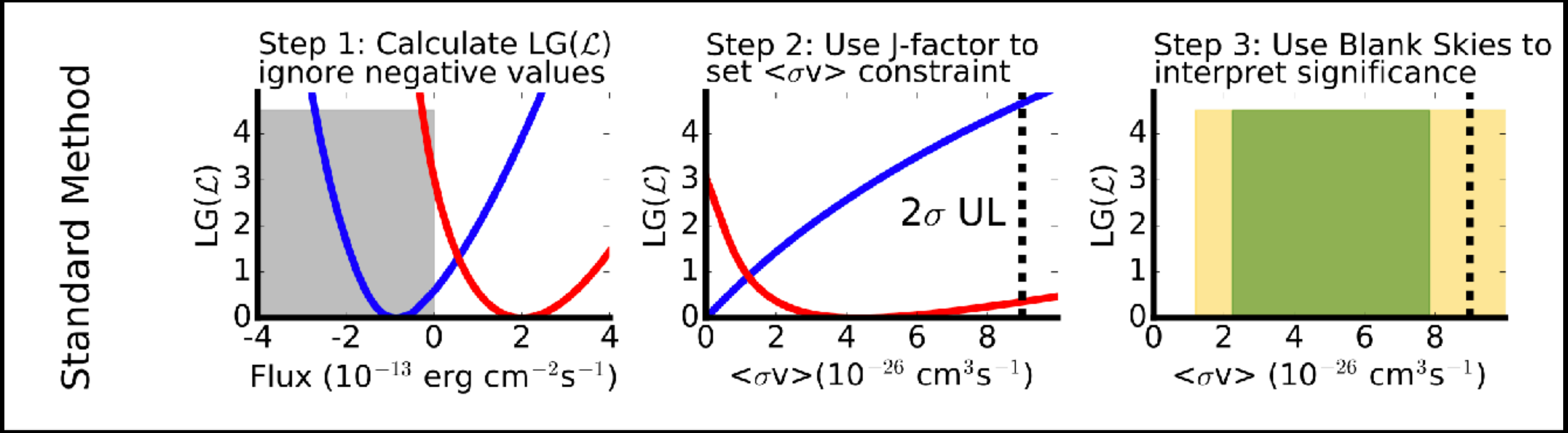
dSphs

- J-factors tell us the relative flux of each dSph
- Can add the likelihood profiles of each source.
- Use Blank Sky locations to test

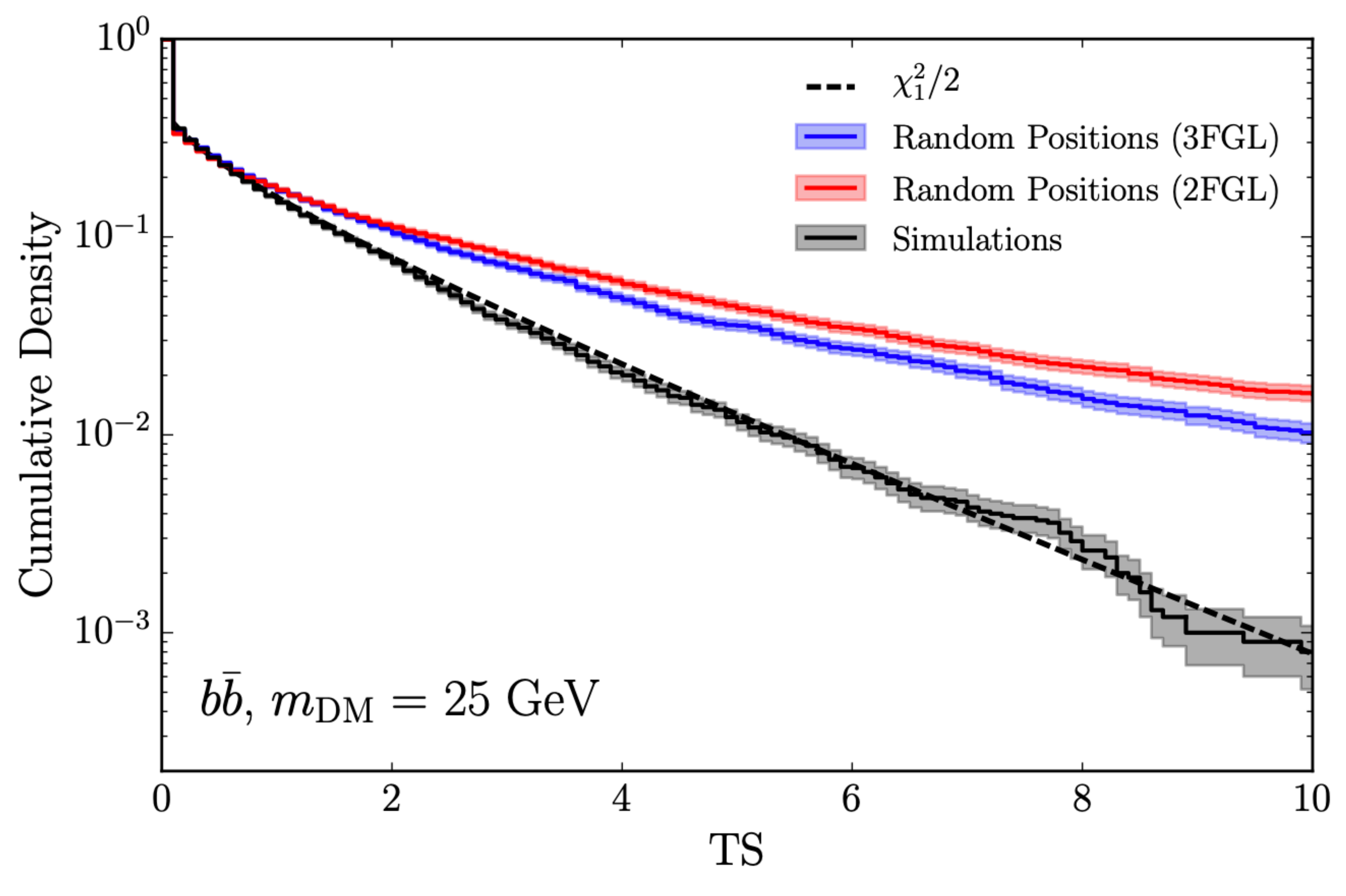


$$\mathcal{L}_J(J_i \mid J_{\mathrm{obs,i}}, \sigma_i) = \frac{1}{\ln(10) J_{\mathrm{obs,i}} \sqrt{2\pi}\sigma_i} \times e^{-(\log_{10}(J_i) - \log_{10}(J_{\mathrm{obs,i}}))^2 / 2\sigma_i^2}$$

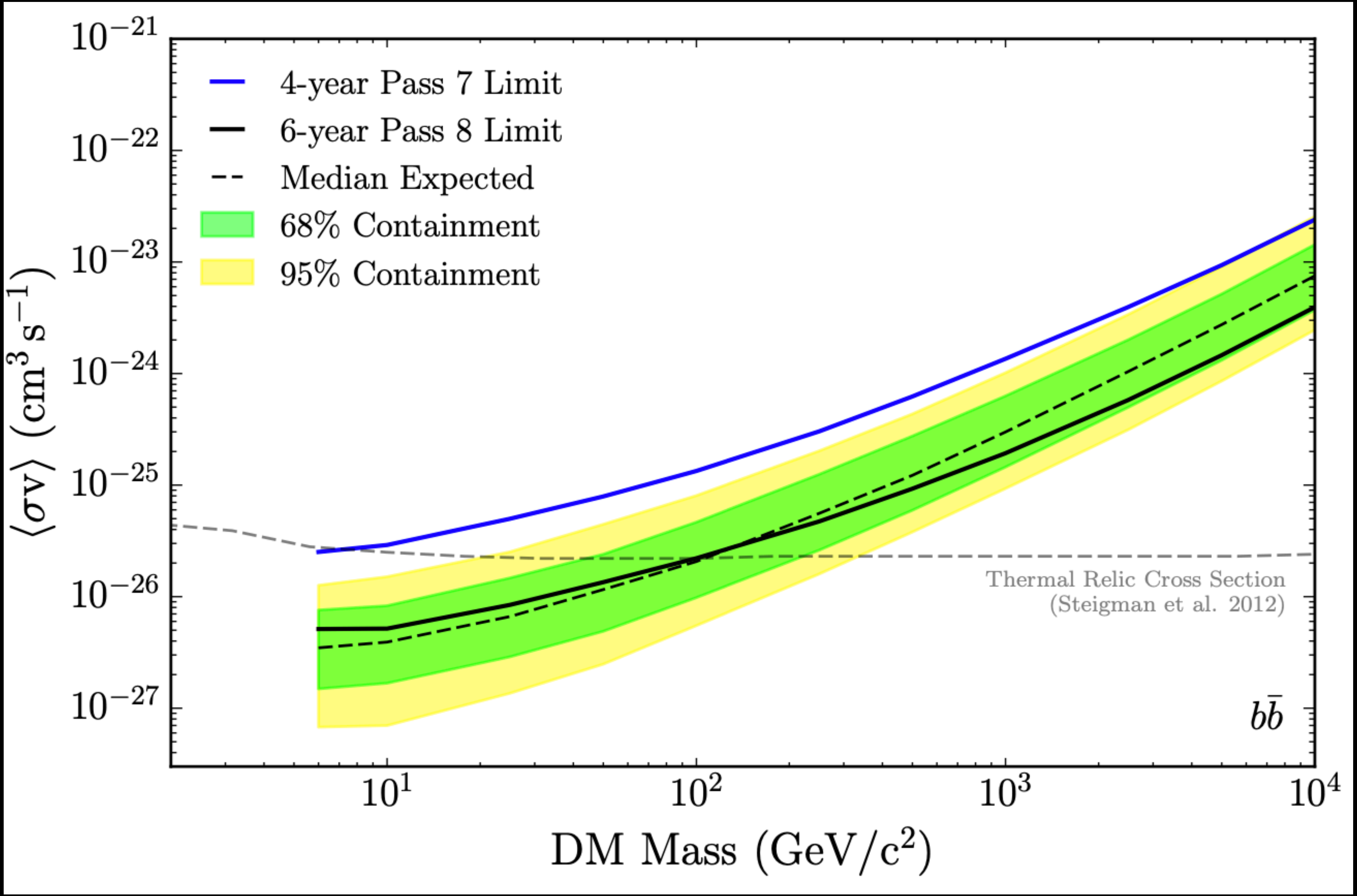
$$\mathcal{L}_i(\boldsymbol{\mu}, \boldsymbol{\theta}_i \mid \mathcal{D}_i) = \prod_j \mathcal{L}_i(\boldsymbol{\mu}, \boldsymbol{\theta}_i \mid \mathcal{D}_{i,j}).$$



dSphs

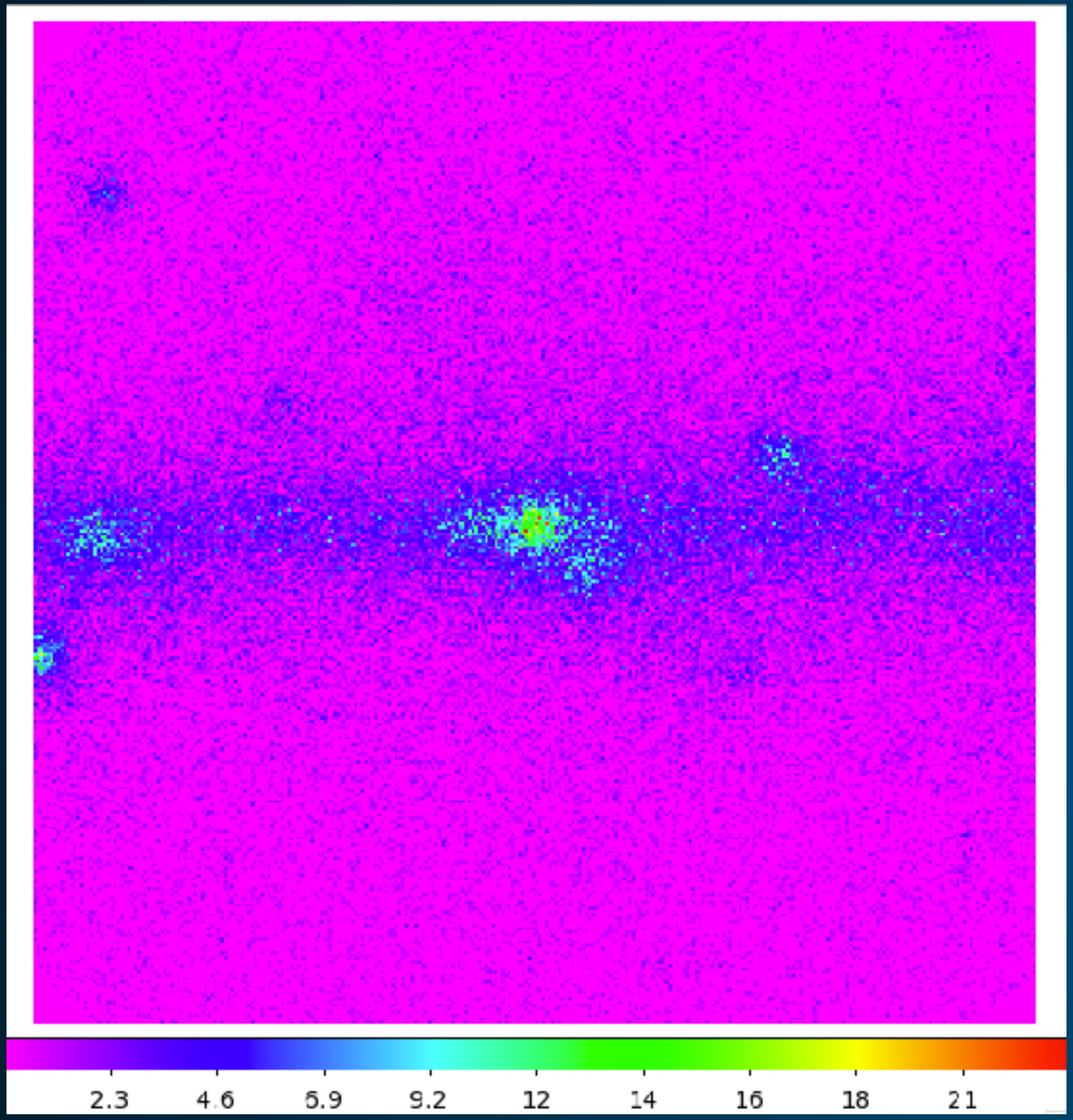

$\chi^2_1/2$
Random Positions (3FGL)
Random Positions (2FGL)
Simulations
$b\bar{b}$, $m_{\rm DM} = 25$ GeV
Cumulative Density
TS
10^0
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
10

dSphs



4-year Pass 7 Limit
6-year Pass 8 Limit
Median Expected
68% Containment
95% Containment
Thermal Relic Cross Section
(Steigman et al. 2012)
$b\bar{b}$
$\langle \sigma v \rangle$ (cm^3 s^{-1})
DM Mass (GeV/c^2)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3
10^4

