AIP Congress 2022, Adelaide

Detection of the Sagittarius Dwarf Spheroidal Galaxy in Gamma-Rays

Roland Crocker

Australian National University

Gamma-Ray Emission from the Sagittarius Dwarf Spheroidal Galaxy due to Millisecond Pulsars,
Crocker, Macias et al., Nature Astr. (2022)
[arXiv:2204.12054]

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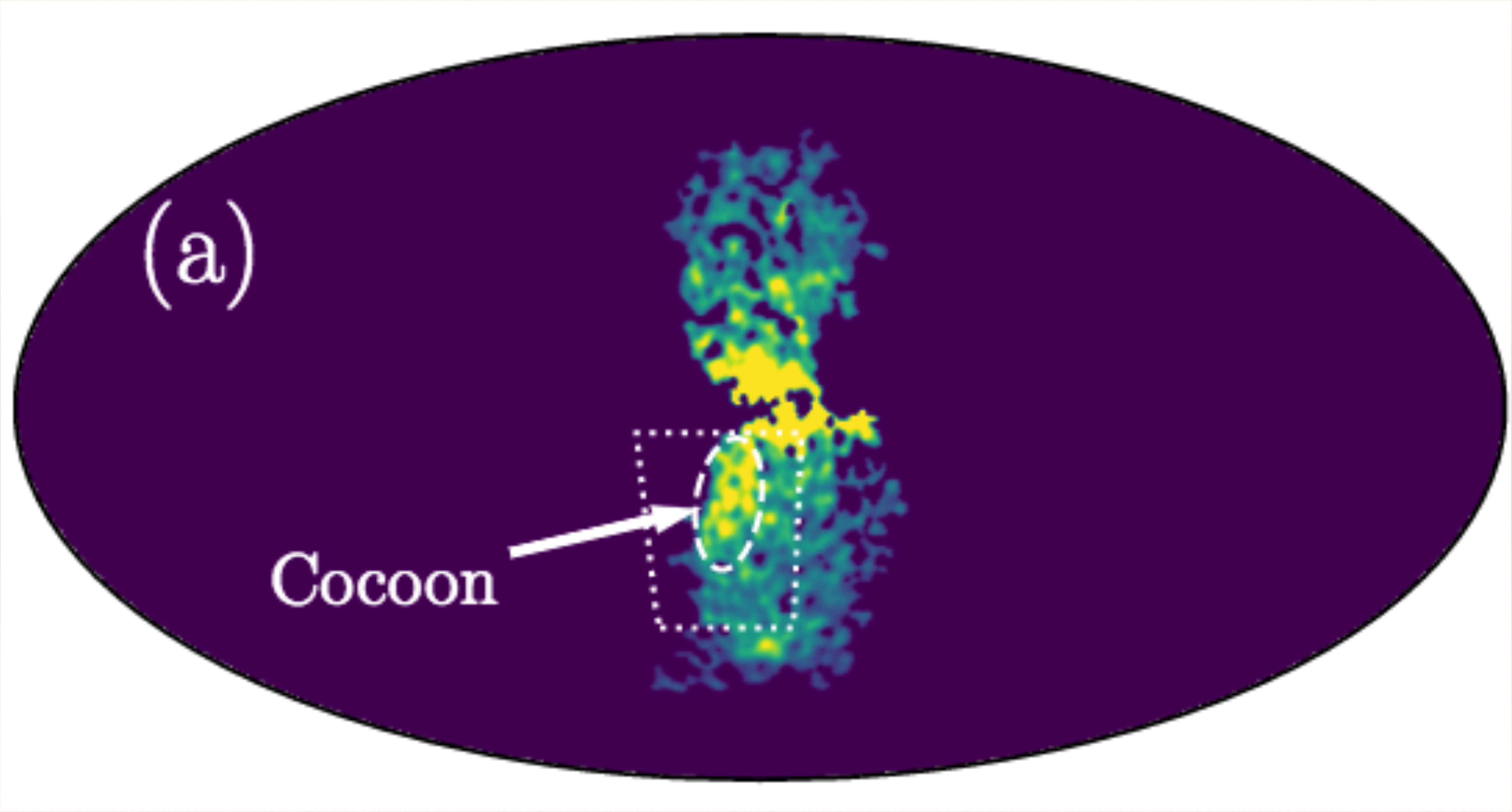
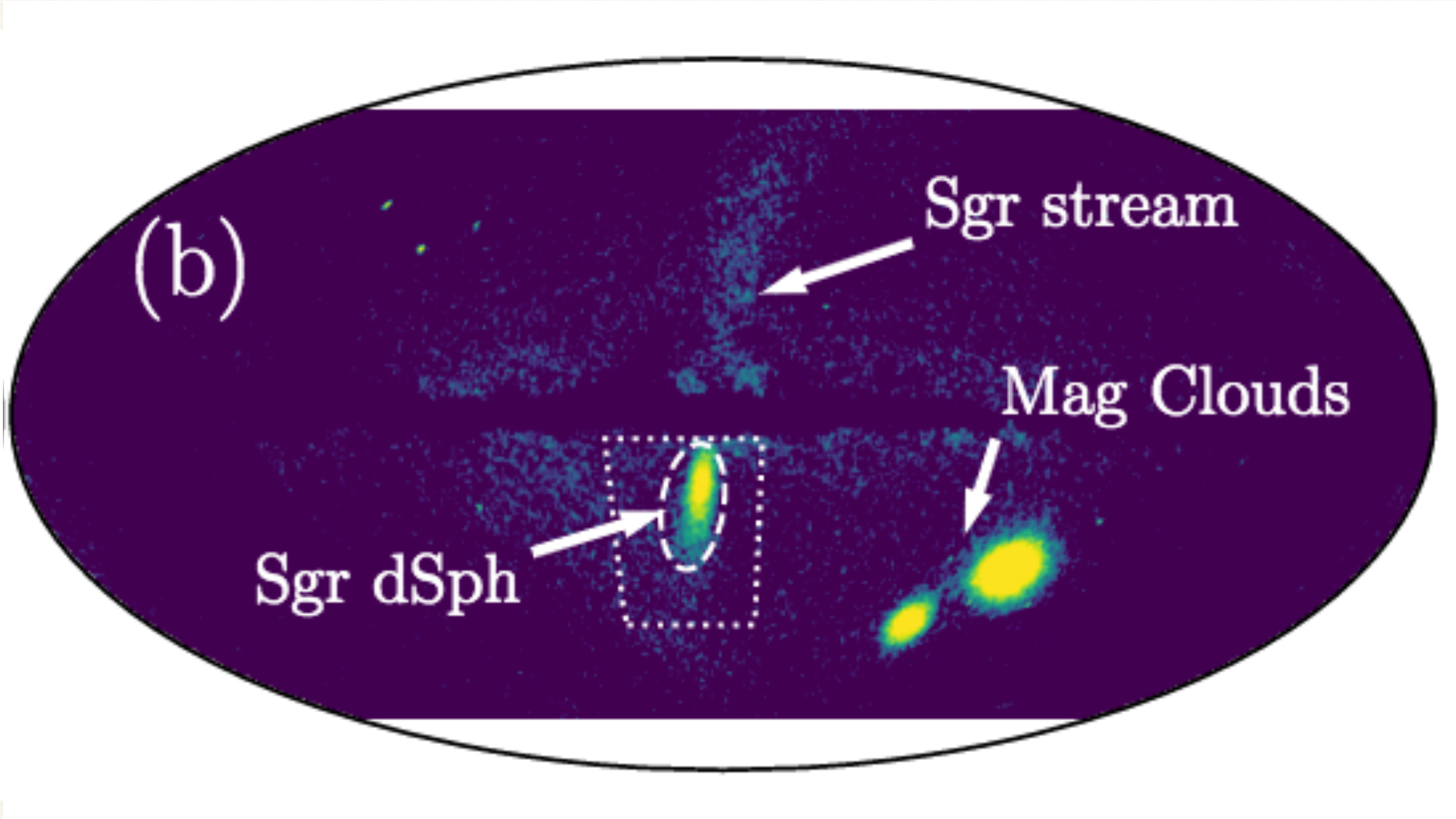
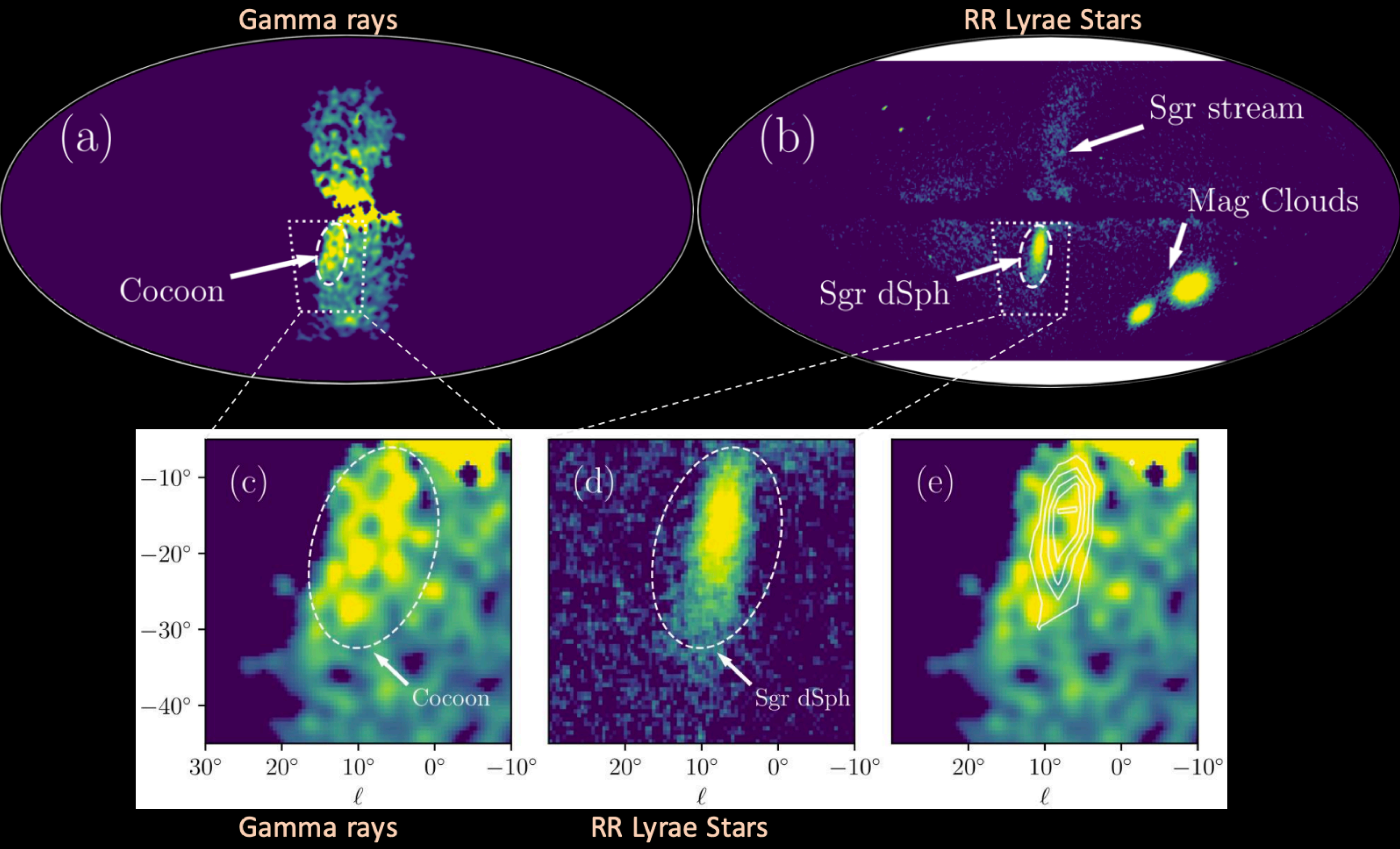
Sgr dSph and Fermi Bubbles 'Cocoon'



Fermi Bubbles **template defined by the** ***Fermi*** **Collaboration**

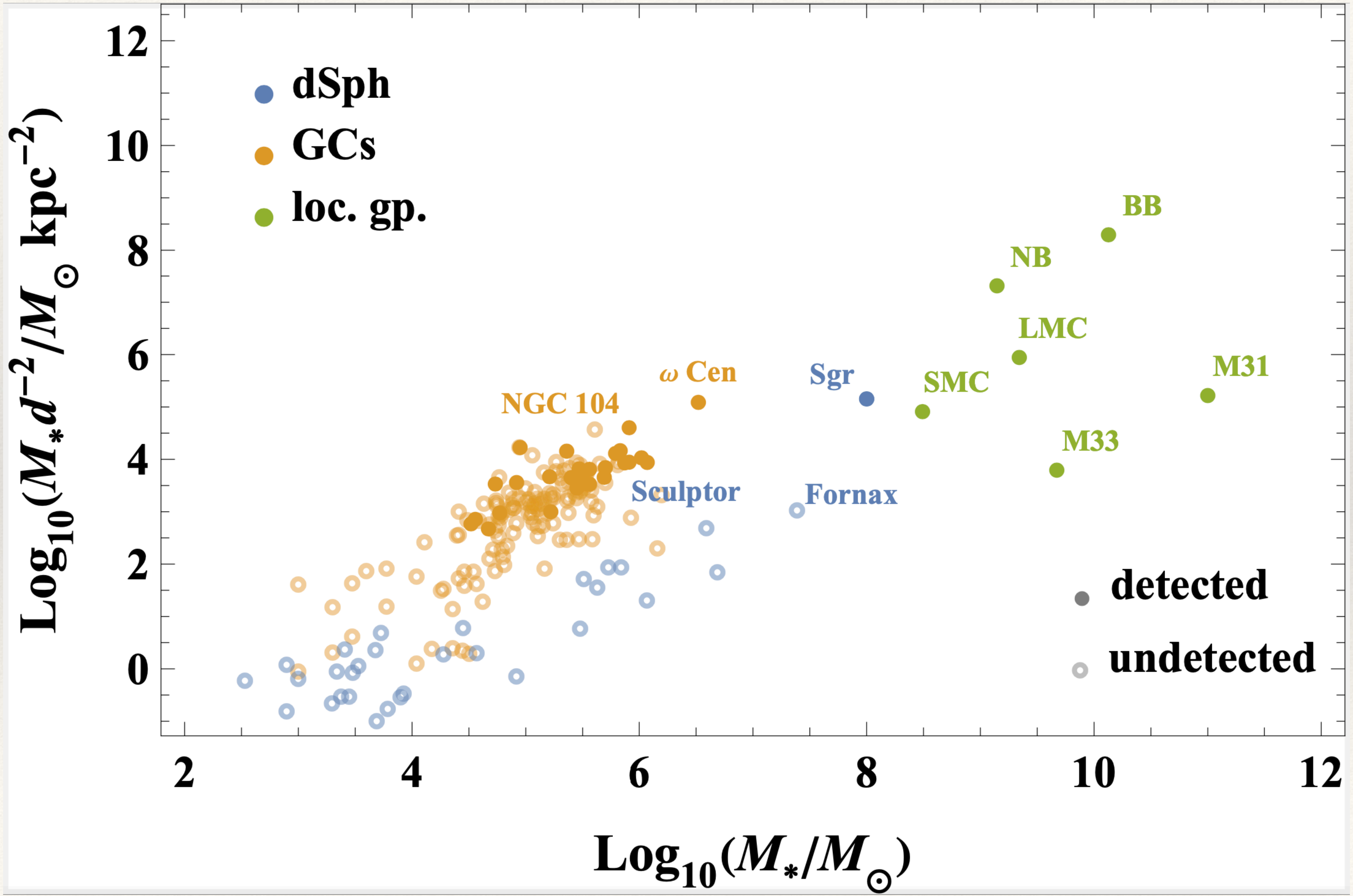
Sgr dSph and Fermi Bubbles ‘Cocoon’





