Gamma-ray Lines in the INTEGRAL Era

INTEGRAL Workshop 2024

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Radioactivity plays a key role …

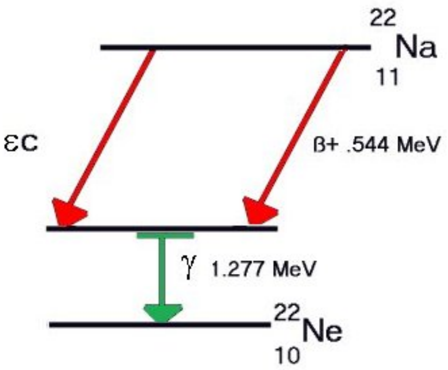
in the understanding of the synthesis of the elements – clearly newly created isotopes.

Not only through gamma-ray observations, but also in early solar system, and in grains condensed from stellar outflows.

Donald D. Clayton
1935 -- 2024

γ-ray lines from radioactive nuclei

- Radioactive nuclei are excellent diagnostics of the burning conditions in nearly inaccessible regions
- Decay rate independent of temperature, density, etc.
- Relevant transitions are practically unique
- Nuclei must reach γ-ray thin regions (see and count the new nuclei)

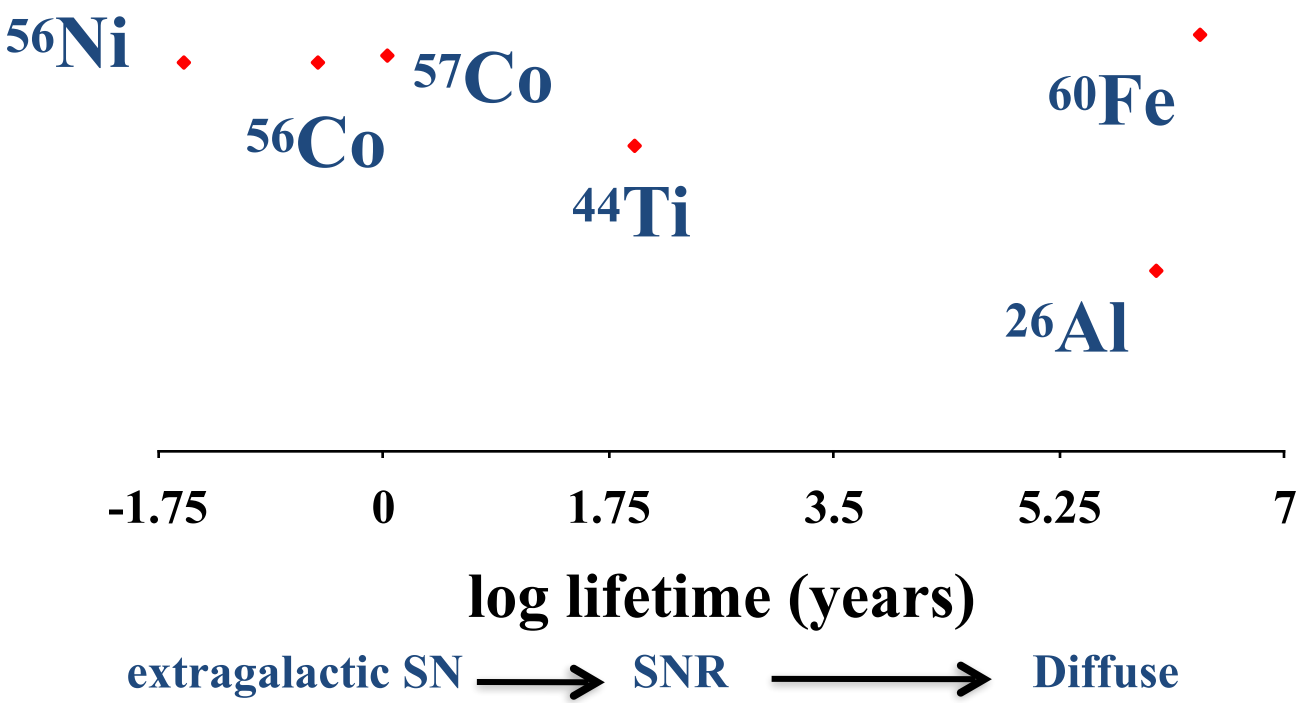


- Some are main source of stable daughter (^{44}Ti,^{56}Ni); some just tracers of nucleosynthesis (^{26}Al, ^{60}Fe)

γ-ray lines from radioactive nuclei

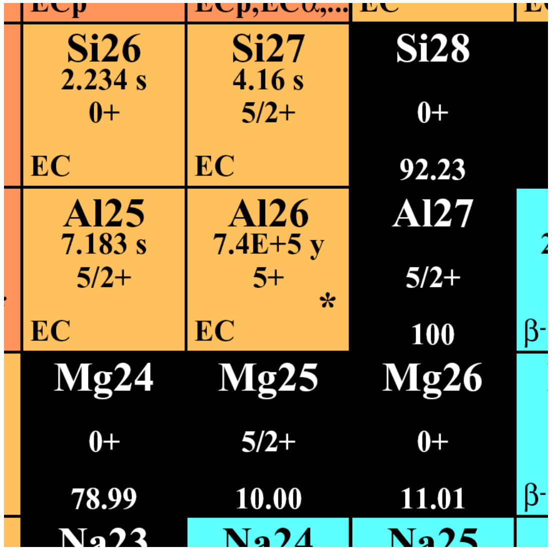
Isotope lifetimes

- Long-lived isotopes (greater than interval between events) → 'diffuse' emission.
- Short-lived isotopes → clarify nuclear processing (and dynamics) of single events.



^{26}Al

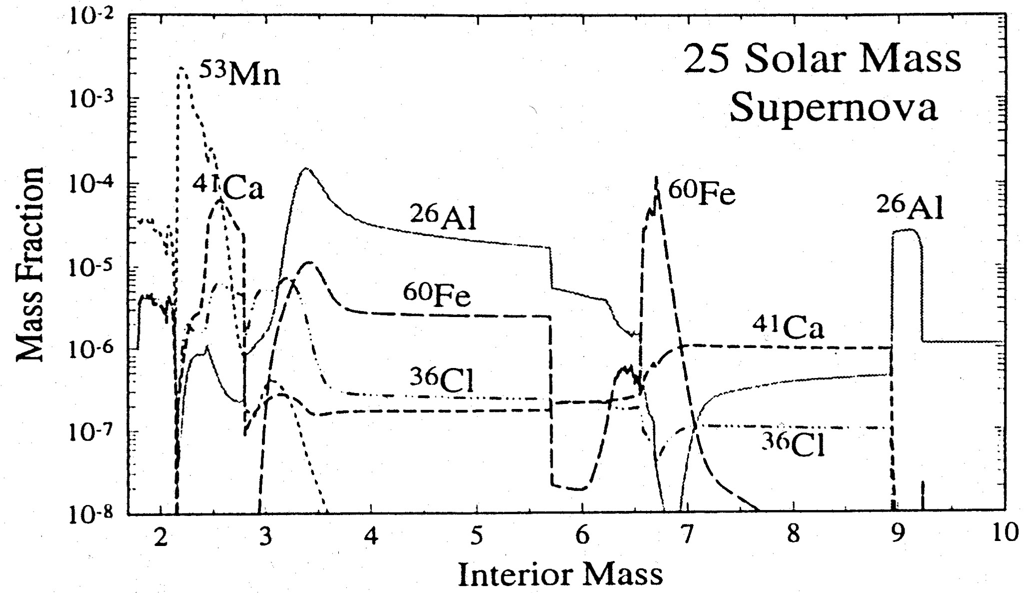
1809 keV   1.04 My



^{25}Mg + p → ^{26}Al + γ

Massive star winds
Core-collapse SNe*
Classical novae*
AGB stars*

Alive in early Solar System, and
*found in presolar grains



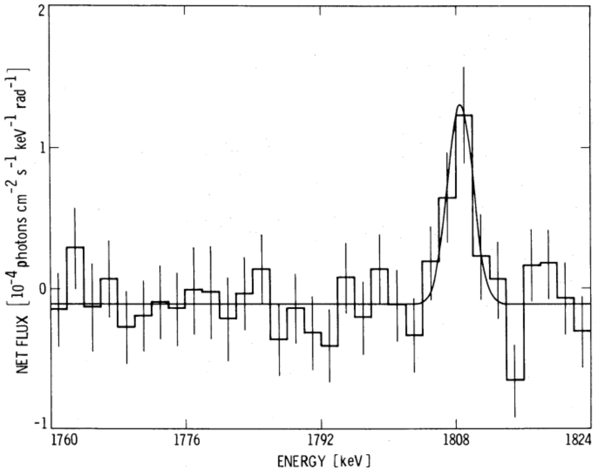
Woosley & Weaver 95

^{26}Al

- Predicted γ-line emitter from supernovae based on general grounds (Arnett 1977, Ramaty & Lingenfelter 1977)
- Discovered by HEAO 3 Ge spectrometer (Mahoney et al. 1982, 1984)

$$4.8 \pm 1.0 \times 10^{-4} \; cm^{-2} \; s^{-1} \; rad^{-1}$$

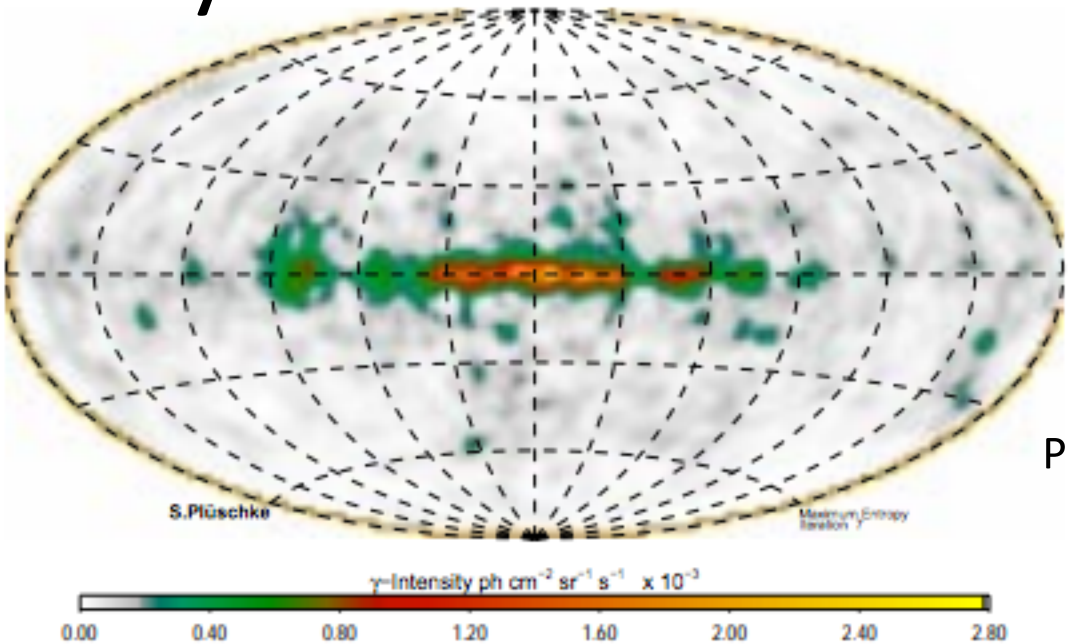
- $$\rightarrow \; 3 M_\odot \text{ in ISM}$$



"more than expected from supernovae … likely … galactic novae"

