Galactic Positrons

Roland Crocker
ANU

- This talk: focusing on low energy, trans-relativistic positrons evidenced by annihilation radiation from the Inner Galaxy

- ~5 x 10^{43} e^{+}/s annihilate in the Galaxy (Siegert et al. 2016)

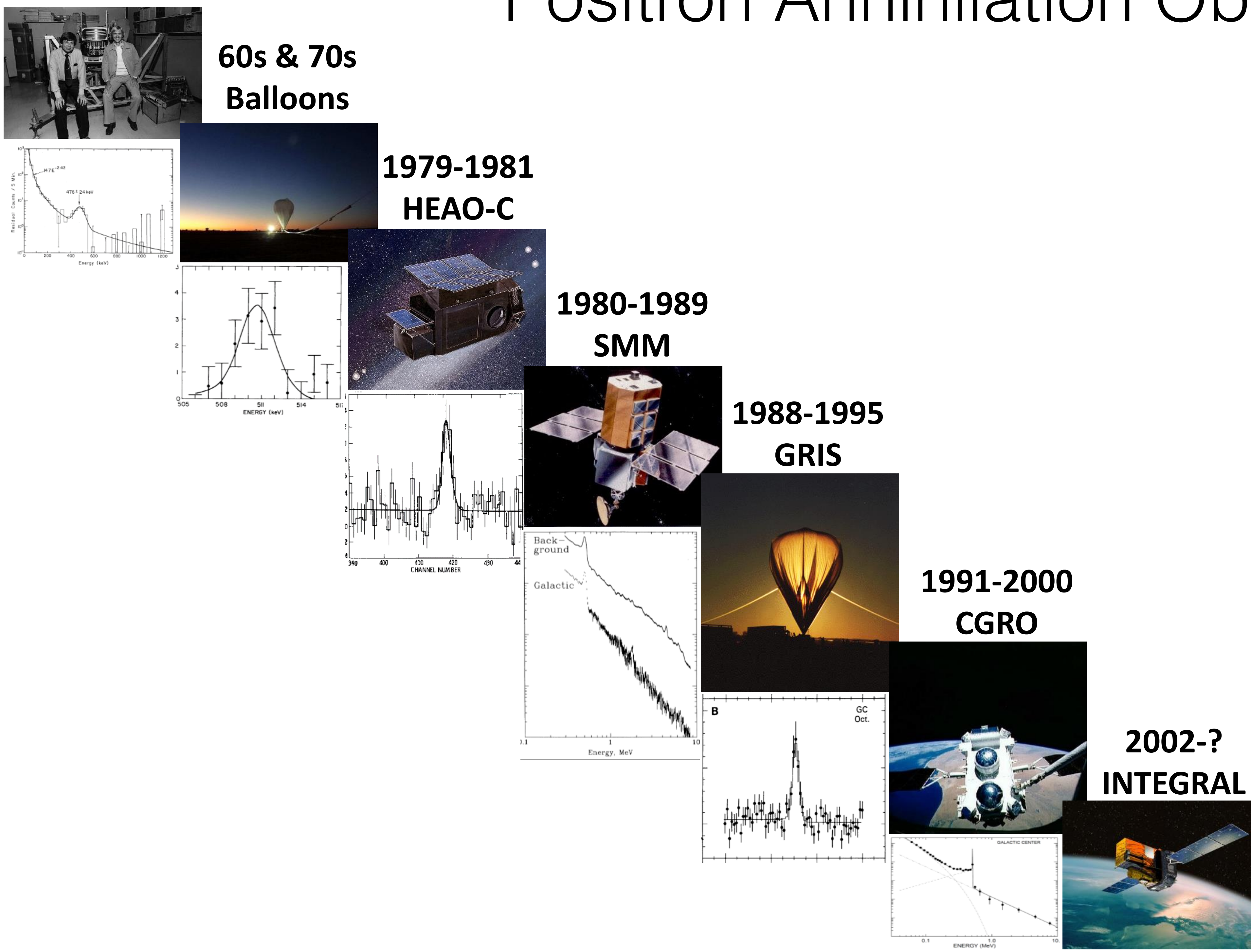
- This talk: focusing on low energy, trans-relativistic positrons evidenced by annihilation radiation from the Inner Galaxy

- ~5 x 10^{43} e^+/s annihilate in the Galaxy (Siegert et al. 2016)

…*where do they come from?*

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

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

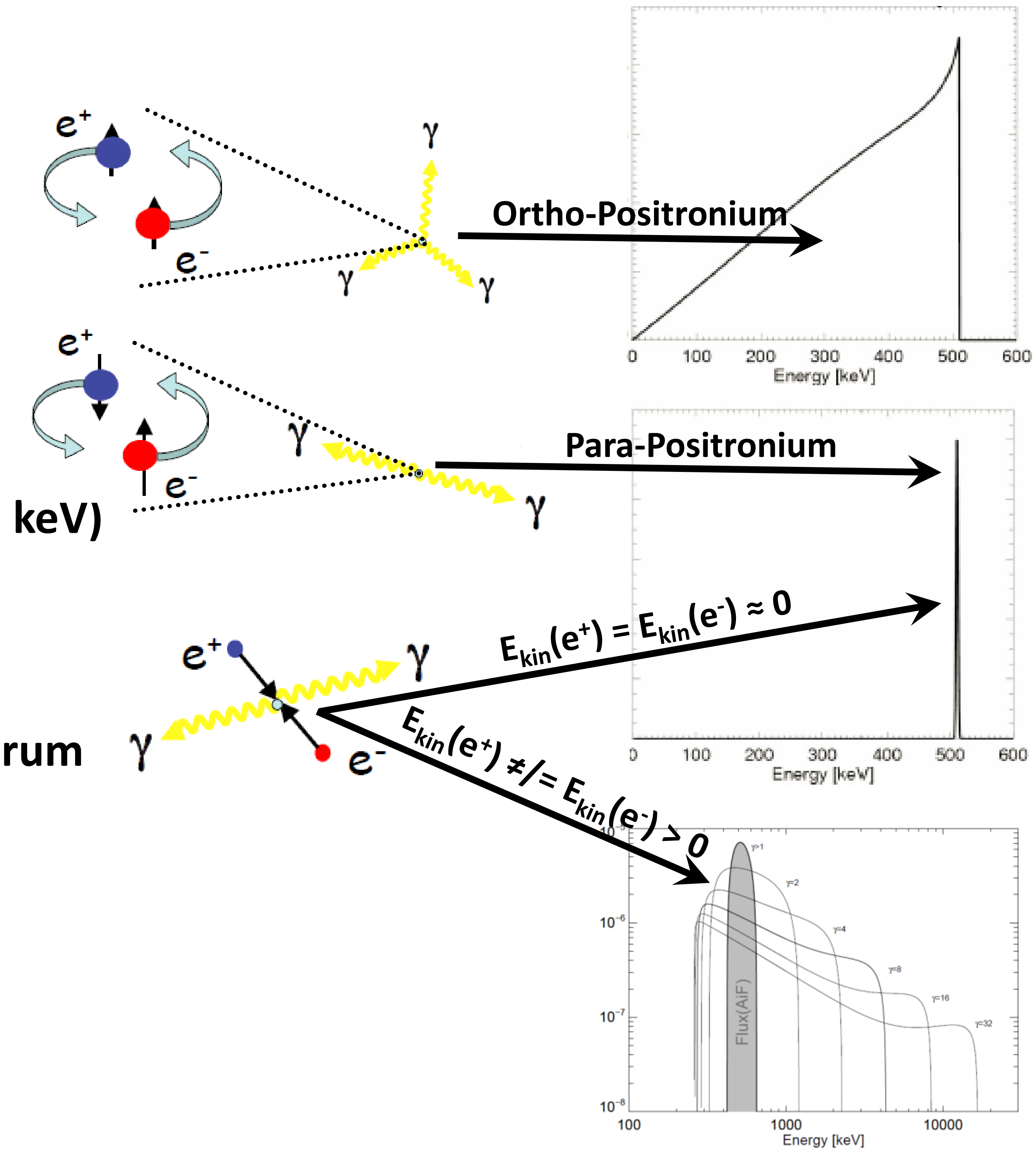
- <u>Formation of Positronium Atom (Ps):</u>

→ Triplet state (S=1): parallel spins
“Ortho-Positronium” o-Ps
Lifetime: $\tau = 1.4\times10^{-7}$ s
3γ: continuous spectrum

→ Singlet state (S=0) antiparallel spins
“Para-Positronium” p-Ps
Lifetime: $\tau = 1.3\times10^{-10}$ s
2γ: monoenergetic gamma-ray line (511 keV)

- <u>Annihilation in Flight (AiF):</u>

→ 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

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…*not seen at any other wavelength*

- ***Historically***: bulge/disk positron luminosity:

  B/D ~ 1.4

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

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

- Large B/D prompted theories of “special source” in the inner Galaxy:
    - Super-Massive Black Hole?
        - need process to transport positrons from nucleus out to scale of bulge; diffusion does not work (Martin et al. 2012)
    - Dark Matter (Boehm et al. 2004)?
        - difficult given positron injection energy constraint from continuum gamma-rays (Aharonian & Atoyan 1983; Becom, Bell & Bertone 2005; Beacom & Yuksel 2006): $\mathbf{T_{e+} \lesssim 3\ MeV}$
    - 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…

- Large B/D prompted theories of “special source” in the inn… Galaxy:
    - Super-Massive Black Hole?
        - need process to transport posi… scale of bulge; diffusion d… …12)
    - Dark Matter (Boehm…
        - difficult … gy constraint from co… …ian & Atoyan 1983; Becom, … om & Yuksel 2006): **T_{e+} ≲ 3 MeV**
        - … us to rule out compact sources like
- … other hand, perfectly consistent with e^+ from β^+ decay of radionuclides synthesised in 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 publication of Siegert et al. 2016:

- much more low surface brightness emission from disk detected

- B/D ~ 1.4 ⟶ **B/D ≃ 0.4**

- newly reduced B/D makes idea for "special" positron source in the GC/bulge less compelling

- but now comes the difficult part: how to explain the "extra" disk positrons?

New observational situation following publication of Siegert et al. 2016:

- much more low surface brightness emission from disk detected

- B/D ~ 1.4 ⟶ **B/D ≃ 0.4**

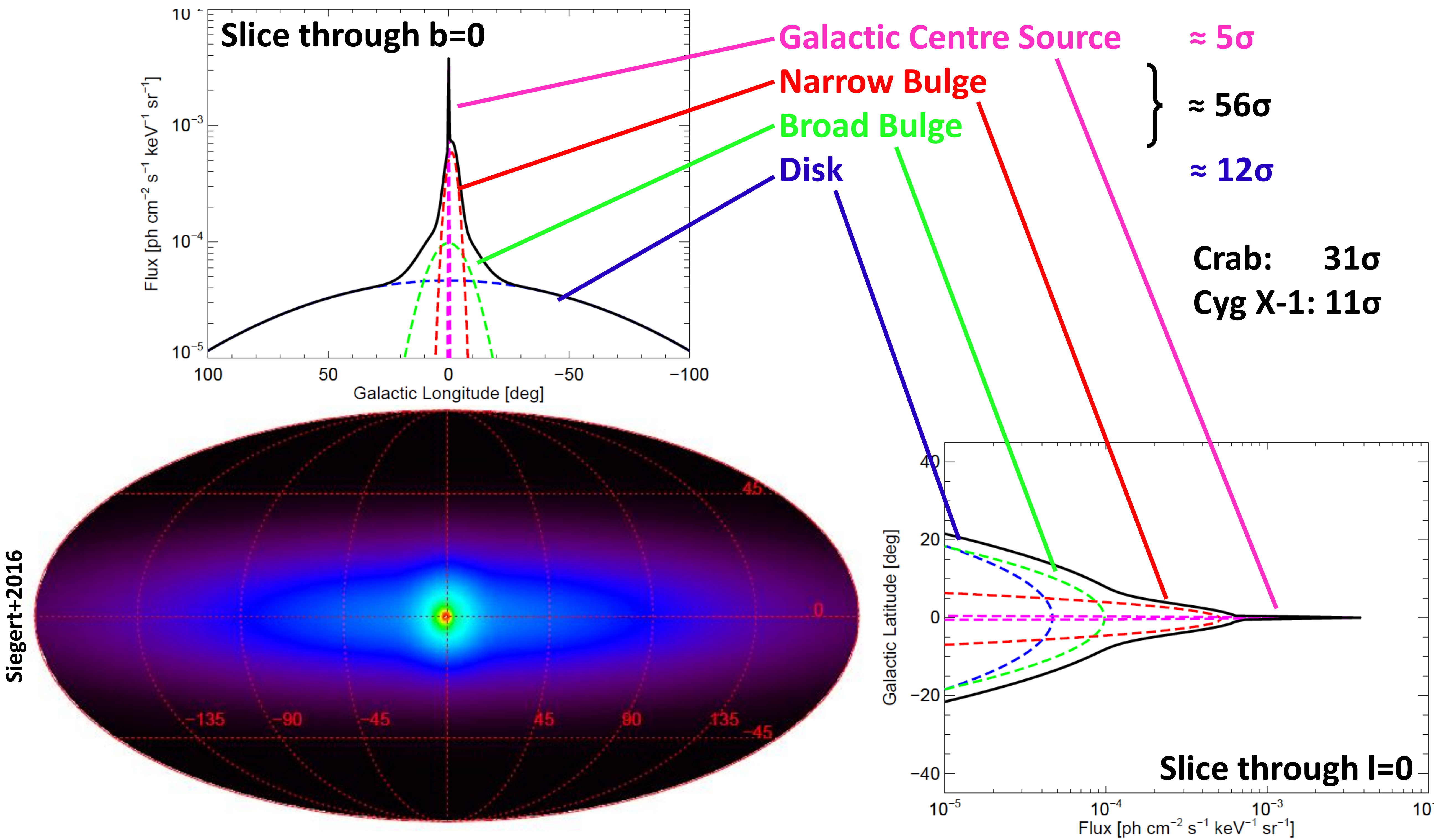
- newly reduced B/D makes idea for “special” positron source in the GC/bulge less compelling

- but now comes the difficult part: how to explain the “extra” disk positrons?

- **B/D ≃ 0.4 ≃ $\mathbf{Mass_{[bulge]}/Mass_{[disk]}}$**

...means that positron source connected to OLD STARS could work

New observational situation following publication of Siegert et al. 2016:



slide credit: Thomas Siegert

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

New observational situation following publication of Siegert et al. 2016:

- Detection (>5σ) of separate positron source in 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 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 ≃ (0.42±0.09)

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

  - NB/B ≃ (0.083±0.021)

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

New observational situation following 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±0.09)

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

  - NB/B $\simeq$ (0.083±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?

More Quantitatively: *Delay Time Distribution*

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

rate of transient event 'X'

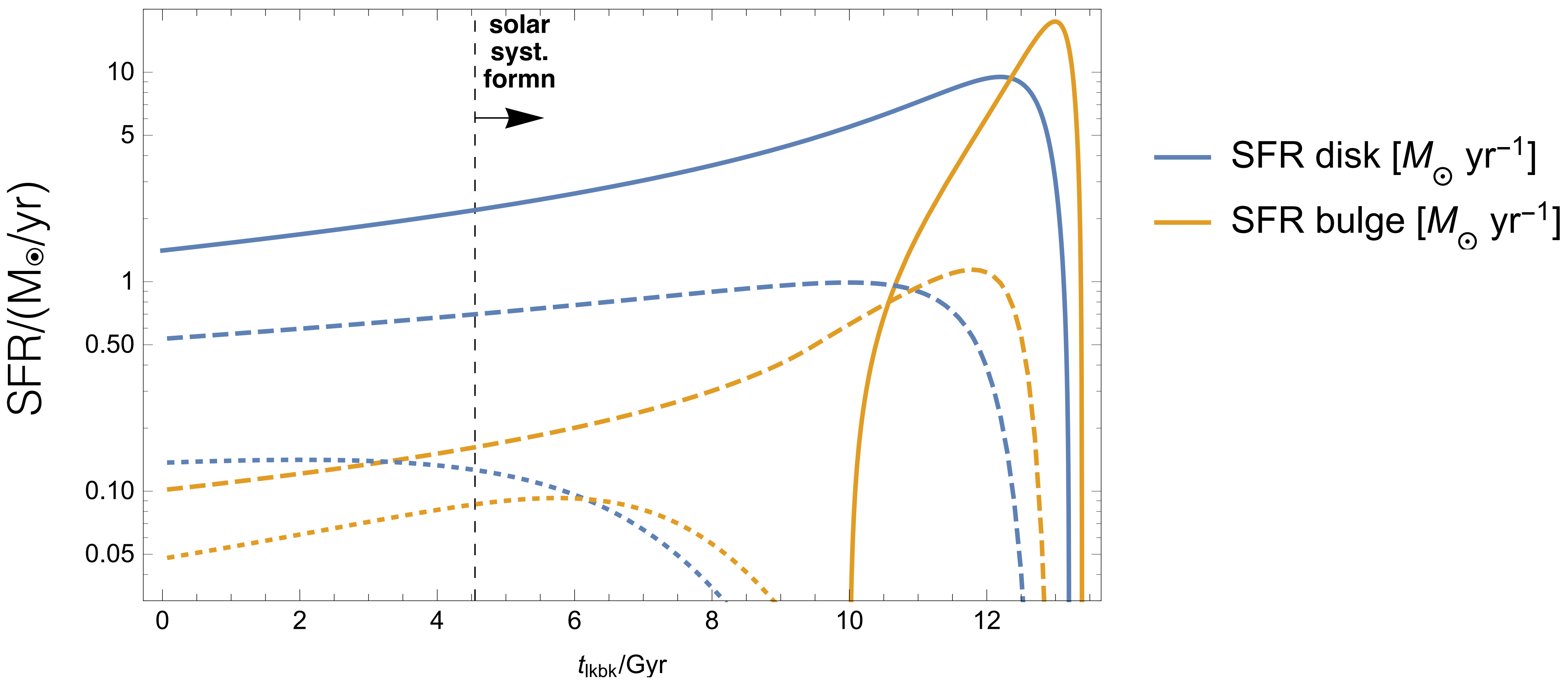
star formation history

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

Childress et al. 2015

t_p: 'delay time'

