The status of the Fermi-LAT γ-ray excess at the Galactic Center

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Rencontres du Vietnam
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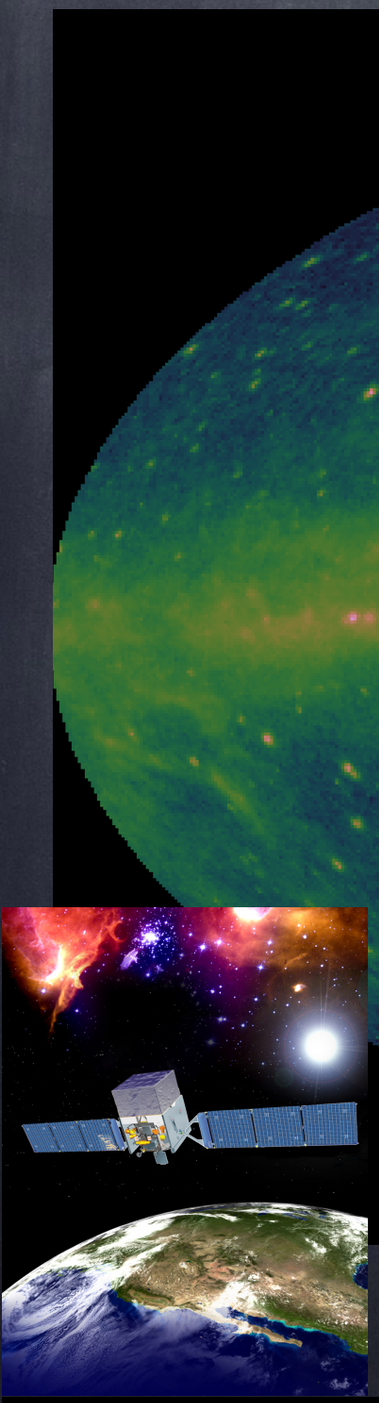
GRAPPA
GRavitation AstroParticle Physics Amsterdam

13 August 2018

UNIVERSITY OF AMSTERDAM

Observations



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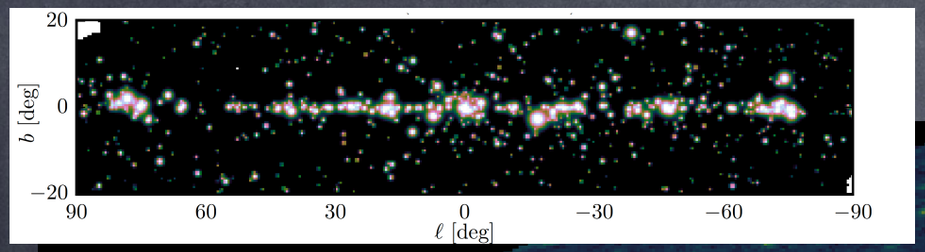

Sources

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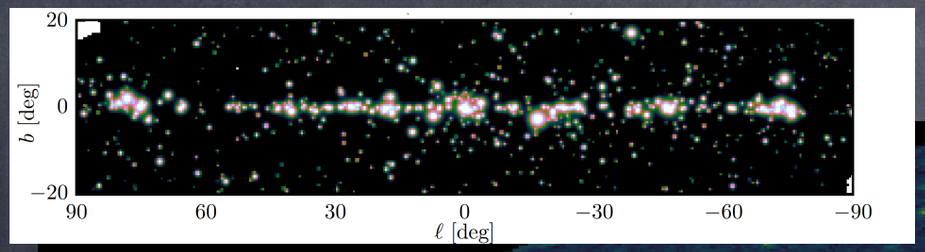

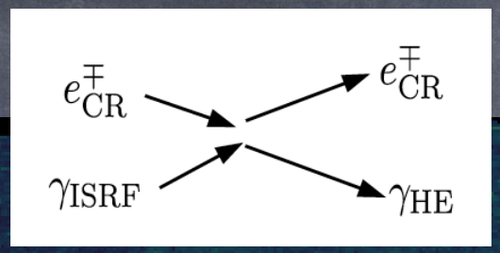

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Richard Bartels (GRAPPA, Amsterdam)

VHEPU, Qui Nhon, Vietnam, 12 August 2018

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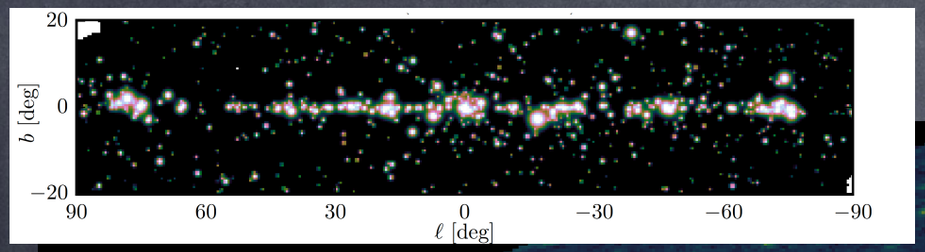

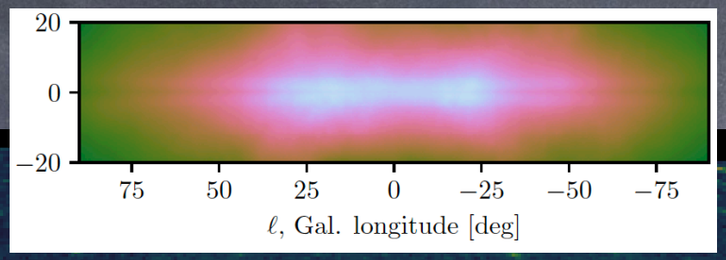

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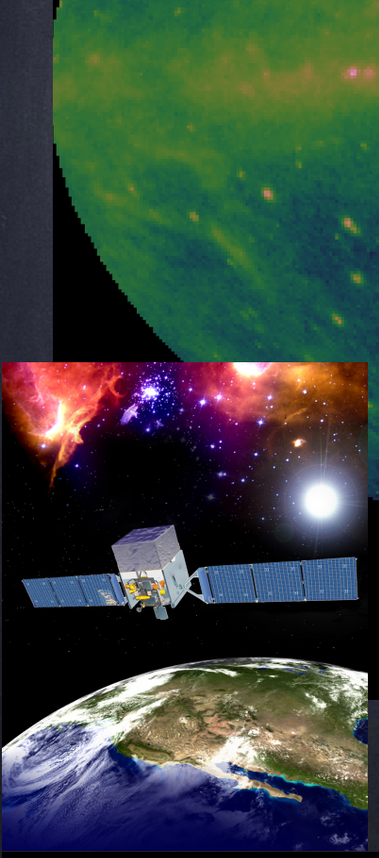

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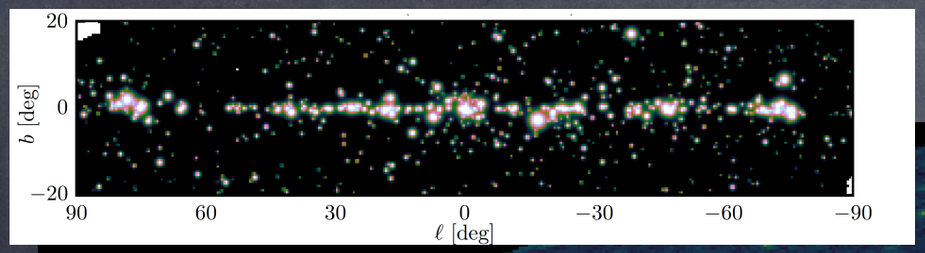

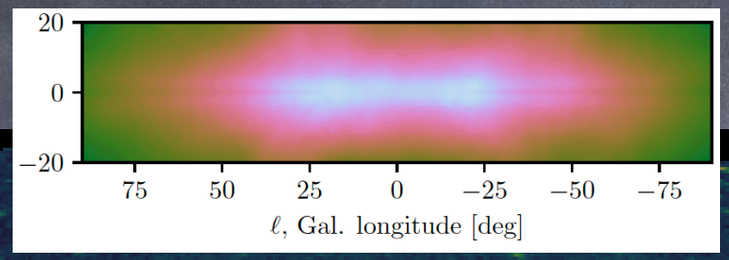

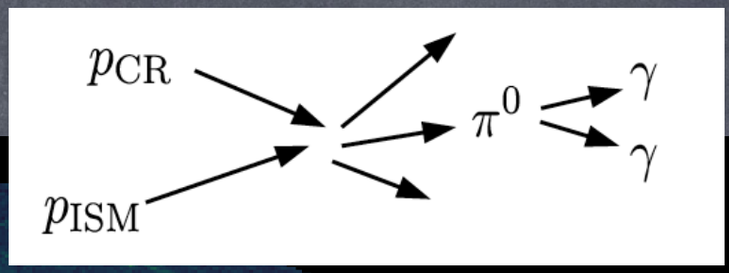

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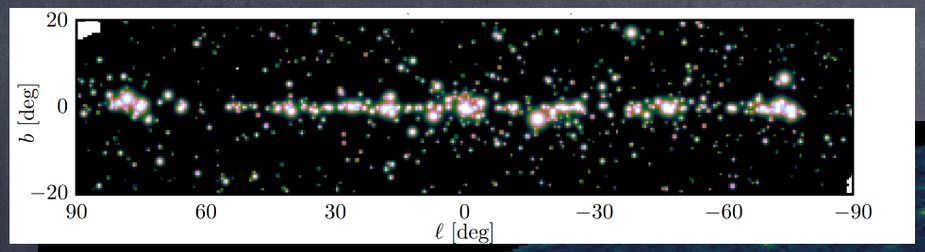

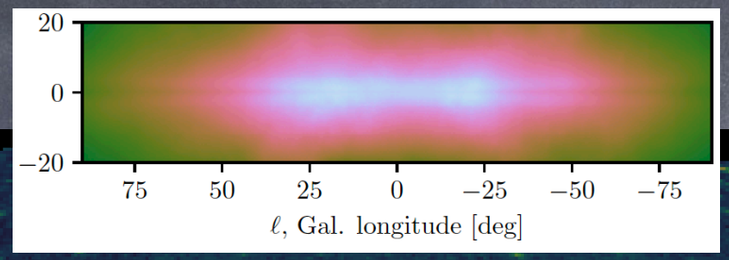

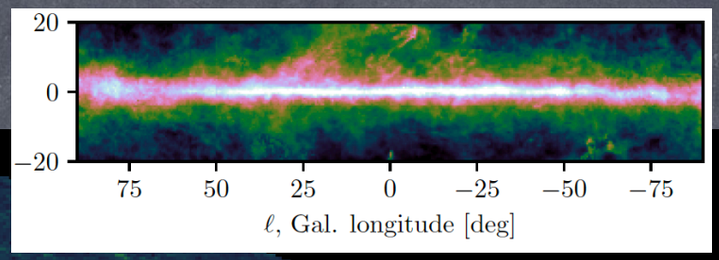

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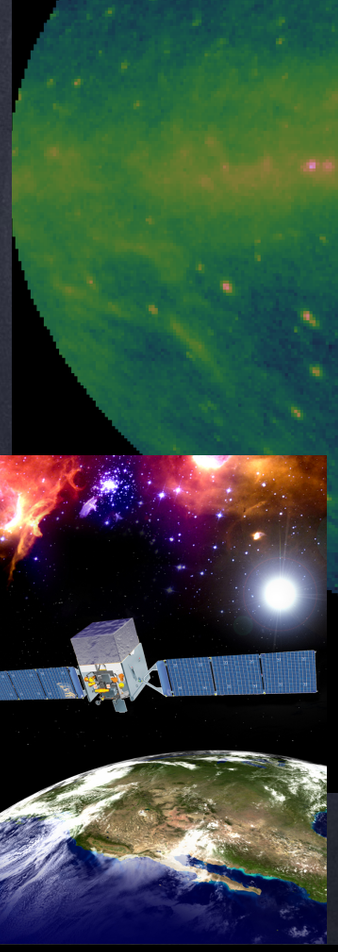

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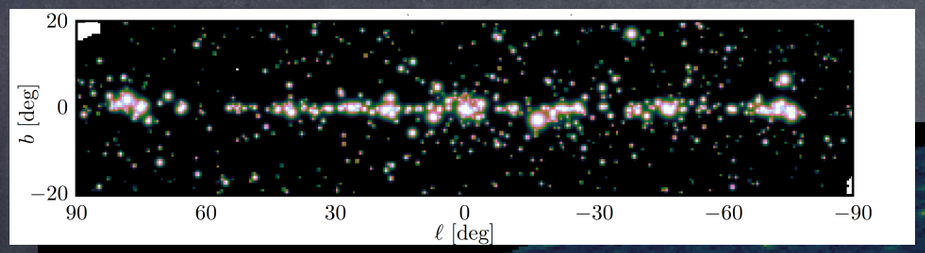
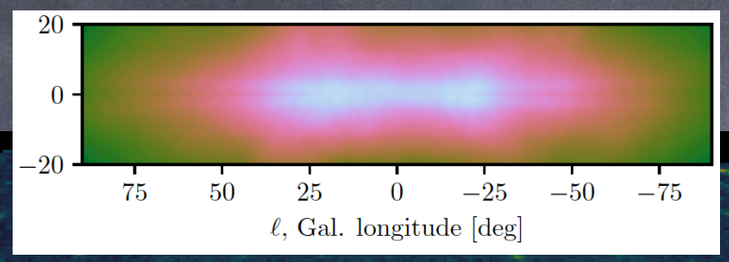
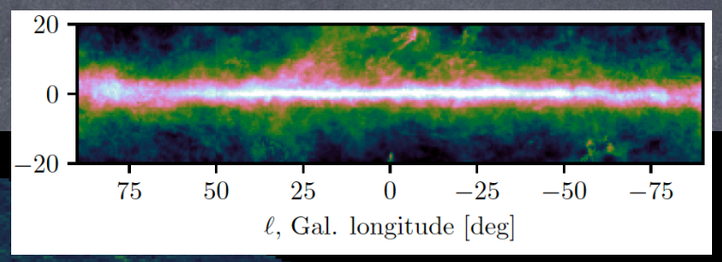
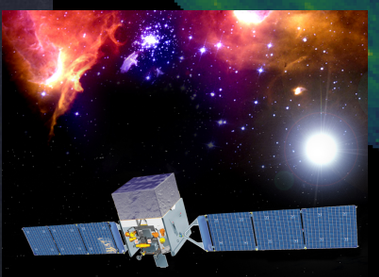


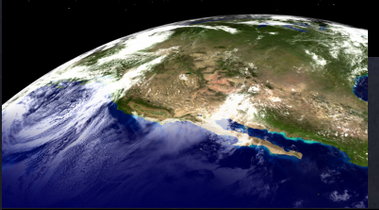




Sources

Diffuse emission





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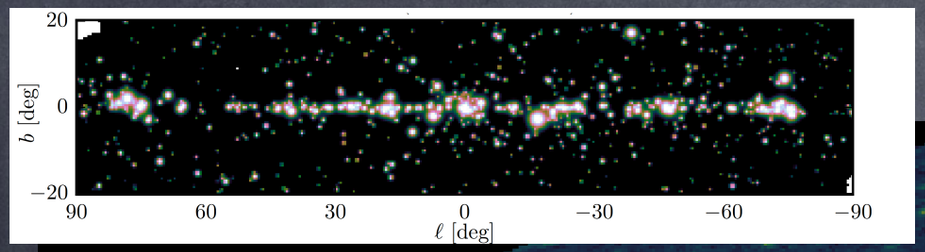

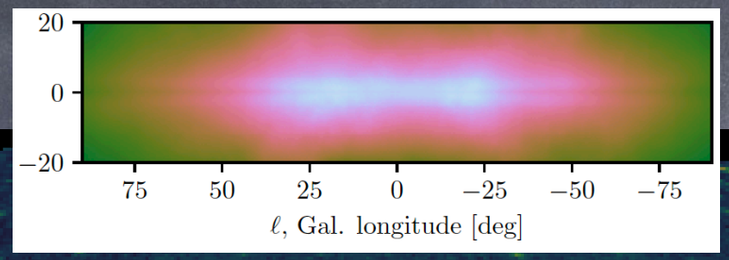

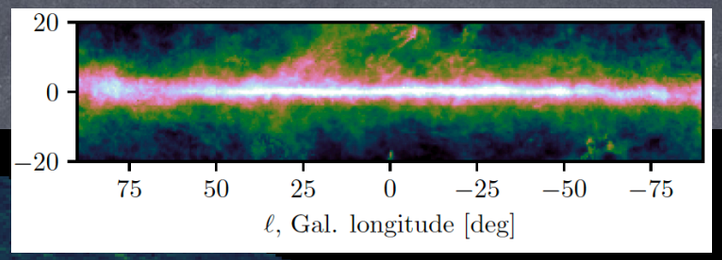

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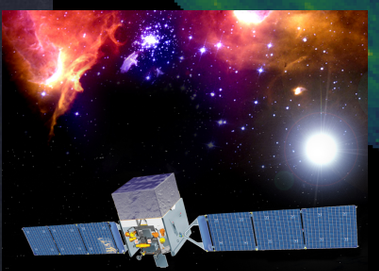

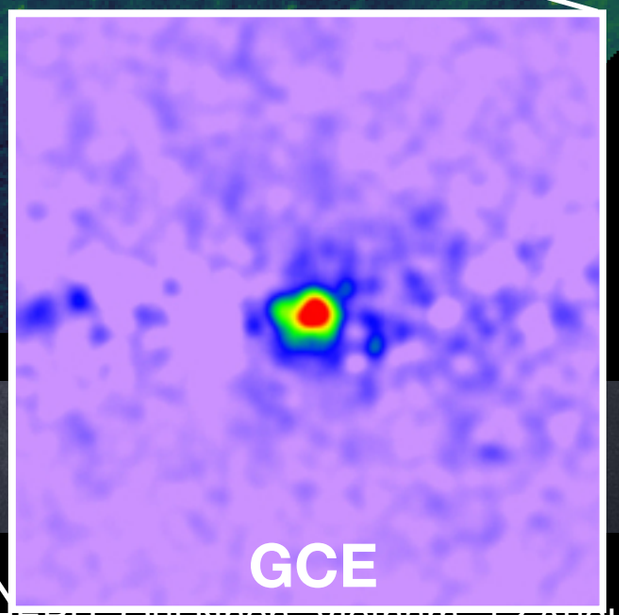

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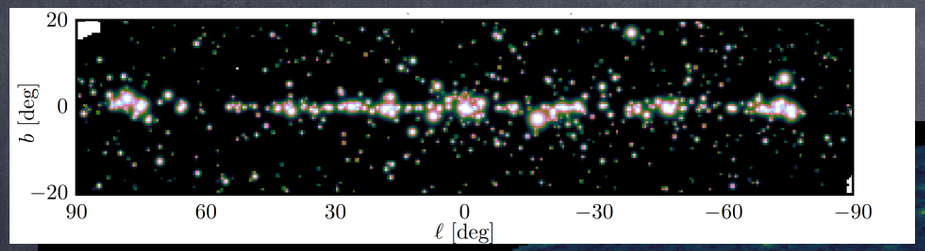
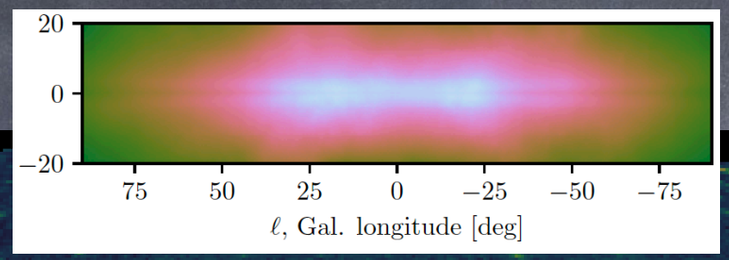
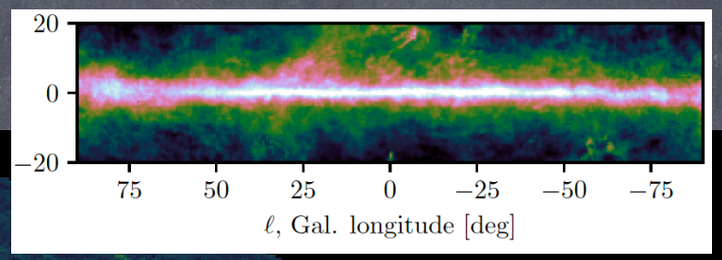
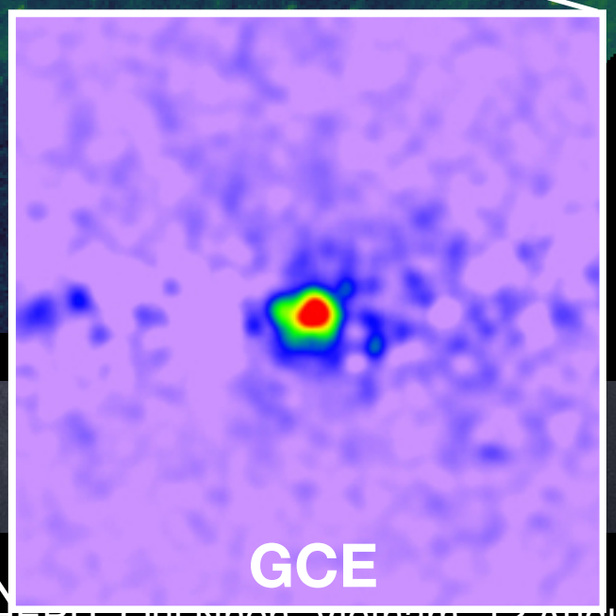




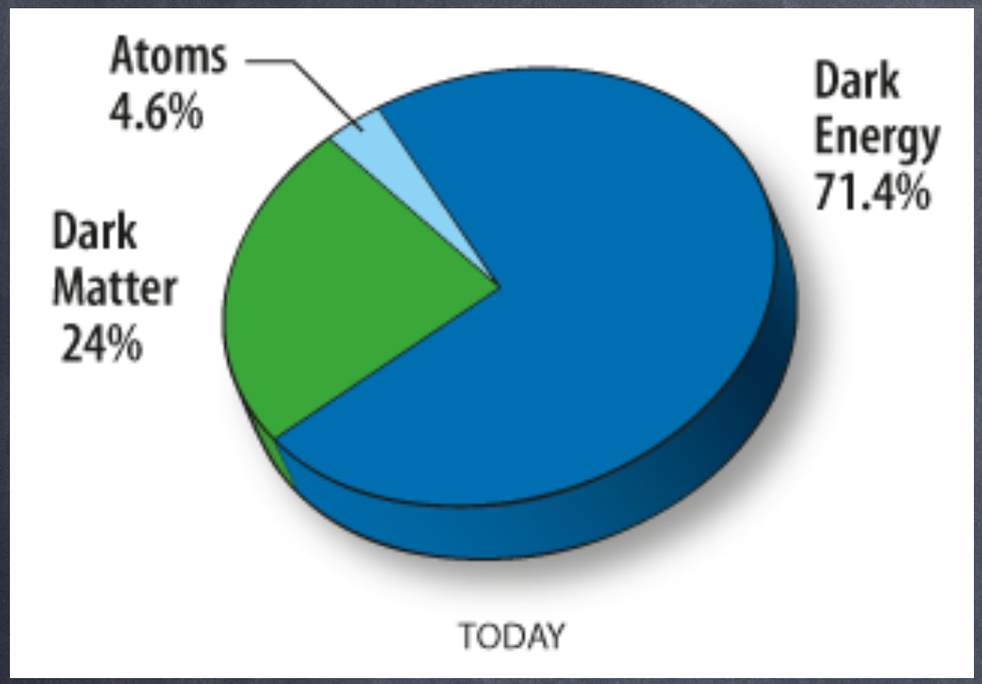


Goodenough & Hooper 2009, Vitale+ (Fermi coll.) 2009, Hooper & Goodenough 2011, Hooper & Linden 2011, Boyarsky+ 2011 (no signal), Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Huang+ 2013, Gordon & Macias 2013, Macias & Gordon 2014, Zhou+2014, Abazajian+ 2014, Daylan+2014, Calore+ 2014, Gaggero+ 2015, Carlson+ 2015, Huang+ 2016, de Boer+ 2017, Fermi-LAT 2017, Macias+ 2017, Bartels+ 2018

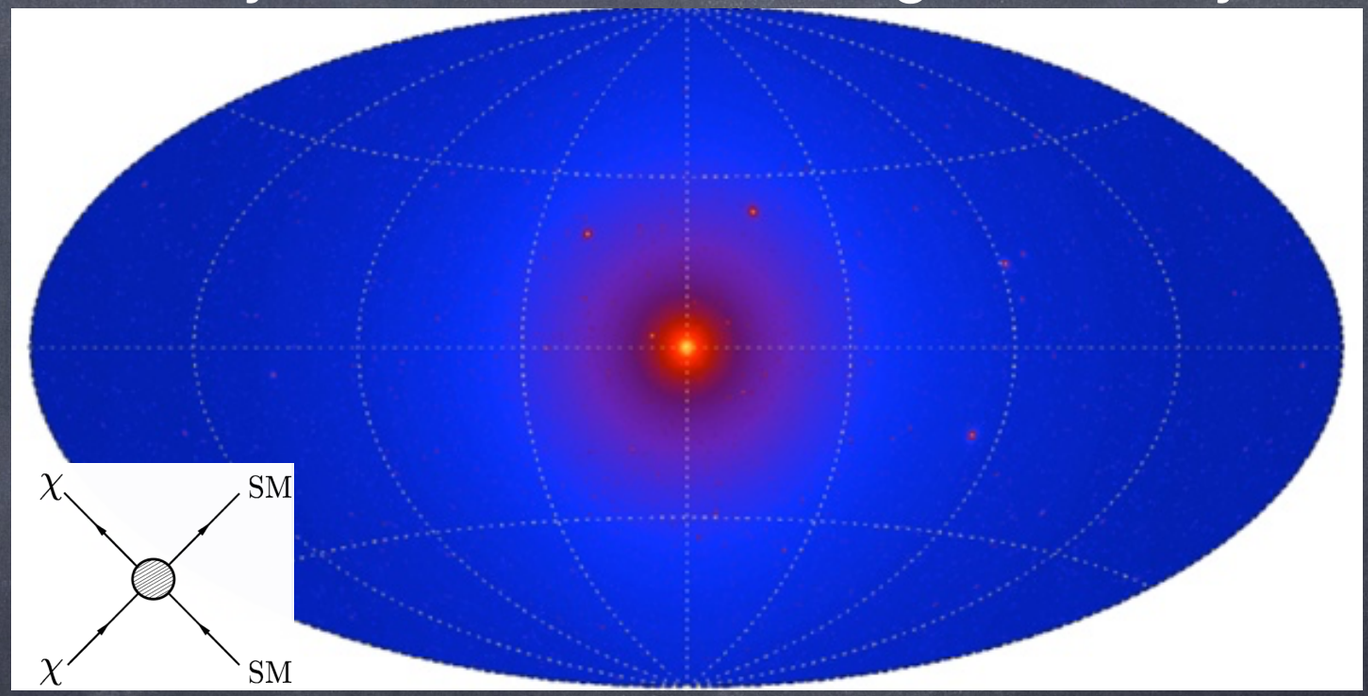
White: Spatial template fitting analyses
Yellow: Spectral template analyses
Blue: Skyfact

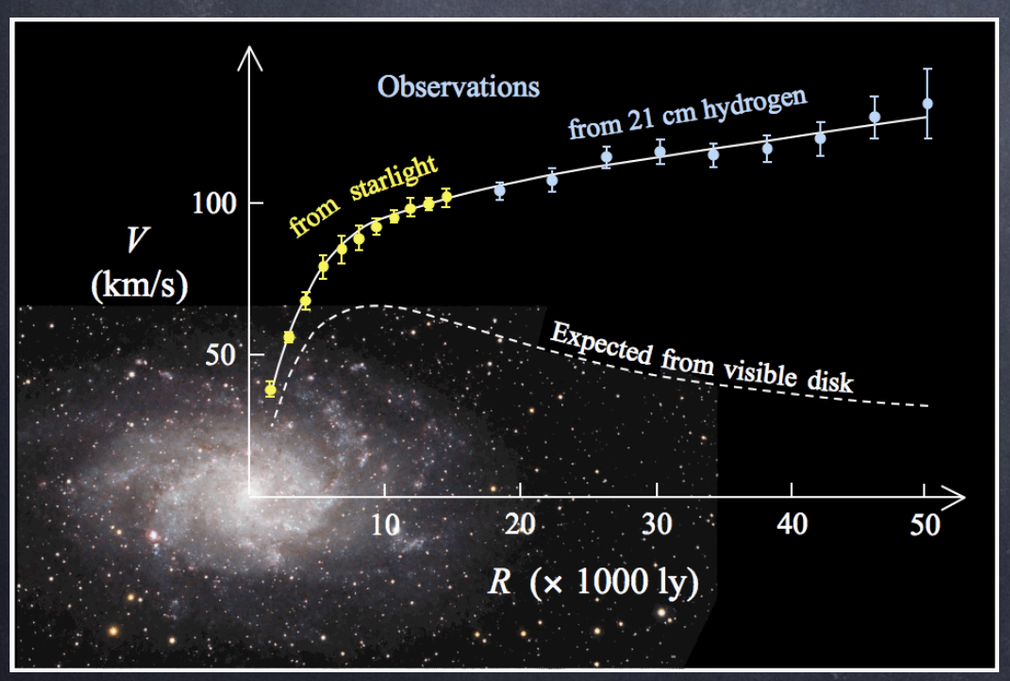


A signal from dark matter?