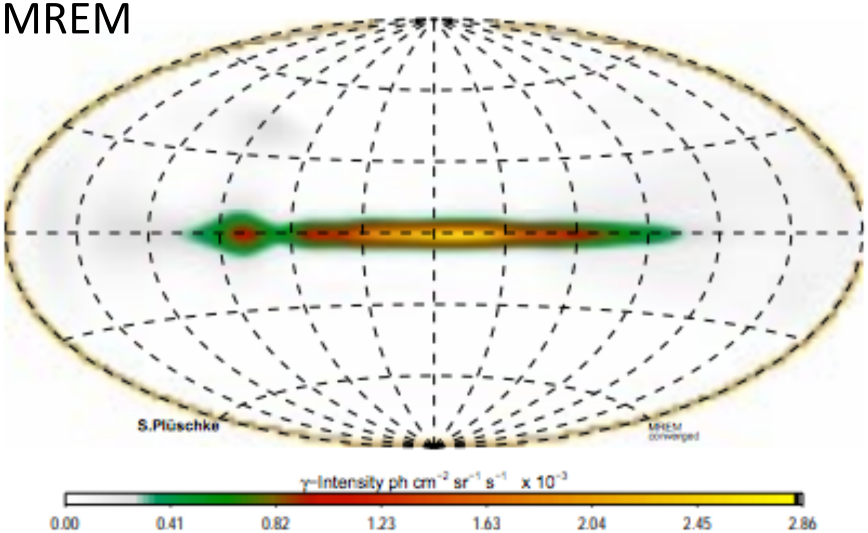
COMPTEL 9 years

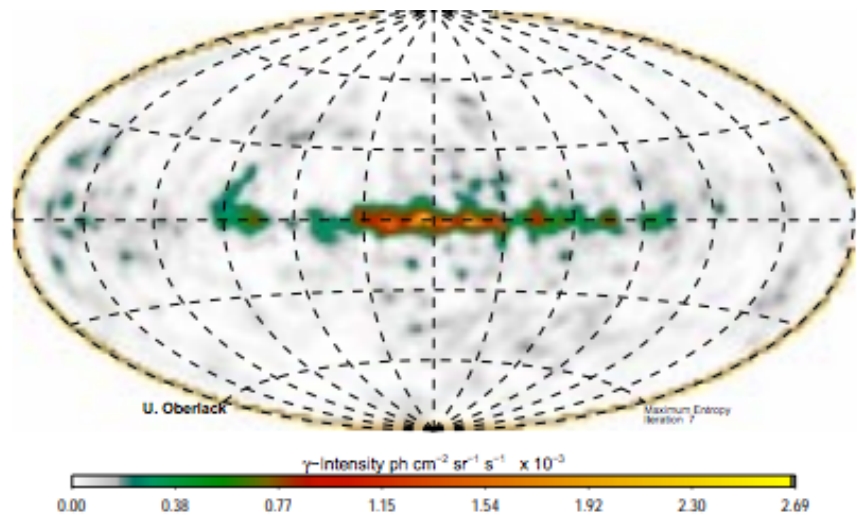
An image for the textbooks



Plüschke et al. 2001

MREM



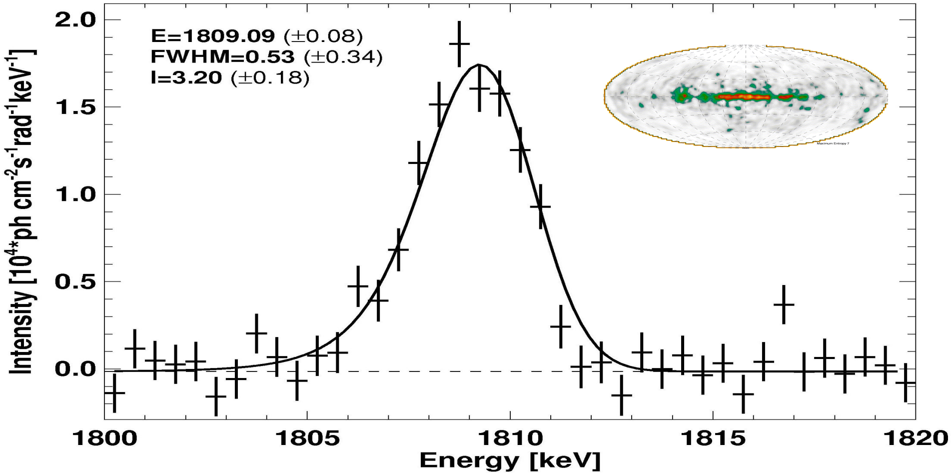


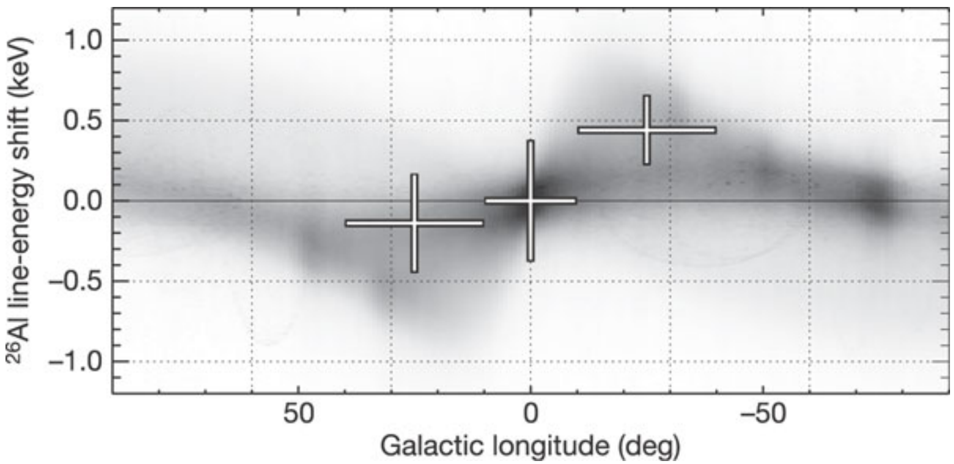
Circa 2002

- How smooth is the actual 26Al distribution?
- Are the maps dominated by whole-disk emission, or mainly relatively local sources?
- What is the ^{26}Al yield from individual sources?
- What are the contributions of classical novae, AGB stars?

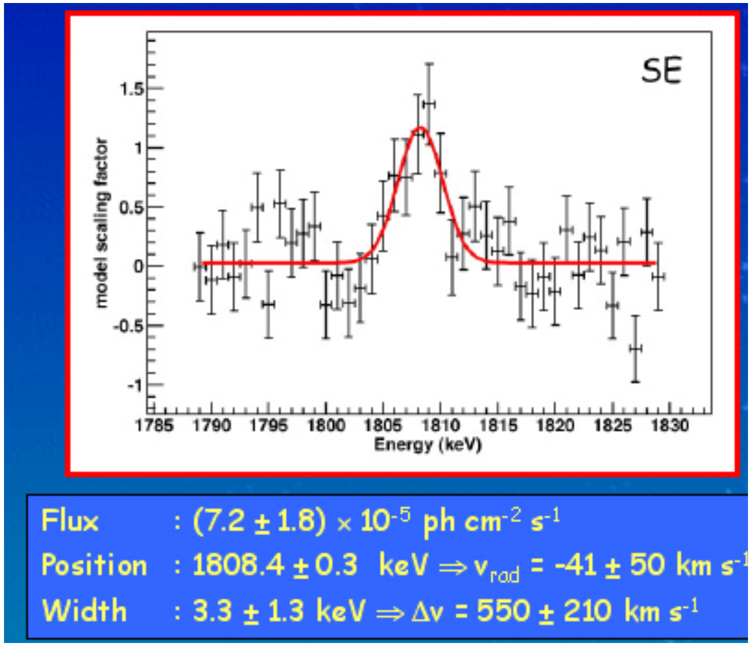
INTEGRAL/SPI ^{26}Al Observations

Central galaxy: Diehl et al. 2006

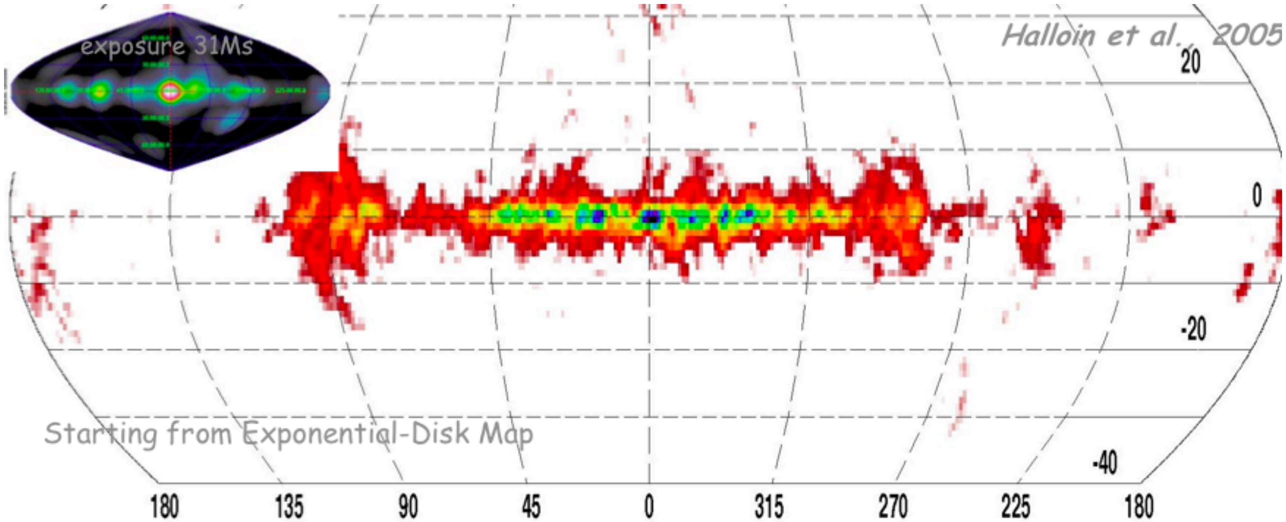


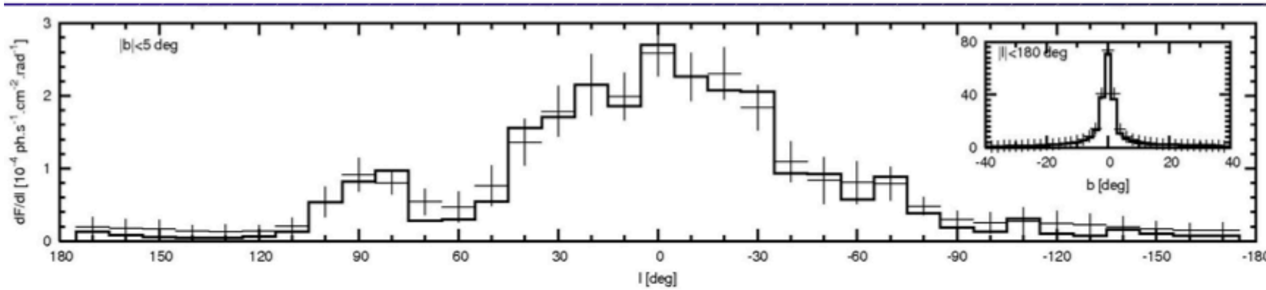


Cygnus OB Association: Knödlseder et al. 2004



INTEGRAL SPI – ^{26}Al





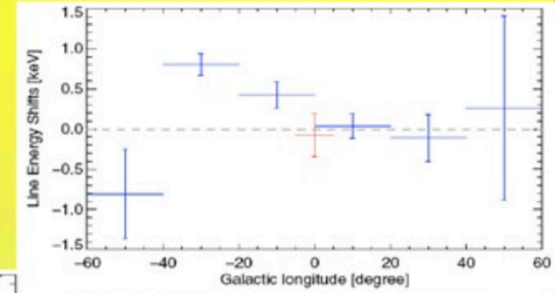
Summary:

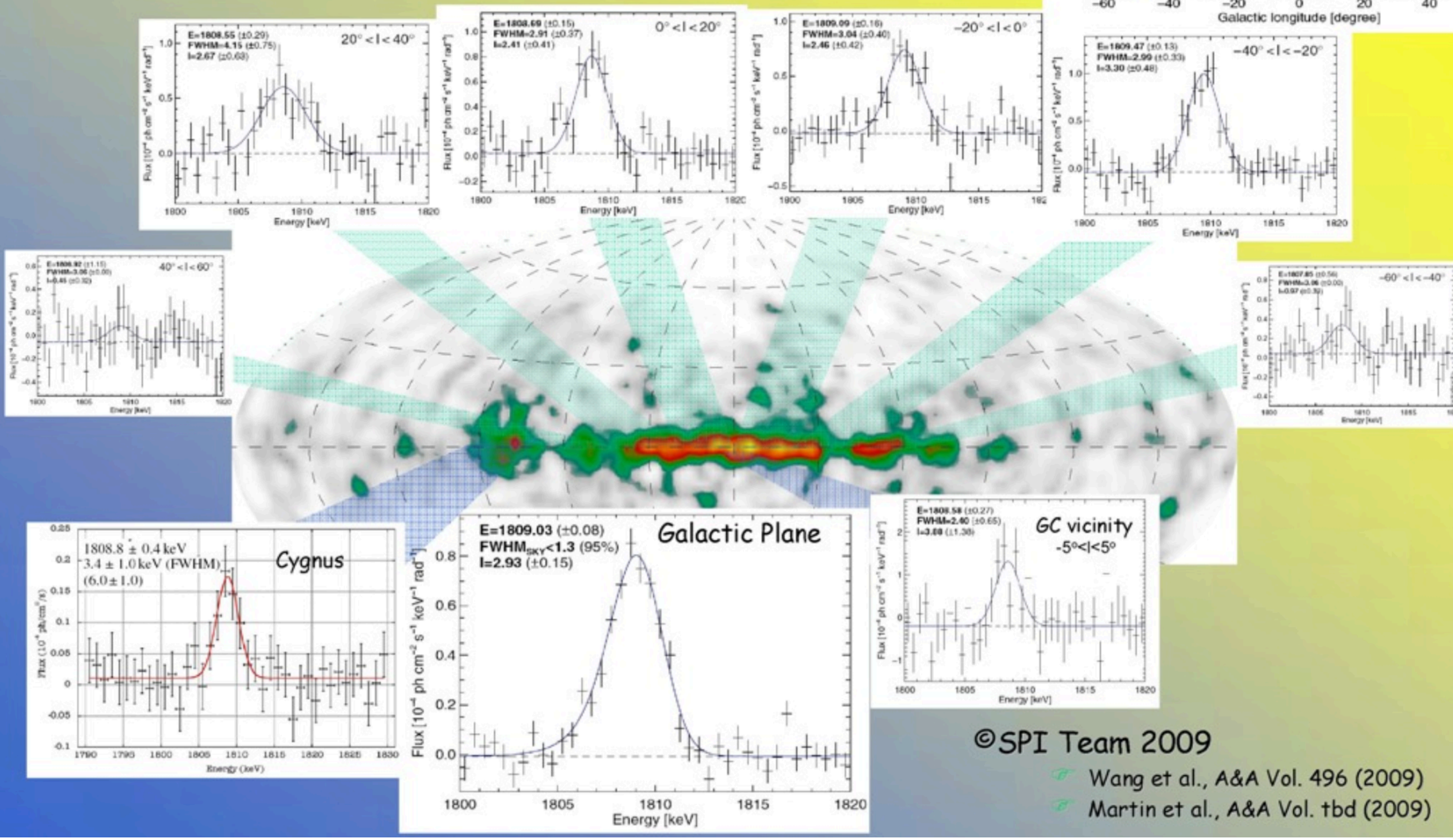
Flux (1.809 MeV) = 4.0 10^{-4} cm^{-2} s^{-1} --> $M_{ism}(^{26}Al)$= 2.5 $M_\odot$

e.g. core collapse SNe at 2.5 century^{-1} with $M_{ej}(^{26}Al)=10^{-4}$ $M_\odot$