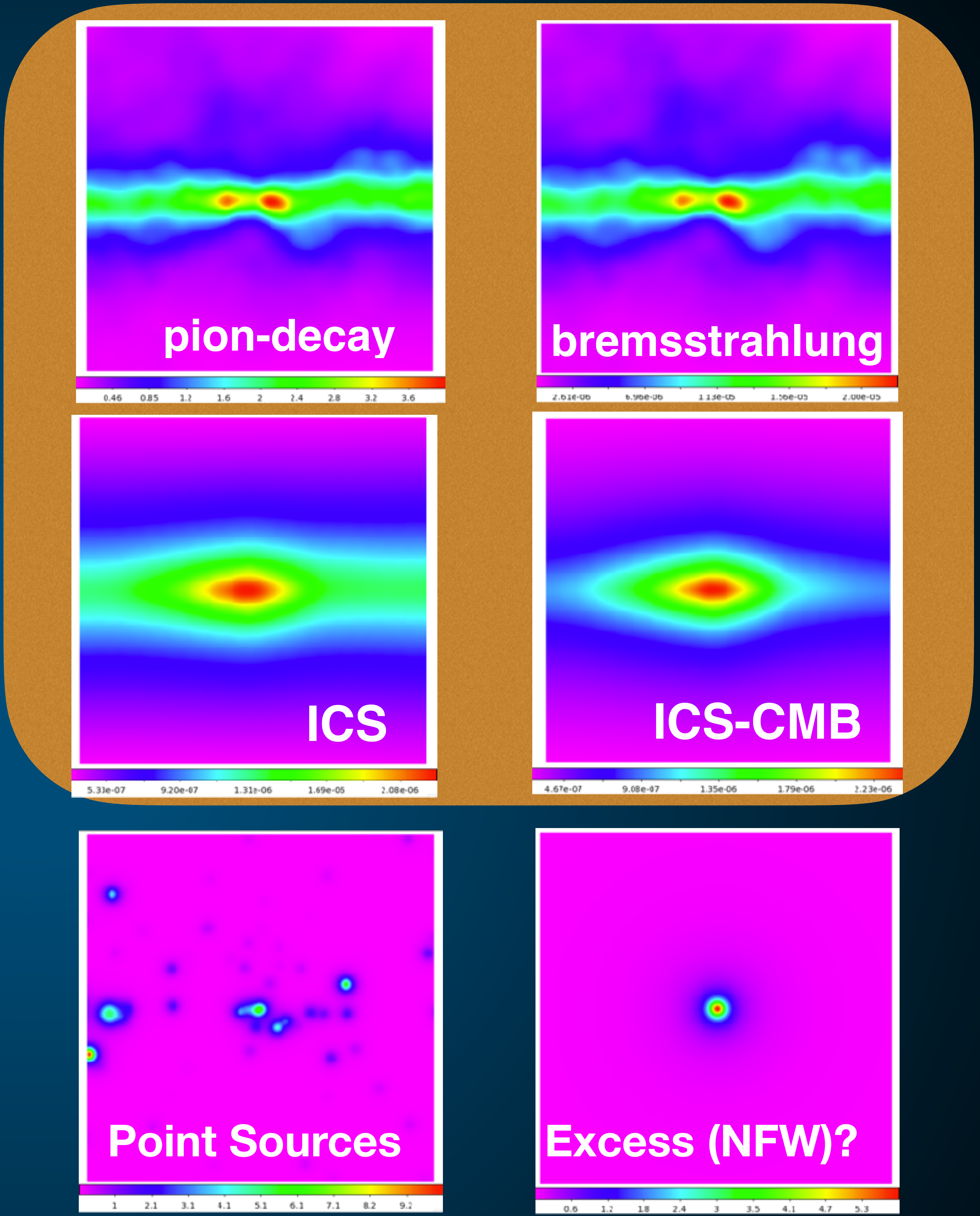
Galatic Center Excess



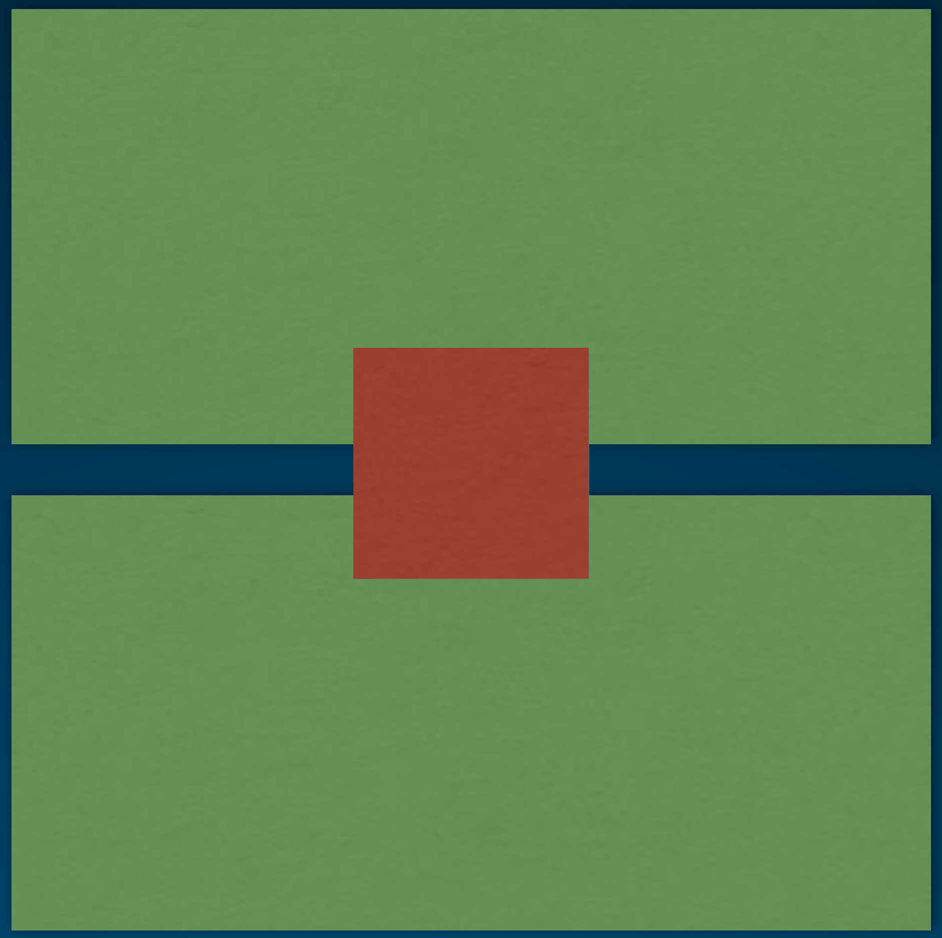
Data

750 — 950 MeV
Best Angular Resolution Cut
10º x 10º ROI

=



Two Regions of Interest

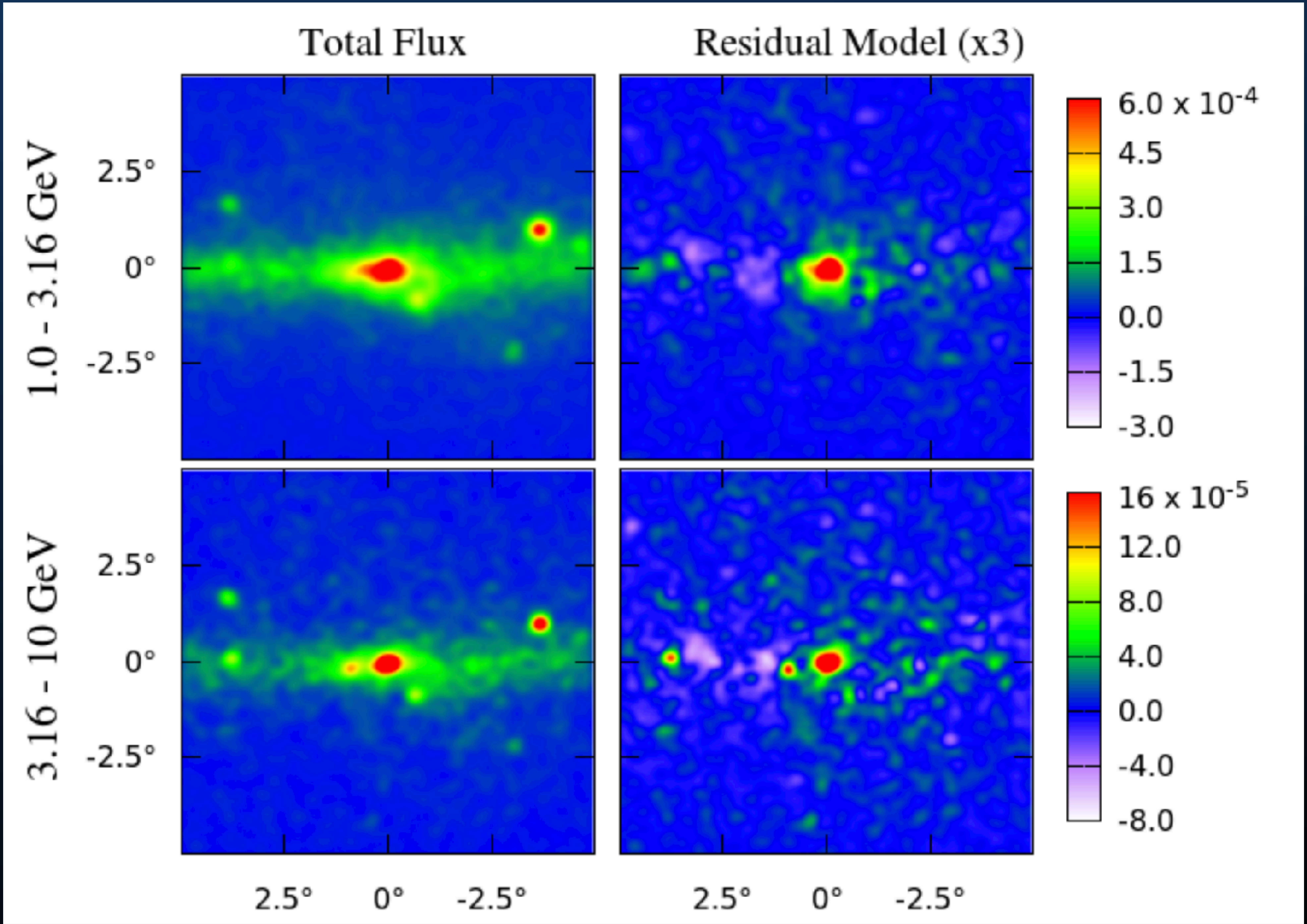


INNER GALAXY

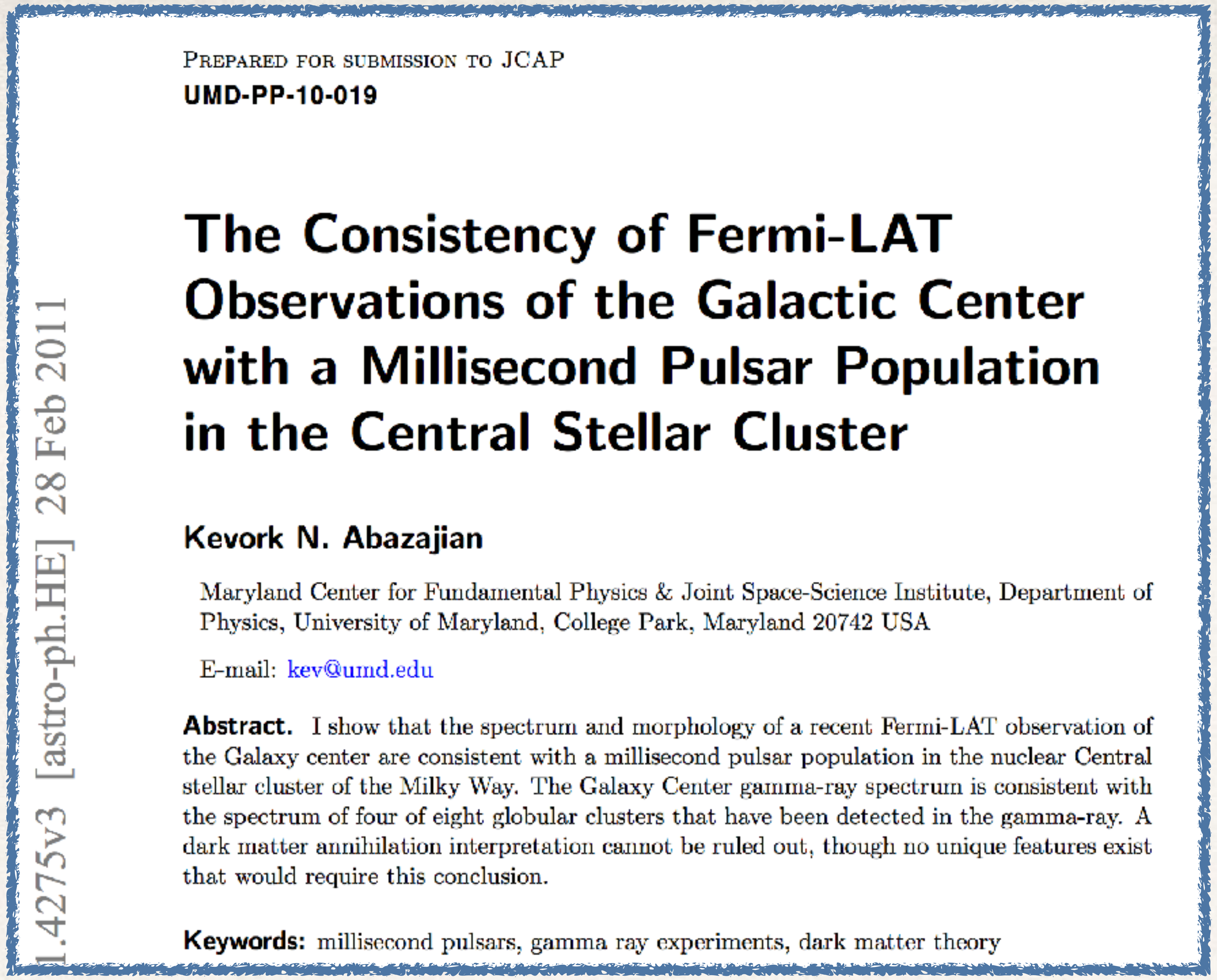
- Mask galactic plane (e.g. $|b| > 1^\circ$), and consider $40^\circ \times 40^\circ$ box
- Bright point sources masked at 2°
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin
- Background systematics controlled

GALACTIC CENTER

- Box around the GC ($10^\circ \times 10^\circ$)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source
- Bright Signal



Total Flux
Residual Model (x3)
1.0 - 3.16 GeV
3.16 - 10 GeV
2.5°
0°
-2.5°
6.0 x 10^-4
4.5
3.0
1.5
0.0
-1.5
-3.0
16 x 10^-5
12.0
8.0
4.0
0.0
-4.0
-8.0



PREPARED FOR SUBMISSION TO JCAP
UMD-PP-10-019

The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster

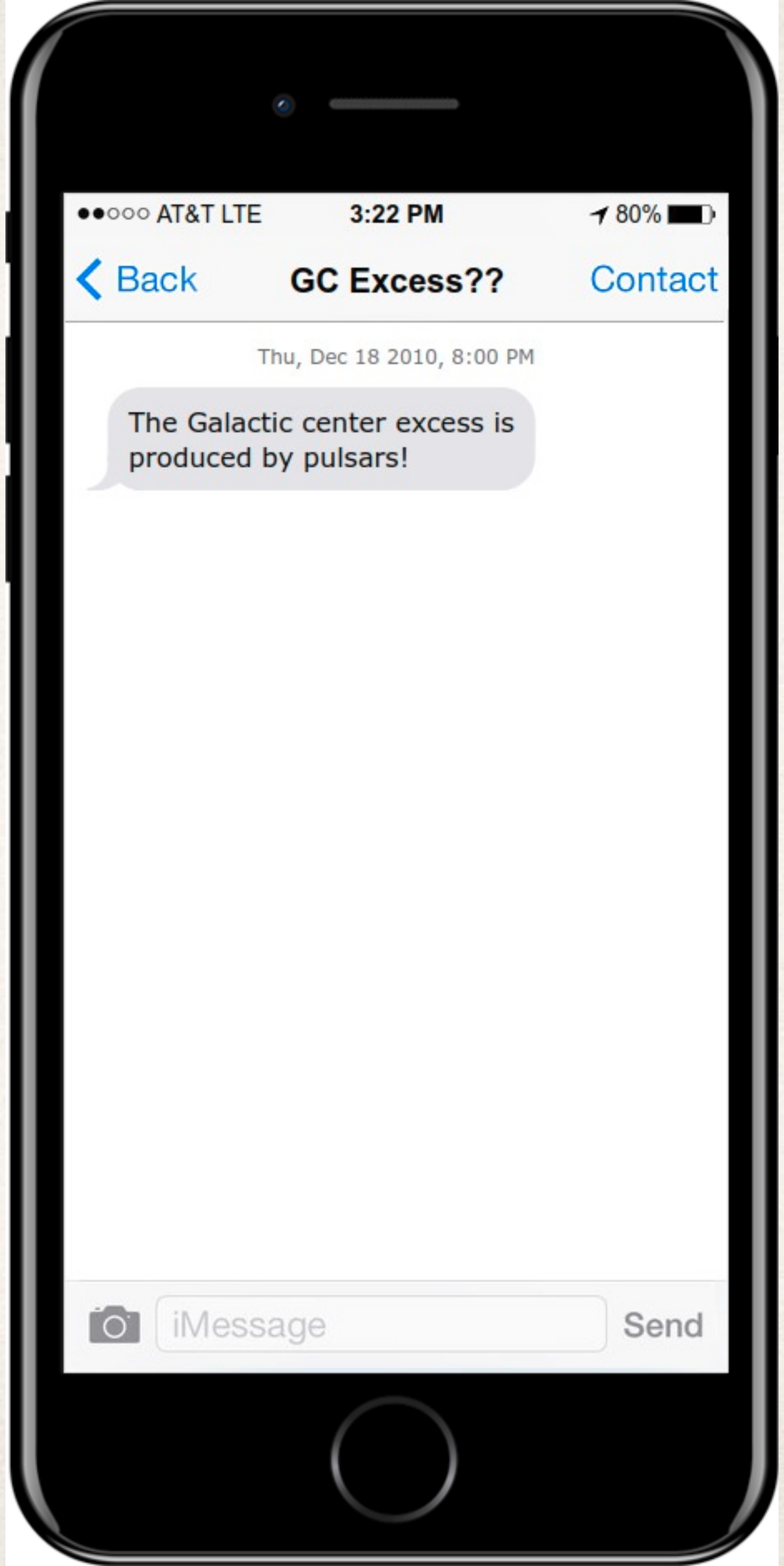
Kevork N. Abazajian

Maryland Center for Fundamental Physics & Joint Space-Science Institute, Department of Physics, University of Maryland, College Park, Maryland 20742 USA

E-mail: kev@umd.edu

Abstract. I show that the spectrum and morphology of a recent Fermi-LAT observation of the Galaxy center are consistent with a millisecond pulsar population in the nuclear Central stellar cluster of the Milky Way. The Galaxy Center gamma-ray spectrum is consistent with the spectrum of four of eight globular clusters that have been detected in the gamma-ray. A dark matter annihilation interpretation cannot be ruled out, though no unique features exist that would require this conclusion.