If only DM would shine in gamma-rays





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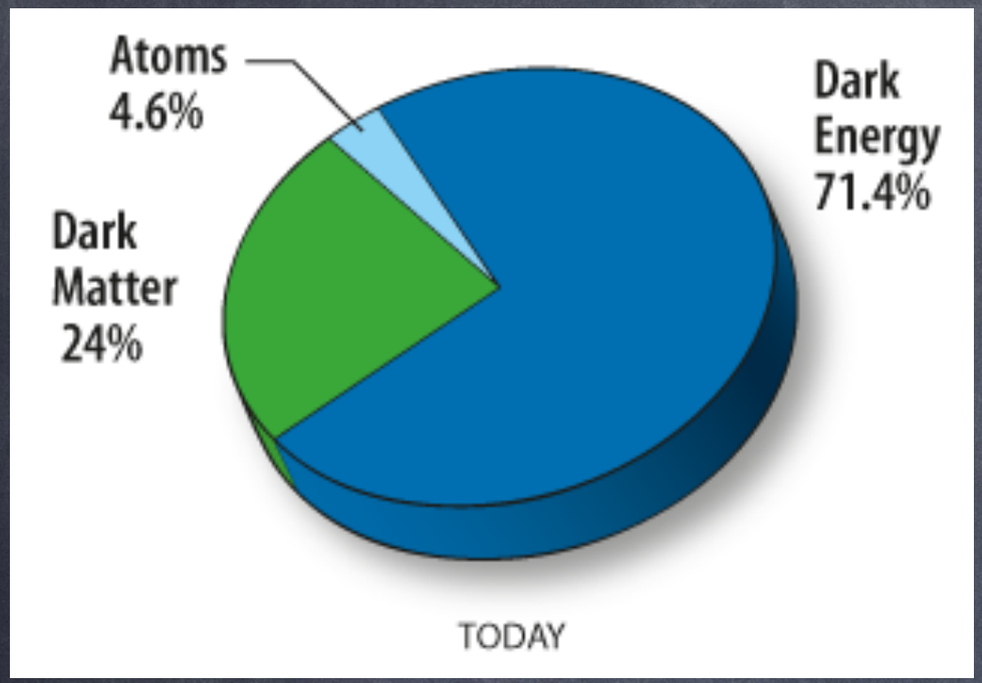

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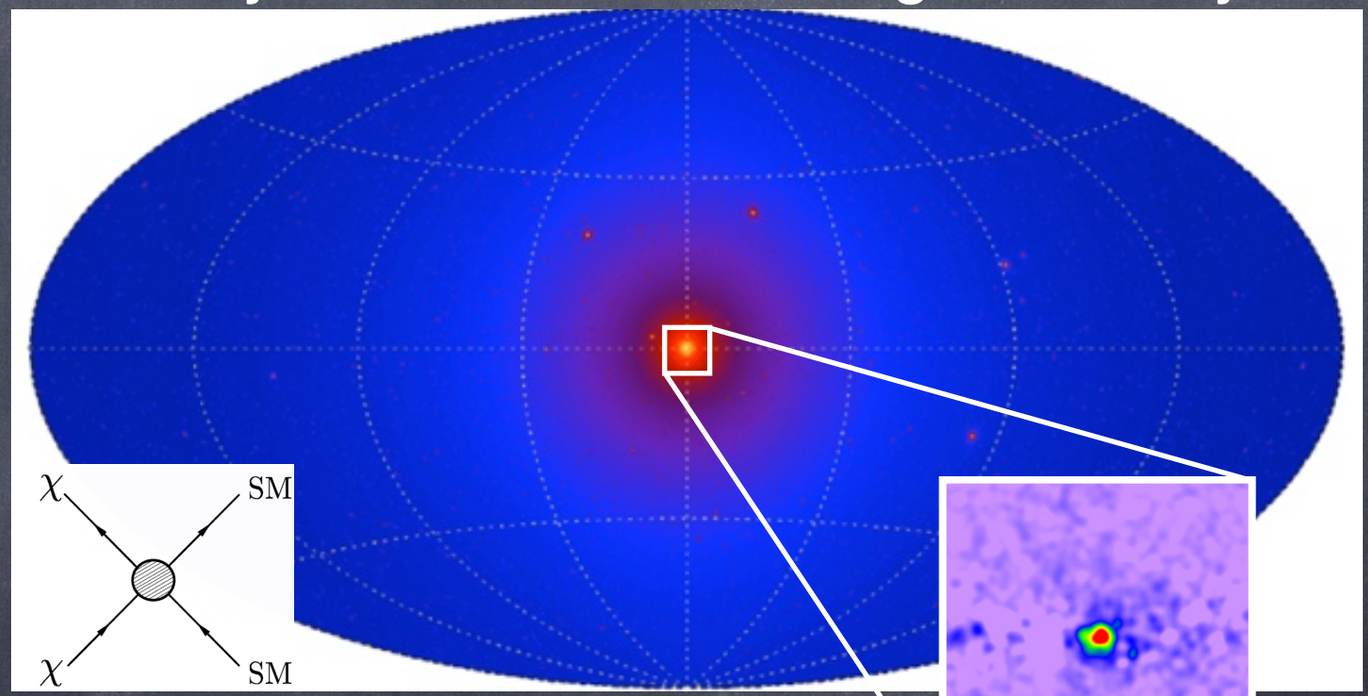
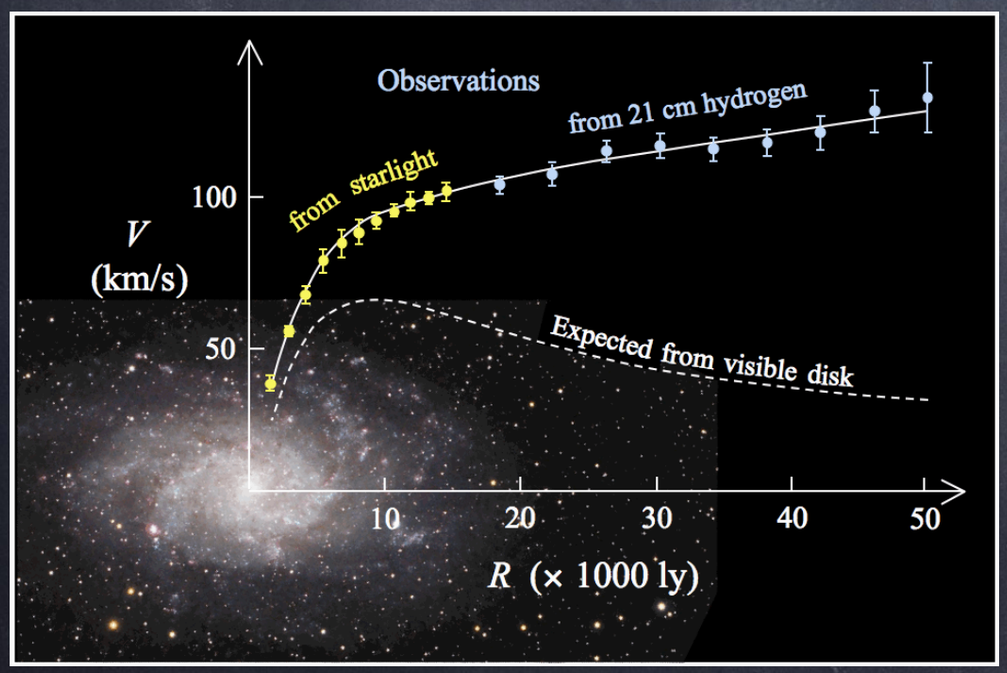
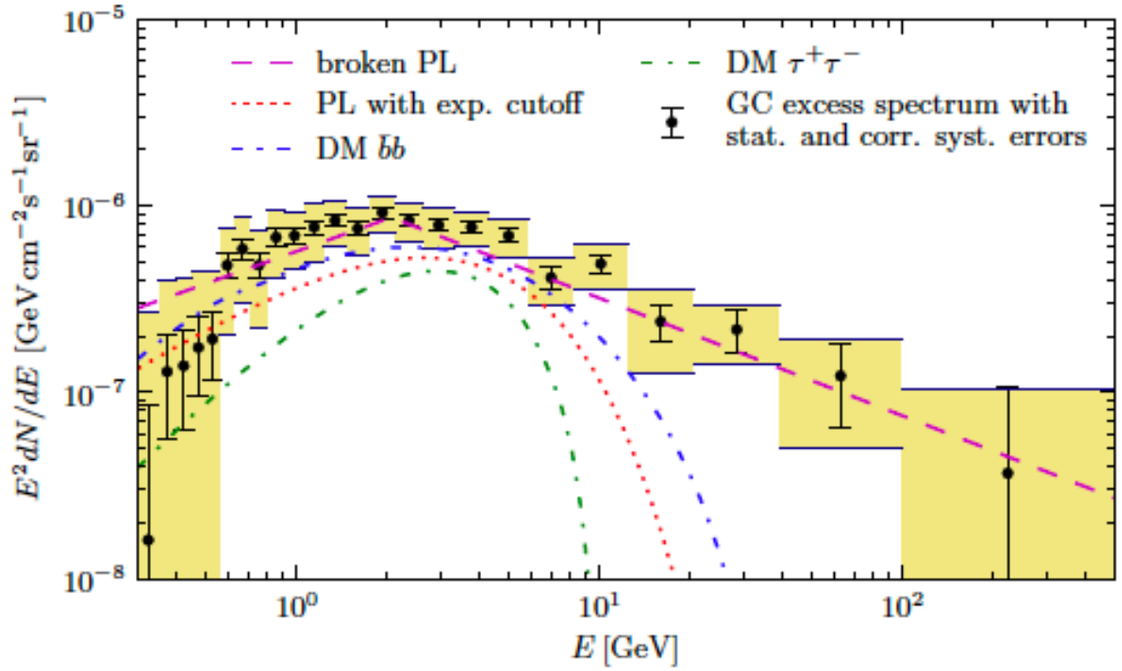




Characteristics

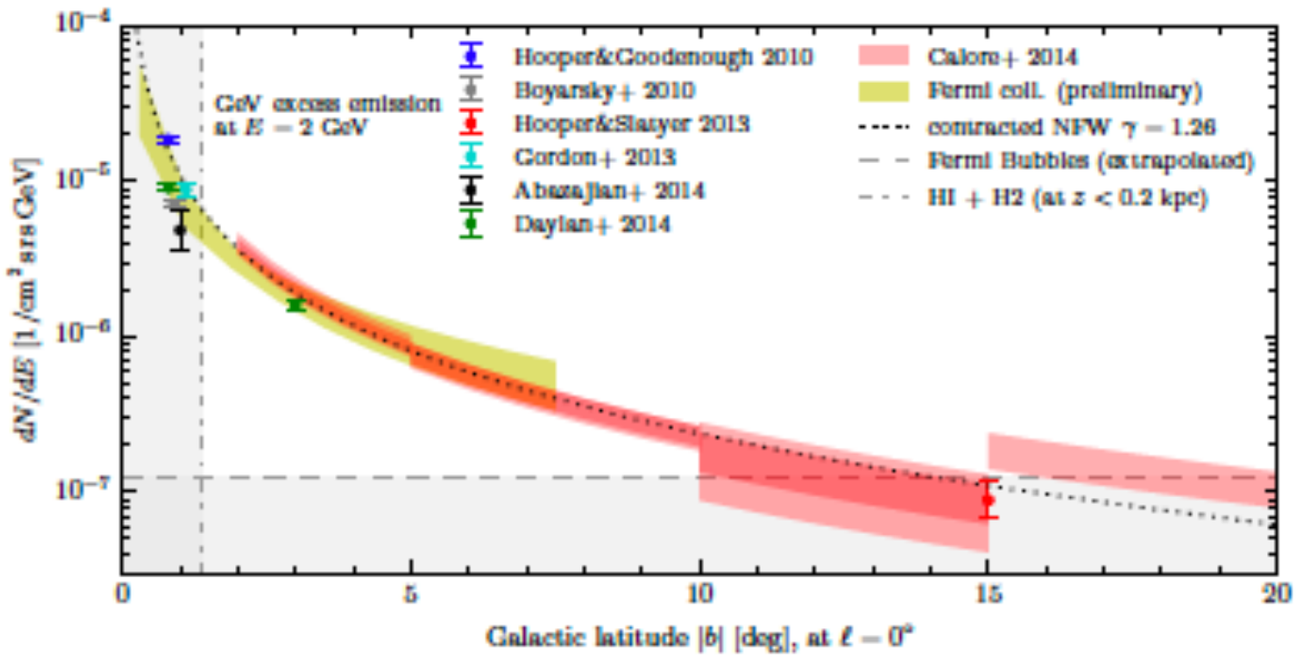
(From traditional template fitting)

Spectrum



Calore, Cholis & Weniger (2014)

Morphology



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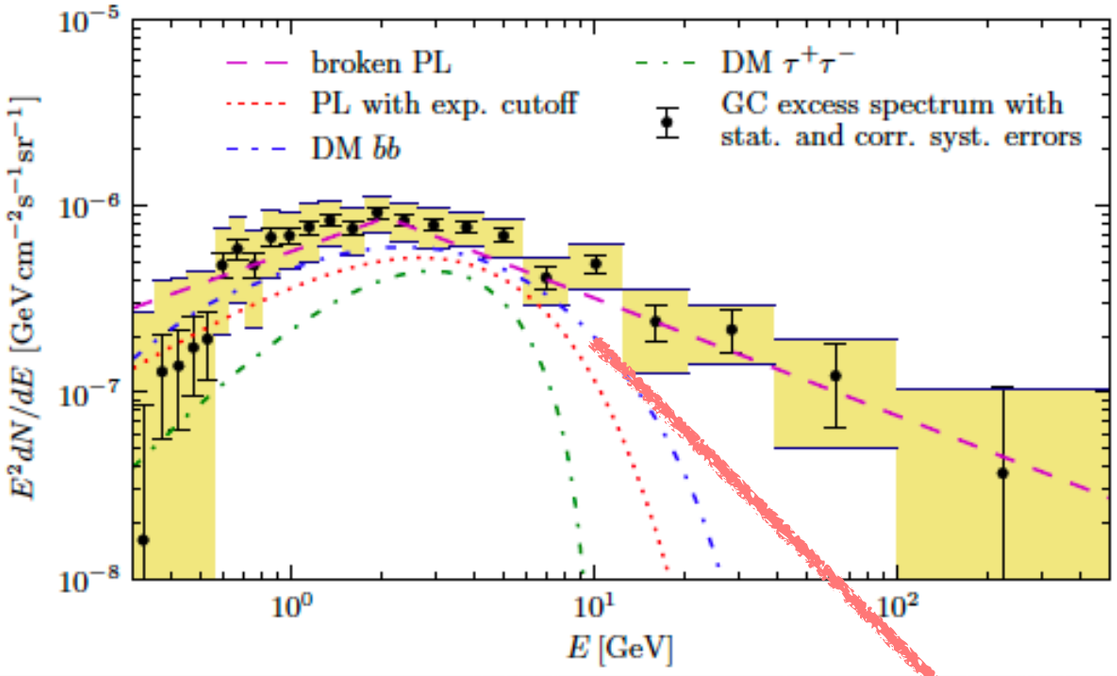

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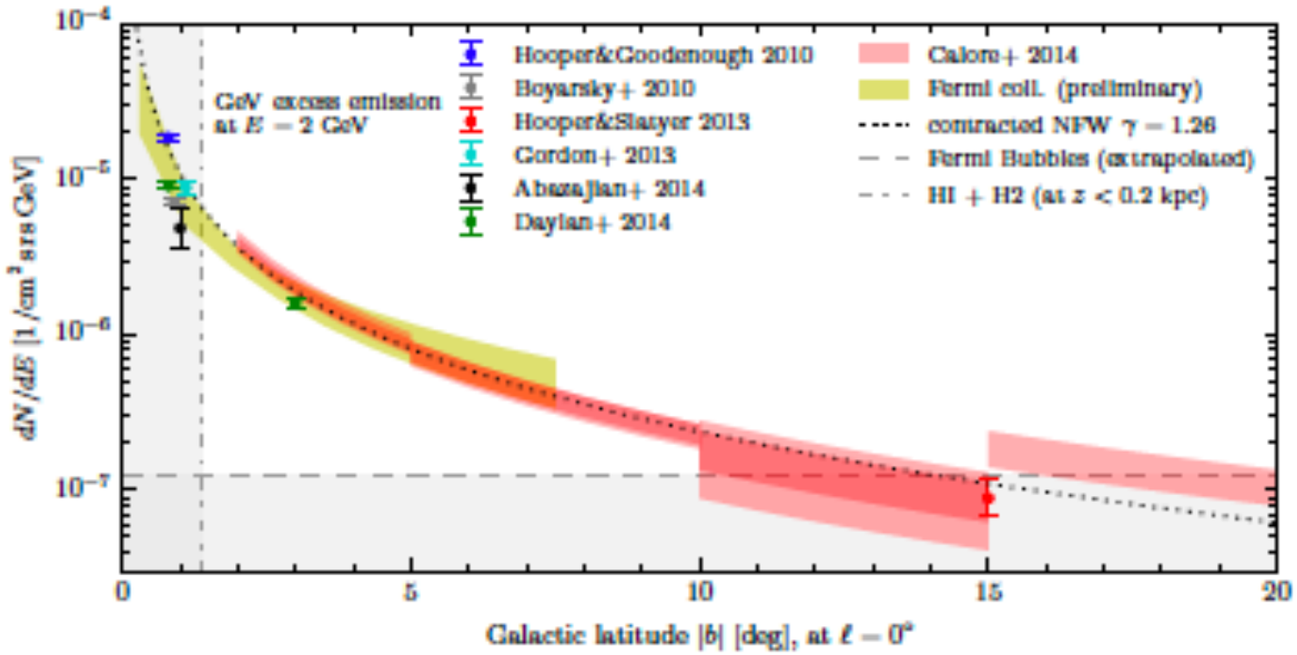

Calore, Cholis & Weniger (2014)

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1) Dark matter?
2) Millisecond pulsars?
3) Something else?

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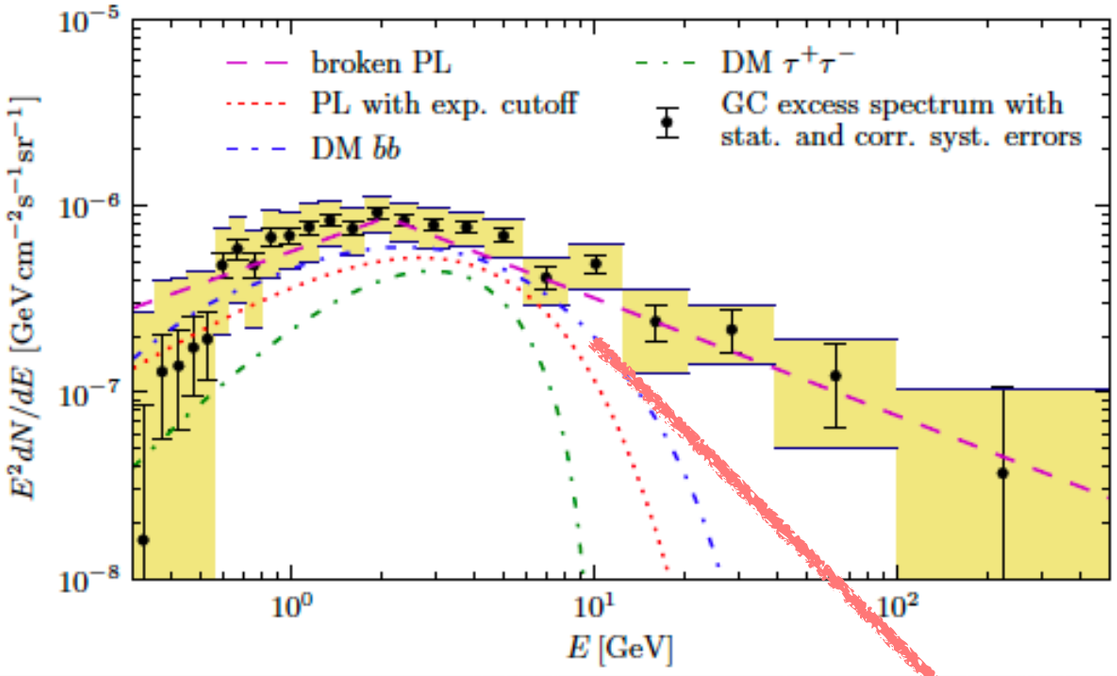

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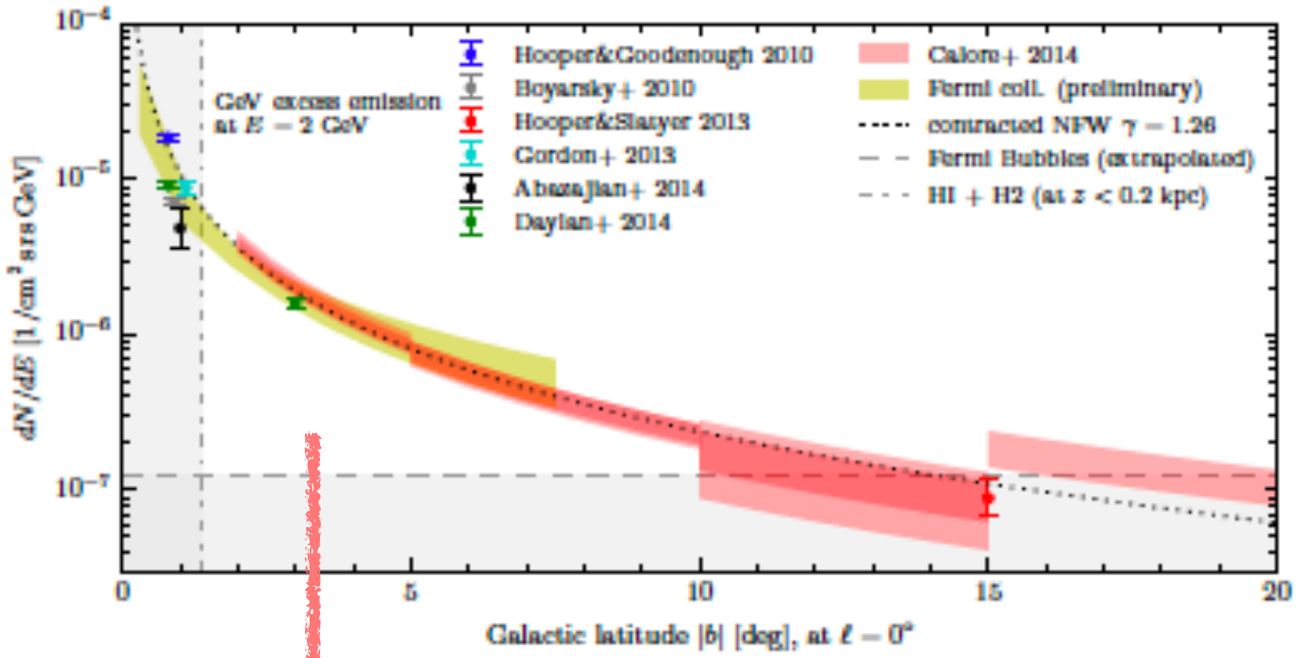