And progenitor winds

^{26}Al Spectra along the Plane of the Galaxy





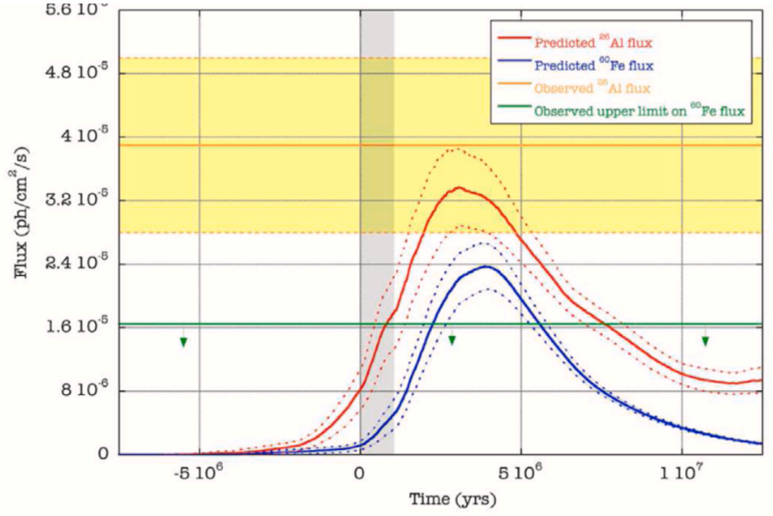
©SPI Team 2009

- Wang et al., A&A Vol. 496 (2009)
- Martin et al., A&A Vol. tbd (2009)

OB associations

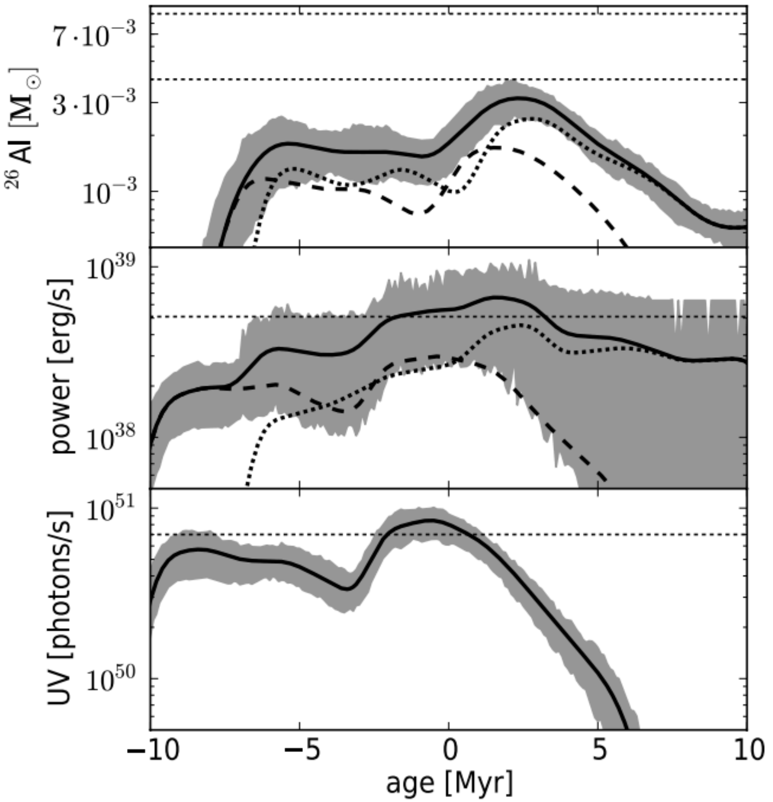
Population synthesis code matched to observed stellar components, predicting radioactive and energy content. Voss et al. 2010, 2012

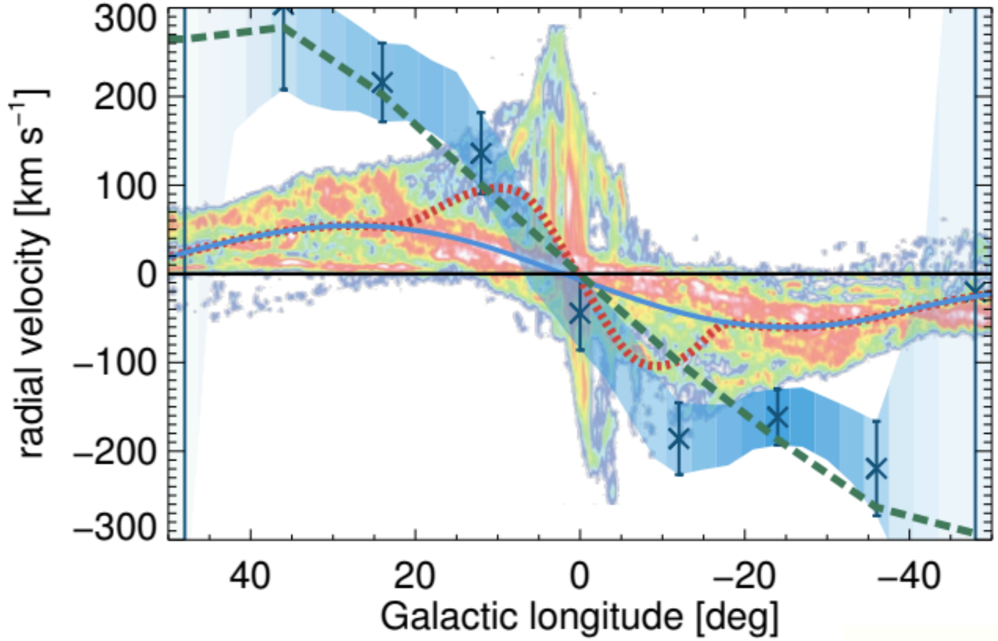
Cygnus



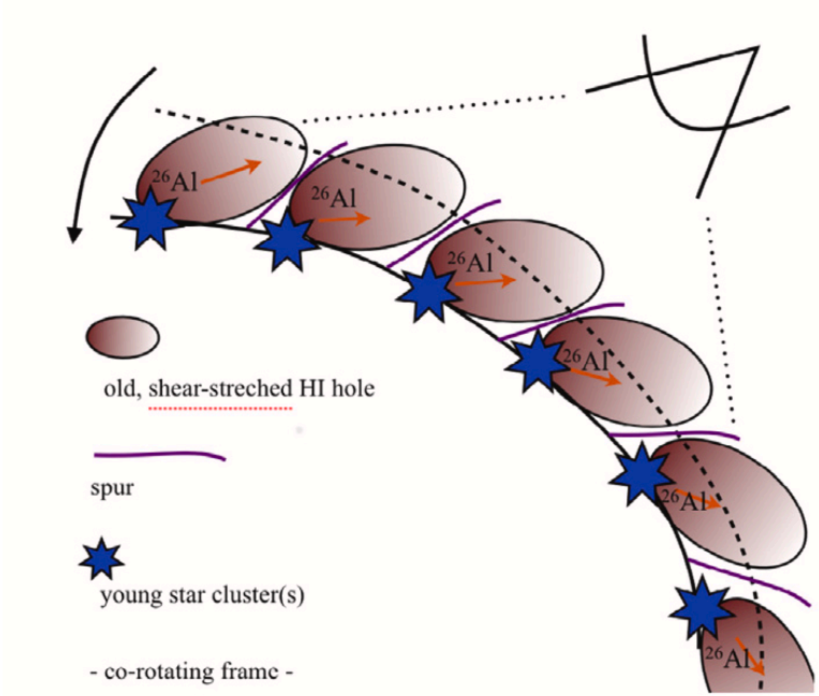
Martin et al. 2010

Carina



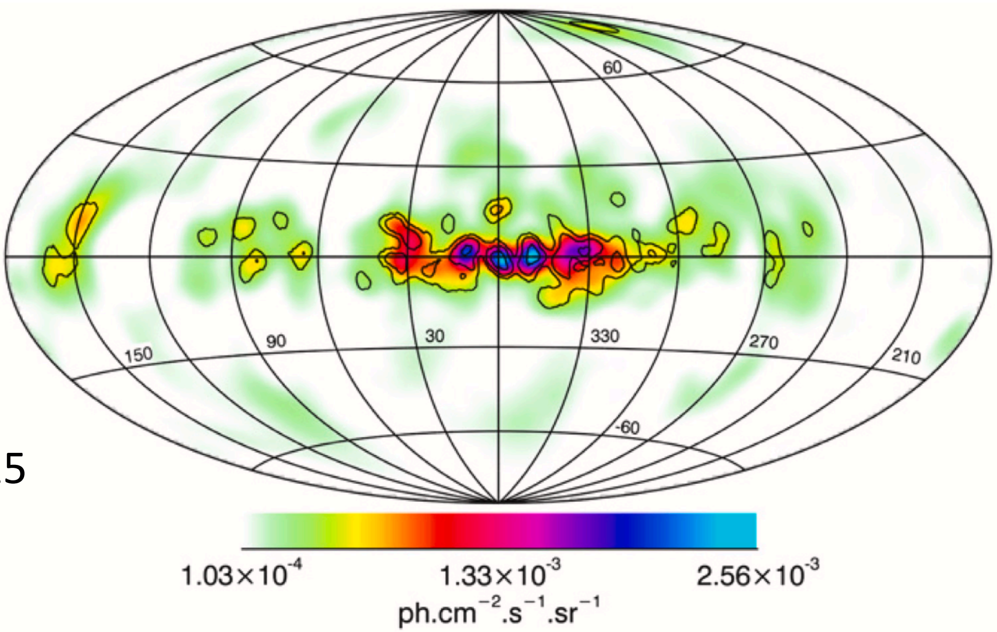


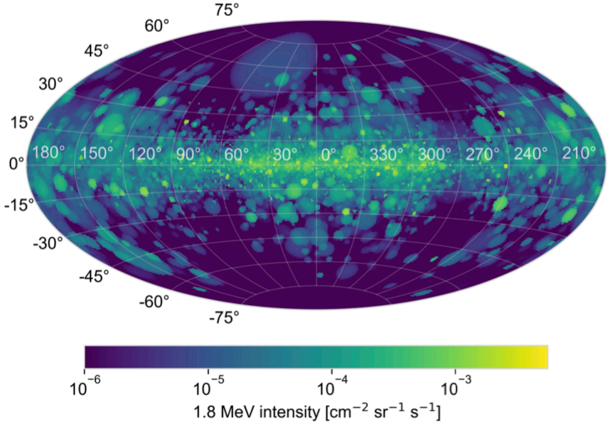
Kretschmer et al. 2013



Krause et al. 2015

SPI mapping





)15

Theoretical studies:

Nuclear rates/nucleosynthesis (Battino et al. 2023)

Population Synthesis – SNe do yield patchy distribution (Siegert et al. 2023)

Chemical Evolution – SNe insufficient; novae required (Vasini et al. 2024)

SPI 15 years

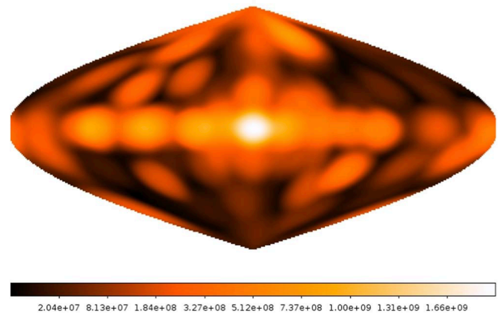


Figure 1. Exposure sky map of the fully coded field of view in Galactic coordinates (the number at the color bar in units of seconds) for the data selected from 15 yr SPI observations for our ^{60}Fe and ^{26}Al study (*INTEGRAL* orbits 43–1950).

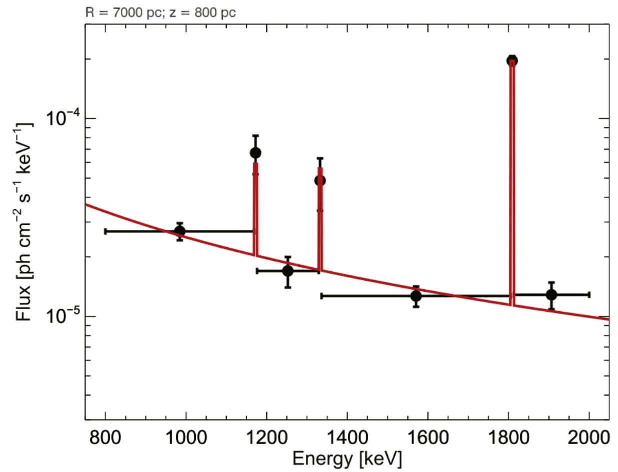
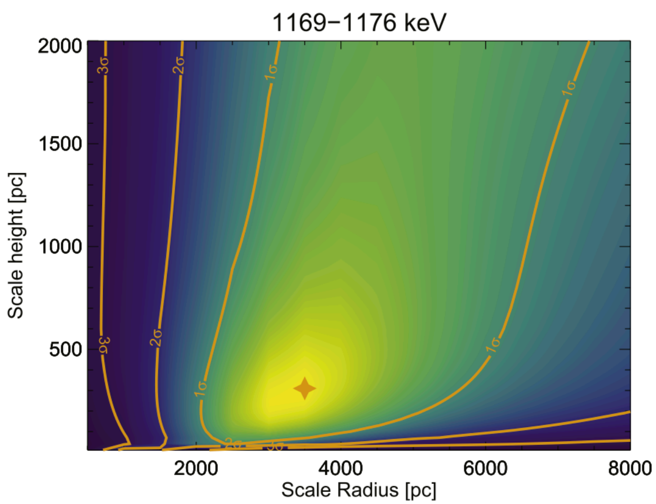
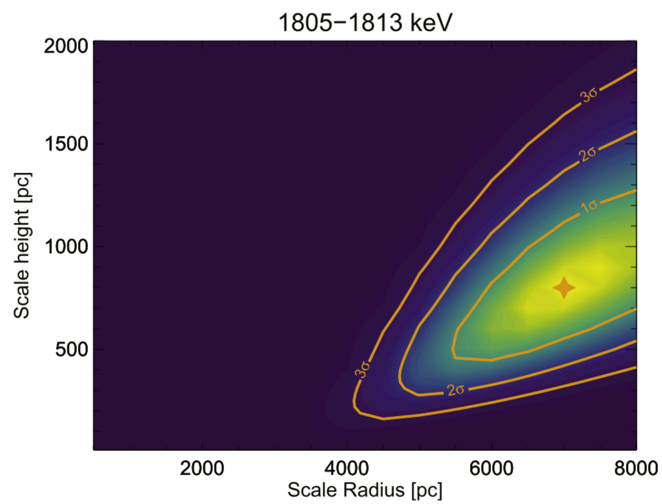


Figure 5. Spectral intensities (black) obtained from the fit to an exponential disk model with $R_0 = 7$ and $z_0 = 0.8$ kpc. The fitted total model, Equation (4), is shown in red.