Keywords: millisecond pulsars, gamma ray experiments, dark matter theory



1.4275v3 [astro-ph.HE] 28 Feb 2011

PREPARED FOR SUBMISSION TO JCAP
UMD-PP-10-019

The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster

astro-ph.HE] 3 May 2013

Pulsars Cannot Account for the Inner Galaxy's GeV Excess

Dan Hooper[1,2], Ilias Cholis[1], Tim Linden[3], Jennifer Siegal-Gaskins[4], and Tracy Slatyer[5]
[1] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
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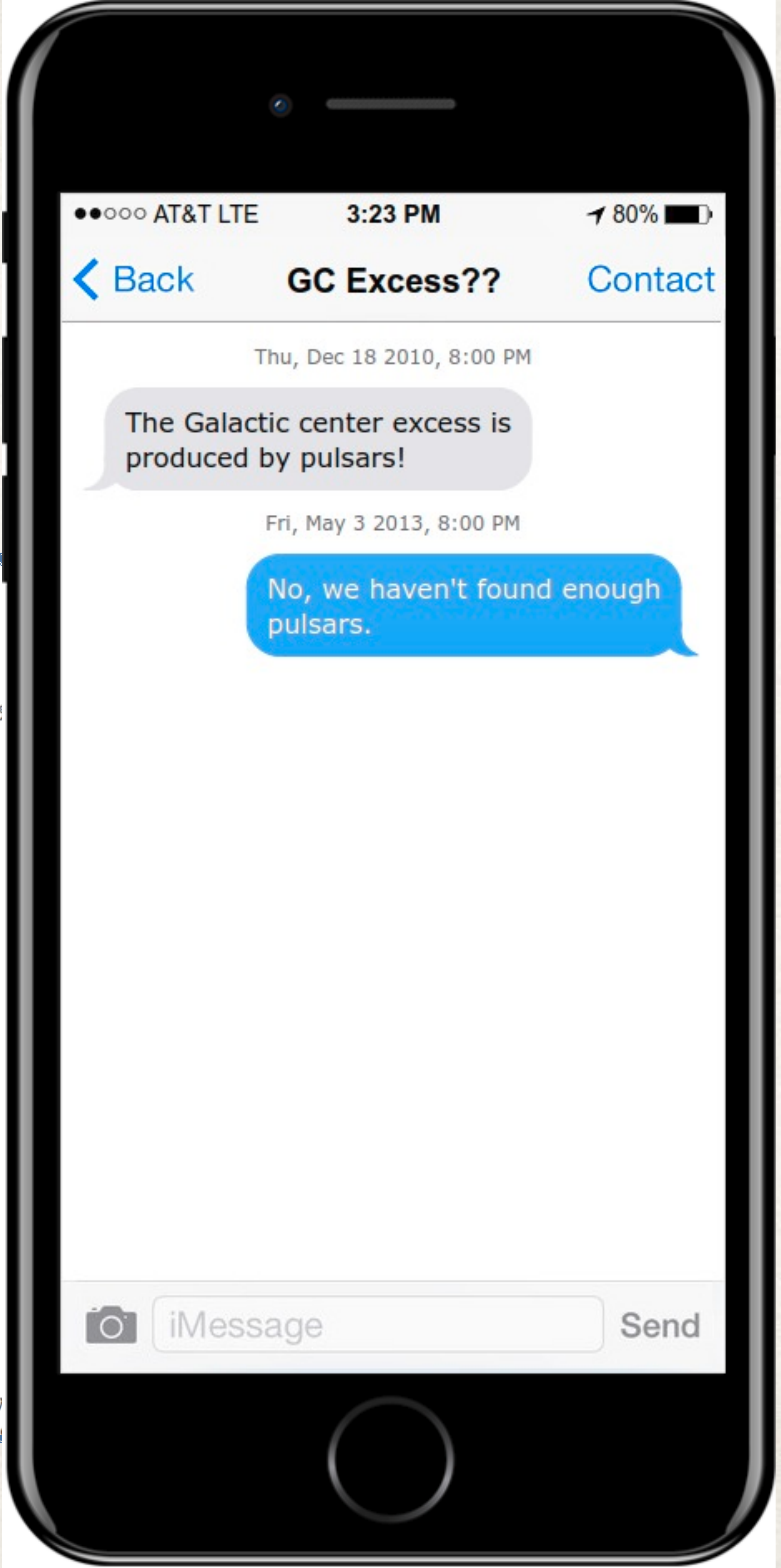
[3] *Department of Physics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064*
[4] *Einstein Fellow, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125 and*
[5] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540*
(Dated: April 16, 2018)

Using data from the Fermi Gamma-Ray Space Telescope, a spatially extended component of gamma rays has been identified from the direction of the Galactic Center, peaking at energies of ~2-3 GeV. More recently, it has been shown that this signal is not confined to the innermost hundreds of parsecs of the Galaxy, but instead extends to at least ~3 kpc from the Galactic Center. While the spectrum, intensity, and angular distribution of this signal is in good agreement with predictions from annihilating dark matter, it has also been suggested that a population of unresolved millisecond pulsars could be responsible for this excess GeV emission from the Inner Galaxy. In this paper, we consider this later possibility in detail. Comparing the observed spectral shape of the Inner Galaxy's GeV excess to the spectrum measured from 37 millisecond pulsars by Fermi, we find that these sources exhibit a spectral shape that is much too soft at sub-GeV energies to accommodate this signal. We also construct population models to describe the spatial distribution and luminosity function of the Milky Way's millisecond pulsars. After taking into account constraints from the observed distribution of Fermi sources (including both sources known to be millisecond pulsars, and unidentified sources which could be pulsars), we find that millisecond pulsars can account for no more than ~10% of the Inner Galaxy's GeV excess. Each of these arguments strongly disfavor millisecond pulsars as the source of this signal.

PACS numbers: 97.60.Gb, 95.55.Ka, 95.35.+d; FERMILAB-PUB-13-129-A

I. INTRODUCTION

trophysical sources or backgrounds. Second



1.4275v3 [astro-ph.HE] 28 Feb 2011

PREPARED FOR SUBMISSION TO JCAP
UMD-PP-10-019

The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster

astro-ph.HE] 3 May 2013

Pulsars Cannot Account for the Inner Galaxy's GeV Excess

3428v2 [astro-ph.HE] 18 Sep 2013

Dark matter vs. pulsars: Catching the impostor

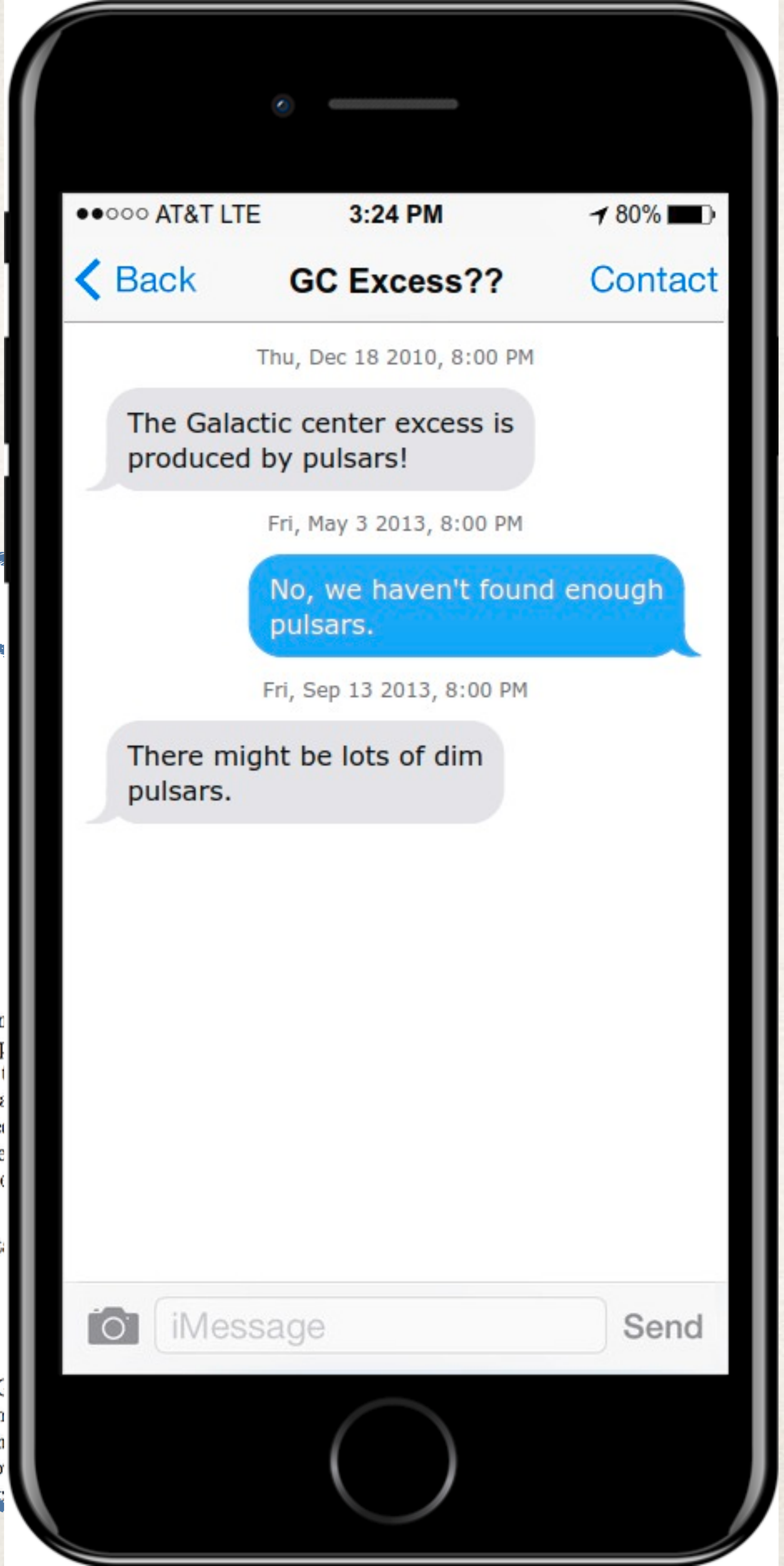
N. Mirabal[1,2⋆]
[1] *Ramón y Cajal Fellow*
[2] *Dpto. de Física Atómica, Molecular y Nuclear, Universidad Complutense de Madrid, Spain*

ABSTRACT
Evidence of excess GeV emission nearly coinciding with the Galactic Cer interpreted as a possible signature of annihilating dark matter. In this pa that it seems too early to discard pulsars as a viable explanation for excess. On the heels of the recently released Second *Fermi* LAT Puls (2FPC), it is still possible that a population of hard ($\Gamma < 1$) millise (MSPs) either endemic to the innermost region or part of a larger nasc of hard MSPs that appears to be emerging in the 2FPC could explain th near the Galactic Centre.

Key words: (cosmology:) dark matter – gamma-rays: observations – (st general

1 INTRODUCTION

At first glance, pulsars and dark matter appear to have nothing in common, the former are magnificent spinning neutron stars with impeccable timing (Bell 1968; Gold 1968), while for dark matter in the purlieus of the C tre. The central concentration of dark n guably the most promising place to search annihilation products. As it turns out, o few years a number of groups have notic



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UMD-PP-10-019

h.HE] 28 Feb 2011

The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster

Pulsars Cannot Account for the Inner Galaxy's GeV Excess

Dark matter vs. pulsars: Catching the impostor

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Challenges in Explaining the Galactic Center Gamma-Ray Excess with Millisecond Pulsars

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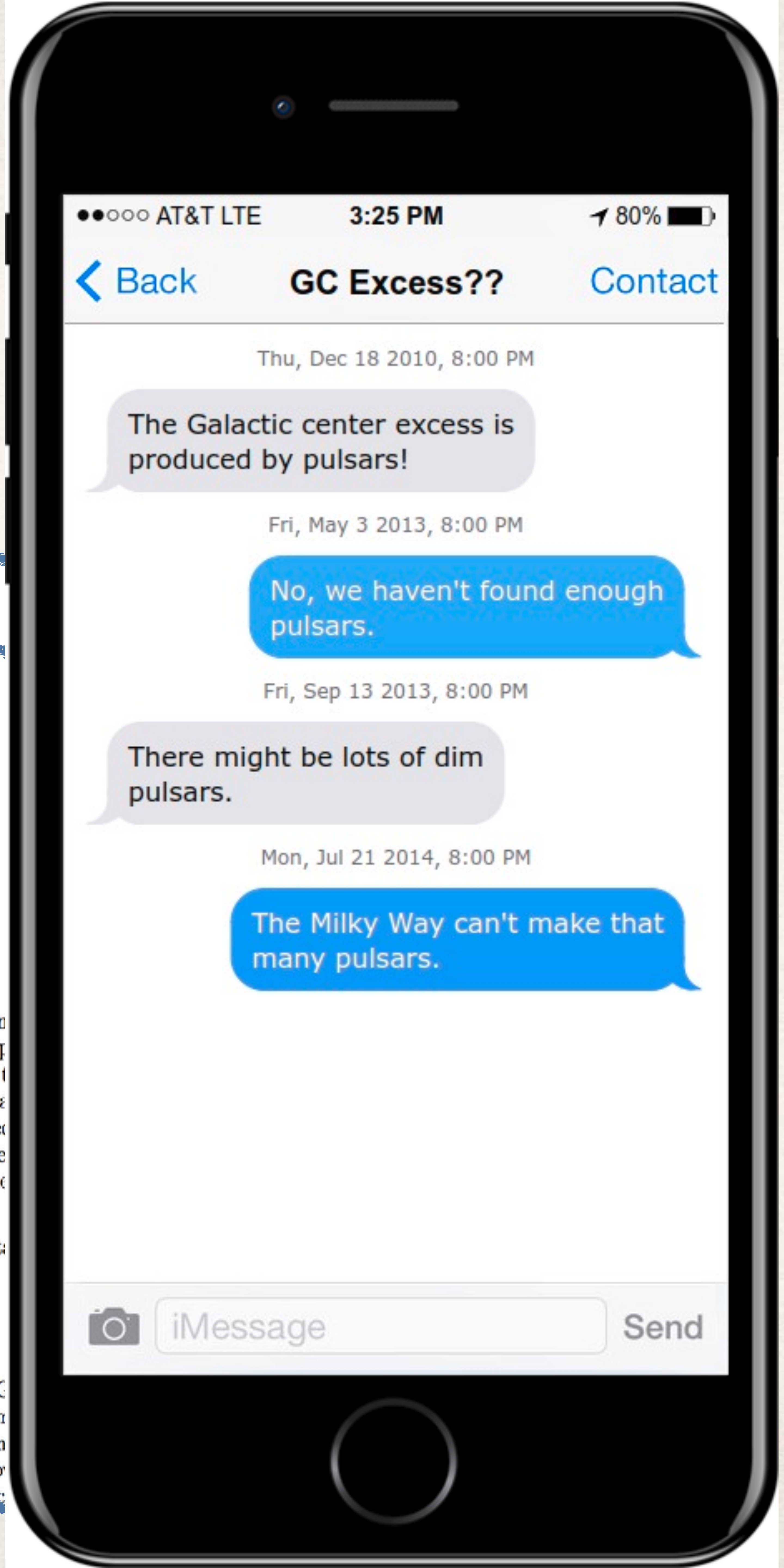
Abstract. Millisecond pulsars have been discussed as a possible source of the gamma-ray excess observed from the region surrounding the Galactic Center. With this in mind, we use the observed population of bright low-mass X-ray binaries to estimate the number of millisecond pulsars in the Inner Galaxy. This calculation suggests that only ∼1-5% of the excess is produced by millisecond pulsars. We also use the luminosity function derived from local measurements of millisecond pulsars, along with the number of point sources resolved by Fermi, to calculate an upper limit for the diffuse emission from such a population. While this limit is compatible with the millisecond pulsar population implied by the number of low-mass X-ray binaries, it strongly excludes the possibility that most of the excess originates from such objects.