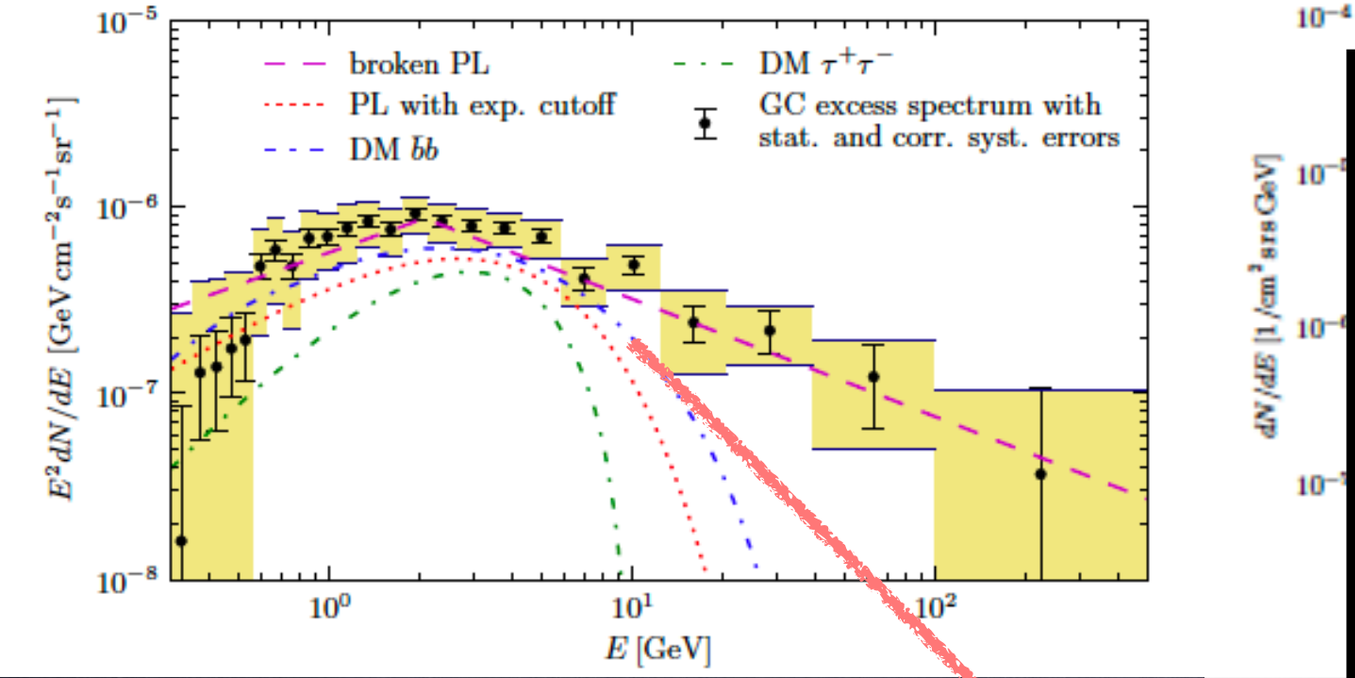
Calore, Cholis, McCabe & Weniger (2015)

Spherically symmetric

Characteristics

(From traditional template fitting)

Spectrum



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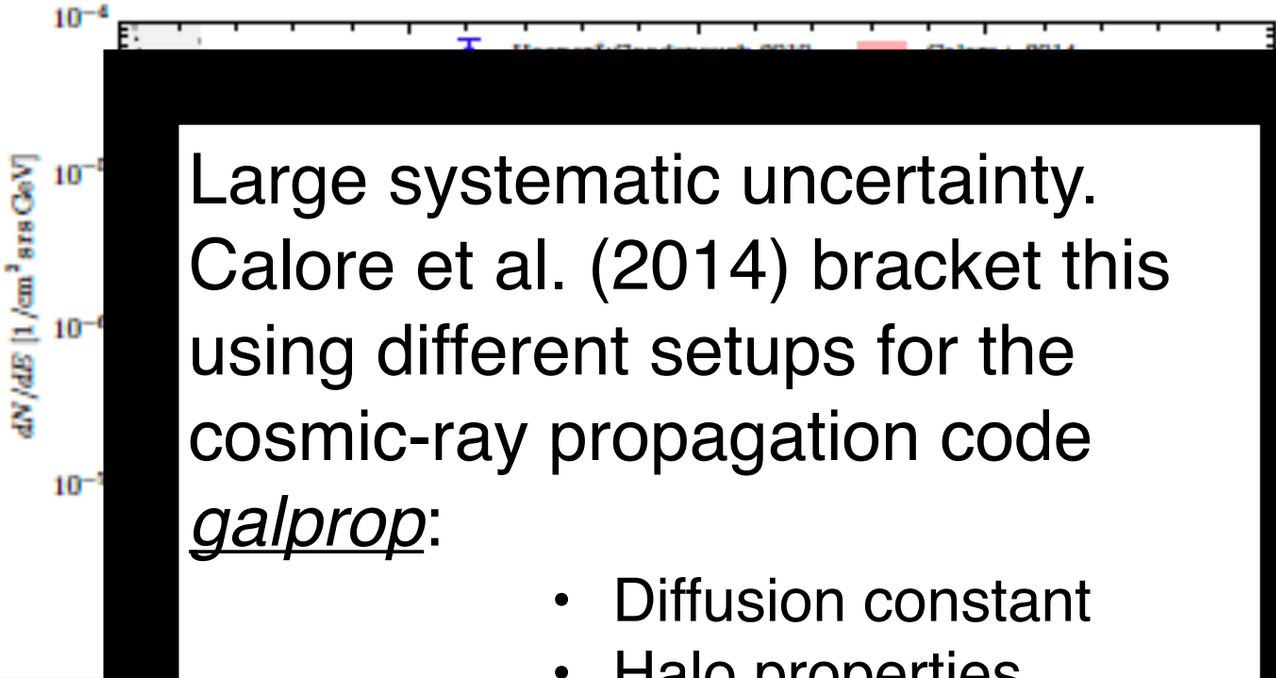


Large systematic uncertainty. Calore et al. (2014) bracket this using different setups for the cosmic-ray propagation code *galprop*:

- Diffusion constant
- Halo properties
- Magnetic field
- Distribution of sources!!
- etc…

But this is still incomplete!

Observational summary (2014)

- Highly significant feature at the Galactic Center, confirmed by many groups and robust w.r.t. interstellar emission modelling
- Spectrum peaks at ~2 GeV
- Roughly spherically symmetric
- Unknown origin

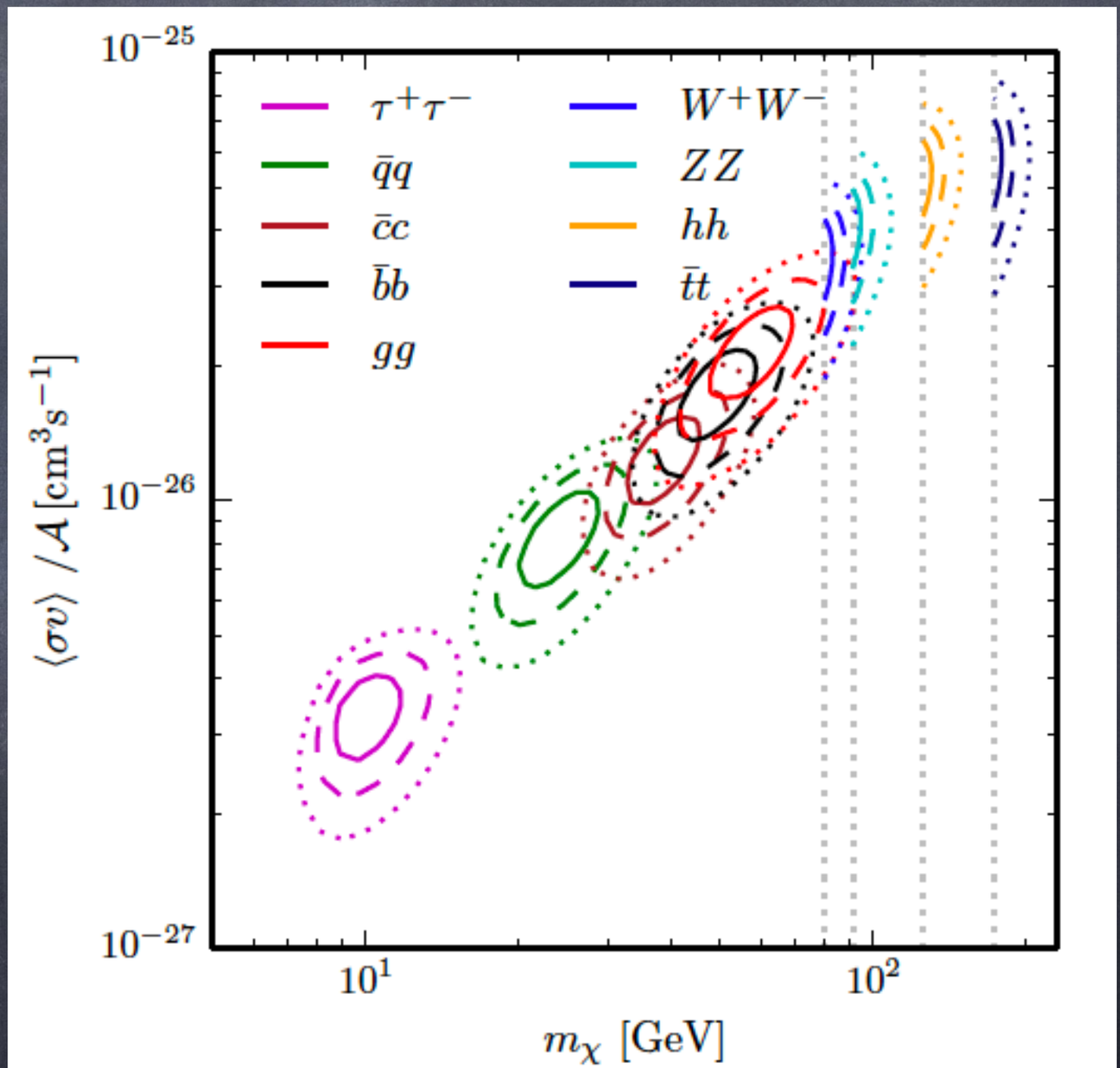
Interpretation

Candidate	Spectrum	Morphology
Dark Matter		
MSPs		
Transient event		
Steady CR source		
Molecular clouds		

Dark Matter 2

- ✅ Sky-distribution
- ✅ GeV scale mass
- ✅ Thermal production

$$\langle \sigma v \rangle \sim 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$



Calore et al. (2015b)

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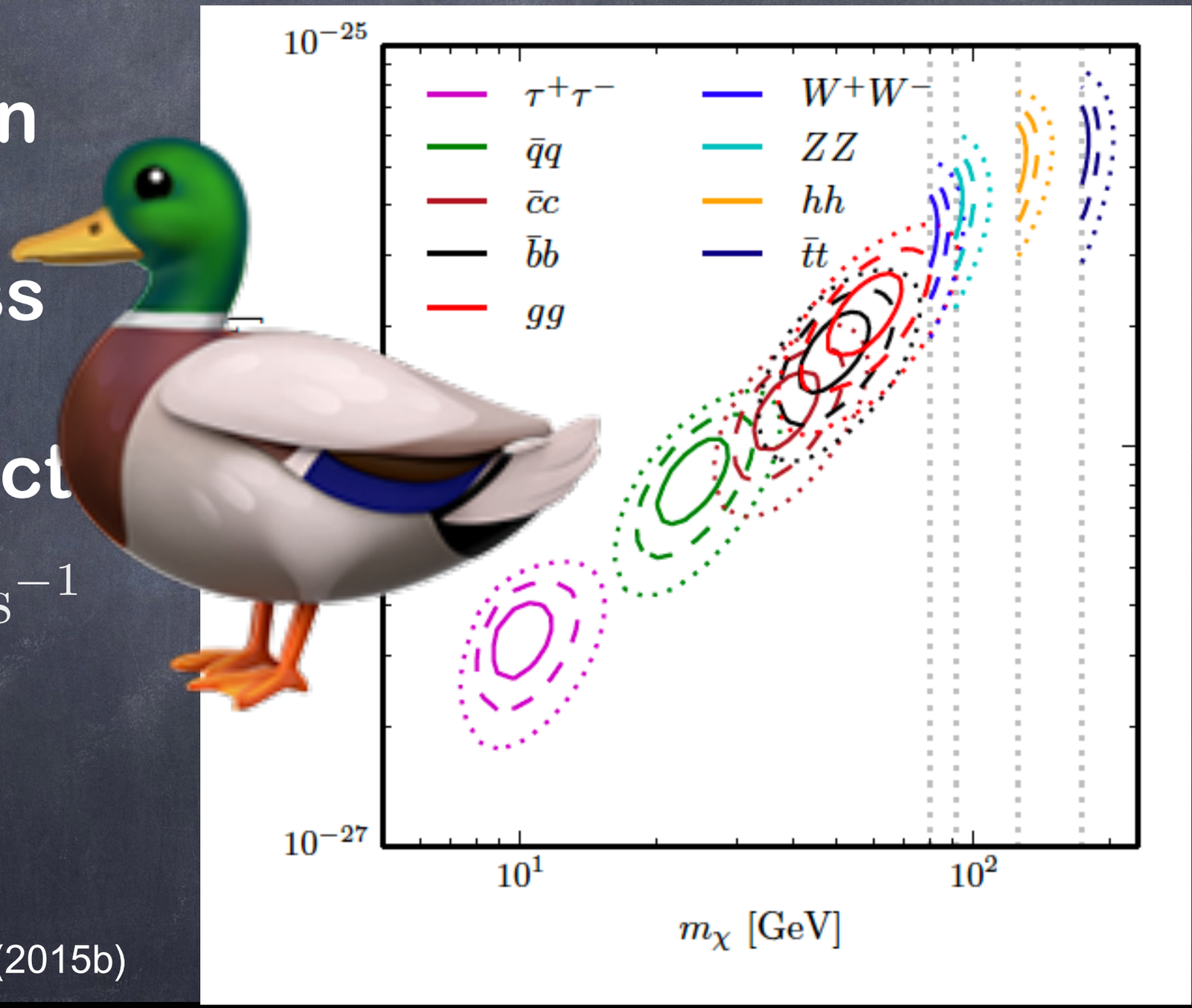
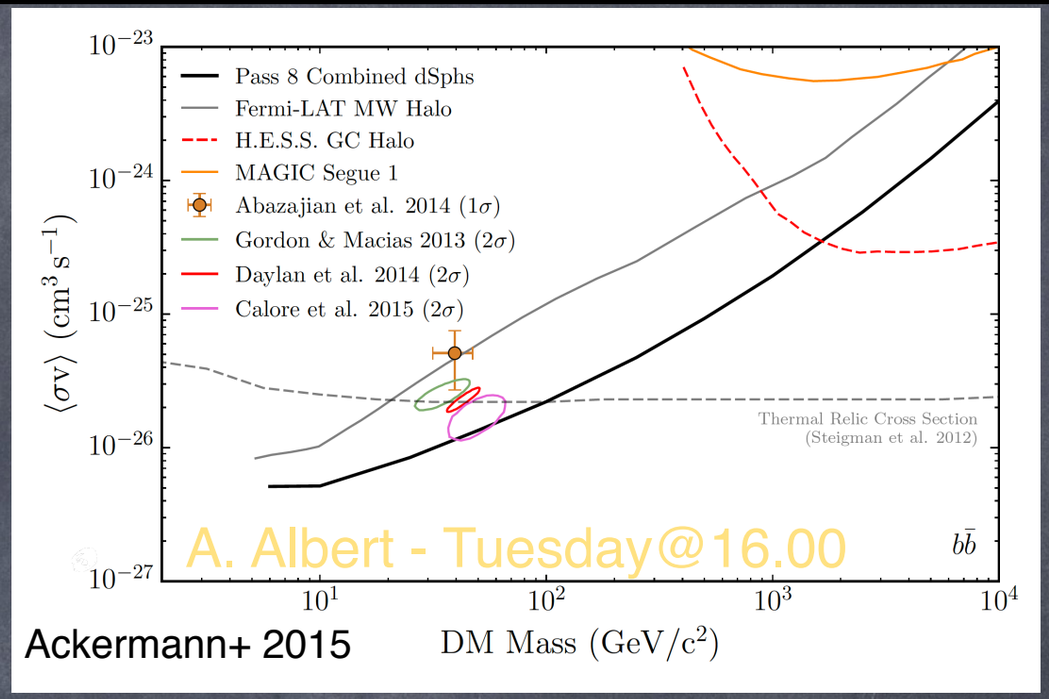


Calore et al. (2015b)

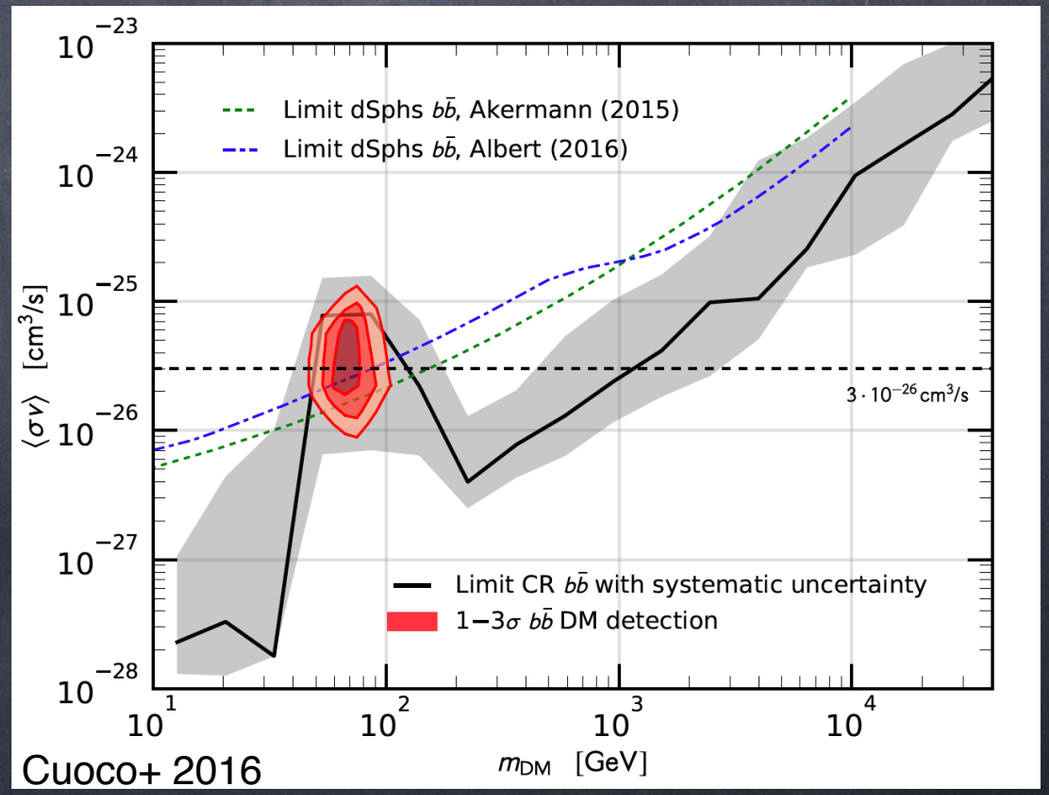
Chances for DM

- There are DM hints compatible with the GCE:
  - Reticulum II dSph: excess —> More dwarf signals soon? (Geringer-Sameth+ 2016)
  - Anti-proton anomaly? (Cuoco+ 2016, Cui+ 2016)



Ackermann+ 2015

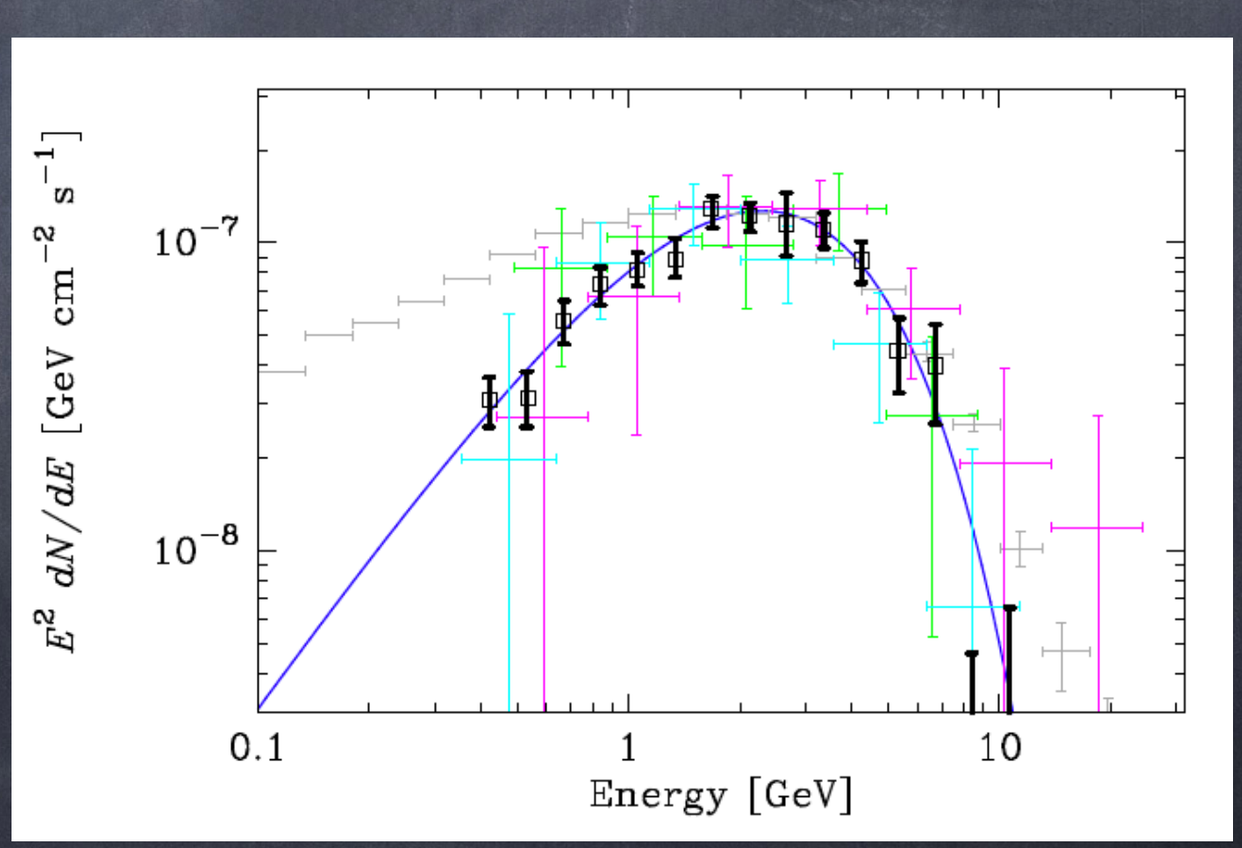
- Chances at LHC?
  - GCE compatible with “natural” SUSY Achterberg+ 2015, van Beekveld+ 2016



Cuoco+ 2016

Millisecond pulsars

- Old stars: likely to be found in the Bulge
  - Formed in-situ or from disrupted globular cluster (e.g. Brandt & Kocsis 2015)
- Correct spectrum
- $\mathcal{O}(10^4)$ MSPs can explain the GCE



Abazajian (2010)

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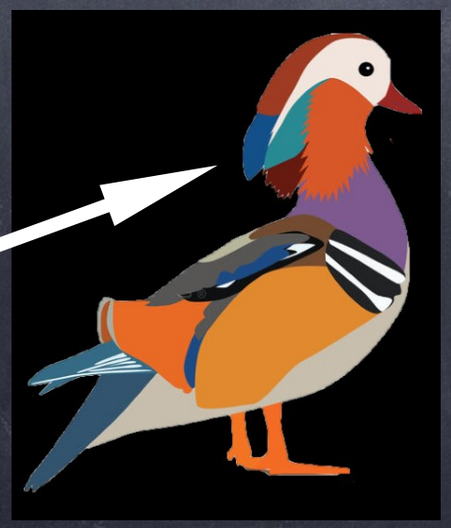
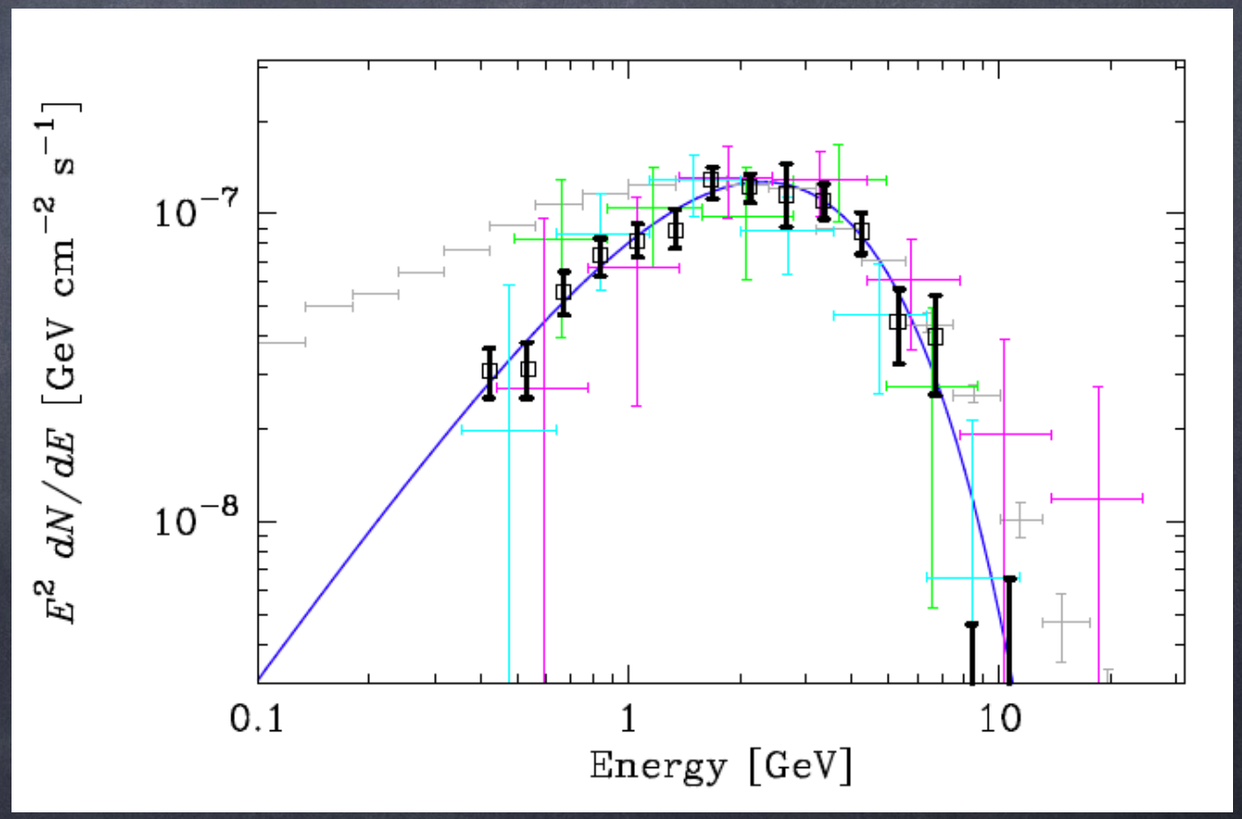
Also a duck





Abazajian (2010)

Arguments Against MSPs

- We should have detected many more γ-ray bright MSPs from the bulge.
  Hooper+ 2013 (1407.5625),
  Hooper & Mohlabeng 2015

- Given the ratio of bright LMXBs-to-MSPs in globular clusters. We should have seen more bright LMXBs in the bulge.
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  - If the same as that of disk MSPs, we only expect a handful.
  - Not surprising that they are not in the ATNF: likely unassociated (due to poor radio sensitivity).

