HUNTING DOWN THE SOURCE OF GALACTIC ANTIMATTER

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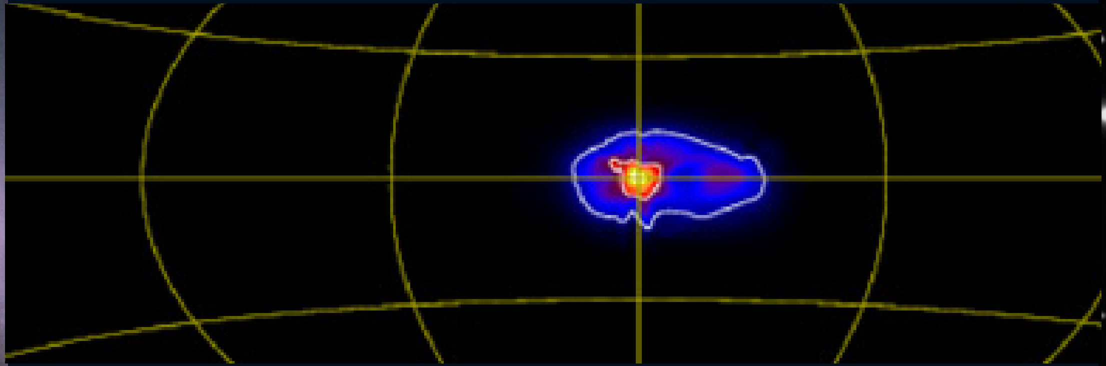

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IAUS322: Multi-messenger Astrophysics of the Galactic Center

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Australian National University

OzDES

An almost half-century old mystery…

- Stringent constraints on injection energy (Aharonian 1981, Beacom+2007) disfavor compact object sources (pulsars and MSPs) and Dark Matter

- The morphology of the annihilation radiation closely matches the distribution of positron sources in the Galaxy (Siegert+2015). **Can we use the SFH of the Milky Way to constrain a stellar source?**

- β^+ decay of radionuclides satisfies the injection energy constraint (Prantzos+2011), but **is there a source of radioactive nuclei that matches the morphology of the positron annihilation signal and the injection rate?**

Delay time distributions and source morphology

- Delay time: time between star formation and transient event (e.g. supernova explosion)

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

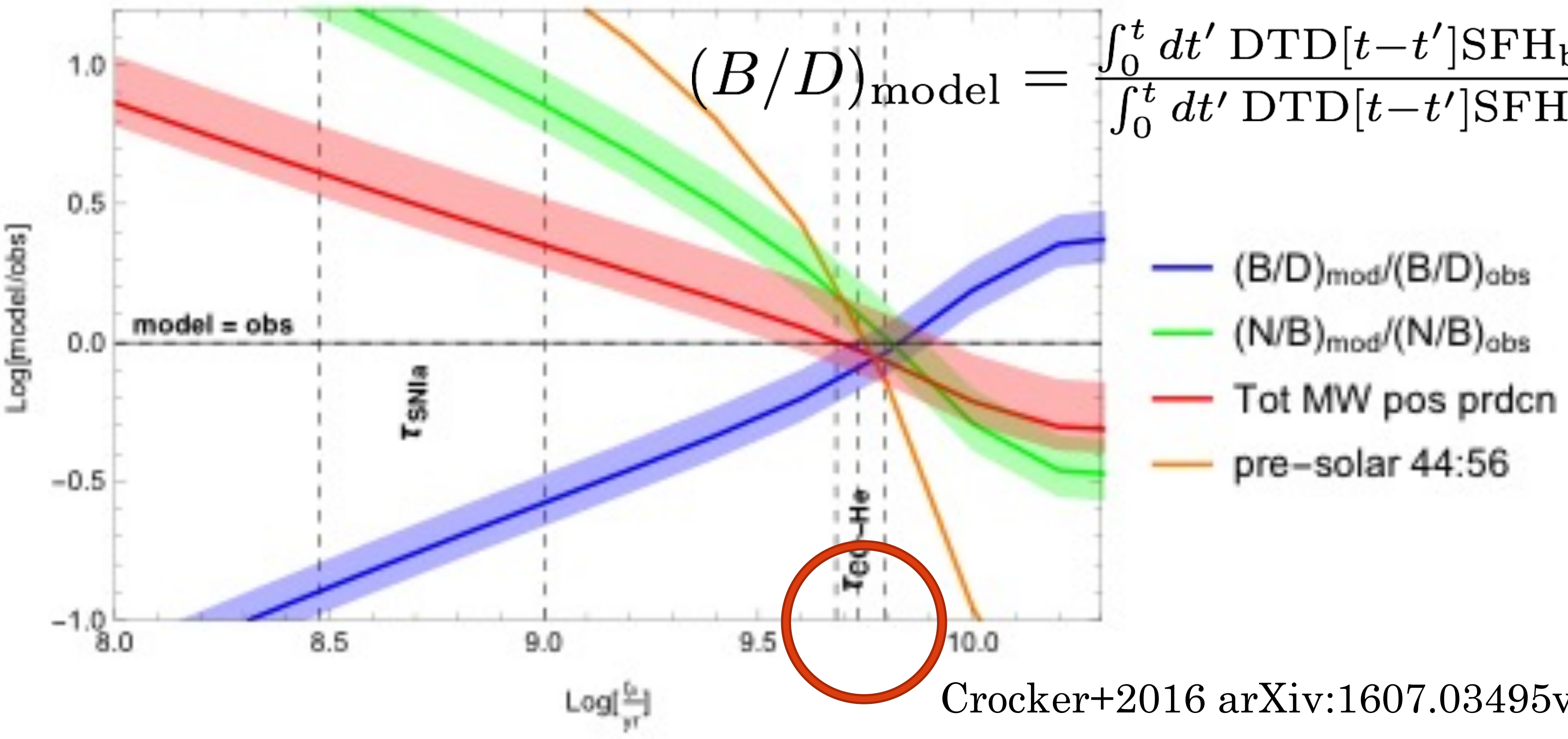
$$DTD[t] \propto \frac{(t/t_p)^{\alpha}}{(t/t_p)^{\alpha - s} + 1}$$

