(Dark Matter Backgrounds to) Multi-wavelength Galactic Centre Astrophysical Signals

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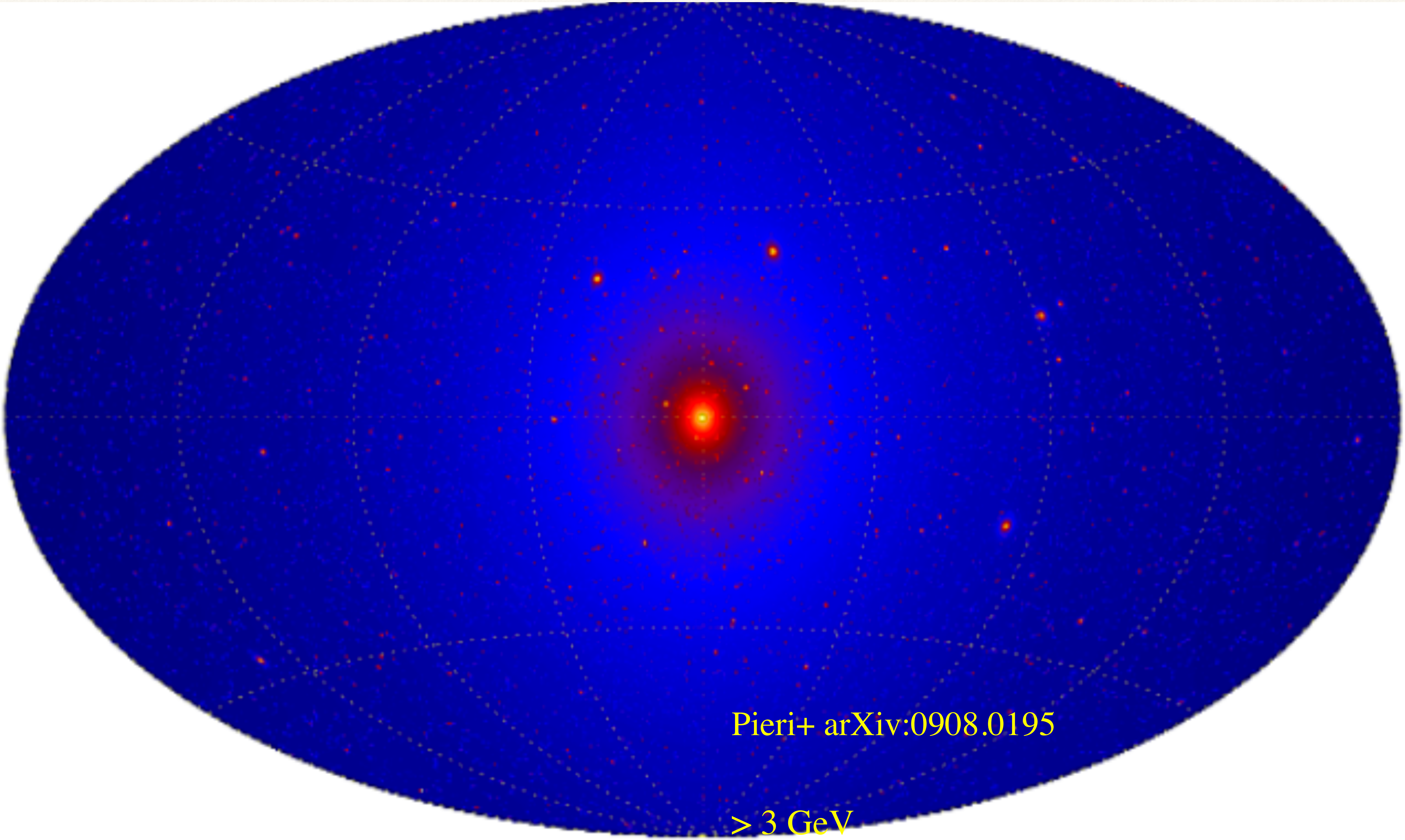
Australian National University

On being an ‘expert’

- I’ve been accused of being an expert on the Galactic Centre…this is only true to the extent that an expert is *somebody who understands the full enormity of our ignorance in a particular field…*

Preface: why is the Galactic Centre interesting?

- 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

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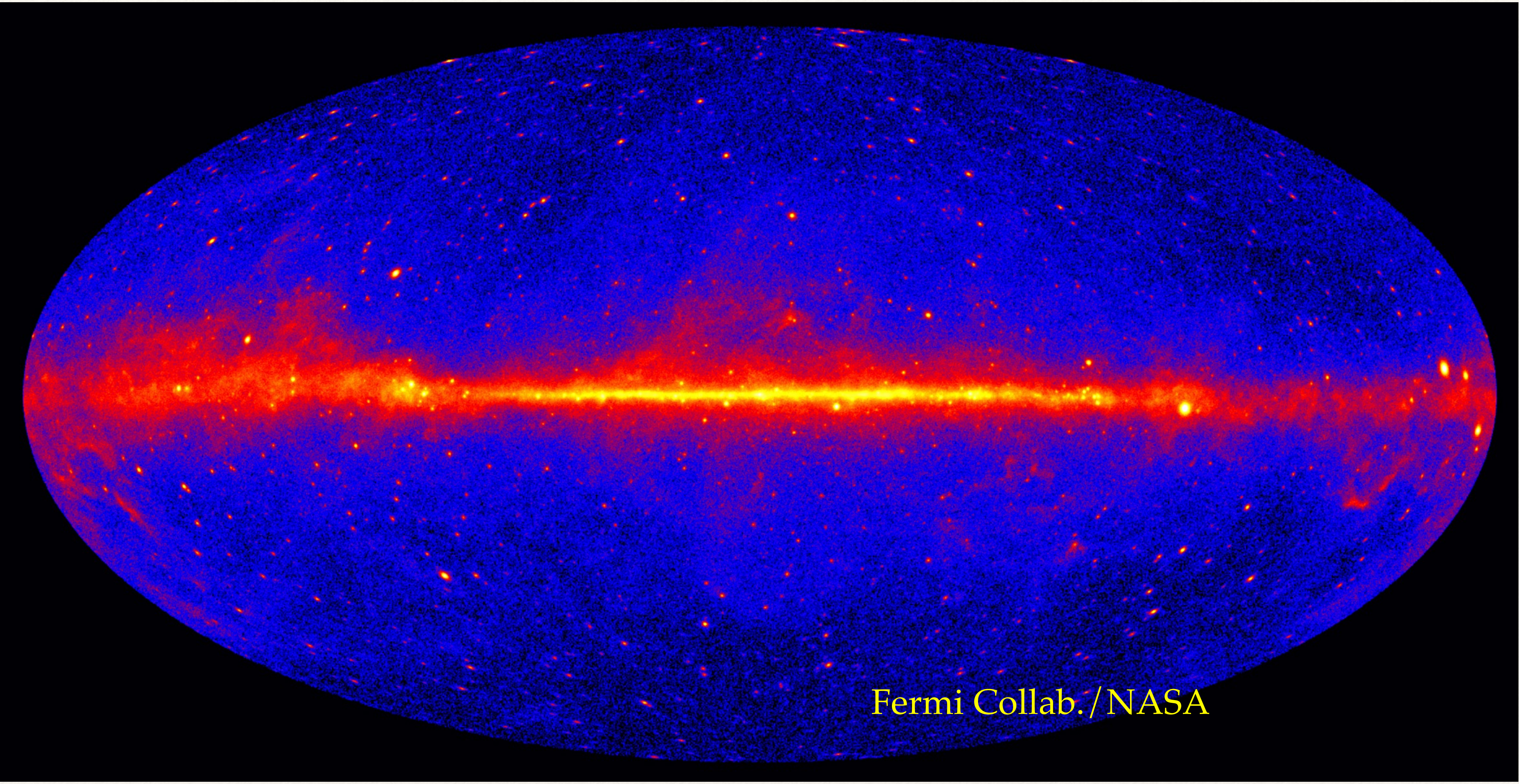
- On the other hand:


Fermi Collab./NASA

Preface: why is the Galactic Centre interesting?

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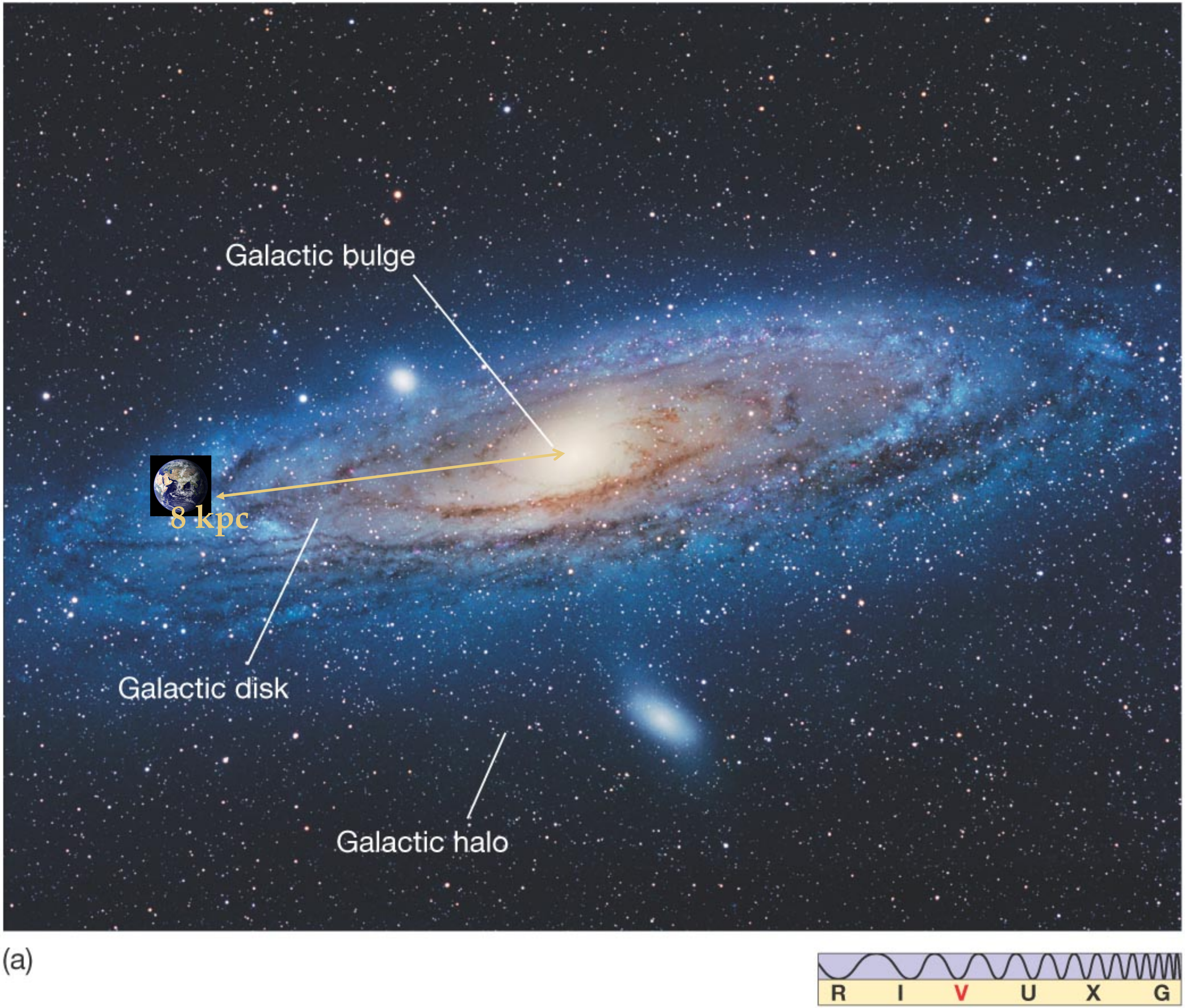
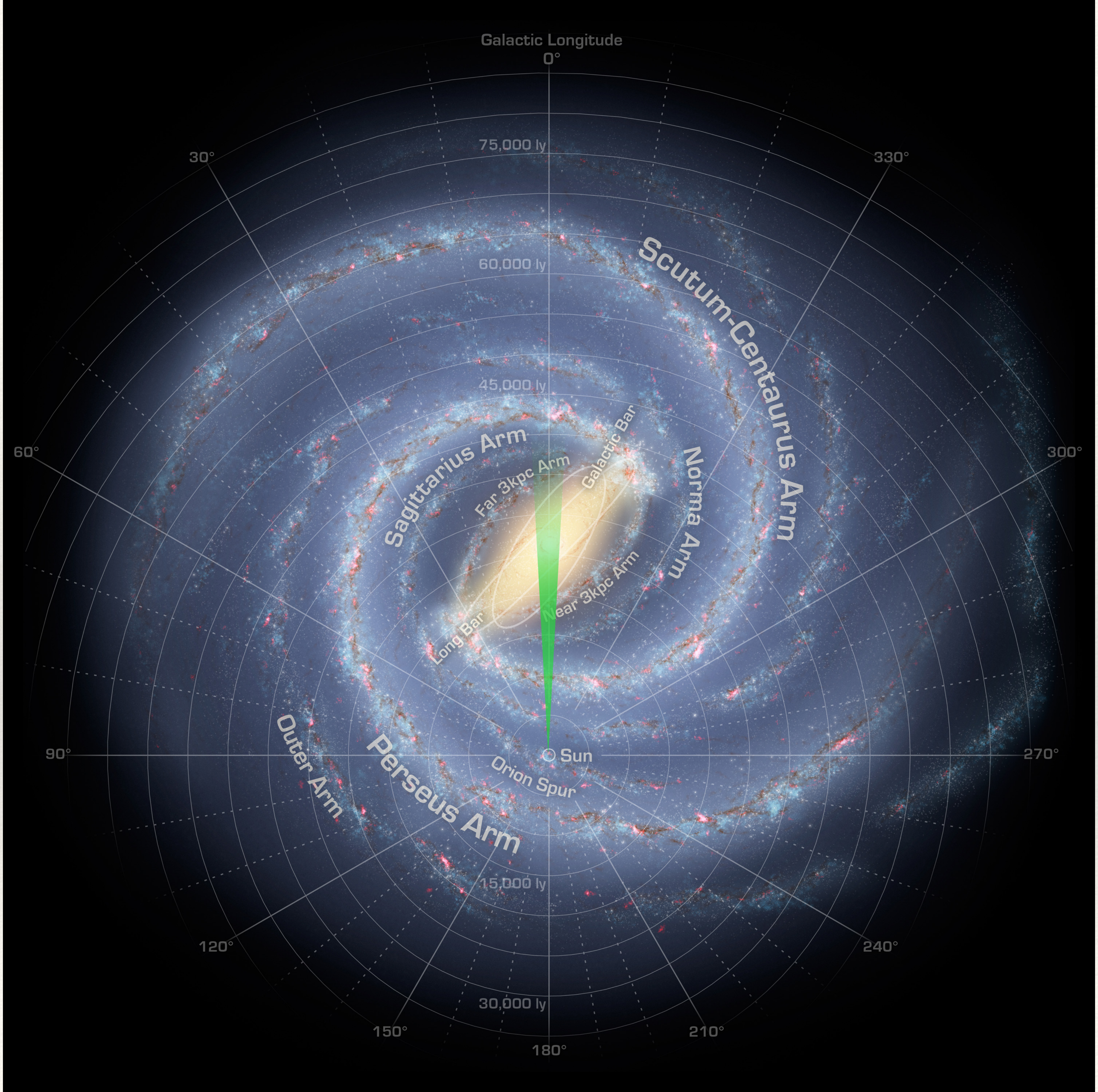
- On the other hand:
  - There's a lot of Galaxy between us and the GC



(a)



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
Sun
Orion Spur
Perseus Arm
Outer Arm


ESO

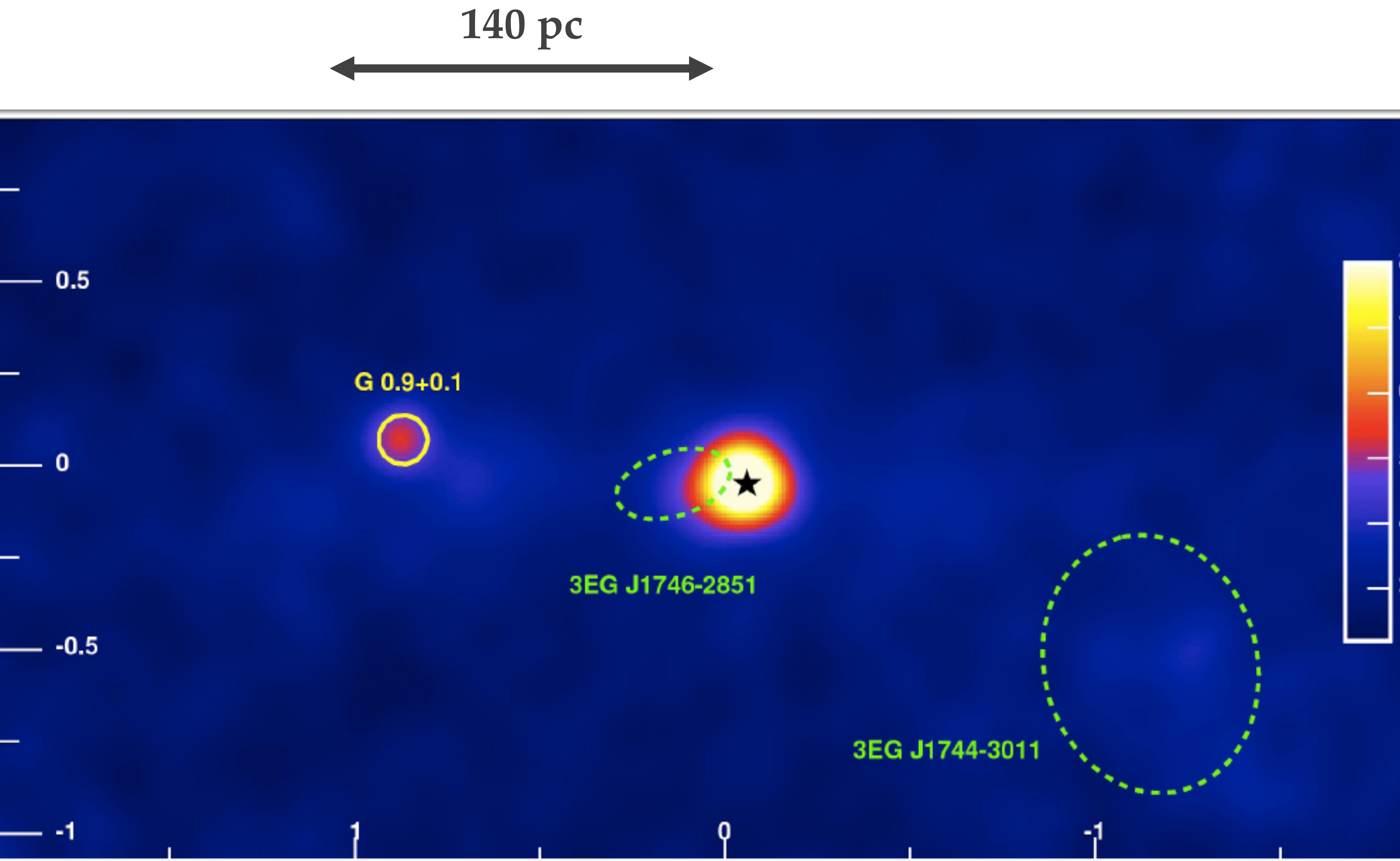
Galactic Centre Dark Matter(?)

