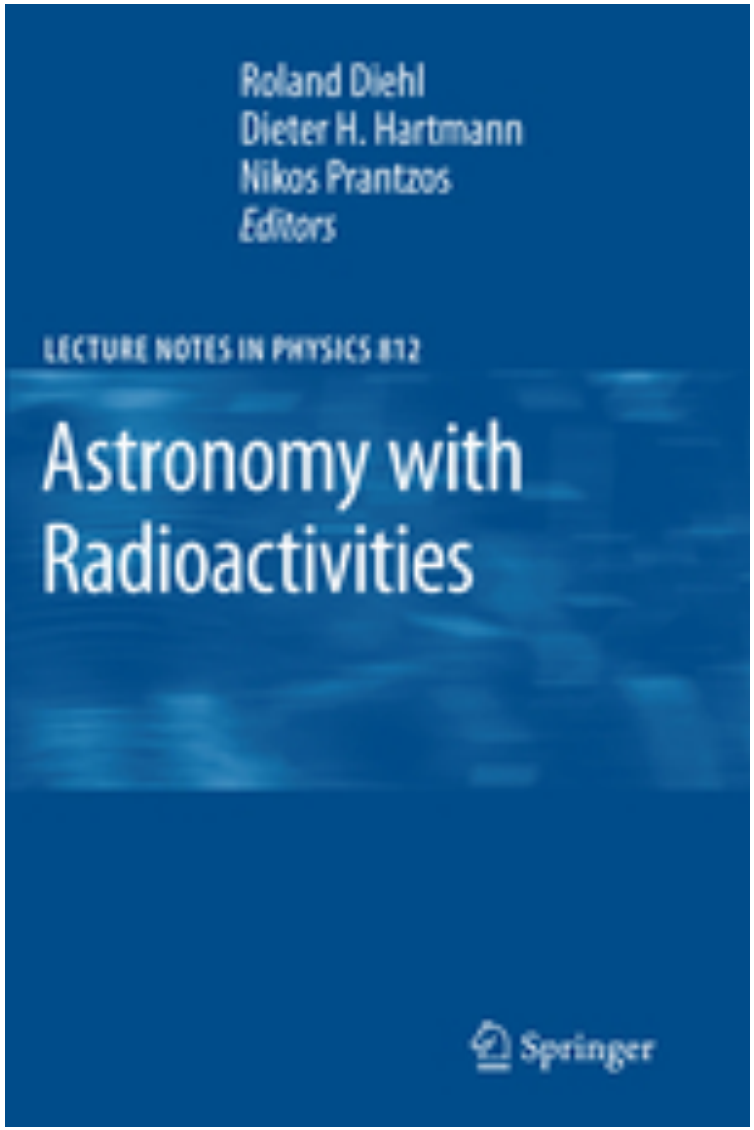
(Nuclear) Gamma-Ray Line Astrophysics

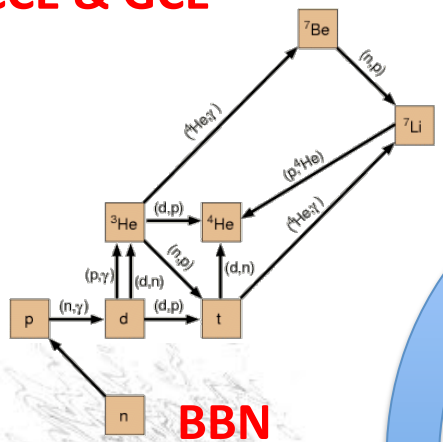
- MeV Lines, Element Production in Dynamic Environments –