Behroozi+2013

- Want to know: **what is the characteristic delay time of events that explains the current B/D and N/B positron luminosities?**

Delay time distributions and source morphology

$$(B/D)_{\mathrm{model}} = \frac{\int_0^t dt'\,\mathrm{DTD}[t-t']\mathrm{SFH}_{\mathrm{bulge}}[t']}{\int_0^t dt'\,\mathrm{DTD}[t-t']\mathrm{SFH}_{\mathrm{disk}}[t']}$$



Crocker+2016 arXiv:1607.03495v1

- Assuming that each transient event yields the same number of positrons, and the positron yield is identical for bulge and disk events, find a characteristic delay-time between 3-6 Gyr

Understanding a 40 year old mystery

- Stringent constraints on injection energy (Aharonian 1981, Beacom+2007) disfavor compact object sources (pulsars and MSPs) and Dark Matter

- The morphology of the annihilation radiation closely matches the distribution of positron sources in the Galaxy (Siegert+2015). **Can we use the SFH of the Milky way to constrain a stellar source?**

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Positrons from nucleosynthesis

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

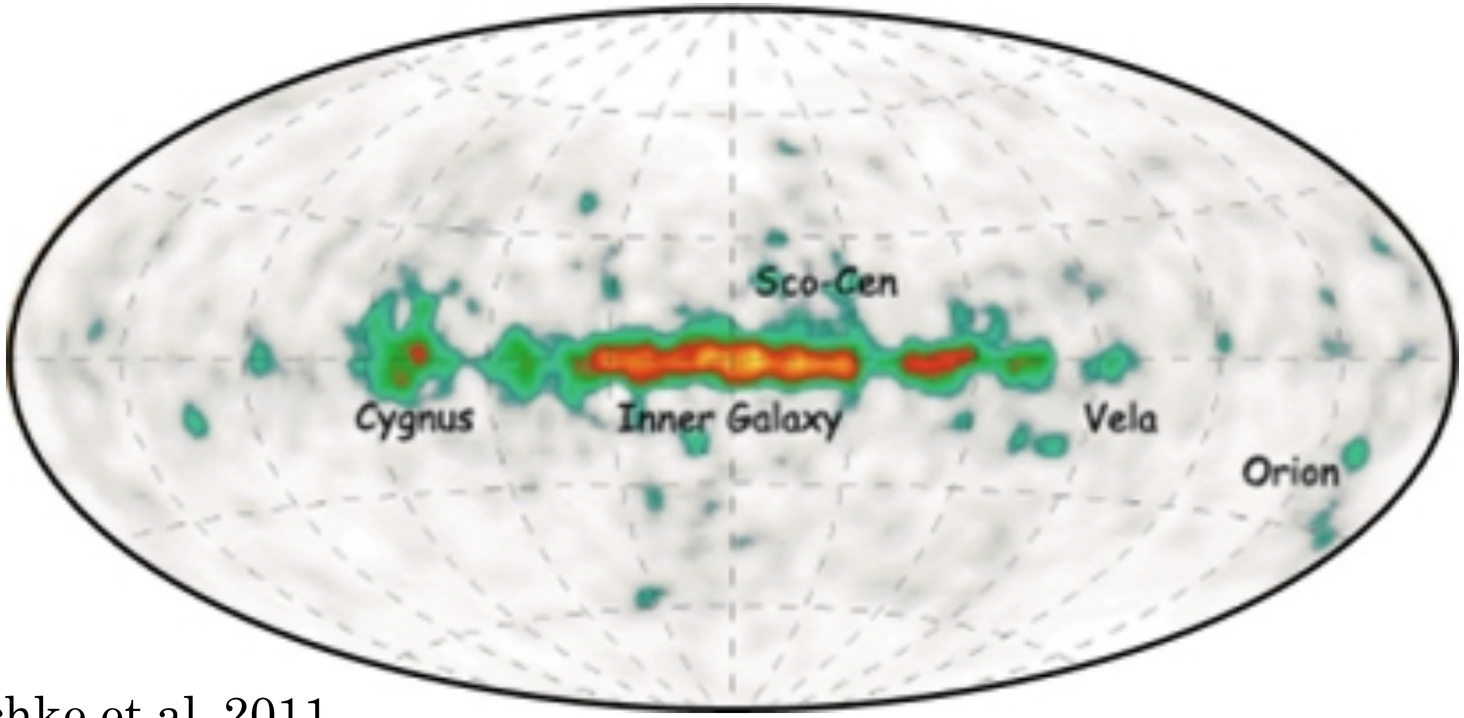
$$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe} + \mathrm{e}^{+}$$ λ = 80 d