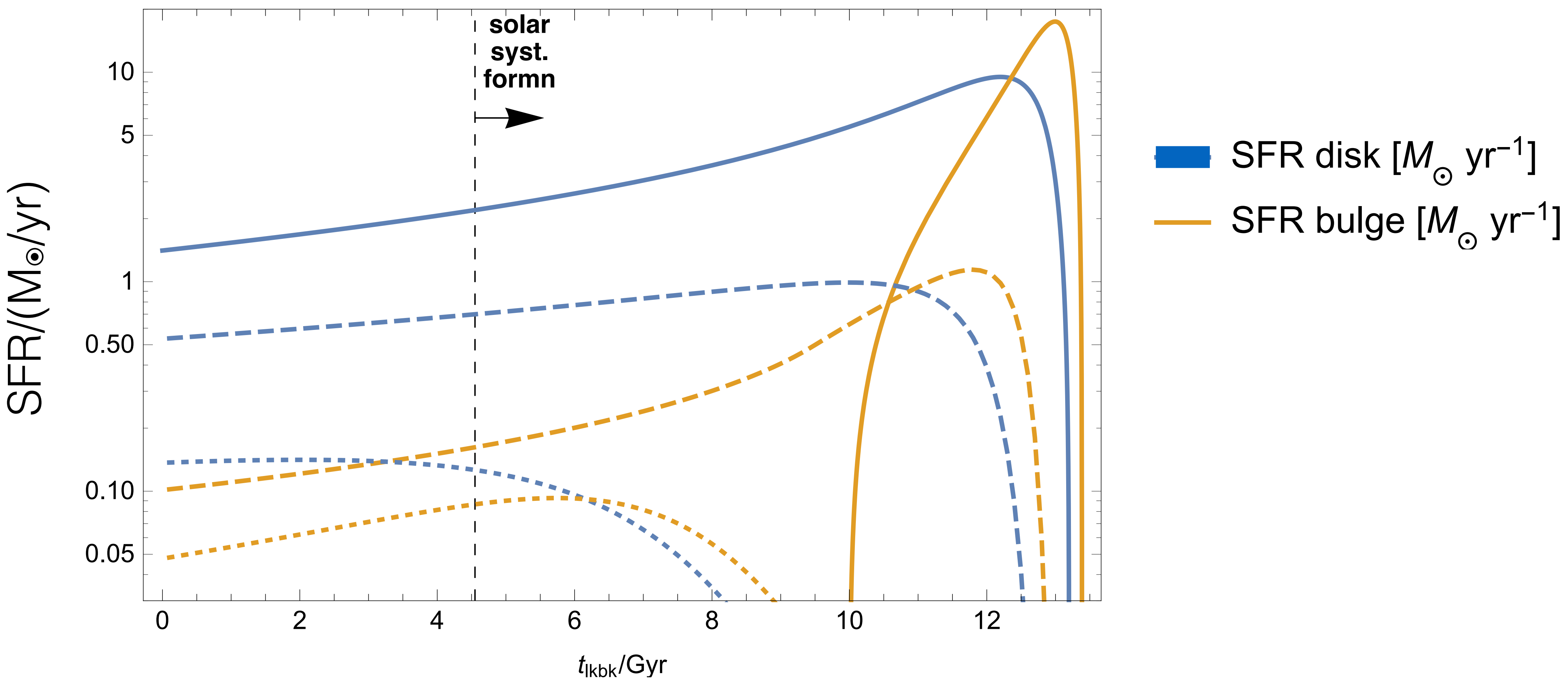
Galactic Star Formation History



today

Big Bang

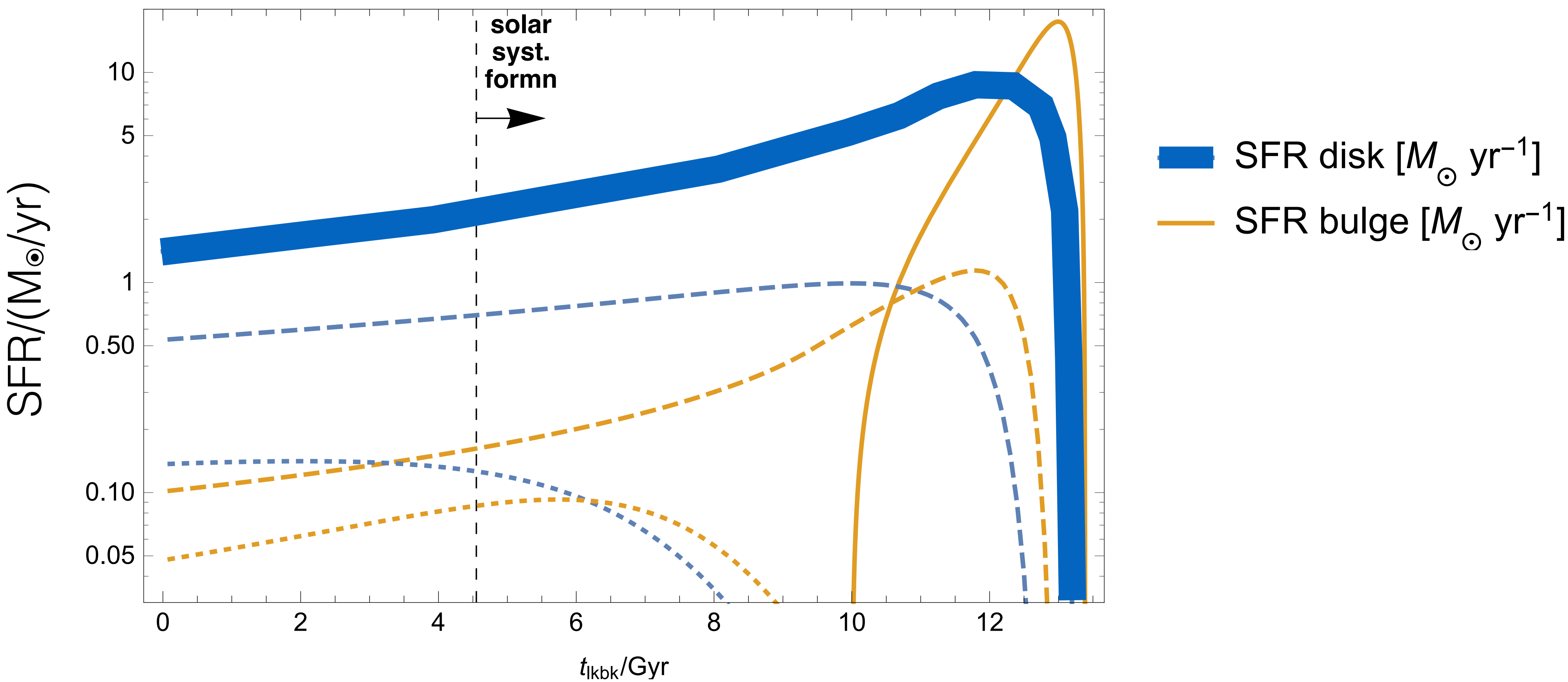
Galactic Star Formation History



today

Big Bang

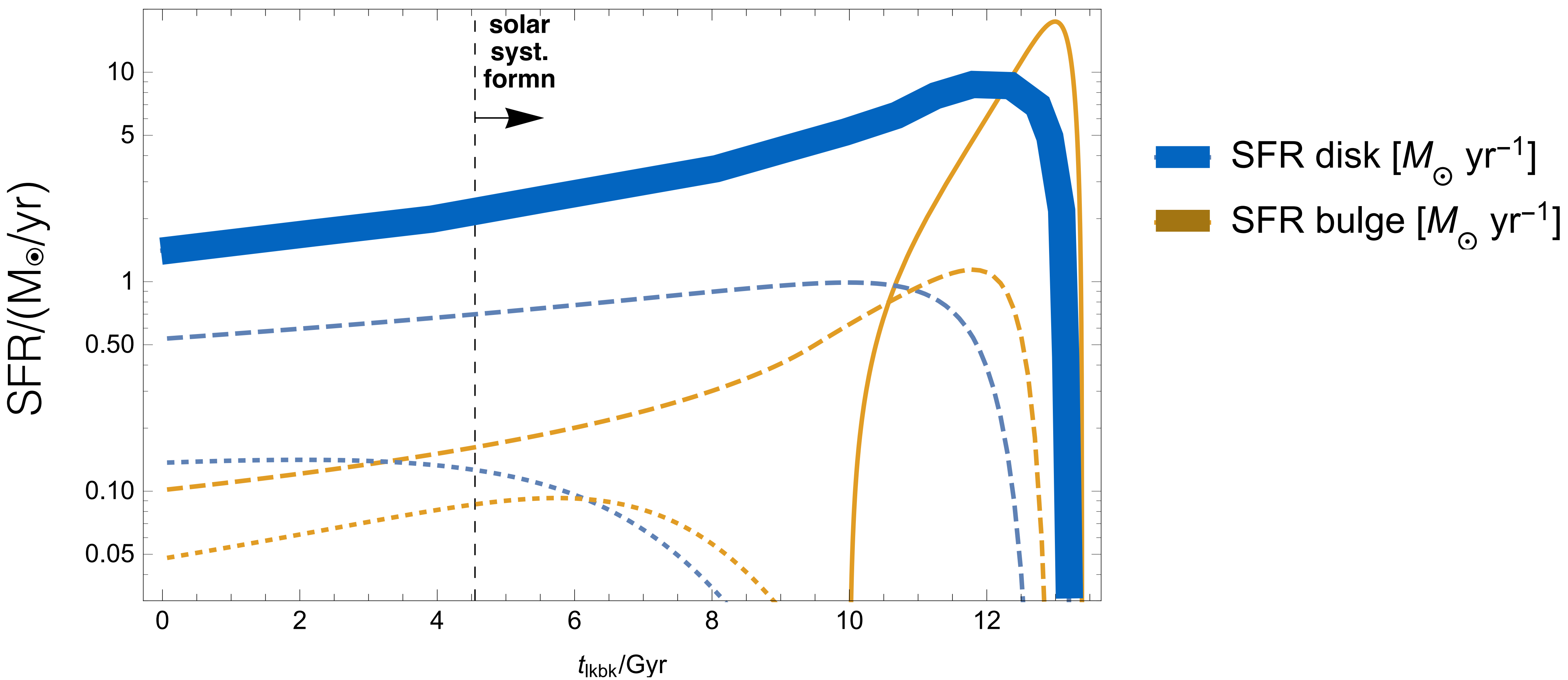
Galactic Star Formation History



today

Big Bang

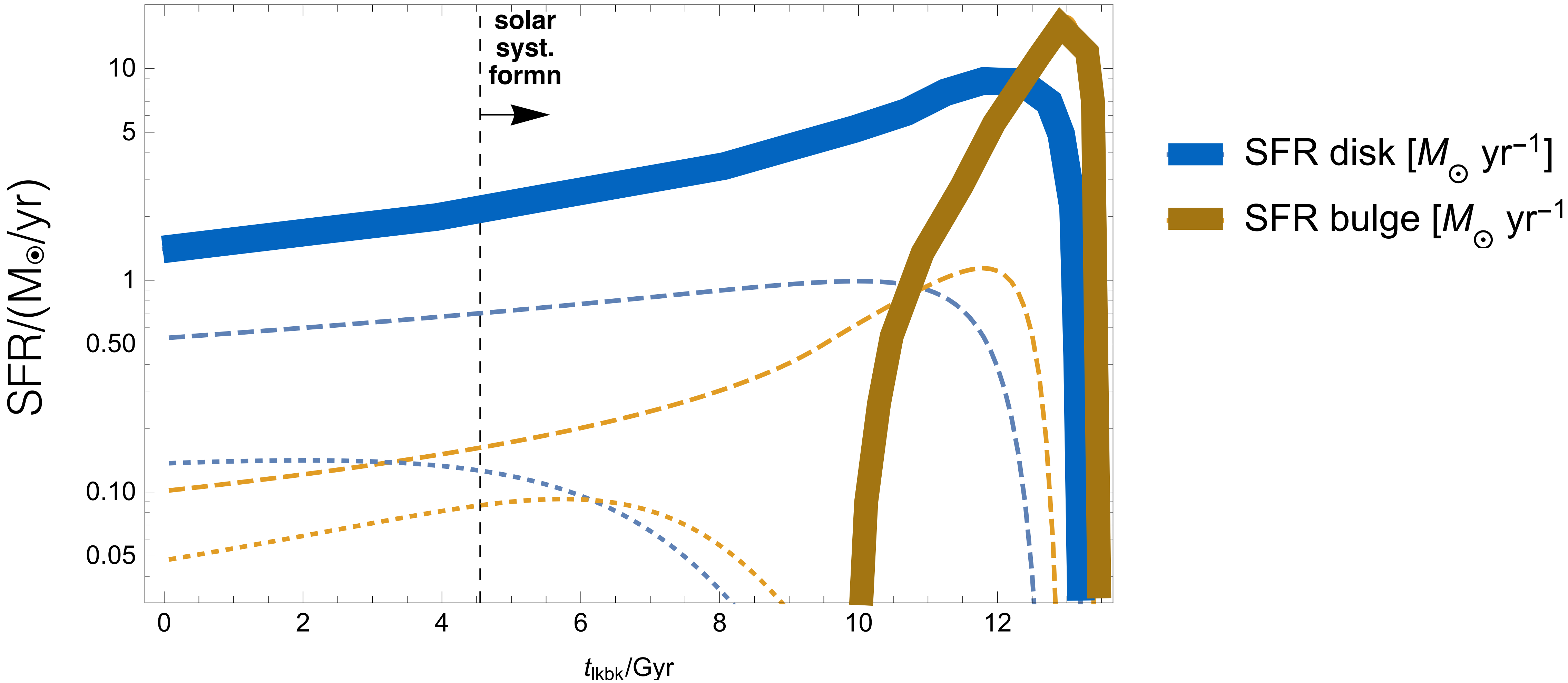
Galactic Star Formation History



today

Big Bang

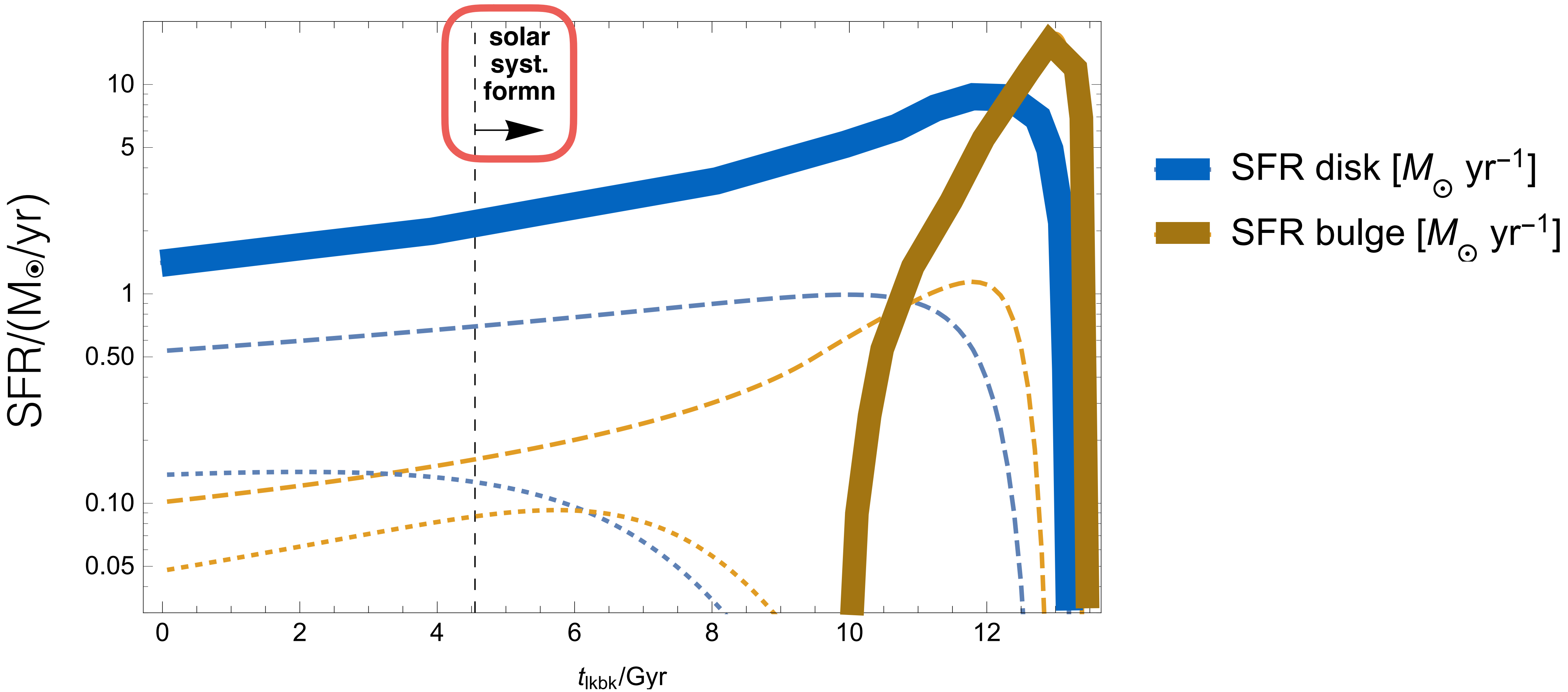
Galactic Star Formation History



today

Big Bang

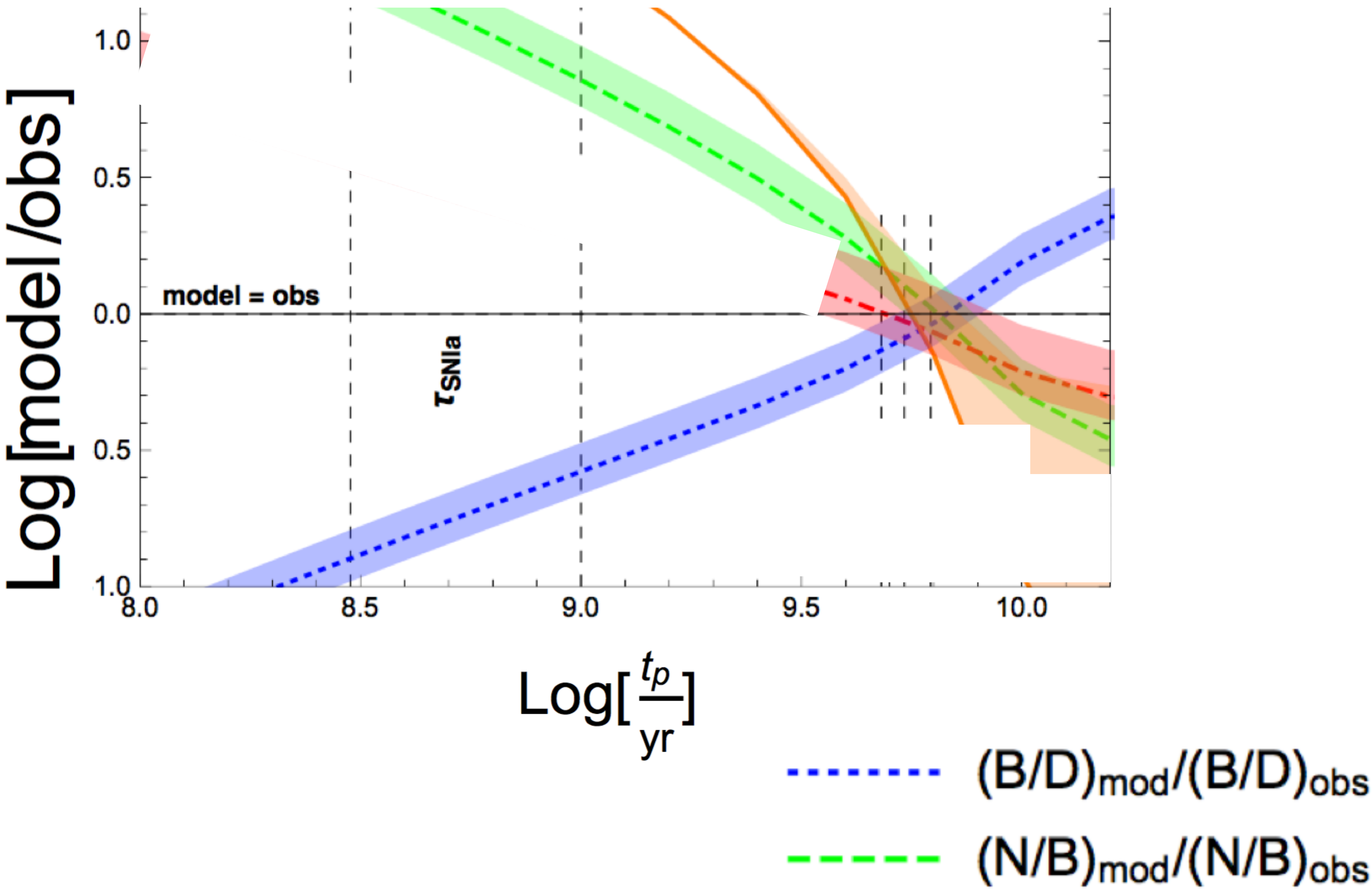