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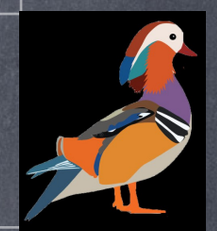
Bottom-line: MSPs in the bulge face no serious difficulties.

Interpretation: summary

Candidate	Spectrum	Morphology
Dark Matter	✅	✅
MSPs	✅	✅
Transient event		
Steady CR source		
Molecular clouds		



Transient event

- Active past of the GC
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- Protons: cannot reproduce the morphology
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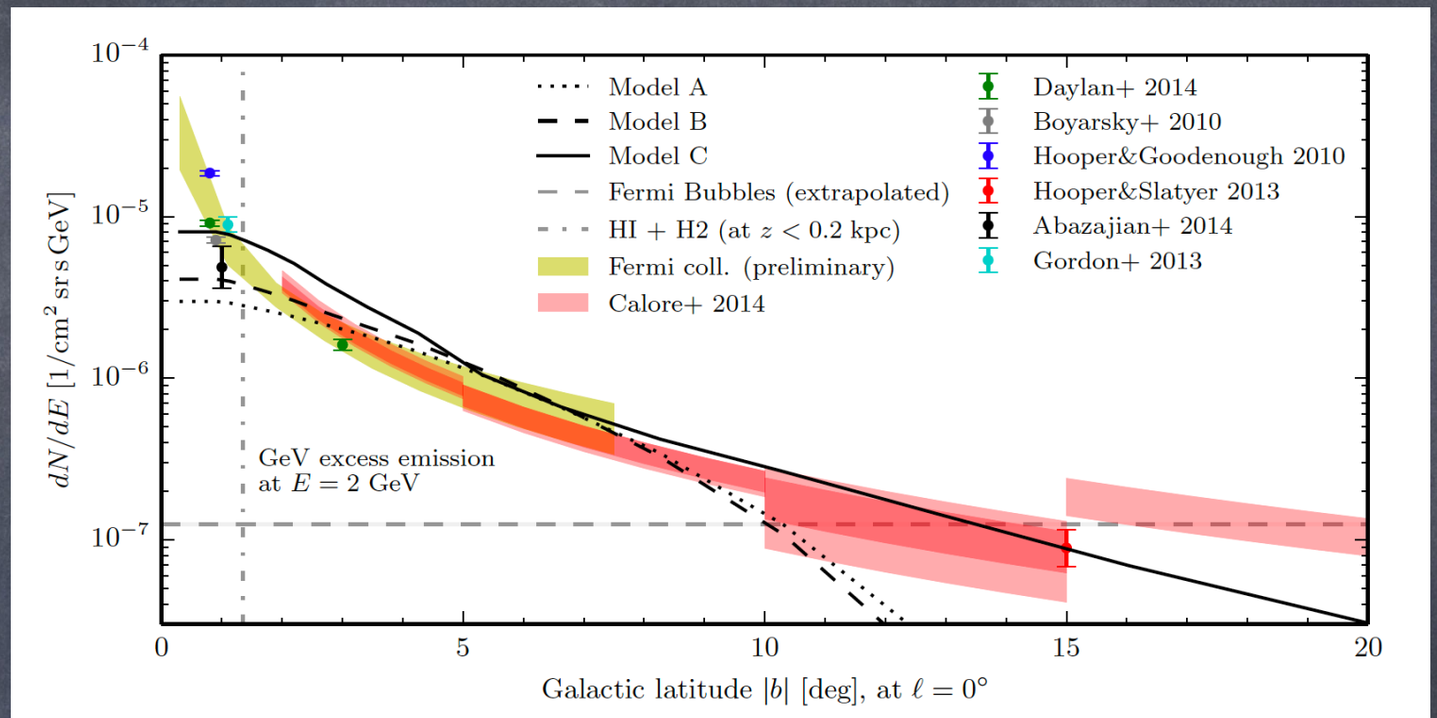
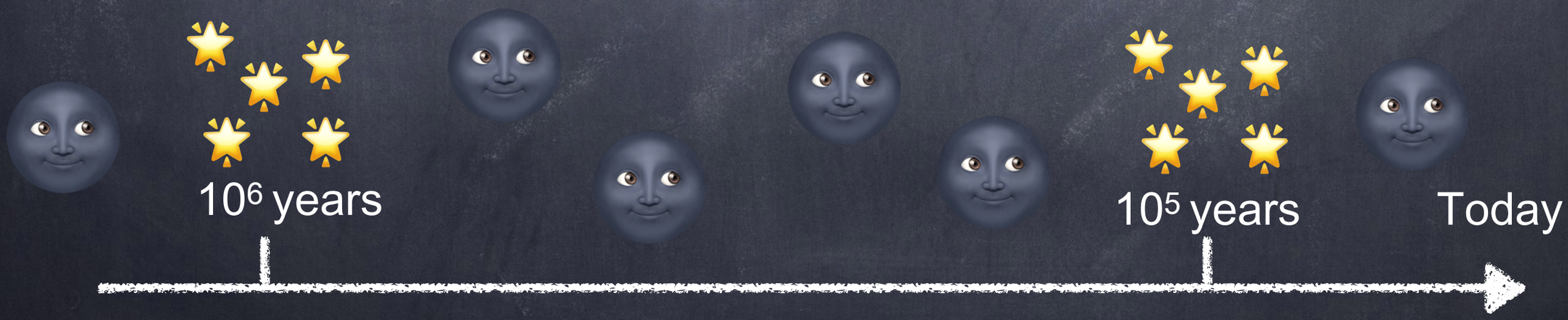


Cholis et al. (2015)



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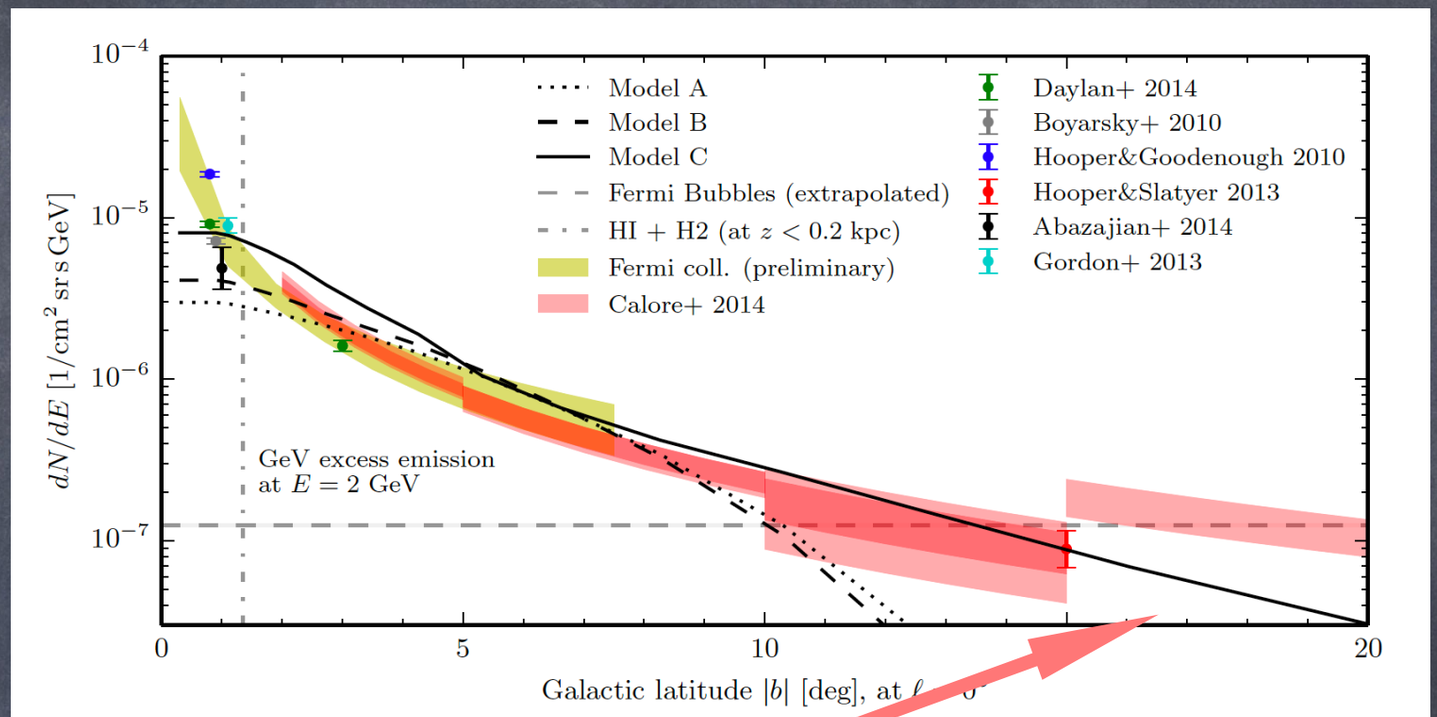

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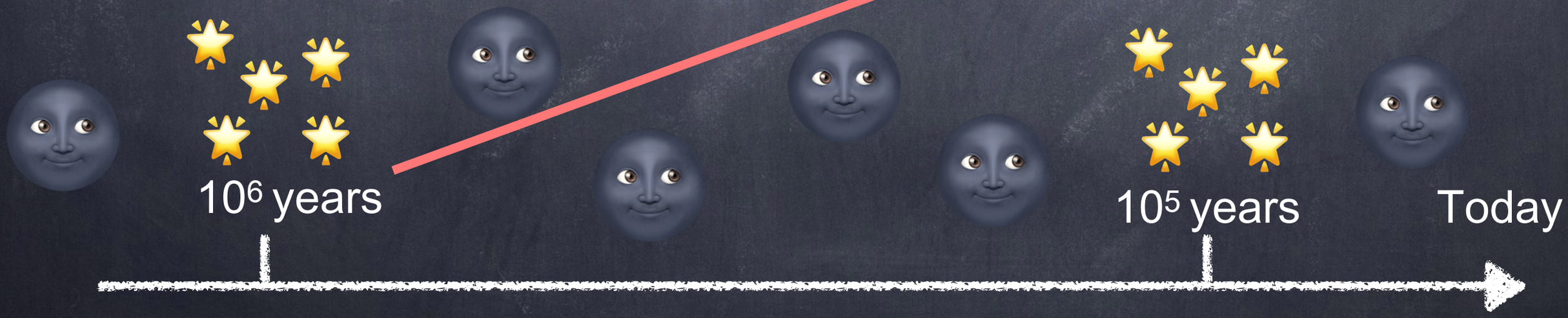

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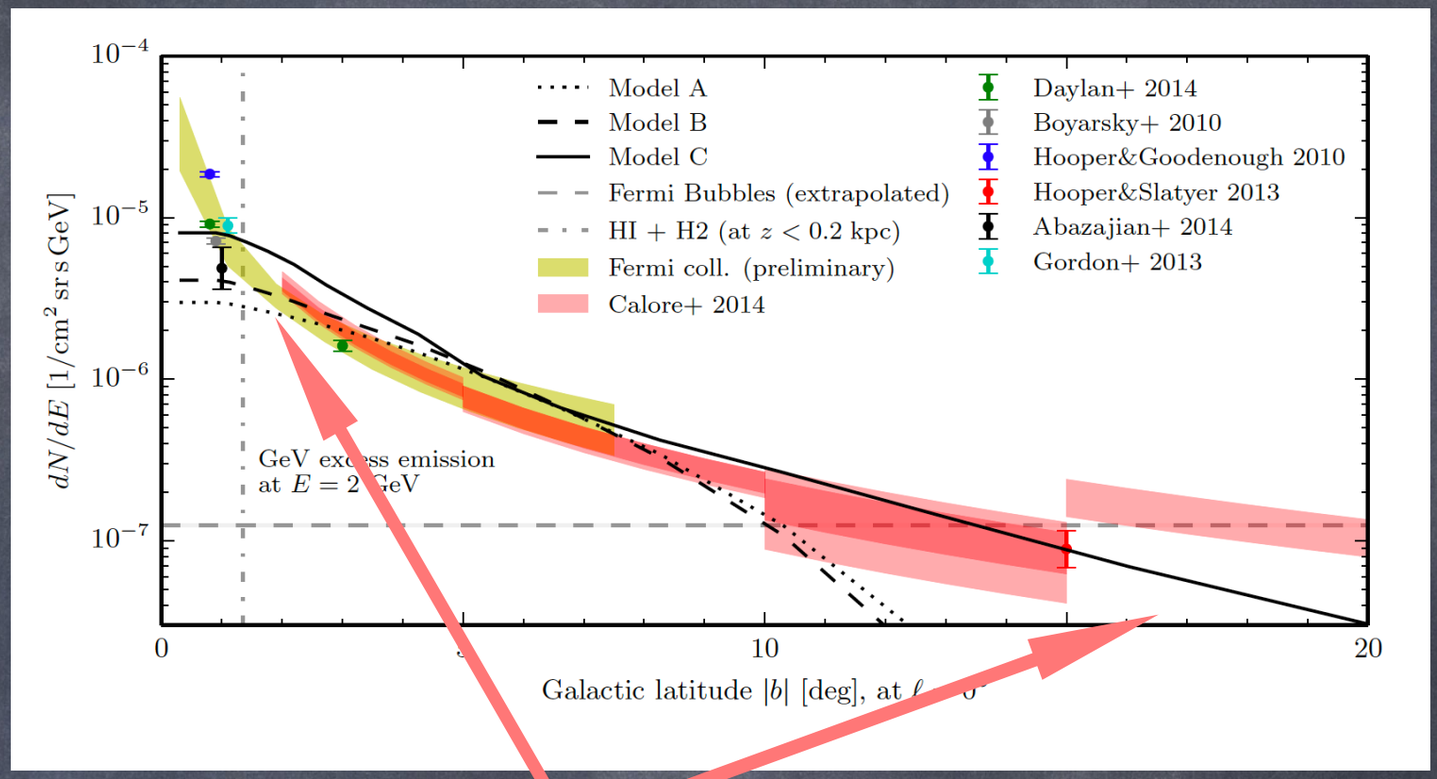

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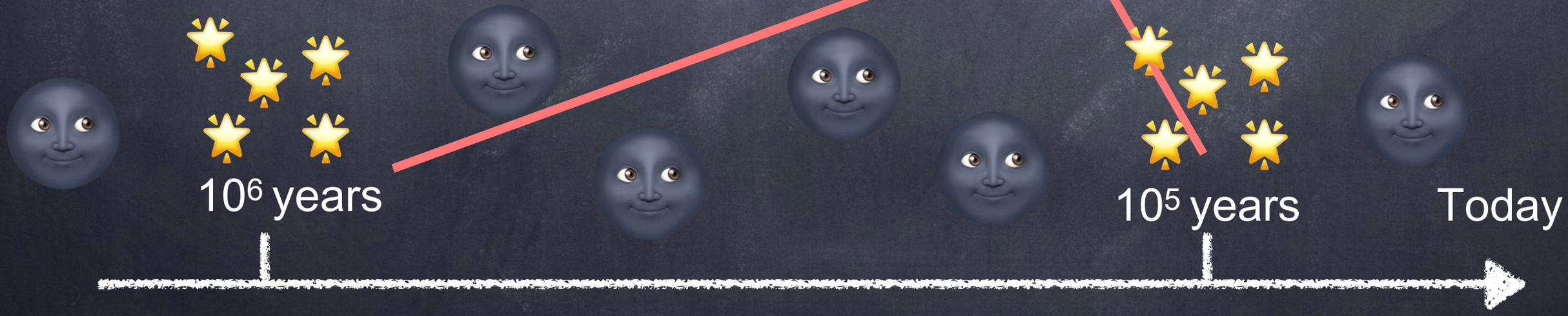
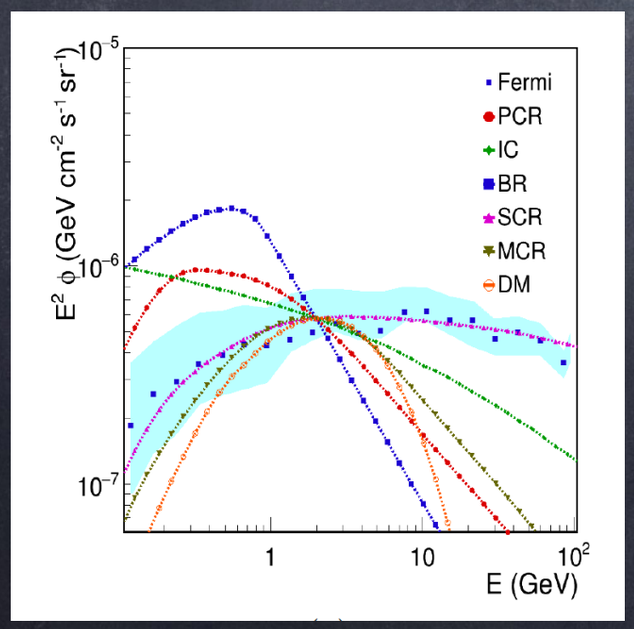
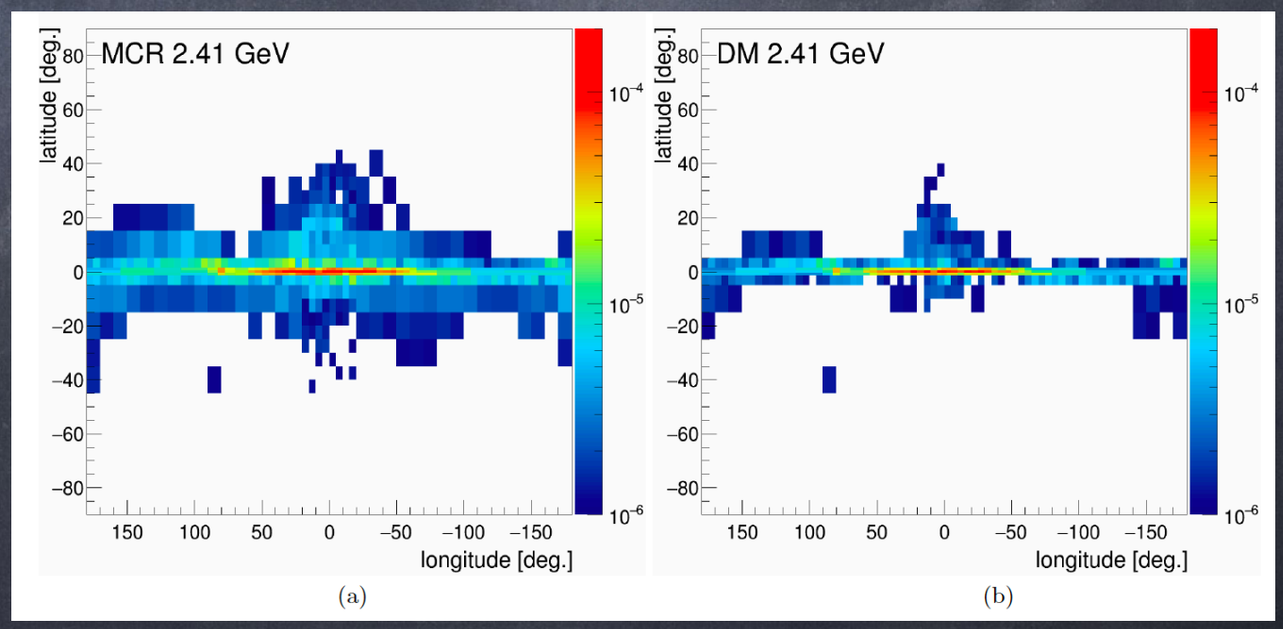


Molecular clouds

- de Boer+ 2017 use a *Spectral* template fit!
- CRs interact with molecular clouds
- Spectrum due to solar-modulation-like effect:
  prevents low-energy CRs from entering cloud

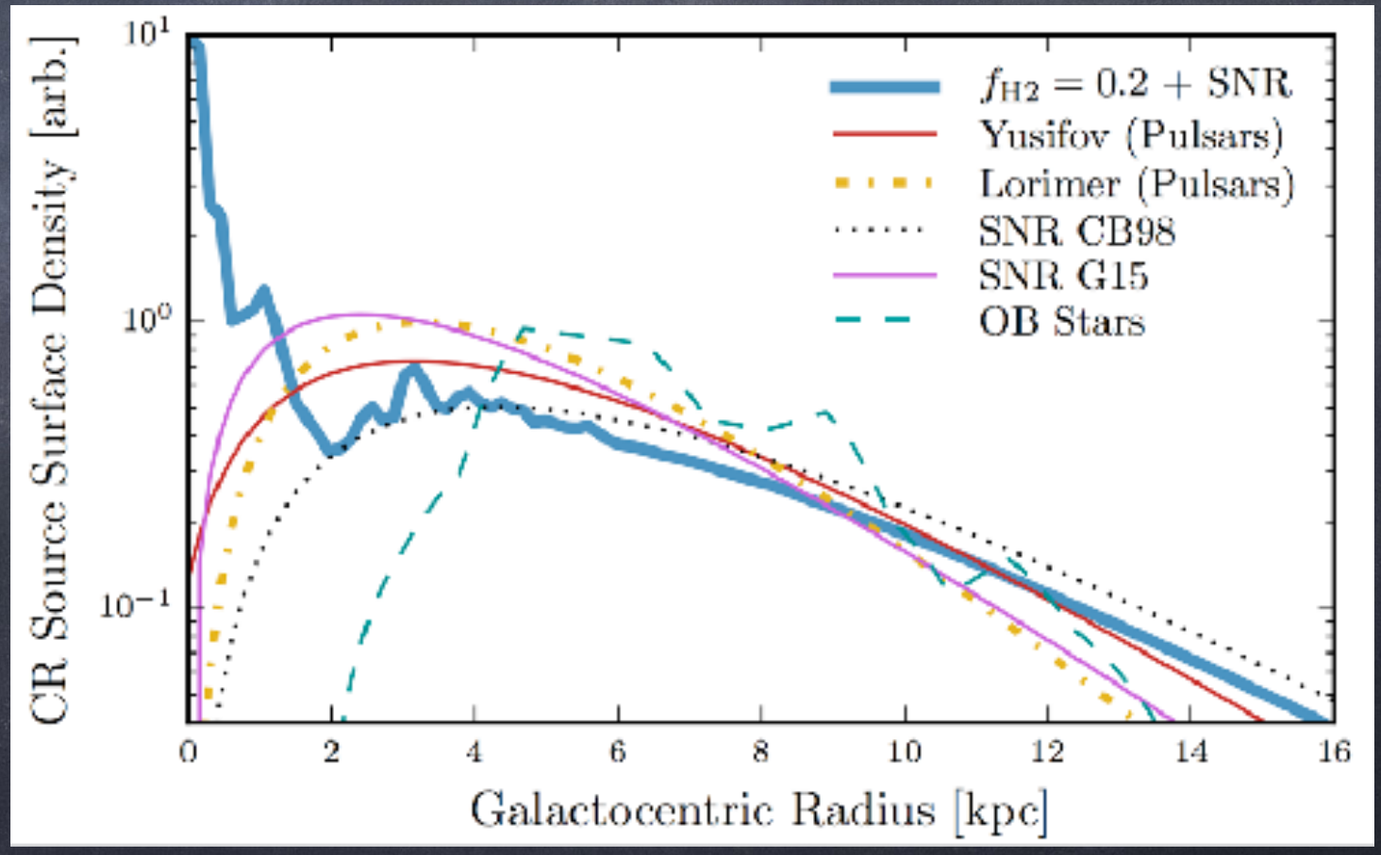




Steady CR source

- Additional source of CRs in the Galactic Center!!! Gaggero et al. (2015); Carlson et al. (2016)
- But spectrum …

By default not present
in Galprop or DRAGON



Carlson et al. (2016)

Steady CR source

Even if it does not absorb all of the GCE, additional CR injection can alter the GCE characteristics! (Carlson et al, 2016; Fermi-LAT 2017)

It will contribute to some extent!

he Galactic

et al. (2016)

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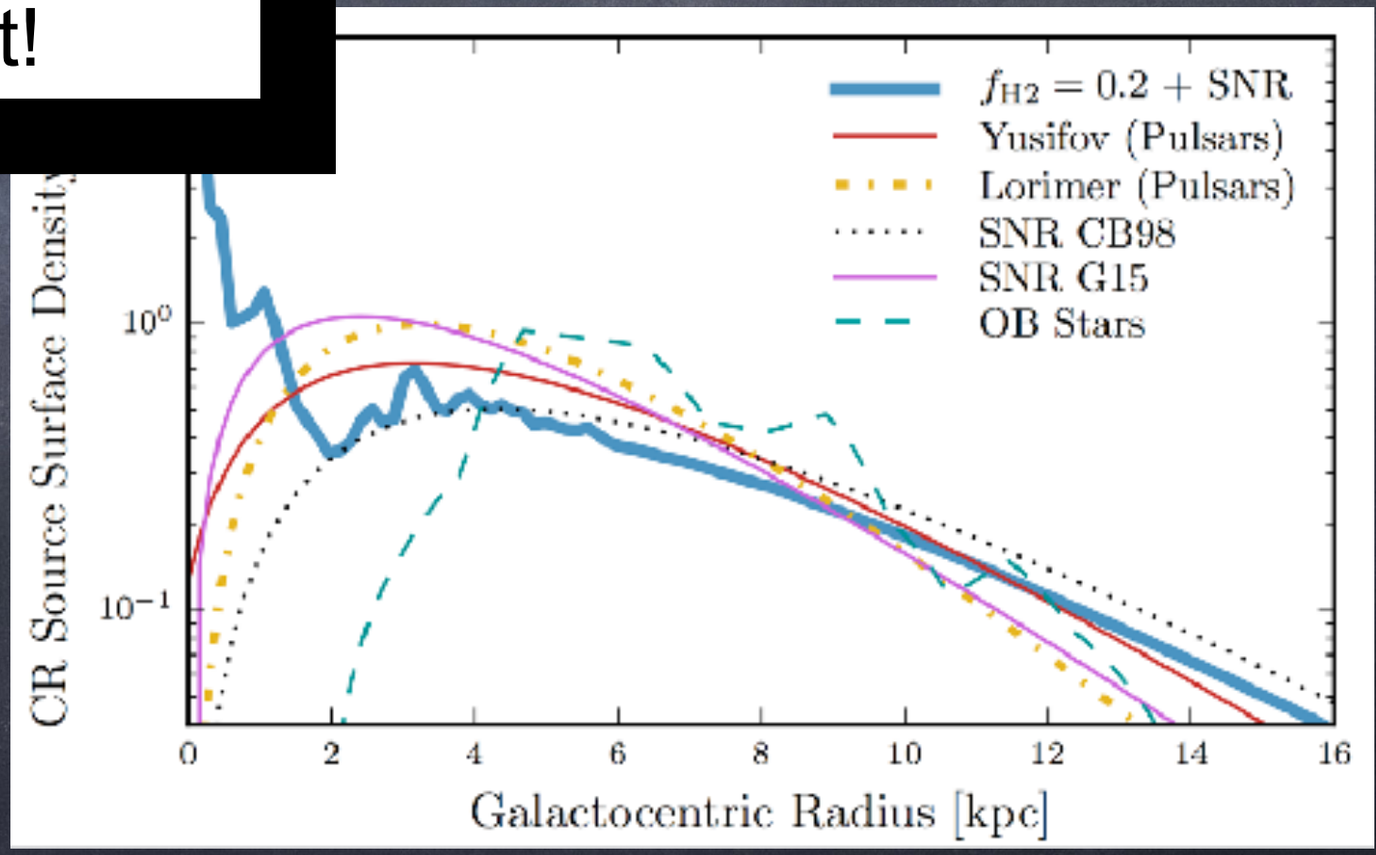