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

Positrons from nucleosynthesis

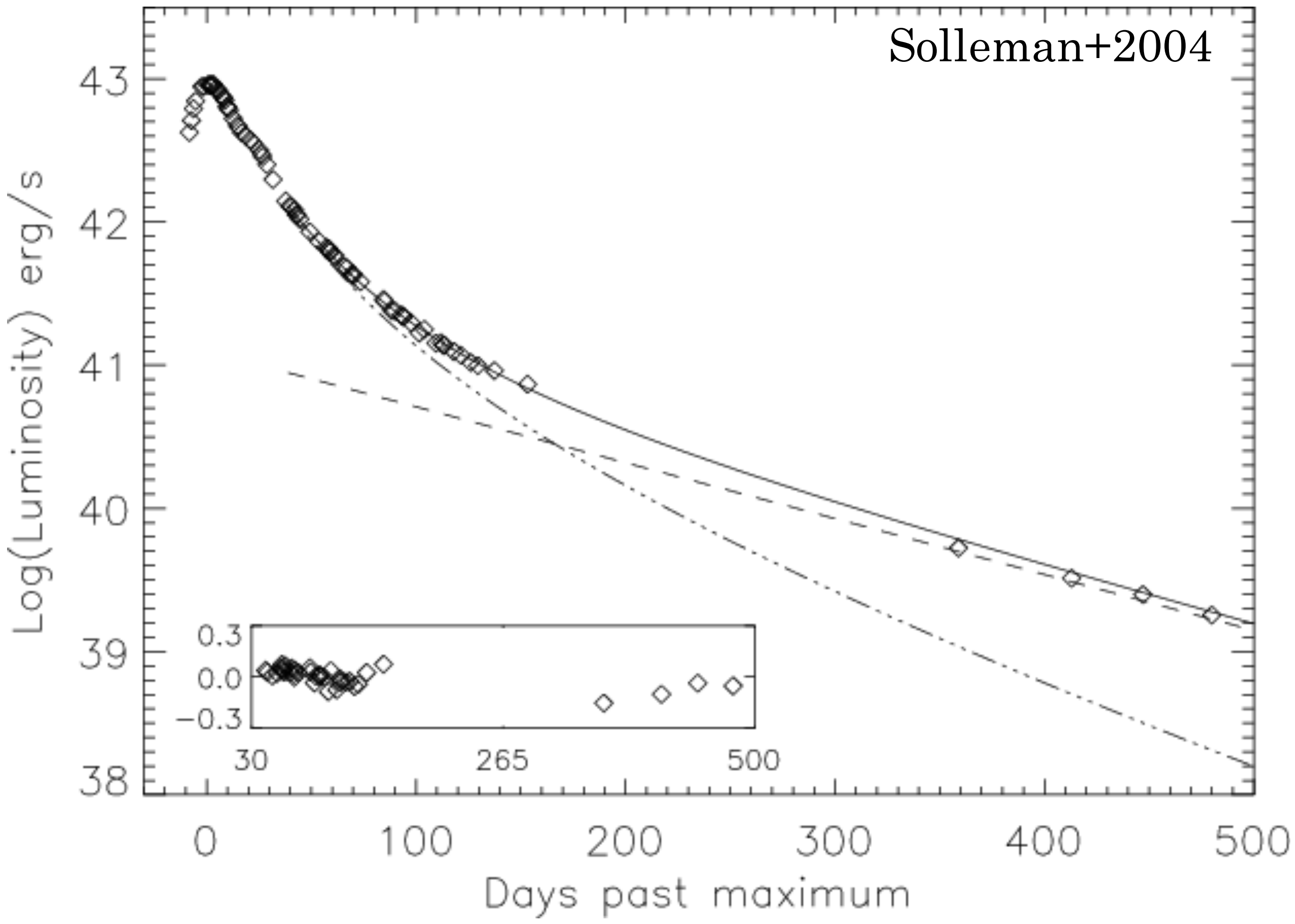
- ^{26}Al positron production can be traced using the 1.8 MeV line

