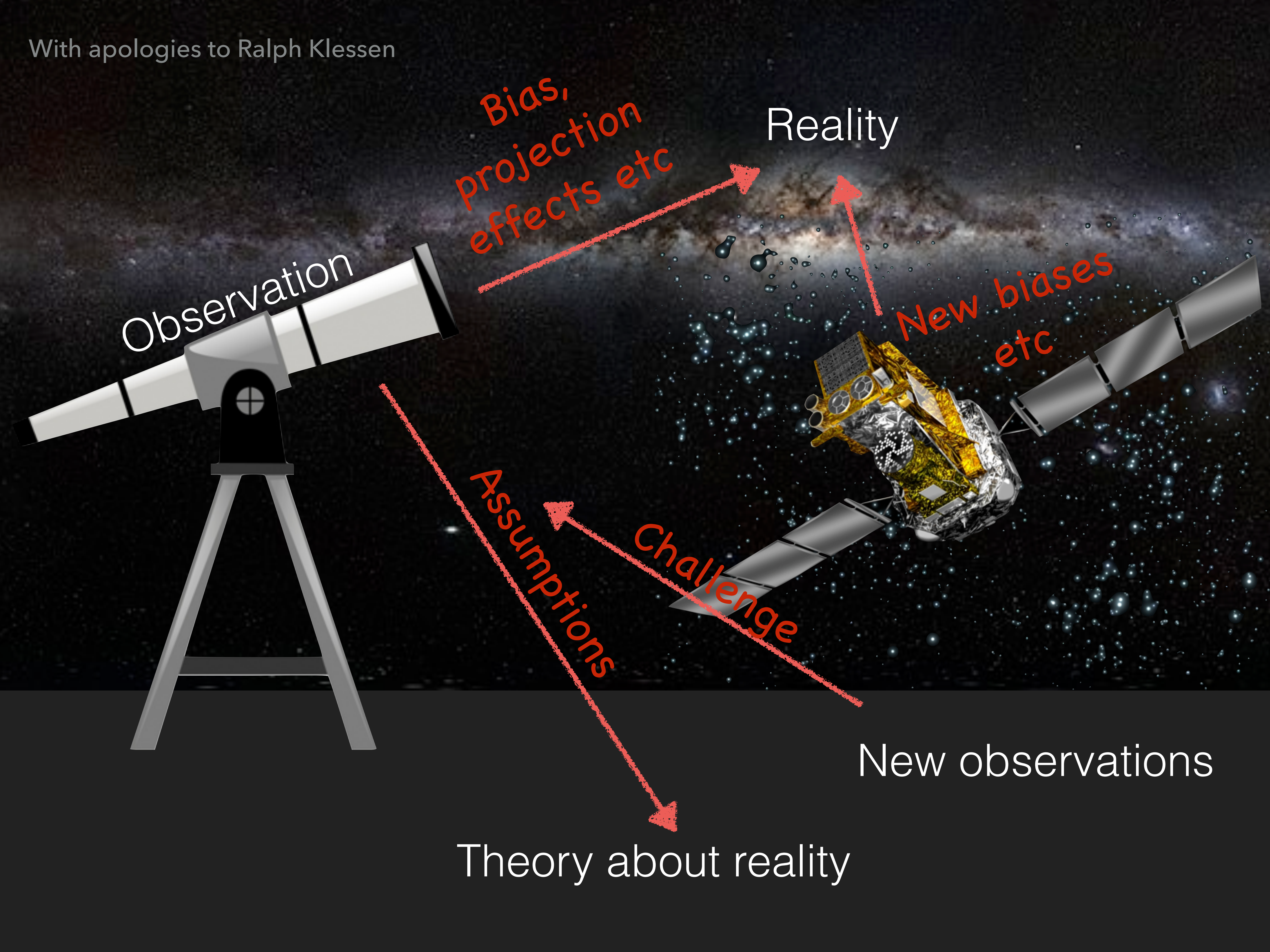
F. H. PANTHER | ANU RSAA | DES

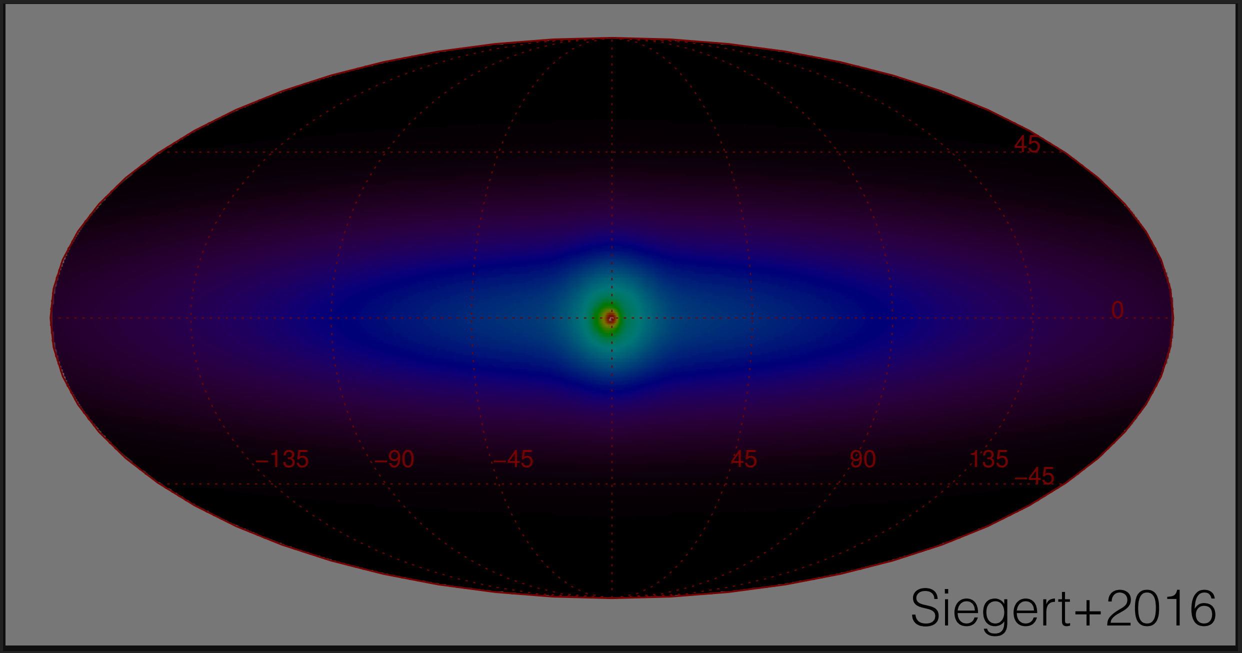
ANTIMATTER IN THE MILKY WAY

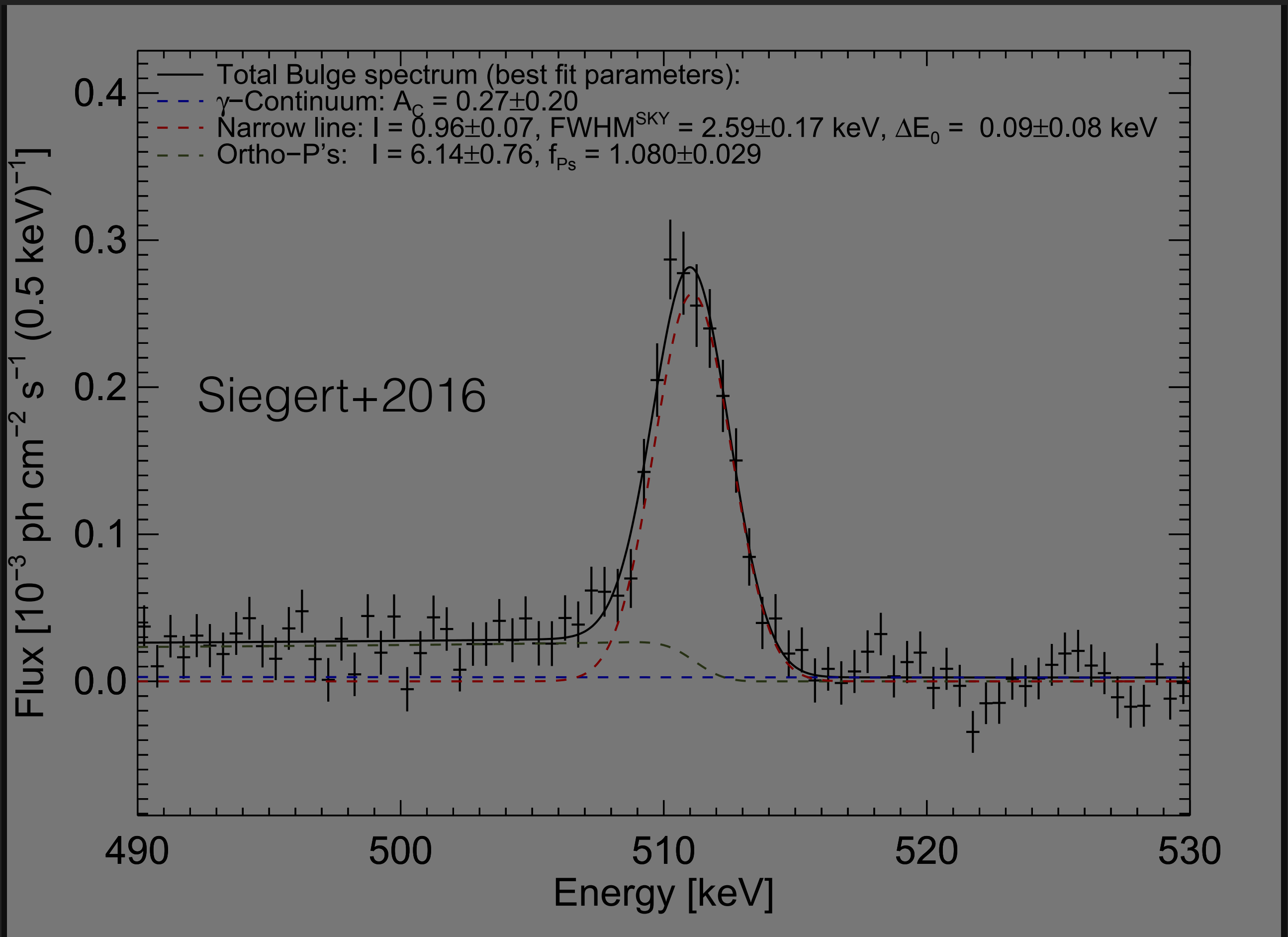
A THEORETICAL PERSPECTIVE


With apologies to Ralph Klessen
Reality
Bias, projection effects etc
Observation
New biases etc
Assumptions
Challenge
New observations
Theory about reality

INTRODUCTION

- 511 keV = rest mass energy of the electron (positron)
- Detection of gamma ray emission at 511 keV unambiguously indicates annihilation of positrons
- ~50 years of observations indicate positron annihilation is occurring in the Milky Way ISM (Johnson+1972 -> Siegert+2018 in prep)
- ~5 x 10^{43} positrons annihilate each second in the Milky Way (Siegert+2016)
- Linewidth, low energy continuum: Annihilation in **10^4 K, partially ionized ISM** (Churazov+2005, Siegert+2016)
- Absence of excess >511 keV: Positrons injected at **less than a few MeV** (Aharonian & Atoyan 1981, Beacom & Yuksel 2007)





(a) Bulge.

Positron production

Information about physics of underlying source (nucleosynthesis? compact objects? Exotic phenomena?)

Positron annihilation

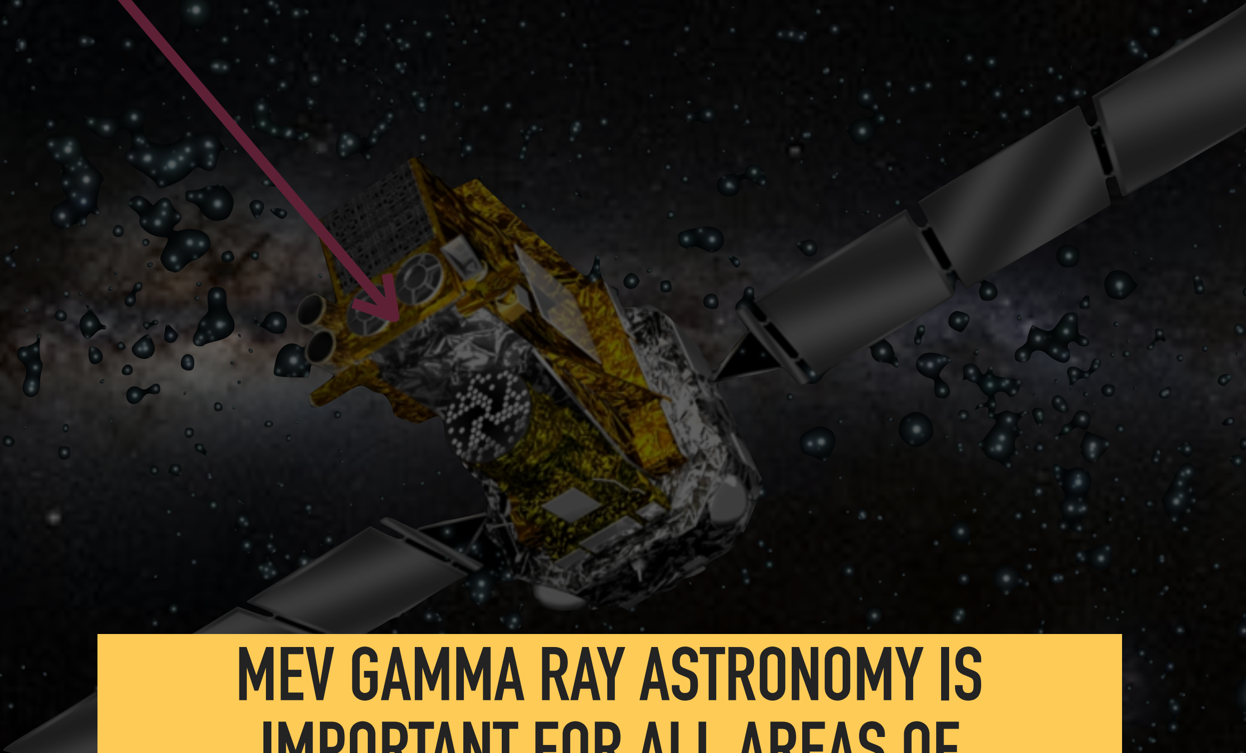
Observable

Information about ISM where annihilation occurs

Positron propagation

Information about diffusion coefficient & cosmic ray propagation

Information about Galactic magnetic field



- Positron astrophysics provides an opportunity to **understand cosmic ray propagation**, if we can better understand the source of positrons
- MeV gamma ray astronomy is vital for obtaining **direct information about nucleosynthesis and galactic chemical evolution**
- MeV gamma ray astronomy also provides an opportunity to develop robust statistical tools and analysis of large, complex, low S/N data sets

MEV GAMMA RAY ASTRONOMY IS IMPORTANT FOR ALL AREAS OF ASTROPHYSICS, PARTICULARLY IN THE 'MULTI-MESSENGER ASTRONOMY' ERA –

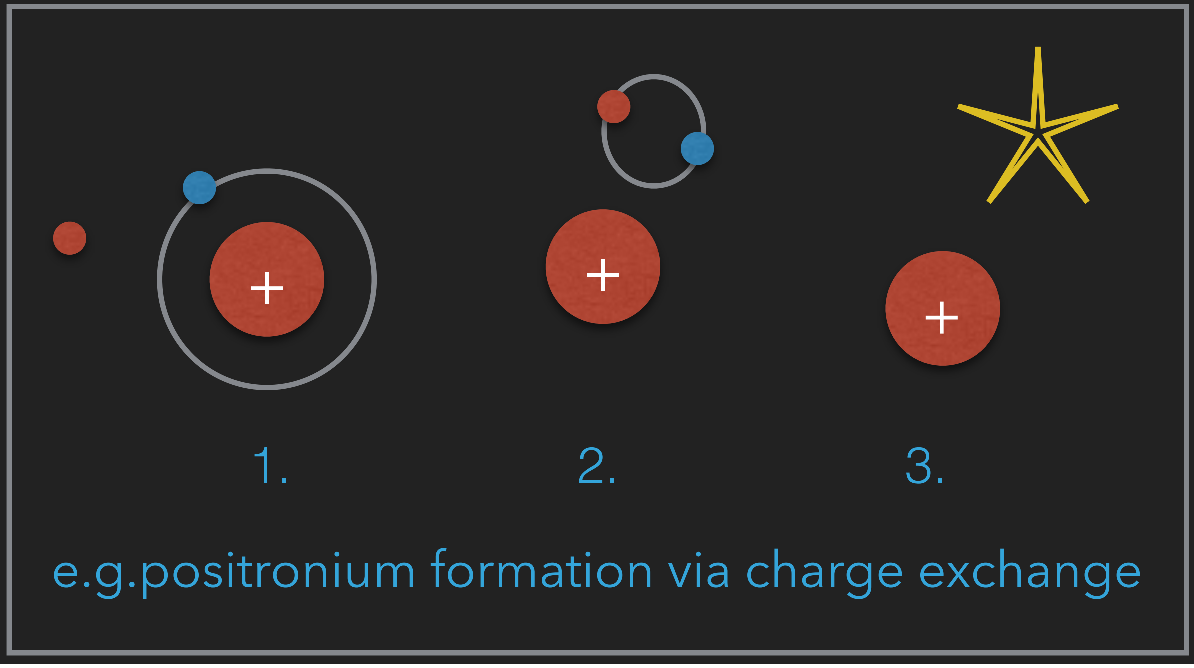
TALK TO THE PEOPLE WHO UNDERSTAND THE GAMMA RAY DATA, THEIR ANALYSIS, AND THEIR IMPLICATIONS FOR YOUR FIELD OF ASTRONOMY.