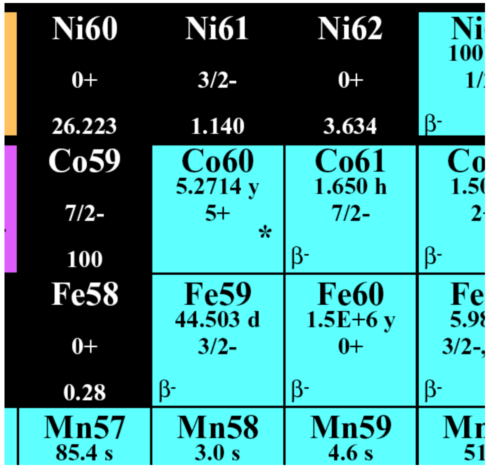


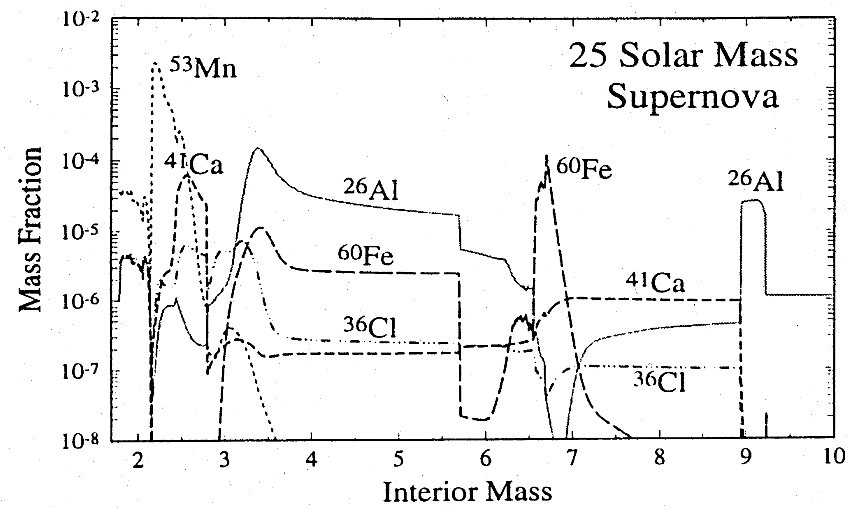


Wang et al. 2020

^{60}Fe 2.6 (3.8) My

1173,
1332 keV





Woosley & Weaver 1995

- Predicted by Clayton 1971, Nature
- HEAO 3 and SMM upper limits
  near some theoretical estimates
- Diehl et al. 1997 set COMPTEL upper limit at 44% of its ^{26}Al flux.
- Also AGB stars, possibly SN Ia

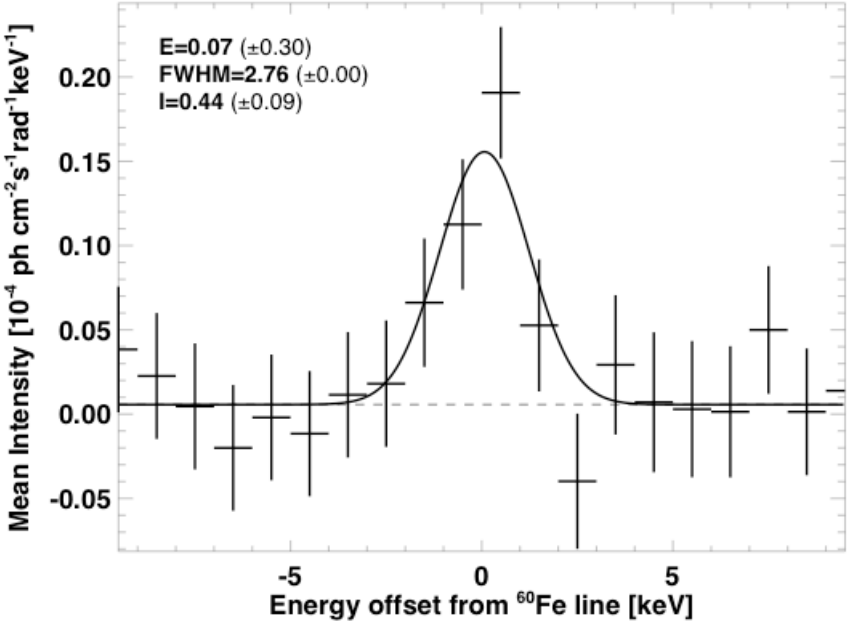
Circa 2002 :
- Is there ^{60}Fe in the ISM?
- How is it distributed?
- A bulge component from SN Ia?
- Can we measure it in a single object?

Only upper limits, some below theoretical expectations, until RHESSI (marginal) detection [Smith, D. M. 2004].

INTEGRAL SPI (Wang et al. 2007)

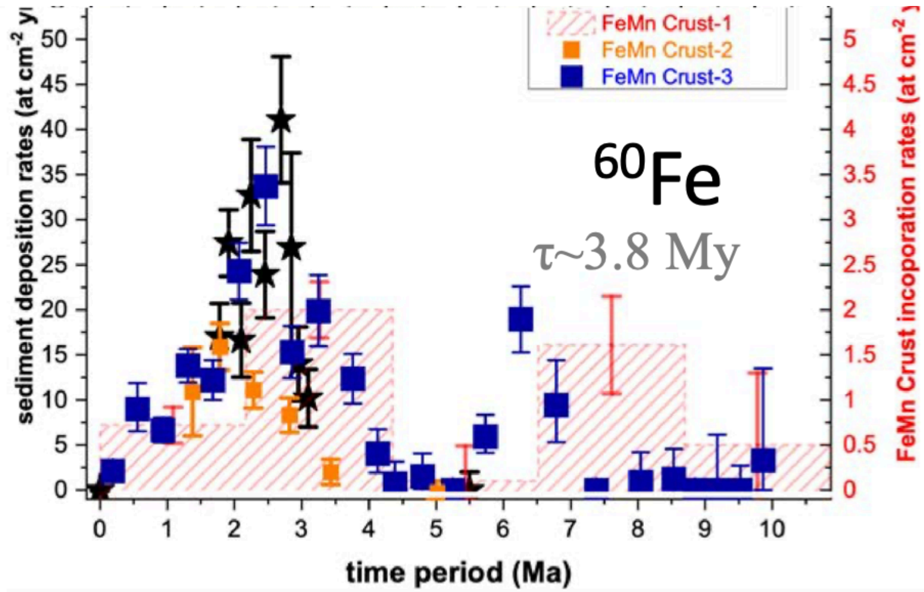
Flux (^{60}Co lines) = 4.4 10^{-5} cm^{-2} s^{-1}

--> $M_{ism}(^{60}Fe)$= 2.2 M_0



^{60}Fe in ocean crusts, cosmic rays, lunar samples

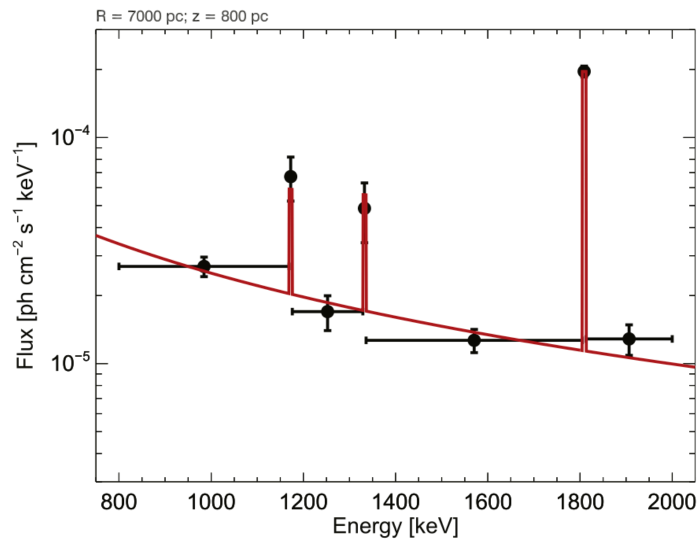
Wallner et al. 2015, 2021



60Fe in the Early Solar System (?)

Early reports of its existence, not confirmed (Trappitsch et al. 2018)

Wang et al. 2020



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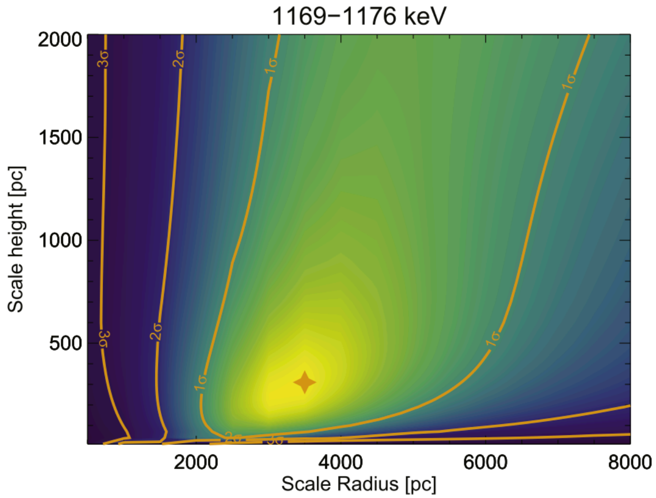
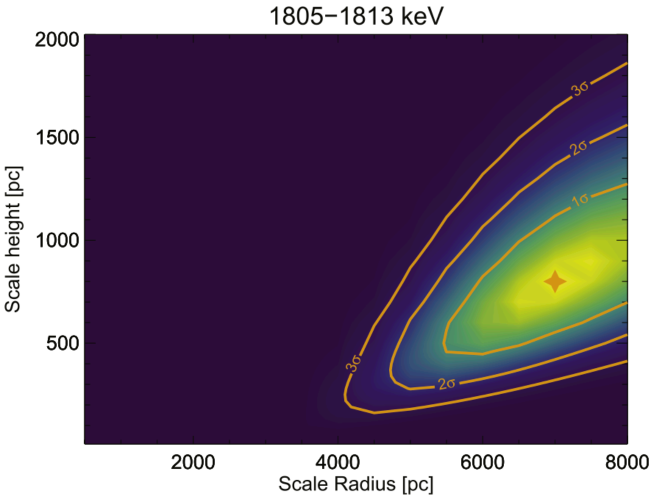




Different morphologies could point to different sources?

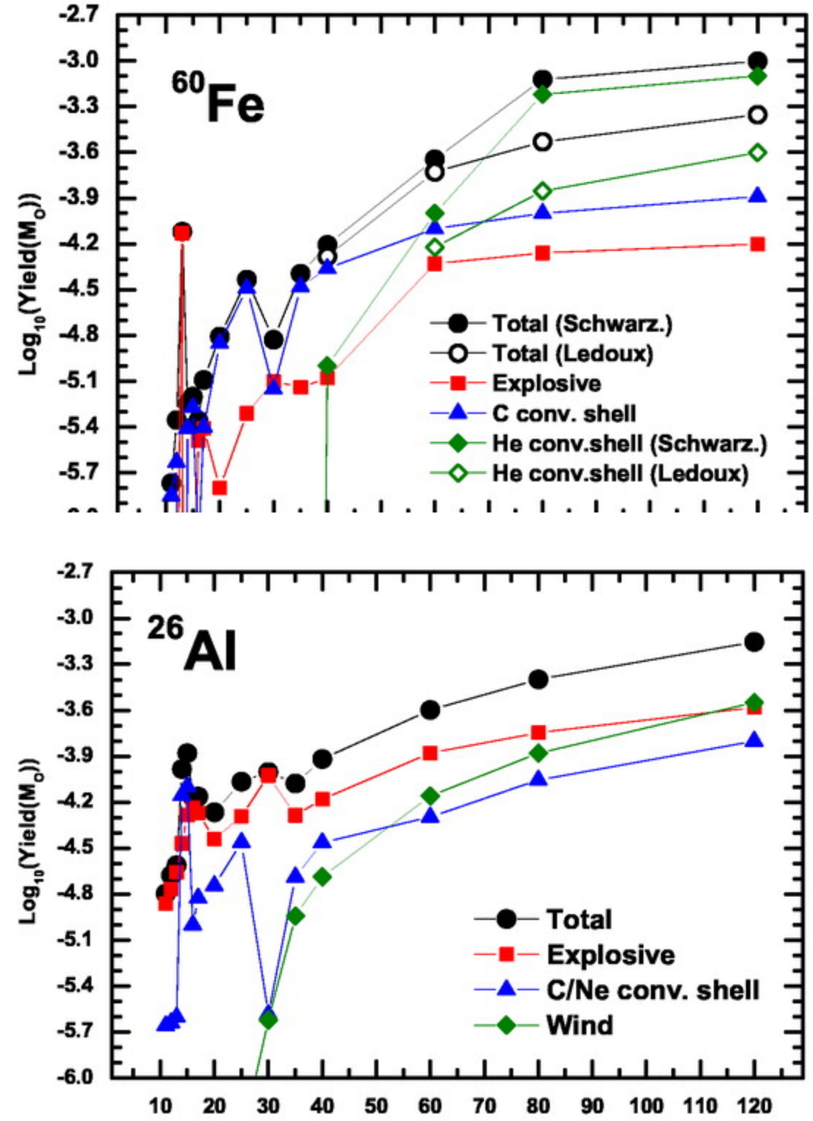
^{60}Fe relative to ^{26}Al

Mass production ratio (SPI only*):

$P(60)/P(26) = 0.25 \pm 0.09$

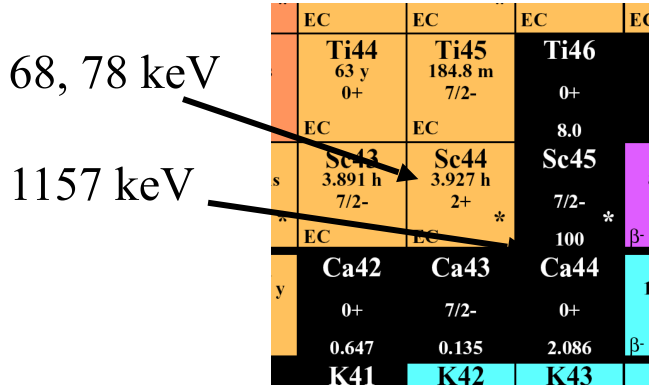
n.b. other ^{26}Al sources (novae, AGB)

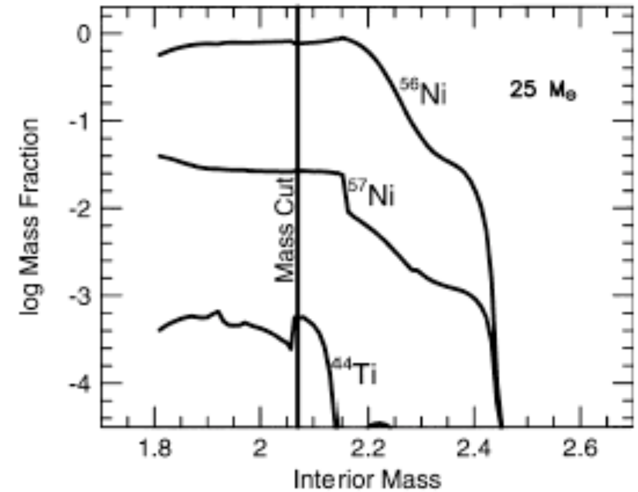
* ~Cancel uncertainties due to angular distribution, etc.