- 1.8 MeV line flux normalizes e^+ production to 10% of the total galactic value (Siegert+2015)



Plüschke et al. 2011

Positrons from nucleosynthesis



- Light curves show that all positrons are trapped until very late times (>900 days) (Kerzendorf+2014)

- It is **implausible that *normal* SNe Ia supply Galactic positrons:**
  - Delay time (~1 Gyr) cannot reproduce morphology
  - Cannot supply the right number of positrons

Positrons from nucleosynthesis

- Neither ^{26}Al or ^{56}Ni are viable positron sources
- We know CCSNe cannot be the sole producers of this ^{44}Ti:
  - We need an additional source to explain the Solar System ^{44}Ca abundance
- With an additional source explaining this phenomenon, can we also explain the origin of Galactic positrons?

Positrons from nucleosynthesis

- Only a transient event with a long recurrence time can explain the synthesis of additional ^{44}Ti
- This source would saturate the Galactic positron signal (minus the contribution from ^{26}Al
- Events would have a characteristic delay time of 3-6 Gyr
- To obey all constraints, require

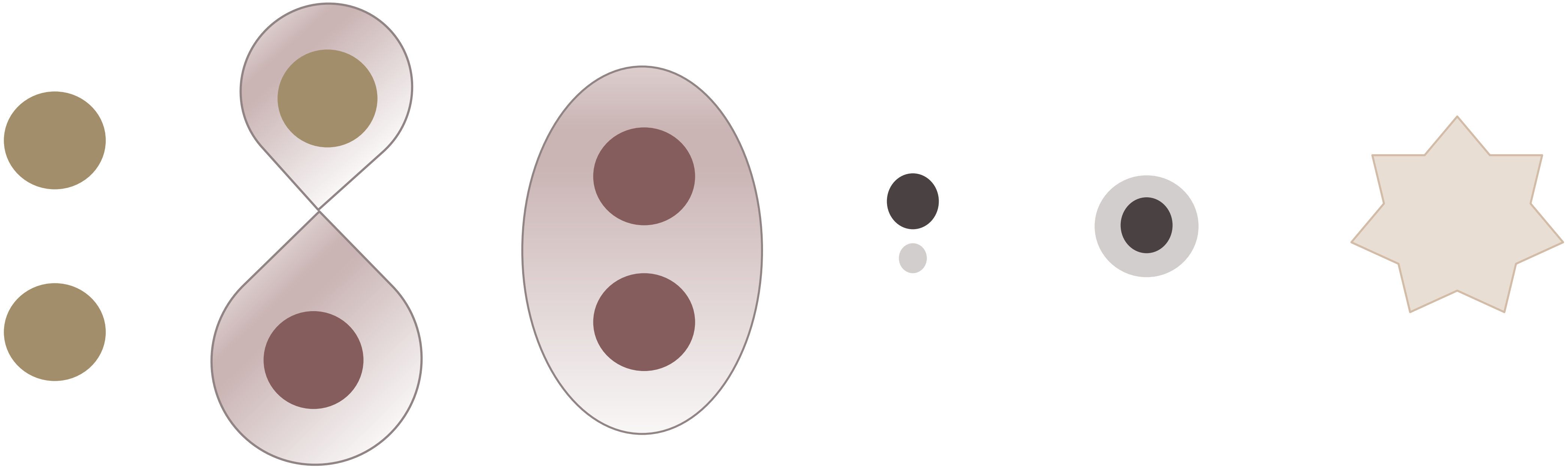
$$\langle M_{^{44}Ti} \rangle \geq 0.013\mathrm{M}_{\odot}\left(\frac{R}{300\ \mathrm{yr}^{-1}}\right)\left(\frac{\dot{N}_{e^+}}{5\times10^{43}\ \mathrm{s}^{-1}}\right)$$

Closing in on a Galactic positron source

- The quantities of ^{44}Ti synthesised in these transient events can be matched with helium detonation – incomplete burning of ^{4}He produces intermediate mass α-elements.