Gamma rays
RR Lyrae Stars
(a)
Cocoon
(b)
Sgr stream
Mag Clouds
Sgr dSph
(c)
Cocoon
(d)
Sgr dSph
(e)
−10°
−20°
−30°
−40°
30°
20°
10°
0°
−10°
ℓ
Gamma rays
RR Lyrae Stars

Context



dSph
GCs
loc. gp.
BB
NB
LMC
M31
SMC
Sgr
ω Cen
NGC 104
M33
Sculptor
Fornax
detected
undetected
$\mathrm{Log}_{10}(M_* d^{-2}/M_\odot\ \mathrm{kpc}^{-2})$
$\mathrm{Log}_{10}(M_*/M_\odot)$
12
10
8
6
4
2
0
2
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10
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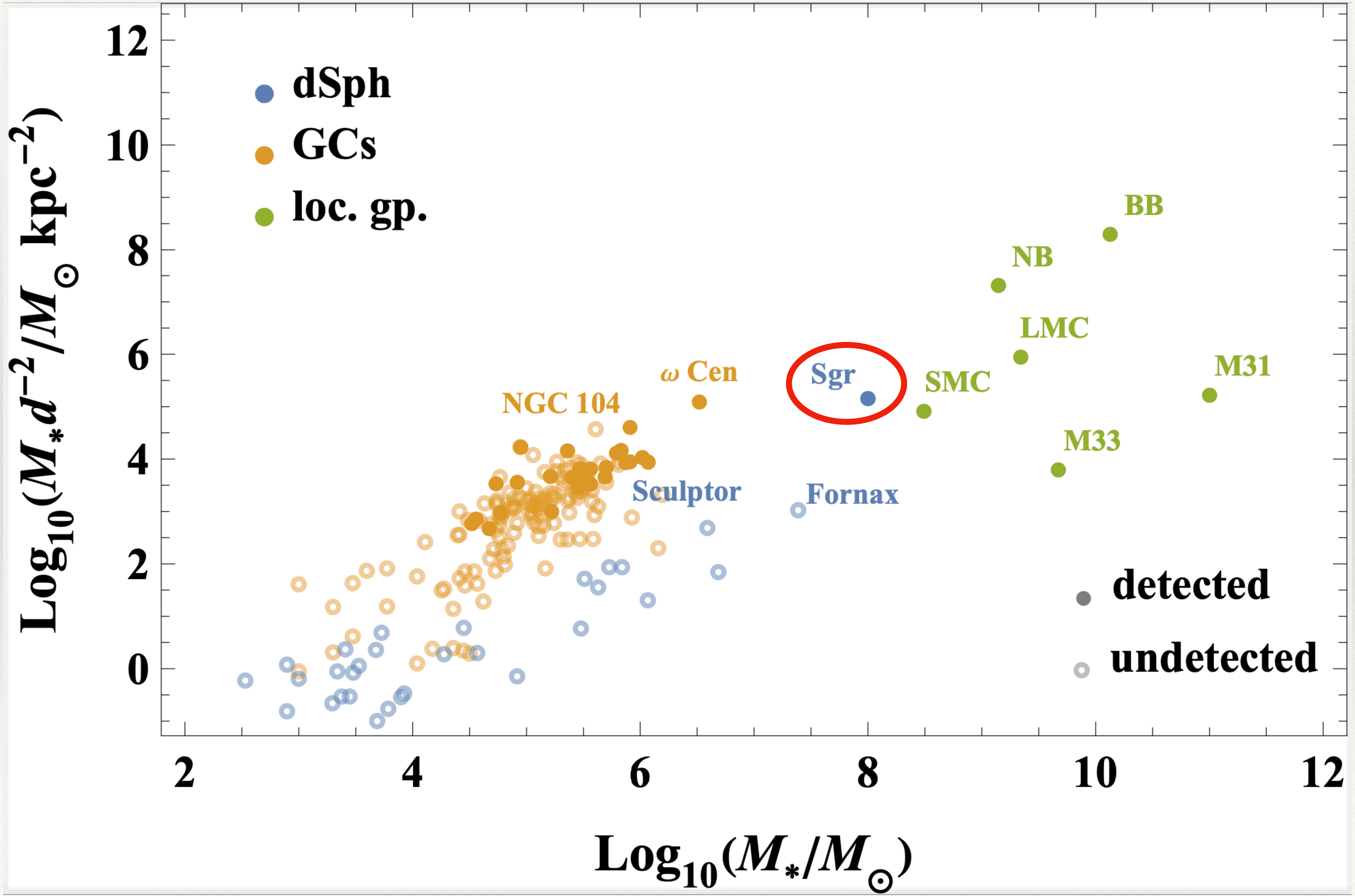

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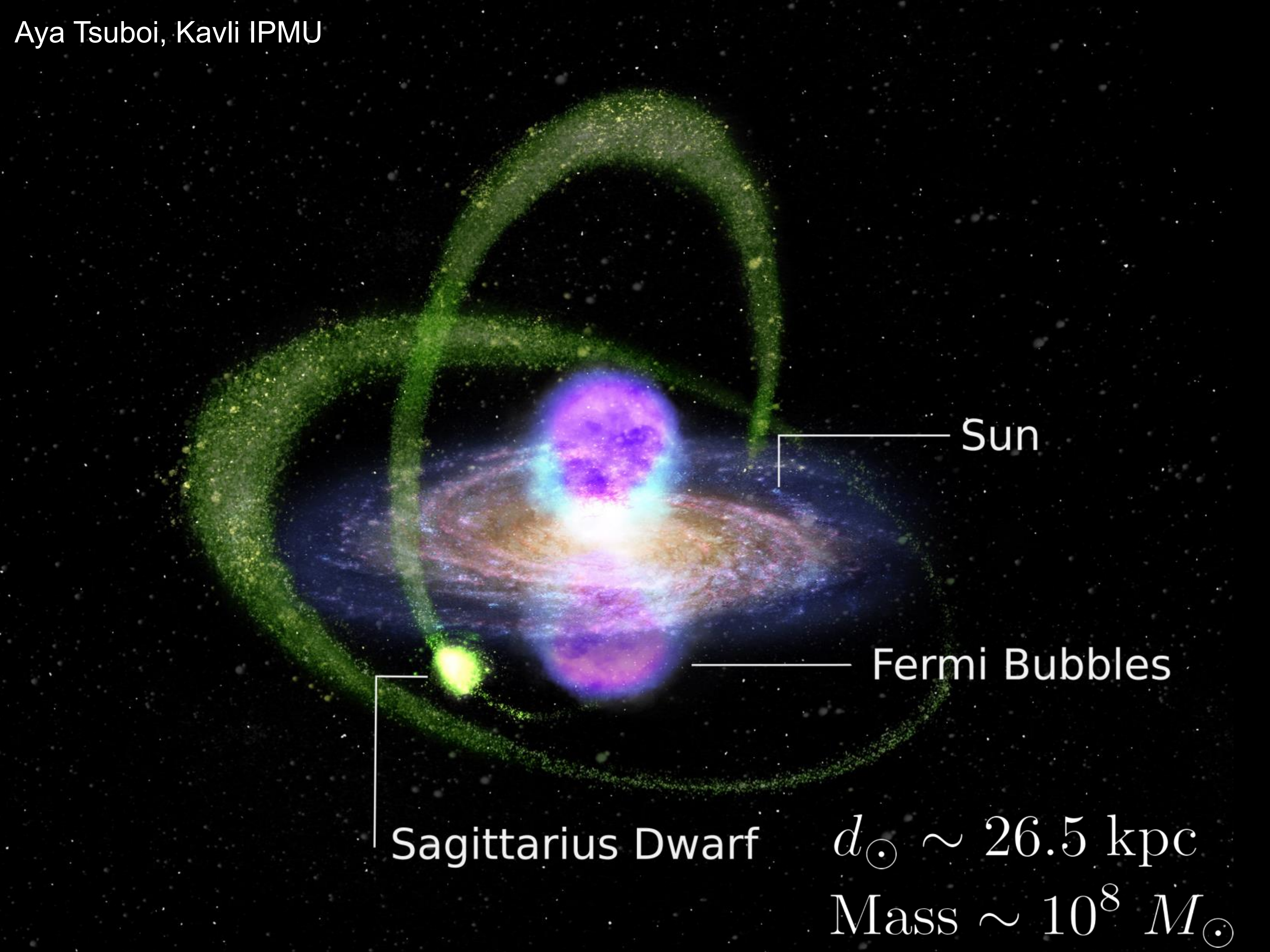
Aya Tsuboi, Kavli IPMU
Sun
Fermi Bubbles
Sagittarius Dwarf
$d_\odot \sim 26.5$ kpc
Mass $\sim 10^8\ M_\odot$

Detection significance

Template choices				Results			
Hadr. / Bremss.	IC	FB	Sgr dSph	$-\log(\mathcal{L}_{\text{Base}})$	$-\log(\mathcal{L}_{\text{Base+Sgr}})$	$\text{TS}_{\text{Source}}$	Significance
Default model							
HD	3D	S	Model I	866680.6	866633.0	95.2	8.1 σ
Alternative background templates							
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Interpolated	3D	U	Model I	867287.4	867081.2	412.4	18.9 σ
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What is the signal?

- No gas (lost to tidal and ram pressure stripping)
- Star formation ceased 2-3 Gyr ago
  - ⇒*Not* hadronic emission (no CR hadrons from SF, no target hadrons)

The Galactic Plane as seen by *Fermi*

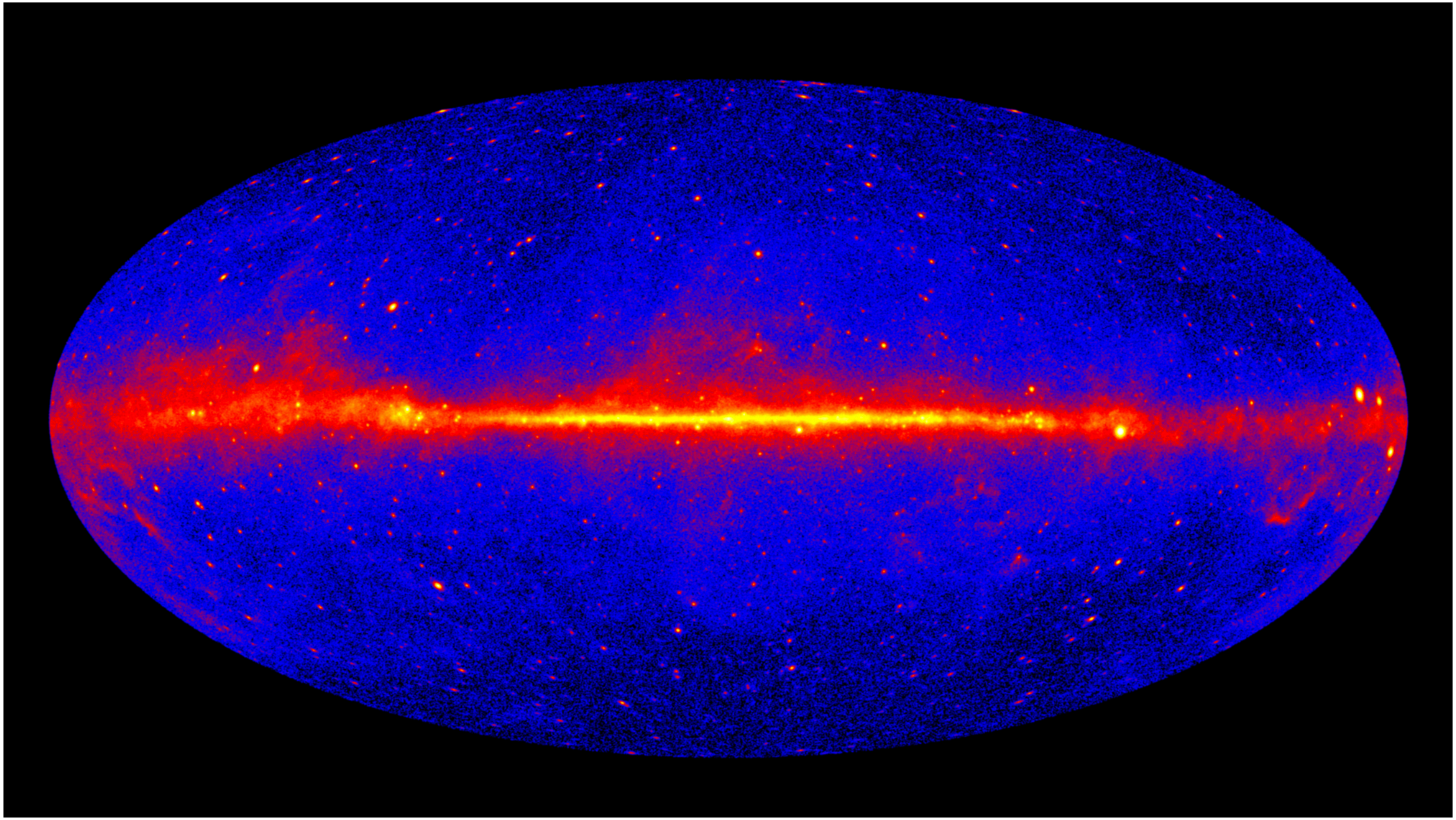


Figure 1: *Fermi*-LAT all sky image in Galactic co-ordinates. Credit: NASA/DoE.