- Researchers motivated to search for anomalous signals from the GC that are potential dark matter signatures have done remarkably well in turning up such signals

Remarkable Non-Thermal Phenomena of the GC/Inner Galaxy:

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

small scales → LARGE SCALES



HESS TeV (Aharonian et al 2006)

Remarkable Non-Thermal Phenomena of the GC/Inner Galaxy:

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- Extended (few degrees) GeV & TeV emission

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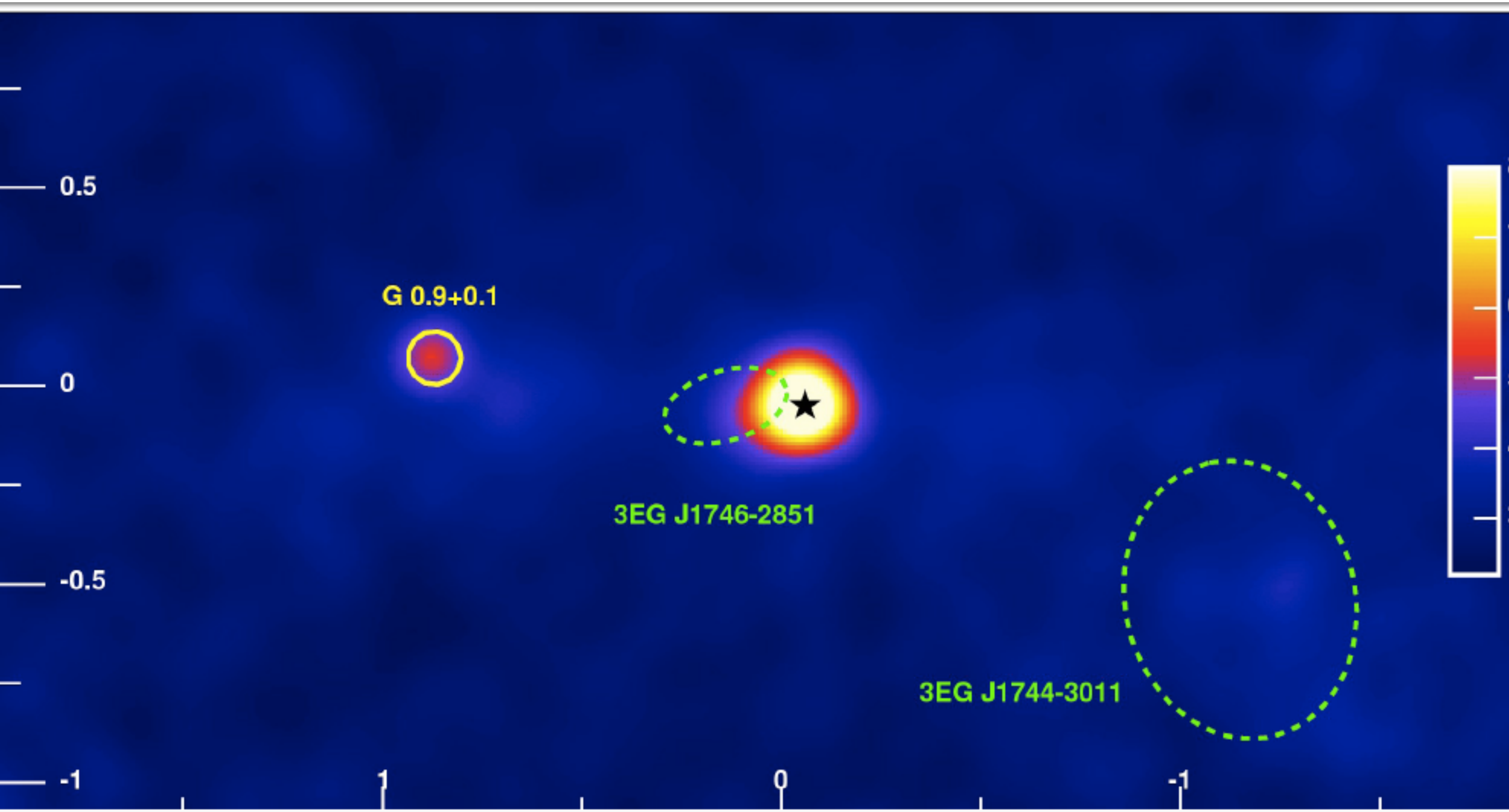
G 0.9+0.1
3EG J1746-2851
3EG J1744-3011
0.5
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-1
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-1

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- Non-Thermal Radio (and X-ray) Filaments (NTFs)

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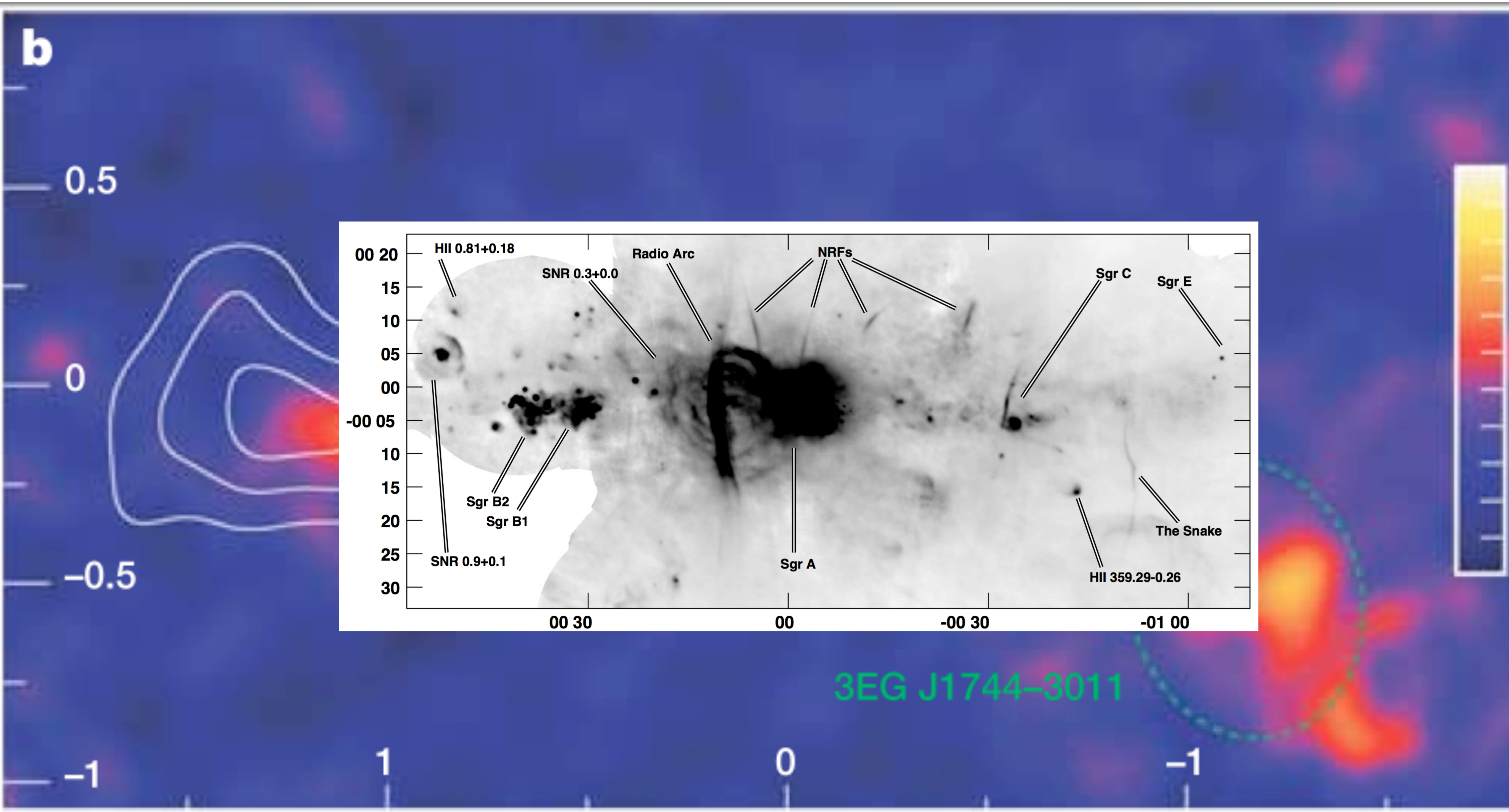

Yusef-Zadeh+2004, 1.4 GHz

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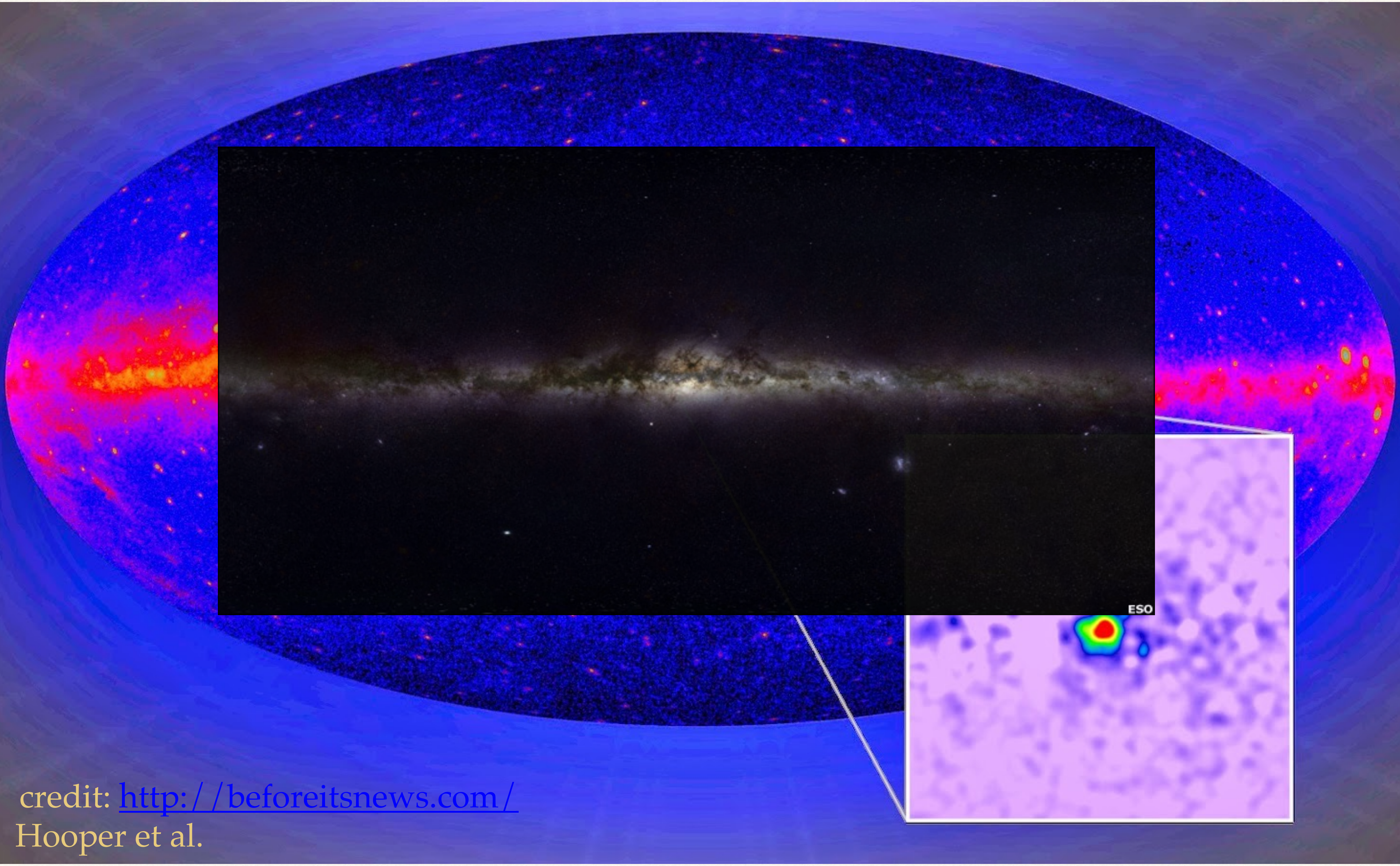
- ~GeV γ-ray spectral bump 'GC Excess'

small scales ⟶ LARGE SCALES

GC Excess



credit: http://beforeitsnews.com/
Hooper et al.

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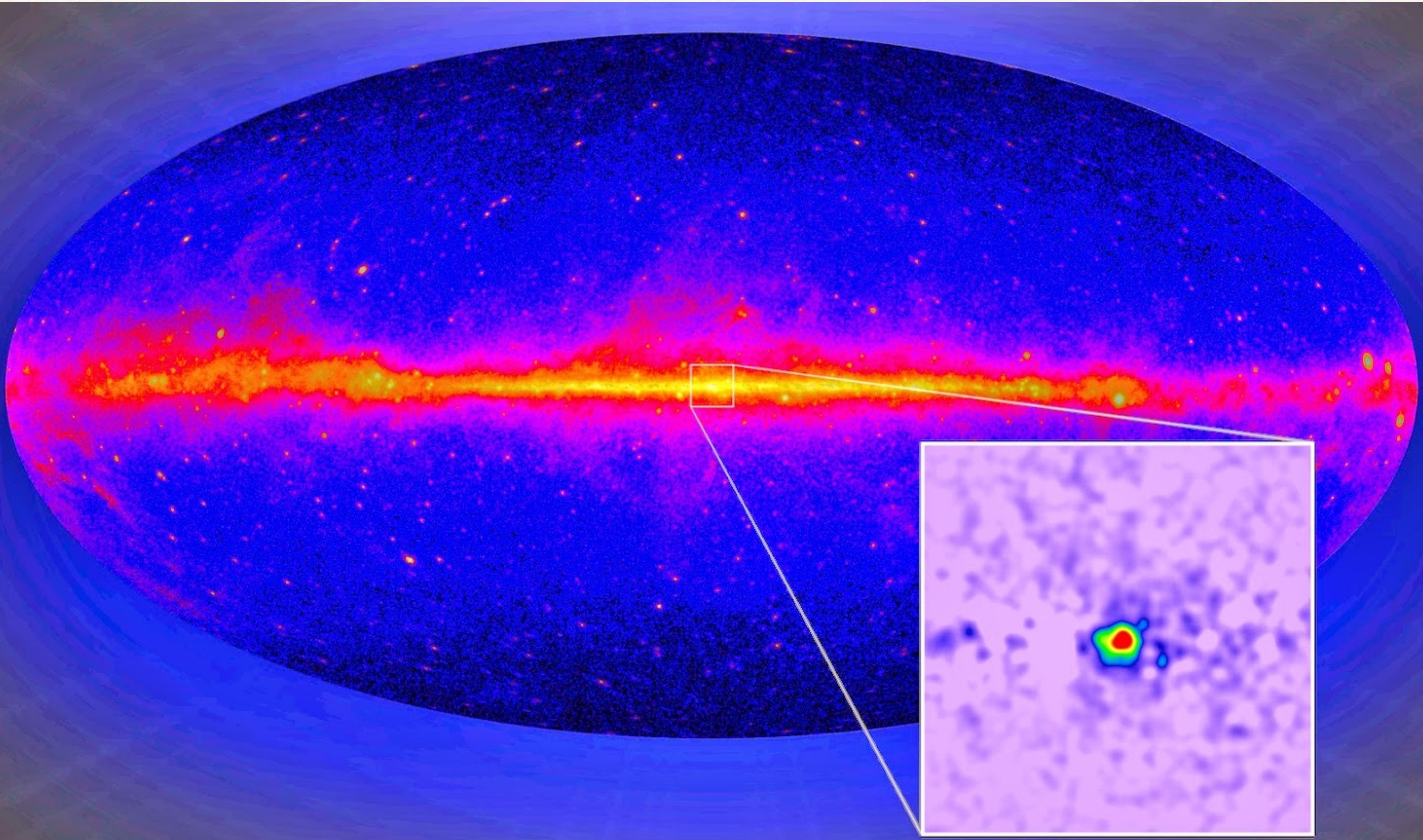
small scales → LARGE SCALES

Bulge Positron Problem



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- 511 keV positron annihilation line
- Non-thermal microwave 'haze'

small scales $\longrightarrow$ LARGE SCALES

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- F

Every one of these has been claimed as a possible dark matter signature

small scales → LARGE SCALES

The Galactic Centre

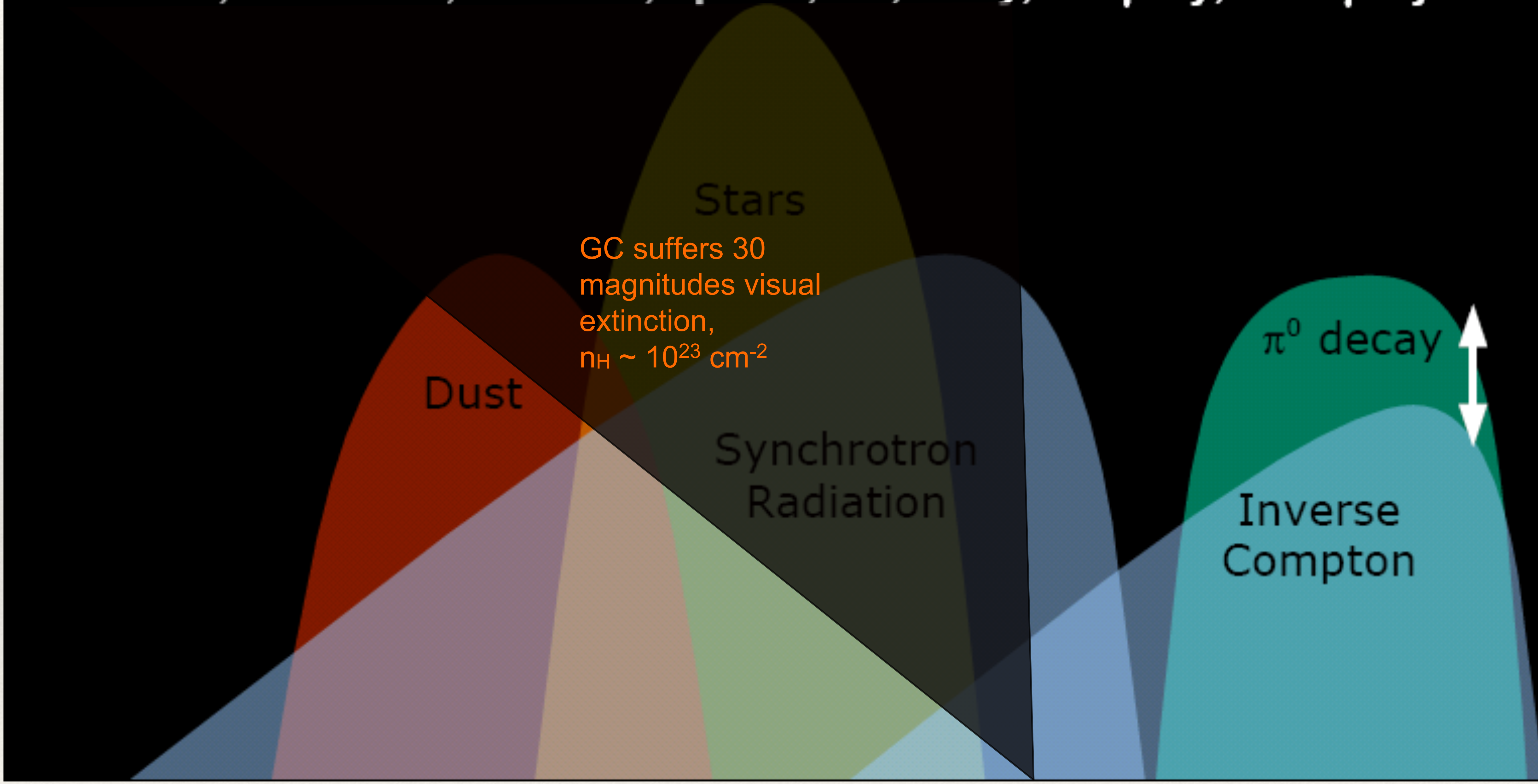
- In very general terms, the GC is a peculiar and remarkable environment within the Galaxy
- We should therefore exercise great caution in 'normalising' our expectations for its astrophysical signals via observations performed locally

