High Energy Astroparticle Physics

Roland Crocker
Sydney Spring School 2019

roland.crocker@anu.edu.au
☞ **EMAIL ME** ☜

High Energy Astroparticle Physics …with a focus on the Galactic Centre

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Australian National University

Part 0: Preliminaries

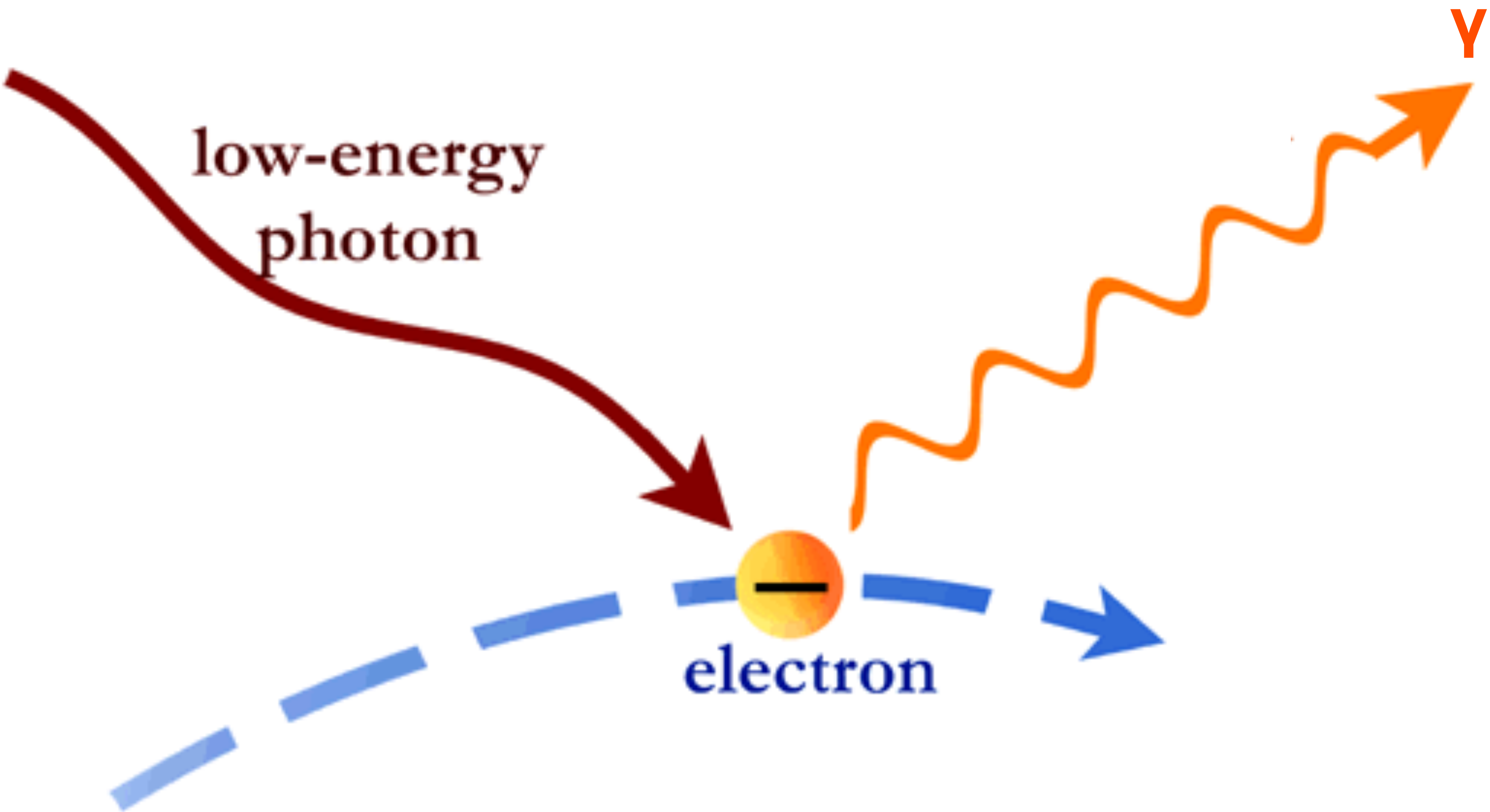
Energy Scales

unit	meaning	
eV		optical/UV regime; atomic transitions
keV	10^3 eV	X-ray regime
MeV	10^6 eV	"soft" γ-rays; nuclear line regime
GeV	10^9 eV	"high energy" γ-ray regime; the orbiting *Fermi*-LAT operates in the 100 MeV - 100 GeV range
TeV	10^{12} eV	"very high energy" γ-ray regime; ground-based imaging air Cherenkov telescopes (IACTs) operate in the 10 GeV - 100 TeV+ range; note: 1 TeV $\sim$ 1 erg
PeV	10^{15} eV	rough energy of cosmic ray "knee"; energy regime of astrophysical neutrinos detected by IceCube
EeV	10^{18} eV	regime of "ultra-high energy" cosmic rays
ZeV	10^{21} eV	approximate energy scale of highest energy cosmic ray ever recorded

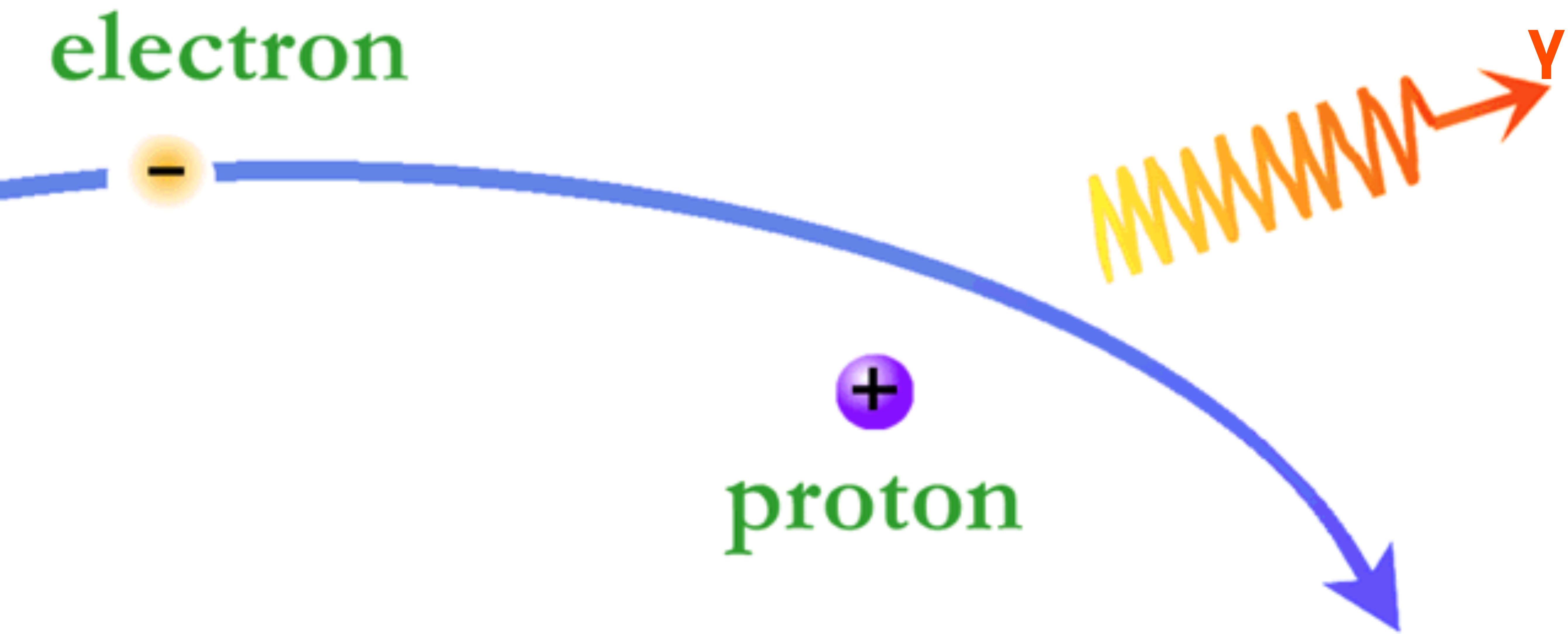
Continuum Emission Processes from Cosmic Rays

Synchrotron

Inverse Compton Scattering



Bremsstrahlung

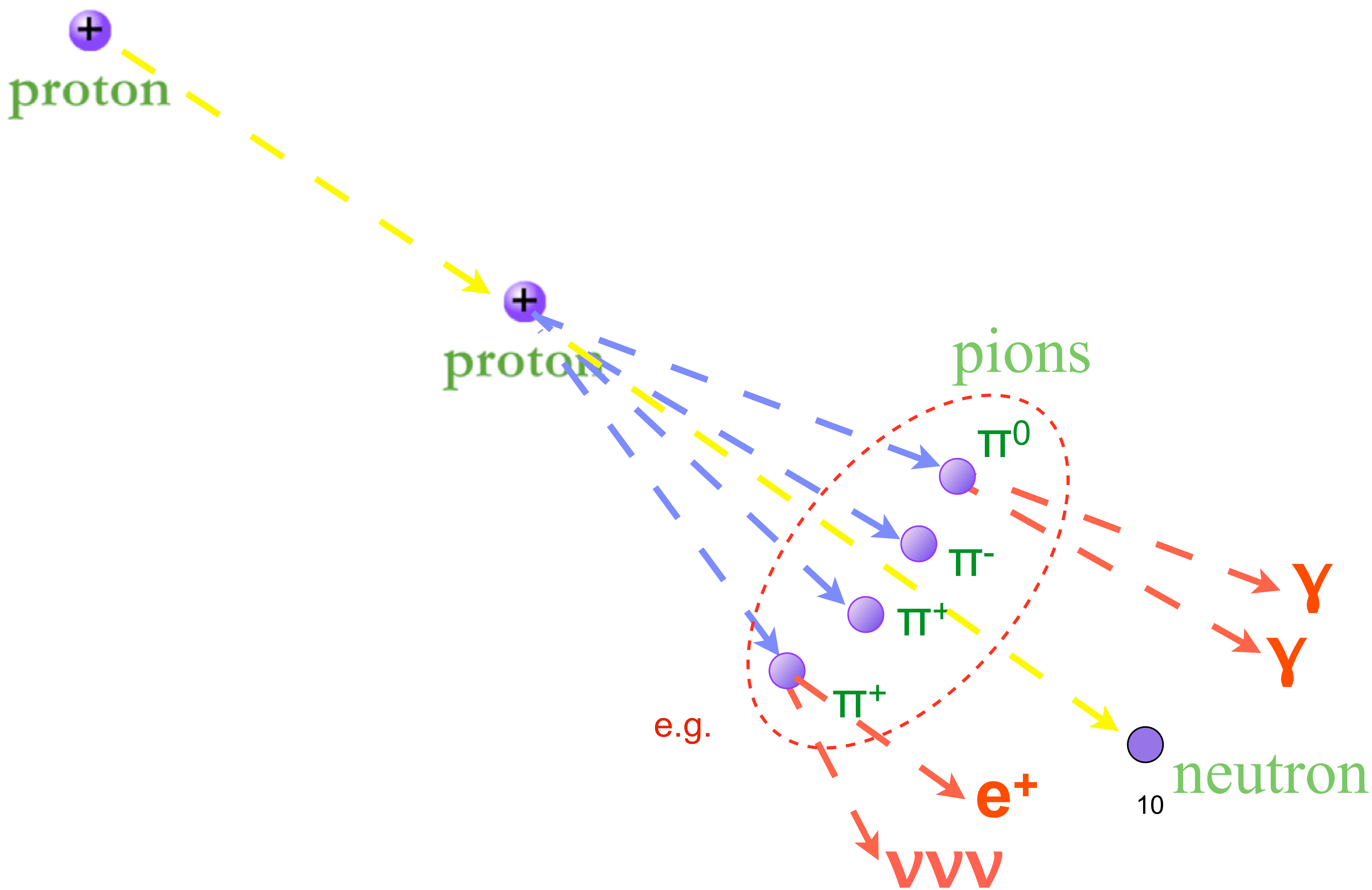


‘Hadronic’ emission:

pp → stuff

pγ → stuff

pp → Pion Decay → secondaries



$$
\begin{aligned}
p+p &\rightarrow p+p+\pi^0 \\
p+p &\rightarrow p+n+\pi^+ \\
p+p &\rightarrow p+p+\pi^+ + \pi^- \\
p+p &\rightarrow p+p+\pi^+ + \pi^- + \pi^0
\end{aligned}
$$

$$
\begin{array}{lclcl}
\pi^0 & \rightarrow & \gamma + \gamma & & \\
\pi^+ & \rightarrow & \mu^+ + \nu_\mu & \text{then} & \mu^+ \rightarrow \mathrm{e}^+ + \nu_\mathrm{e} + \bar{\nu}_\mu \\
\pi^- & \rightarrow & \mu^- + \bar{\nu}_\mu & \text{then} & \mu^- \rightarrow \mathrm{e}^- + \bar{\nu}_\mathrm{e} + \nu_\mu
\end{array}
$$

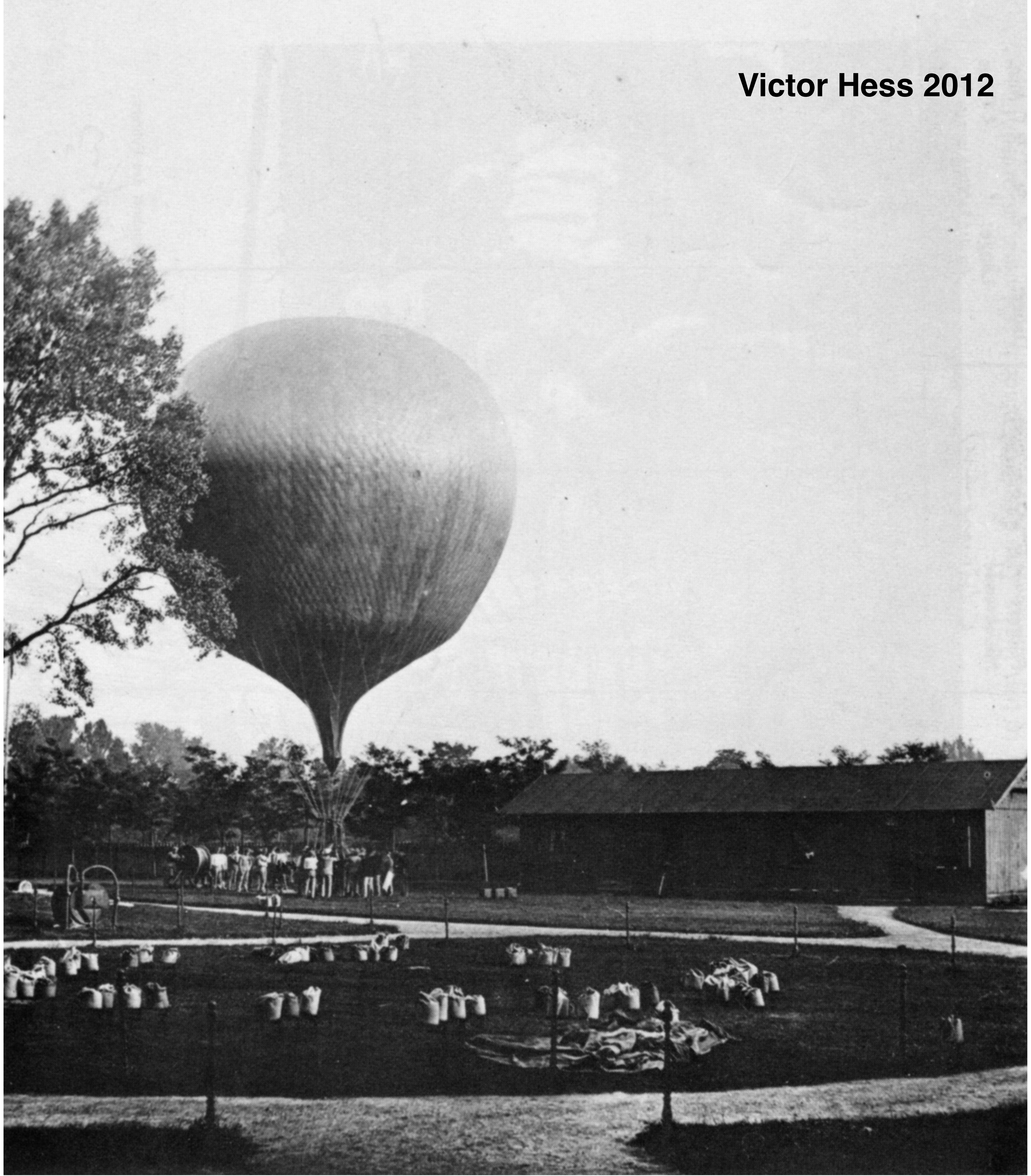
LHC: The Large Hadron Collider

Part I: Cosmic Rays:

What are they good for?

…the beginnings of astroparticle physics

Victor Hess 2012

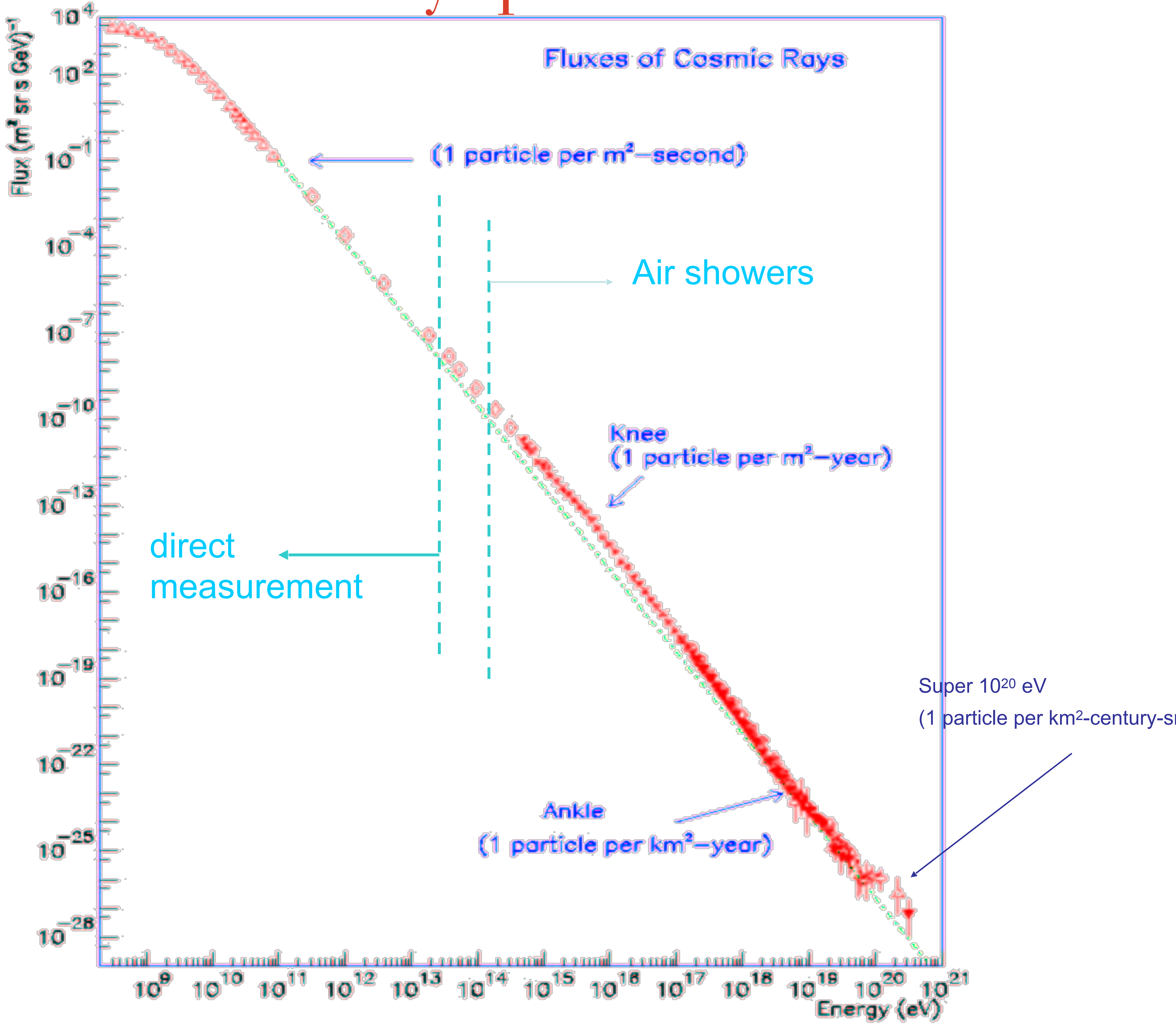


Teshima 2004 Erice Summer School

Cosmic Rays:
What are they good for?

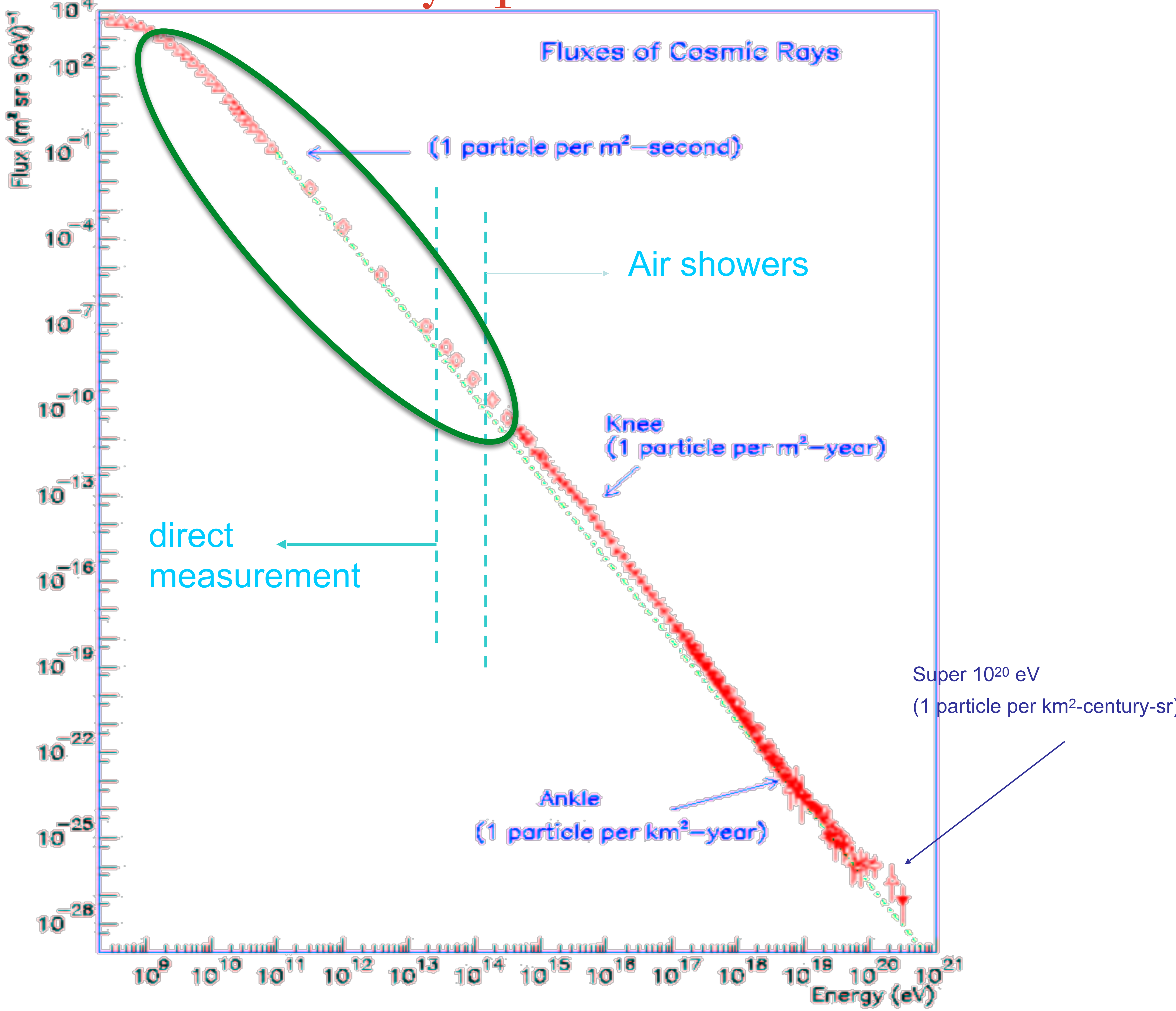
- Q: What are they?
- A: non-thermal, charged particle populations; dominantly protons and heavier ions and electrons
- low energy CRs accelerated in the Sun
- Sun's magnetic activity affects flux we detect

The Cosmic Ray Spectrum at Earth



G. Sigl, http://www.iap.fr/users/sigl/homepage.html

The Cosmic Ray Spectrum at Earth



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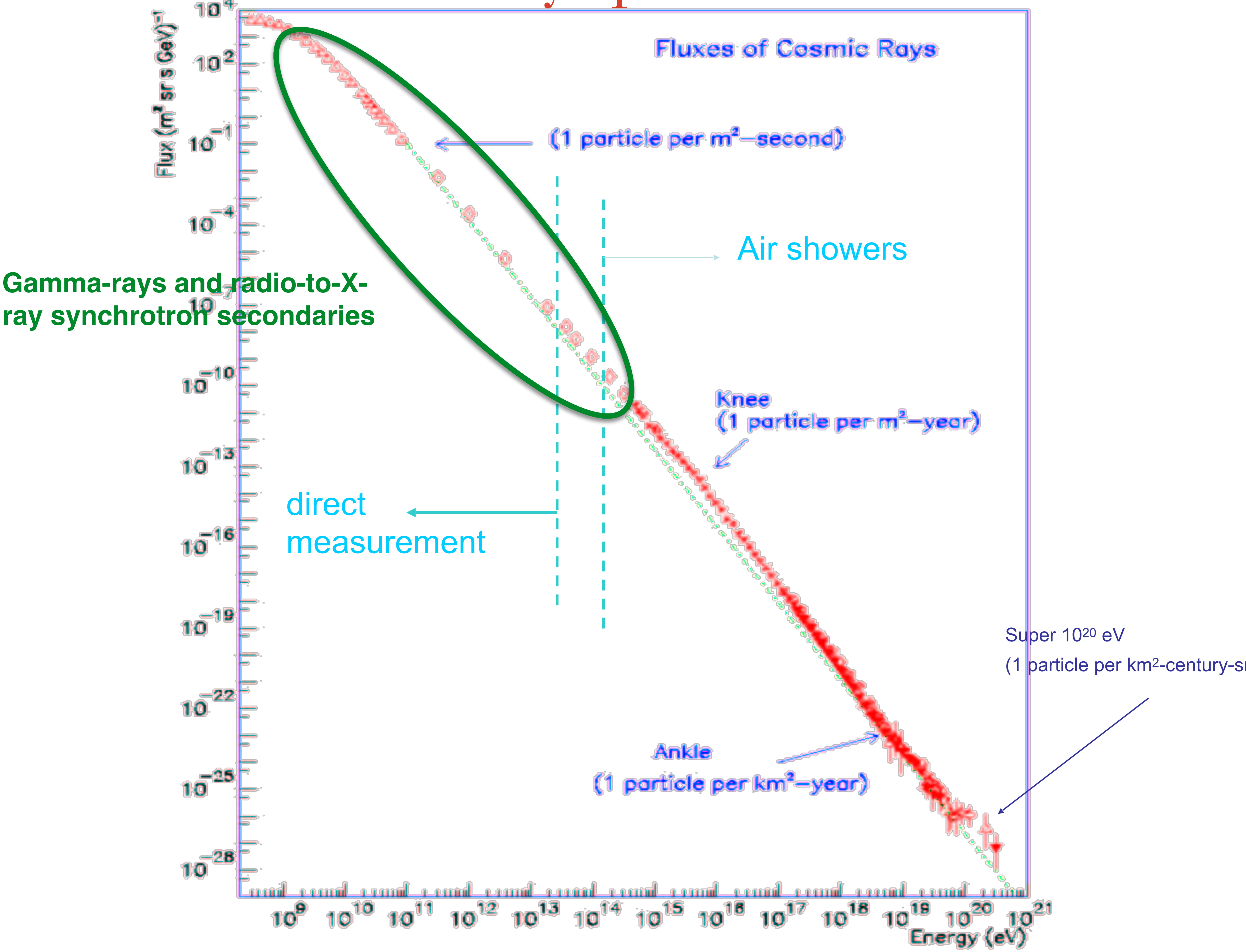

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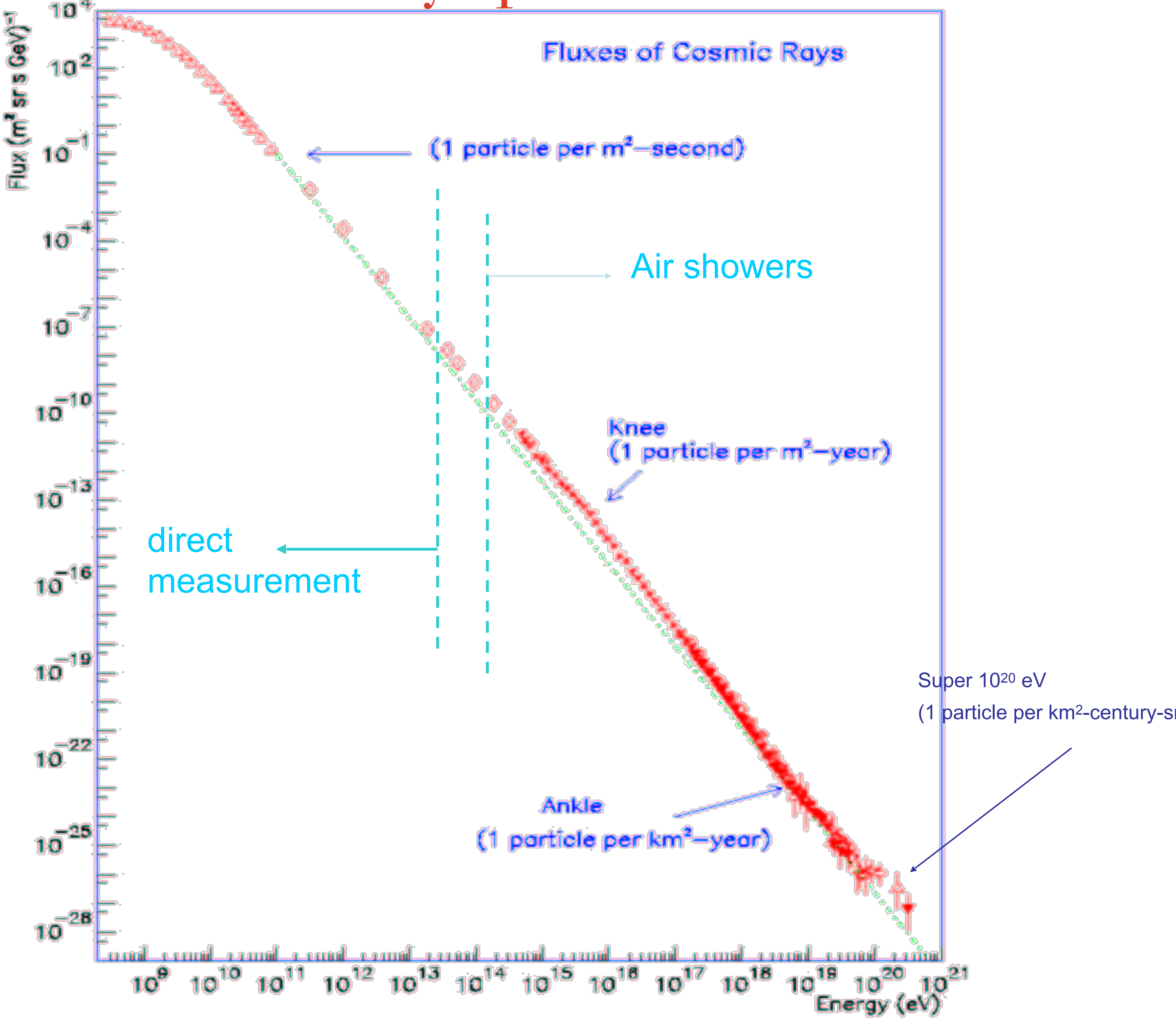
Cosmic Ray Spectrum: Features

- Almost featureless (slightly broken) POWER LAW $\sim E^{-2.7}$ over 10+ decades in energy / 33+ decades in flux
- Low energy turn-over: solar modulation
- Knee
- Ankle
- High energy turn-over: GZK "cut-off" (?)

Spallation/Confinement: Energy-dependence of 2ndary/primary CR nuclei

- Abundance ratio: $B/C \propto E^{-0.6}$
- Observed spectrum:
- $\phi(E) = dN/dE \propto E^{-2.7}$
- Interpretation:
- Propagation depends on E
- Confinement time: $\tau(E) \propto E^{-0.6}$…but why this exponent? Expect $\propto E^{-0.3}$ (for Kolmogorov spectrum of turbulence)
- Implication: Injection spectrum $Q(E) \propto E^{-2.1}$ …this is consonant with expectations for astrophysical **shock acceleration**

The Cosmic Ray Spectrum at Earth



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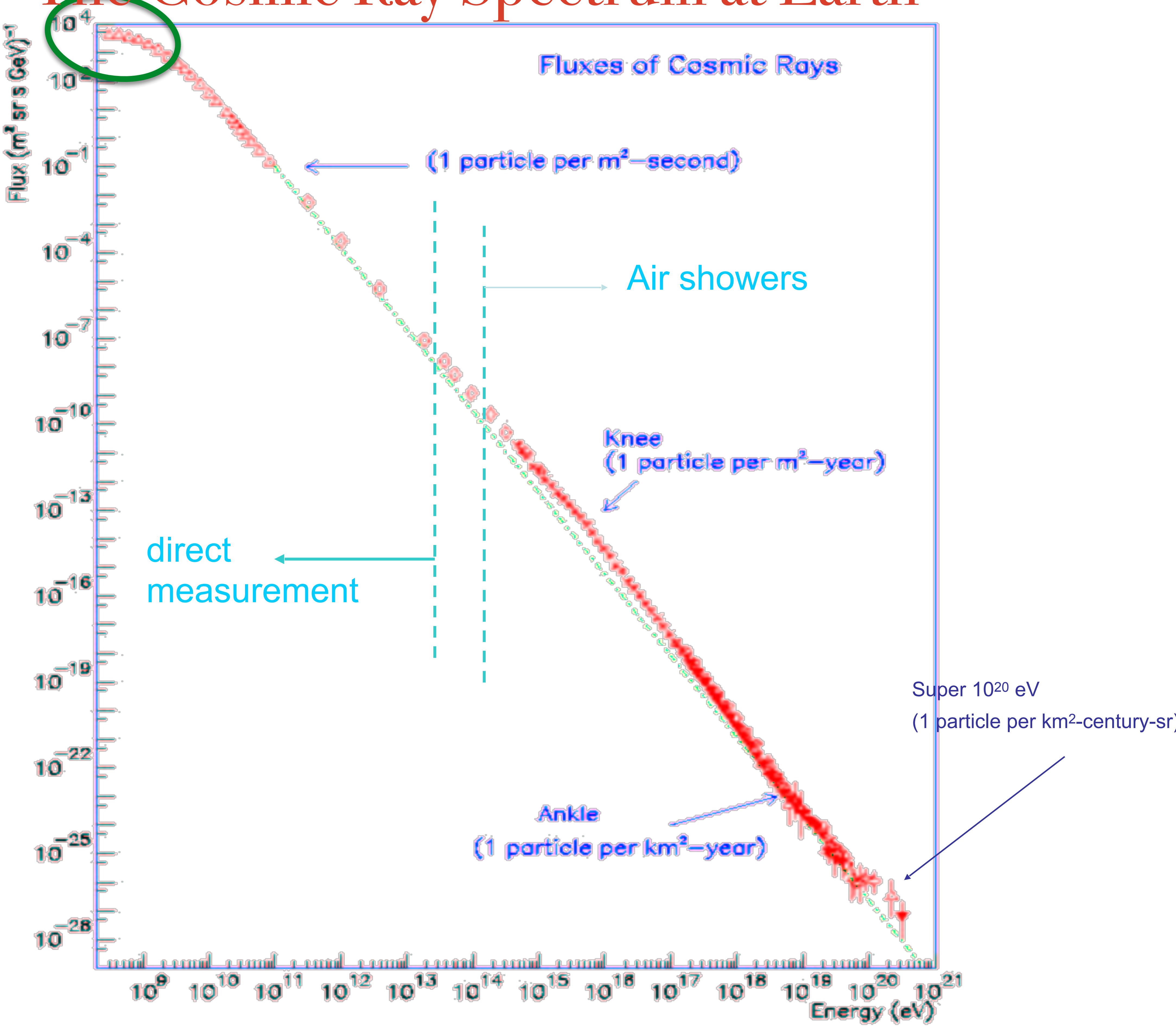
The Cosmic Ray Spectrum at Earth



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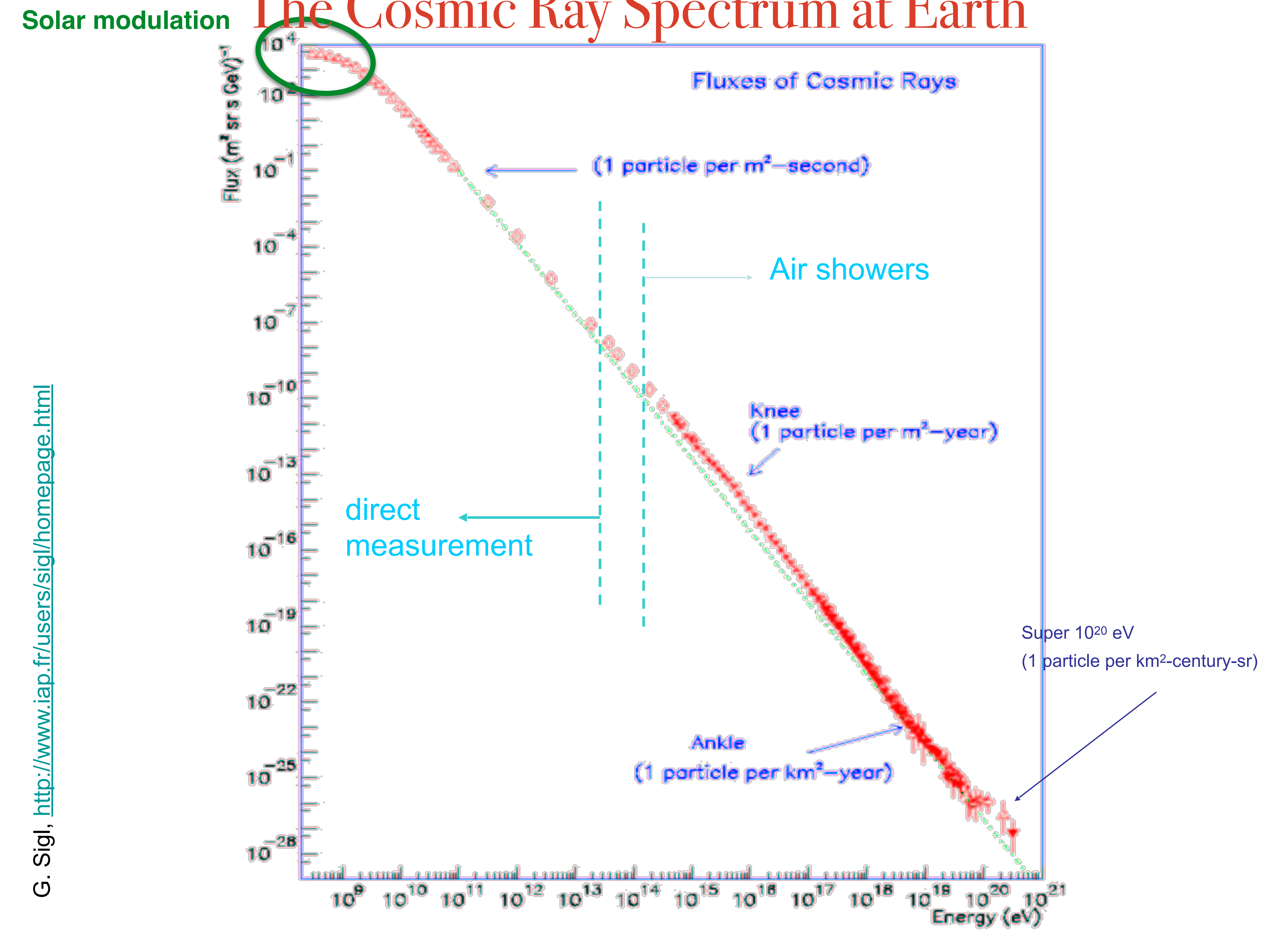
The Cosmic Ray Spectrum at Earth



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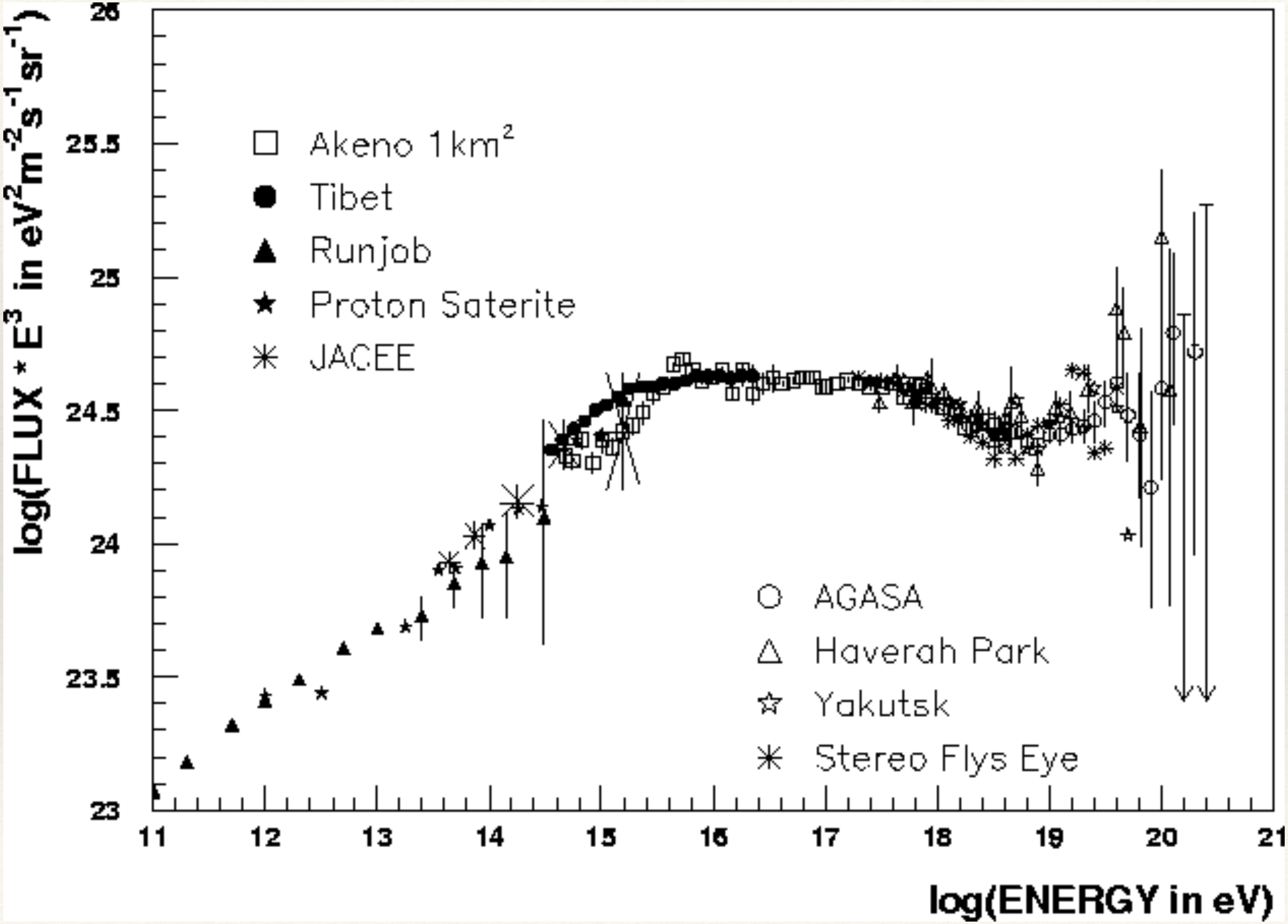
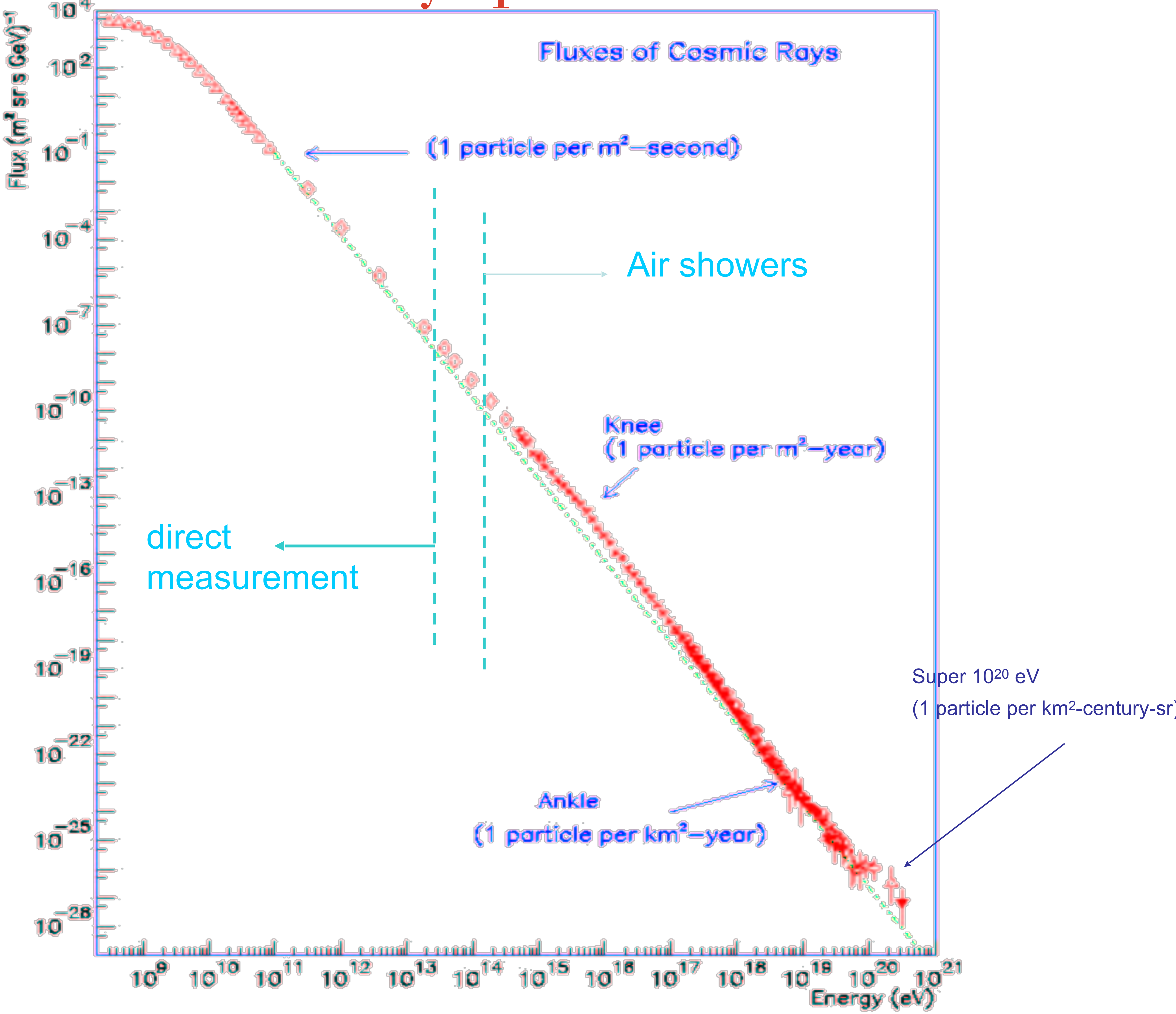
E^3-Weighted Cosmic Ray Spectrum



The Cosmic Ray Spectrum at Earth



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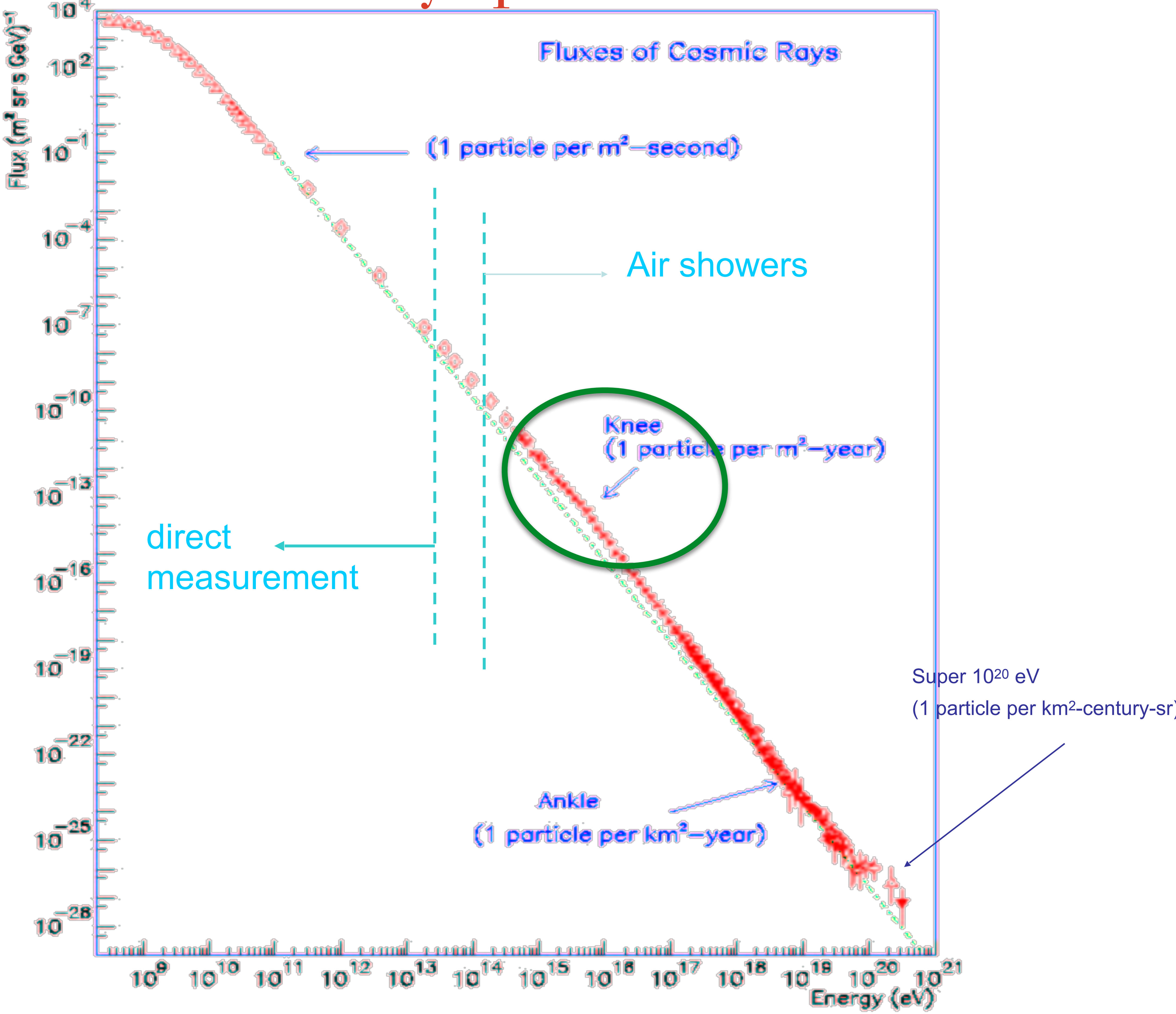
The Cosmic Ray Spectrum at Earth



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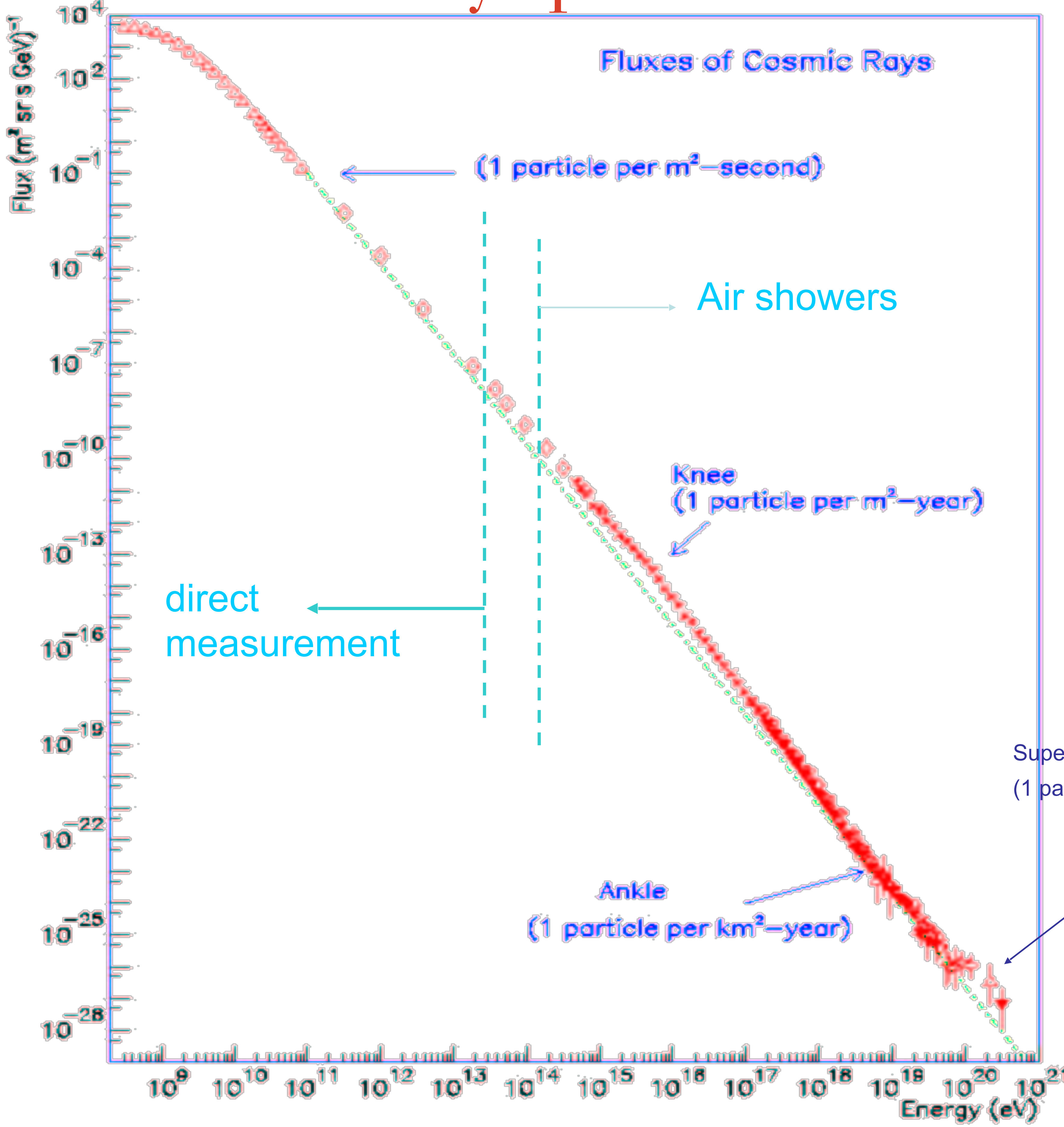
The Cosmic Ray Spectrum at Earth



Super 10^{20} eV
(1 particle per km^2-century-sr)

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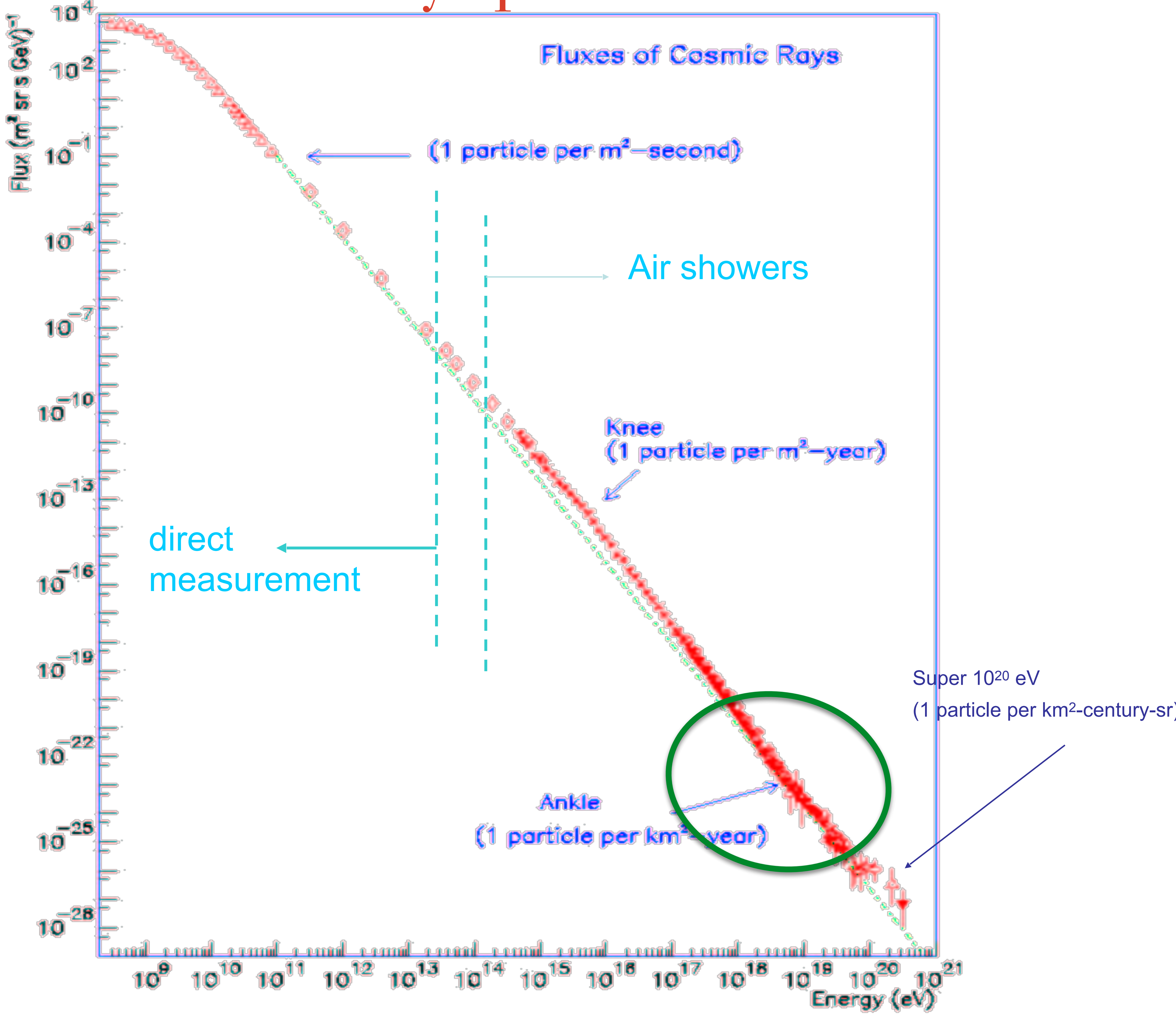
The Cosmic Ray Spectrum at Earth



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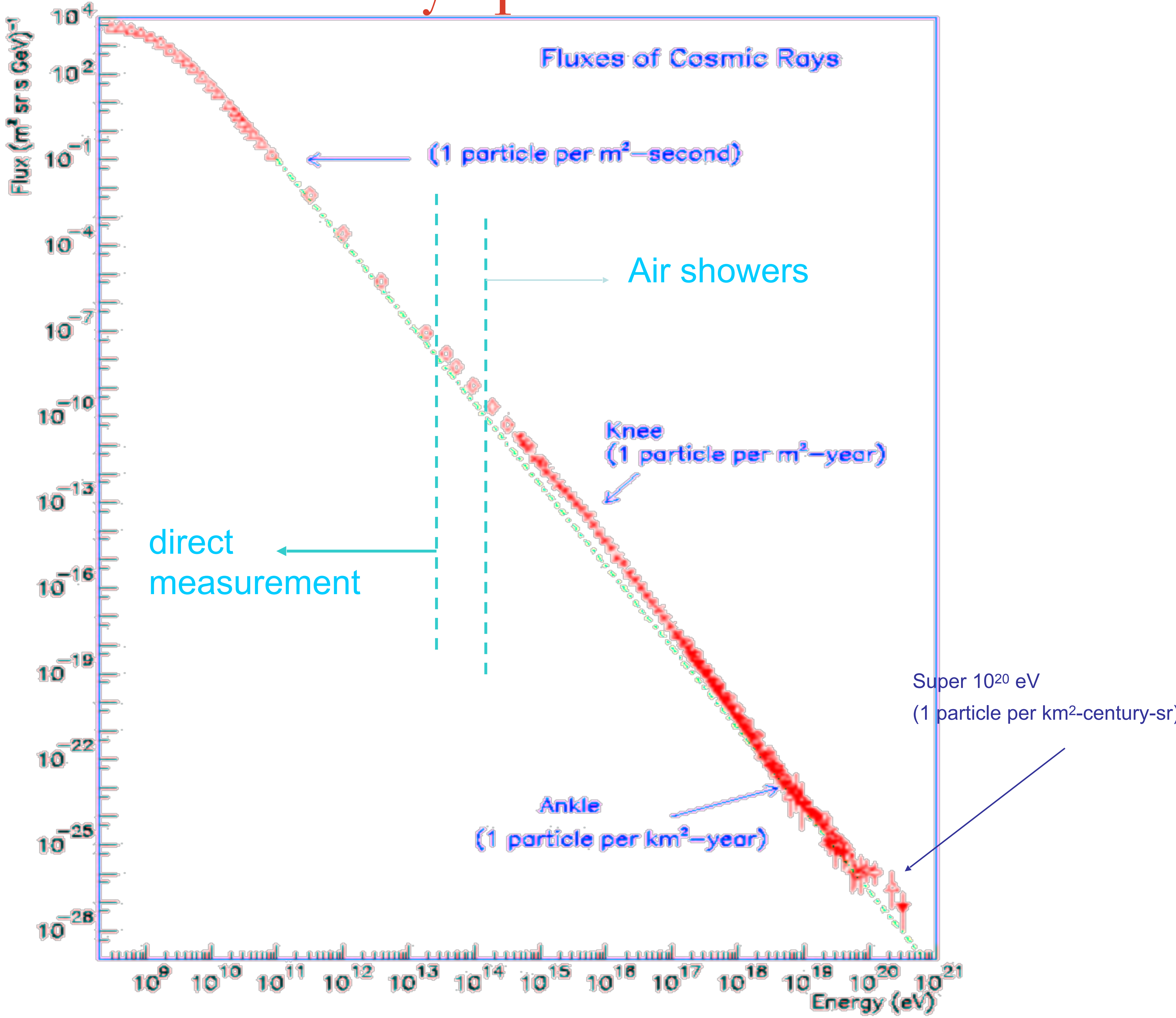

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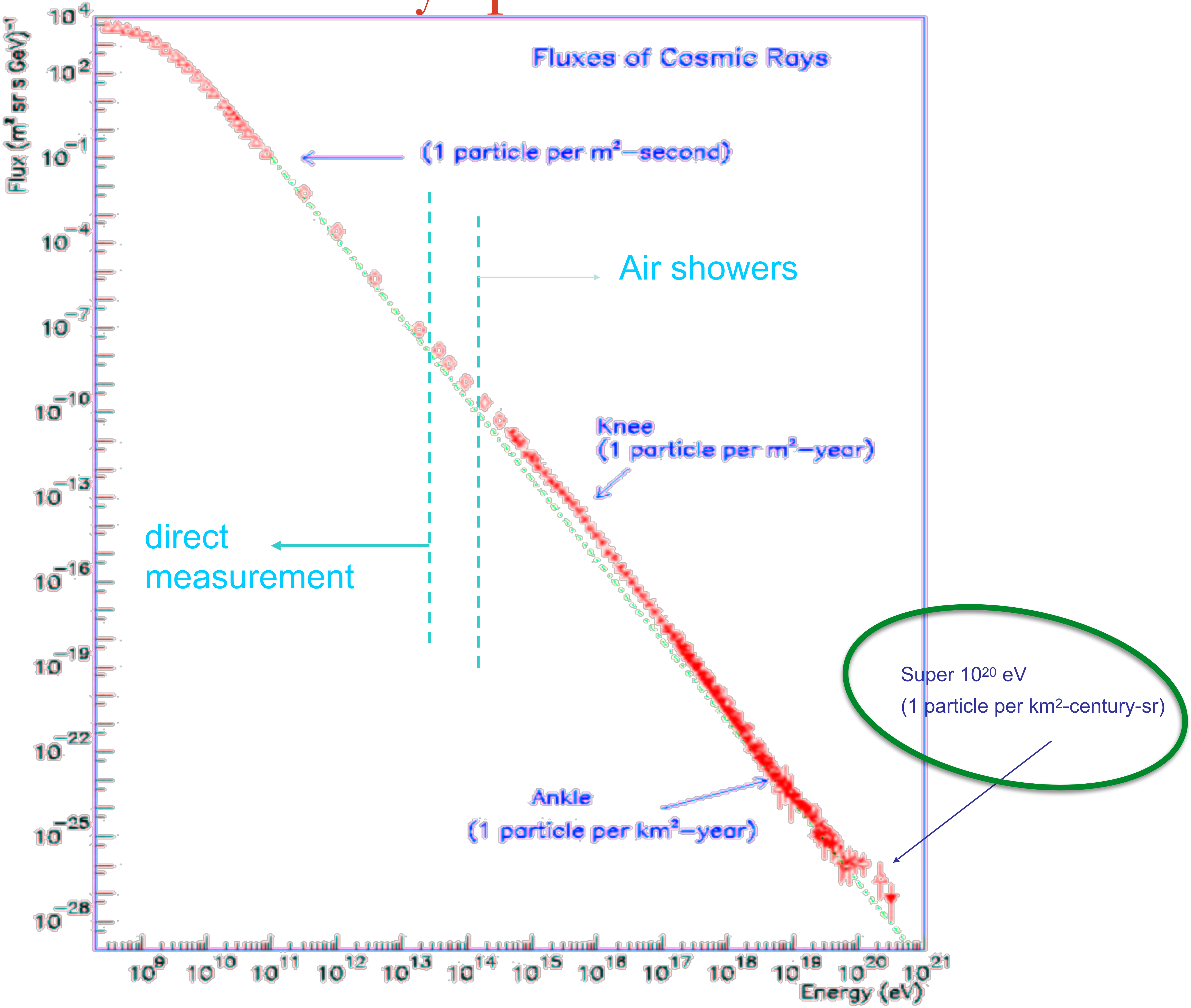

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The Cosmic Ray Air Shower

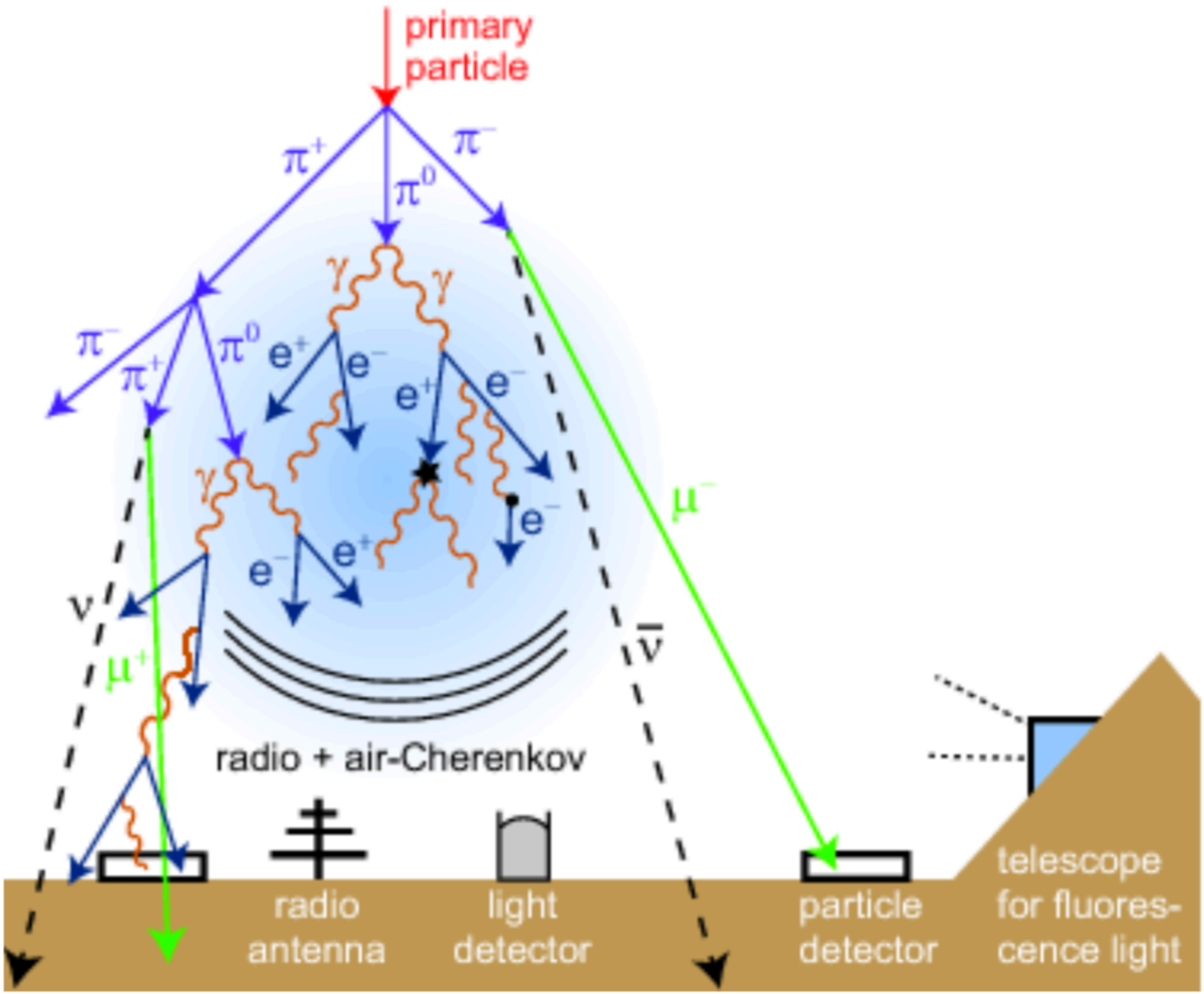


Figure 10: Schematic of cosmic ray extensive air shower with different detector technologies (credit: F. Schröder et al. 2017). Different techniques have advantages in different energy ranges.

Why are CRs of astrophysical interest?

- provide energy density / pressure equivalent to other ISM phases

  $\Rightarrow$ help to support the scale height of the gaseous disk

- dominate heating and ionisation of H2

  $\Rightarrow$ maintain temp of H2 and ensure it is coupled to magnetic fields

    $\Rightarrow$ affects star formation

- probably help to launch galactic outflows
- mutagenic effect on terrestrial life

Aside: particles first discovered in/as comic rays:

- **Positron** – 1932 by Anderson (shared 1936 Nobel Prize with Victor Hess)
- **Muon** – 1936 by Anderson and Nedermeyer
- **Pion** – 1947 by Powell and co-workers (Nobel Prize 1950)
- **Kaon** – 1947 by Rochester and Butler
- CRs interaction are even today detected at centre-of-mass energies (up to ~PeV) many orders of magnitude higher than available in collider experiments (LHC: ~14 TeV)

Cosmic Rays:
What are they good for?

- Cosmic rays can be measured locally and their presence throughout the Galactic disk can be inferred from its gamma-ray emission
- Similarly, we know from gamma-ray observations that there are diffuse cosmic ray populations suffusing the disks of external galaxies (local group, nearby starbursts)

The Galactic Plane as seen by Fermi

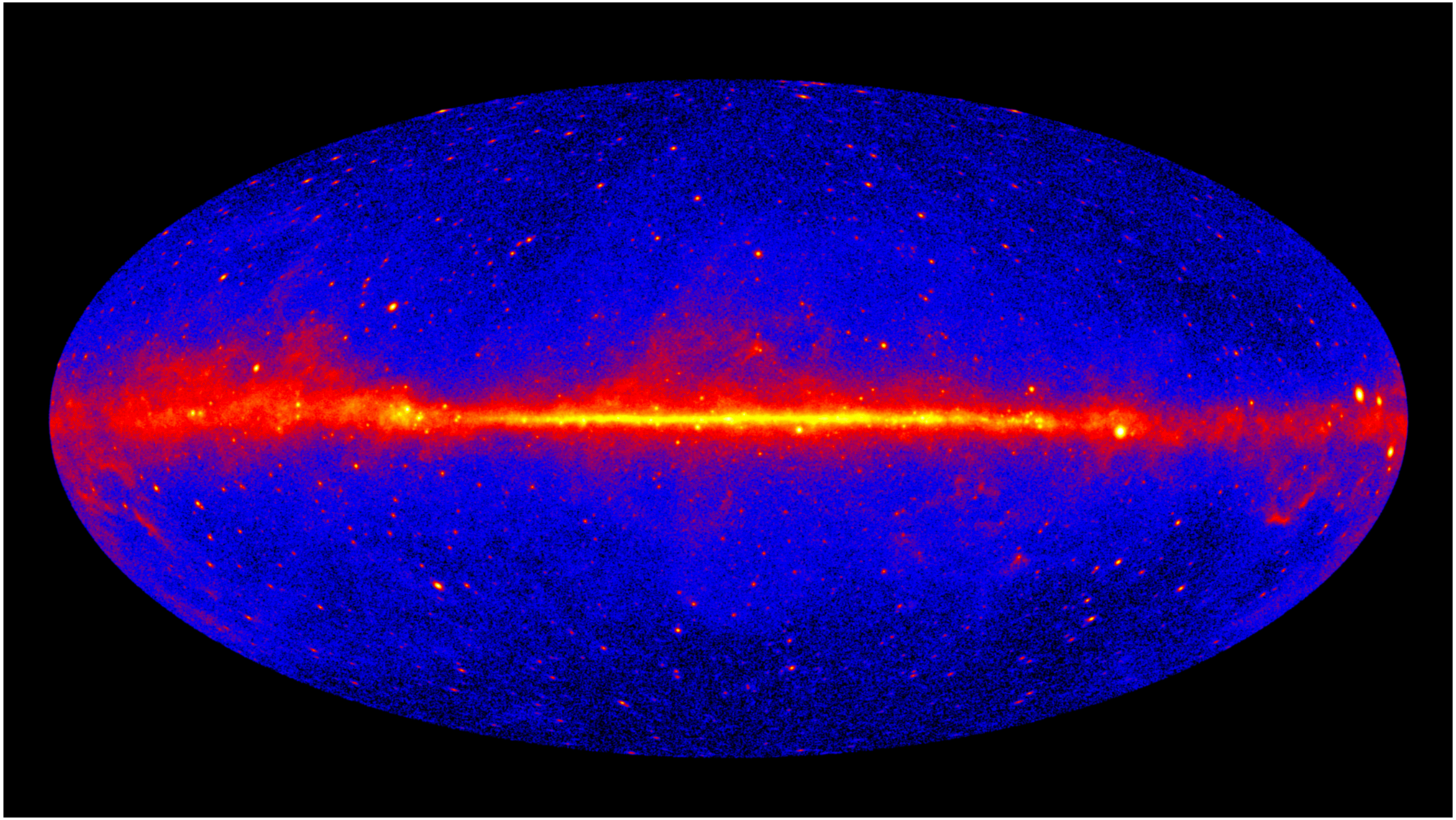
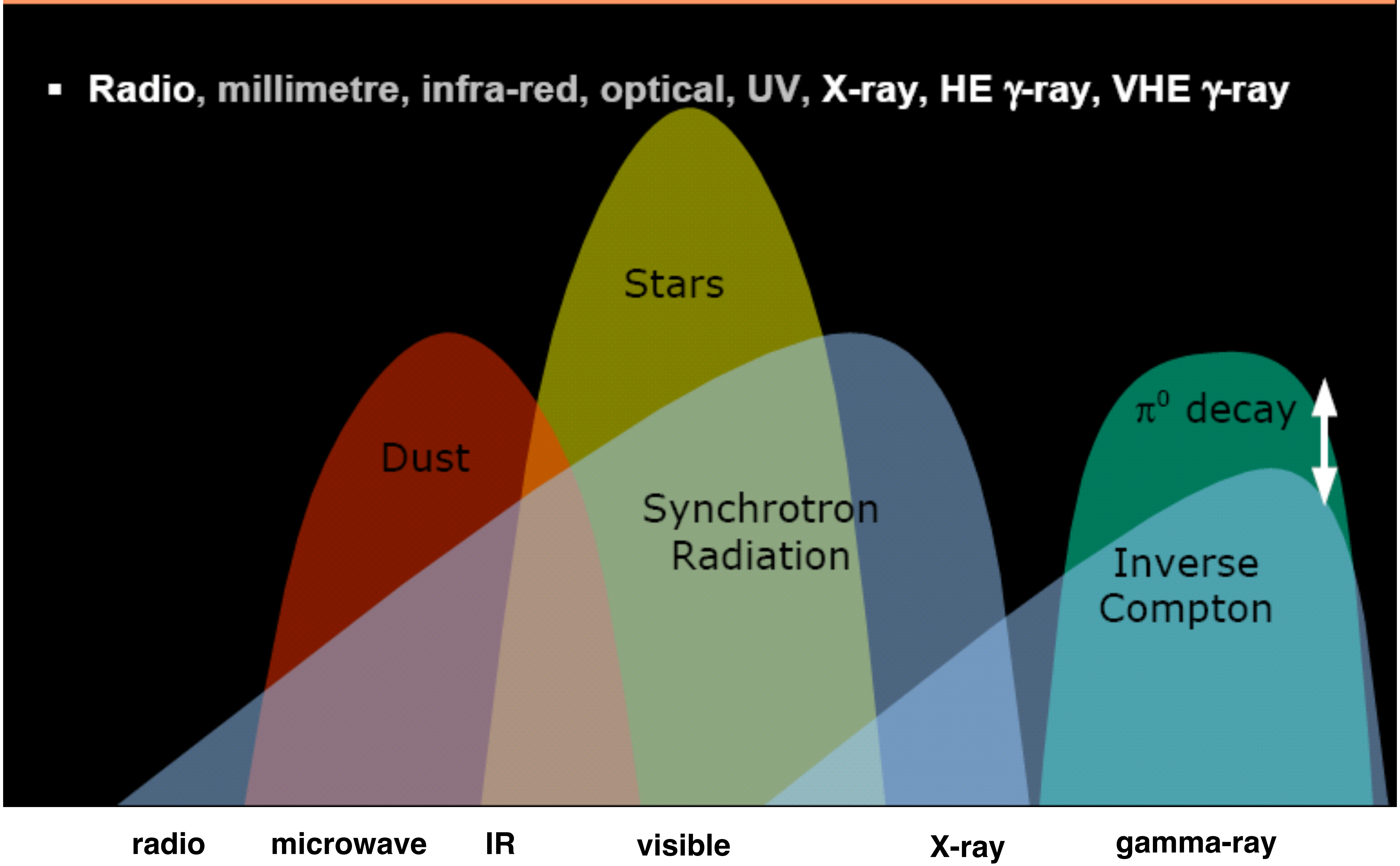
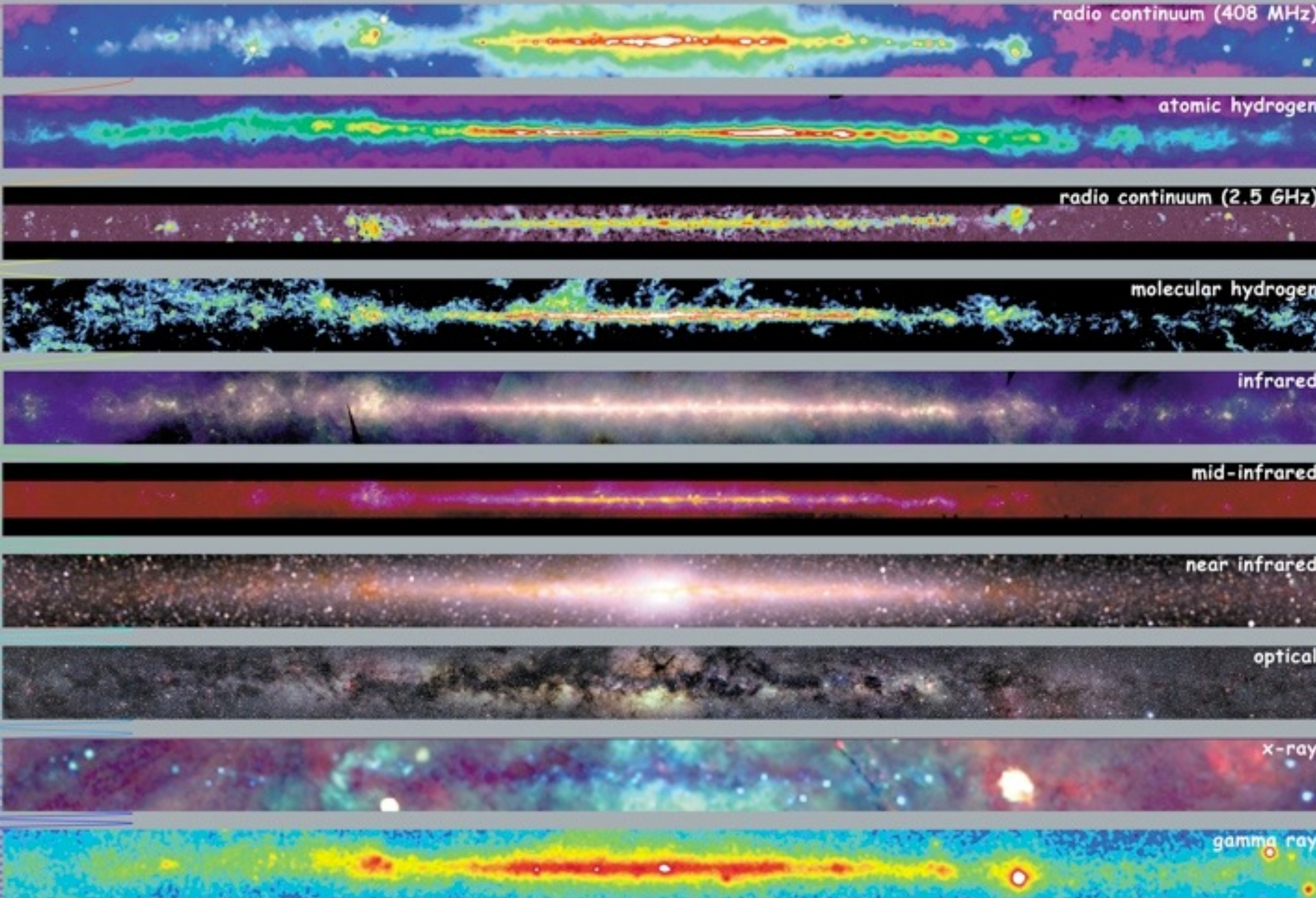


Figure 1: *Fermi*-LAT all sky image in Galactic co-ordinates. Credit: NASA/DoE.