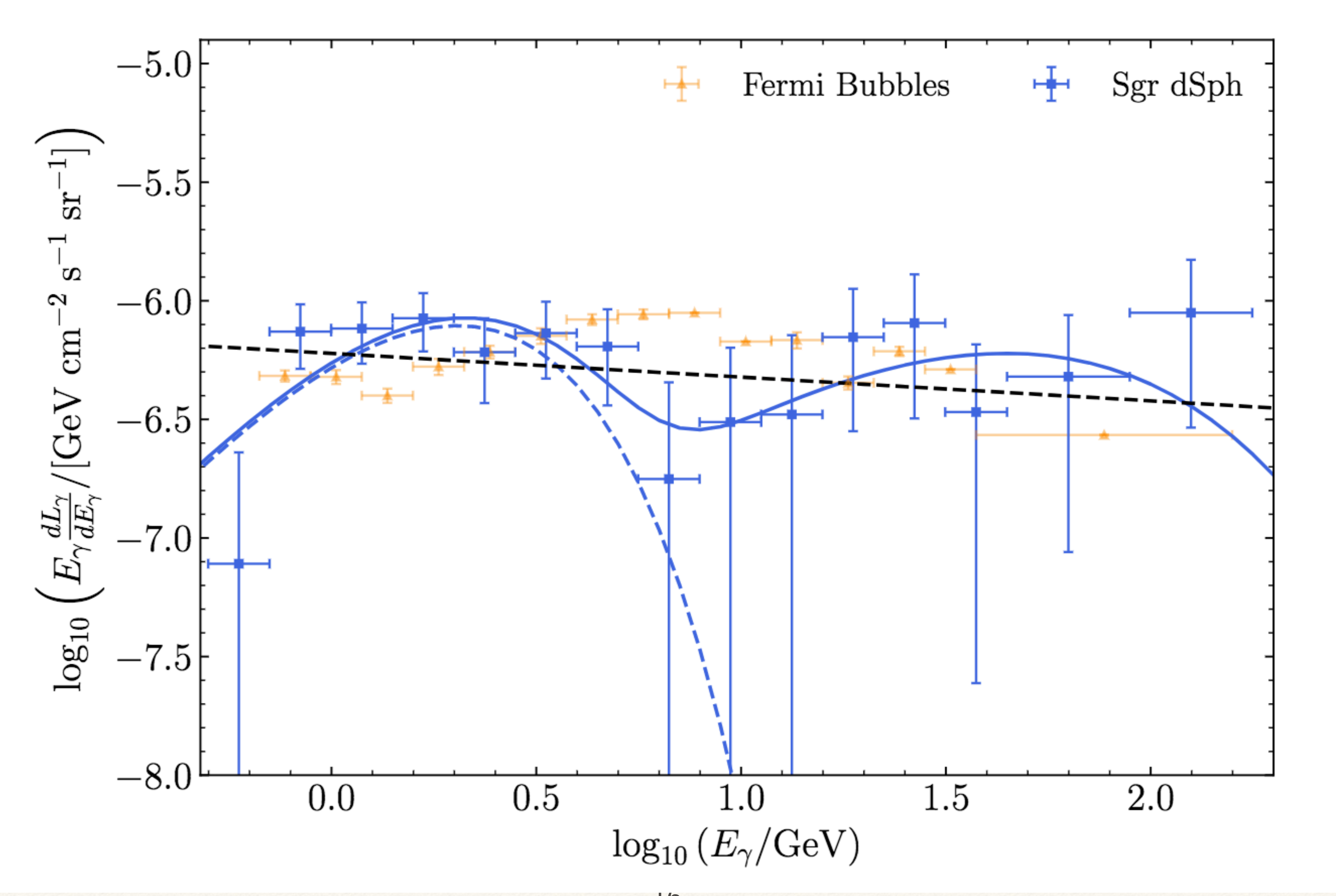
What is the signal?

- No gas (lost to tidal and ram pressure stripping)
- Star formation ceased 2-3 Gyr ago
  - ⇒*Not* hadronic emission (no CR hadrons from SF, no target hadrons
- Signal traces stars (proviso: see below)
  - ⇒*Not* dark matter

What is the signal?

- Millisecond pulsars (MSPs)?
  - Pros:
    - MSPs generate ~GeV γ-ray signals amongst old stellar populations (e.g., globular clusters, 'GCE', M31…)
    - Signal expected to trace stars
  - Cons:
    - At first sight, spectrum is wrong for MSPs

Spectrum


Fermi Bubbles
Sgr dSph
−5.0
−5.5
−6.0
−6.5
−7.0
−7.5
−8.0
0.0
0.5
1.0
1.5
2.0
$\log_{10}\left(E_\gamma \frac{dL_\gamma}{dE_\gamma}/[\mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}]\right)$
$\log_{10}(E_\gamma/\mathrm{GeV})$

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    - Signal expected to trace stars
  - Cons:
    - At first sight, spectrum is wrong for MSPs
    - γ-ray luminosity per stellar mass is much higher than for some other putatively MSP-dominated systems

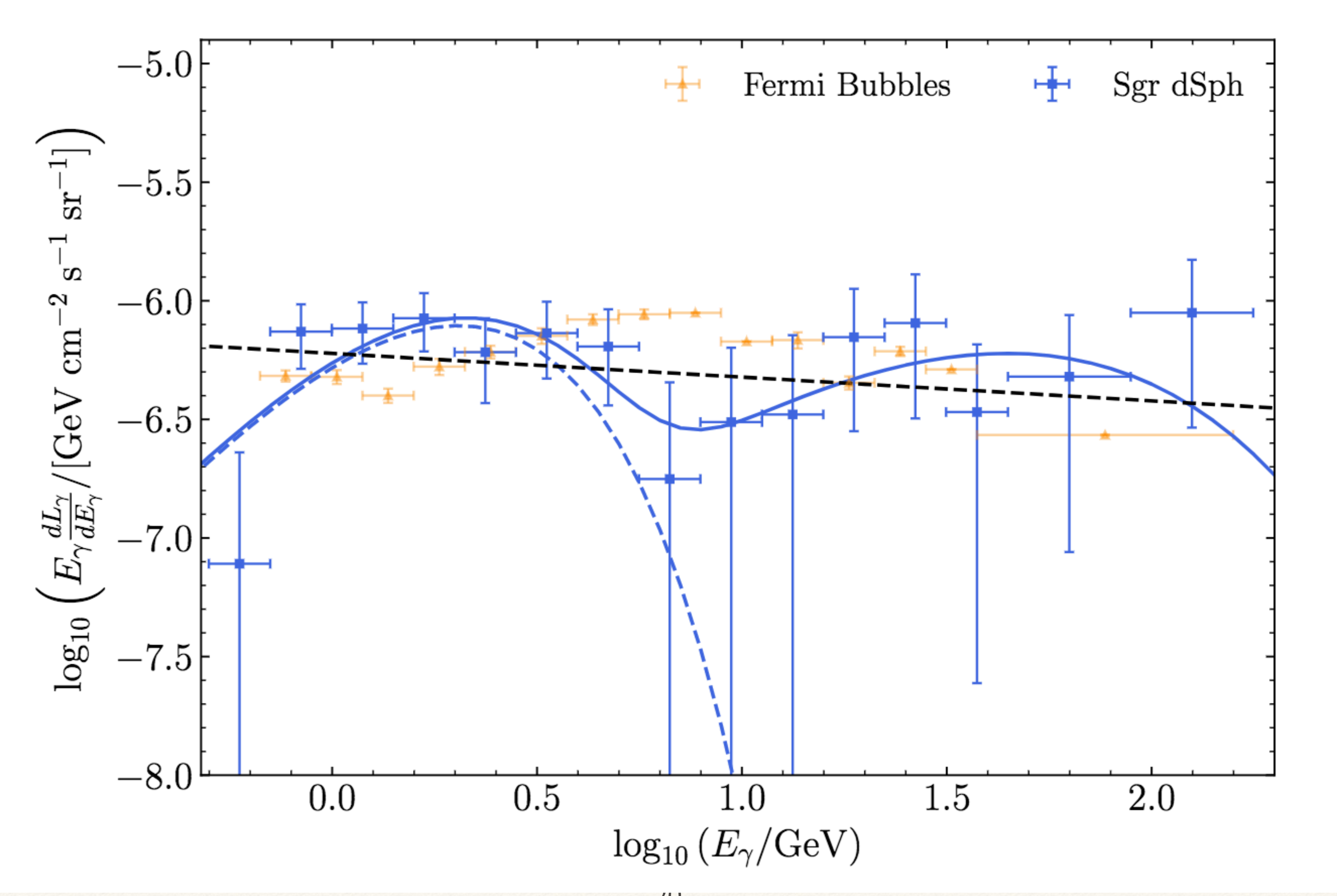
What is the signal?

- Unusual ISM conditions in Sgr dSph:
  - no gas
    - $\Rightarrow$ no way to anchor magnetic field lines
    - $\Rightarrow u_{ISRF}$ $(= u_{CMB}) \gg u_B$
    - $\Rightarrow$ CR $e^{\pm}$ released into ISM *can only* radiate via Inverse Compton (negligible synchrotron in contrast to 'usual' situation for MSP pairs)

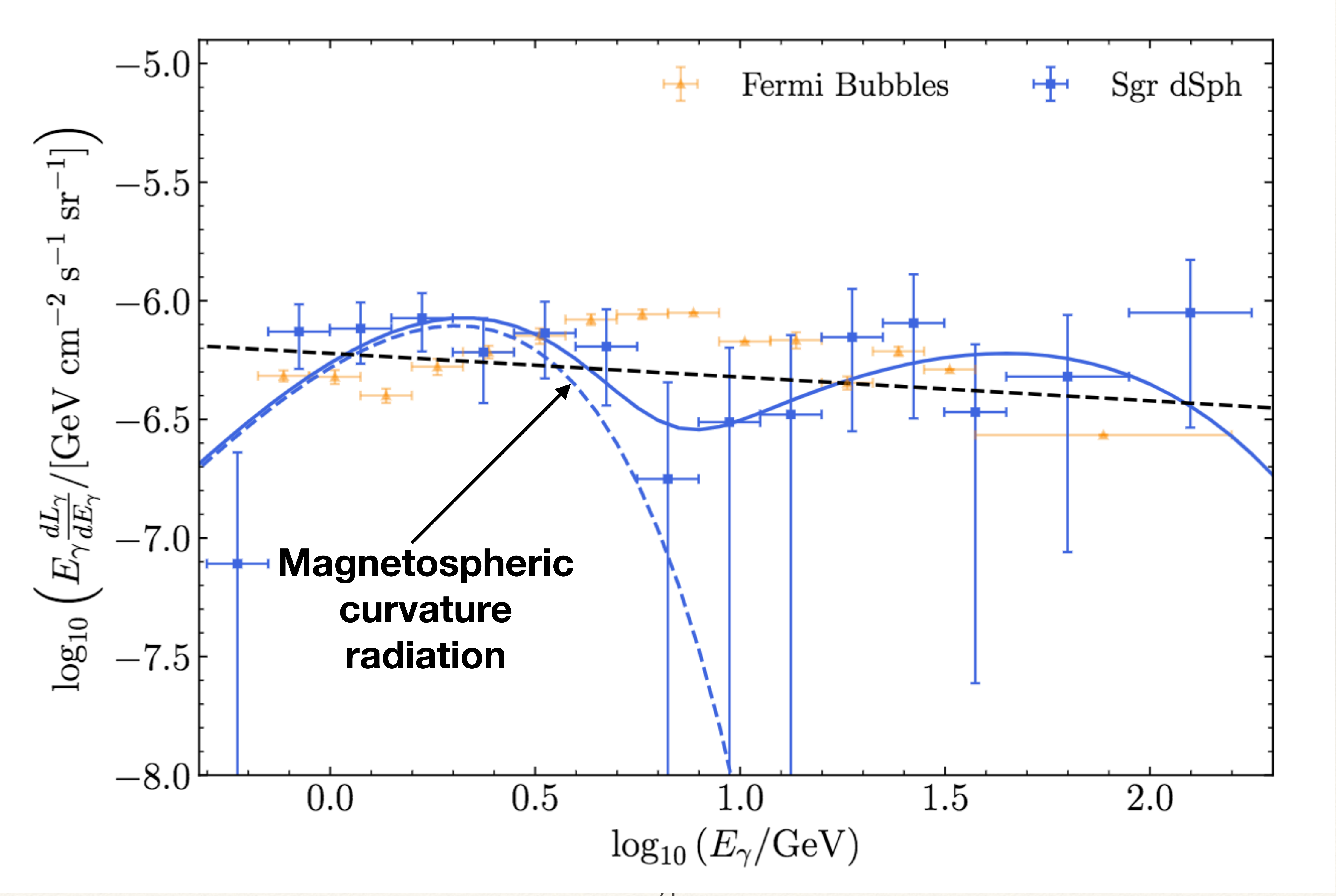
What is the signal?

- Physics of curvature radiation:
  - ~few GeV peak in SED of curvature radiation
    - ⇒ ~few TeV CR $e^{\pm}$
    - ⇒ ~few TeV CR $e^{\pm}$'s do ~100 GeV IC off CMB *as required*
  - Can also self consistently relate the spectrum of the putative magnetospheric curvature radiation and the spectrum of the IC from the pairs released into the ISM