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

Generic Galactic 'SED' (Spectral Energy Distribution)

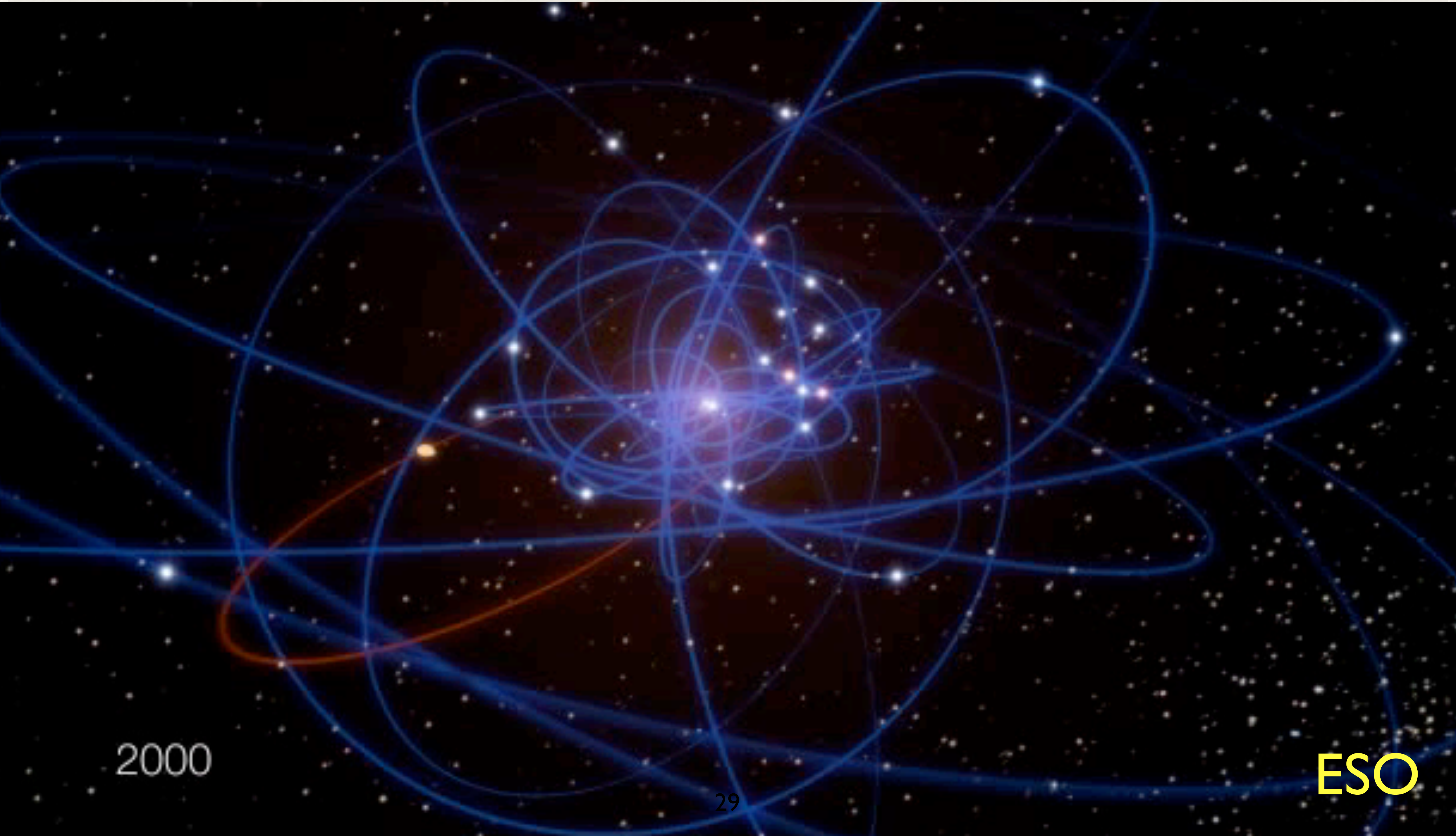
- Radio, millimetre, infra-red, optical, UV, X-ray, HE γ-ray, VHE γ-ray



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

Given all this, what do we actually know about the Galactic Centre?

It *certainly* contains dark matter: there is a 4 Million Solar Mass chunk at the Galaxy's dynamical



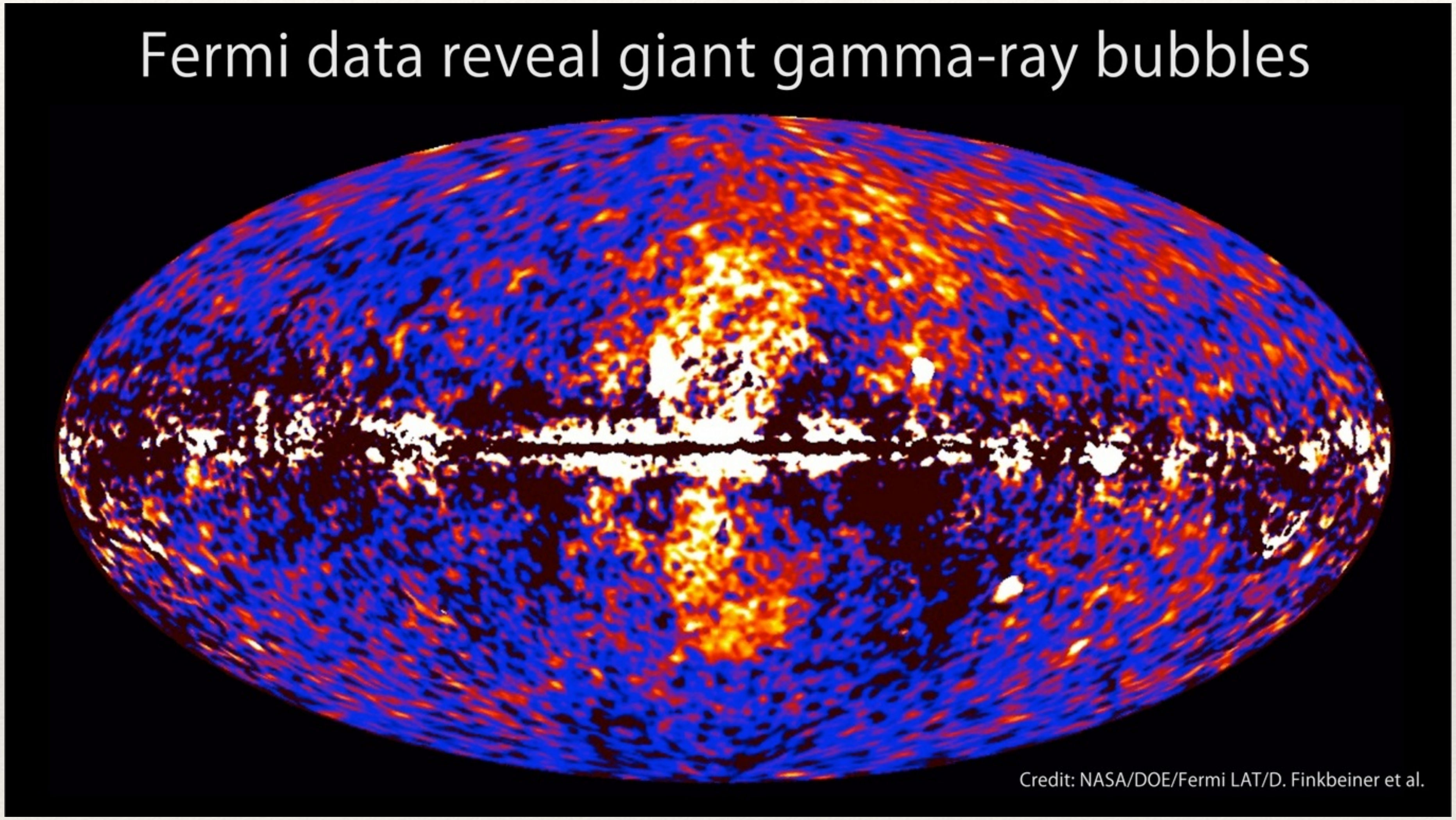
A Quiescent (?) Giant

- SMBH itself exhibits remarkably little activity across the EM spectrum

A Quiescent (?) Giant

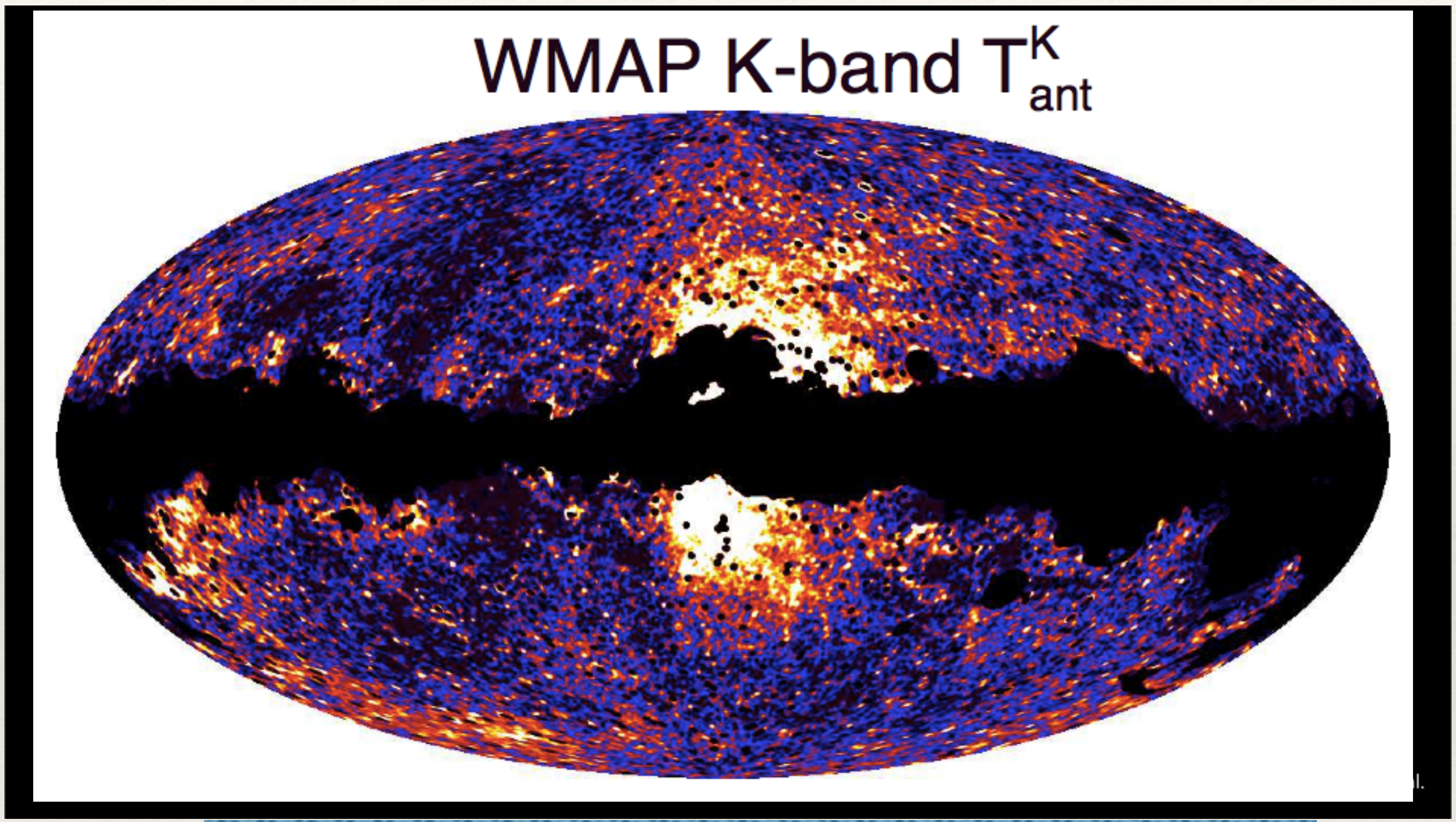
- SMBH itself exhibits remarkably little activity across the EM spectrum
- In contrast, we know that for some external galaxies, energy liberated in accretion on to a SMBH can 'feedback' to have an influence on galactic or even galaxy cluster scales

Fermi Bubbles



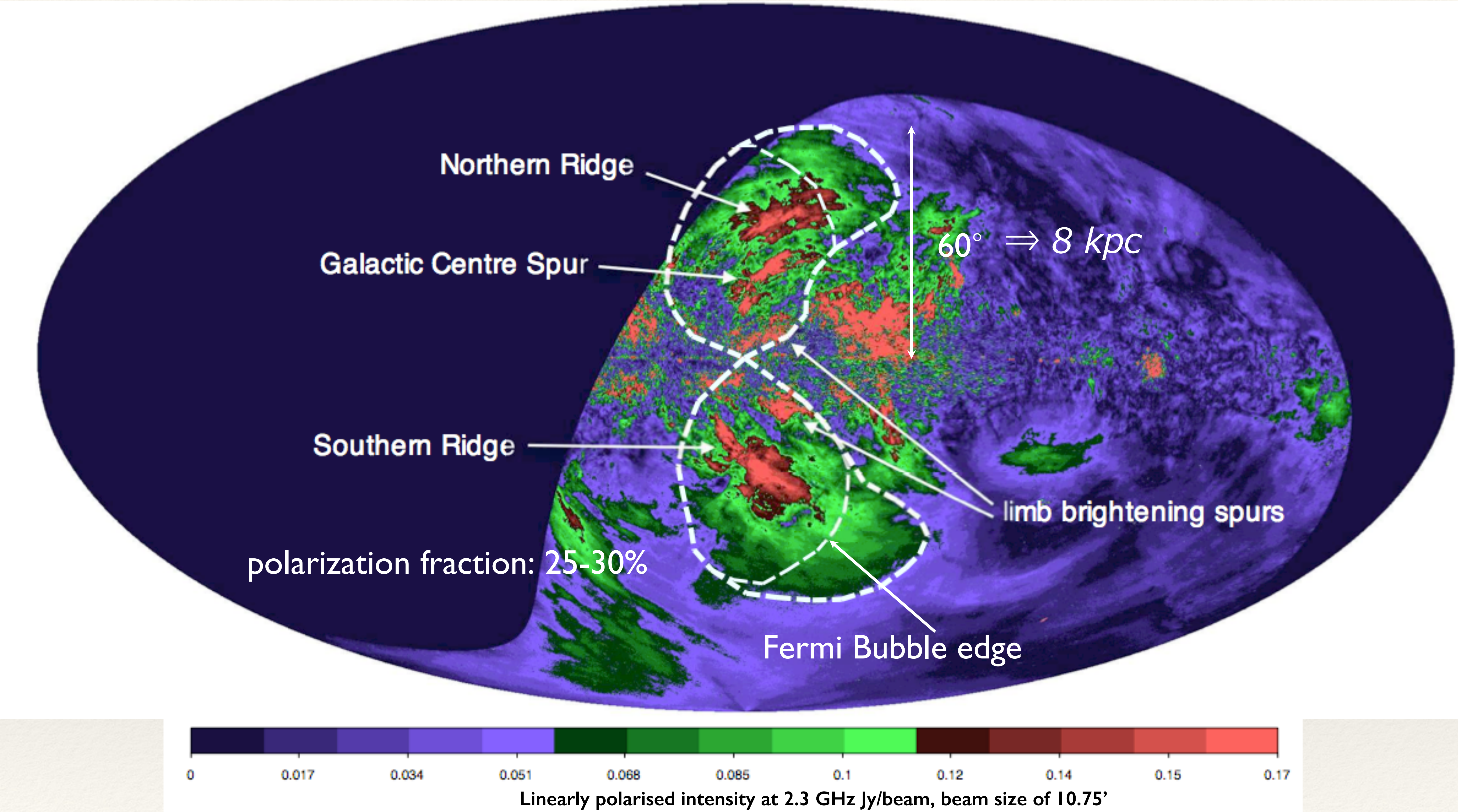
Su, Slatyer and Finkbeiner 2010 (ApJ)

WMAP Haze



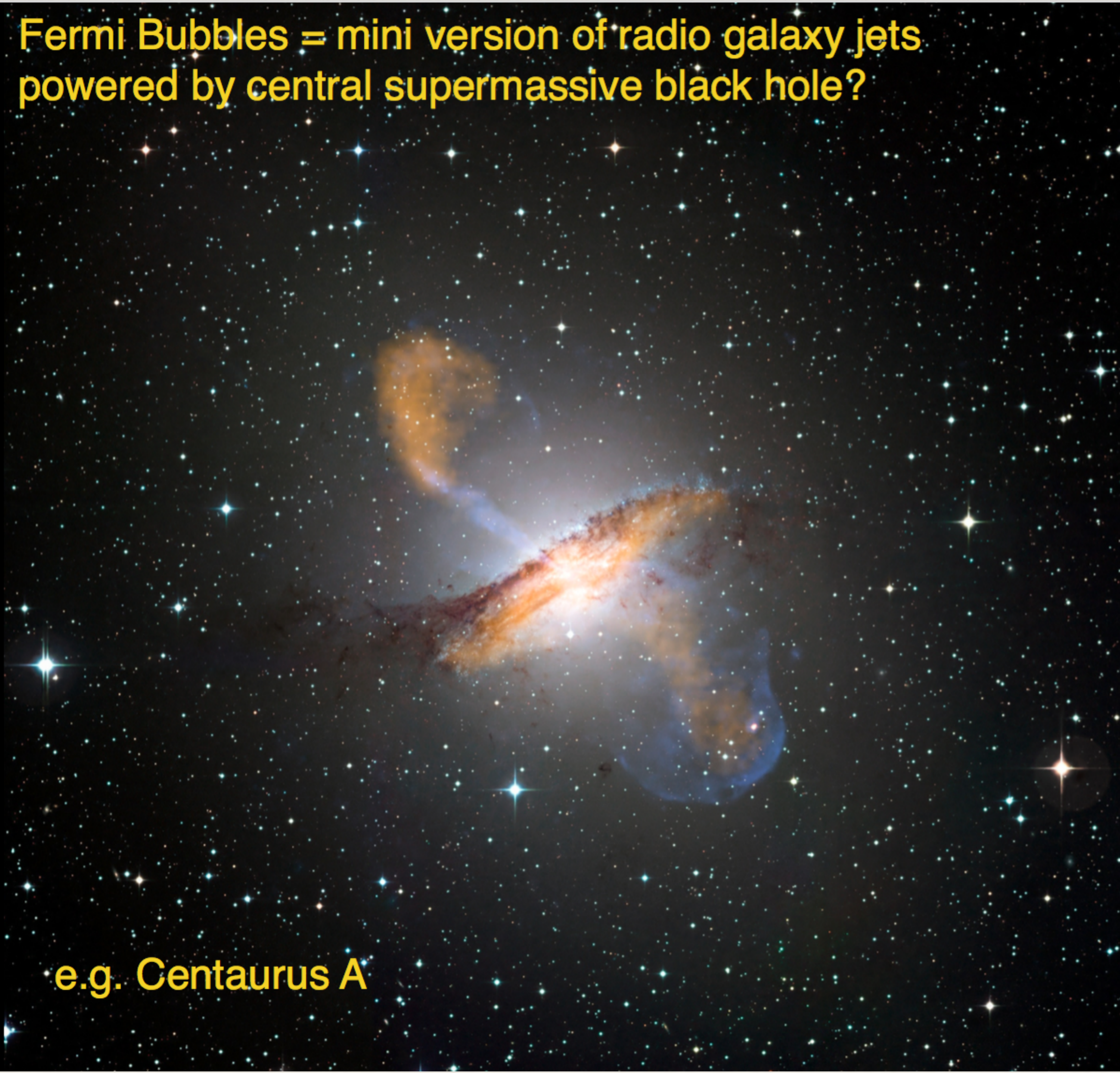
Dobler (2012)