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Challenges in Explaining the Galactic Center Gamma-Ray Excess with Millisecond Pulsars

Millisecond pulsars and the Galactic Center gamma-ray excess: the importance of luminosity function and secondary emission

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Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

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(Dated: February 4, 2016)

We present a new method to characterize unresolved point sources (PSs), generalizing traditional template fits to account for non-Poissonian photon statistics. We apply this method to *Fermi* Large Area Telescope gamma-ray data to characterize PS populations at high latitudes and in the Inner Galaxy. We find that PSs (resolved and unresolved) account for ~50% of the total extragalactic gamma-ray background in the energy range ~1.9 to 11.9 GeV. Within 10° of the Galactic Center with $|b| \geq 2°$, we find that ~5–10% of the flux can be accounted for by a population of unresolved PSs, distributed consistently with the observed ~GeV gamma-ray excess in this region. The excess is fully absorbed by such a population, in preference to dark-matter annihilation. The inferred source population is dominated by near-threshold sources, which may be detectable in future searches.

Dark-matter (DM) annihilation in the Galactic halo can contribute to the flux of high-energy gamma rays detected by experiments such as the *Fermi* Large Area

excess. The choice of this energy range keeps the signal-to-background ratio in the region of interest (ROI) high, maintains a sufficiently large number of photons over the

Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess

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(Dated: 4 February 2016)

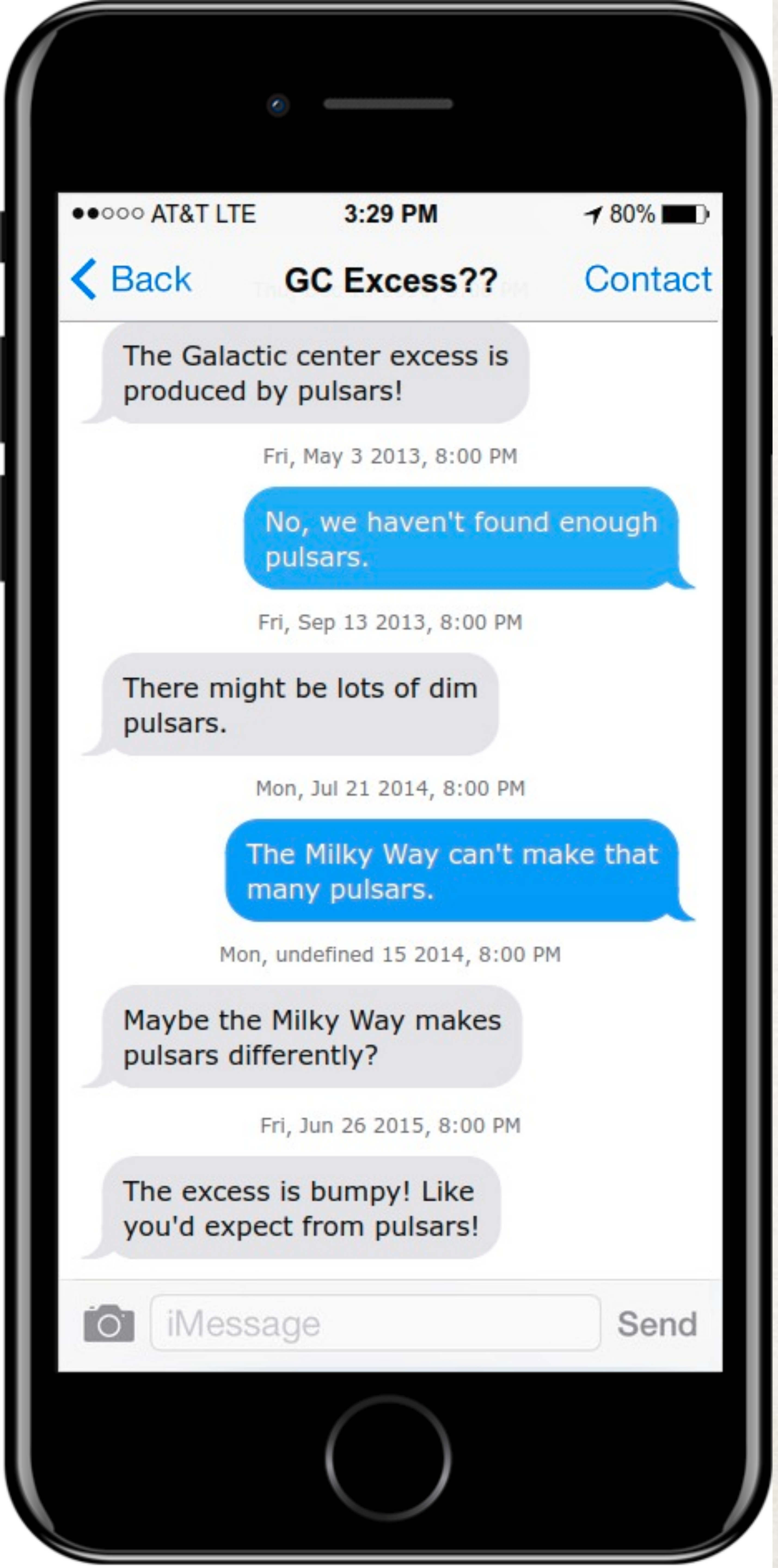
Using γ-ray data from the *Fermi* Large Area Telescope, various groups have identified a clear excess emission in the Inner Galaxy, at energies around a few GeV. This excess resembles remarkably well a signal from dark-matter annihilation. One of the most compelling astrophysical interpretations is that the excess is caused by the combined effect of a previously undetected population of dim γ-ray sources. Because of their spectral similarity, the best candidates are millisecond pulsars. Here, we search for this hypothetical source population, using a novel approach based on wavelet decomposition of the γ-ray sky and the statistics of Gaussian random fields. Using almost seven years of *Fermi*-LAT data, we detect a clustering of photons as predicted for the hypothetical population of millisecond pulsar, with a statistical significance of 10.0σ. For plausible values of the luminosity function, this population explains 100% of the observed excess emission. We argue that other extragalactic or Galactic sources, a mismodeling of Galactic diffuse emission, or the thick-disk population of pulsars are unlikely to account for this observation.

Introduction. Since its launch in 2008, the *Fermi* Large Area Telescope (LAT) has revolutionized our understanding of the γ-ray sky. Among the major successes are the detection of more than 3000 γ-ray sources [1], the discovery of the *Fermi* bubbles [2], some of the most stringent limits on dark-matter annihilation [3] and, most recently, the detection of cross-correlations between the extragalactic γ-ray background and various galaxy catalogs [4].

One of the most interesting γ-ray signatures identified in the *Fermi*-LAT data by various groups [5–16], is an excess emission in the Inner Galaxy at energies around a few GeV. This excess attracted great attention because it has properties typical for a dark-matter annihilation signal. This Galactic center excess (GCE) is detected both within the inner 10 arcmin of the Galactic Center (GC) [7, 9, 10] and up to Galactic latitudes of more than 10° [13, 15, 17, 18]. It features a remarkably uniform

ther possible support for the MSP hypothesis might come from *Chandra* observations of low-mass x-ray binaries (which are progenitor systems of MSPs) in M31, which show a centrally peaked profile in the inner 2 kpc [27, 28], as well as the recent observation of extended hard X-ray emission from the Galactic Center by *NuSTAR* [29].

It was claimed that an interpretation of 100% of the GCE emission in terms of MSPs would be already ruled out: a sizeable fraction of the required 10^3–10^4 MSPs should have been already detected by the *Fermi*-LAT [30, 31], but no (isolated) MSP has been identified so far in the bulge region. This conclusion depends crucially, however, on the adopted γ-ray luminosity of the brightest MSPs in the bulge population, on the effective source sensitivity of *Fermi*-LAT, and on the treatment of unassociated sources in the Inner Galaxy [25, 32]. A realistic sensitivity study for MSPs in the context of the GeV excess, taking into account all these effects, was lacking



Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

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DISRUPTED GLOBULAR CLUSTERS CAN EXPLAIN THE GALACTIC CENTER GAMMA RAY EXCESS

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Draft version September 1, 2015

ABSTRACT

The *Fermi* satellite has recently detected gamma ray emission from the central regions of our Galaxy. This may be evidence for dark matter particles, a major component of the standard cosmological model, annihilating to produce high-energy photons. We show that the observed signal may instead be generated by millisecond pulsars that formed in dense star clusters in the Galactic halo. Most of these clusters were ultimately disrupted by evaporation and gravitational tides, contributing to a spherical bulge of stars and stellar remnants. The gamma ray amplitude, angular distribution, and spectral signatures of this source may be predicted without free parameters, and are in remarkable agreement with the observations. These gamma rays are from fossil remains of dispersed clusters, telling the history of the Galactic bulge.

Subject headings:

1. INTRODUCTION

While there are strong indications for the existence of cold dark matter from its gravitational effects (e.g. Planck Collaboration et al. 2014), there has not yet been any conclusive direct or indirect detection of the corresponding dark matter particles. One promising avenue to look for these particles is through annihilation in which two dark matter particles (a particle and its antiparticle) convert into high energy photons that we can observe. The dark matter annihilation signal is expected to be strongest where the density of dark matter is highest, i.e., in the centers of galaxies.

Detailed analyses of the *Fermi* satellite's map of the gamma-ray sky have revealed an excess around the Galactic center peaking at energies of ∼2 GeV (e.g. Hooper & Goodenough 2011; Gordon & Macías 2013; Daylan et al. 2014). This excess appears to be roughly

the central few pc around Sgr A* itself, extending fro soft X-rays to ∼100 TeV gamma rays (Baganoff et a 2001; Aharonian et al. 2004; Bélanger et al. 200 Perez et al. 2015). The origin of this emission is sul ject to debate; see van Eldik (2015) for a review. The r gion near the event horizon of Sgr A* is likely responsib for bright outbursts in soft X-rays (Baganoff et al. 2001 but this scenario struggles to explain the steady emissic at much higher energies. Alternative explanations for tl GeV and TeV flux include the supernova remnant Sgr East (Crocker et al. 2005), though this is strongly di favored based on its observed offset from the very hig energy emission centered on Sgr A* (Acero et al. 2010 Secondary emission from particles accelerated by Sgr A is another candidate, either in a steady state or fro a past burst of accretion (e.g. Atoyan & Dermer 200 Aharonian & Neronov 2005; Chernyakova et al. 2011

Introduction. Since its launch in 2008, the *Fermi* Large Area Telescope (LAT) has revolutionized our understanding of the γ-ray sky. Among the major successes are the detection of more than 3000 γ-ray sources [1], the discovery of the *Fermi* bubbles [2], some of the most stringent limits on dark-matter annihilation [3] and, most recently, the detection of cross-correlations between the extragalactic γ-ray background and various galaxy catalogs [4].

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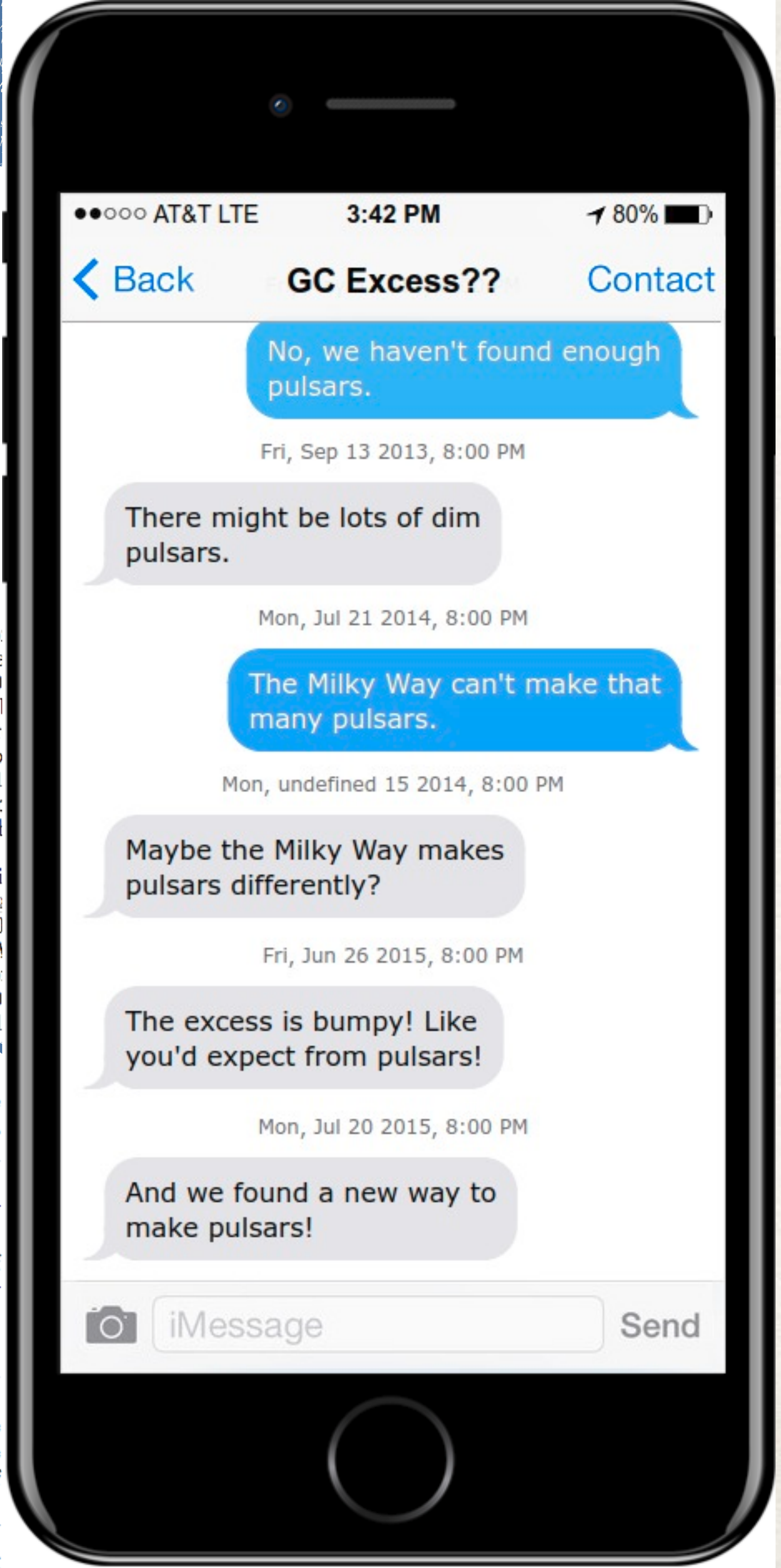

Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

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DISRUPTED GLOBULAR CLUSTERS CAN EXPLAIN THE GALACTIC CENTER GAMMA RAY EXCESS

Timothy D. Brandt[1,3] and Bence Kocsis[1,2]
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Low Mass X-Ray Binaries in the Inner Galaxy: Implications for Millisecond Pulsars and the GeV Excess

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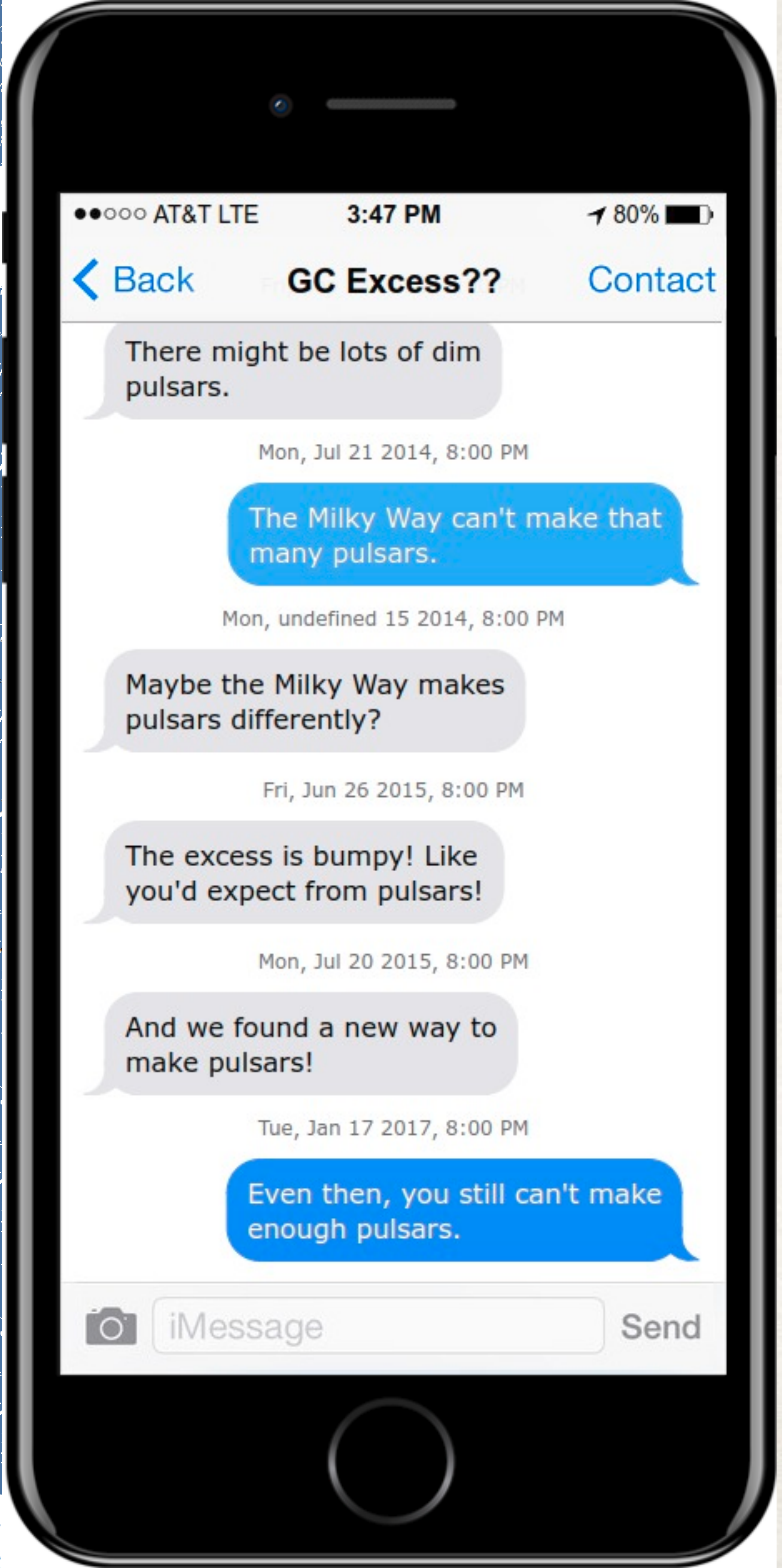
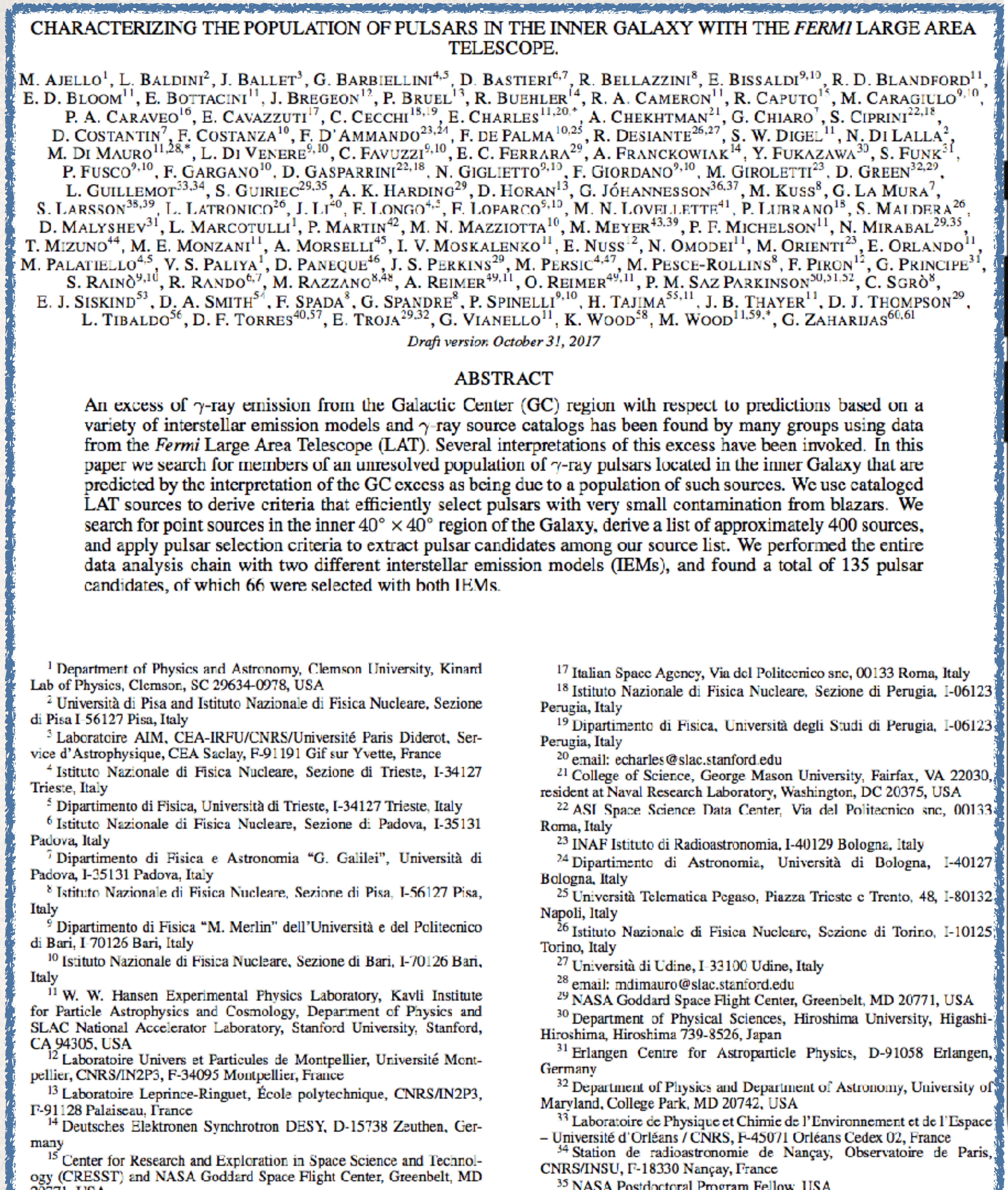
Abstract. If millisecond pulsars (MSPs) are responsible for the excess gamma-ray emission observed from the region surrounding the Galactic Center, the same region should also contain a large population of low-mass X-ray binaries (LMXBs). In this study, we compile and utilize a sizable catalog of LMXBs observed in the the Milky Way's globular cluster system and in the Inner Galaxy, as well as the gamma-ray emission observed from globular clusters, to estimate the flux of gamma rays predicted from MSPs in the Inner Galaxy. From this comparison, we conclude that only up to $\sim$4-23% of the observed gamma-ray excess is likely to originate from MSPs. This result is consistent with, and more robust than, previous estimates which utilized smaller samples of both globular clusters and LMXBs. If MSPs had been responsible for the entirety of the observed excess, INTEGRAL should have detected $\sim 10^3$ LMXBs from within a $10°$ radius around the Galactic Center, whereas only 42 LMXBs (and 46 additional LMXB candidates) have been observed.

both within the inner 10 arcmin of the Galactic Center (GC) [7, 9, 10] and up to Galactic latitudes of more than

unassociated sources in the Inner Galaxy [25, 32]. A realistic sensitivity study for MSPs in the context of the GeV excess, taking into account all these effects, was lacking





CHARACTERIZING THE POPULATION OF PULSARS IN THE INNER GALAXY WITH THE *FERMI* LARGE AREA TELESCOPE.

M. Ajello[1], L. Baldini[2], J. Ballet[3], G. Barbiellini[4,5], D. Bastieri[6,7], R. Bellazzini[8], E. Bissaldi[9,10], R. D. Blandford[11], E. D. Bloom[11], E. Bottacini[11], J. Bregeon[12], P. Bruel[13], R. Buehler[14], R. A. Cameron[11], R. Caputo[15], M. Caragiulo[9,10], P. A. Caraveo[16], E. Cavazzuti[17], C. Cecchi[18,19], E. Charles[11,20,*], A. Chekhtman[21], G. Chiaro[7], S. Ciprini[22,18], D. Costantin[7], F. Costanza[10], F. D'Ammando[23,24], F. de Palma[10,25], R. Desiante[26,27], S. W. Digel[11], N. Di Lalla[2], M. Di Mauro[11,28,*], L. Di Venere[9,10], C. Favuzzi[9,10], E. C. Ferrara[29], A. Franckowiak[14], Y. Fukazawa[30], S. Funk[31], P. Fusco[9,10], F. Gargano[10], D. Gasparrini[22,18], N. Giglietto[9,10], F. Giordano[9,10], M. Giroletti[23], D. Green[32,29], L. Guillemot[33,34], S. Guiriec[29,35], A. K. Harding[29], D. Horan[13], G. Jóhannesson[36,37], M. Kuss[8], G. La Mura[7], S. Larsson[38,39], L. Latronico[26], J. Li[40], F. Longo[4,5], F. Loparco[9,10], M. N. Lovellette[41], P. Lubrano[18], S. Maldera[26], D. Malyshev[31], L. Marcotulli[1], P. Martin[42], M. N. Mazziotta[10], M. Meyer[43,39], P. F. Michelson[11], N. Mirabal[29,35], T. Mizuno[44], M. E. Monzani[11], A. Morselli[45], I. V. Moskalenko[11], E. Nuss[12], N. Omodei[11], M. Orienti[23], E. Orlando[11], M. Palatiello[4,5], V. S. Paliya[1], D. Paneque[46], J. S. Perkins[29], M. Persic[4,47], M. Pesce-Rollins[8], F. Piron[12], G. Principe[31], S. Rainò[9,10], R. Rando[6,7], M. Razzano[8,48], A. Reimer[49,11], O. Reimer[49,11], P. M. Saz Parkinson[50,51,52], C. Sgrò[8], E. J. Siskind[53], D. A. Smith[54], F. Spada[8], G. Spandre[8], P. Spinelli[9,10], H. Tajima[55,11], J. B. Thayer[11], D. J. Thompson[29], L. Tibaldo[56], D. F. Torres[40,57], E. Troja[29,32], G. Vianello[11], K. Wood[58], M. Wood[11,59,*], G. Zaharijas[60,61]

Draft version October 31, 2017

ABSTRACT

An excess of γ-ray emission from the Galactic Center (GC) region with respect to predictions based on a variety of interstellar emission models and γ-ray source catalogs has been found by many groups using data from the *Fermi* Large Area Telescope (LAT). Several interpretations of this excess have been invoked. In this paper we search for members of an unresolved population of γ-ray pulsars located in the inner Galaxy that are predicted by the interpretation of the GC excess as being due to a population of such sources. We use cataloged LAT sources to derive criteria that efficiently select pulsars with very small contamination from blazars. We search for point sources in the inner $40° \times 40°$ region of the Galaxy, derive a list of approximately 400 sources, and apply pulsar selection criteria to extract pulsar candidates among our source list. We performed the entire data analysis chain with two different interstellar emission models (IEMs), and found a total of 135 pulsar candidates, of which 66 were selected with both IEMs.

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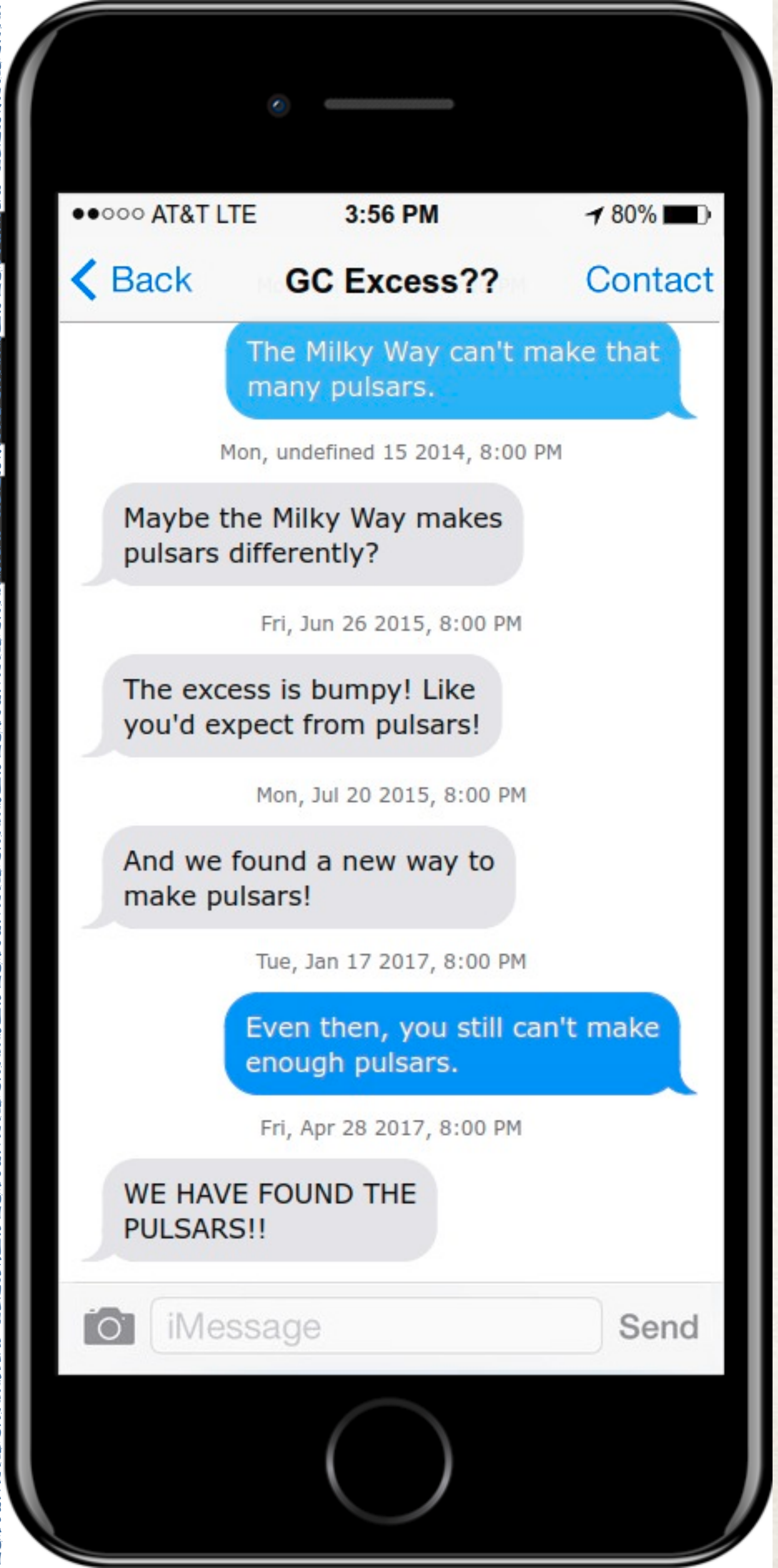