- We use `StarTrack` (Belczynski+) to search for an evolutionary channel that aggregates large masses of helium at high densities, at long timescales after star formation.

Closing in on a Galactic positron source



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

Closing in on a Galactic positron source

- The low ^{56}Ni yield (~0.1 solar mass) of this evolutionary track together with their proclivity to synthesise large quantities of ^{44}Ti identifies these supernovae as subluminous SN1991bg-like supernovae (Fillipenko+1992)

- These supernovae, observed in external galaxies, emperically match the requirements of a Galactic positron source:
  - Relatively frequent (~15% of all SNe Ia) (Li+2011)
  - Occur almost exclusively in old stellar environments (elliptical galaxies) (Silverman+2012)
  - Cosmological rate is increasing (Gonzales-Gaitain+2011)
  - Synthesise titanium, unlike normal SNe Ia

Closing in on a Galactic positron source

- The current Galactic disk, bulge and nucleus rates of SNe 91bg can be derived from the LOSS SN survey (Li+2011)

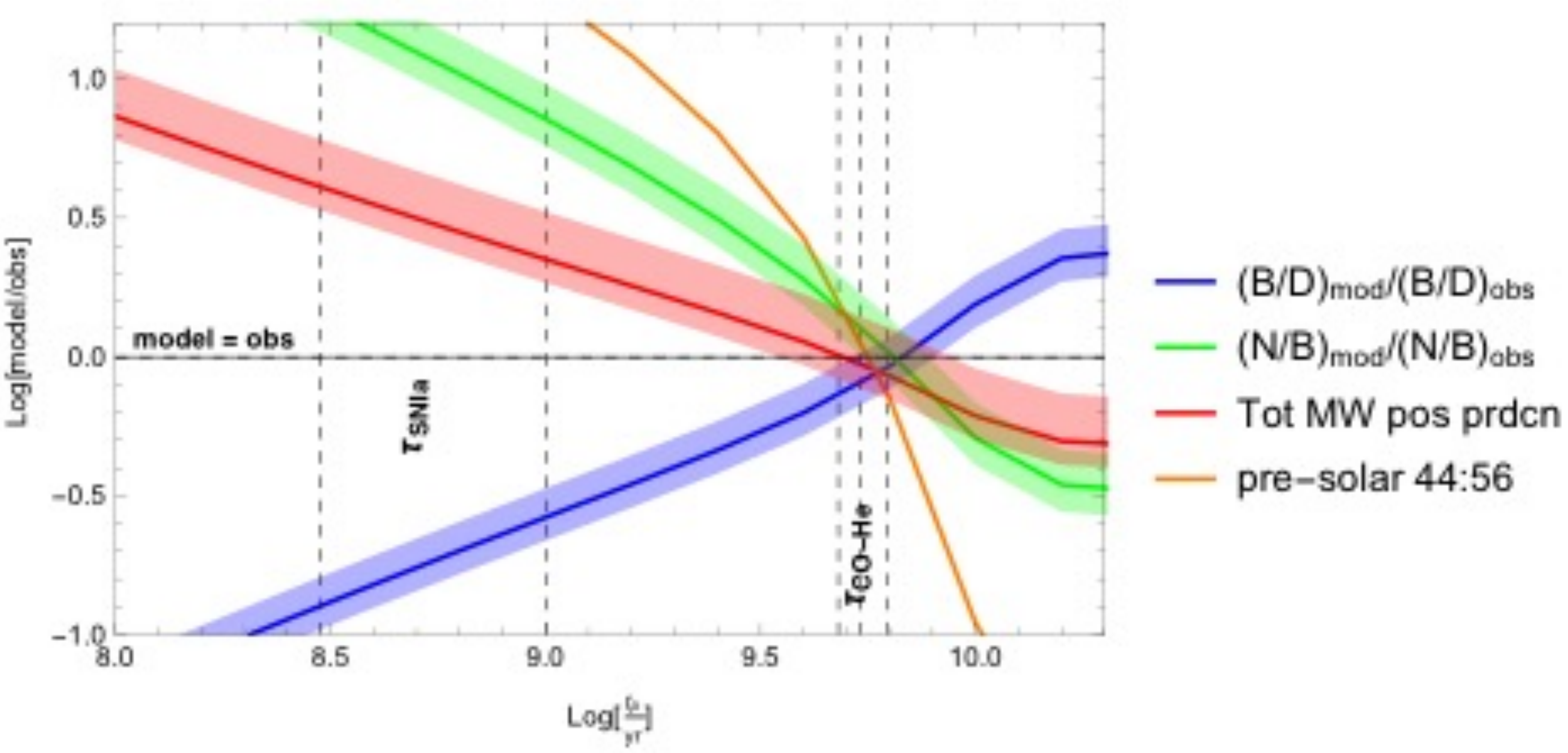
$$R_{\mathrm{SNe91bg,bulge}} = 4.6^{+4.4}_{-2.7} \times 10^{-2}\,\mathrm{century}^{-1}$$

