Elephants in the Bulge

Roland Crocker
ANU

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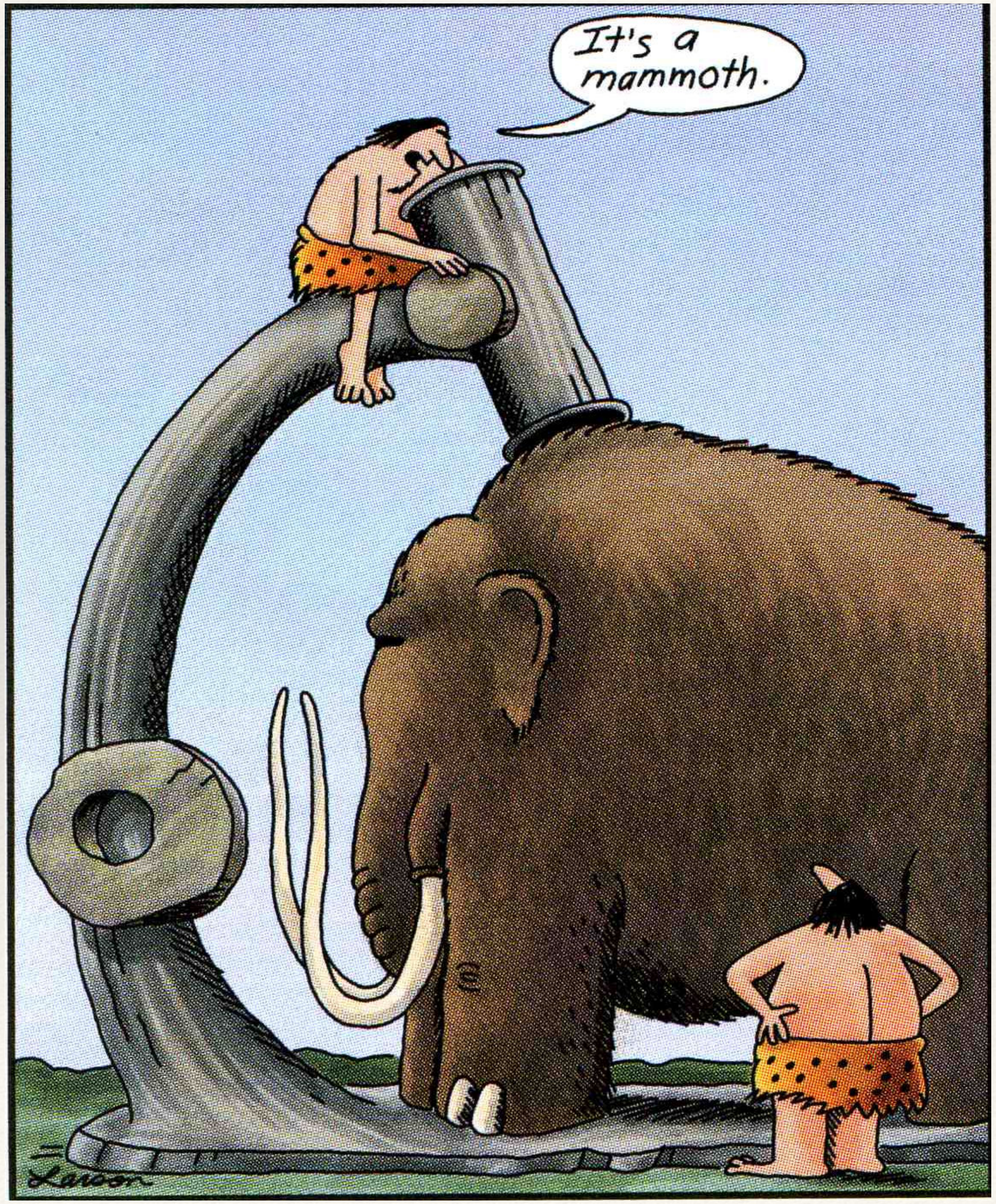