Limongi & Chieffi 2006

44Ti (85y)



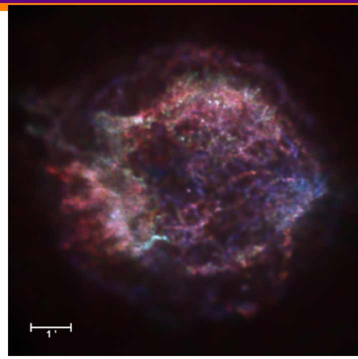


Woosley & Weaver 1995

Background

- Suggested as γ-ray target by Clayton et al. 1969
- Source of natural ^{44}Ca
  - Requires a *few 10^{-4}* $M_{\odot}$ per century now.
  - Typical cc-SN yields are *0.5 10^{-4}* $M_{\odot}$
- Upper limits from HEAO 3 and SMM
- Inferred in SN 1987A from late power and ionization/excitation

44Ti



Cas A

D ~ 3.4 kpc

Age = 350y

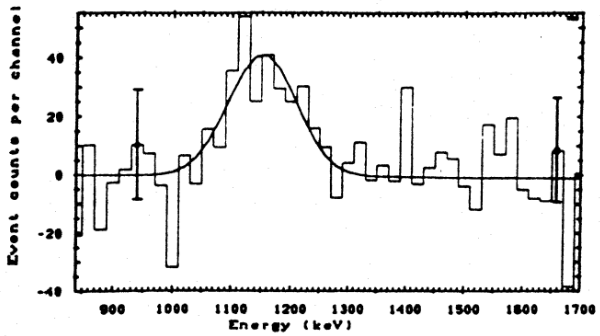
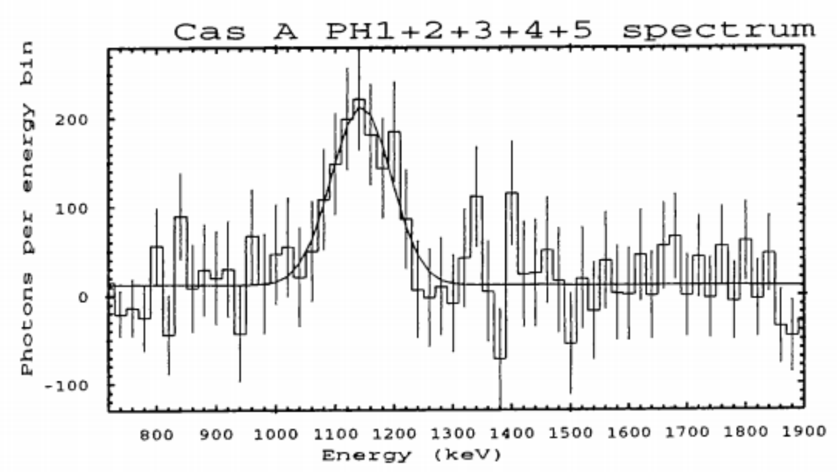
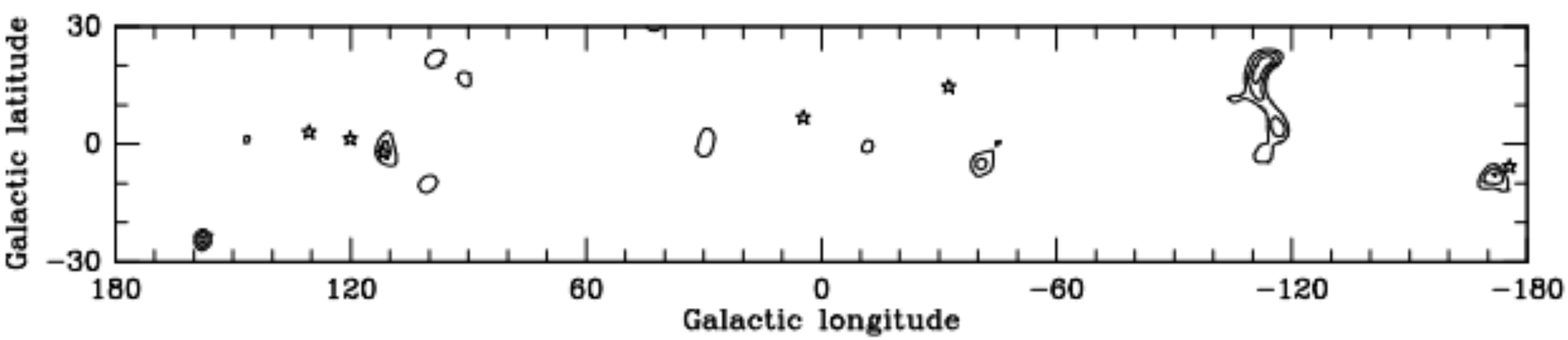


Fig. 1. Sum of the background-subtracted spectra of observation periods 34 and 211. Typical error bars are shown

Iyudin et al. 1994



Iyudin et al. 1997



1.17 MeV Dupraz et al. 1997

Circa 2002 – ^{44}Ti

- Where are all the (younger, inner galaxy) ^{44}Ti remnants?
- Can we confirm SN 1987A yield directly?
- What does ^{44}Ti show about SN kinematics?
- Are there rare events producing much of the cosmic ^{44}Ca abundance?

^{44}Ti -- Cas A, IBIS

Summary: all instruments consistent with:
Line fluxes = 2.5 10^{-5} cm^{-2} s^{-1}

M_{44} = 1.6 10^{-4} M_O

Renaud et al. 2006

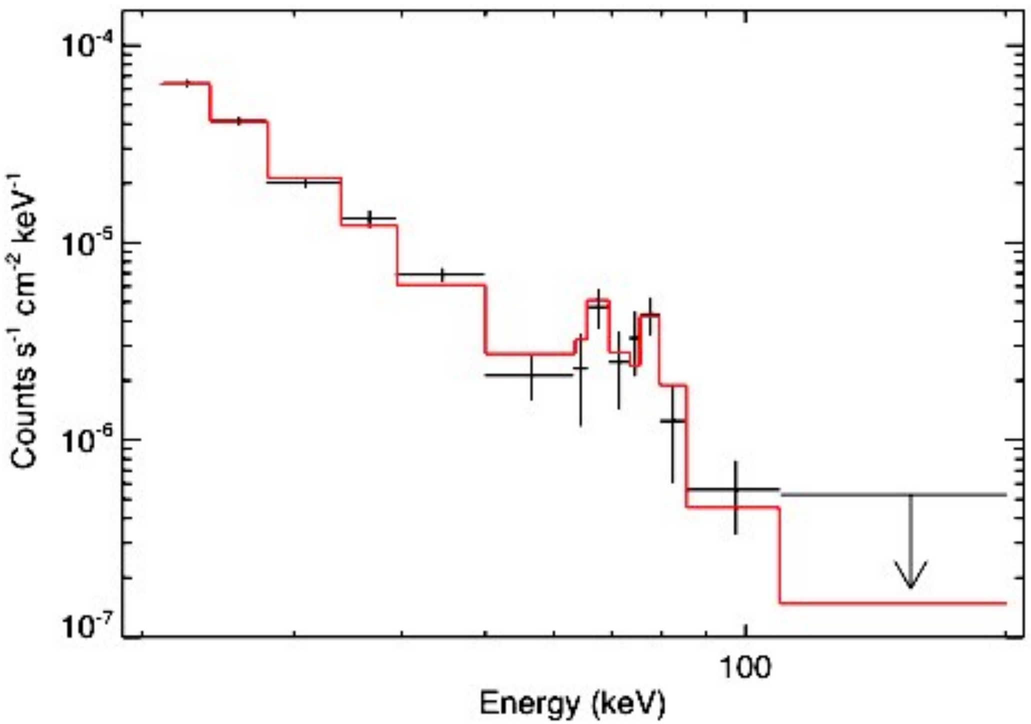
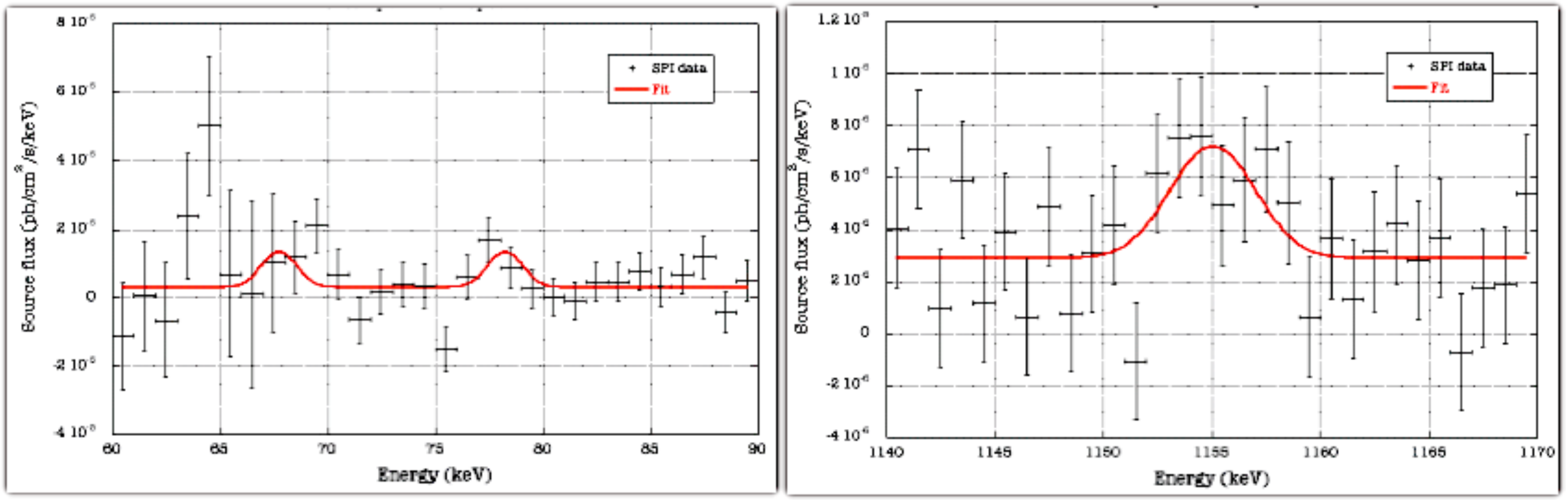


FIG. 3.— IBIS/ISGRI spectrum of Cas A and the best-fit model as descril

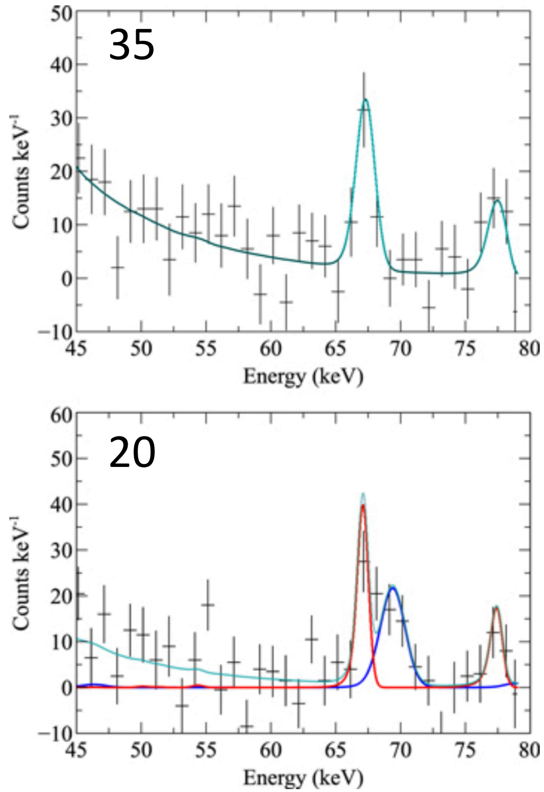
SPI – Cas A ^{44}Ti

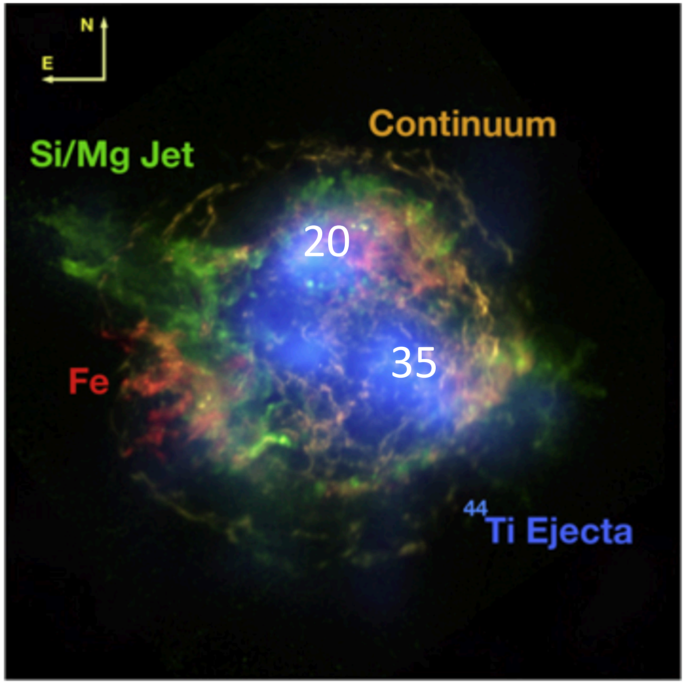
Martin et al. 2008 NAR



Flux consistent with IBIS
Narrow lines (~400 km/s, central ejecta)
Hint for redshift? (~500 km/s)