The S-PASS Lobes

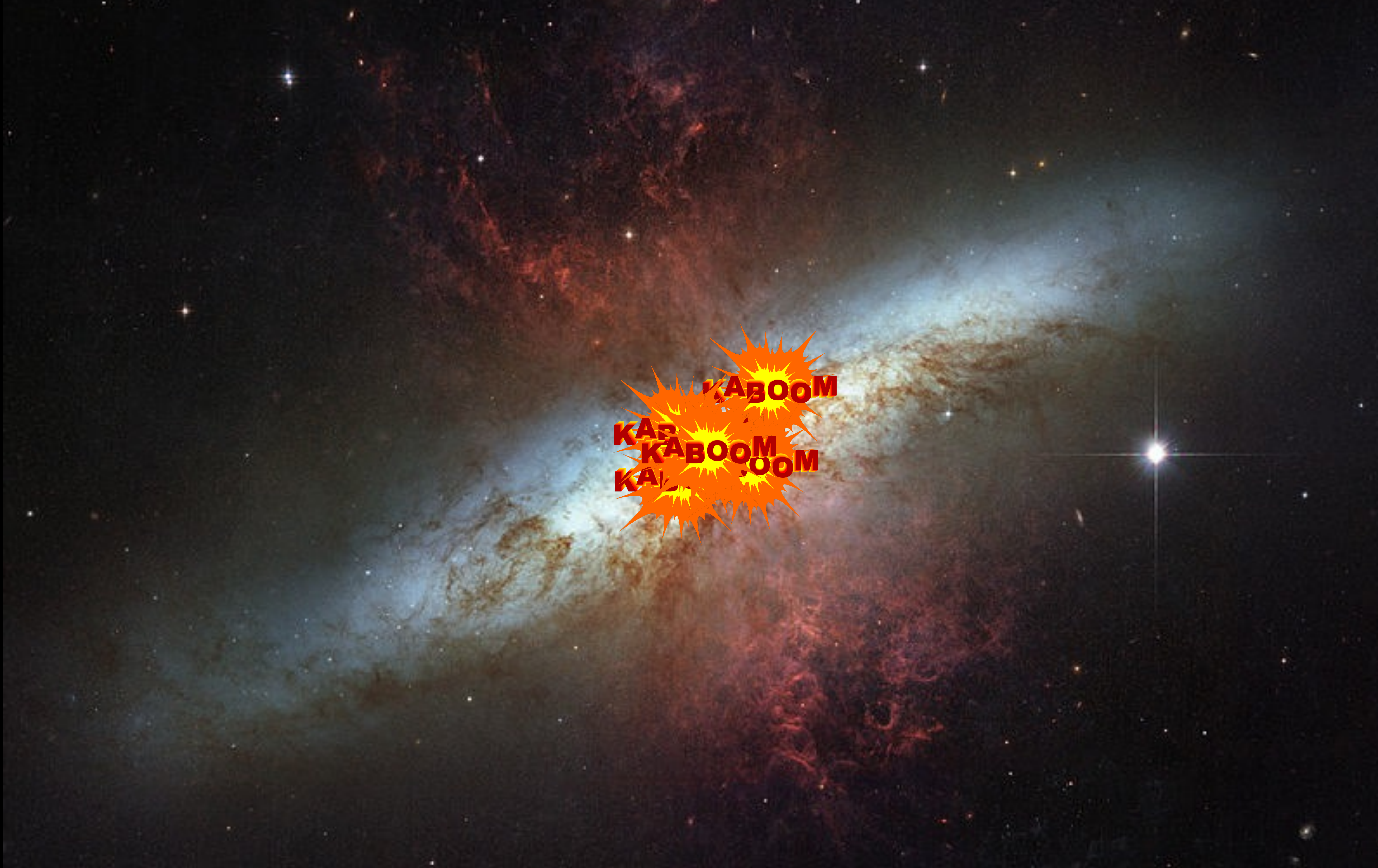


Ettore **Carretti**, Roland M. Crocker, Lister Staveley-Smith, Marijke Haverkorn, Cormac Purcell, B. M. Gaensler, Gianni Bernardi, Michael J. Kesteven & Sergio Poppi

Nature 2013


Fermi Bubbles = mini version of radio galaxy jets
powered by central supermassive black hole?
e.g. Centaurus A

Fermi Bubbles = nuclear starburst with outflowing winds?



e.g. M82

The SMBH is surrounded by a region hosting intense star formation

Why?

- 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…*and a similar fraction of all Galactic star formation*

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 star formation activity produces a highly energised interstellar medium

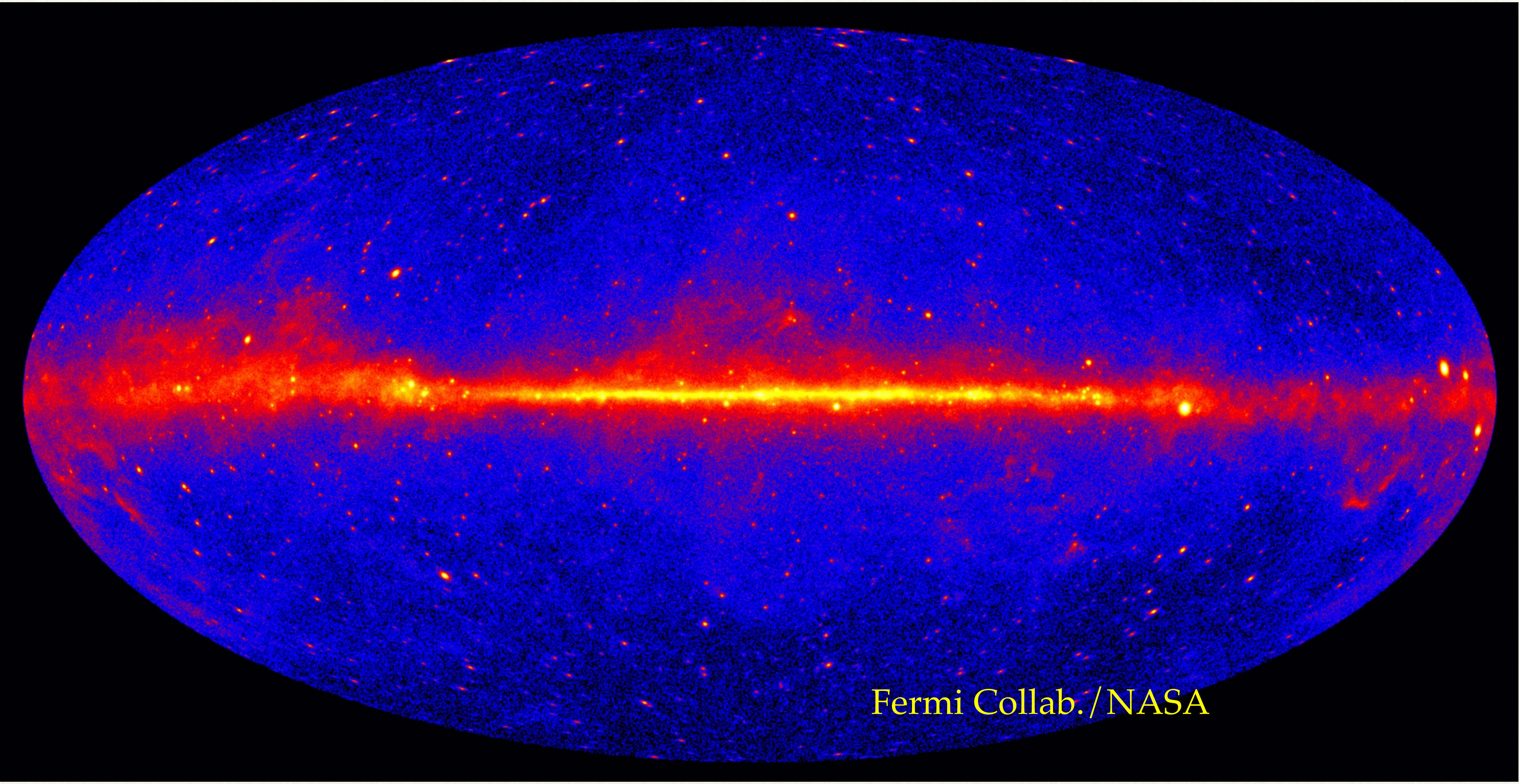
An Extreme ISM in GC…

- SFR surface density over CMZ $\gtrsim$ **3 orders of magnitude** larger than mean in disk ($\partial_t \Sigma_* \sim 2\ M_\odot\ yr^{-1}\ kpc^{-2}$) 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: $U_B \sim U_{turb} \sim U_{plasma} \sim U_{ISRF} \sim 100\ eV\ cm^{-3}$

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

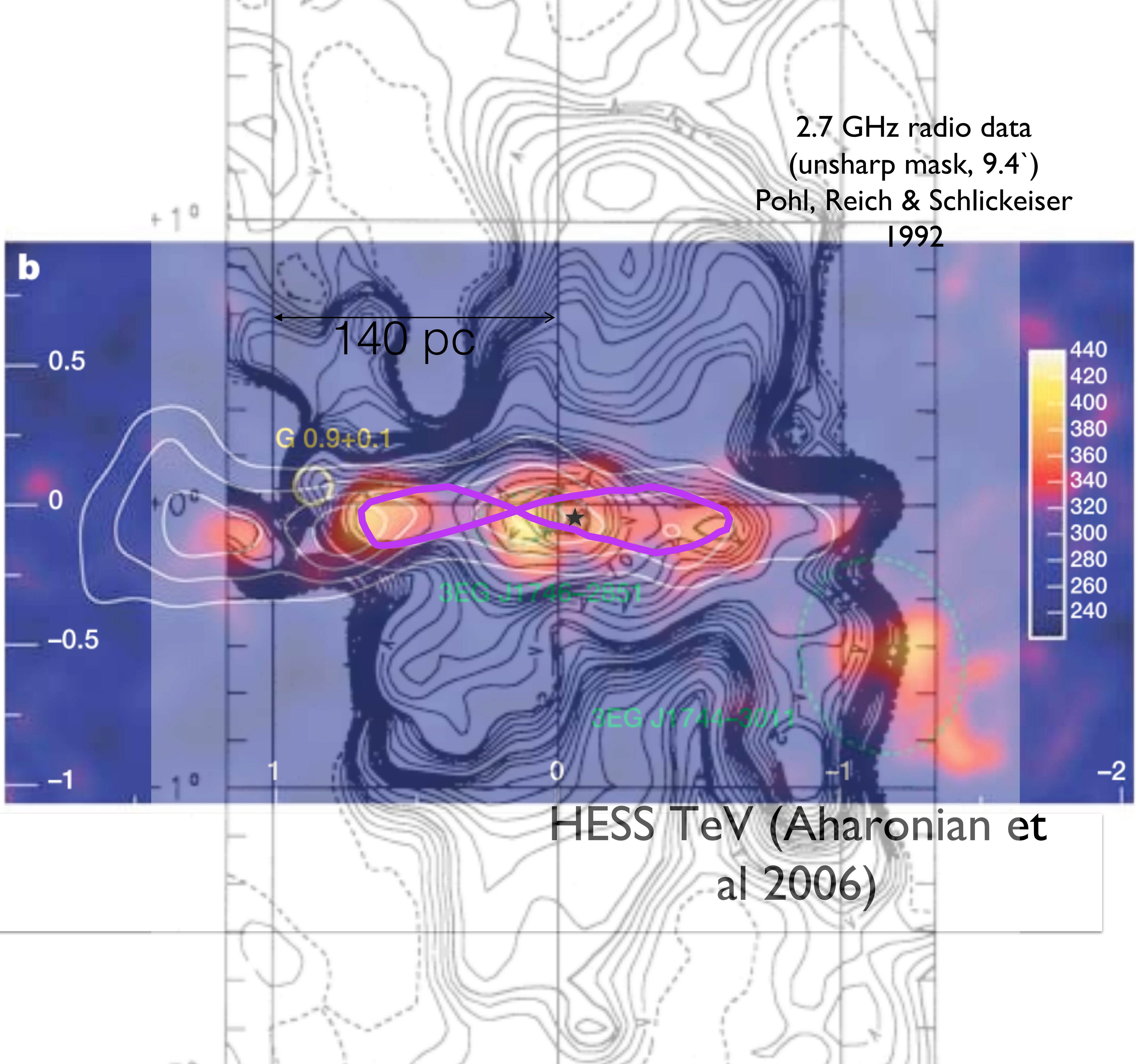
Where is the Galactic Centre?



Central Molecular Zone

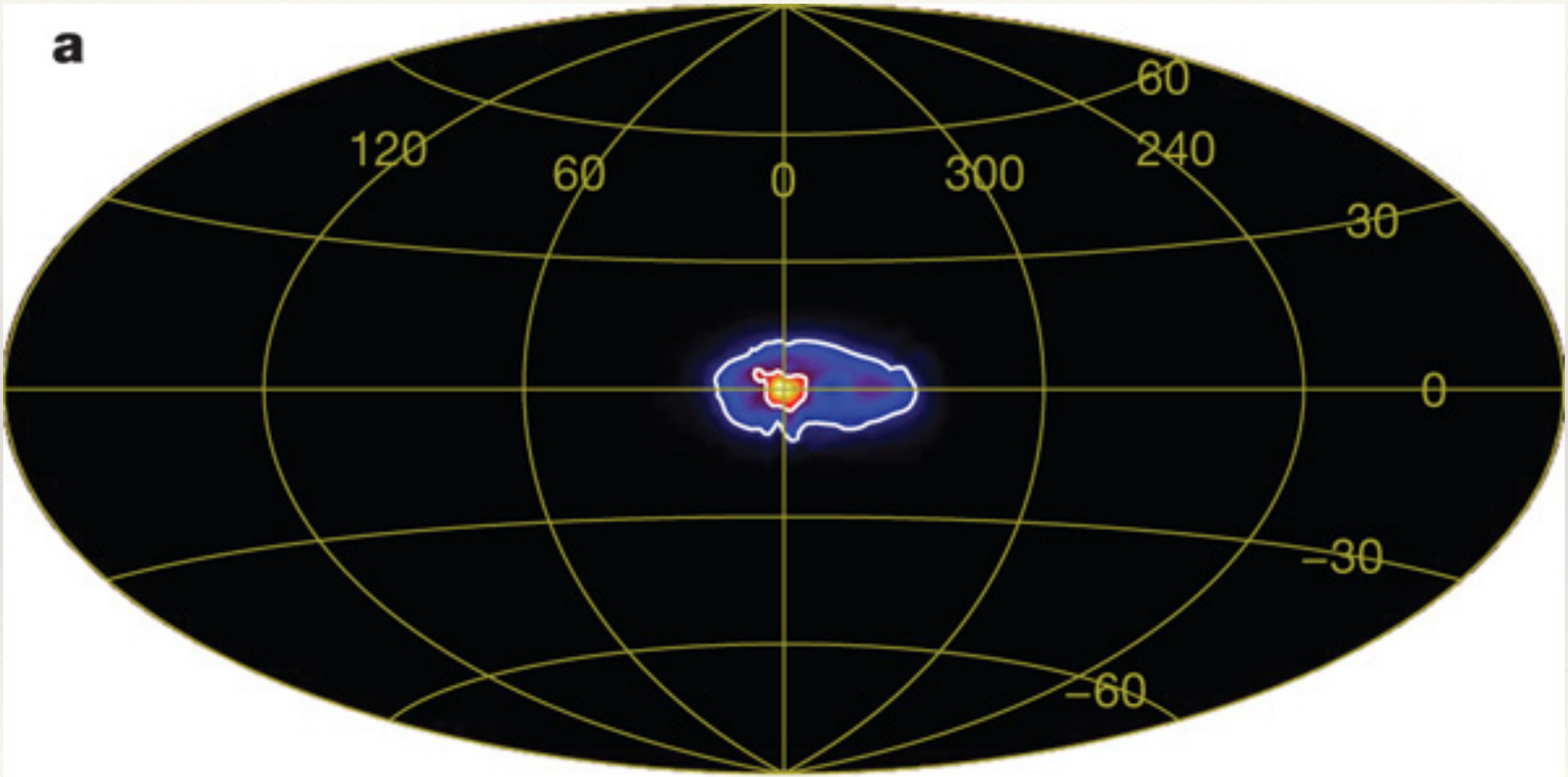
- The nuclear star formation activity is also *easily intense enough to launch a nuclear wind*

2.7 GHz radio data
(unsharp mask, 9.4`)
Pohl, Reich & Schlickeiser
1992



HESS TeV (Aharonian et al 2006)

A Few More Words on the Origin of Galactic Positrons



credit: Weidenspointner et al. 2008

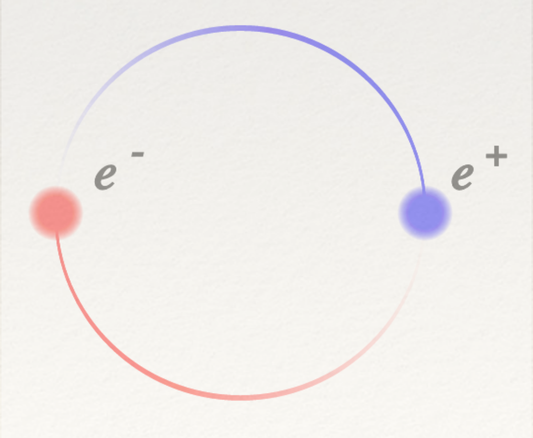
Galactic, low-energy positron population

- 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)

where do they come from?