Galactic Star Formation History



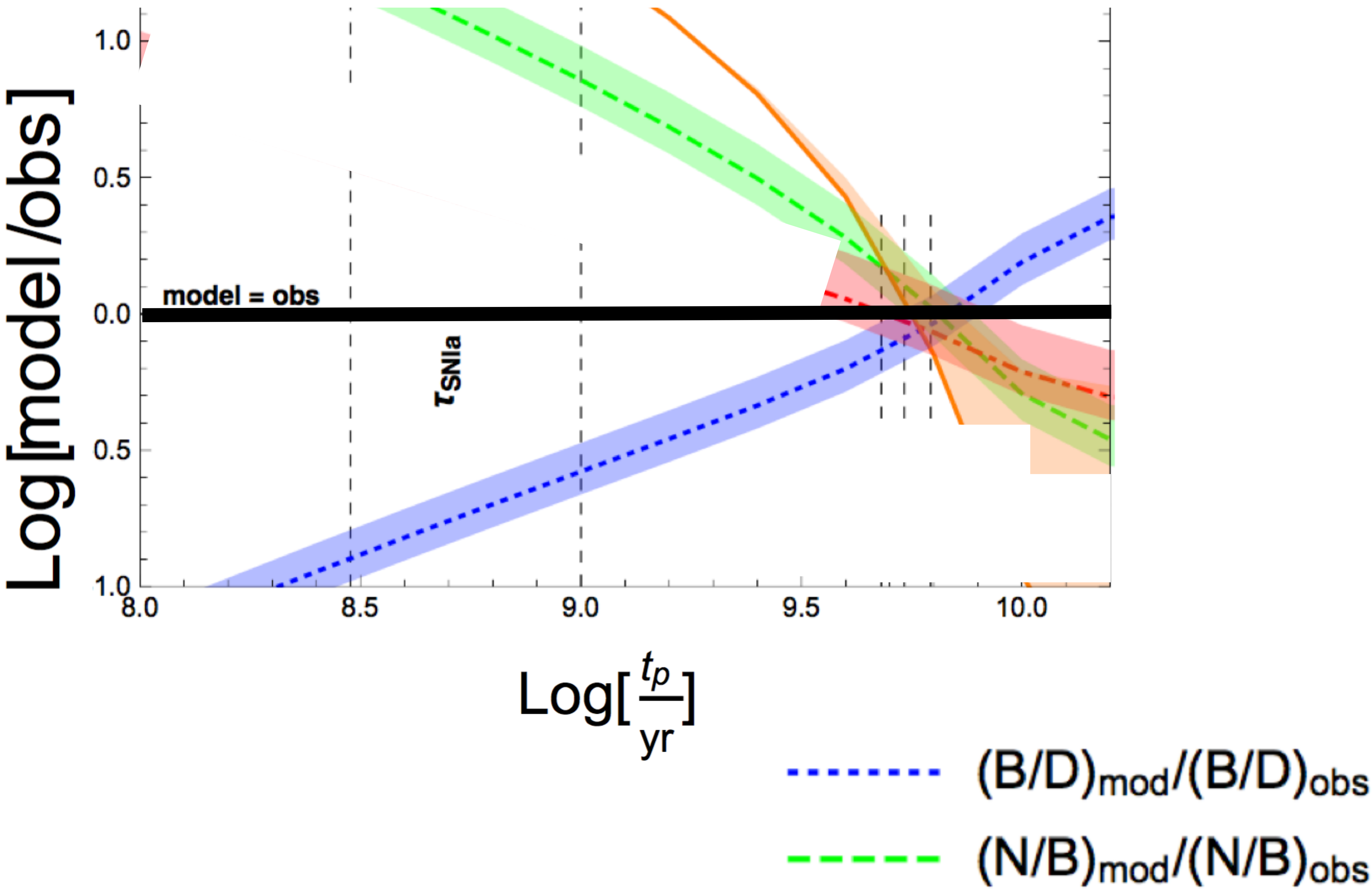
today

Big Bang

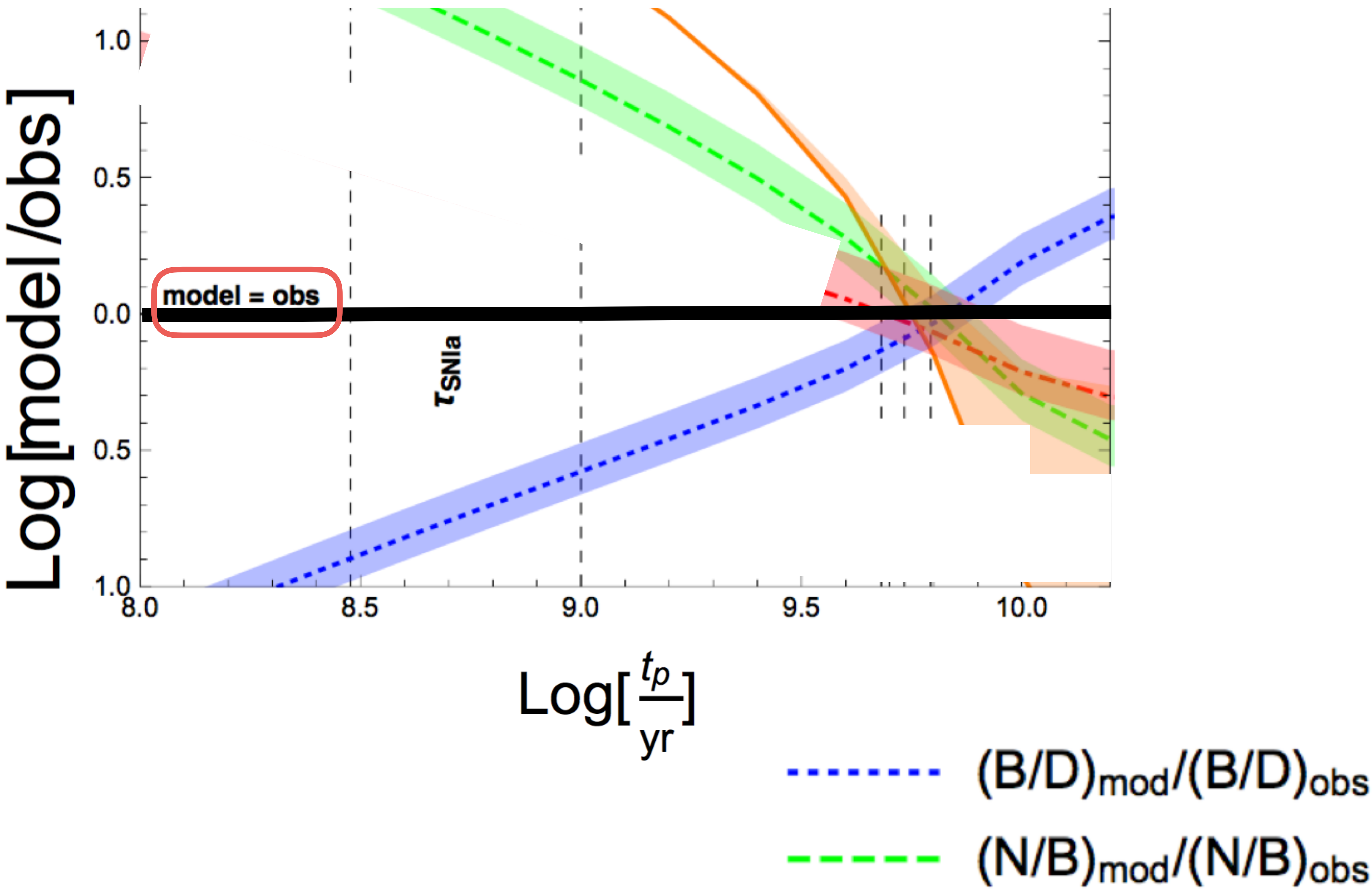
How old does a stellar positron source need to be?



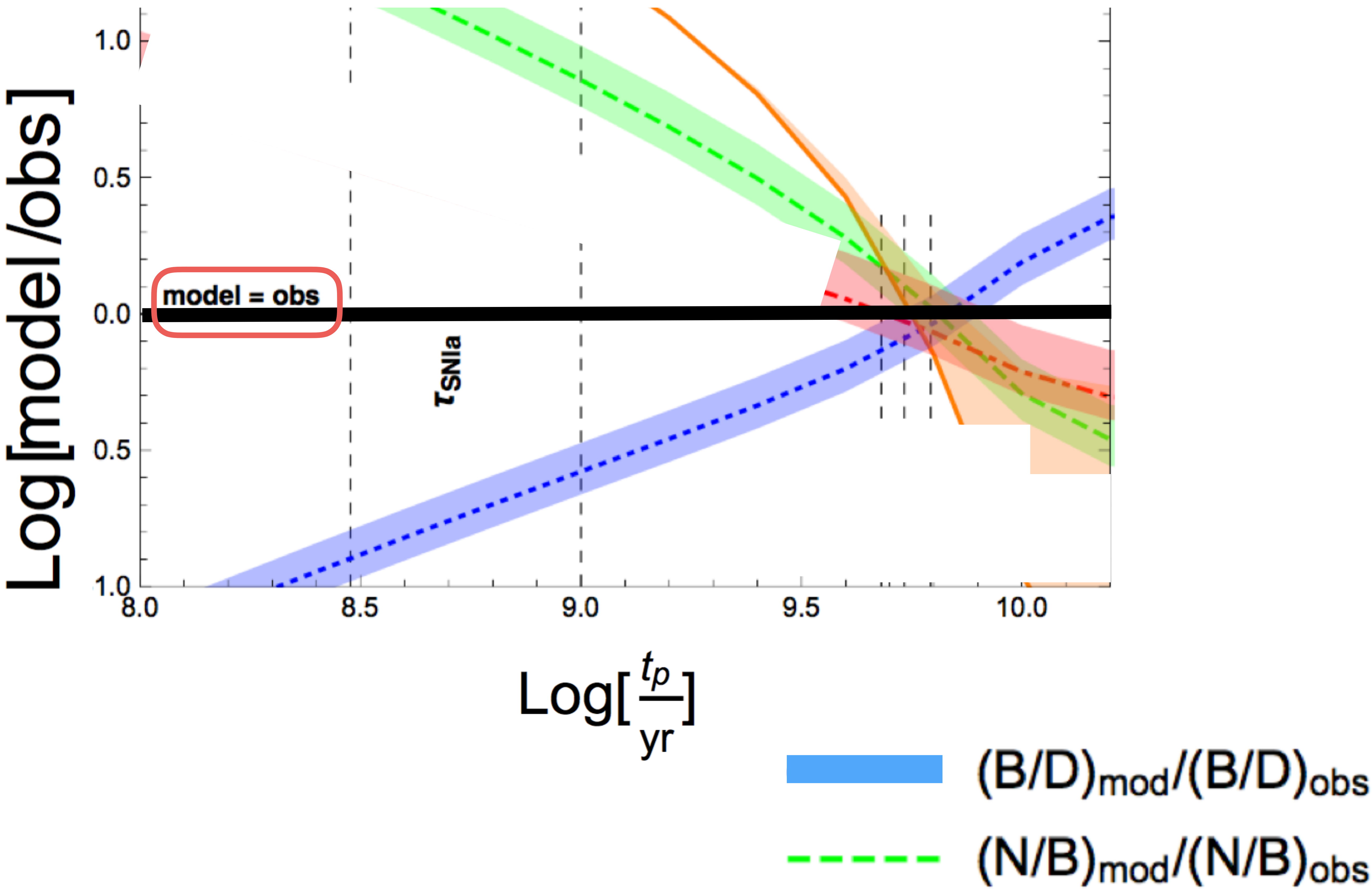
How old does a stellar positron source need to be?



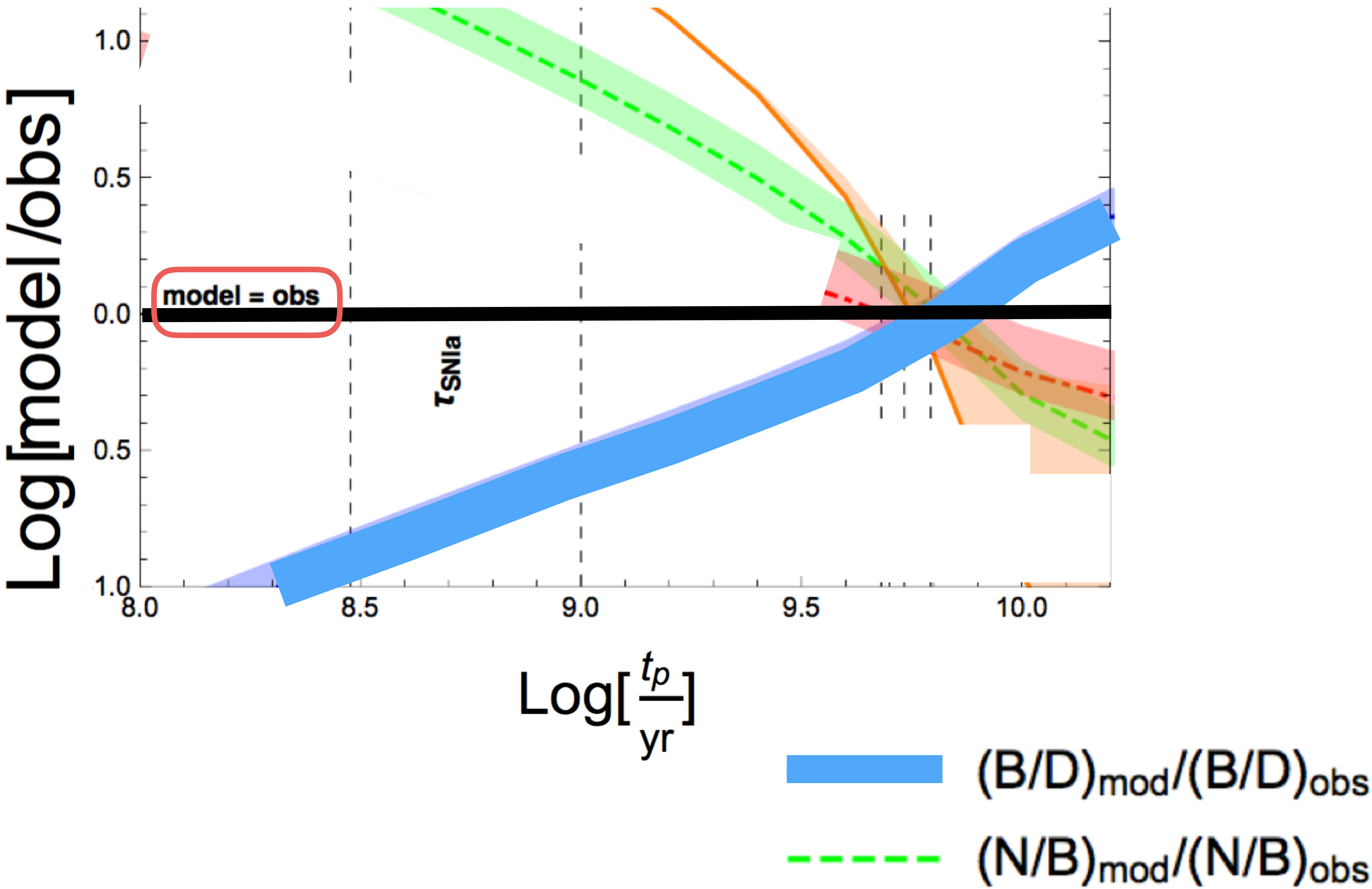
How old does a stellar positron source need to be?



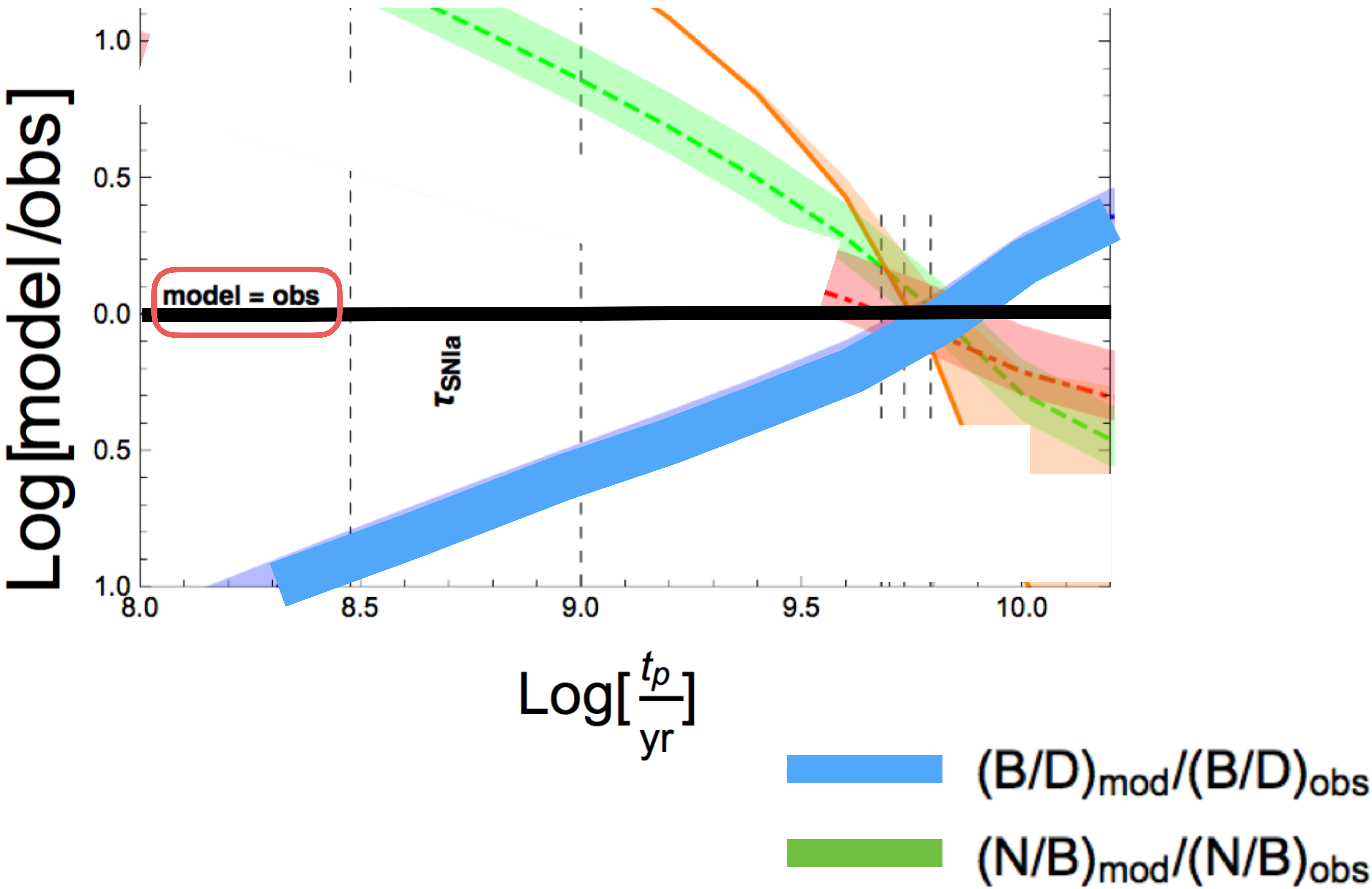
How old does a stellar positron source need to be?