Roland Crocker
ANU
Australian National University

Acknowledgements

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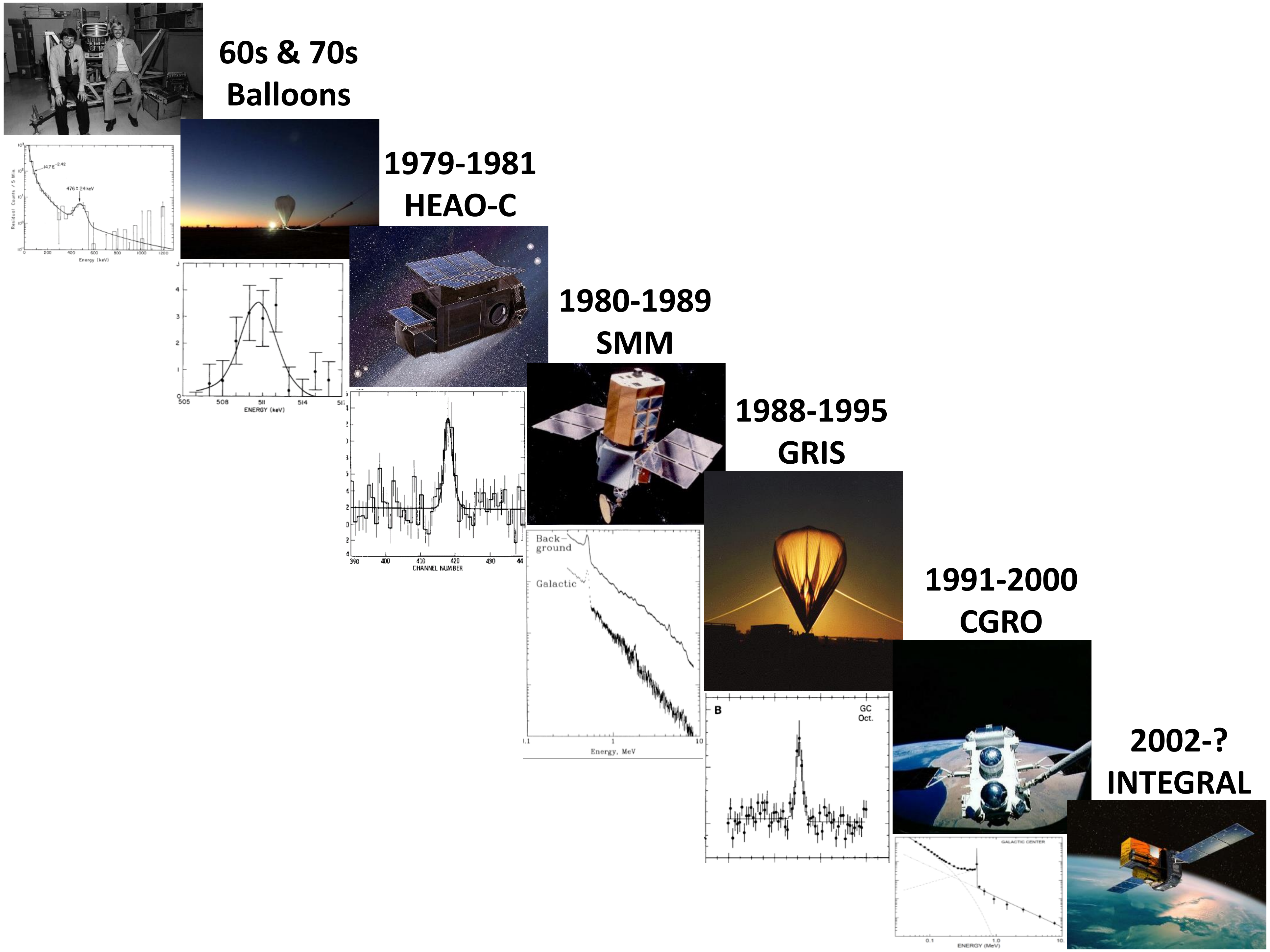
See Nature Astronomy, vol 1, id. 0135 (2017) for details

This talk…

- Focusing on low energy, trans-relativistic positrons (**e^+**) evidenced by annihilation radiation from the Inner Galaxy
- ~5 x 10^{43} e^+/s annihilate in the Galaxy (Siegert et al. 2016)