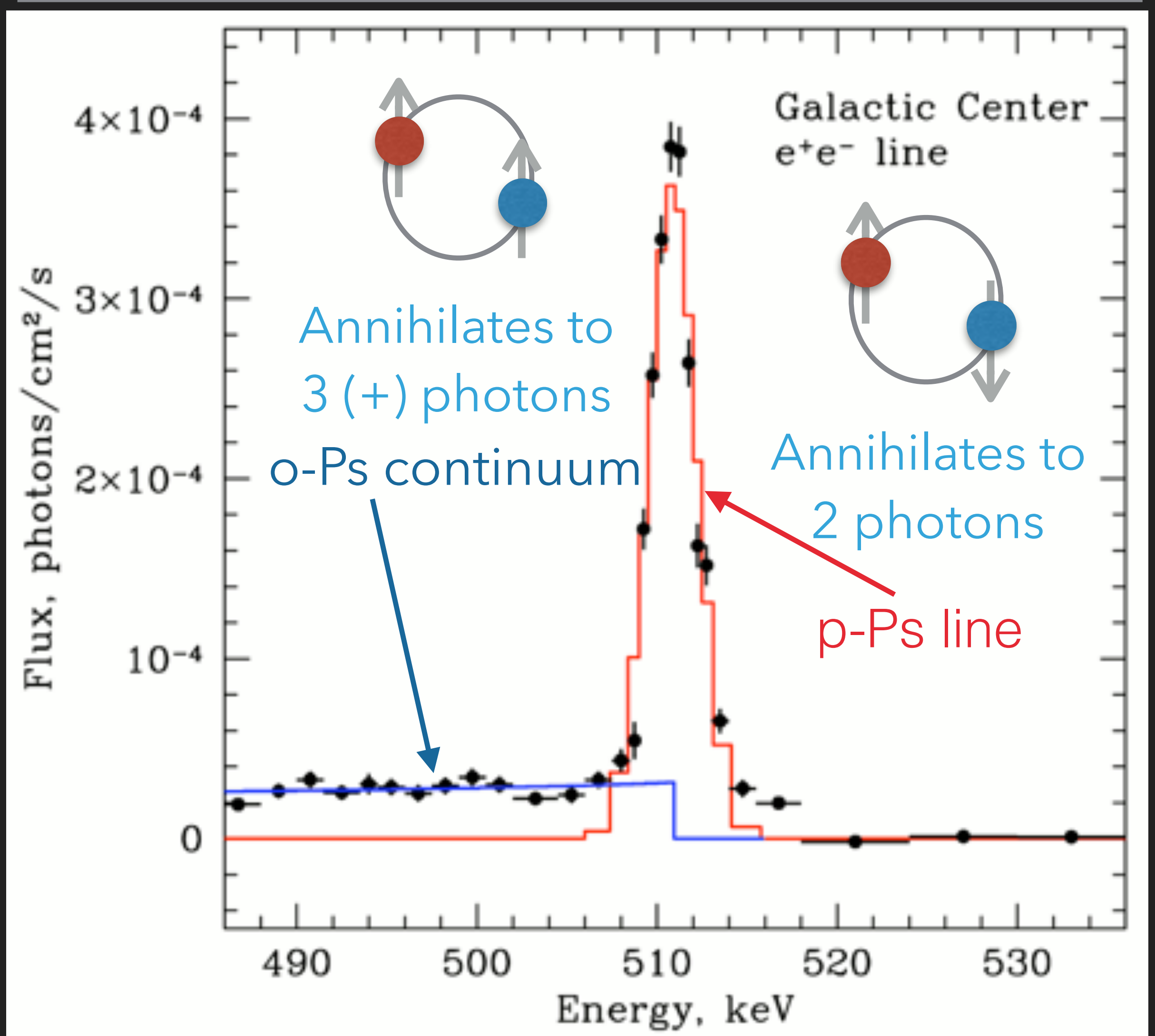
POSITRON MICROPHYSICS

with Roland M. Crocker, Ivo Seitenzahl, Joshua Machacek, Daniel Murtagh, Danny Cocks, Xi Ella Wang*, Thomas Siegert, Roland Diehl, Gleb Gribakin

POSITRON MICROPHYSICS

- Positrons can annihilate with any electron, even those bound to atoms. **Positronium formation** is thought to be the most common annihilation mechanism in the ISM (Jean+06, Churazov+2011, Siegert +2016)
- The annihilation of positronium results in a complex spectrum, not a simple delta function or Gaussian at m_{e+} = 511 keV. This can be seen in the Galactic e^+e^- line
- We usually split the lives astrophysical positrons into two phases: 'in-flight' and 'thermalized'





E. Churazov, MPA press release 2005

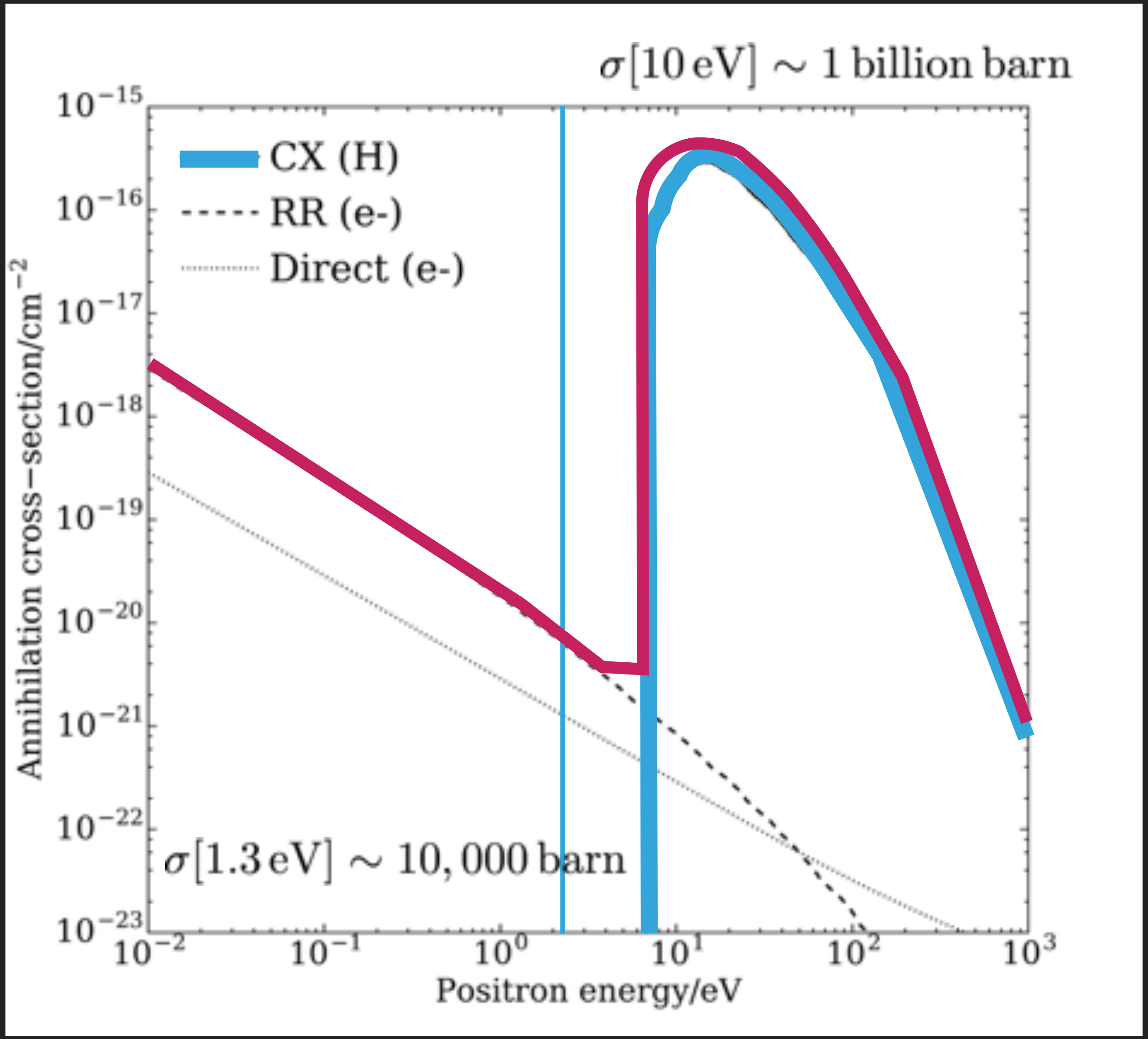
POSITRON MICROPHYSICS

Panther+2018c, published today in Phys Rev D

- ~100% of positrons are annihilating via positronium formation.
- **Charge exchange with hydrogen** is usually assumed to be the sole channel for positronium formation, as hydrogen is so abundant and the cross-section for annihilation is large
- In order to undergo this process, positrons must have an energy that exceeds the **'charge exchange threshold'**:

$$w \geq w_{IP} - 6.8\,\mathrm{eV}$$

$$w \geq 13.6\,\mathrm{eV} - 6.8\,\mathrm{eV}$$



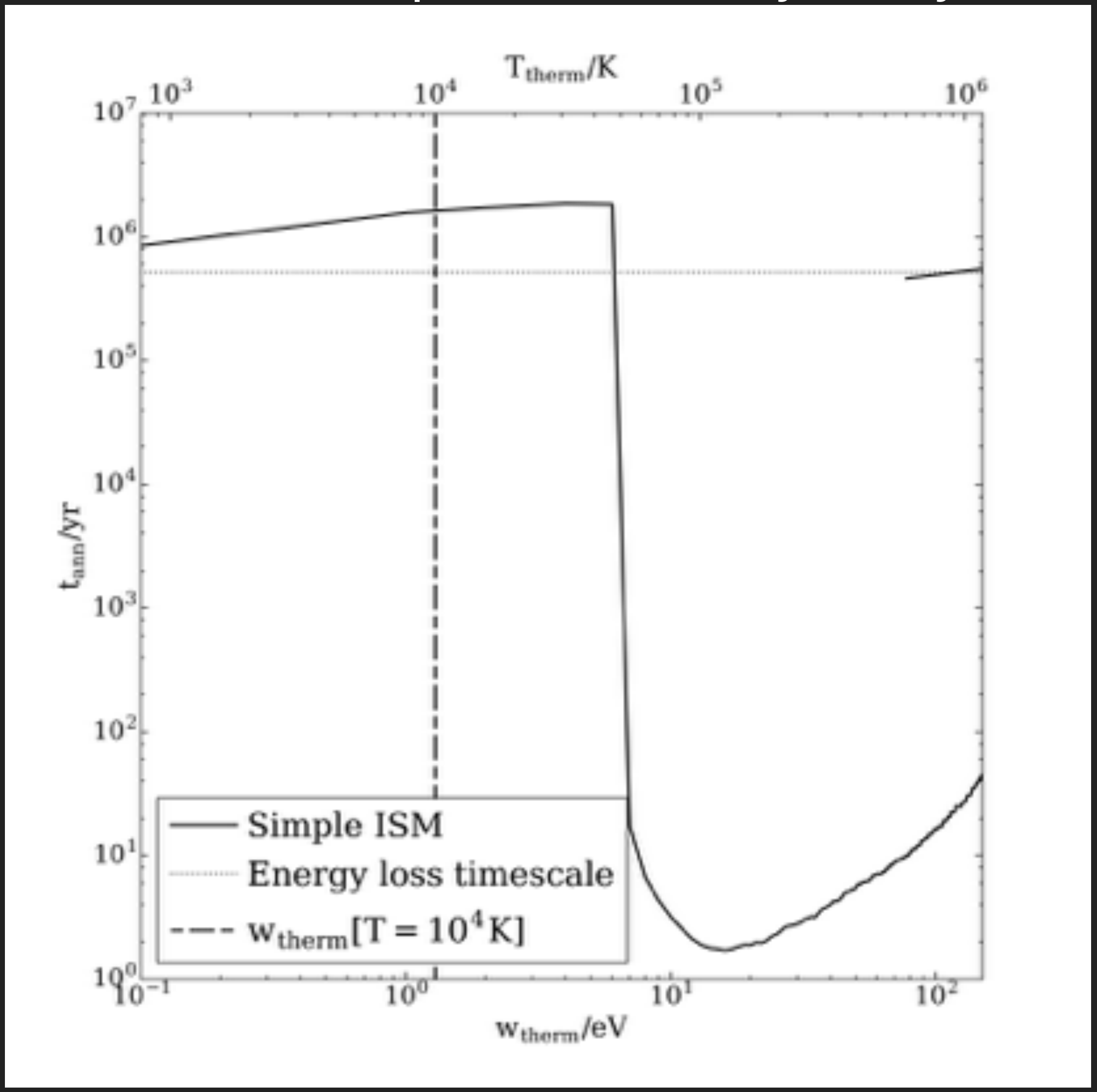
Thermalized positrons in the ISM have energies w~1.3 eV