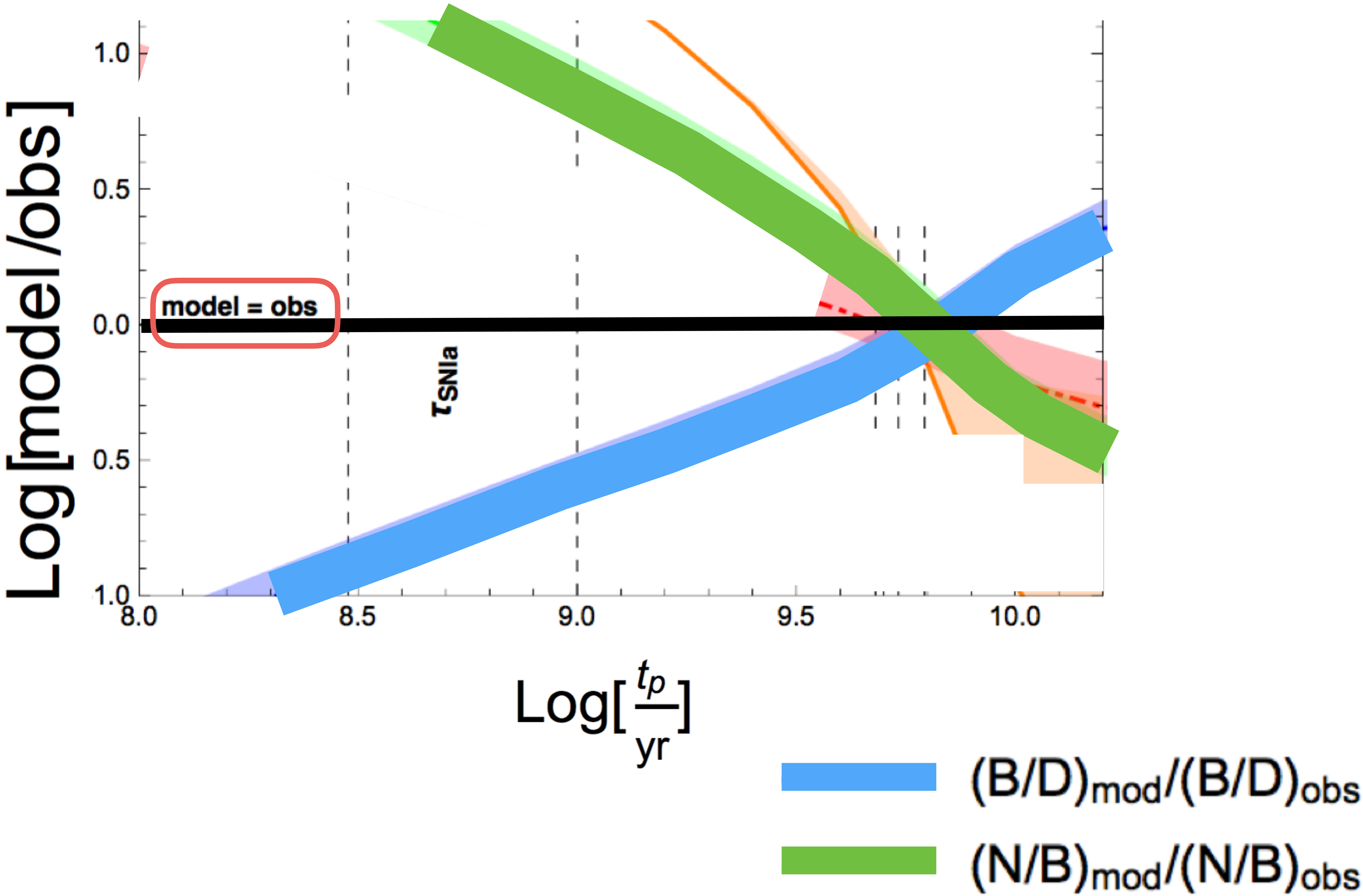
How old does a stellar positron source need to be?



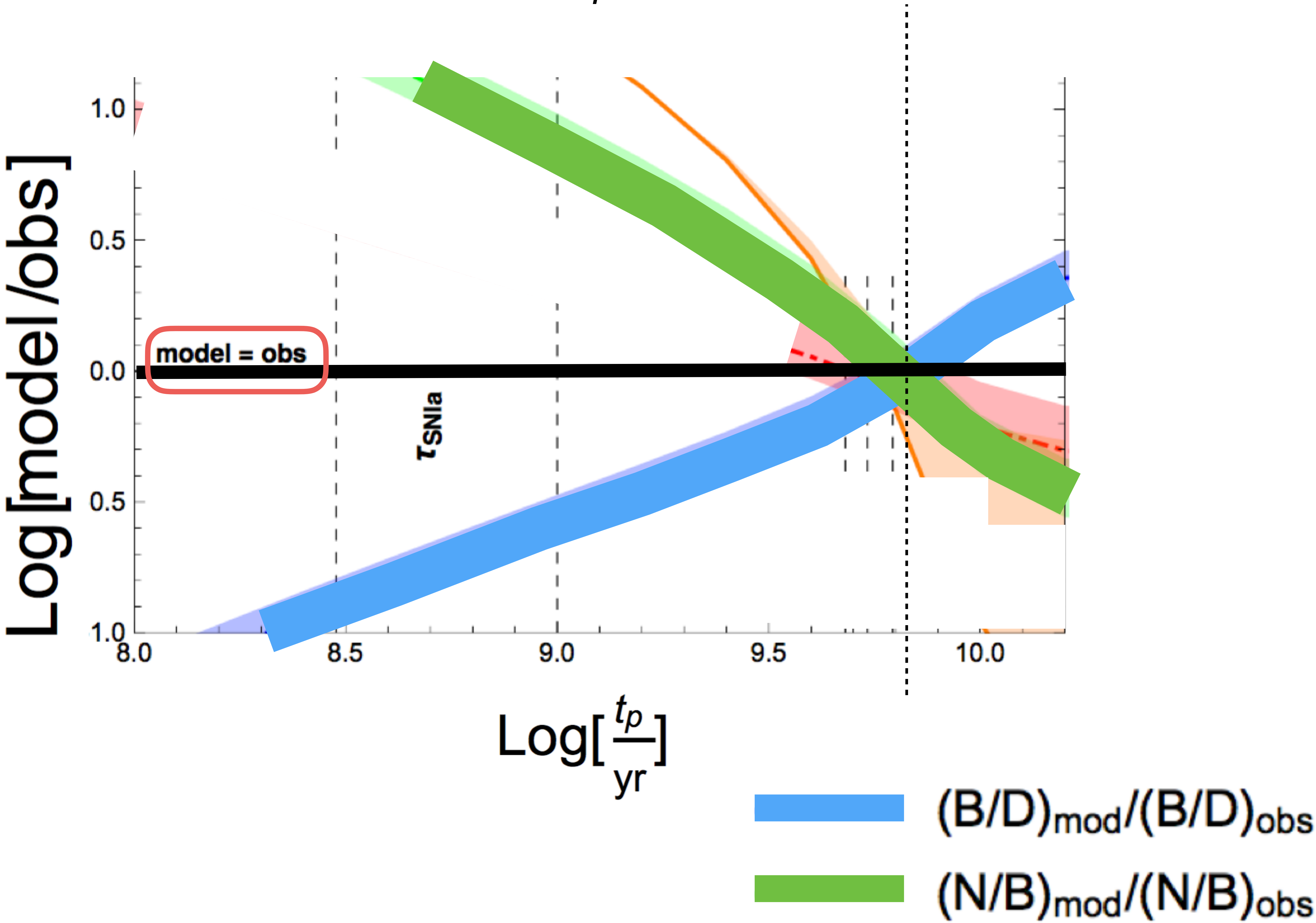
How old does a stellar positron source need to be?



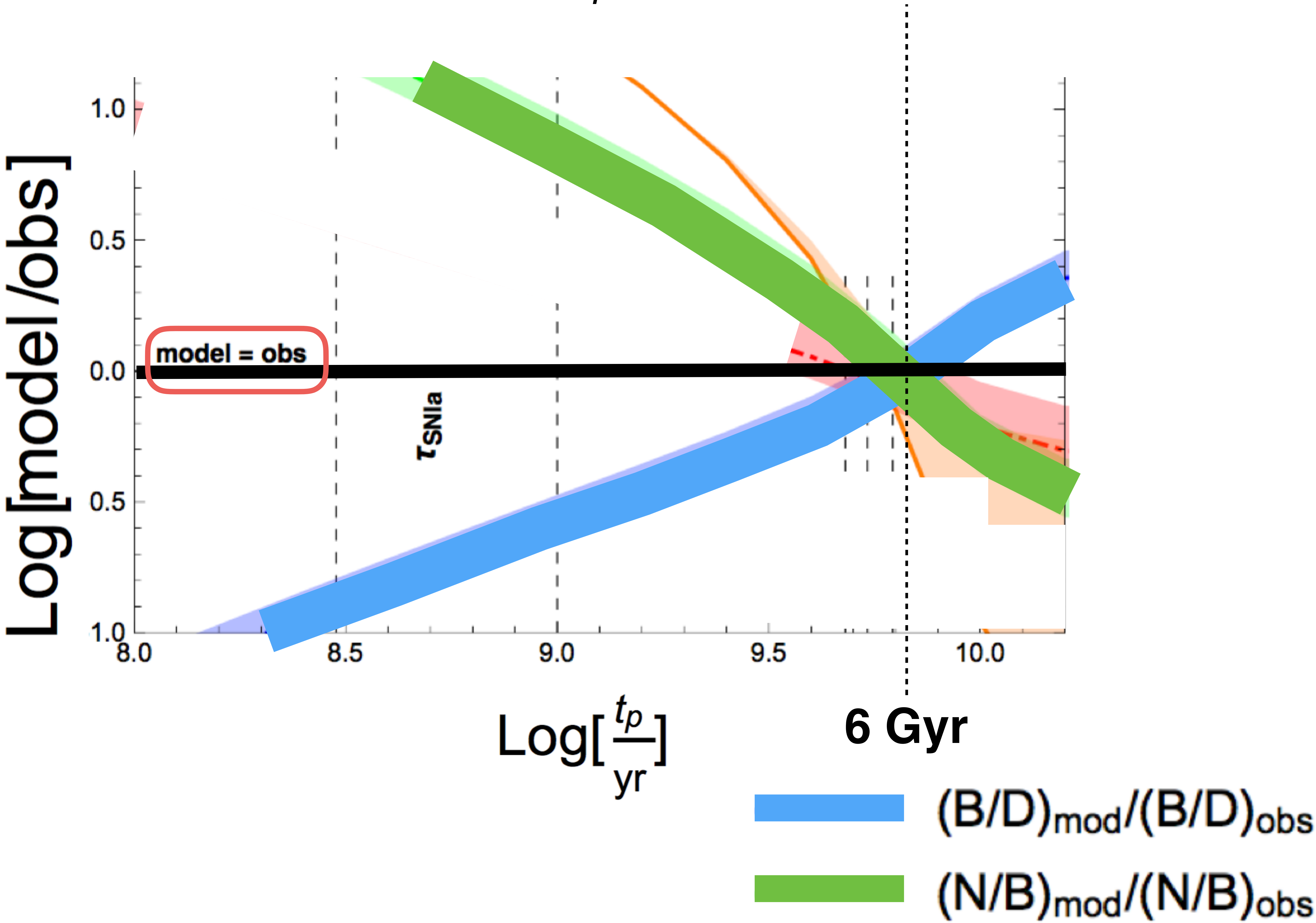
How old does a stellar positron source need to be?



How old does a stellar positron source need to be?



How old does a stellar positron source need to be?



What else do we know?

- Positron injection energy constraint: perfectly consistent with e^+ from β^+ decay of radionuclides.
- Astrophysically-relevant radionuclides: **^{26}Al, ^{56}Ni, ^{44}Ti**
- **^{26}Al**: associated 1.8 MeV γ-ray line; line flux normalises ^{26}Al positrons to ~10% of MW positron luminosity; wrong morphology

What else do we know?

- Positron injection er
  e^+ from β^+ decay of
- Astrophysically-rele
- **^{26}Al**: associated 1.8
  positrons to ~10% c
  morphology

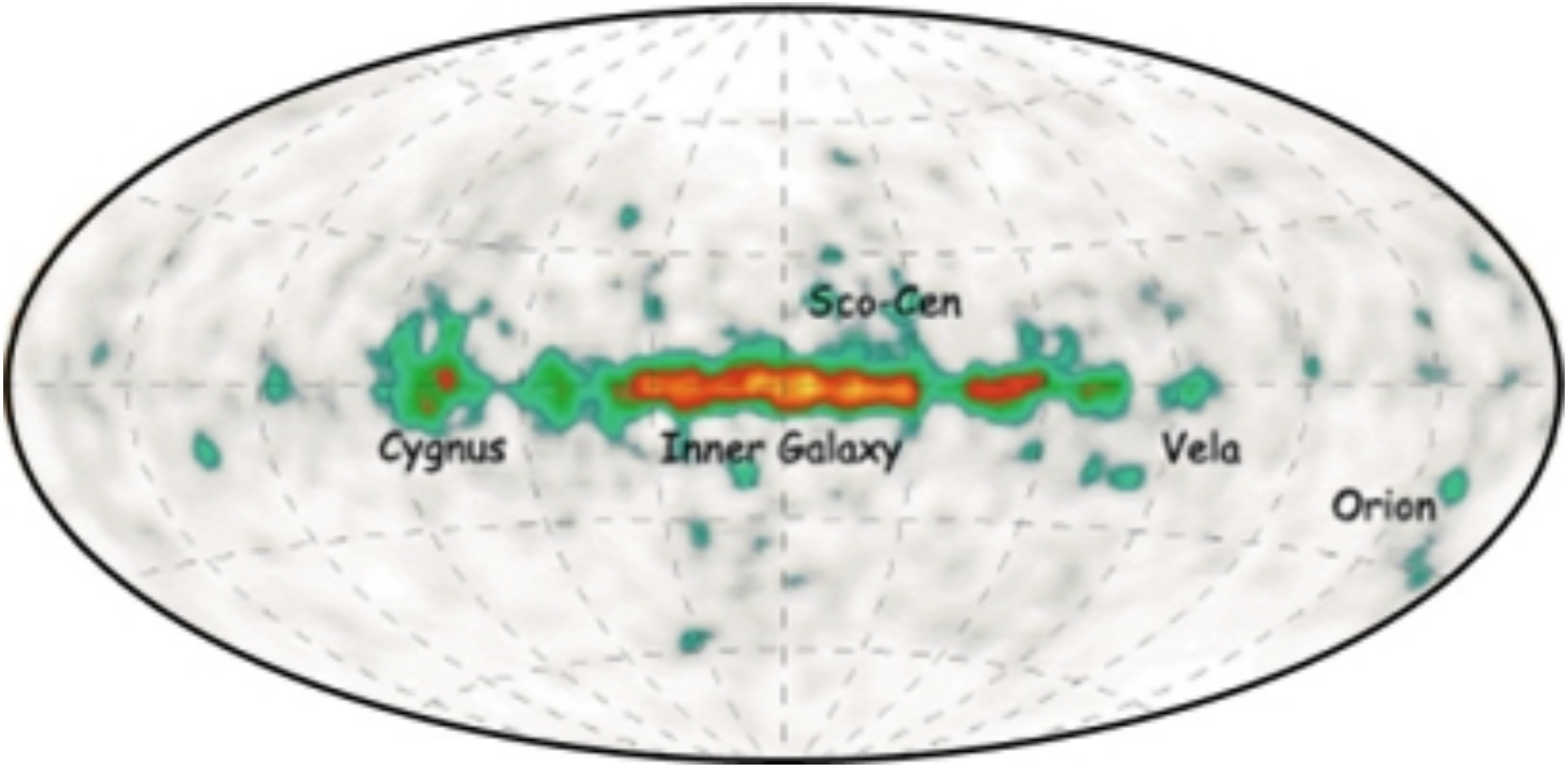
$$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg} + e^+ \qquad \lambda = 717{,}000 \text{ yr}$$

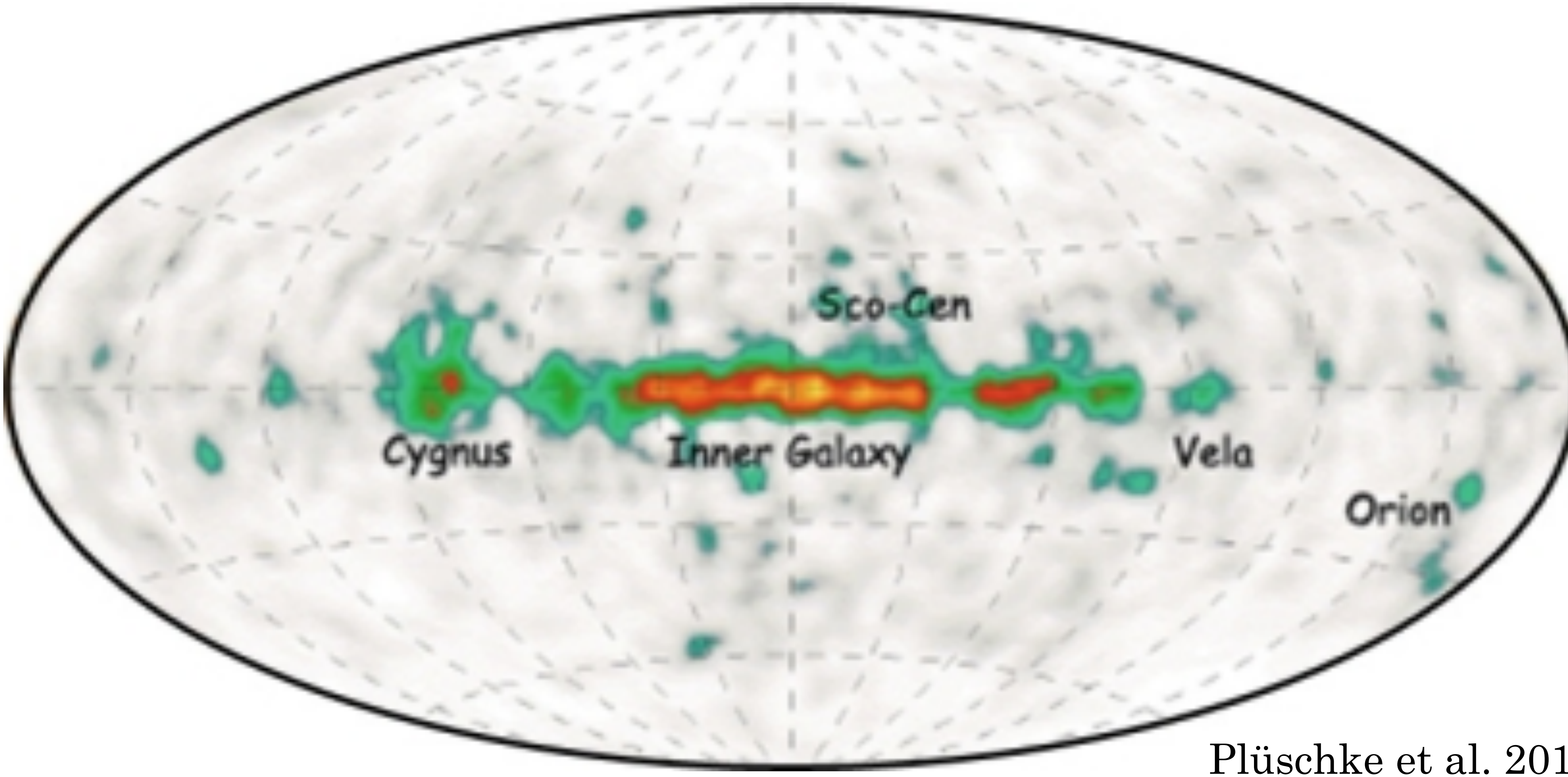
$$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe} + \mathrm{e}^+ \qquad \lambda = 80 \text{ d}$$

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

What else do we know?

- Positron injection energy constraint: perfectly consistent with e^+ from β^+ decay of radionuclides.
- Astrophysically-relevant radionuclides: **^{26}Al, ^{56}Ni, ^{44}Ti**
- **^{26}Al**: associated 1.8 MeV γ-ray line; line flux normalises ^{26}Al positrons to ~10% of MW positron luminosity; wrong morphology


Sco-Cen
Cygnus
Inner Galaxy
Vela
Orion



Plüschke et al. 2011

What else do we know?

- Positron injection energy constraint: perfectly consistent with e^+ from β^+ decay of radionuclides.
- Astrophysically-relevant radionuclides: **^{26}Al, ^{56}Ni, ^{44}Ti**
- **^{26}Al**: associated 1.8 MeV γ-ray line; line flux normalises ^{26}Al positrons to ~10% of MW positron luminosity; wrong morphology

Plüschke et al. 2011

What else do we know?