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ABSTRACT

An excess of γ-ray emission from the Galactic Center (GC) region with respect to predictions based on a variety of interstellar emission models and γ-ray source catalogs has been found by many groups using data from the *Fermi* Large Area Telescope (LAT). Several interpretations of this excess have been invoked. In this

COMMENT ON "CHARACTERIZING THE POPULATION OF PULSARS IN THE GALACTIC BULGE WITH THE *FERMI* LARGE AREA TELESCOPE" [ARXIV:1705.00009V1]

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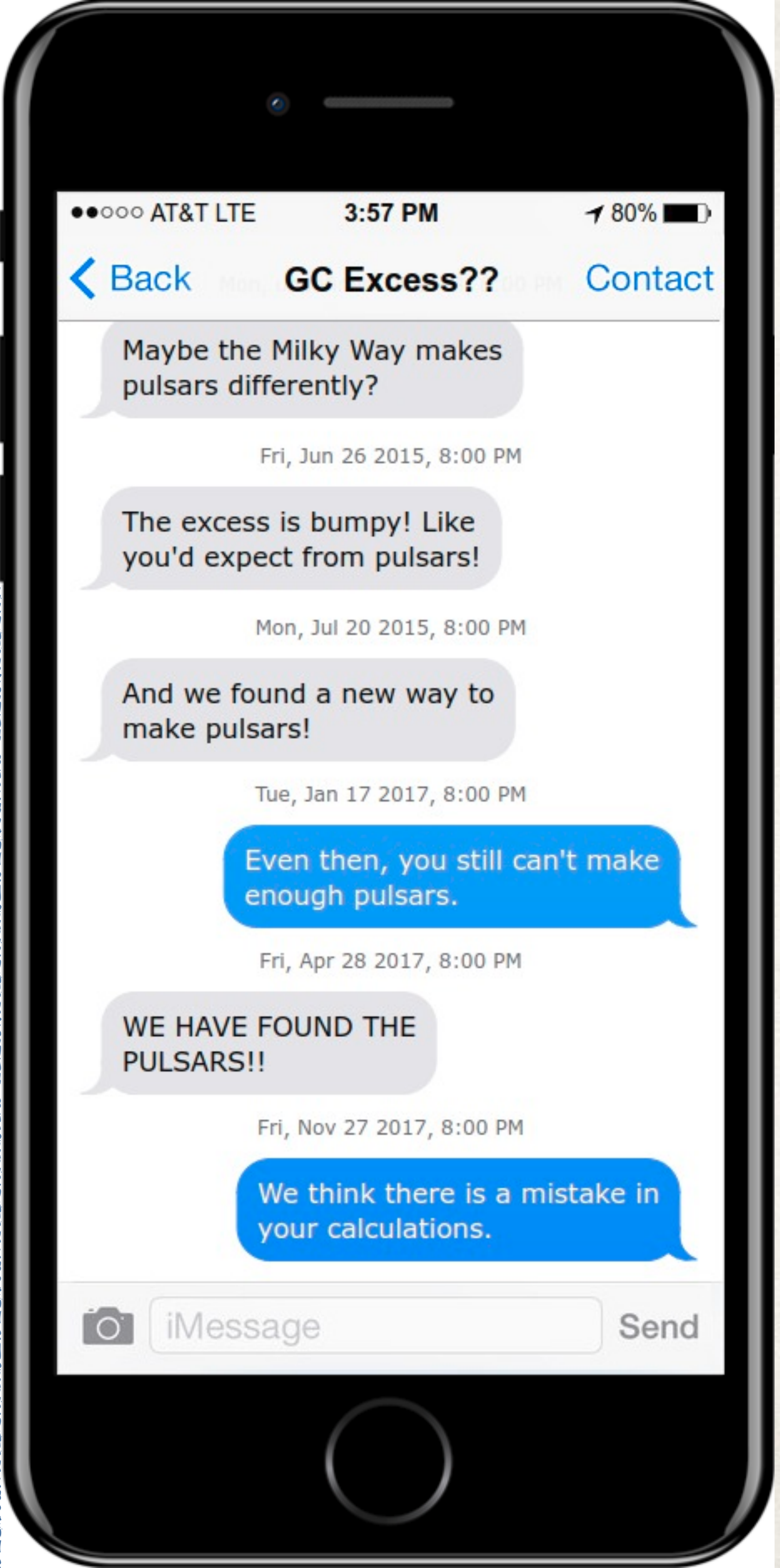
ABSTRACT

The *Fermi*-LAT Collaboration recently presented a new catalog of gamma-ray sources located within the $40^\circ \times 40^\circ$ region around the Galactic Center (Ajello et al. 2017) – the Second Fermi Inner Galaxy (2FIG) catalog. Utilizing this catalog, they analyzed models for the spatial distribution and luminosity function of sources with a pulsar-like gamma-ray spectrum. Ajello et al. (2017) v1 also claimed to detect, in addition to a disk-like population of pulsar-like sources, an approximately 7σ preference for an additional centrally concentrated population of pulsar-like sources, which they referred to as a "Galactic Bulge" population. Such a population would be of great interest, as it would support a pulsar interpretation of the gamma-ray excess that has long been observed in this region. In an effort to further explore the implications of this new source catalog, we attempted to reproduce the results presented by the *Fermi*-LAT Collaboration, but failed to do so. Mimicking as closely as possible the analysis techniques undertaken in Ajello et al. (2017), we instead find that our likelihood analysis favors a very different spatial distribution and luminosity function for these sources. Most notably, our results do not exhibit a strong preference for a "Galactic Bulge" population of pulsars. Furthermore, we find that masking the regions immediately surrounding each of the 2FIG pulsar candidates does *not* significantly impact the spectrum or intensity of the Galactic Center gamma-ray excess. Although these results refute the claim of strong evidence for a centrally concentrated pulsar population presented in Ajello et al. (2017), they neither rule out nor provide support for the possibility that the Galactic Center excess is generated by a population of low-luminosity and currently largely unobserved pulsars. In a spirit of maximal openness and transparency, we have made our analysis code available at `https://github.com/bsafdi/GCE-2FIG`.

1. A COMPARISON WITH AJELLO *ET AL.*

The *Fermi*-LAT Collaboration recently presented the Second Fermi Inner Galaxy (2FIG) source catalog (Ajello et al. 2017).[1] This catalog consists of 374 sources that have been detected with a test statistic (TS) of 25 or greater, located within the $40^\circ \times 40^\circ$ region surrounding the Galactic Center. Among this list, there are 104 sources (86 of which are not contained in the 3FGL catalog (Acero et al. 2015)) that exhibit best-fit spectral parameters that are characterized as pulsar-like by Ajello et al. (2017).[2] More specifically, Ajello et al. (2017) classifies a source as a pulsar candidate if its spectrum prefers a power-law with an exponential cutoff over that of a simple power-law at a level of TS > 9 and is best-fit by a spectral index $\Gamma < 2$ and a cutoff energy $E_{\rm cut} < 10$ GeV.

By combining the Galactic coordinates and fluxes of these sources with an efficiency function that describes the probability of detecting a given source at a particular sky location and flux, one can test various models for the underlying spatial distribution and luminosity function of the pulsar-like source population. For the disk-like component of pulsars, Ajello et al. (2017) adopt the standard Lorimer distribution (Lorimer



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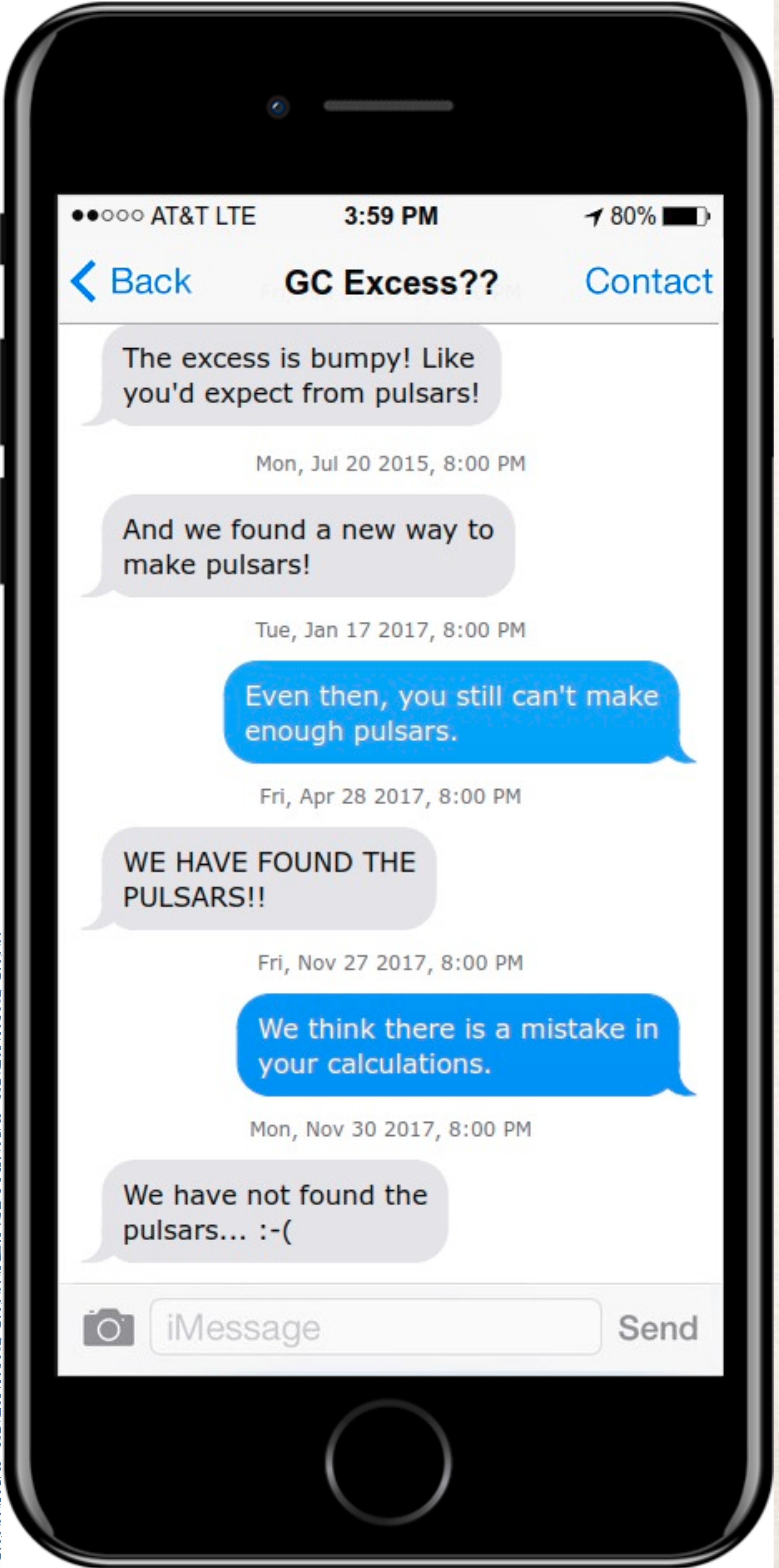

THE FERMI-LAT GEV EXCESS TRACES STELLAR MASS IN THE GALACTIC BULGE

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(Received November 15, 2017; Revised; Accepted)

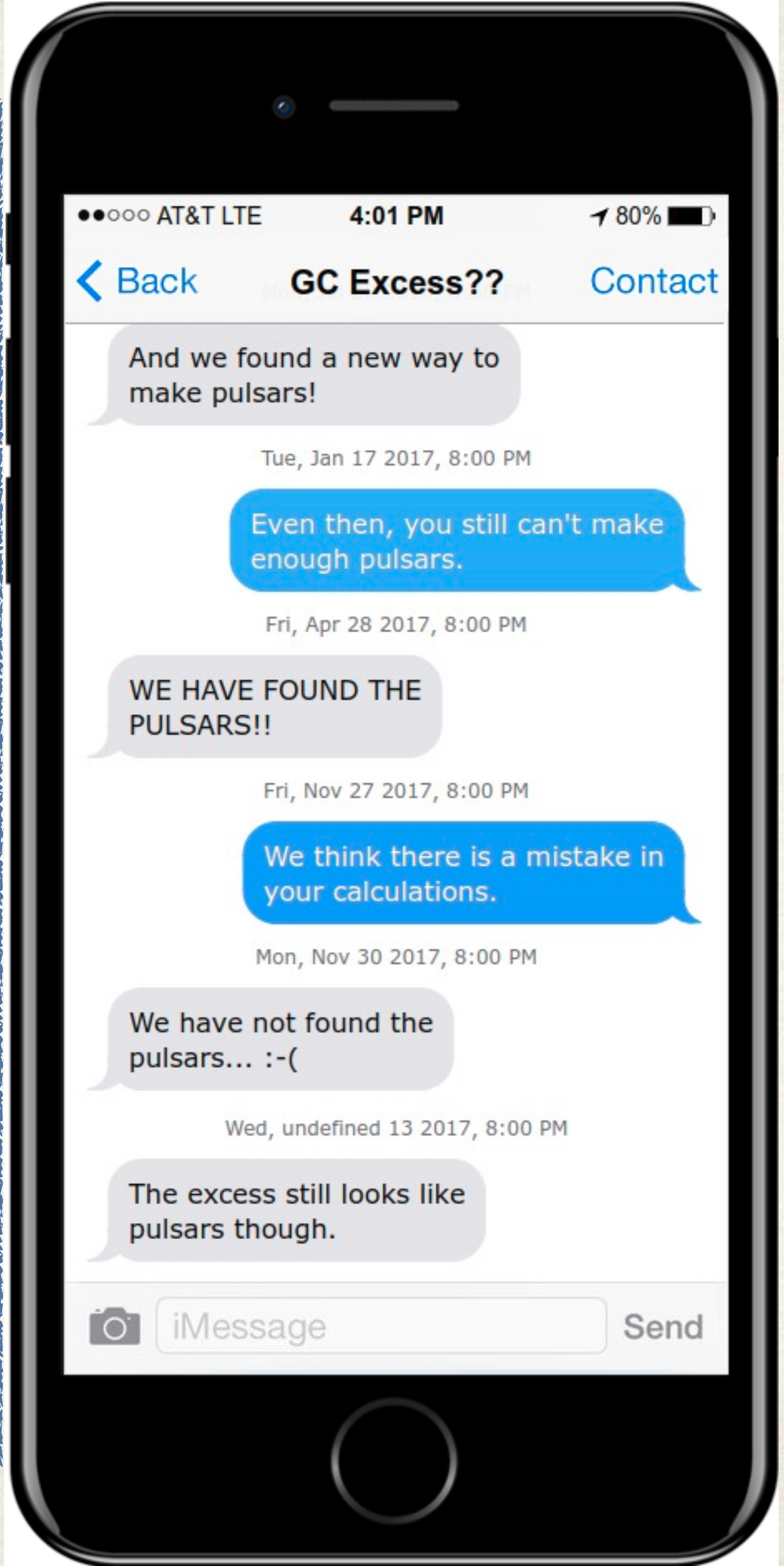
ABSTRACT

An anomalous emission component at energies of a few GeV and located towards the inner Galaxy is present in the *Fermi*-LAT data. It is known as the *Fermi*-LAT GeV excess. Using almost 8 years of data we reanalyze the characteristics of this excess with SkyFACT, a novel tool that combines image reconstruction with template fitting techniques. We find that an emission profile that traces stellar mass in the boxy and nuclear bulge provides the best description of the excess emission, providing strong circumstantial evidence that the excess is due to a stellar source population in the Galactic bulge. We find a luminosity to stellar mass ratio of $(2.1 \pm 0.2) \times 10^{27}\,\mathrm{erg\,s^{-1}\,M_\odot^{-1}}$ for the boxy bulge, and of $(1.4 \pm 0.6) \times 10^{27}\,\mathrm{erg\,s^{-1}\,M_\odot^{-1}}$ for the nuclear bulge. Stellar mass related templates are preferred over conventional DM profiles with high statistical significance.