The cross-section for annihilation interactions is very small at these energies

ANNIHILATION TIMESCALES

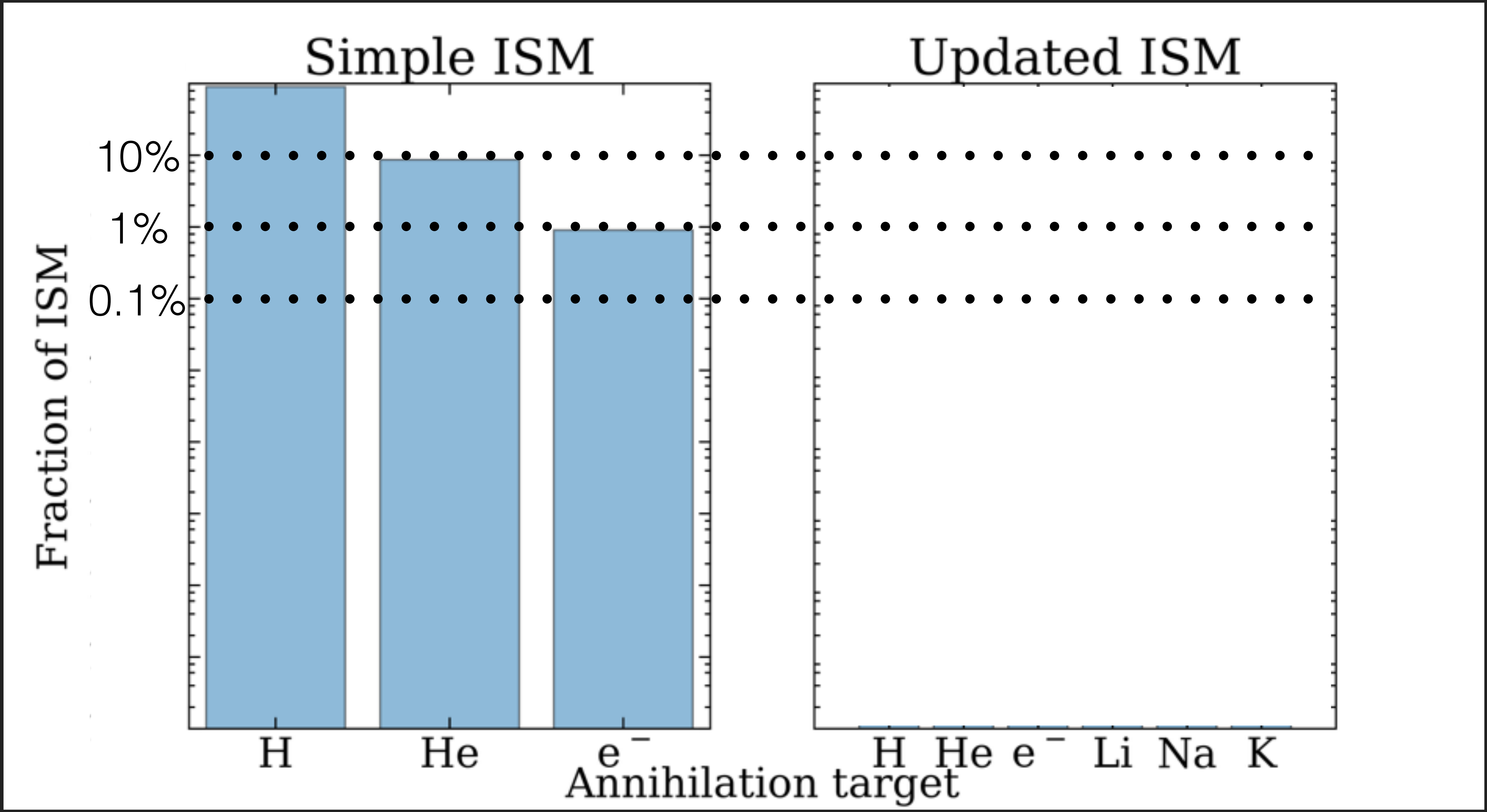
- t_{loss} ~ 1 Myr
- t_{ann} ~ 5 Myr
- Thermalized positrons annihilating today may have sat around in a ‘low energy reservoir’ for several Myr
- Allows for the possibility that positrons were injected in some kind of outburst ~ 10 Myr ago (e.g. from SMBH/AGN Dermer+1997, Totani 2006, Cheng +2007)

Panther+2018c, published today in Phys Rev D



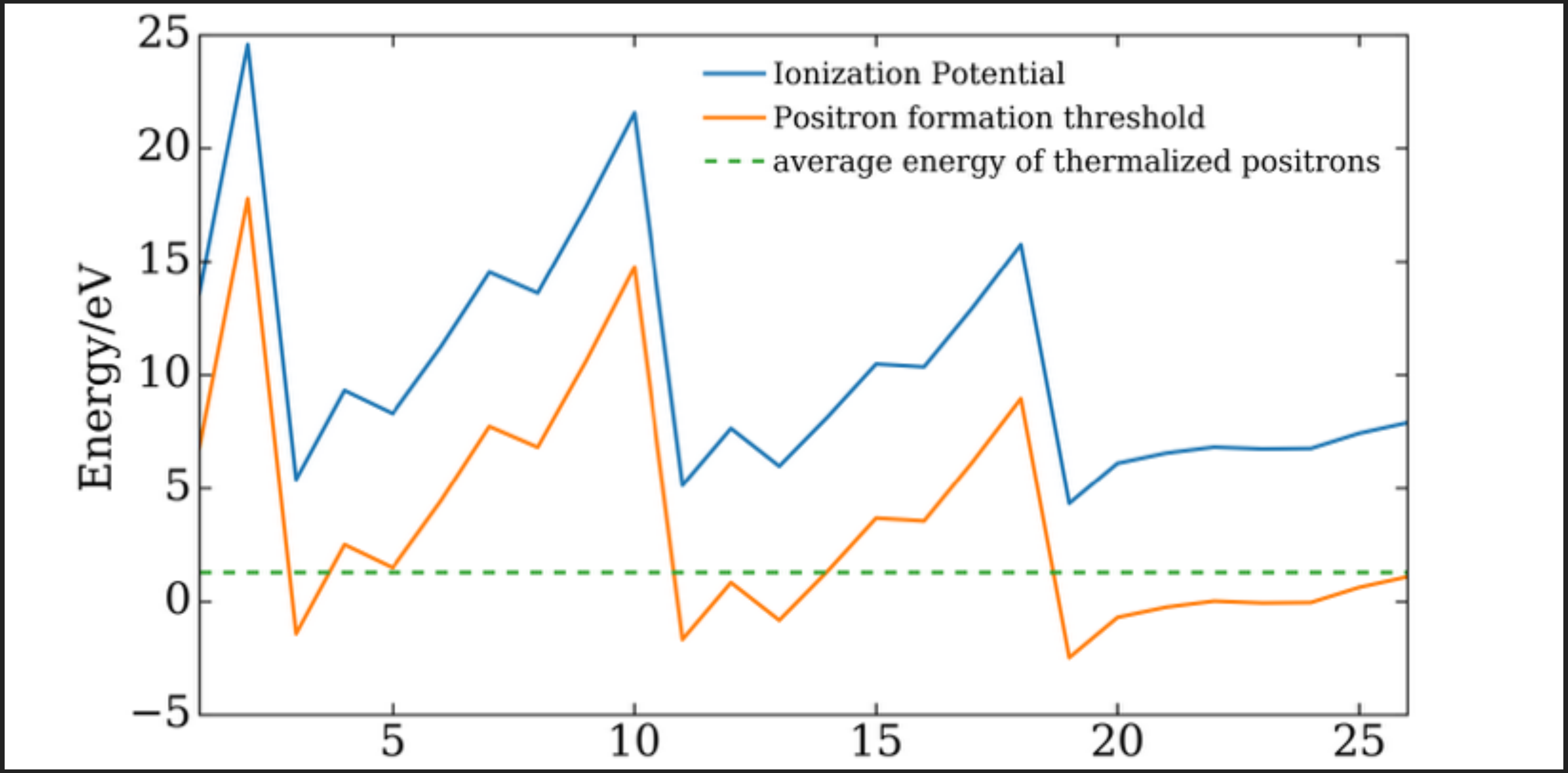
$$\tau[w] = \left(\beta c \sum_T \sigma_T n_T\right)^{-1}$$