- Positron injection energy constraint: perfectly consistent with e^+ from β^+ decay of radionuclides.
- Astrophysically-relevant radionuclides: **^{26}Al, ^{56}Ni, ^{44}Ti**
- **^{26}Al**: associated 1.8 MeV γ-ray line; line flux normalises ^{26}Al positrons to ~10% of MW positron luminosity; wrong morphology

What else do we know?

- Positron injection energy constraint: perfectly consistent with e^+ from β^+ decay of radionuclides.

- Astrophysically-relevant radionuclides: **^{26}Al, ^{56}Ni, ^{44}Ti**

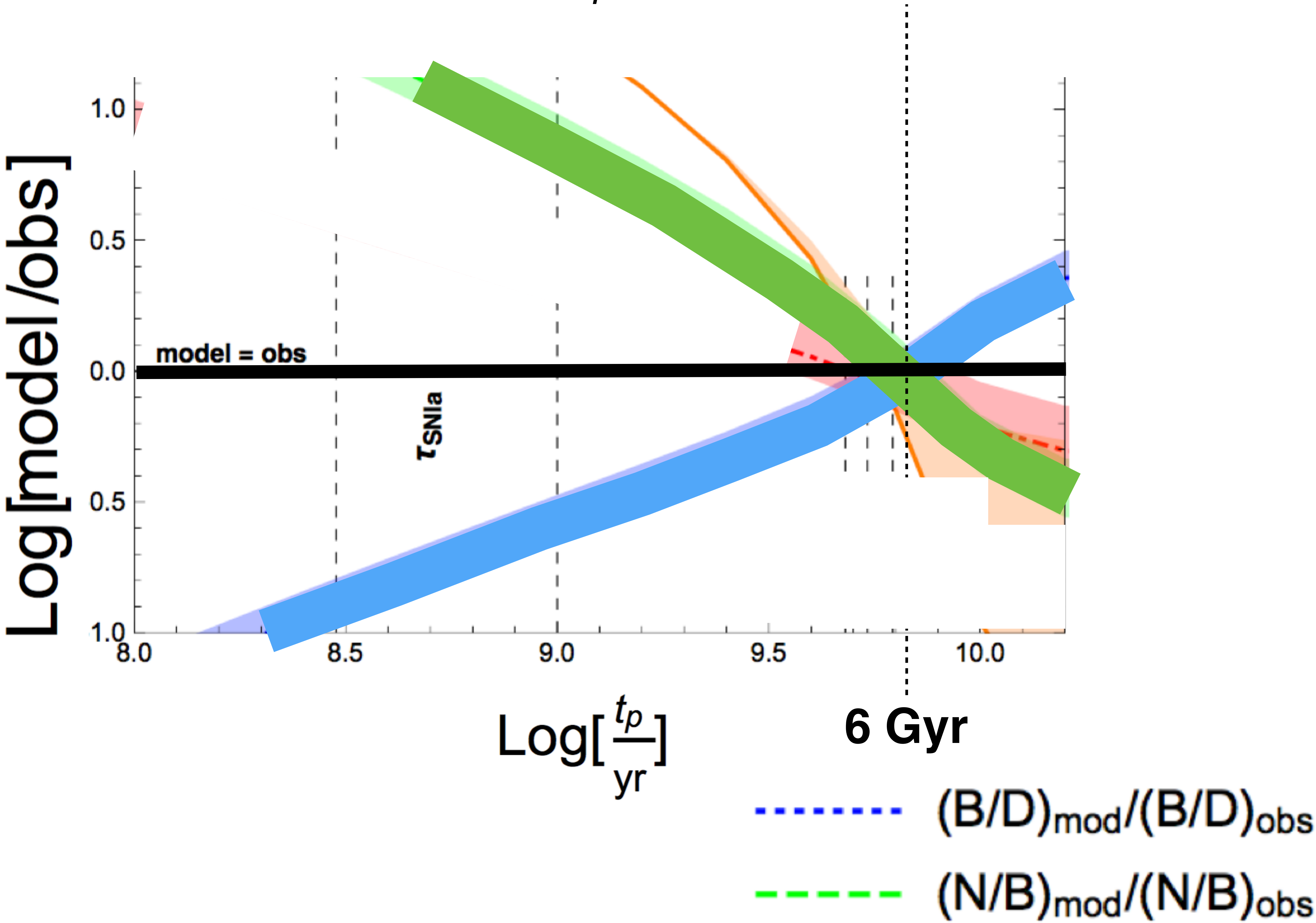
- **^{26}Al**: associated 1.8 MeV γ-ray line; line flux normalises ^{26}Al positrons to ~10% of MW positron luminosity; wrong morphology

- **^{56}Ni**: traditionally considered most favourable candidate as copiously produced in Type Ia supernovae BUT …

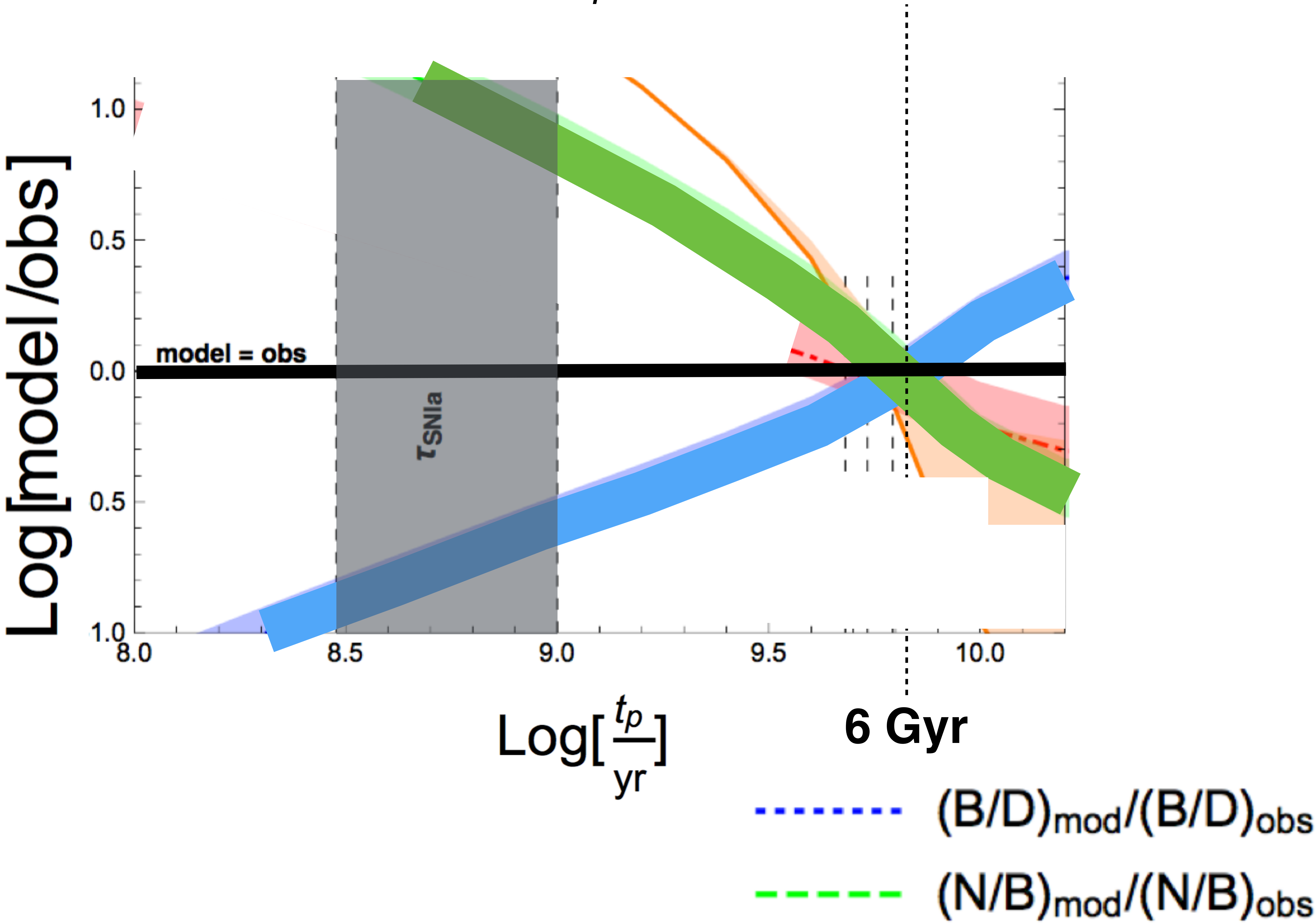
What else do we know?

- Positron injection energy constraint: perfectly consistent with e^+ from β^+ decay of radionuclides.
- Astrophysically-relevant radionuclides: **^{26}Al, ^{56}Ni, ^{44}Ti**
- **^{26}Al**: associated 1.8 MeV γ-ray line; line flux normalises ^{26}Al positrons to ~10% of MW positron luminosity; wrong morphology
- **^{56}Ni**: traditionally considered most favourable candidate as copiously produced in Type Ia supernovae BUT …
- SNIa happen at too short a delay time to explain morphology

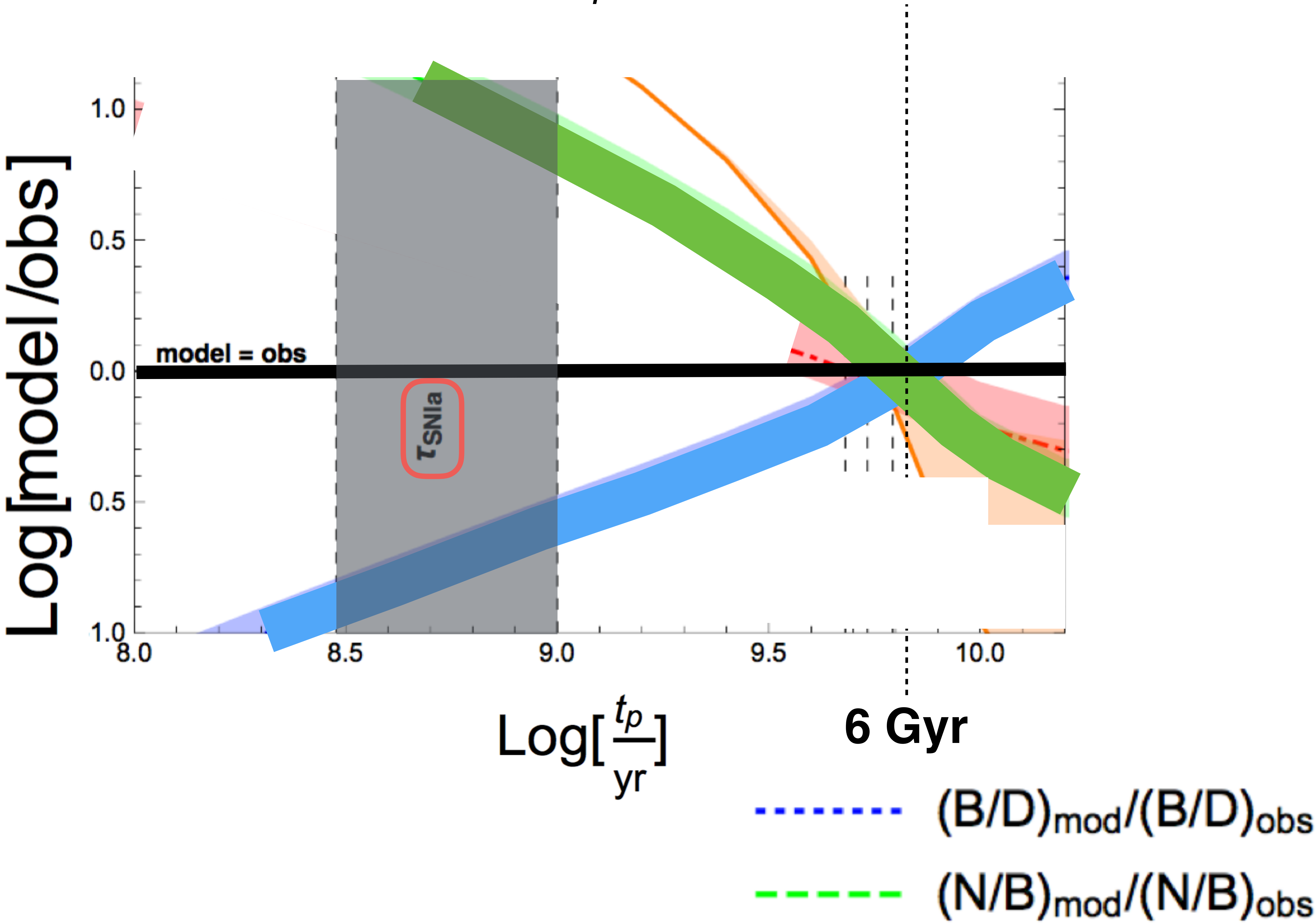
How old does a stellar positron source need to be?



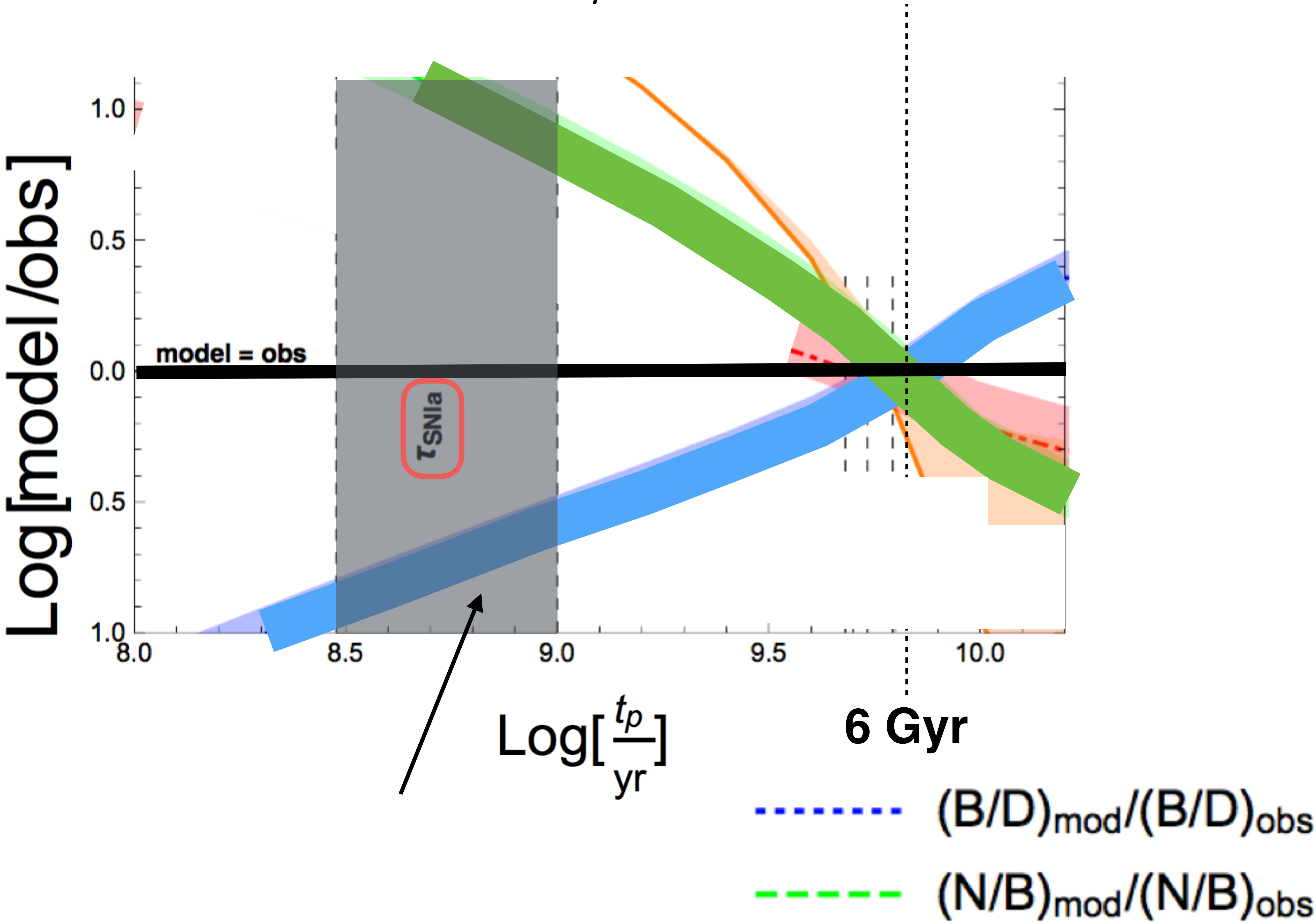
How old does a stellar positron source need to be?



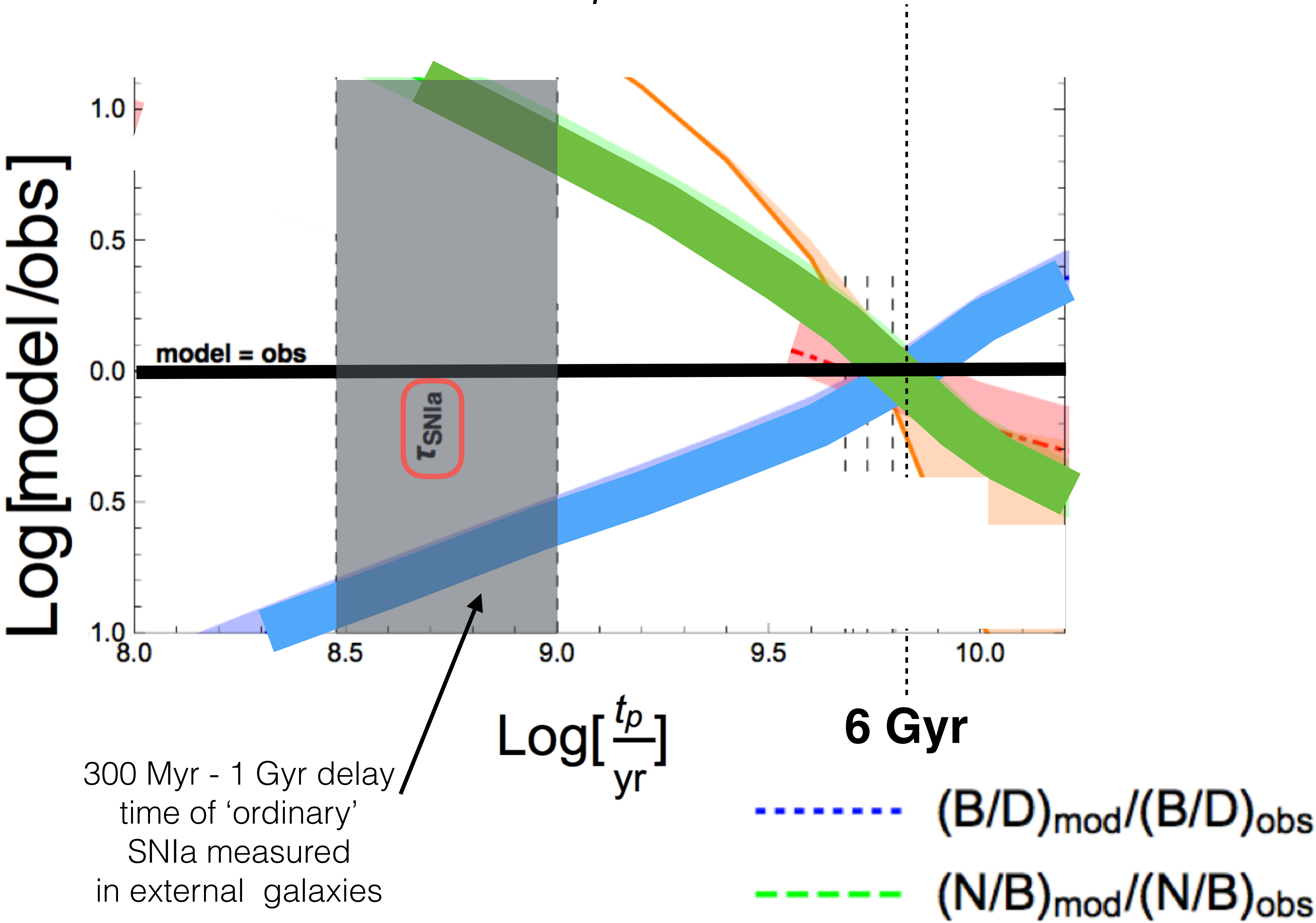
How old does a stellar positron source need to be?