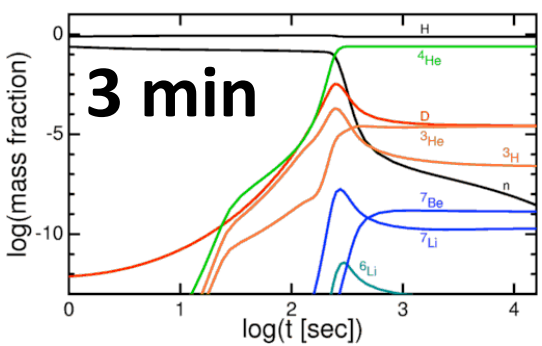
March 24-25, 2016

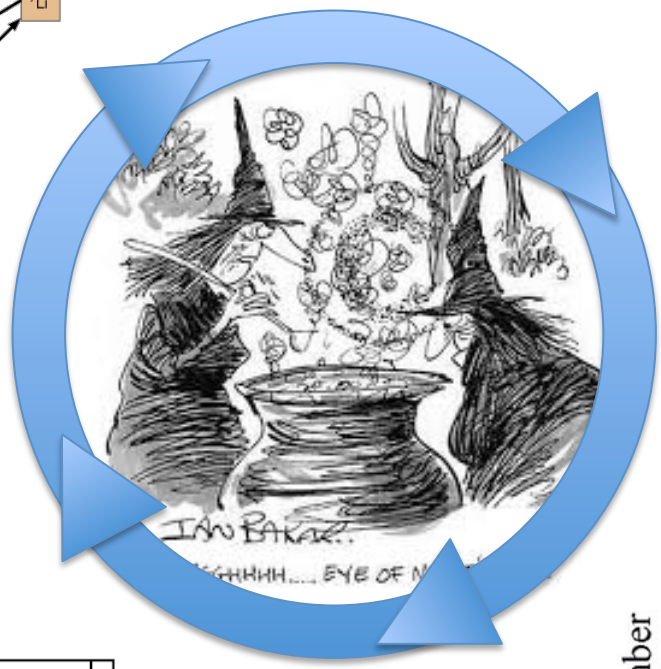
Dieter H. Hartmann
Clemson University

Chemical Evolution
Element Synthesis
CCE & GCE



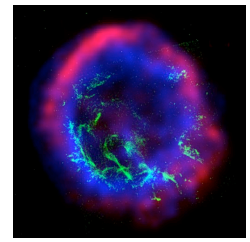
BBN



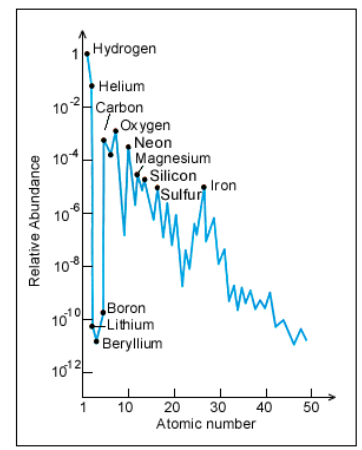


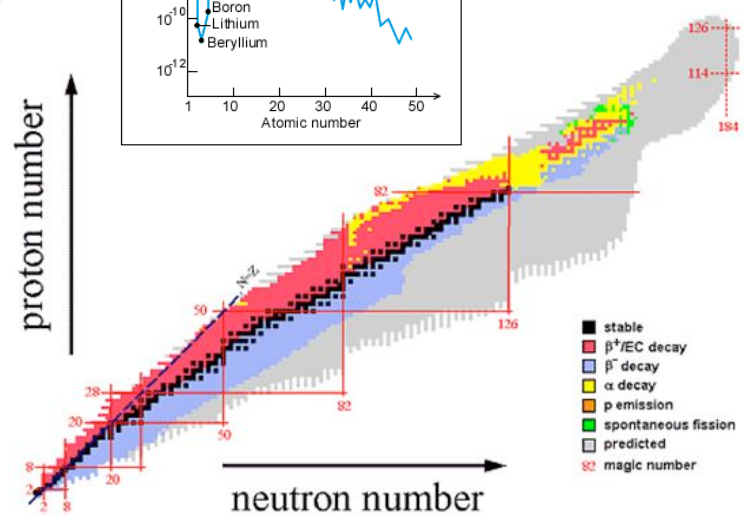
Multi-Messenger:
⊙, Stellar atmospheres
ISM gas abundances
Meteorites
Radioactivites, γ-lines

Production (stars, CR spallation)
& Redistribution SN-SNR-ISM
Star Formation History & IMF