1. INTRODUCTION

An anomalous emission component, often referred to as the Galactic center GeV excess (GCE), has been identified in the *Fermi*-LAT data by many groups (e.g. Goodenough & Hooper 2009; Vitale & Morselli 2009; Hooper & Linden 2011; Abazajian & Kaplinghat 2012; Macias & Gordon 2014; Daylan et al. 2016; Zhou et al. 2015; Calore et al. 2015b; Huang et al. 2016; de Boer et al. 2016; Ajello et al. 2016). Its spectrum peaks at energies of a few GeV and it appears to be uniform over the emission region. The morphology is usually described as almost spherically symmetric around the Galactic center, with a radial extent of $\sim 10°$. Intriguingly, a signal from dark matter (DM) annihilation into b-quark pairs and a DM mass $\sim 50\,\mathrm{GeV}$ has been shown to be consistent with the GCE (Goodenough & Hooper 2009; Abazajian & Kaplinghat 2012; Macias & Gordon 2014; Daylan et al. 2016; Calore et al. 2015a), provided the centrally peaked DM distribution in the Galactic bulge follows a radial power-law profile with index $\gamma \sim 1.2$. However, the exact details of the morphology and spectrum remain sub- et al. 2010; Su et al. 2010; Ackermann et al. 2014), the low-latitude behavior of which is not well-characterized (Ackermann et al. 2017a; Linden et al. 2016).

Besides DM, more 'conventional' astrophysical explanations do exist, with various degrees of plausibility. These are either related to a large number of hitherto unresolved point sources in the Galactic bulge, just at and below the detection threshold of *Fermi*-LAT, or to diffuse photons coming from a central population of cosmic rays. Nowadays, a population of unresolved millisecond pulsars (MSPs), whose γ-ray spectrum was shown to match that of the GCE (Abazajian 2011; Abazajian et al. 2014; Calore et al. 2015b), represents the most promising astrophysical interpretation to the GCE (Abazajian 2011; Gordon & Macias 2013; Petrović et al. 2015; Yuan & Zhang 2014). Corroborative evidence for this interpretation was recently found in analyses of the γ-ray data using wavelet fluctuations, and non-Poissonian template fits (Bartels et al. 2016; Lee et al. 2016). Spectral classification of low-significance γ-ray sources and analyses of their distribution remain however inconclusive about the



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Analyzing the Gamma-ray Sky with Wavelets

Bhaskaran Balaji,[1,*] Ilias Cholis,[1] Patrick J. Fox,[2] and Samuel D. McDermott[3]
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(Dated: March 7, 2018)

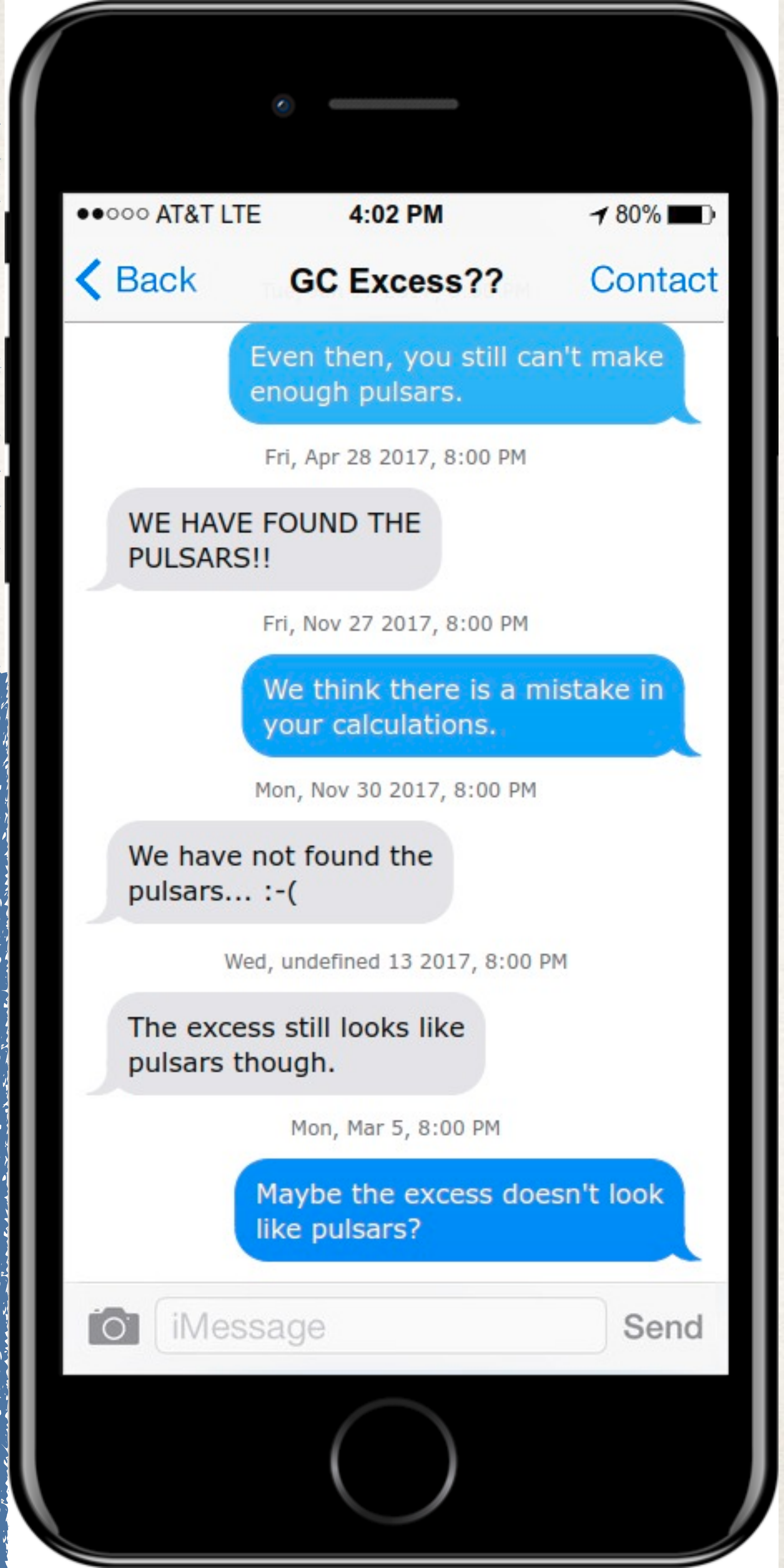
We analyze the gamma-ray sky at energies of 0.5 to 50 GeV using the undecimated wavelet transform on the sphere. Focusing on the inner $60^\circ \times 60^\circ$ of the sky, we identify and characterize four separate residuals beyond the expected Milky Way diffuse emission. We detect the *Fermi* Bubbles, finding compelling evidence that they are diffuse in nature and contain very little small-scale structure. We detect the "cocoon" inside the Southern Bubble, and we also identify its northern counterpart above 2 GeV. The Northern Cocoon lies along the same axis but is $\sim 30\%$ dimmer than the southern one. We characterize the Galactic center excess, which we find extends up to 20° in $|b|$. At latitudes $|b| \leq 5^\circ$ we find evidence for power in small angular scales that could be the result of point-source contributions, but for $|b| \geq 5^\circ$ the Galactic center excess is dominantly diffuse in its nature. Our findings show that either the Galactic center excess and *Fermi* Bubbles connect smoothly or that the Bubbles brighten significantly below 15° in latitude. We find that the Galactic center excess appears off-center by a few degrees towards negative ℓ. Additionally, we find and characterize two emissions along the Galactic disk centered at $\ell \simeq +25^\circ$ and -20°. These emissions are significantly more elongated along the Galactic disk than the Galactic center excess.

[astro-ph.HE] 5 Mar 2018

I. INTRODUCTION

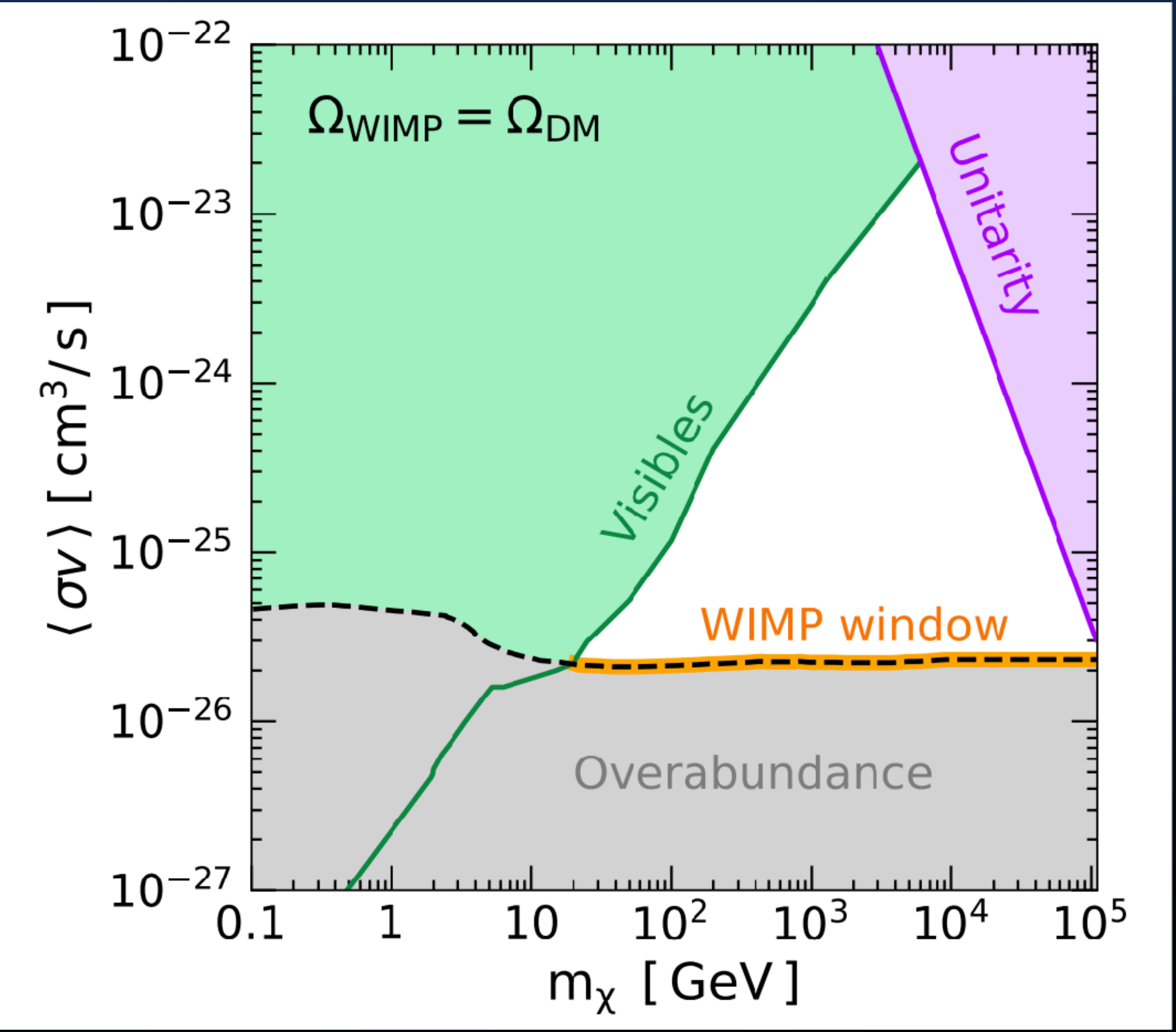
Electromagnetic radiation has allowed us a gateway to the mysteries of the Universe since time immemorial. Over the ages, we have become sensitive to radiation of increasingly higher energy. The highest energy photons are classified as gamma rays. Gamma-ray astronomy started in 1961 with 22 events observed by *Explorer 11* [1]. This was followed by *OSO-3*, which observed 621 photons and provided the first proof of emission from our own Milky Way [2]. Observations ensued with the *SAS-2*

cosmic rays (CRs) propagating in the Galaxy and interacting with the interstellar medium (ISM). The mechanism of diffuse emission is conventionally broken down into three classes, depending on the type of CR and the type of target it impinges upon. The dominant contribution to diffuse emission is from inelastic collisions of CR *nuclei* with ISM gas; these collisions produce neutral particles, predominantly π^0 and η mesons, whose decay products include photons. This emission is conventionally referred to as π^0-emission [14, 15]. CR *electrons* can also interact with the ISM gas [16]. The resulting photons



WIMP Parameter Space is not Dead

Leane et al. (2018; 1805.10305)