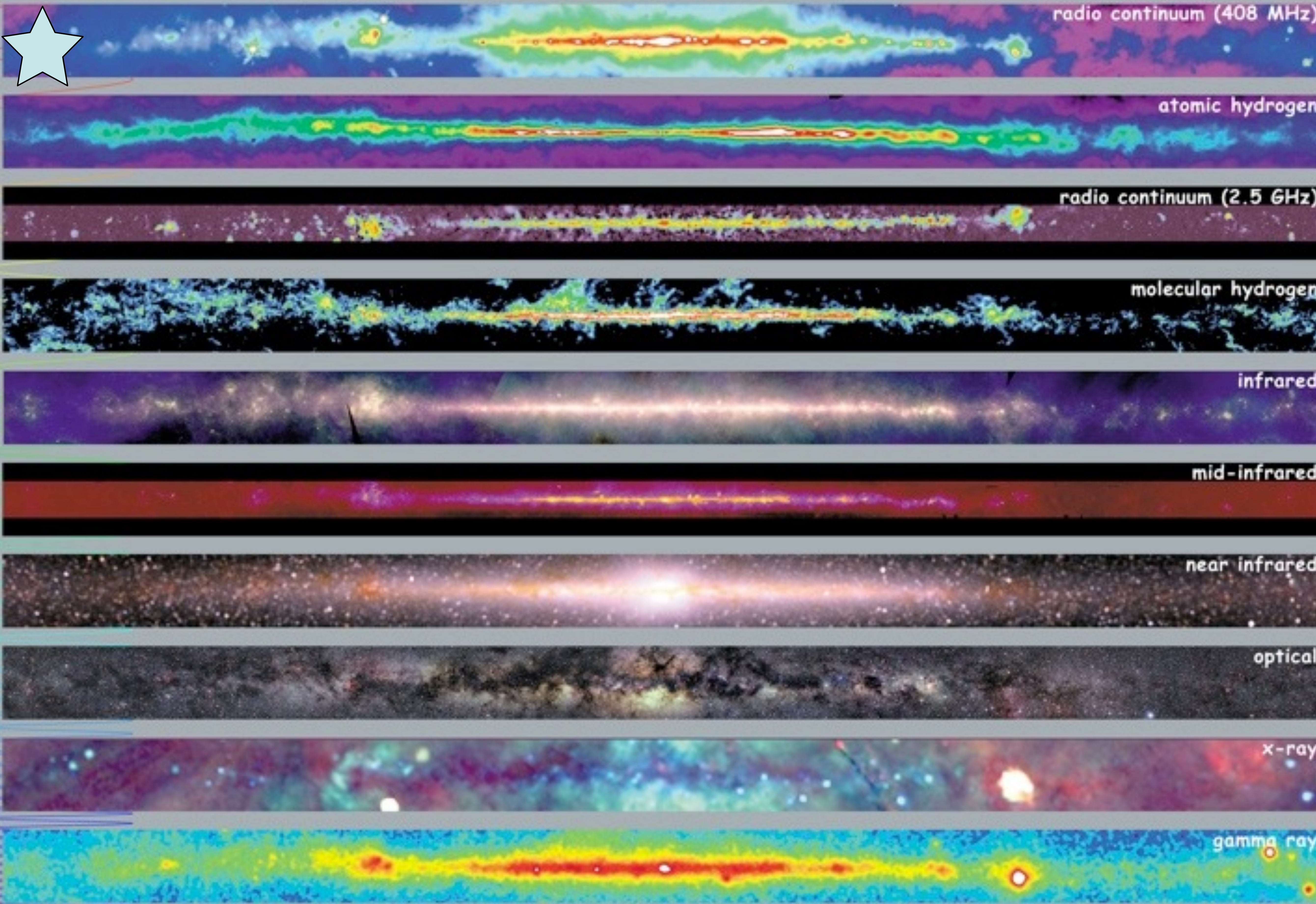
Generic Galactic 'SED' (Spectral Energy Distribution)



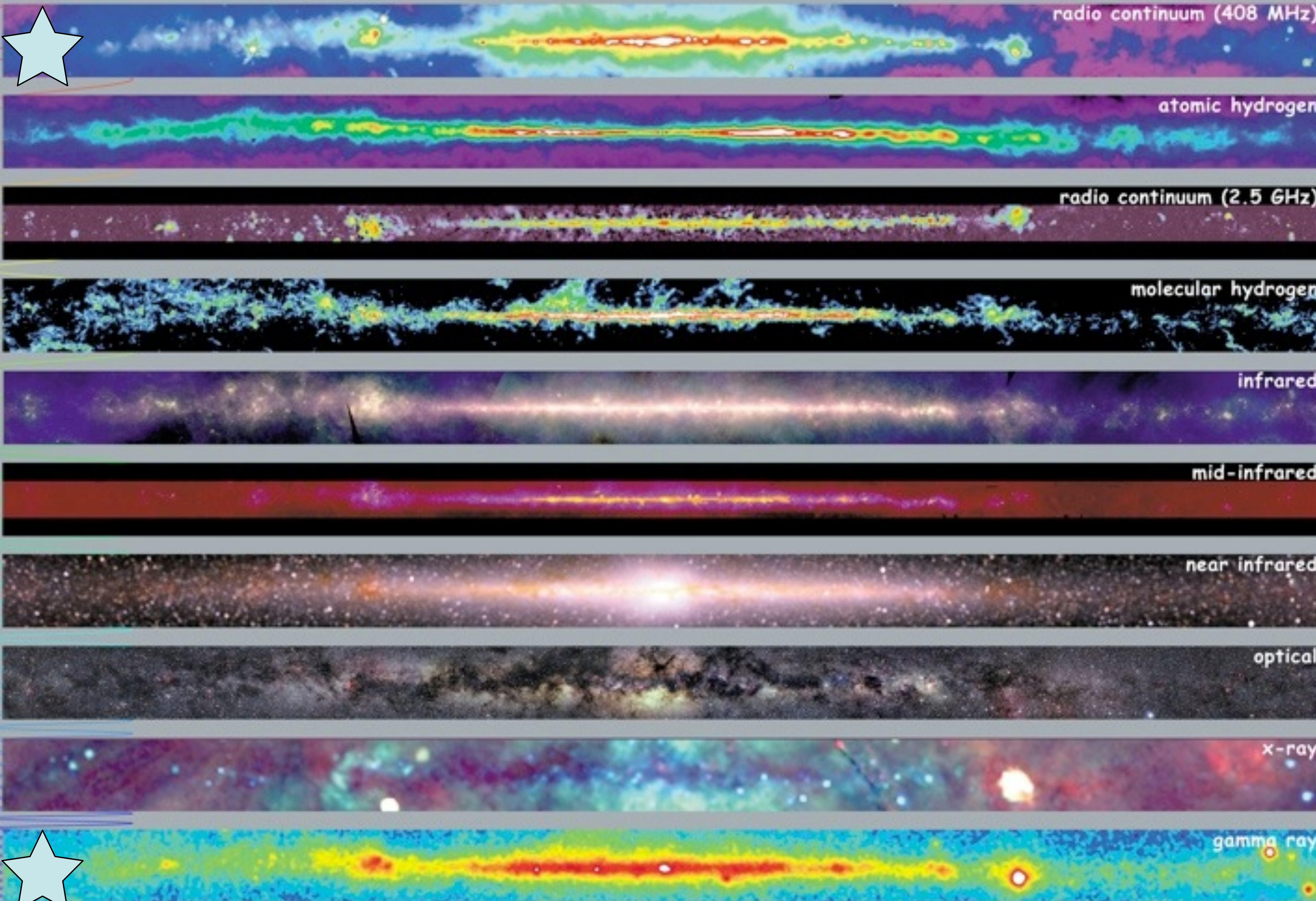
http://www-zeuthen.desy.de/astro-workshop/vortraege/donnerstag/puehlhofer_zeuthen.pdf



Multiwavelength Milky Way



Multiwavelength Milky Way



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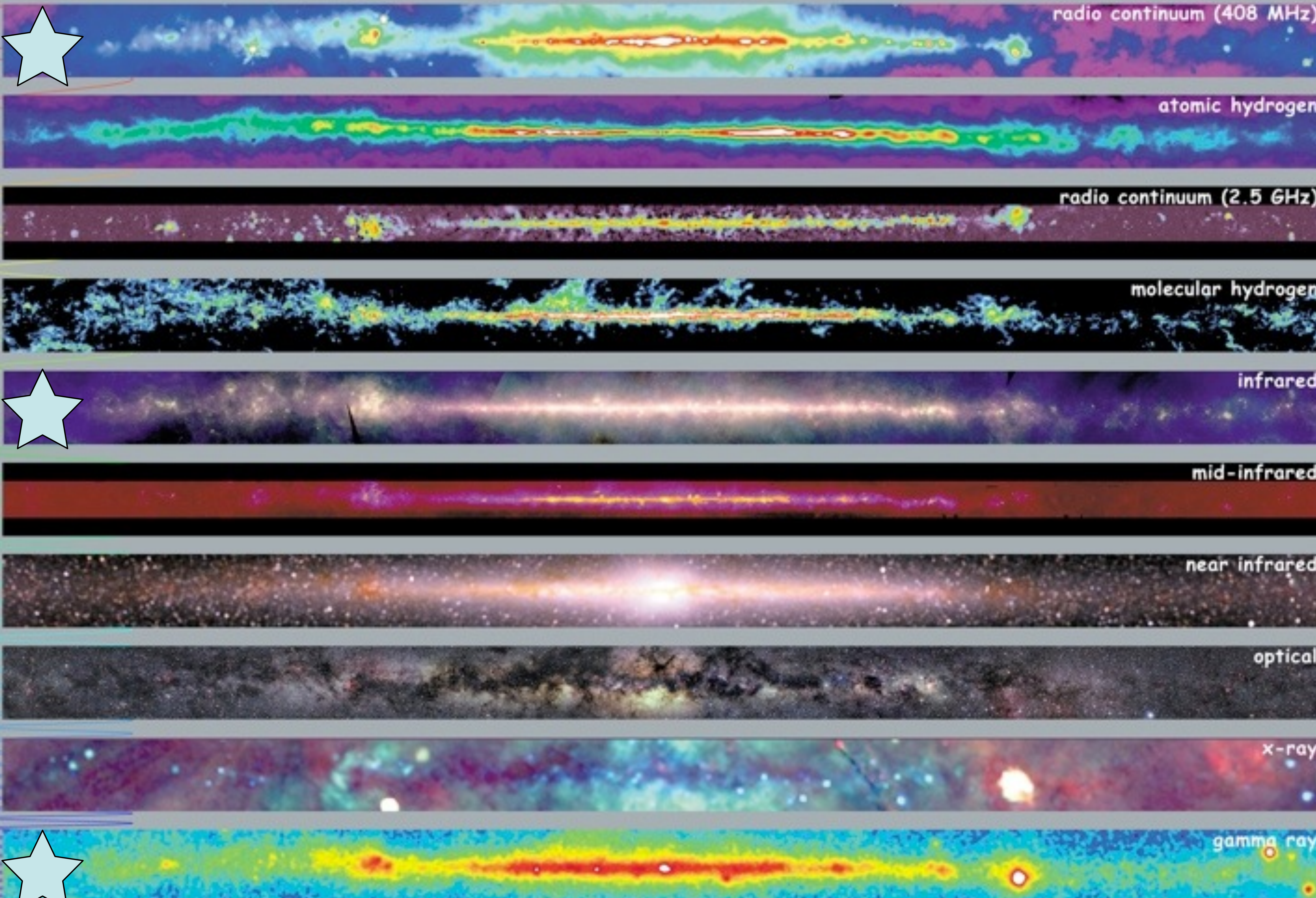
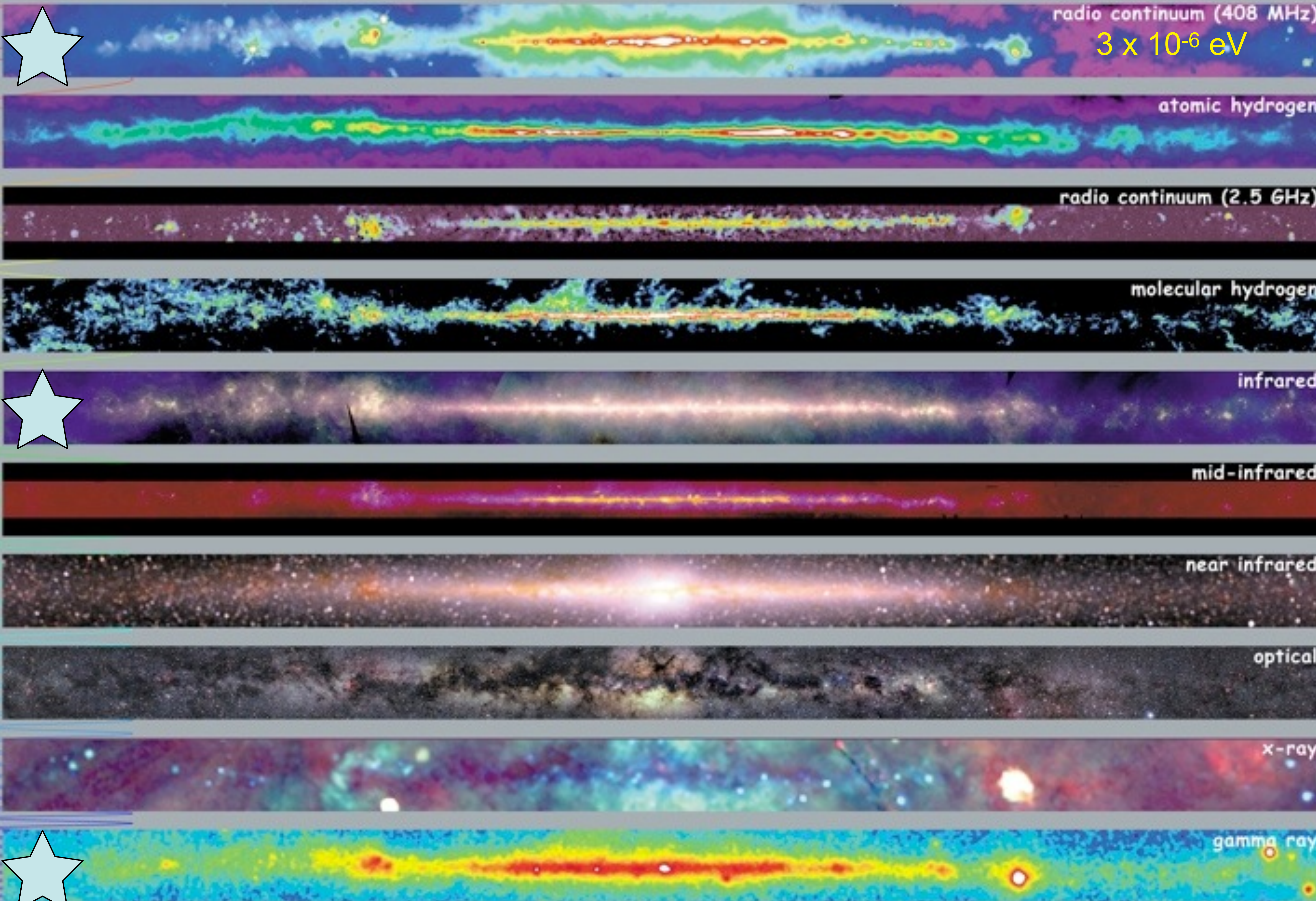


Multiwavelength Milky Way



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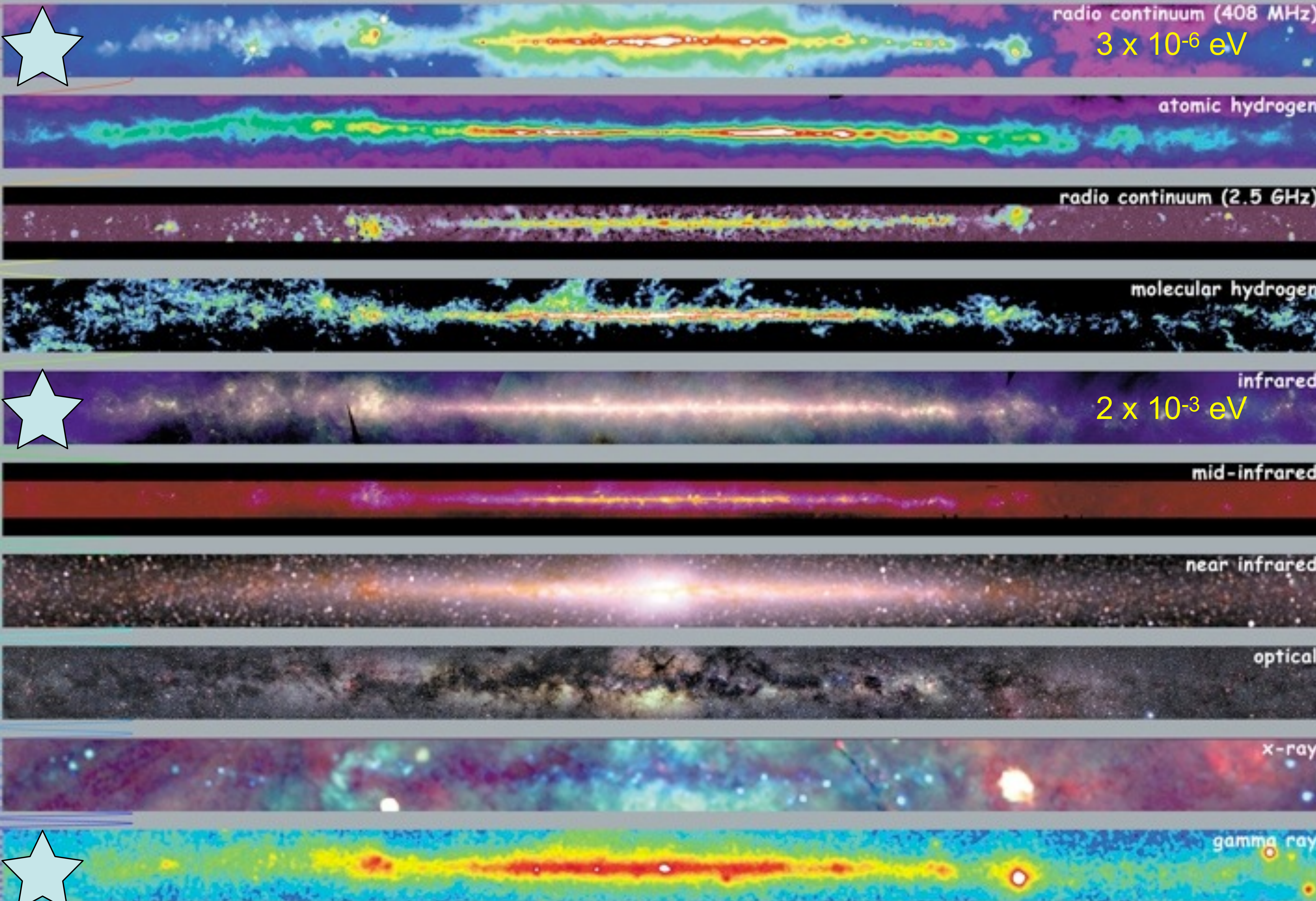

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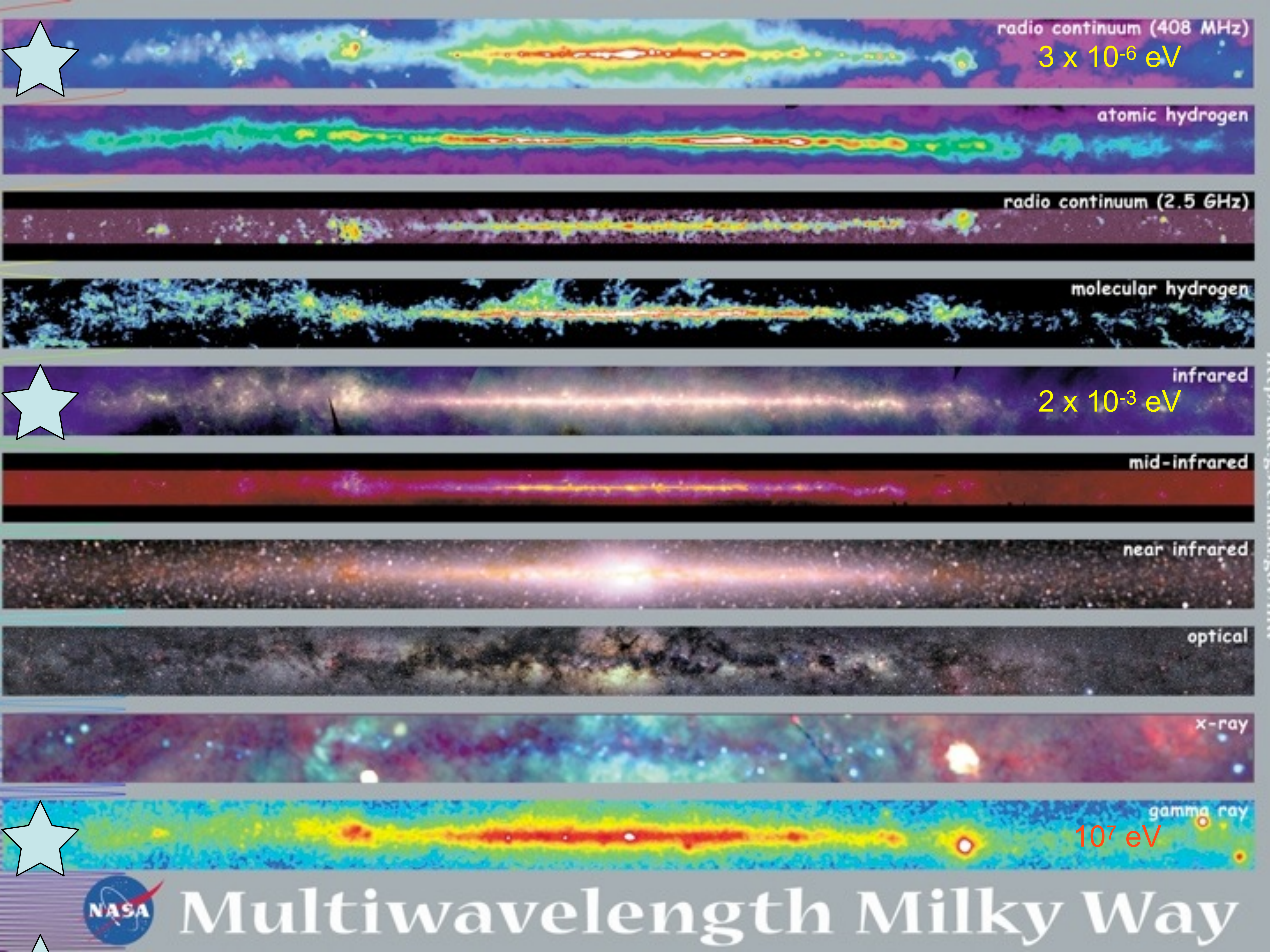
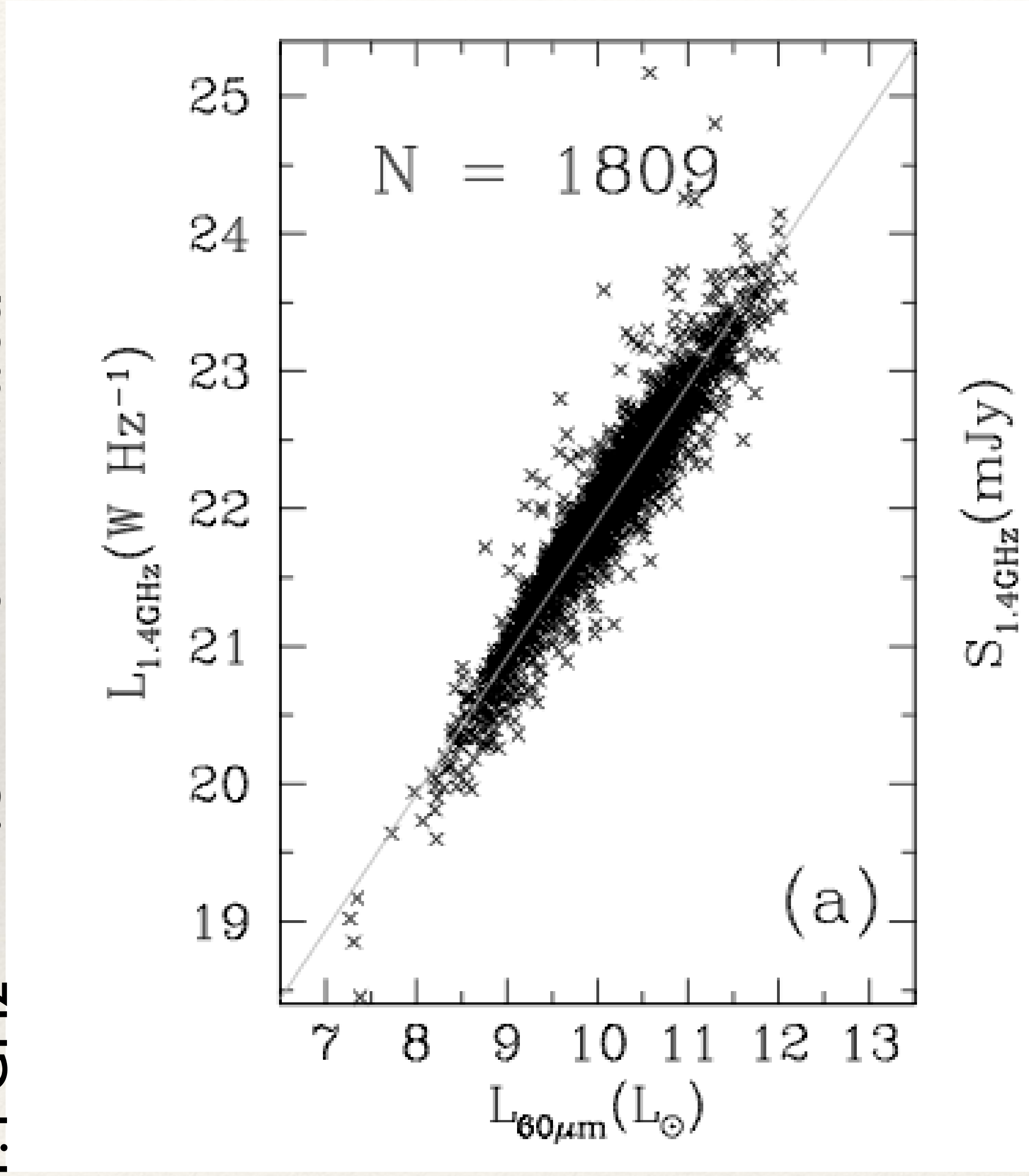

radio continuum (408 MHz)
3 x 10-6 eV
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
2 x 10-3 eV
mid-infrared
near infrared
optical
x-ray
gamma ray
107 eV
NASA
Multiwavelength Milky Way

‘Far Infrared-Radio Continuum Correlation’



$L_{1.4\,GHz} = 1.5 \times 10^{20}$ Watt/Hz

$L_{60\mu m} = 1.3 \times 10^{8}\ L_\odot$

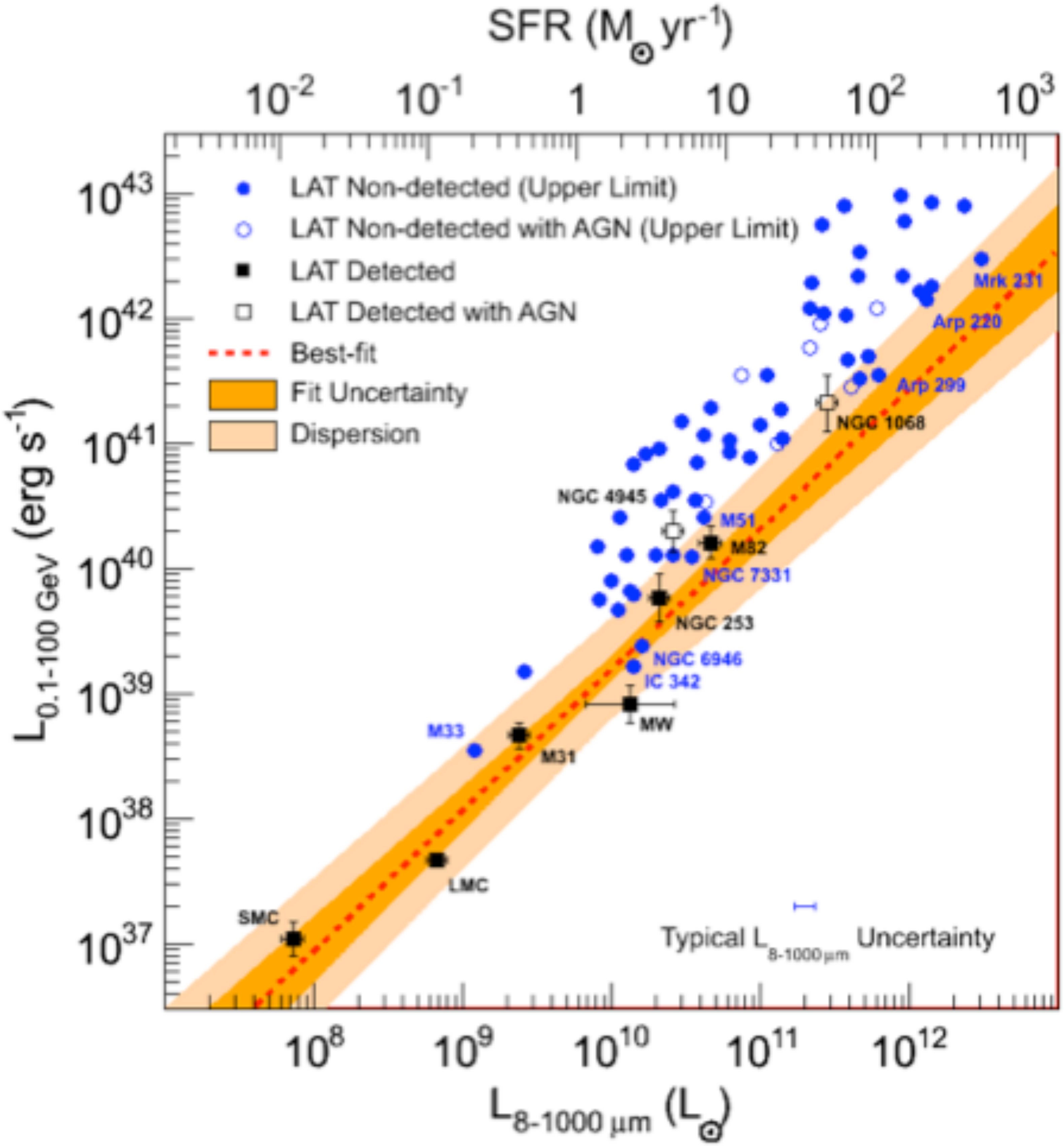
Yun et al. 2001 ApJ 554, 803 fig 5

Sidebar: origin of FIR-RC?

- correlation between FRC and RC ultimately tied back to massive star formation (Voelk 1989)
- massive stars → UV → (dust) → IR
- massive stars → supernovae → SNRs → acceleration of CR e's → (B field) → synchrotron

FIR-γ-ray Correlation?

- SNR accelerate CR p's (and heavier ions)
- there should exist a global scaling b/w FIR and gamma-ray emission from region (Thompson et al. 2007): $L_{GeV} \sim 10^{-5} L_{TIR}$ (assuming 10^{50} erg per SN in CRs)



Martin, *Fermi collab*

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).

Cosmic Rays:
What are they good for?

- Because CRs are charged, they respond to ISM magnetic fields

  $\Rightarrow$ we cannot do CR astronomy (except maybe at highest energies)

- Scatter most strongly on magnetic field inhomogeneities of same scale as their *gyro radius*

  $\Rightarrow$ CRs execute a random walk through turbulent ISM magnetic field structure

‘Gyroradius’ = ‘Larmor Radius’

$$r_{gyro} \simeq 1.1 \times 10^{-6}\ \mathrm{pc}\ \ (p_{perp}/\mathrm{GeV})\ \ (B/\mu\mathrm{G})\ \ 1/Z$$

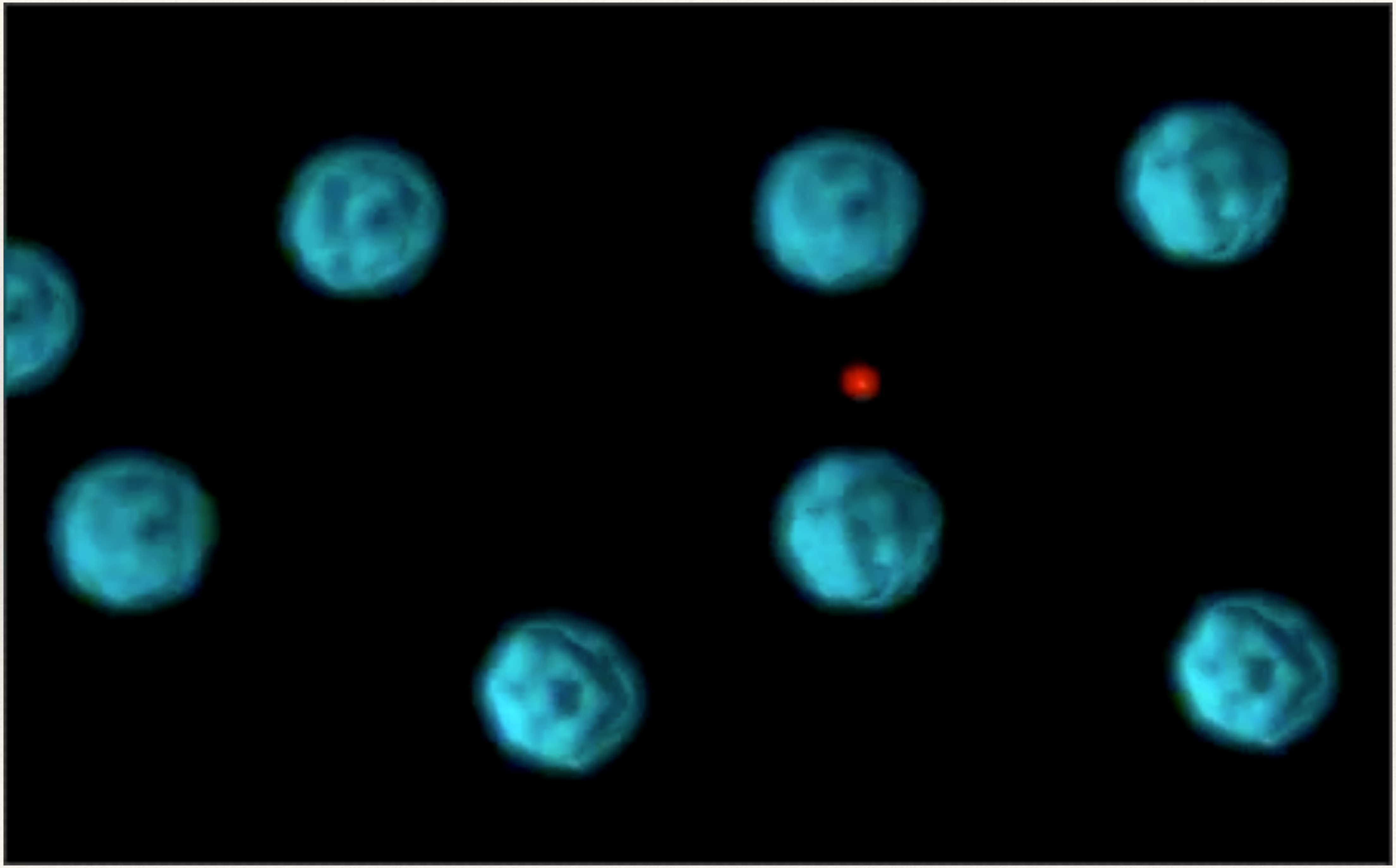
.

$$rigidity \equiv \frac{\mathrm{pc}}{\mathrm{Ze}} \approx \frac{\mathrm{E}}{\mathrm{Ze}}$$

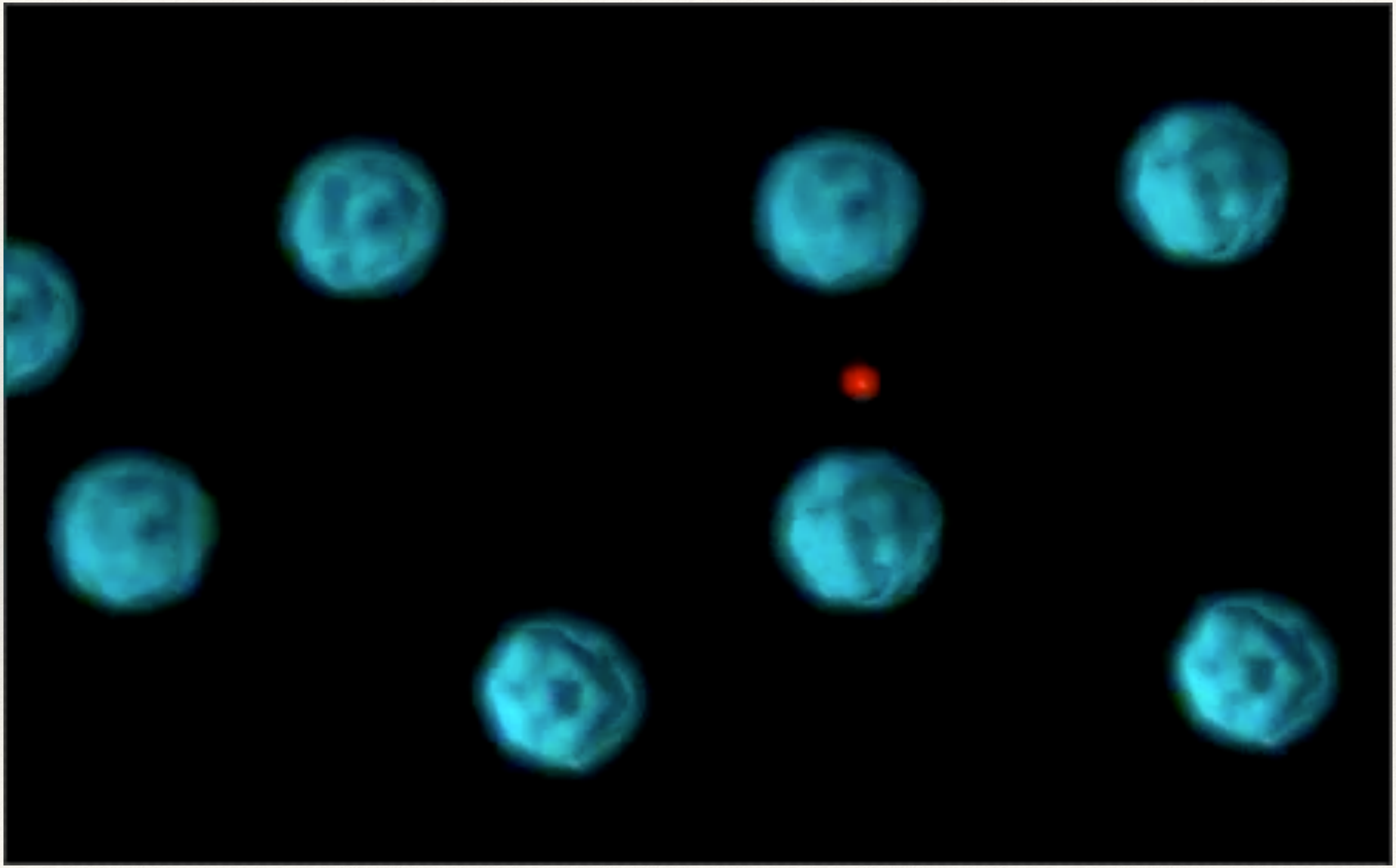
Cosmic Rays:
What are they good for?

- Q: Where do they come from?
- A: accelerated in astrophysical shocks (1st order Fermi acceleration in converging flows), primarily shocks from SN explosions (also stellar winds, etc, also 2nd order acceleration on ISM turbulence)

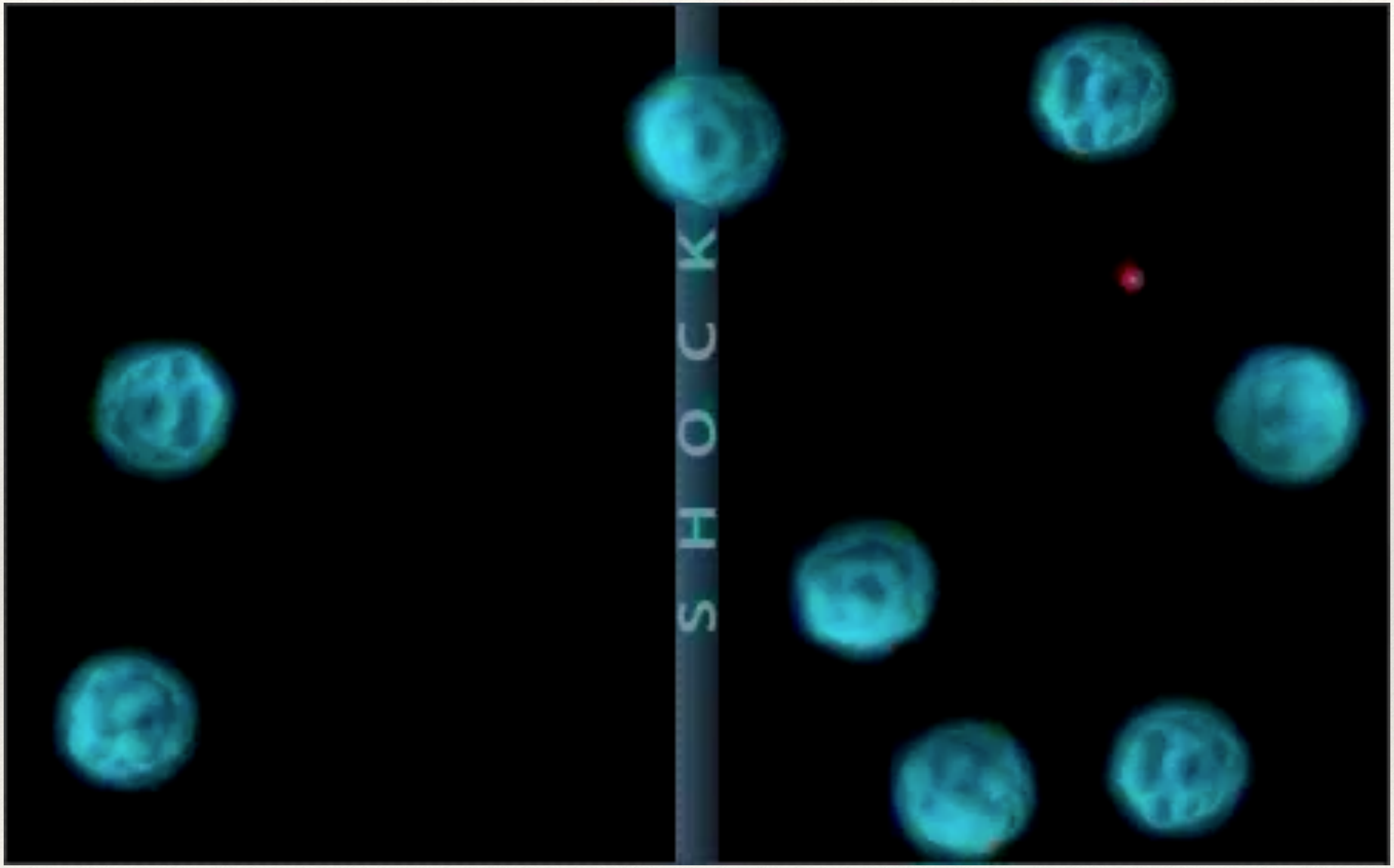
Fermi-II



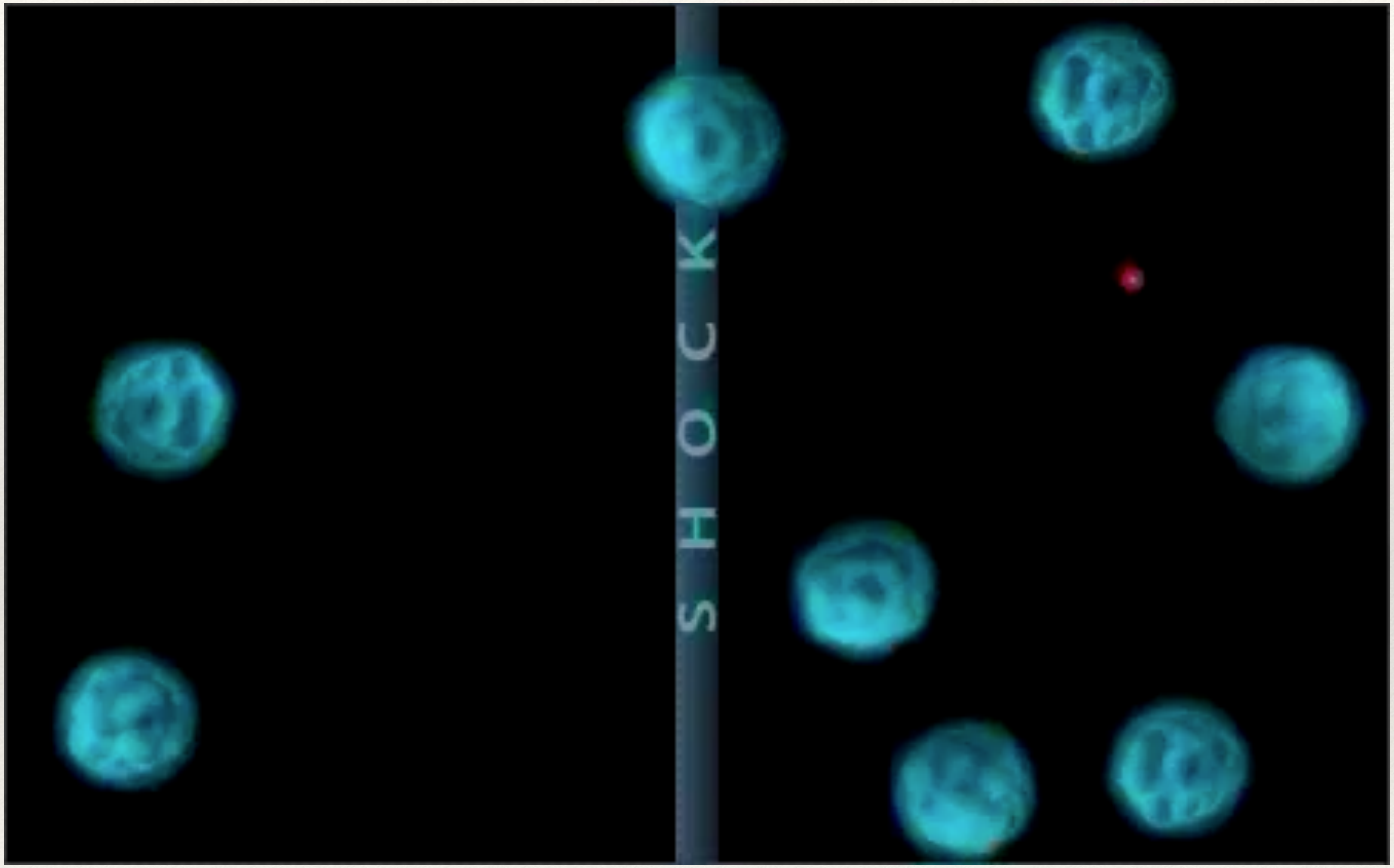
Fermi-II



Fermi-I



Fermi-I



Cosmic Rays:

- Energetic match to power available from SNe
- $L_{CR} \sim 10^{-3}\, L_{light}$
- Q: why energy density in different ISM components ~the same?:

  $u_{CR} \sim u_{ISRF} \sim u_{turb} \sim u_{therm} \sim 1$ eV cm^{-3}

- A: because long CR escape/energy loss times, $>10^7$ years
- $u_{CR} \sim L_{CR}\, t/V_{CR}$
- $t_{CR} \sim \mathrm{Min}[t_{esc}, t_{loss}]$
- $t_{esc} \sim 0.1\, t_{loss}$ in MW
- $L_{CR} \sim$ SFR/(100 M_{Sun}/CCSN) x 0.1

  $\sim 3\times10^{40}$ erg/s

Cosmic Rays:

- $V_{CR} \sim 2\ \mathrm{Pi}\ 2\ \mathrm{kpc}\ (8\ \mathrm{kpc})^2 \sim 2\ 10^{67}\ \mathrm{cm}^3$
- $u_{CR} \sim L_{CR}\ t/V_{CR}$

$\sim 3\ 10^{40}\ \mathrm{erg/s}\ \ 3\ 10^{7}\ \mathrm{year}/(2\ 10^{67}\ \mathrm{cm}^3)$

$\sim 1.5\ \mathrm{eV\ cm}^{-3}$

Cosmic Rays:

- CR transport in Gal disk = random walk
- CRs effectively diffuse with λ_{CR}~pc scattering length
- As CRs scatter on B field they exchange momentum with the B field

  $\Rightarrow$ they exert an effective pressure to the gas into which the B field is "frozen in"

Cosmic Rays:

- Can make sense of the analogue of an "Eddington limit" in CRs (Socrates et al. 2008)
- Momentum flux imparted by CRs, **dot{P}$_{CR}$,** can be significantly enhanced because of the large effective optical depth they experience
- dot{P}$_{CR}$ ~ $\boldsymbol{\tau}_{CR}$ L_{CR} ; $\boldsymbol{\tau}_{CR}$: cosmic ray optical depth
- $\boldsymbol{\tau}_{CR} \sim R/\lambda_{CR} \sim 100$ pc/10 pc ~ 10^3 ;

[λ_{CR} : N.B. CR mean free path $\lambda_{CR} \gg r_{gyro}$]

$\Rightarrow$ dot{P}$_{CR}$ ~ 10^3 x 10^{-3} L_{light} ~ L_{light}

Cosmic Rays:

- CRs effectively behave as a relativistic fluid with adiabatic index $\gamma = 4/3$
- adiabatic losses are smaller than for non-rel fluid in an expanding outflow

  $\Rightarrow$ CRs become progressively more important the more a wind expands

Where do UHE CRs come from?
'Hillas Criterion'

- in any accelerator where the cosmic rays are magnetically confined by a field of characteristic amplitude B, their gyro- radius has to be smaller than the size of the system L:
- i.e., $r_{gyro} < L \Rightarrow E < Z\,e\,c\,B\,L$ (very generous upper limit
- More realistically: $c \rightarrow v$, where v is a characteristic velocity
- $E < Z\,e\,\mathbf{v}\,B\,L$

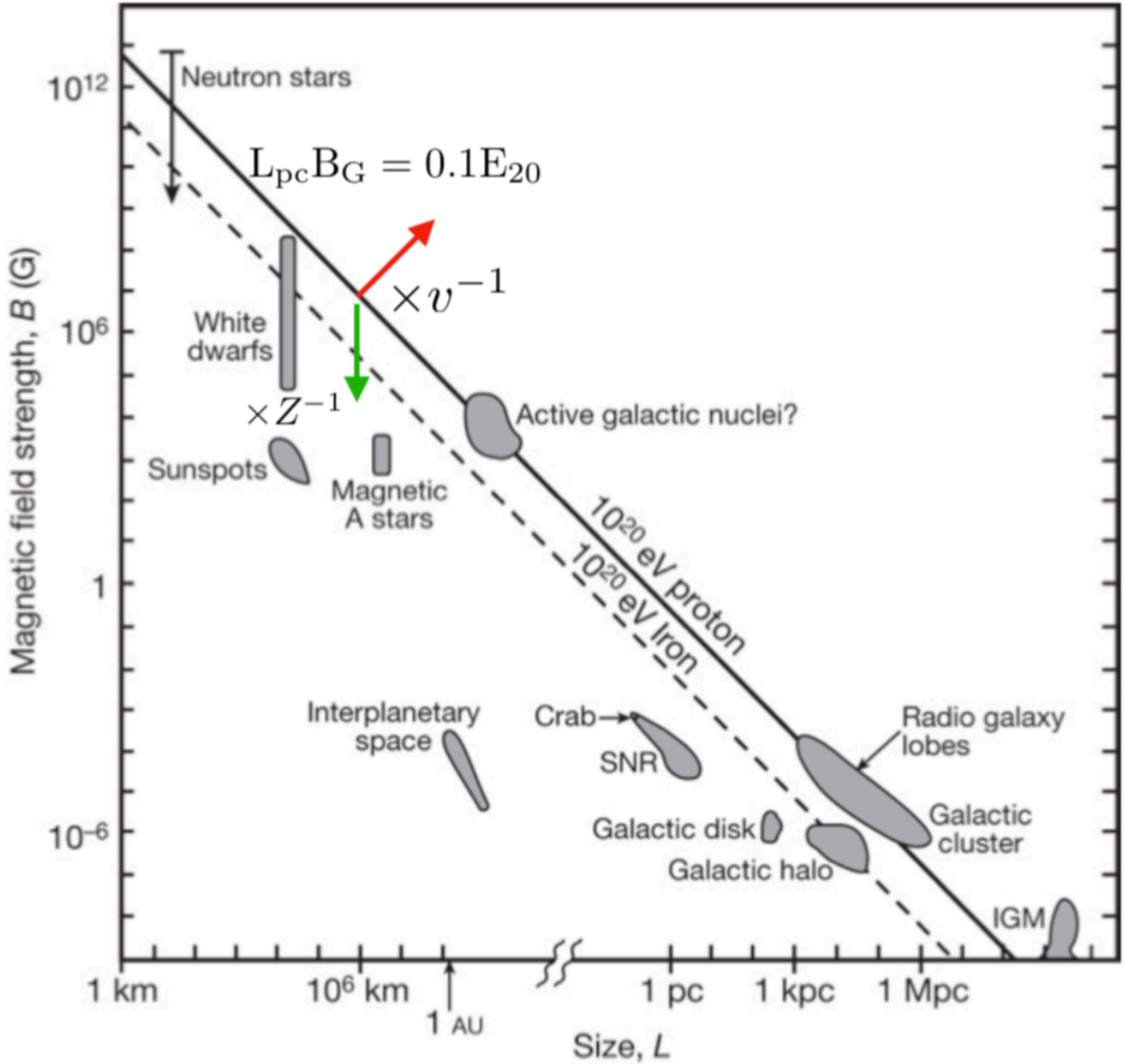
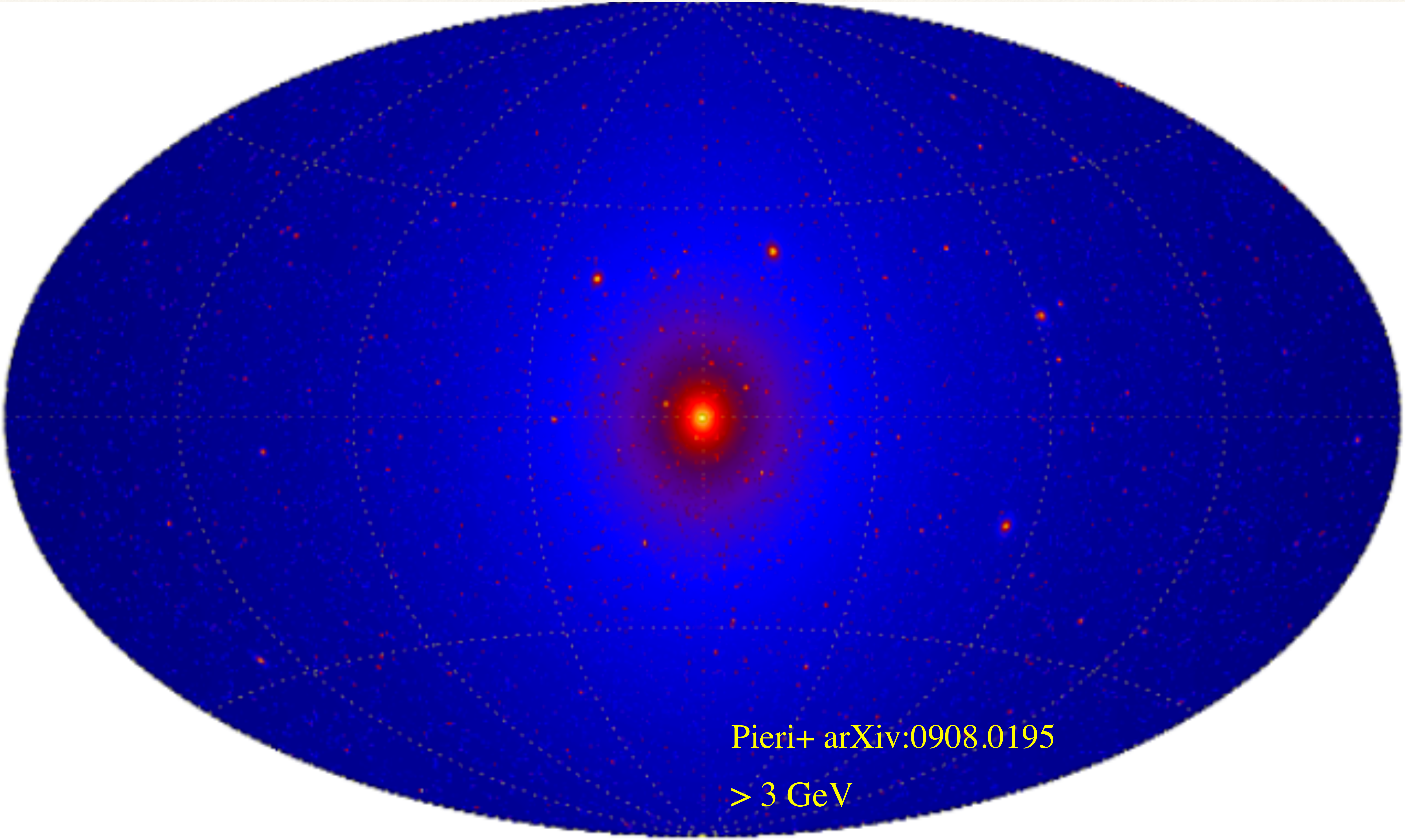


Figure 3: Hillas plot showing the maximum energy achievable in various astrophysical source of given characteristic size and magnetic field amplitude (credit: F. Aharonian).

Part II: The Galactic Centre:

Preface: why is the Galactic Centre interesting for (e.g.) a particle physicist?

- High dark matter density should mean that the Galactic Centre is one of the best places in the sky to seek indirect evidence of its annihilation (Bergström+97)


Pieri+ arXiv:0908.0195
> 3 GeV

Preface: why is the Galactic Centre interesting?

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- On the other hand:

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  - There's a lot of Galaxy between us and the GC

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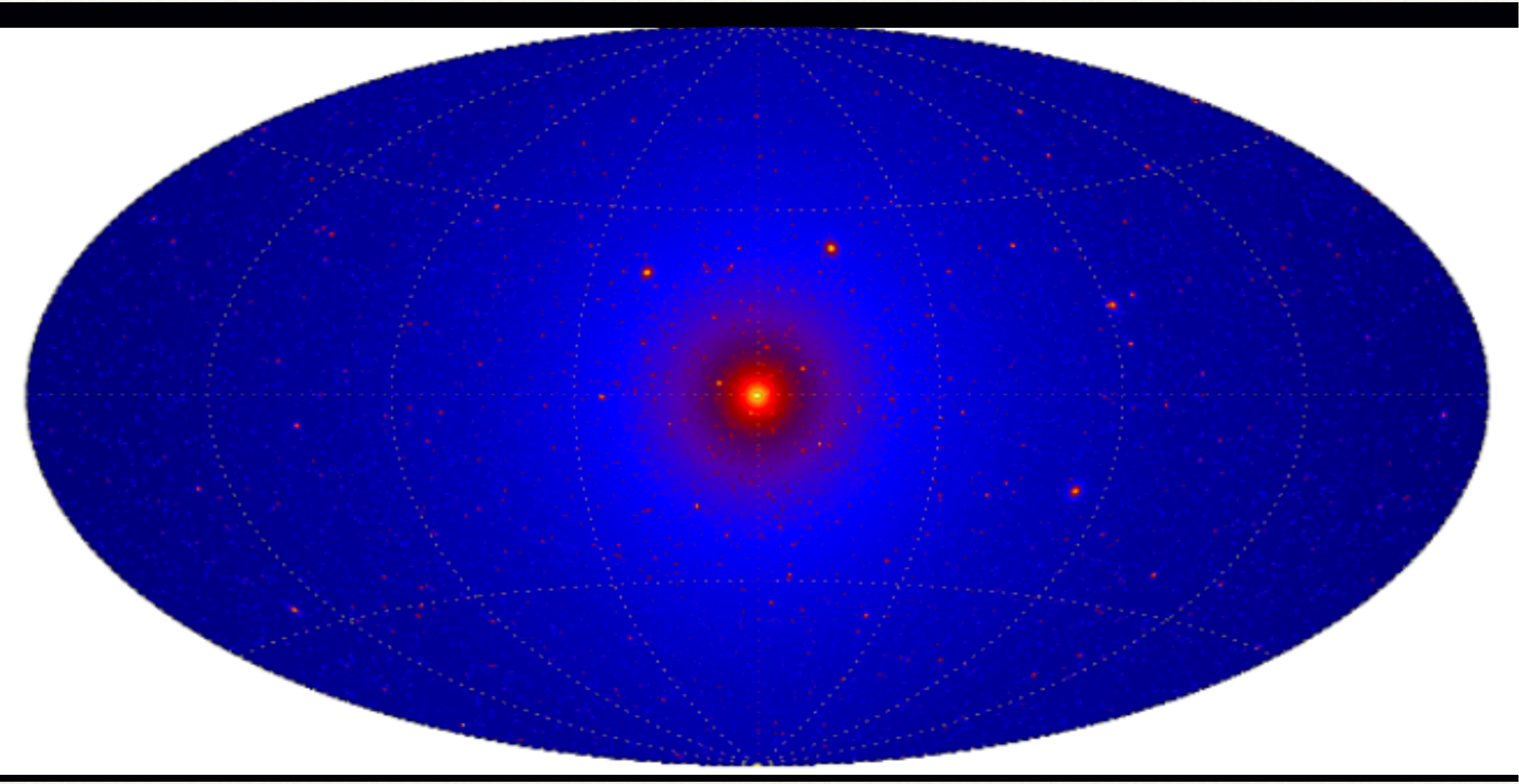
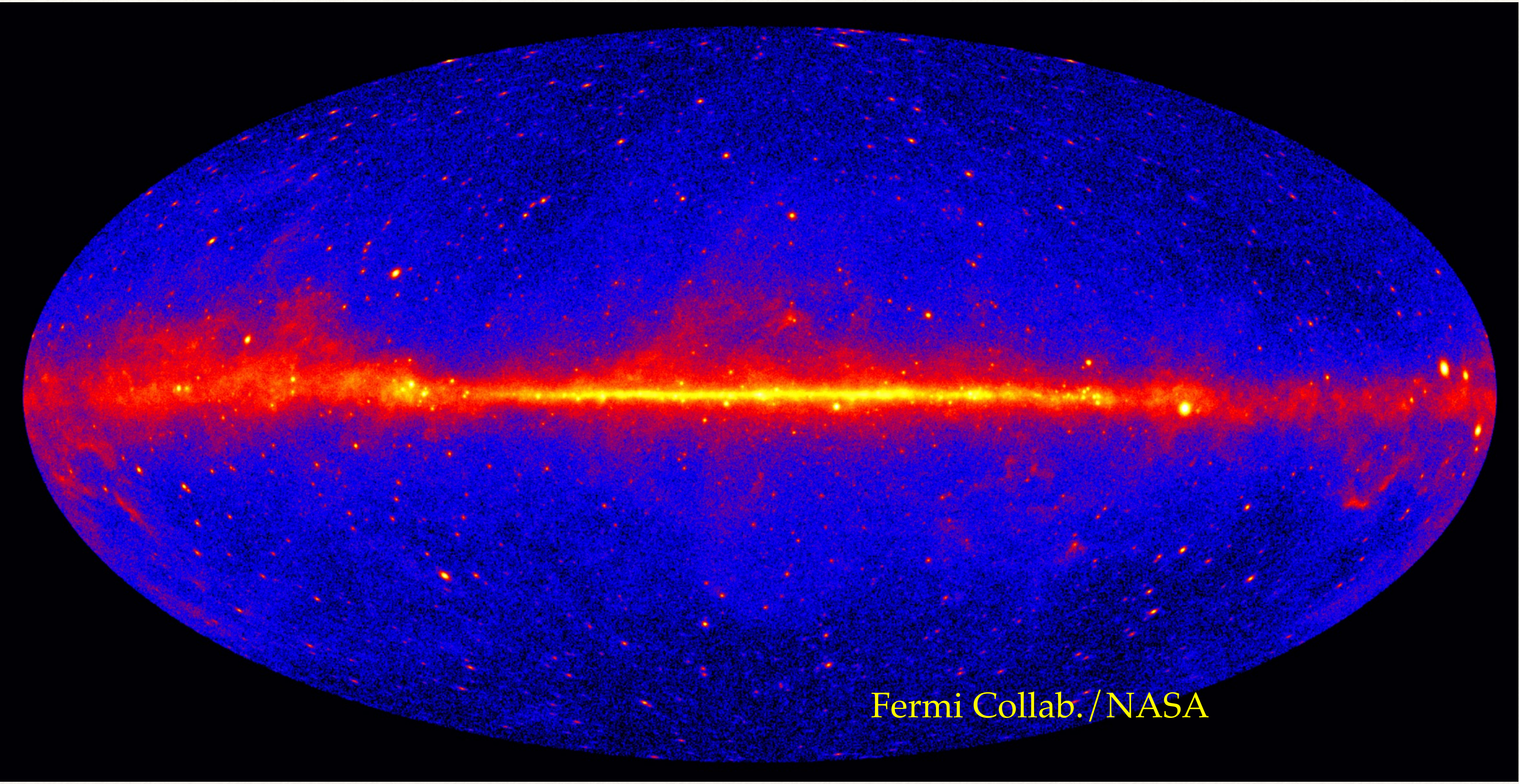
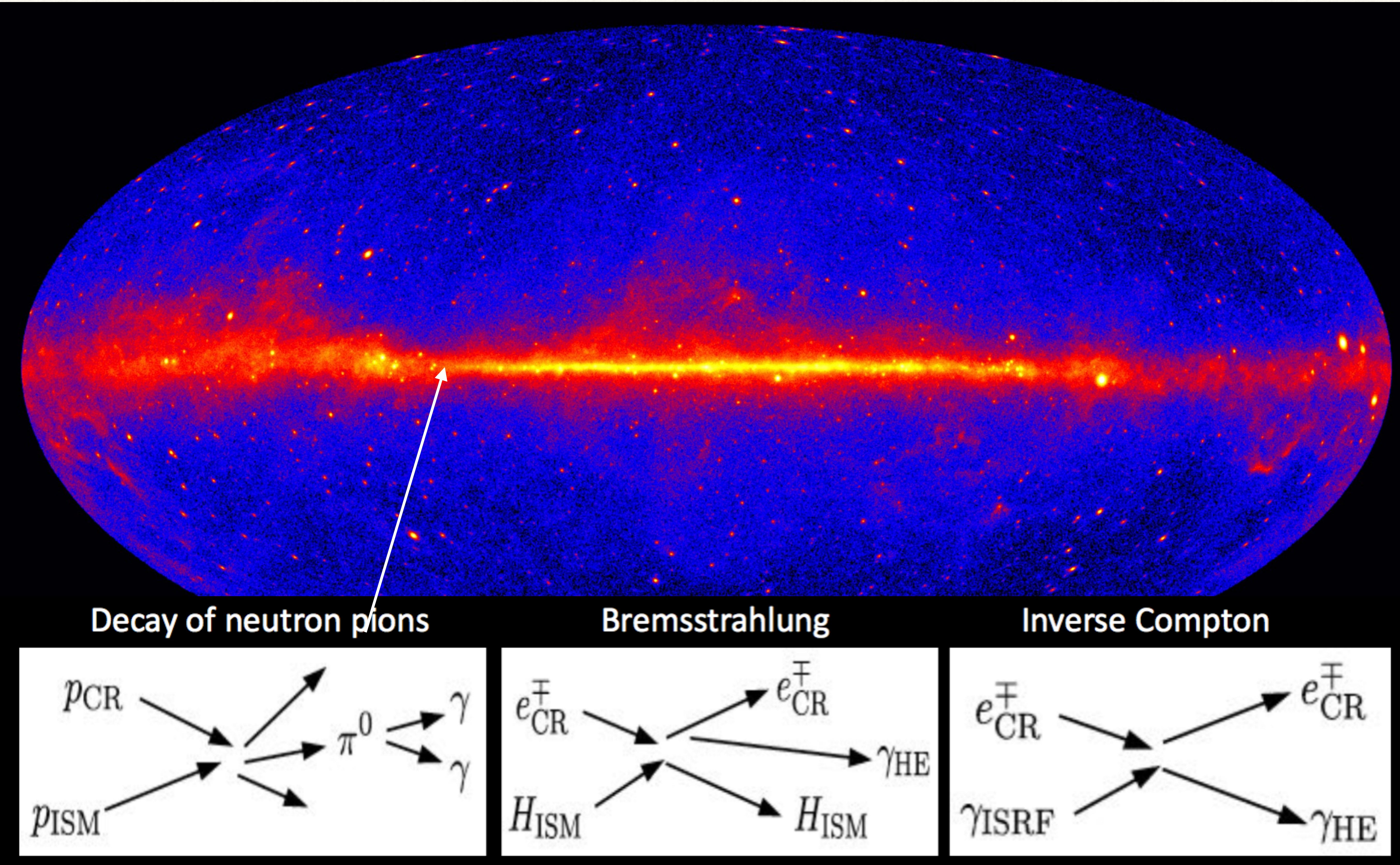
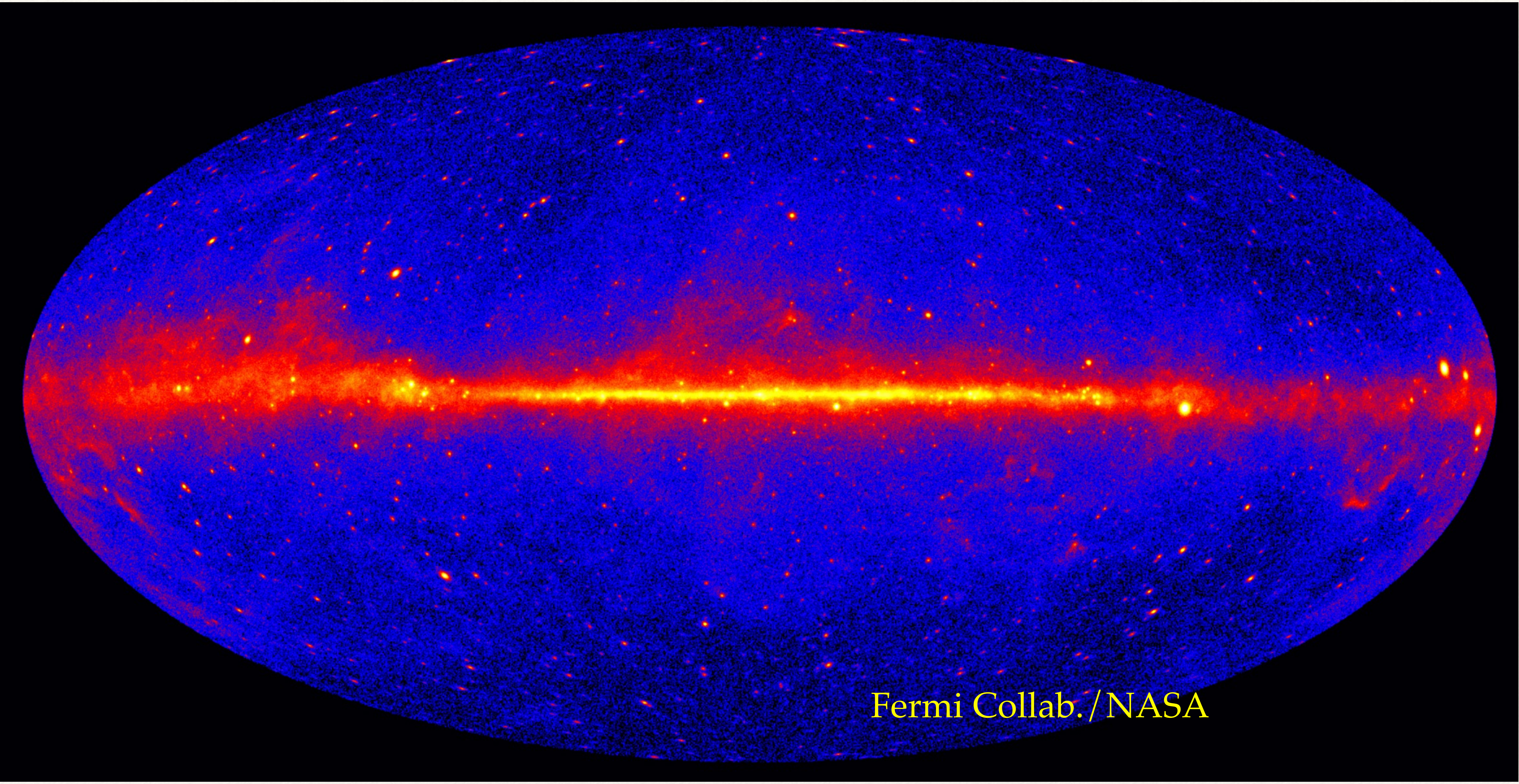
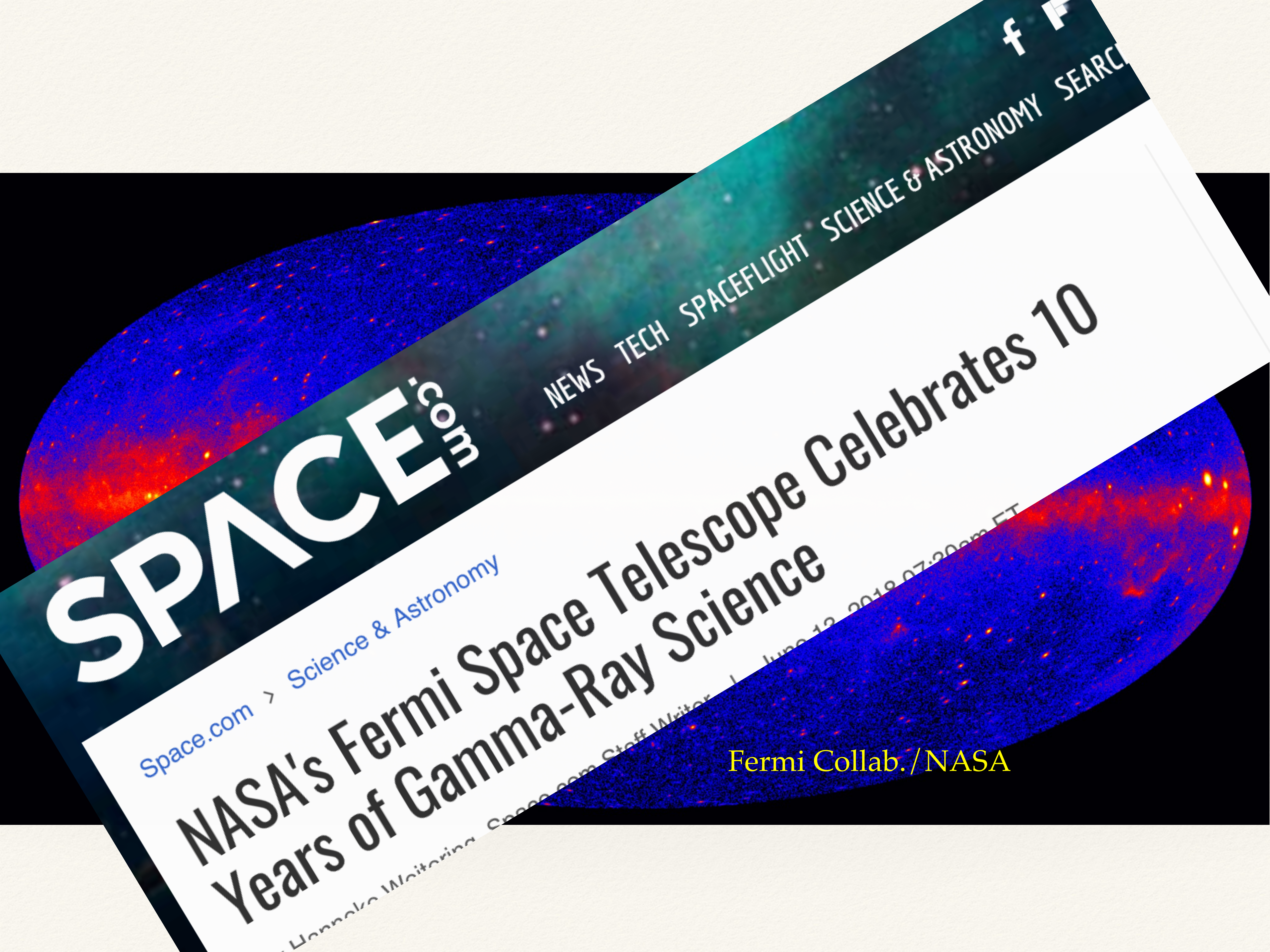



Fermi Collab. / NASA



Decay of neutron pions
Bremsstrahlung
Inverse Compton
$p_{\rm CR}$
$p_{\rm ISM}$
π^0
γ
γ
$e^{\mp}_{\rm CR}$
$H_{\rm ISM}$
$e^{\mp}_{\rm CR}$
$\gamma_{\rm HE}$
$H_{\rm ISM}$
$e^{\mp}_{\rm CR}$
$\gamma_{\rm ISRF}$
$e^{\mp}_{\rm CR}$
$\gamma_{\rm HE}$


Fermi Collab. / NASA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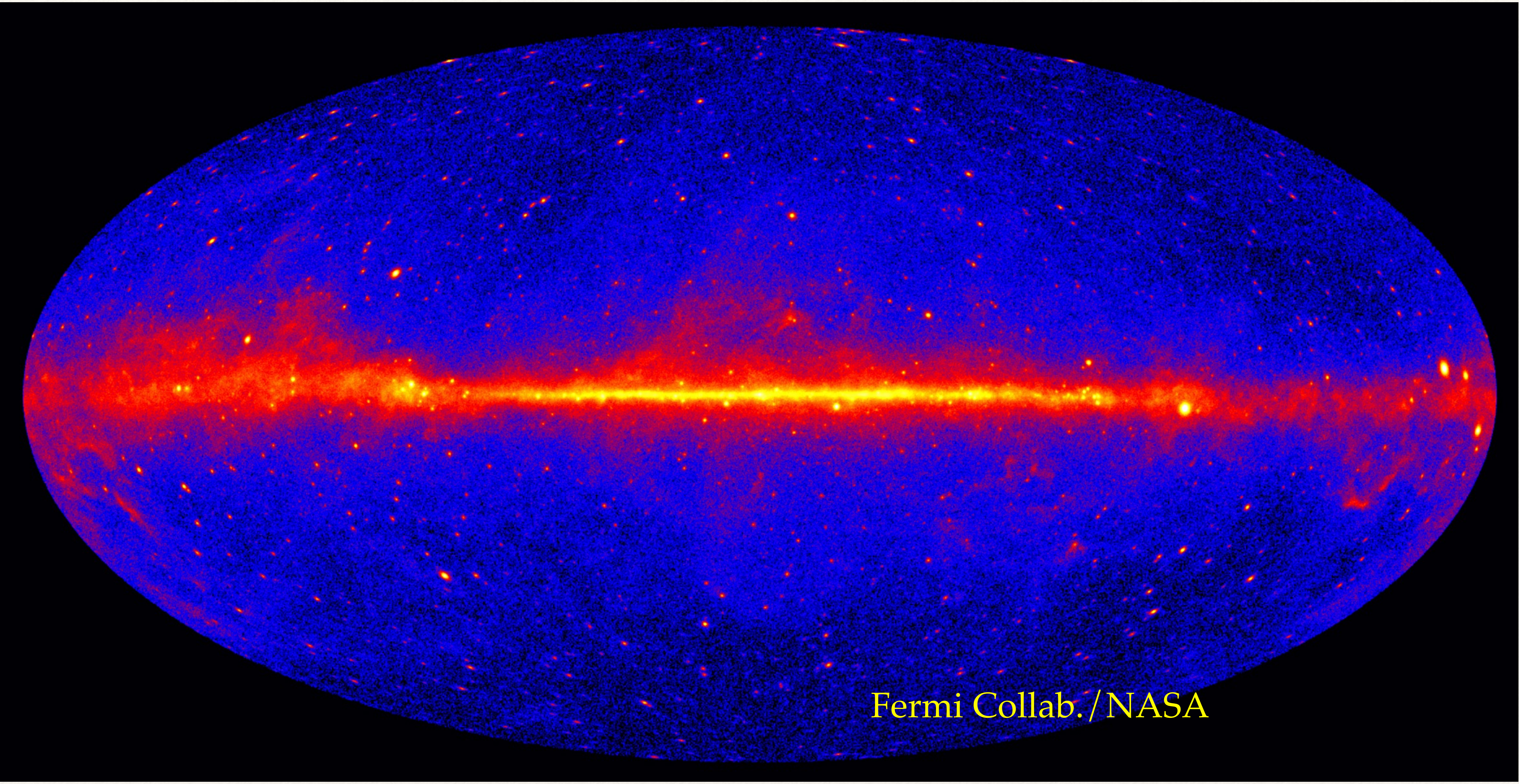
SPACEFLIGHT
SCIENCE & ASTRONOMY
Space.com > Science & Astronomy
NASA's Fermi Space Telescope Celebrates 10 Years of Gamma-Ray Science
Fermi Collab./NASA


Fermi Collab. / NASA

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- High dark matter density should mean that the Galactic Centre is one of the best places in the sky to seek indirect evidence of its annihilation (Bergström+97)
- On the other hand:
  - There's a lot of Galaxy between us and the GC

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- On the other hand:
  - There's a lot of Galaxy between us and the GC
  - Moreover, the Galactic Centre is a quite different environment to the rest of the Galaxy: astrophysical backgrounds are not only strong but also *poorly understood*

Galactic Centre Dark Matter(?)