UPDATING THE ISM MODEL



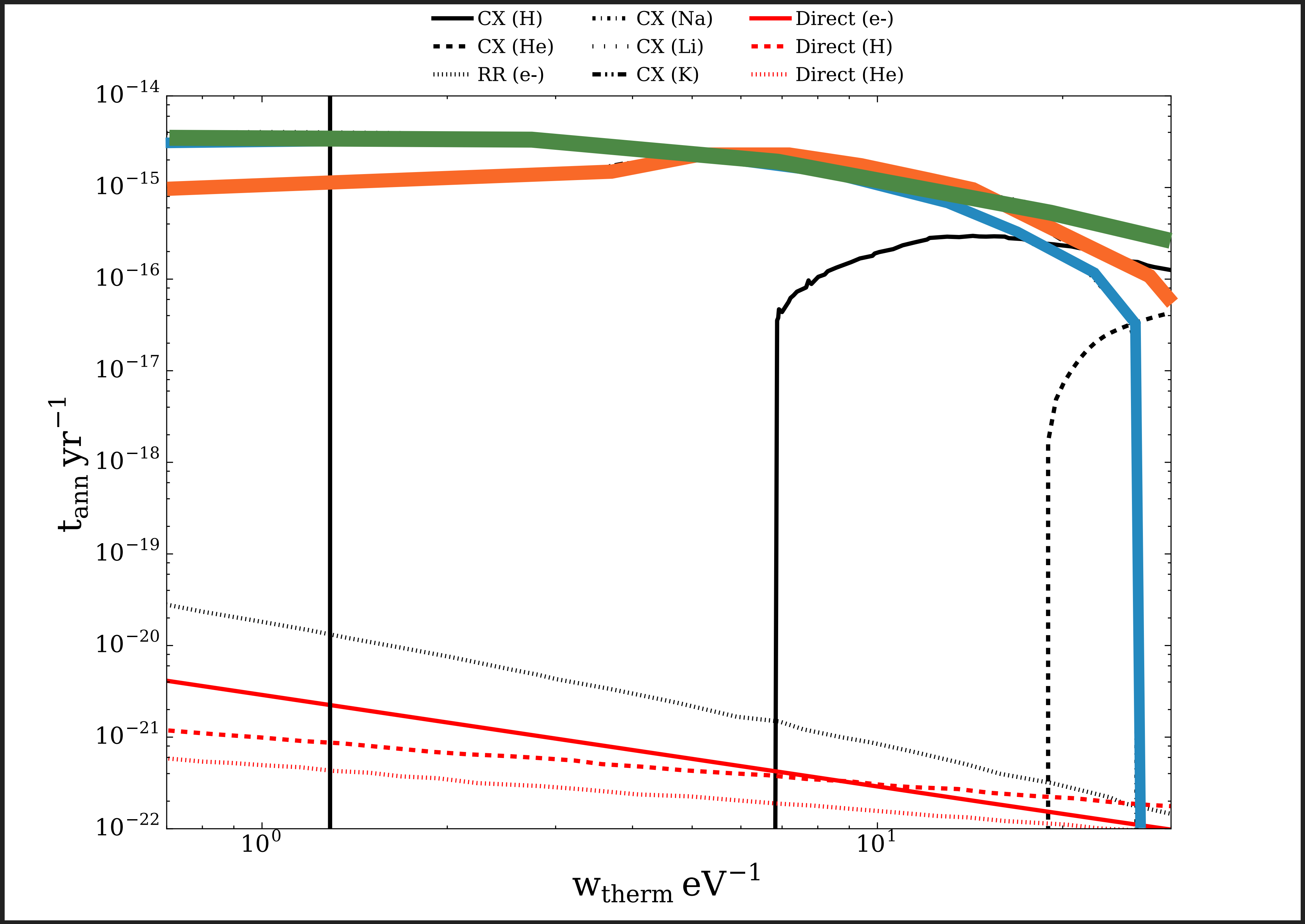
POSITRONIUM FORMATION

$$w \geq w_{IP} - 6.8\,\mathrm{eV}$$



Atomic number

ALKALI METAL CROSS-SECTIONS

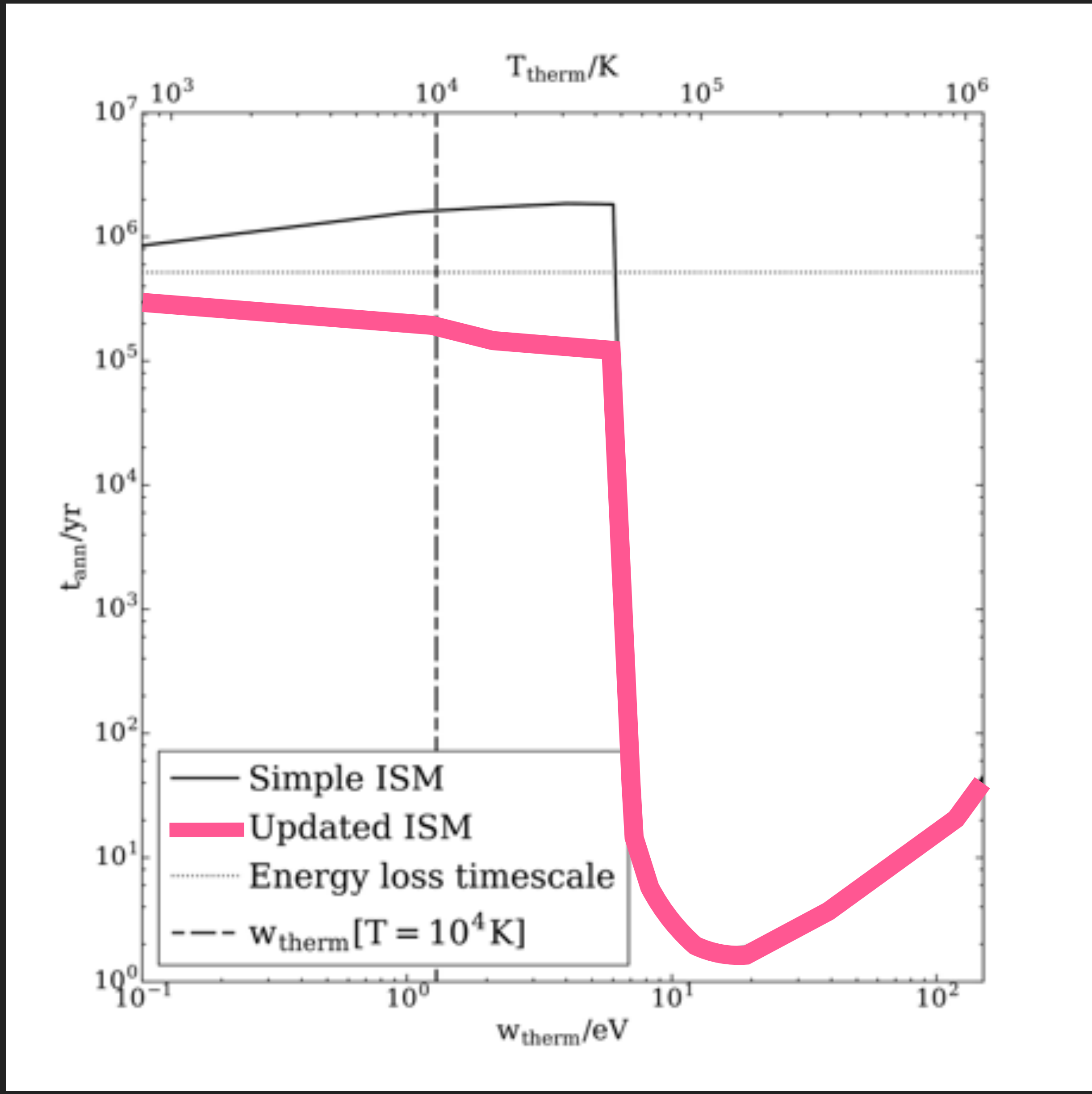


Panther+2018c, published today in Phys Rev D

NEW ANNIHILATION TIMESCALES

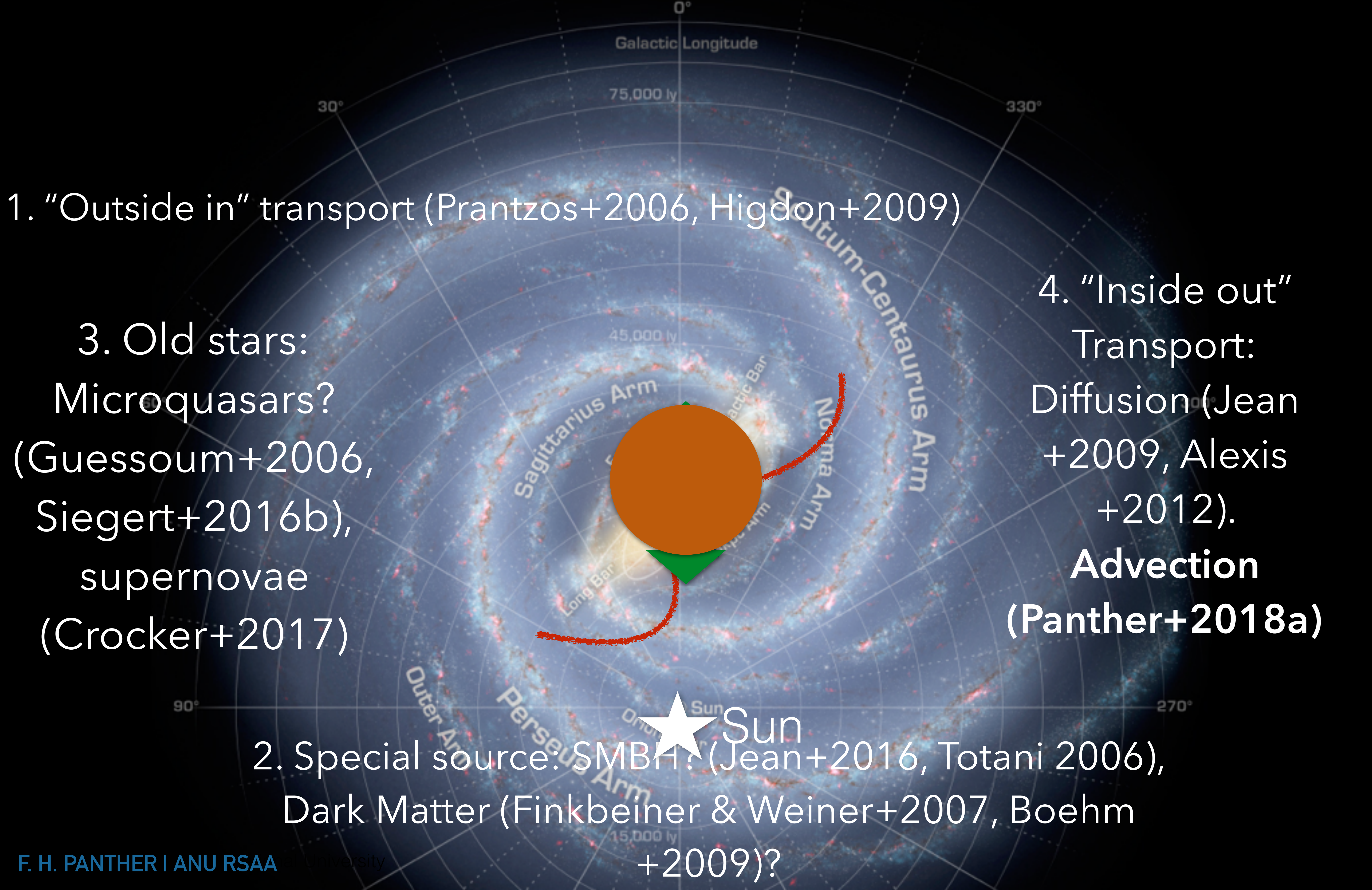
- t_{loss} ~ 1 Myr
- t_{ann} < 1 Myr
- Positrons annihilating today, including thermalised positrons, **must have been produced in the last ~1 Myr**
- Rules out a number of episodic positron injection scenarios
- There is still a lot of opportunity to connect plasma physics experiment and theory to astrophysical positrons

Panther+2018c, published today in Phys Rev D



Some positron production and transport scenarios

See Panther 2018b for a recent review



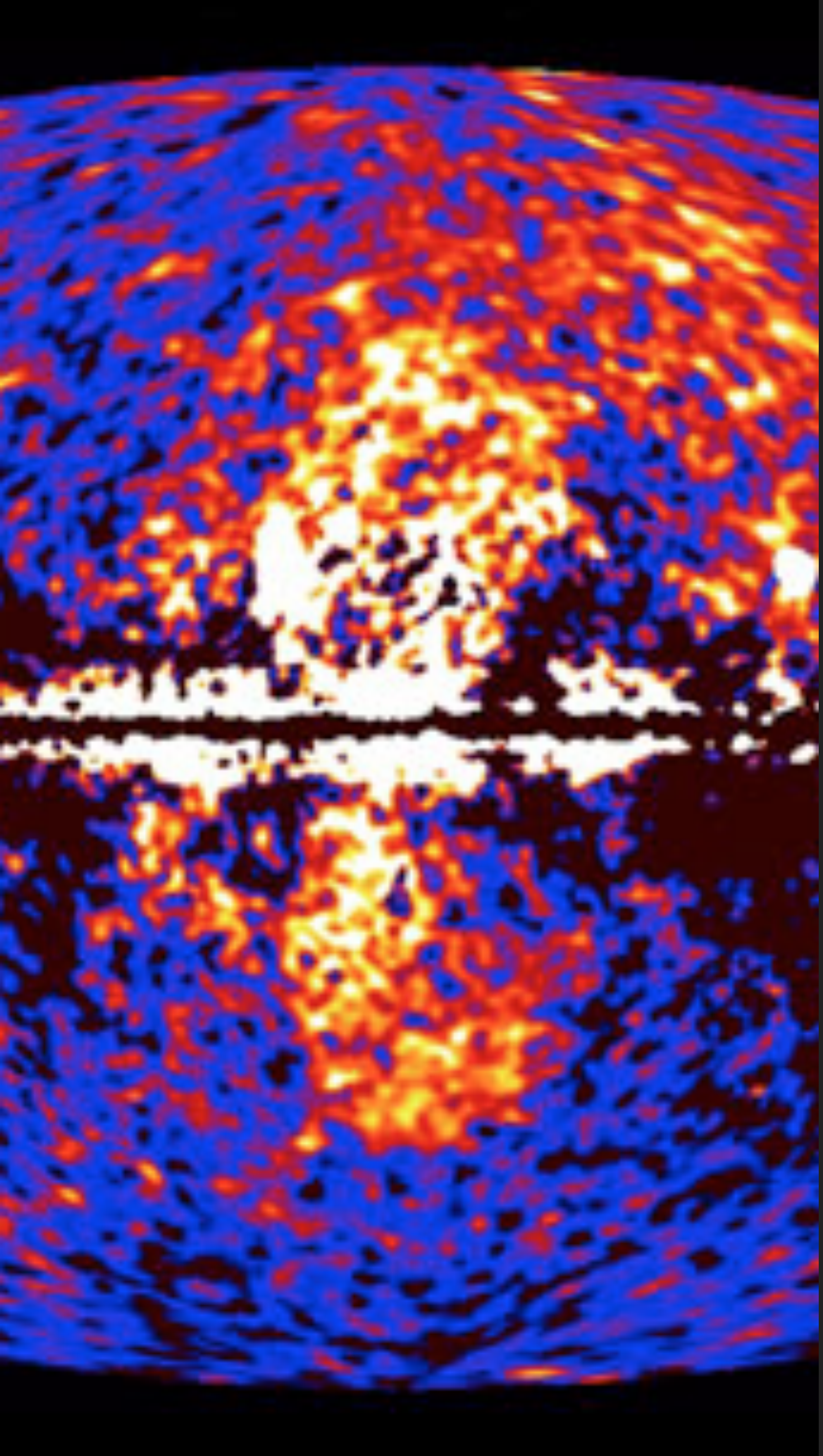
1. “Outside in” transport (Prantzos+2006, Higdon+2009)

3. Old stars: Microquasars? (Guessoum+2006, Siegert+2016b), supernovae (Crocker+2017)

4. “Inside out” Transport: Diffusion (Jean +2009, Alexis +2012). **Advection (Panther+2018a)**

Sun

2. Special source: SMBH? (Jean+2016, Totani 2006), Dark Matter (Finkbeiner & Weiner+2007, Boehm +2009)?

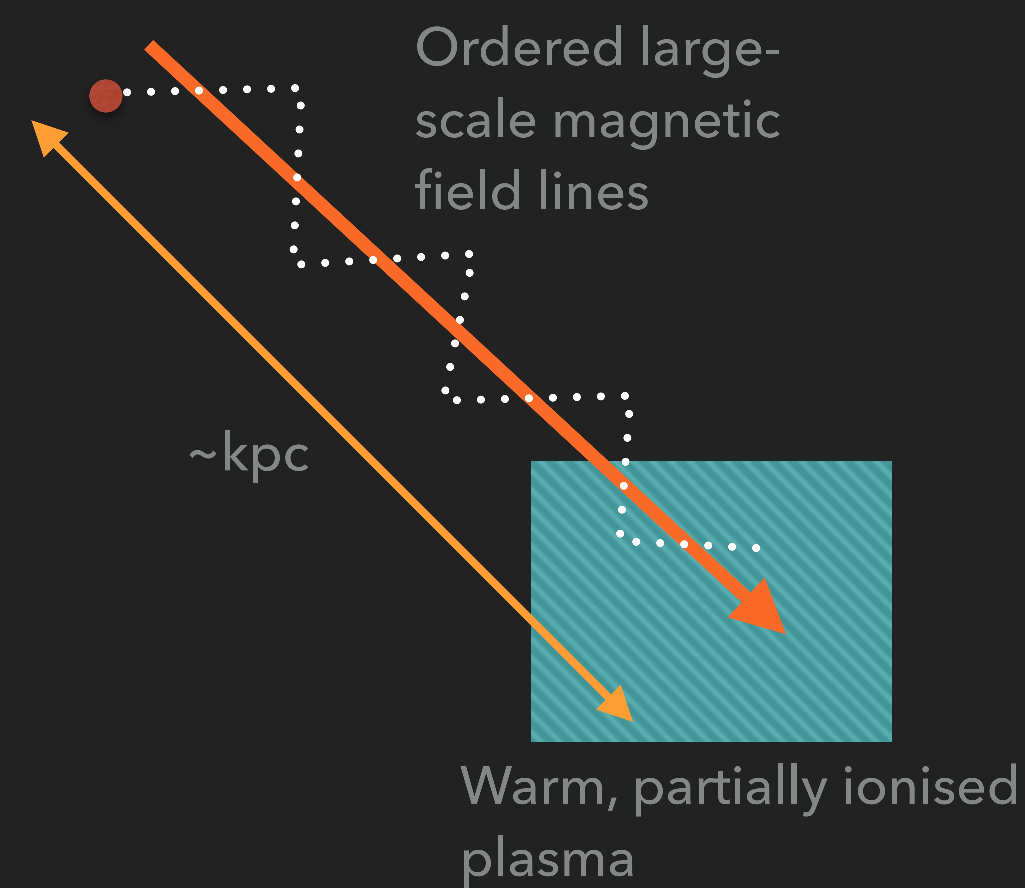


POSITRON ANNIHILATION IN THE NUCLEAR OUTFLOWS OF THE MILKY WAY

with Roland M. Crocker, Yuval Birnboim, Ivo Seitenzahl, Ashley Ruiter

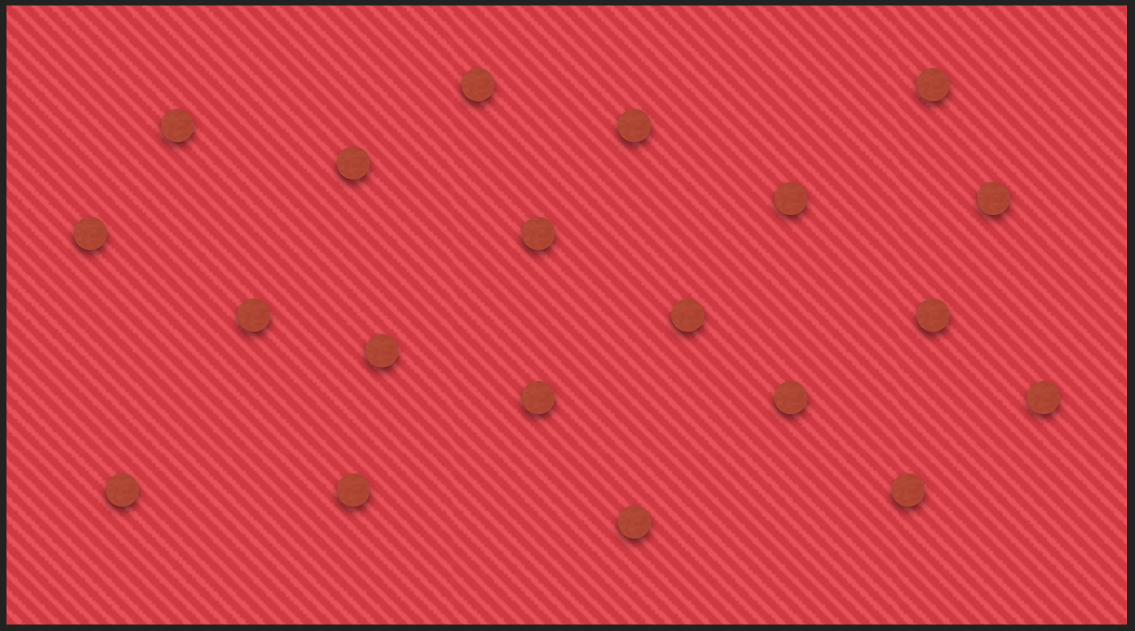
POSITRONS ARE TETHERED BY THE MAGNETIC FIELD

- The idea of positrons being able to propagate over several kpc isn't new (Dermer+1997, Cheng+2006, Prantzos+2006, Higdon+2009)
- The propagation of positrons over large distances from the centre of the Galaxy was investigated in Jean+2009, Martin+2011, Alexis+2014
- Most works come to the same conclusion: positrons can only travel large distances via diffusion if they interact predominantly with large scale magnetic fields.

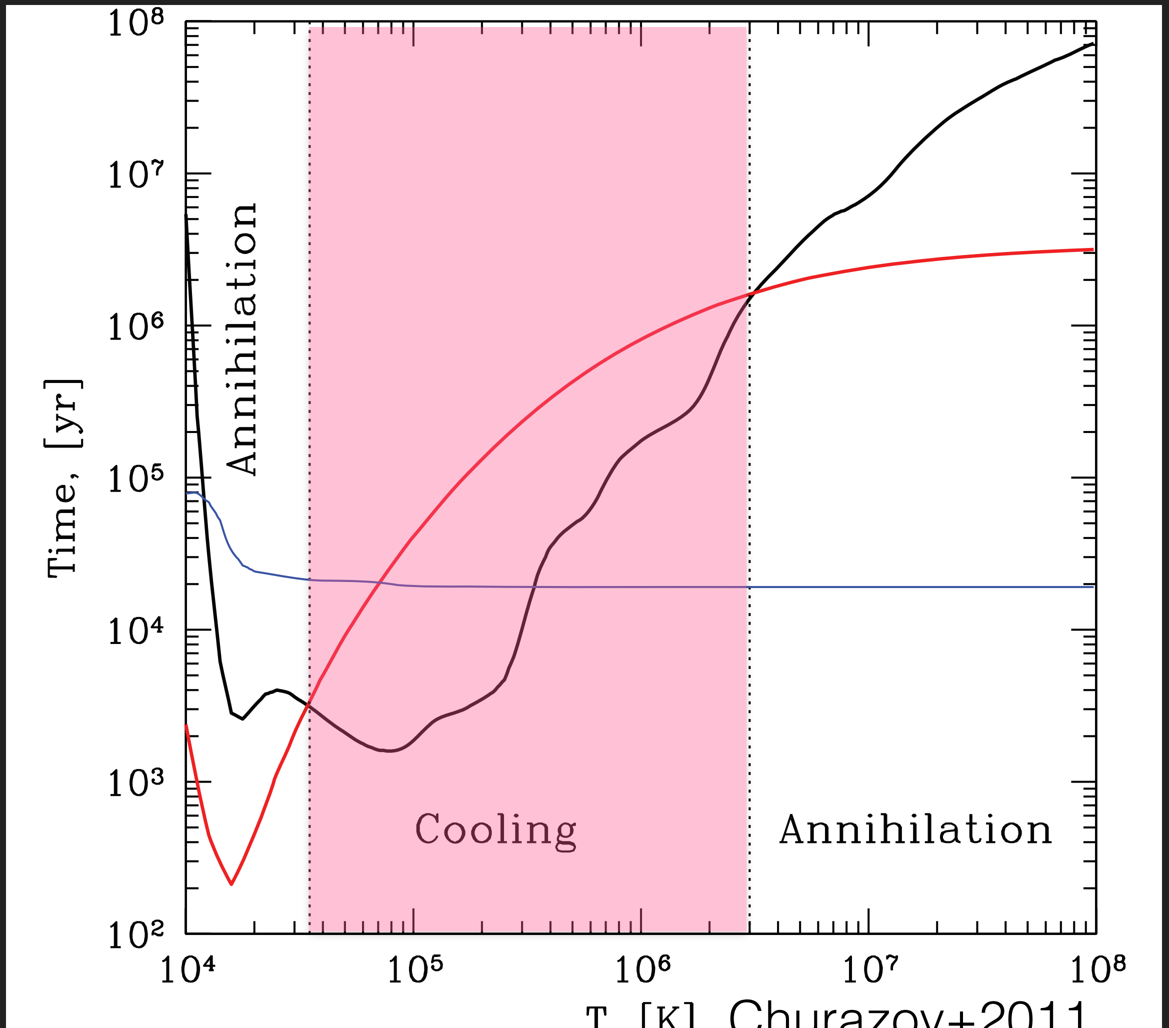


- Reality: Magnetic field in the ISM is dominated by small-scale magnetic fluctuations
- Turbulent magnetic field tends to confine positrons within ~100pc of their production sites
- What if the plasma has some kind of motion?