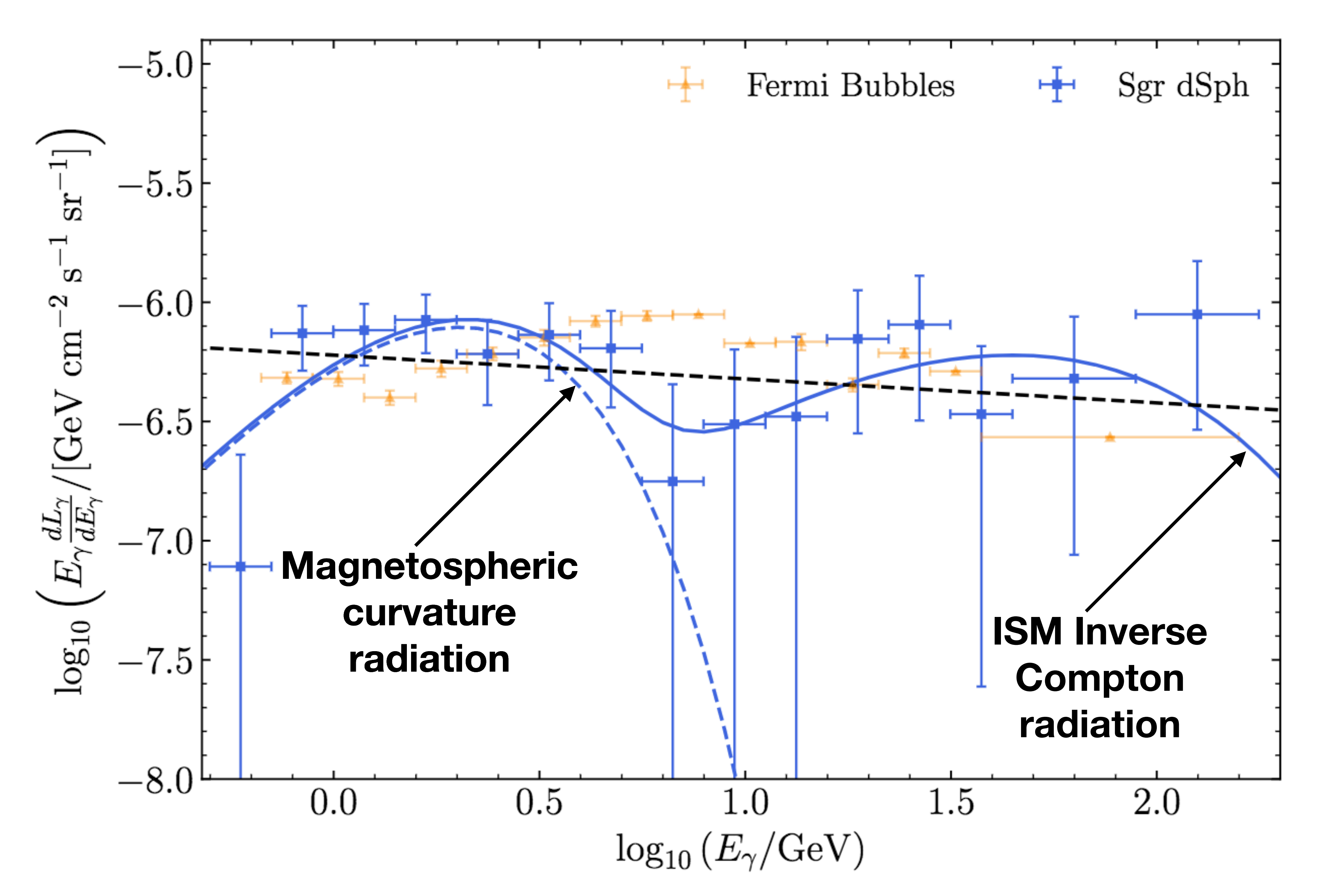
Spectrum: interpretation



Spectrum: interpretation



Spectrum: interpretation

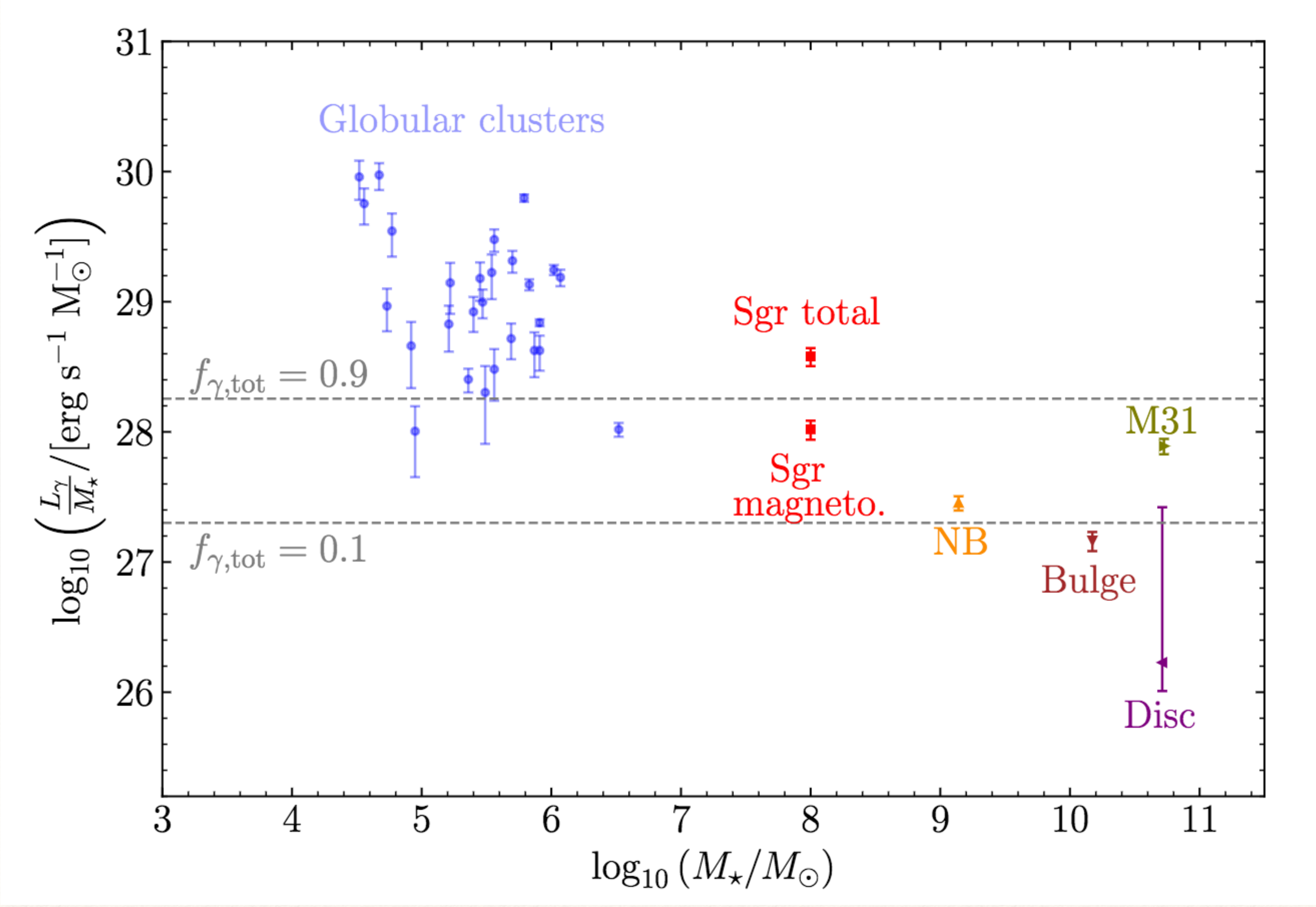


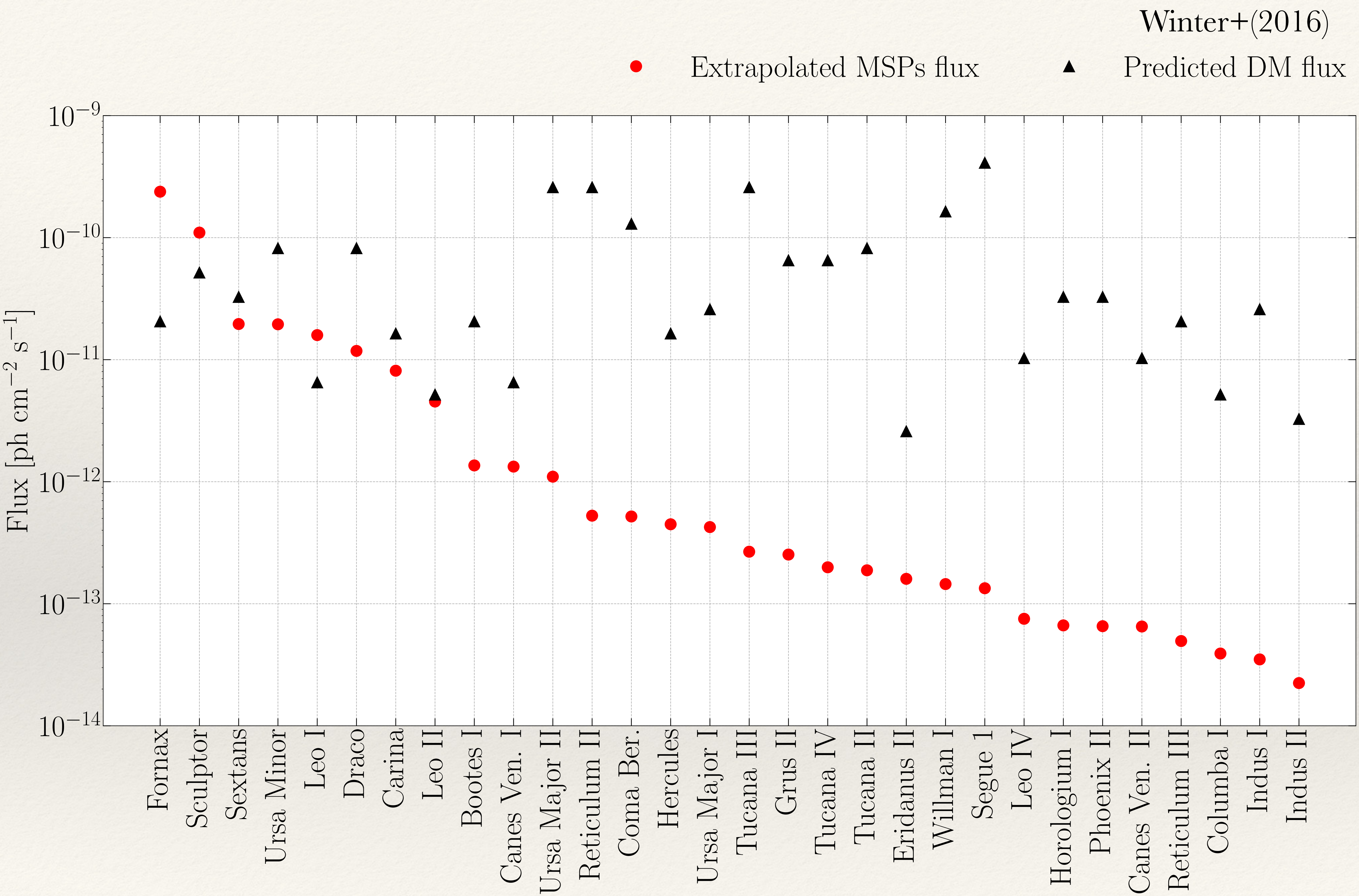
Spectrum: interpretation

- Overall spectrum consistent with same population of CR $e^{\pm}$ radiating in MSP magnetospheres
- …then leaking into ISM
- …then cooling/radiating via IC off CMB

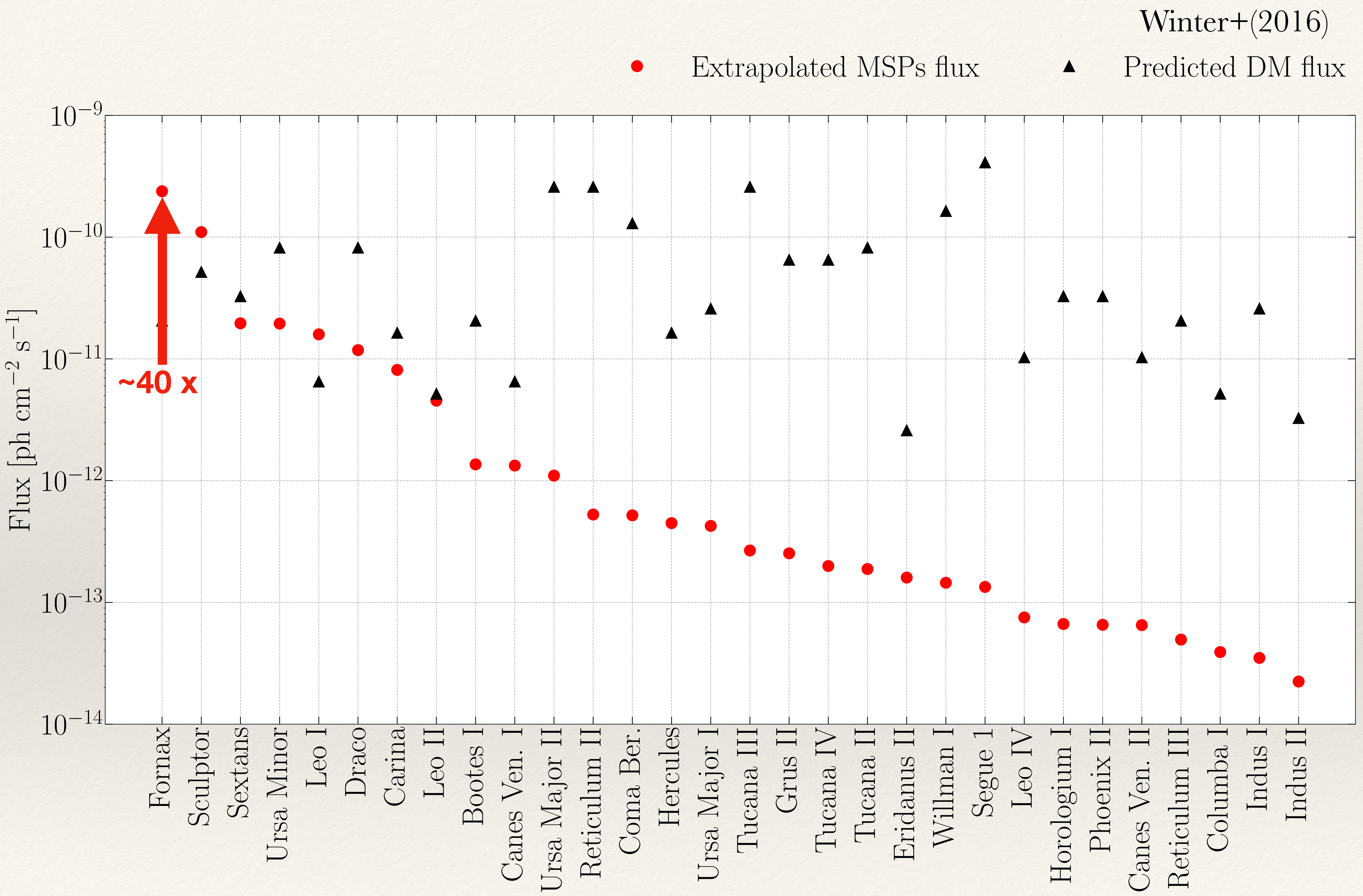
Implications

γ-ray luminosity normalised to stellar mass





Winter+(2016)
Extrapolated MSPs flux
Predicted DM flux
Flux [ph cm^{-2} s^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
Fornax
Sculptor
Sextans
Ursa Minor
Leo I
Draco
Carina
Leo II
Bootes I
Canes Ven. I
Ursa Major II
Reticulum II
Coma Ber.
Hercules
Ursa Major I
Tucana III
Grus II
Tucana IV
Tucana II
Eridanus II
Willman I
Segue 1
Leo IV
Horologium I
Phoenix II
Canes Ven. II
Reticulum III
Columba I
Indus I
Indus II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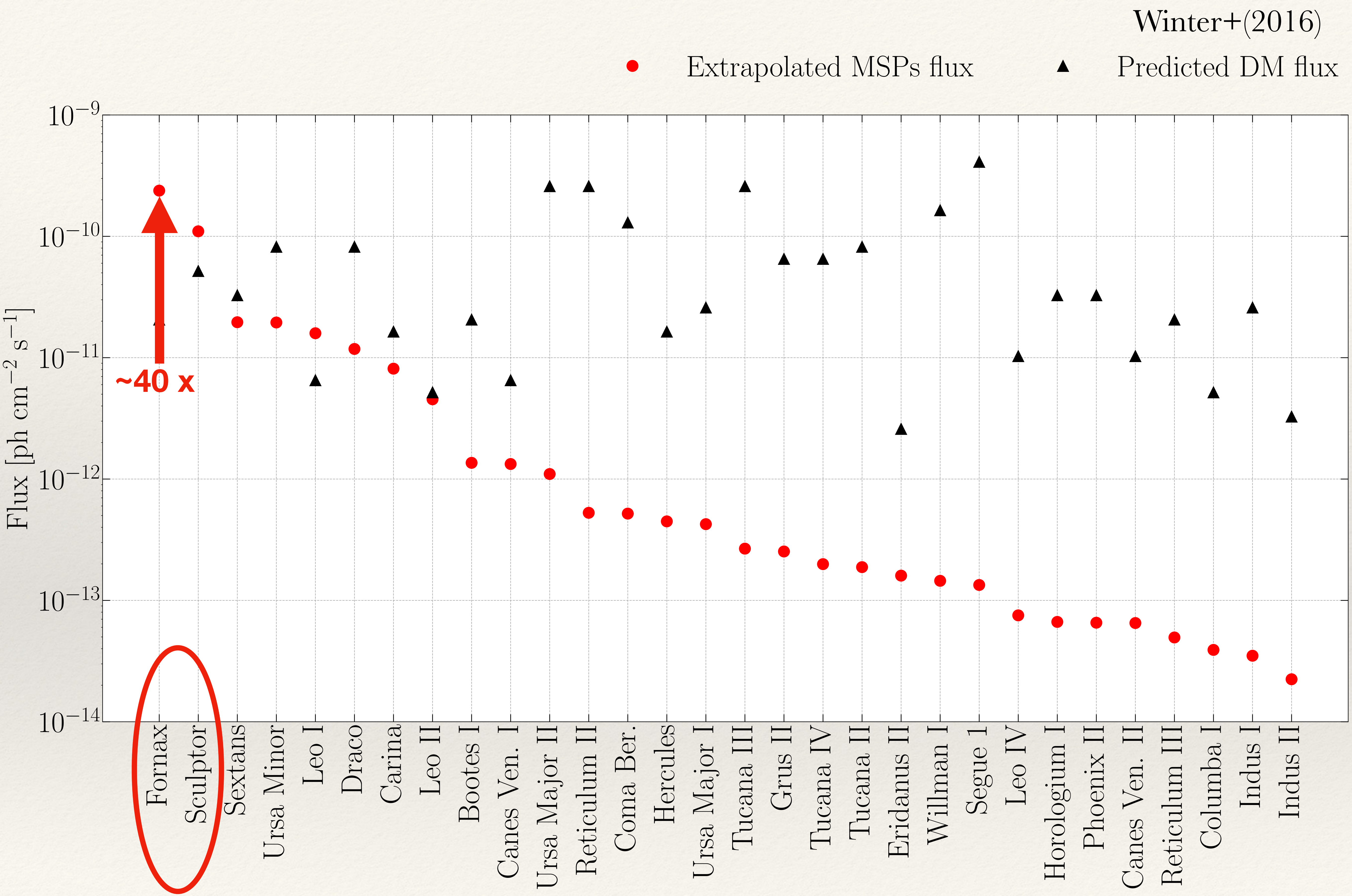