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- But, historically, many such signals have either evaporated or come to be understood as likely or definitely astrophysical in origin…

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- (Quasi) point-like GeV and TeV γ-ray source coincident with Sgr A*

small scales $\longrightarrow$ LARGE SCALES

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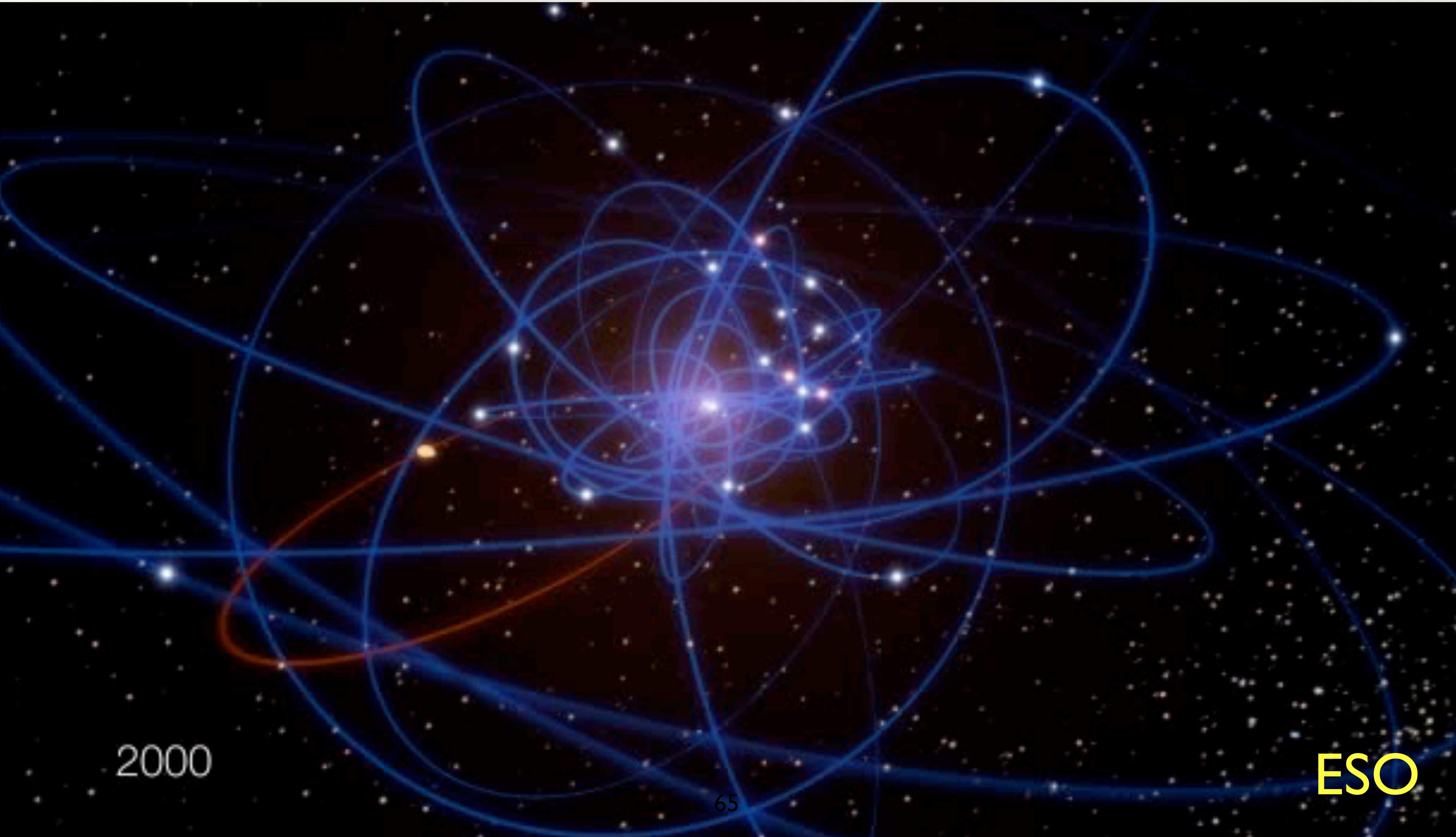
However: the GC *certainly* does contain dark matter: there is a 4 Million Solar Mass chunk at the Galaxy's dynamical centre…



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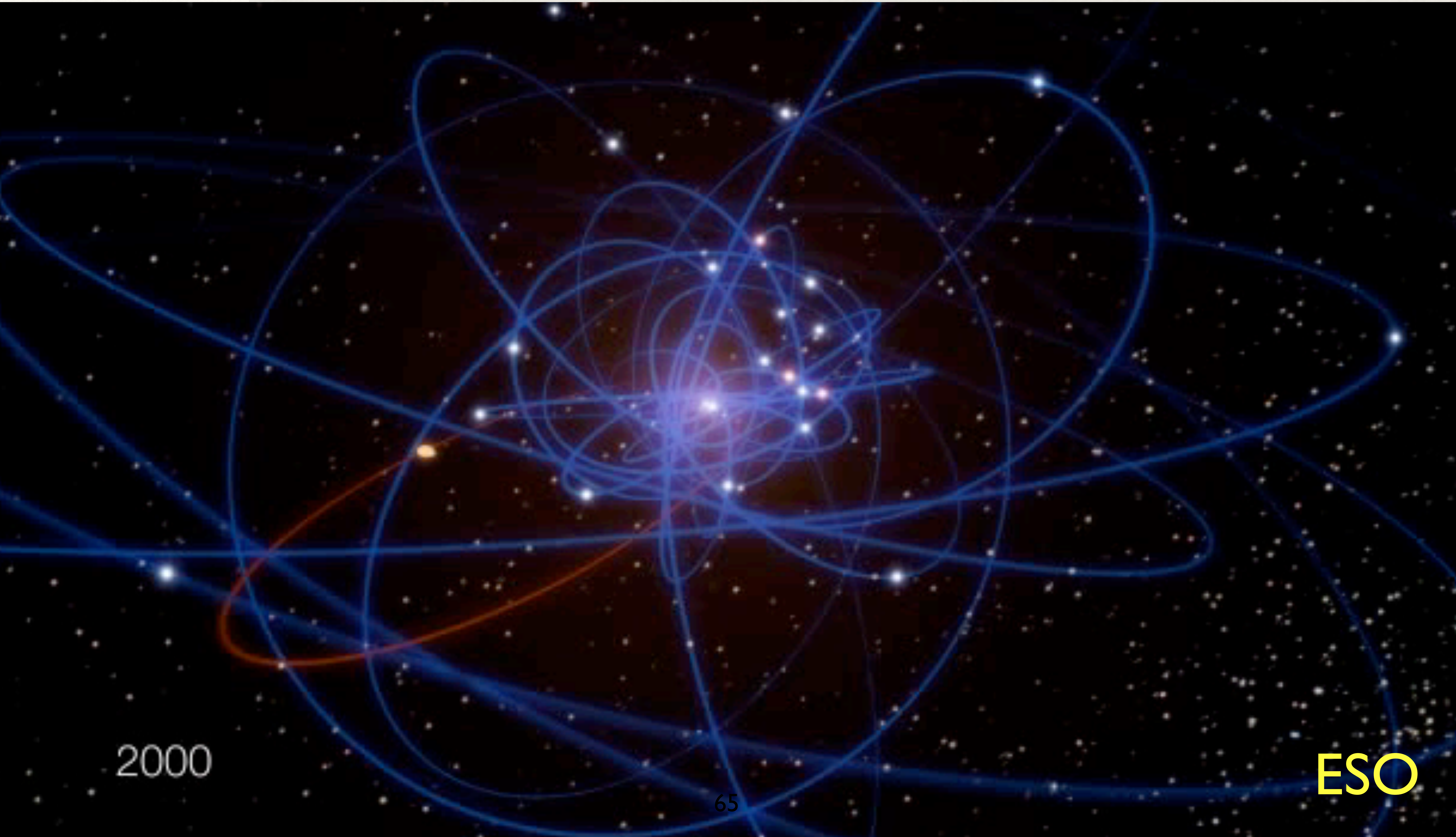

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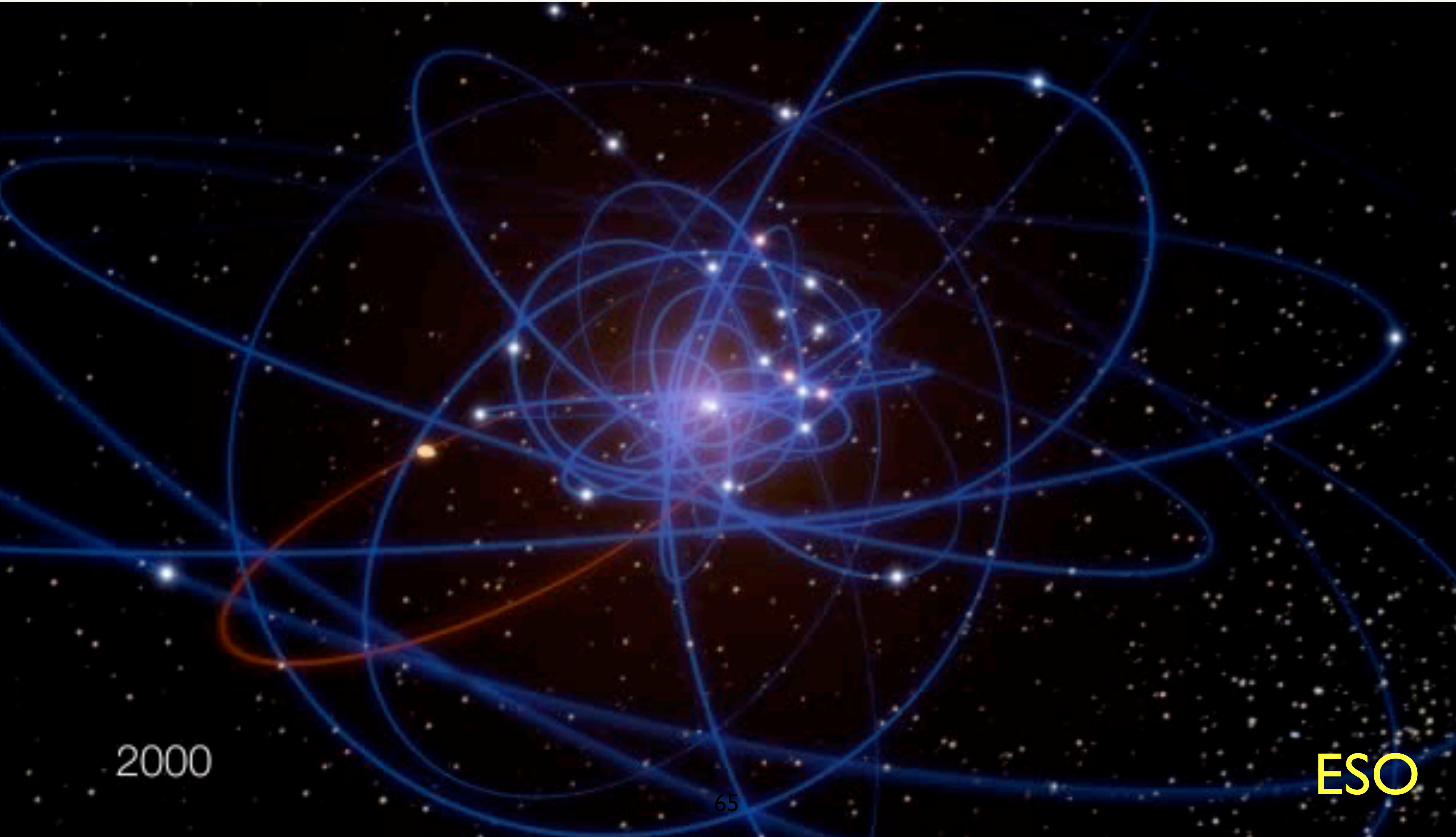

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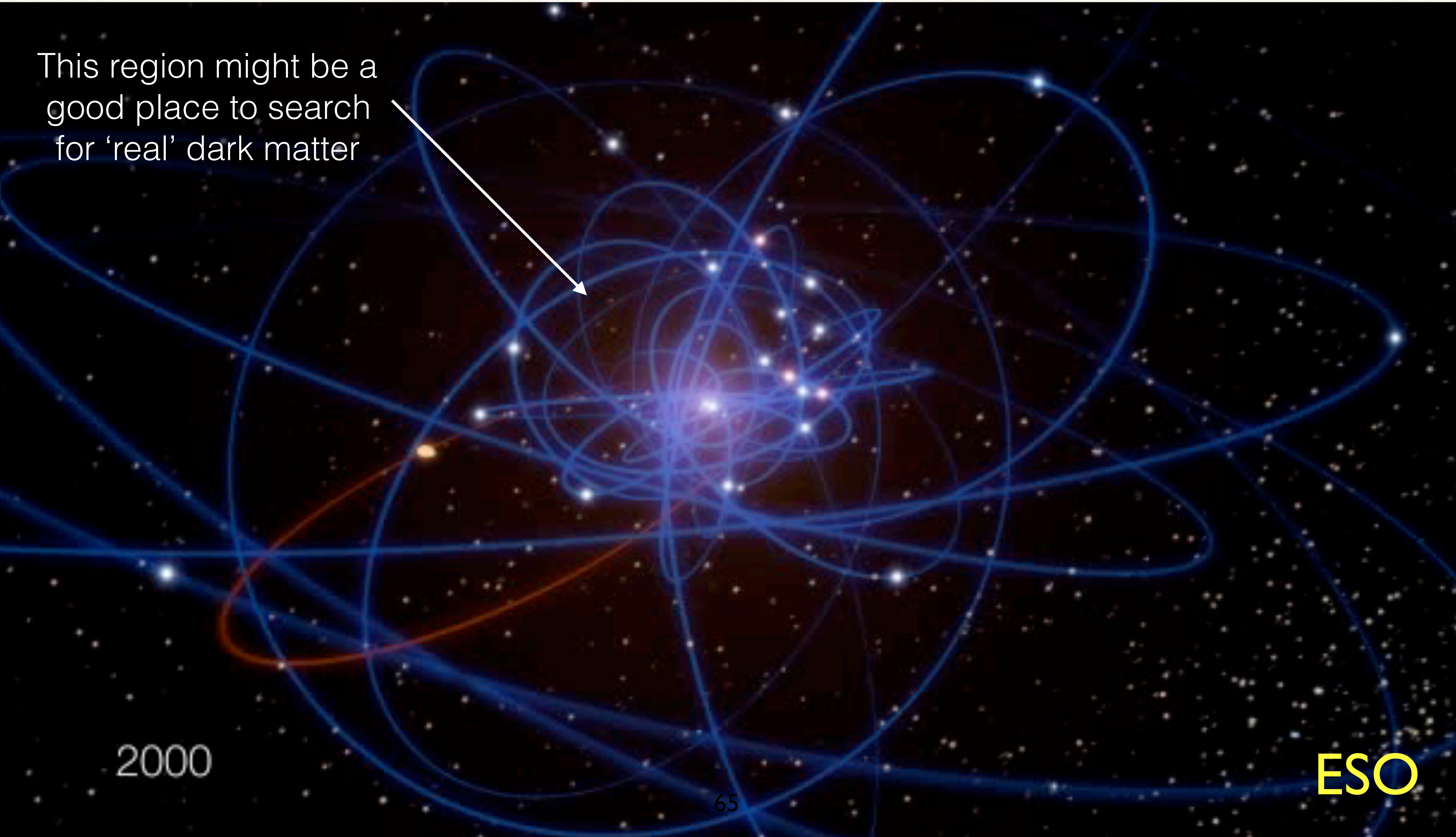
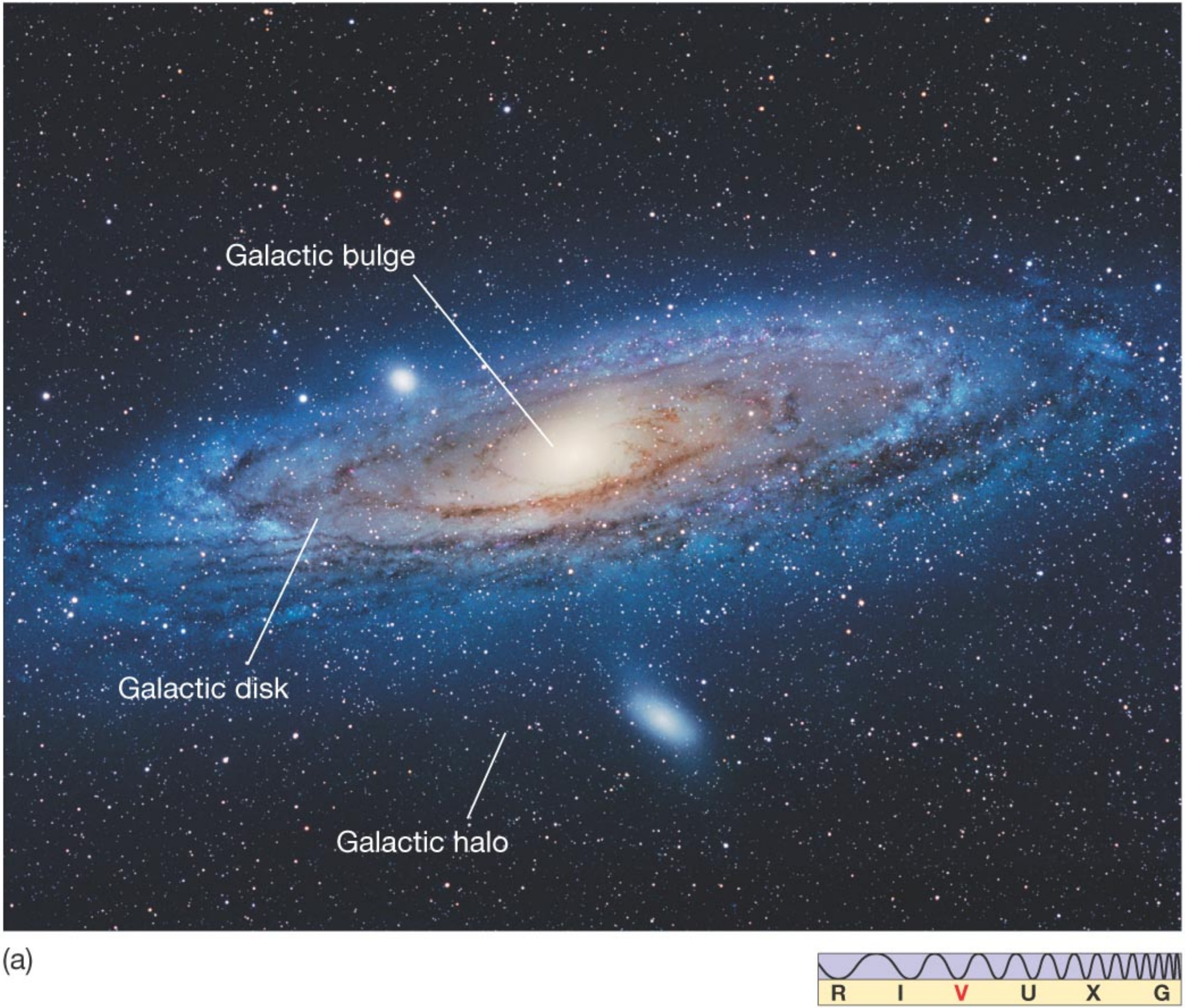


In summary…

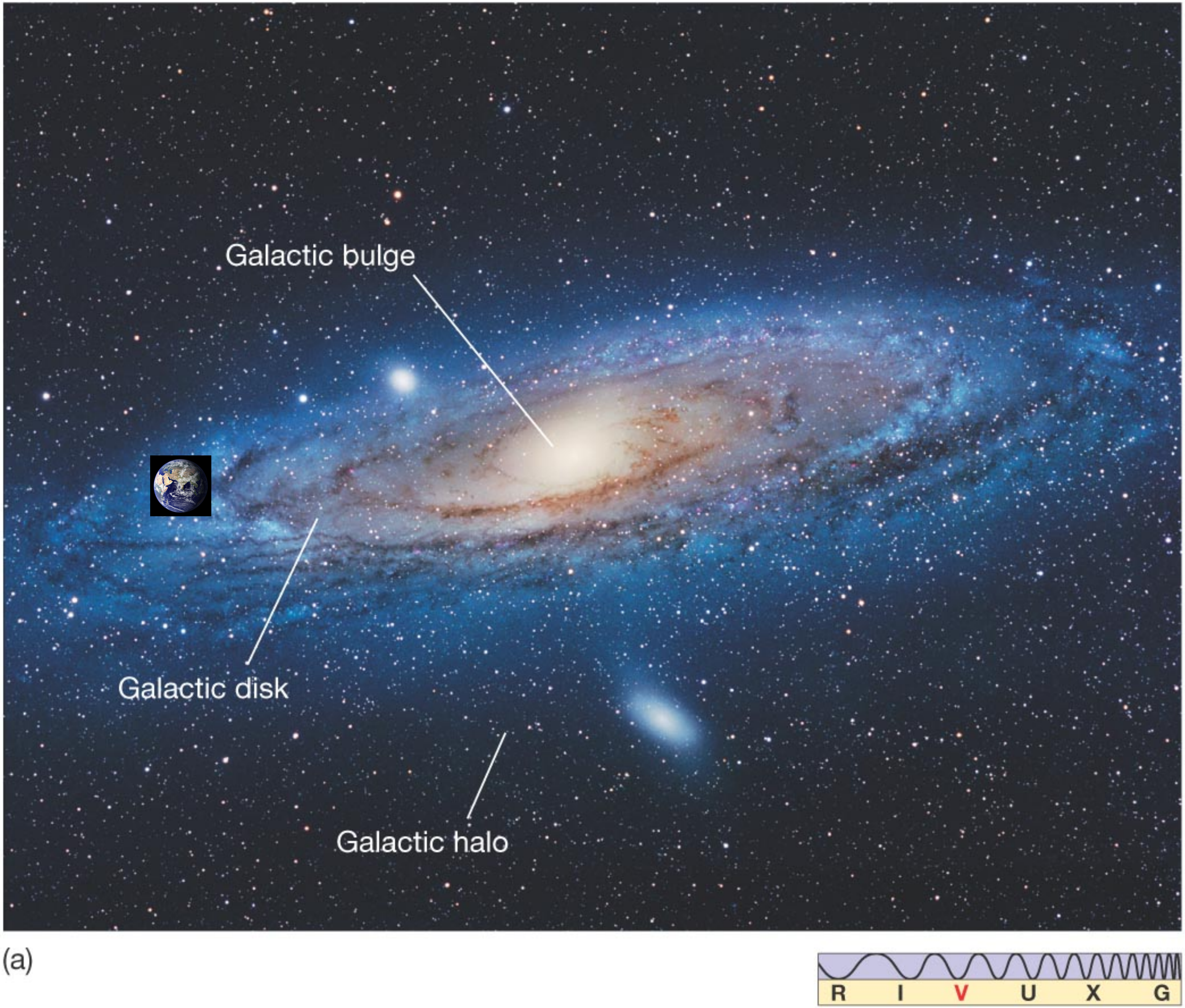
- The GC remains perhaps the best-motivated place in the sky to search for indirect dark matter signals
- But in astrophysical terms, the GC is also a peculiar and remarkable environment within the Galaxy
- To best constrain dark matter, we need to understand the astrophysical foregrounds very well

Part III: The Galactic Centre:

Non-thermal and High Energy Astrophysics



(a)



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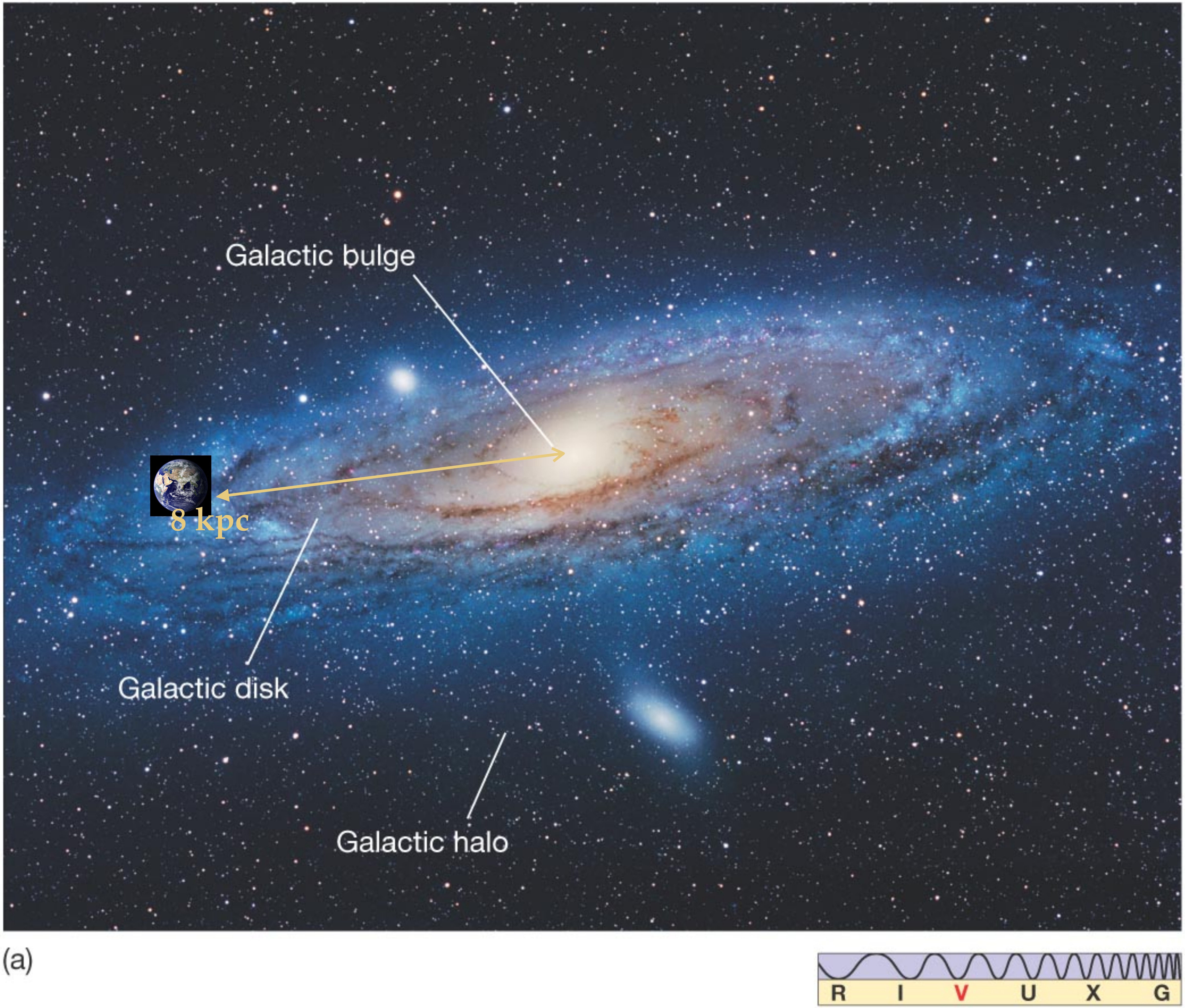

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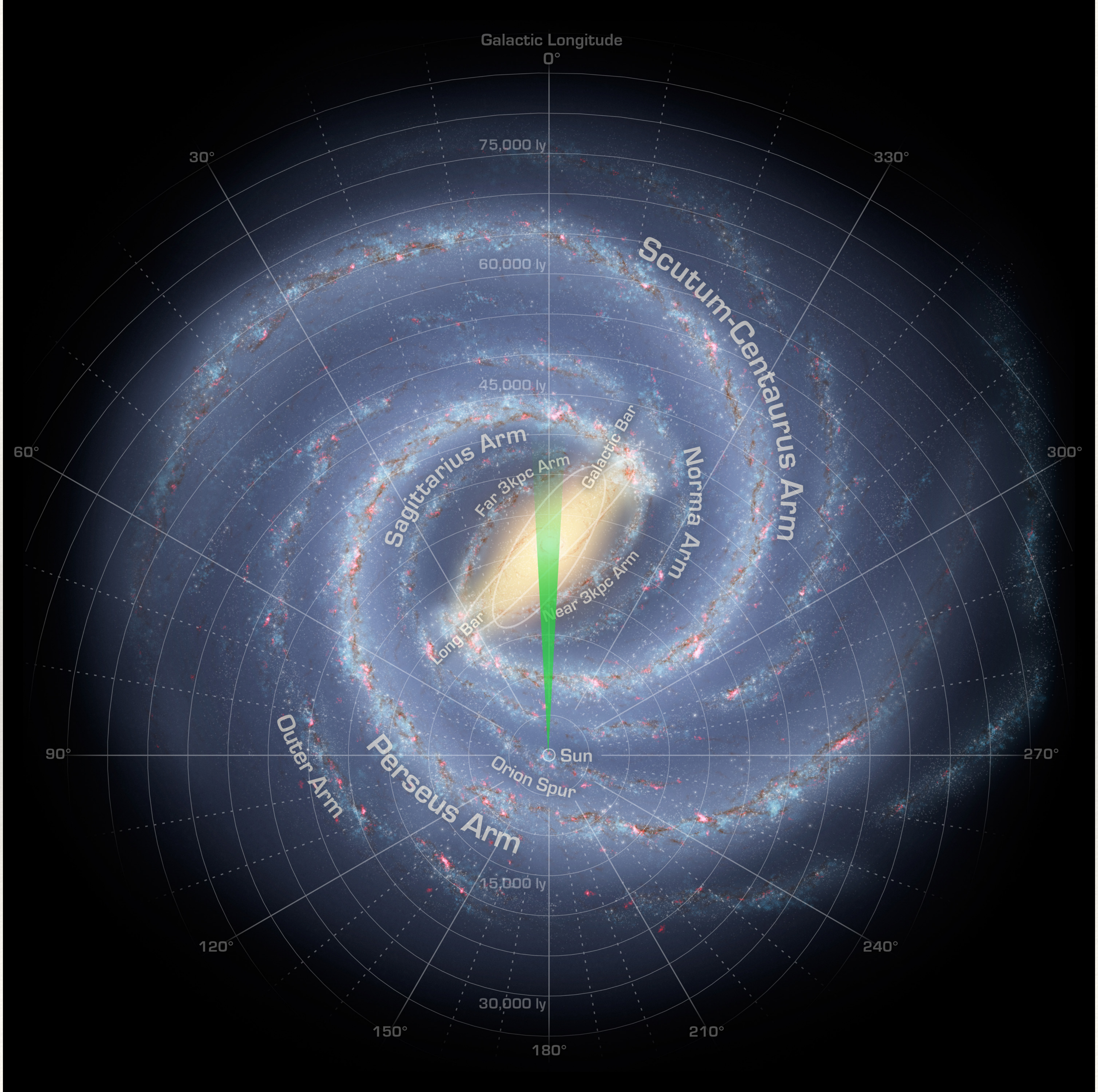


Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

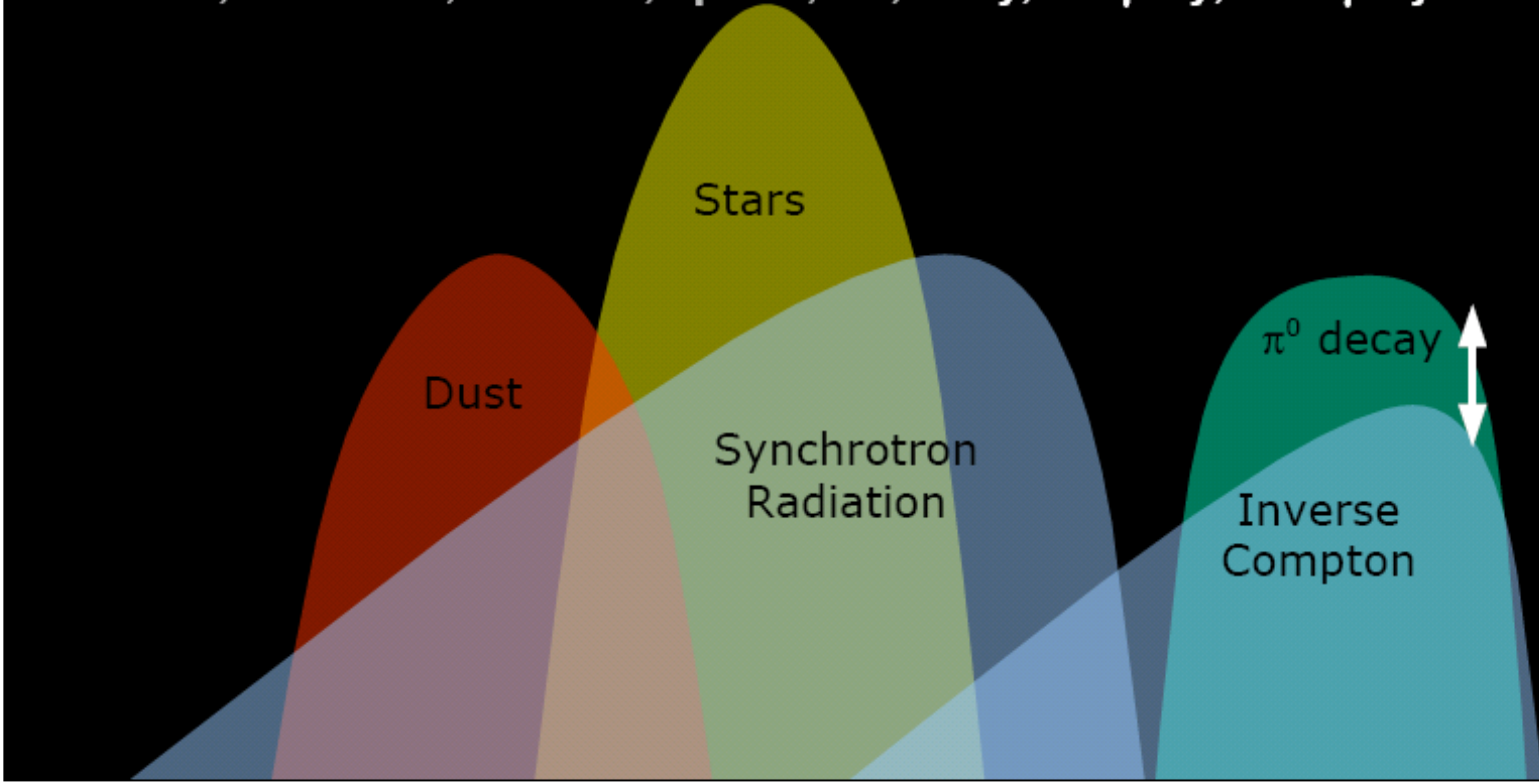

ESO

Our view of the GC

- Spectral windows: we can observe the GC at radio, sub-millimeter, infrared, X-ray and γ-ray wavelengths
- A lot of our information about the GC is from non-thermal emission
- With adaptive NIR optics can image individual massive stars in the Galactic centre

Generic Galactic 'SED' (Spectral Energy Distribution)

- **Radio, millimetre, infra-red, optical, UV, X-ray, HE γ-ray, VHE γ-ray**



http://www-zeuthen.desy.de/astro-workshop/vortraege/donnerstag/puehlhofer_zeuthen.pdf

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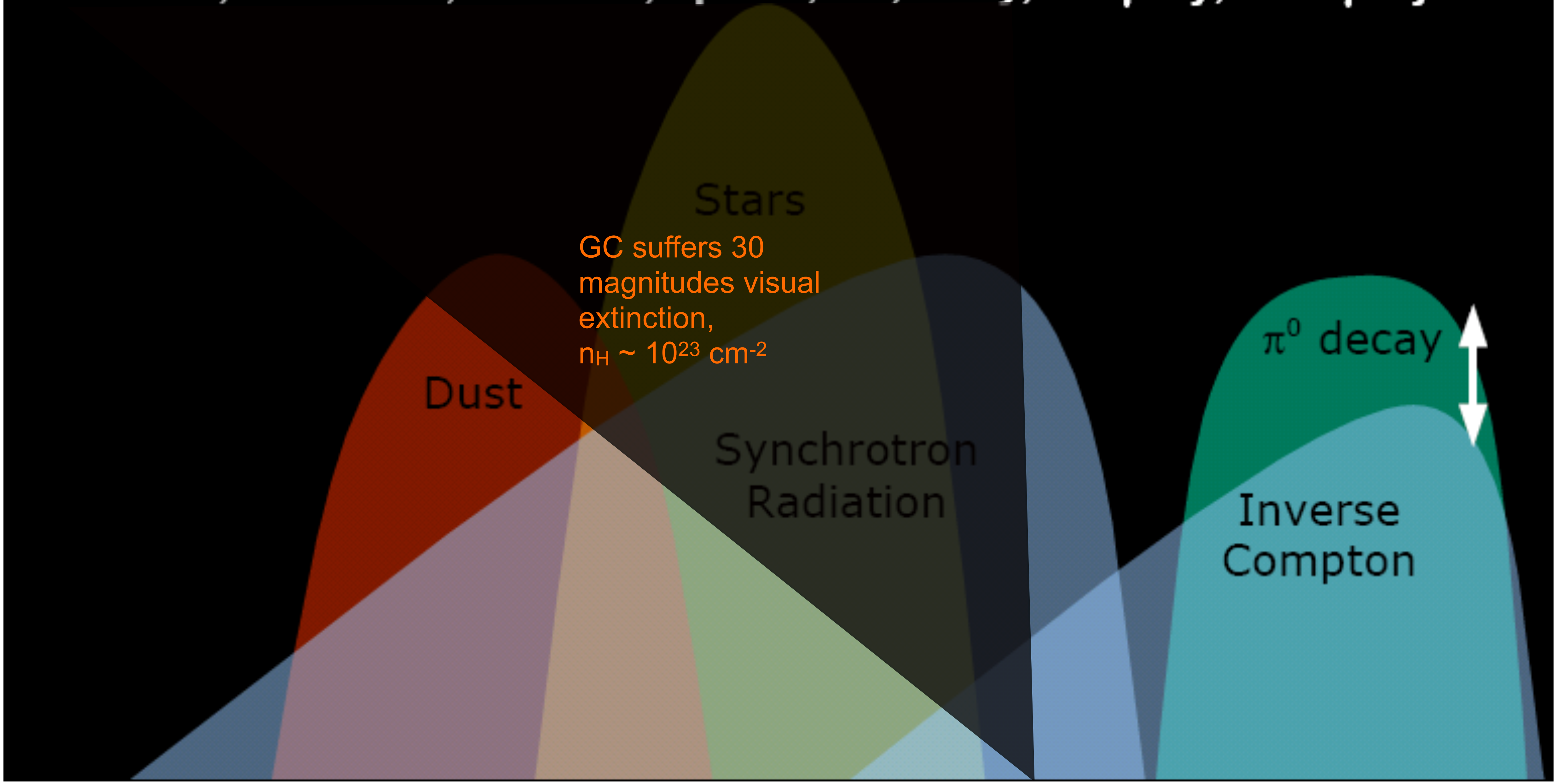

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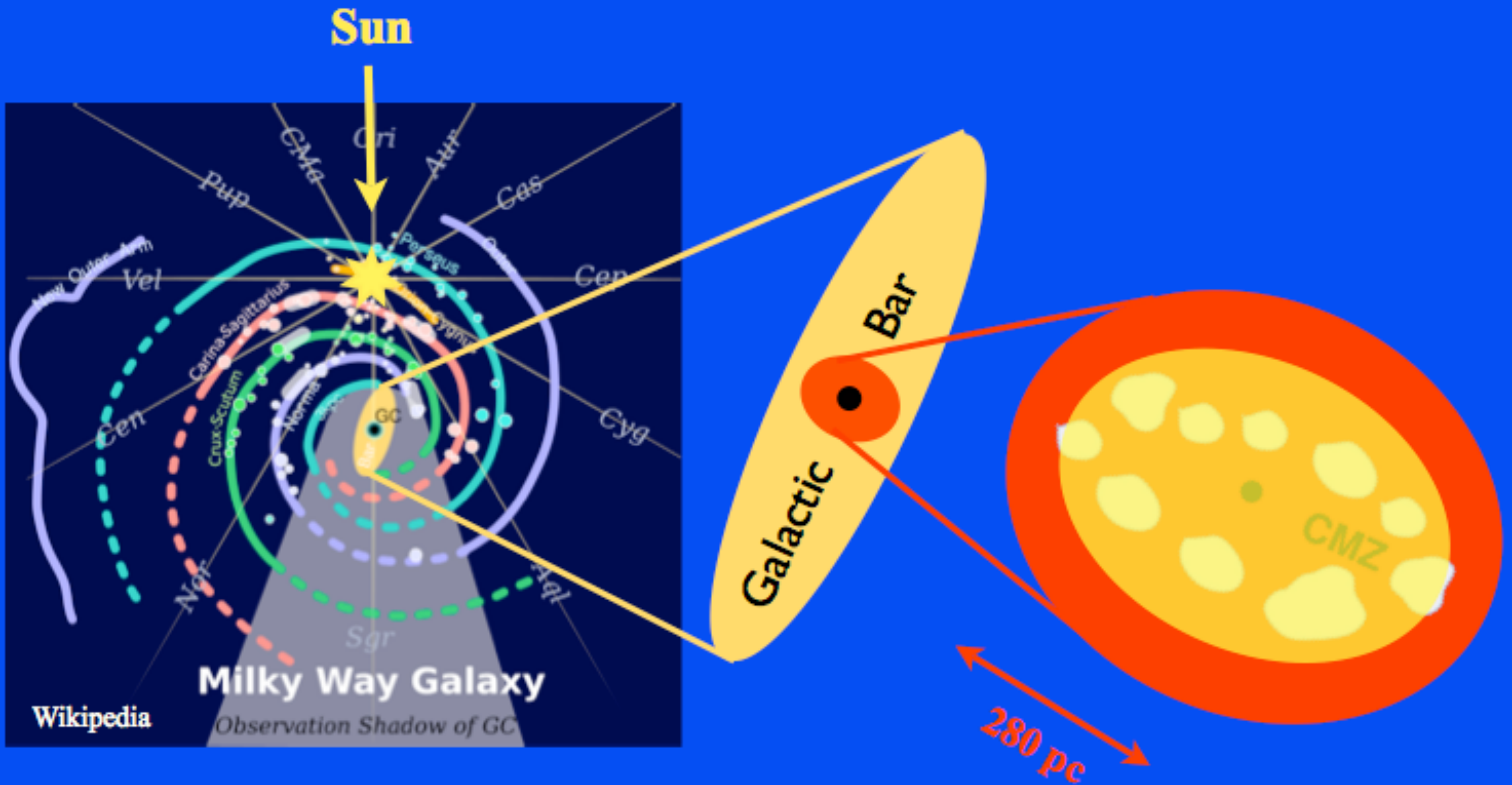
From spiral arms to the center of the Milky Way

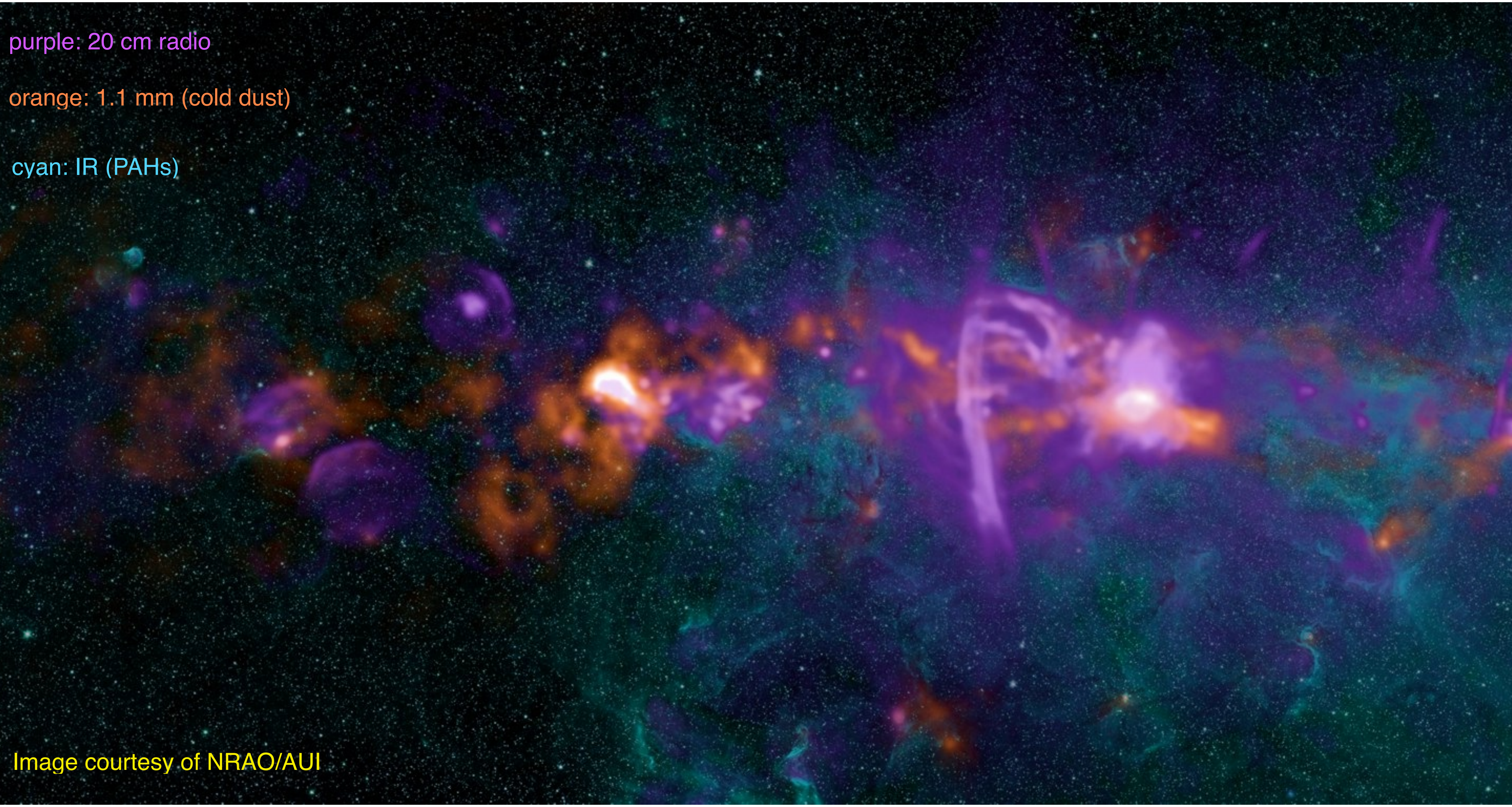


Andrea Stolte

The GC is privileged…

- Any process that causes disk matter to lose angular momentum sends it inwards; *the GC is always accreting gas* (at some level)
- In particular, the non-axisymmetric bar potential torques gas inwards
- 5-10% of the Galaxy's H_2 is located in the GC

A complicated region…



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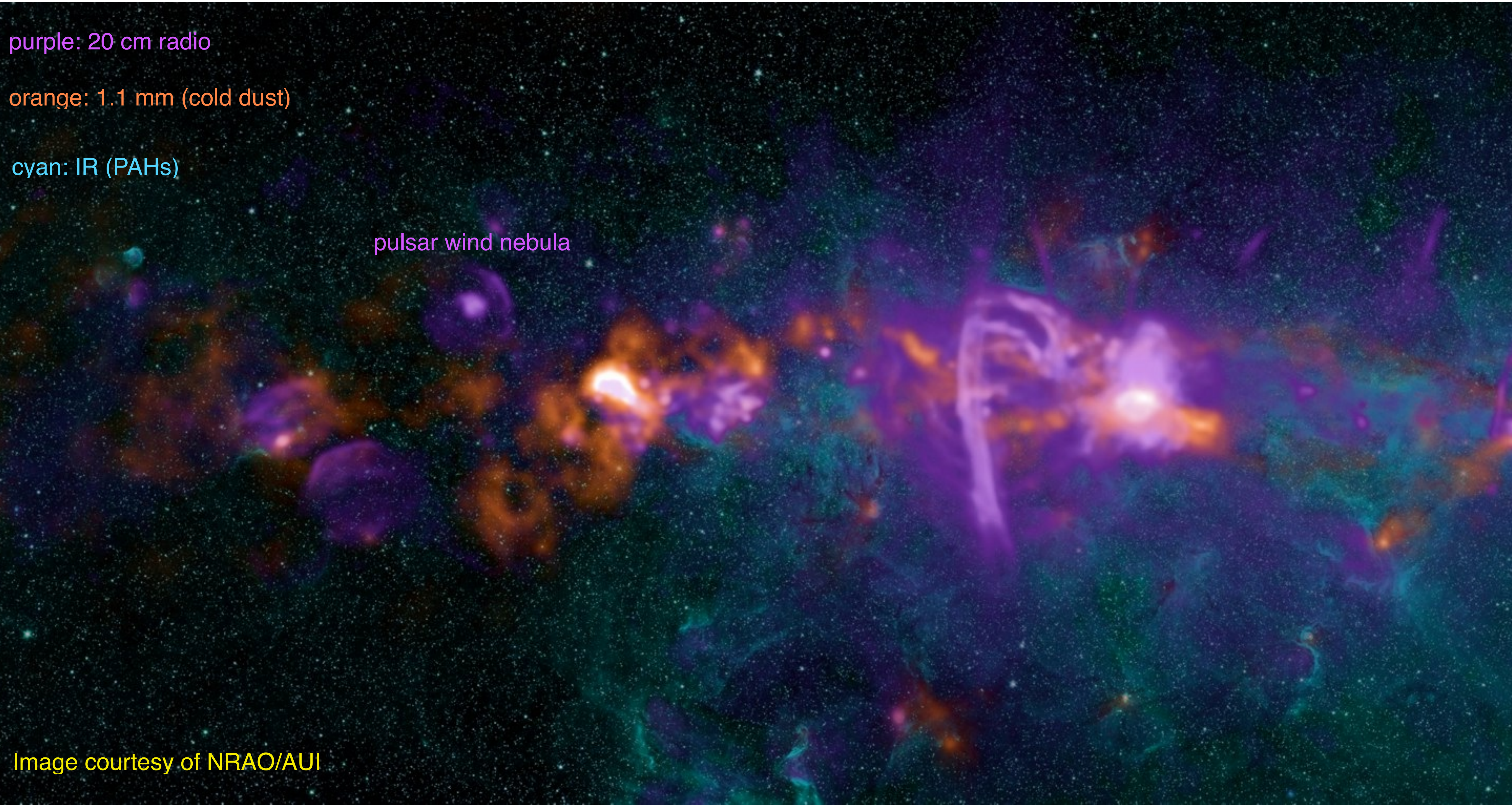

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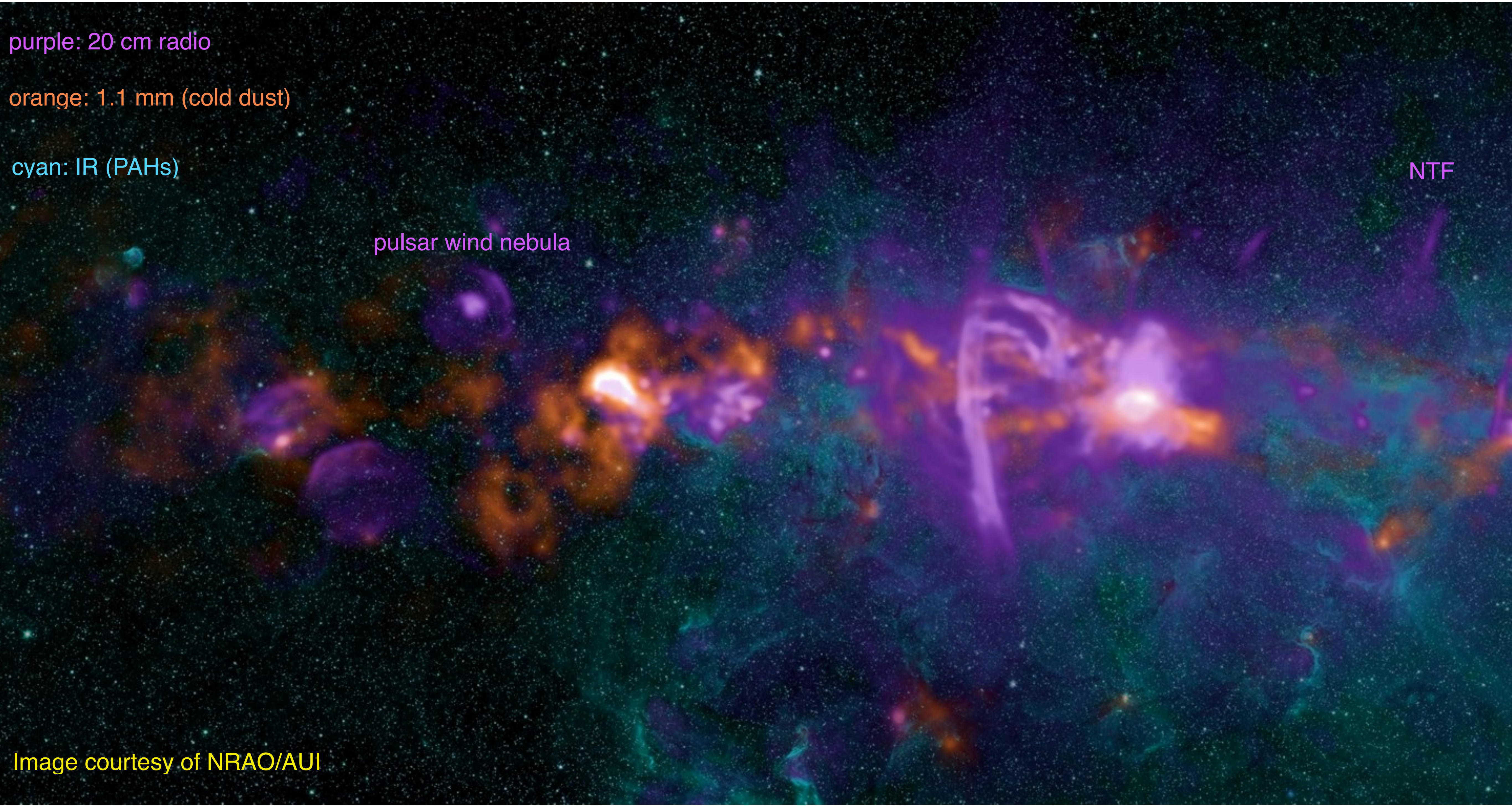

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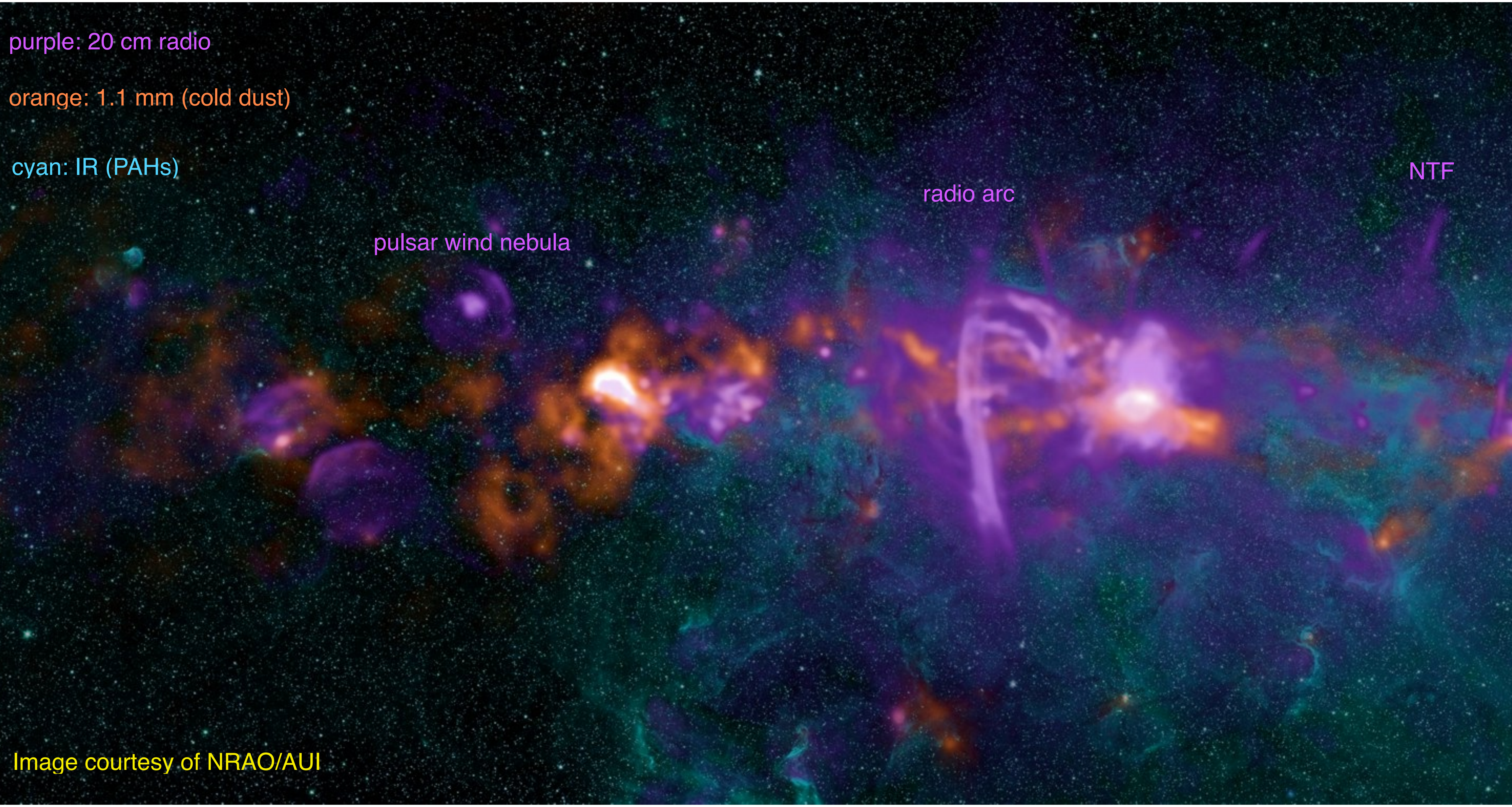

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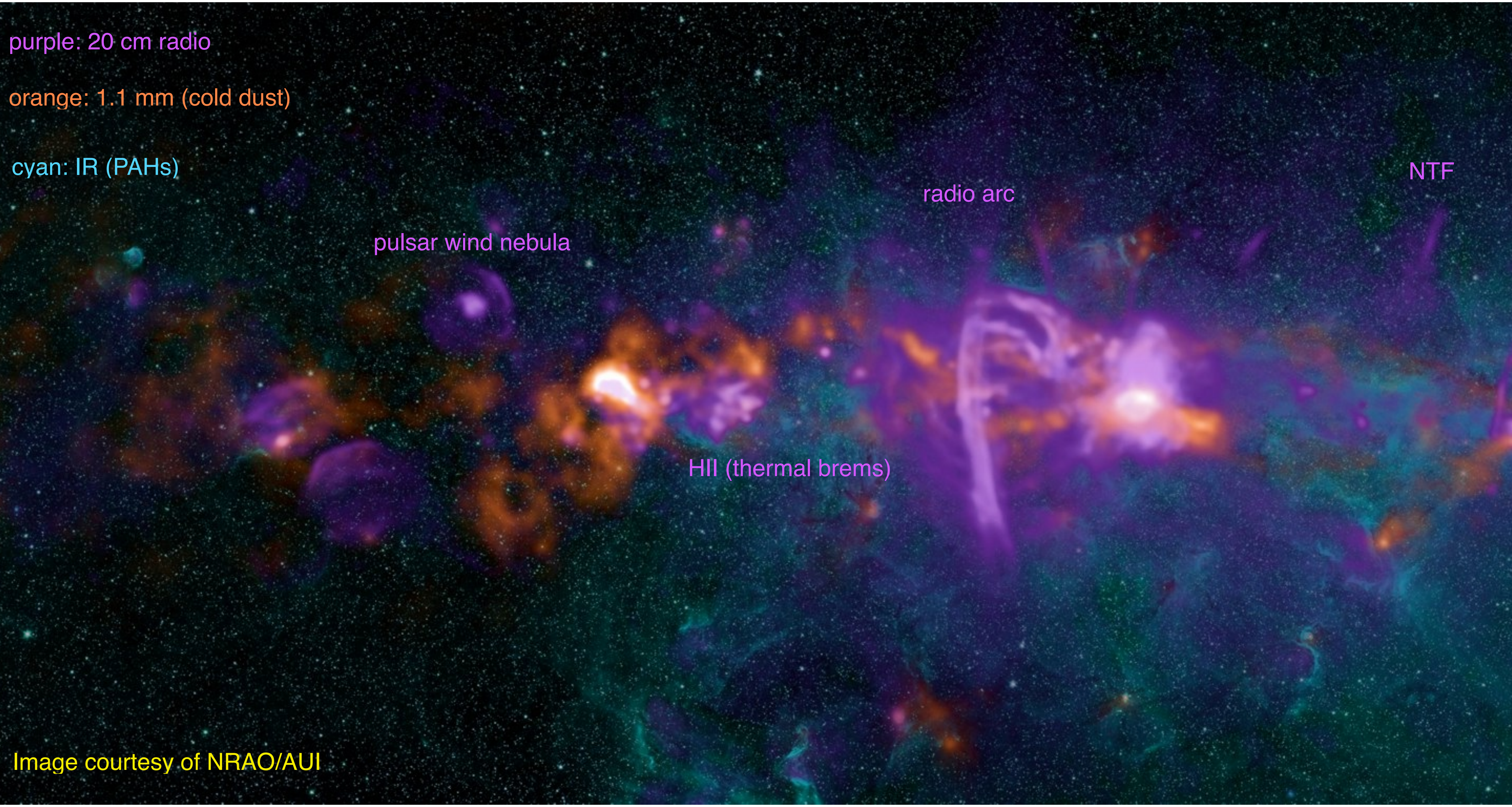

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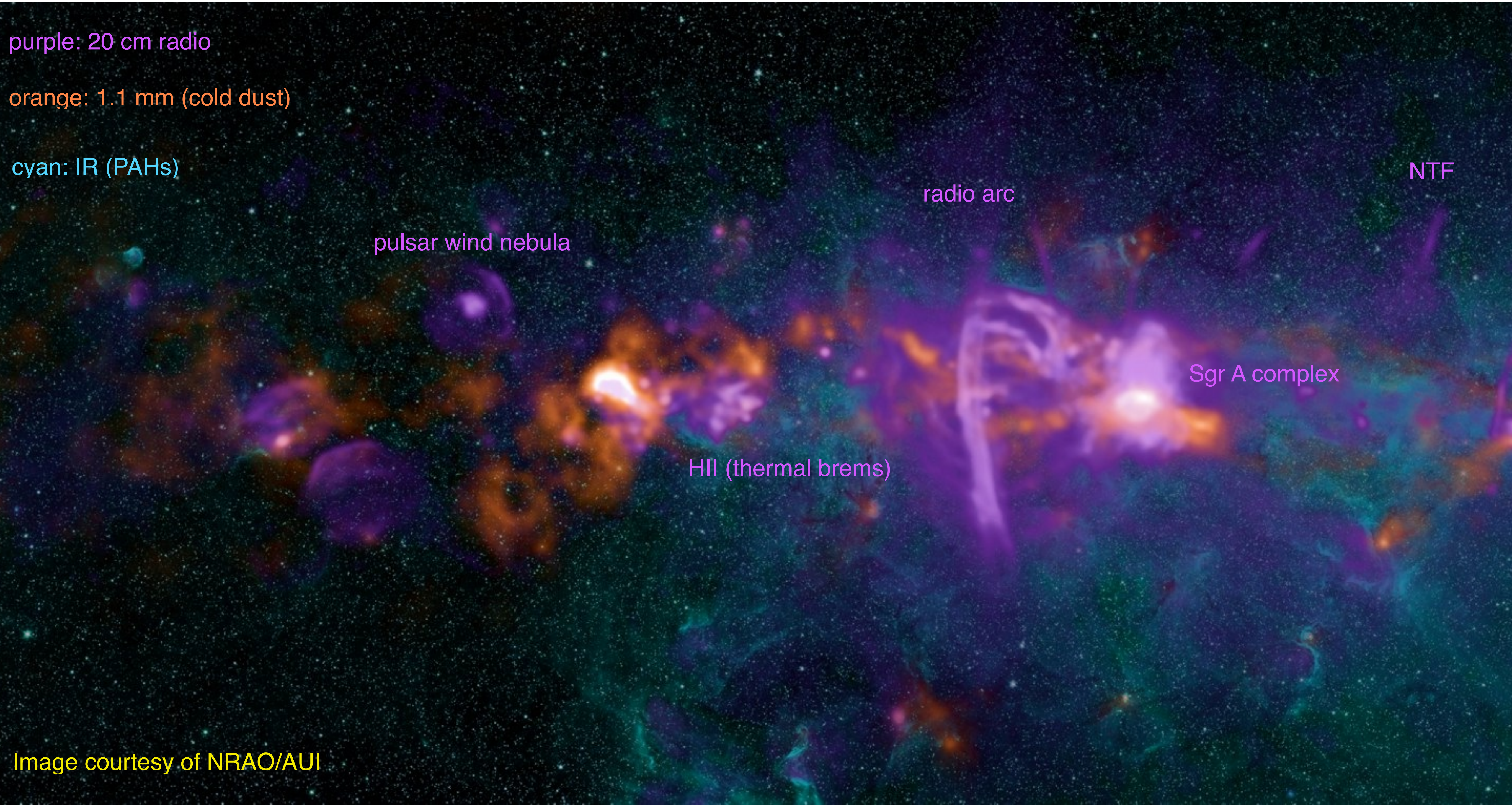

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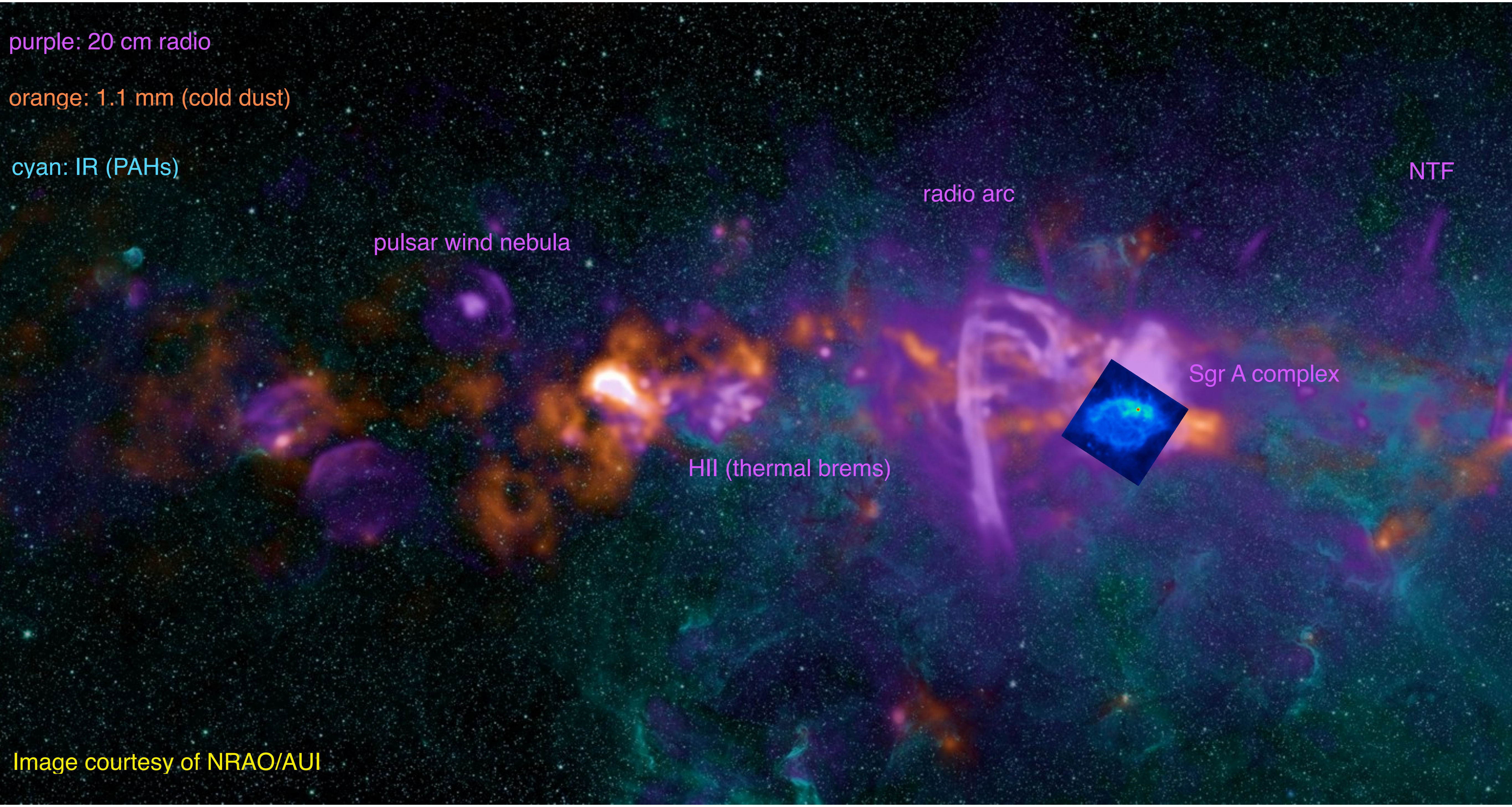

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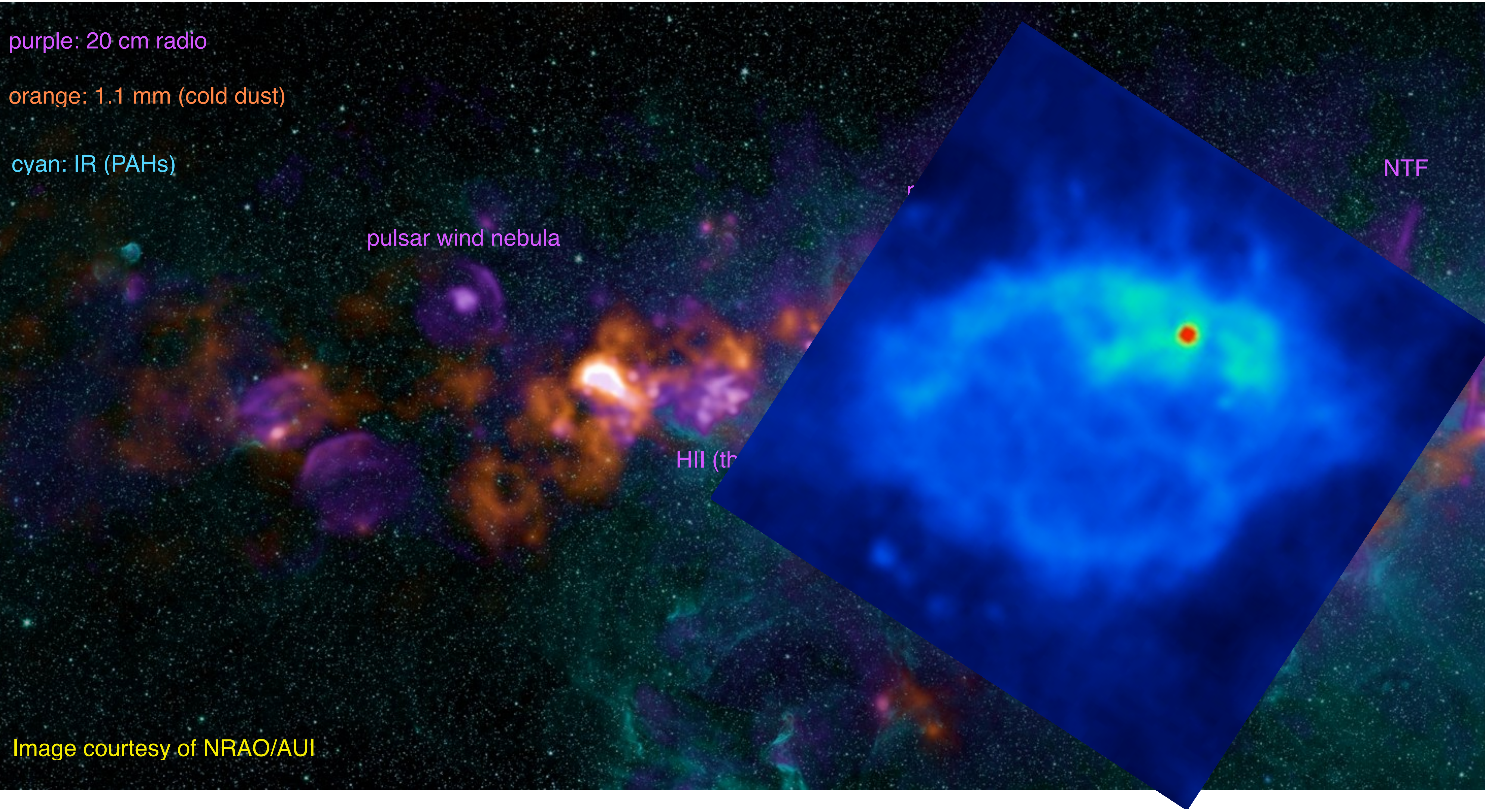

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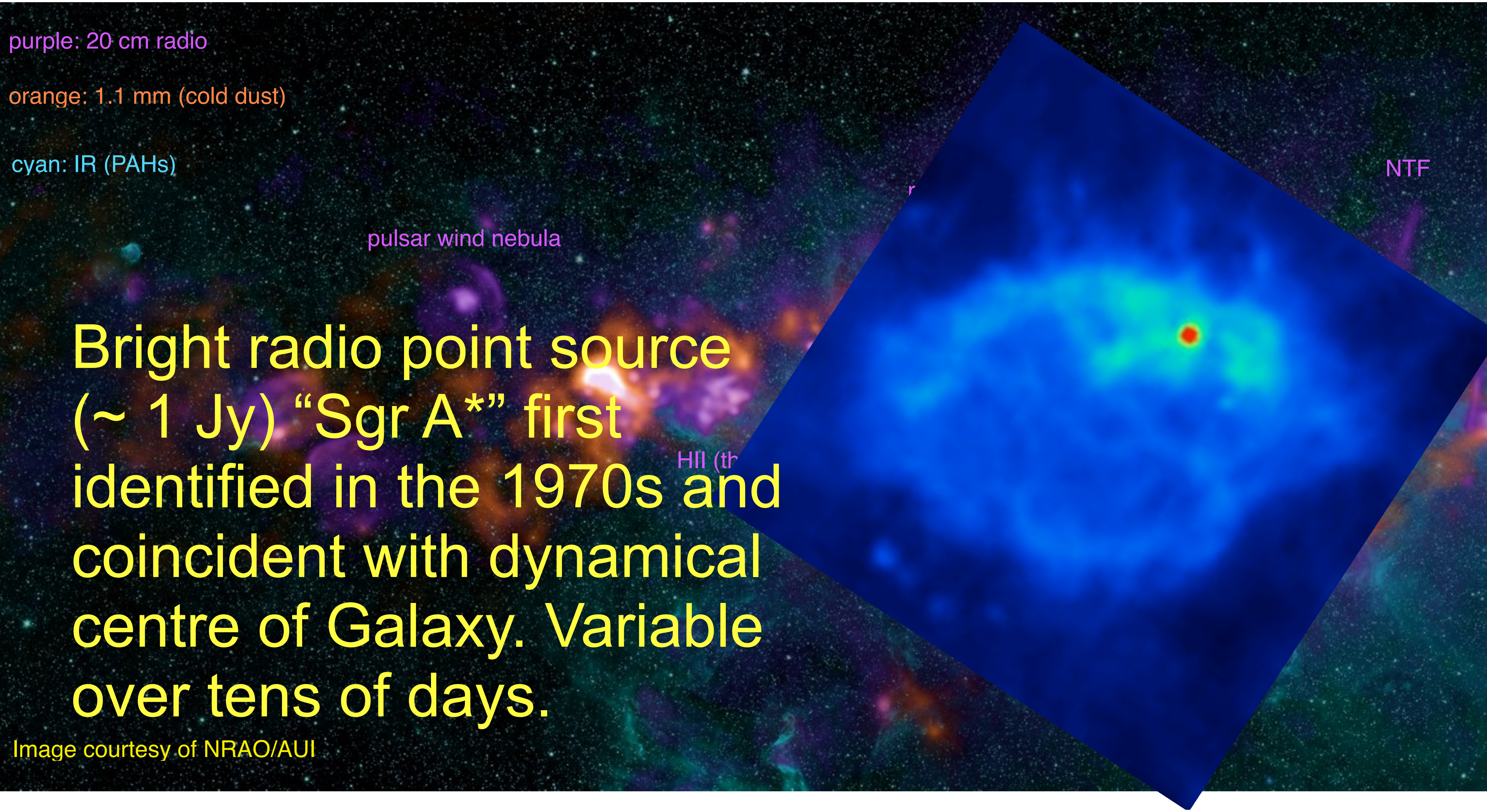

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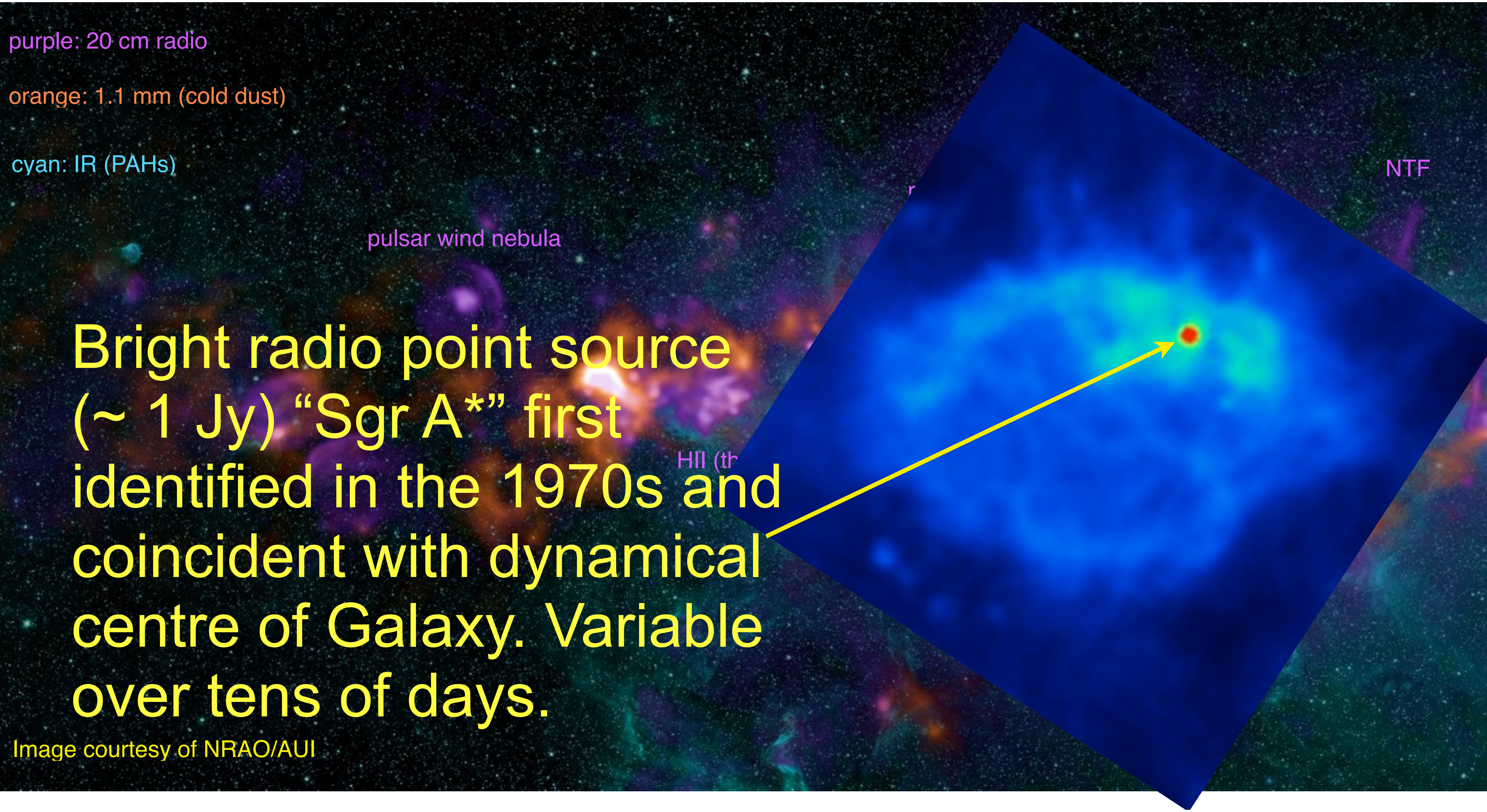
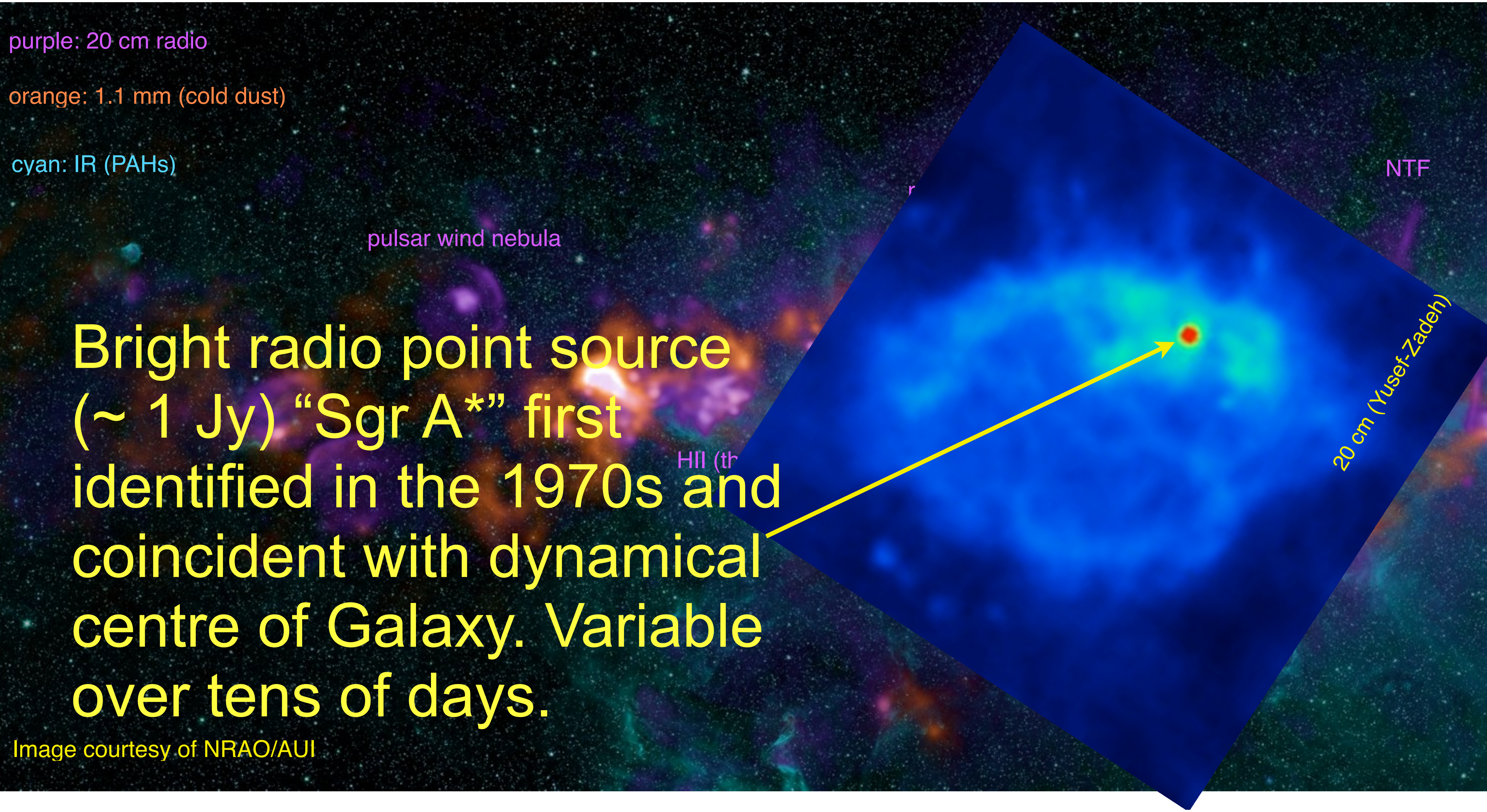


Bright radio point source (~ 1 Jy) “Sgr A*” first identified in the 1970s and coincident with dynamical centre of Galaxy. Variable over tens of days.