Positron Annihilation Observations

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



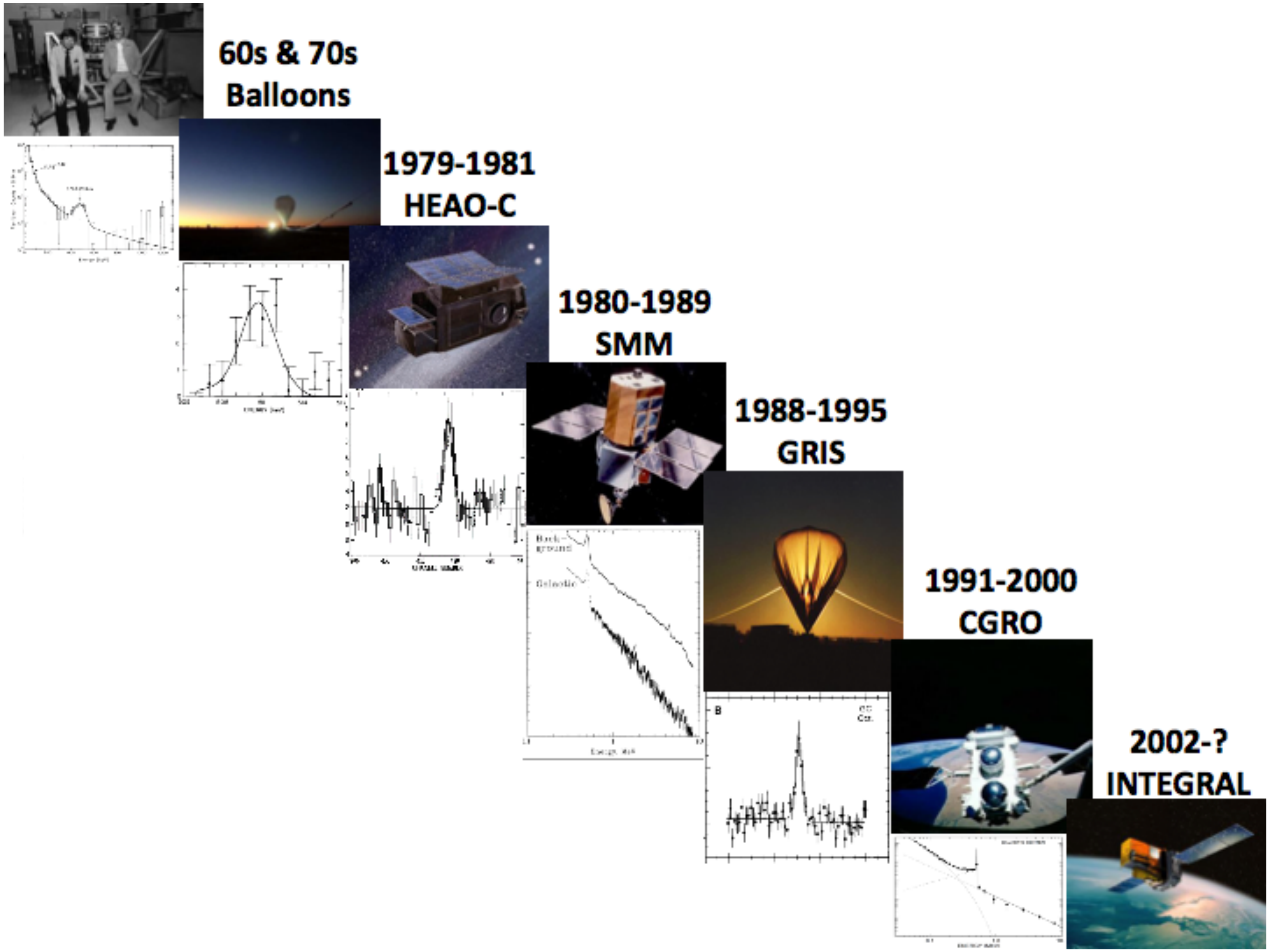
Positron Annihilation Observations

- 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)

slide credit:
Thomas Siegert

Positron Annihilation Observations



Diffuse, Galactic positron annihilation signal detected for more thar

Positron Annihilation Observations

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

  B/D ~ 0.4

  > Star Formation Rate$_{[bulge]}$/SFR$_{[disk]}$ ~ 0.1

large B/D

- Large B/D prompted theories of "special sour…
  - Super-Massive Black Hole?
    - need process to transport p… …cale of bulge; diffusion does not wor…
  - Dark Matter (Boe…
    - difficult… …gy constraint from continuum gamma-ray… …ecom, Bell & Bertone 2005; Beacom &
  - … rule out compact sources like pulsars
  - …d, perfectly consistent with e^+ from β^+ decay of radionuclides … in stars and/or supernovae…

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

Recent Discovery (Siegert et al. 2016):

- Detection (>5σ) of separate positron source in 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 situation after publication of Siegert et al. 2016:

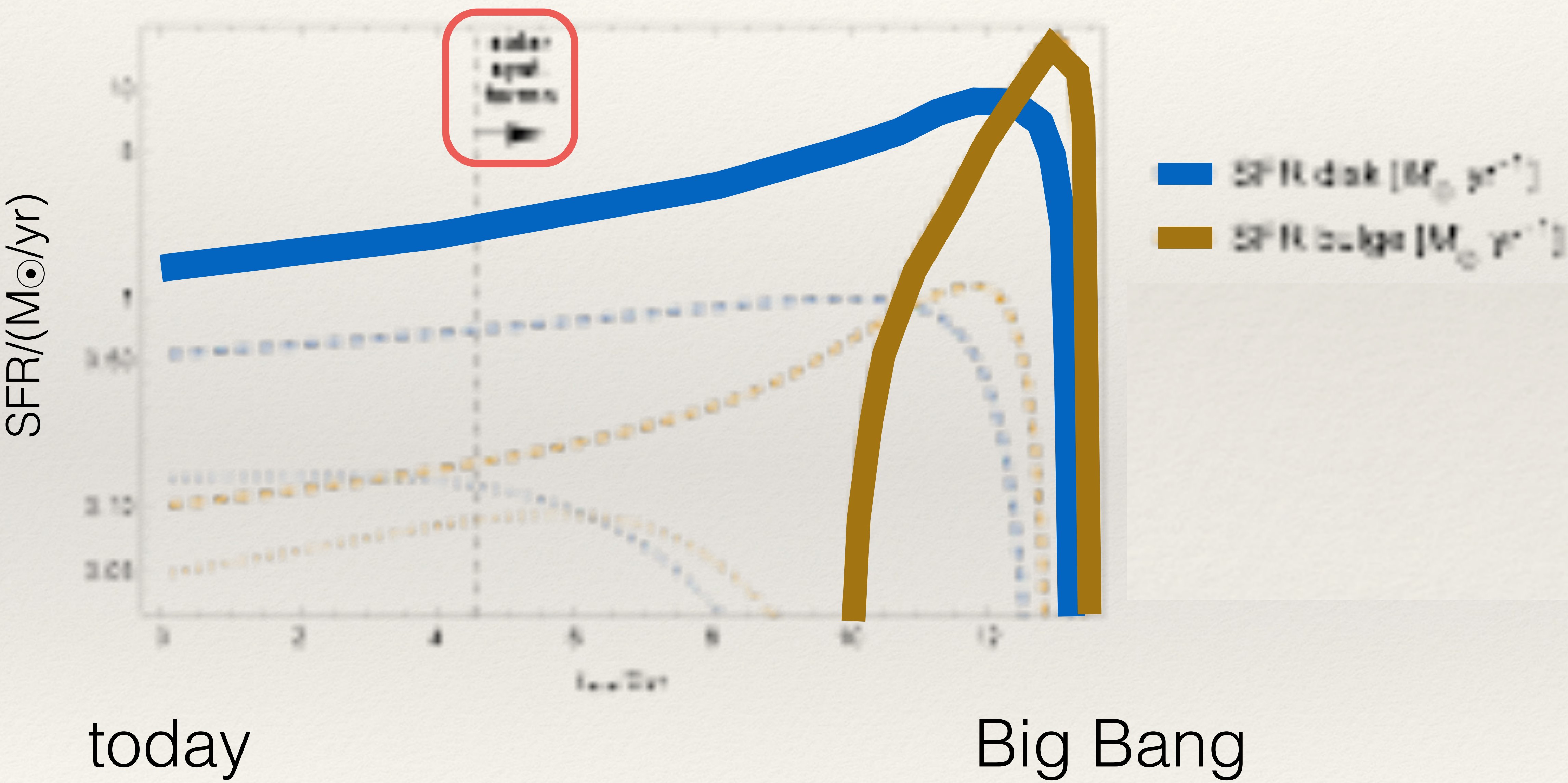
- Note that a stellar positron source connected to OLD stars could explain entirety of gross, Galactic positron injection morphology because
  - $B/D \simeq (0.42 \pm 0.09)$

    $\simeq \mathrm{Mass}_{[\mathrm{bulge}]} / \mathrm{Mass}_{[\mathrm{disk}]}$
  - $NB/B \simeq (0.083 \pm 0.021)$

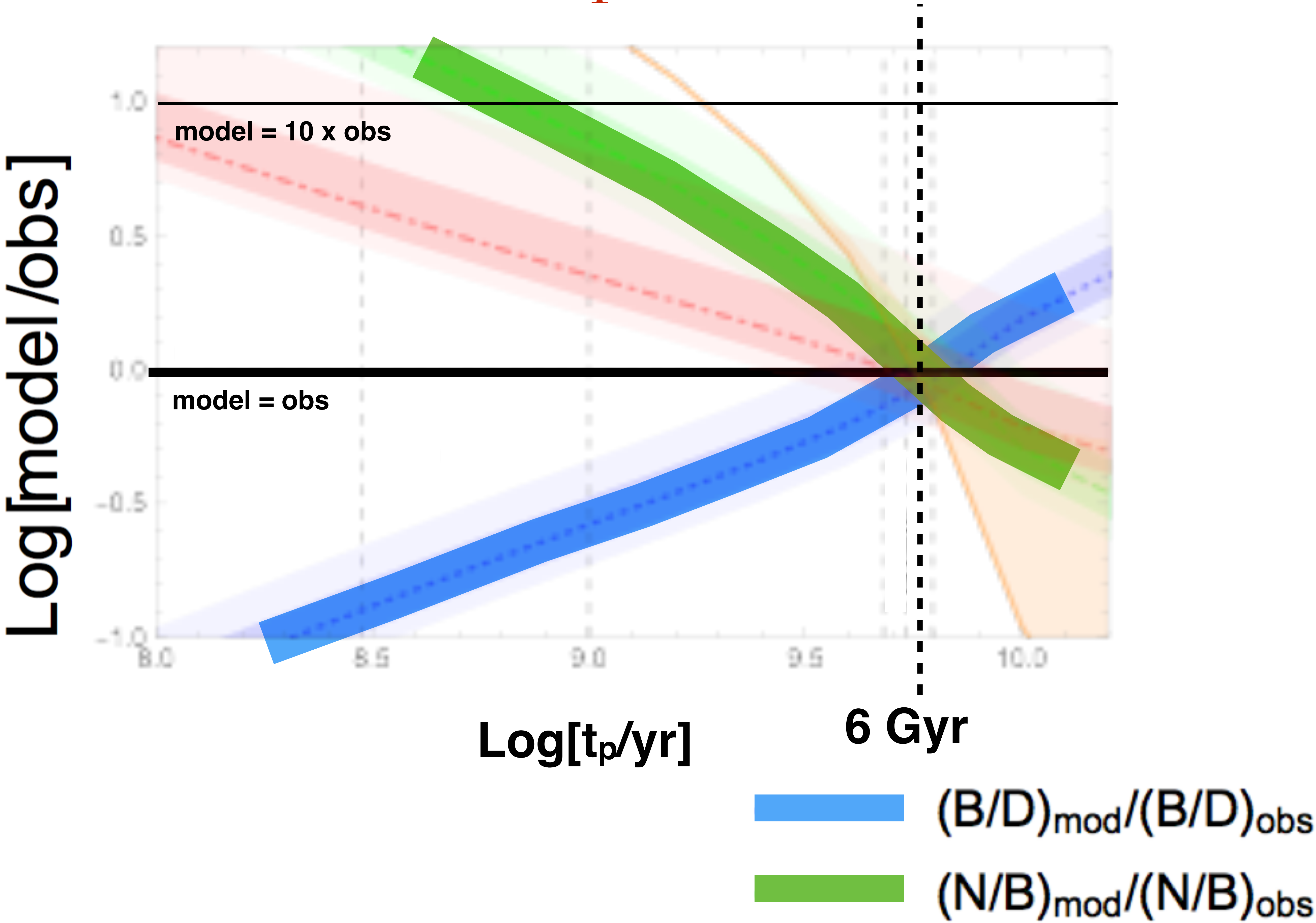
    $\simeq \mathrm{Mass}_{[\mathrm{nuclear\ bulge}]} / \mathrm{Mass}_{[\mathrm{bulge}]} \simeq 0.09$

...but exactly how old would stellar positron sources need to be?

Galactic Star Formation History



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



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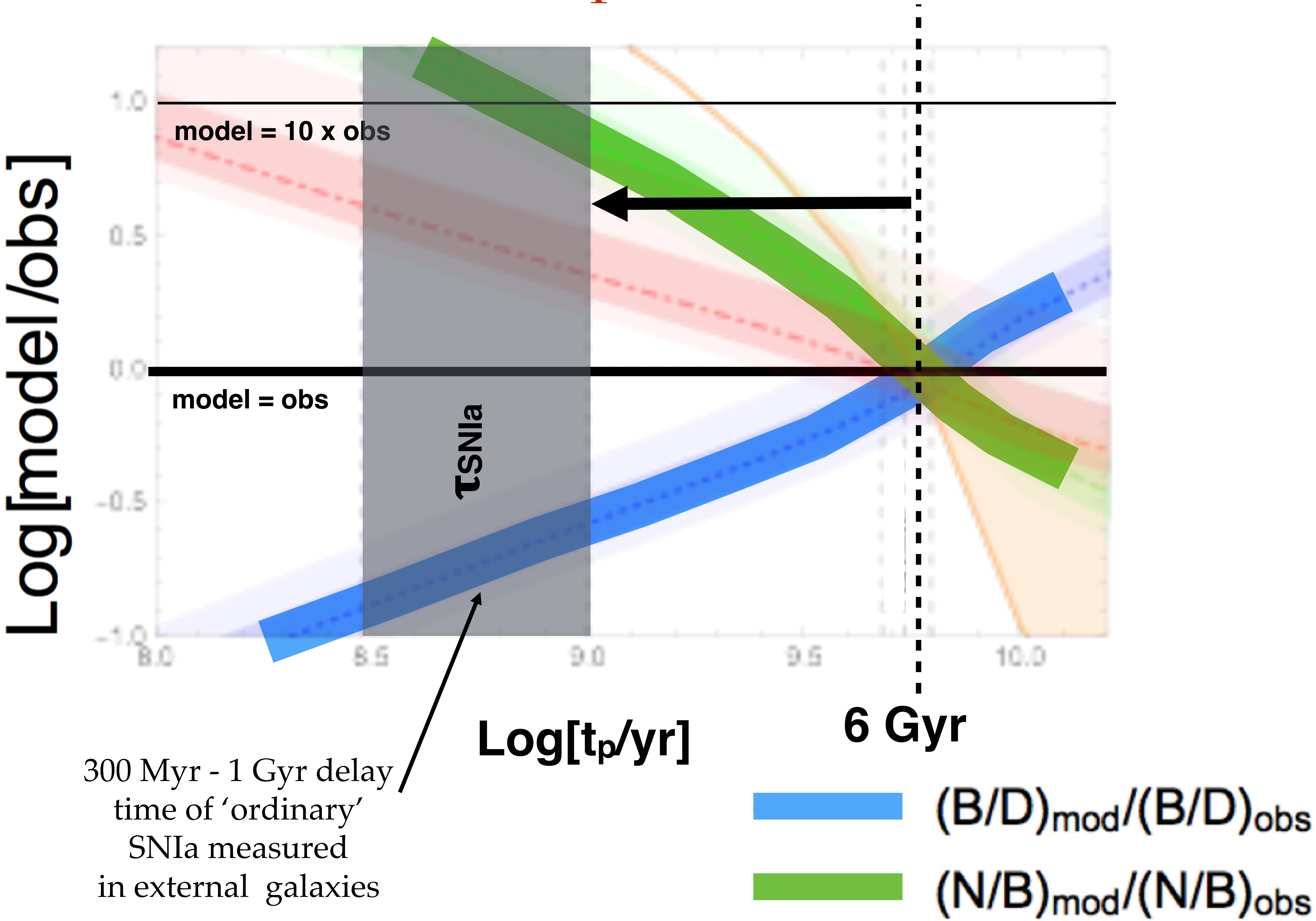


What are these events?

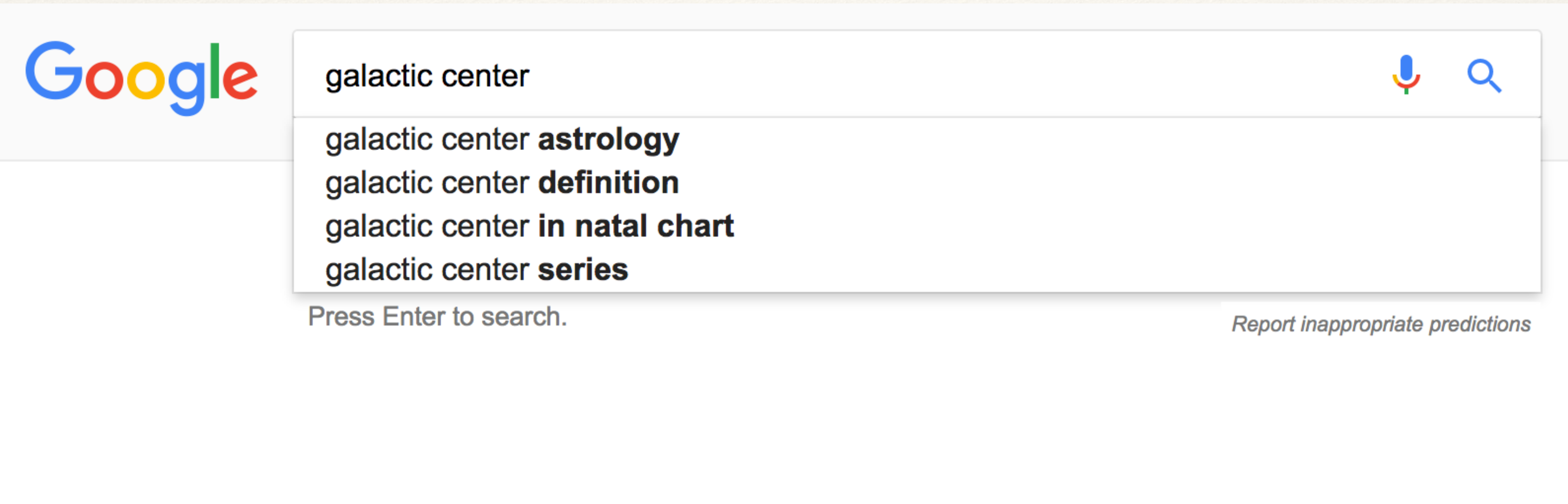
- Our answer: 'SN1991bg-like' supern
- These are sub-luminous Type I onuclear) supernovae that occur in old populations
- 15% of SNIa in all gala
- Direct, spectrosco ence they synthesise Ti
- Frequency se e increasing with cosmic time as required by ou nalysis

see Crocker +2017 Nature Astronomy
arXiv:1607.03495v2

Summary

- Our main GC background: the unknown

Questions?