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Implications

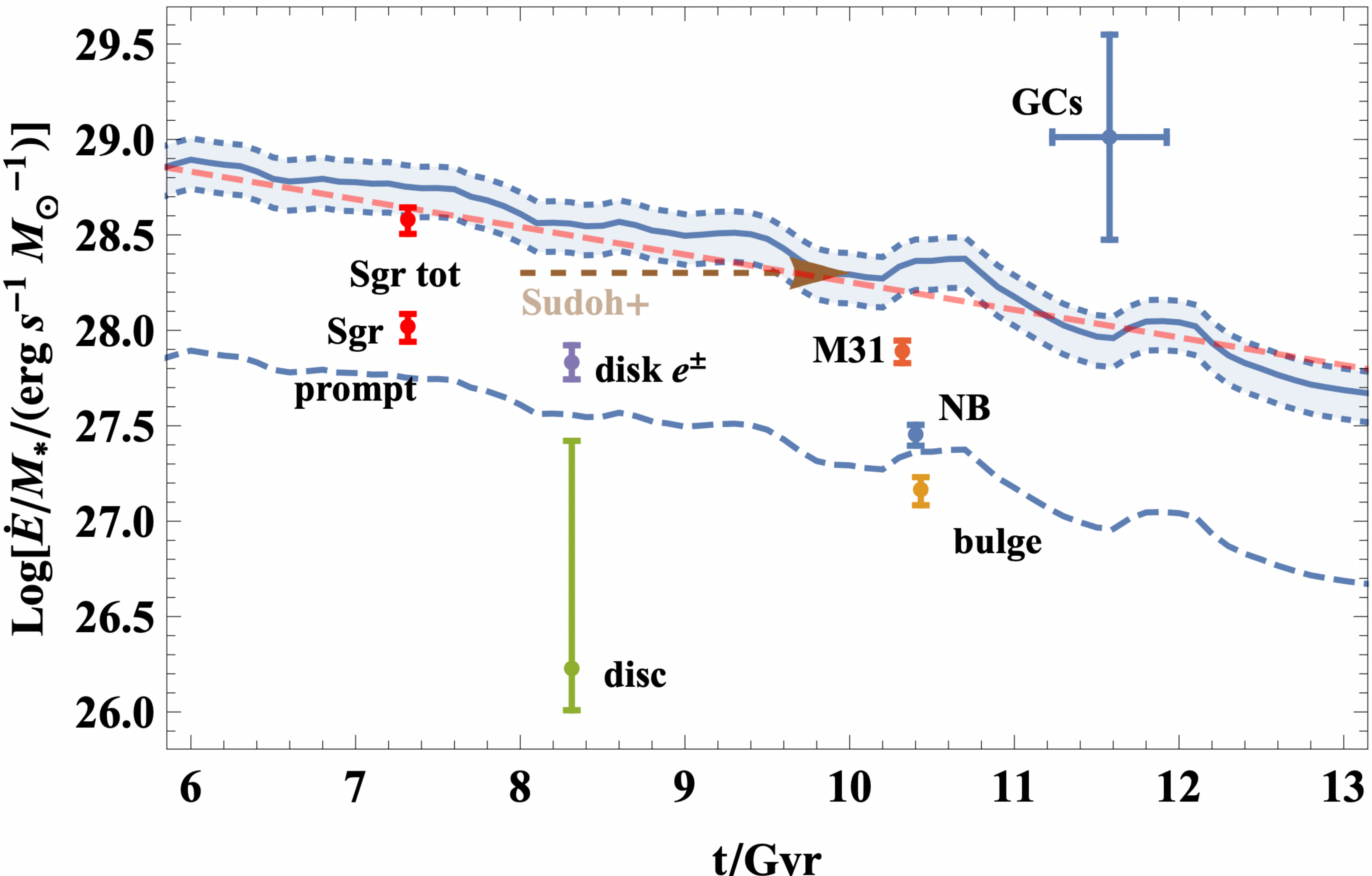
- Largely removes any residual motivation for the idea that Fermi Bubbles sub-structure be interpreted as γ-ray jets launched from the Galactic nucleus.
- WRT searches for the signatures of DM annihilation: astrophysical backgrounds in dwarf spheroidal galaxies can be stronger than previously appreciated. In general, a salutary example of how MSPs are a problem for indirect WIMP detection (cf. GCE).
- Our study lends support to the argument that MSPs contribute significantly to the energy budget of CR $e^{\pm}$ in galaxies with low specific star-formation rates.

Take-away messages

- We have detected ~1-100 GeV γ-ray emission from the Sagittarius dwarf spheroidal, the third-most massive satellite of the Milky Way (after LMC and SMC)
- The signal seems to be explained by millisecond pulsars belonging to the dwarf
- This discovery casts new light on MSPs as sources of non-thermal radiation and particles

Extra Slides

γ-ray luminosity normalised to stellar mass



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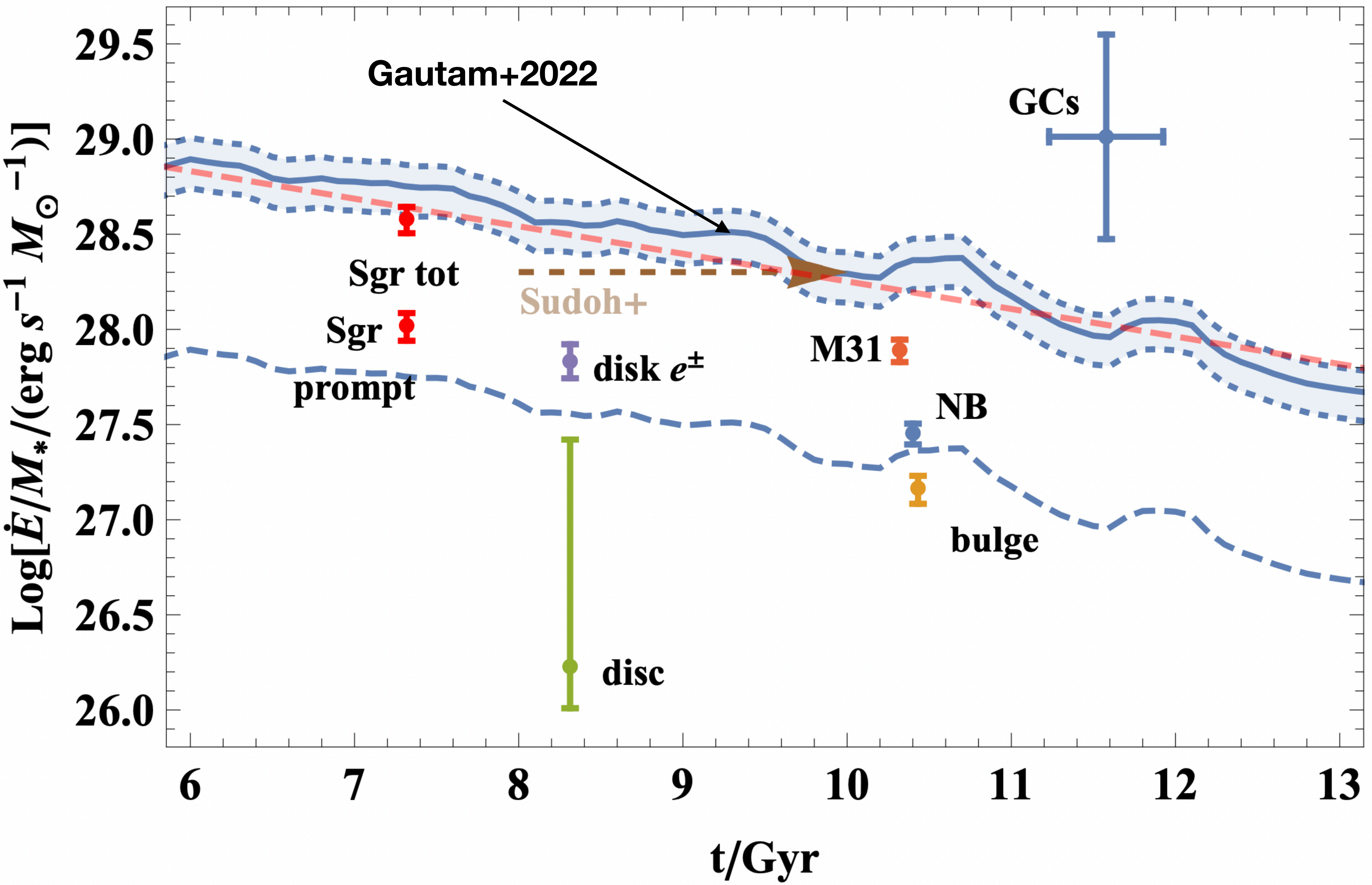

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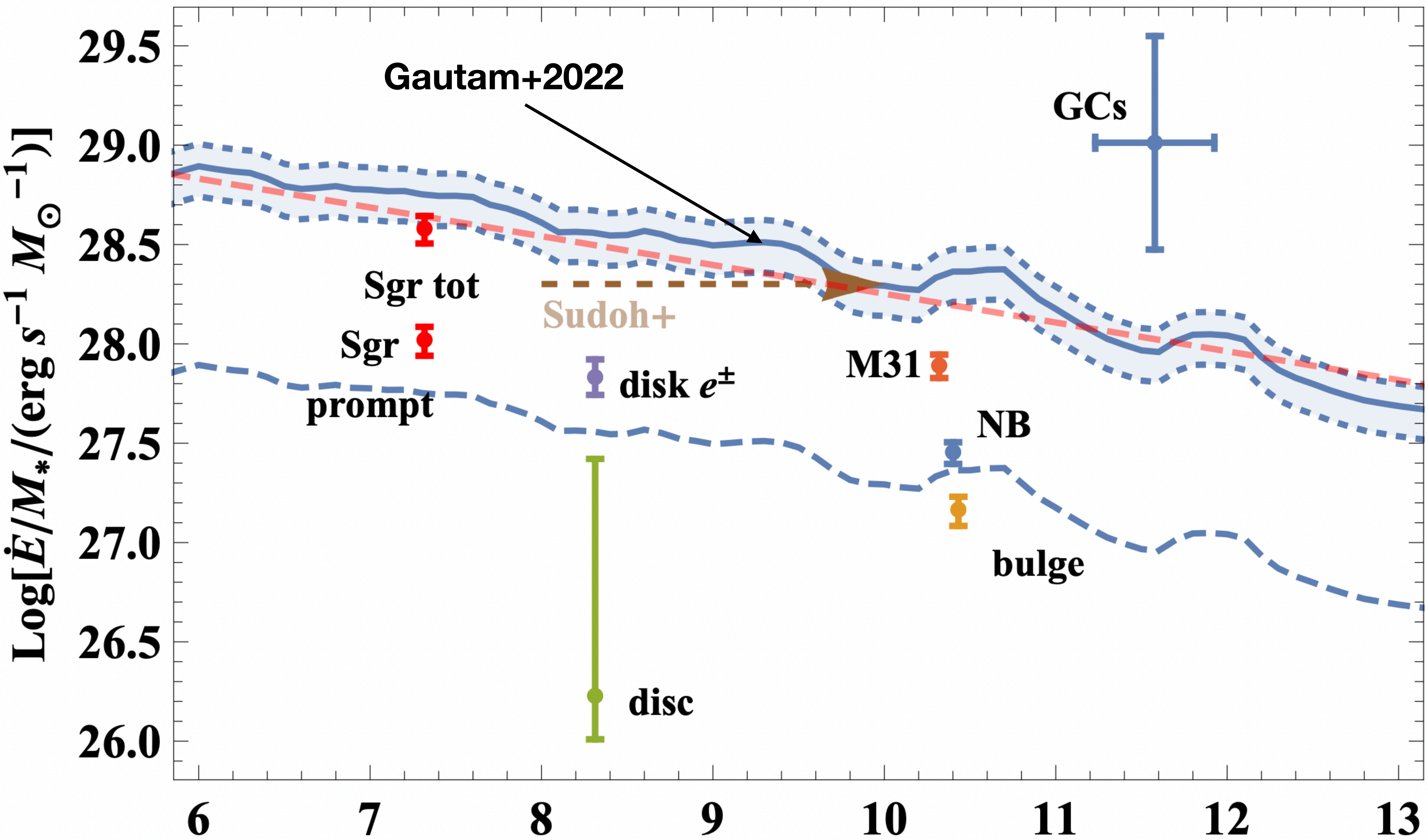