slide credit:
Thomas Siegert

Positron Annihilation Observations

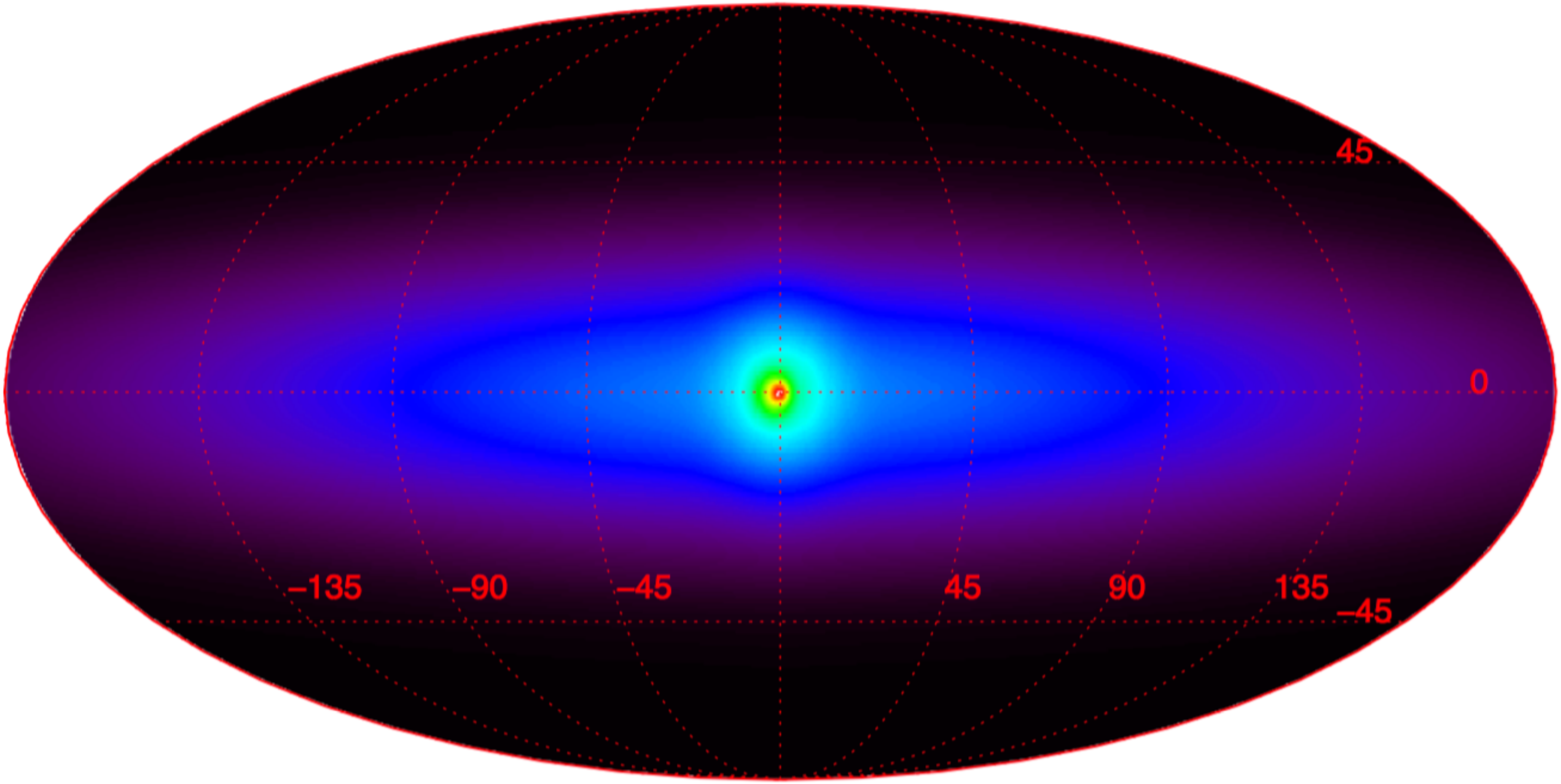


Diffuse, Galactic positron annihilation signal detected for more than 40 years, first with balloon-borne, and more recently satellite (COMPTEL, INTEGRAL) experiments

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

- 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

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

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

large B/D

- Large B/D prompted theories of "special source" ir
  - Super-Massive Black Hole?
    - need process to transport pos ... of bulge; diffusion does not work (Martin+2 ... ot work (Panther+2017)
  - Dark Matter (e.g., Bo
    - difficult ... onstraint from continuum gamma-rays (Ah ... Bell & Bertone 2005; Beacom & Yuksel 2006):
    - ... e out compact sources like pulsars
    - ... perfectly consistent with e^+ from β^+ decay of radionuclides ... 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
- B/D ~ 1.4 (previously) ⟶ **B/D ≃ 0.4** (now)
- newly reduced B/D makes idea for "special" positron source in the GC/bulge less compelling
- BUT now we have to explain the "extra" disk positrons!
- Point: **B/D ≃ 0.4 ≃ $\mathbf{Mass_{[bulge]}/Mass_{[disk]}}$**

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)

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

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

…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'