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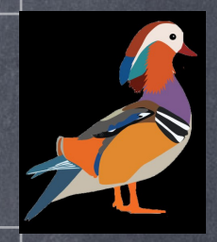

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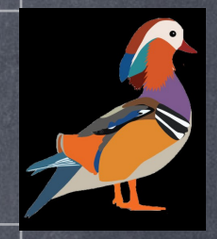
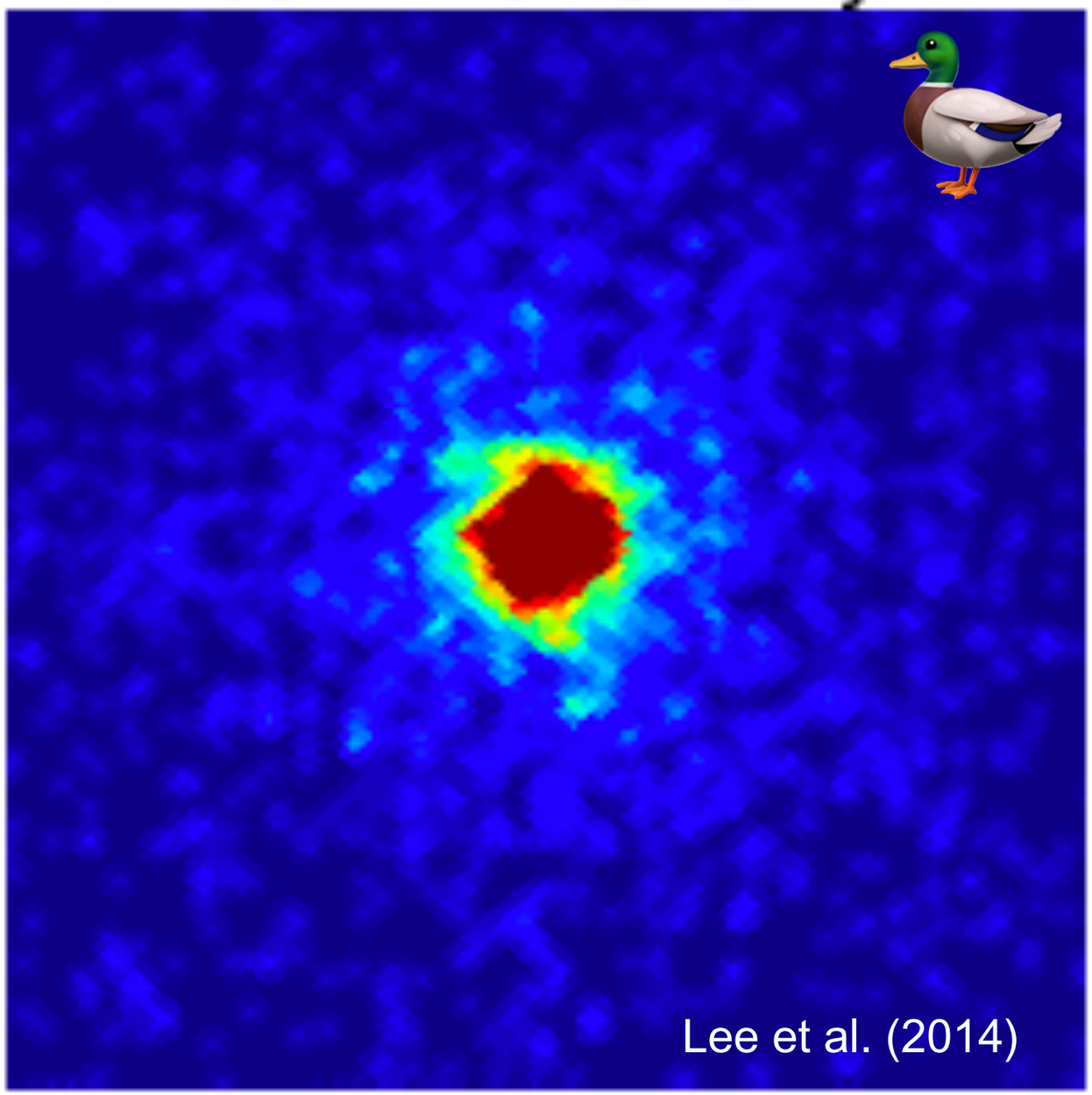


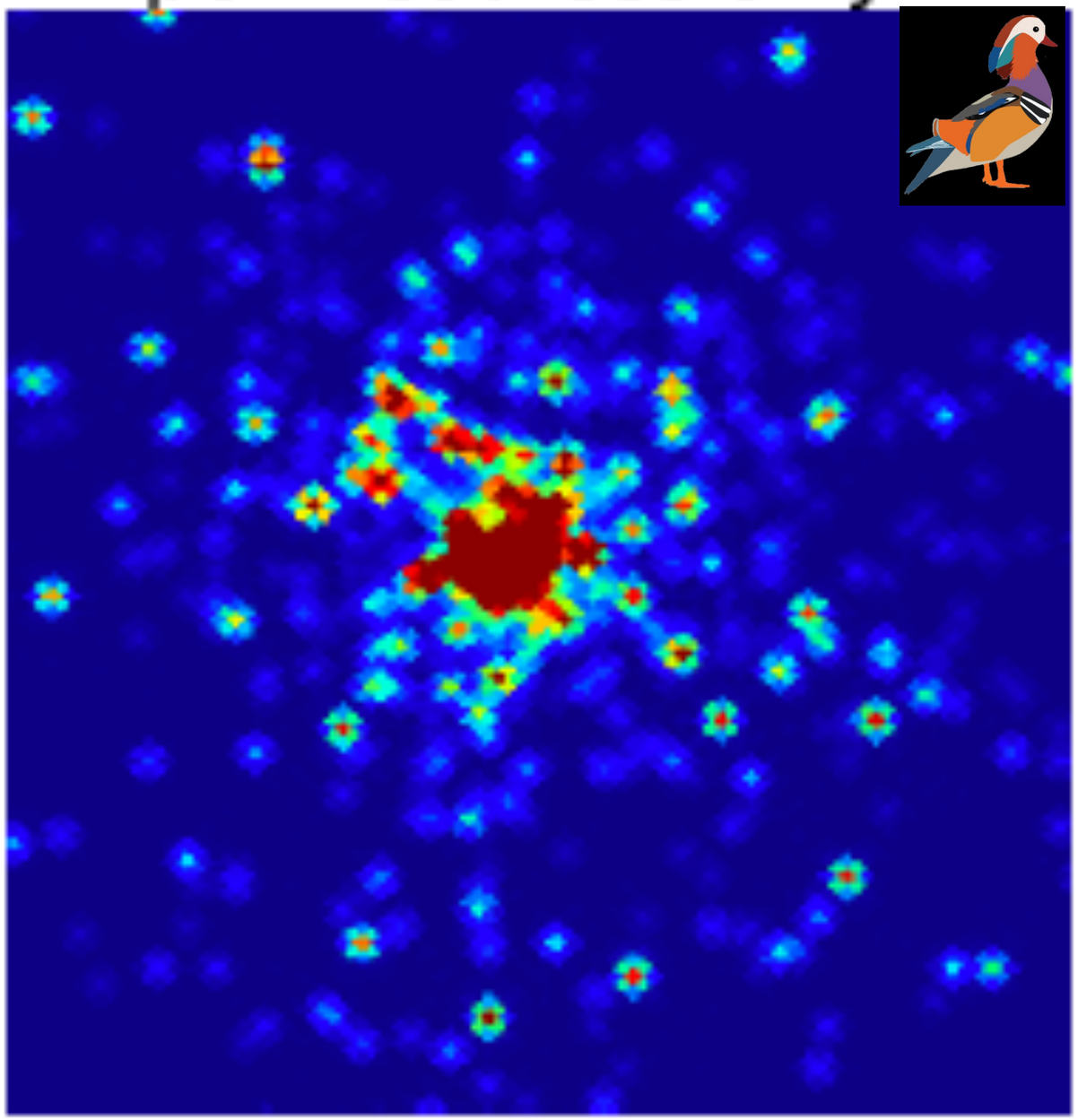
How to tell two ducks apart?

dark matter only



Lee et al. (2014)

point sources only



DM or MSPs?

or: diffuse vs. point-like

- If MSPs cause the GCE, they are likely dim and not yet identified as point sources.
- Now ~4 complementary methods to study this

1. Wavelets RB+ 2015 (but also see Balaji+ 2018)
2. NPTF Lee+ 2015
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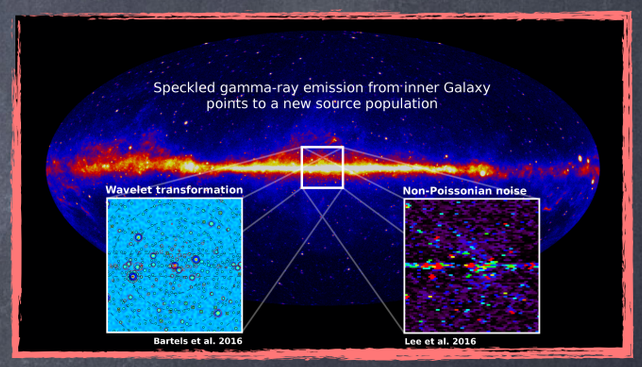

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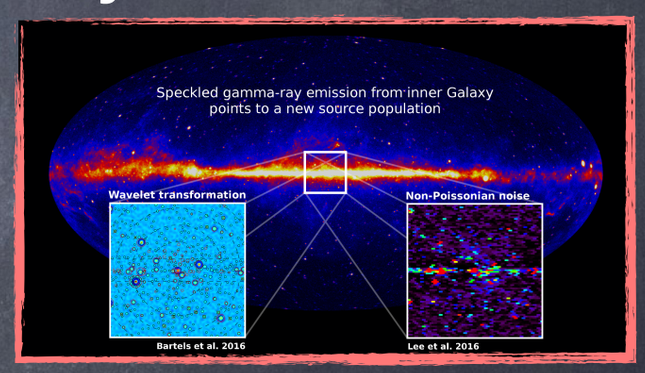


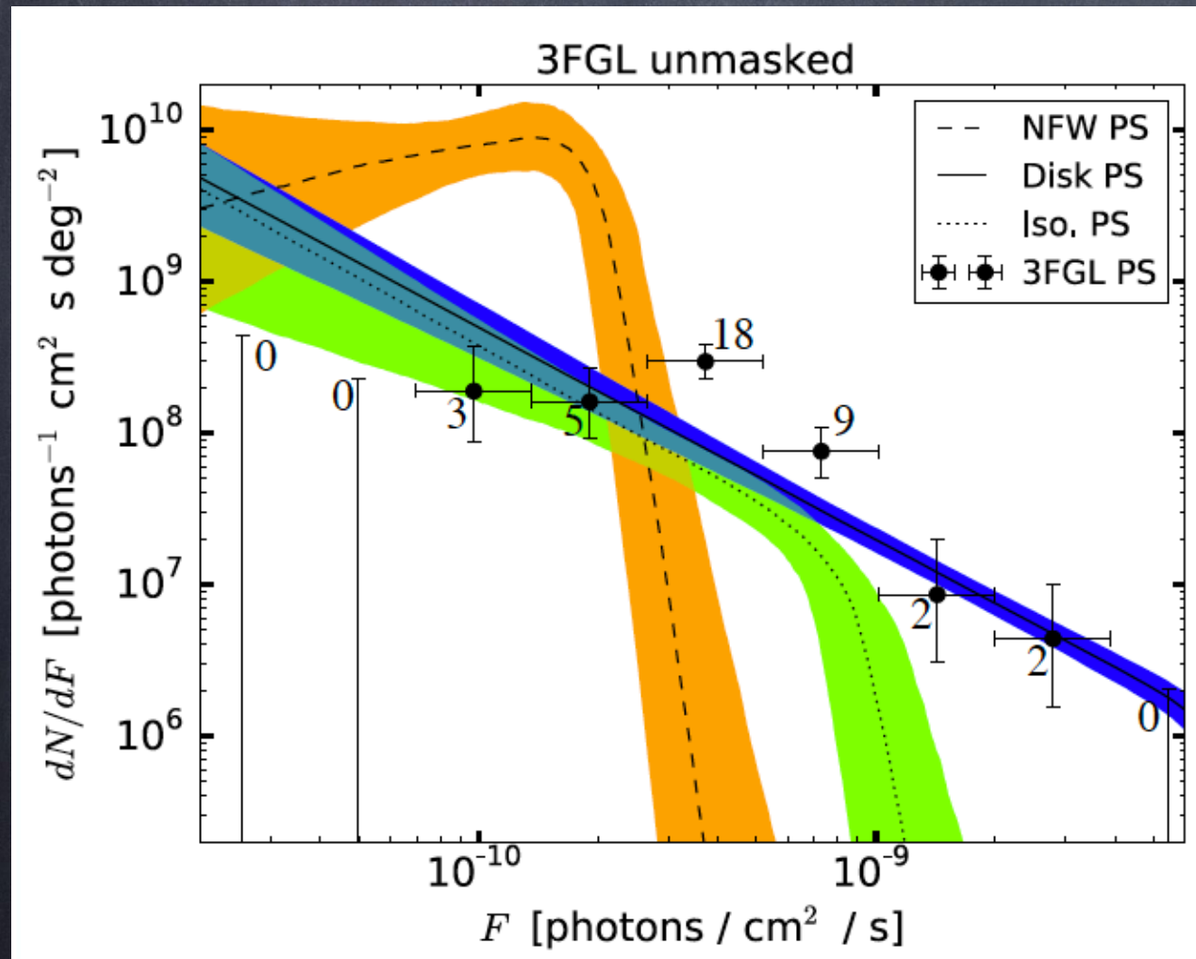
?

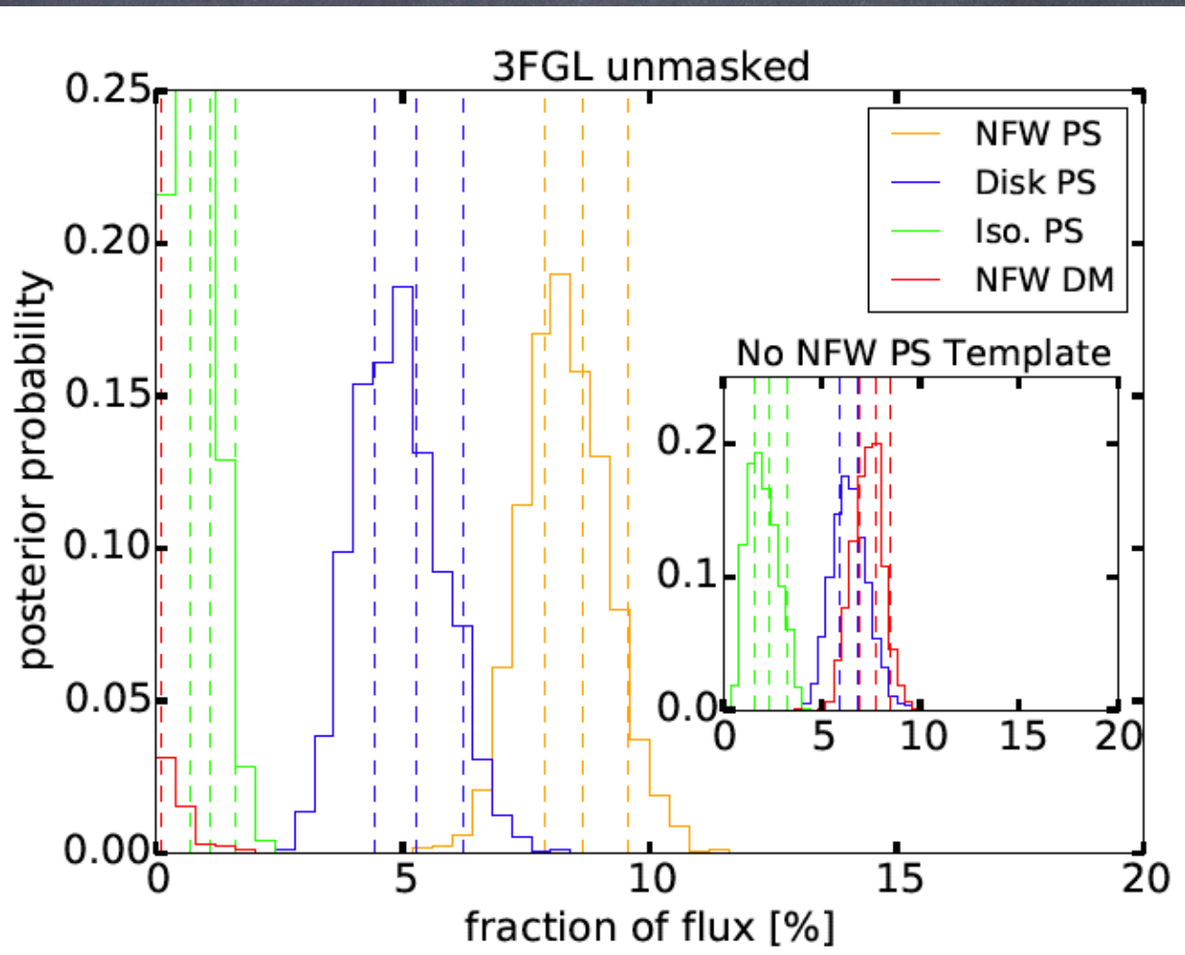
?

NPTF

Lee et al. PRL 116 (2016)

- Template fitting analysis including a non-poissonian templates (Here: NFW PS).

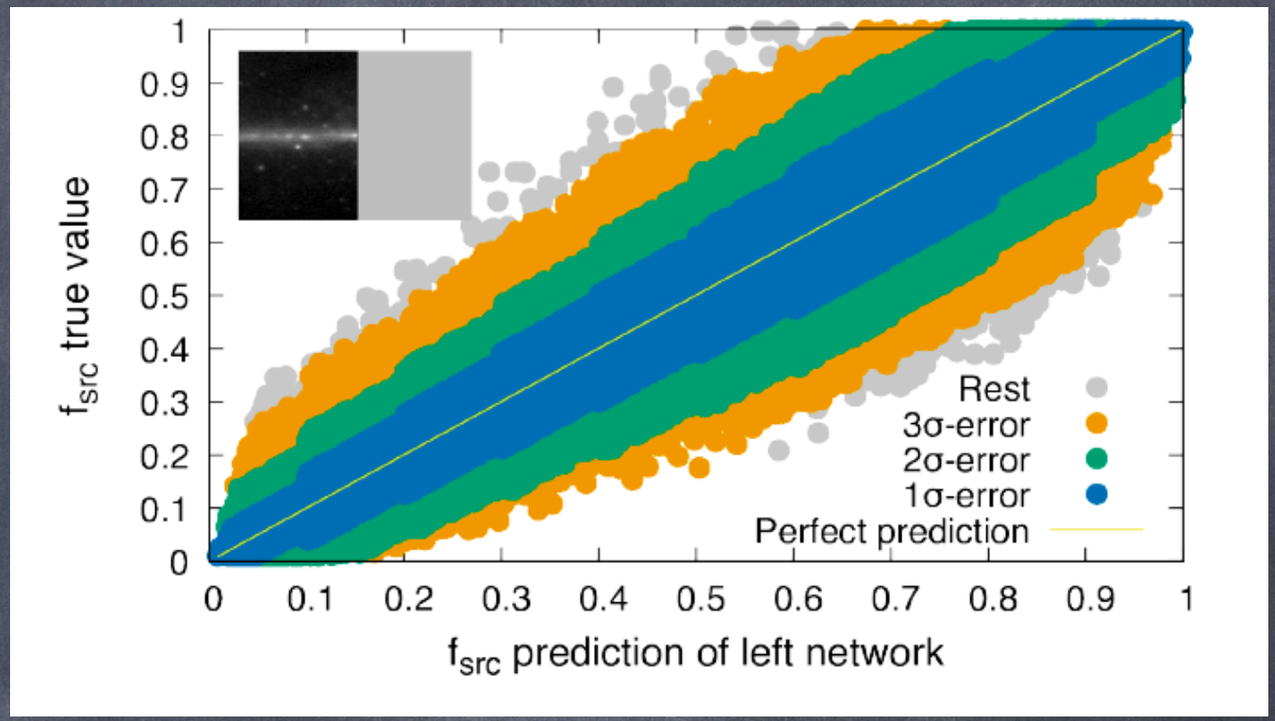


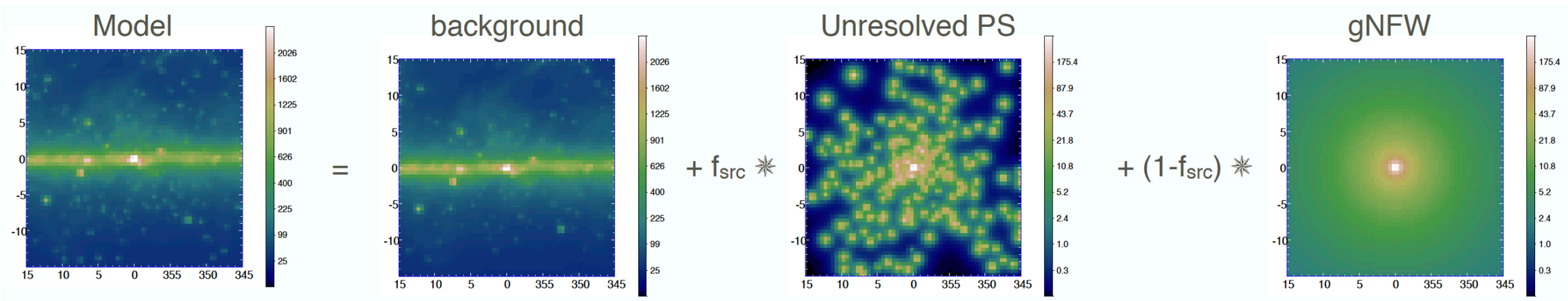


Deep Learning

Caron et al., JCAP 1805 (2018) no.05, 058

- ConvNet (for image recognition)





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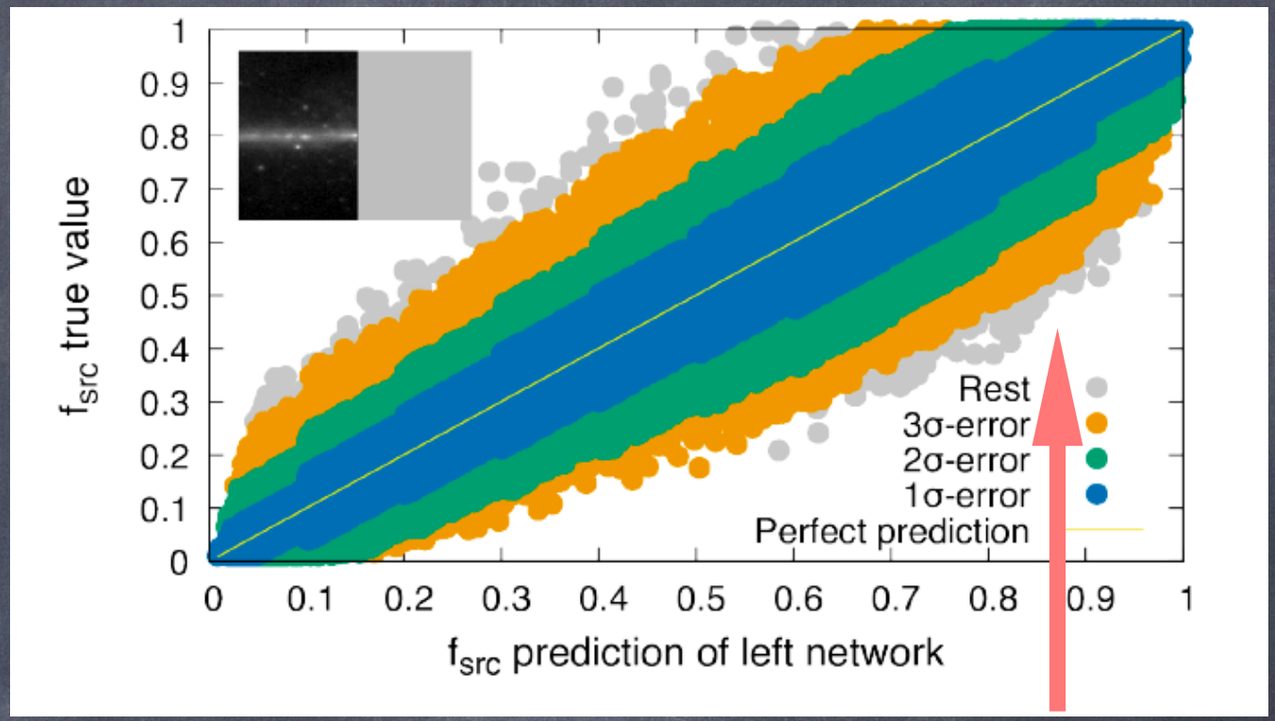