➡ The Sgr dSph is brighter than other systems because its stars are younger

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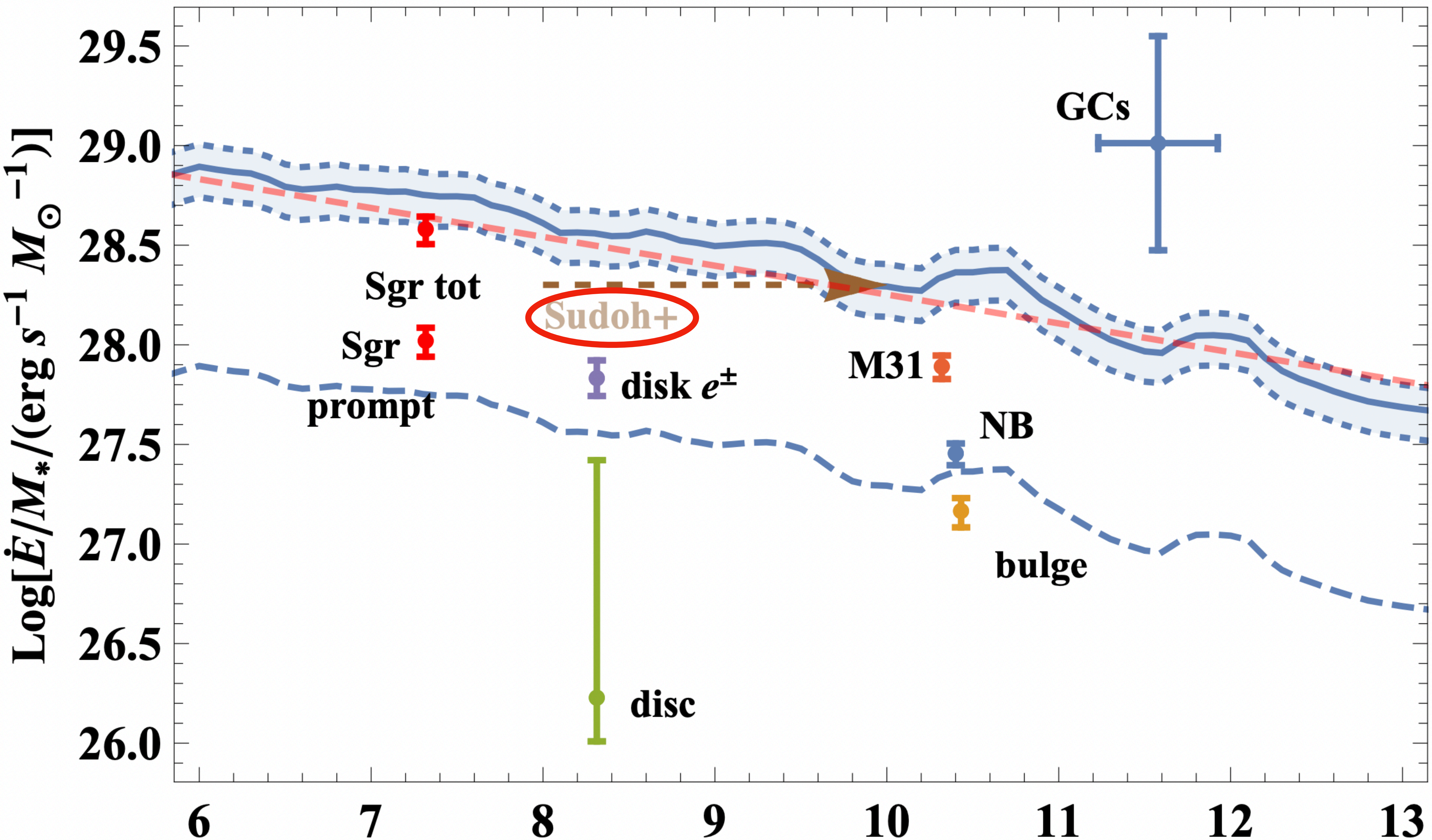

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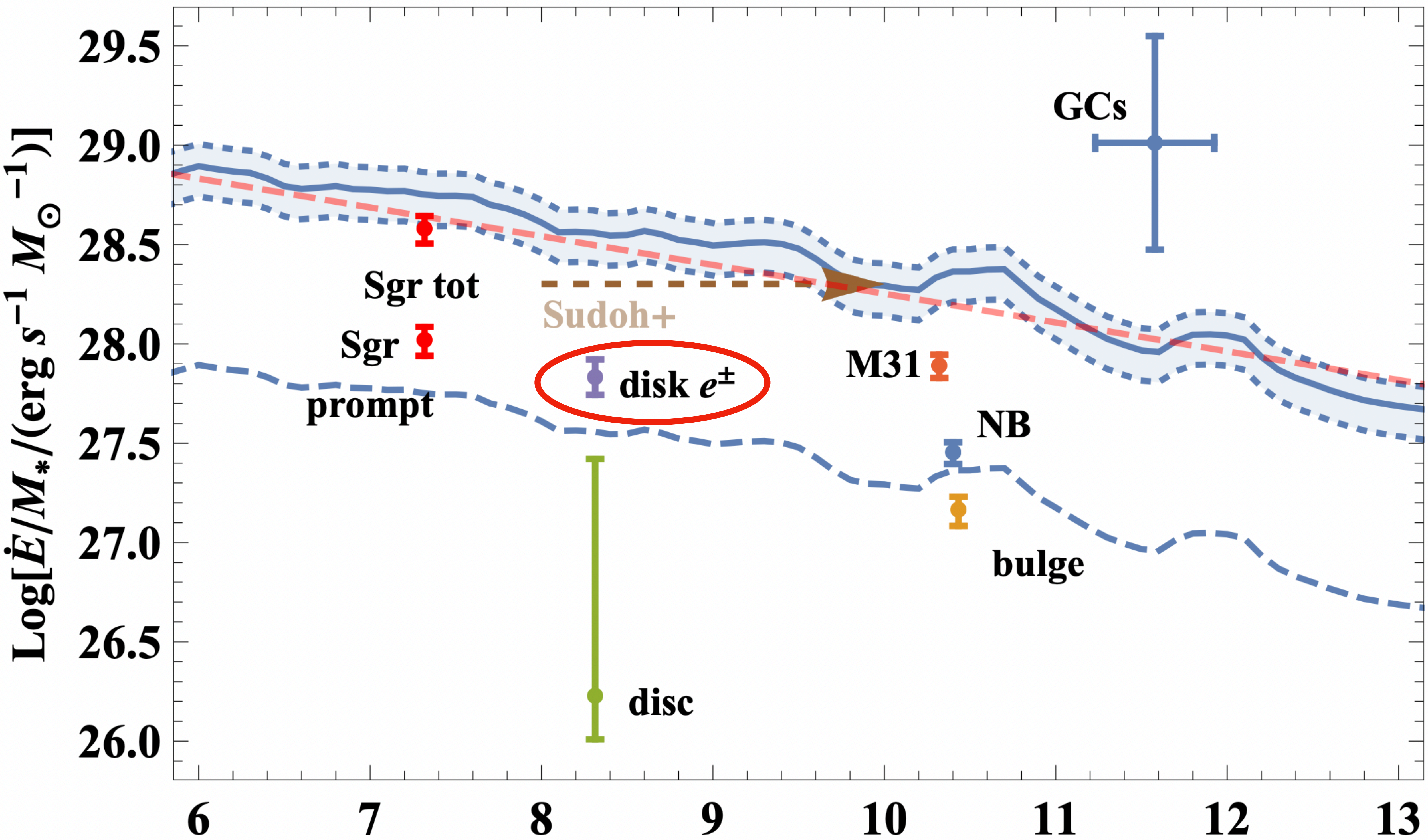

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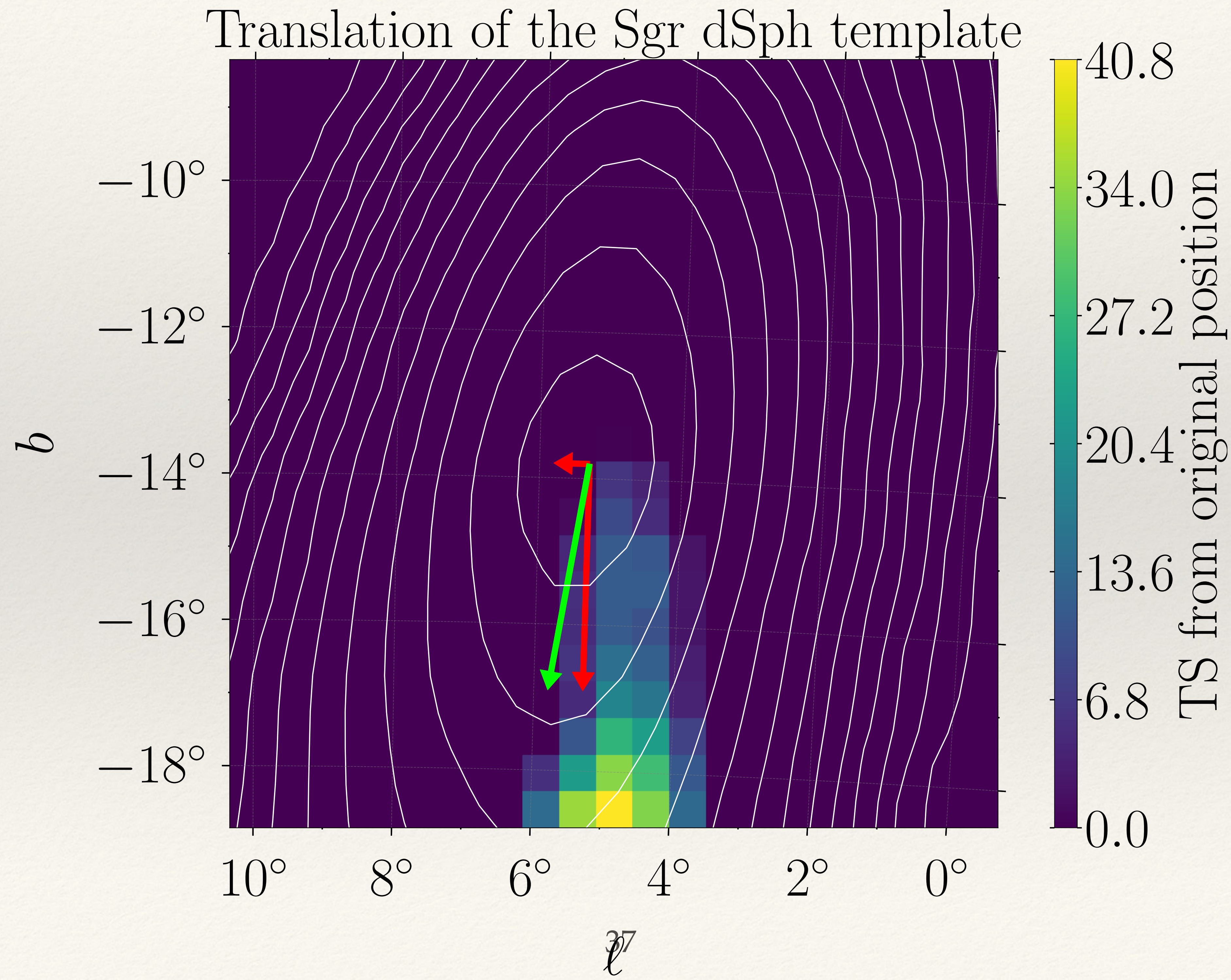
(Slight) displacement of signal



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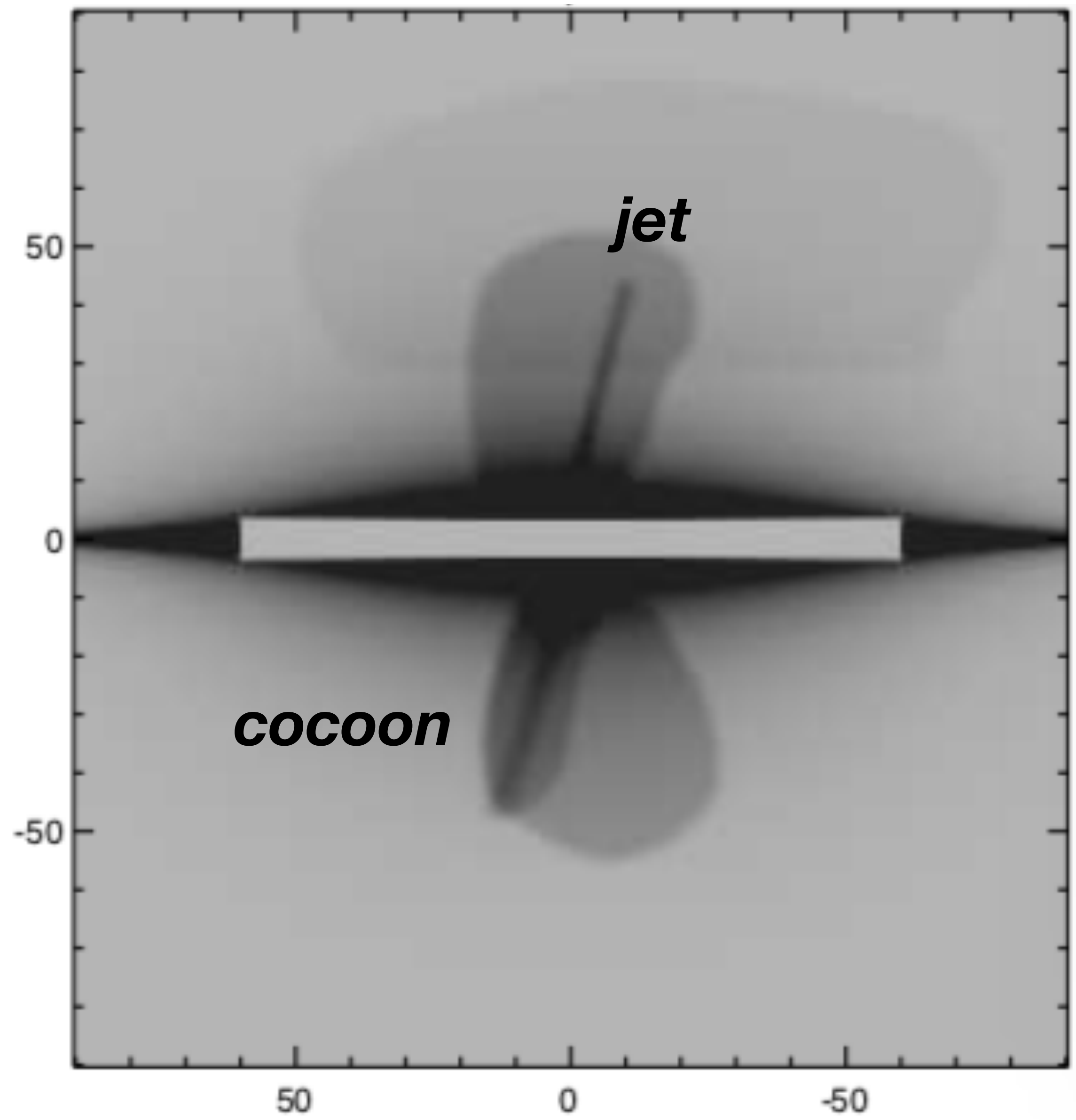
Fermi Bubbles substructure (?)