A complicated region…



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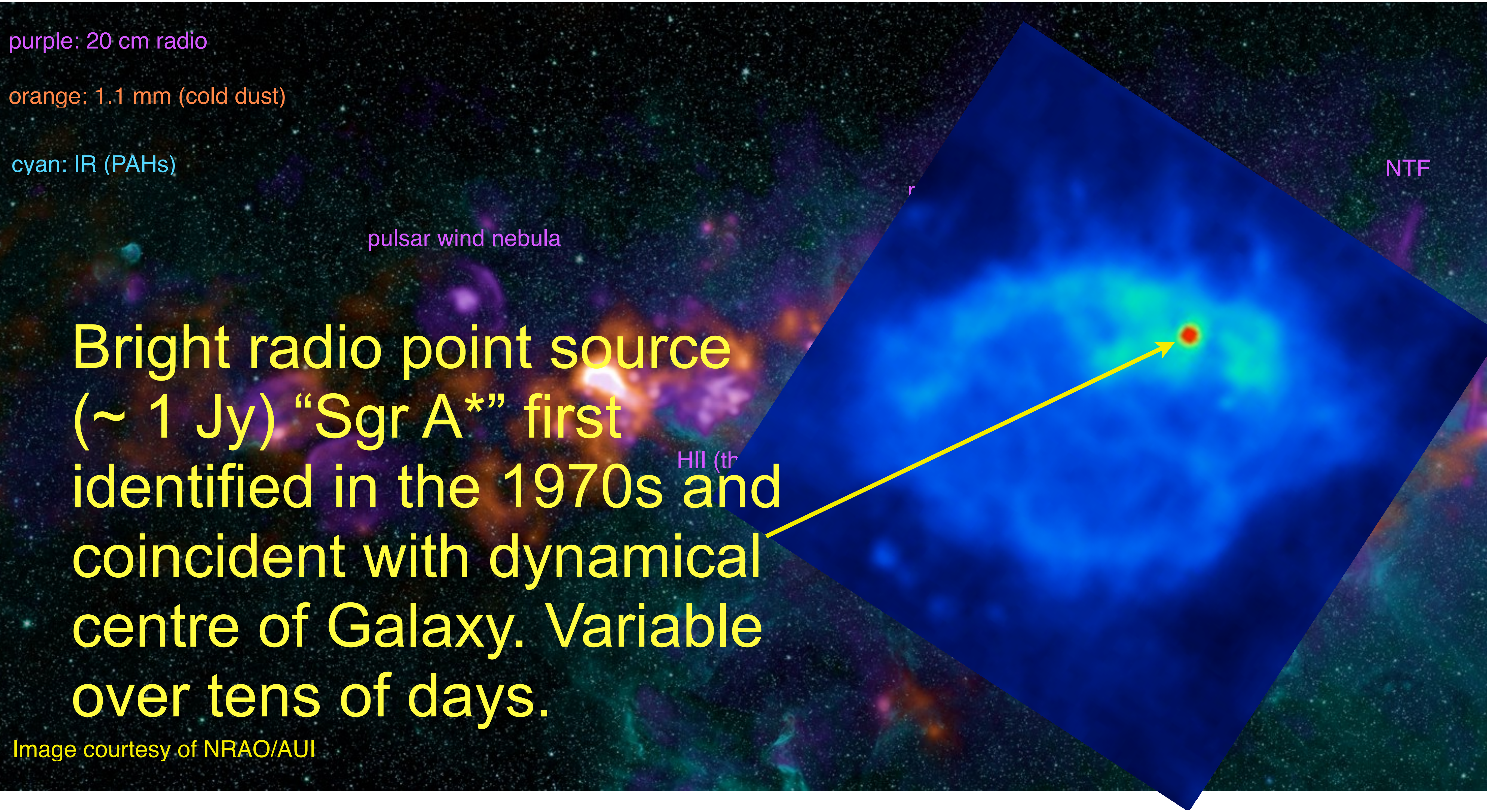

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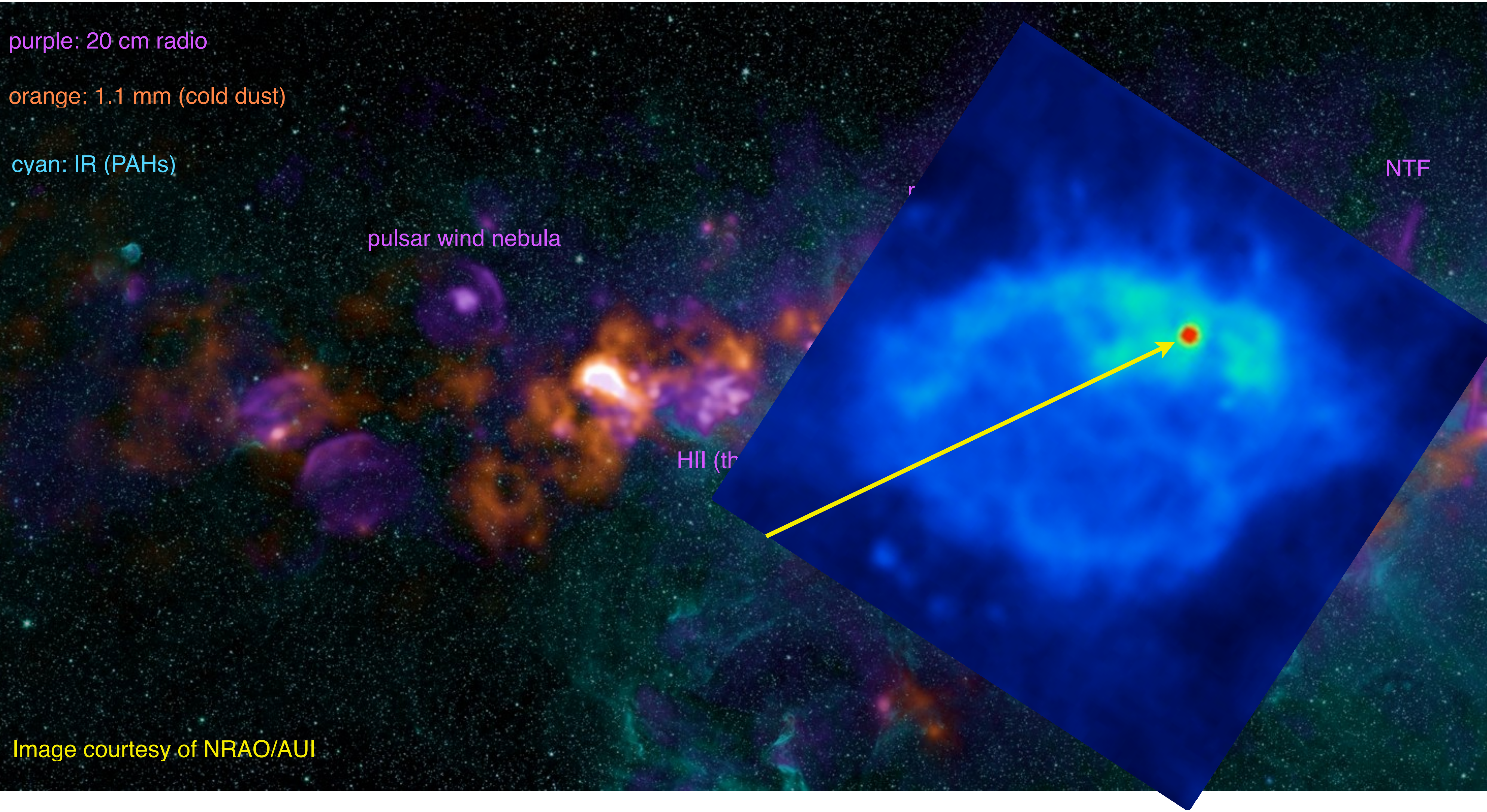

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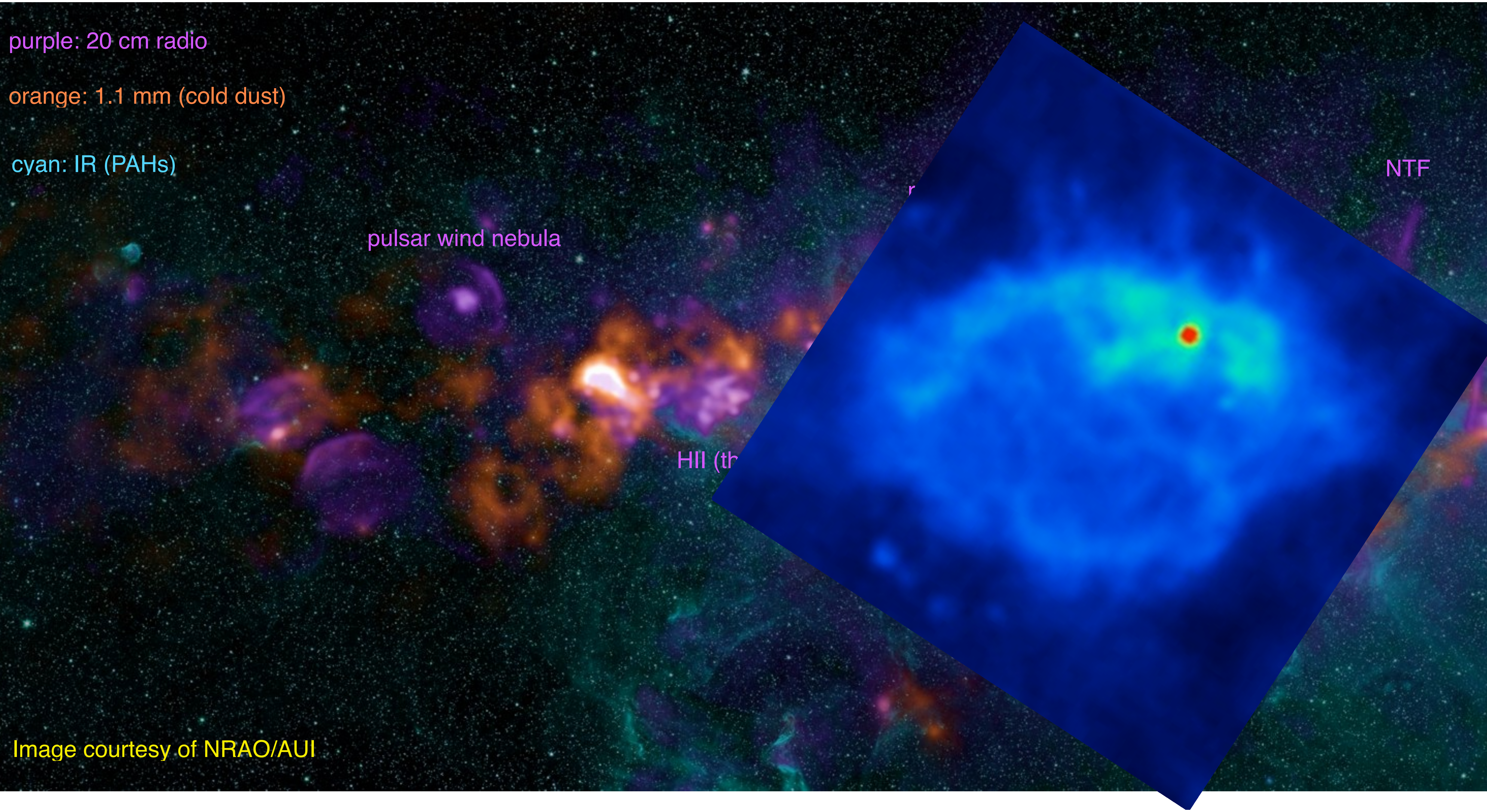

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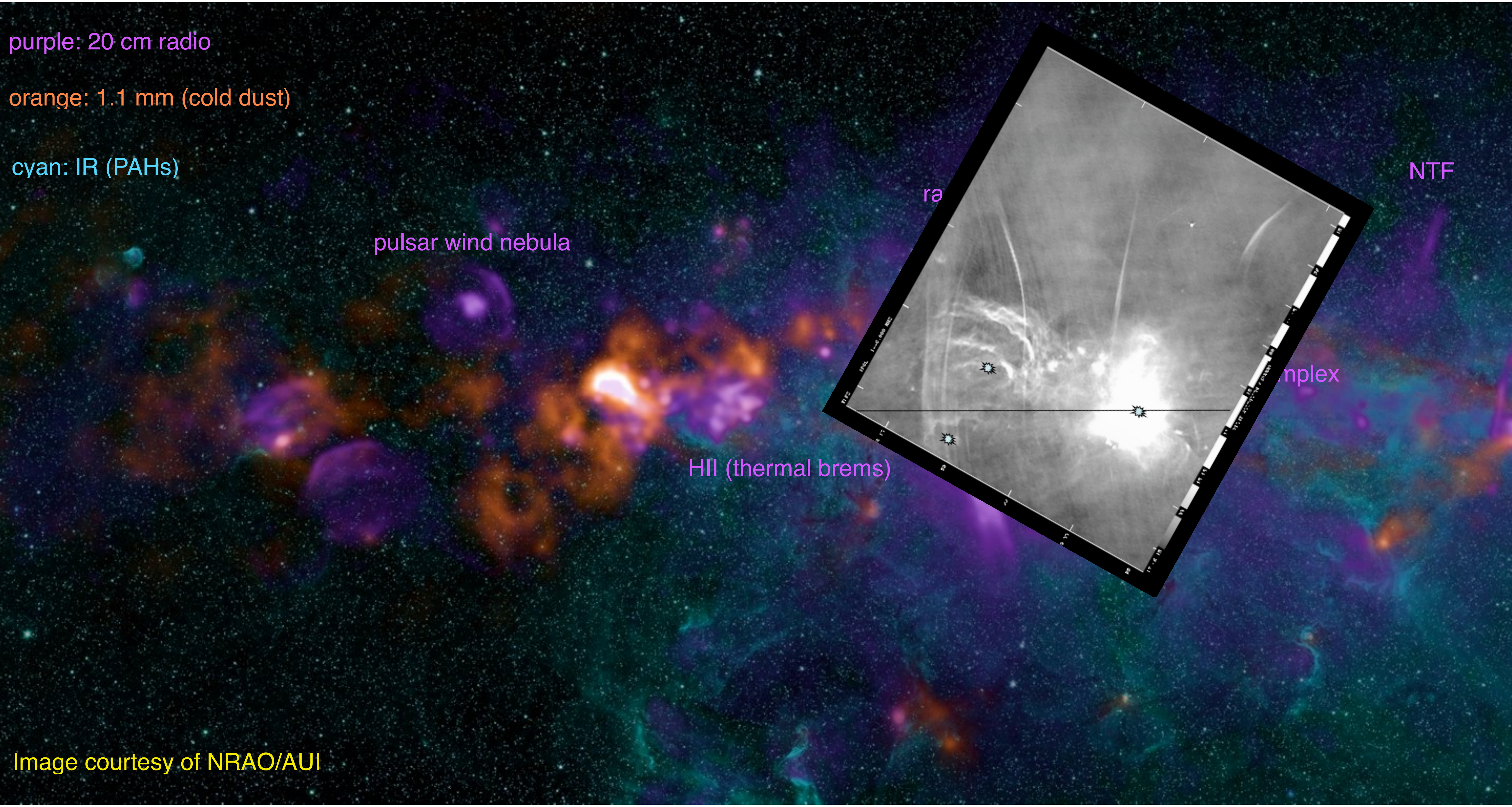

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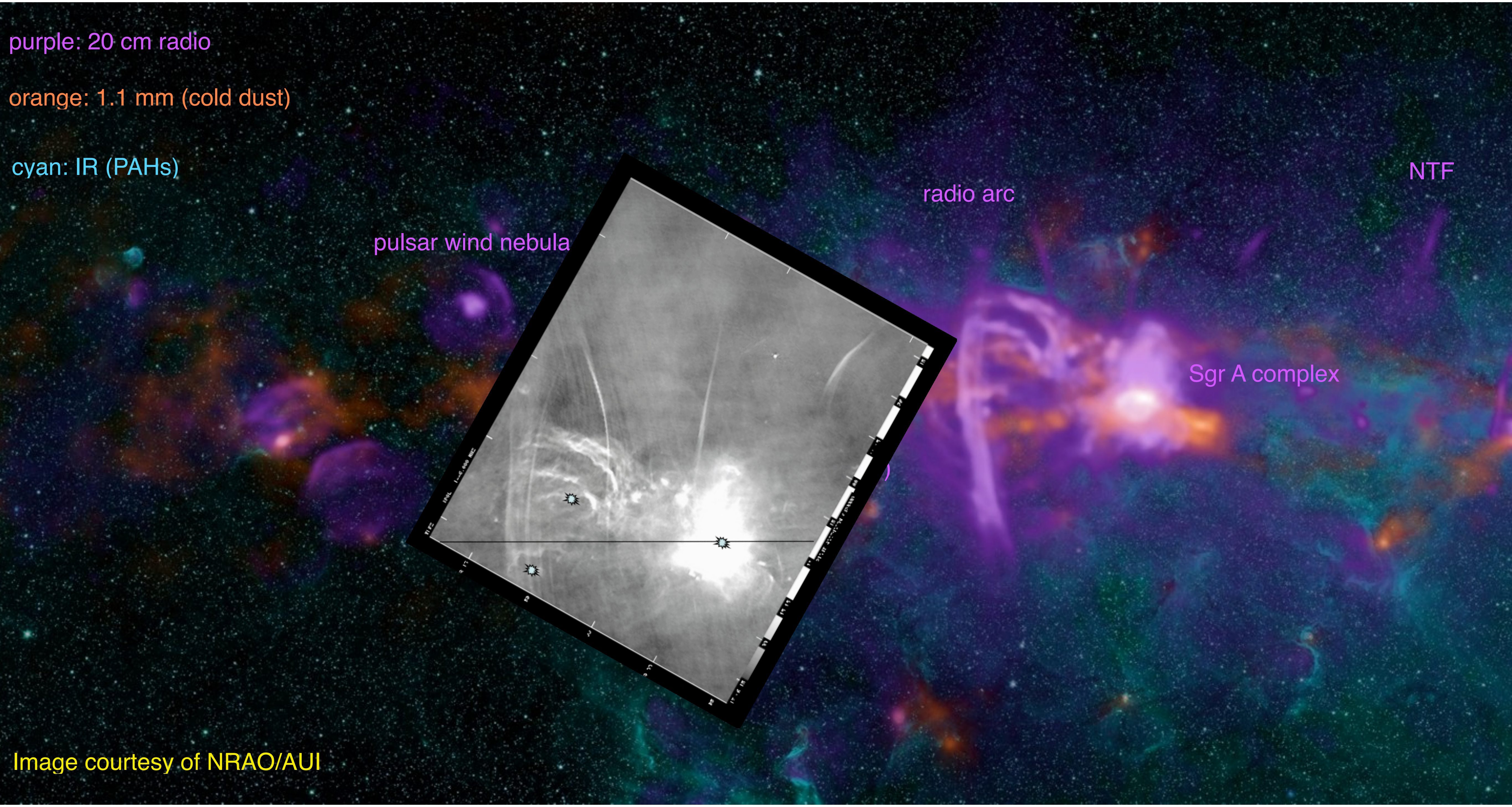

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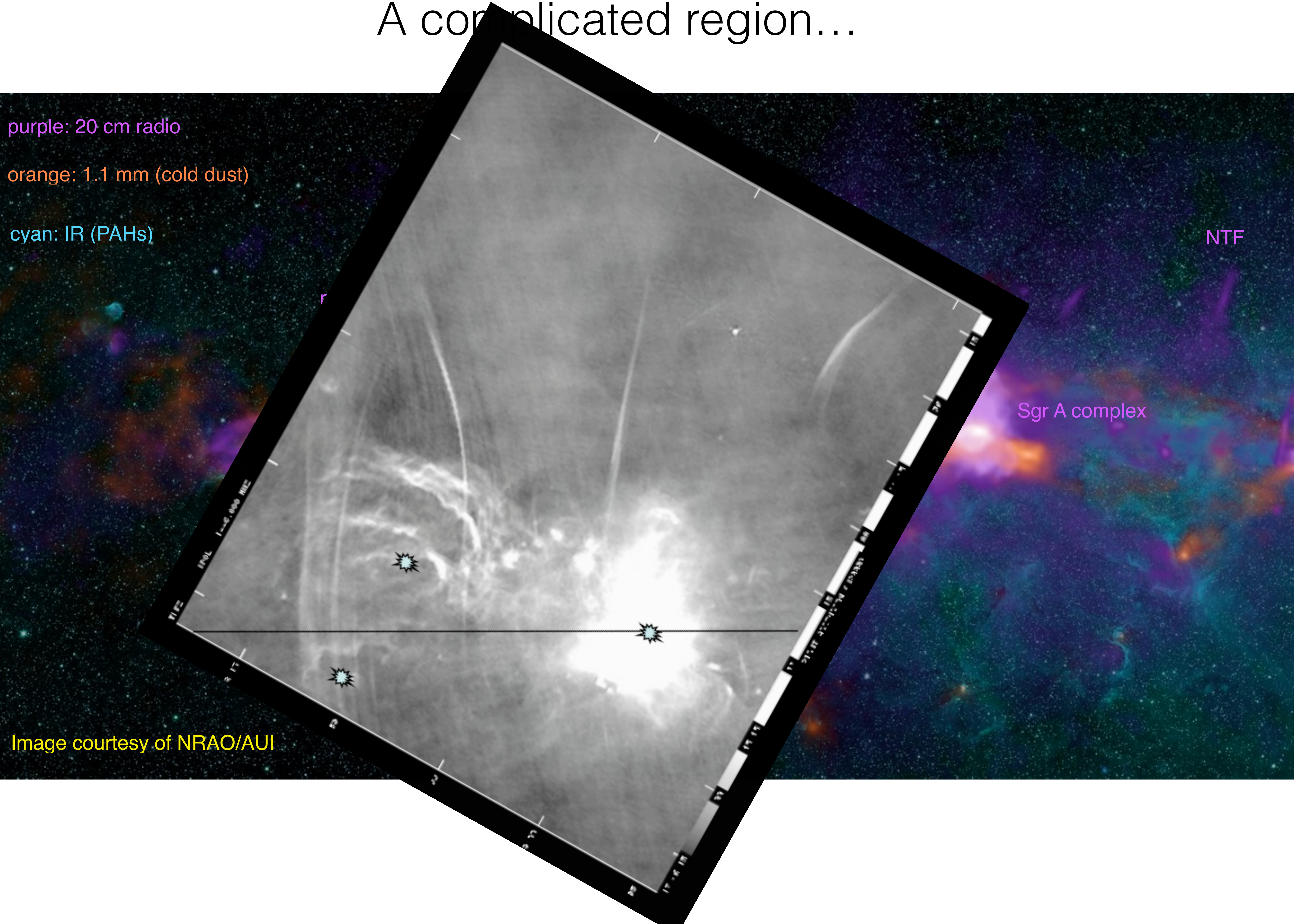


Central Molecular Zone

- Much of the GC's H_2 is located in a ~30 million solar mass torus of gas
- The torus hosts on-going, intensive, localized star-formation
- This seems to be a small version of the nuclear star forming rings seen in other barred spiral galaxies
- GC hosts ~5-10% of Galaxy's *massive* star formation → important to Galactic star formation ecology

An Extreme ISM in GC...

- SFR surface density over CMZ ≳ **3 orders of magnitude** larger than mean in disk ($\partial_t \Sigma_* \sim 2\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$) and ***sustained***
- The SF activity (stellar winds, supernovae) sustains an energy density in the different GC Interstellar Medium (ISM) phases about **2 orders of magnitude** larger than typically found in the local ISM

GC: $U_B \sim U_{turb} \sim U_{plasma} \sim U_{ISRF} \sim 100\ \mathrm{eV\ cm^{-3}}$

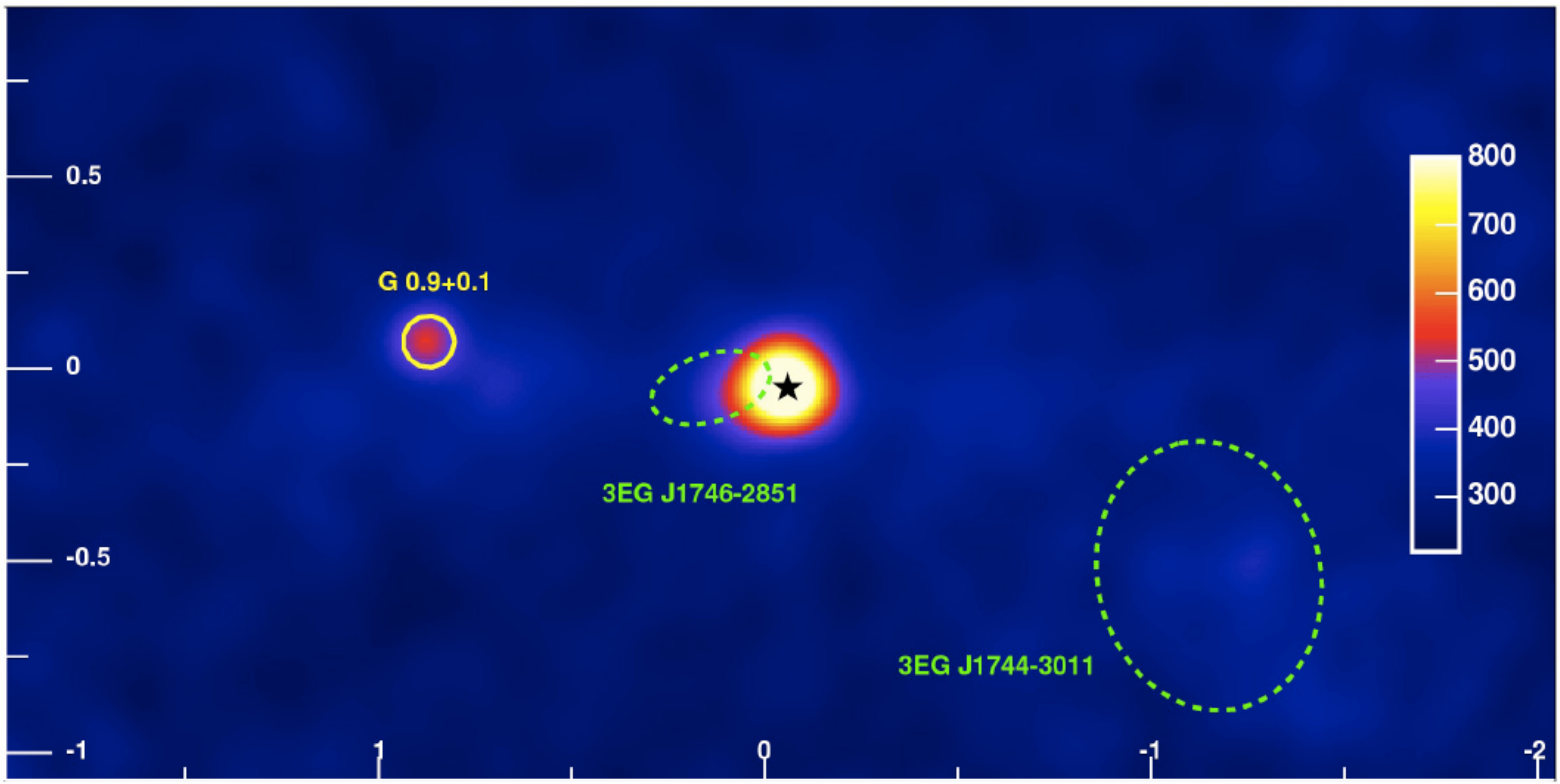
local: $U_B \sim U_{turb} \sim U_{plasma} \sim U_{ISRF} \sim 1\ \mathrm{eV\ cm^{-3}}$

Non-Thermal Galactic Centre

Gamma-ray source coincident with Sgr A*

- Detected by Fermi (~GeV) and HESS, MAGIC, VERITAS (~TeV)
- Steady, point-like source for HESS; may be slightly extended for Fermi
- Fermi and HESS spectra off-set from each other; neither is featureless:
  - Fermi spectrum exhibits a bump at few GeV
  - HESS spectrum cut-off above few 10s TeV

Diffuse γs in H.E.S.S. data?



- 50 hour H.E.S.S. Observation of GC in 2005
- Need to subtract the two bright sources

Credit: HESS Collab

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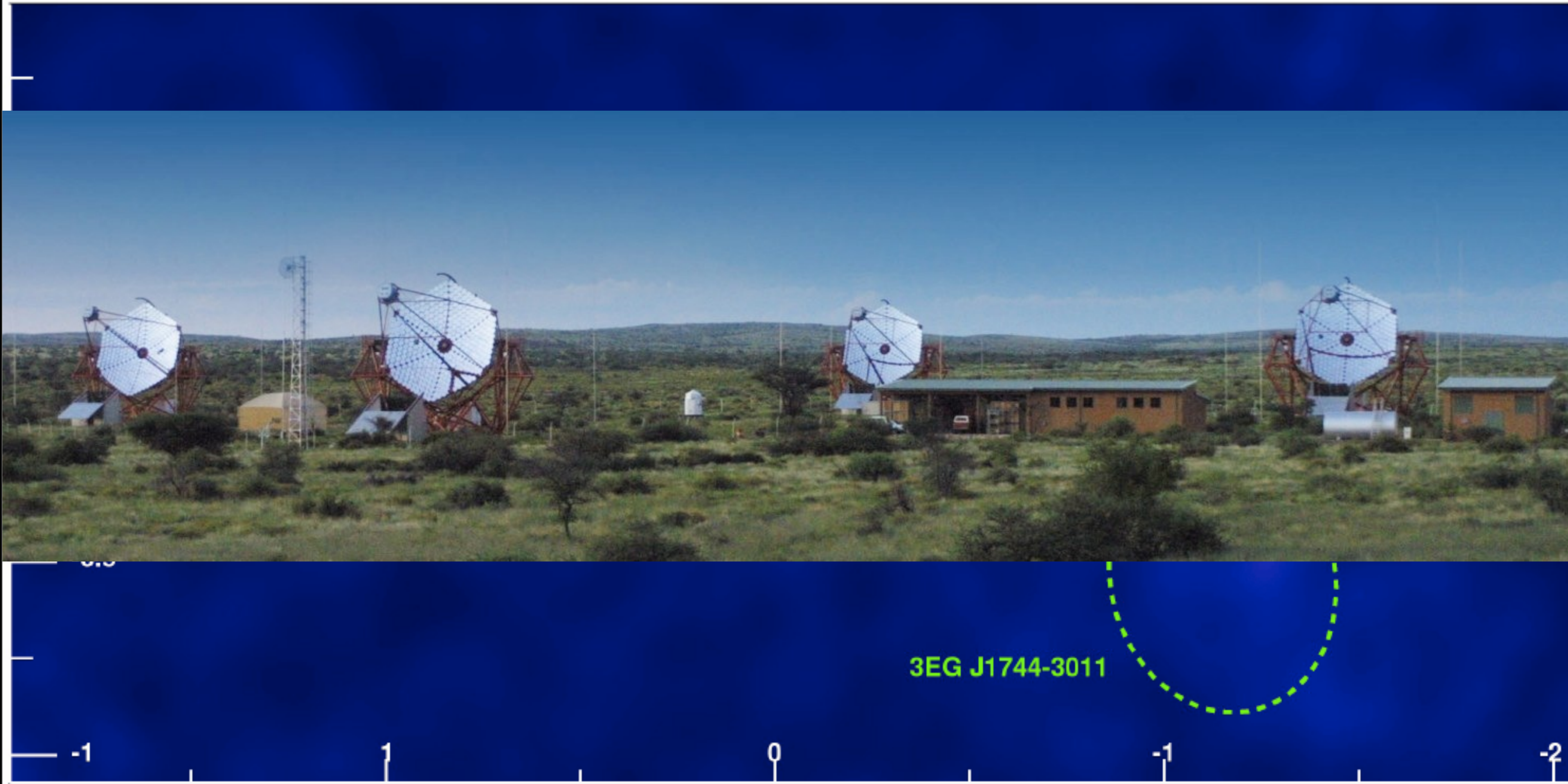

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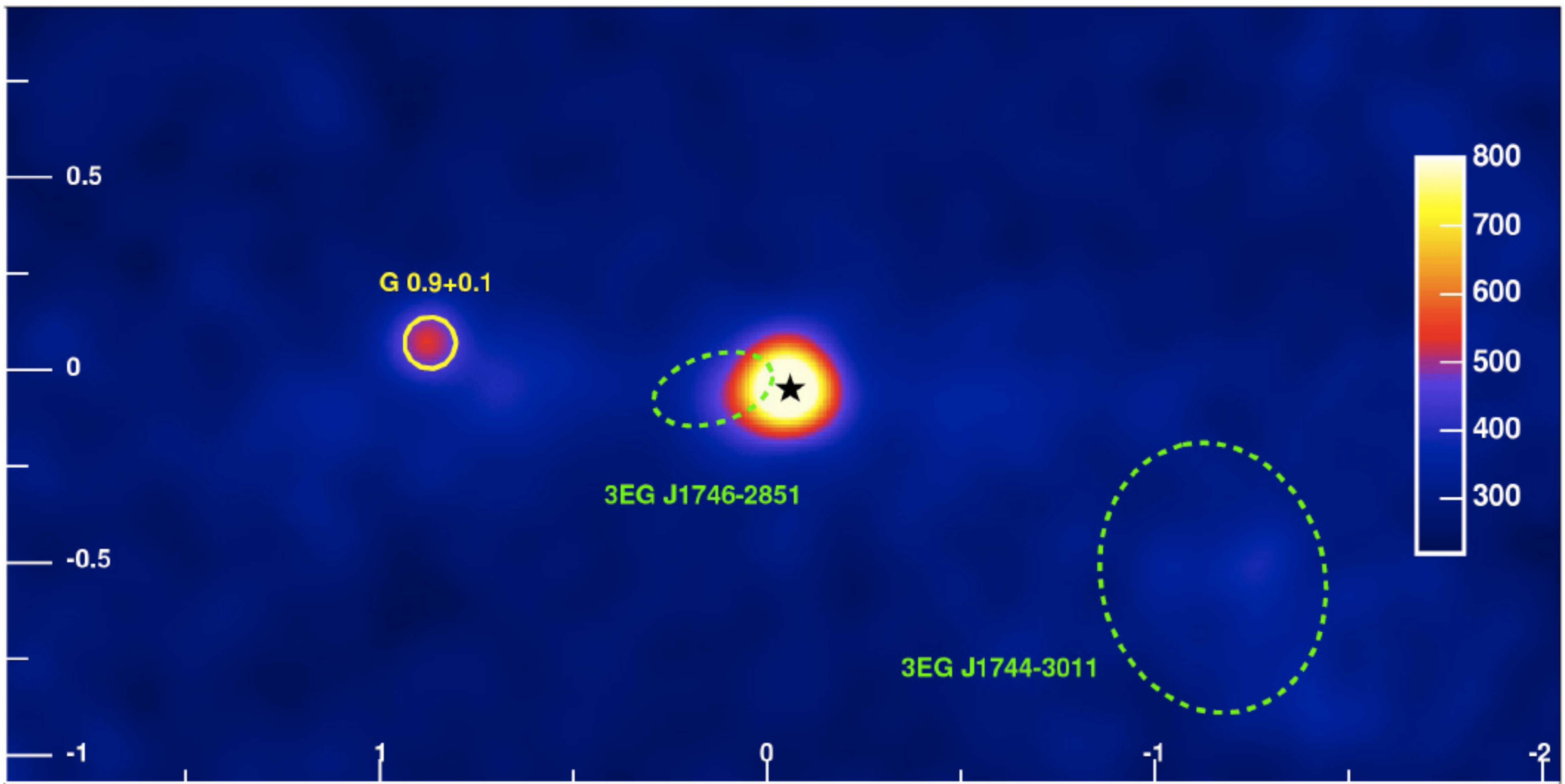

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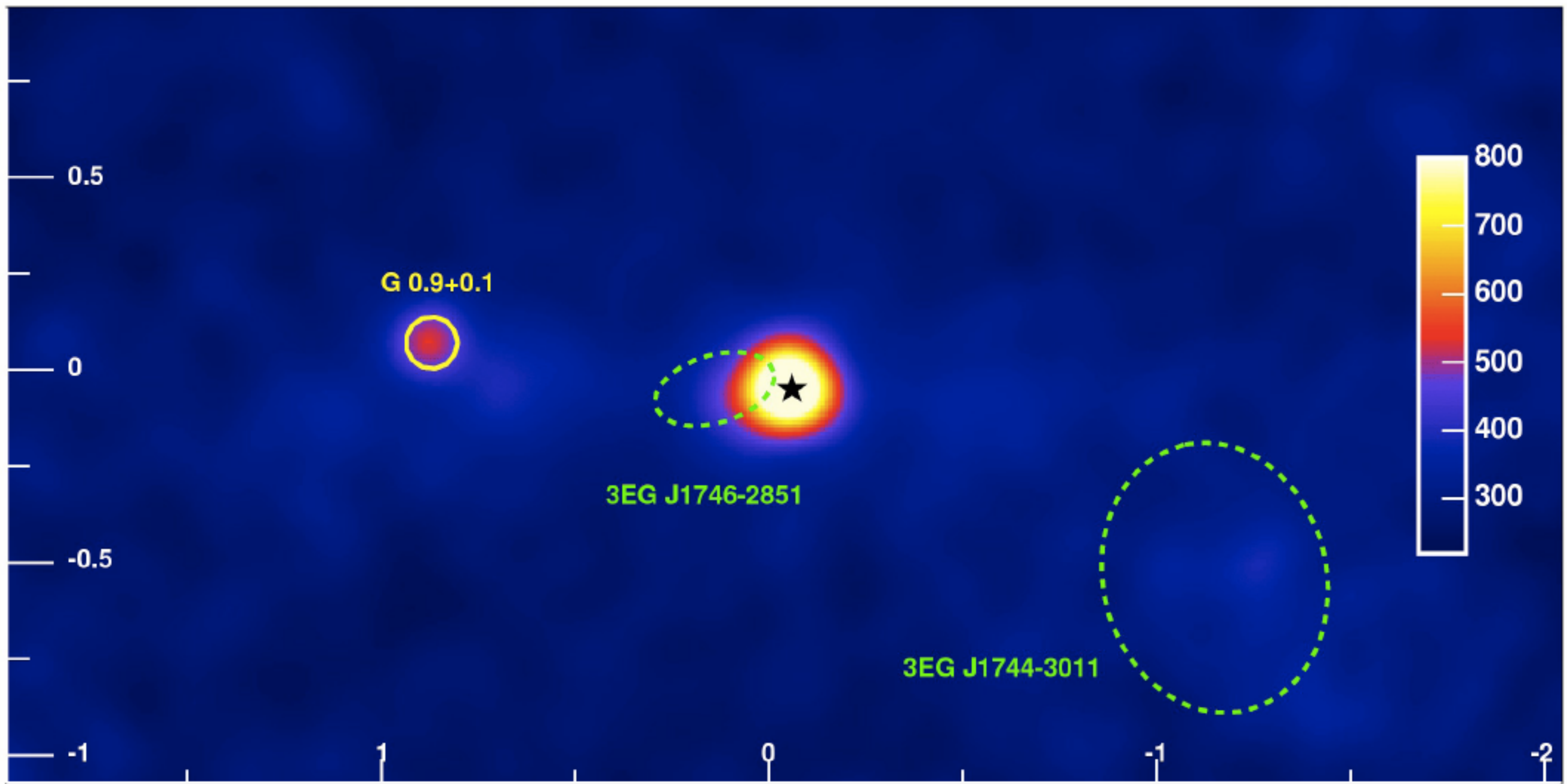

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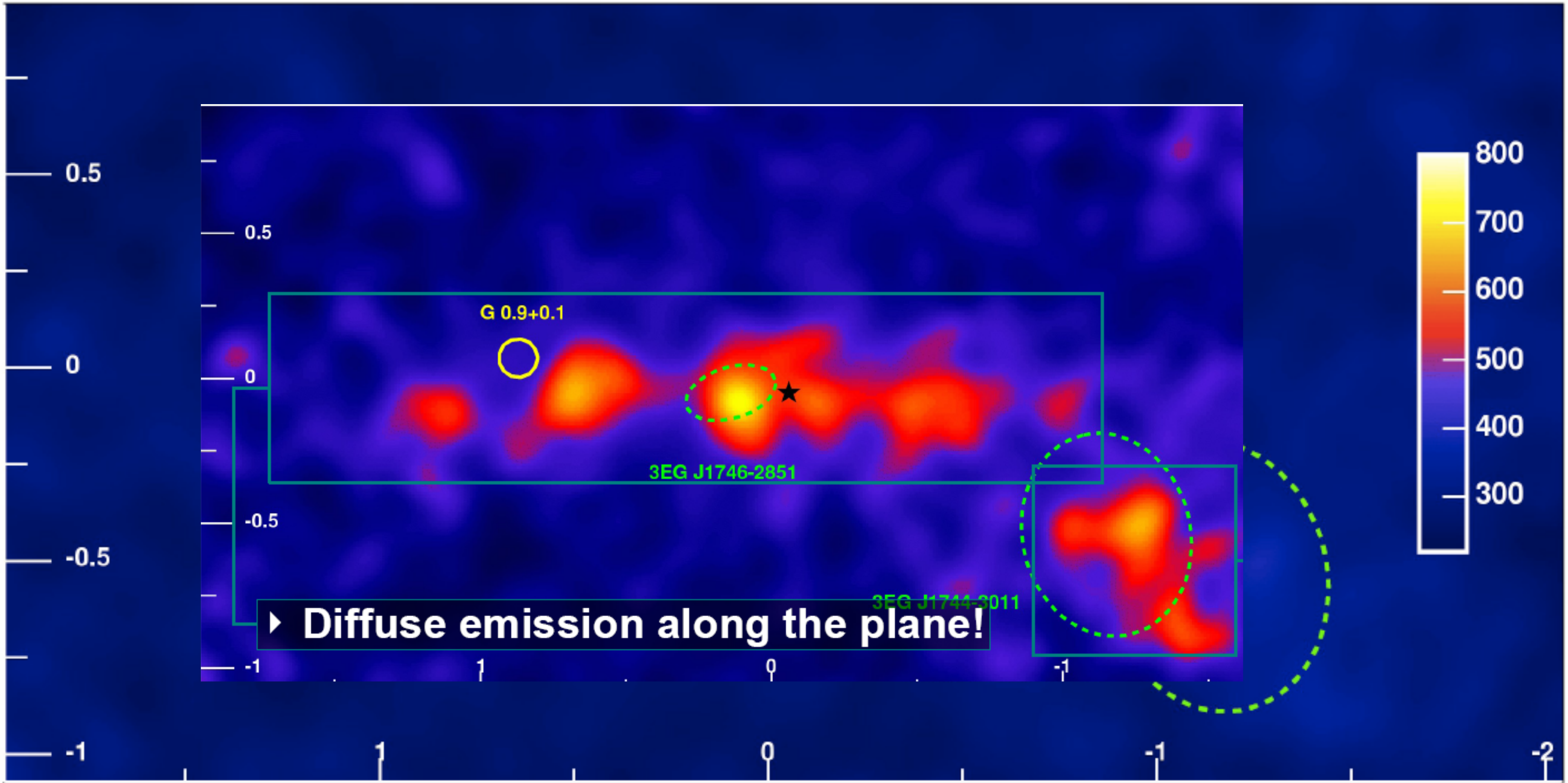

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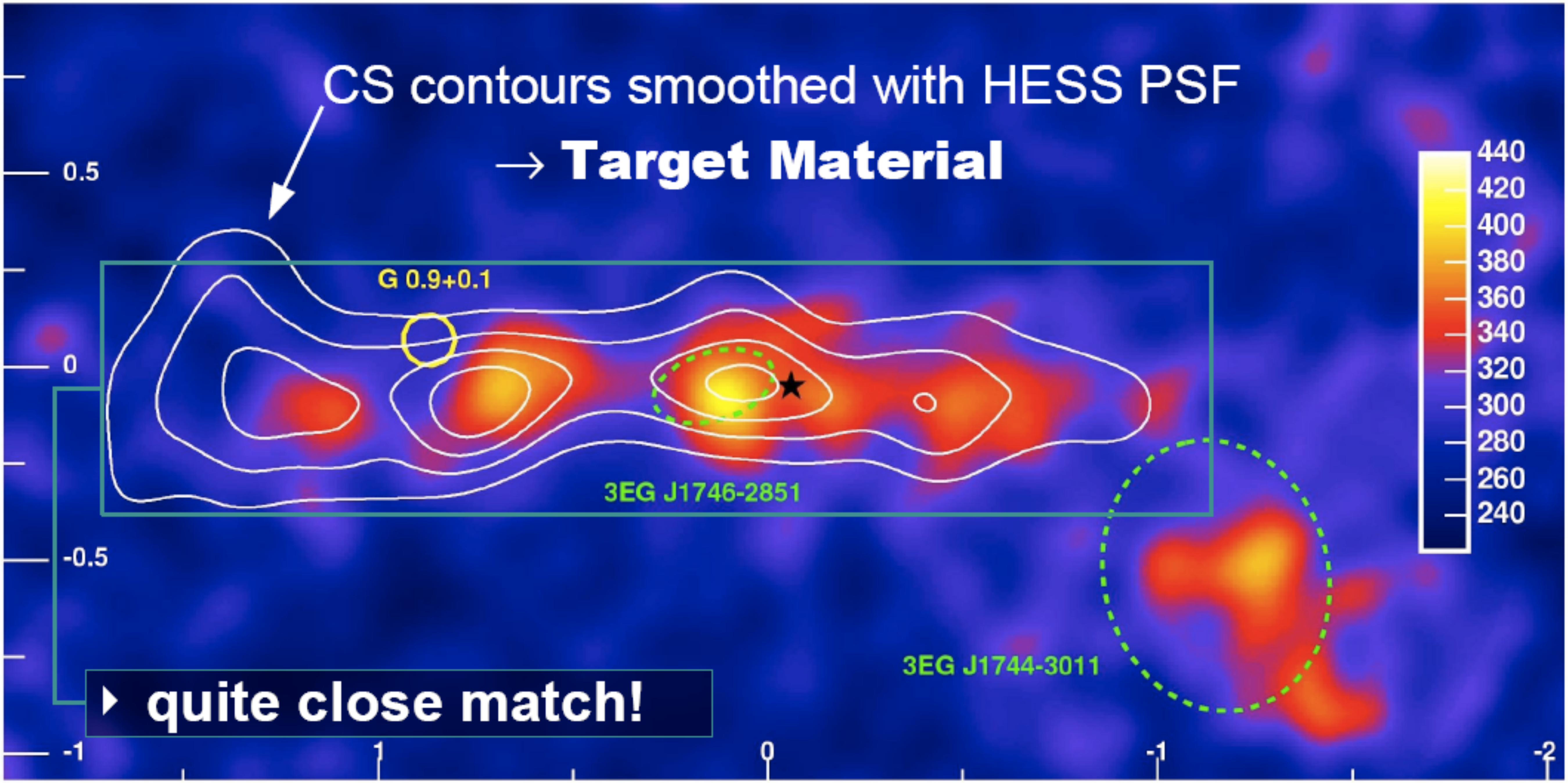
CS contours over H.E.S.S. map



Credit: HESS Collab

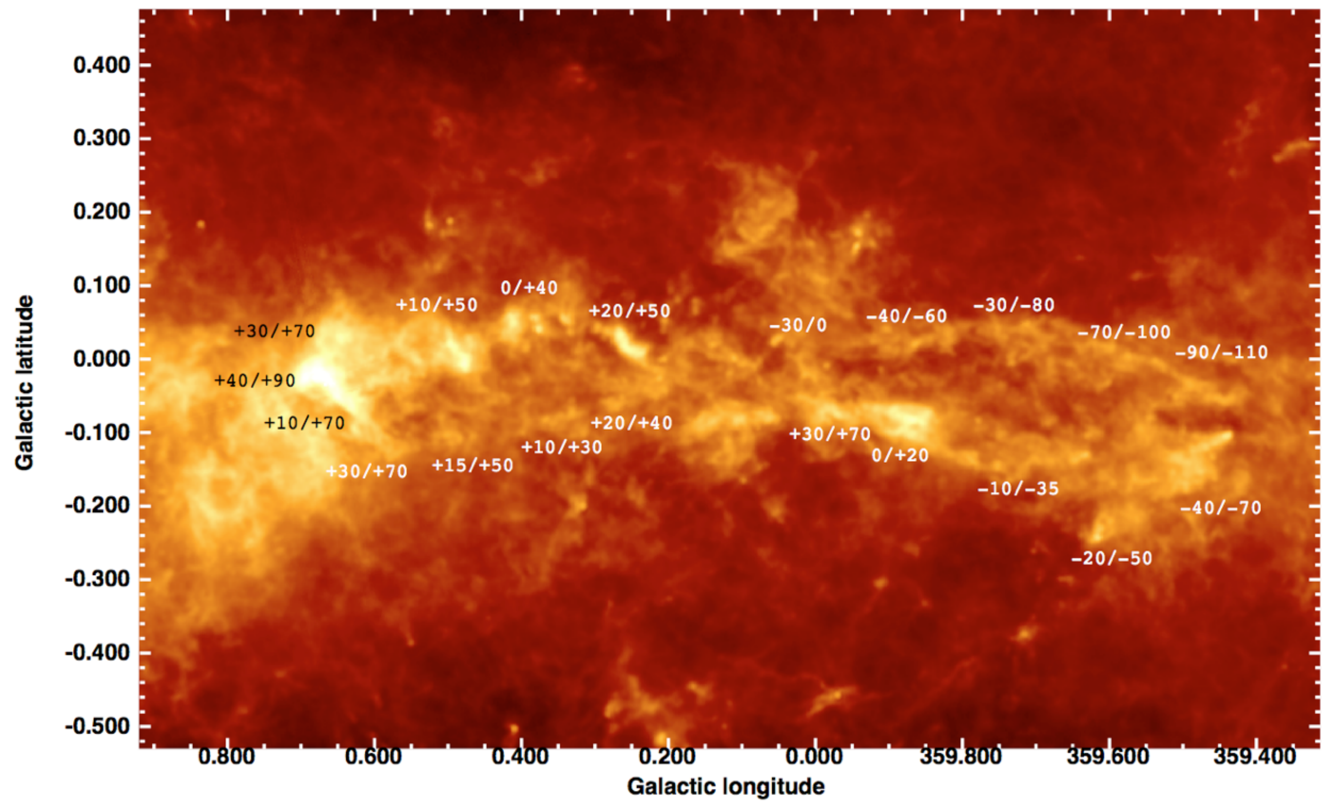
CS contours from Tsuboi et al. (1999)

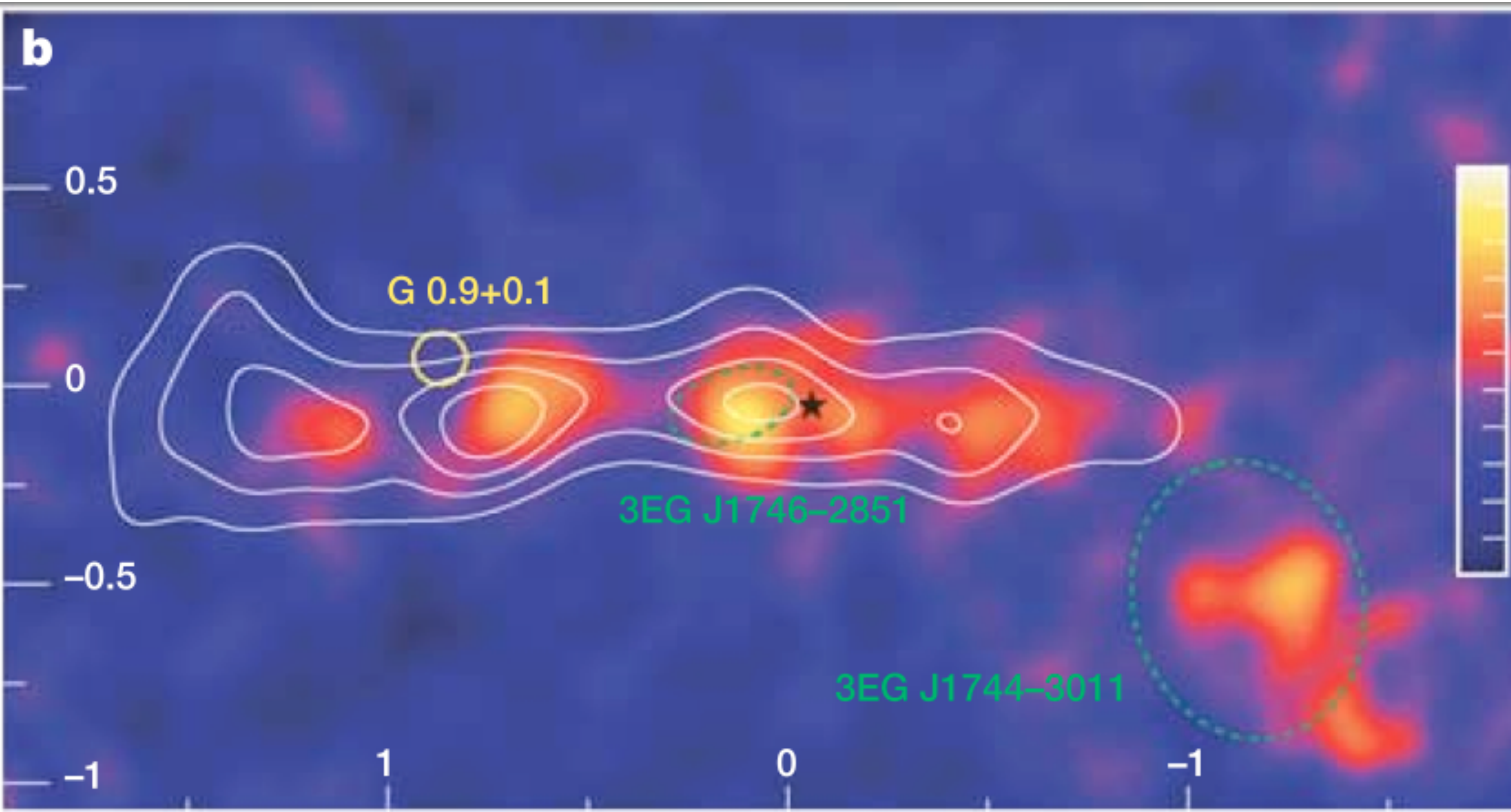
Cosmic Ray Transport on ~100 pc scales in the GC

- Both transport and cooling processes affect the steady-state distributions of non-thermal particles
- In the disk, diffusive escape of cosmic ray ions steepens the steady state population because higher energy particles scatter less and escape the disk more quickly
- In the GC, the star-formation intensity is sufficient to drive a large-scale outflow akin to a (low power) nuclear star-burst wind
- This wind advects most non-thermal particles before they can lose their energy radiatively

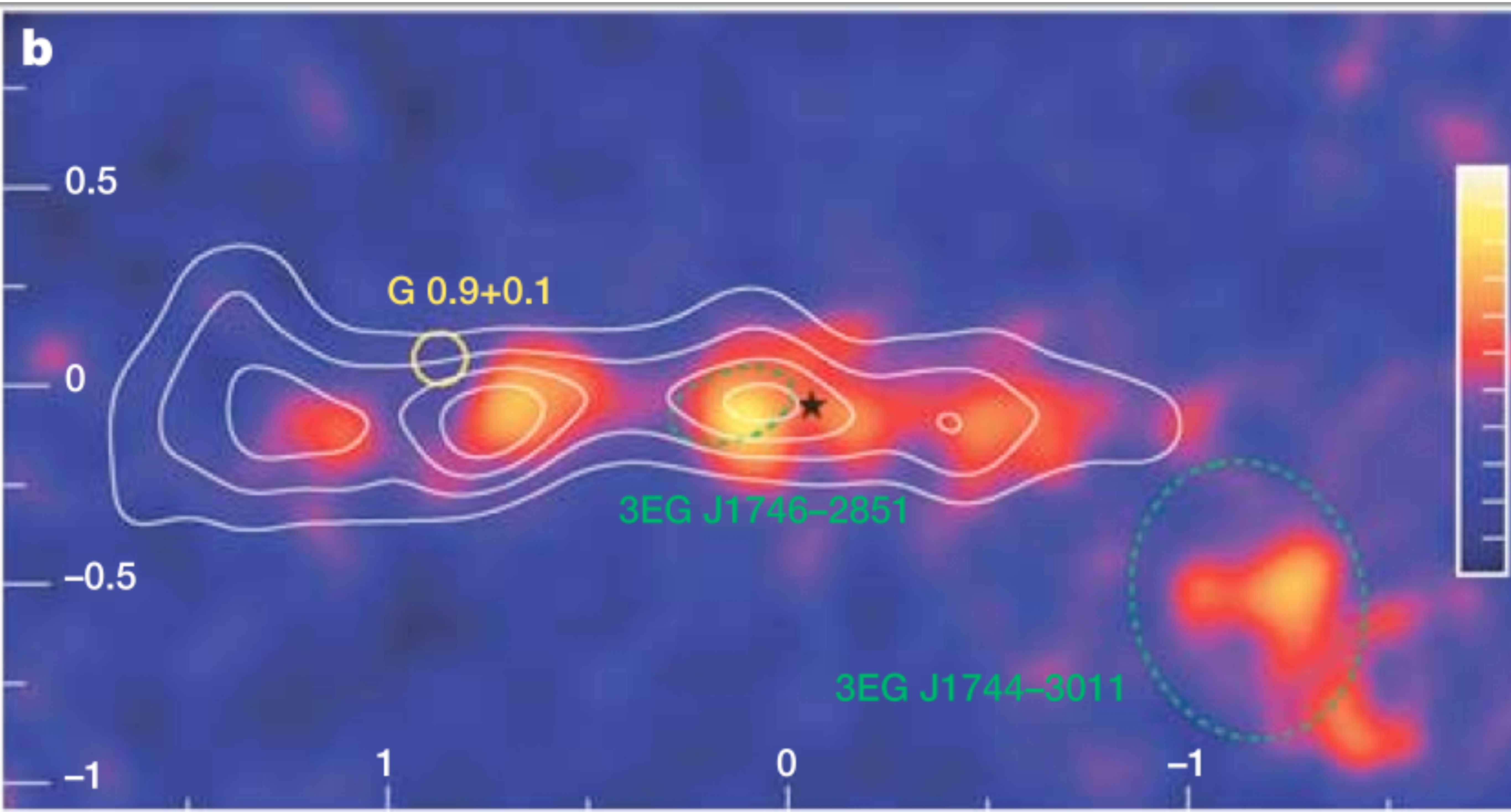
Cosmic Ray Transport in the GC

- *Hard* spectrum of in-situ electron **and** proton population $\rightarrow$ transport is advective not diffusive, i.e. via a *wind*
- there is much prior evidence for such a wind

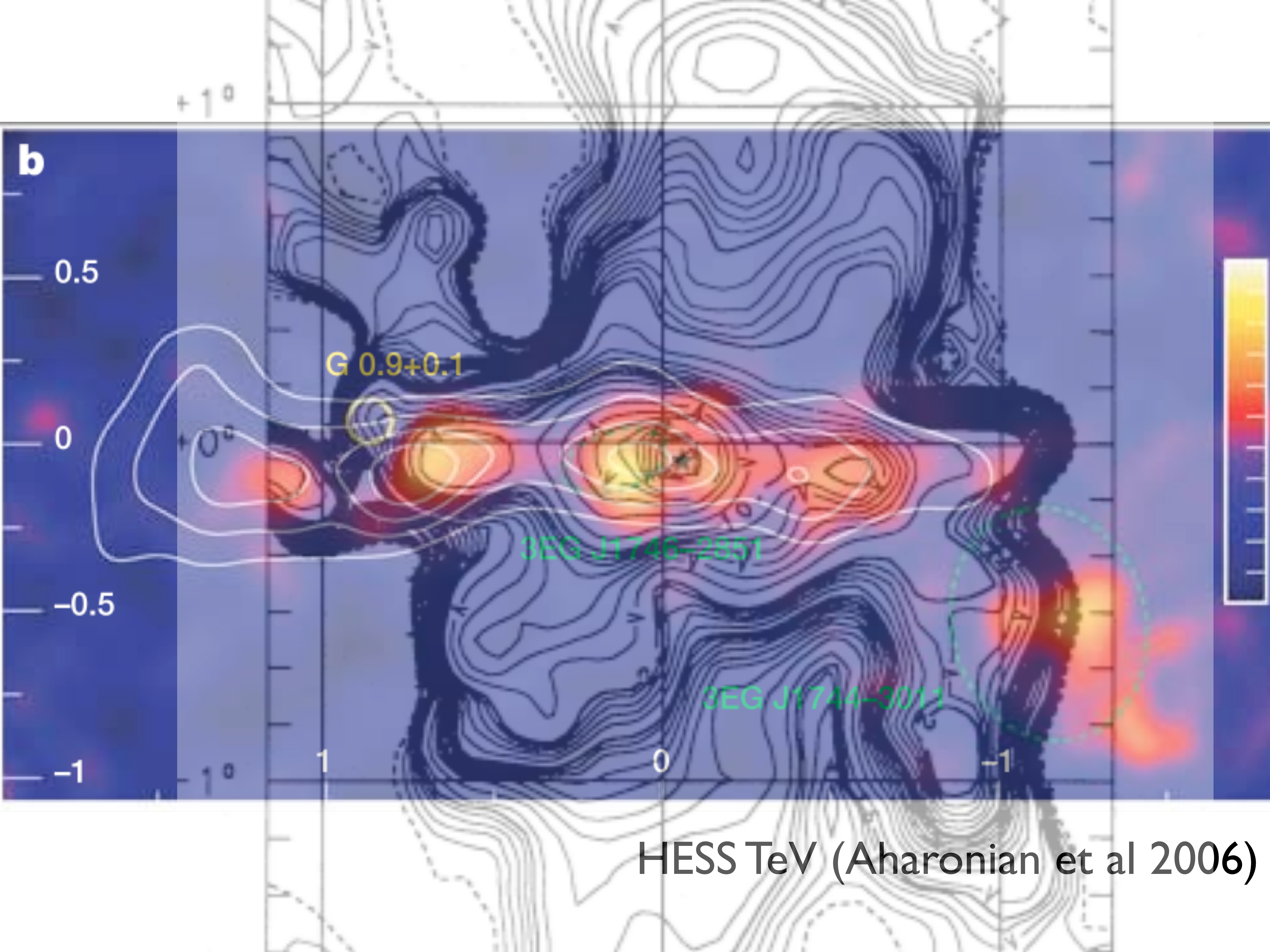

0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
Galactic latitude
0.800
0.600
0.400
0.200
0.000
359.800
359.600
359.400
Galactic longitude
+30/+70
+40/+90
+10/+70
+30/+70
+10/+50
0/+40
+15/+50
+10/+30
+20/+50
+20/+40
-30/0
+30/+70
0/+20
-40/-60
-30/-80
-70/-100
-90/-110
-10/-35
-40/-70
-20/-50



b
0.5
0
–0.5
–1
G 0.9+0.1
3EG J1746–2851
3EG J1744–3011
1
0
–1



HESS TeV (Aharonian et al 2006)



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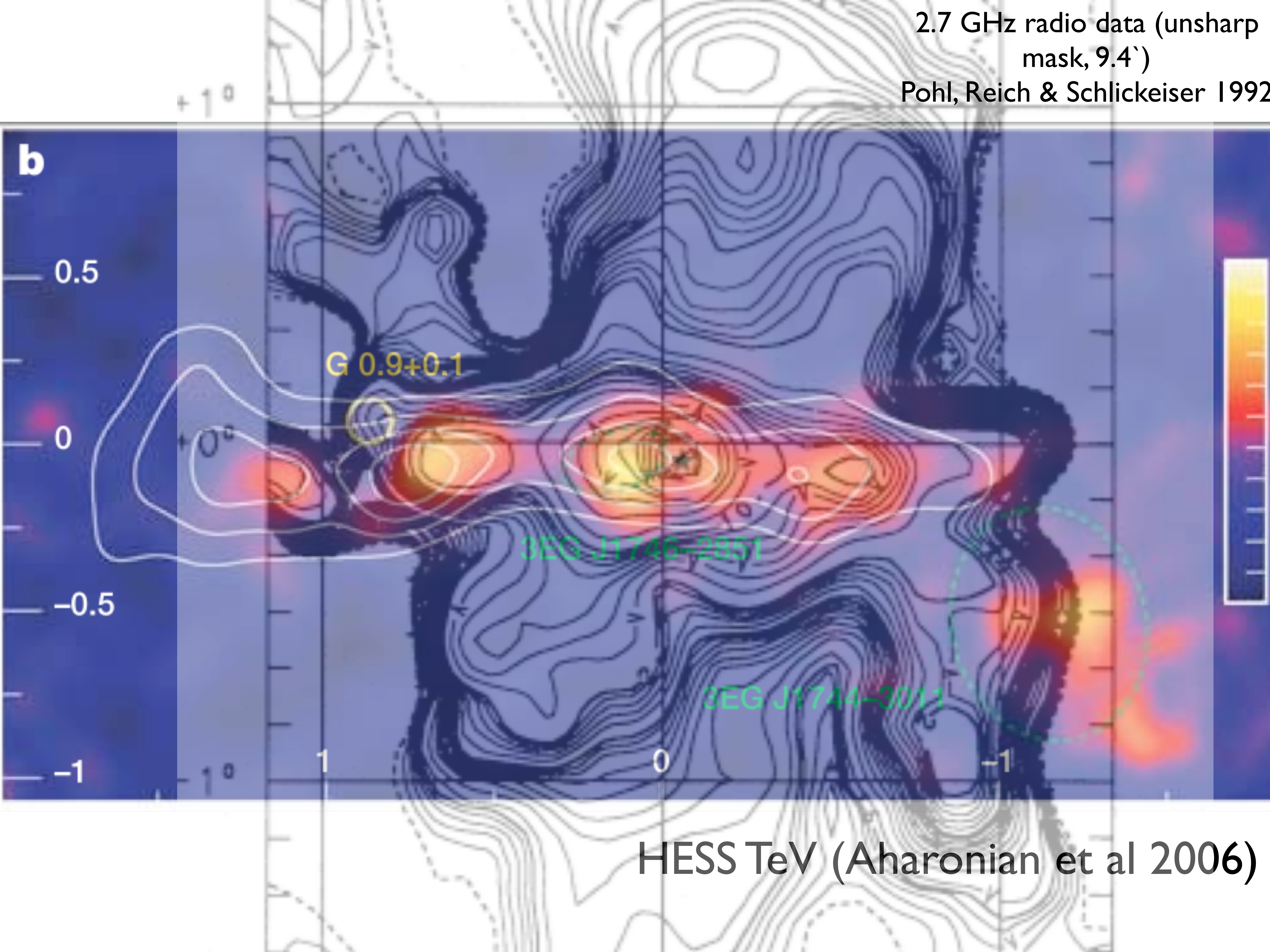
2.7 GHz radio data (unsharp mask, 9.4`)
Pohl, Reich & Schlickeiser 1992
b
0.5
0
−0.5
−1
G 0.9+0.1
3EG J1746−2851
3EG J1744−3011
1
0
−1
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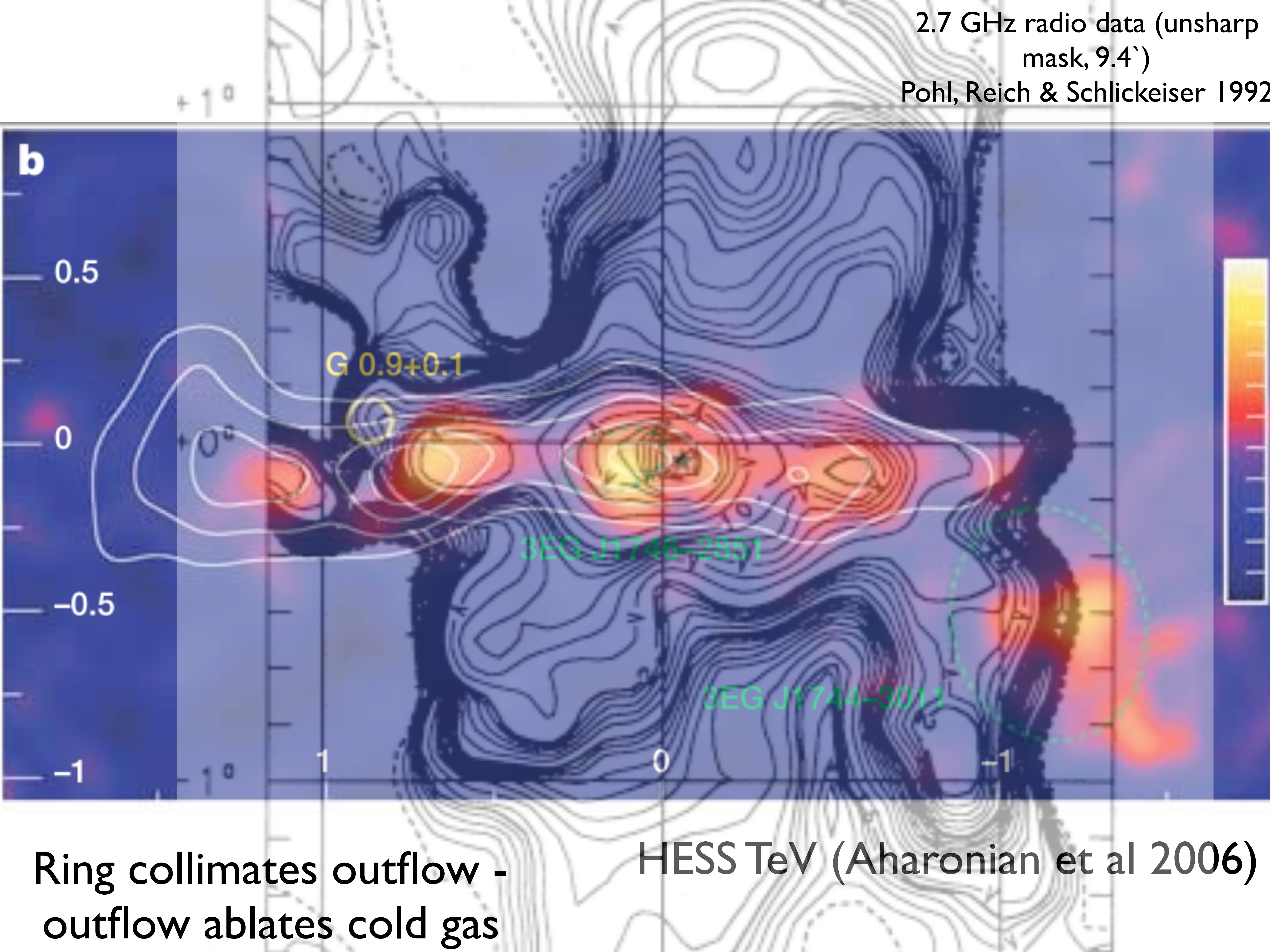


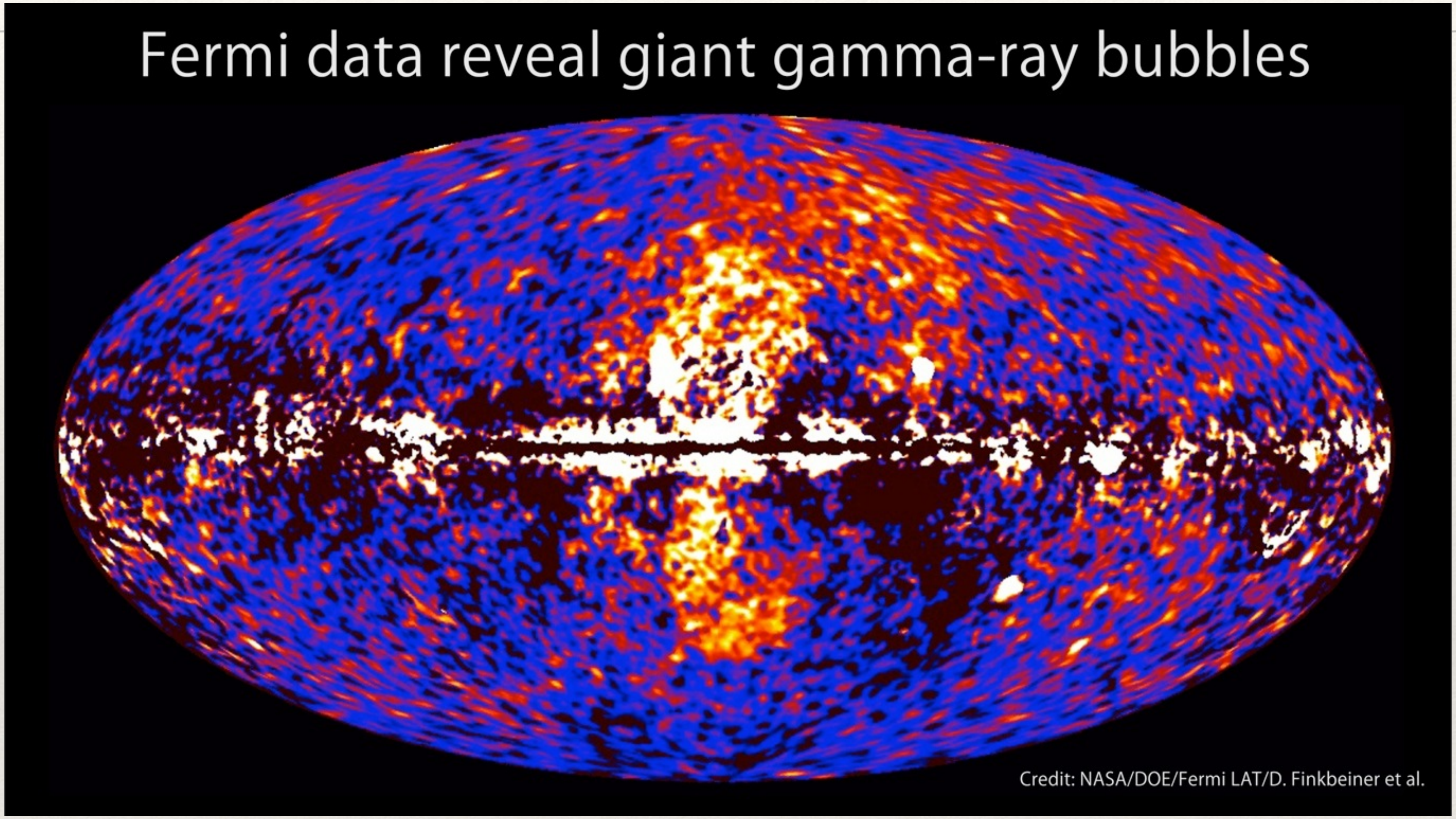
Ring collimates outflow - outflow ablates cold gas

HESS TeV (Aharonian et al 2006)

…so, what is the fate of the advected cosmic rays?