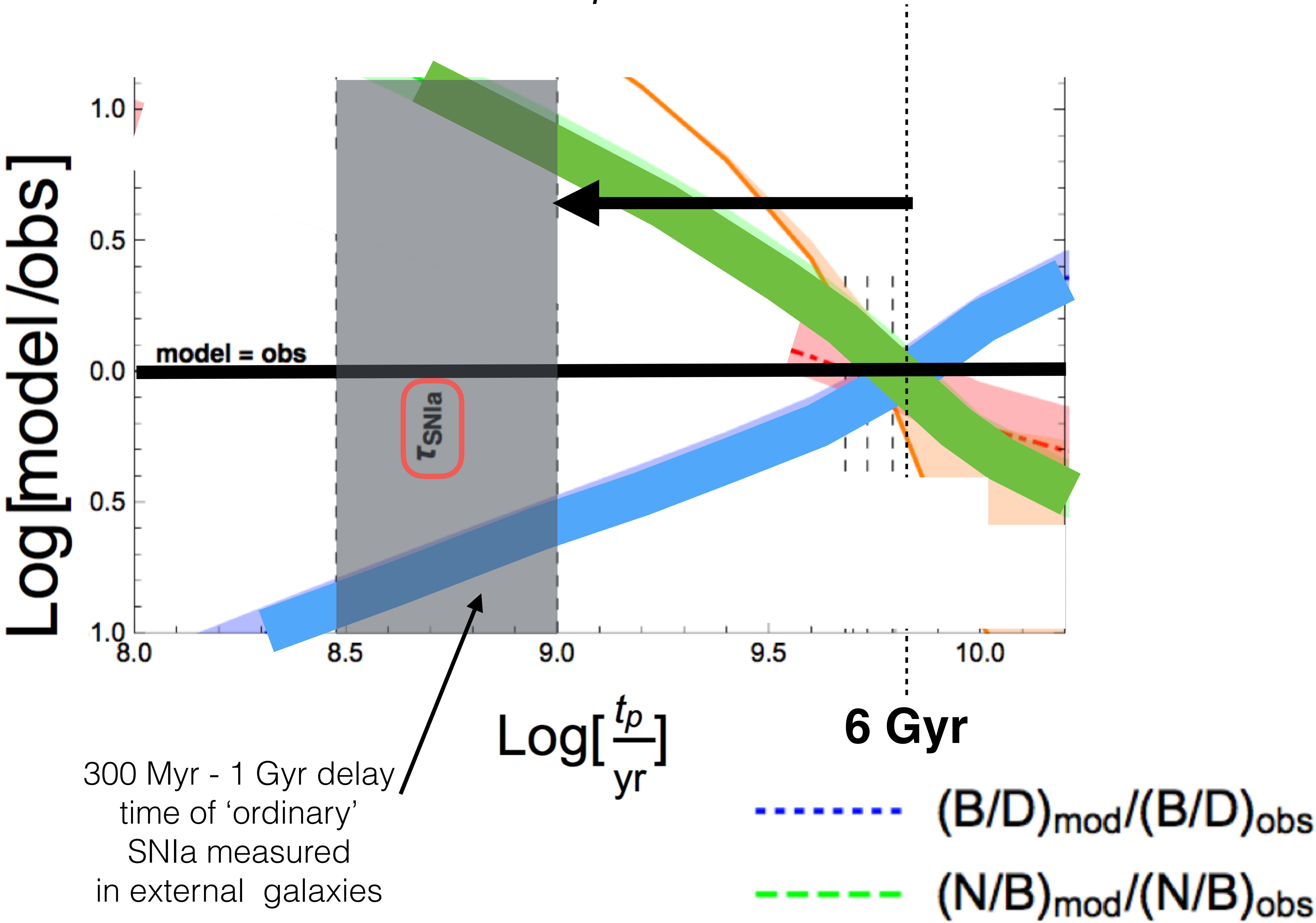
How old does a stellar positron source need to be?



How old does a stellar positron source need to be?



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:

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

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
  - the events are rare, separated by a typical

    t_{wait} > few x t_{decay} ~ 300 year

    (so we do not expect to see strong 44Ti lines in sky)

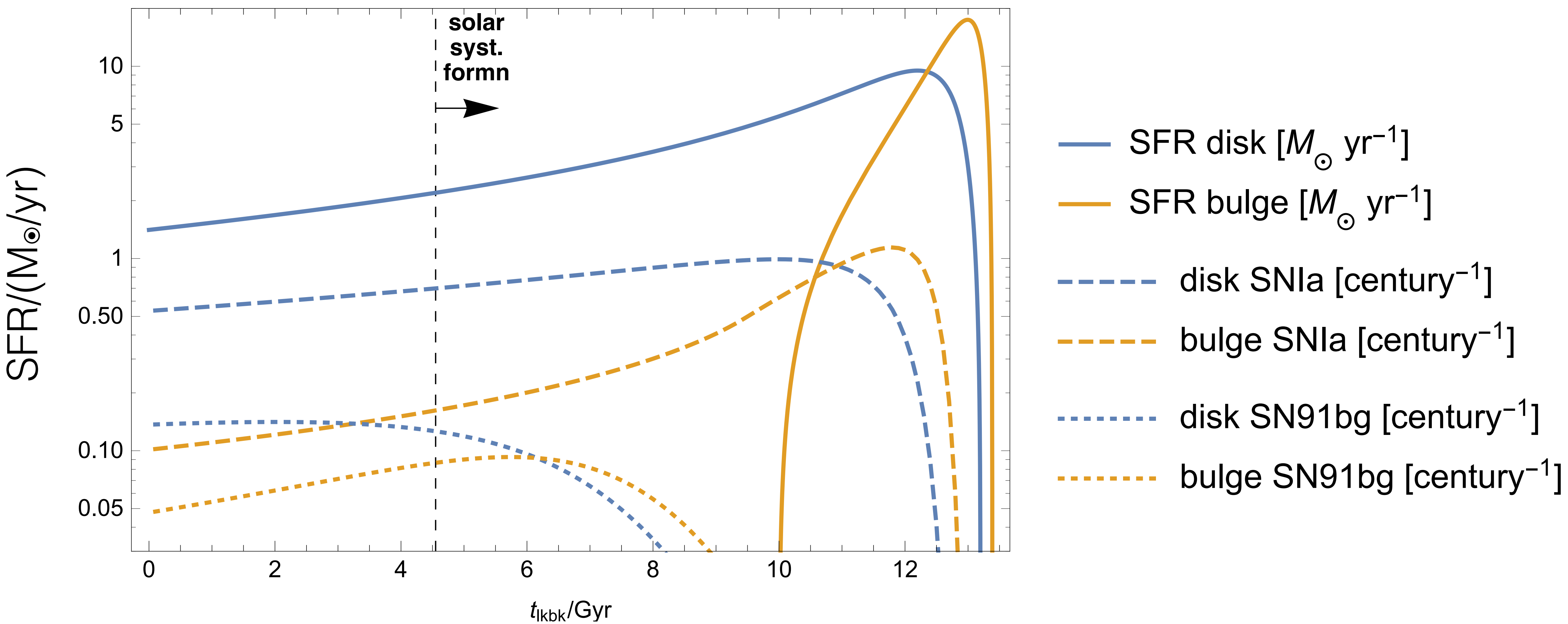
Is ^{44}Ti ruled out?

- 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
  - the events are rare, separated by a typical

    t_{wait} > few x t_{decay} ~ 300 year

    (so we do not expect to see strong 44Ti lines in sky)
- …but must produce large mass of ^{44}Ti, ~0.03 $M_\odot$