Su and Finkbeiner 2012

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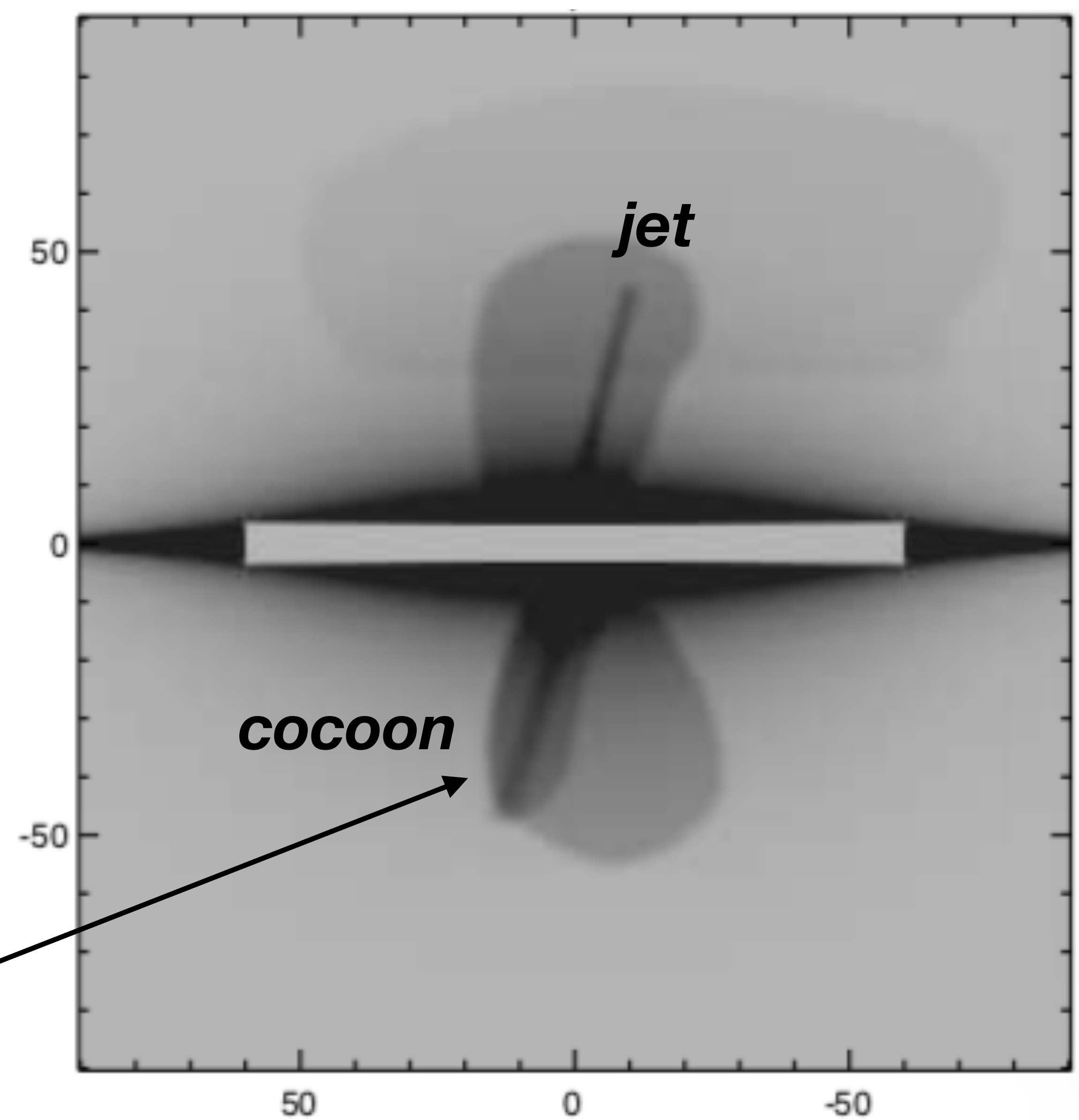
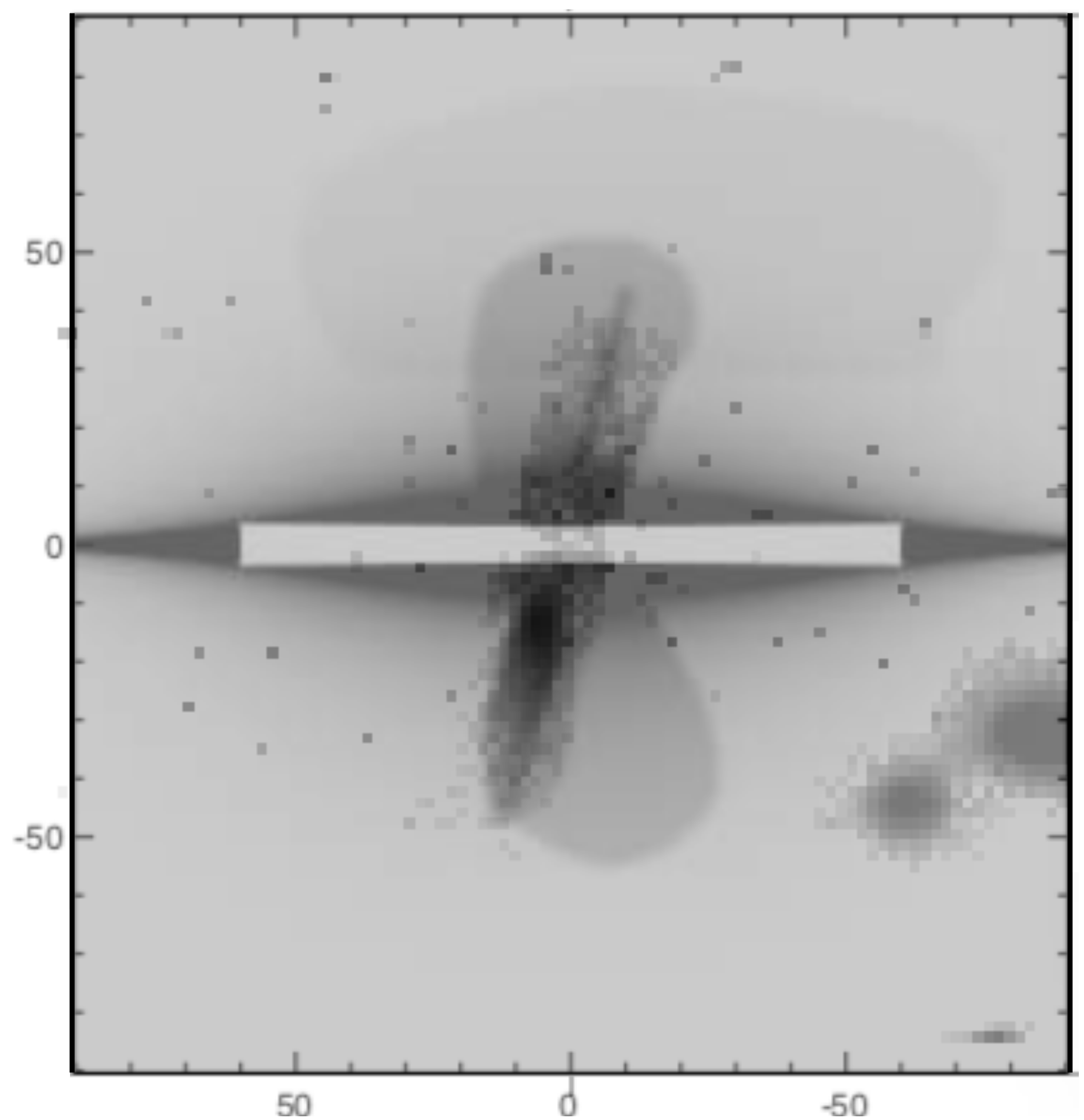


Templates developed for *Fermi* ~GeV γ-ray analysis

Su and Finkbeiner 2012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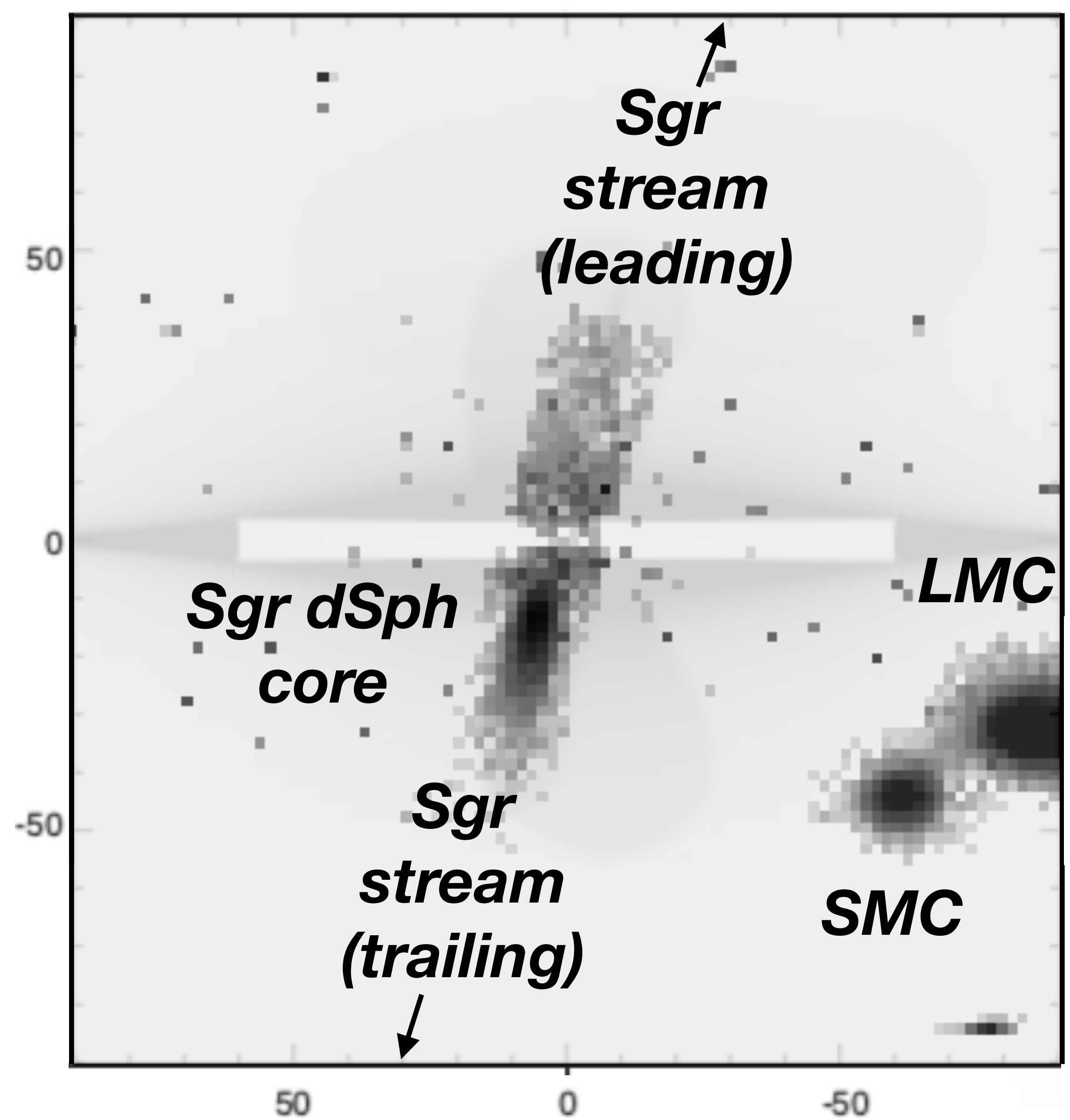
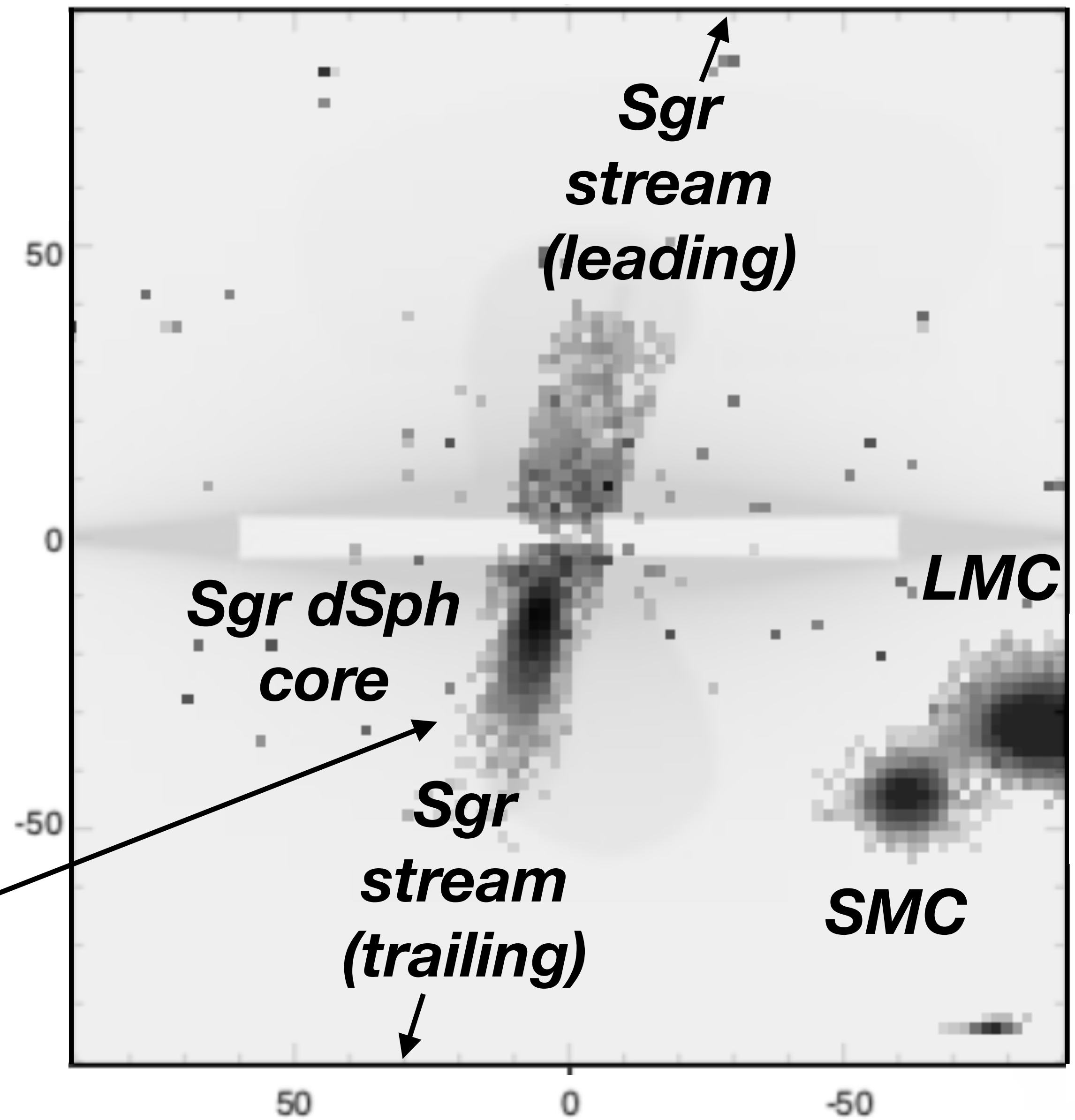