13.4 Gyrs later
z_{ISM} ~ 2%



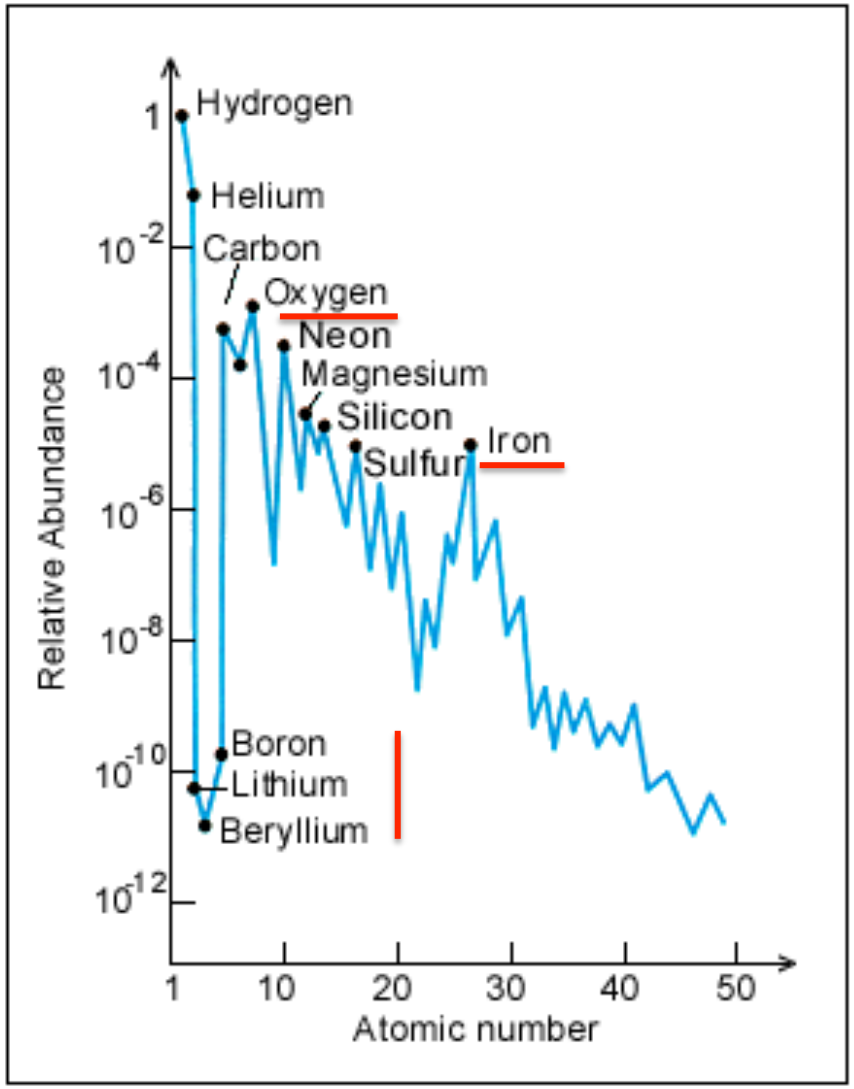


Key: $(M_{ej}/\tau)\ R_{event}\ F_{escape}$

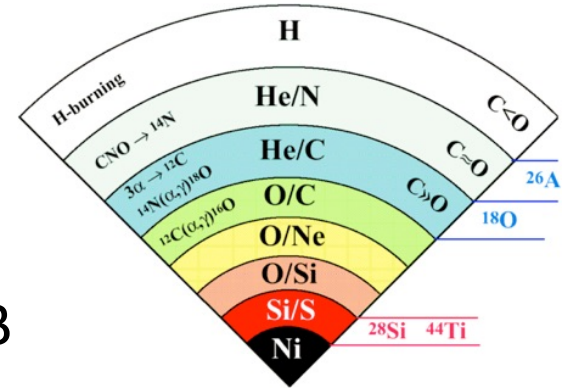
Sources

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^{*}$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^{*} \rightarrow {}^{56}Fe^{*} + e^{+}$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^{*}$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+}$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^{*} \rightarrow {}^{44}Ca^{*} + e^{+}$	78, 68; 1157
^{26}Al	$1.04\ 10^{6}$y	$^{26}Al \rightarrow {}^{26}Mg^{*} + e^{+}$	1809
^{60}Fe	$2.0\ 10^{6}$y	$^{60}Fe \rightarrow {}^{60}Co^{*} \rightarrow {}^{60}Ni^{*}$	59, 1173, 1332
e^{+}	.... 10^{5}y	$e^{+} + e^{-} \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