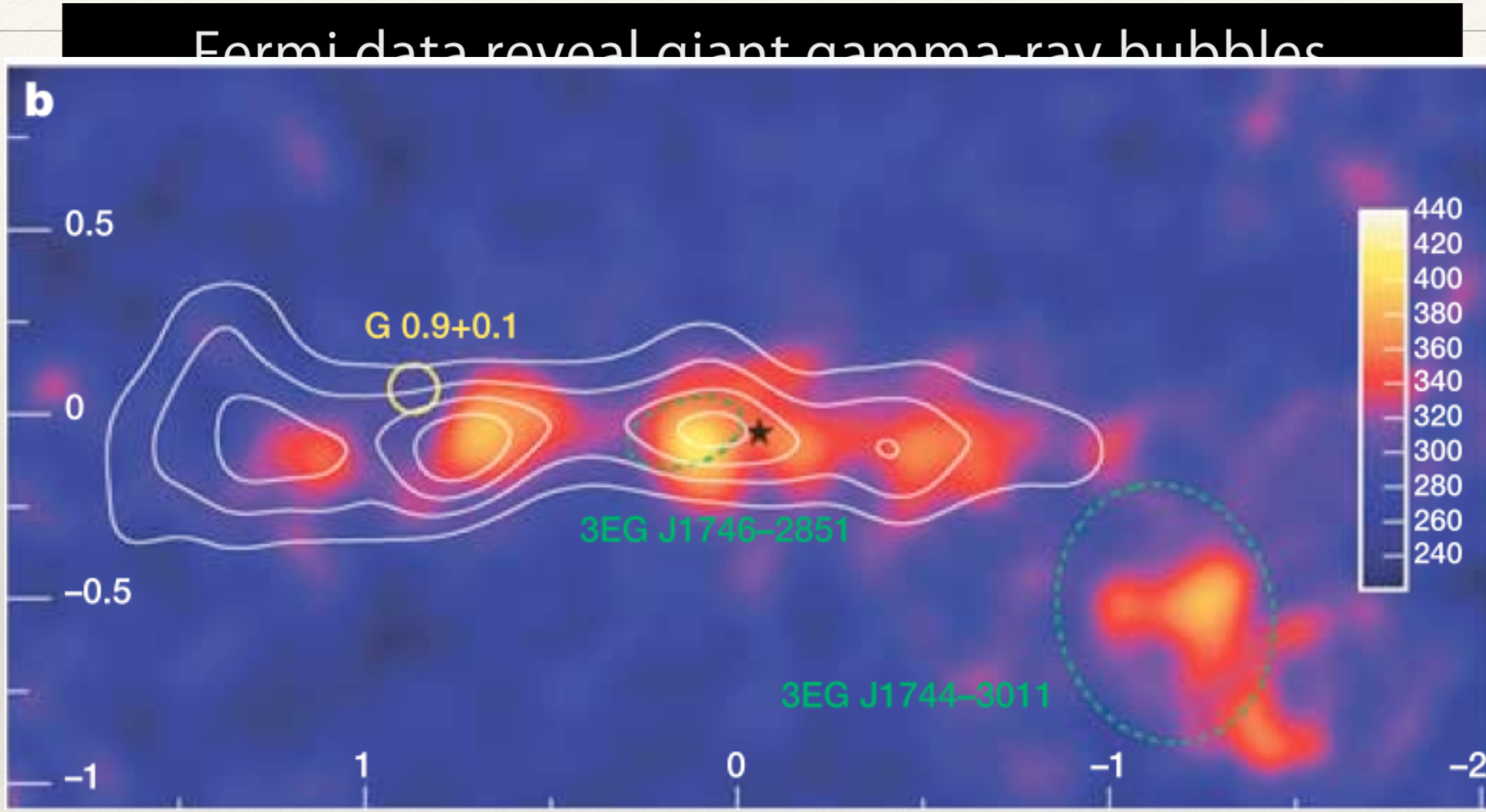
Much Wider Scales

Fermi Bubbles



Su, Slatyer and Finkbeiner 2010 (ApJ)

Fermi Bubbles



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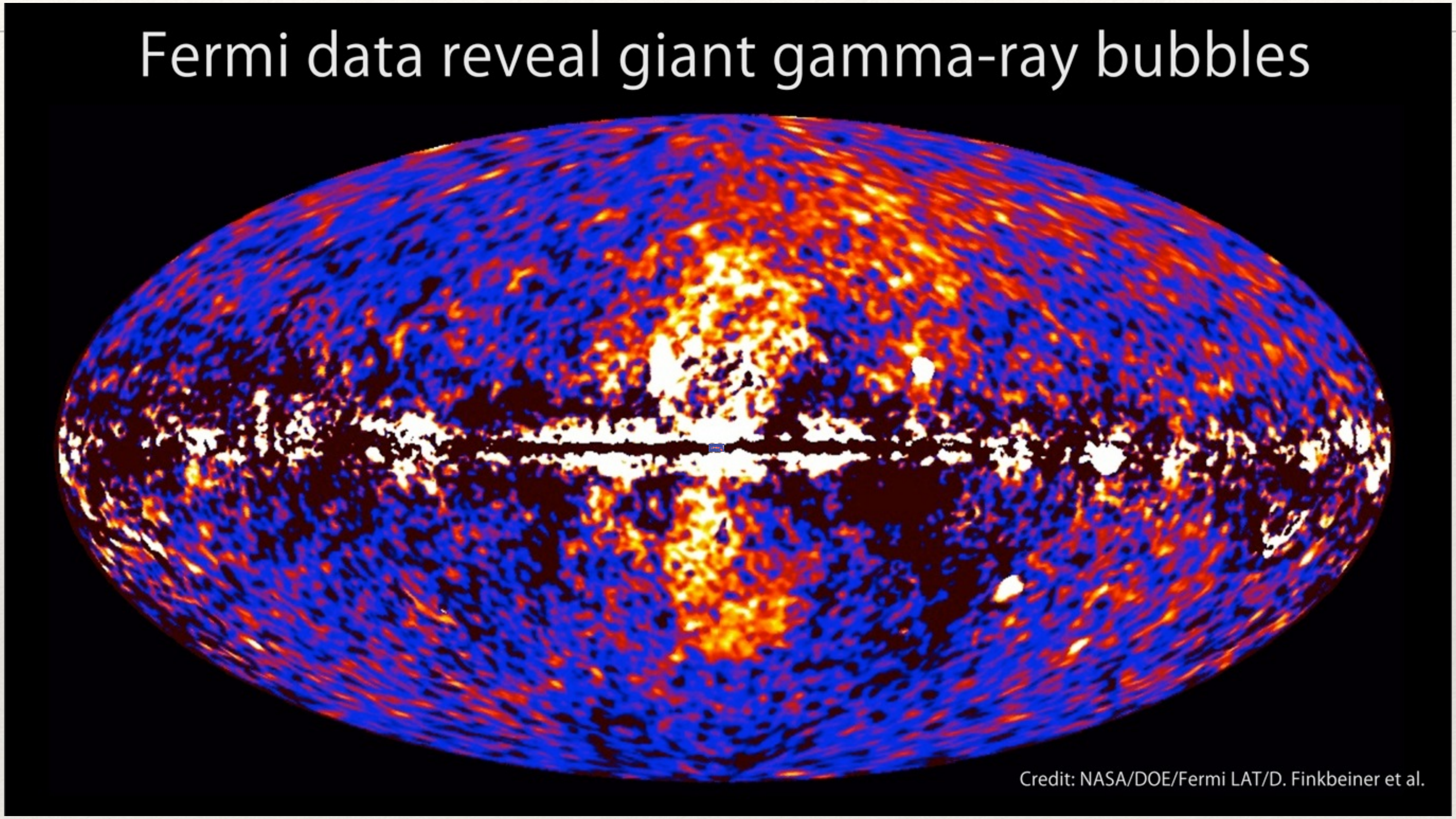
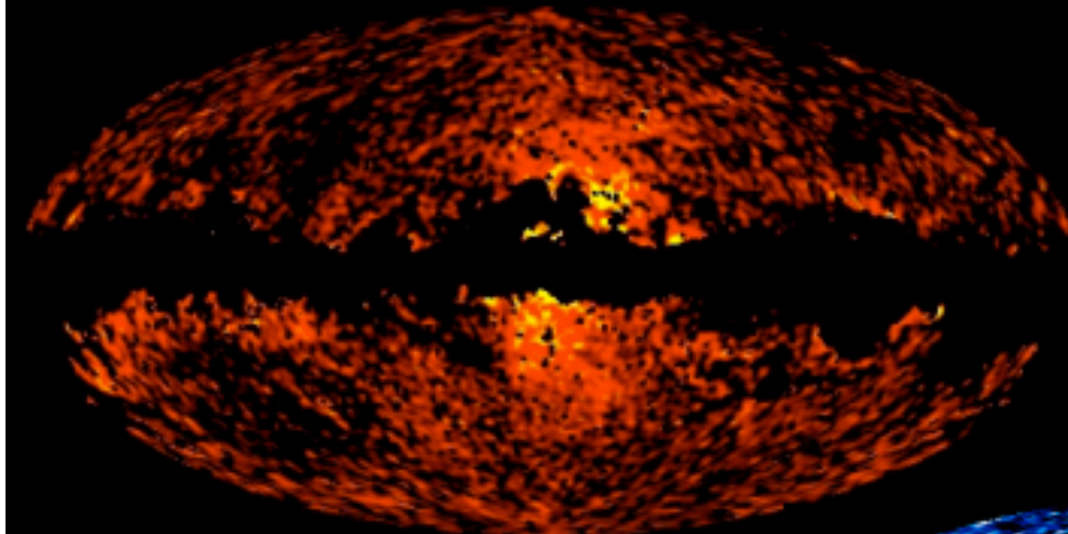
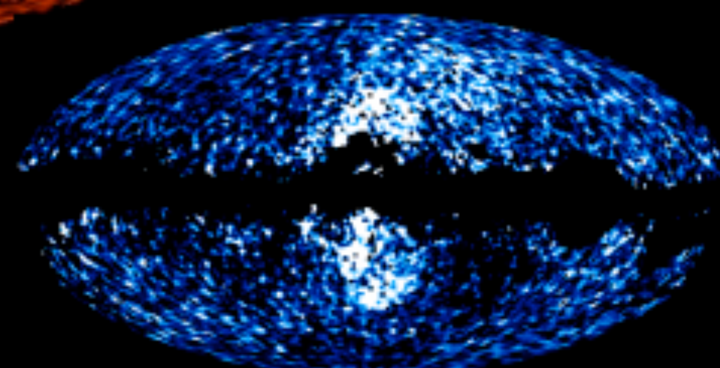


Su, Slatyer and Finkbeiner 2010 (ApJ)

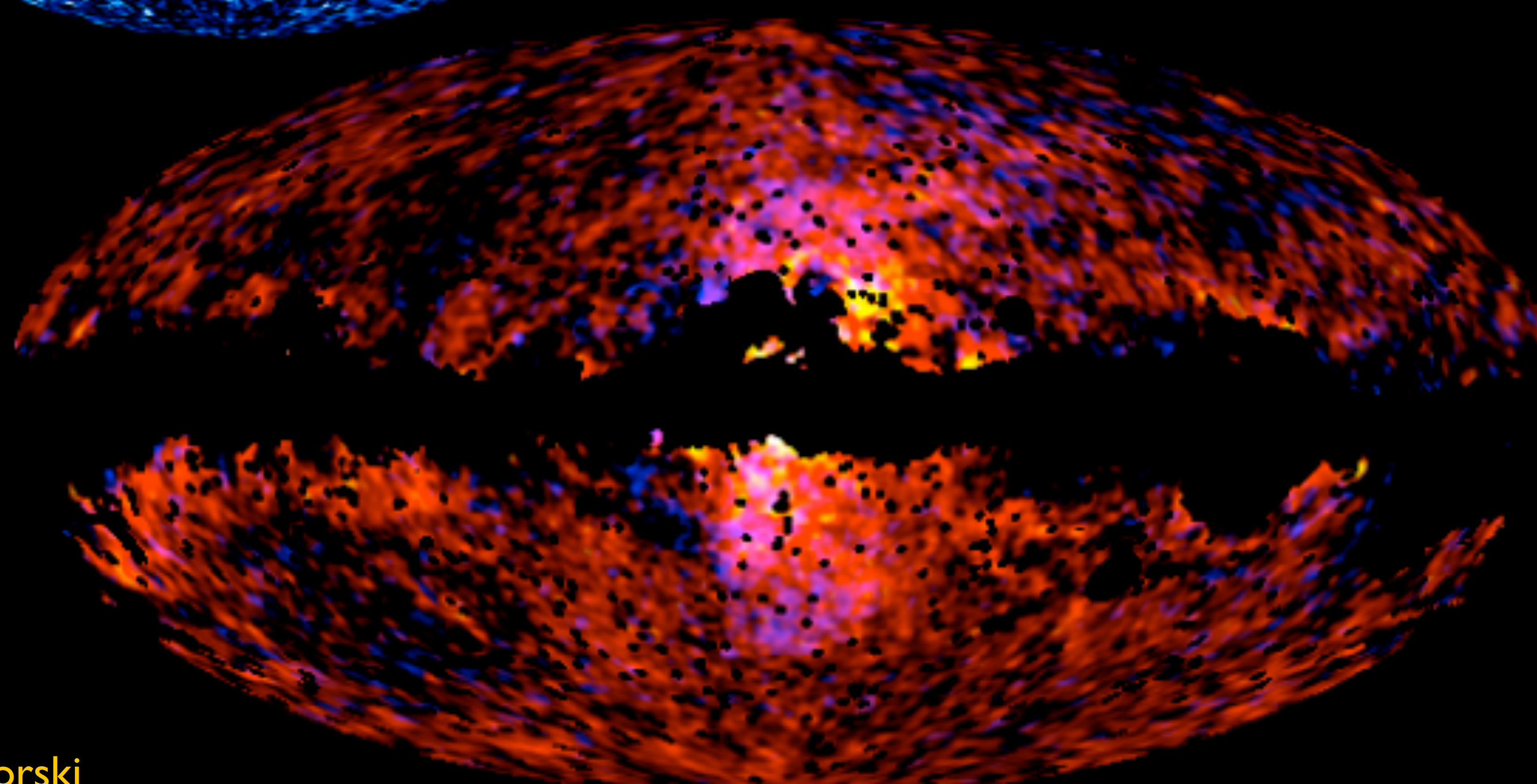
PLANCK images a giant eruption from the heart of the Milky Way



The Galactic haze/bubbles is shown here in *PLANCK* data from *30-44* GHz



The same structure at 2-5 GeV as seen by the *Fermi Gamma-Ray Space Telescope*



A multi-wavelength composite image showing both microwaves and gamma-rays: *PLANCK 30* GHz (red), *44* GHz (green), and *Fermi* 2-5 GeV (blue).

Slide credit: D. Pietrobon & K.M. Gorski
Planck Collab.

Fermi Bubbles

- 2×10^{37} erg/s [1-100 GeV]
- hard spectrum, but spectral down-break below ~ GeV in SED
- uniform intensity
- sharp edges
- coincident emission at other wavelengths
- vast extension: ~7 kpc from plane
- $\gtrsim$ few 10^{55} erg

Fermi Bubbles: Two Interlocking Questions

1. What is the radiation mechanism?

Cosmic ray electrons / Inverse Compton emission

OR Cosmic ray protons / gas collisions

2. What energizes the outflow?

Recent Seyfert-like activity of Sgr A*

OR Nuclear star formation **OR** tidal disruption of stars by SMBH **OR** dark matter **OR ….**

S-PASS Survey

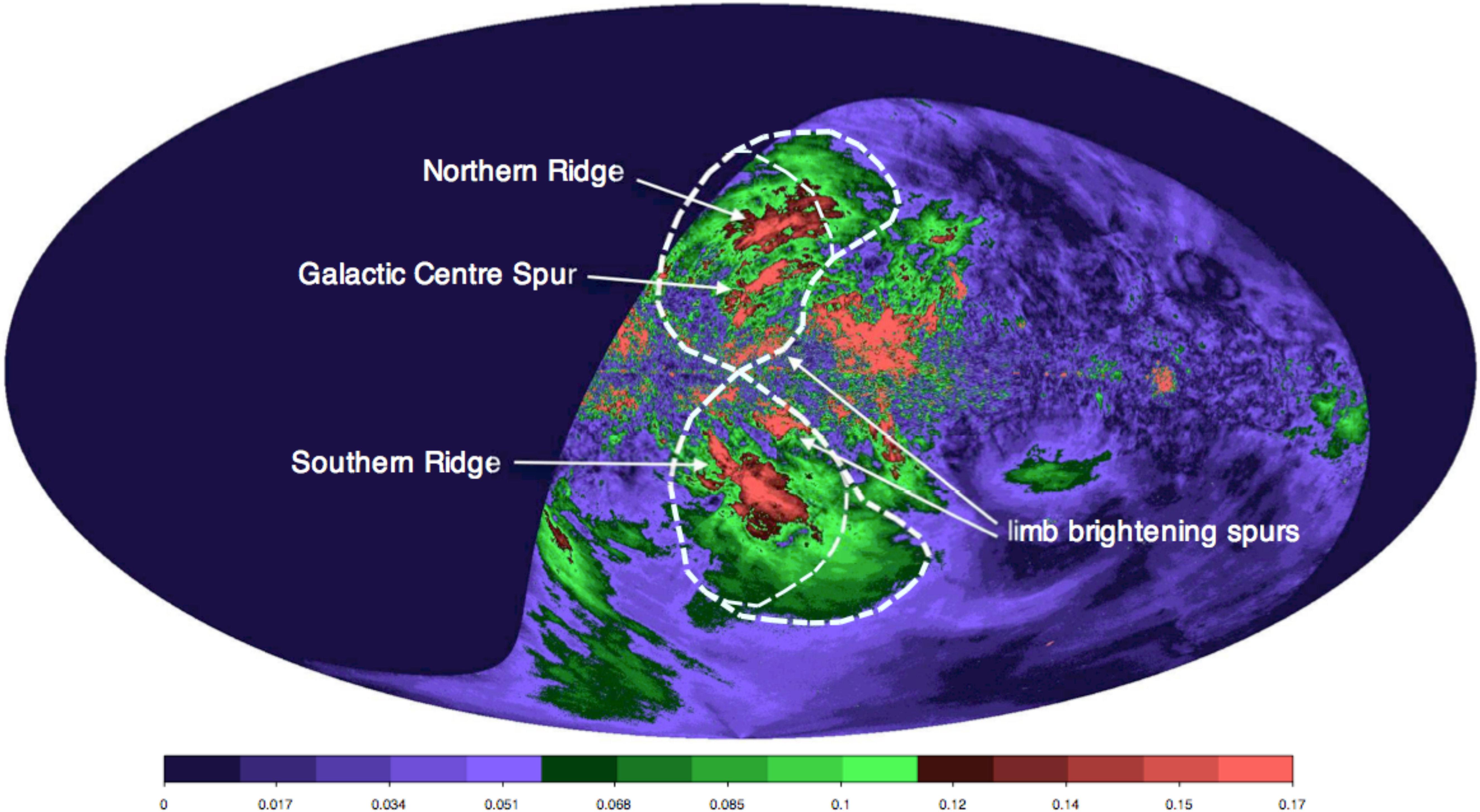
2.3 GHz RC polarization survey of southern sky with Parkes 64-m single disk, 184 MHz BW

S-PASS Survey

2.3 GHz RC polarization survey of southern sky with Parkes 64-m single disk, 184 MHz BW

‘The Dish’, 55 years old

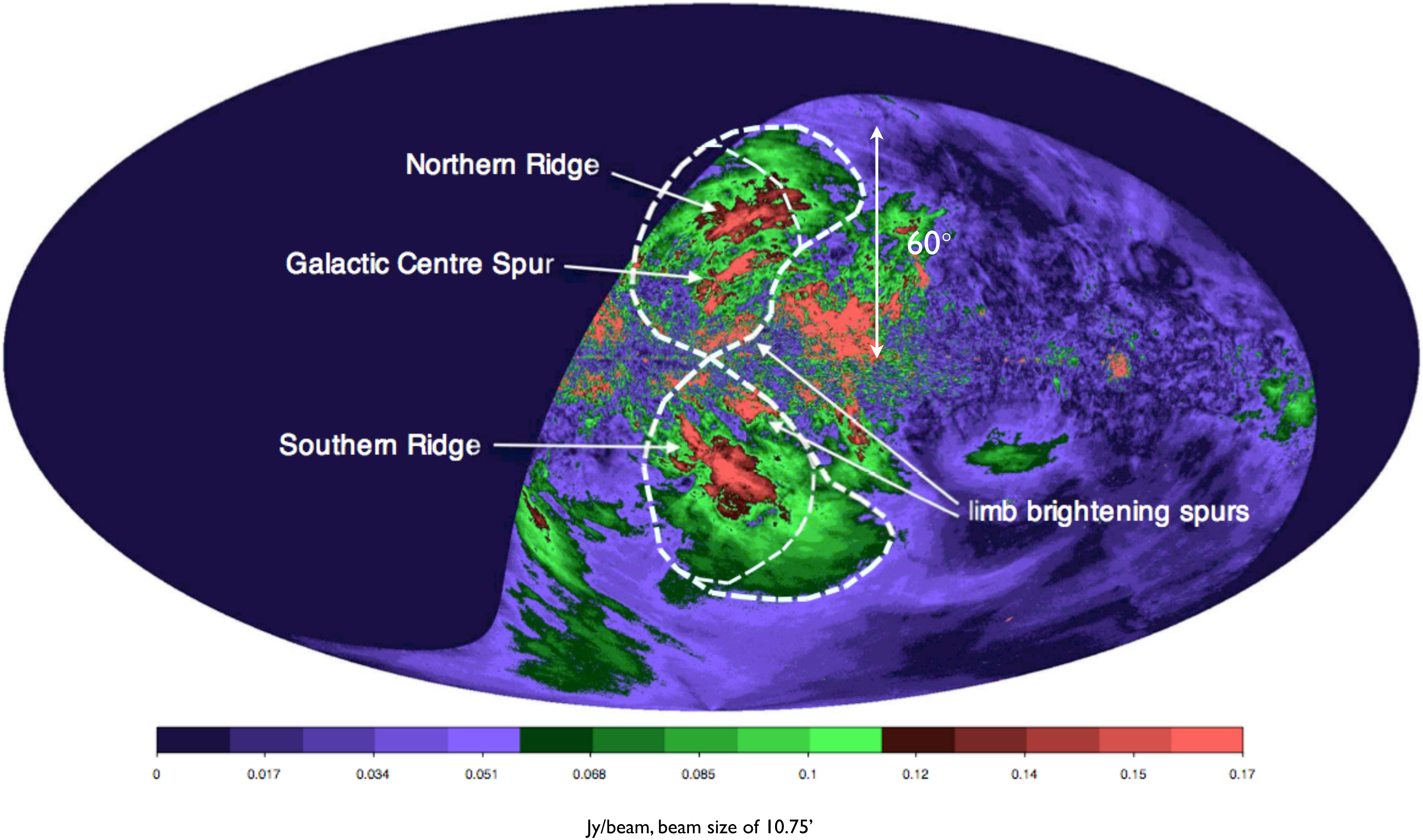
The 'S-PASS Lobes'



Jy/beam, beam size of 10.75'

Carretti et al. Nature 2013

The ‘S-PASS Lobes’



Carretti et al. Nature 2013

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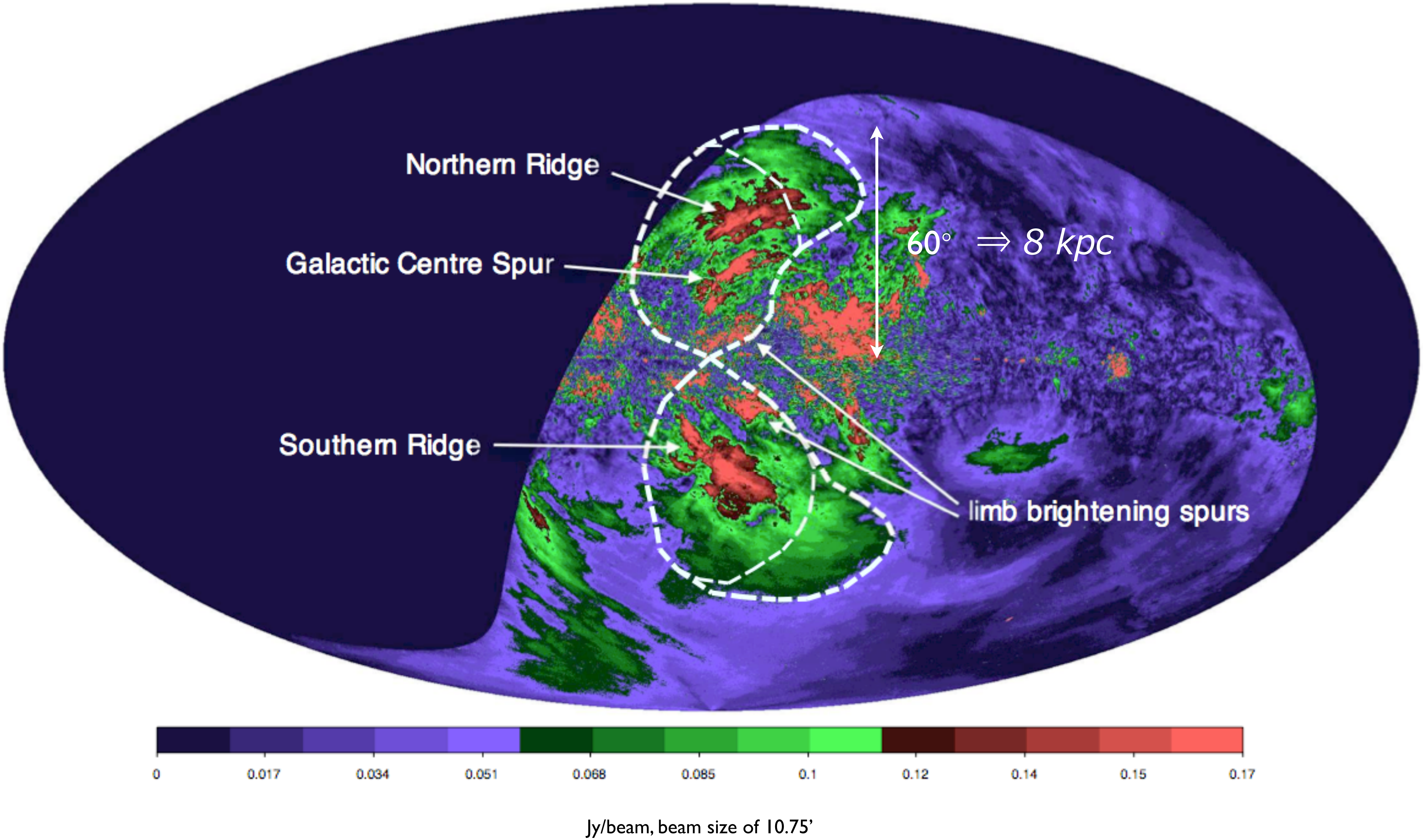

Carretti et al. Nature 2013

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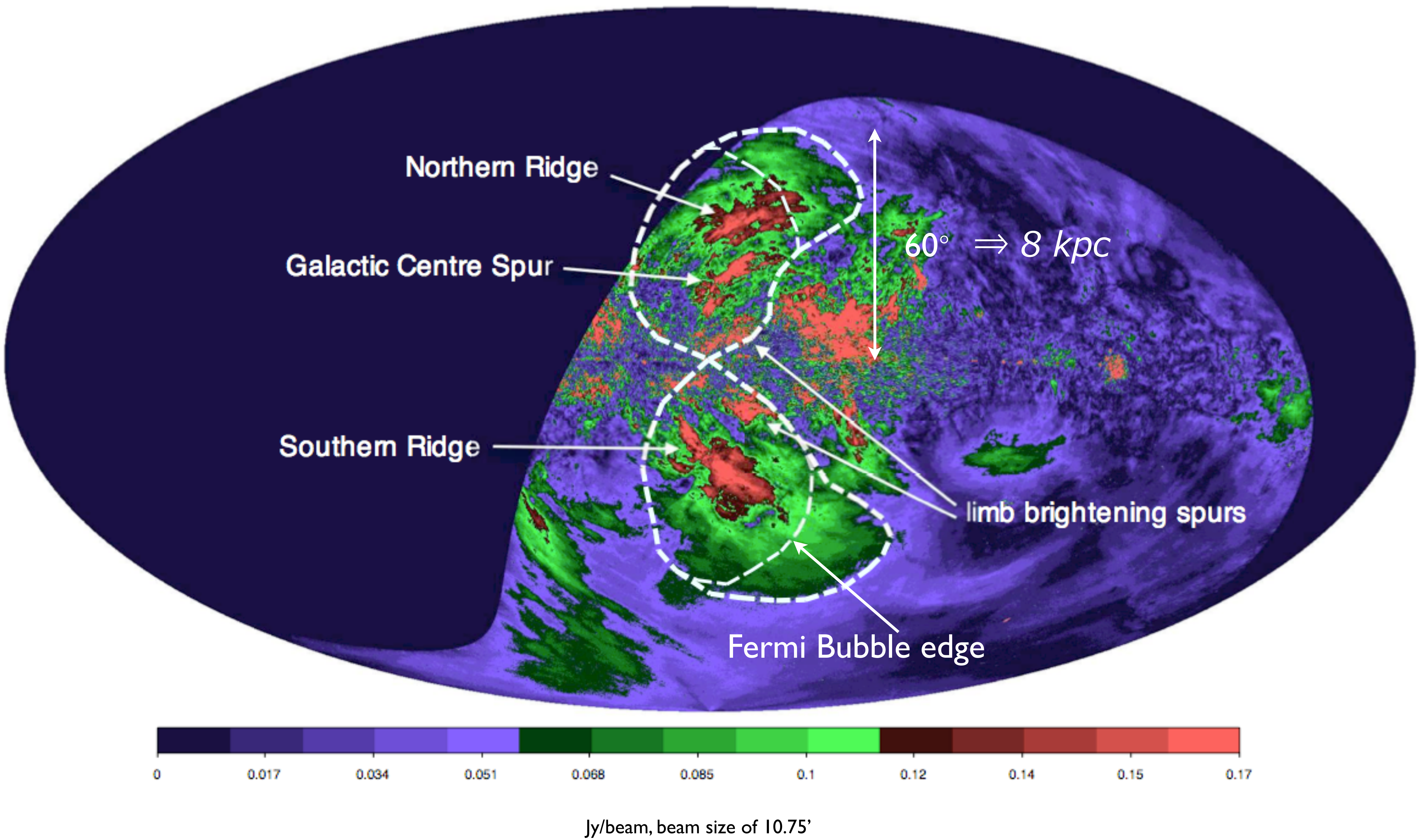
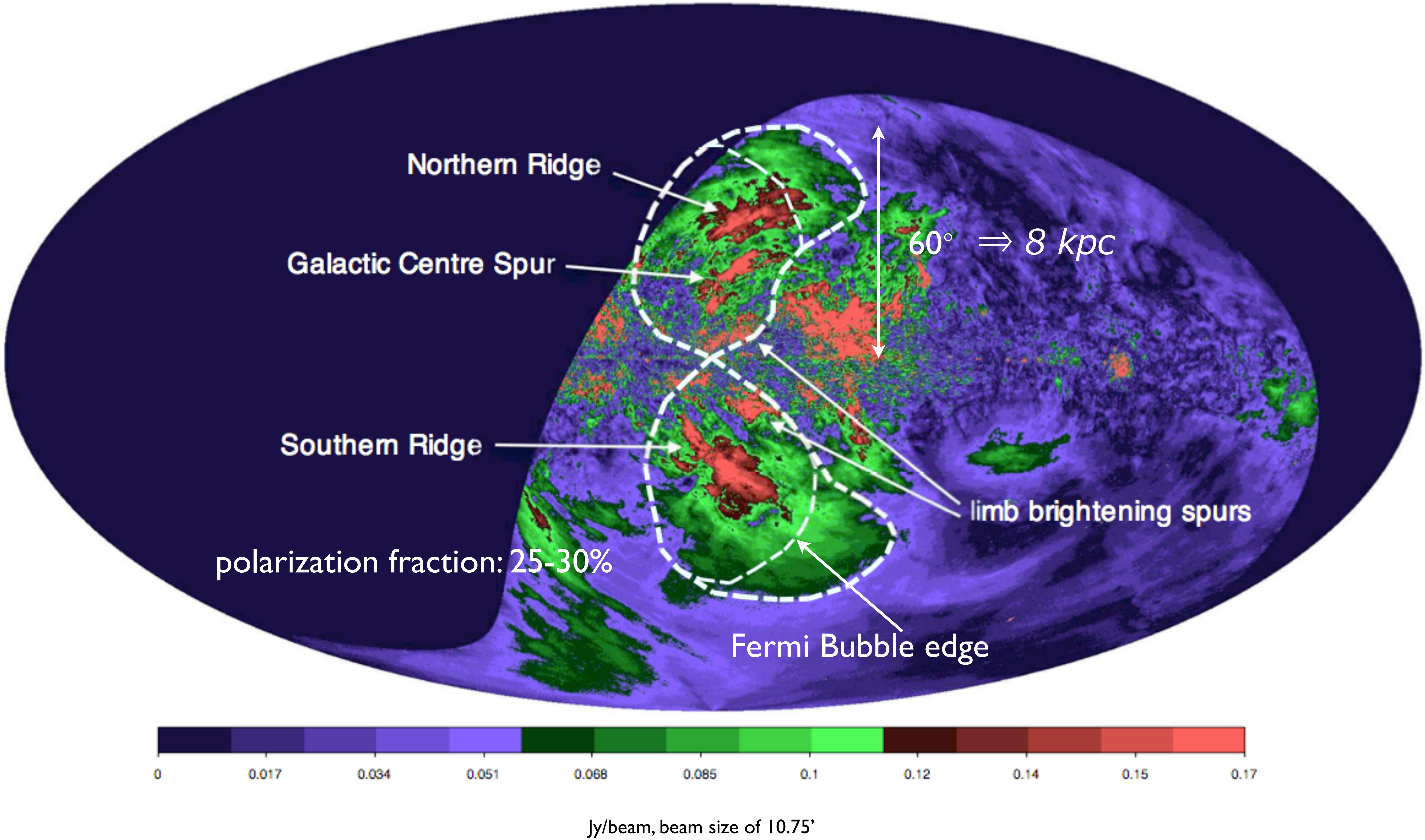


Carretti et al. Nature 2013

The ‘S-PASS Lobes’



Carretti et al. Nature 2013

Part III: The Galactic Centre:

Two Persistent High Energy Anomalies

Two intriguing, high-energy signals from the Inner Galaxy:

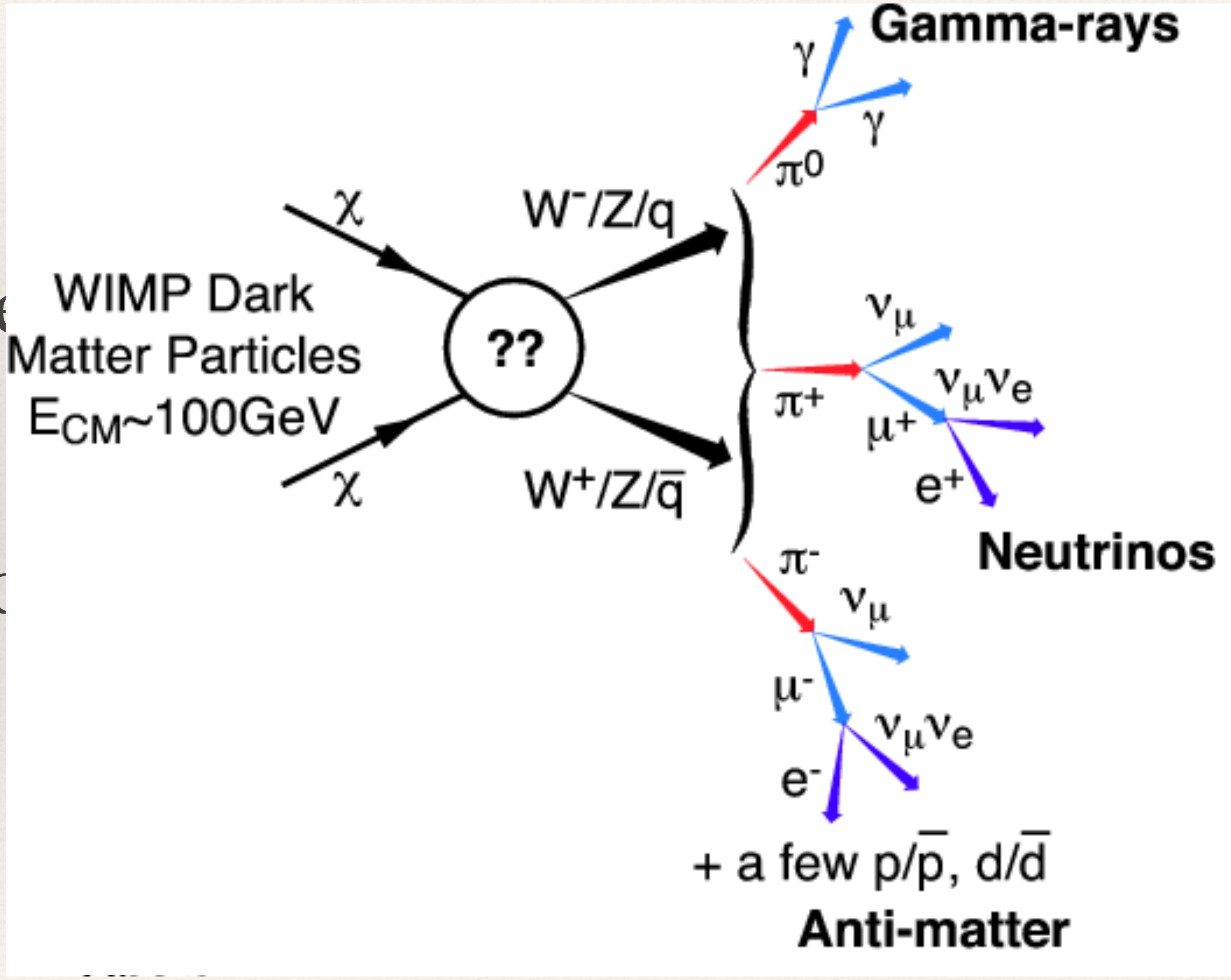
- Galactic Centre Excess ‘GCE’ ~few GeV gamma-ray signal

Two intriguing, high-energy signals from the Inner Galaxy:

- Galactic Centre Excess ‘GCE’ ~few GeV gamma-ray signal
- Galactic positron annihilation radiation

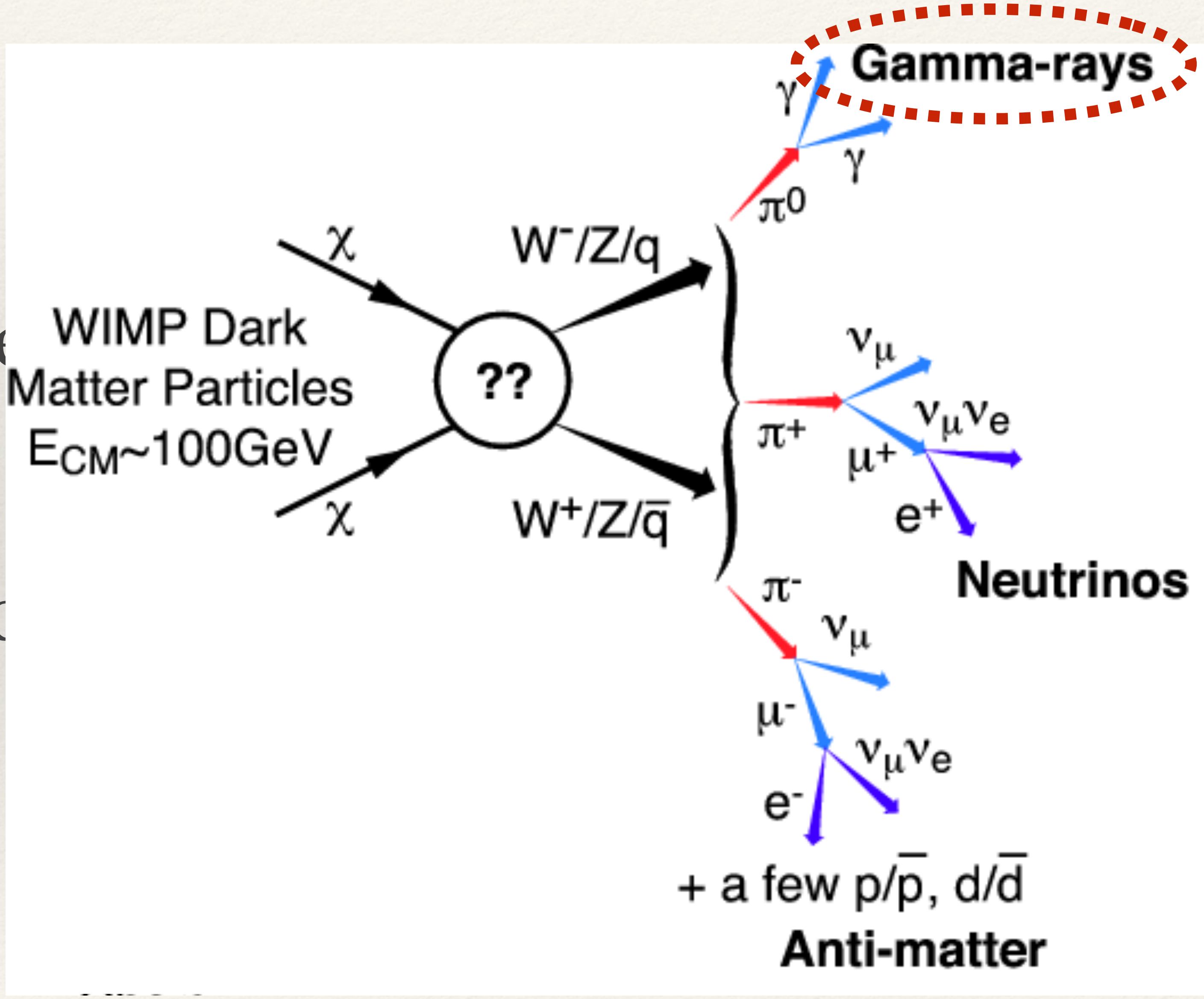
Two intriguing, high-energy signals from the Inner Galaxy:

- Galactic Ce nma-ray signal
- Galactic pc



Two intriguing, high-energy signals from the Inner Galaxy:

- Galactic Ce… …mma-ray signal
- Galactic po…



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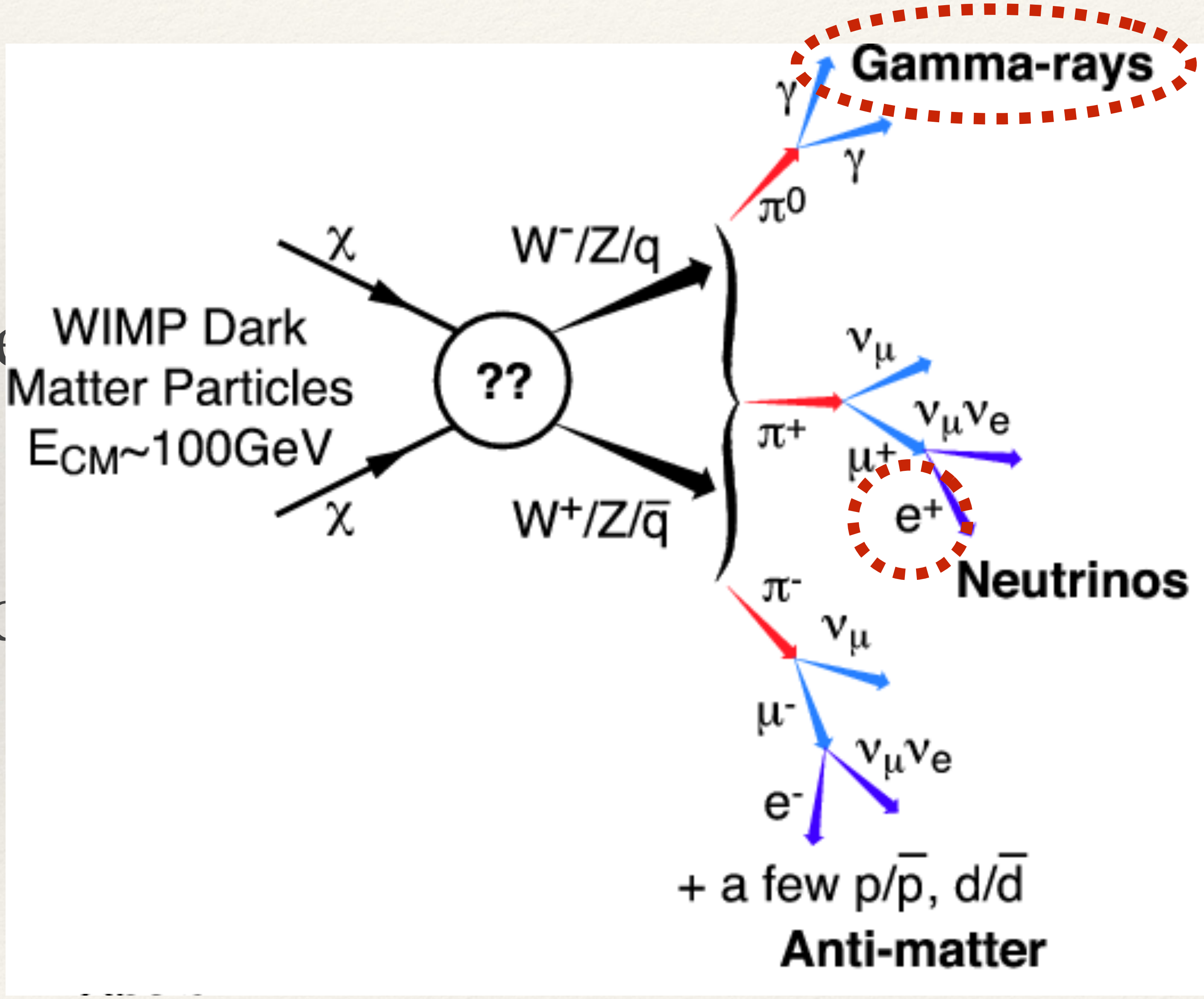

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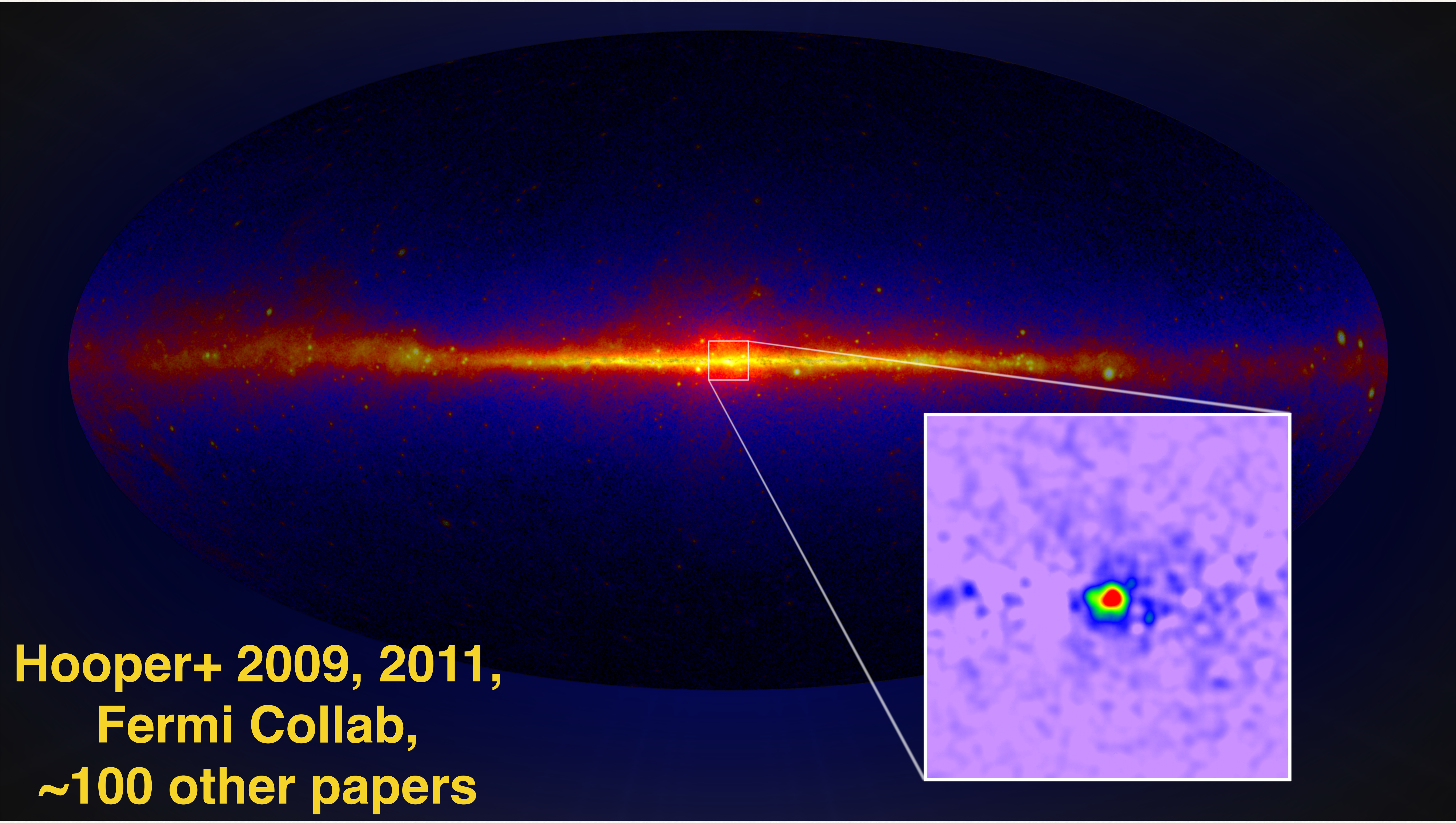
- Galactic po

Galactic Centre Excess



Galactic Center Excess (GCE)

From the Galactic Center out to mid-latitudes

Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
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Selig et al (2015)
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Gaggero et al (2015)
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Yand & Aharonian (2016)
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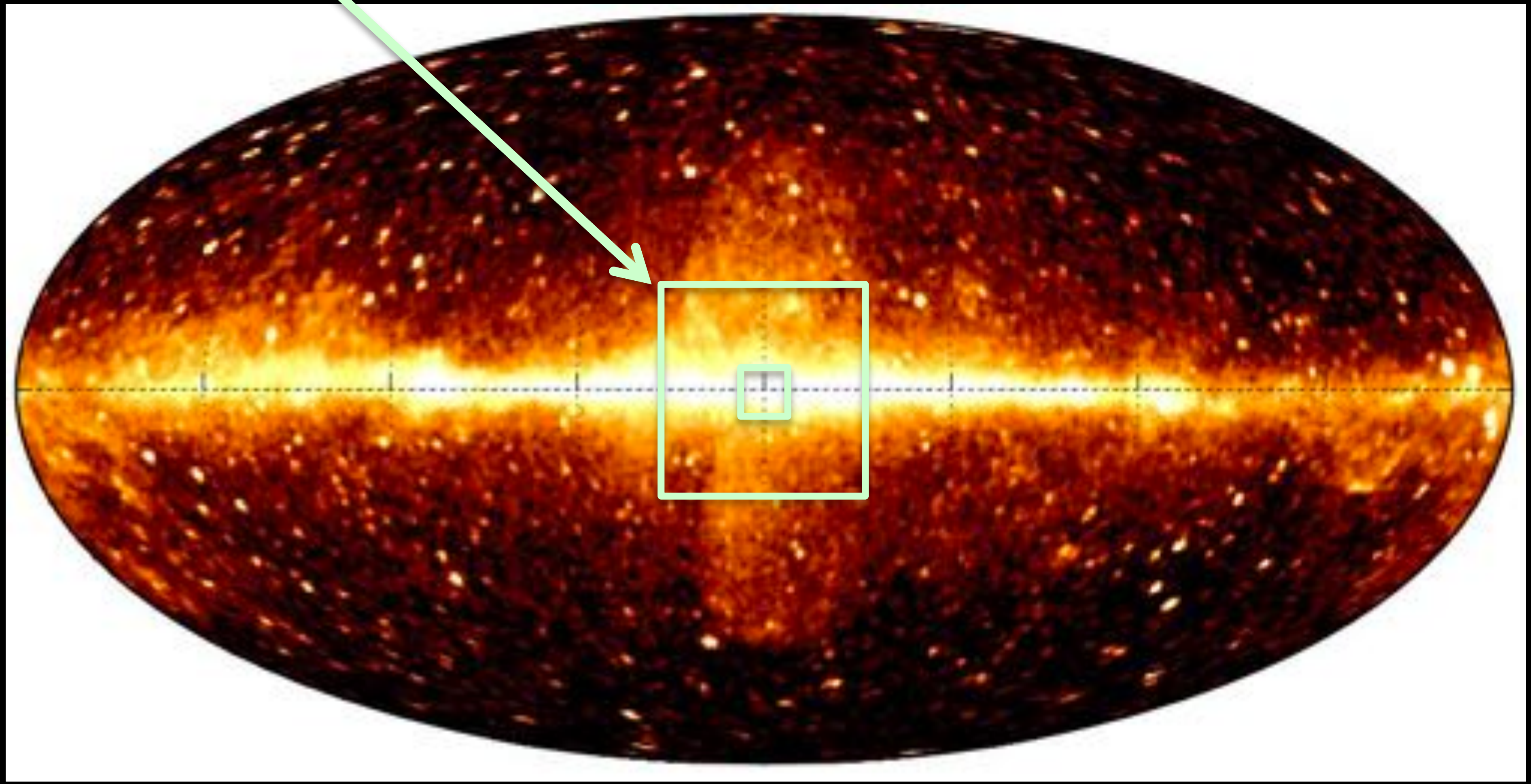
Lee et al (2016)
Bartels et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Ajello et al (2017)
Macias et al (2017)
Bartels et al (2017)
...

(not a complete list)

Method

Found by morphological template fitting



Fermi (2017)

slide credit:

Shunsaku Horiuchi (Virginia Tech)

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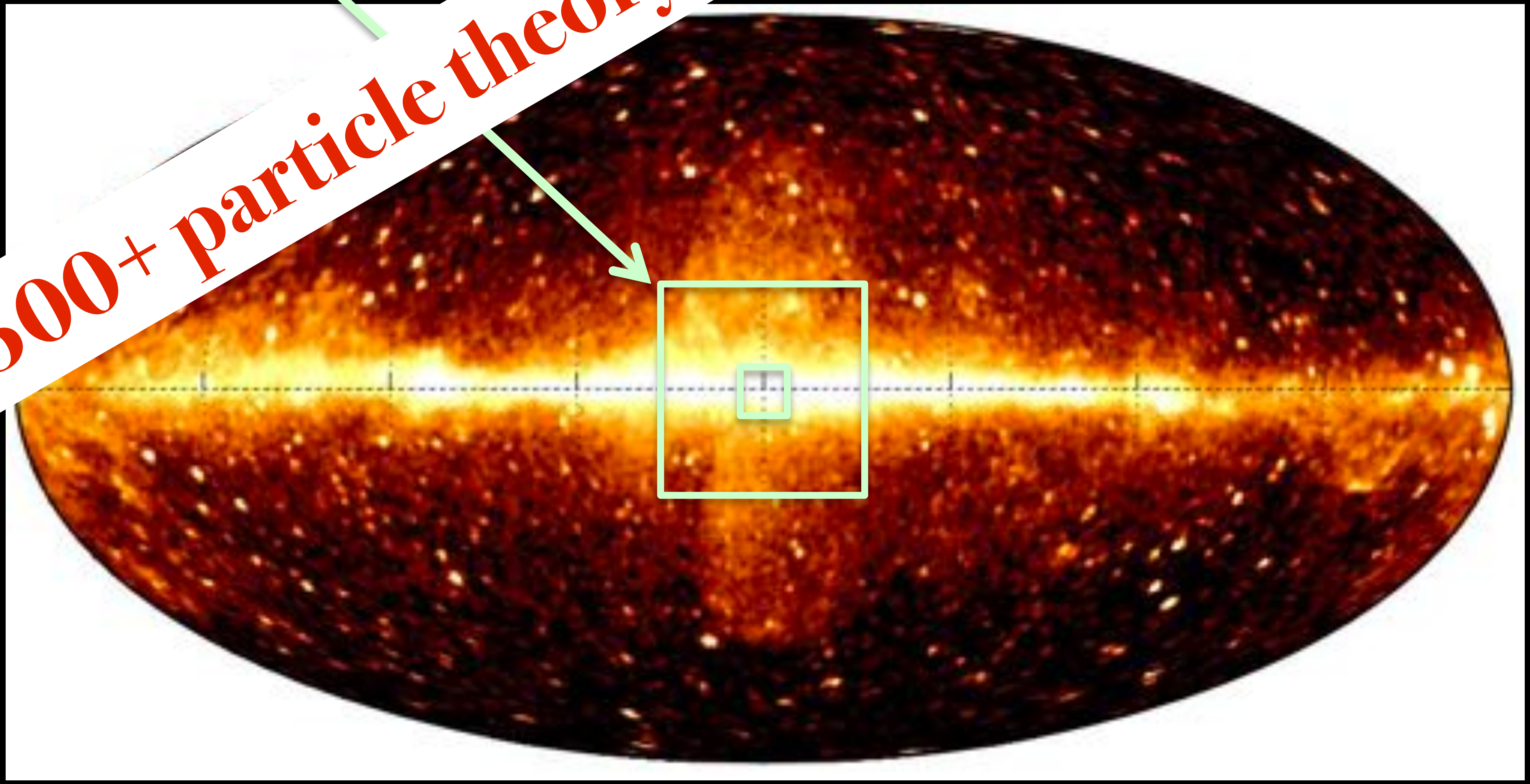
Macias et al (2017)
Bartels et al (2017)
...

(not a complete list)

Method

Found by morpholog... plate fitting

500+ particle theory papers



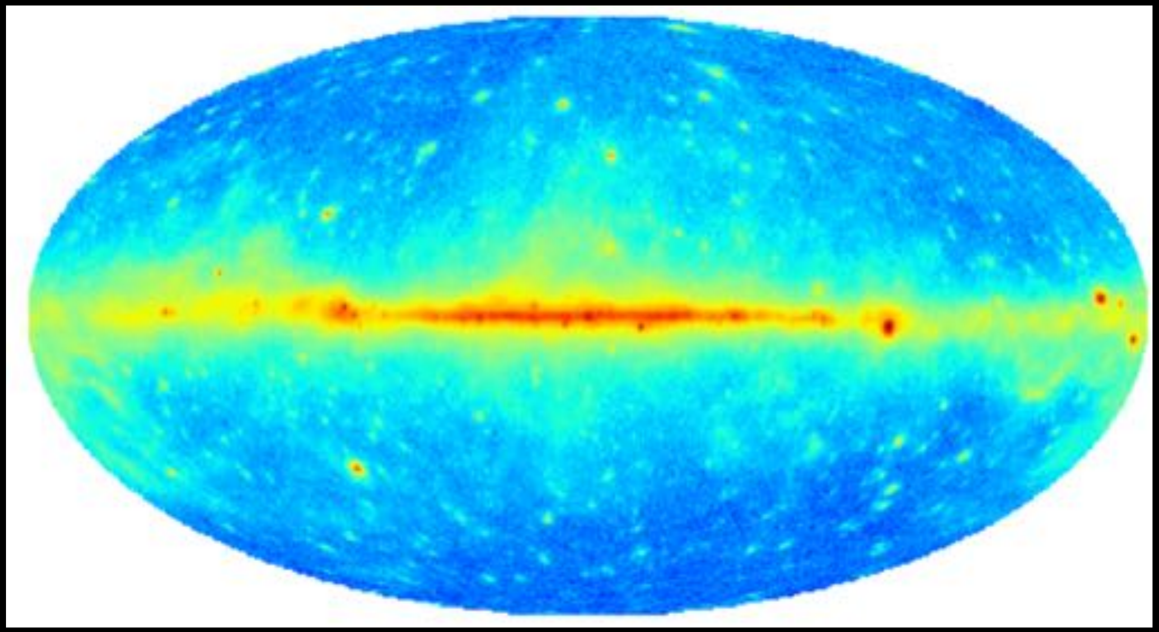
Fermi (2017)

slide credit:

Shunsaku Horiuchi (Virginia Tech)

Modeling strategy: template fitting

Data



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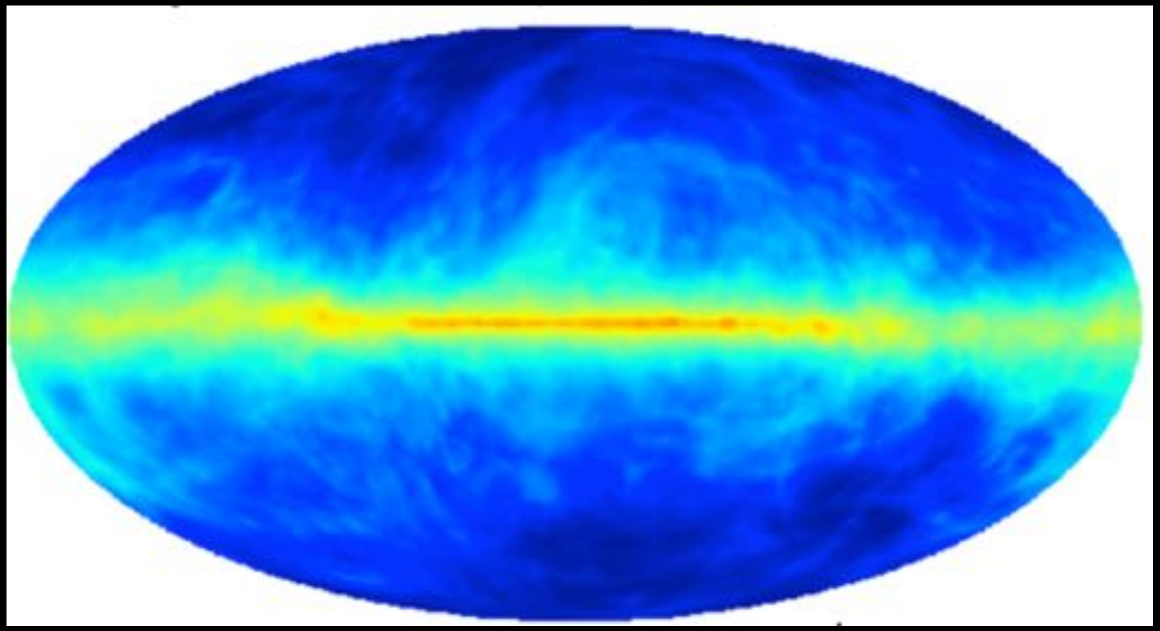
Galactic diffuse emission



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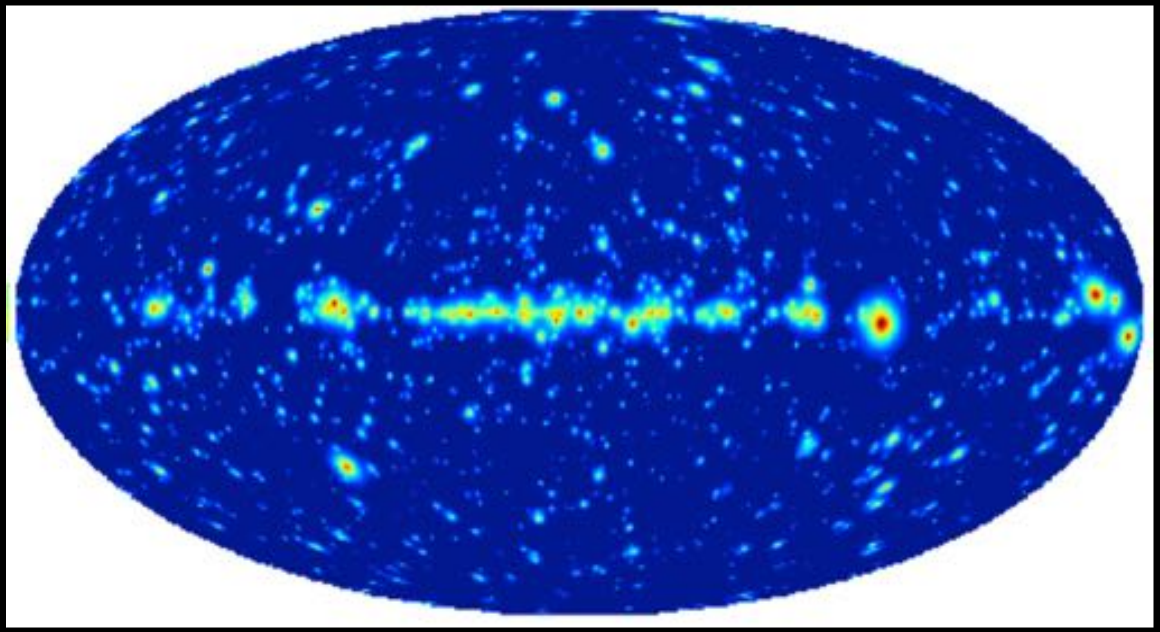
Known sources



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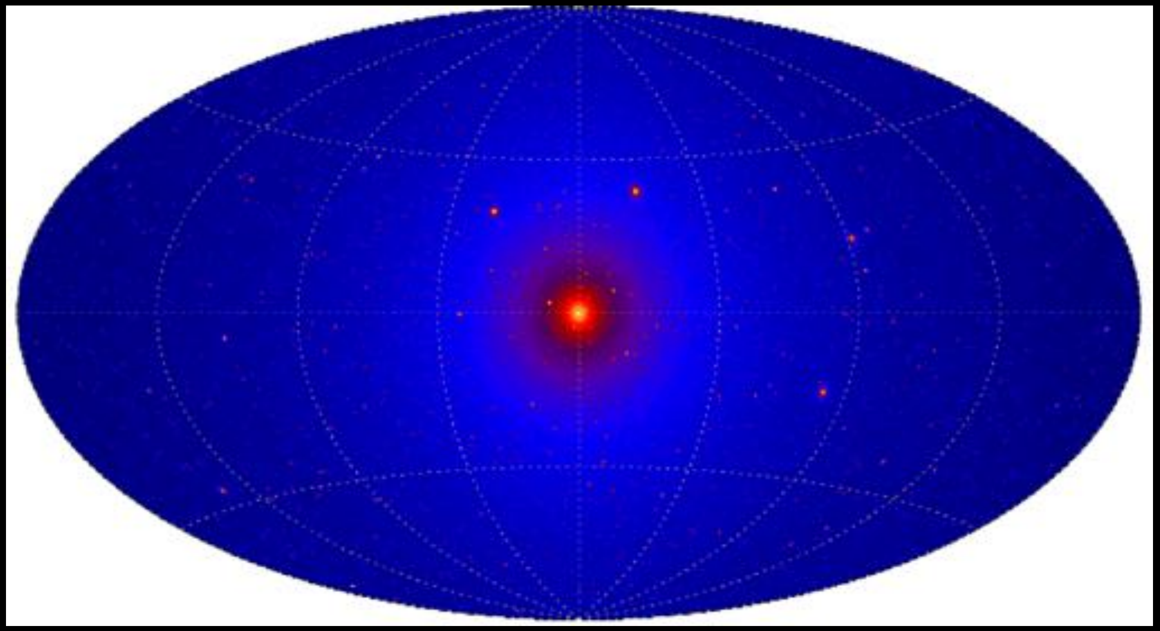
New sources, e.g., dark matter

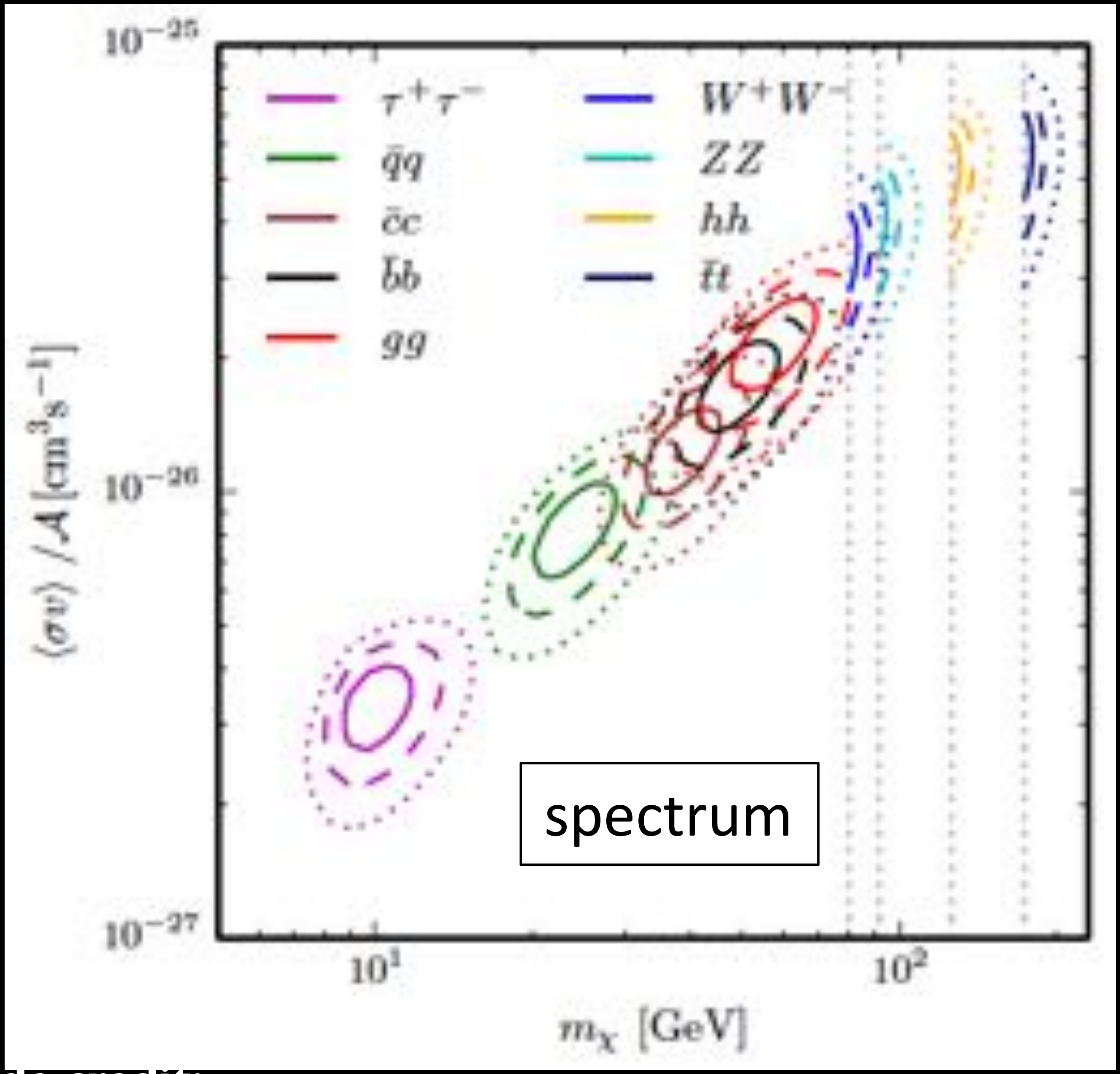


slide credit:

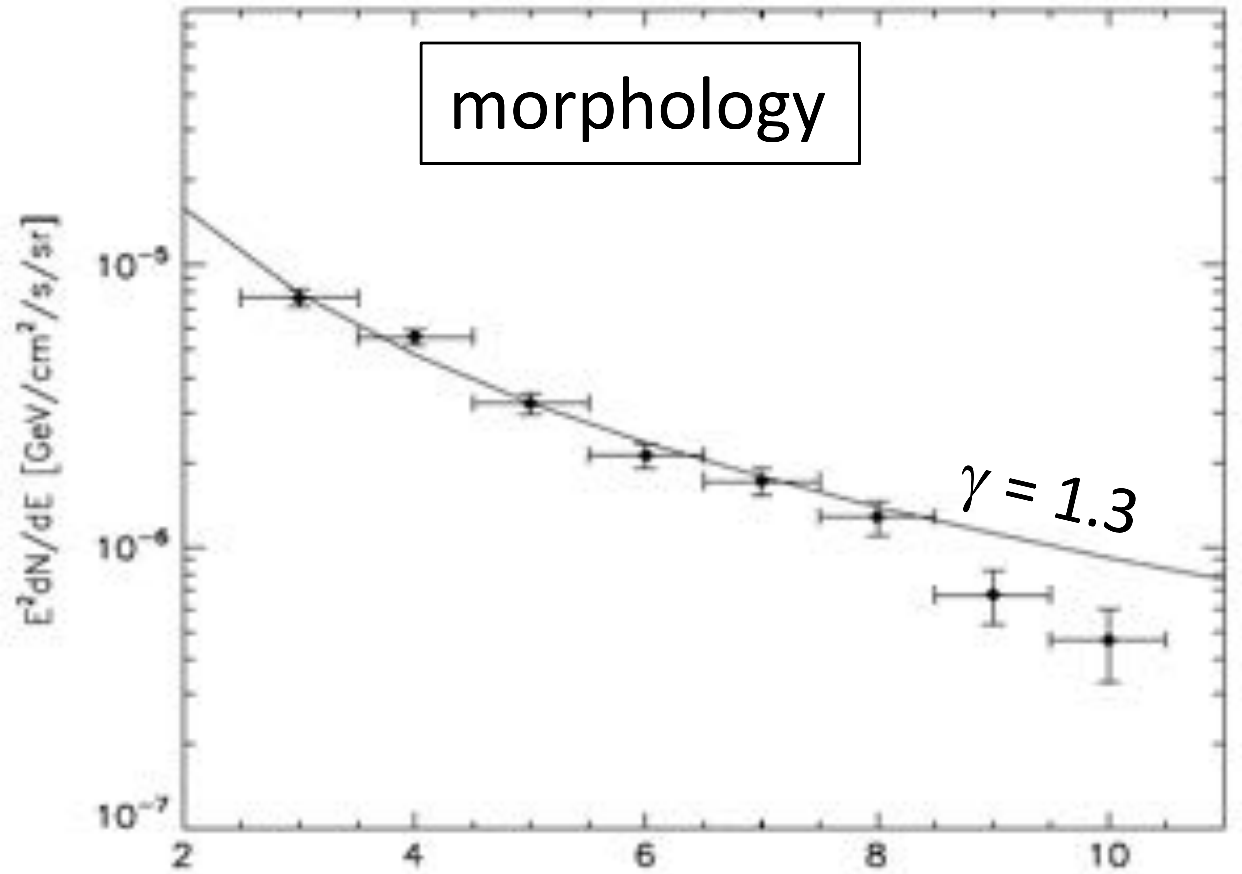
Shunsaku Horiuchi (Virginia Tech)

Dark Matter

Dark matter can explain the observations
Annihilation of thermally produced WIMPs explains the spectrum and morphology well



Calore et al (2014)



Daylan et al (2016)

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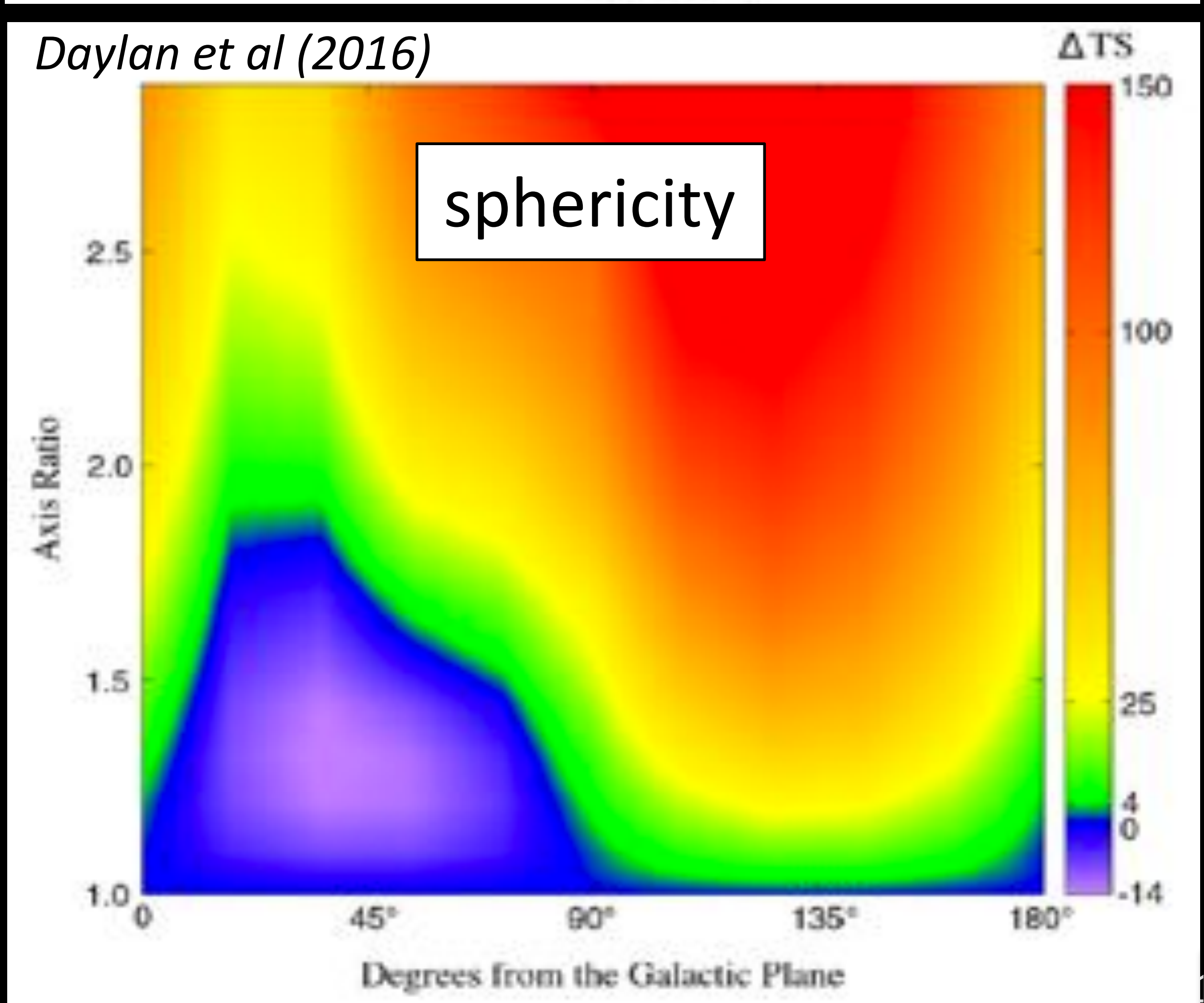


slide credit:
Shunsaku Horiuchi (Virginia Tech)