$$R_{\mathrm{SNe91bg,disk}} = (1.4 \pm 2.7) \times 10^{-1}\,\mathrm{century}^{-1}$$

$$R_{\mathrm{SNe91bg,nucleus}} = (4.7 \pm 2.3) \times 10^{-3}\,\mathrm{century}^{-1}$$

- Recurrence time of SNe 91bg in the Galaxy: 530 years

Closing in on a Galactic positron source



$$\langle M_{^{44}Ti}\rangle \sim 0.029\mathrm{M}_\odot\left(\frac{f_{\mathrm{SNe91bg,bulge}}}{0.32}\right)$$

Summary

- We find that a single type of transient … 991bg-like supernova – can supply the req… positrons to explain the origin of most Galactic …

- The scenario is mult… 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

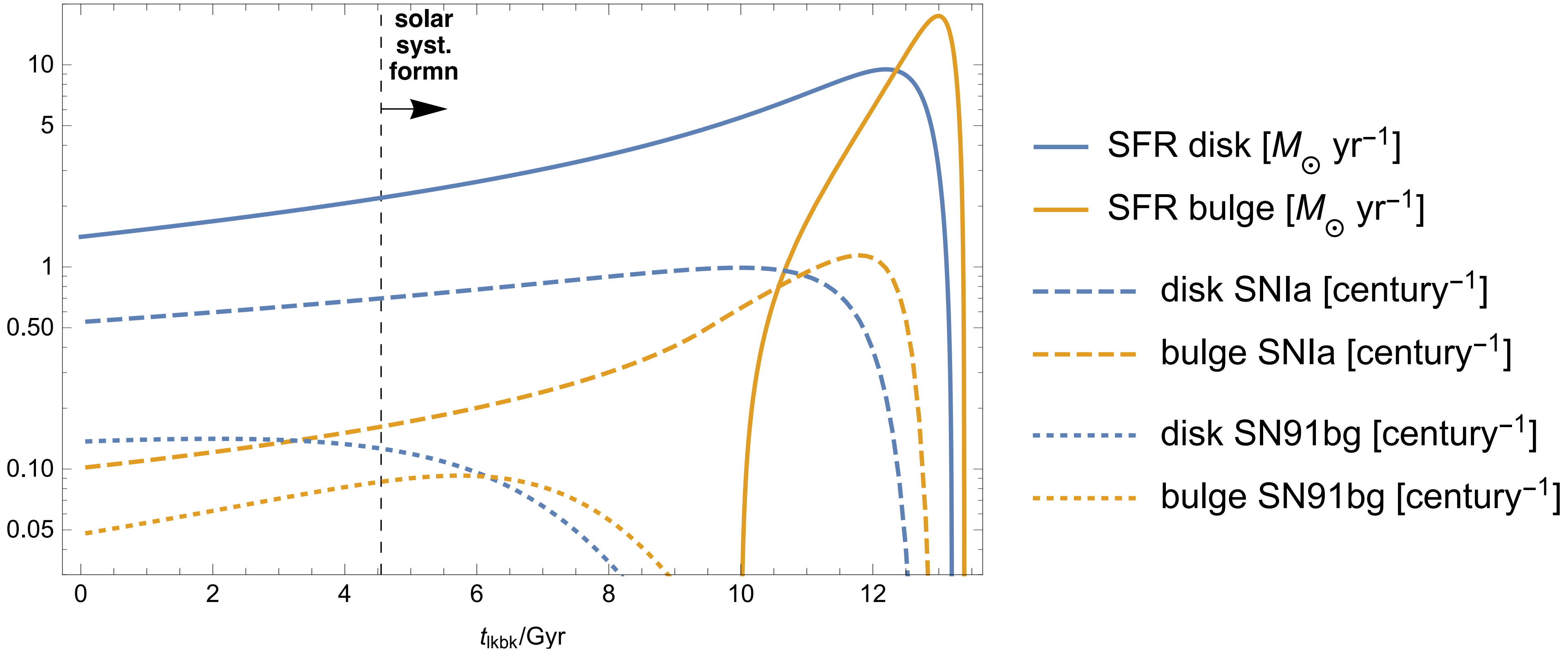
- Further work is planned using data from the Dark Energy Survey and from a survey of SNe 91bg host galaxies (both PI Panther) to place better constraints on the rate of SNe 91bg and the evolution of this rate over cosmic time.