POSITRON ANNIHILATION IN COOLING GAS



- Positron annihilation occurs in plasma with a temperature of ~10^4 K
- Annihilation spectrum only encodes information about the ISM conditions when the positron annihilates
- Can the ISM cool to a state that explains the spectrum in a shorter time than the positron annihilates?
- **Churazov+2011**: Yes, for Collisional Ionisation Equilibrium (CIE) cooling and a range of initial temperatures



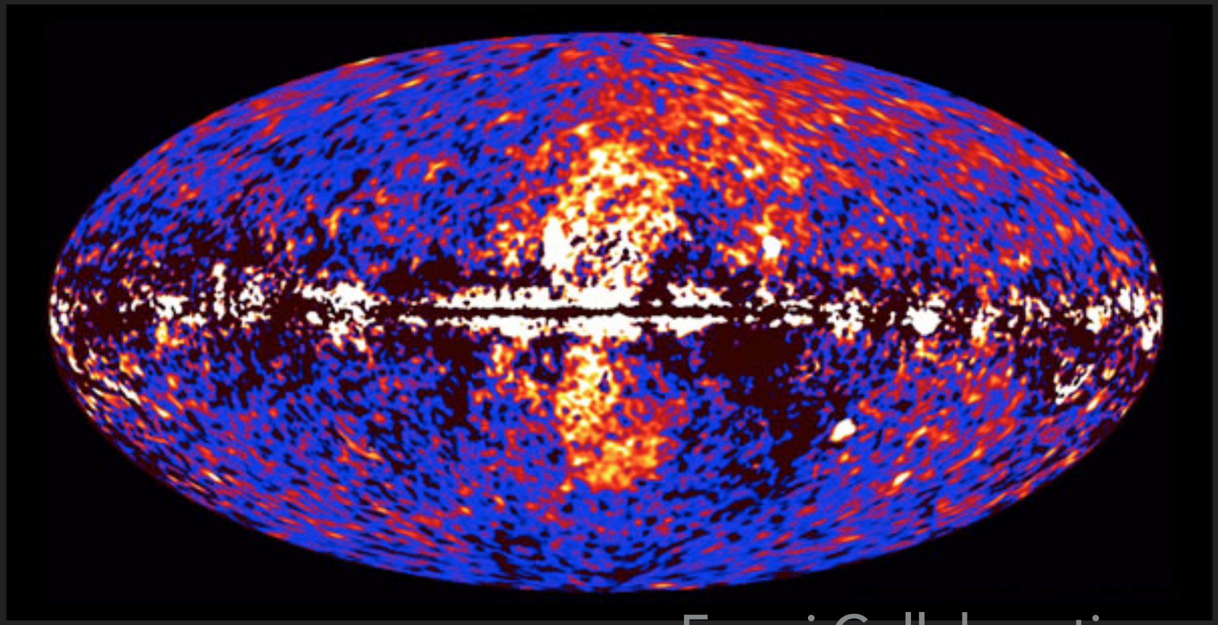
Churazov+2011

POSITRON TRANSPORT AND THE FERMI BUBBLES

- Evidence for a bipolar nuclear outflow in the Milky Way originated in ~2003 (Bland-Hawthorn & Cohen 2003)

- The 2010 discovery of the Fermi Bubbles (Su+2010, Dobler+2010) provide additional **evidence of an outflow from the Galactic nuclear region,** casting doubts on the model of a static ISM in this region

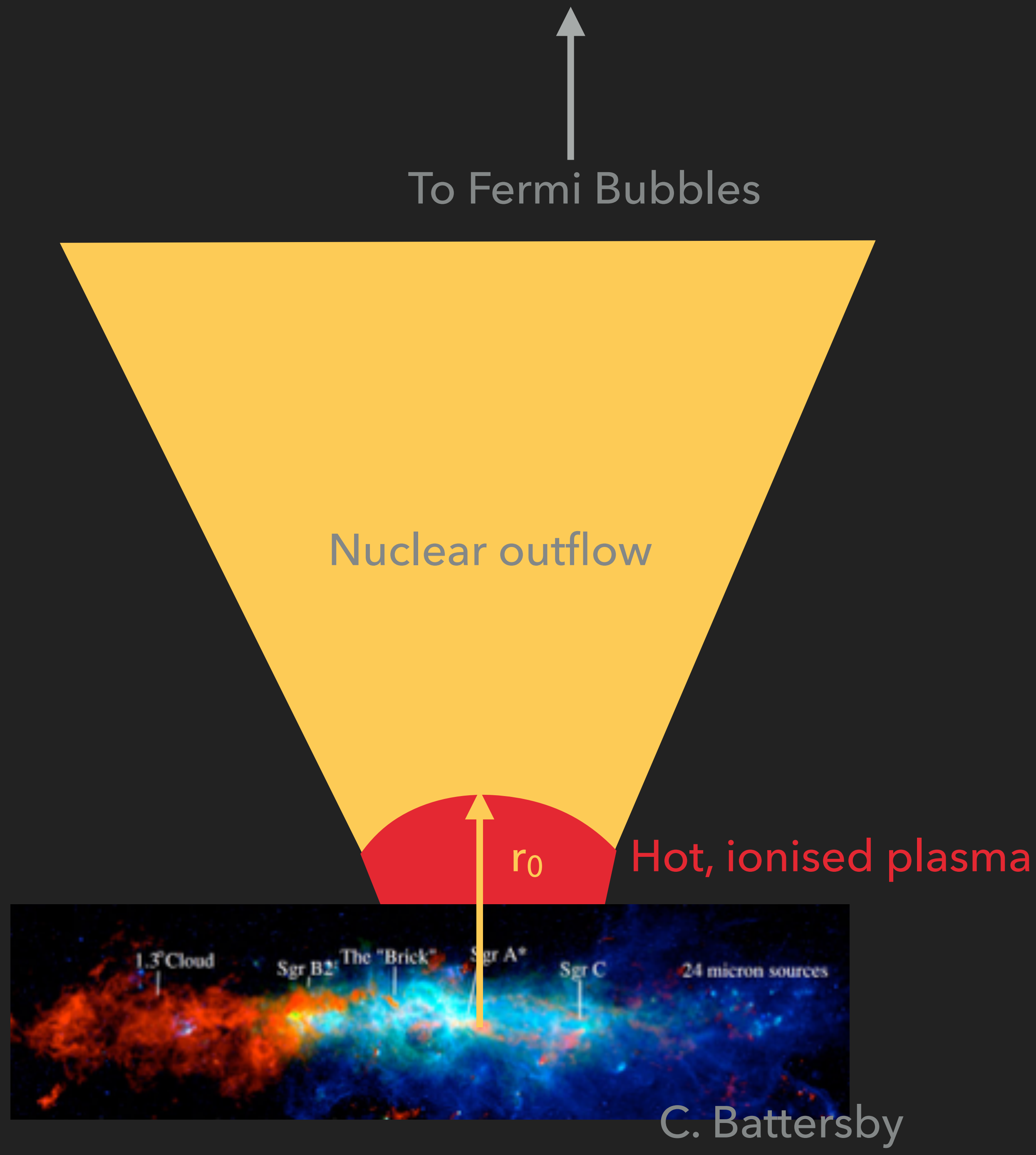
Are positrons “catching a ride” in the outflow that inflates the Fermi Bubbles, and cools as it does so (e.g. Crocker+2011)? Can they explain the annihilation in the Galactic bulge?



Fermi Collaboration

MODELLING THE NUCLEAR OUTFLOW

- r_0 ~ r(Central Molecular Zone) ~ 100 pc
- mass and energy injected by CMZ star formation (observed ~ 0.1Msun/yr)
- wind accelerated to v_0 at r_0 (v_0 ~ 200 - 1500 km s^{-1})
- Initial temperature -> kinetic power ~ thermal component (T_0 ~ 10^5 - 10^8 K)
- Opening angle -> pi Str (results insensitive to choice of opening angle)



MODELLING THE NUCLEAR OUTFLOW

- Explore properties of steady-state wind **up to 2 kpc** from the Galactic centre for range of parameter space:

Energy flux -> 10^{38} - 10^{40} erg s^{-1}
Mass flux -> 10^{-3} - 10^{0} M_{sun} yr^{-1}

- Positrons move passively at the wind velocity (c.f. Jean +2009, magnetic confinement)
- Wind decelerates due to Galactic potential (Breitschwert+1991)
- Identical physics for lower 2kpc in Crocker+2015

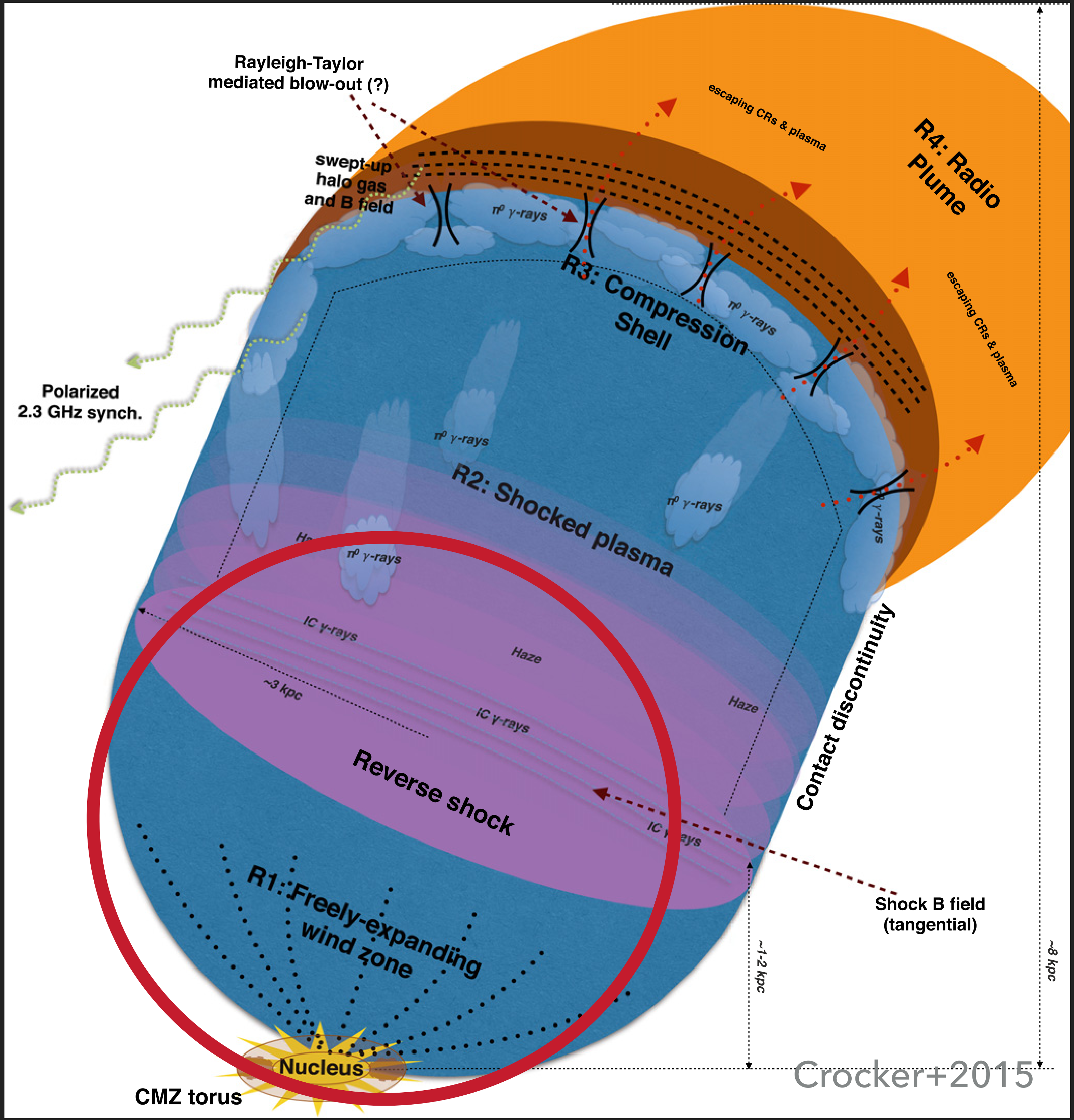


Figure 1. Schematic showing the main features of the north bubble according to our model.

MODELLING THE NUCLEAR OUTFLOW

- For a given point in parameter space calculate trajectories as a function of galactocentric radius:
  - Mass density
  - Temperature
  - Wind velocity
  - Ionization fraction of hydrogen based on CIE (Sutherland & Dopita 1993)

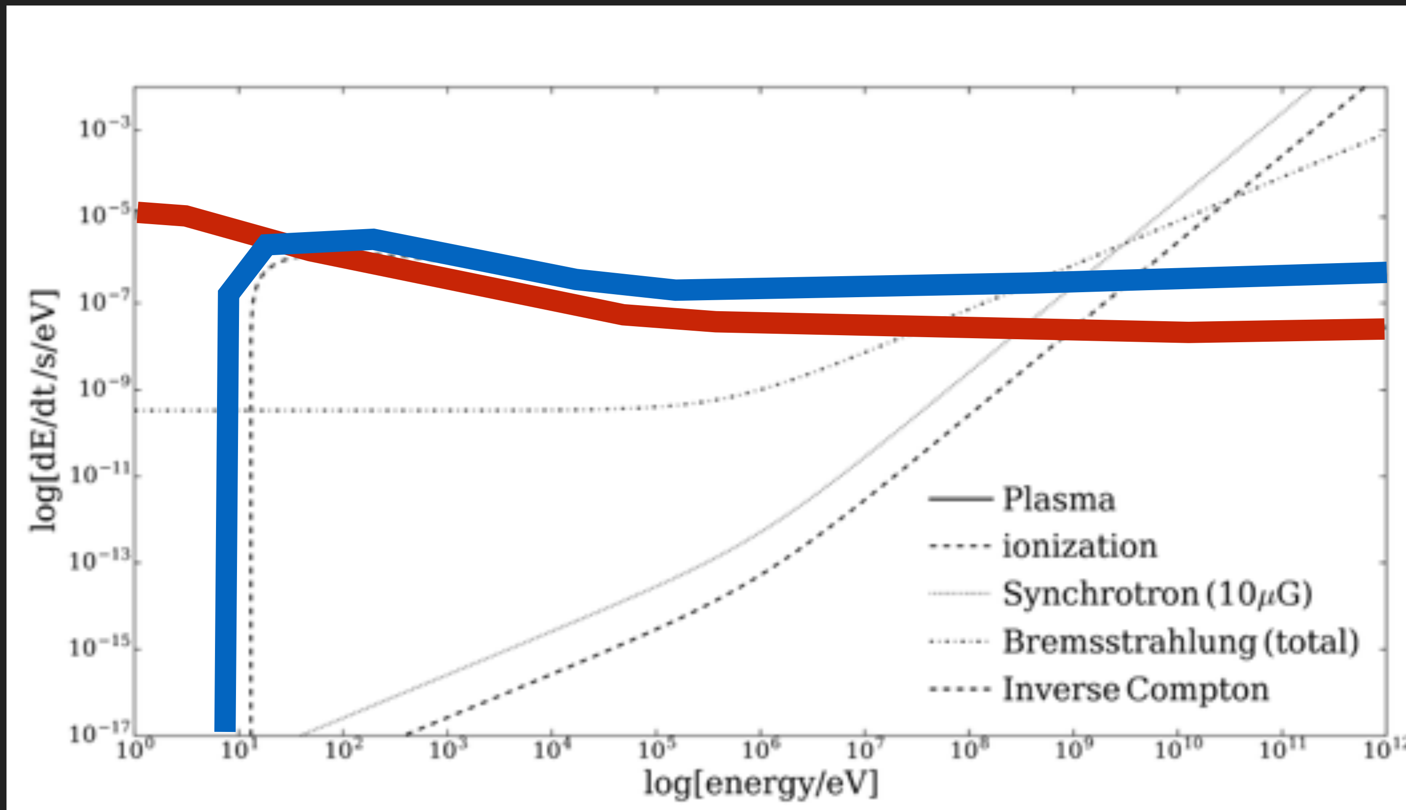
- Each trajectory represents the trajectory of a positron in the model.