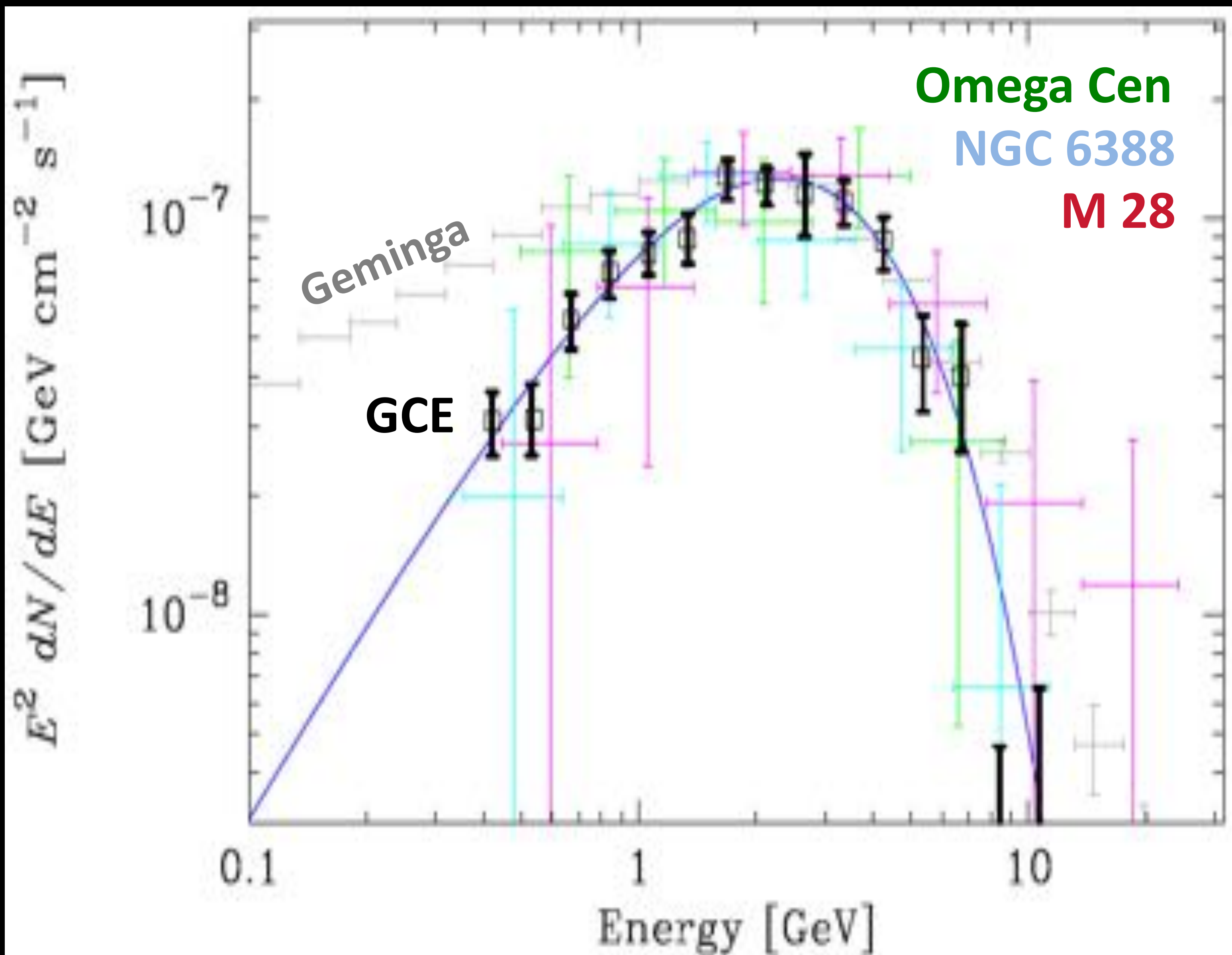
Three points about the GCE

- The signal is spectrally similar to that detected from pulsars and millisecond pulsars (MSPs)
- Photon count statistics suggest sub-threshold point sources are contributing ~100% of the signal
- GCE is spatially correlated with old stellar population of the Inner Galaxy

Spectral similarity with millisecond pulsars

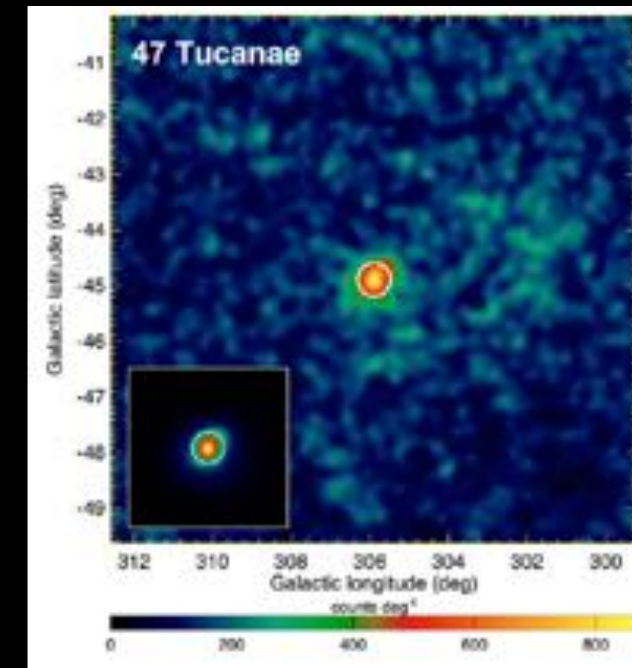
Millisecond pulsars

- Millisecond pulsars are gamma-ray sources with similar spectra to the GCE.
- *O*(5,000) needed in the Galactic Center

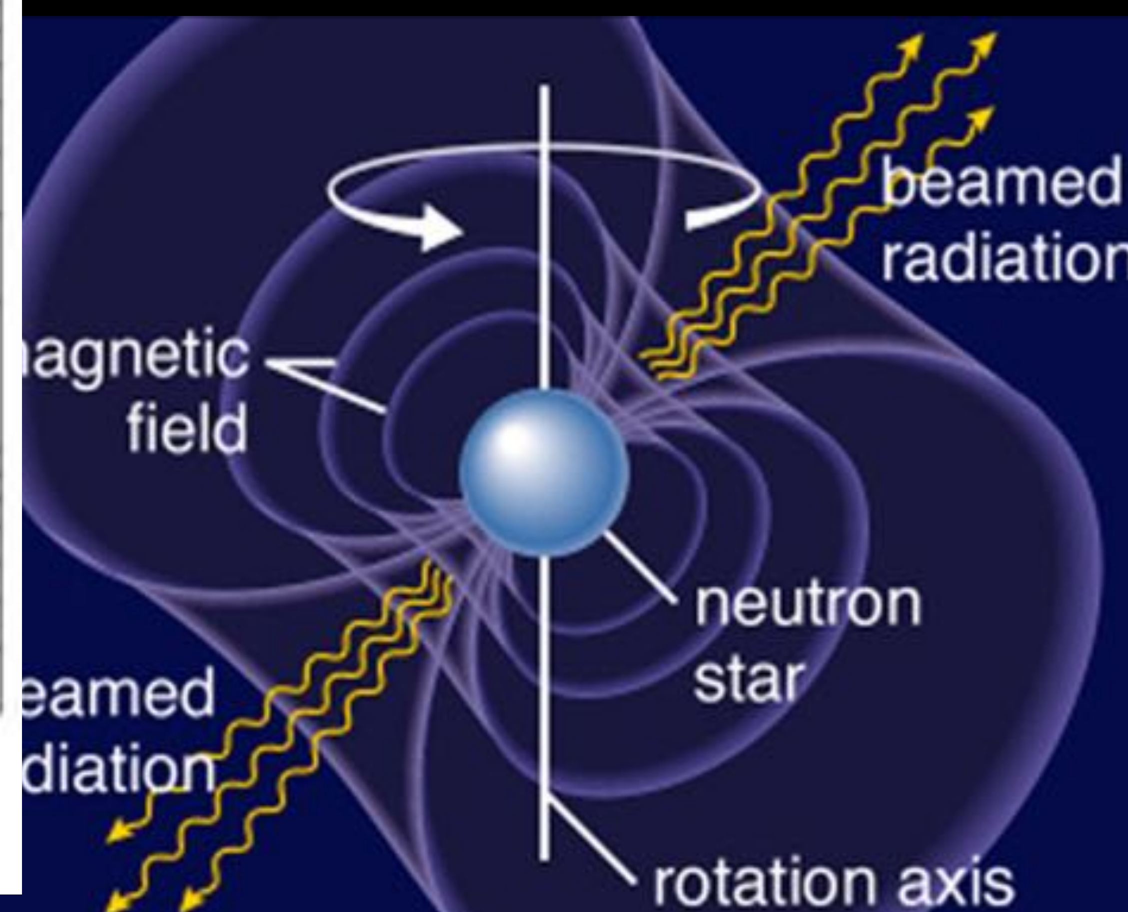


Abazajian (2011)

Globular clusters detected in gamma rays

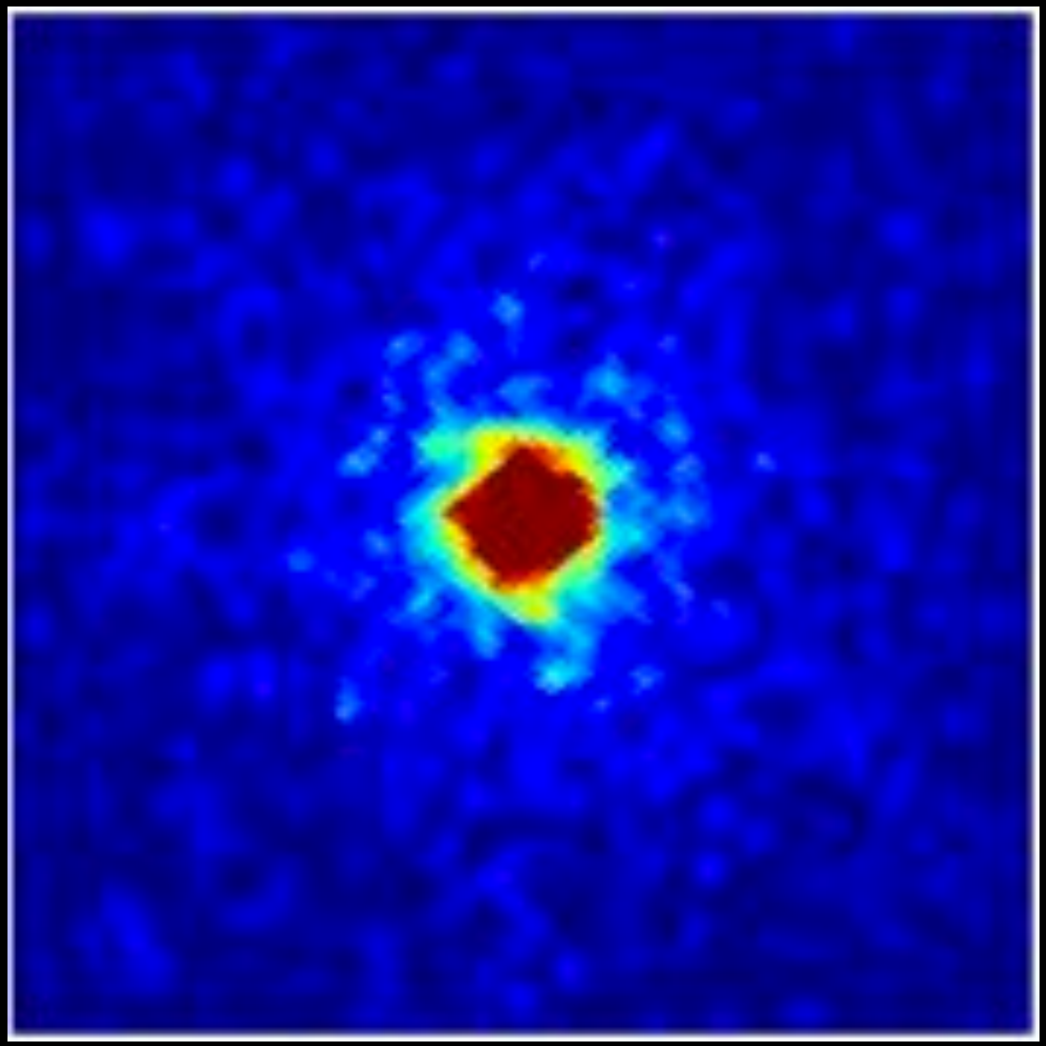


Fermi (2010)

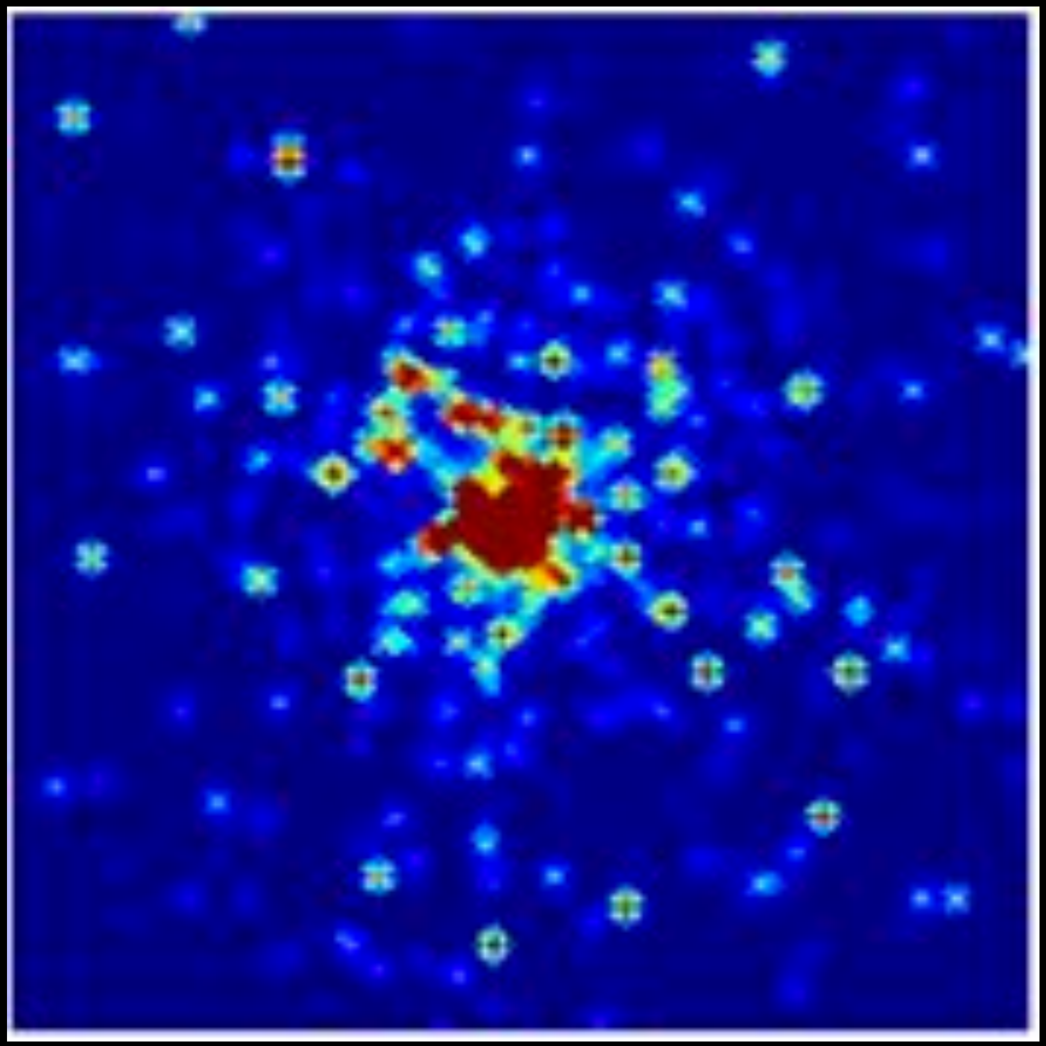


slide credit:
Shunsaku Horiuchi (Virginia Tech)

point source vs diffuse source



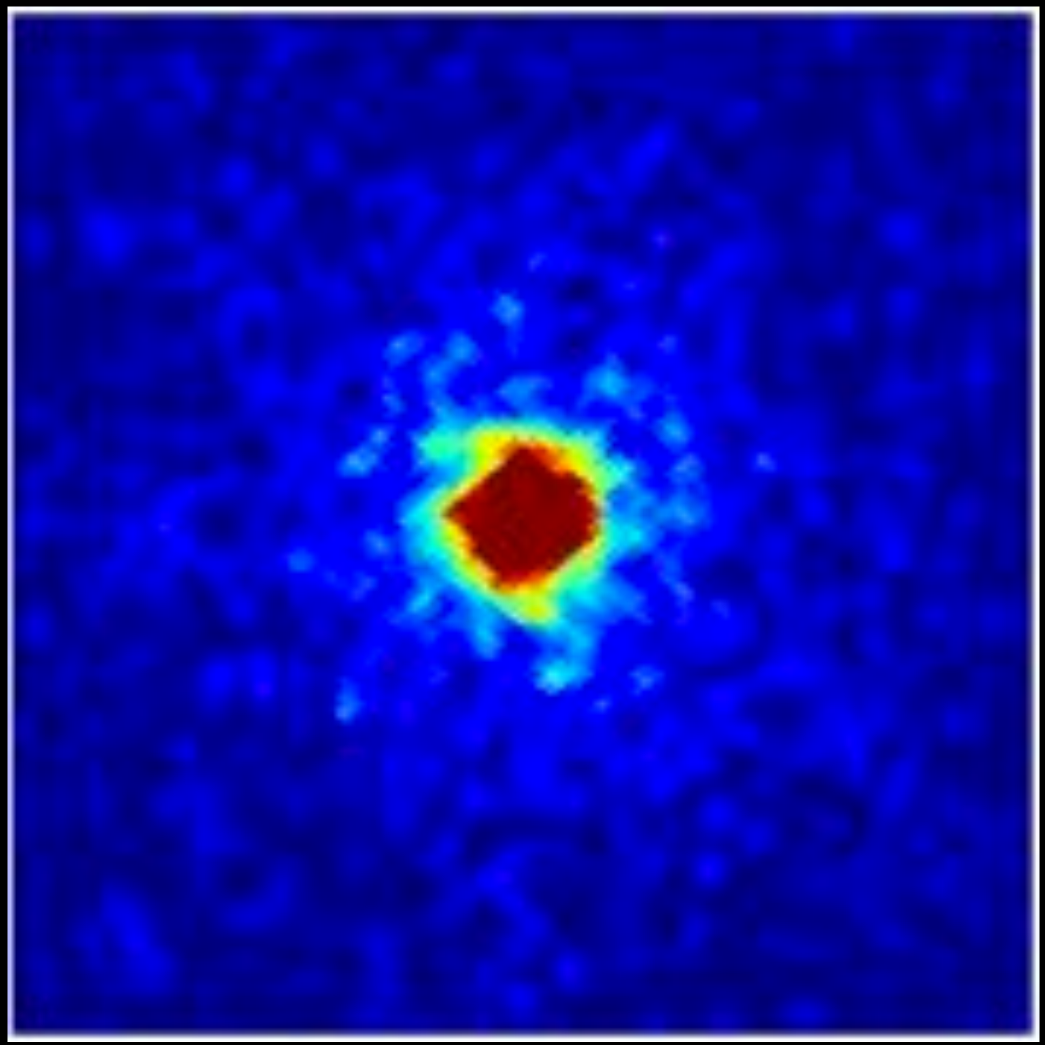
vs



Lee et al (2016)

slide credit:
Shunsaku Horiuchi (Virginia Tech)

point source vs diffuse source



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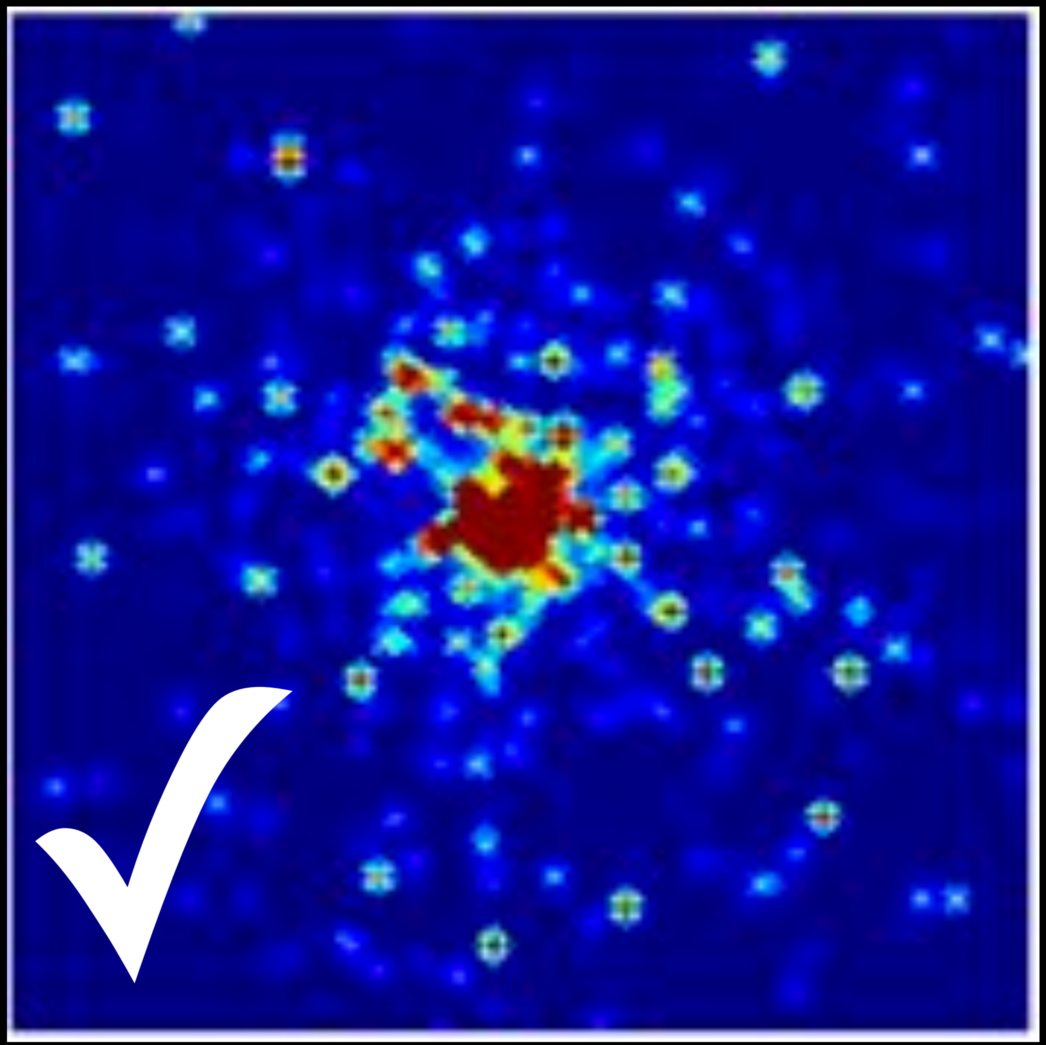


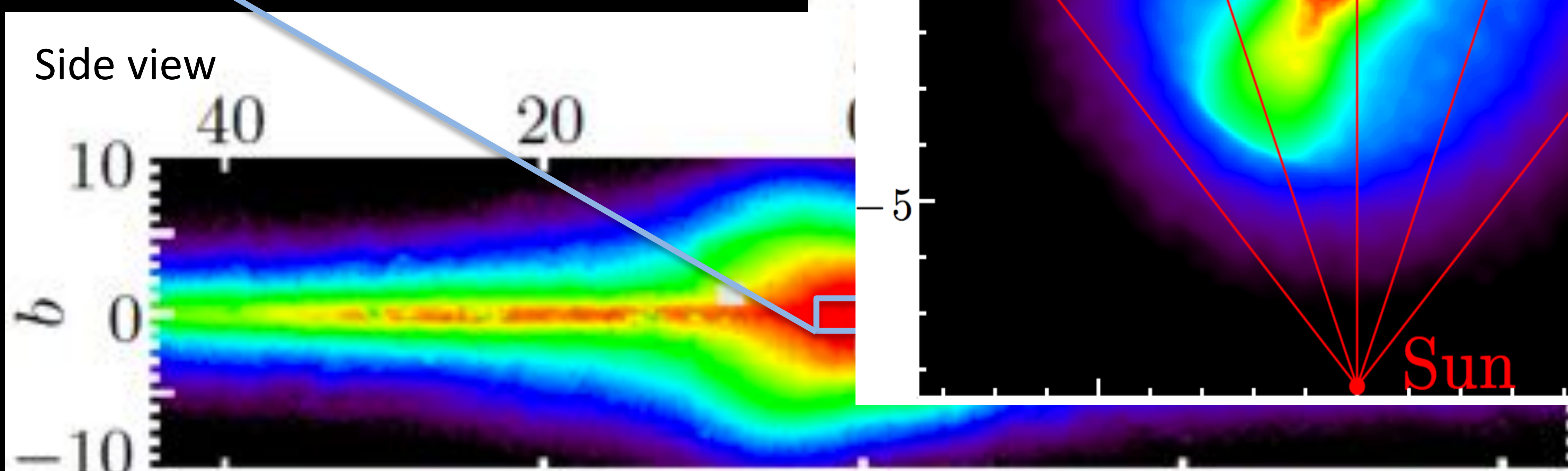
Lee et al (2016)

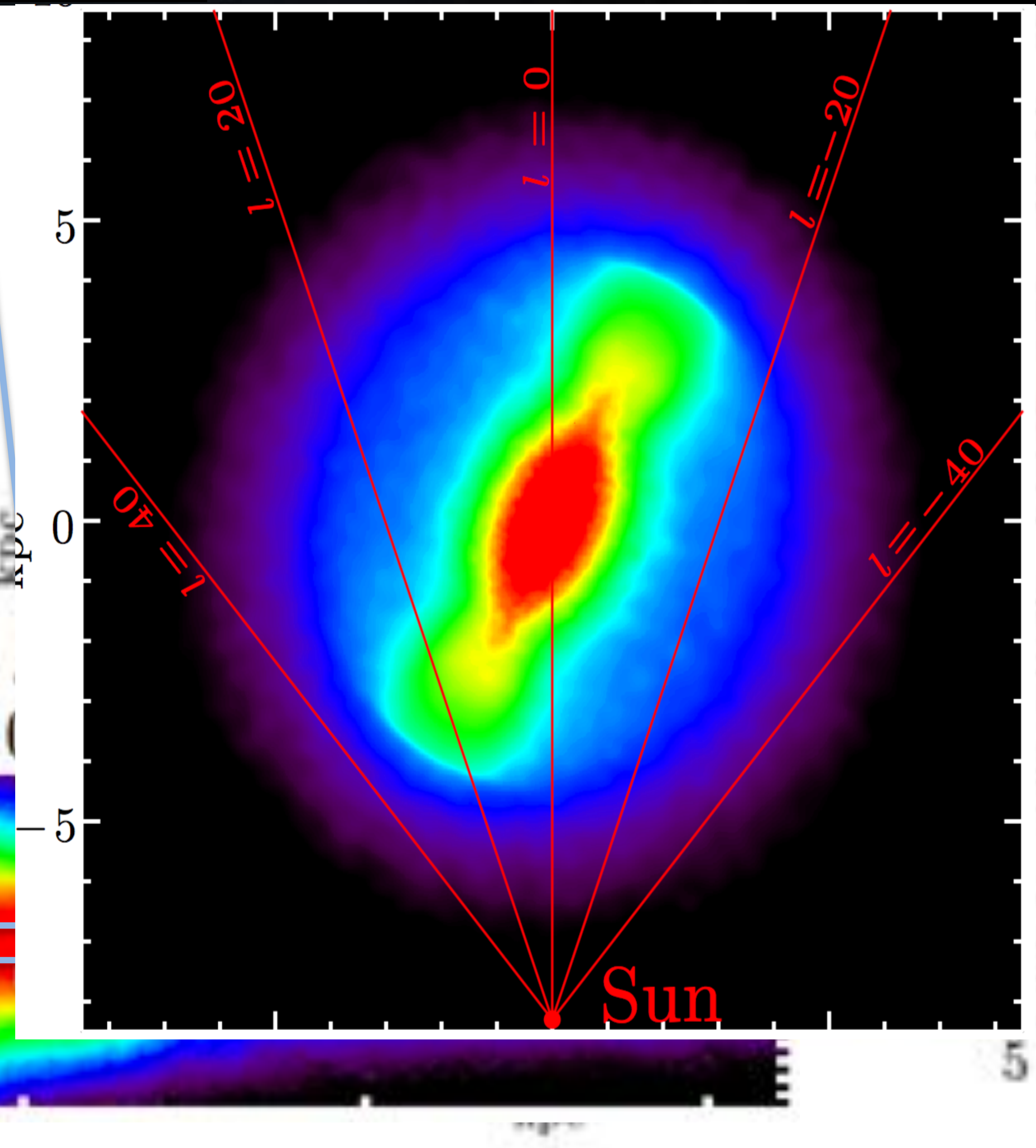
slide credit:
Shunsaku Horiuchi (Virginia Tech)

The Galactic Bulge

Nuclear Bulge: central stellar cluster + disk

The boxy bulge:
rectangle, not symmetric





slide credit:
Shunsaku Horiuchi (Virginia Tech)

Bland-Hawthorn & Gerhard (2017)

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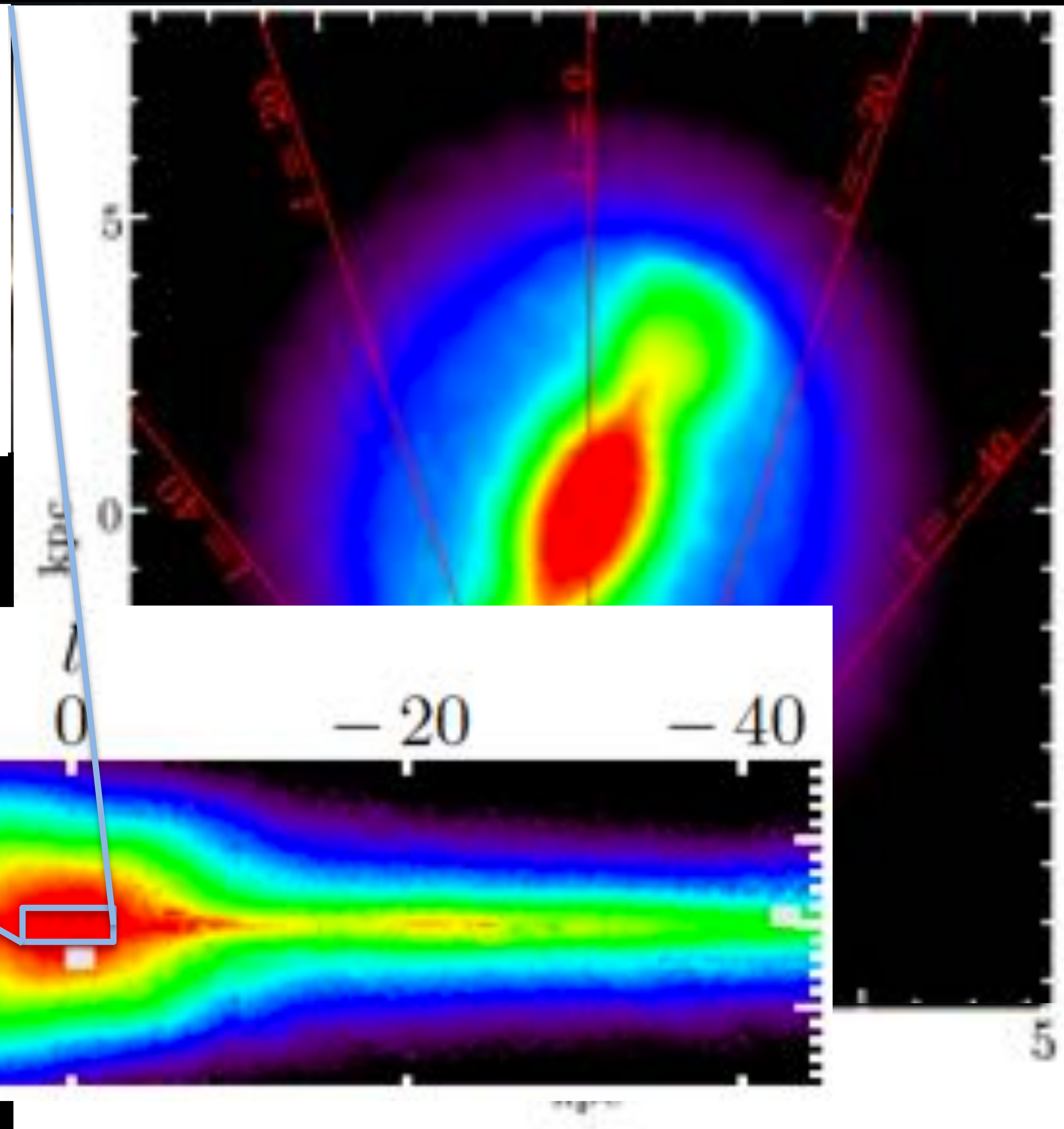

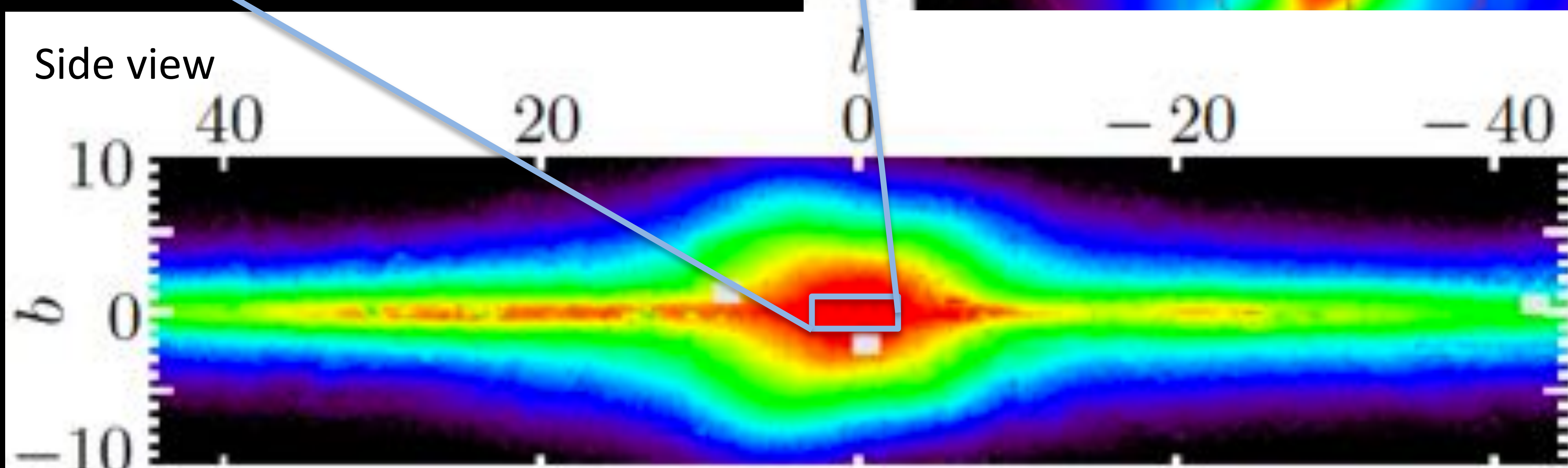

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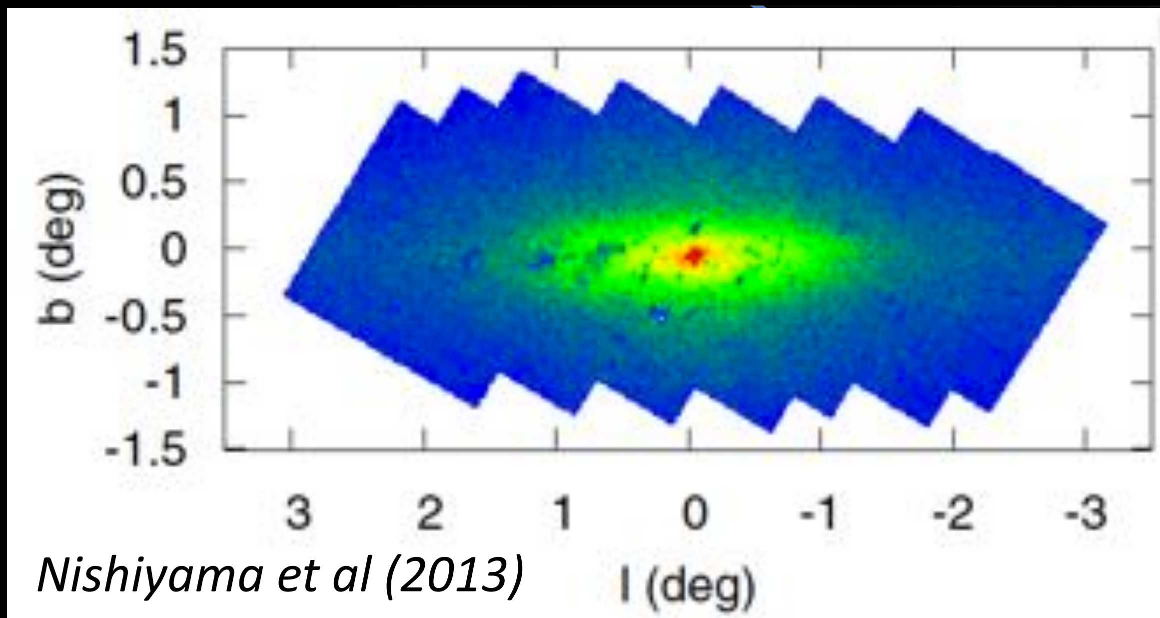

Nishiyama et al (2013)

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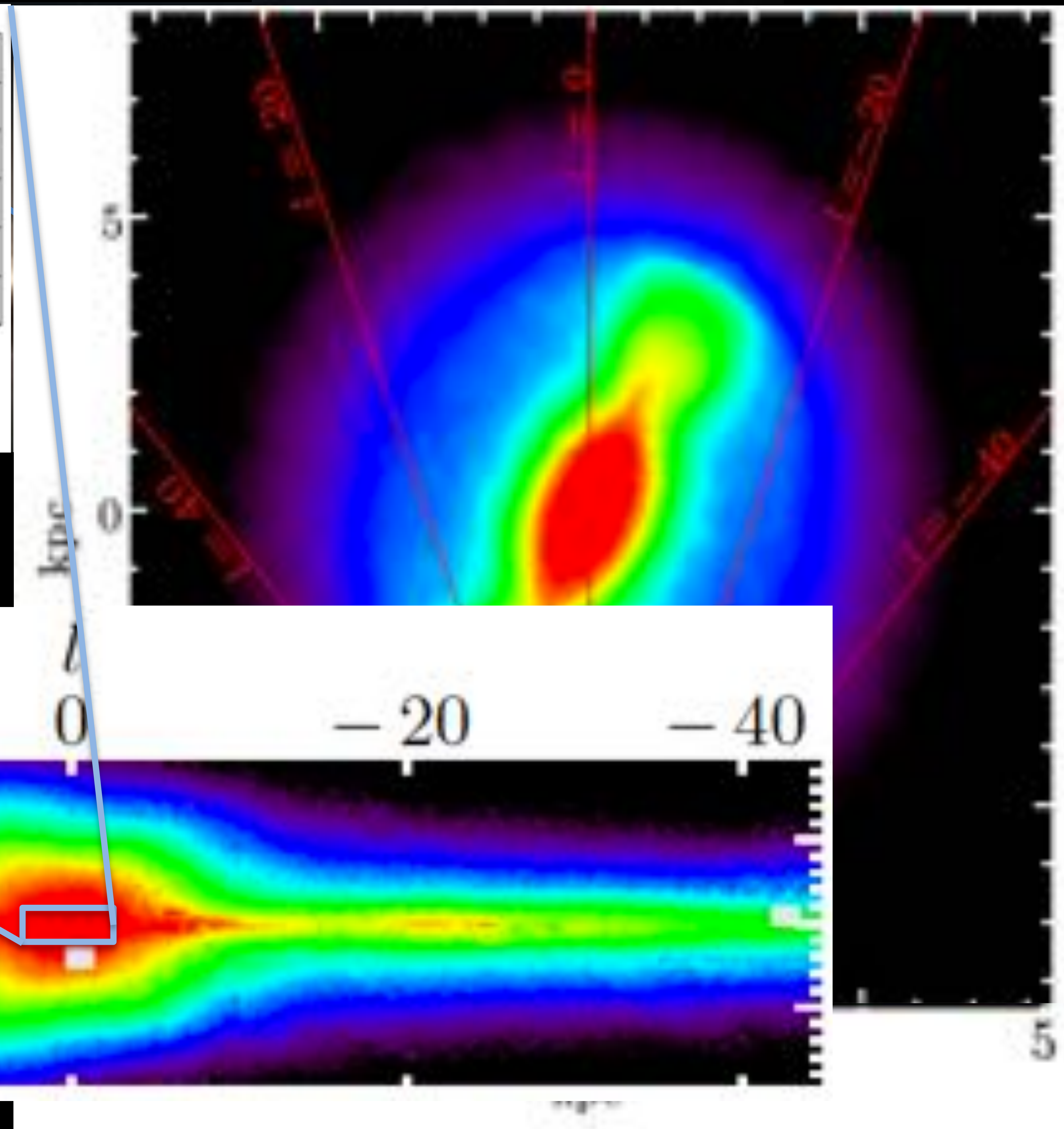
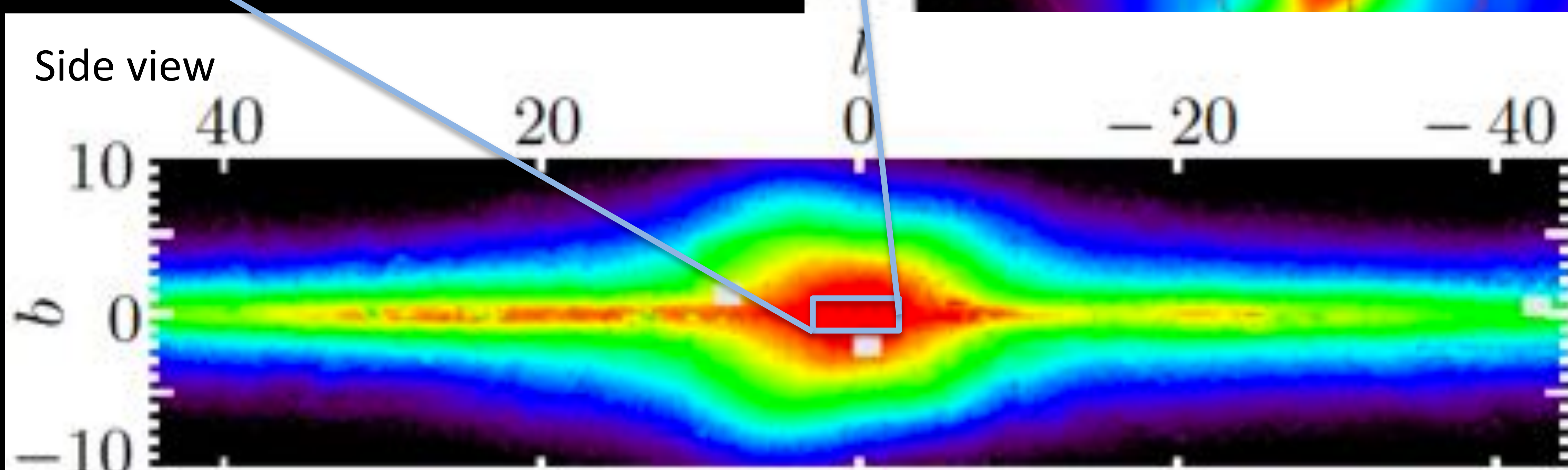




slide credit:
Shunsaku Horiuchi (Virginia Tech)

Bland-Hawthorn & Gerhard (2017)

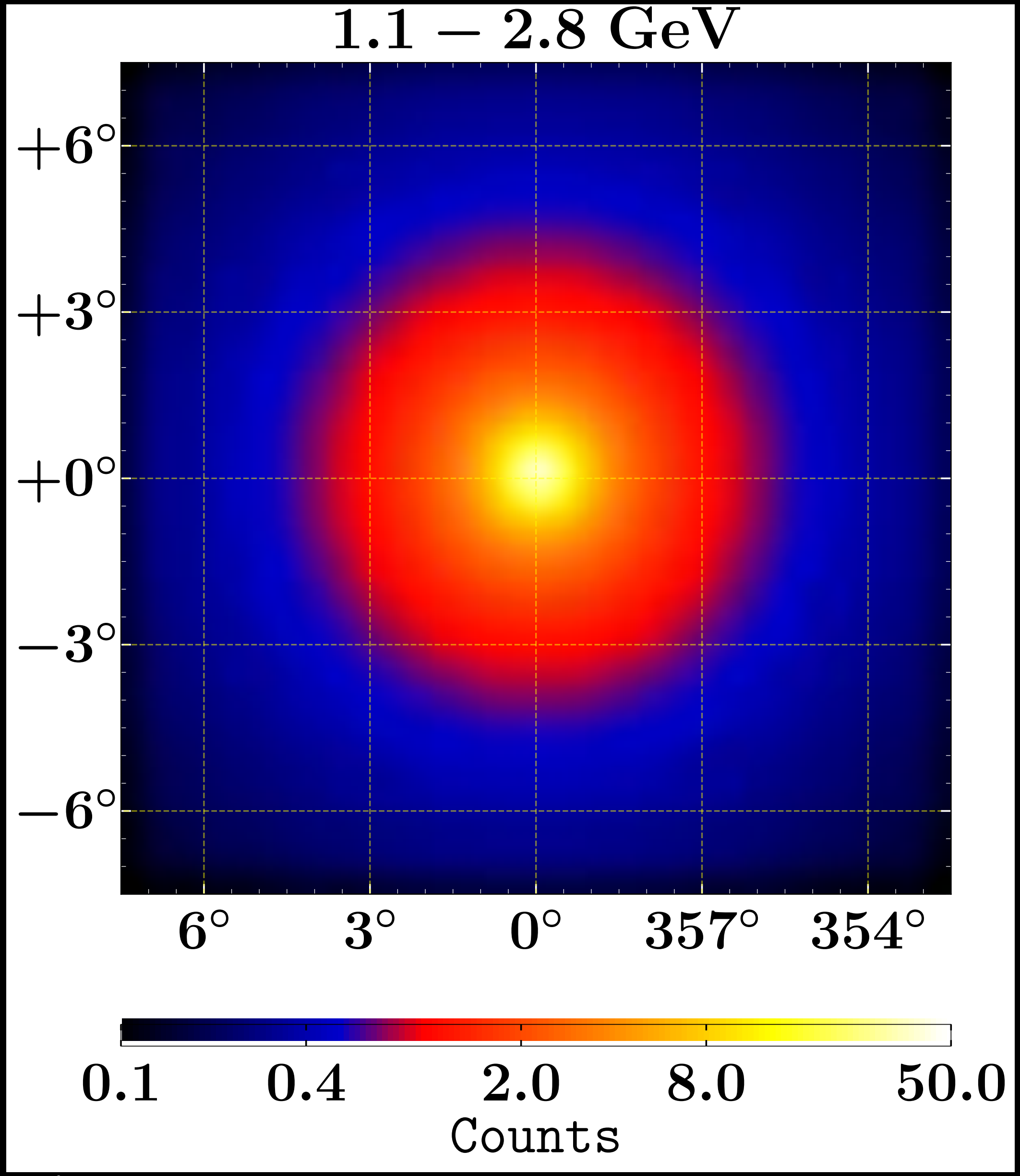
Bulge preferred over spherical symmetry

Bulge over NFW²

When a bulge model is included, the detection of NFW² falls ($\sigma < 3$) while bulge significance is $\sigma > 10$.

This is robust to

- Point sources used
- Diffuse emission models used
- Galactic mask



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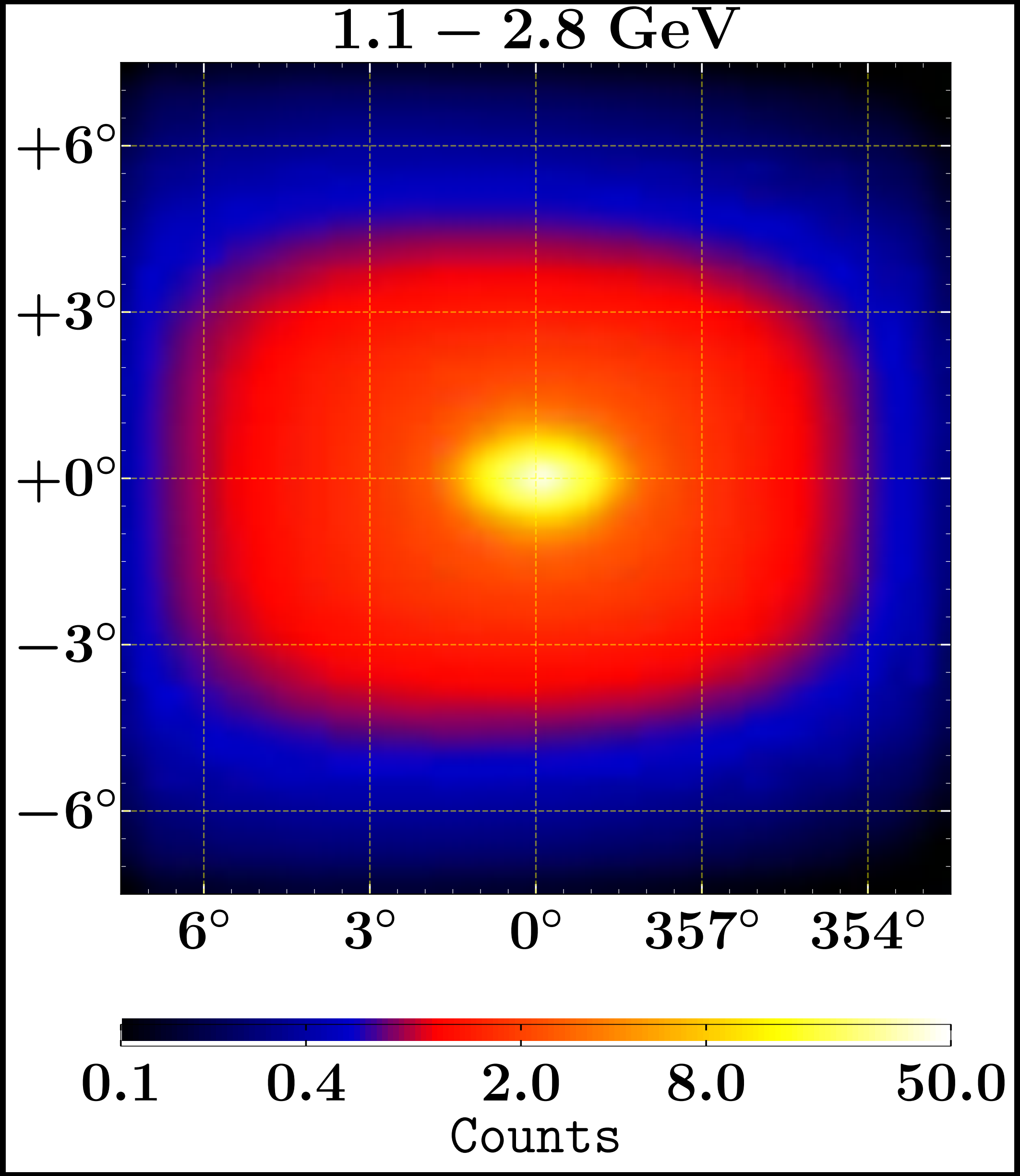

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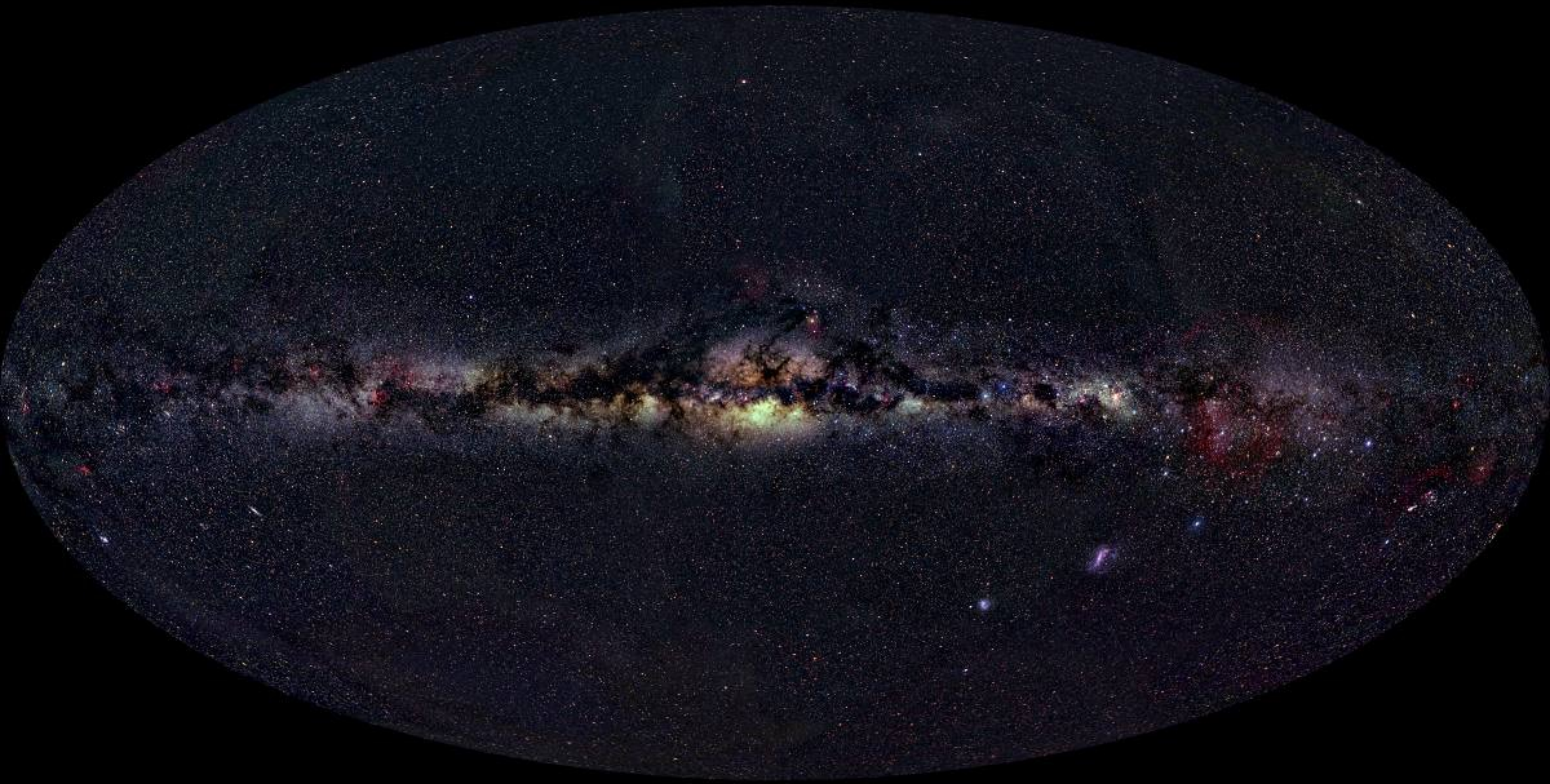
Shunsaku Horiuchi (Virginia Tech)

A Few Words on the Origin of Galactic Positrons



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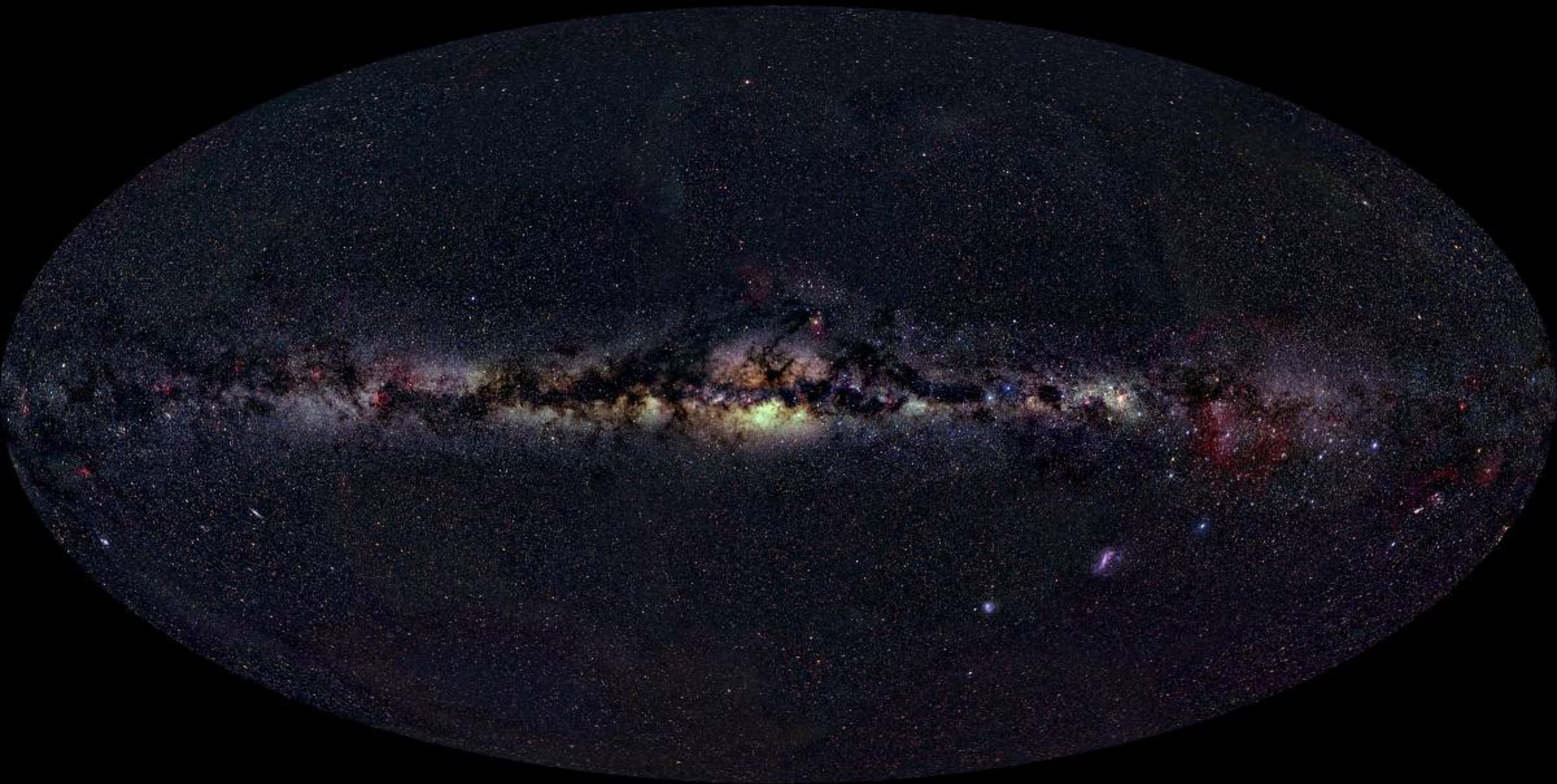

Crocker, Ruiter, Seitenzahl, Panther+ 2017 (Nature Astronomy)

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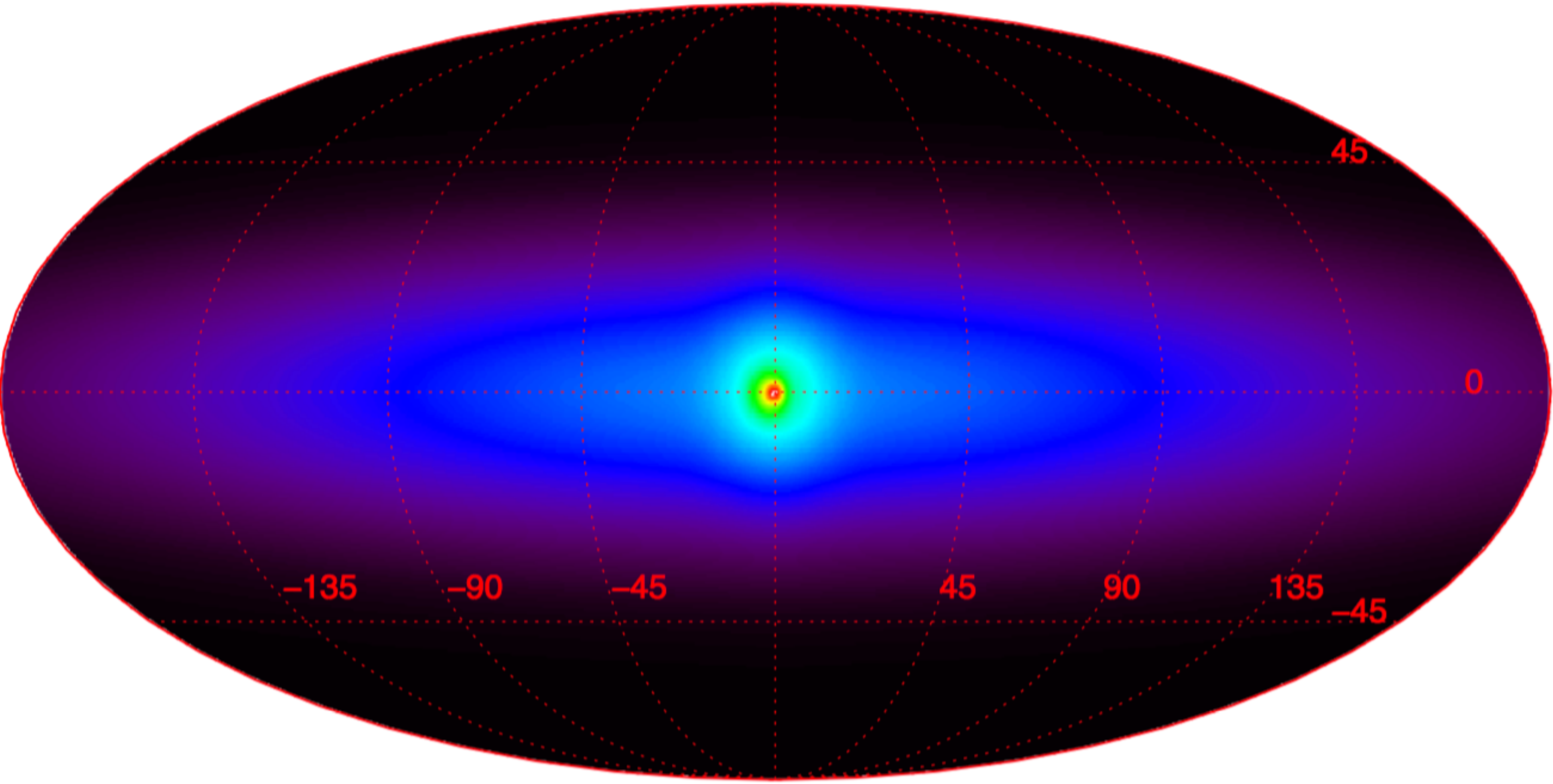

Crocker, Ruiter, Seitenzahl, Panther+ 2017 (Nature Astronomy)

Galactic, low-energy positron population

- Existence of low energy, trans-relativistic positron (**e^+**) population demonstrated by annihilation radiation from the Inner Galaxy
- [Not to be confused with the directly-detected local cosmic ray positron population]
- ~5 x 10^{43} e^+/s annihilate in the Galaxy (Siegert et al. 2016)

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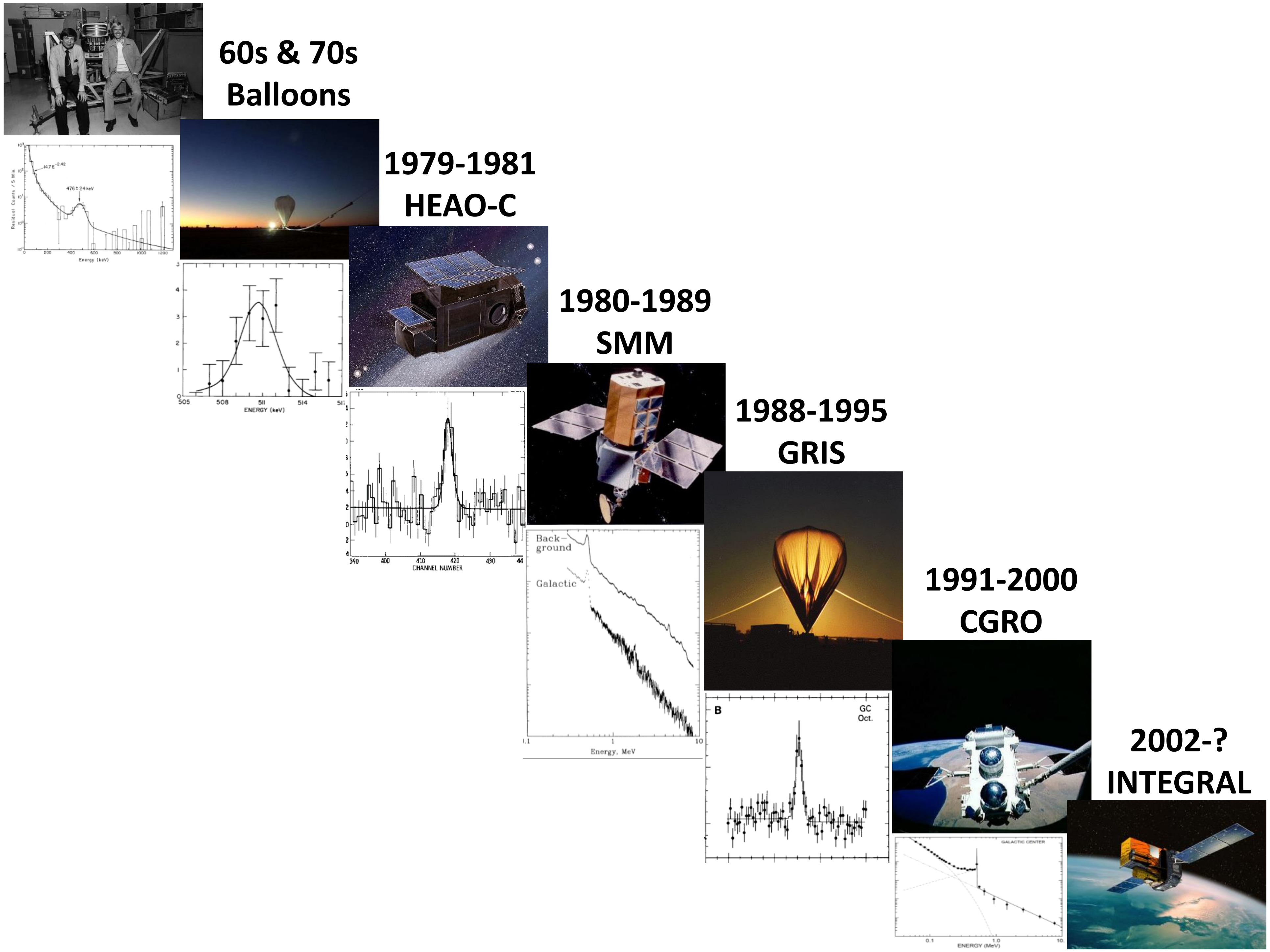
slide credit:
Thomas Siegert

Positron Annihilation Observations

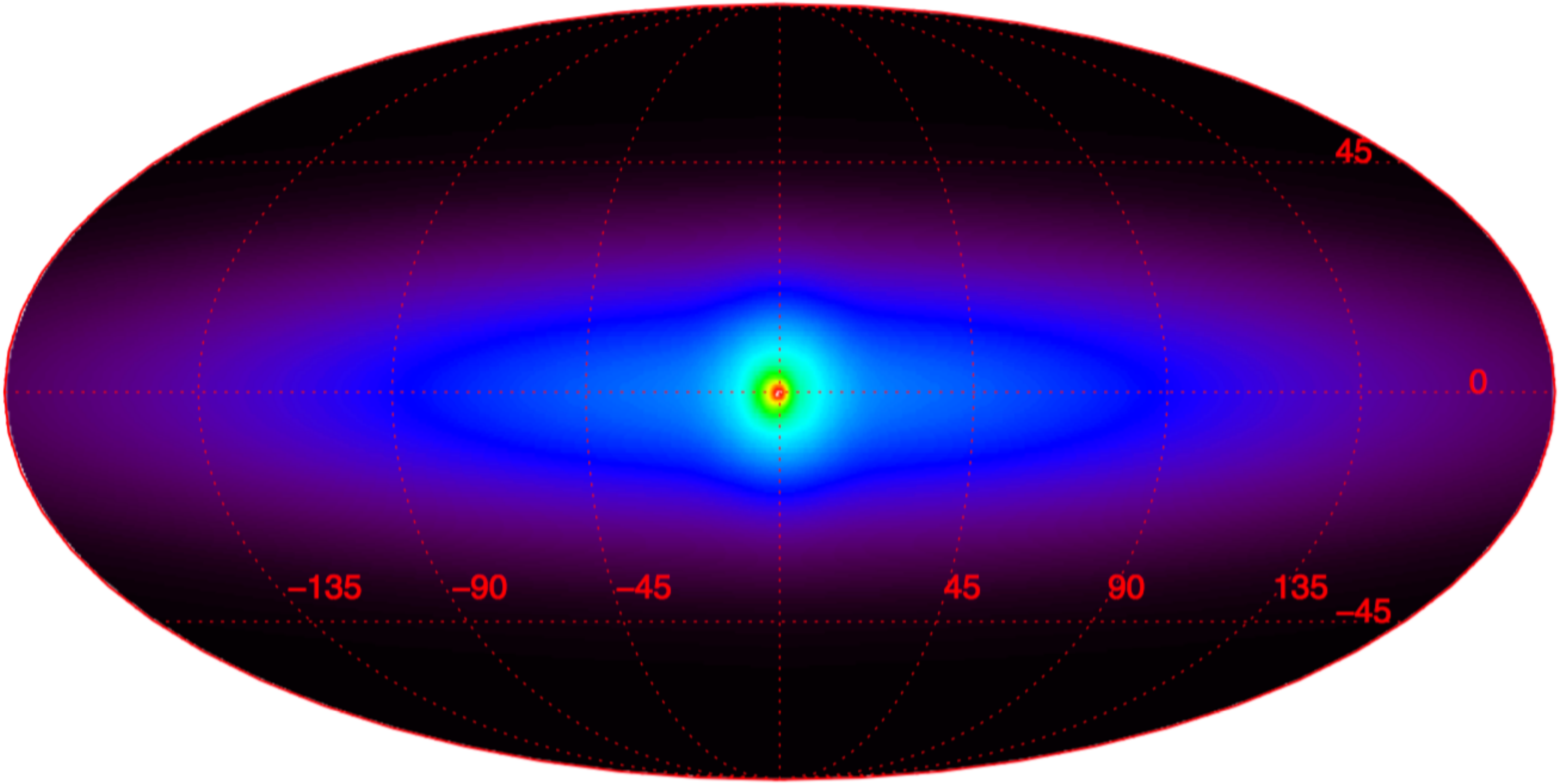


Diffuse, Galactic positron annihilation signal detected for more than 40 years, first with balloon-borne, and more recently satellite (COMPTEL, INTEGRAL) experiments

Positron Annihilation Observations

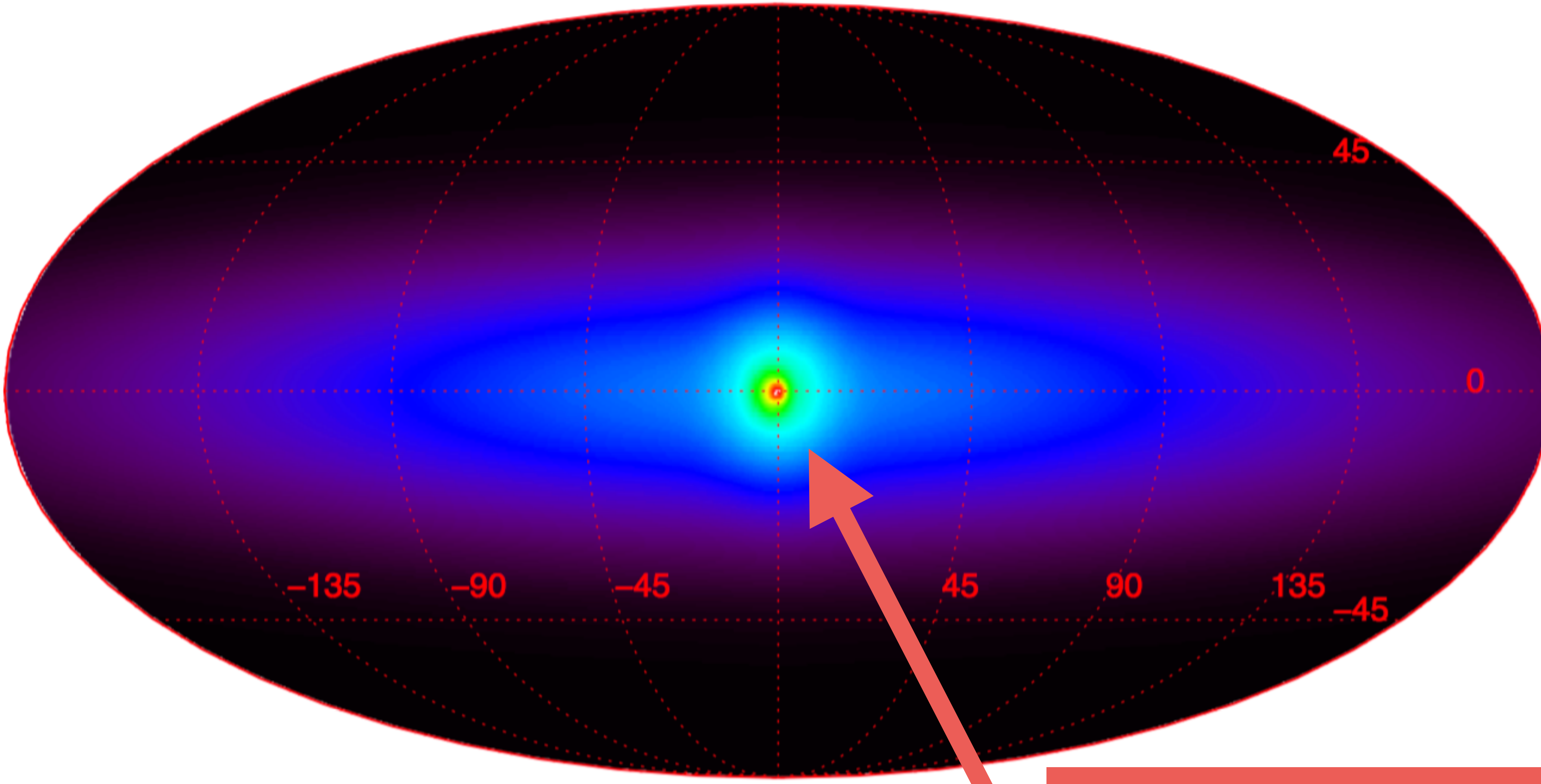
- Coded mask instruments (non-focusing) with poor angular resolution (~3°)
- Very strong cosmic ray backgrounds due to space environment
- Construct *models* for 511 keV sky distribution rather than *images*

Positron Annihilation Observations



Siegert et al. 2016

Positron Annihilation Observations

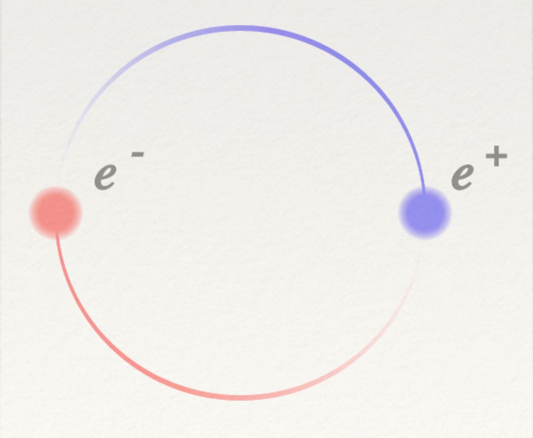


NB: this is a model, not an image

Siegert et al. 2016

Positron Annihilation Observations

- Depending on ISM conditions, positrons annihilate in flight or form a *positronium* atom and then annihilate



Positron Annihilation Observations

- Continuum gamma-rays below 511 keV and 511 keV line widths inform us that most (~100%) of positrons annihilate through the formation of positronium

- Positron annihilation is tracing the moderately warm and partly ionised interstellar gas:
$T \approx 8000$ K, $n_H \approx 0.1$-0.3, $x_{ion} \approx 0.05$-0.2 (Siegert et al. 2016)

Positron Annihilation Observations

- Central mystery: very large positron luminosity ratio bulge:disk (**B/D**)…*not seen at any other wavelength*
- ***Historically***: bulge/disk positron luminosity:

  B/D ~ 1.4

  $\gg$ Star Formation Rate$_{[\text{bulge}]}$/SFR$_{[\text{disk}]}$ ~ 0.1

  > Mass$_{[\text{bulge}]}$/Mass$_{[\text{disk}]}$ ≃ 0.4

large B/D

- Large B/D prompted theories of “special source” in the inner Galaxy:

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  - same constraint tends to rule out compact sources like pulsars
  - on the other hand, perfectly consistent with e^+ from β^+ decay of radionuclides synthesised in stars and/or supernovae…

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    - ...ule out compact sources like pulsars
    - ..., perfectly consistent with e⁺ from β^+ decay of radionuclides ...n stars and/or supernovae…

Energy constraints imply that e⁺ do not travel far (<kpc) in their lifetimes ⇒ the annihilation line distribution traces the positron source distribution

New observational situation following Siegert+2016 results:

- now much more low surface brightness emission from disk detected
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…means that positron source connected to OLD STARS could work

New observational situation following Siegert+2016 results:

- Also new: detection (>5σ) of separate positron source in the Galactic nucleus
- Poor angular resolution of INTEGRAL SPI (~3°) means that we do not know whether this source is
  - truly the super-massive black hole ***or***
  - the Nuclear Bulge/Central Molecular Zone region of ~300 pc width surrounding the SMBH

New observational situation following Siegert+2016 results:

- Note that a stellar positron source connected to OLD stars could explain entirety of gross, Galactic positron injection morphology because
  - B/D ≃ (0.42±0.09)

    $\simeq \mathrm{Mass}_{[\mathrm{bulge}]}/\mathrm{Mass}_{[\mathrm{disk}]}$
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...but exactly how old would stellar positron sources need to be?