Diffuse



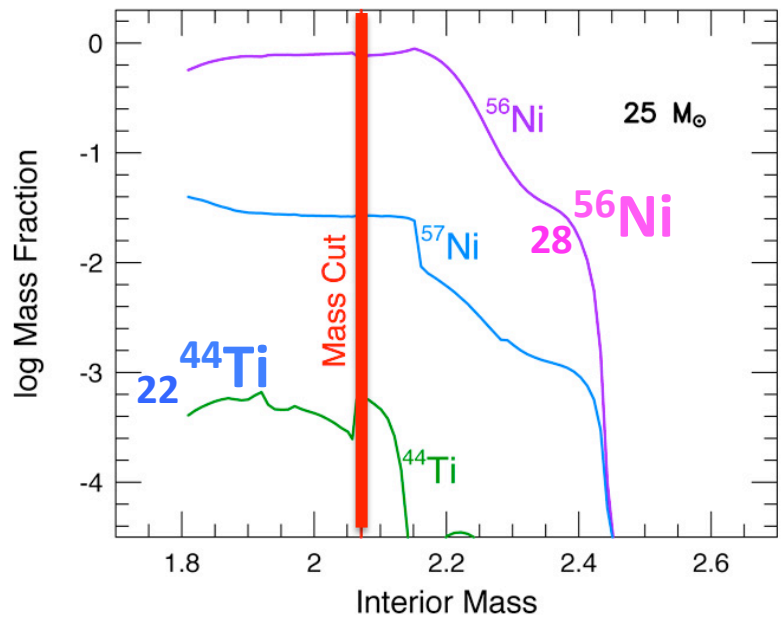
Processes (r,s,p,rp,γ, α-rich freeze-out, QSE,NSE,….. Hoyle 1954, B^{2}FH 1957 …..