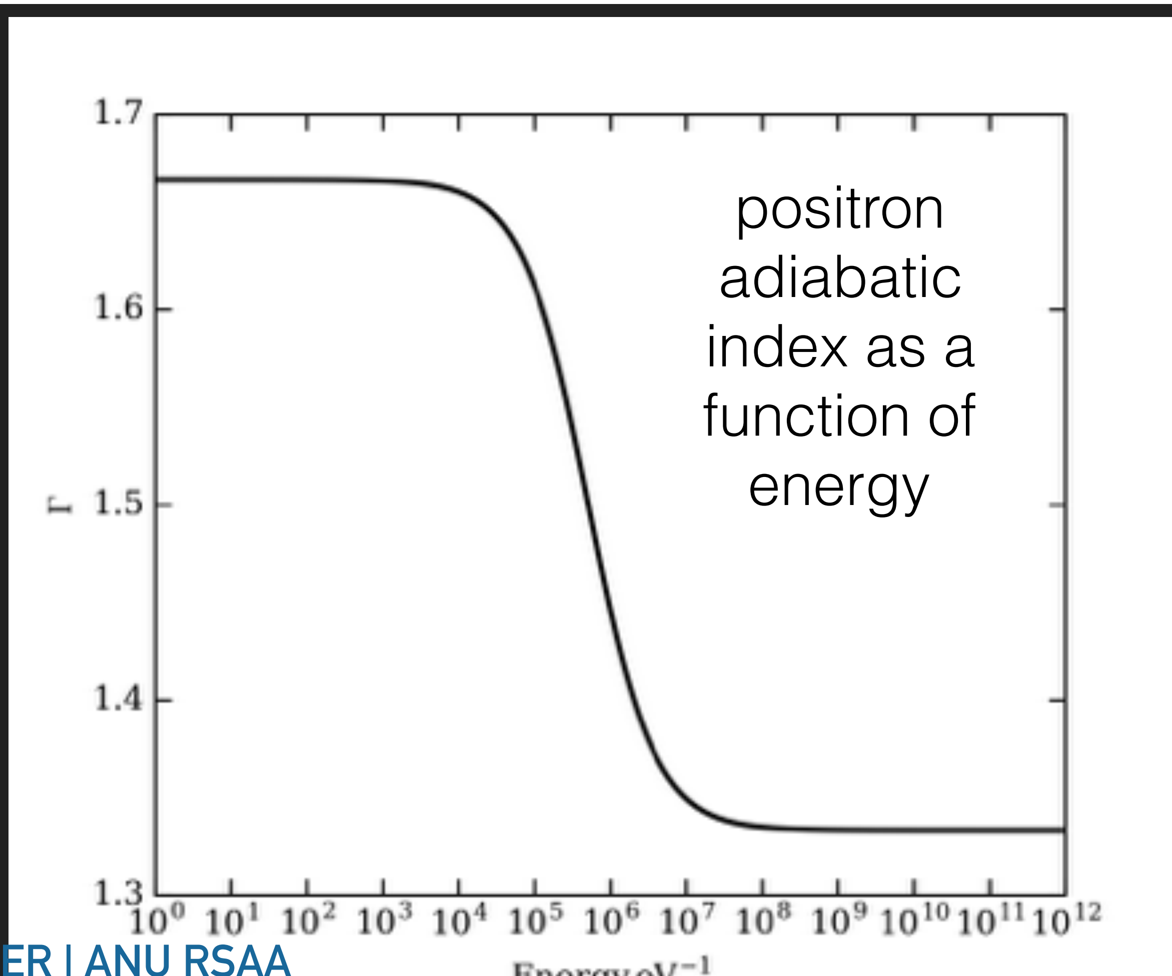
- Positrons travel outwards at wind velocity v

- Positrons are injected at the wind launching radius with initial energy w_0 and followed until they thermalize (and annihilate 'instantly' - cf Panther+2018c)

- The radius at which the positron annihilates is recorded, as is the ISM temperature where the positron annihilates

POSITRON MICROPHYSICS





Positrons are 'mildly' relativistic:
Radiative losses through ionisation and coulomb losses. Other processes make negligible contribution

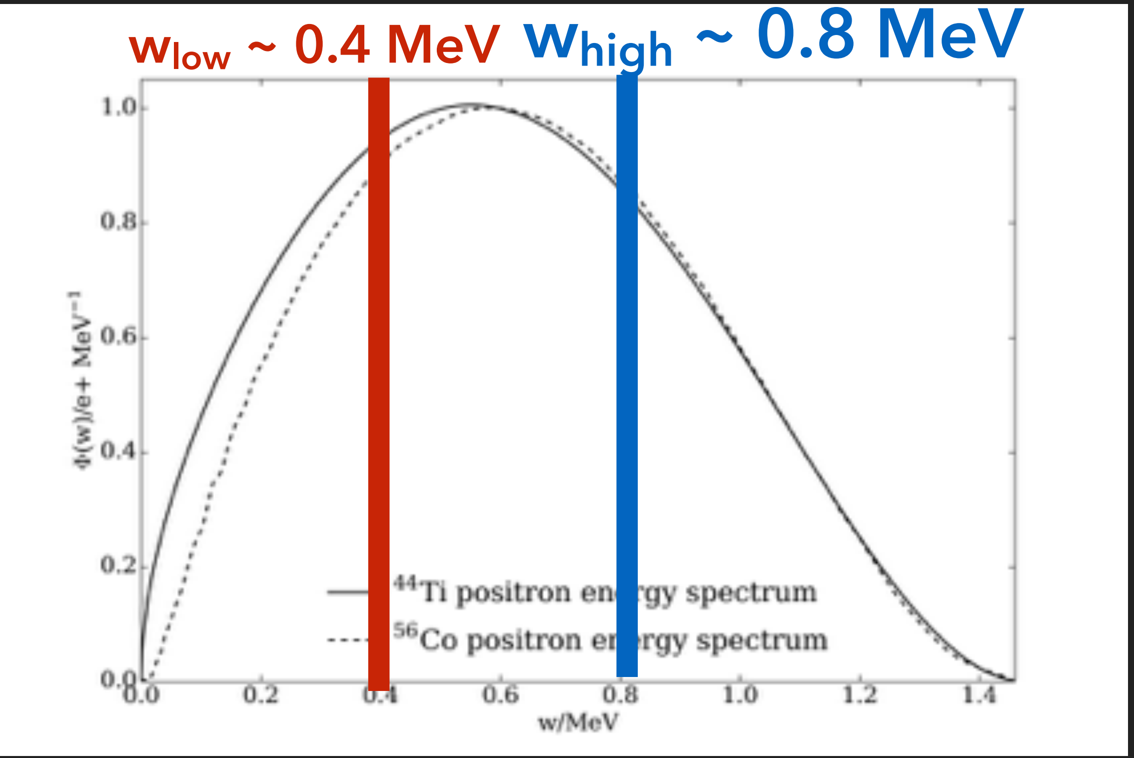
Adiabatic losses dominate over radiative processes:
Adiabatic index allowed to vary (w/ assumption of ideal EoS)

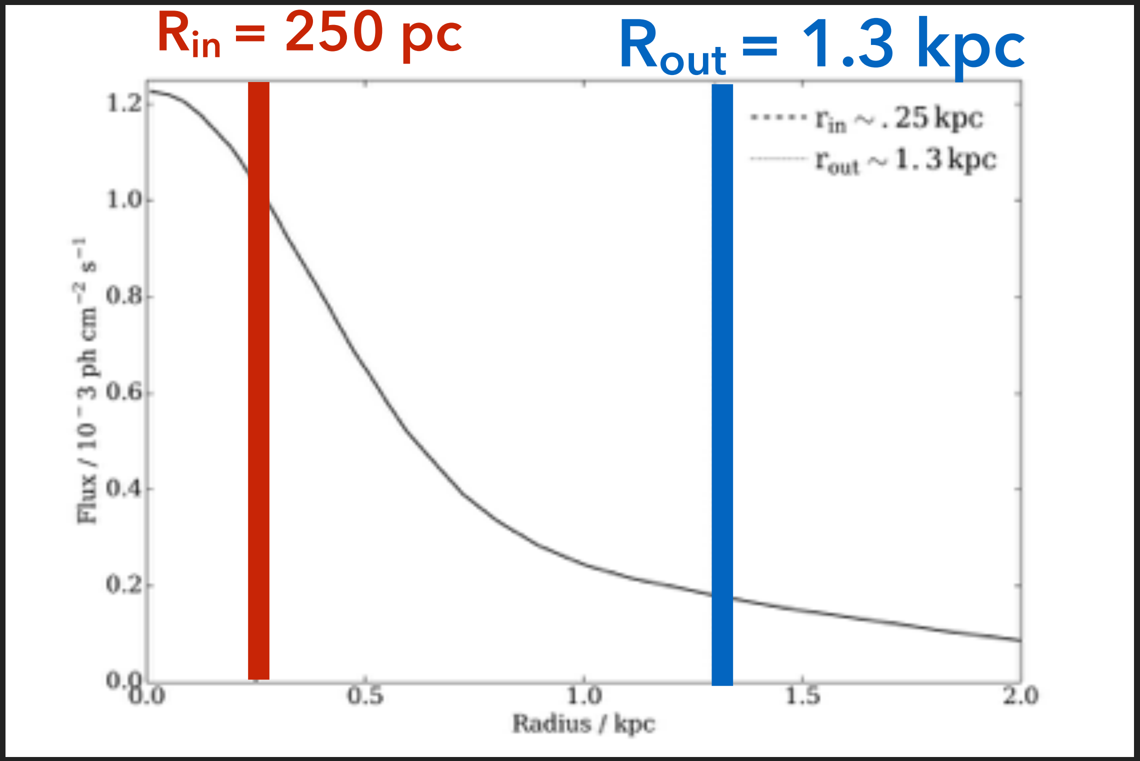
$$\left.\frac{dw}{dt}\right|_{\mathrm{ad}} = -2\frac{(\Gamma-1)v[t]w_0}{(r_0+v[t]t)}\left(\frac{\rho[t]}{\rho_0}\right)^{\Gamma-1}$$

Panther+2018a

ANALYSIS

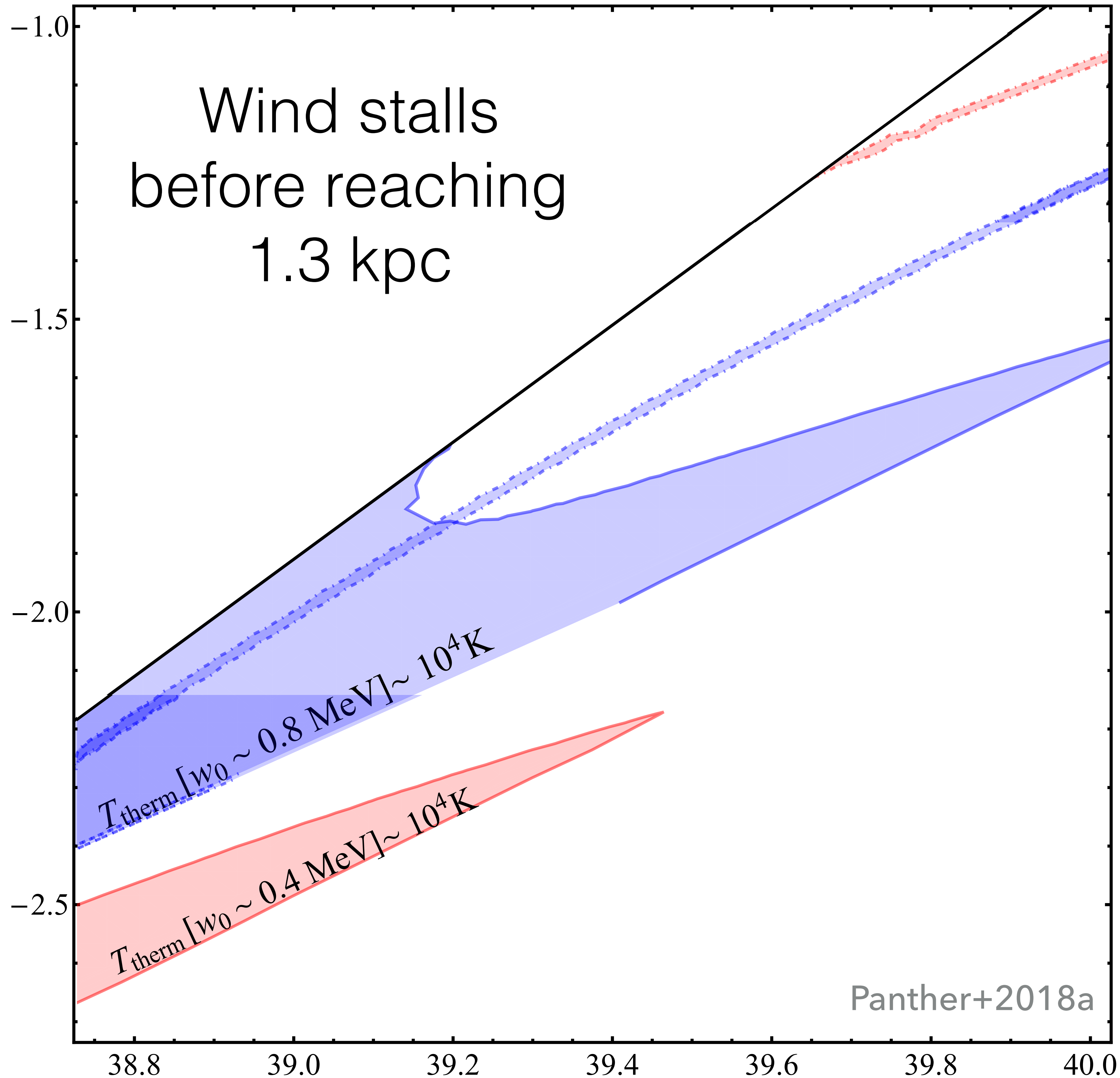
- We introduce a parameterisation of the Galactic bulge model intensity profile, and the positron injection energy spectrum
- The smooth, Gaussian model describing the 511keV morphology is a model and care should be taken not to overinterpret the model. The real emission may not be smooth.
  - w_{low}, w_{high}: mean energy at which 50% of positrons are injected into the ISM
  - R_{in}, R_{out}: mean radii at which 50% of positrons annihilate based on the intensity profile





RESULTS

Log[Mass flux in Solar masses per year] (from stellar winds, SNe)



Log[Energy flux in erg per second] (from stellar winds, SNe)

POSITRONS AND THERMONUCLEAR SUPERNOVAE

with Roland M. Crocker, Ivo Seitenzahl, Ashley Ruiter, Stuart Sim, Chris Lidman

INTROUCTION

- The optical light curves of SNe Ia are powered by the decay of radioactive material, specifically from the ^{56}Ni decay chain