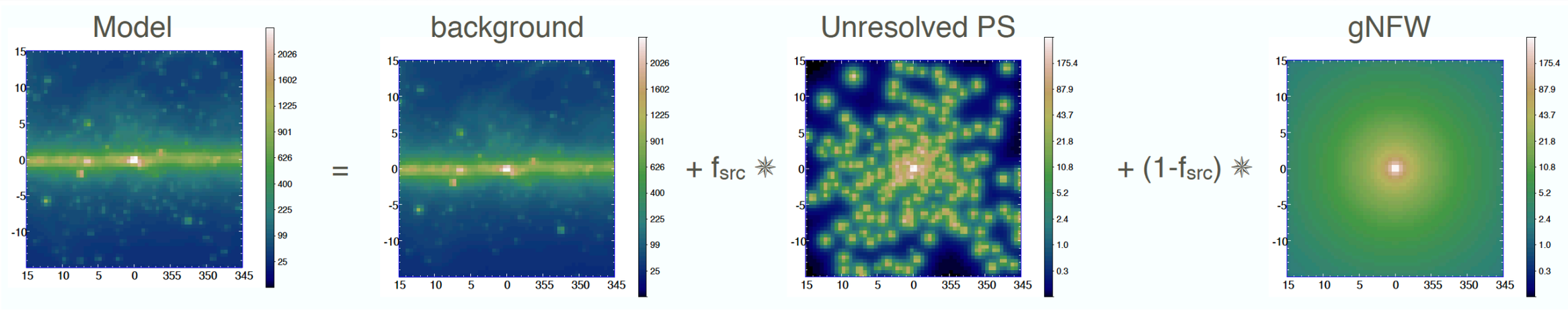

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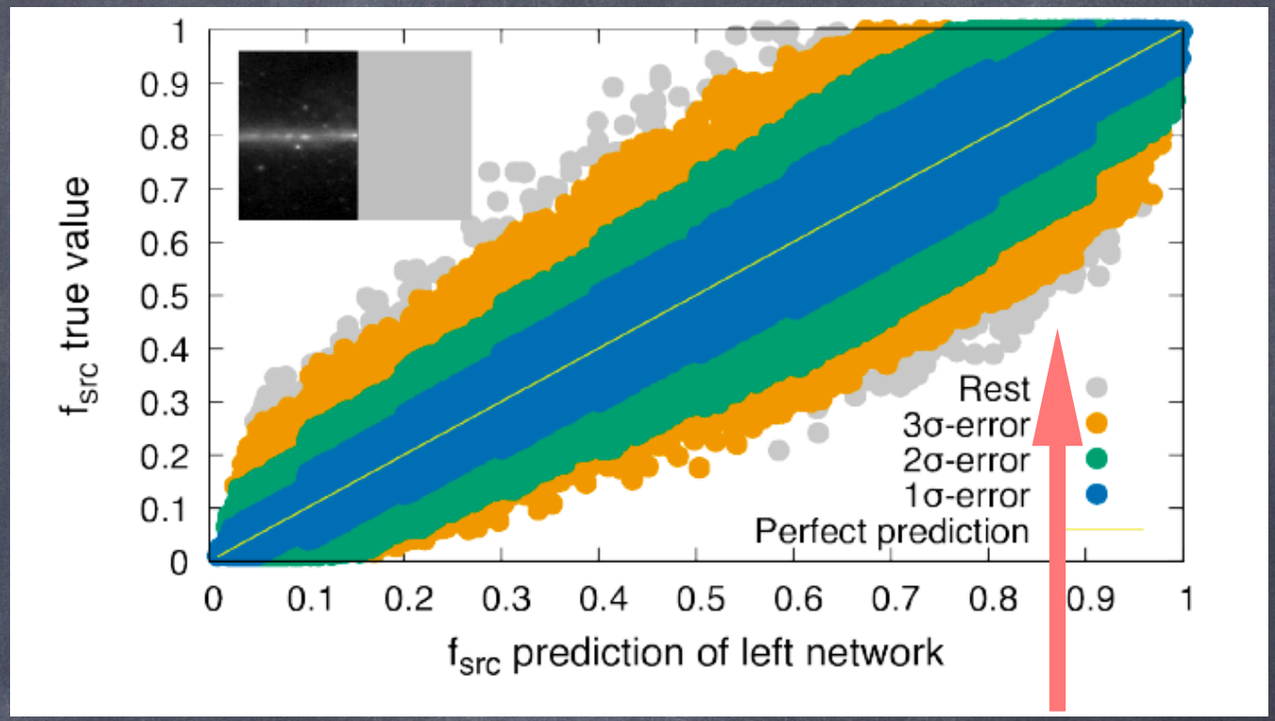

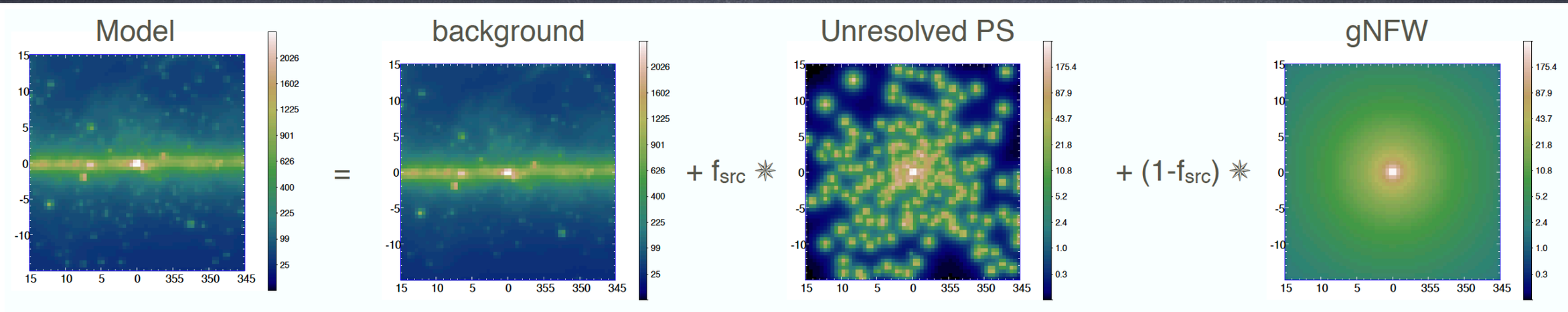

Classification of sources

Fermi-LAT, arXiv:1705.00009

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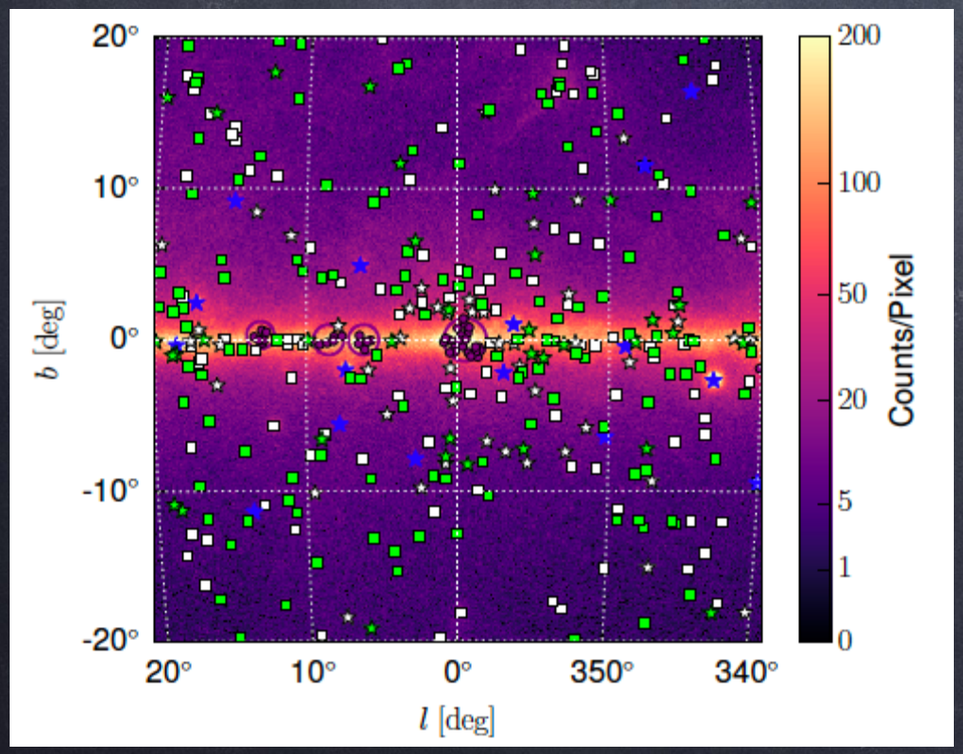

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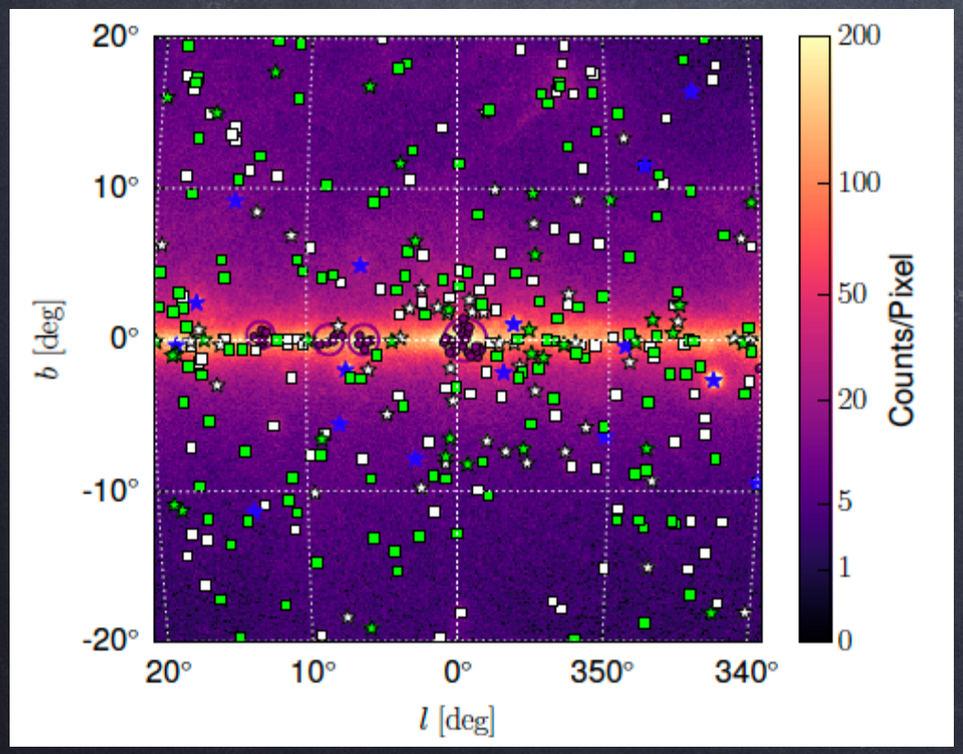

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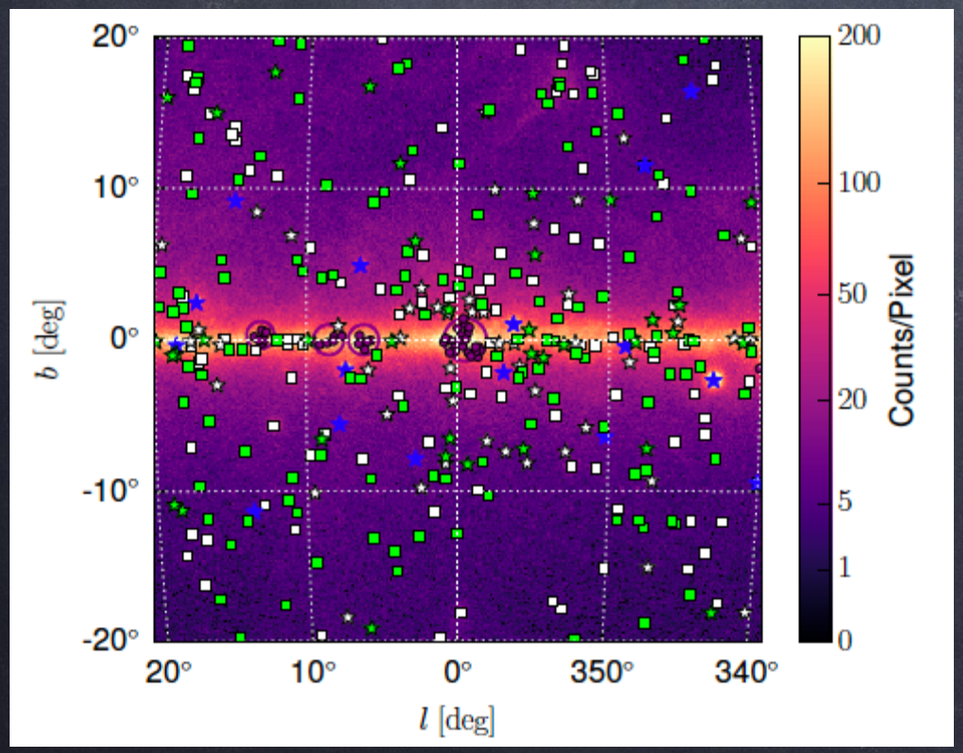

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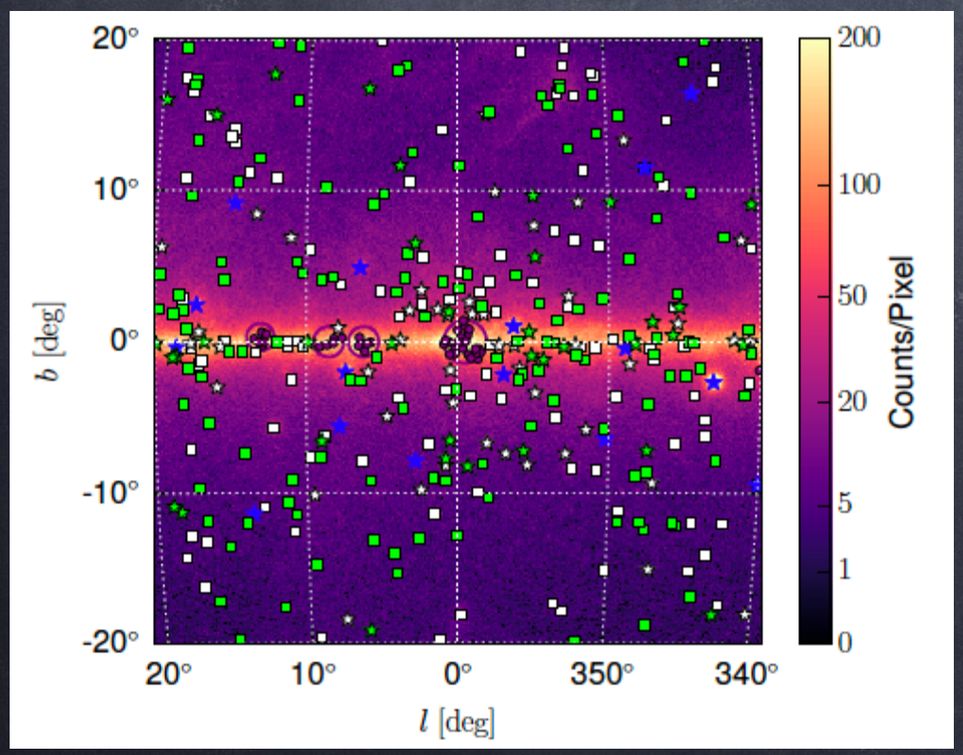

Stay tuned!

Photon clustering summary

- Corroborative evidence for bulge sources
- *Caveat:* do we model the small scale gas correctly?

Assumed background

True background

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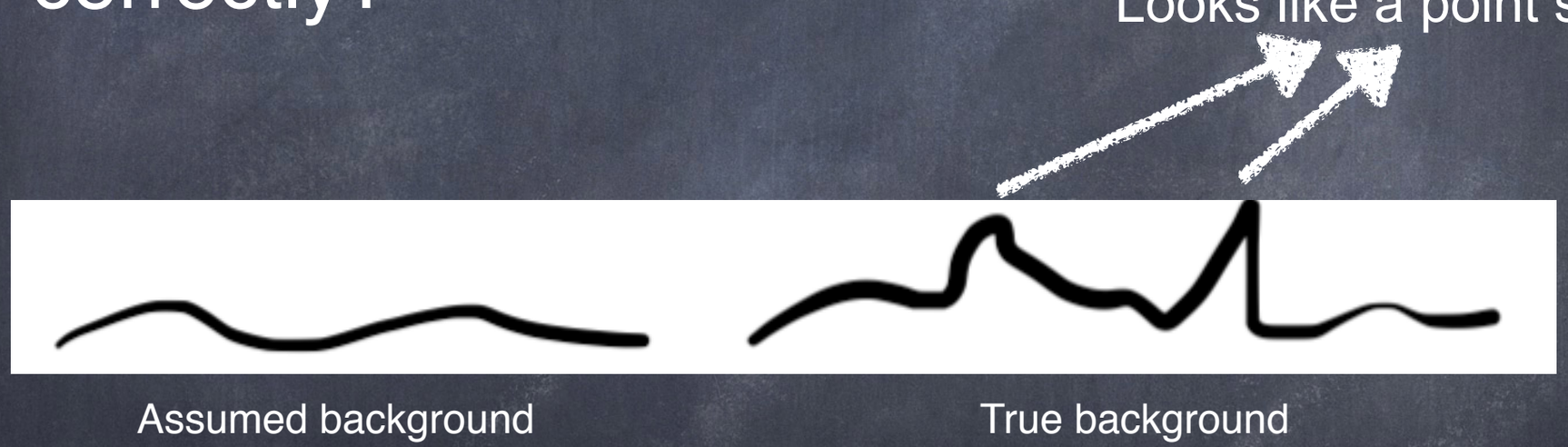

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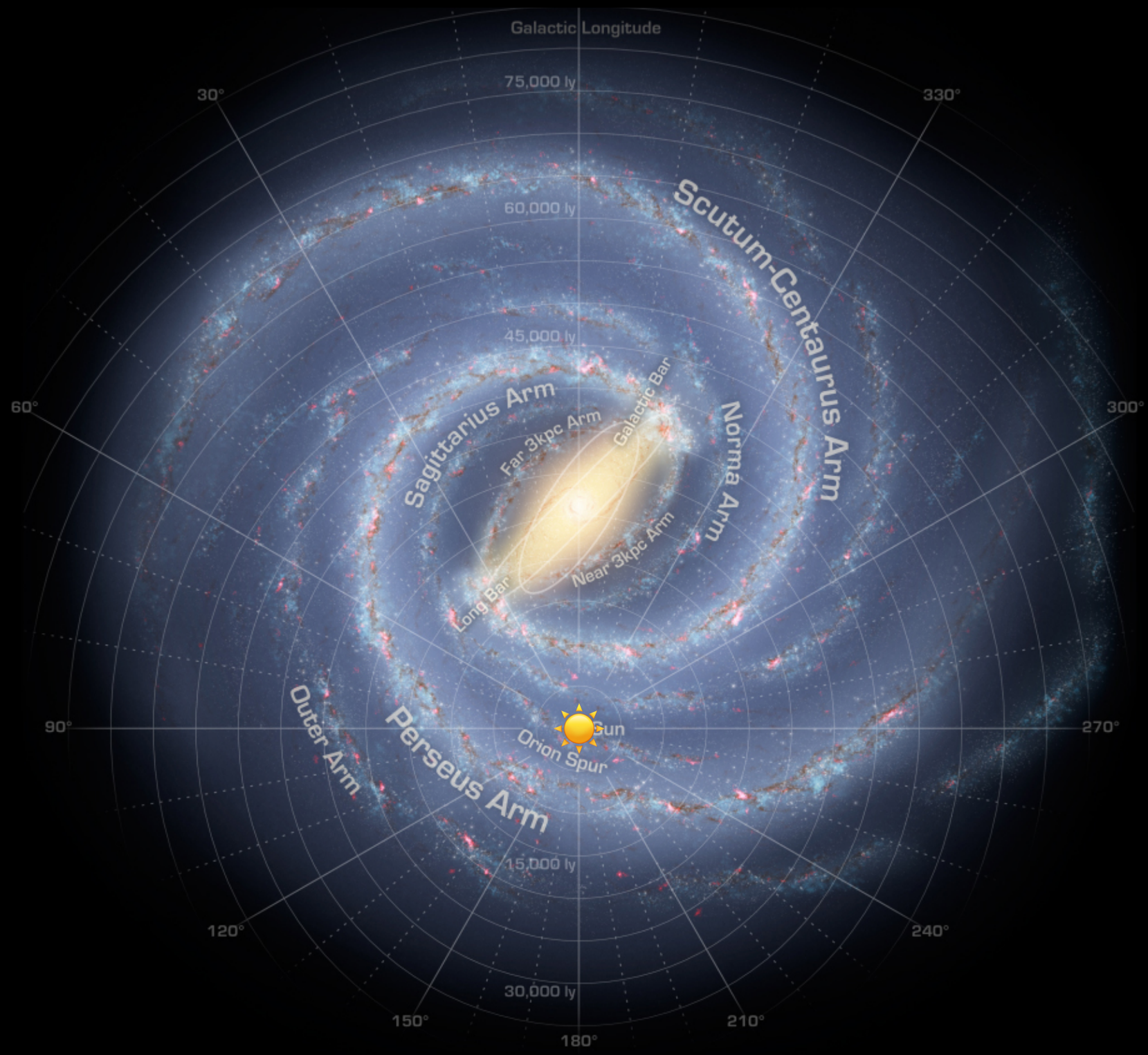
A new look at the GCE characteristics



https://www.nasa.gov/mission_pages/sunearth/news/gallery/galaxy-location.html

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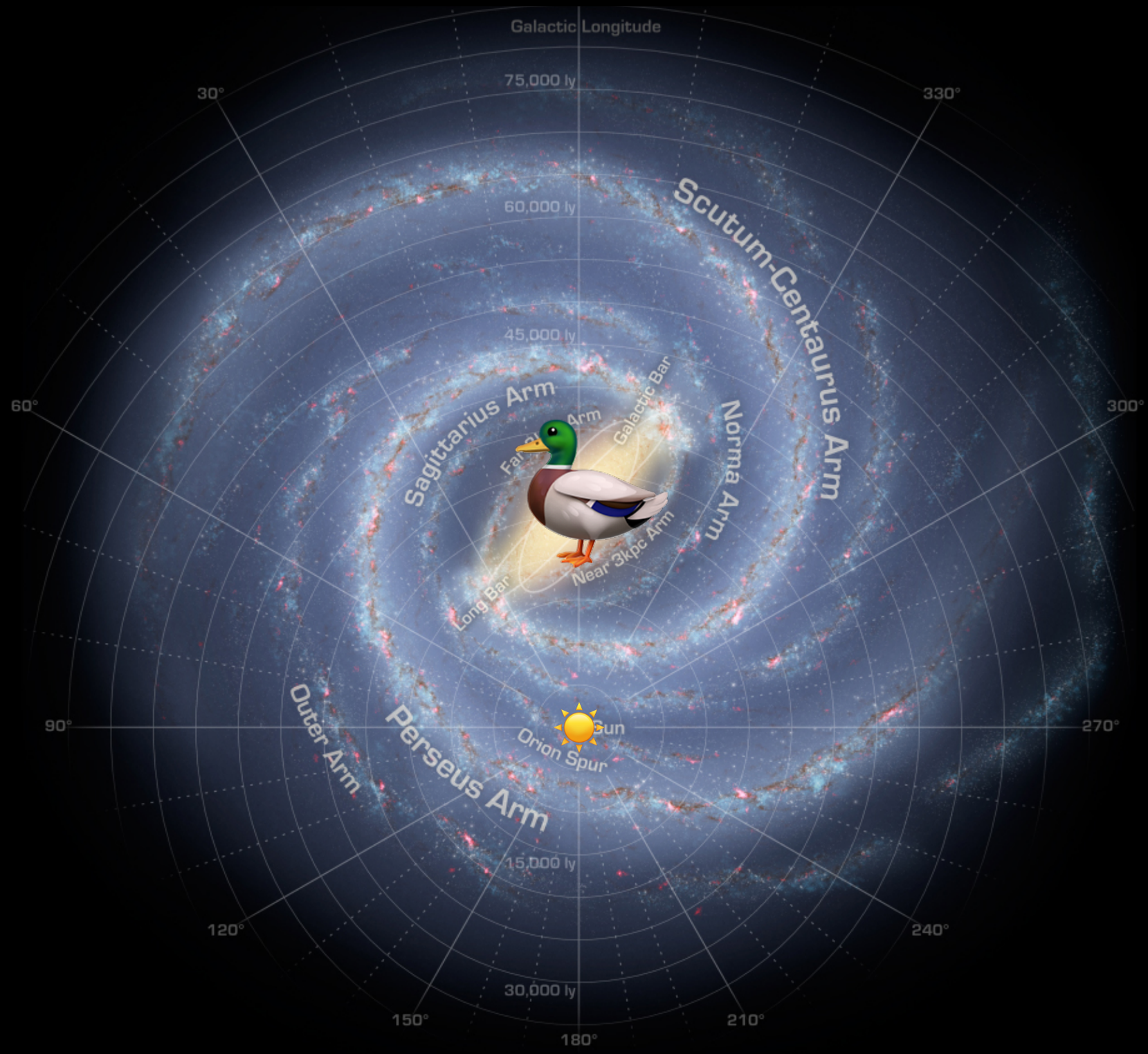

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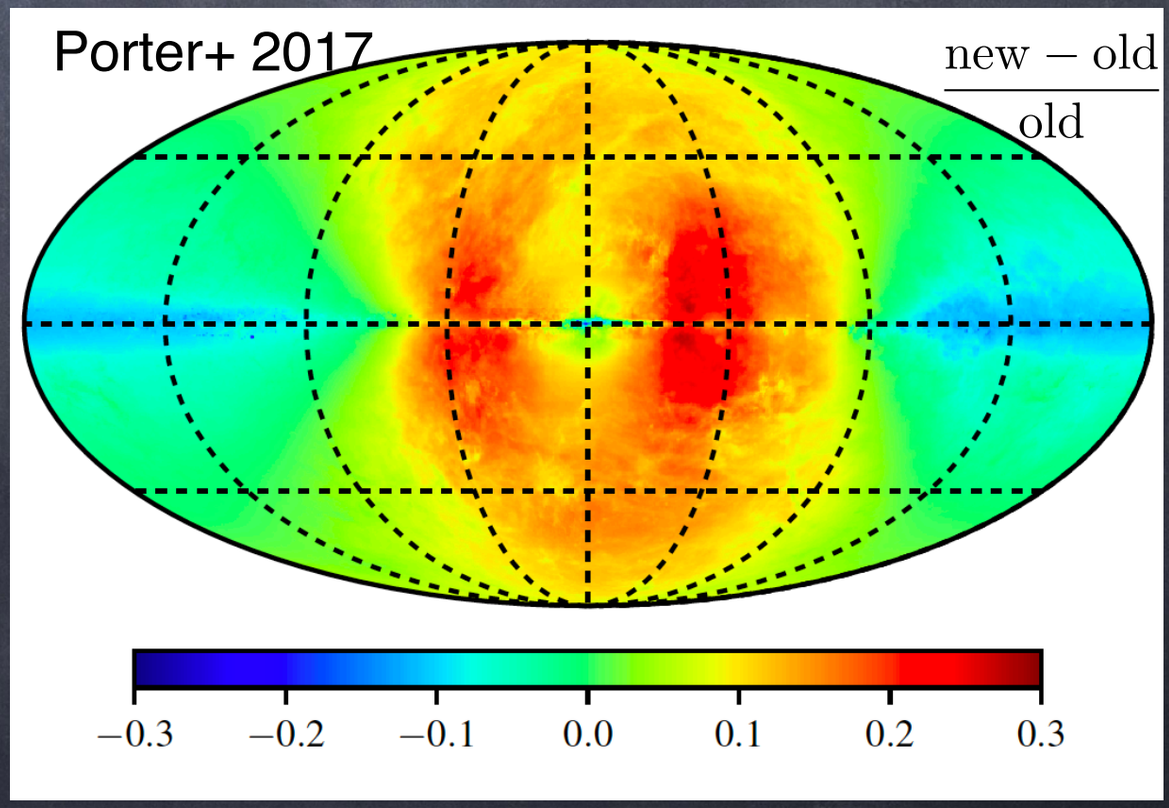
See G. Johannesson, Tuesday@16.20