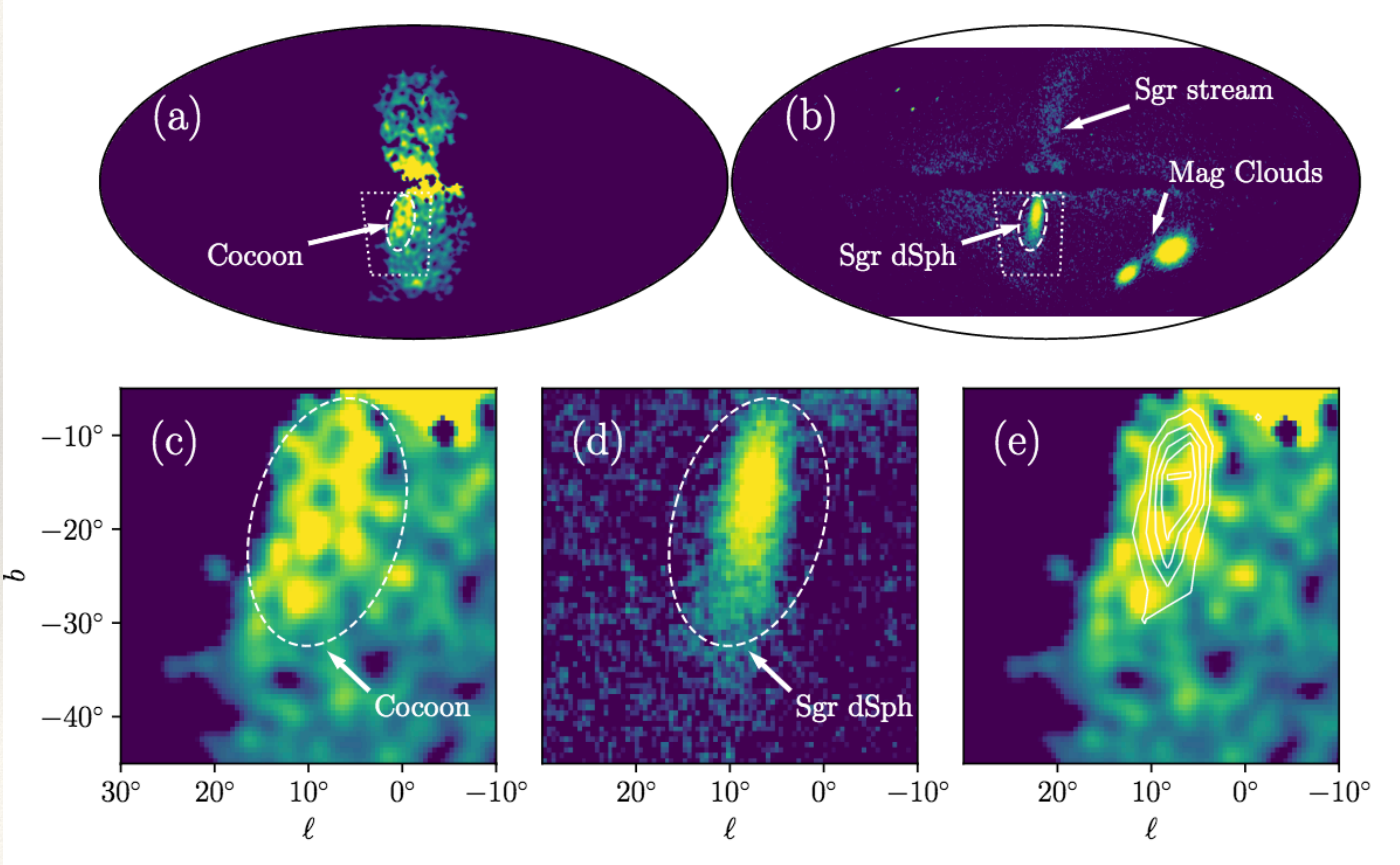
Iorio and Belokurov 2018



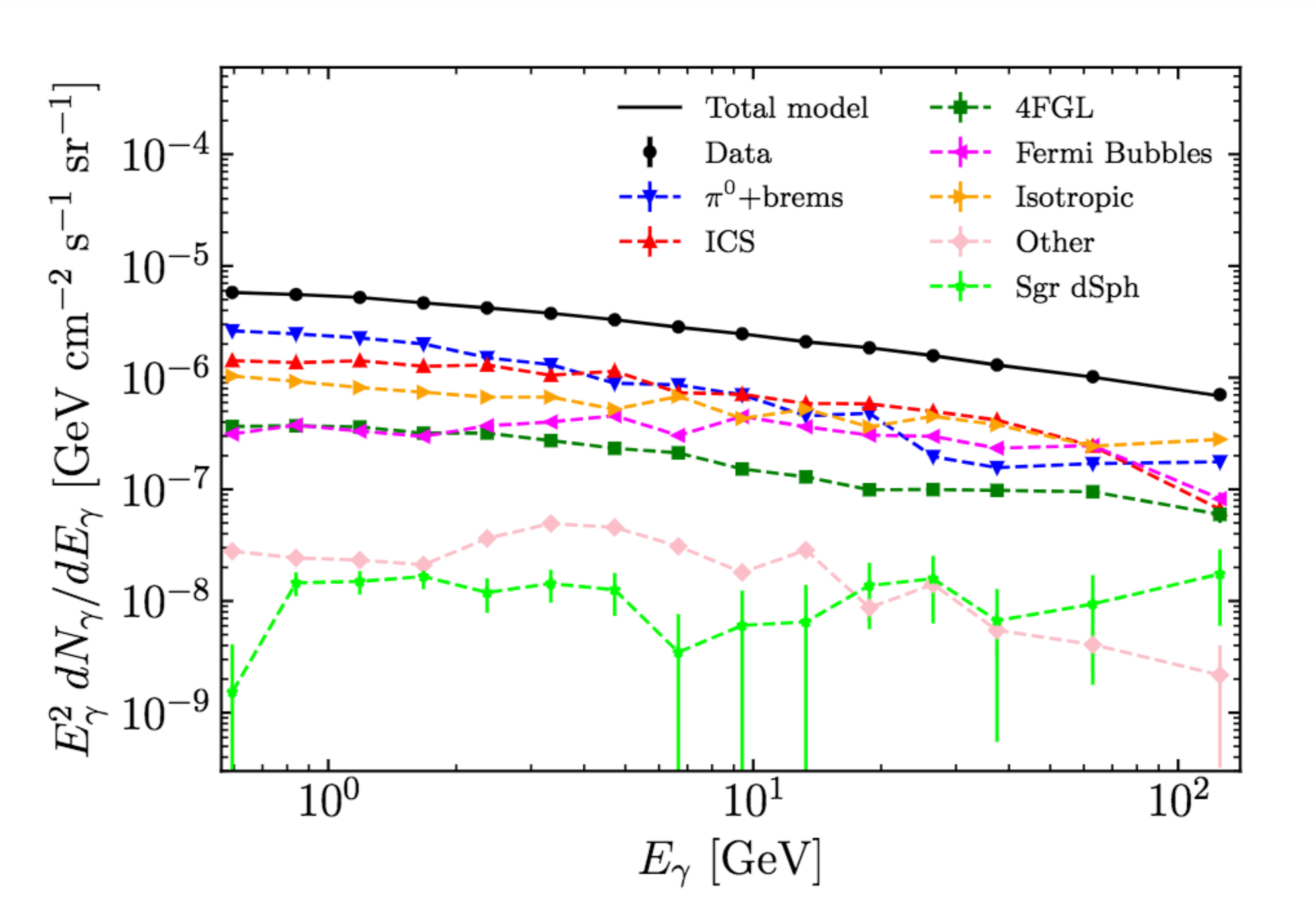
RR Lyrae stars
From Gaia

Iorio and Belokurov 2018

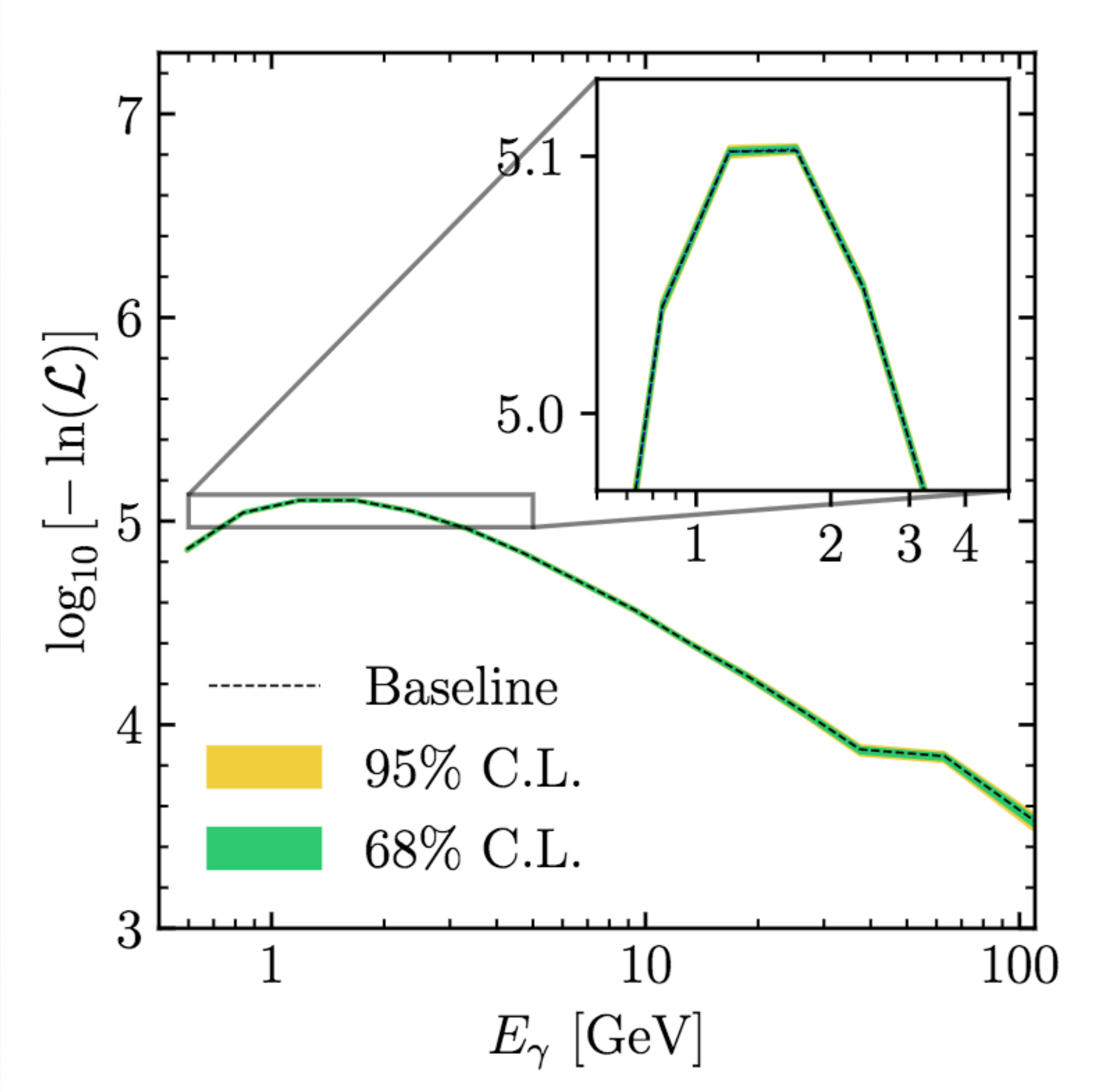
Sgr dSph and Fermi Bubbles ‘Cocoon’



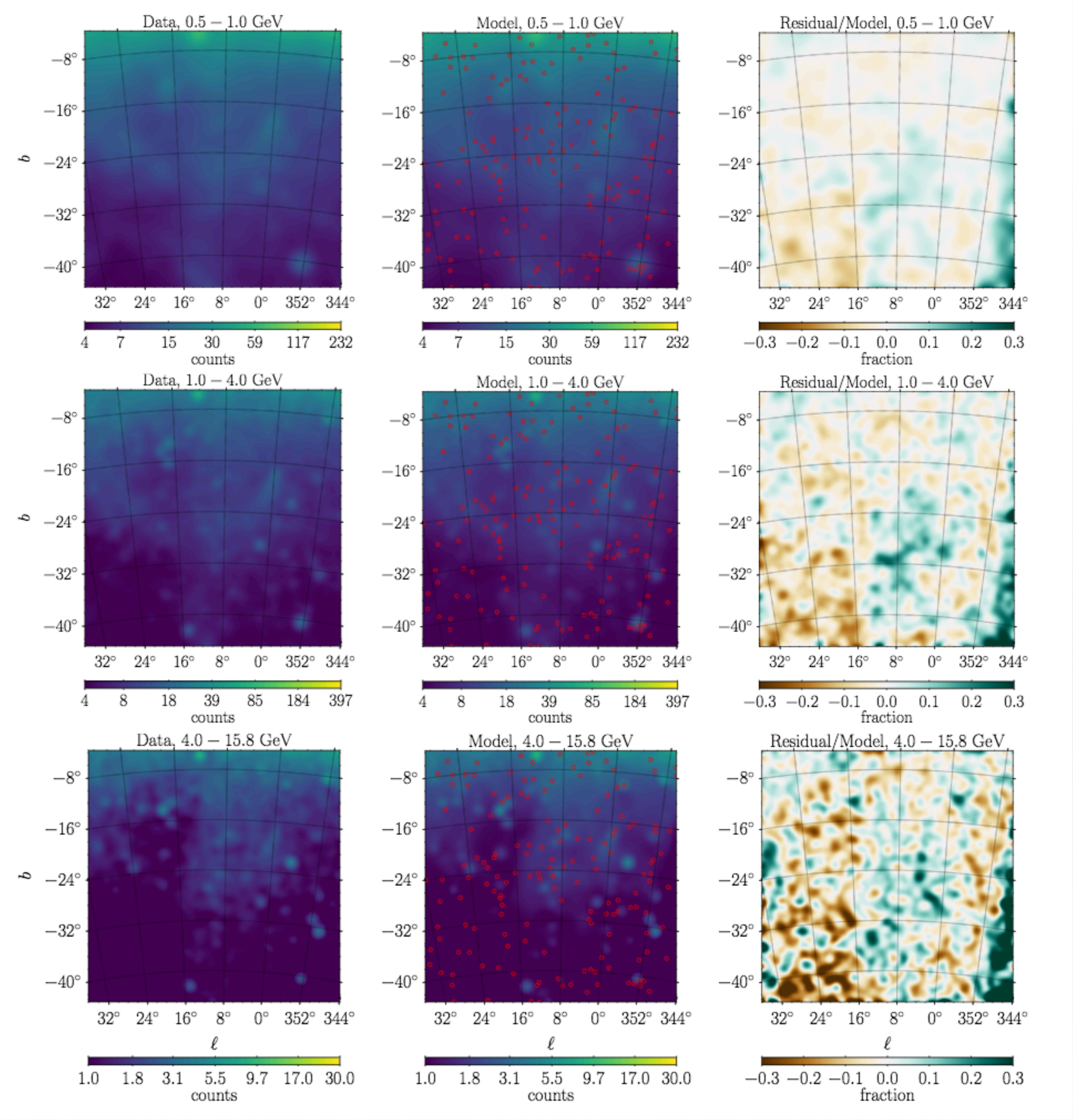
Overall spectral fit



Goodness of fit computation



Photon count residuals



Abstract

The Fermi Bubbles are giant, γ-ray emitting lobes emanating from the nucleus of the Milky Way discovered in ~ 1-100 GeV data collected by the Large Area Telescope on board the *Fermi* Gamma-Ray Space Telescope. Previous work has revealed substructure within the Fermi Bubbles that has been interpreted as a signature of collimated outflows from the Galaxy's super-massive black hole. Here we show that much of the γ-ray emission associated tothe brightest region of substructure -- the so-called cocoon -- is actually due to the Sagittarius dwarf spheroidal (Sgr dSph) galaxy. This large Milky Way satellite is viewed through the Fermi Bubbles from the position of the Solar System. As a tidally and ram-pressure stripped remnant, the Sgr dSph has no on-going star formation, but we demonstrate that its γ-ray signal is naturally explained by inverse Compton scattering of cosmic microwave background photons by high-energy electron-positron pairs injected by the dwarf's millisecond pulsar (MSP) population, combined with these objects' magnetospheric emission. This finding suggests that MSPs likely produce significant γ-ray emission amongst old stellar populations, potentially confounding indirect dark matter searches in regions such as the Galactic Centre, the Andromeda galaxy, and other massive Milky Way dwarf spheroidals.