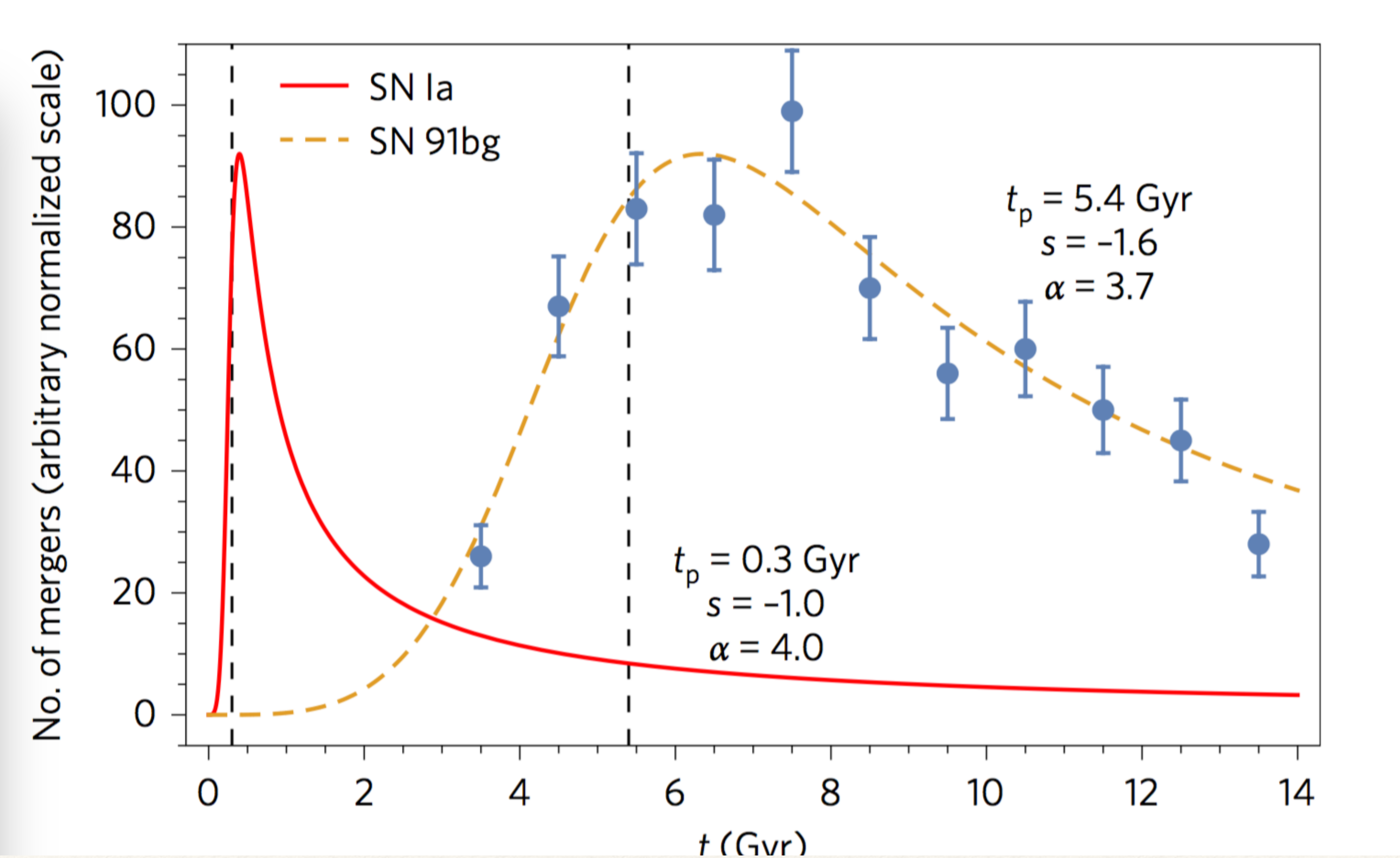
star formation history

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

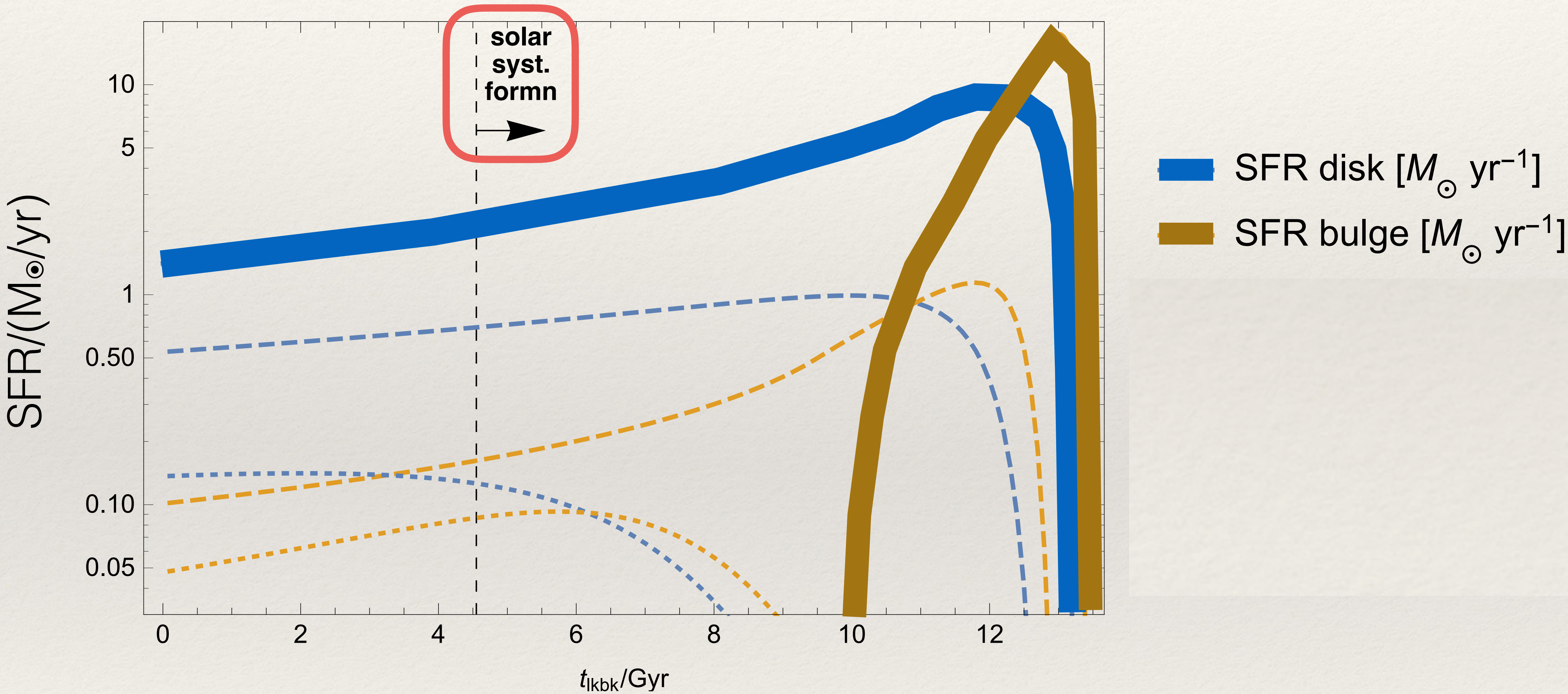
Childress et al. 2015

t_p: 'delay time'

DTD


SN Ia
SN 91bg
t_p = 5.4 Gyr
s = −1.6
α = 3.7
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
t (Gyr)