NuSTAR Cas A



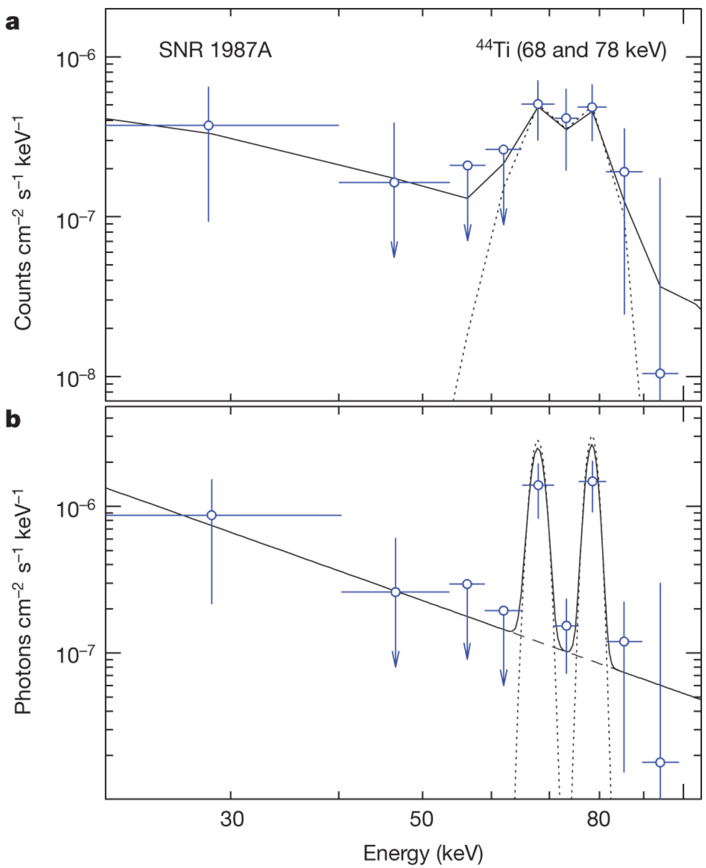


Greffenstette et al. 2017

F_{68}=1.84 x 10^{-5} cm^{-2} s^{-1}

M_{44} = 1.5 x 10^{-4} $M_\odot$

SN 1987A IBIS/ISGRI

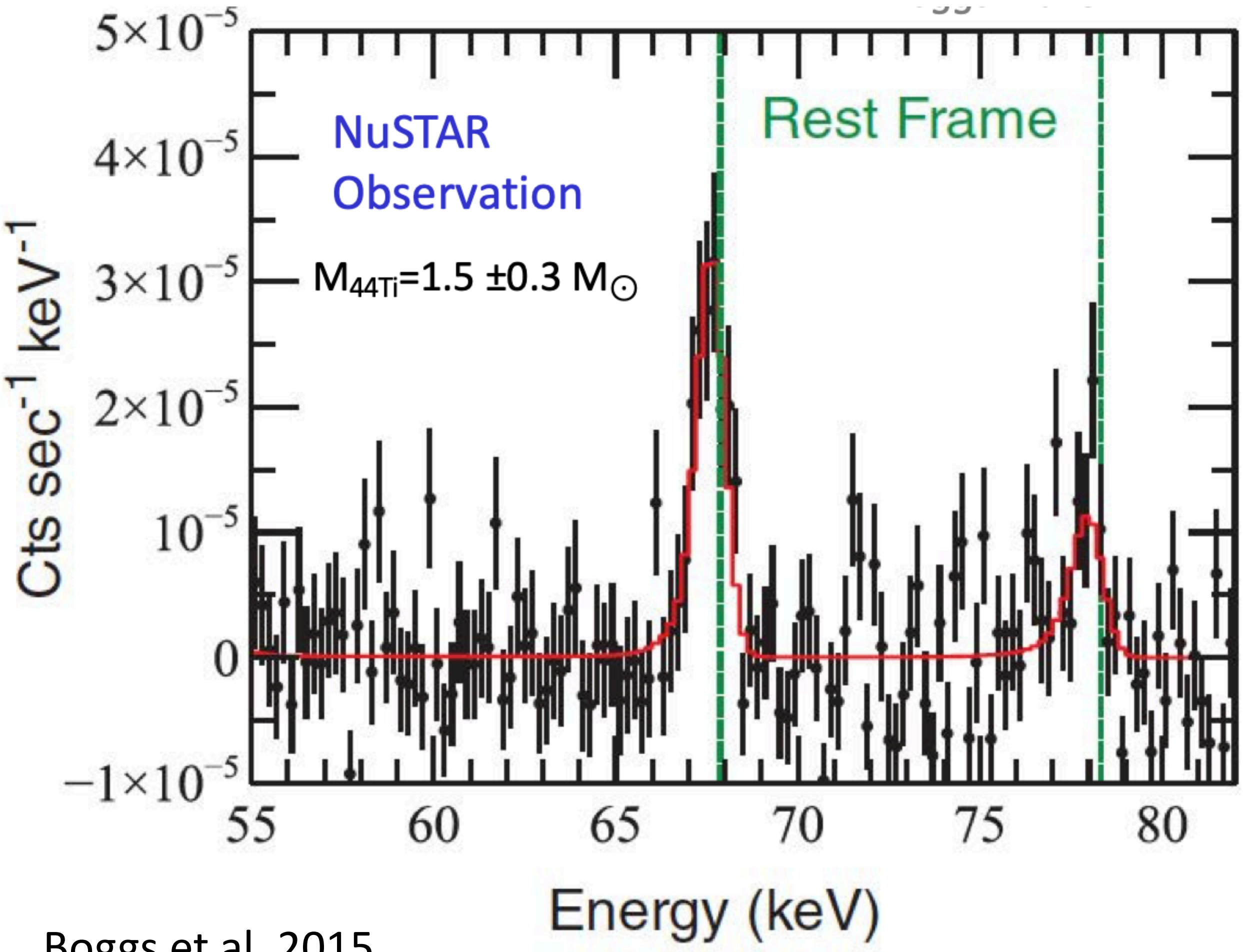


$$F_{68+78} \approx (1.7 \pm 0.4) \times 10^{-5} \text{ photons cm}^{-2}\,\text{s}^{-1}$$

$$M_{44} \approx (3.5 \pm 0.8) \times 10^{-4} M_{\odot}$$

Grebenev et al. 2012

NuSTAR SN 1987A



$M_{44} = 1.5 \times 10^{-4} M_{\odot}$

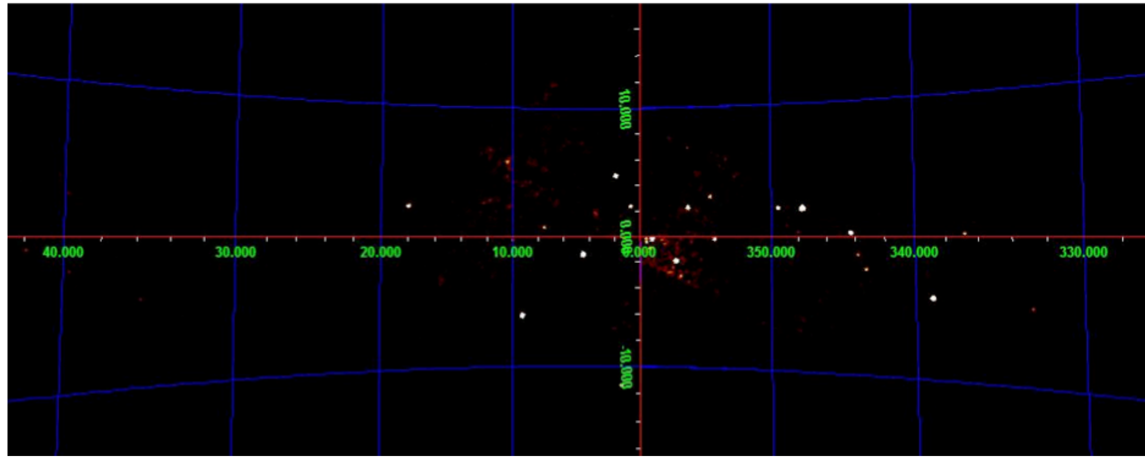
Boggs et al. 2015

Also, electron capture K-alpha X-ray fluxes appear consistent

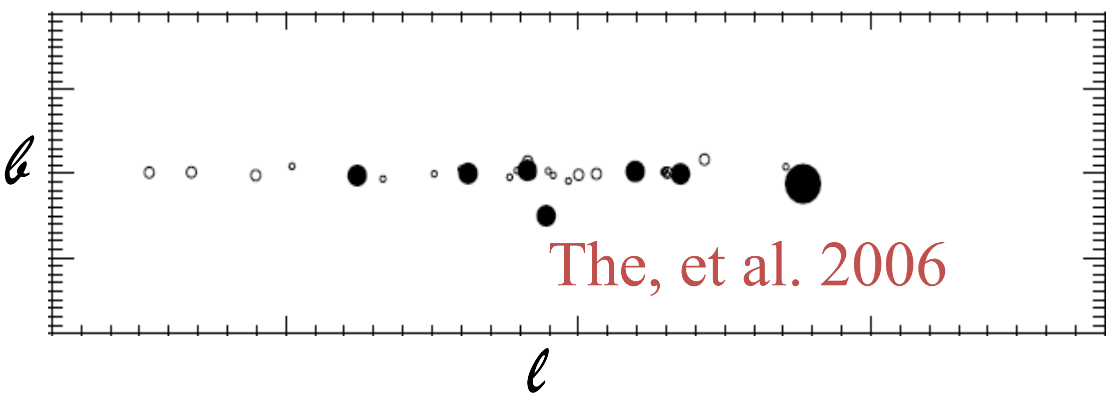
Where are the other ^{44}Ti SNR?

IBIS -

Renaud et al. 2004,
following many others



Re: Cas A
standard rates/yields
^{44}Ca abundance



The, et al. 2006

See
Wang & Burrows 2024

Classical Nova Gamma Rays

Clayton & Hoyle 1974
Clayton 1981
....
Hernanz et al.

Upper limits from HEAO-C1, SMM, CGRO

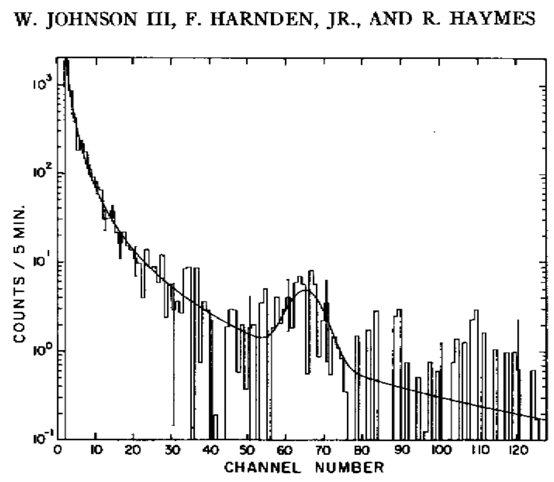
Circa 2002:

- Why don't we see them?
- When will a nova be detected?

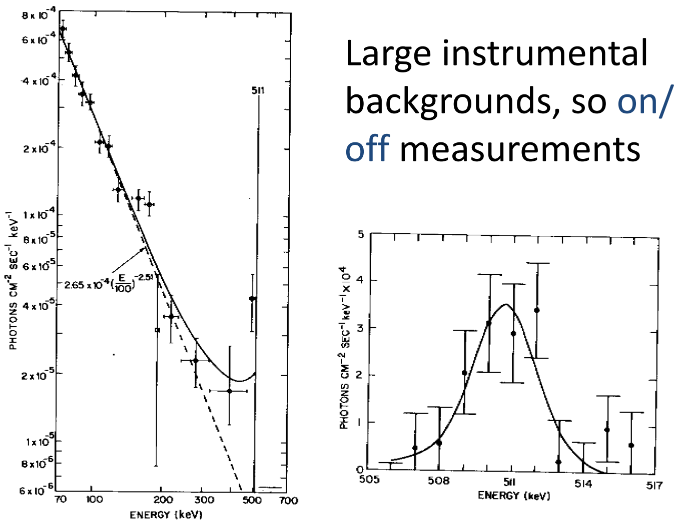
… and now

^{13}N	511 keV	10 m
^{18}F	511 keV	110 m
^{7}Be	478 keV	53 d
^{22}Na	1275 keV	2.6 y
^{26}Al	1809 keV	0.7 My

Electron-positron annihilation (briefly)



Rice University (1971)

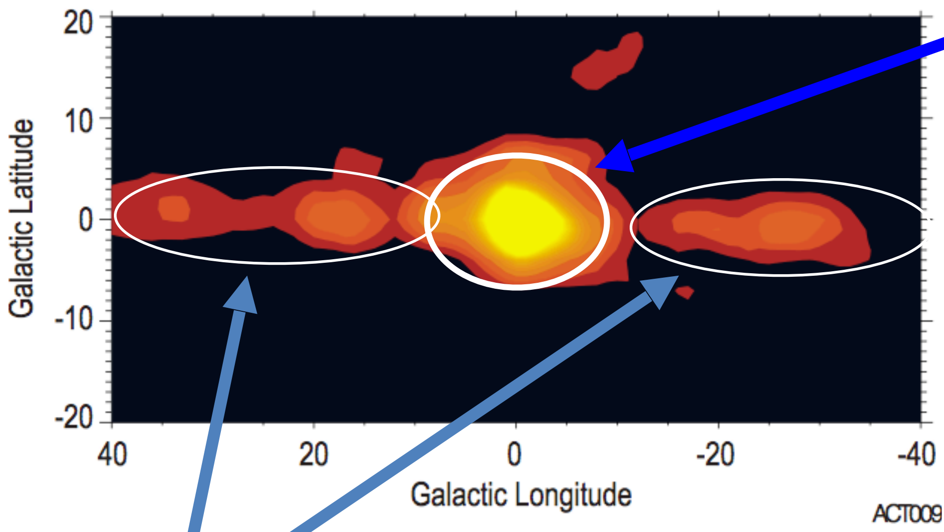


Large instrumental backgrounds, so on/off measurements

Bell Labs./Sandia (1977)

Measurements through early 1980's found varying 511 keV line fluxes, suggesting a compact source (< light years in extent.)