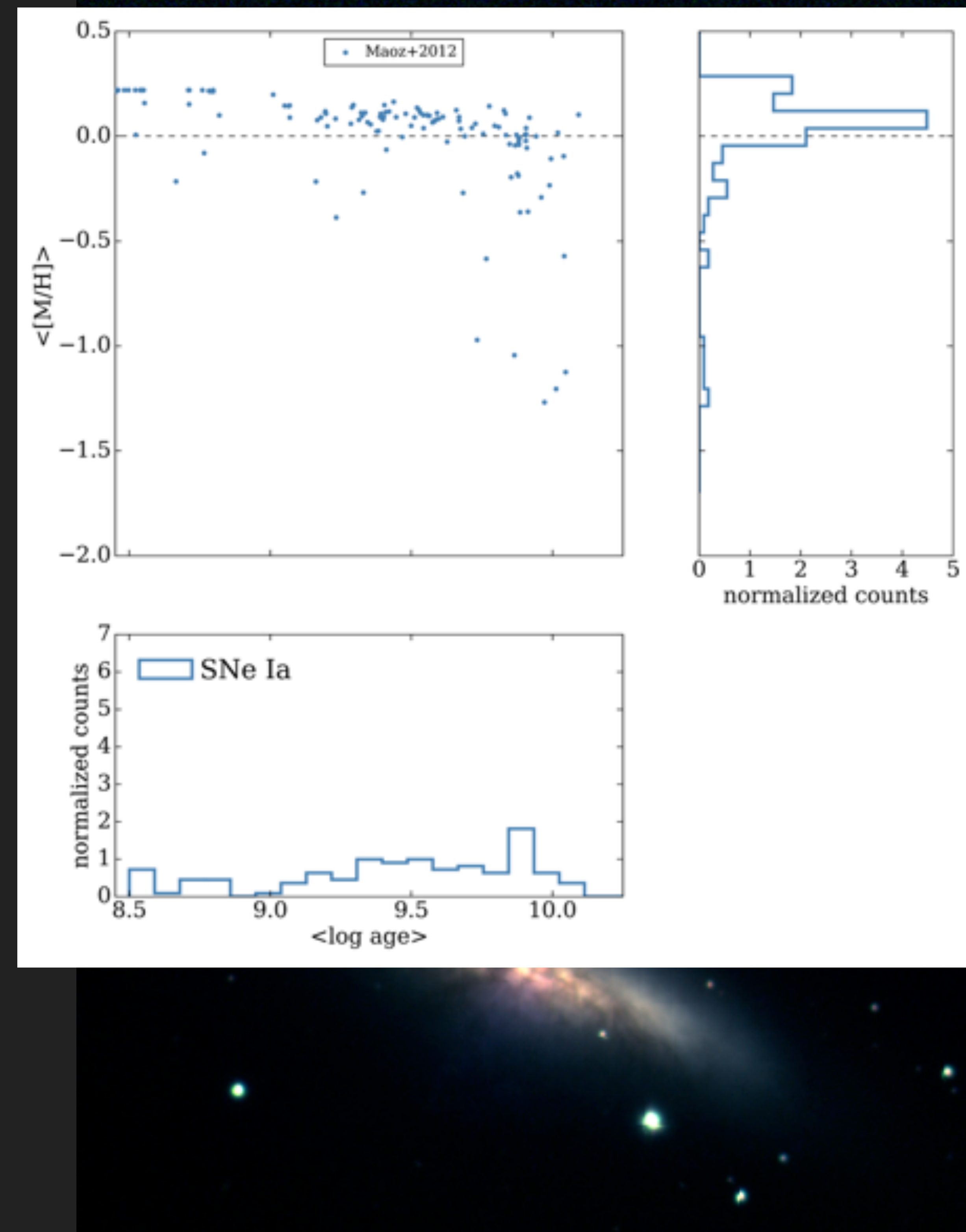
- ^{56}Ni -> ^{56}Co + y -> ^{56}Fe + e^{+} + y

- The deposition of e^{+} kinetic energy powers the IR light curve at late times (100+ days)

INTRODUCTION

- Gamma ray observations of SN2014J provided direct evidence for the synthesis of radioactive ^{56}Ni (Churazov+2014, Siegert & Diehl 2015, Churazov+2015)
- Thermonuclear supernovae have been suggested as the origin of Galactic positrons for a long time (Chan & Lingenfelter 1991, Milne+1999, Prantzos +2006, 2011) but escape fractions are uncertain by up to an order of magnitude
- The expected distribution of SNe Ia in the Milky Way does not reflect the distribution of positron annihilation - **SNe Ia are NOT associated with 'old' stellar populations** (Panther+2018 in prep)

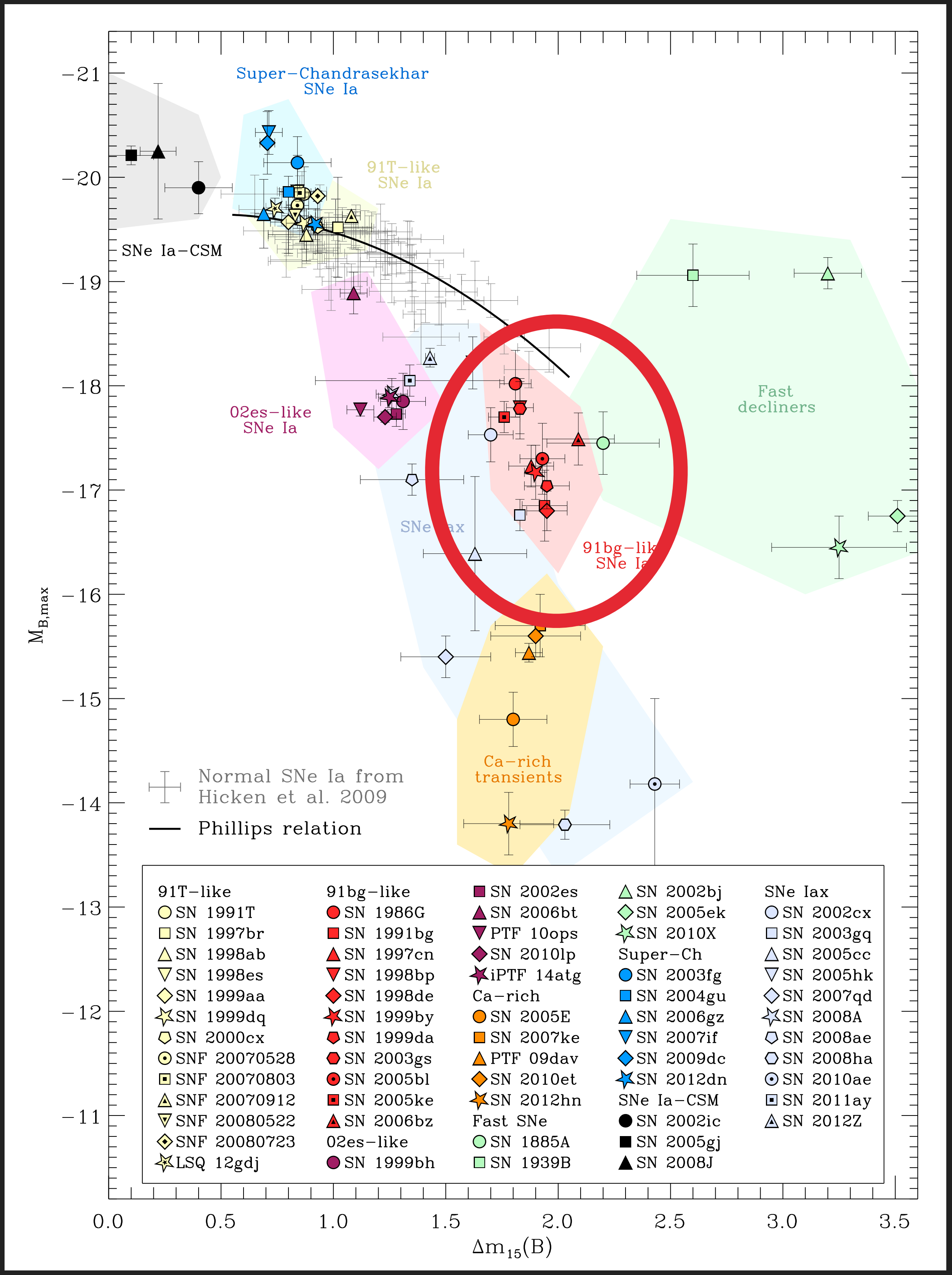
Panther+2018d in prep.



TYPE IA SUPERNOVA DIVERSITY

- Not all SNe Ia are the same: even 'normal' SNe Ia (the ones used as standardisable candles) show diversity

- We do not fully understand the progenitors, explosion mechanisms nor nucleosynthesis in thermonuclear supernovae



Taubenberger 2017

WHAT SORT OF TRANSIENT COULD EXPLAIN GALACTIC POSITRONS

- Require a transient that replicates the total rate of positron production in the Galaxy, and the relative production rates in the Galactic bulge, disk and nuclear bulge

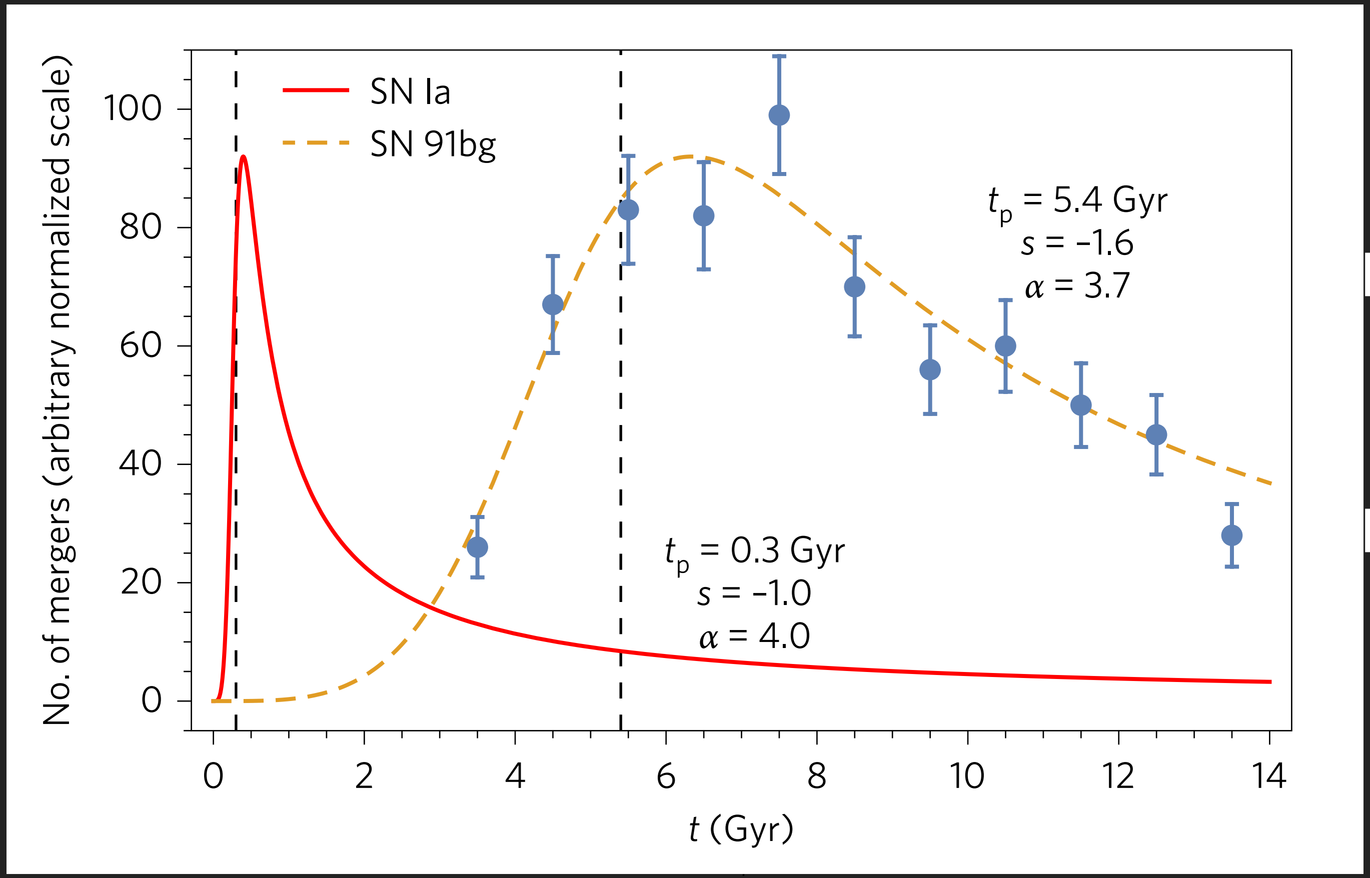
$$B{:}D_{observed}/B{:}D_{model} = 1$$

A number (from Siegert+2016)

$$B{:}D_{model} = \frac{\text{Rate of e+ prod. in disk}}{\text{Rate of e+ prod. in bulge}}$$

$$B{:}D_{model} = \frac{\text{Rate of transient in disk} * \text{e+ per event}}{\text{Rate of transient in bulge} * \text{e+ per event}}$$

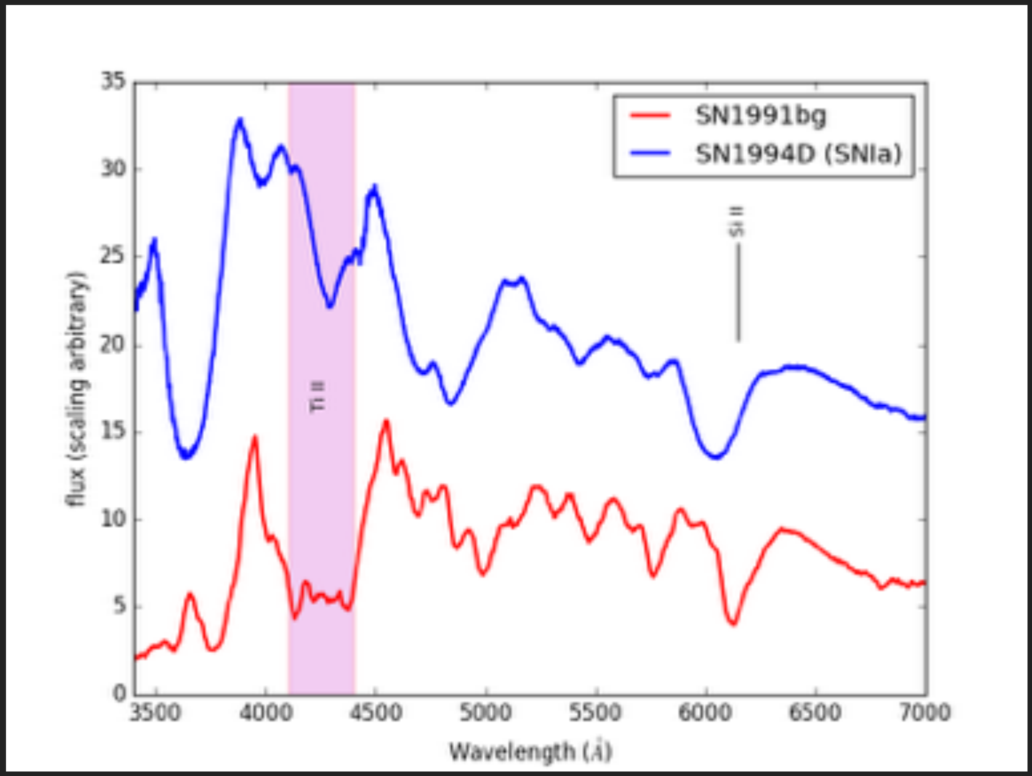
$$B{:}D_{model}[tp] = \frac{\text{Rate of transient in disk [tp]}}{\text{Rate of transient in bulge [tp]}}$$