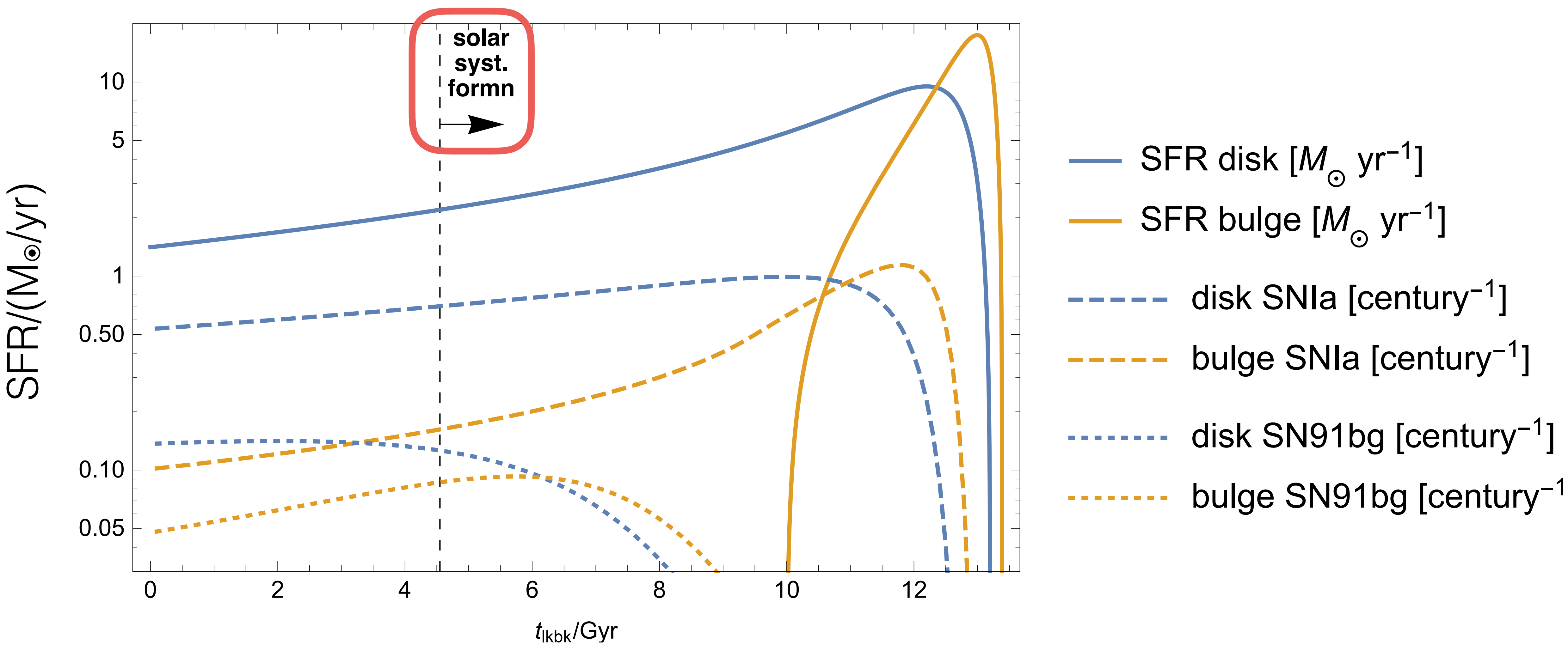
Galactic Star Formation History



today

Big Bang

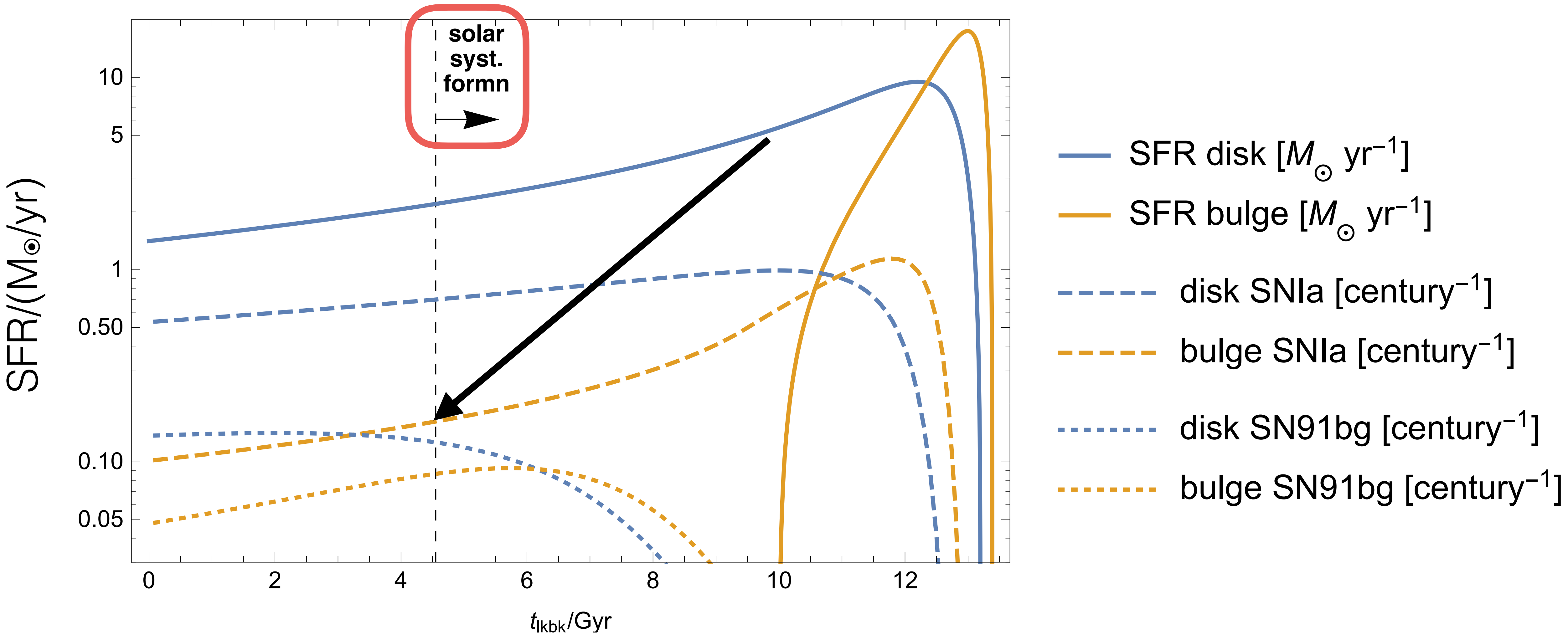
Galactic Star Formation History



today

Big Bang

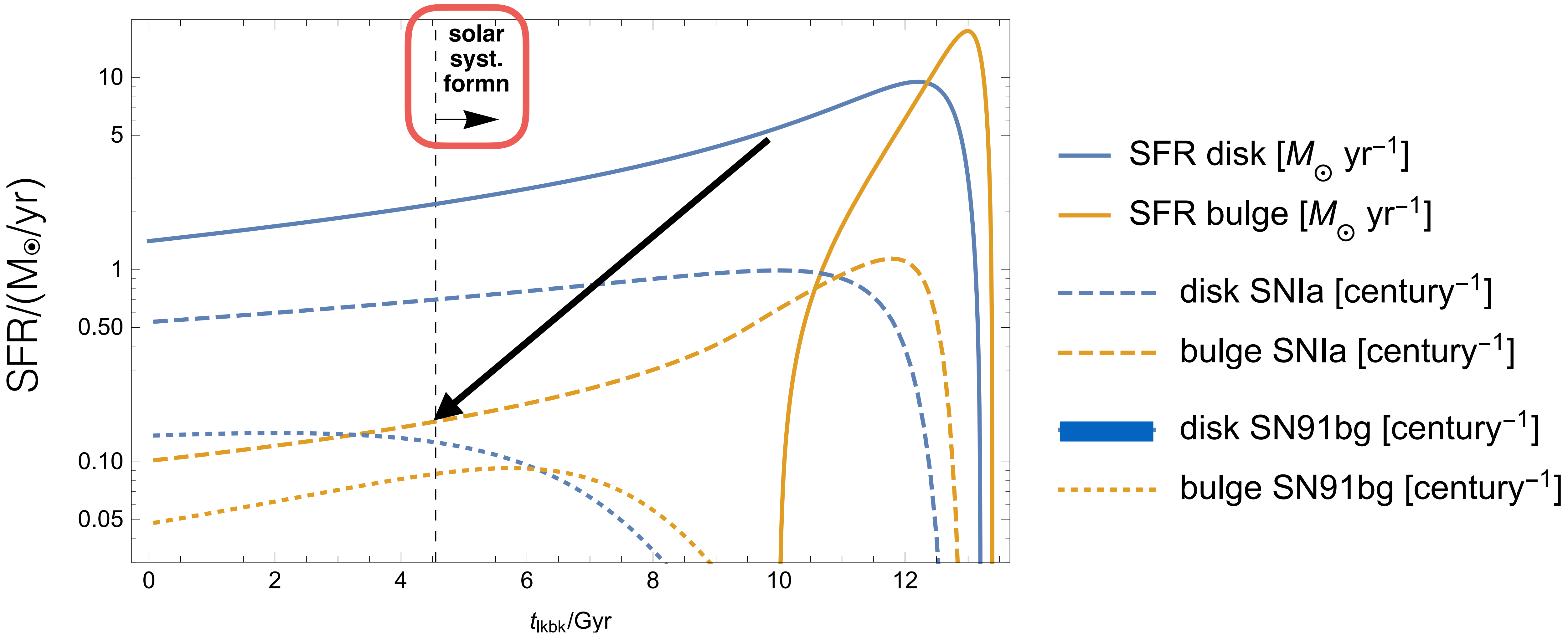
Galactic Star Formation History



today

Big Bang

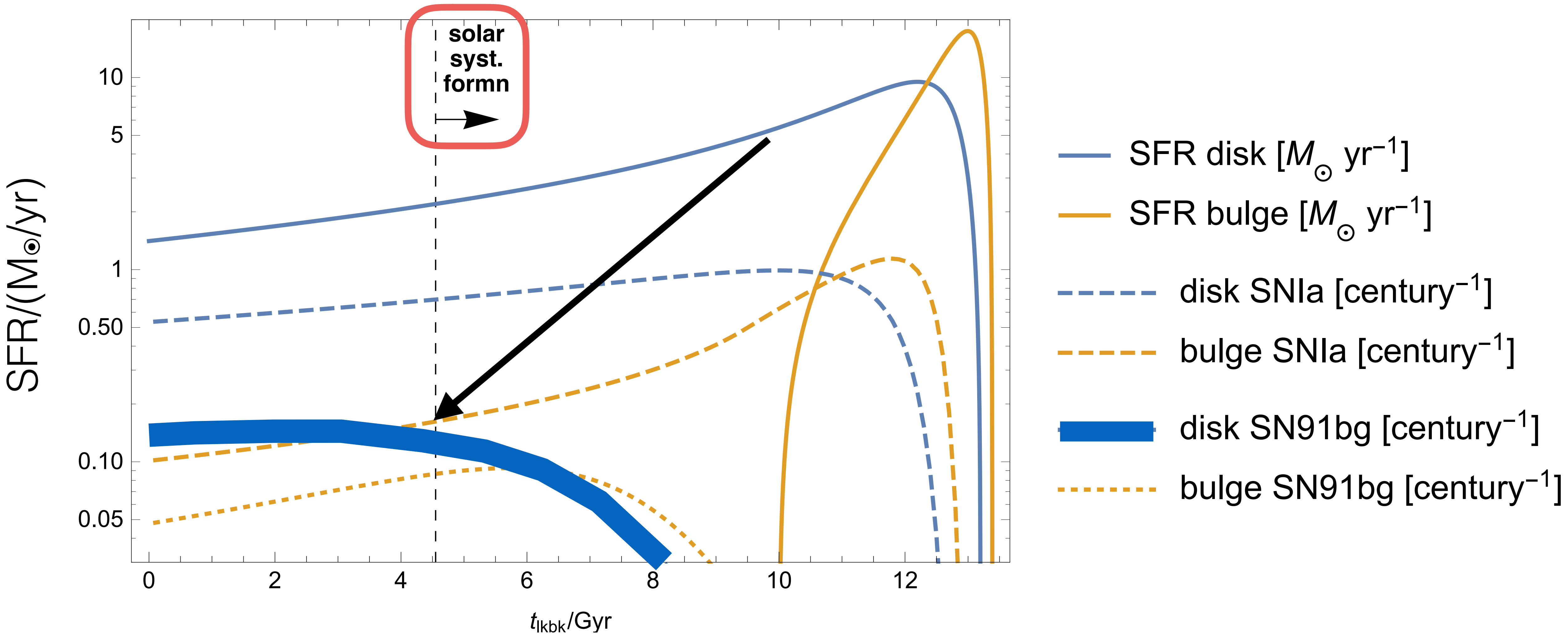
Galactic Star Formation History



today

Big Bang

Galactic Star Formation History



today

Big Bang

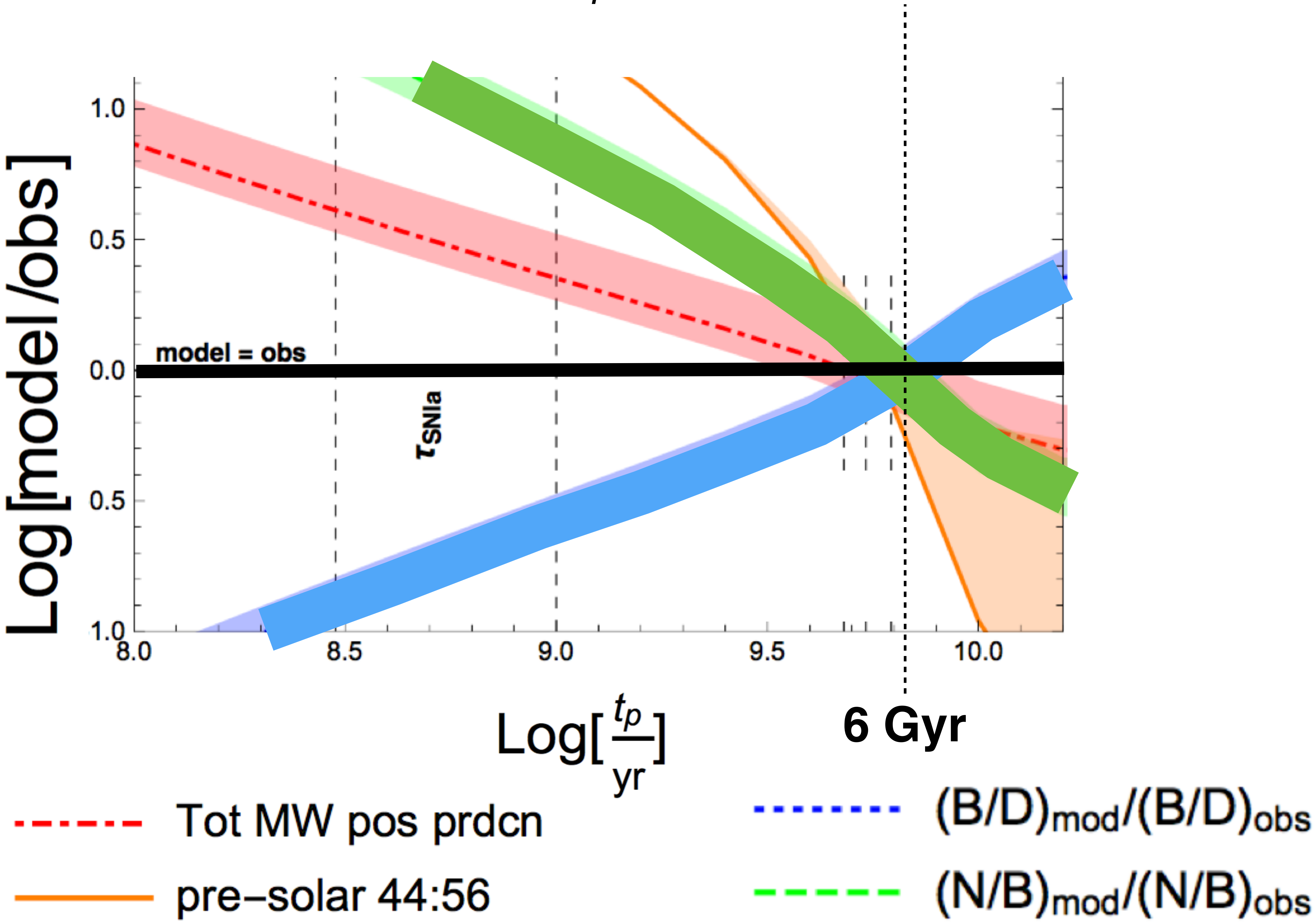
A Galactic ^{44}Ti source that…

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

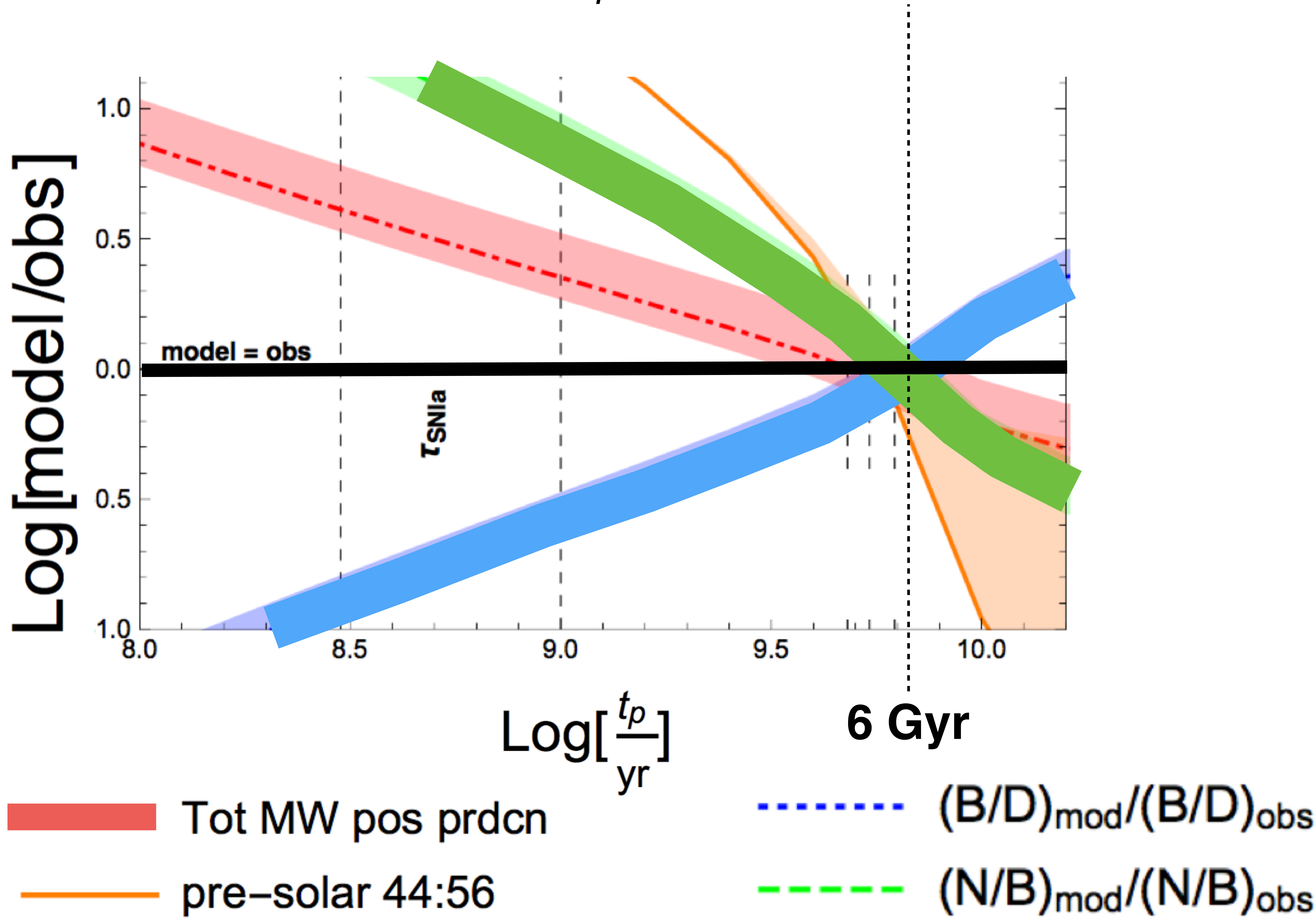
would

- 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

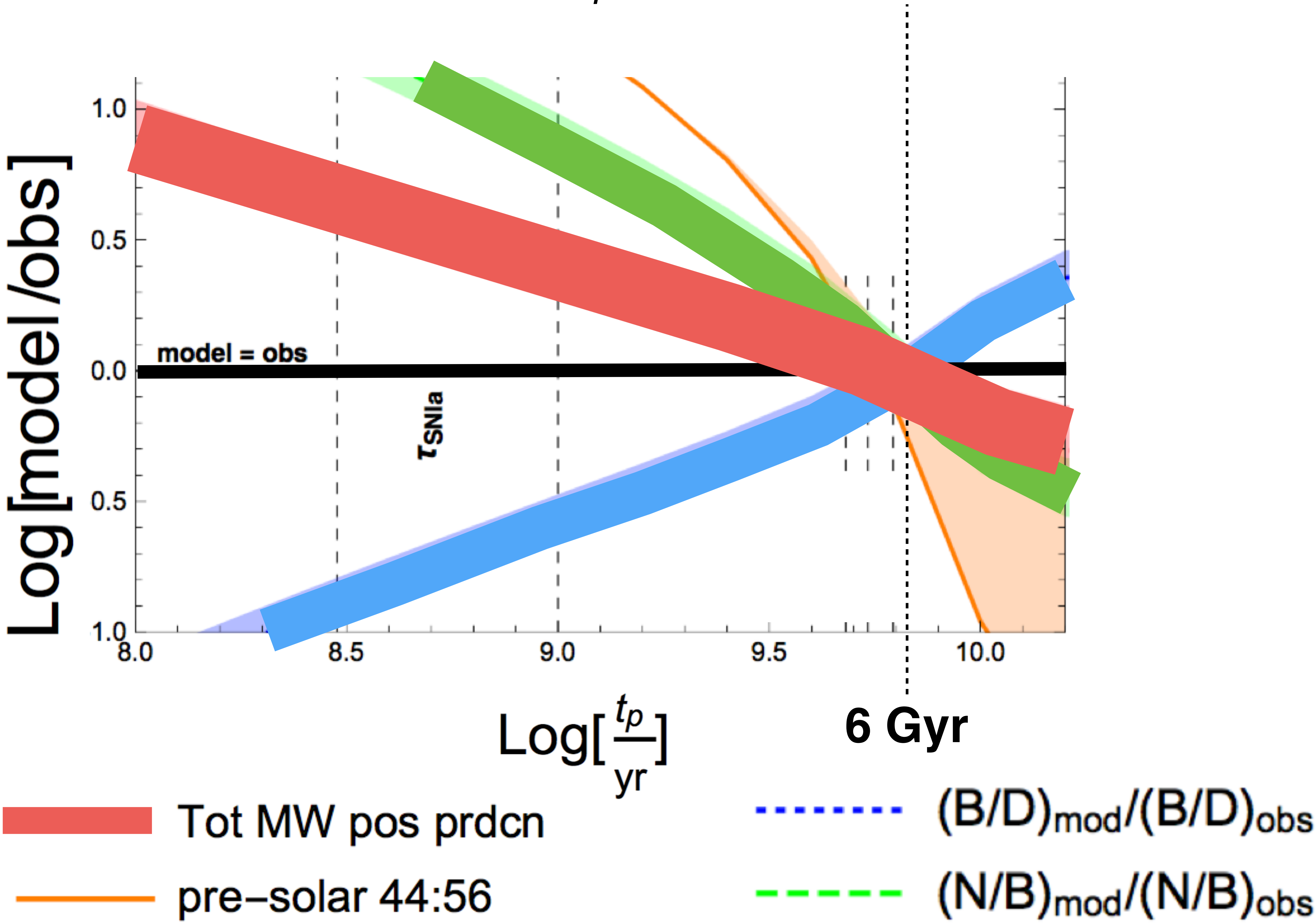
How old does a stellar positron source need to be?



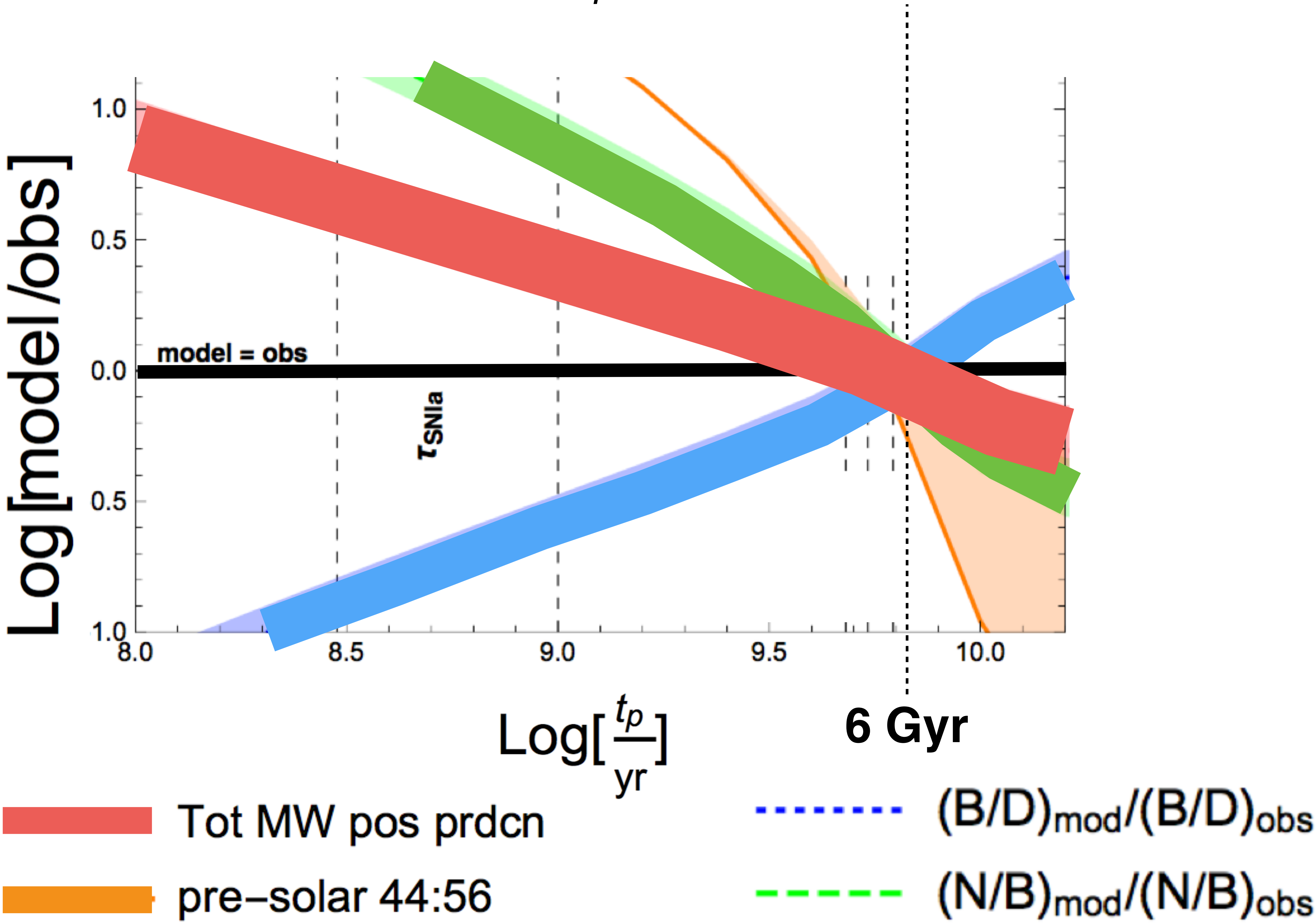
How old does a stellar positron source need to be?



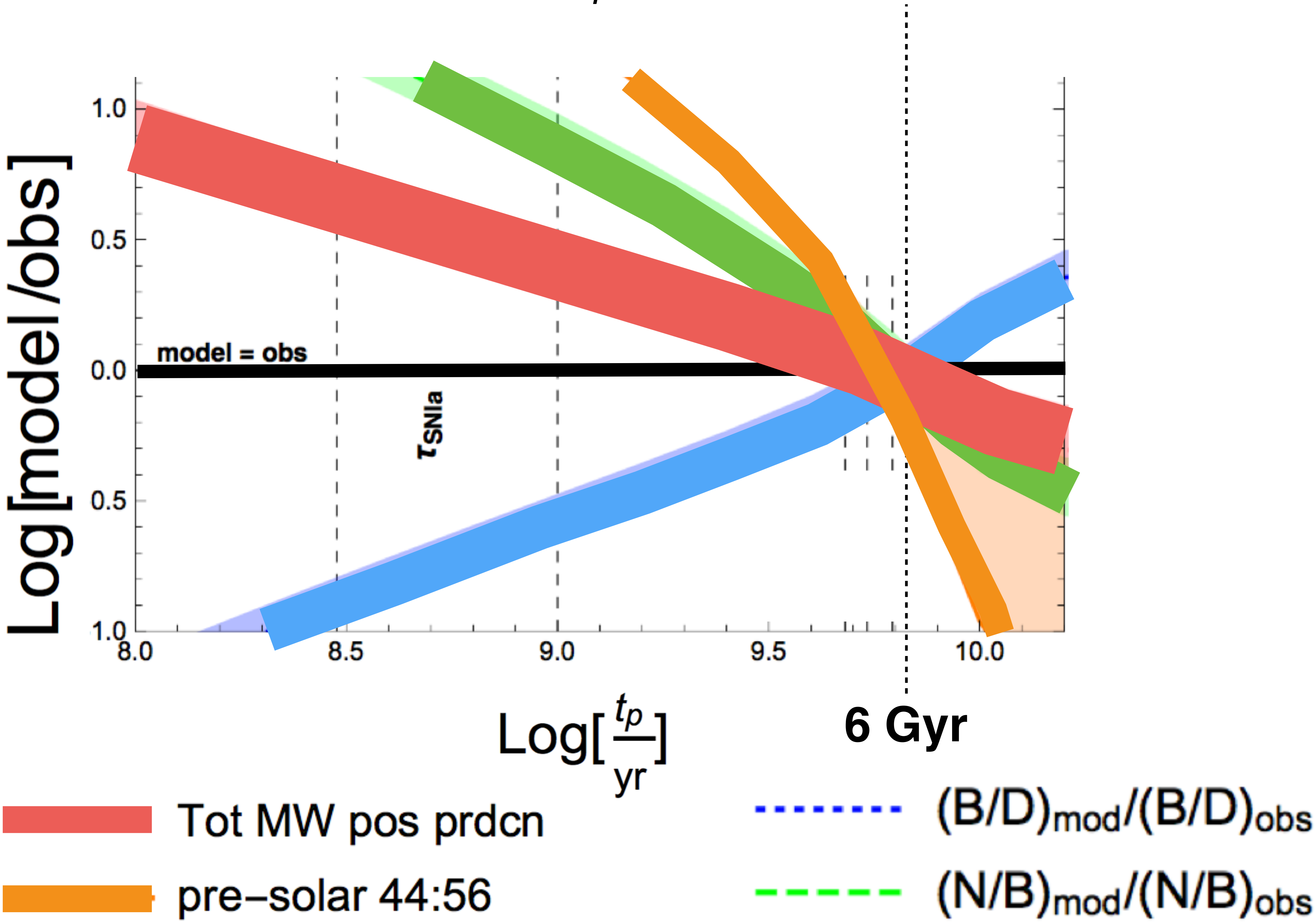
How old does a stellar positron source need to be?