Circa 2002: Compton Observatory OSSE

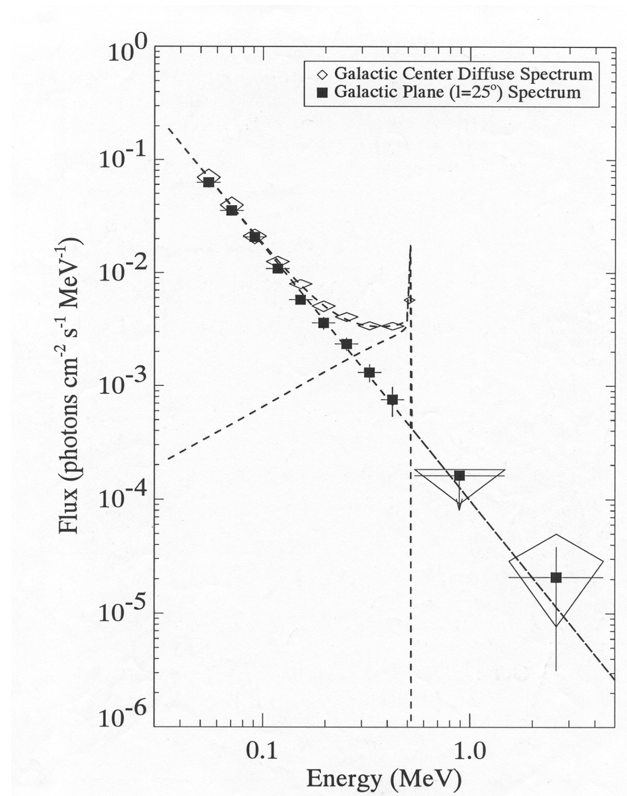


Bulge emission:
astrophysical sources fall short;
- light dark matter particle annihilations?
- Central BH outburst(s)?

Milne et al. 2001

Disk emission: known radioactivity, pulsar winds, black holes (disks & jets)?, cosmic ray interactions

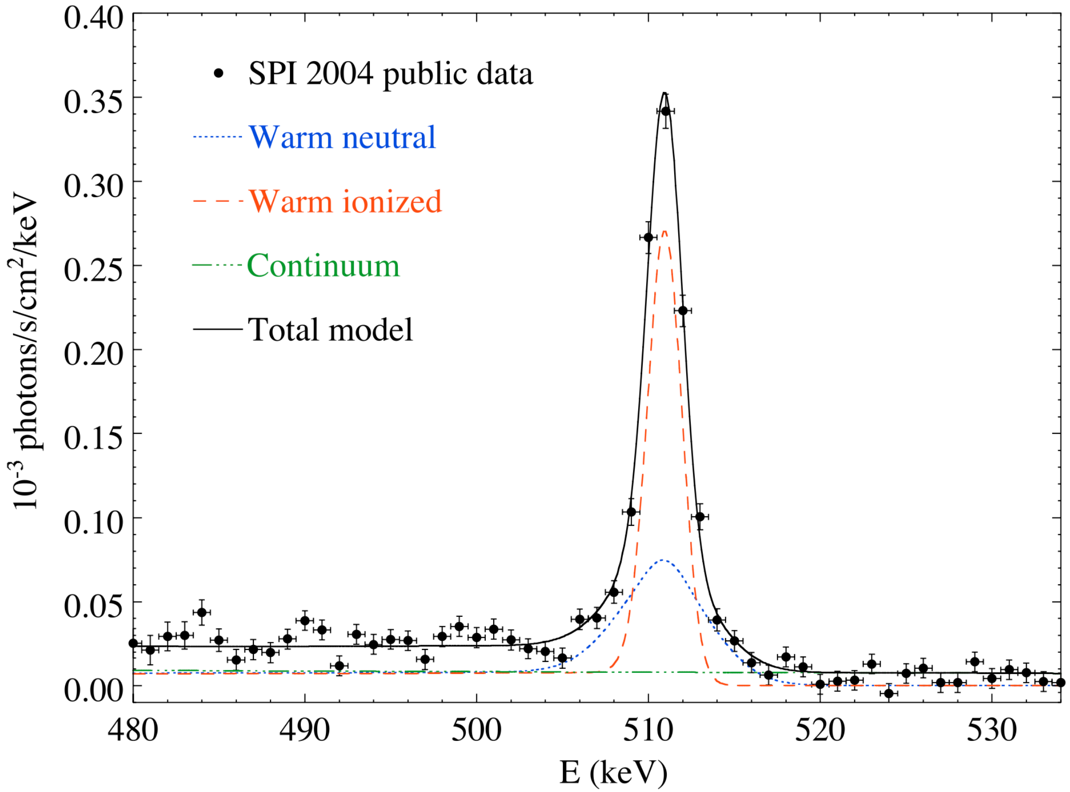
- What is the source(s) of bulge positrons?
- What is the actual disk extent/flux?
- What are the details of the bulge morphology?
- Can we detect individual source(s)?
- What are the annihilation conditions?



Purcell et al. 1994

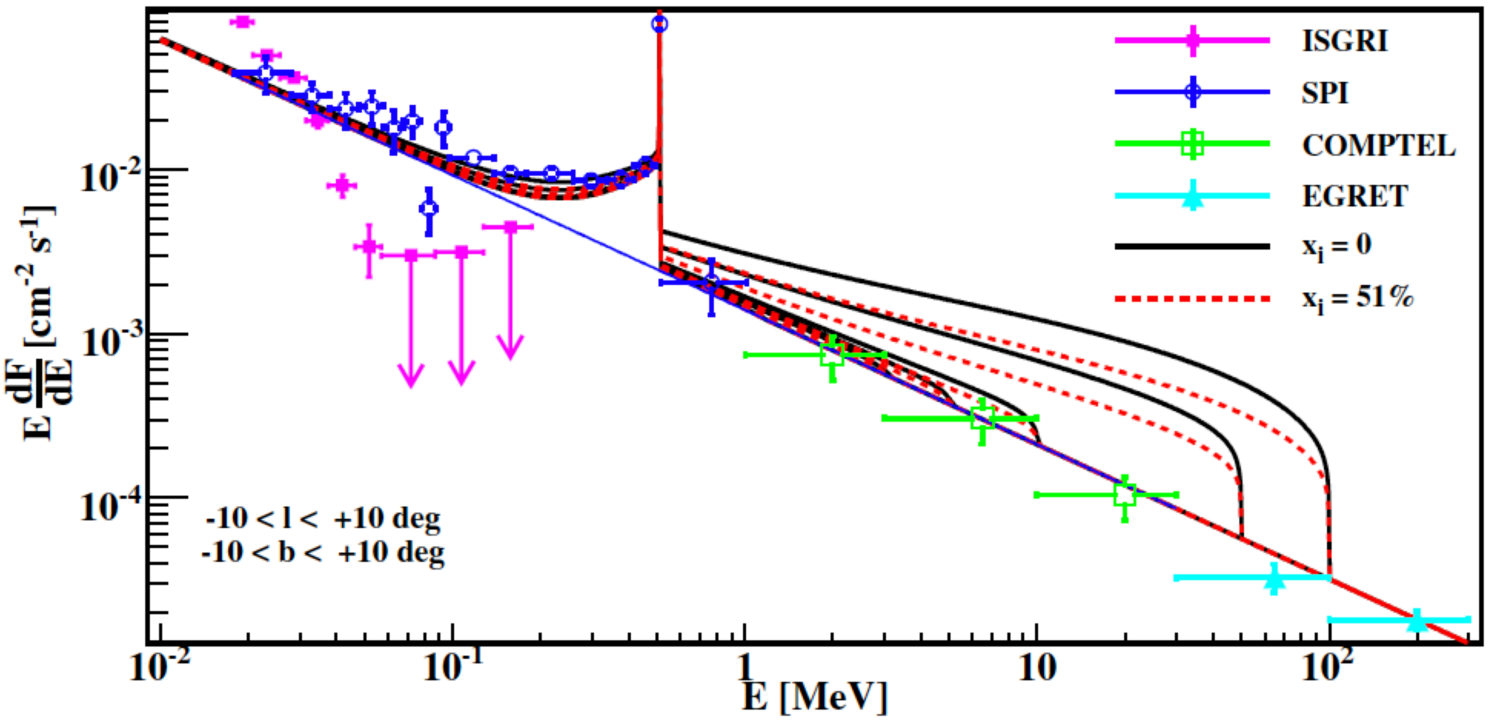
SPI spectrum

Jean et al. 2005



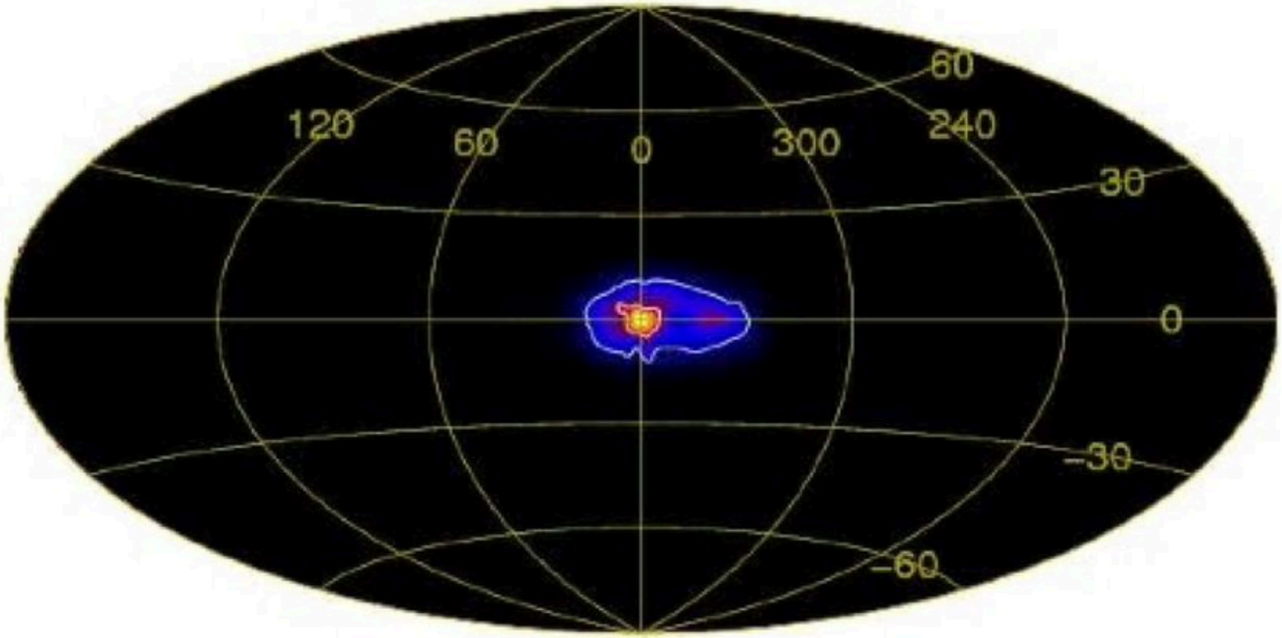
Positron source energy constraint

Sizun+2006



with caveats ...

Early SPI maps



511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner et al., 2008a).

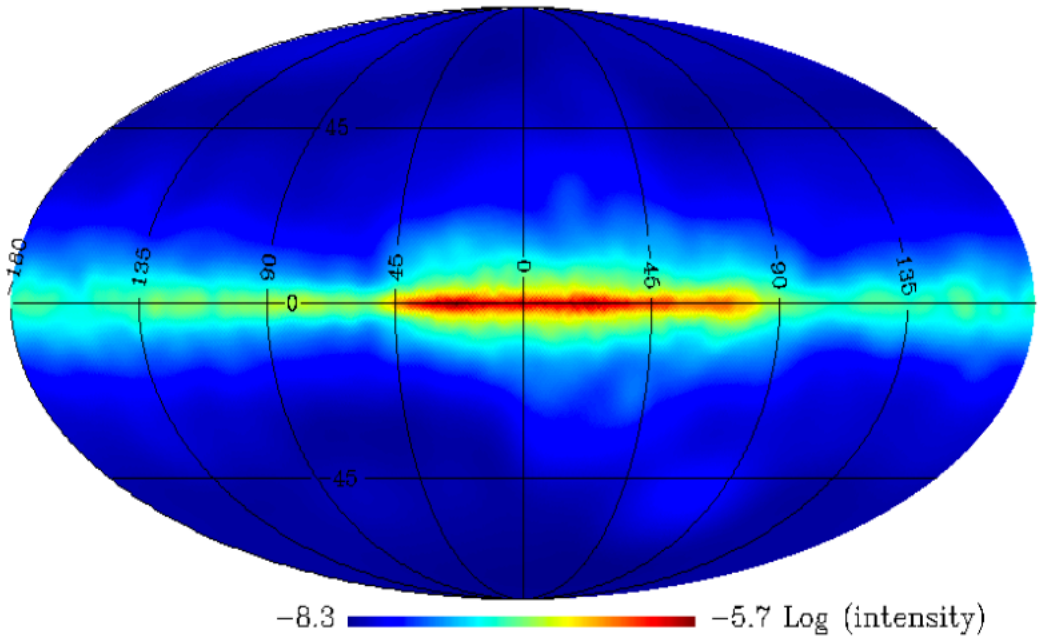
Limits on many point sources (Knoedlseder et al. 2005)

Positron propagation?