Source Age More Quantitatively with *Delay Time Distribution*

$$R_X[t] = \nu_X \int_0^t DTD[t-t']\, SFH[t']\, dt',$$

rate of transient event ‘X’

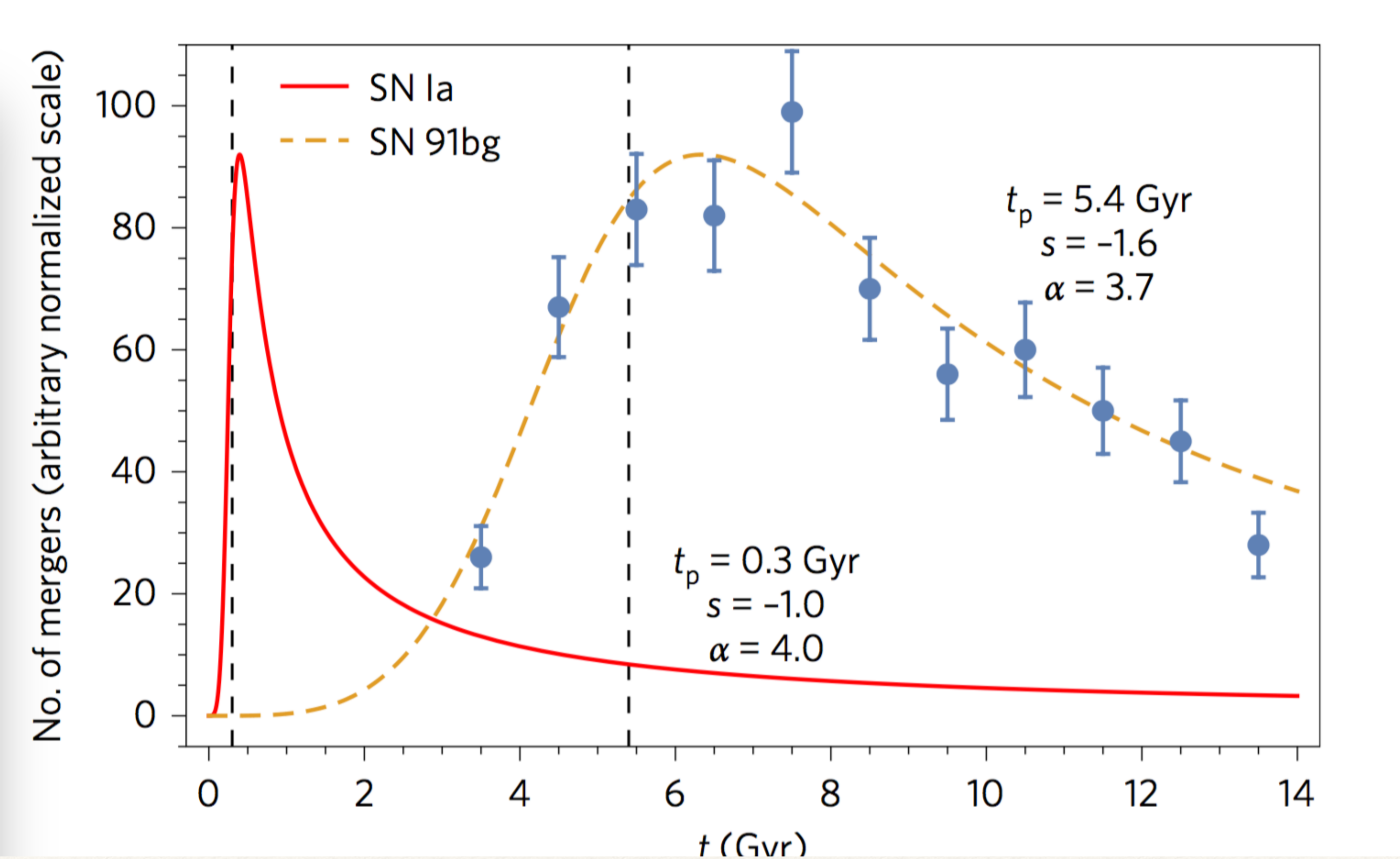
star formation history

$$DTD[t] \propto \frac{(t/t_p)^\alpha}{(t/t_p)^{\alpha-s}+1}$$

Childress et al. 2015

t_p: ‘delay time’

DTD



SN Ia
SN 91bg
t_p = 5.4 Gyr
s = –1.6
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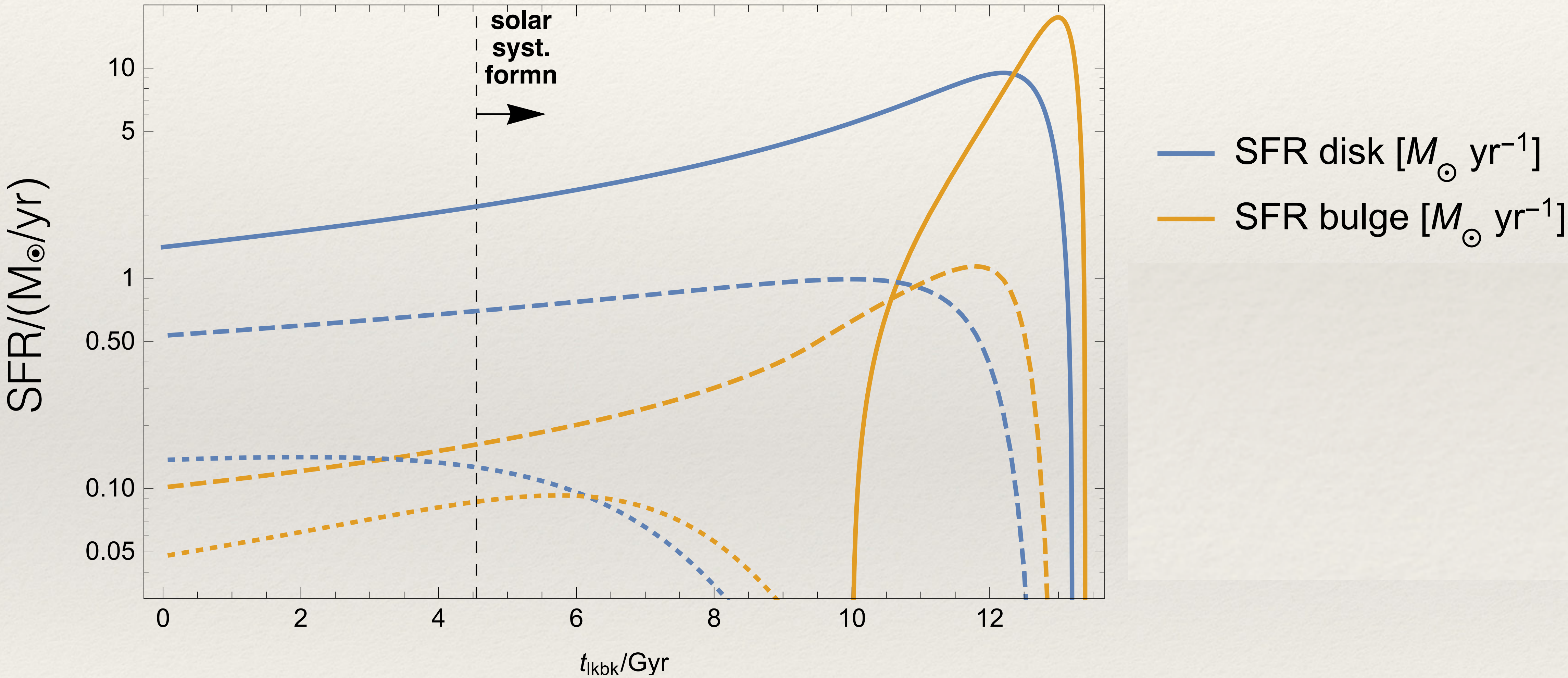
t_p = 0.3 Gyr
s = -1.0
α = 4.0
No. of mergers (arbitrary normalized scale)
0
20
40
60
80
100
0
2
4
6
8
10
12
14

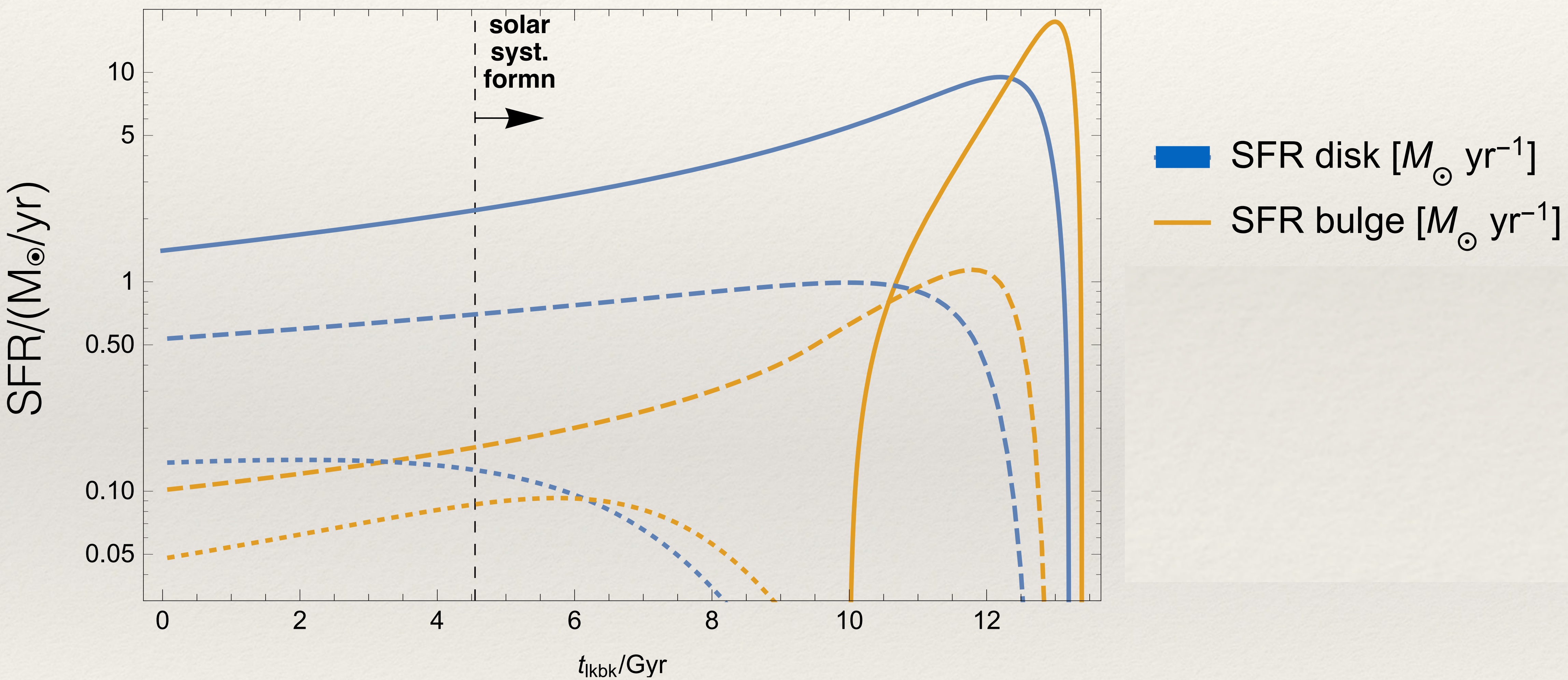
Galactic Star Formation History



today

Big Bang

Galactic Star Formation History



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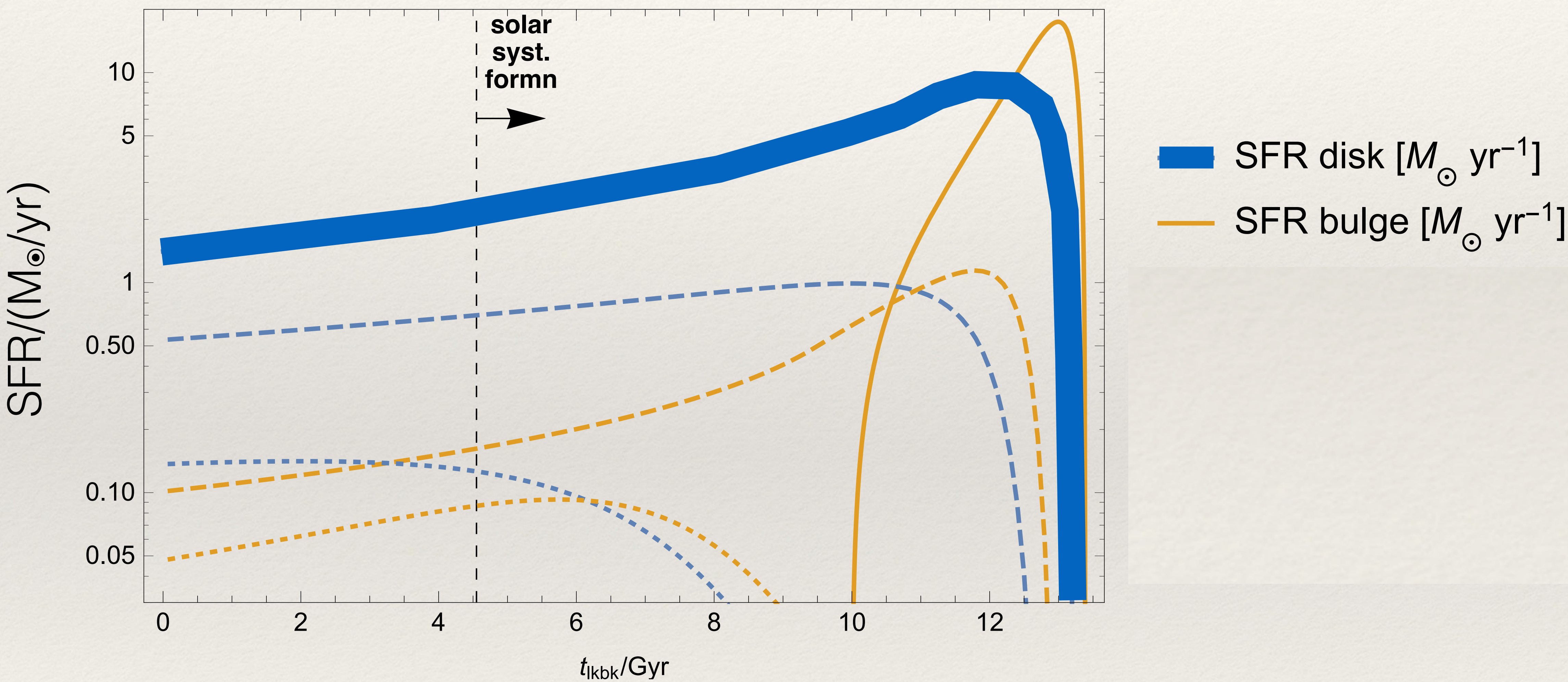

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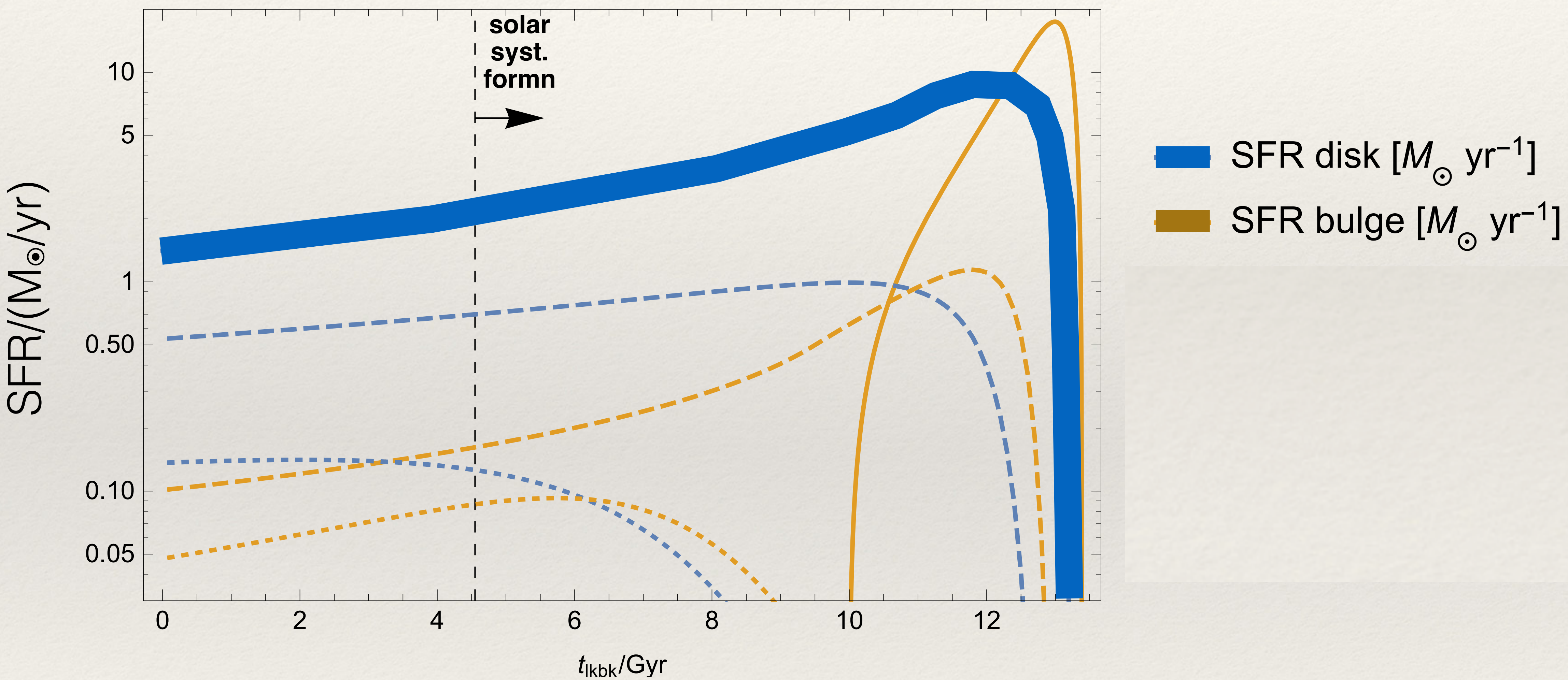

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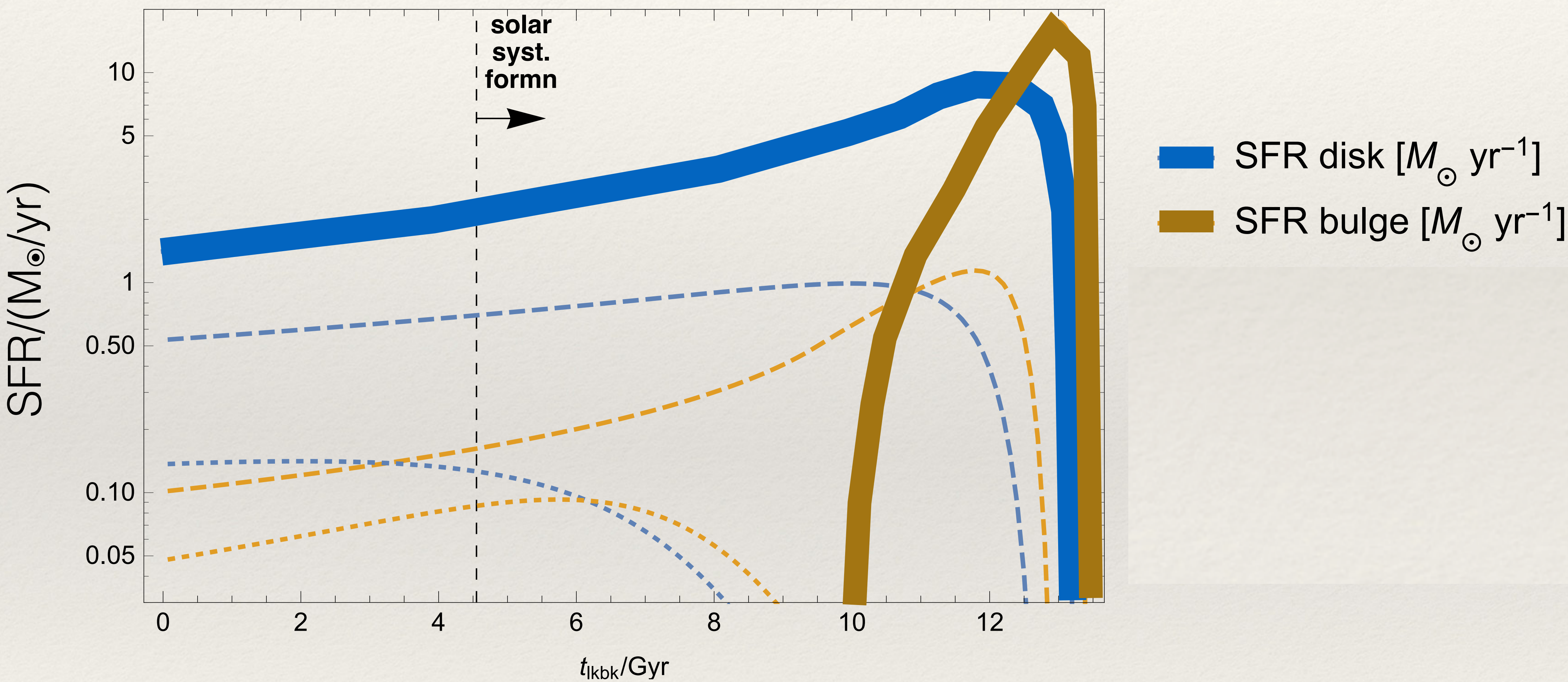

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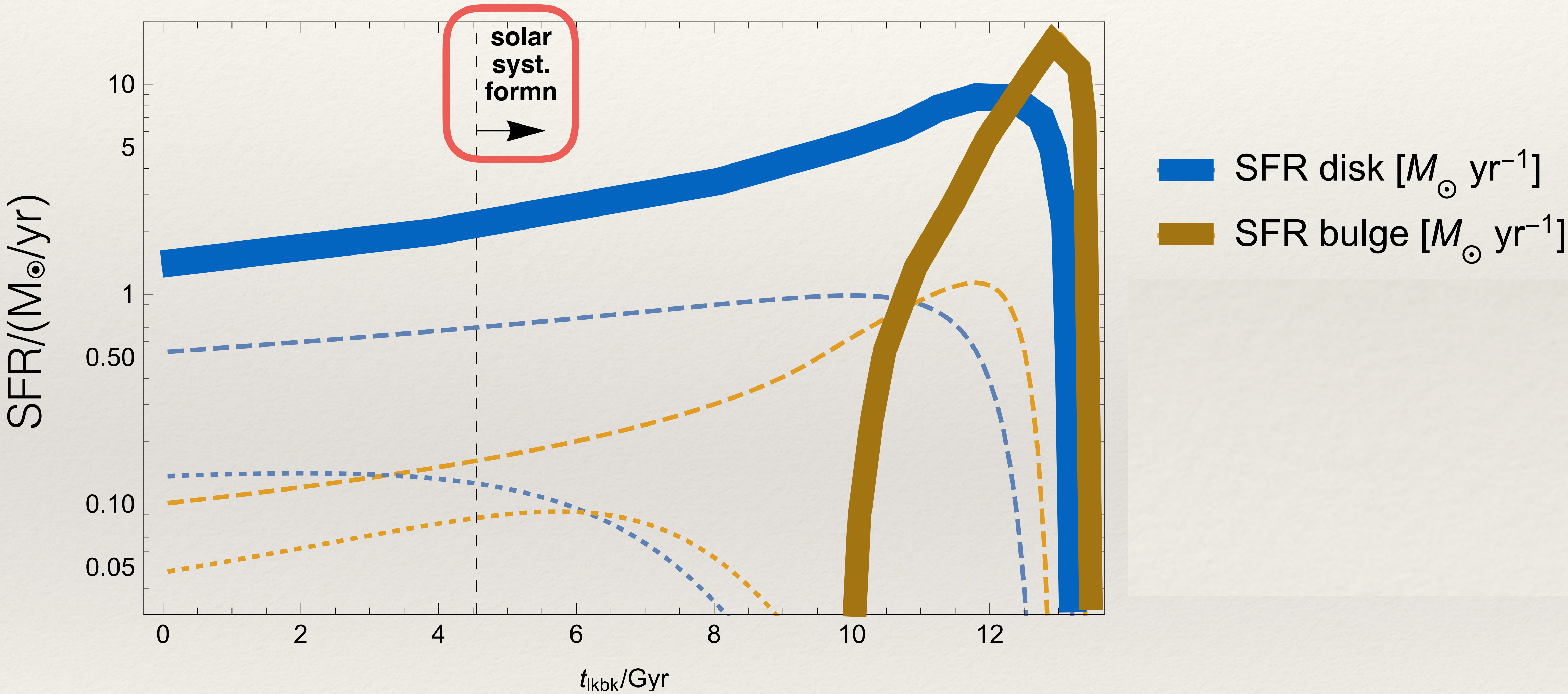

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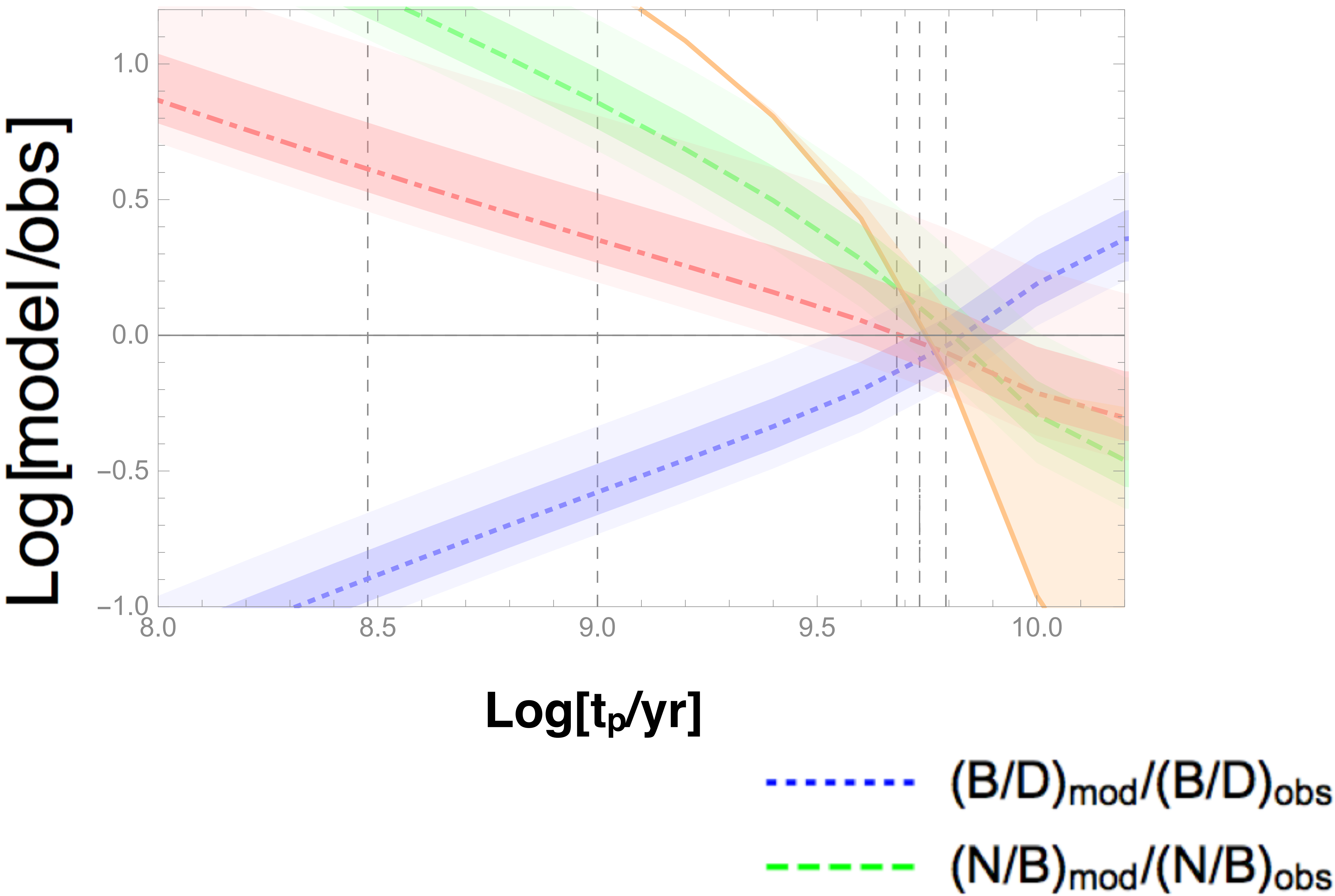
Big Bang

How old does a *stellar* positron source need to be?



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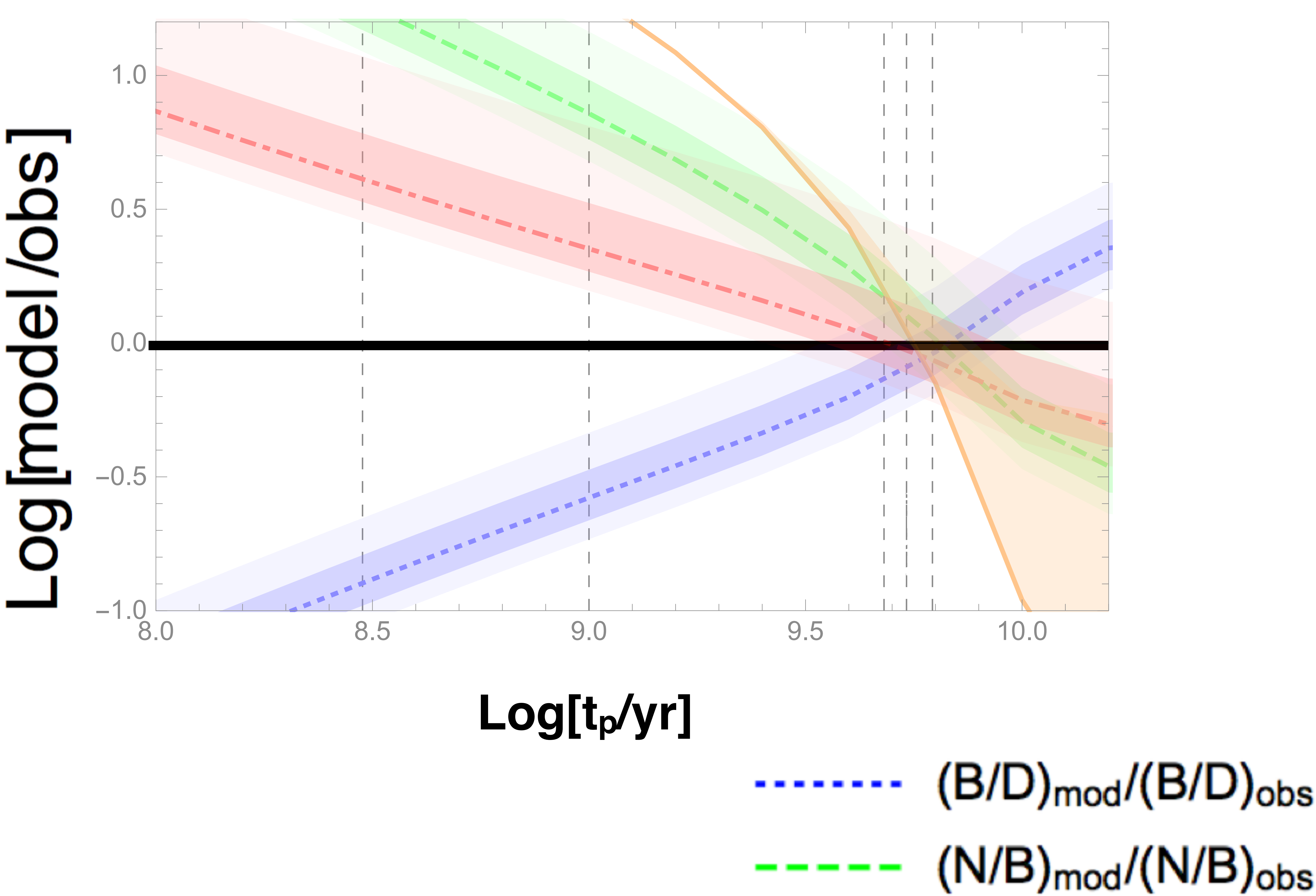

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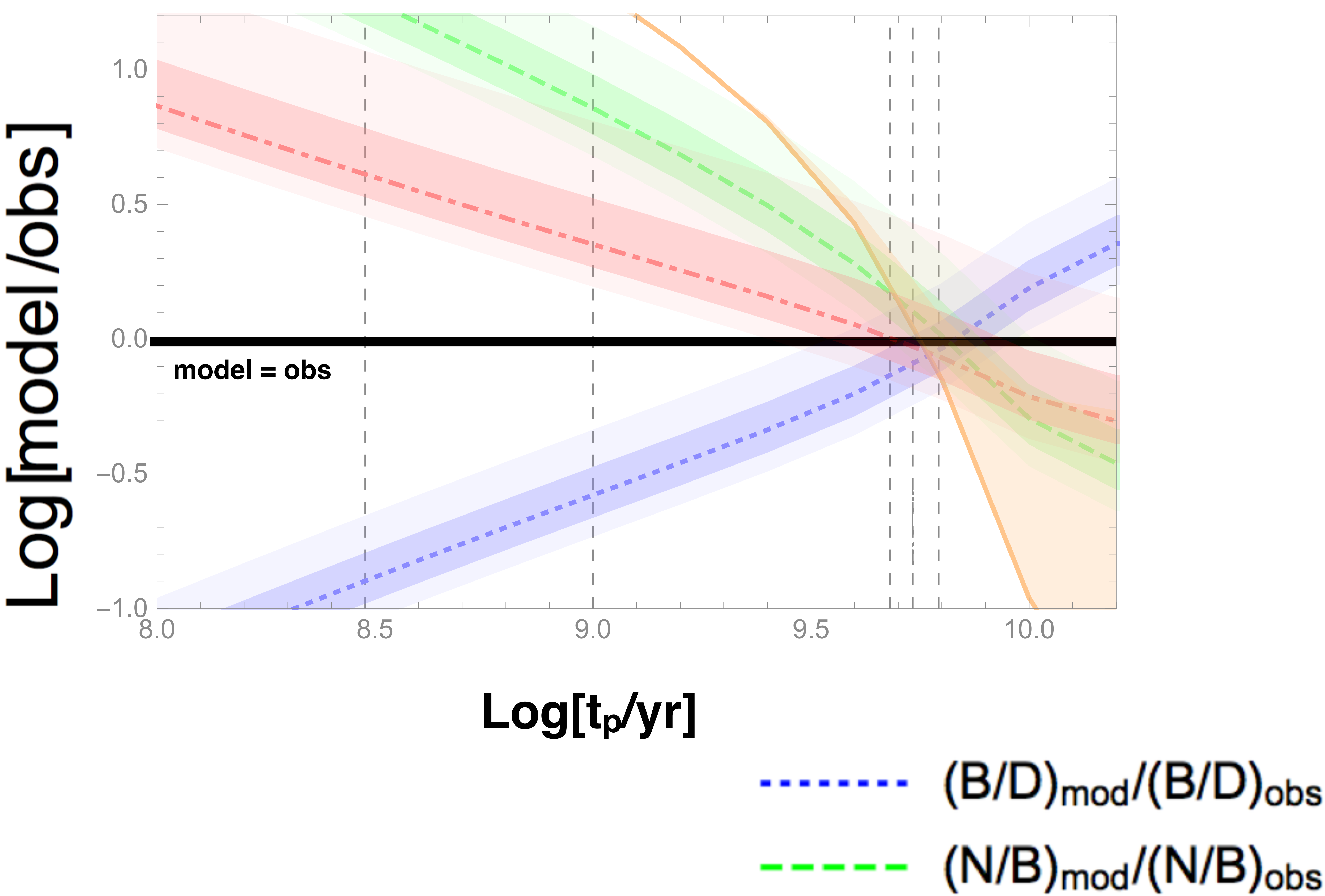

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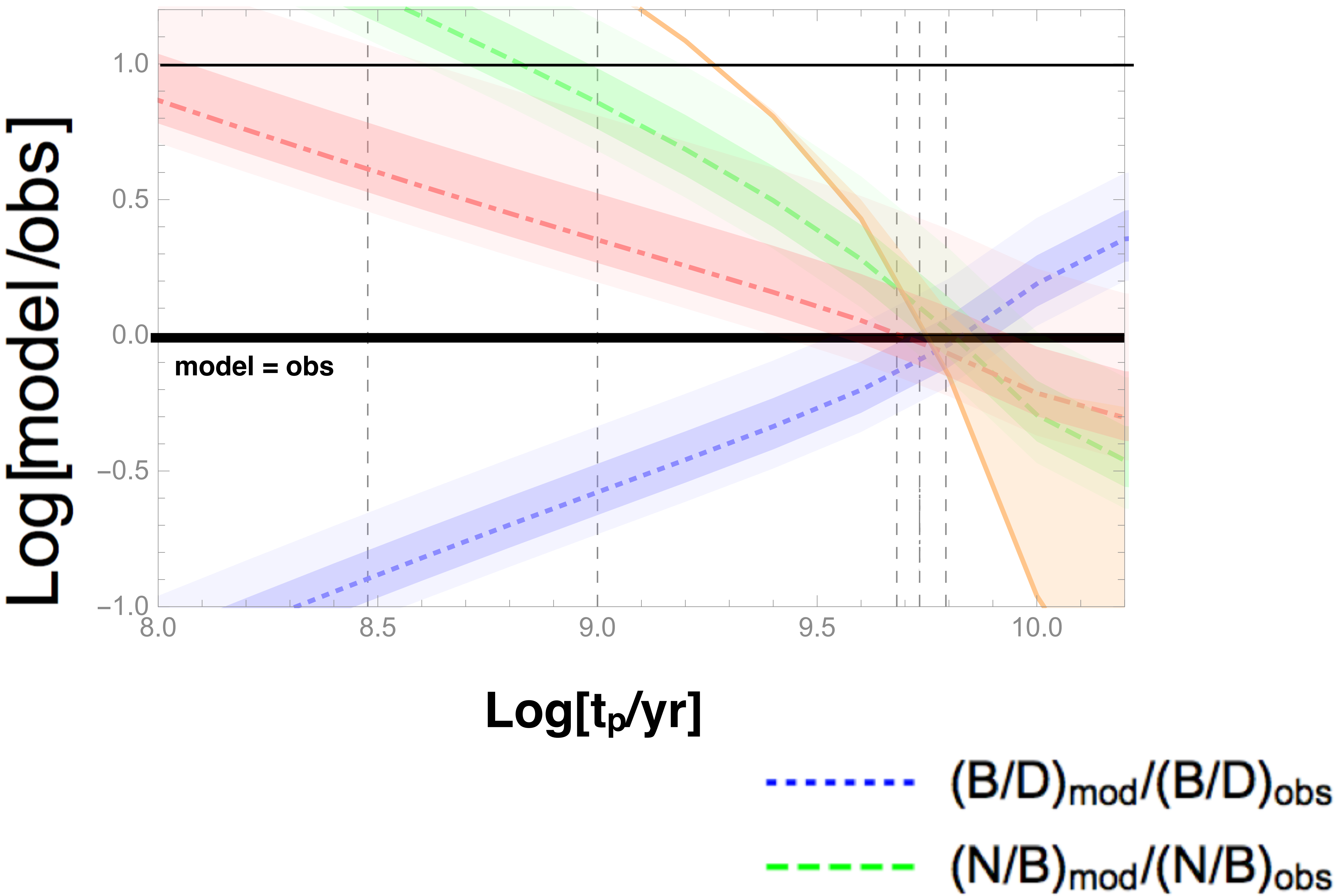

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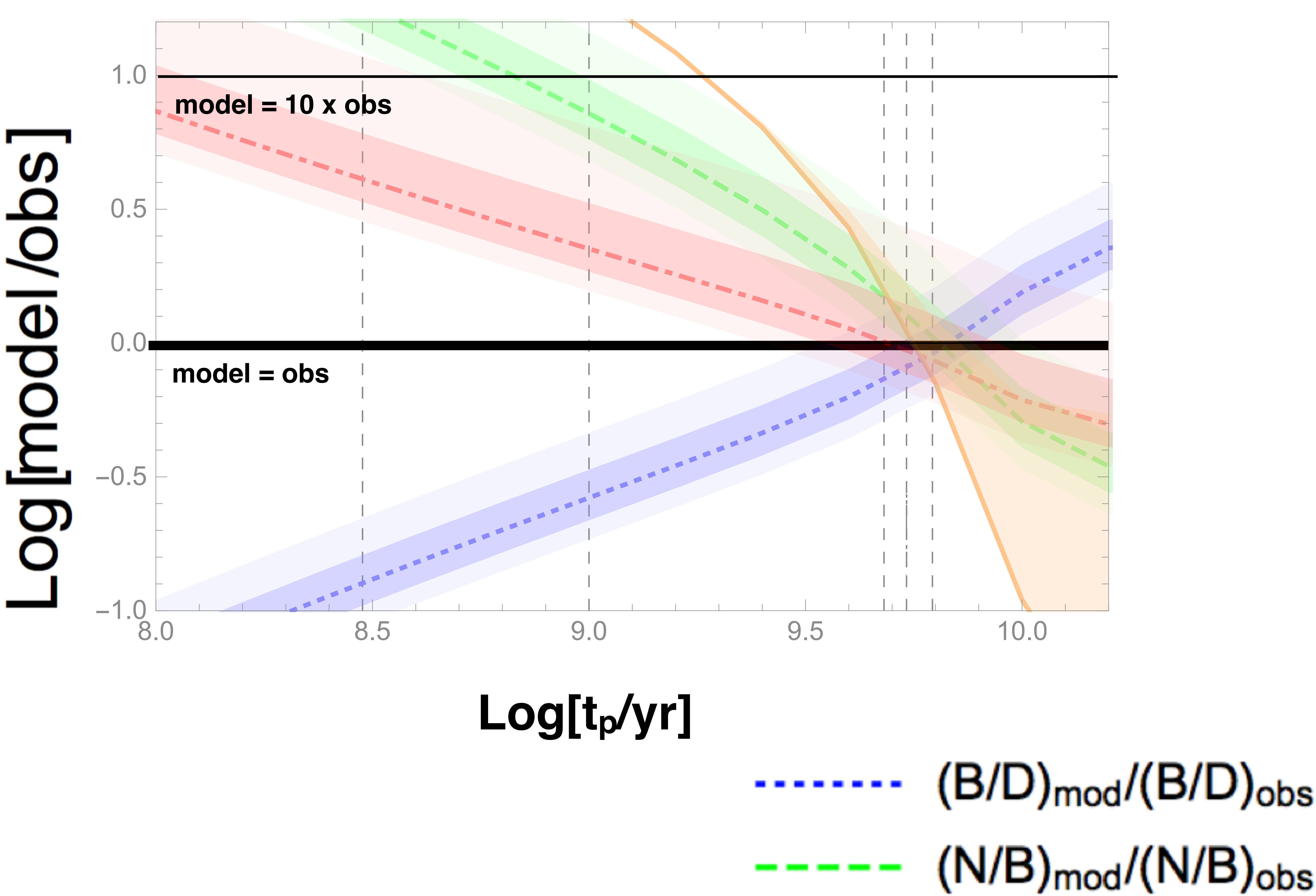

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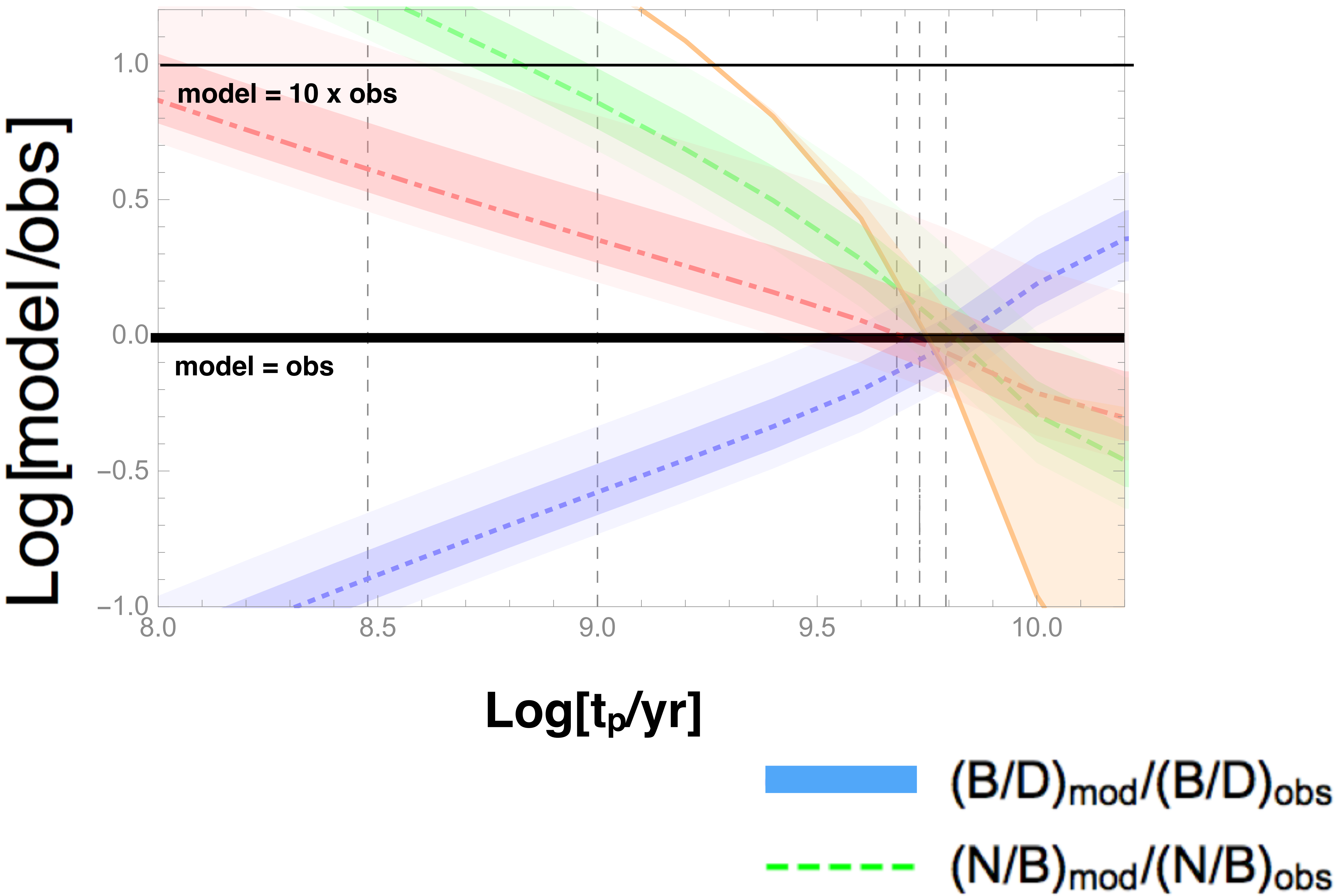

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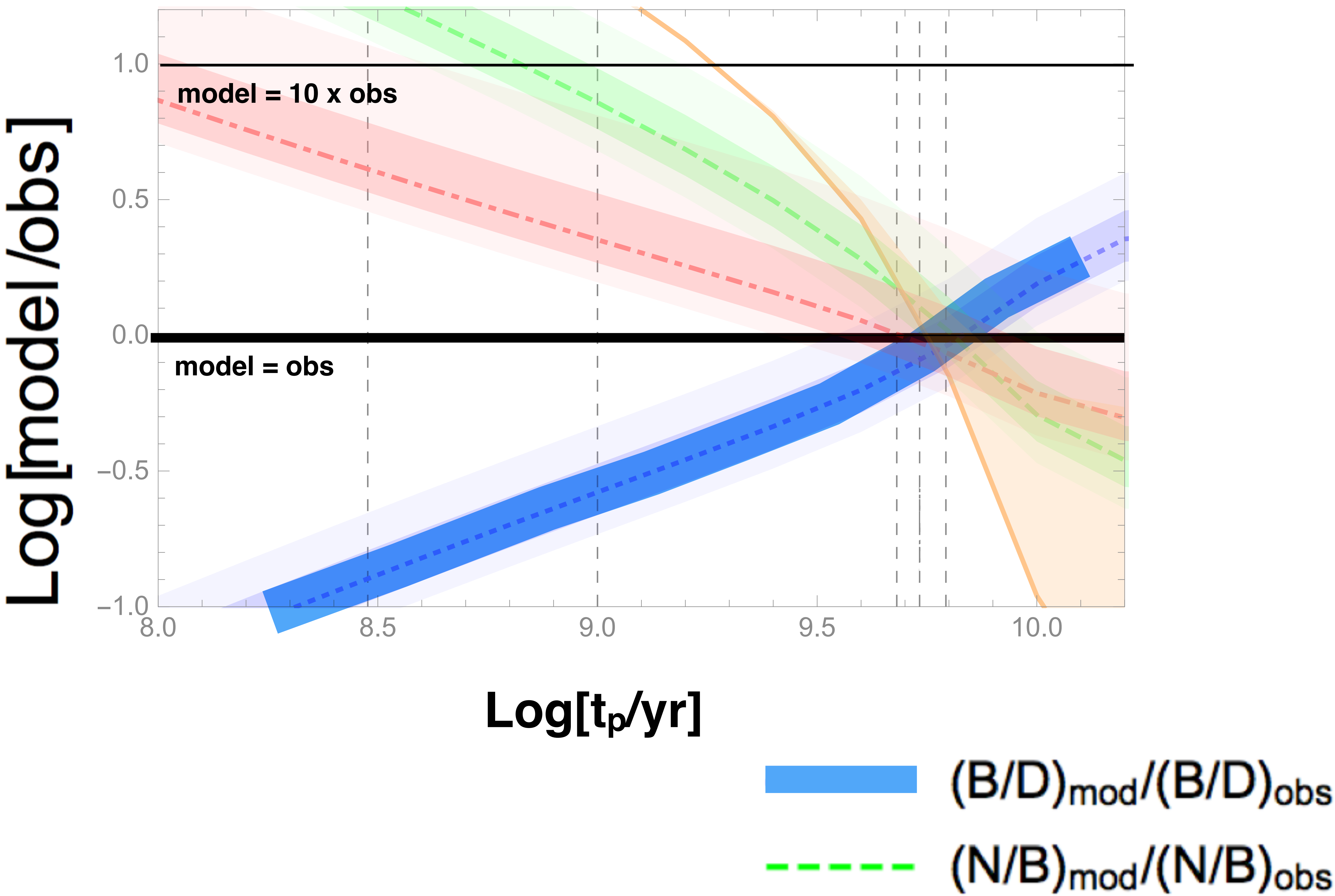

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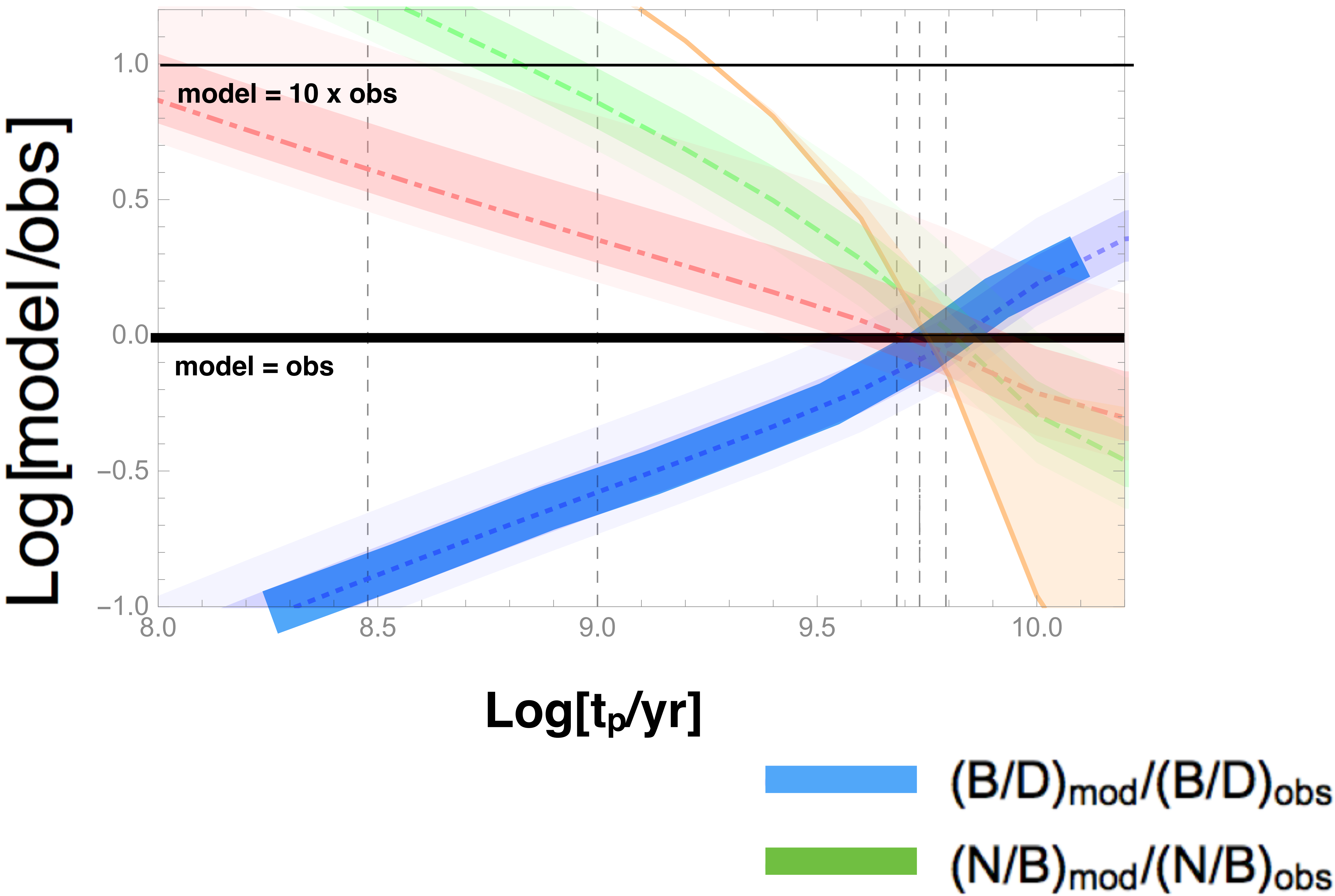

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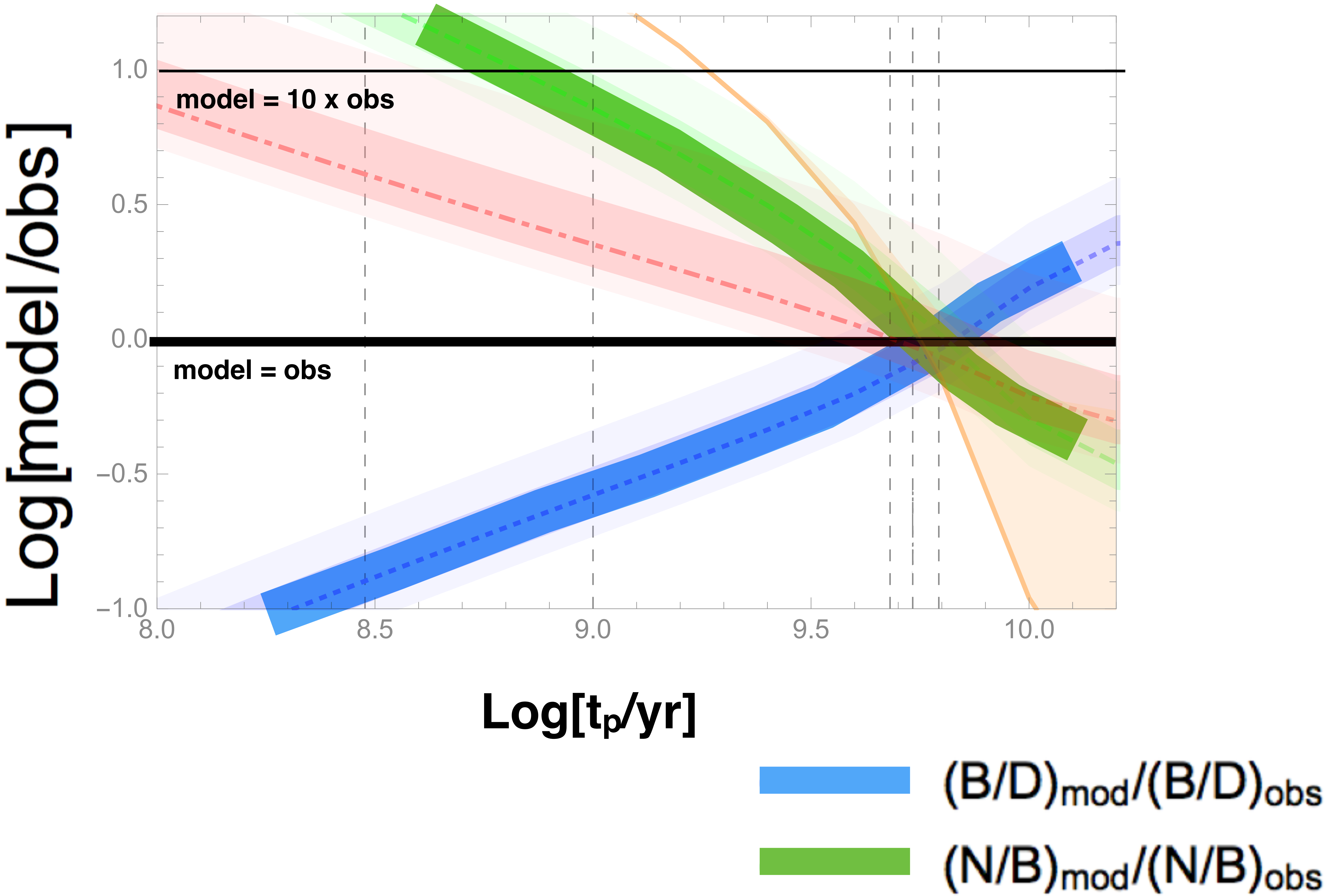

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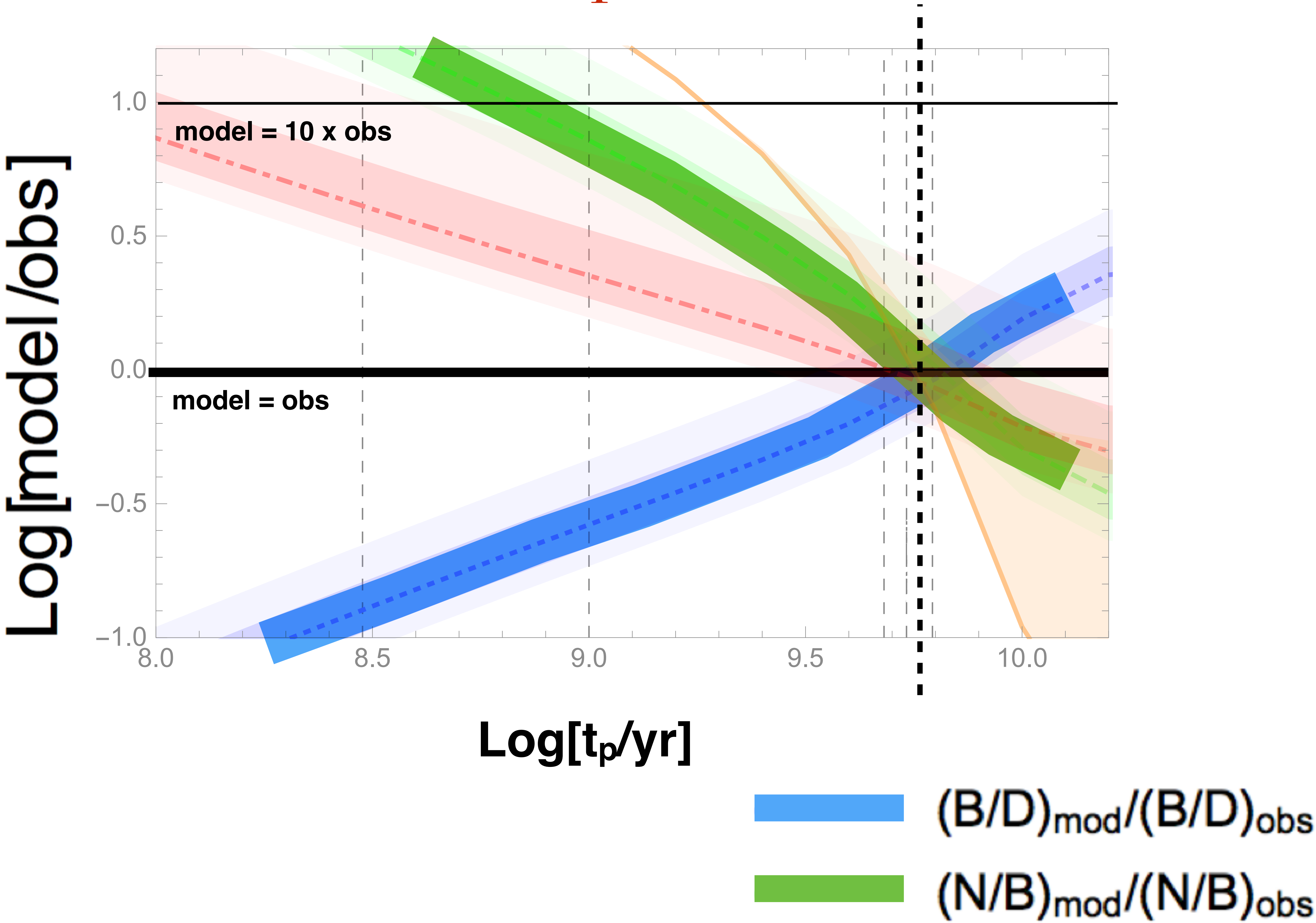

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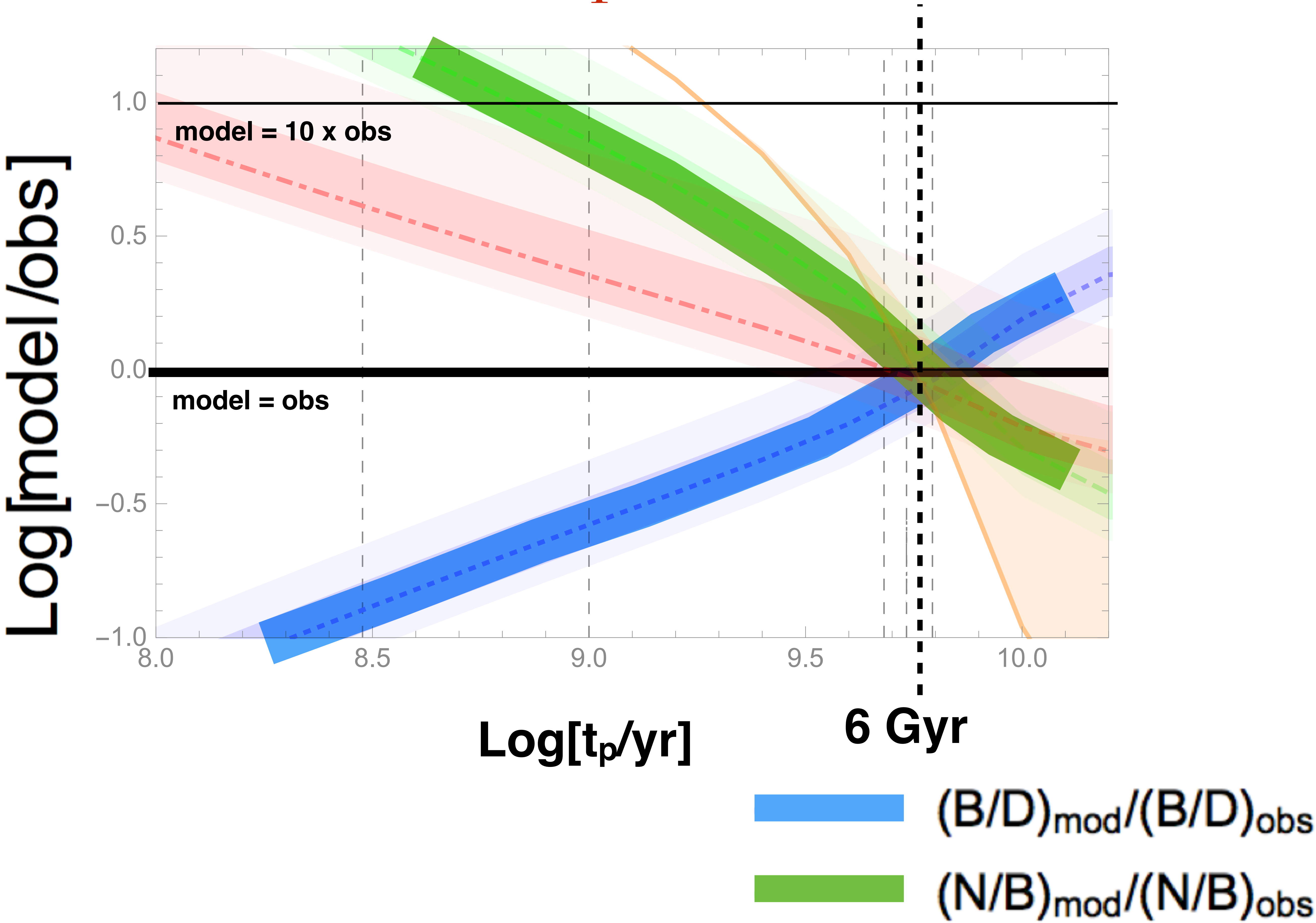

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$$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe} + \mathrm{e}^{+} \qquad \lambda = 80 \text{ d}$$

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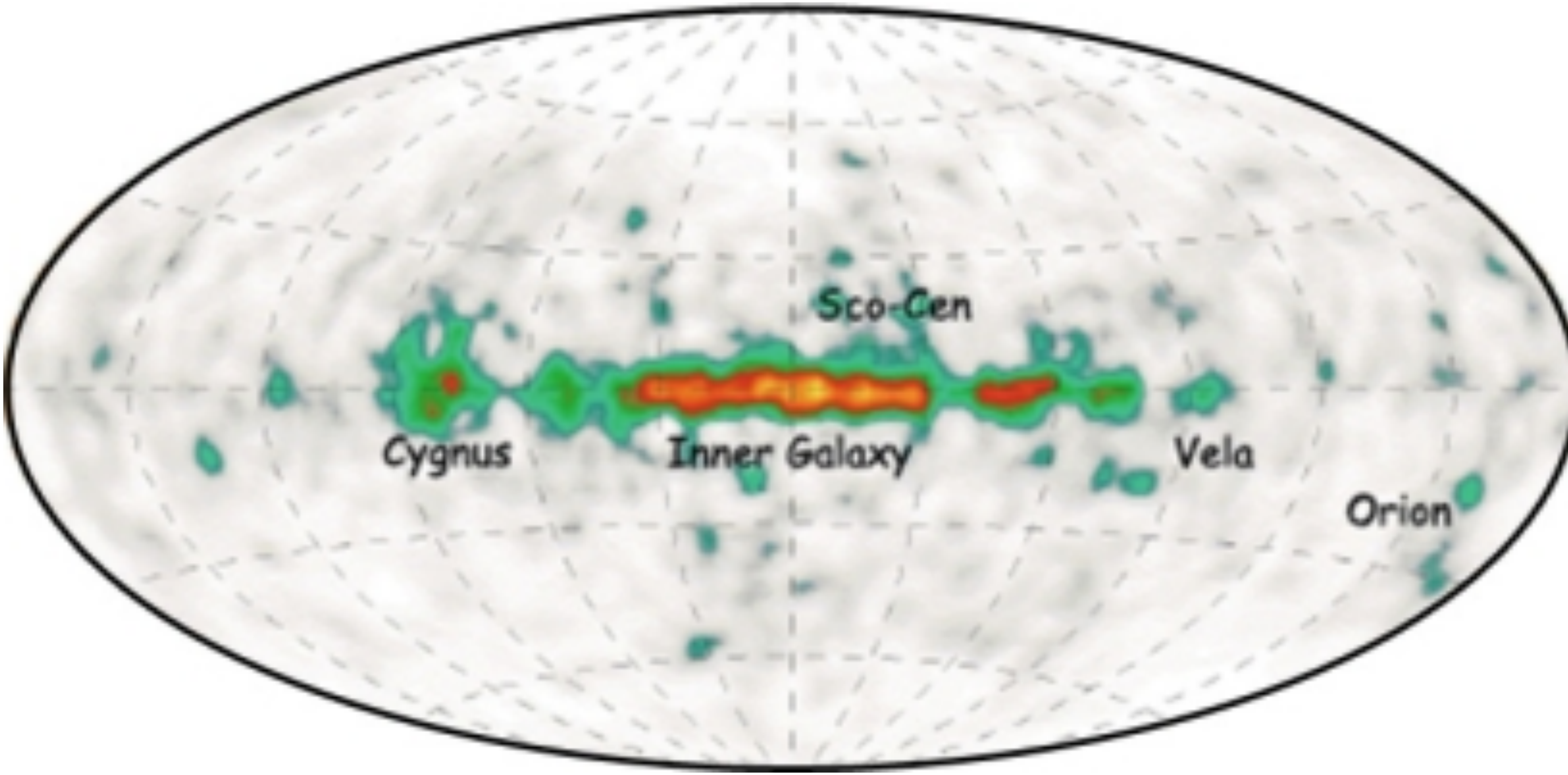
Sco-Cen
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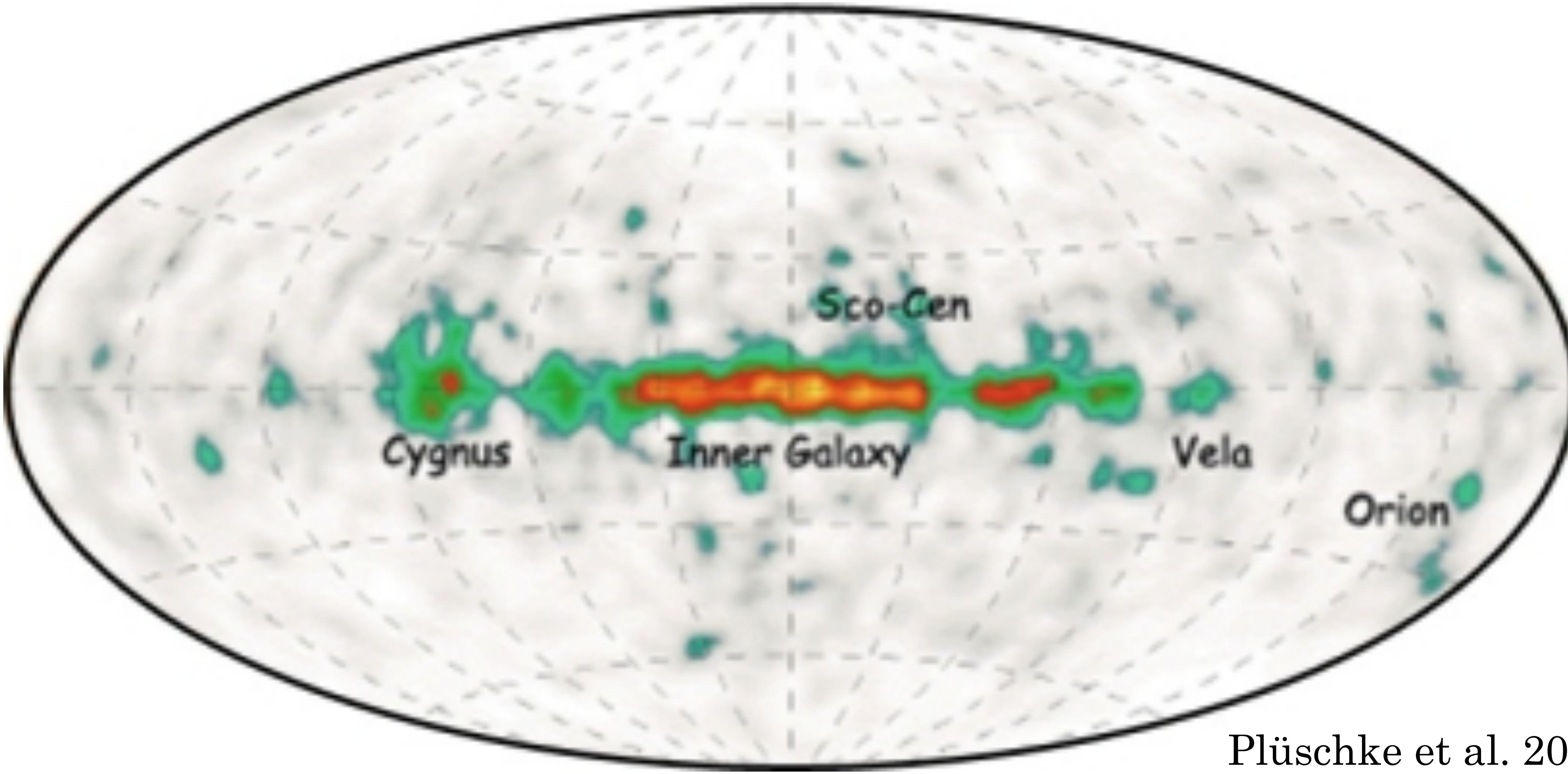
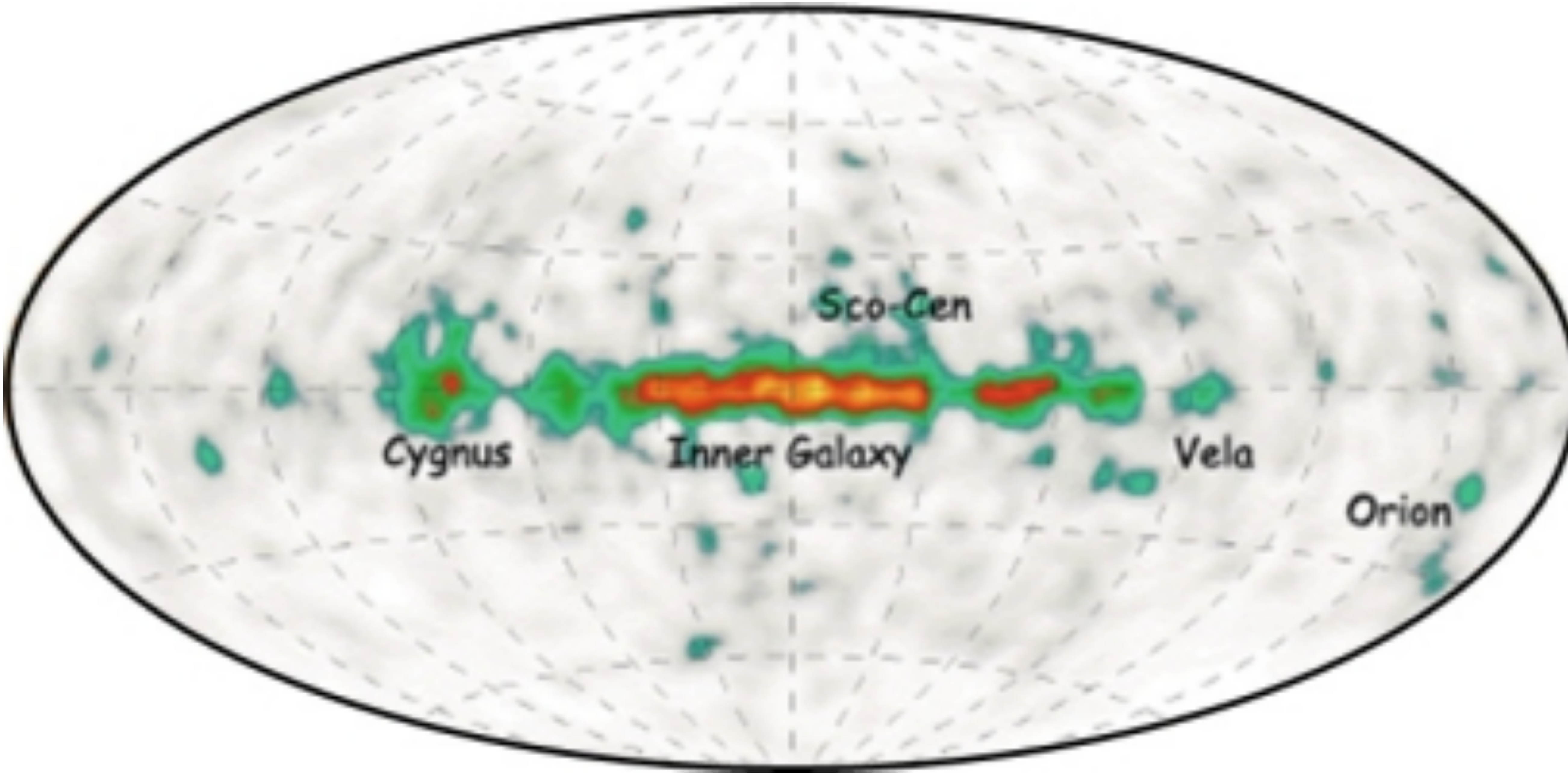


Plüschke et al. 2011



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- SNIa happen at too short a delay time to explain morphology

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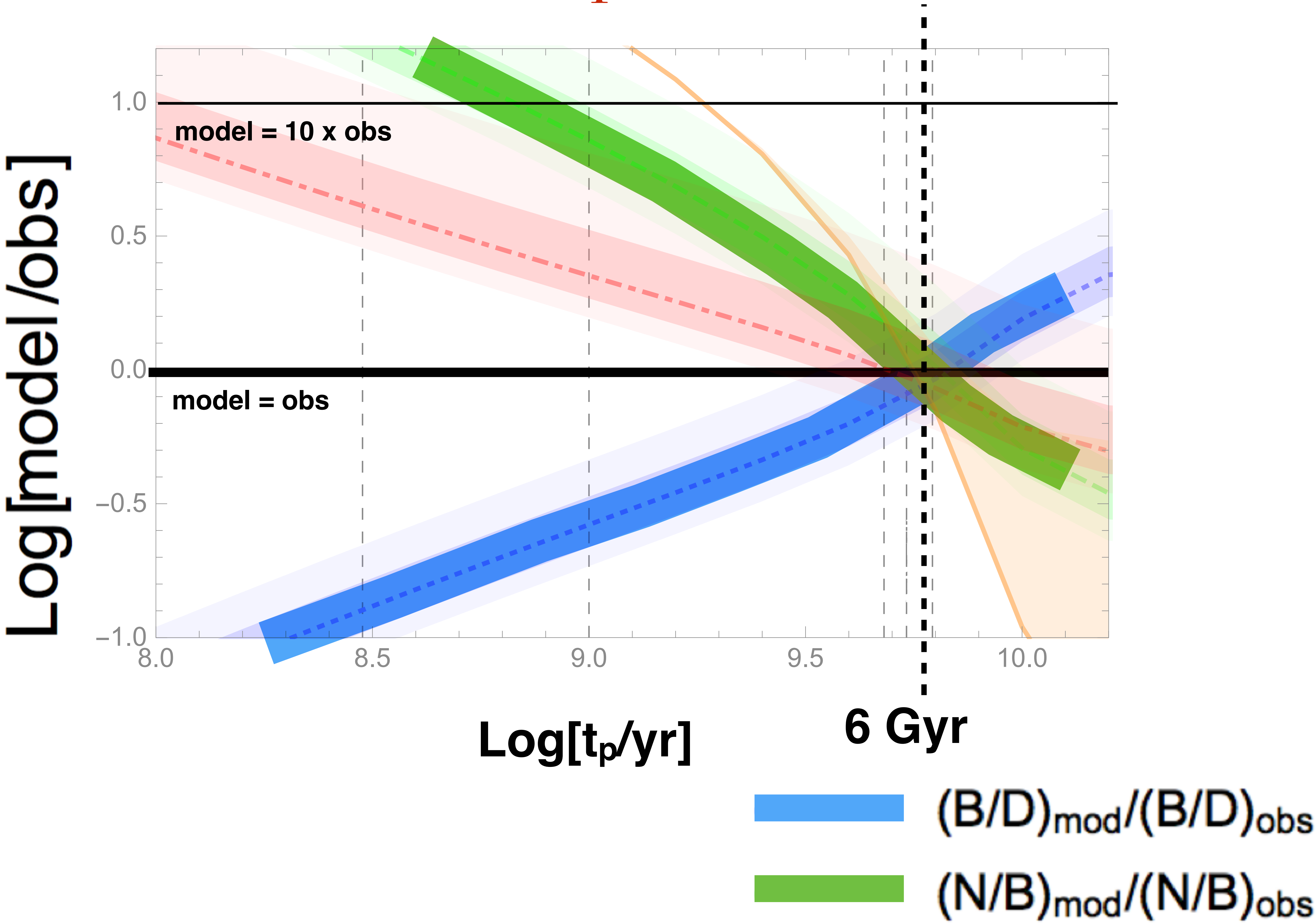

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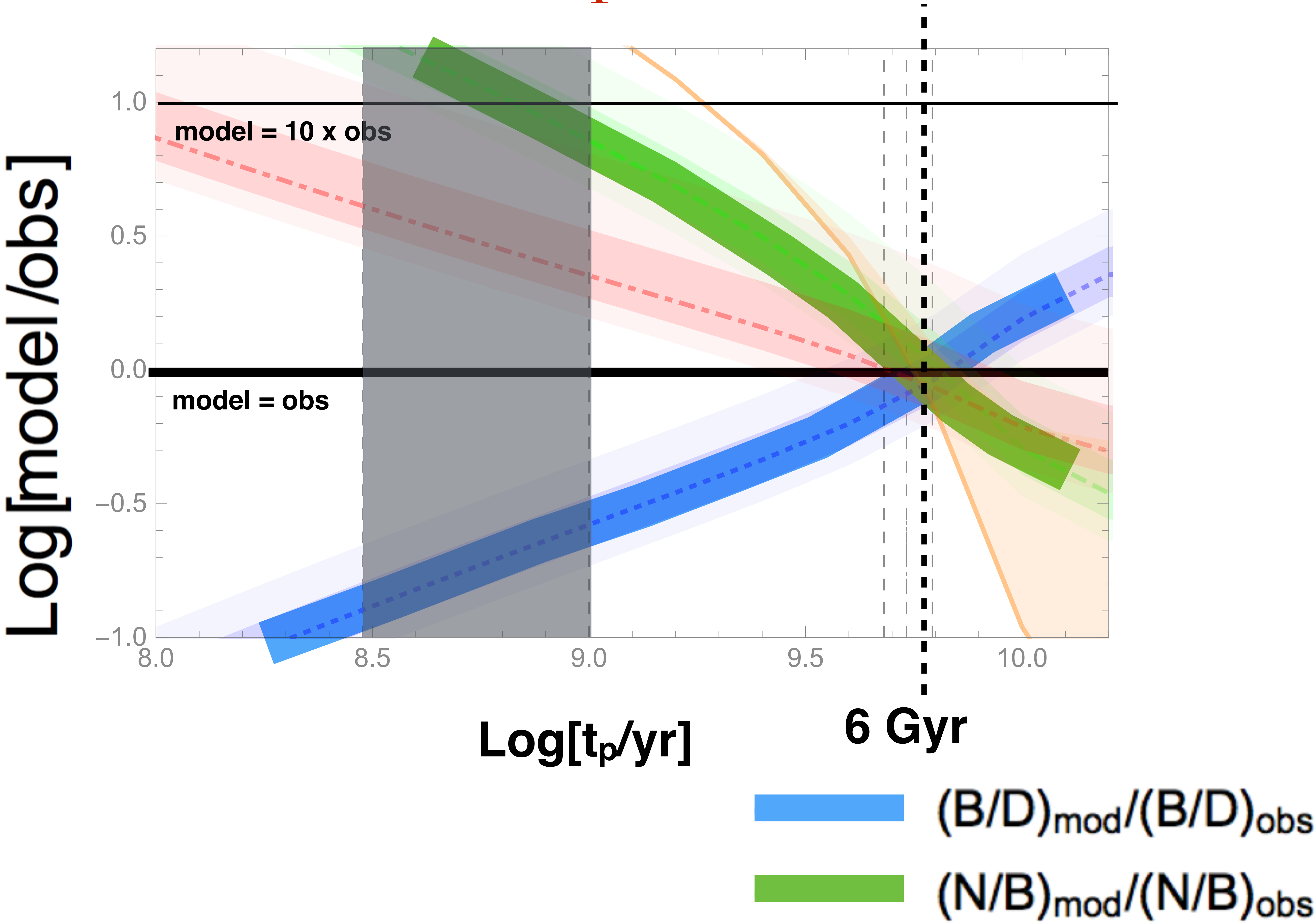