SNIa ➔ Fe

SNII ➔ O

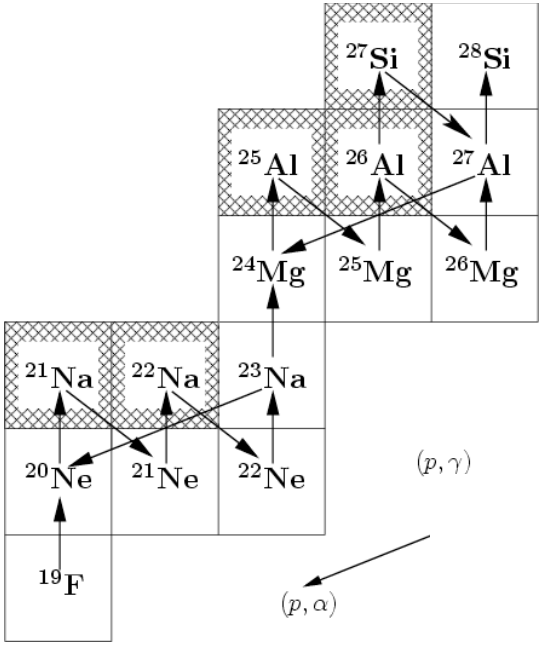
CR ➔ LiBeB



^{44}Ti only from explosive, complete Si-burning

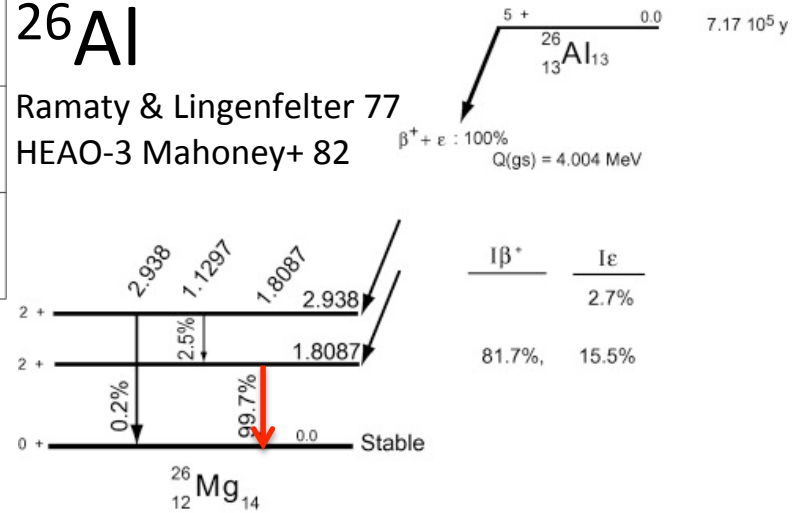
α-rich freeze-out: dynamics near the "mass cut"

How do core collapse SNe work?