Maybe, e.g., bulge positrons originate in disk (Prantzos 2006)

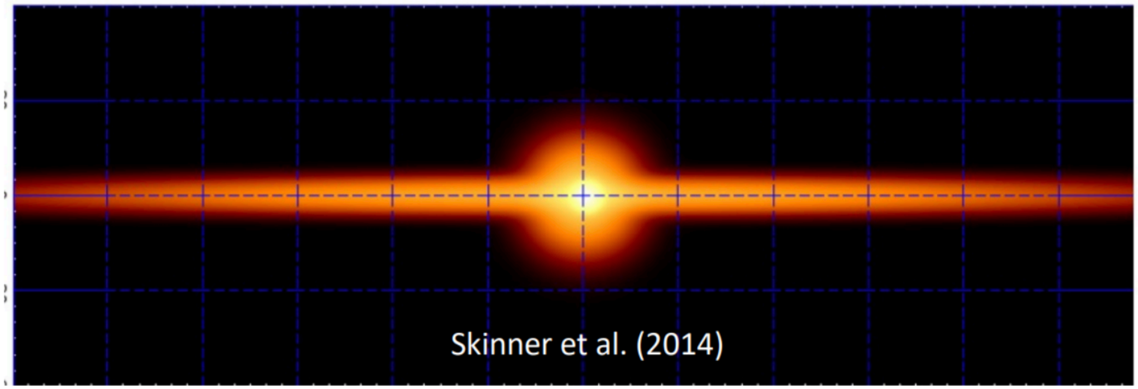
Alexis et al. 2014
disk positrons

~1 kpc spread

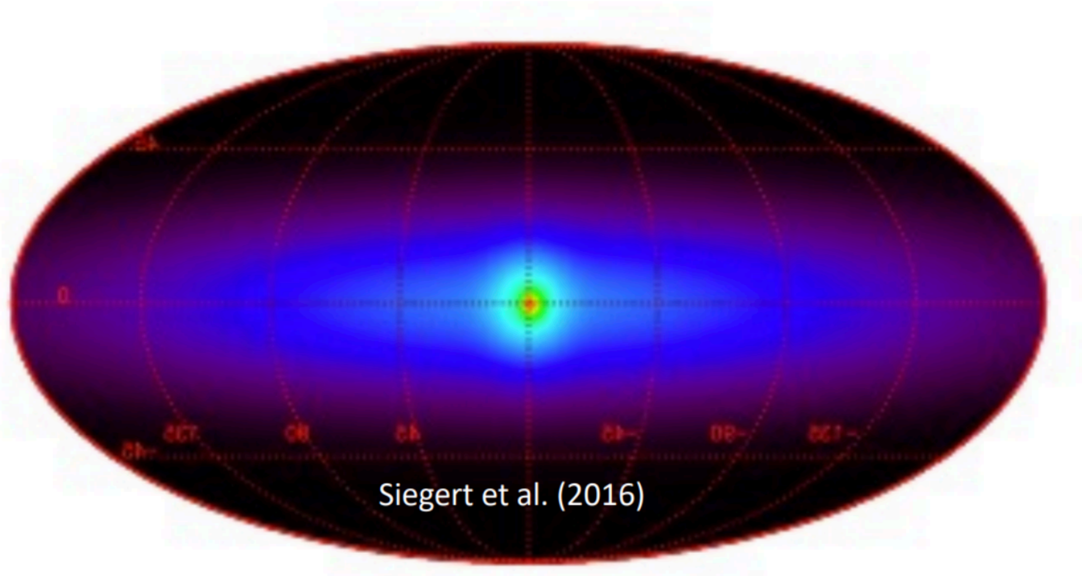


Geometric Model fits

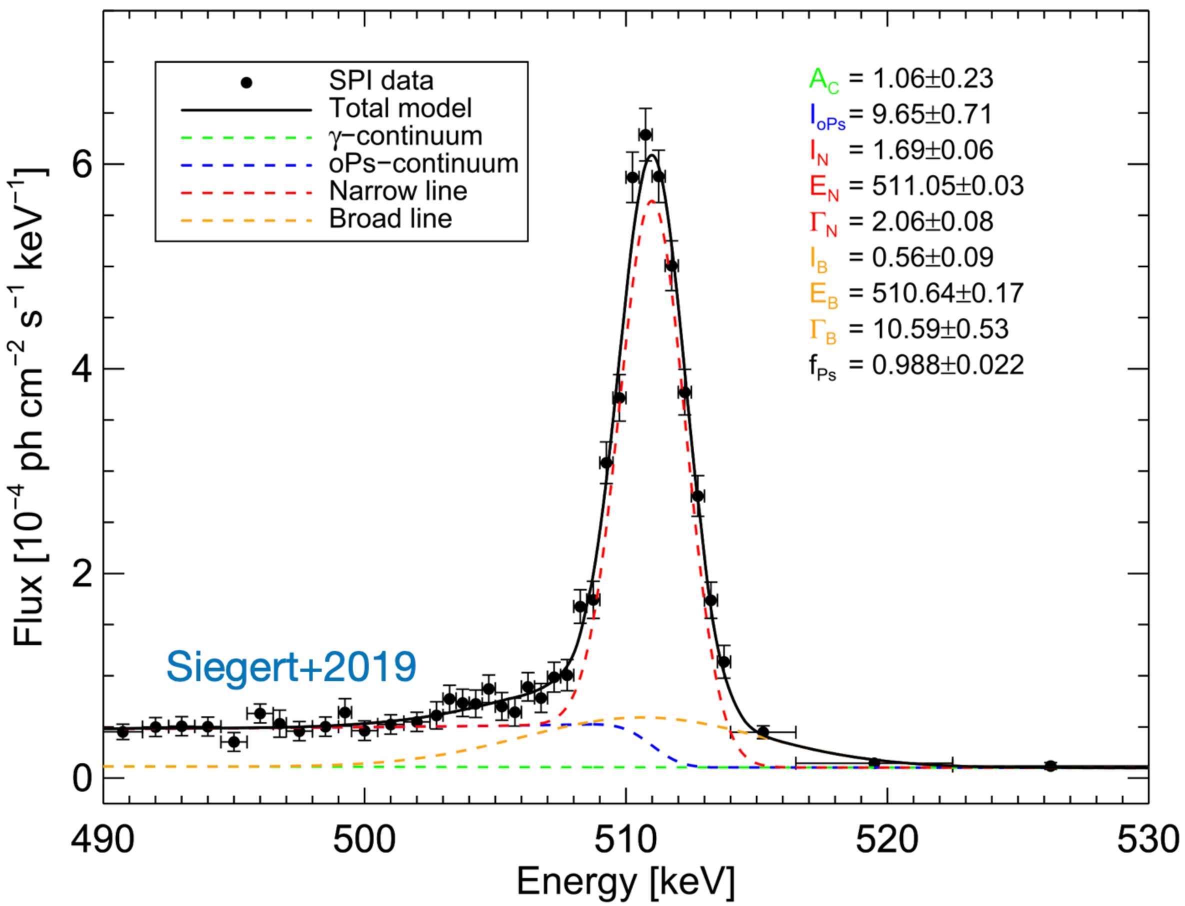
Line data fit ~equally well with thin or thick disk, requiring different disk annihilation rates.



60-70% of disk from 26Al, 44Ti



25-30% of disk from 26Al, 44Ti



SPI data
Total model
γ−continuum
oPs−continuum
Narrow line
Broad line
A_C = 1.06±0.23
I_{oPs} = 9.65±0.71
I_N = 1.69±0.06
E_N = 511.05±0.03
Γ_N = 2.06±0.08
I_B = 0.56±0.09
E_B = 510.64±0.17
Γ_B = 10.59±0.53
f_{Ps} = 0.988±0.022
Siegert+2019
Flux [10^{-4} ph cm^{-2} s^{-1} keV^{-1}]
Energy [keV]
0
2
4
6
490
500
510
520
530

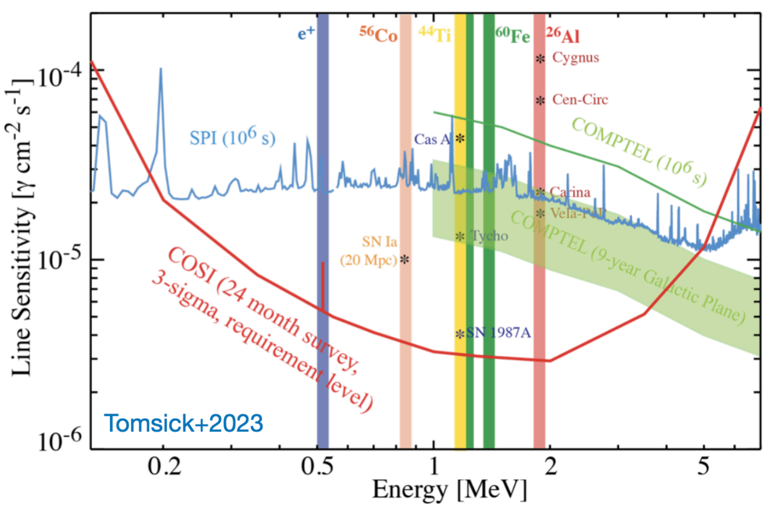
Future Prospects

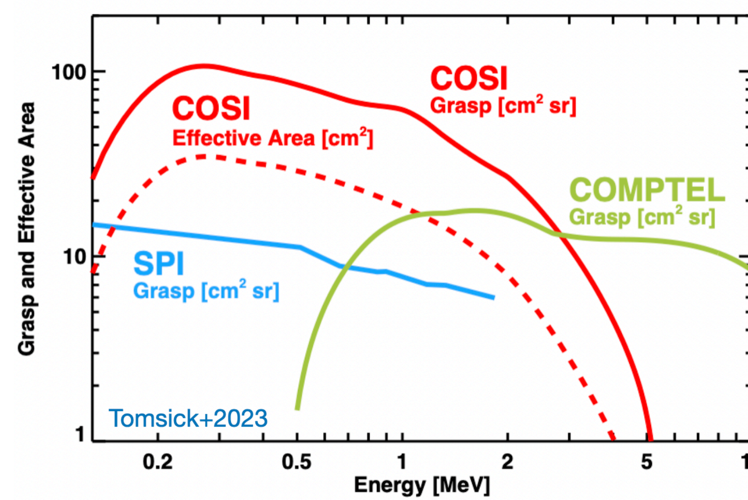
- Improving analyses of full INTEGRAL data sets
  (keep not only data, but mass models, etc. available)

- Compton Spectrometer and Imager (COSI) 2027

- eAstrogam et al.

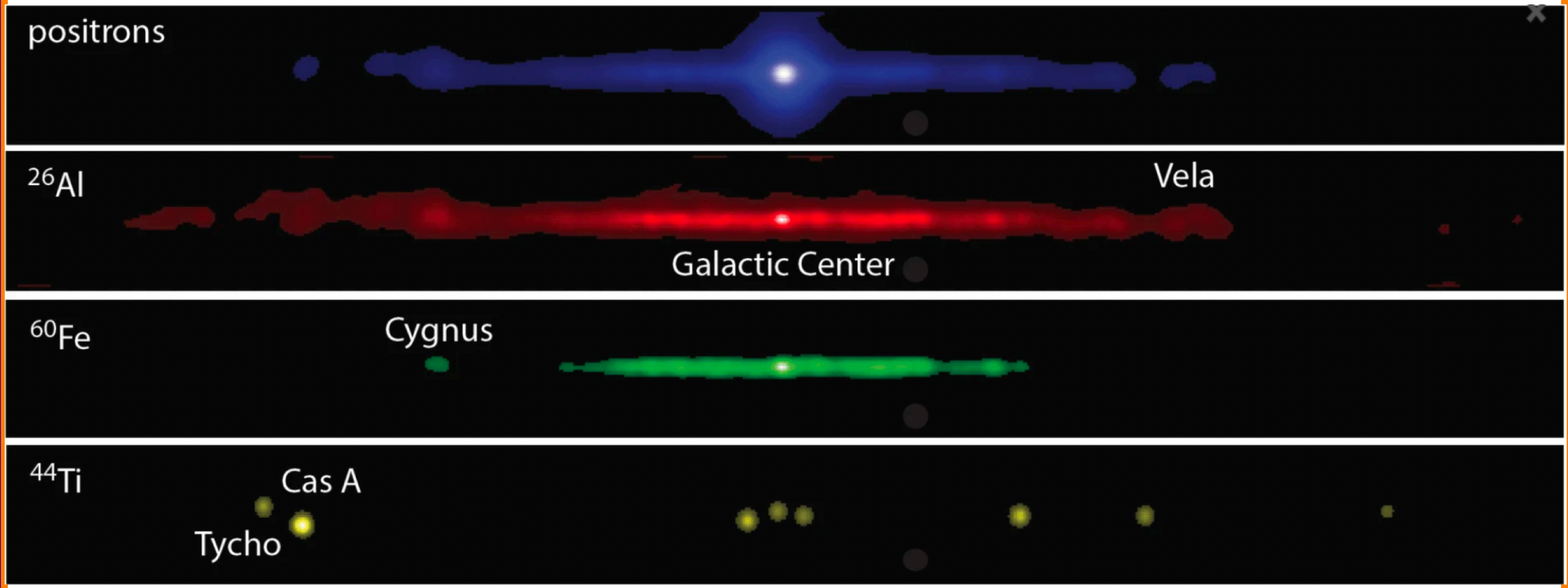
Tomsick et al. 2023





INTEGRAL 2024 Madrid

Two Year Simulated COSI Line maps



Summary:

- Many of our questions are being answered (especially due to INTEGRAL's long success)
  line widths, shapes, total masses
- Many remain
  - *different source contributions*
  - *missing supernovae, novae*
- New ones
  - *Fast 26Al*