Google
galactic center
galactic center **astrology**
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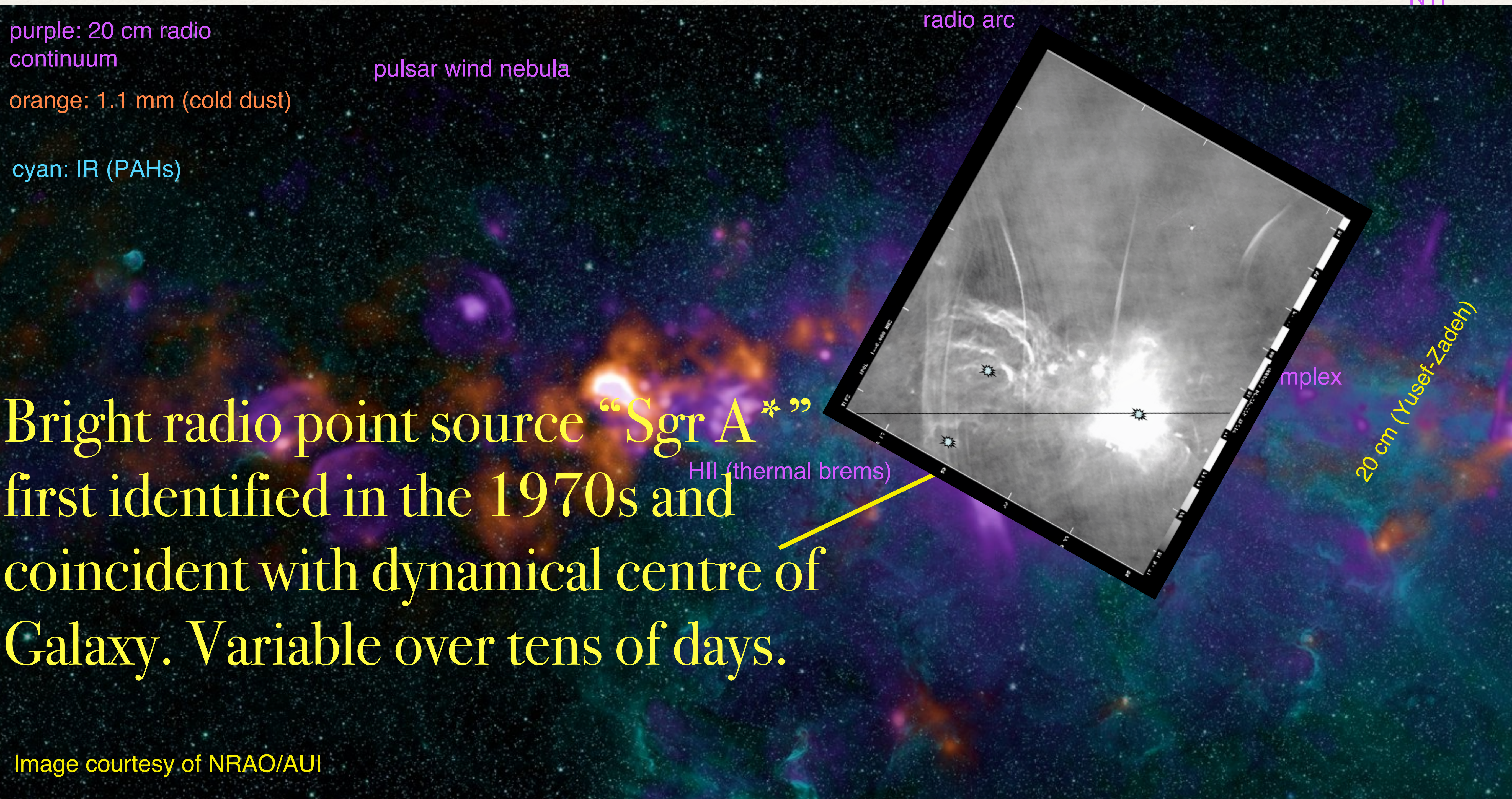
Press Enter to search.
Report inappropriate predictions

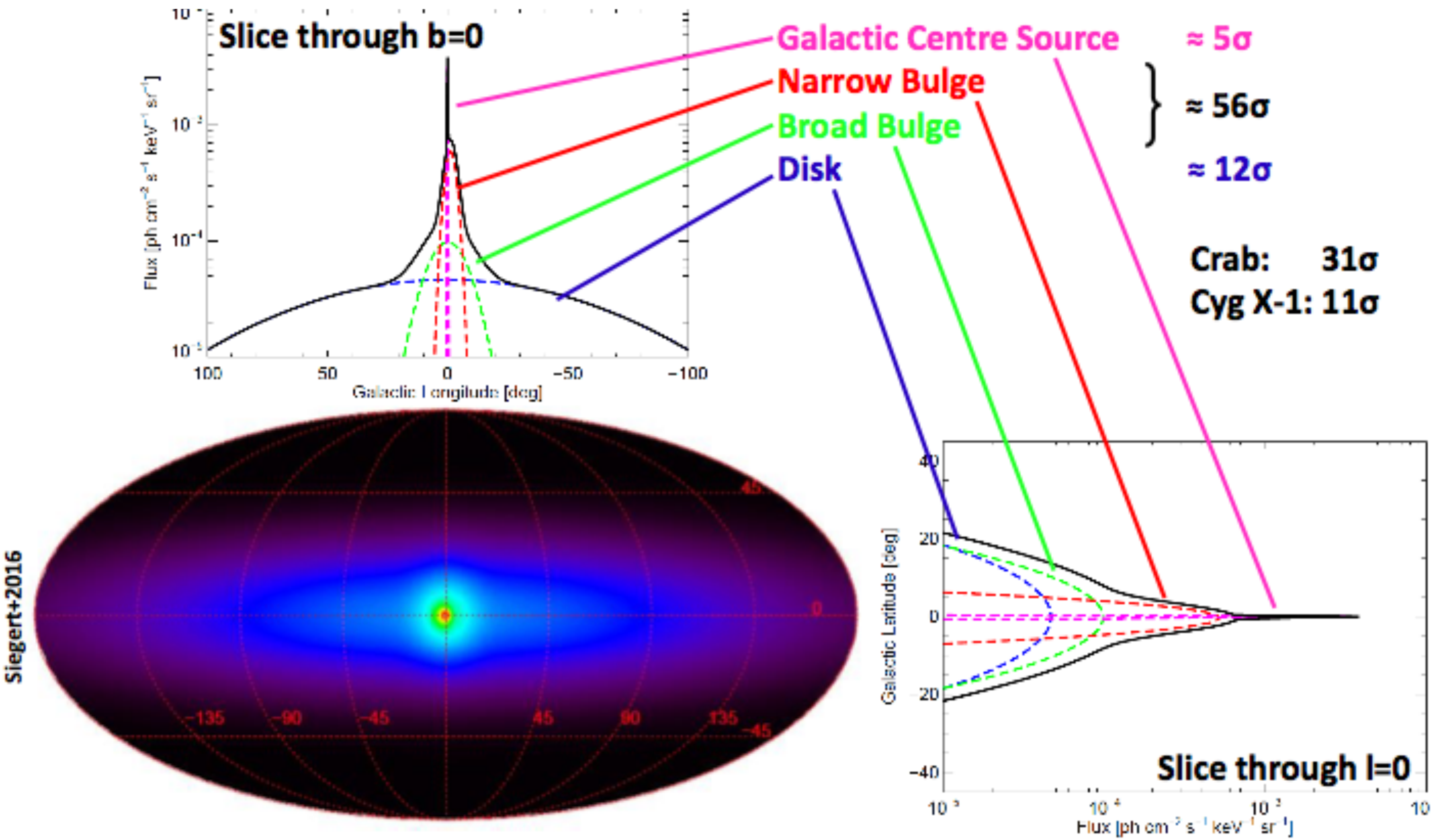
Extra Slides

The GC is a complicated region



Bright radio point source "Sgr A* " first identified in the 1970s and coincident with dynamical centre of Galaxy. Variable over tens of days.

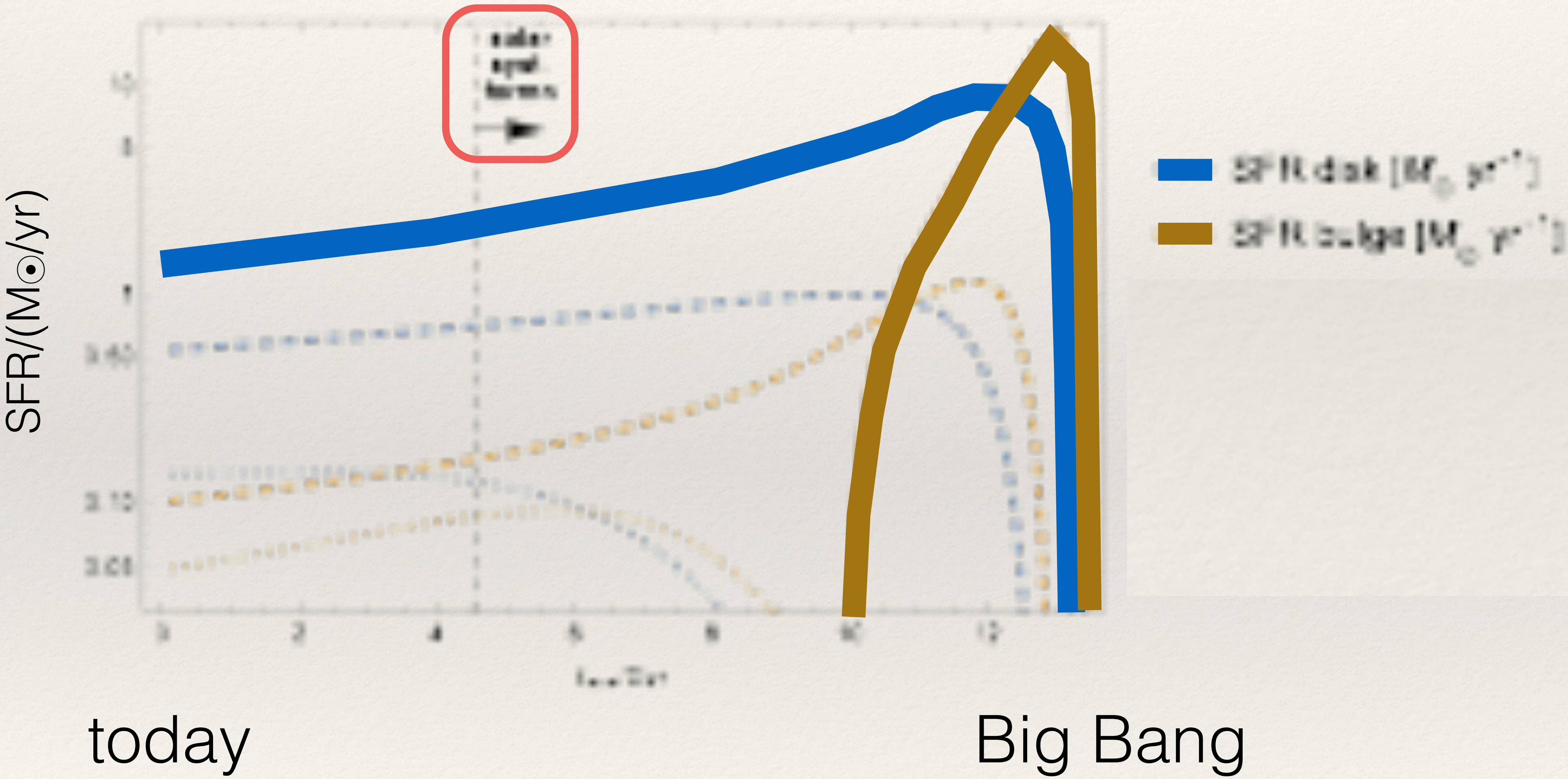
New observational situation following Siegert+2016 results:



slide credit: Thomas Siegert

- Disk size: 140^{+25}_{-10} deg FWHM longitude; 25^{+6}_{-4} deg FWHM latitude

Galactic Star Formation History



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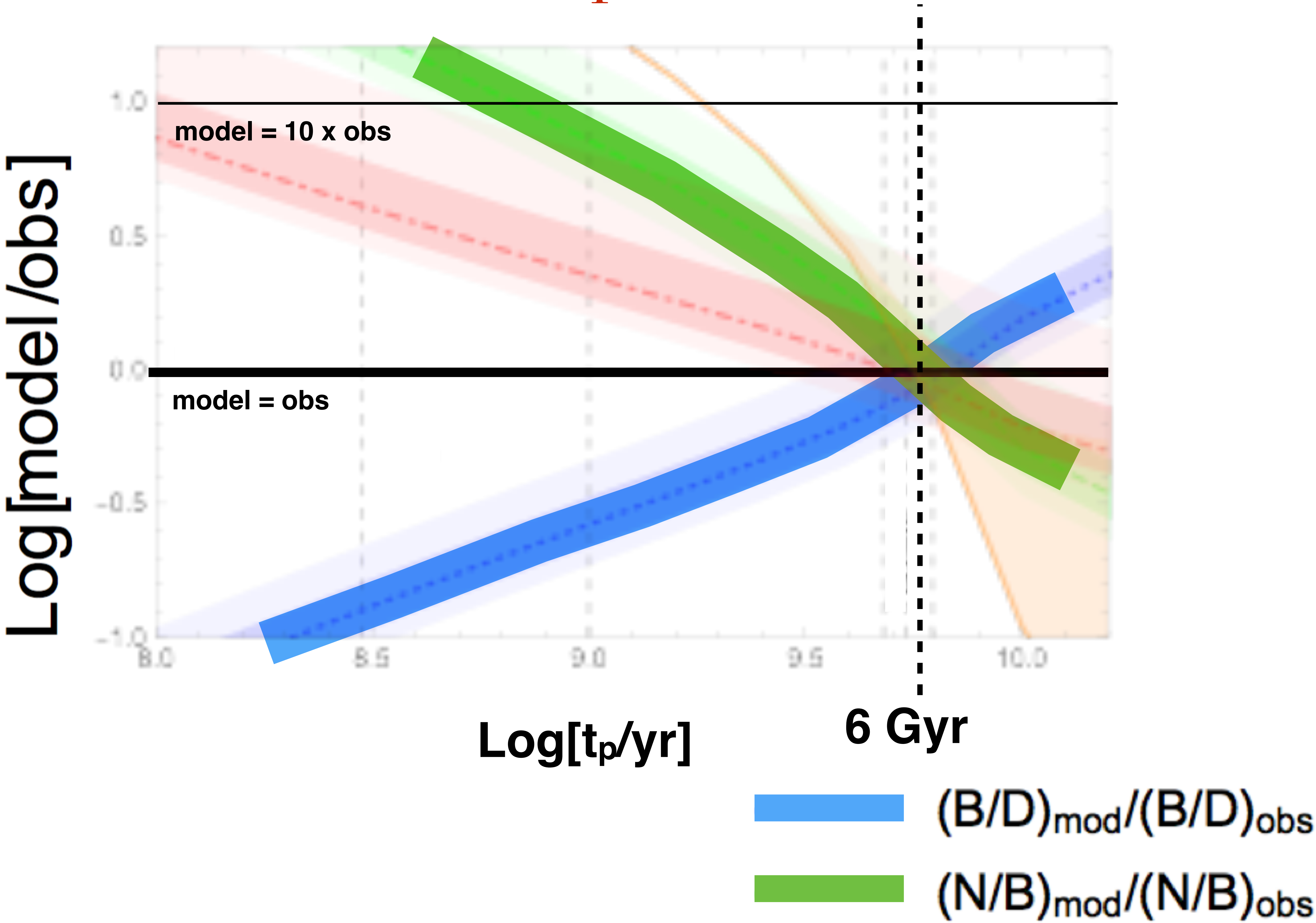
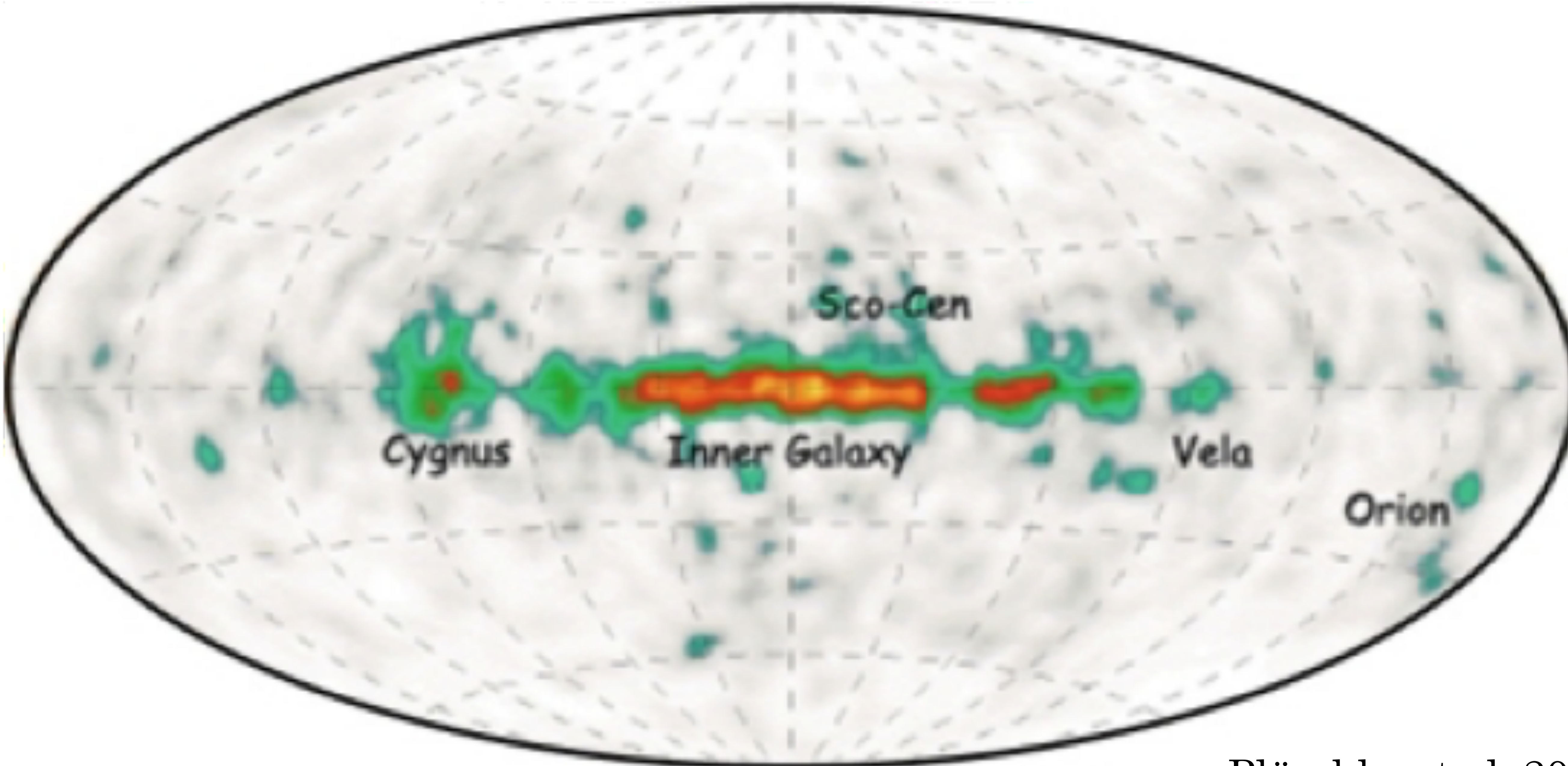




Plüschke et al. 2011

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

$$^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca} + e^{+} \qquad \lambda = 60\ \mathrm{yr}$$

Another problem for ^{56}Ni positrons from SNIa

- $^{56}Ni \longrightarrow {}^{56}Co \longrightarrow {}^{56}Fe$ ~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*

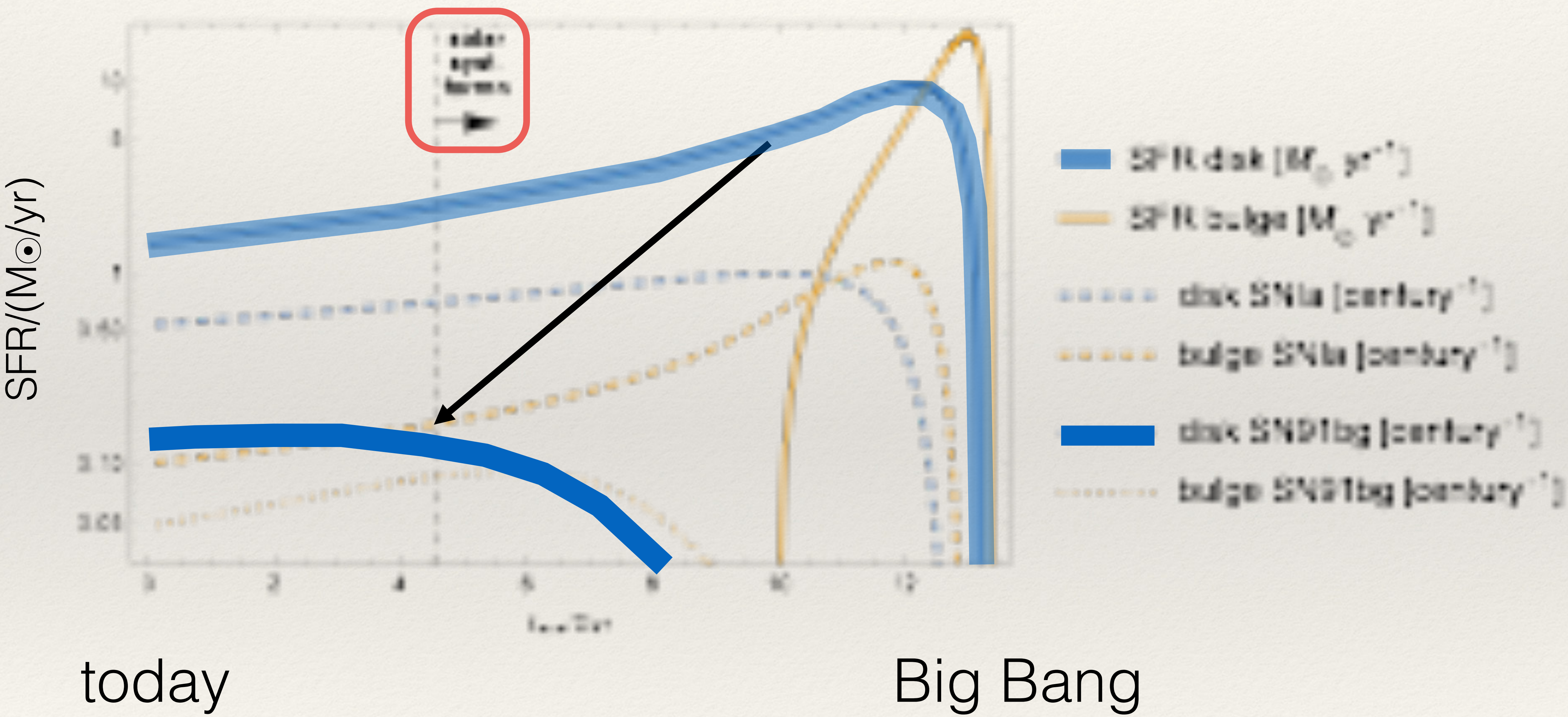
…Trapping not a problem for ^{44}Ti:

- $^{44}Ti \longrightarrow {}^{44}Sc \longrightarrow {}^{44}Ca$ ~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

Is ^{44}Ti ruled out?