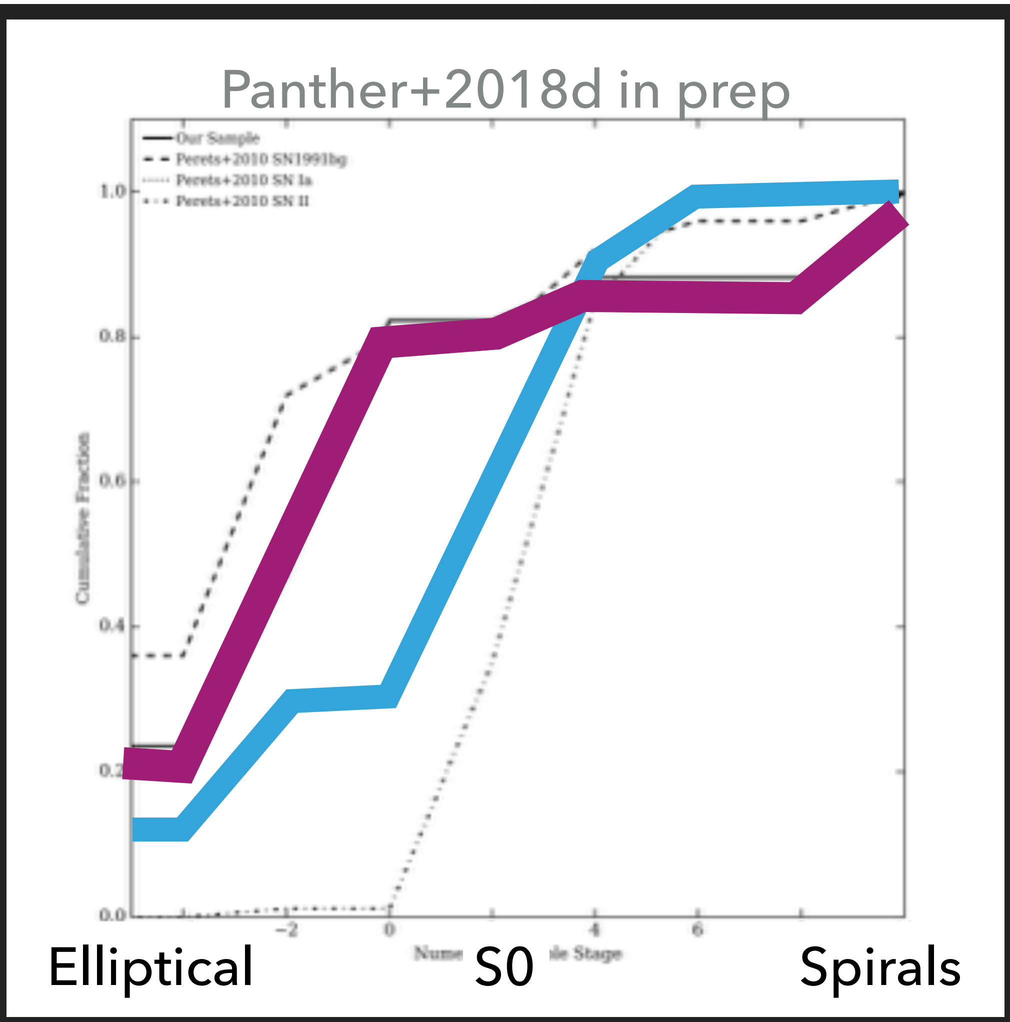


$$\text{Rate of transient in region [tp]} = \int \text{Star Formation Rate [t]} * \text{Delay Time Distribution [t, tp]} \; dt$$

ONE POSSIBILITY: 1991BG-LIKE SUPERNOVAE

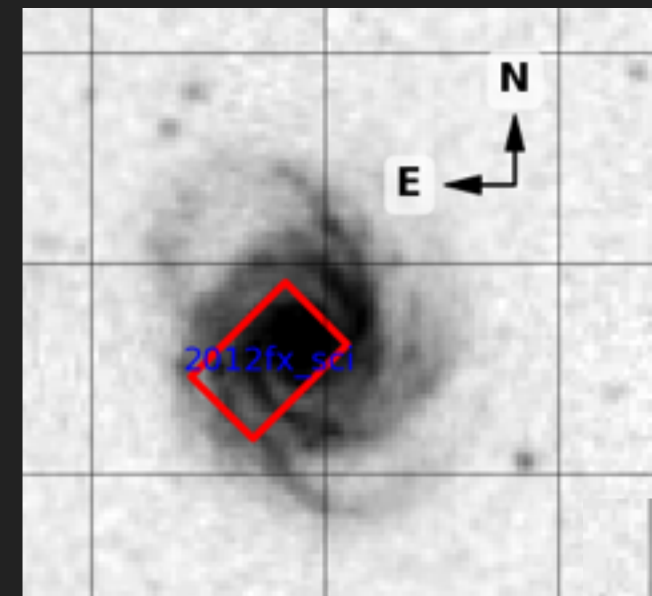
- In Crocker+2017, we identified SN1991bg-like supernovae as a possible positron source
- Subclass of thermonuclear supernovae (Type Ia supernovae - SNe Ia)
  - No hydrogen in spectra, strong Si II in absorption
- The largest subclass of peculiar SNe Ia - ~15% of all SNe Ia, and ~30% in early-type galaxies
- Peculiar both **spectroscopically** and **photometrically**:
  - Photometrically: sub-luminous at maximum light, “fast decliners”
  - Spectroscopically: Strong Ti II in absorption



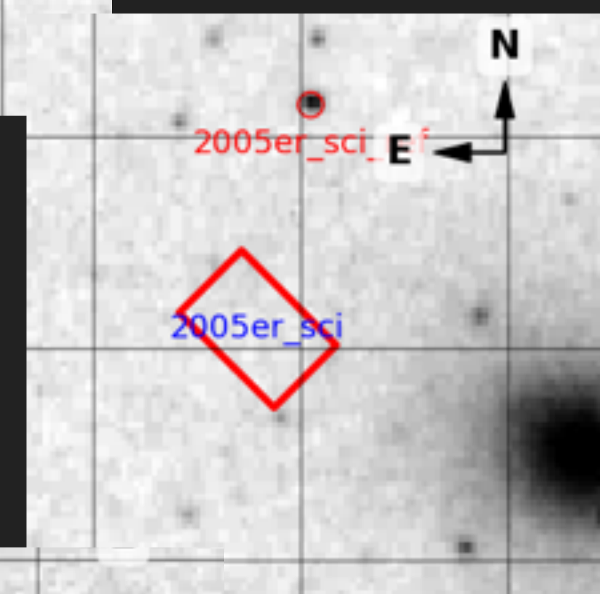


OBSERVING THE HOST GALAXIES OF ‘POSITRON FACTORY’ SUPERNOVAE

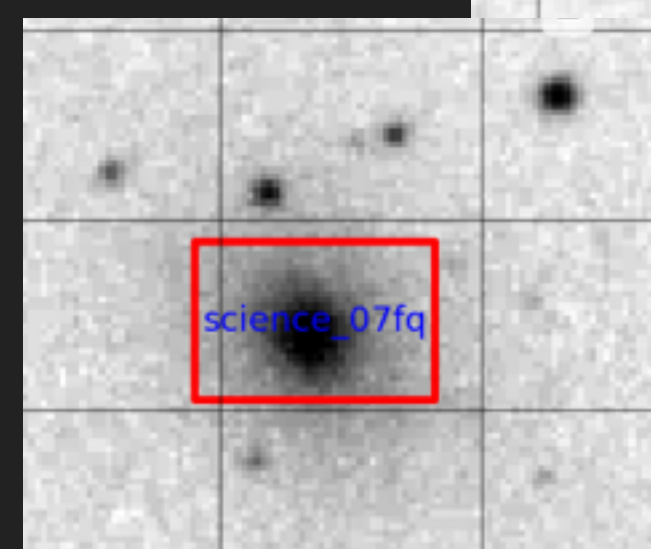
- Wide Field IFU observations with ANU 2.3m Telescope and WiFeS
- 38″ x 25″ aperture centered on SN location, even if SN is offset from host - want the properties local (~few kpc) of the SN location
- SNe 91bg are selected from the spectroscopically confirmed BSNIP sample (Silverman+2012)
- Classical observing, with 4-6 x 1200s science exposures, with 2 x 900s sky exposures
- Final sample of 12 spectra extracted from 3″ x 3″ seeing-limited aperture centered on SN location
- Ask me if you’re interested - I could give an entire separate talk on this



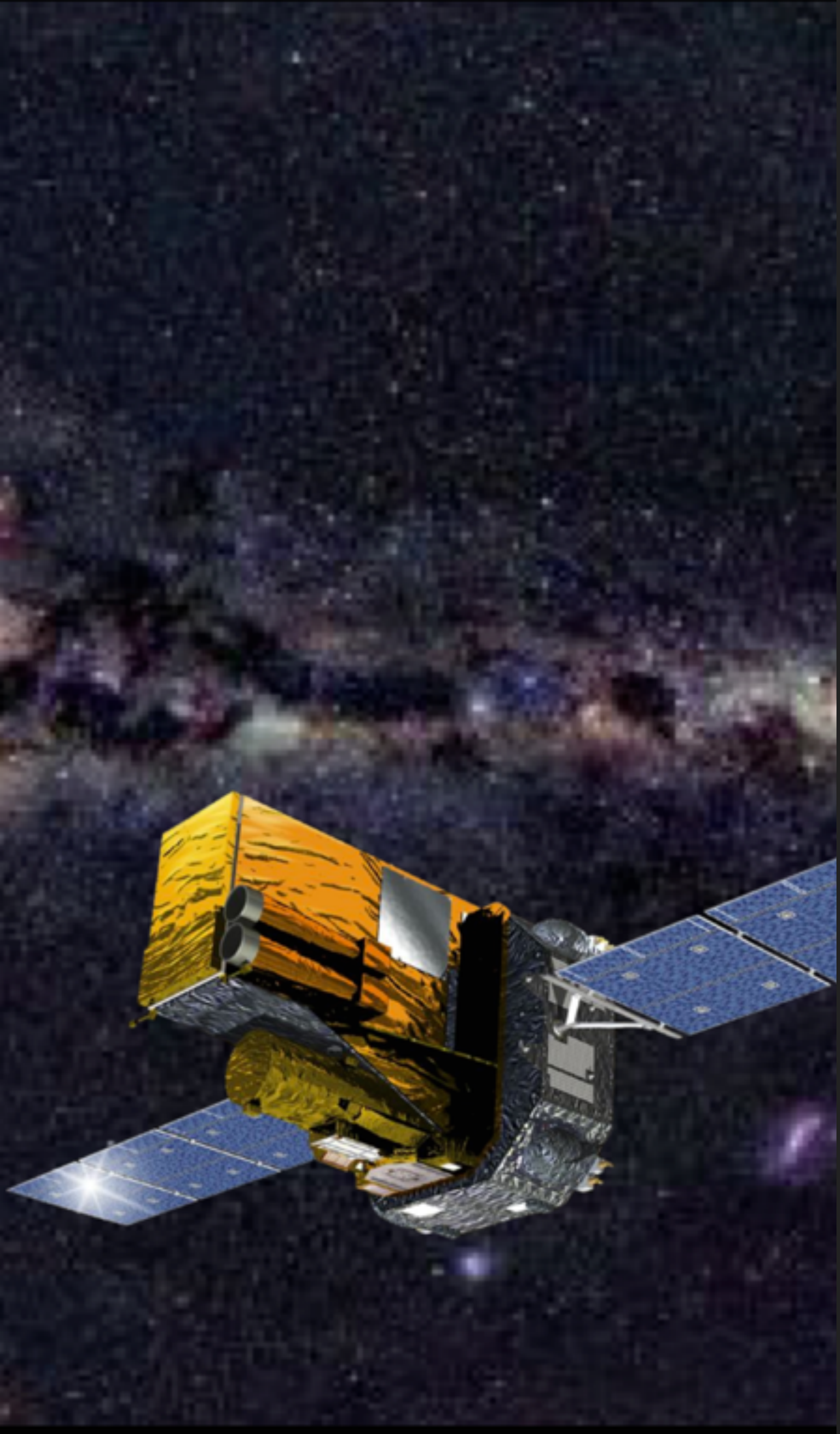
Spirals



Large offset



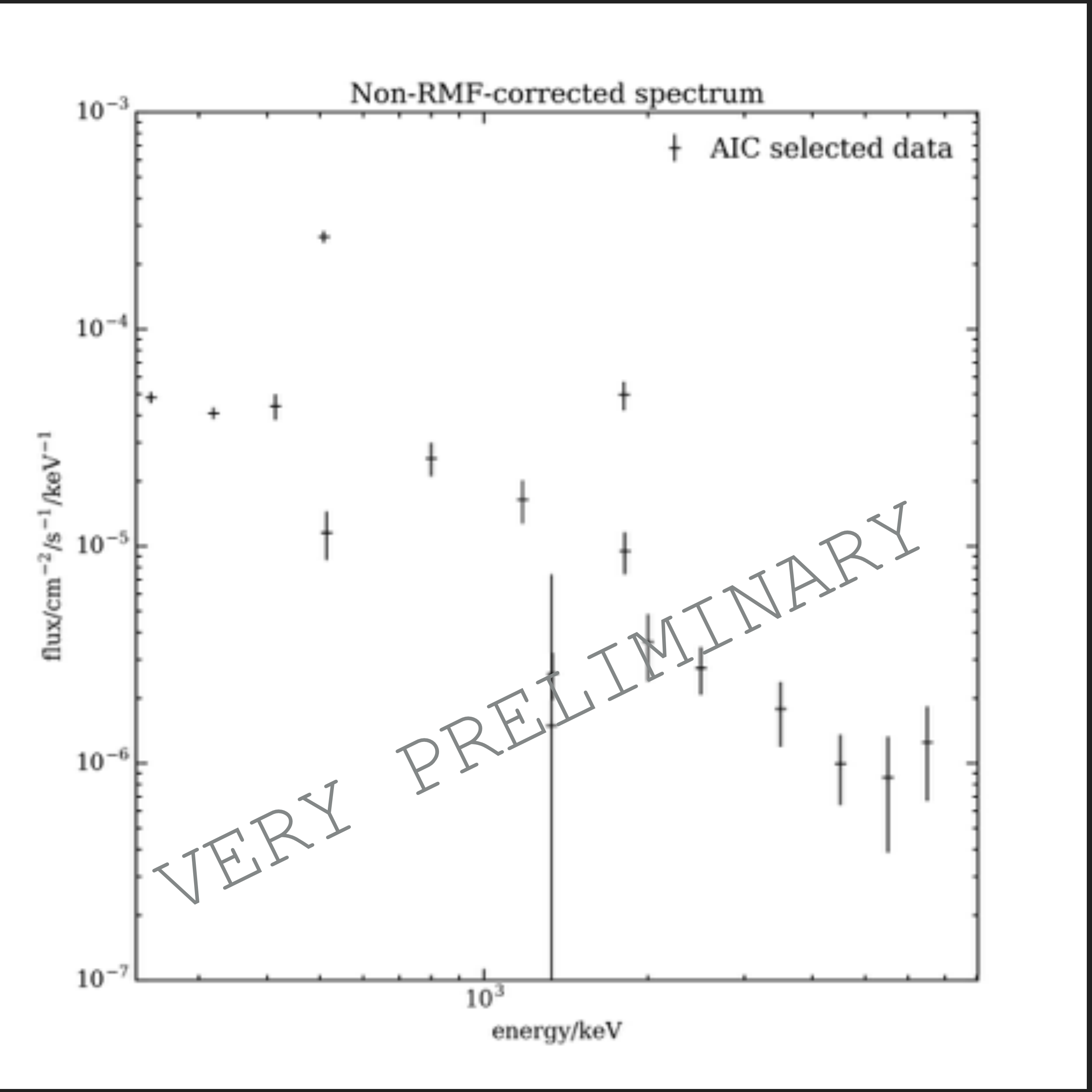
Ellipticals/S0



LOOKING FORWARD WITH INTEGRAL

LOOKING FORWARD WITH INTEGRAL

- Understanding of the backgrounds associated with INTEGRAL (Diehl+2018) means we are are in an exciting time for MeV gamma-ray astronomy
- Longitude-velocity diagram of the 511keV line in the Galaxy (Siegert+2018 subd.)
- New constraints on positron injection energy in the inner Galaxy
- Extending INTEGRAL coverage to high latitudes - the Milky Way halo and the Fermi Bubbles (TIMELESS, PI Bodaghee)
- Lots of other exciting work happening here at MPE



SUMMARY

- Positron astrophysics is still in its early days of development, but provides a **unique possibility of understanding cosmic ray propagation**
- **Connecting lab-based experiments to astrophysical observations via simulation** will be key to decoding information in the positron annihilation spectrum
- Understanding the origin of Galactic positrons is key to better understanding the **chemical evolution and nucleosynthesis in our Galaxy** and external galaxies
- **The MeV gamma-ray regime is an important window into processes that shape galaxies** across cosmic time in the multi-messenger era
- We are only beginning to scratch the surface of **understanding the diversity of thermonuclear supernovae**
- I am on the job market, and will be at MPE until tomorrow afternoon if you have questions about my work.

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