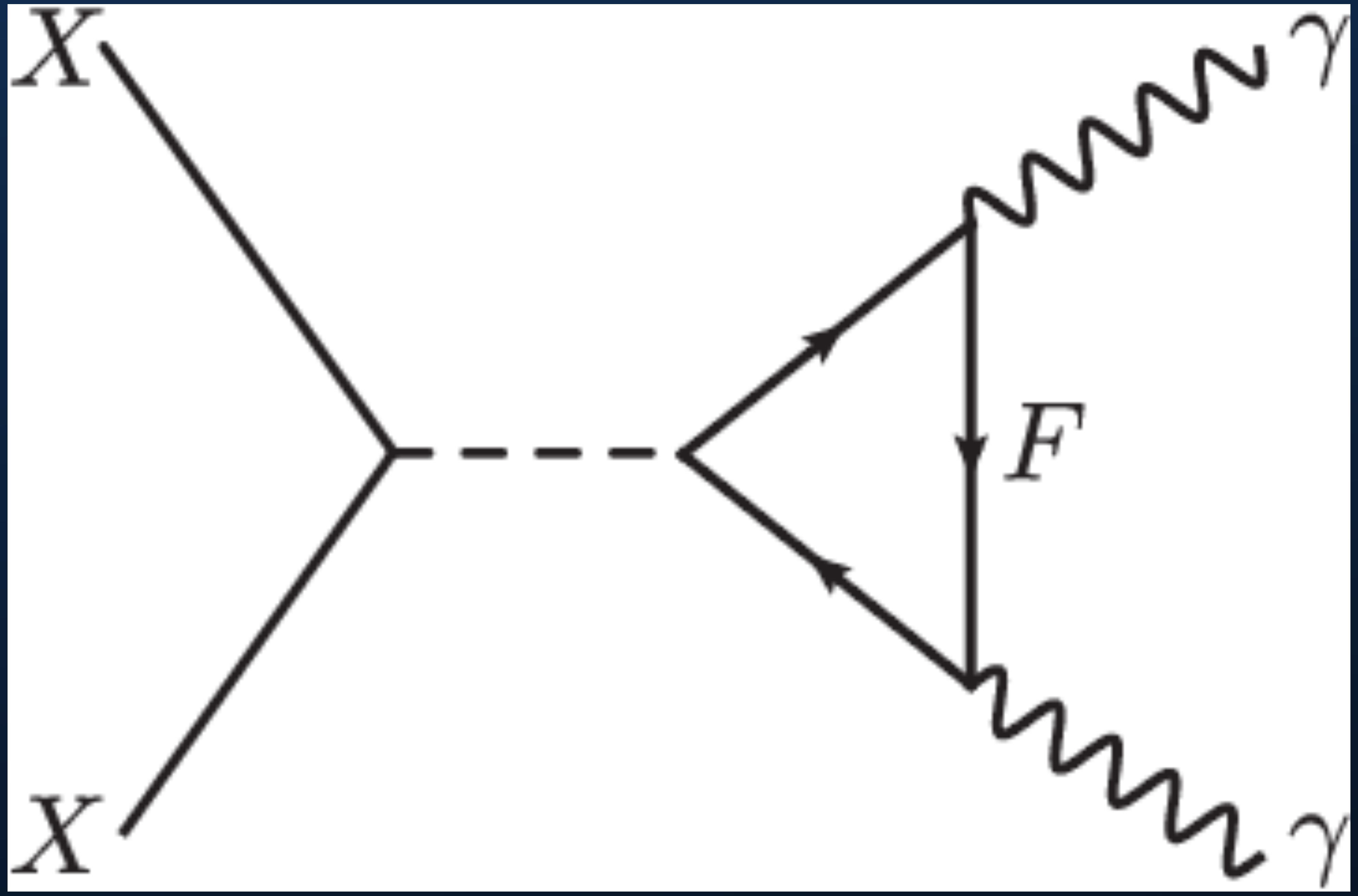
Gamma-Ray Lines

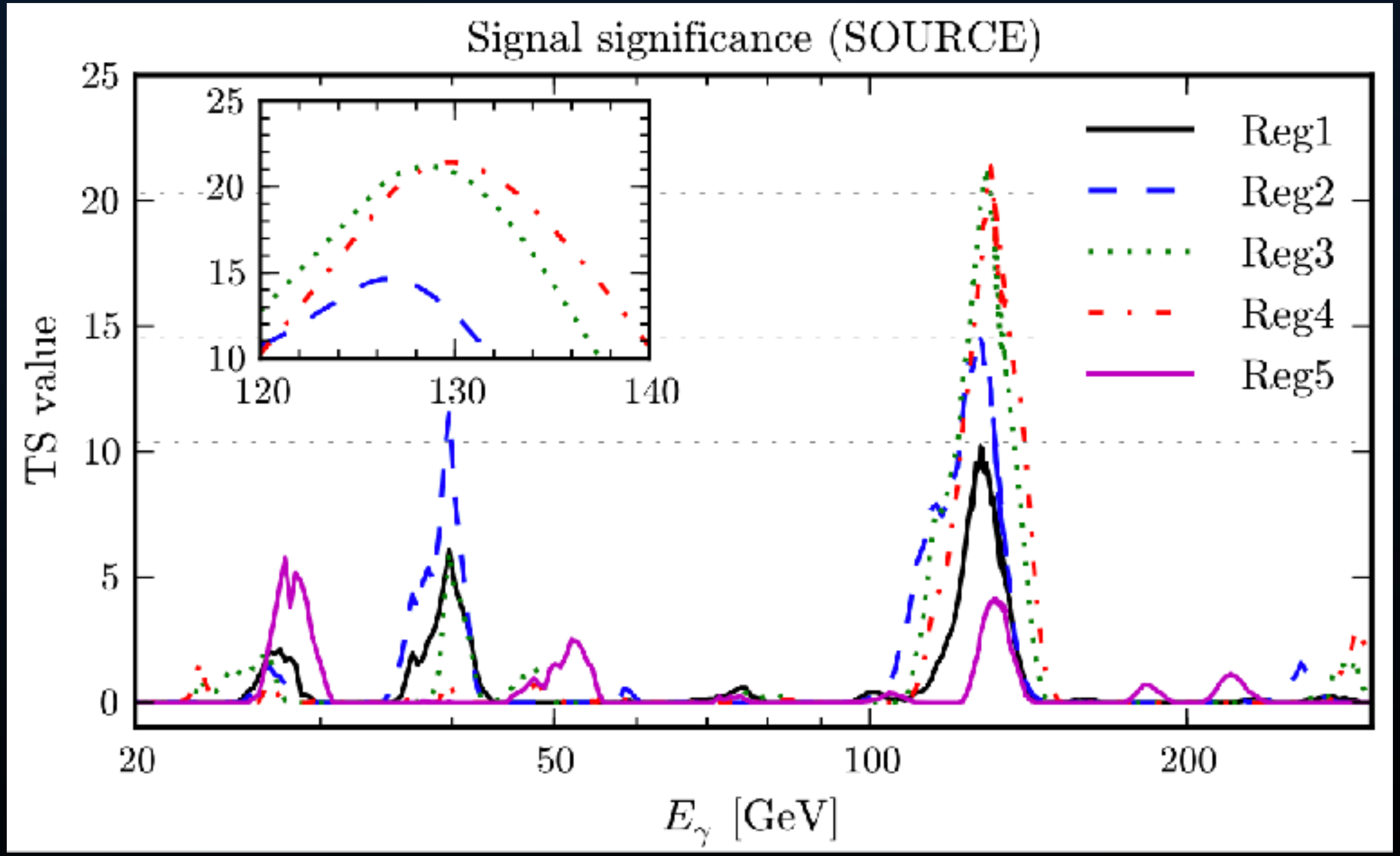
-Standard dark matter should not couple directly to photons (“dark, remember”)

-Can couple at loop level, while obeying limits

-In general - smaller coupling by factor α_{EM}^2, but many models exist

-Line potentially detected by Weniger (2012)





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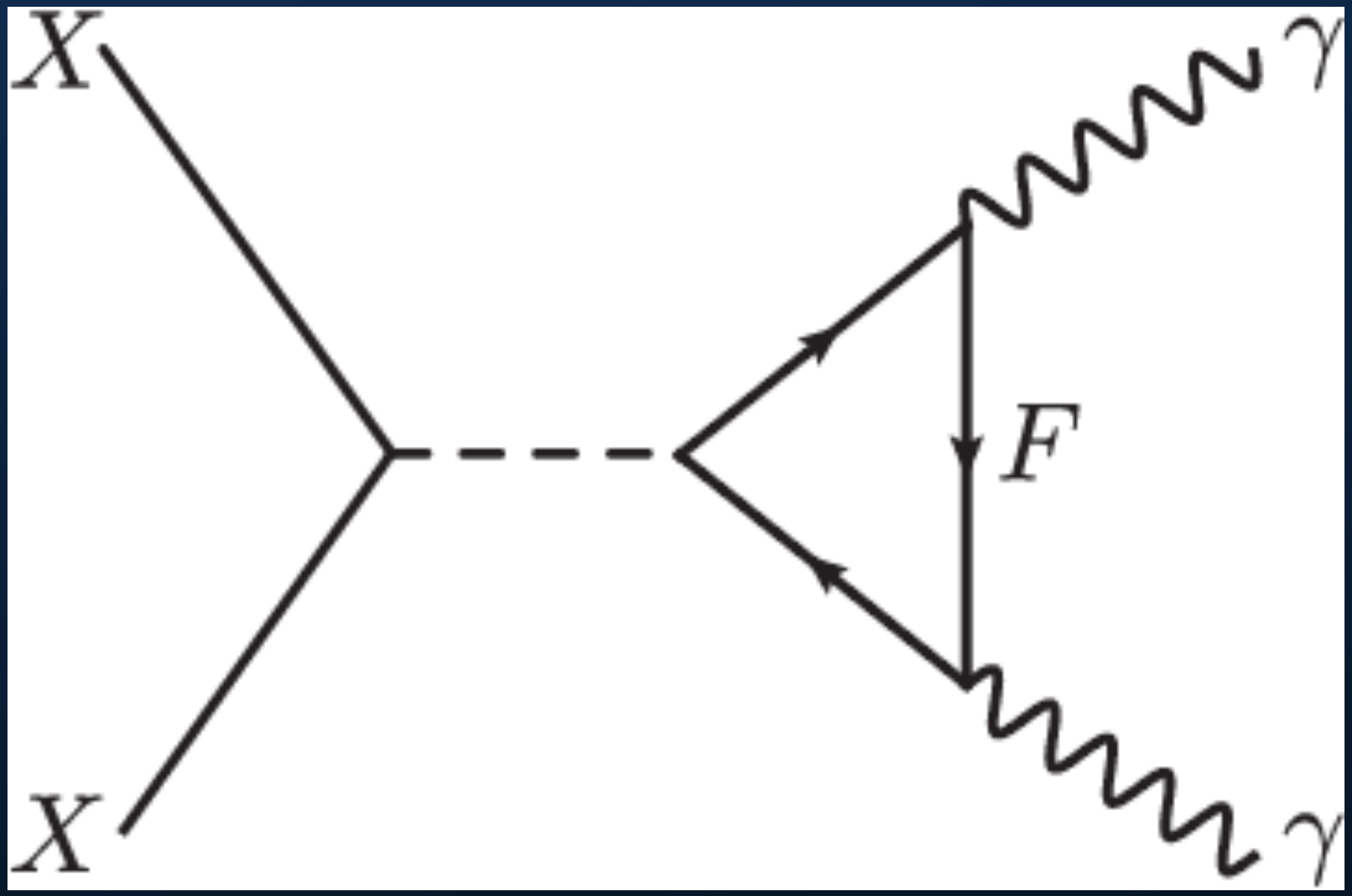

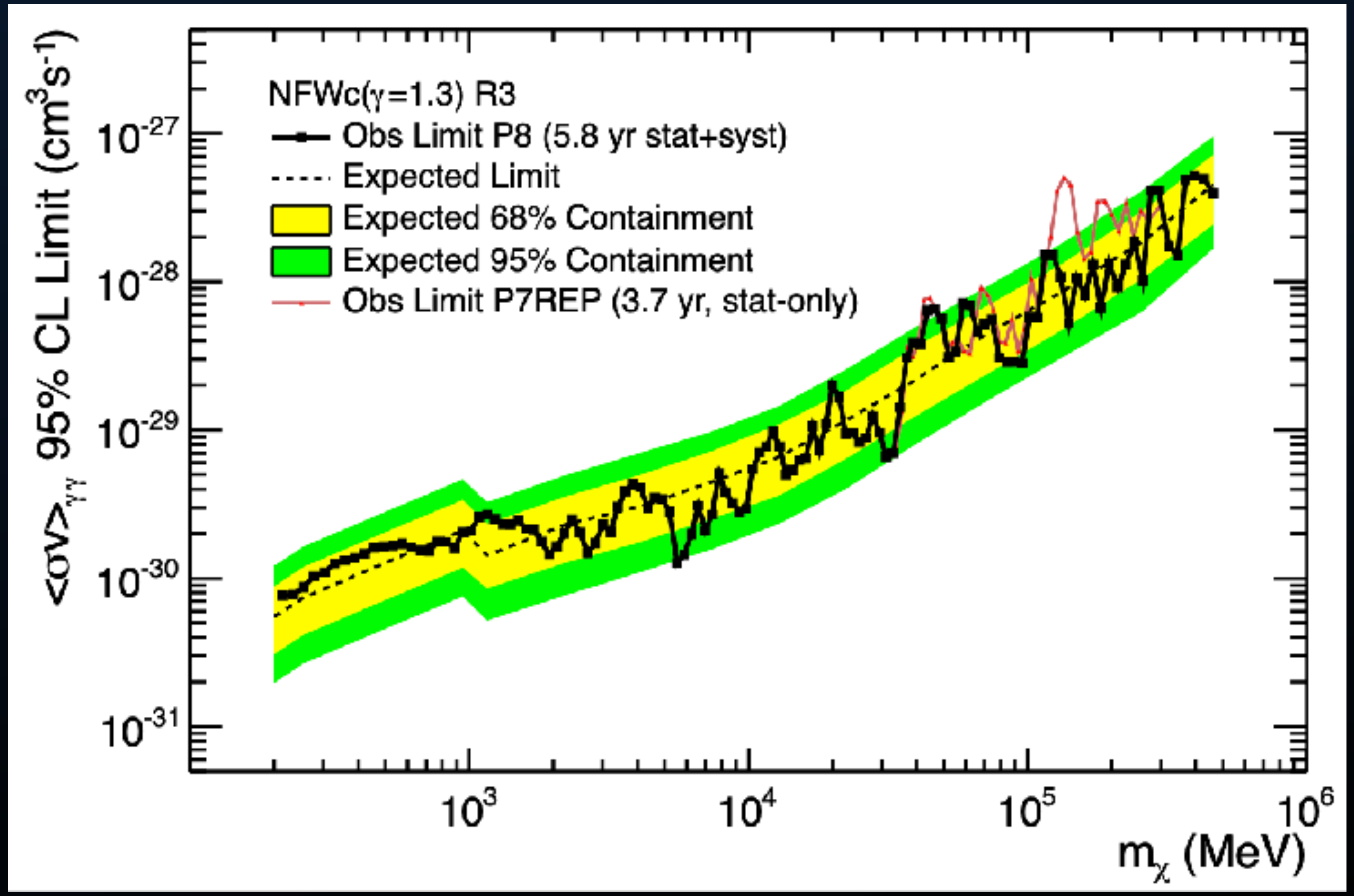

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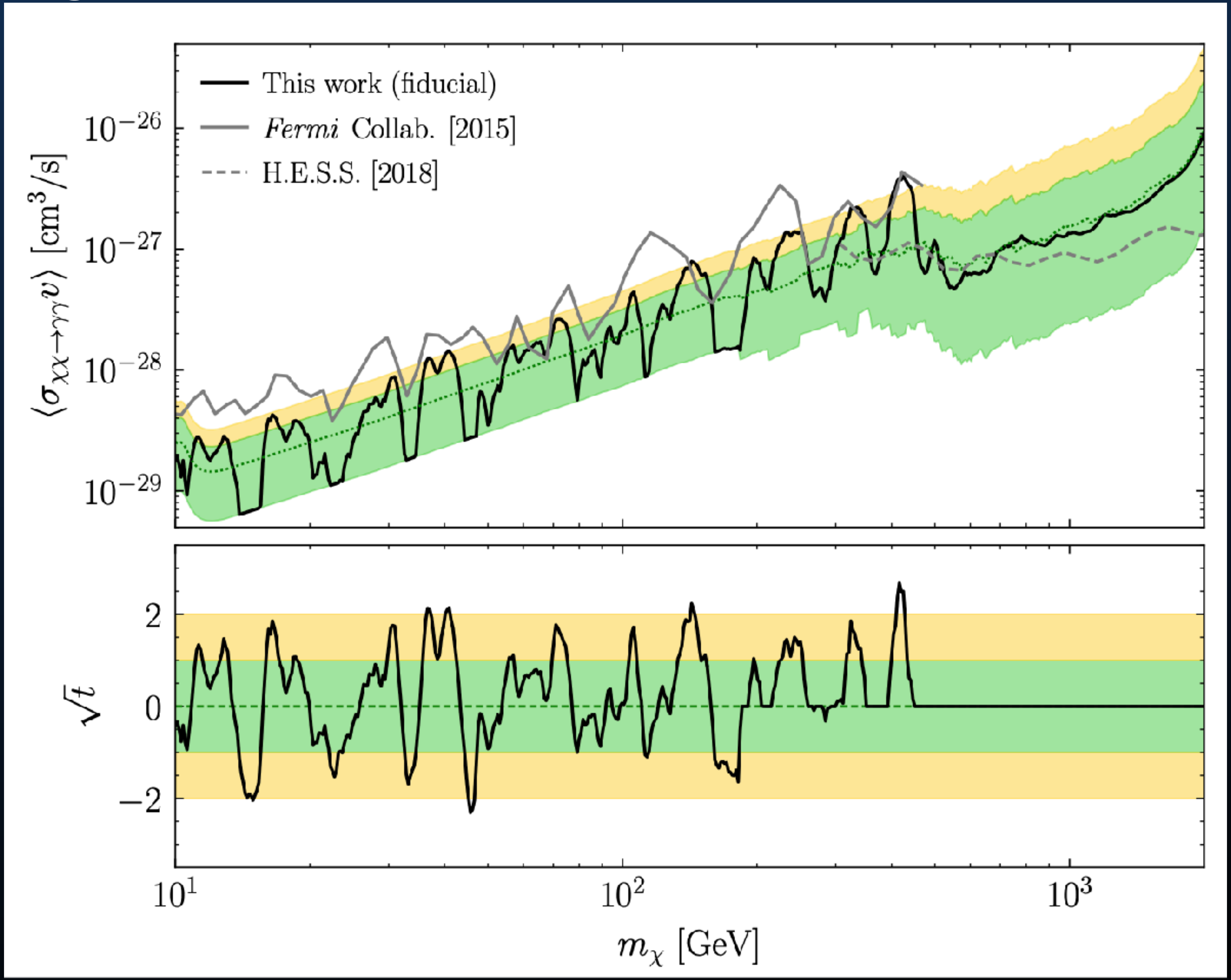

Other Dark Matter Searches

-Axions are one of the lightest dark matter particles (energies usually below 1 eV).

- Can get resonant conversion when photon effective mass in plasma equals axion mass.

-For 1 T magnetic fields (Earth experiments), this is in the radio range.

-For 1 μG magnetic fields (astrophysics) this is in the GeV range.