- NO! What is required to evade these problems is that:

Galactic Star Formation History



Is ^{44}Ti ruled out?

- NO! What is required to evade these problems is that:
  - ^{44}Ti-producing events are *more common today* than in the period leading up to the formation of the solar system 4.55 Gyr ago; naturally occurs if the stellar sources of ^{44}Ti have a ~6 Gyr delay time

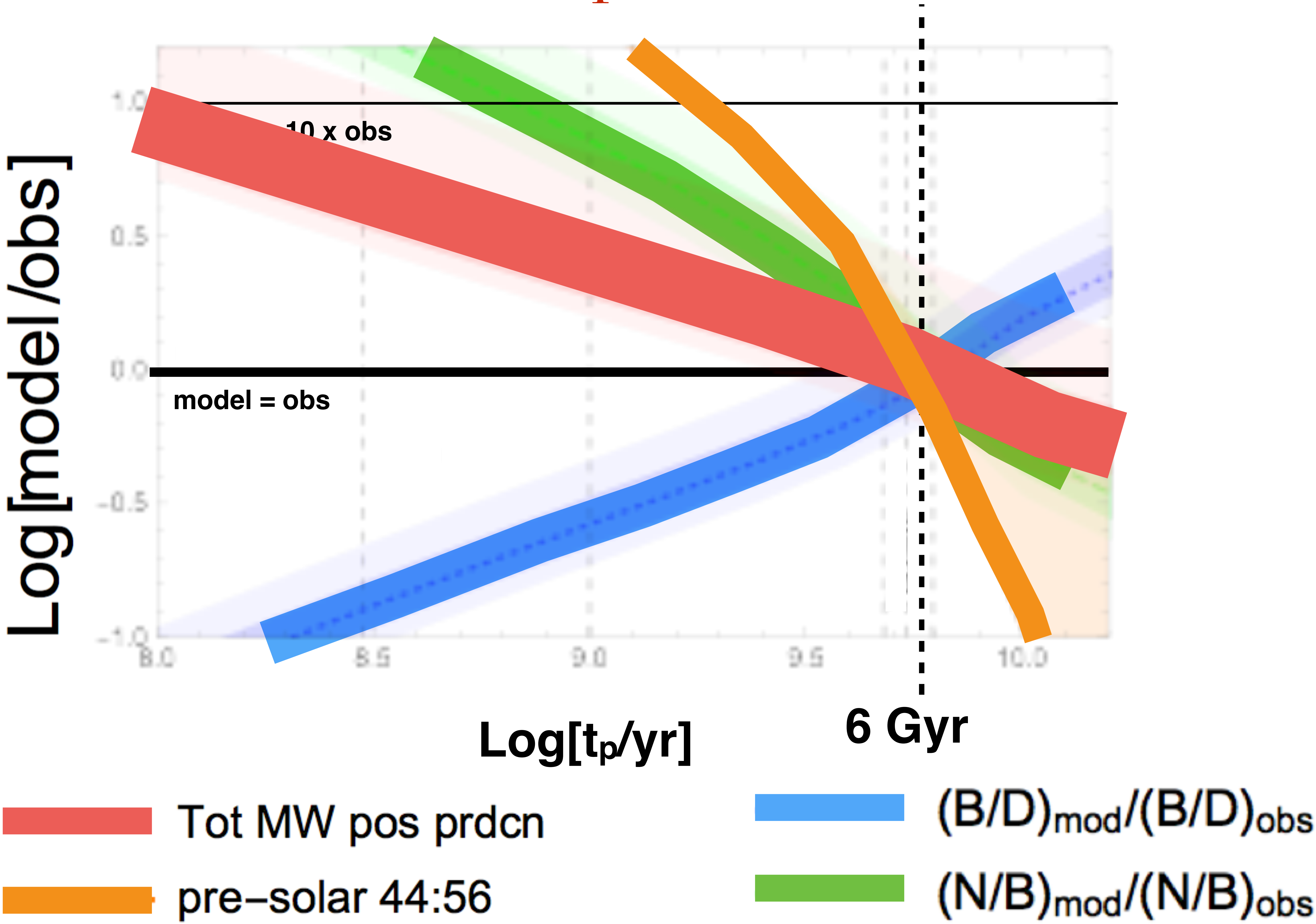
A Galactic ^{44}Ti source that…

- …occurs every $\gtrsim$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

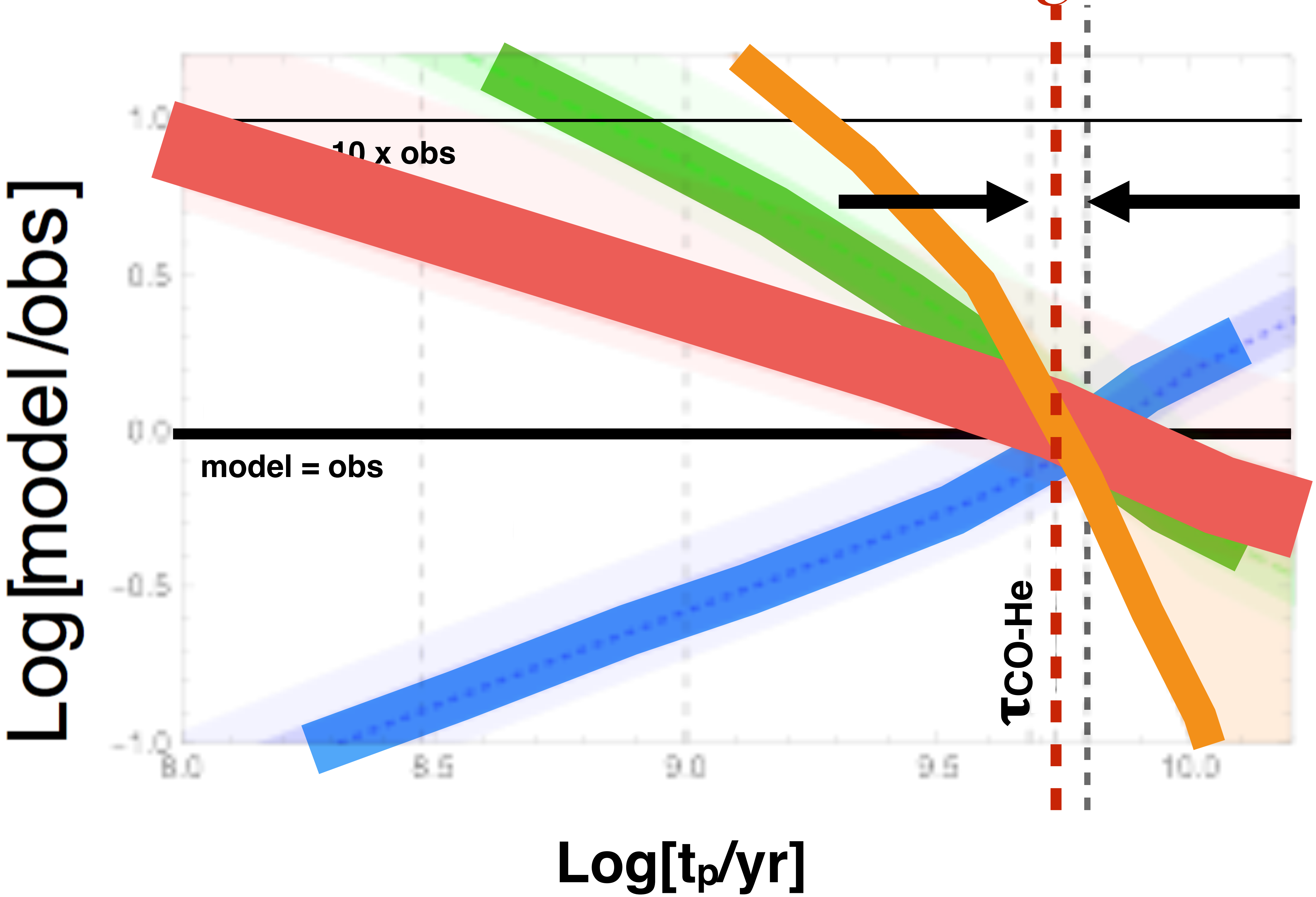
How old does a *stellar* positron source need to be?



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/He-WD mergers occur at ~3-6 Gyr in our binary population synthesis model (`StarTrack`; Belczynski+); *this is the time scale required by positron phenomenology*

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 (ther nonuclear) supernovae that occur in old stell pulations
- 30% of SNIa in elliptical gala
- 15% of SNIa in all galaxi
- Direct, spectroscop idence they synthesise Ti
- Frequency seems to be increasing with cosmic time as required by our analysis

see arXiv:1607.03495v1

Connection to the Galactic Centre Excess?

- The bulge positron annihilation signal emerges from the SAME REGION 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
  - Our binary population synthesis model produces the 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

- direct (in)detection
- indirect (in)detection
- The Galactic Centre: the location in the Galaxy where good astro- (and particle?) physicists go off to die

On being an 'expert'

- I've been accused of being an expert on the Galactic Centre…this is only true to the extent that an expert is somebody who understands the full enormity of our ignorance in a particular field…
- The Galactic Centre: the location in the Galaxy where good astro- (and particle?) physicists go off to die

Fermi Bubbles: Two Interlocking Questions

- **Q1. What energizes the outflow?**

SMBH at Sgr A*

OR

nuclear star formation

Energetics

- The (photon) Eddington luminosity of Sgr A* (4×10^6 M_{Sun}): 5×10^{44} erg/s

⇒EXPLOSION

- Star formation in the Galactic Centre at a rate ~0.08 M_{Sun}/yr (Crocker at al. 2011) *…the Galactic Centre is not a Starburst*

- This injects mechanical power (supernova explosions, stellar winds) of

$P_{mech} \sim 0.08\ M_{Sun}/yr \times 1\ SN/(90\ M_{Sun}) \times 10^{51}$ erg/SN

⇒SLOW INFLATION

$= 3 \times 10^{40}$ erg/s

Fermi Bubbles: Two Interlocking Questions

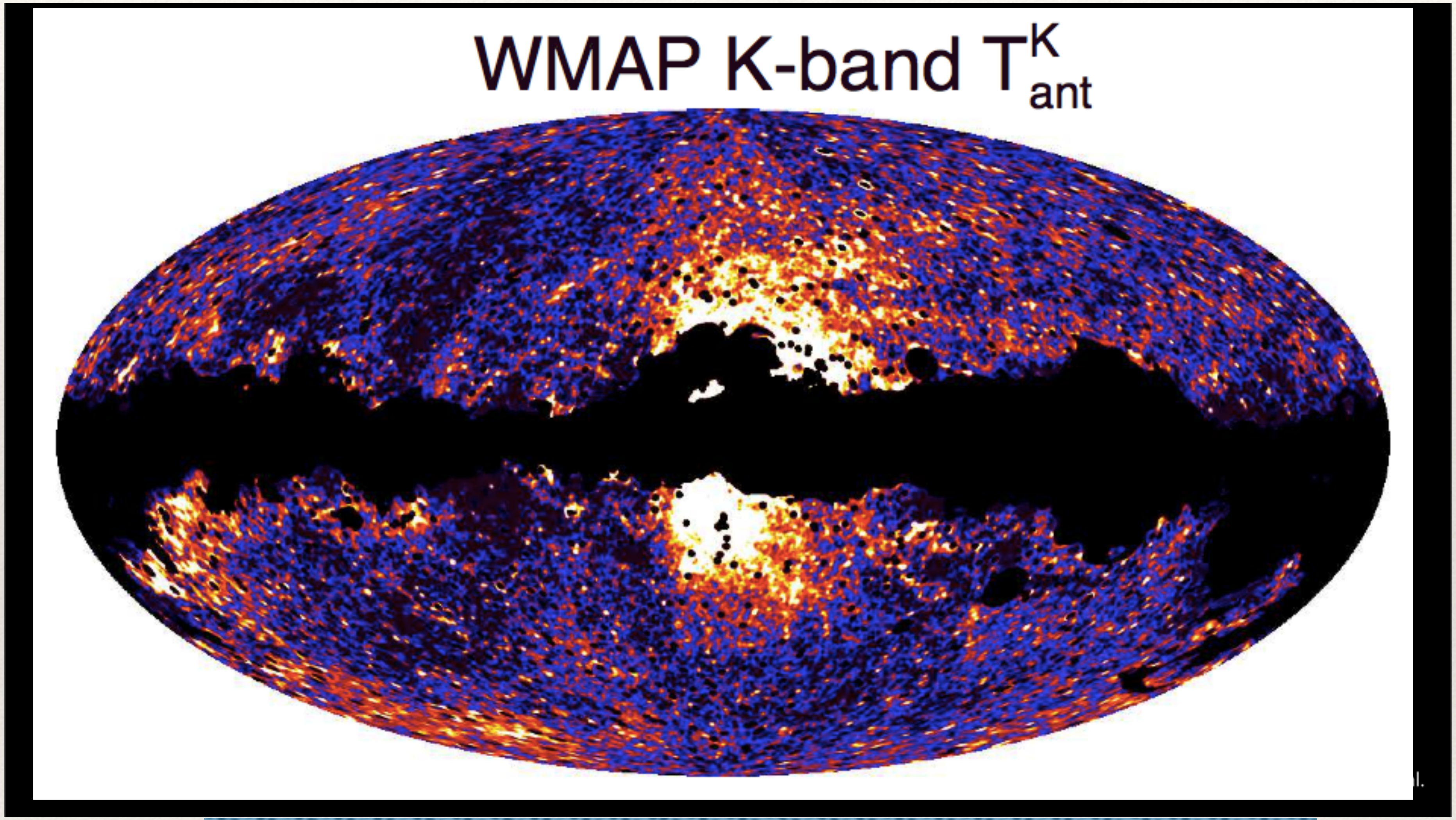
- **Q2. What is the radiation mechanism?**

‘leptonic’: Cosmic ray electrons / Inverse Compton emission

OR

‘hadronic’: Cosmic ray protons / gas collisions

WMAP Haze



Dobler (2012)

Fermi Bubbles

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

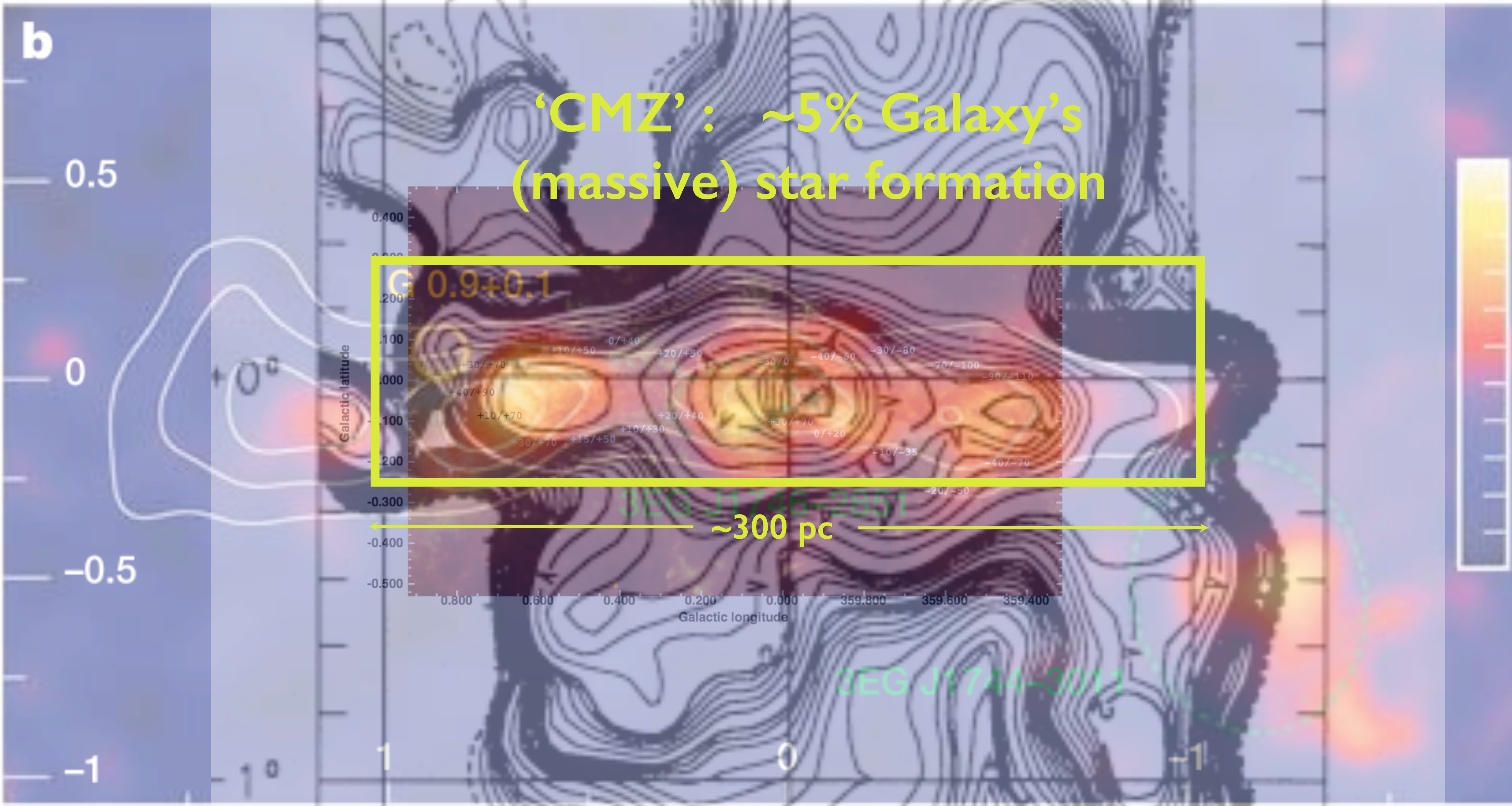
Points for/against AGN/IC scenarios

- PRO: single electron population can explain both the Bubbles' gamma-ray emission (as IC) and the microwave haze (as synchrotron)
- PRO: Hα measurements suggest a hard UV "flash" may have irradiated the Magellanic Stream above the nucleus 1-3 Myr ago (Bland-Hawthorn et al. 2013) [but the Hα emission might also be explained by shocks: Bland-Hawthorn et al. 2007]
- CON: we are required to be seeing the Bubbles at a privileged time
- CON: Lack of a bright/hot X-ray edge suggests that Bubbles are expanding, at most, at the sound speed 300 km/s (Tahara et al. 2015, Karaoke et al. 2015)
- CON: Steep-spectrum polarized radio lobes coincident with Bubbles imply an electron population with age > 30 Myr
- CON: Difficult to understand why gamma-ray spectrum does not evolve strongly (may even harden) with latitude in an IC model
- CON: haze cuts off while gamma-rays continue to high lat — claimed as a result of magnetic field effects but there is no obvious magnetic field structure where haze cuts off in 2.3 GHz polarisation maps
- How to explain geometry of windings?
- Why do RC structures feed down to objects other than Sgr A*?