How old does a stellar positron source need to be?



How old does a stellar positron source need to be?



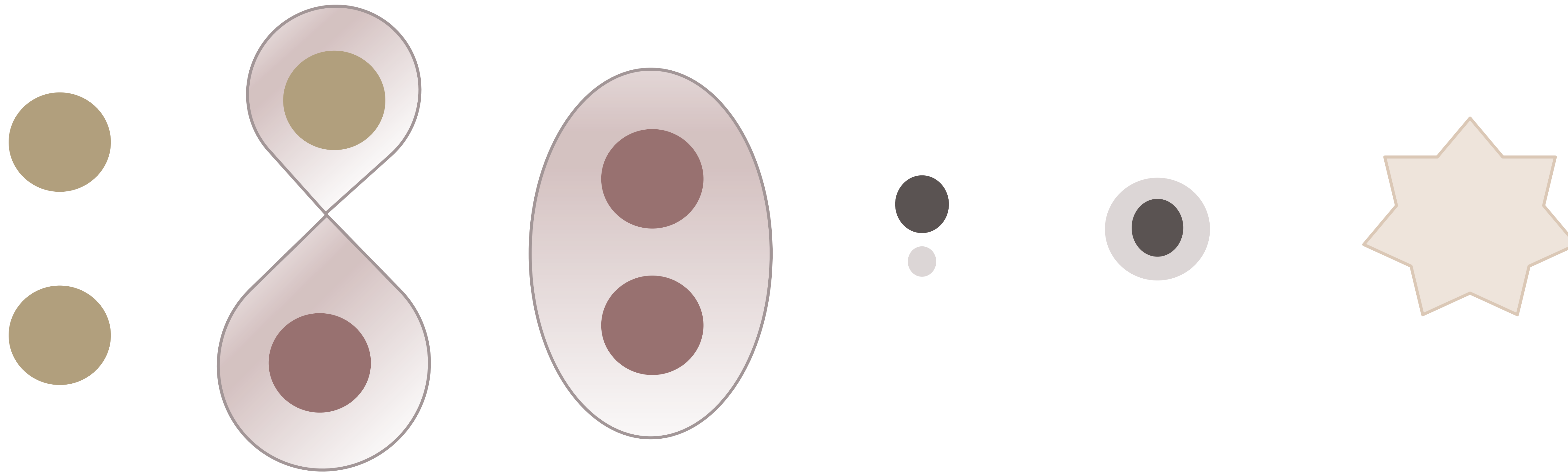
What could such a source be?

- Relatively large ^{44}Ti mass requires a HELIUM DETONATION; requires assembly large He mass at correct density (~10^6-10^7 g/cm^3)

- Mergers of low mass white dwarf binaries can achieve this

- Specifically: 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*

COWD-HeWD merger leading to He detonation



1.4 – 2 solar mass interacting binary system

1 mass transfer event

1 common envelope interaction

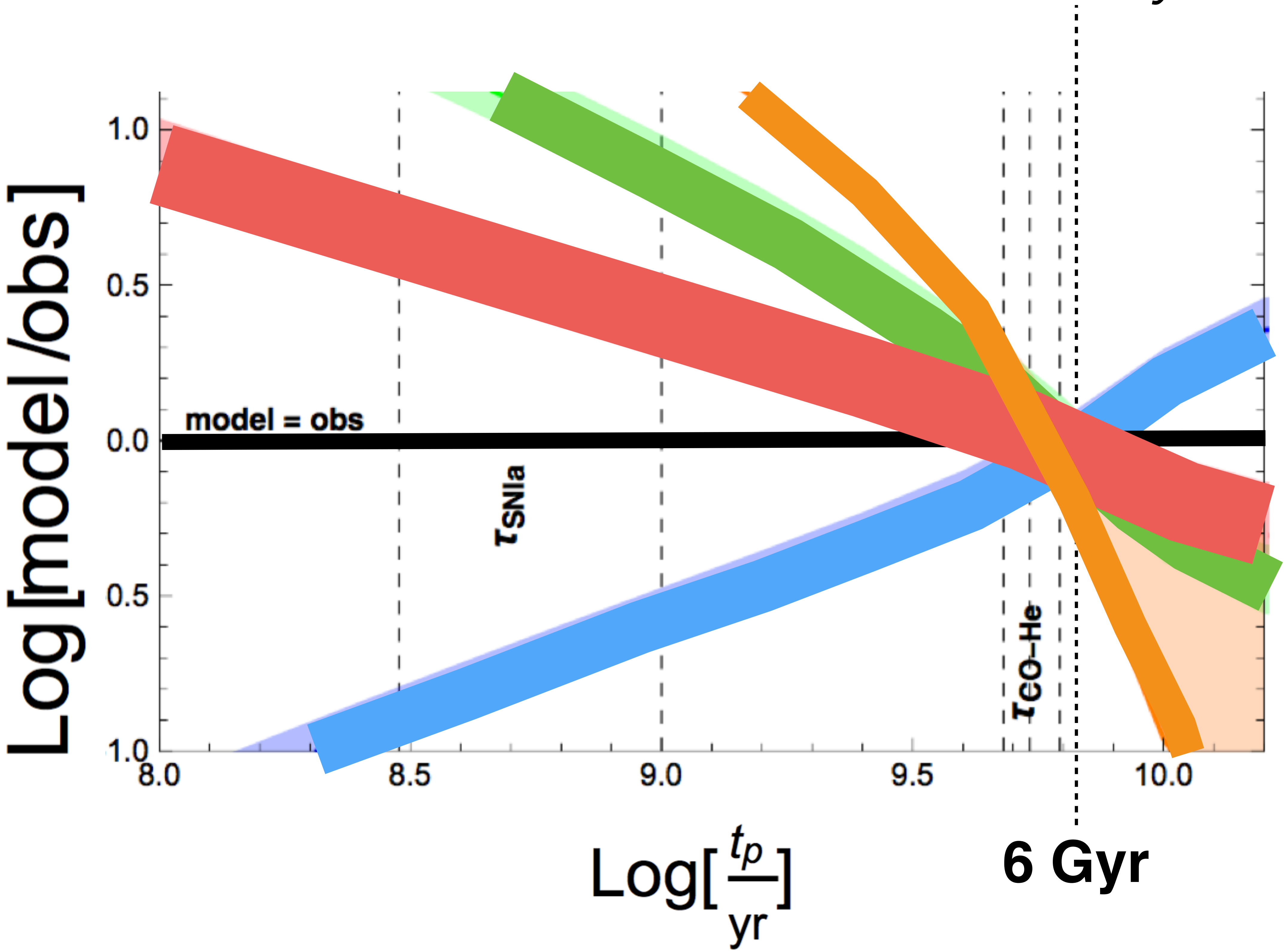
COWD + pure 0.31-0.37 solar mass HeWD

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

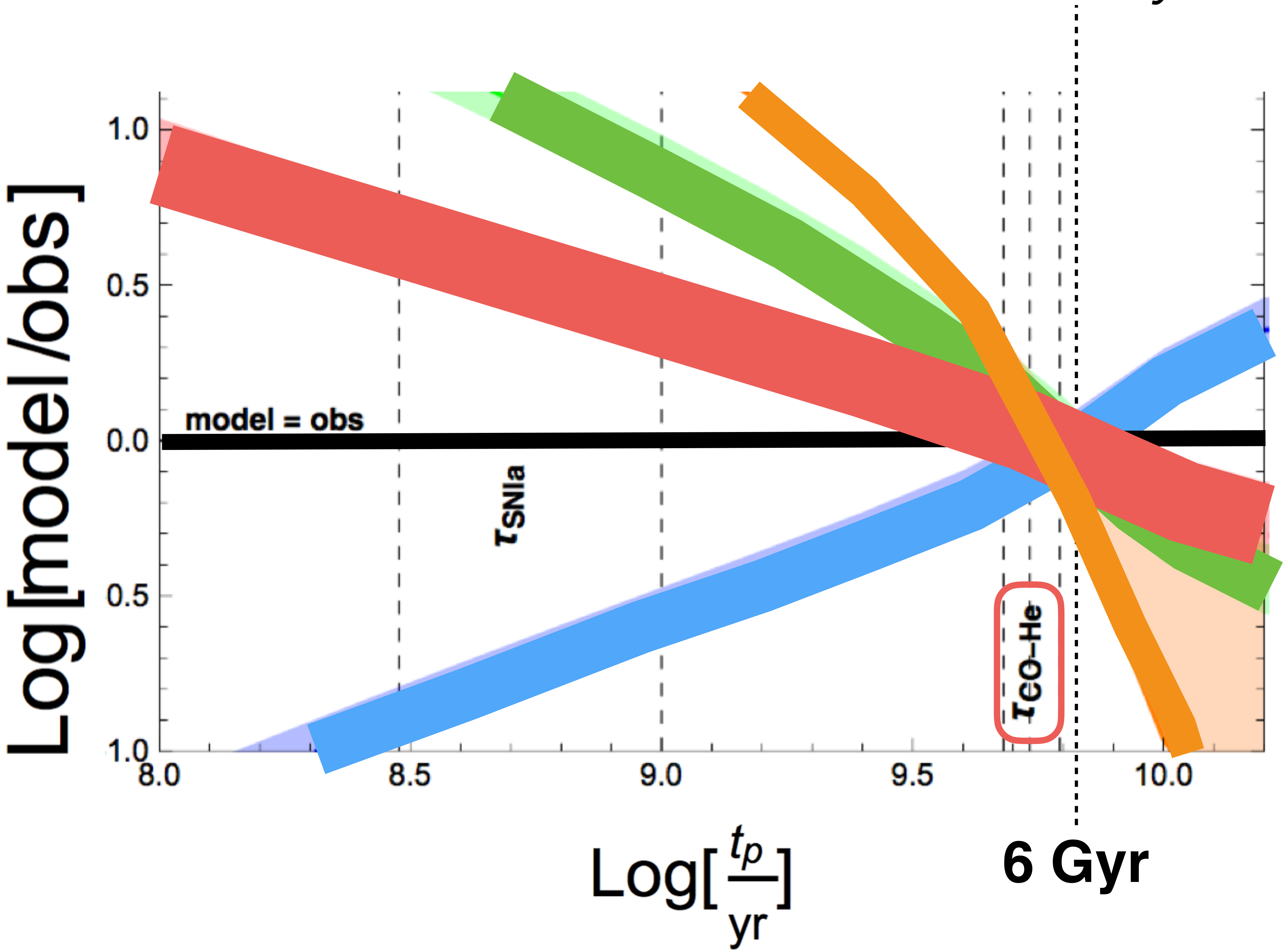
Helium detonates, triggering carbon ignition

slide credit: Fiona Panther

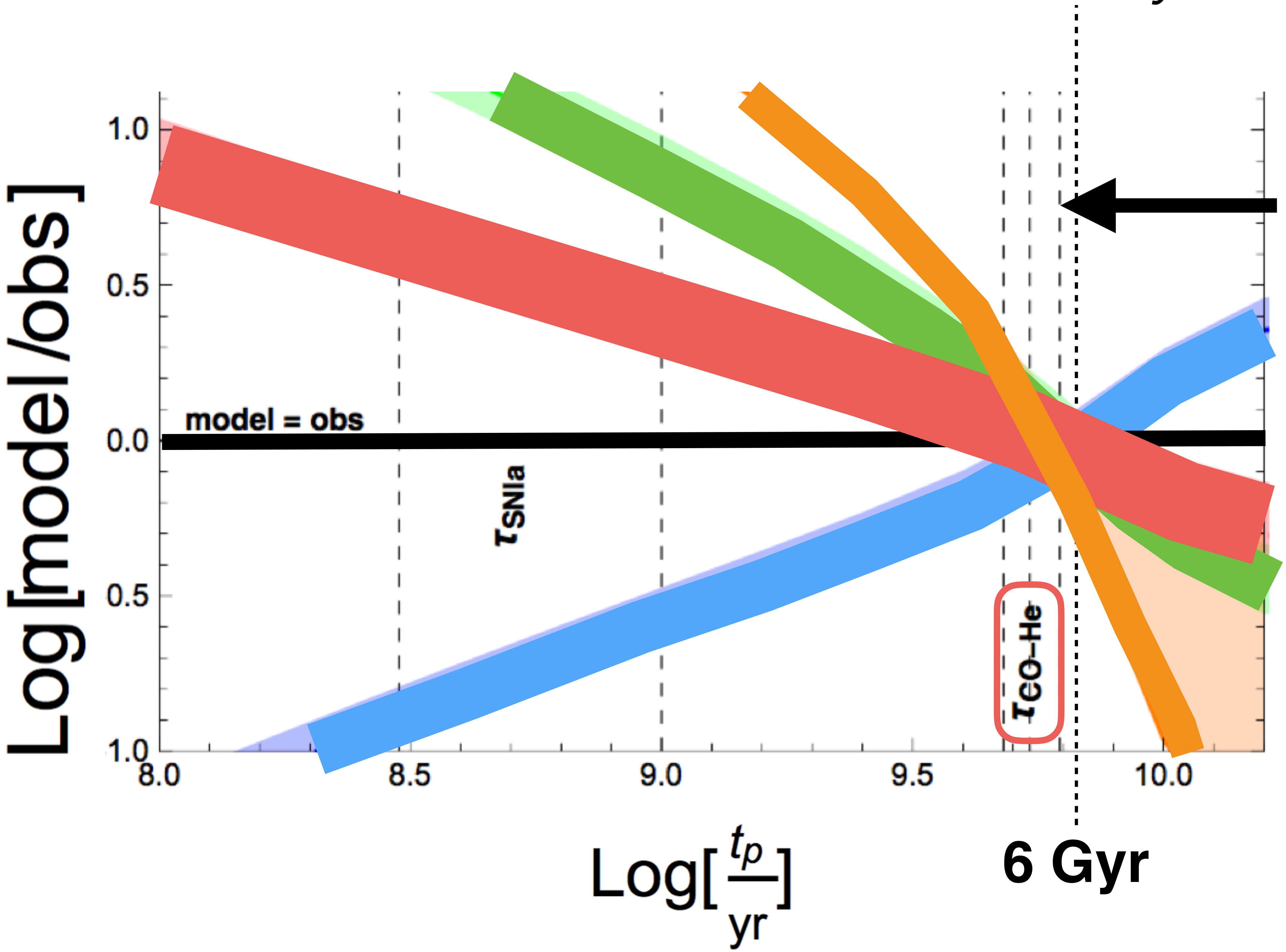
COWD-HeWD occur at 3-6 Gyr



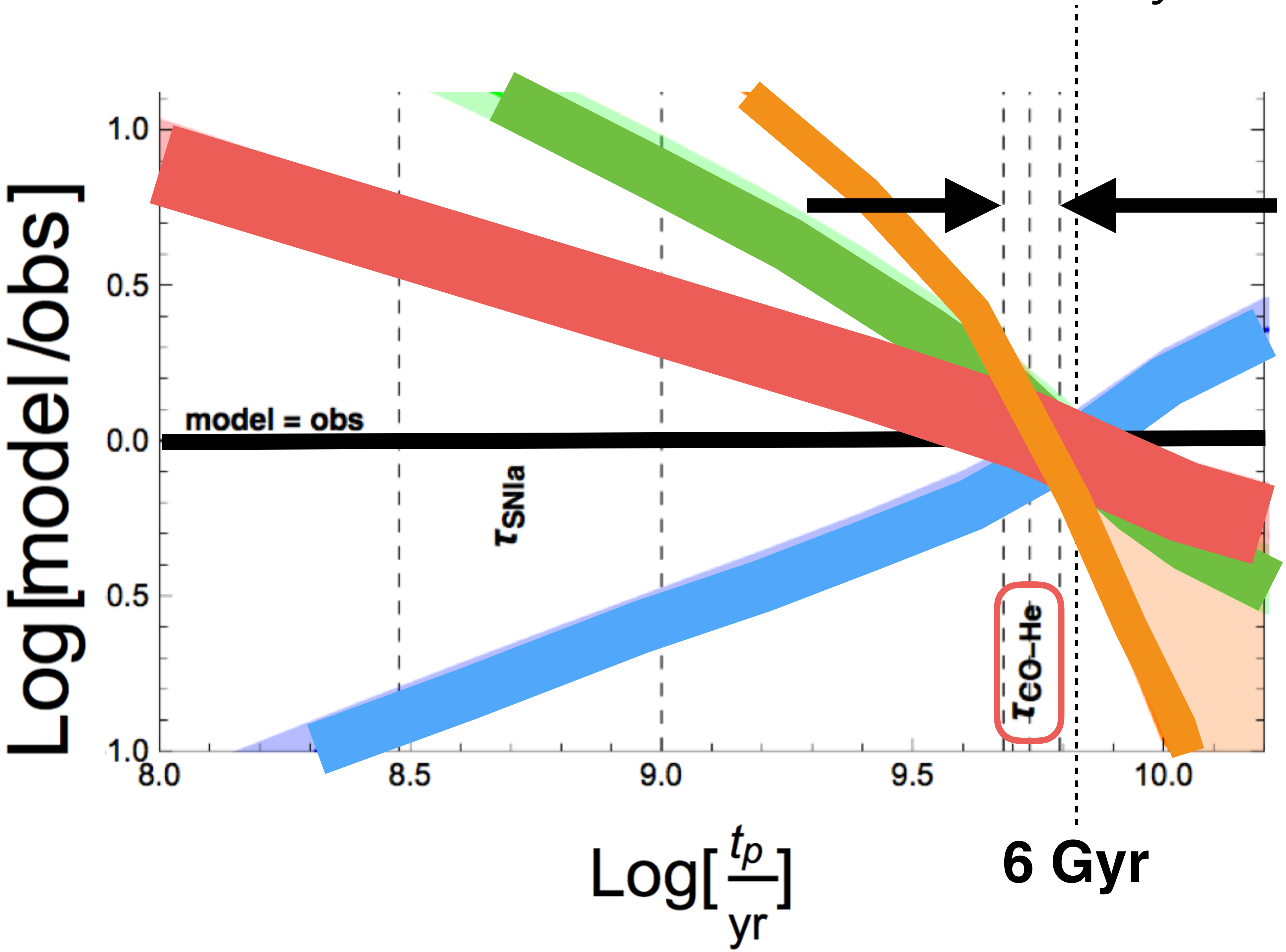
COWD-HeWD occur at 3-6 Gyr



COWD-HeWD occur at 3-6 Gyr



COWD-HeWD occur 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

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

Speculation: Connection to 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 its companion

Summary

- The Galactic disk is a brighter positron source than previously reckoned; B/D positron luminosity ~ B/D stellar mass
- 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
- Our claim: 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

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

- (Quasi) point-like GeV and TeV γ-ray source coincident with Sgr A* (= radio source coincident with SMBH)
- Extended (few degrees) GeV & TeV emission
- Non-Thermal Radio (and X-ray) Filaments
- 130 GeV ‘line’
- ~GeV γ-ray spectral bump ‘GC Excess’
- 511 keV positron annihilation line
- Non-thermal microwave ‘haze’
- Fermi Bubbles

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

- (Quasi) point-like GeV and TeV γ-ray source coincident Sgr A* (= radio source coincident with SMBH)
- Extended (few degrees) GeV & TeV em
- Non-Thermal Radio (and X-ra
- 130 GeV 'line'
- ~GeV γ-ra ... Excess'
- ... nihilation line
- ... nal microwave 'haze'
- Fermi Bubbles

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

General Point

While the GC is a logical place to look for signs of dark matter, astrophysical uncertainties attached to it are large *… it is a very different environment to the local disk*