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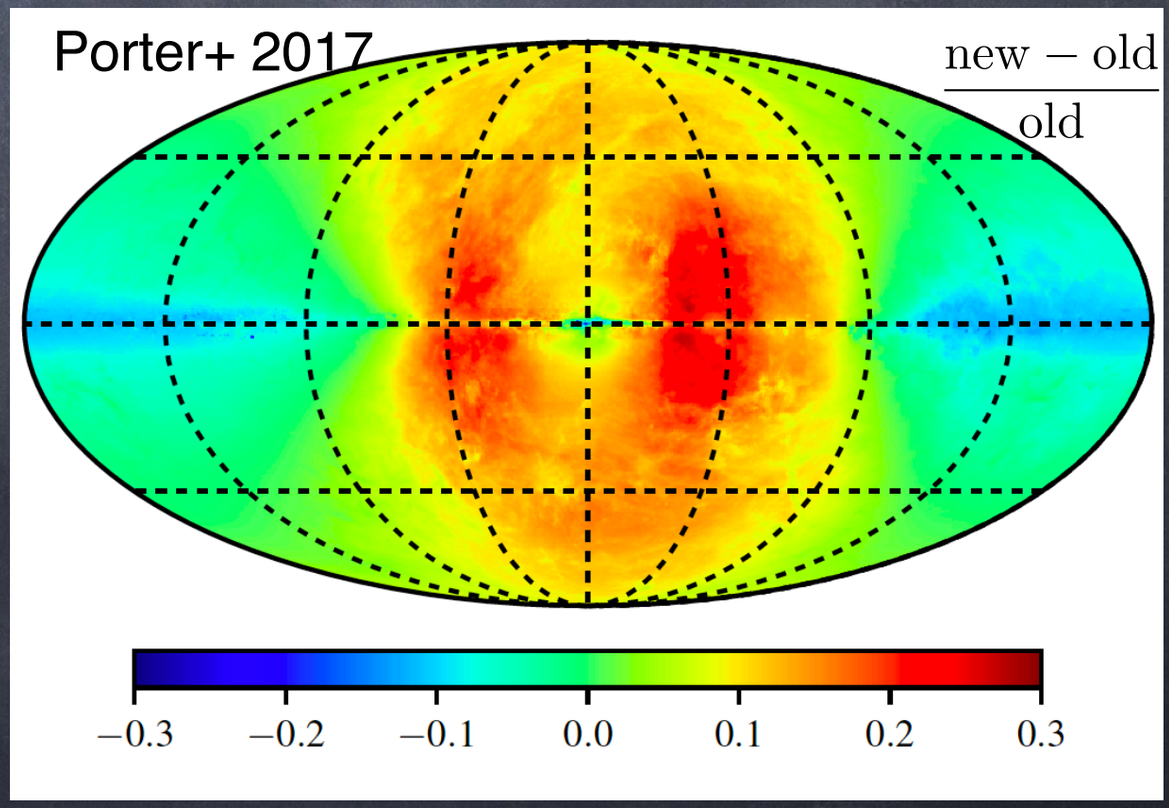
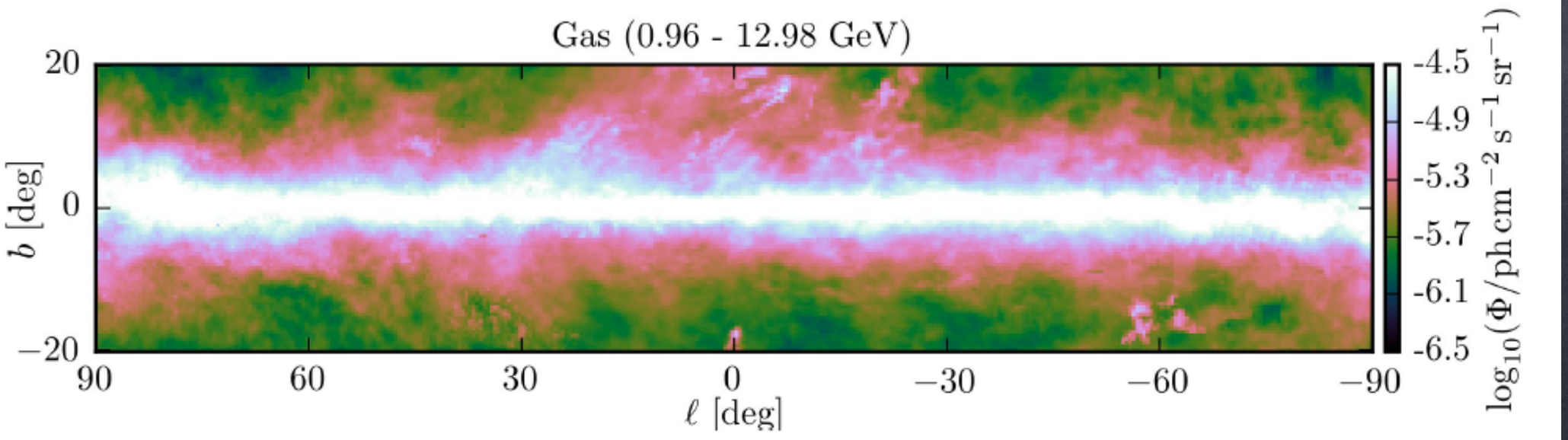
Have not yet been applied in analyses of the GCE



SkyFACT in a Nutshell

- Hybrid between image reconstruction & template fitting

Original Template



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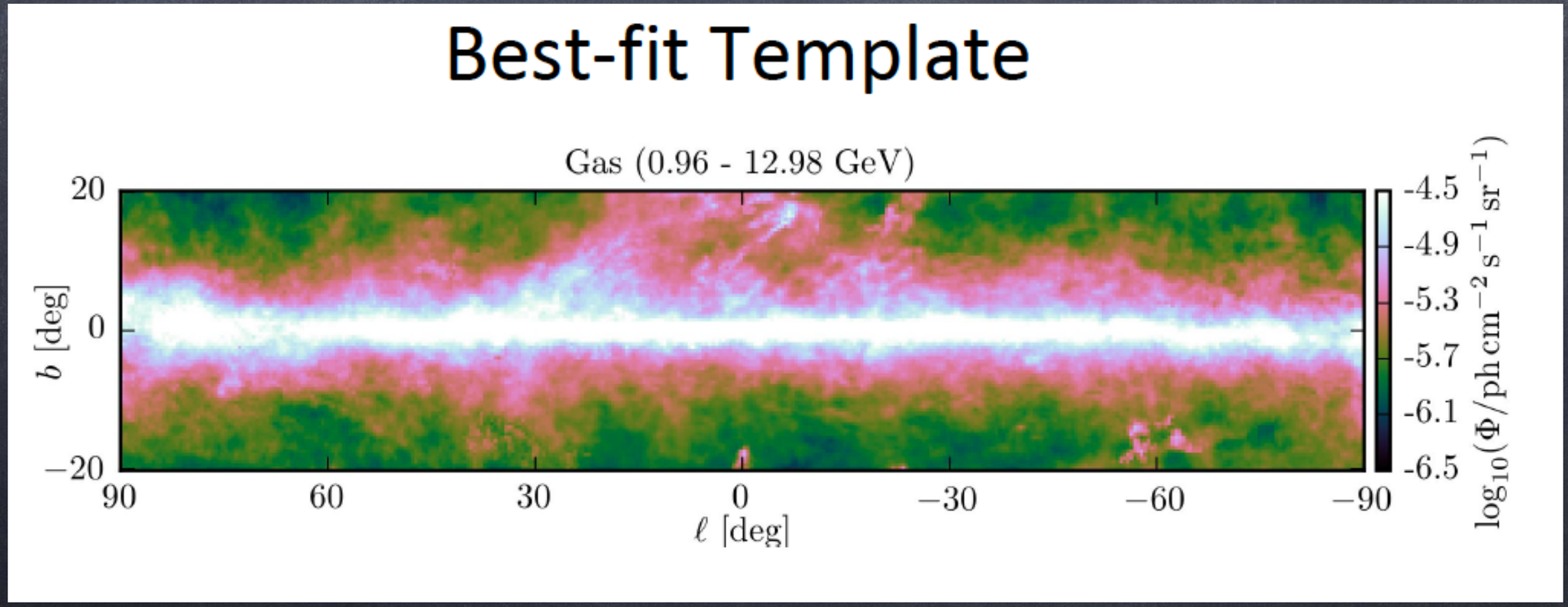

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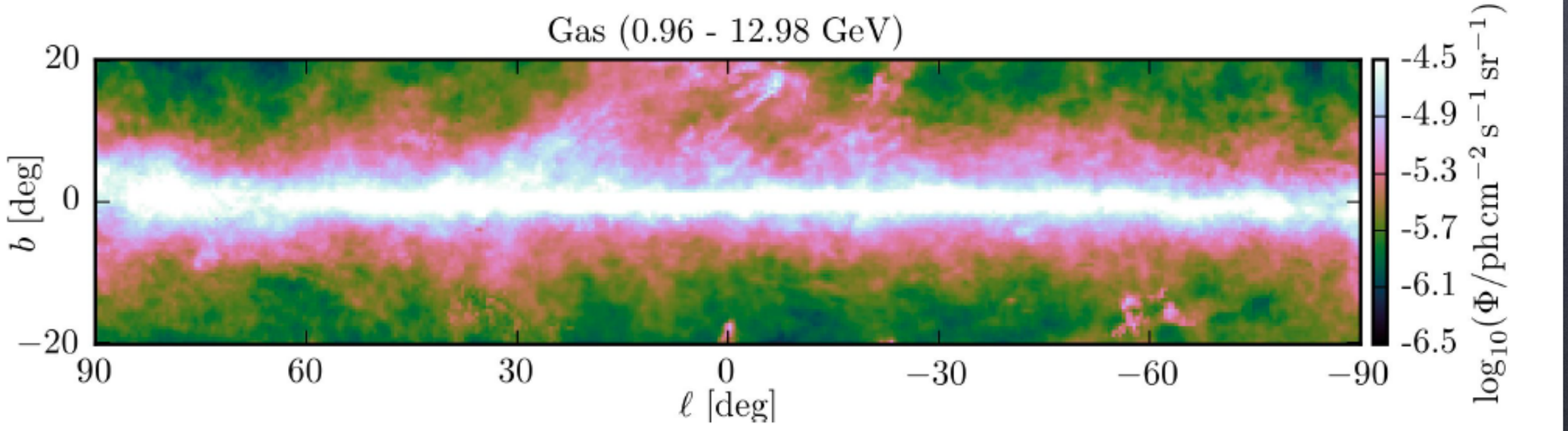
This means:
freedom in spectral and spatial templates to adapt to errors/incompleteness!

e.g. “dark gas”

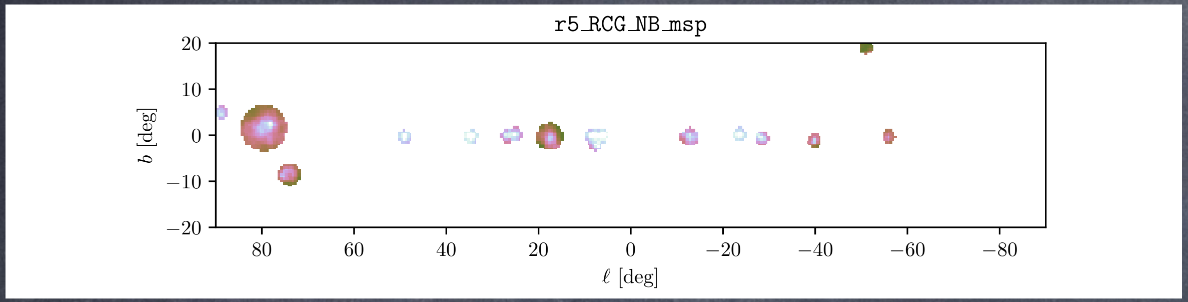
Best-fit Template



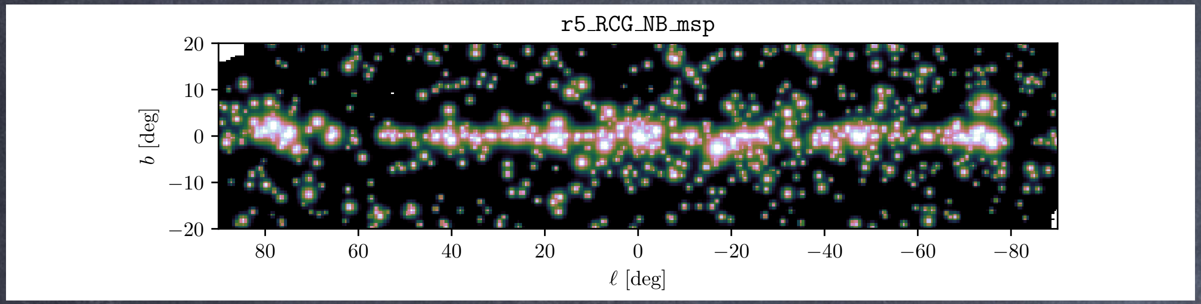
Revisit GCE morpholgy

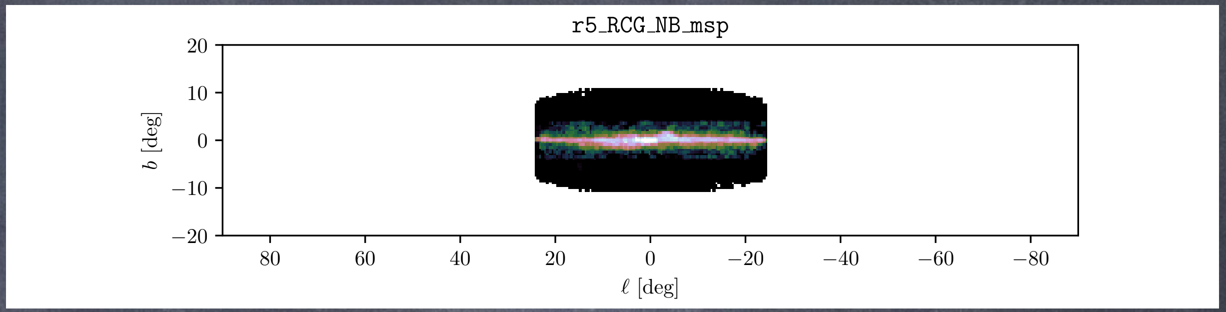
RB, Storm, Weniger & Calore, Nature Astronomy (2018)

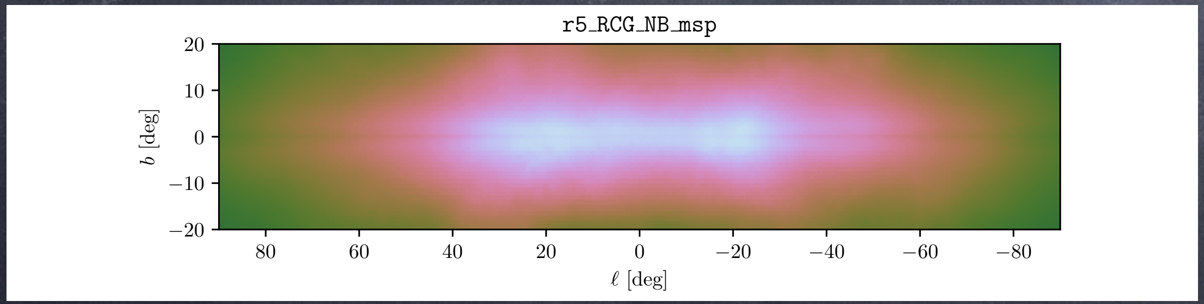
- Use usual templates, but with modulation

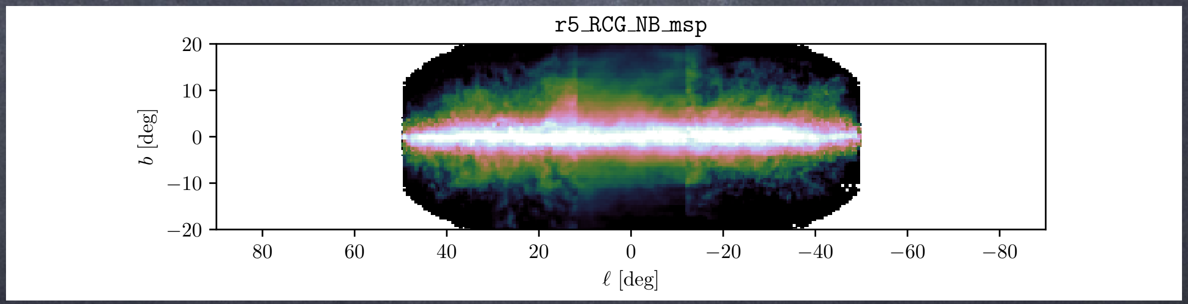


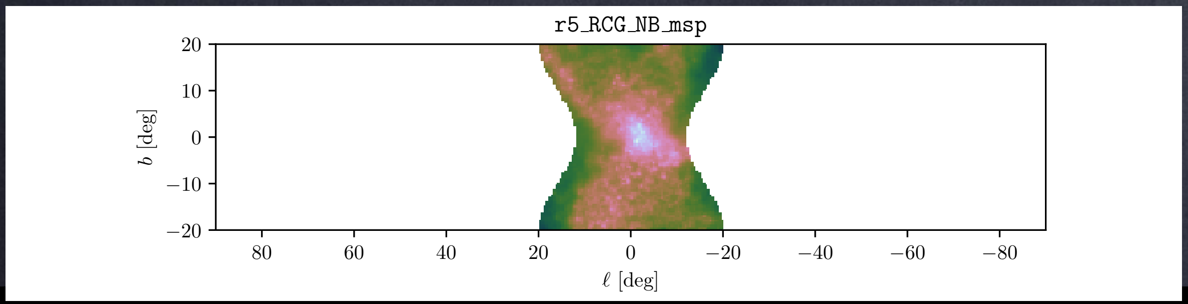
Isotropic

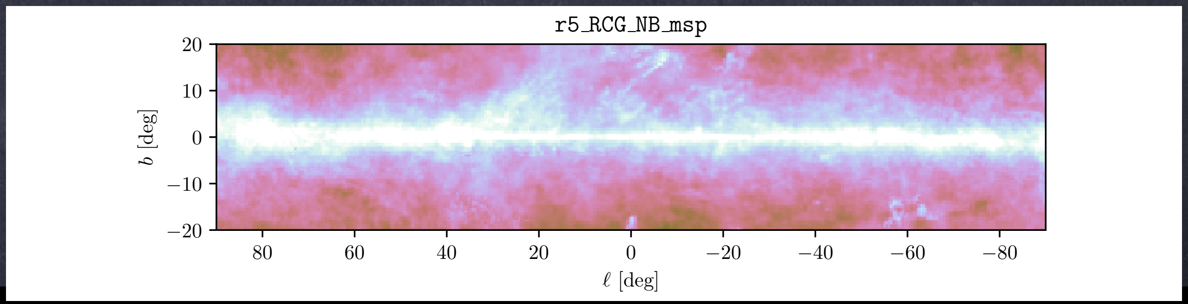








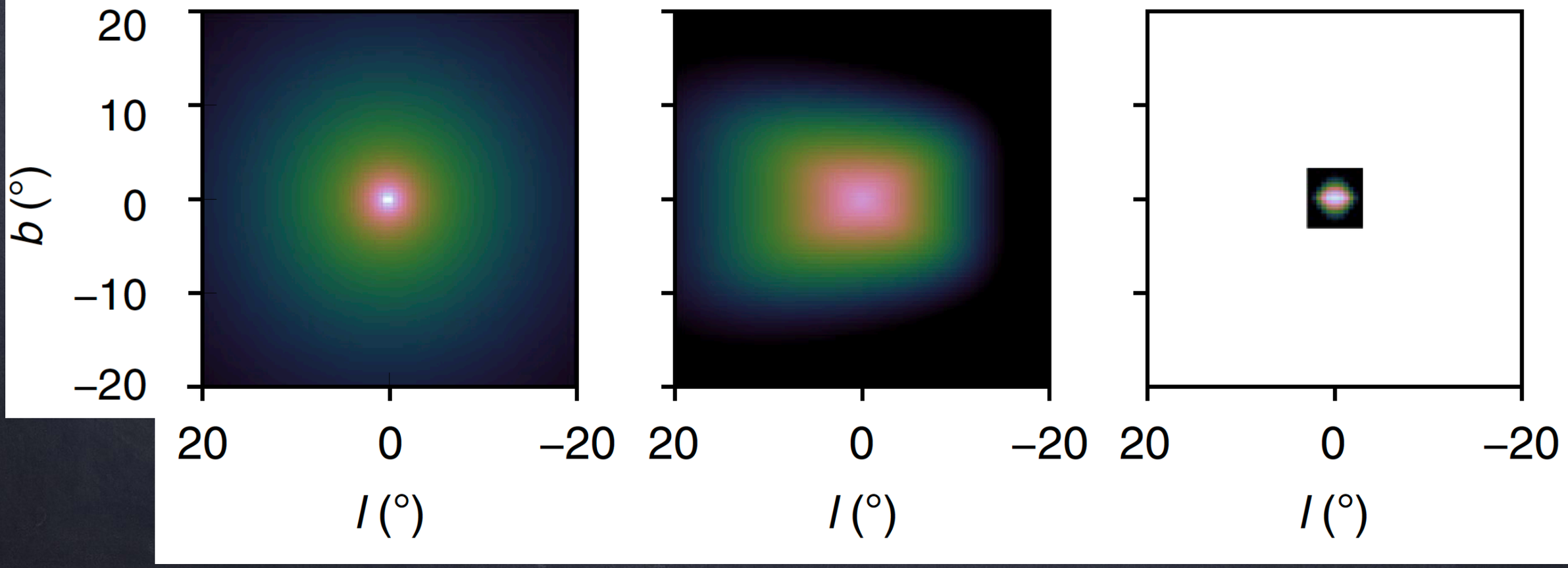




DM vs. Galactic Bulge

NFW (DM)

Boxy + Nuclear bulge (stars)