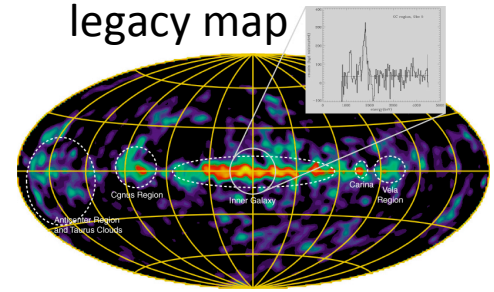


^{26}Al

Ramaty & Lingenfelter 77
HEAO-3 Mahoney+ 82



COMPTEL/CGRO
legacy map

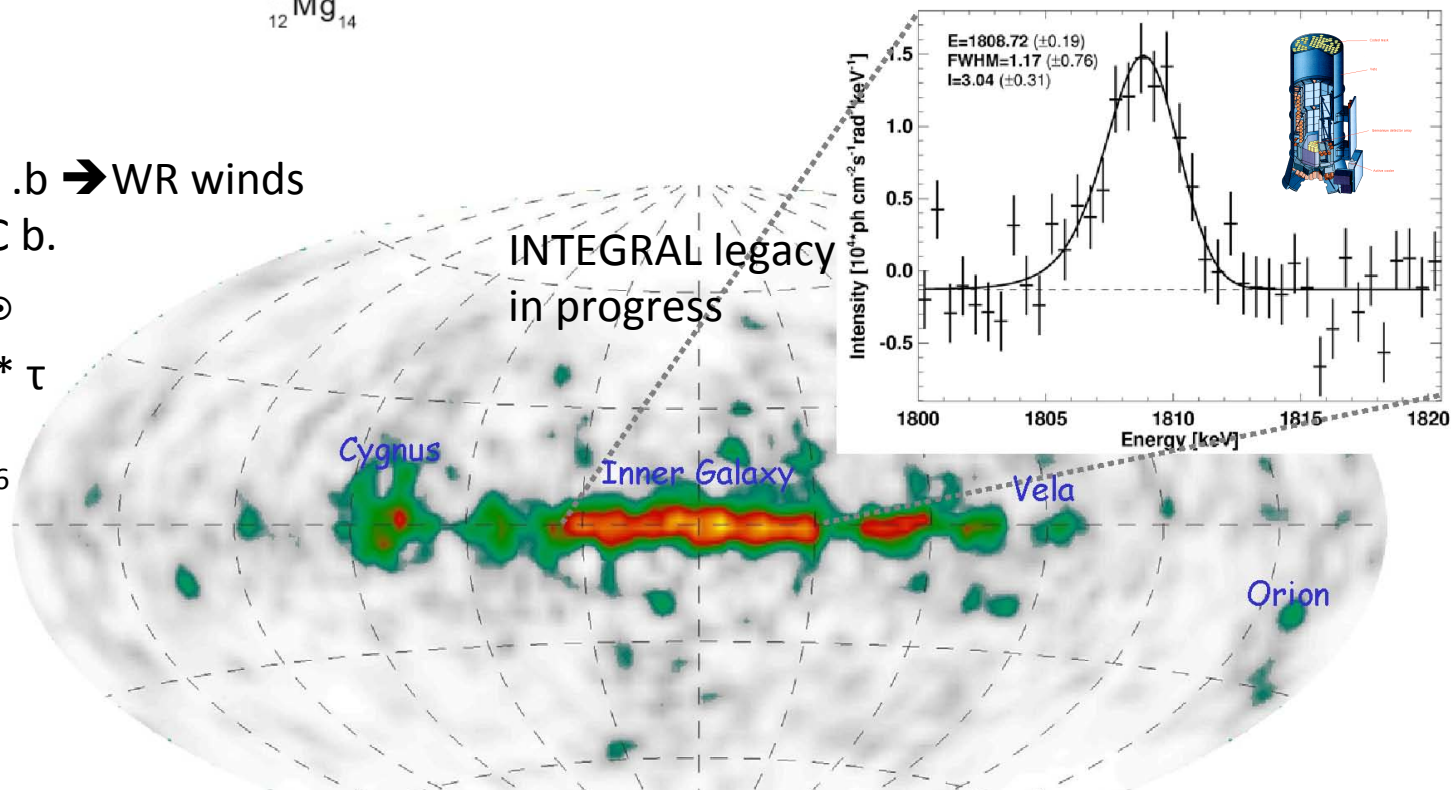


Static H/He-shell .b ➔WR winds
& explosive Ne/C b.
<Yield> ~ 10^{-4} $M_\odot$

M_{ISM} = SNR * M_{ej} * τ

~ 10^{-2} 10^{-4} $M_\odot$ 10^6

INTEGRAL legacy
in progress



The Global galactic SFR ~ 2-3 $M_\odot$ yr^{-1}

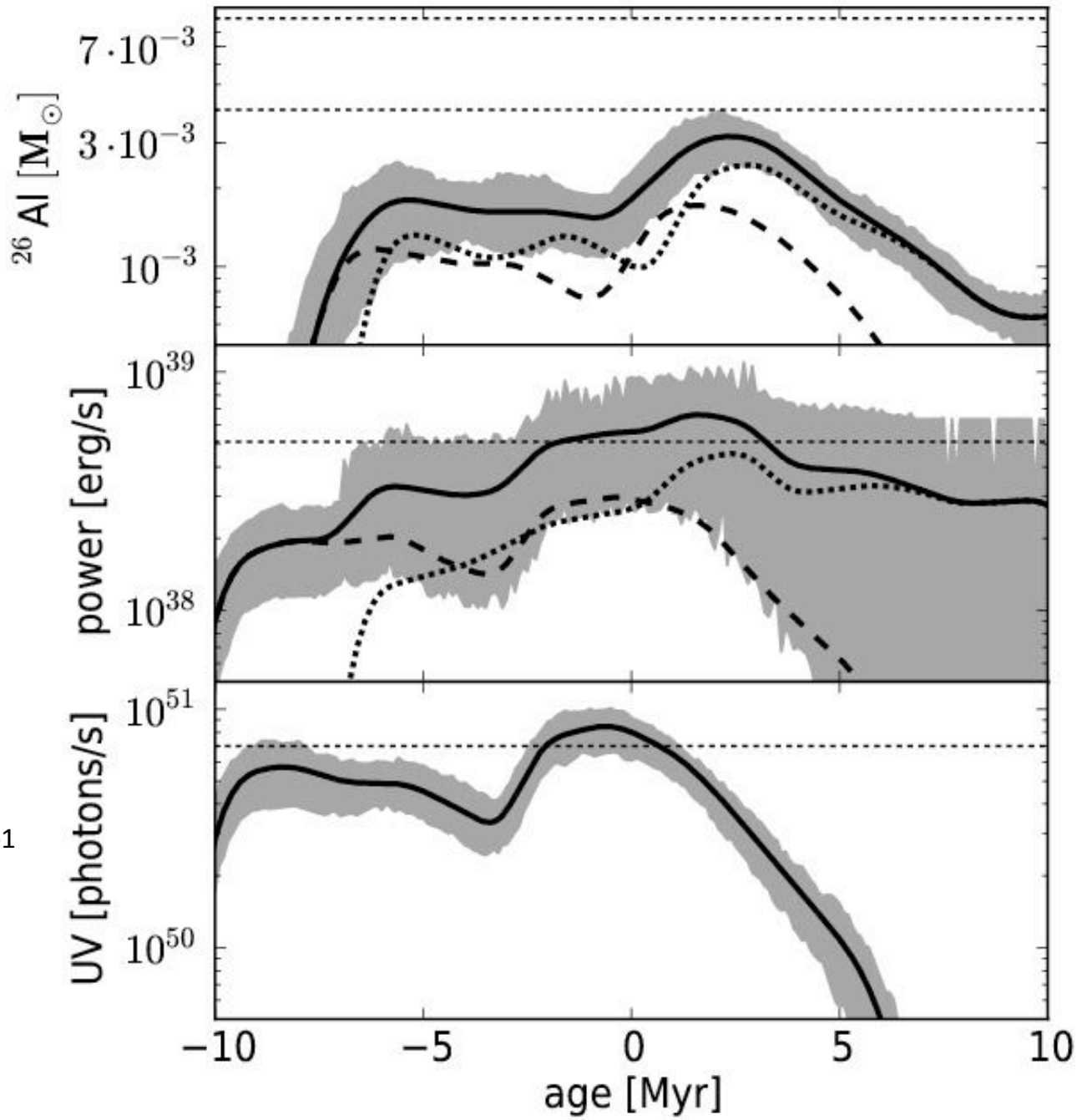
Energetic feedback and ^{26}Al from massive stars and their SNe in Carina