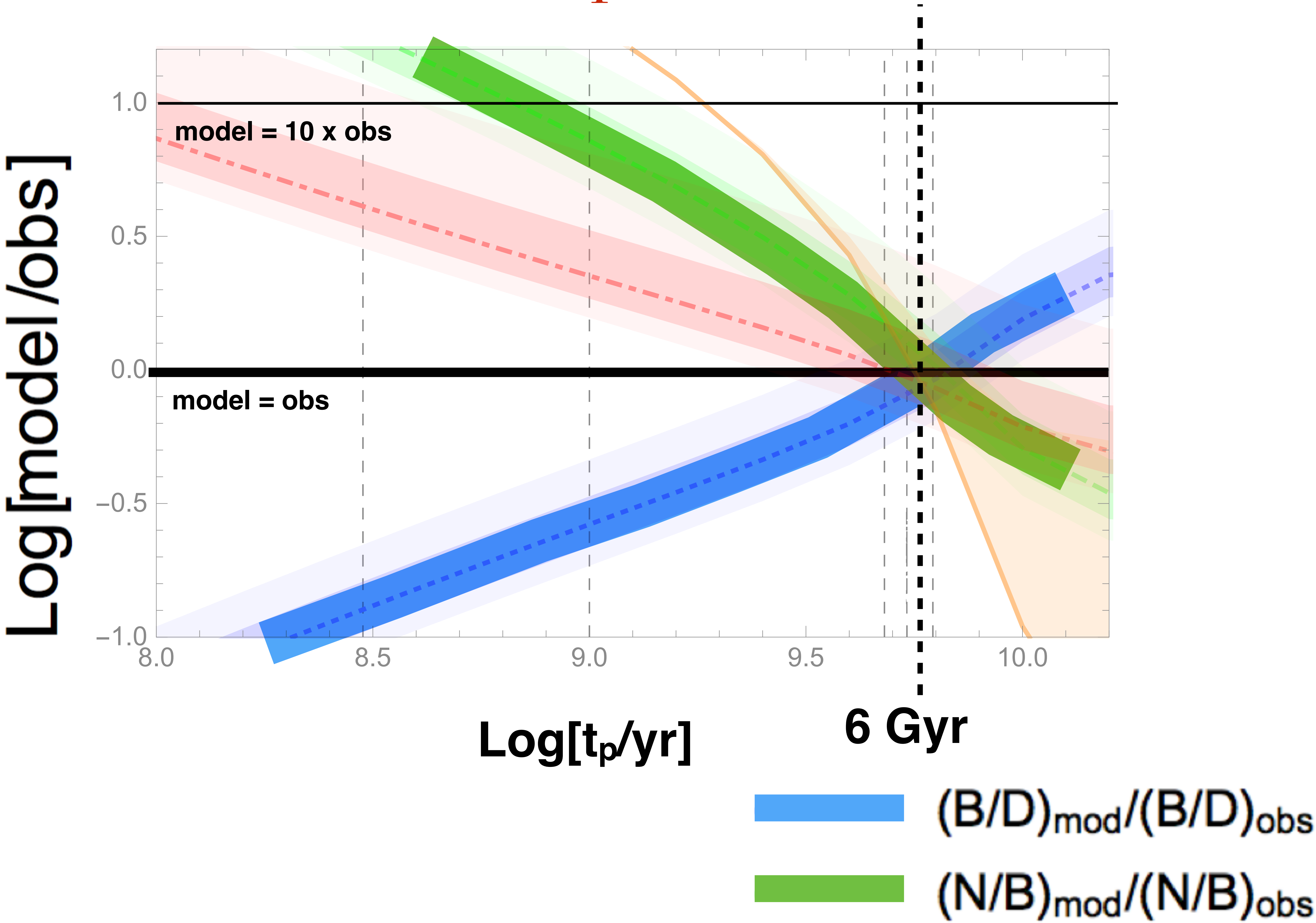
Galactic Star Formation History

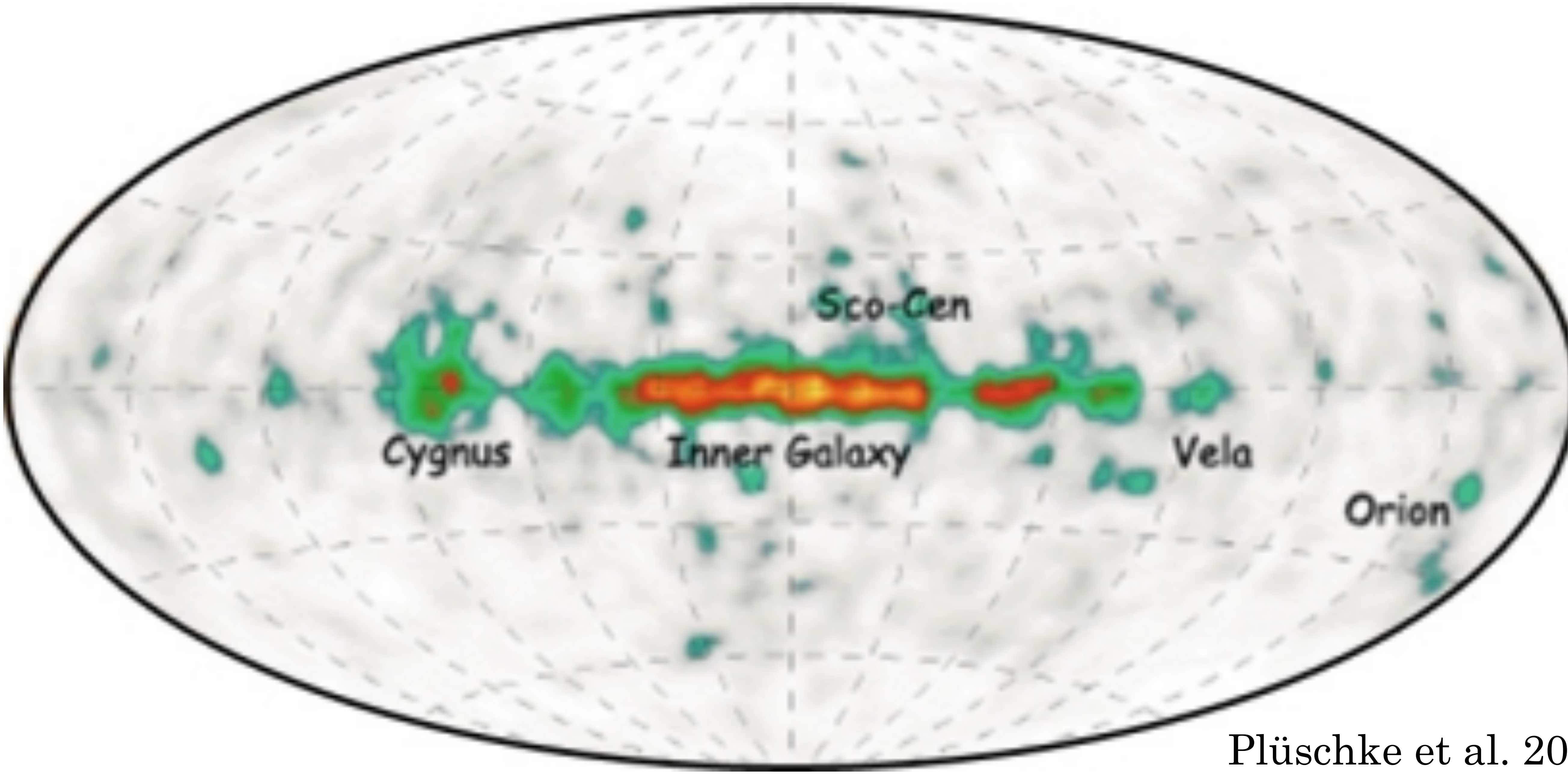


today

Big Bang

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