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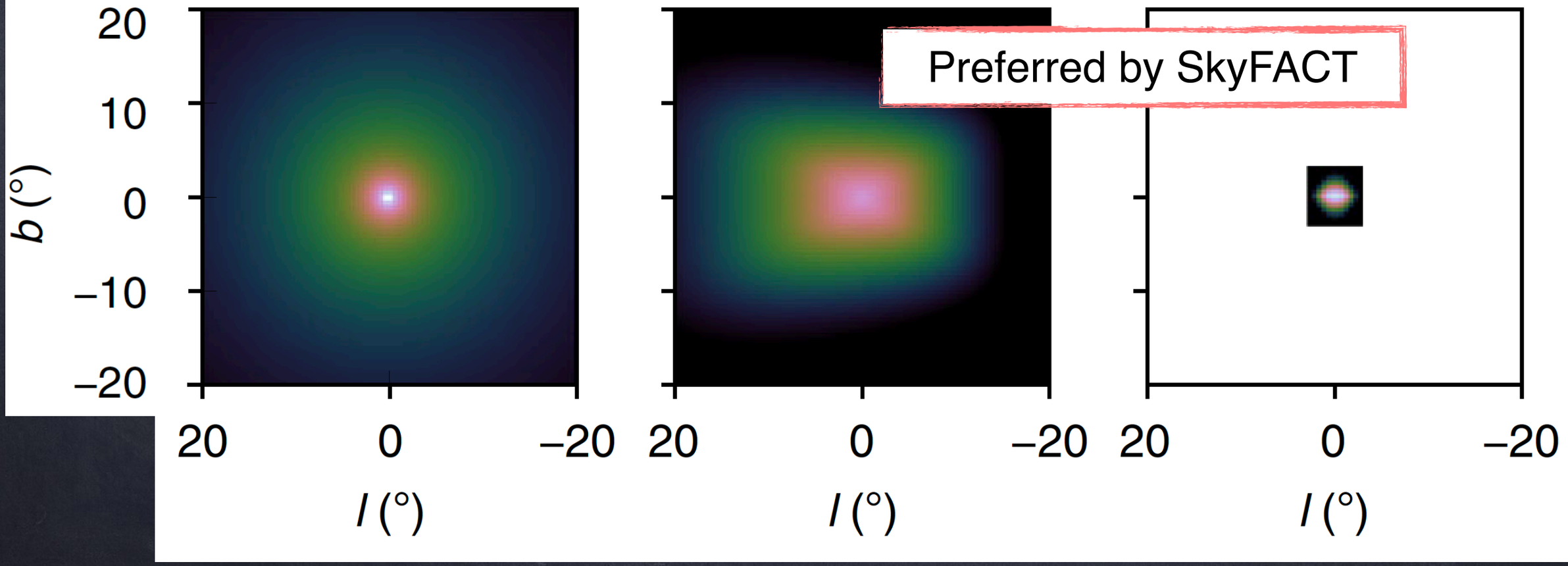
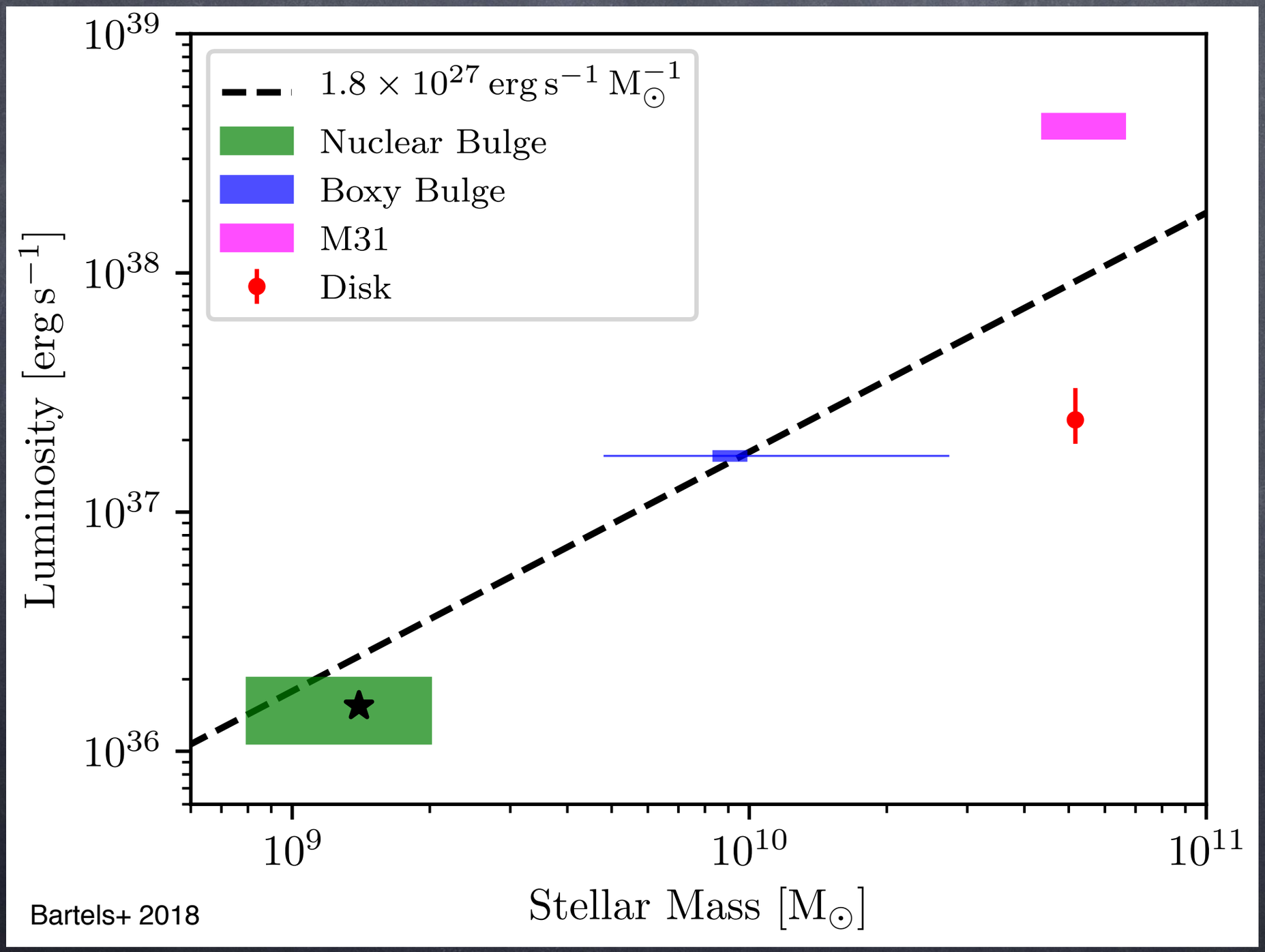
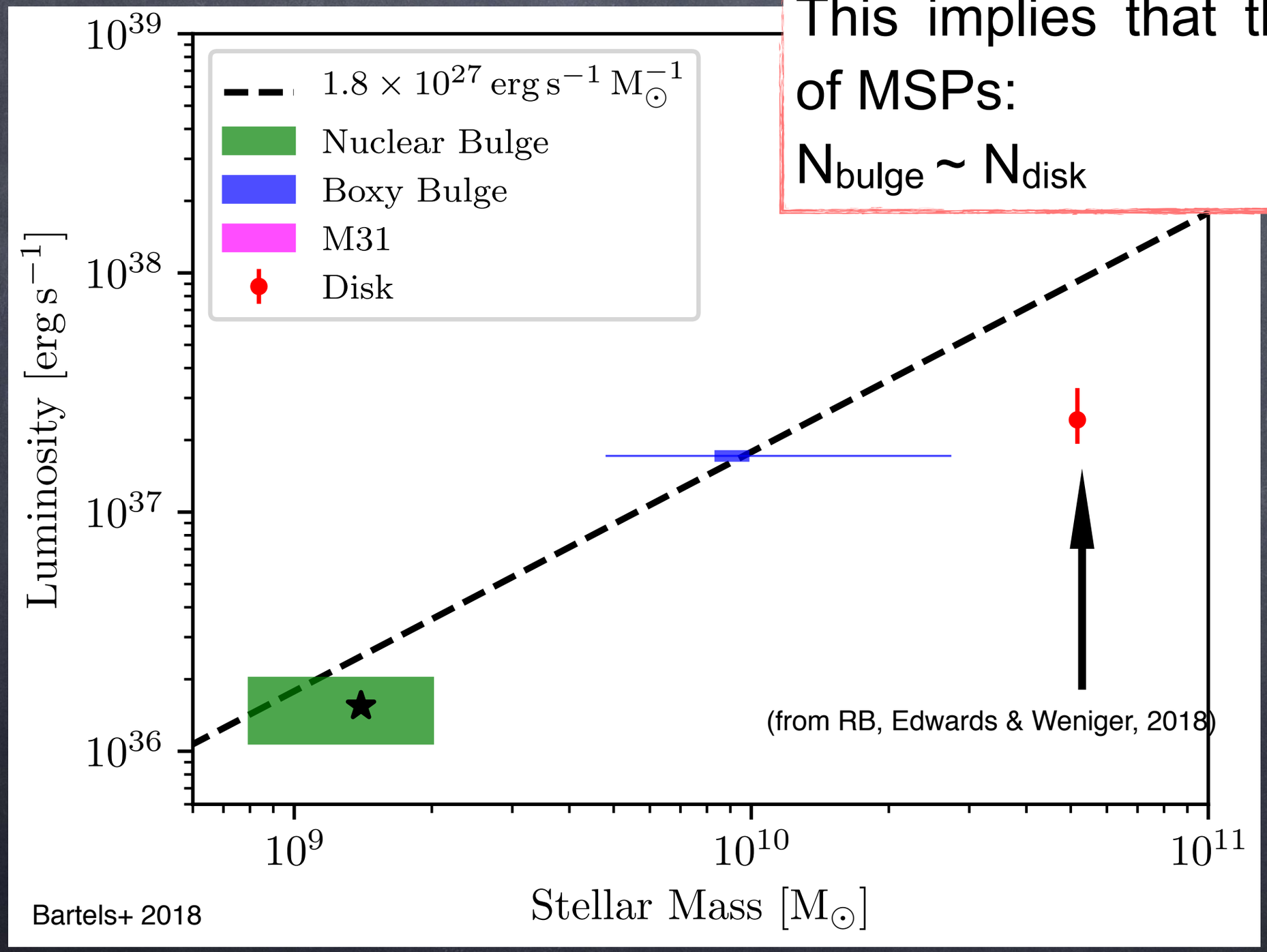



$1.8 \times 10^{27}\,\mathrm{erg\,s^{-1}\,M_\odot^{-1}}$
Nuclear Bulge
Boxy Bulge
M31
Disk
10^{39}
10^{38}
10^{37}
10^{36}
Luminosity [erg s^{-1}]
10^{9}
10^{10}
10^{11}
Stellar Mass [$M_\odot$]
Bartels+ 2018

This implies that the number of MSPs:
$N_{bulge} \sim N_{disk}$



X-shaped GCE

Macias et al., Nature Astronomy (2018)

- Macias+ 2018 use new gas models in the inner galaxy.
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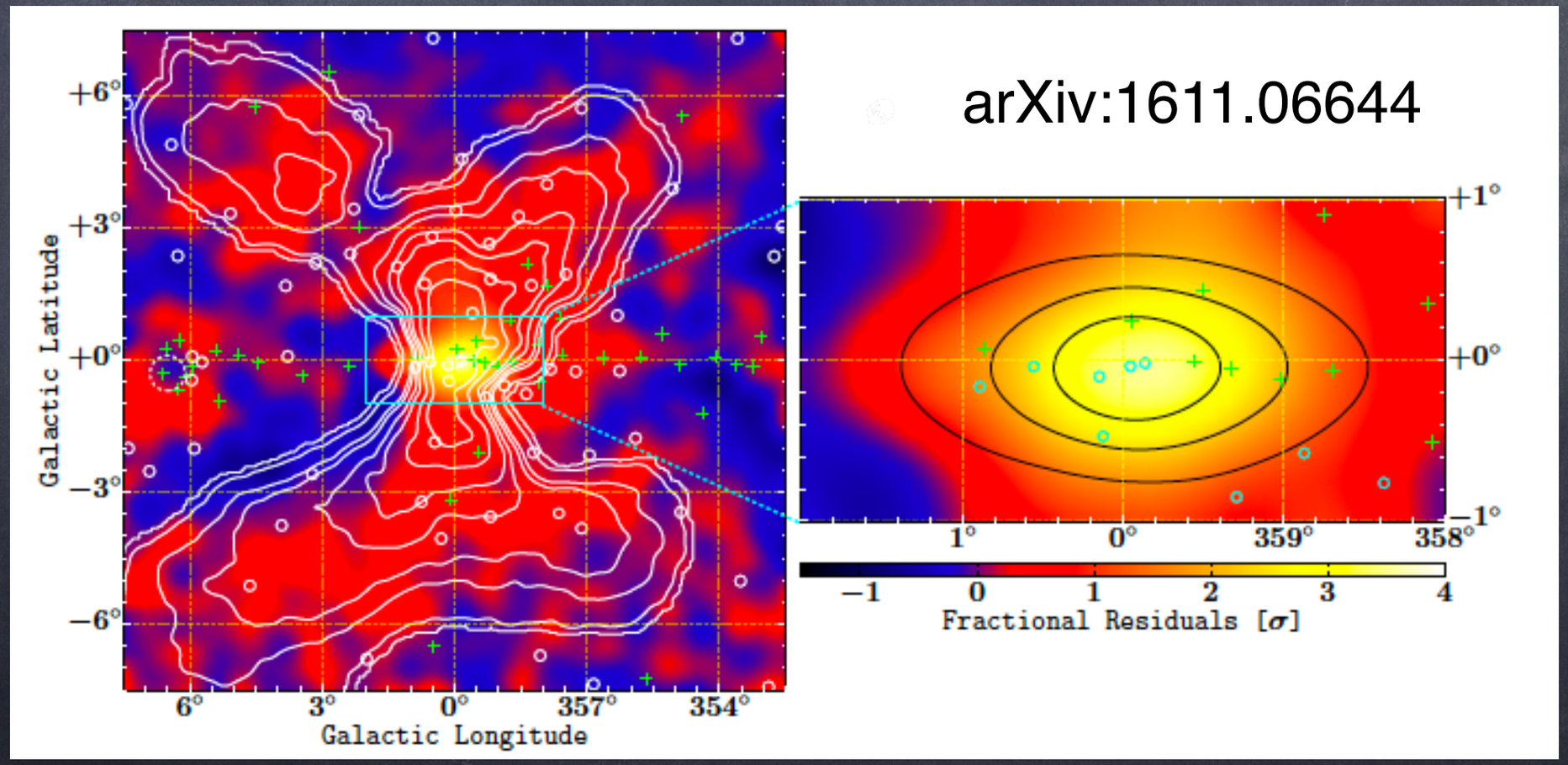

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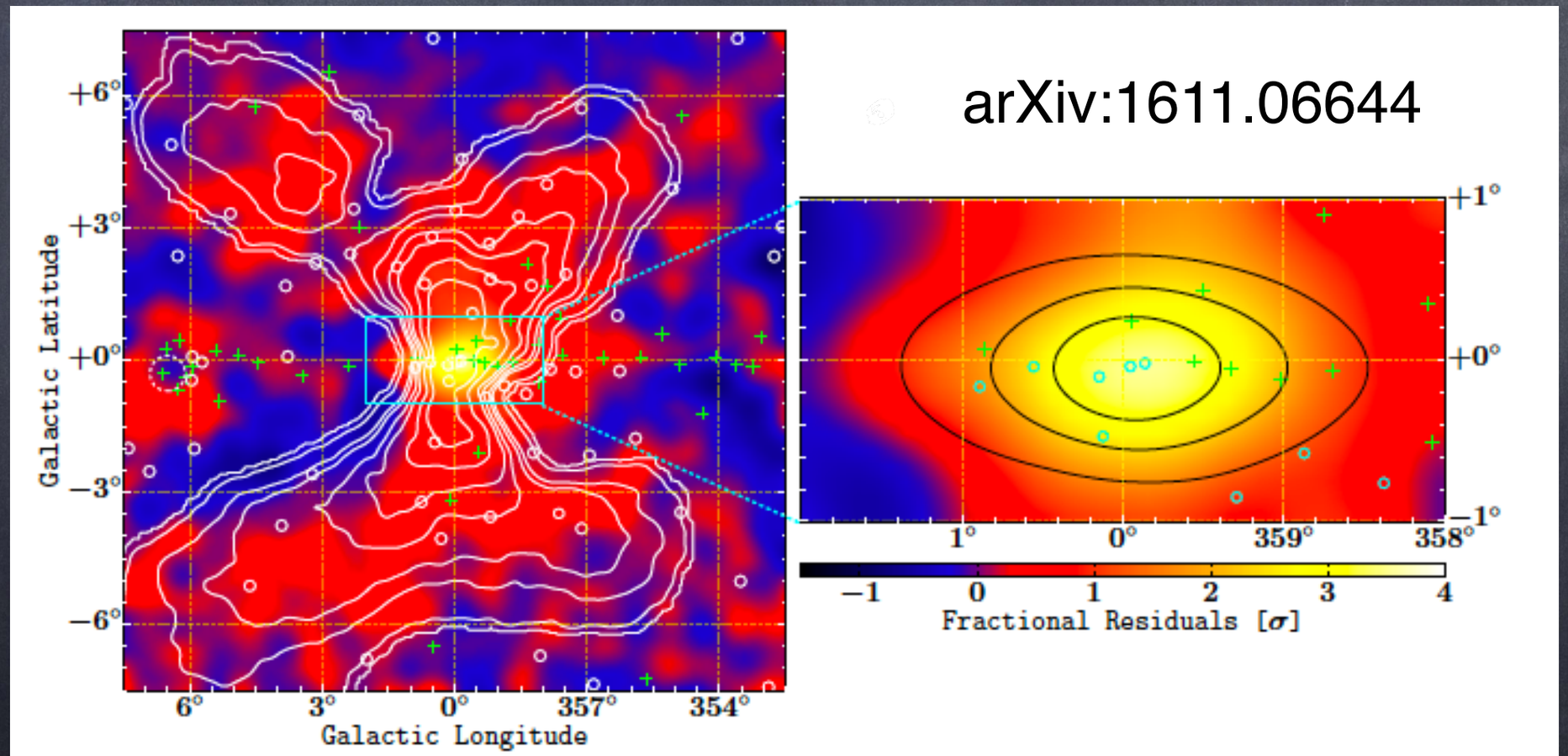

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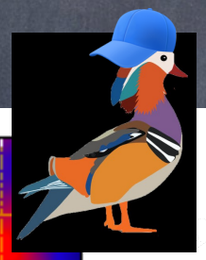

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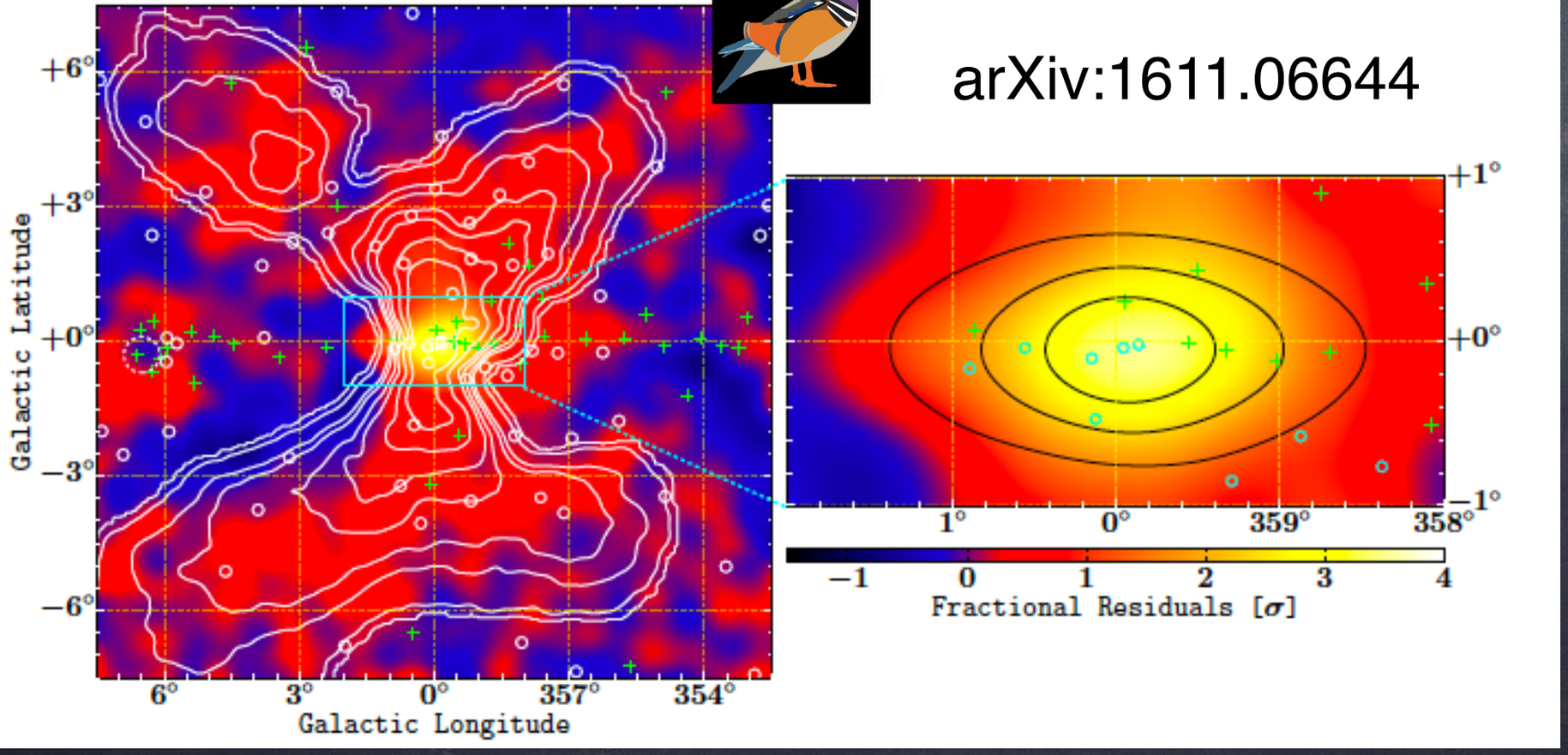

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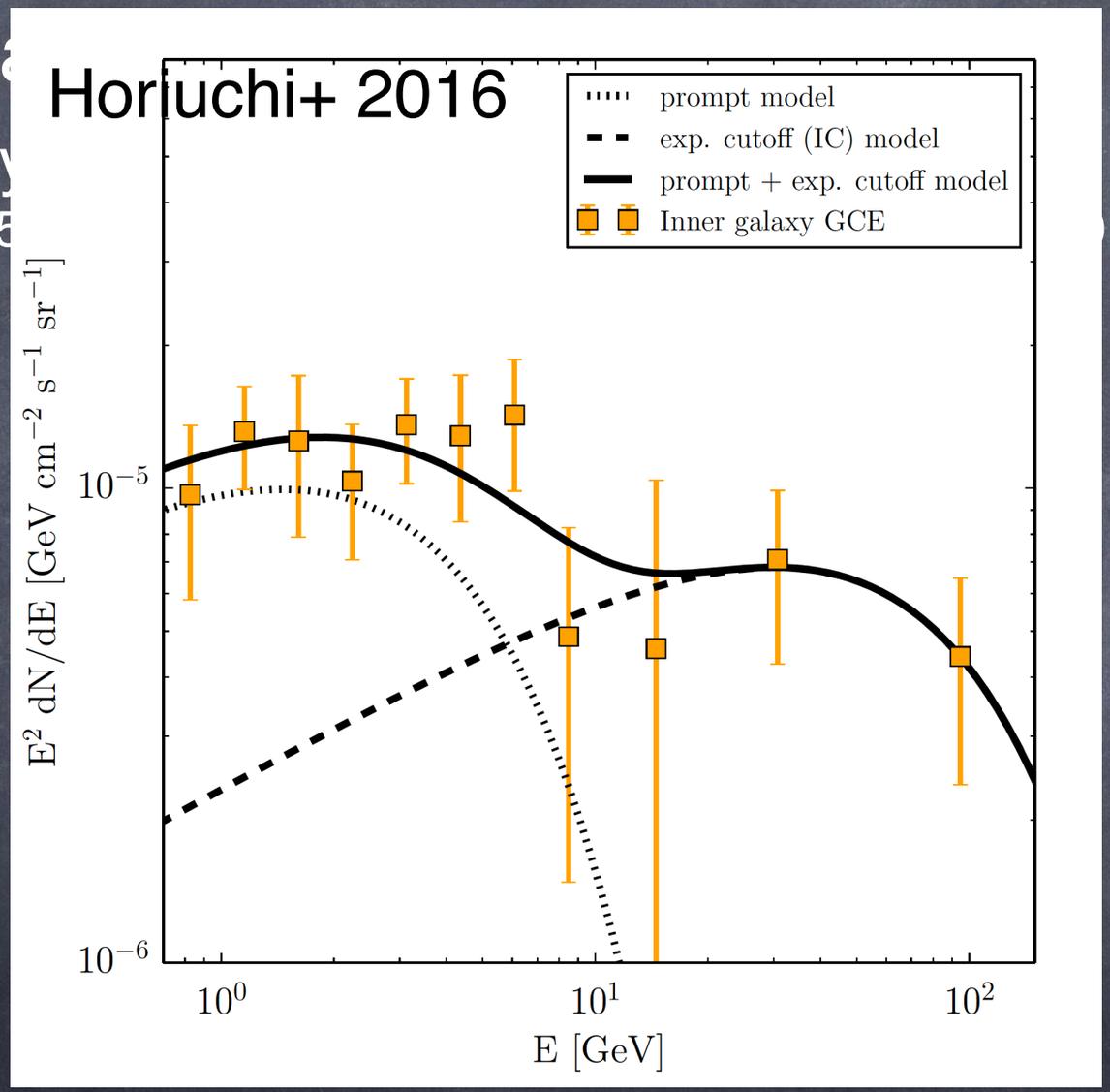
16



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   E.g. Ajello et al. (2017) or Saz-Parkinson et al. (2016)
   J. Ballet, Friday@11.00

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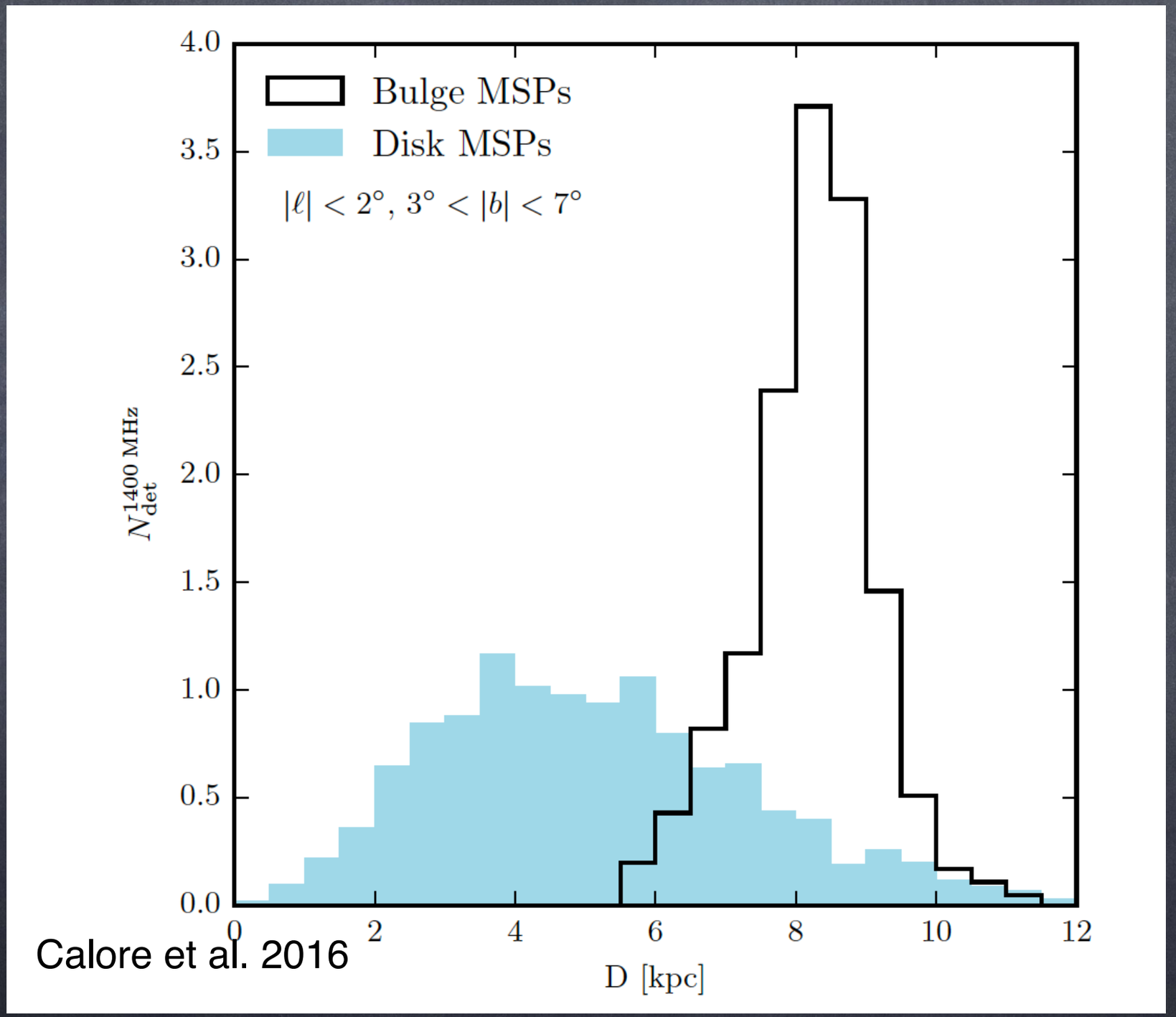
4. If MSPs: present (Meerkat) and upcoming (SKA) radio surveys will likely detect bulge MSPs! Calore et al. 2016

Radio prospects



Calore et al. 2016

The current status

- The GCE is a significant feature that so-far stood the test of time (9 years) despite ever improving background models.
- Although its characteristics have been altered.
  No longer preference for NFW with γ~1.26
- ~50 GeV DM and bulge MSPs look very similar…
- Evidence in favour of MSPs is slowly accumulating
- Improved γ-ray analyses can maybe teach us a little more, but radio will probably be the next breakthrough.