Points for/against SF/hadronic scenarios

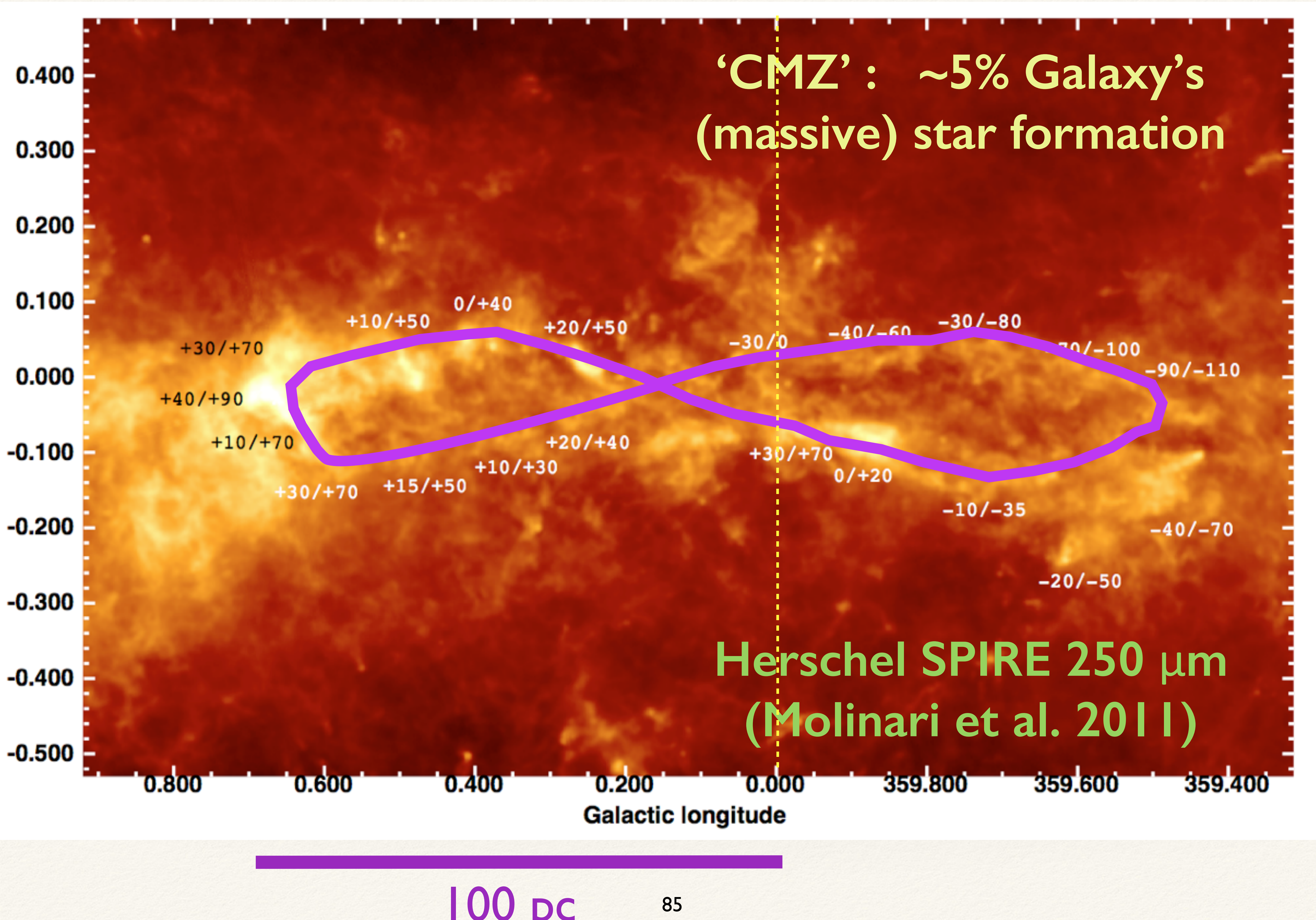
- PRO: Bubbles' gamma-ray luminosity requires a source of protons of power ~1039 erg/s in saturation…this is the approximate power supplied by nuclear SF to cosmic rays that escape the GC
- CON: Secondary electrons can supply microwave synchrotron radiation but predict a too-steep spectrum to explain the haze
- CON: Structures have to maintain coherence for very long timescales

Herschel SPIRE 250 μm (Molinari et al. 2011)



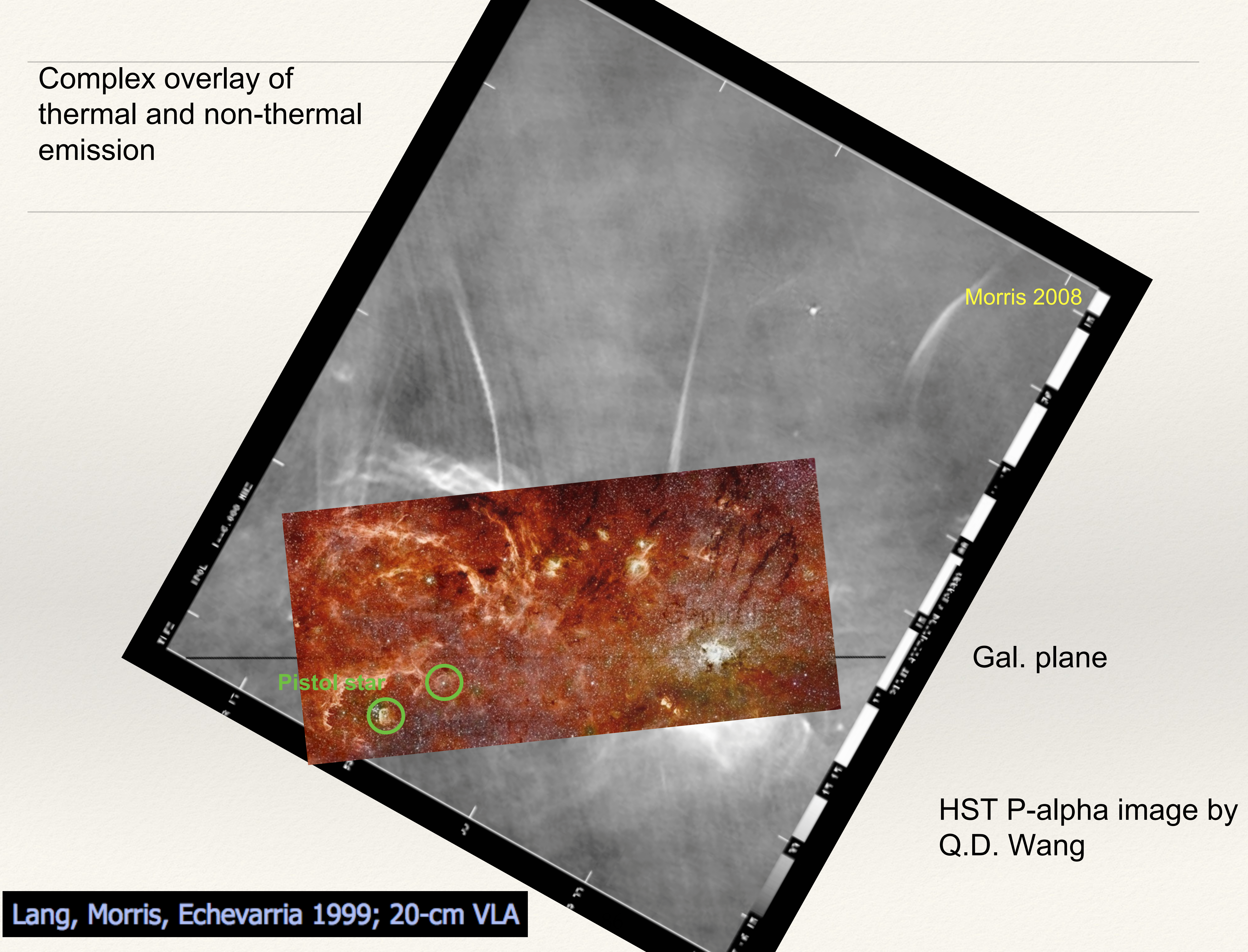
Ring collimates outflow - outflow ablates cold gas

HESS TeV (Aharonian et al 2006)



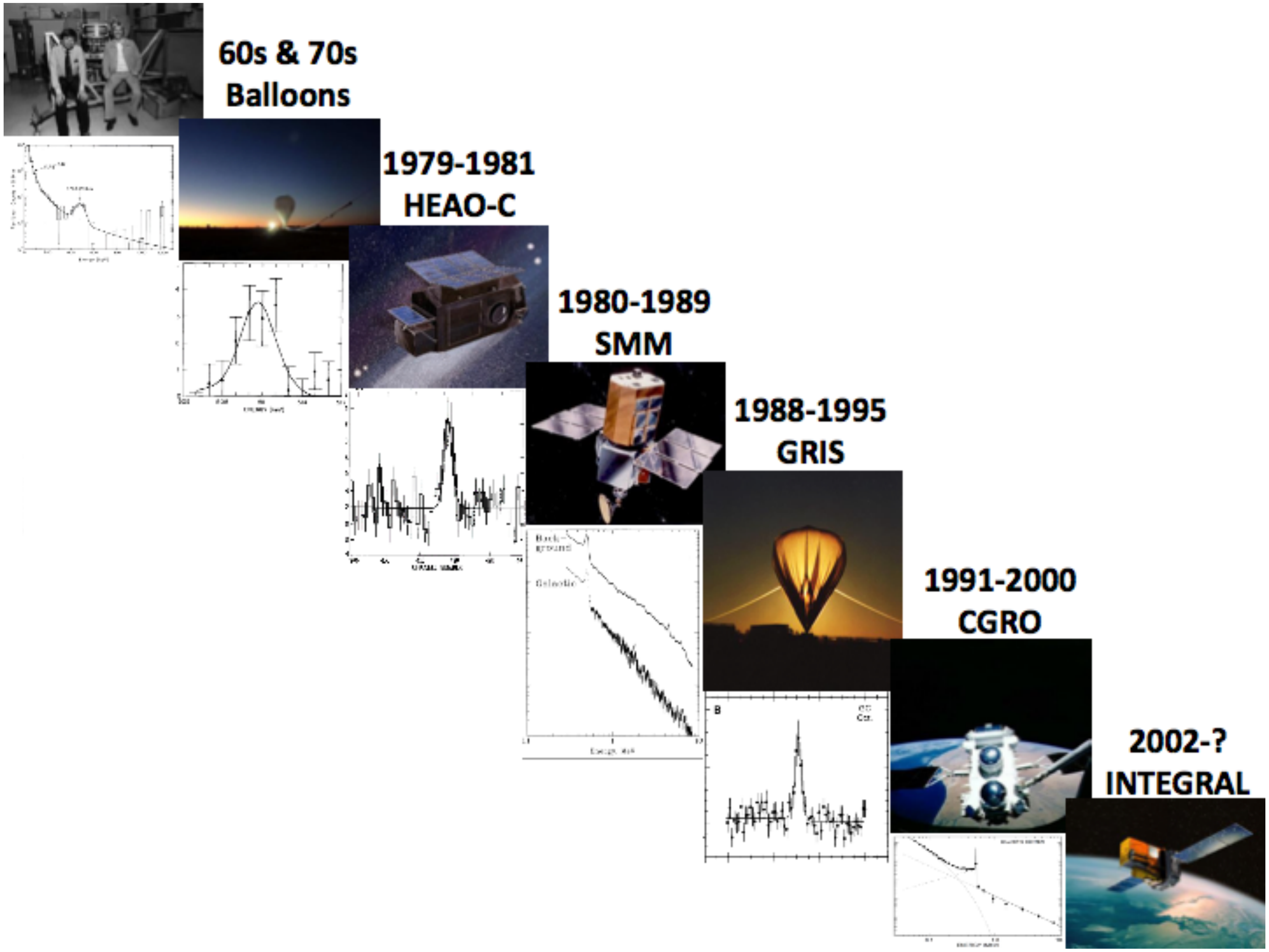
'CMZ' : ~5% Galaxy's
(massive) star formation
Herschel SPIRE 250 μm
(Molinari et al. 2011)
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
0.800
0.600
0.400
0.200
0.000
359.800
359.600
359.400
Galactic longitude
+30/+70
+40/+90
+10/+70
+30/+70
+10/+50
0/+40
+20/+50
+15/+50
+10/+30
+20/+40
-30/0
-40/-60
-30/-80
-90/-110
+30/+70
0/+20
-10/-35
-40/-70
-20/-50
100 pc

Complex overlay of thermal and non-thermal emission



slide credit:
Thomas Siegert

Positron Annihilation Observations



Diffuse, Galactic positron annihilation signal detected for more than

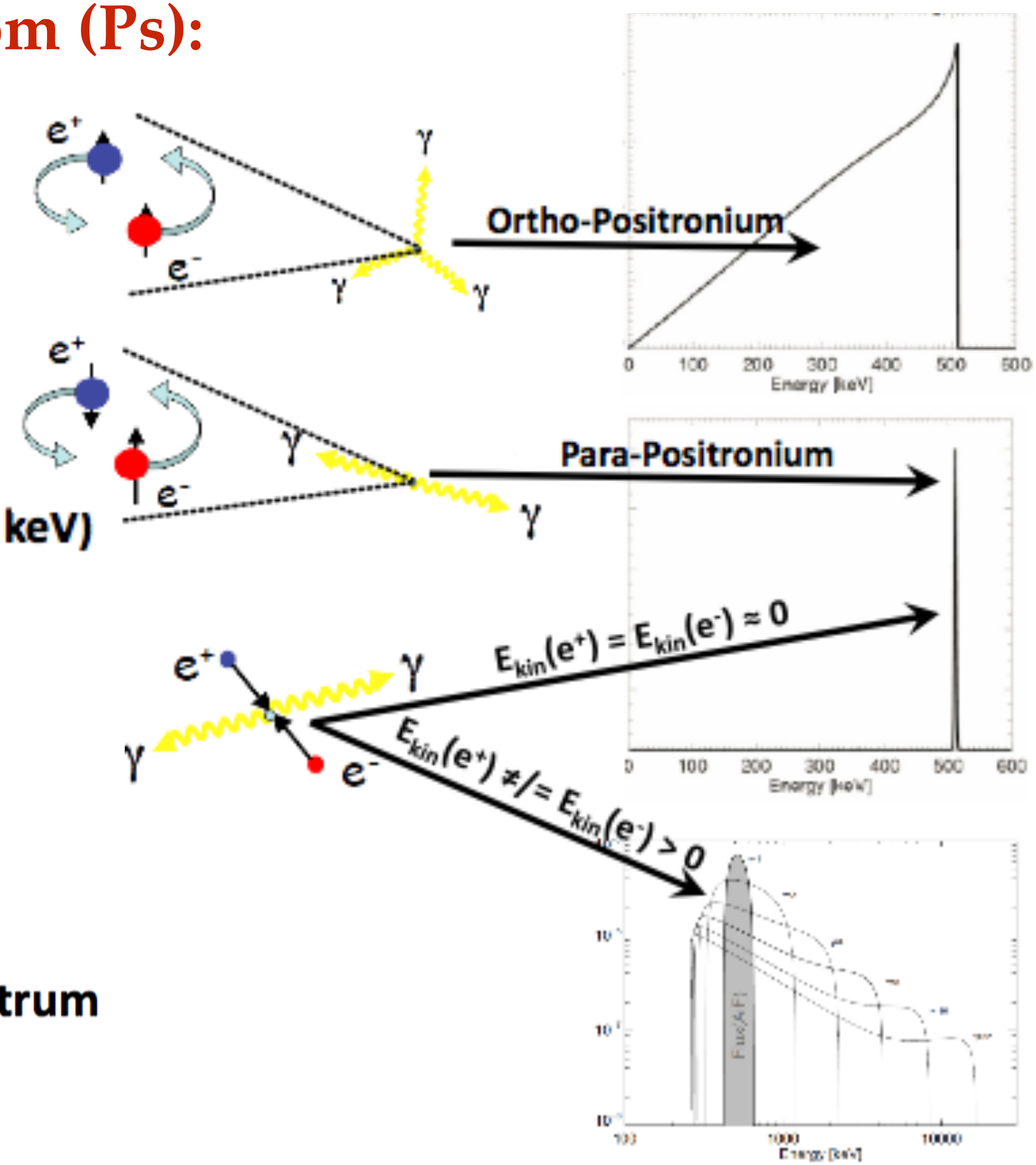
Gamma Rays from Positron Annihilation

Formation of Positronium Atom (Ps):

→ Triplet state (S=1): parallel spins
"Ortho-Positronium" o-Ps
Lifetime: $\tau = 1.4 \times 10^{-7}$ s
3γ: continuous spectrum

→ Singlet state (S=0) antiparallel spins
"Para-Positronium" p-Ps
Lifetime: $\tau = 1.3 \times 10^{-10}$ s
2γ: monoenergetic gamma-ray line (511 keV)

- Annihilation in Flight (AiF):



Annihilation in Flight (AiF):

- Annihilation in Flight (AiF):

→ Direct annihilation with $E_{kin}(e^{\pm}) \geq 0$:
$E_{kin}(e^+) = E_{kin}(e^-) \approx 0$: **511 keV line**
$E_{kin}(e^+) \neq/= E_{kin}(e^-) > 0$: **continuous spectrum**

slide credit: Thomas Siegert

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

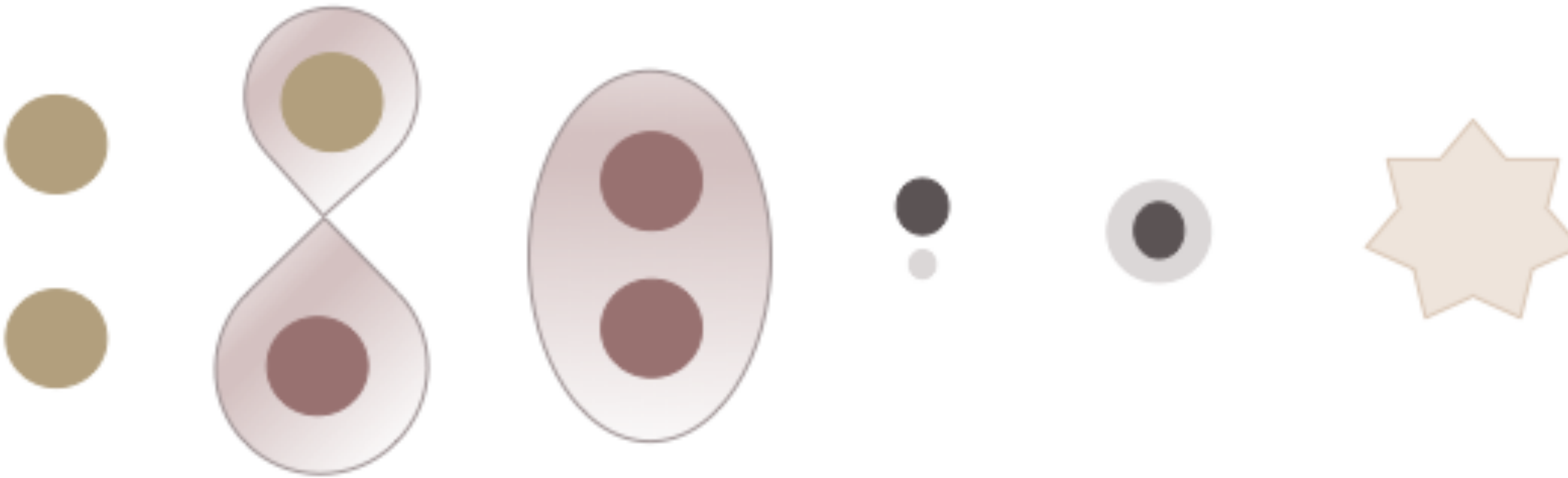
t_p: 'delay time'

Summary

- Siegert et al have changed the empirical situation with respect to Galactic positron annihilation:
  - 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

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