Additional

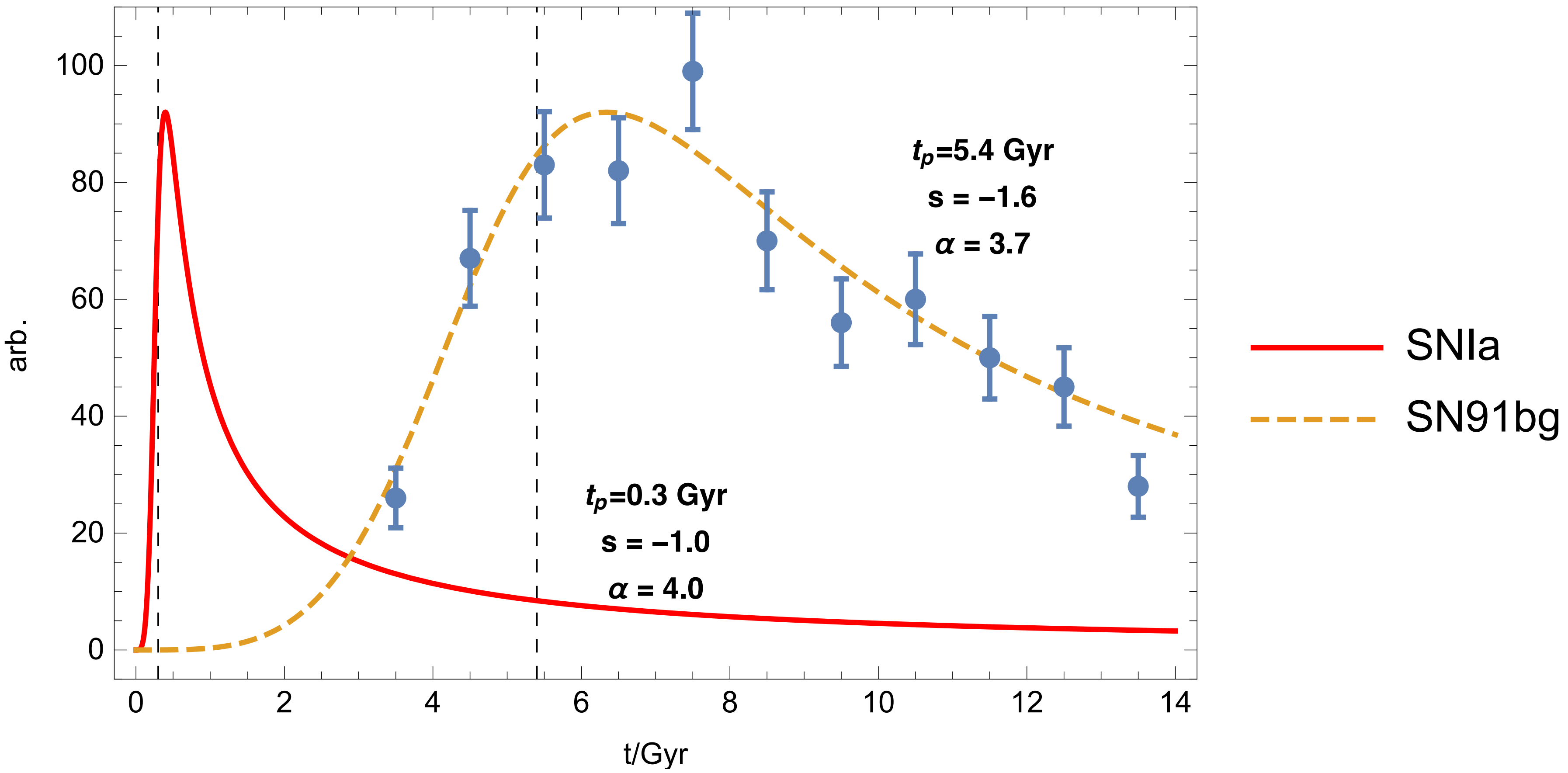
$$\log_{10}[SFR + D] = \max[Az^2 + Bz + C, 0]\,.$$

van Dokkum+ 2013 fitted to Snaith+2014 and renormalized to match the disk mass determined by the VVV survey. Gives a present day SFR of ~1.4 solar mass/yr

For the bulge, this must integrate to the total bulge mass and have SF peak at 13 Gyr ago and finish at 10 Gyr ago