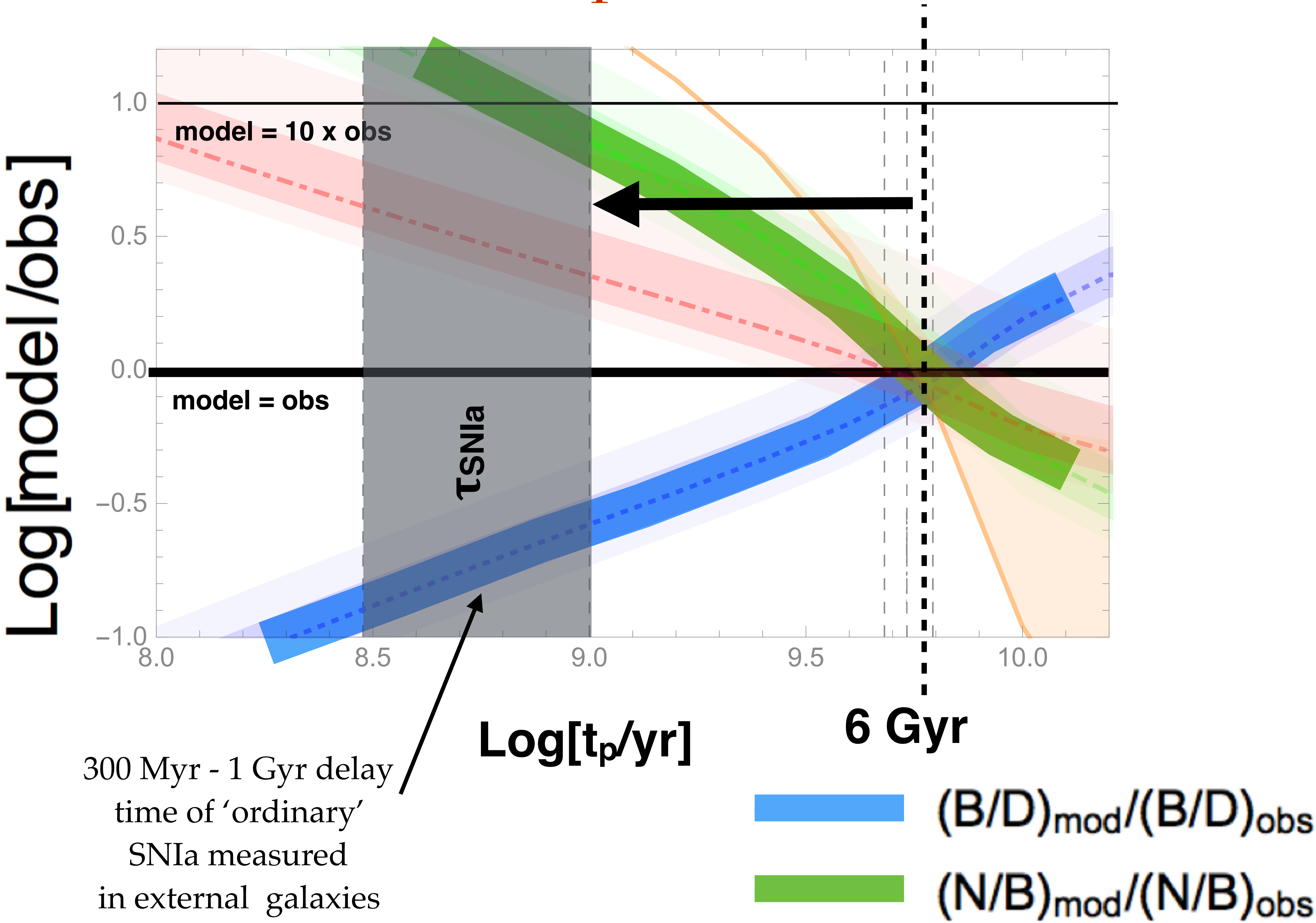


Plüschke et al. 2011

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

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