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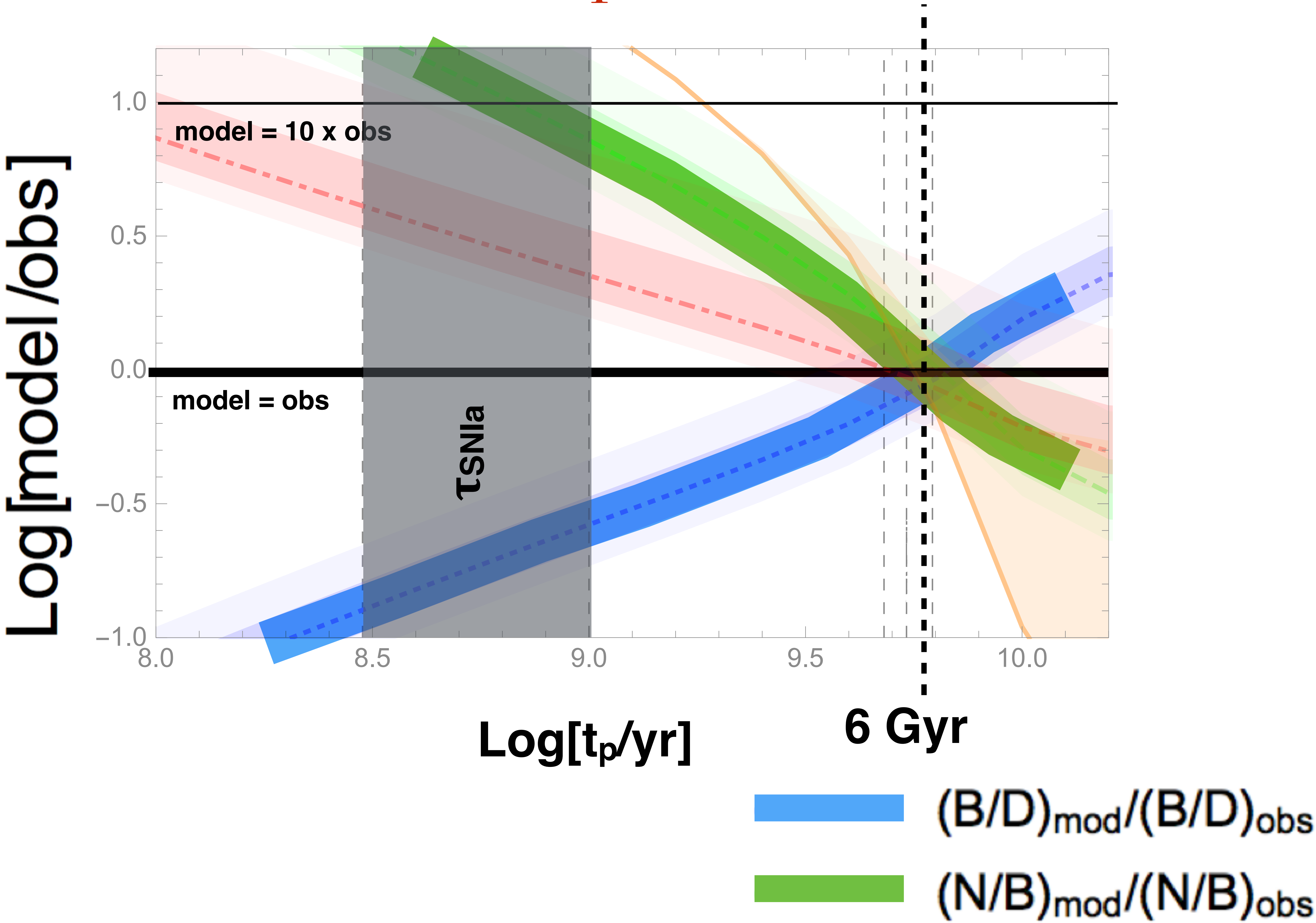

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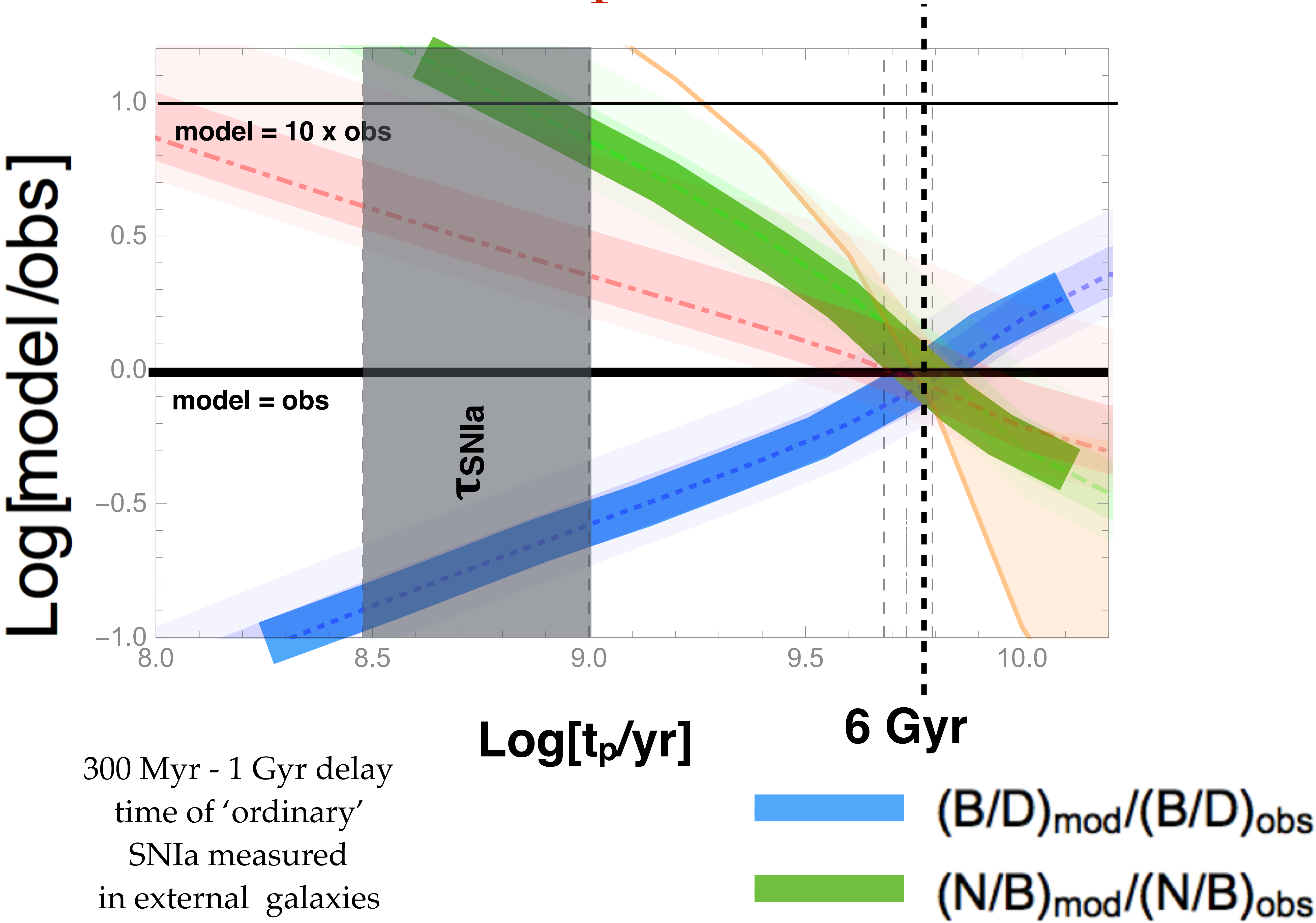

300 Myr - 1 Gyr delay time of 'ordinary' SNIa measured in external galaxies

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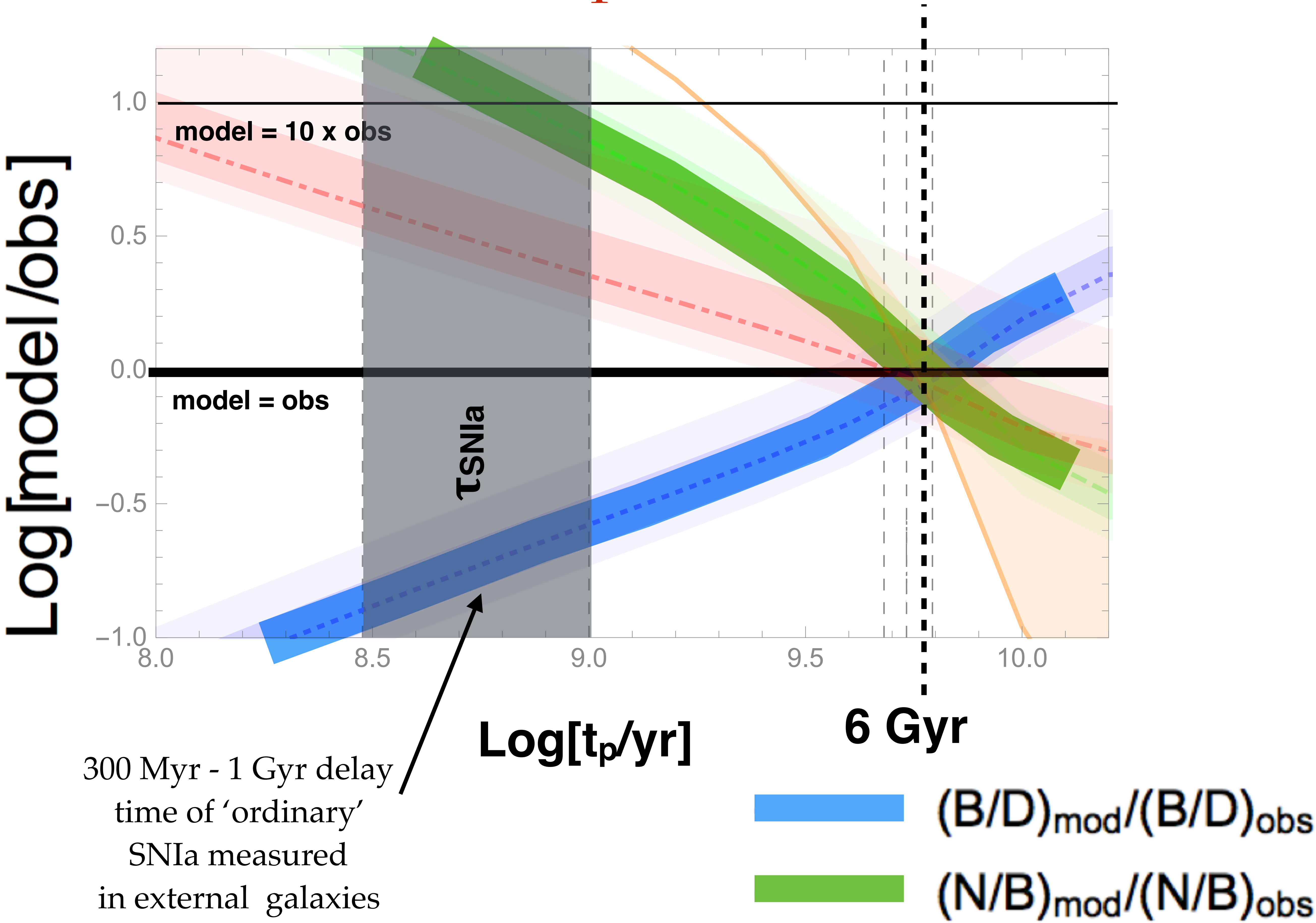

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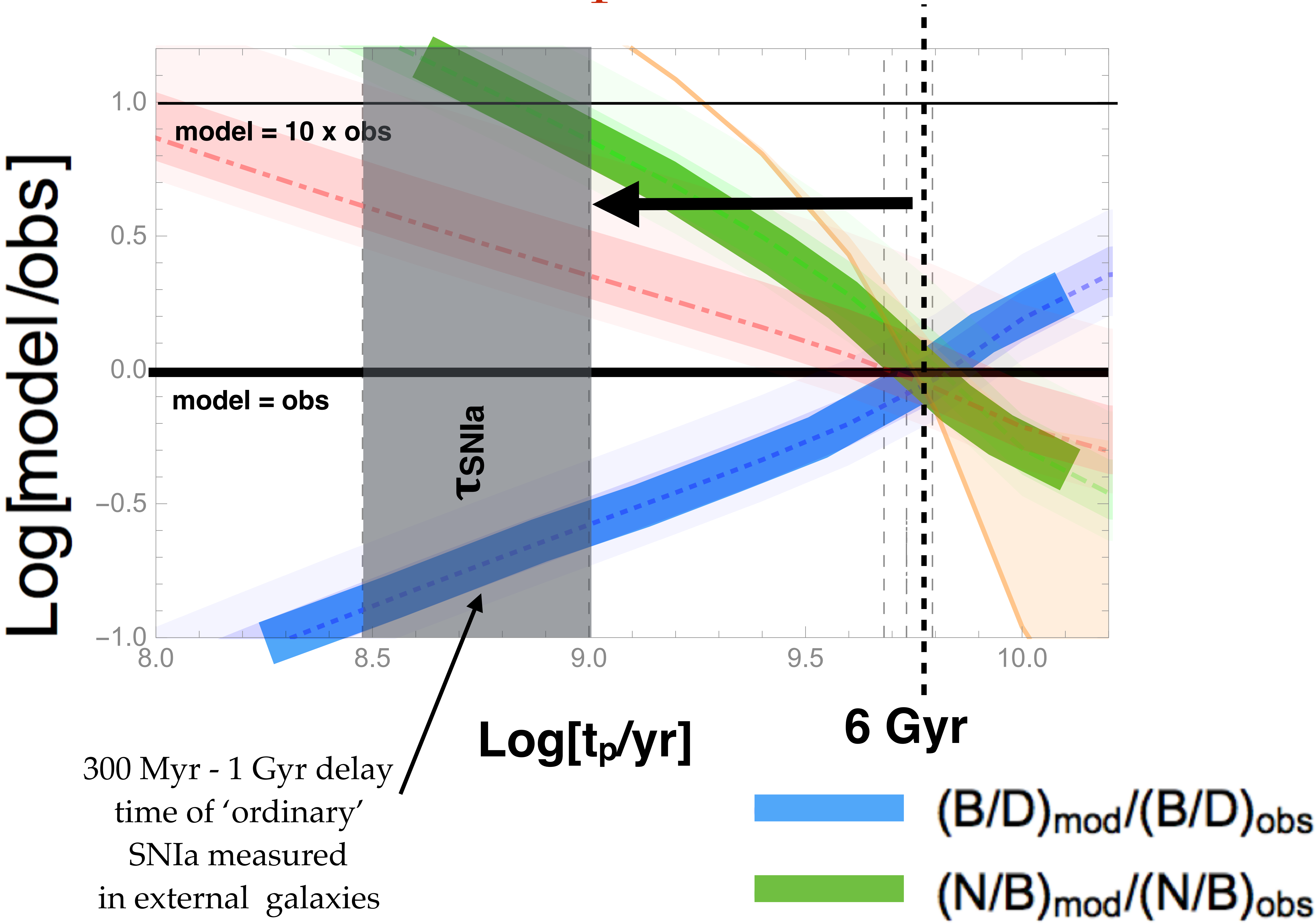

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Another problem for ^{56}Ni positrons from SNIa

- ^{56}Ni ⟶ ^{56}Co ⟶ ^{56}Fe ~80 day decay time: positron trapping in SN ejecta
- Late-time pseudo-bolometric light curves of SNIa indicate *complete trapping*: vast majority of positrons from SNIa ^{56}Ni *never reach the ISM*

…Trapping not a problem for ^{44}Ti:

- $^{44}\mathrm{Ti} \longrightarrow {}^{44}\mathrm{Sc} \longrightarrow {}^{44}\mathrm{Ca}$ ~70 YEAR decay time: supernova positrons can reach ISM
- BUT also γ-ray and X-ray line associated with this decay chain and ***measured*** total luminosity of ^{44}Ti sky lines too small to account for Galactic positron injection rate
- Moreover, daughter nucleus ^{44}Ca measured in solar system material; inferred production rate too small to account for Galactic positron injection rate

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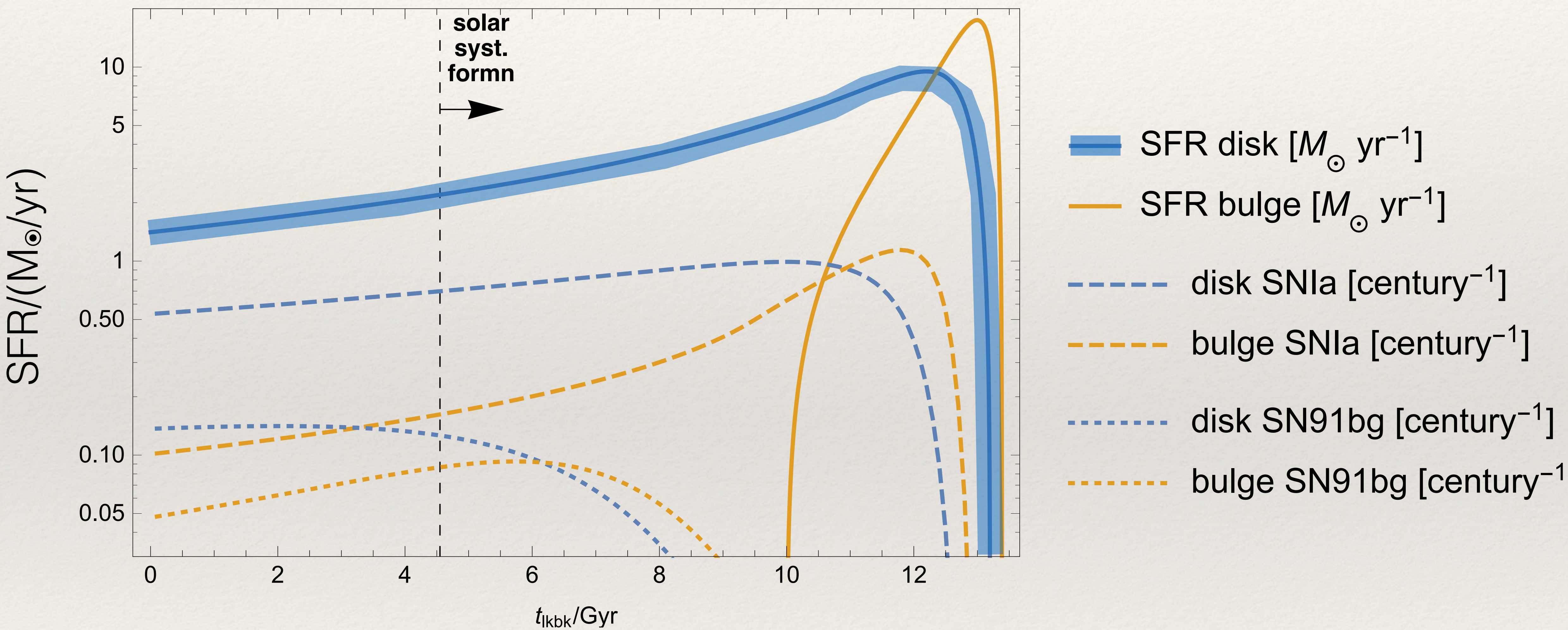
Galactic Star Formation History



today

Big Bang

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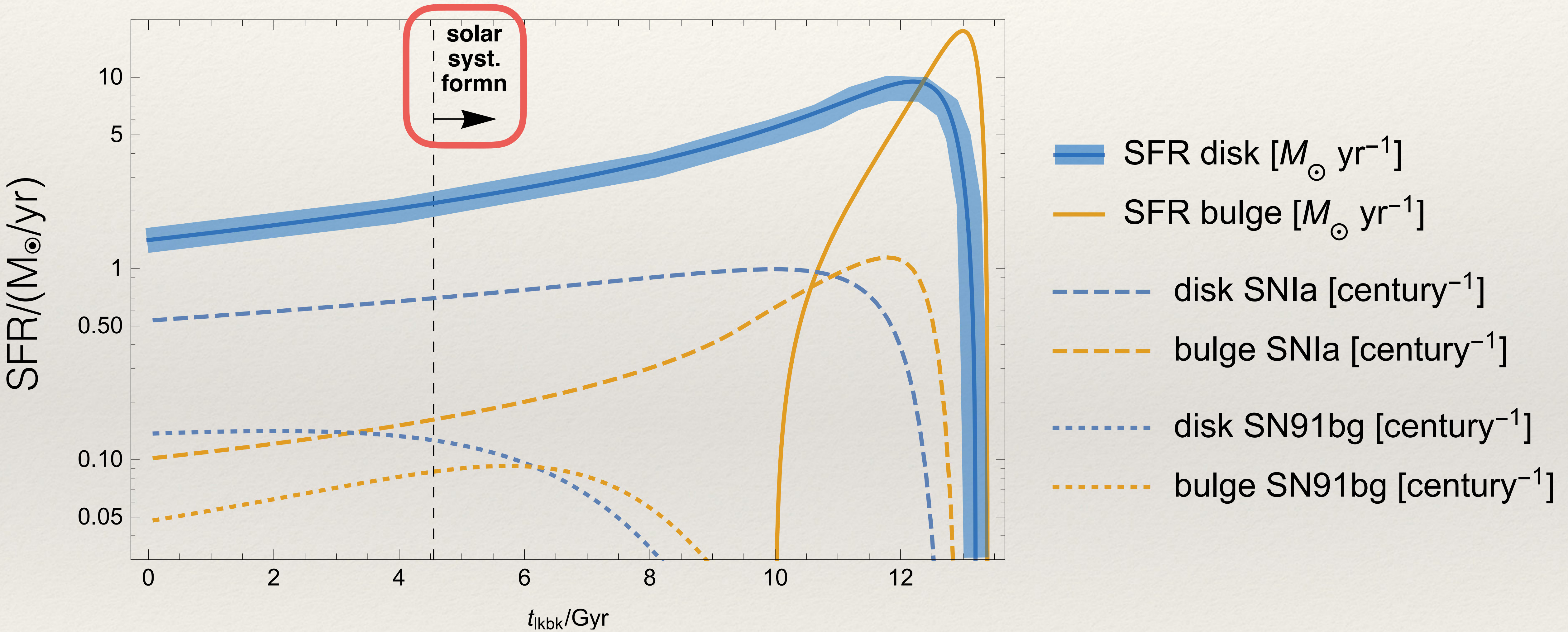

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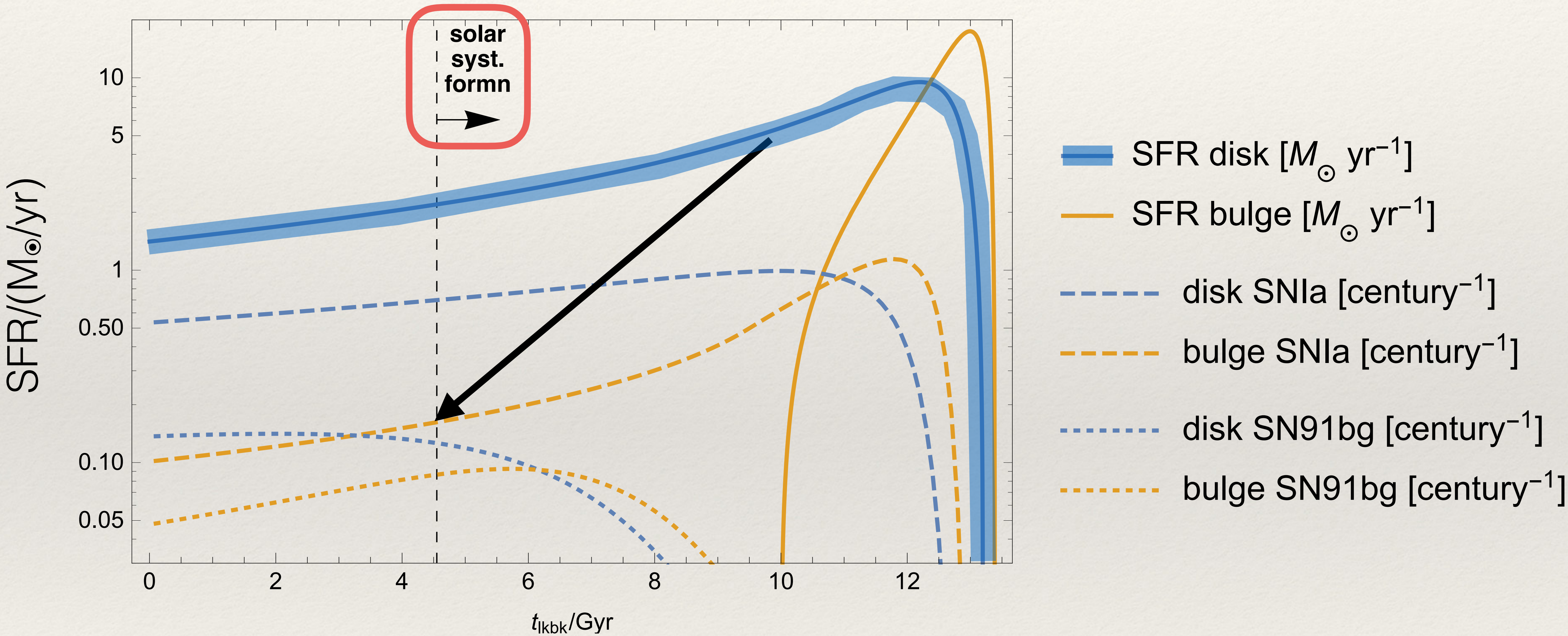

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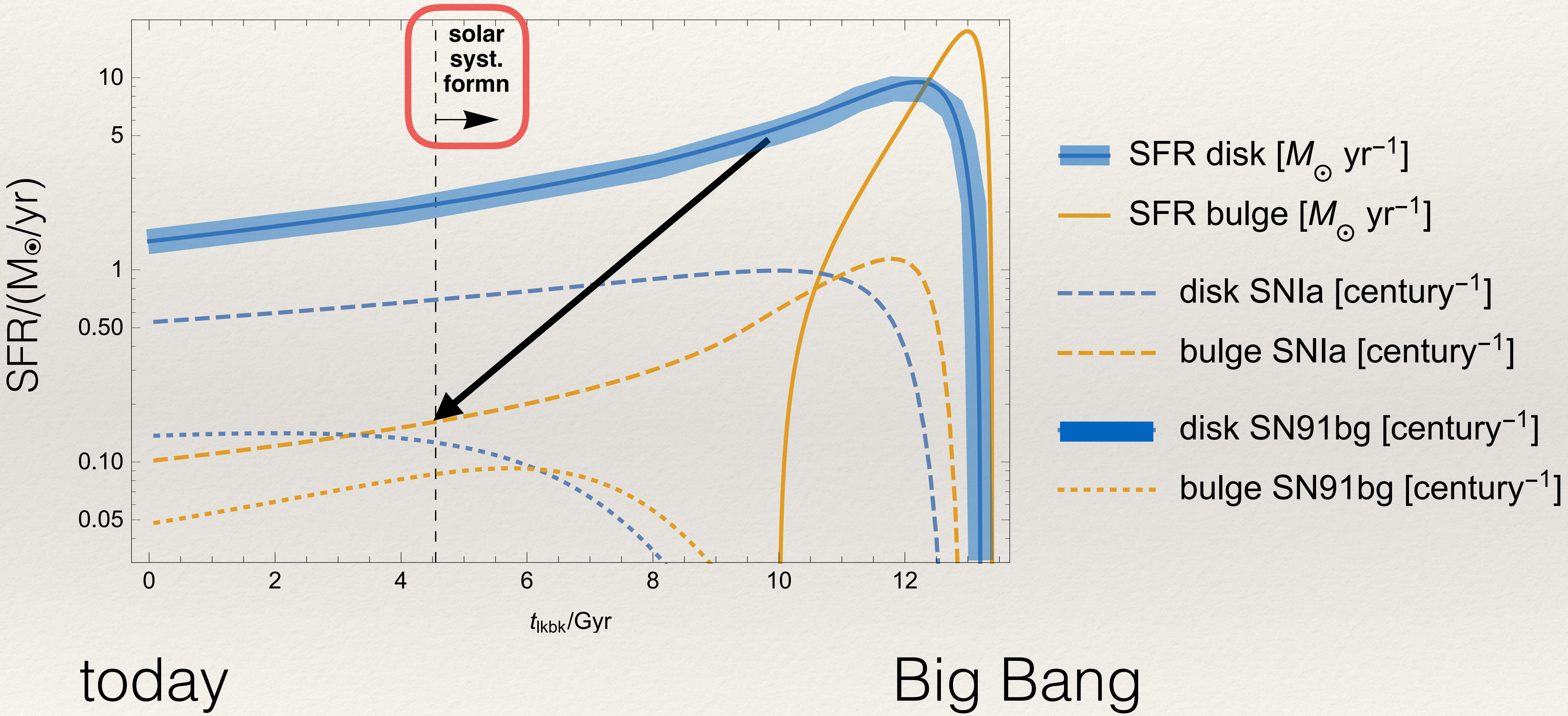

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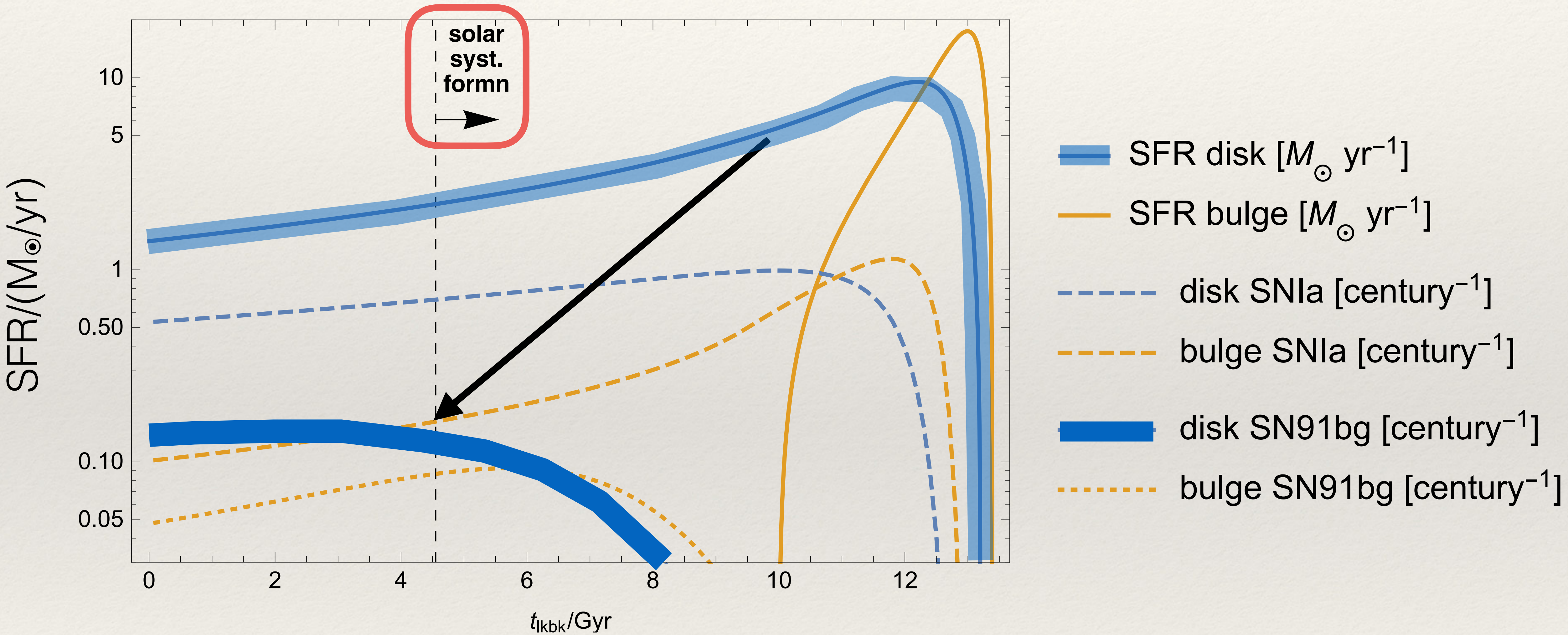

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Big Bang

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  - …but each event must produce large mass of ^{44}Ti, 0.02-0.03 $M_\odot$

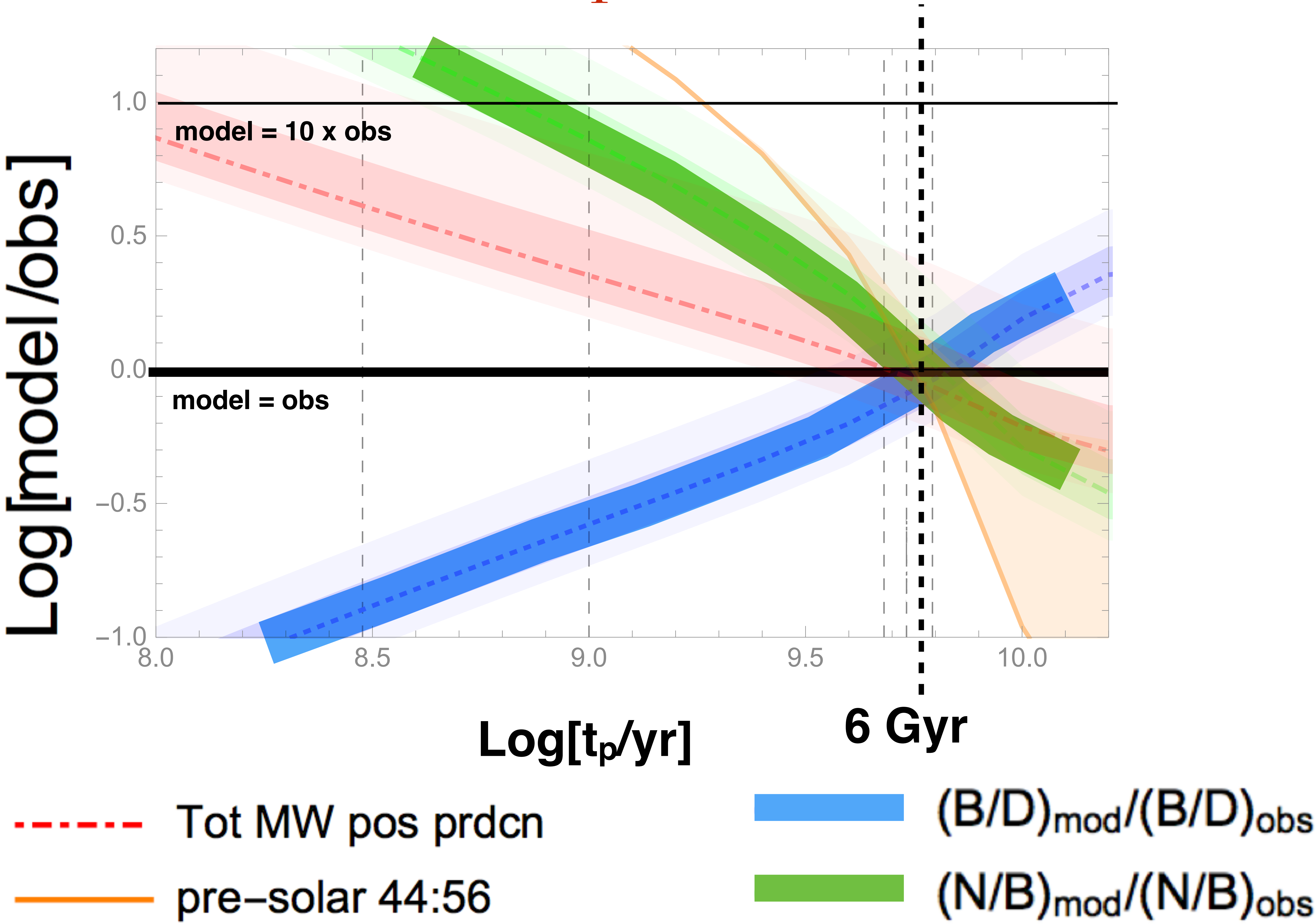
A Galactic ^{44}Ti source that…

- …occurs every ≳300 years
- …synthesises 0.02-0.03 $M_\odot$ of ^{44}Ti
- …happens at a delay time of ~6 Gyr post star formation

would:

- explain the absolute positron luminosity of the Galaxy
- explain the ^{44}Ca abundance in pre-solar material
- explain the bulge to disk positron luminosity ratio
- explain the nuclear bulge to bulge positron luminosity ratio

How old does a *stellar* positron source need to be?



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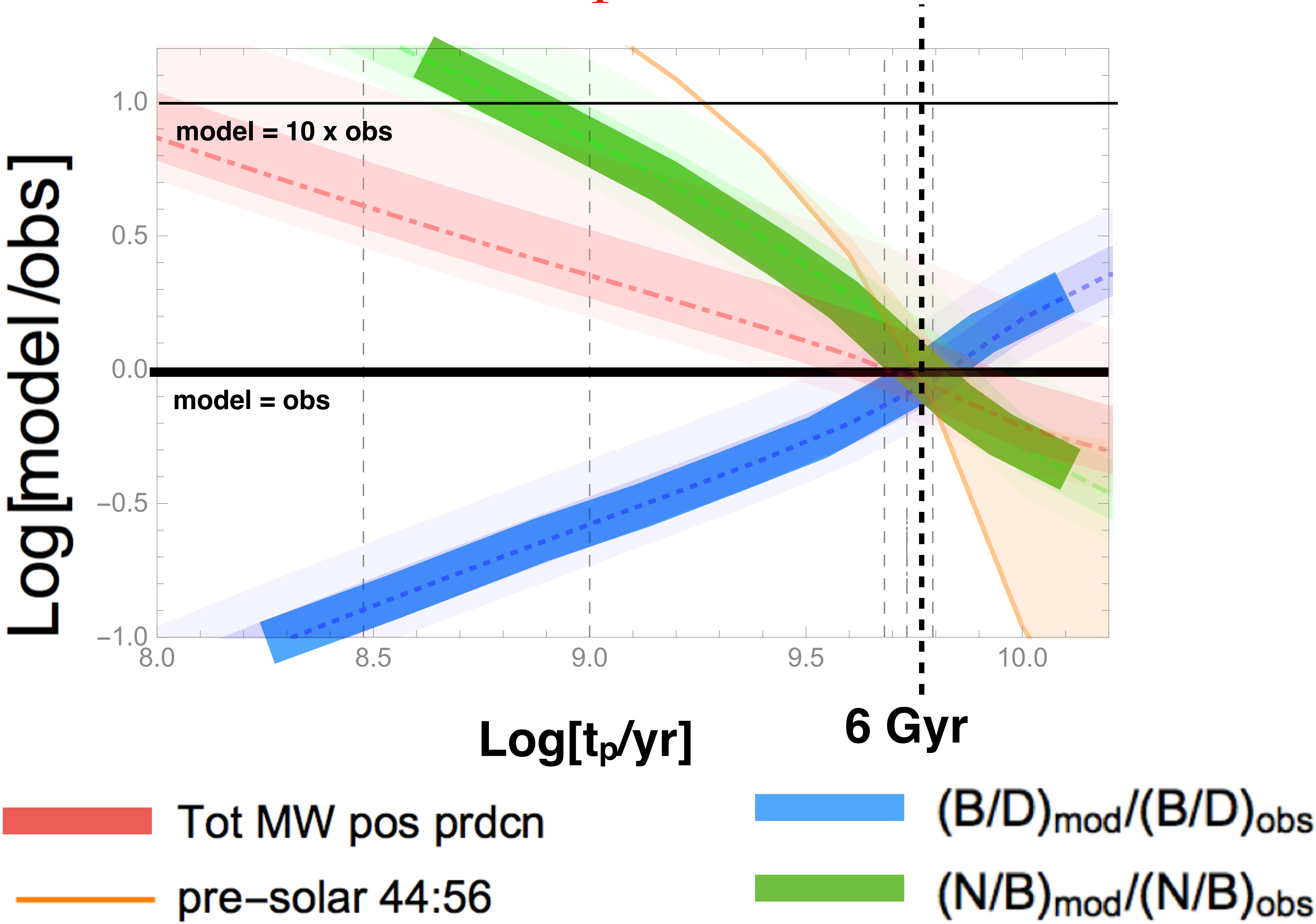

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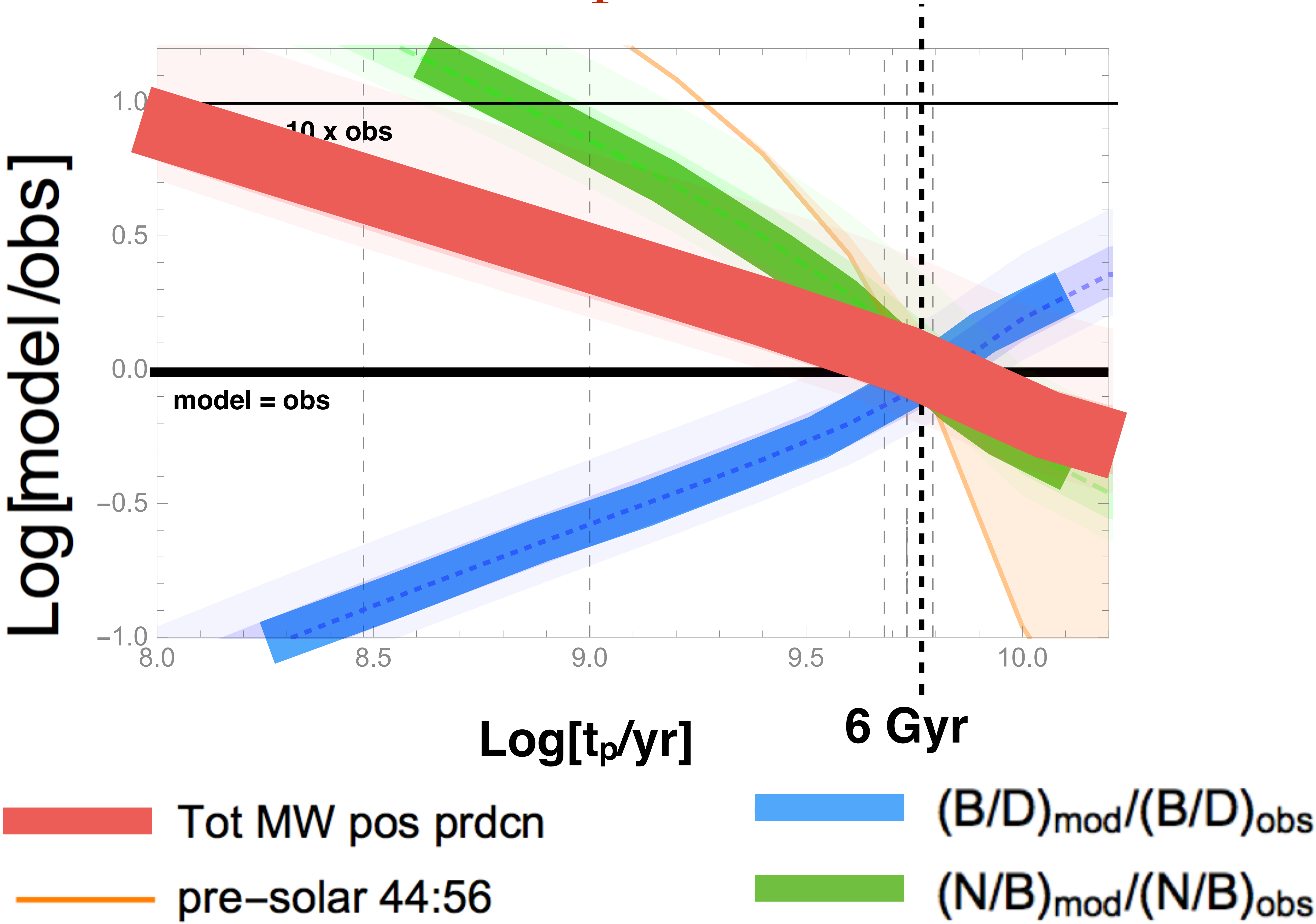

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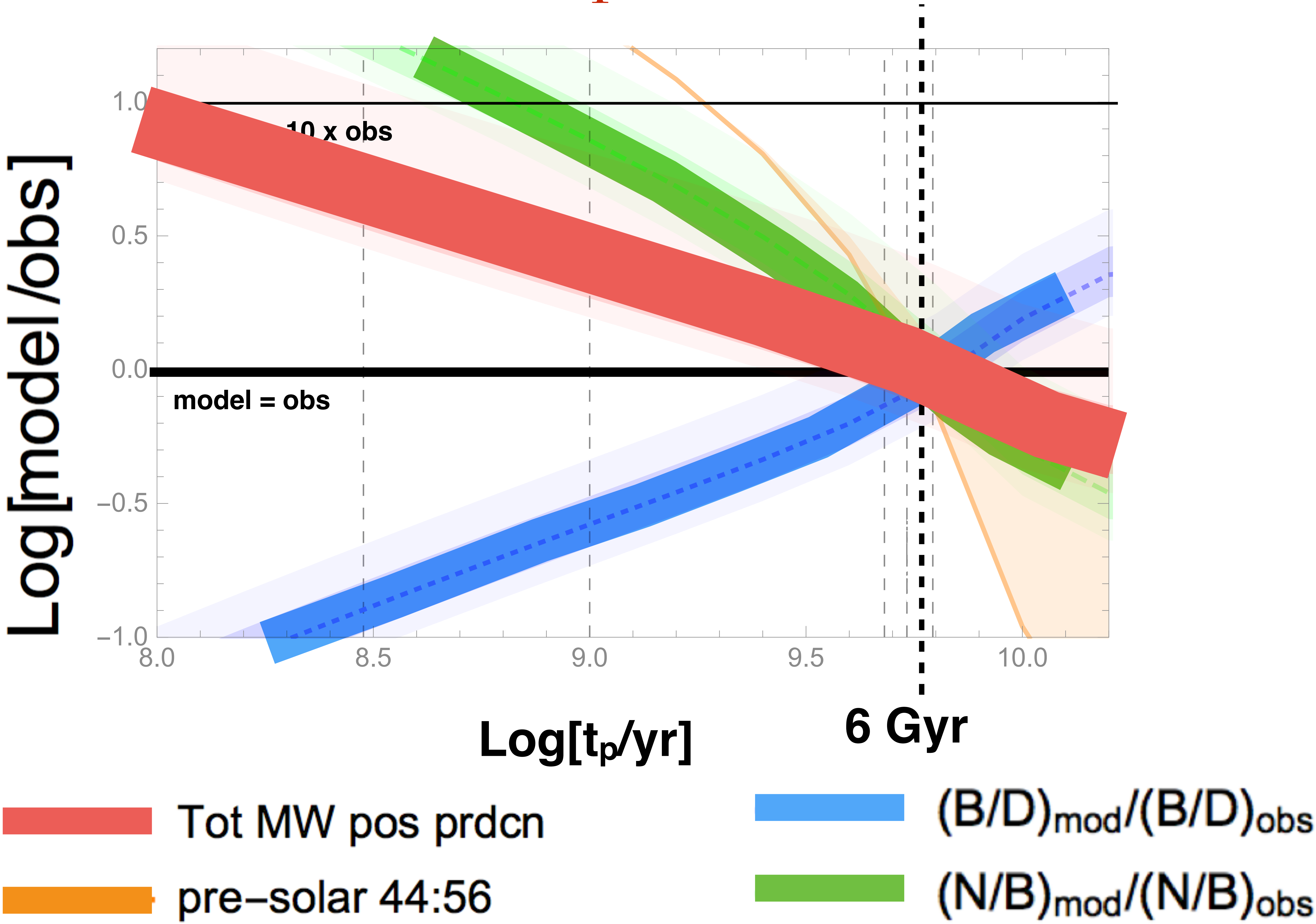

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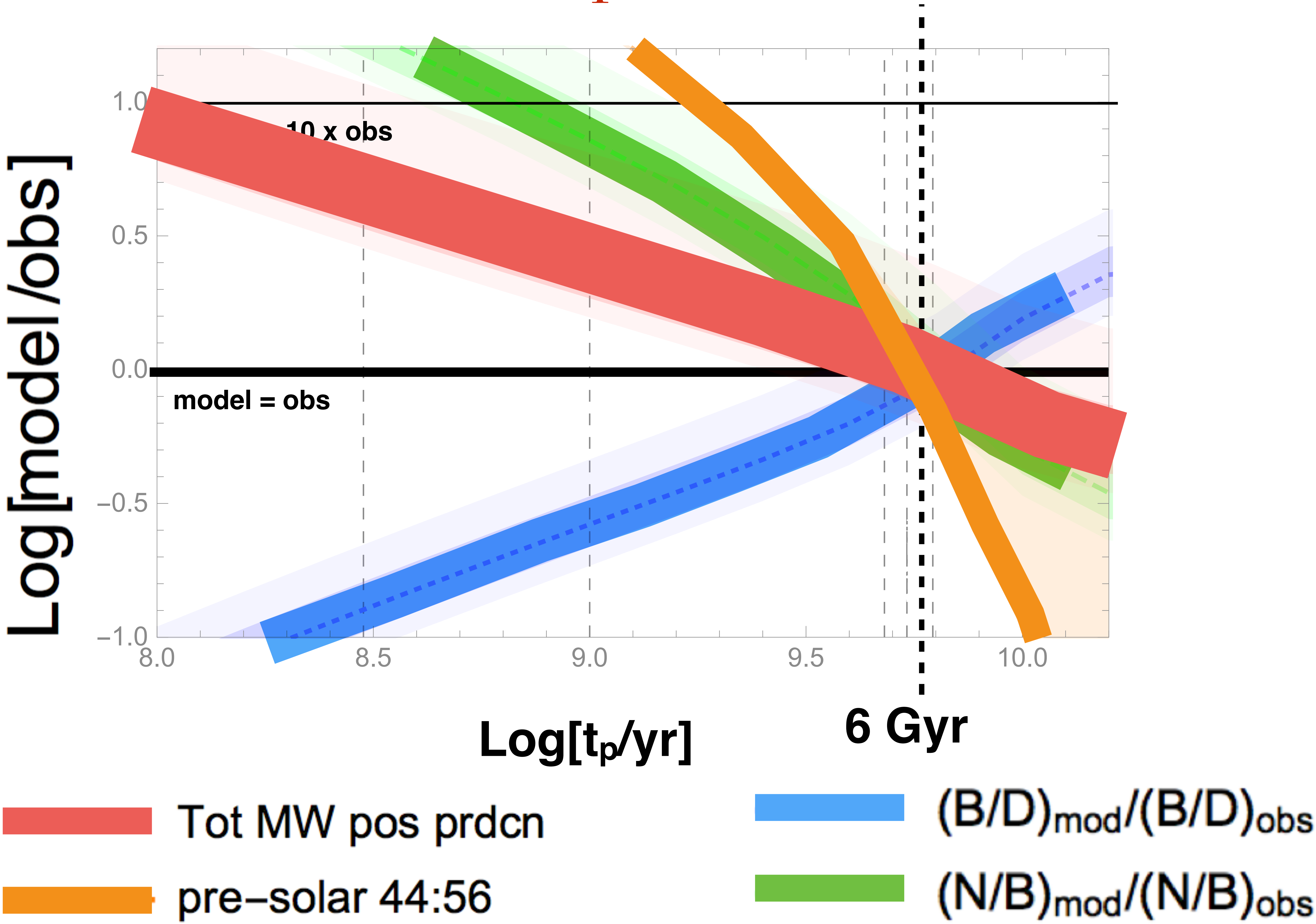
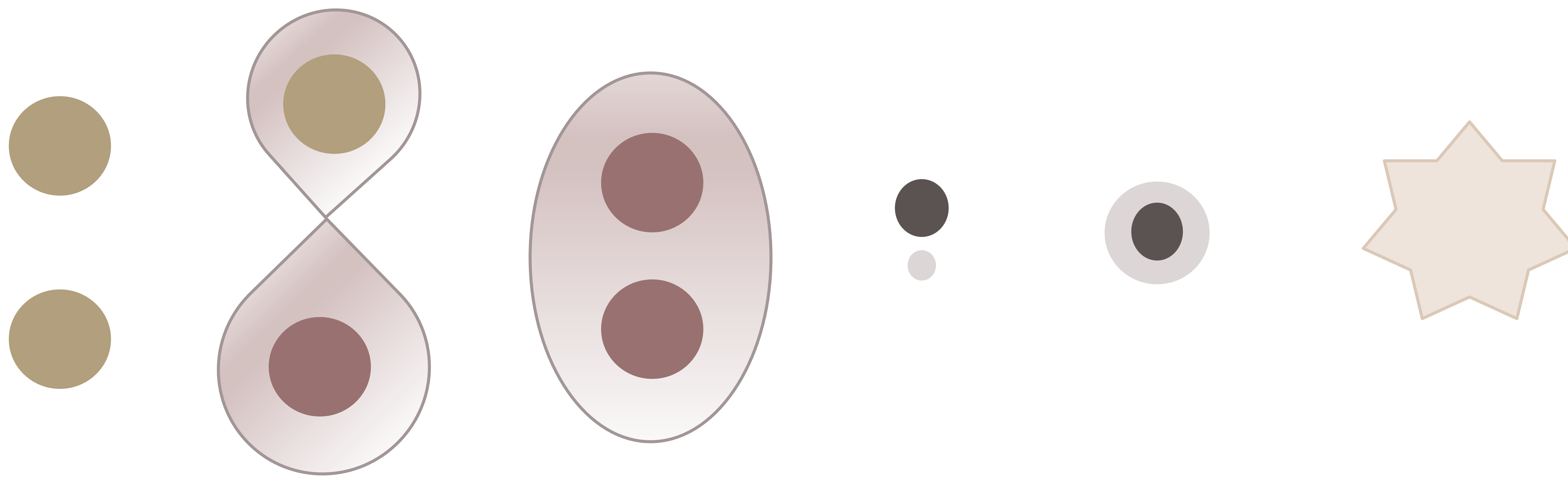


What could such a source be?

- Relatively large ^{44}Ti mass requires a *helium detonation*; requires assembly large He mass at correct density (~10^5-10^6 g/cm^3)
- Mergers of low mass white dwarf binaries can achieve this
- CO-WD/(pure) He-WD mergers occur at ~3-6 Gyr in Ashley's binary population synthesis model (`StarTrack`; Belczynski+); *this is the time scale required by positron phenomenology*
- Mergers also occur with approximately correct rate

COWD-HeWD merger leading to He detonation



1.4 – 2 solar mass interacting binary system

1 mass transfer event

1 common envelope interaction

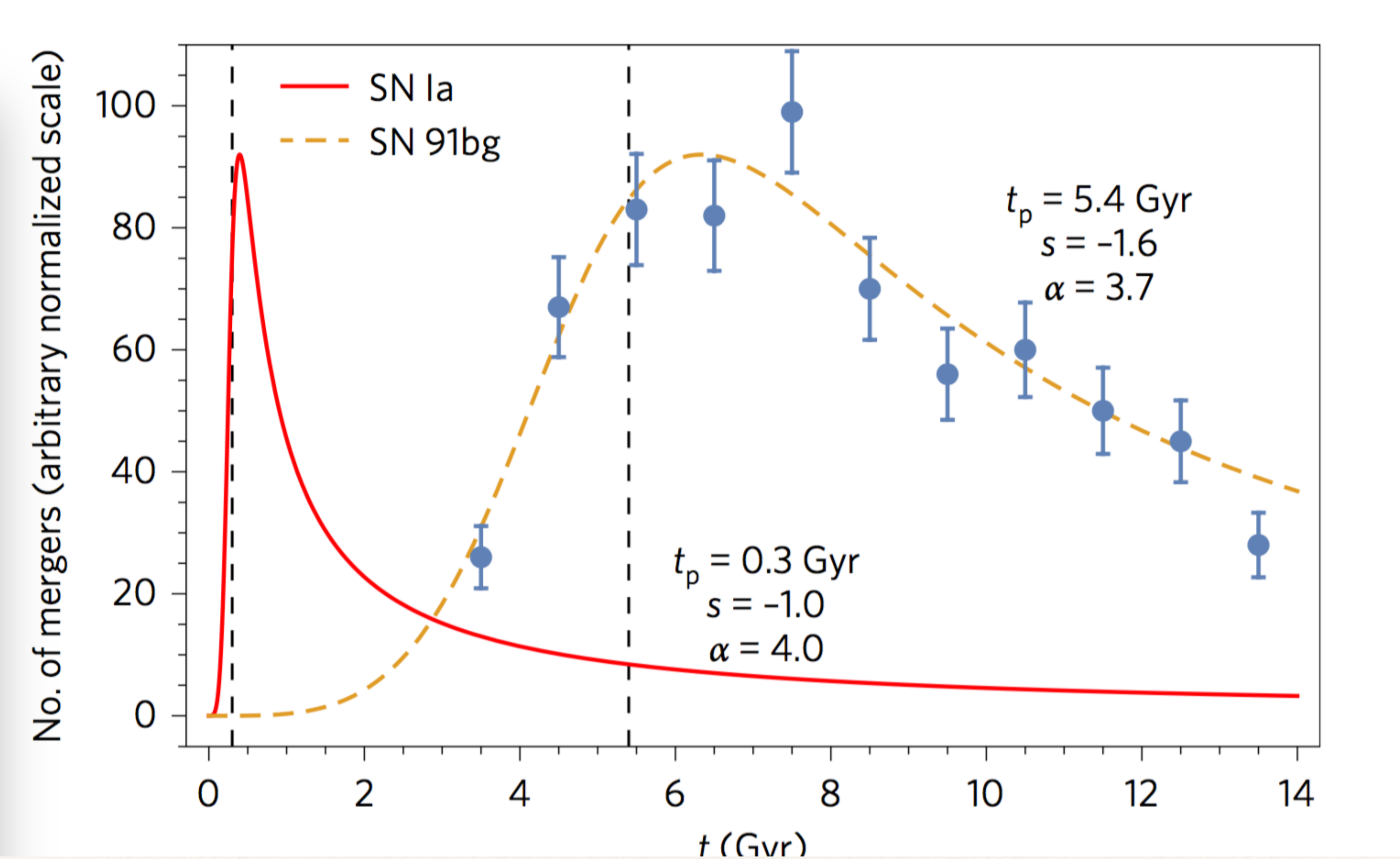
COWD + pure 0.31-0.37 solar mass HeWD

Merger at t~5.4 Gyr, system reaches quasi-HS equilibrium

Helium detonates, triggering carbon ignition

slide credit: Fiona Panther

DTD



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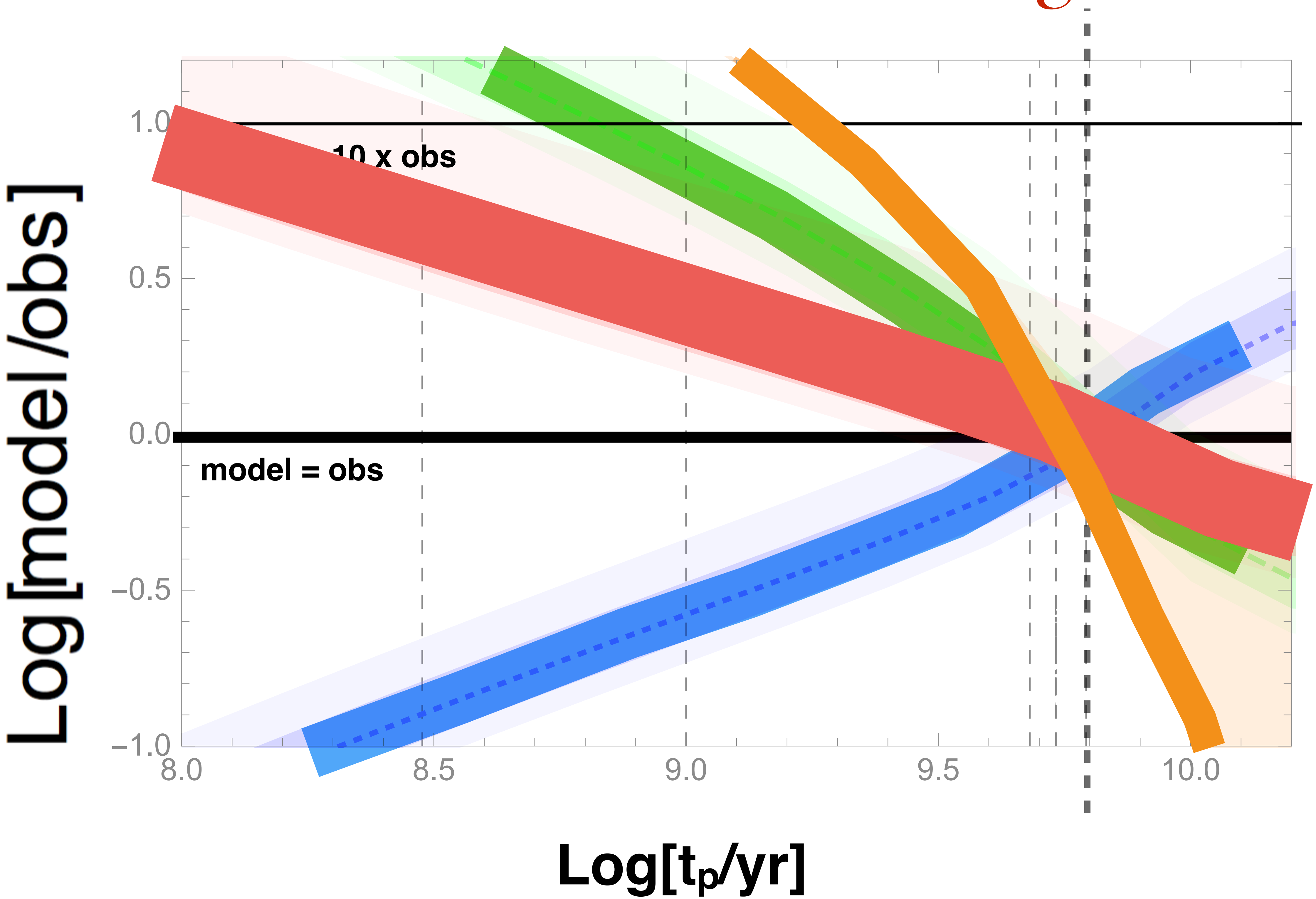
t (Gyr)

CO-He white dwarf binaries merge at 3-6 Gyr



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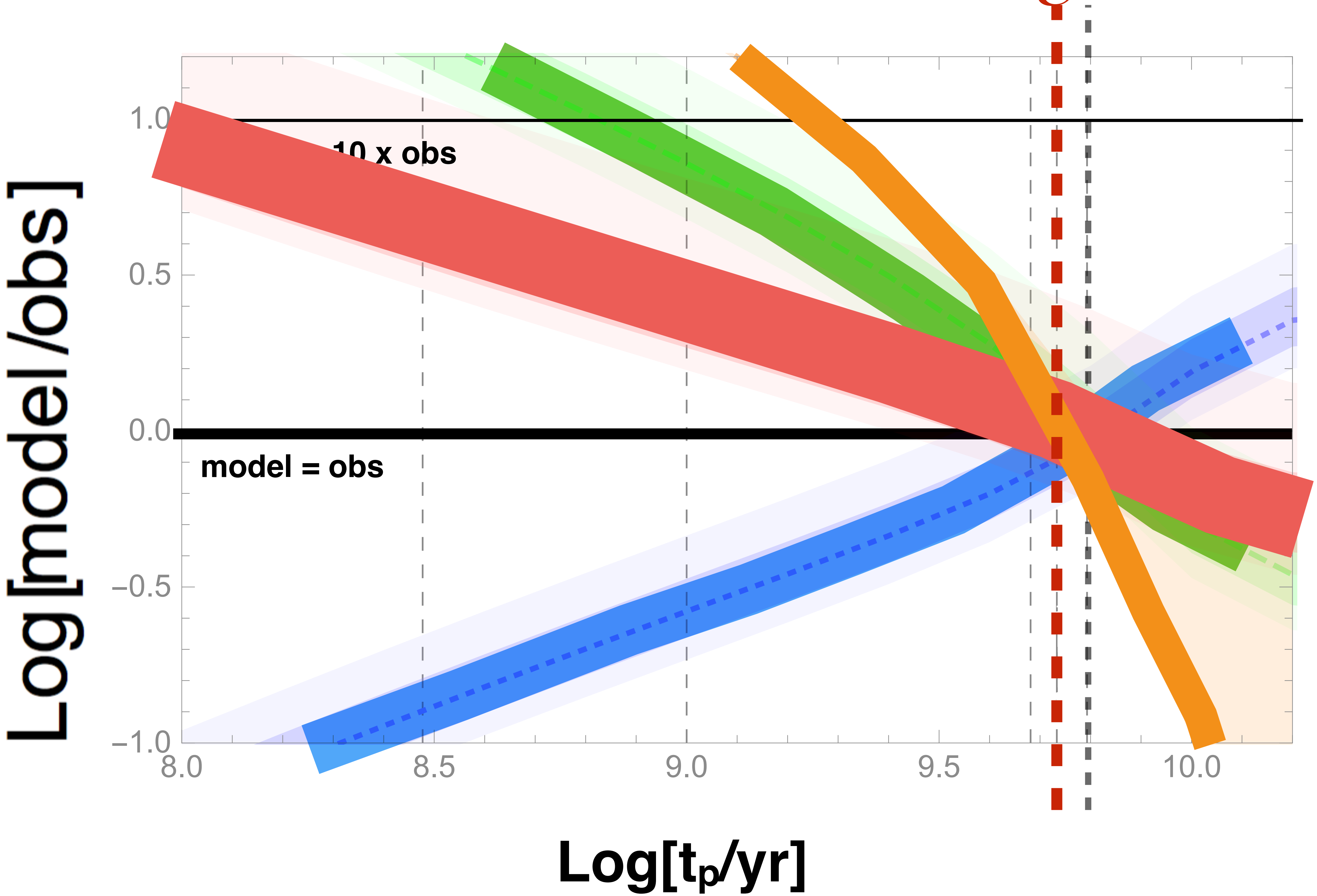

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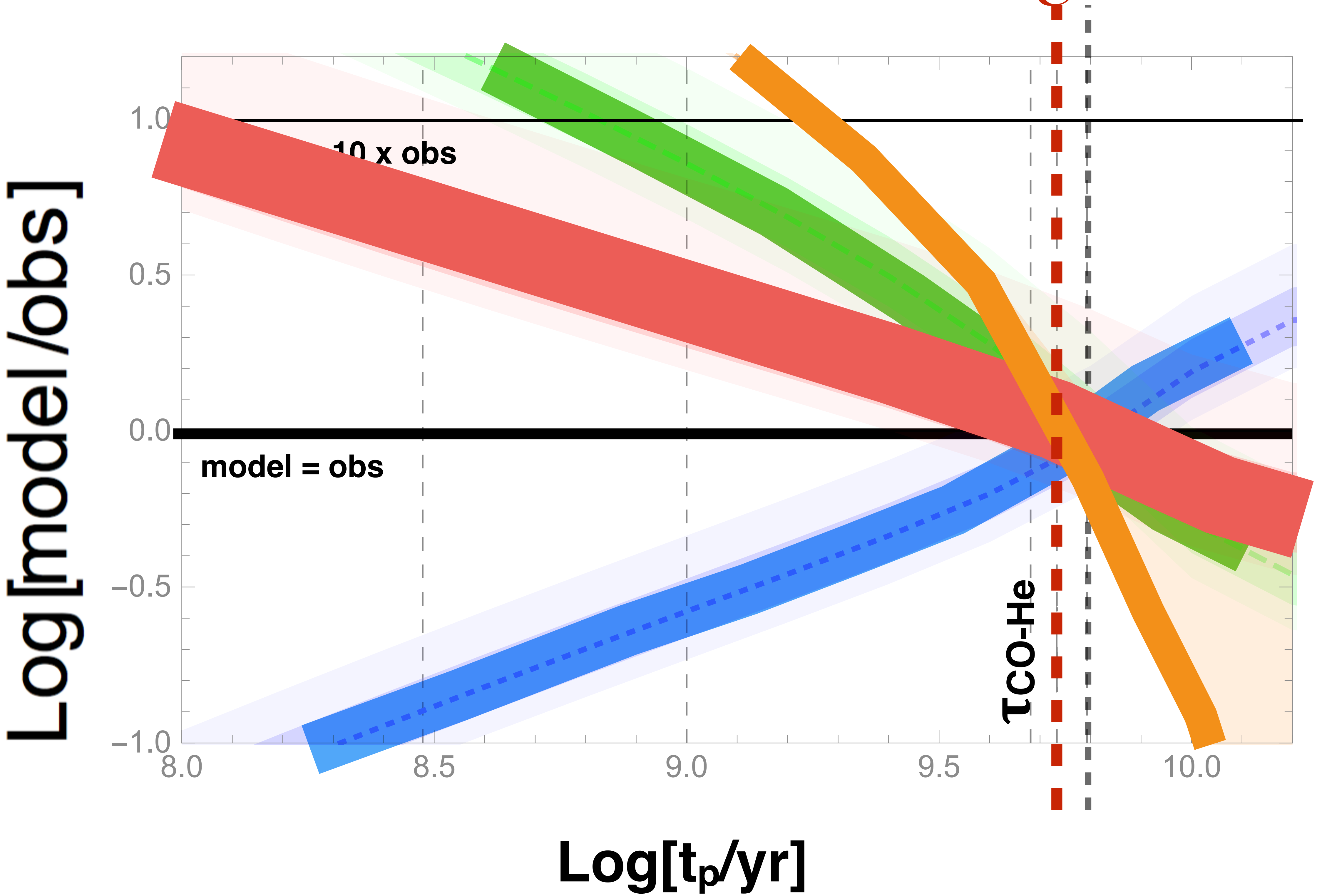

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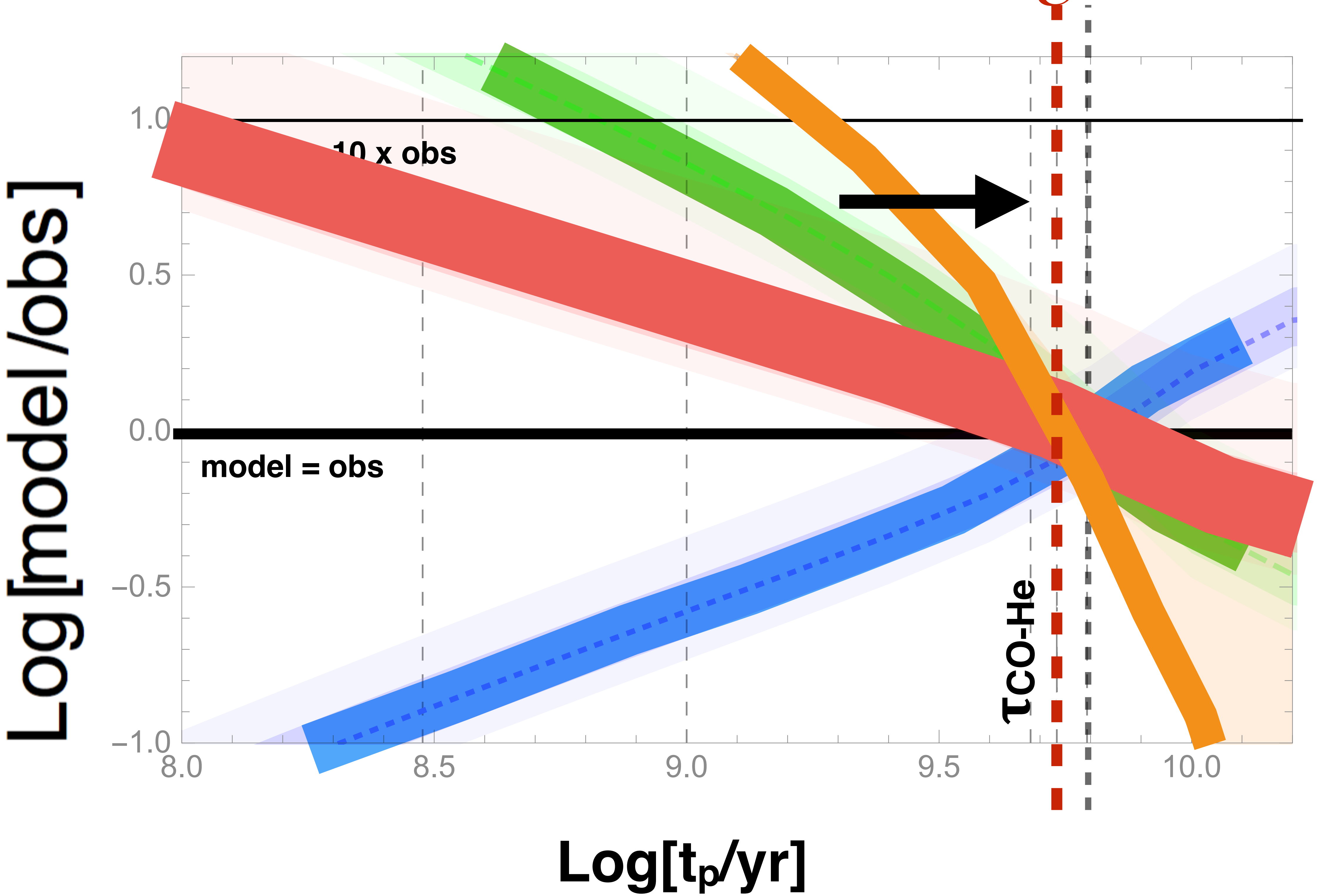
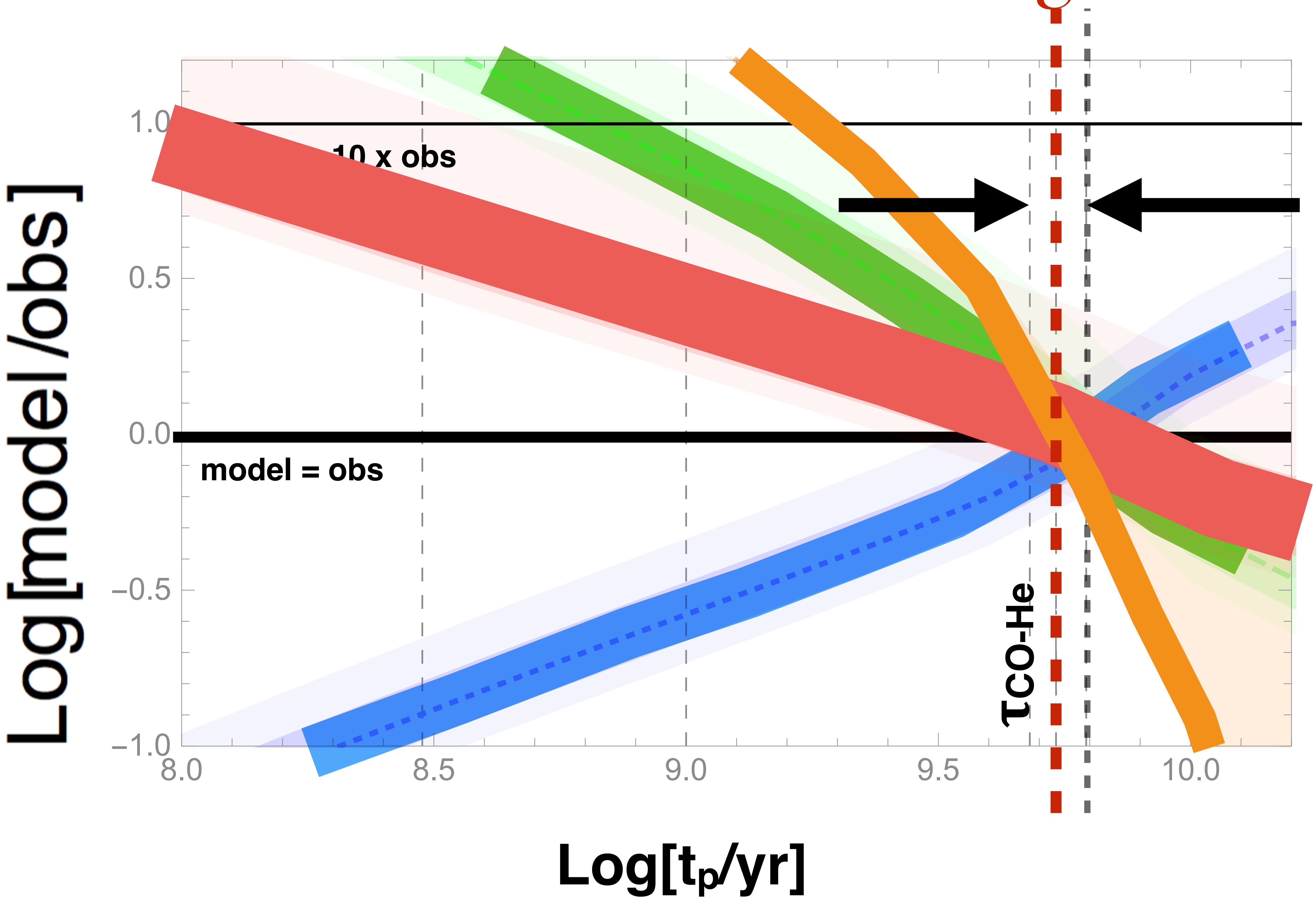


CO-He white dwarf binaries merge at 3-6 Gyr



What are these events?

- Our answer: ‘SN1991bg-like’ supernovae
- These are sub-luminous Type Ia (thermonuclear) supernovae that occur in old stellar populations
- 30% of SNIa in elliptical galaxies
- 15% of SNIa in all galaxies
- Direct, spectroscopic evidence they synthesise Ti
- Frequency seems to be increasing with cosmic time as required by our analysis

Summary Galactic Positrons:

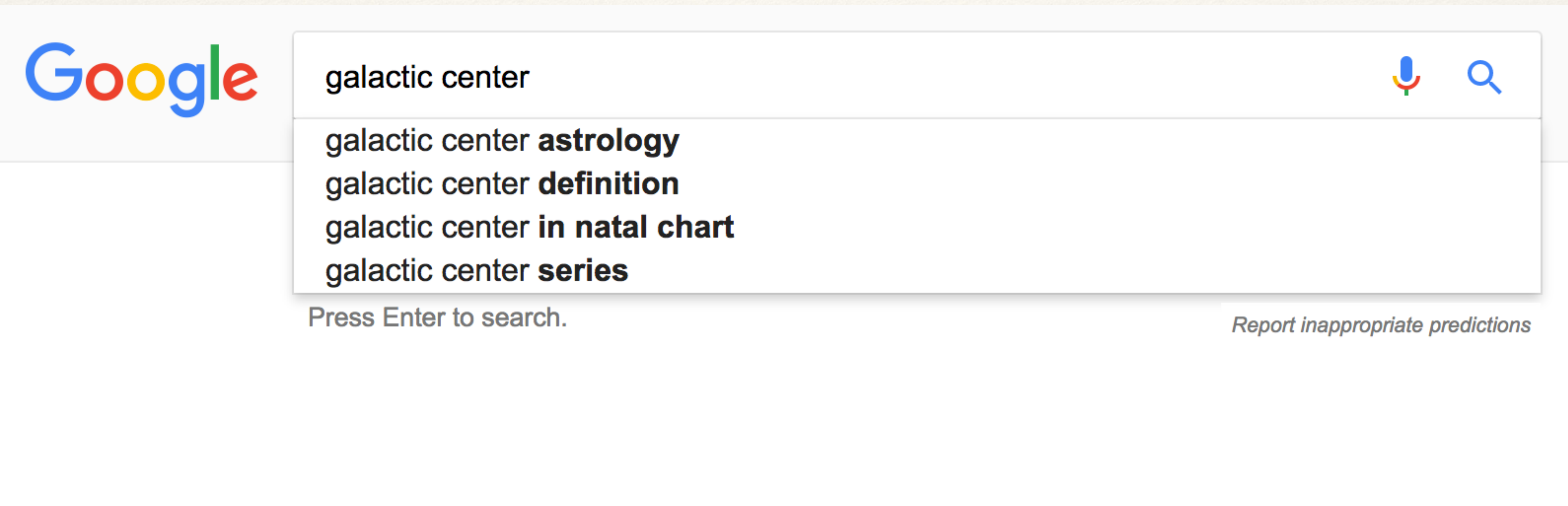
- The Galactic disk is a brighter positron source than previously reckoned;

  B/D positron luminosity ratio ~ B/D stellar mass ratio
- The nucleus has now been detected as a separate positron source
- Generically, this phenomenology can be explained with a positron source connected to old stars in the Galaxy
- A single type of transient event – SN1991bg-like supernovae – can supply the requisite number of positrons in the correct distribution to explain the origin of most Galactic antimatter
- This scenario is multiply constrained, and also suffices to explain the anomalous abundance of ^{44}Ca, the decay product of the ^{44}Ti that births the Galactic positrons, in pre-solar grains

GCE and Bulge Positrons Connected?

- The bulge positron annihilation signal emerges from the SAME REGION (Boehm+2014) and implies the SAME ENERGETICS as the ‘GC Excess’ ~GeV γ-ray signal…***are they connected?***
- Maybe:
  - The GC Excess spectrum resembles that from pulsars or millisecond pulsars
  - Binary WD systems can produce millisecond pulsars directly through ‘Accretion Induced Collapse’ of ONeMg WDs accreting from companions
  - Binary population synthesis model produces approx. right number of MSPs to explain the GC Excess signal
  - The great age of the bulge stars explains why the luminosity function of the MSPs is systematically dimmer than local MSPs as demanded by observations

Questions?



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