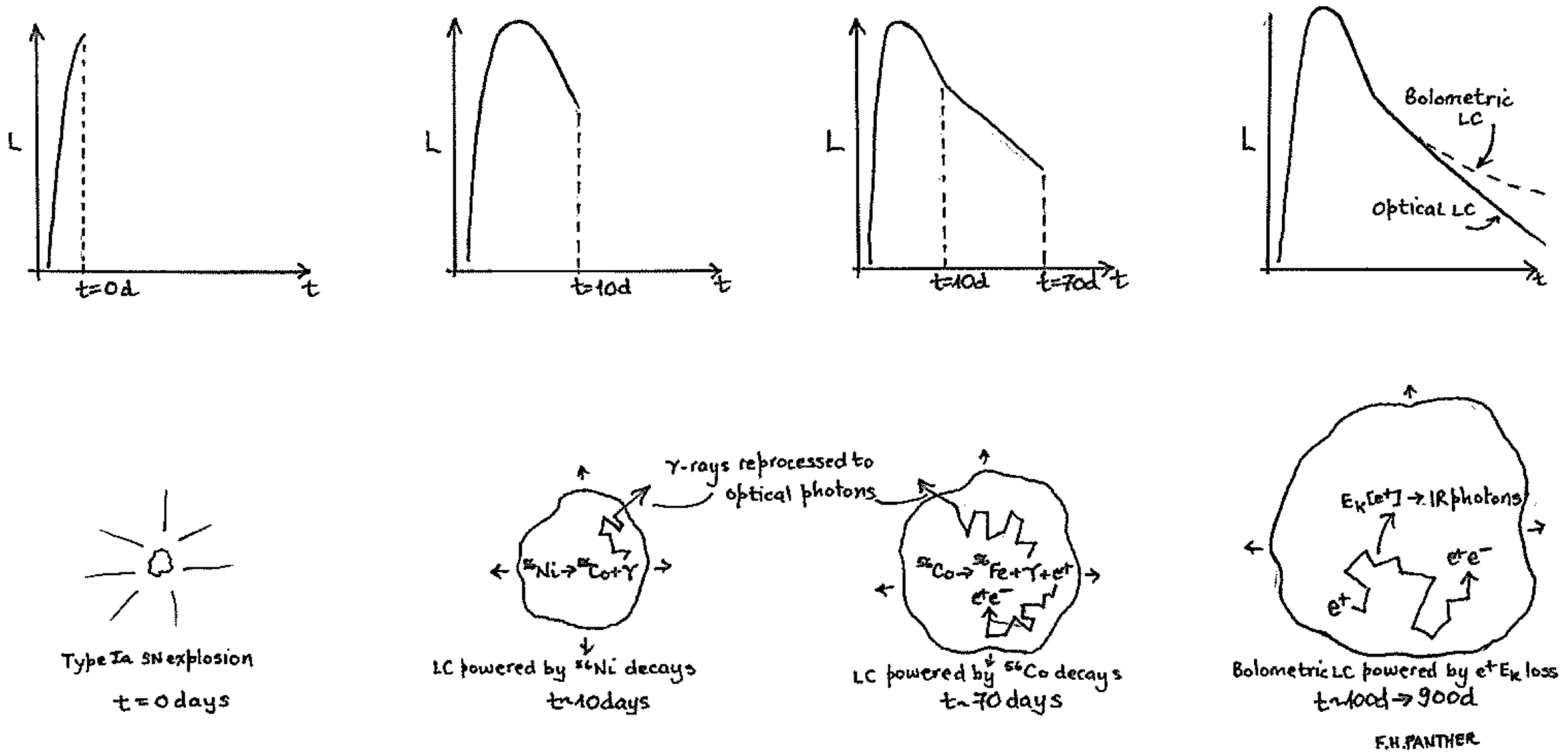


solar
syst.
formn
10
5
1
0.50
0.10
0.05
0
2
4
6
8
10
12
t_{lkbk}/Gyr
SFR disk [$M_\odot$ yr^{-1}]
SFR bulge [$M_\odot$ yr^{-1}]
disk SNIa [century^{-1}]
bulge SNIa [century^{-1}]
disk SN91bg [century^{-1}]
bulge SN91bg [century^{-1}]



100
80
60
40
20
0
arb.
0
2
4
6
8
10
12
14
t/Gyr
t_p=5.4 Gyr
s = −1.6
α = 3.7
t_p=0.3 Gyr
s = −1.0
α = 4.0
SNIa
SN91bg

Positrons from nucleosynthesis



Positrons from nucleosynthesis

- Is ^{44}Ti a viable positron source?

- Synthesised in small quantities (~10^{-4} solar masses) in CCSNe (constrained via γ-ray emission from CCSNe remnants)

- This production rate (yield x recurrence rate of CCSNe) cannot explain the abundance of ^{44}Ca relative to ^{56}Fe in solar system material.

- Explanation?