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



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*

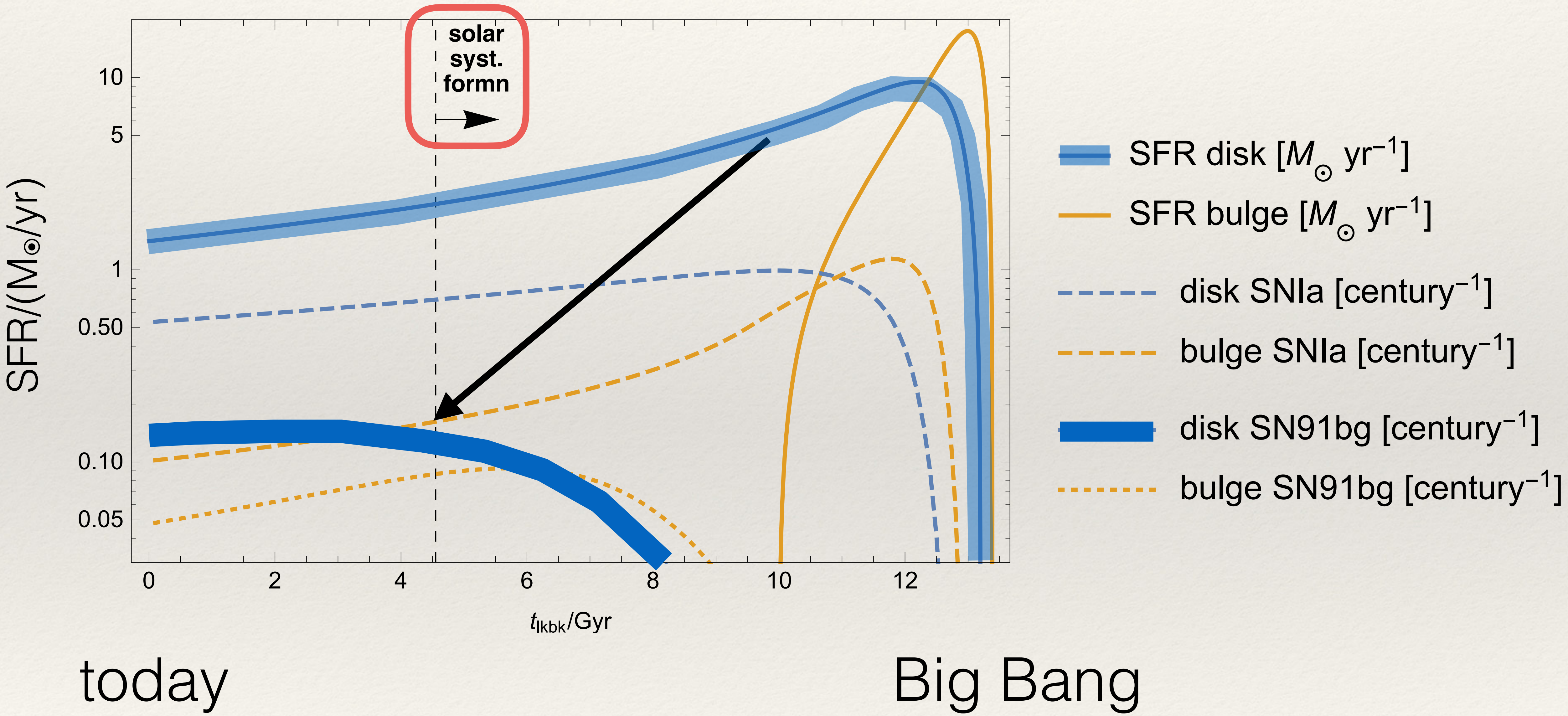
…Trapping not a problem for ^{44}Ti:

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

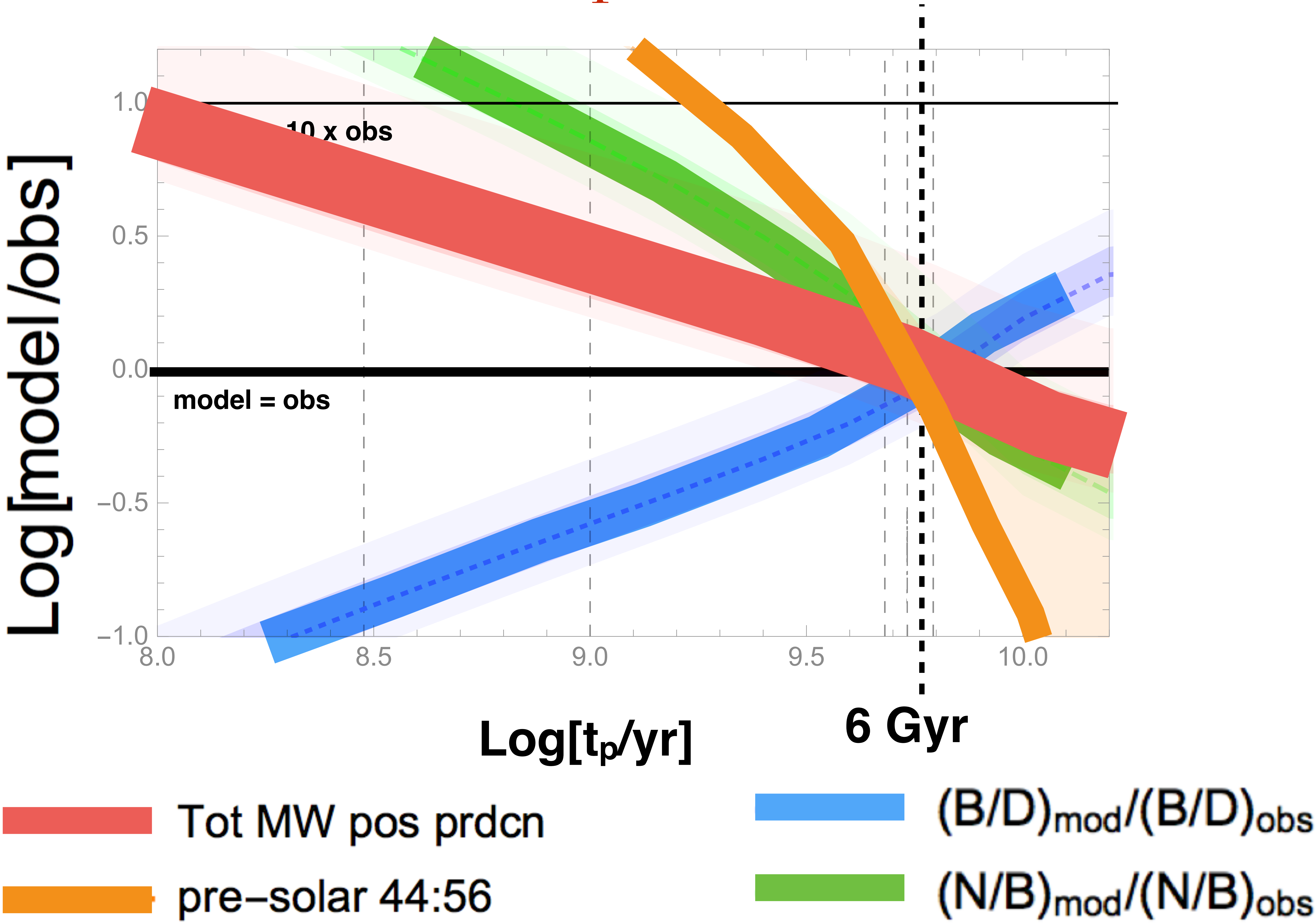
A Galactic ^{44}Ti source that…

- …occurs every ≳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

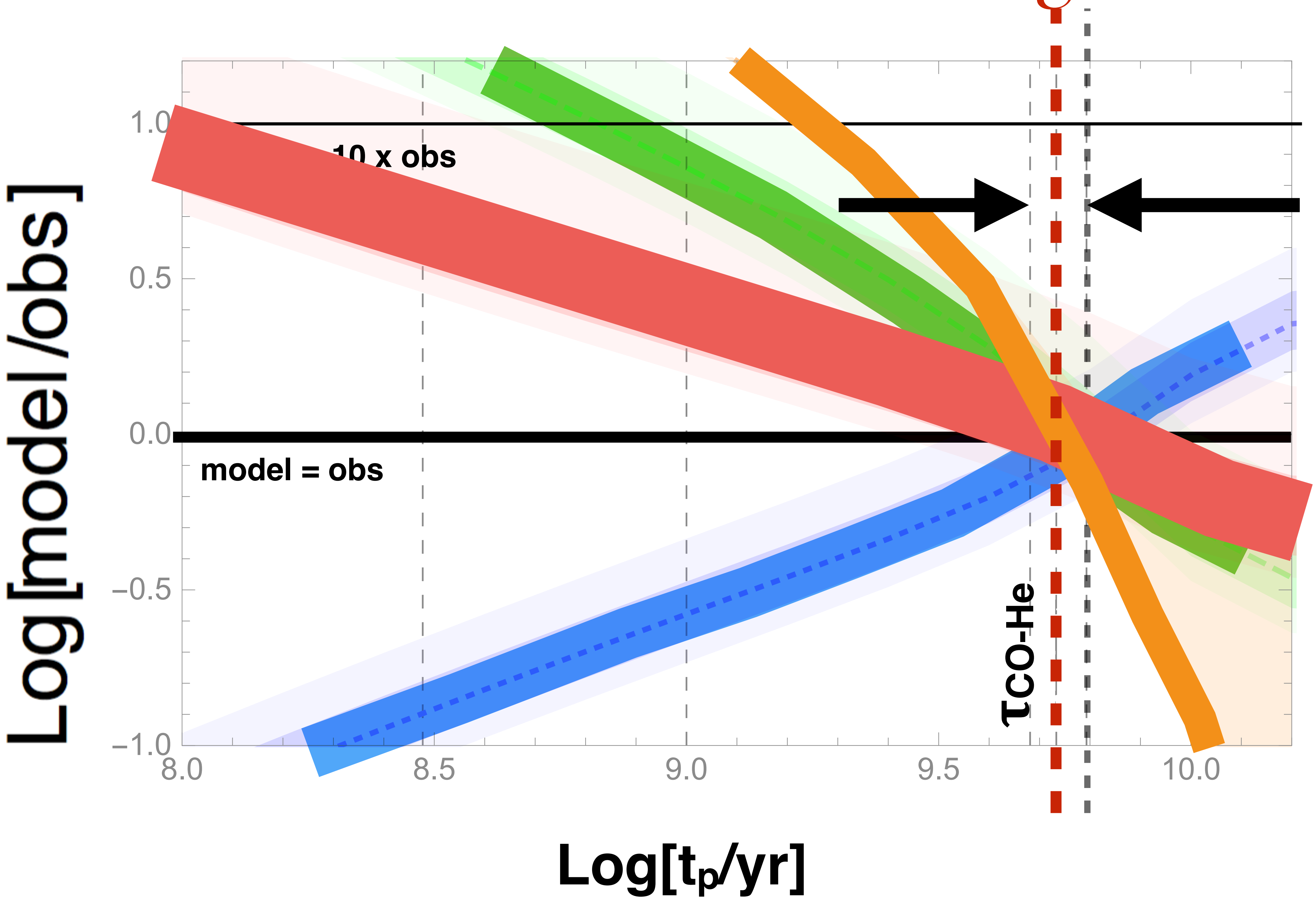
How old does a *stellar* positron source need to be?



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/(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

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 (to be confirmed with DES: Panther PhD)

Summary

- The GC Excess seems to trace particular stellar populations in the inner Galaxy
- Siegert et al have changed the empirical situation with respect to Galactic positron annihilation, in particular, the Galactic disk is a brighter positron source than previously reckoned
- B/D positron luminosity ratio ~ B/D stellar mass ratio
- 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