Voss, Martin, Diehl, Vink, DH and Preibisch, A&A 539, A66 (2012)

⊙INTEGRAL

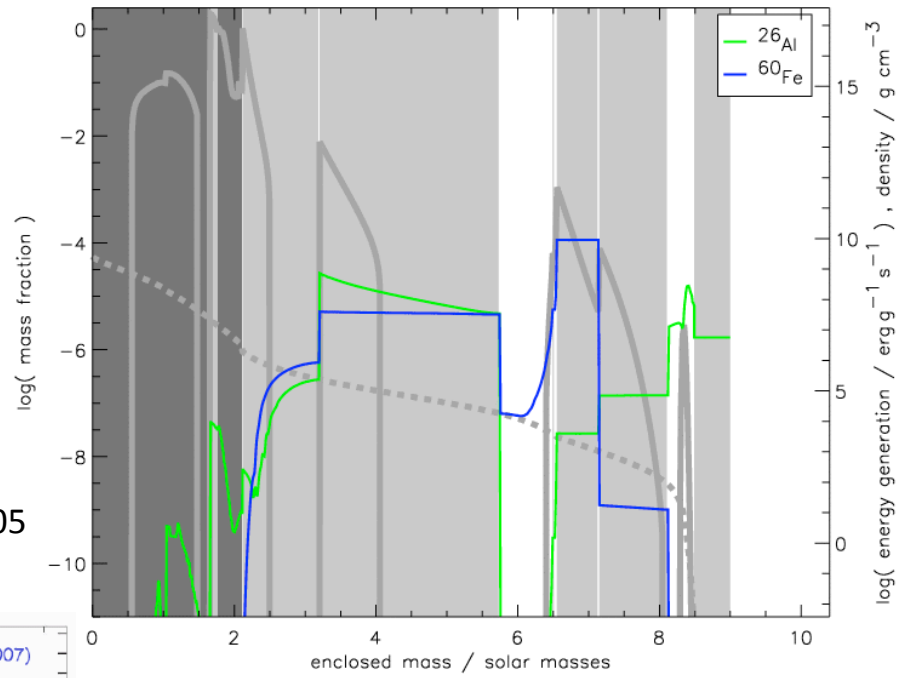
F ~1.5 ± 1.0 × 10^{-5} cm^{-2} s^{-1}

⊙ ~half observed

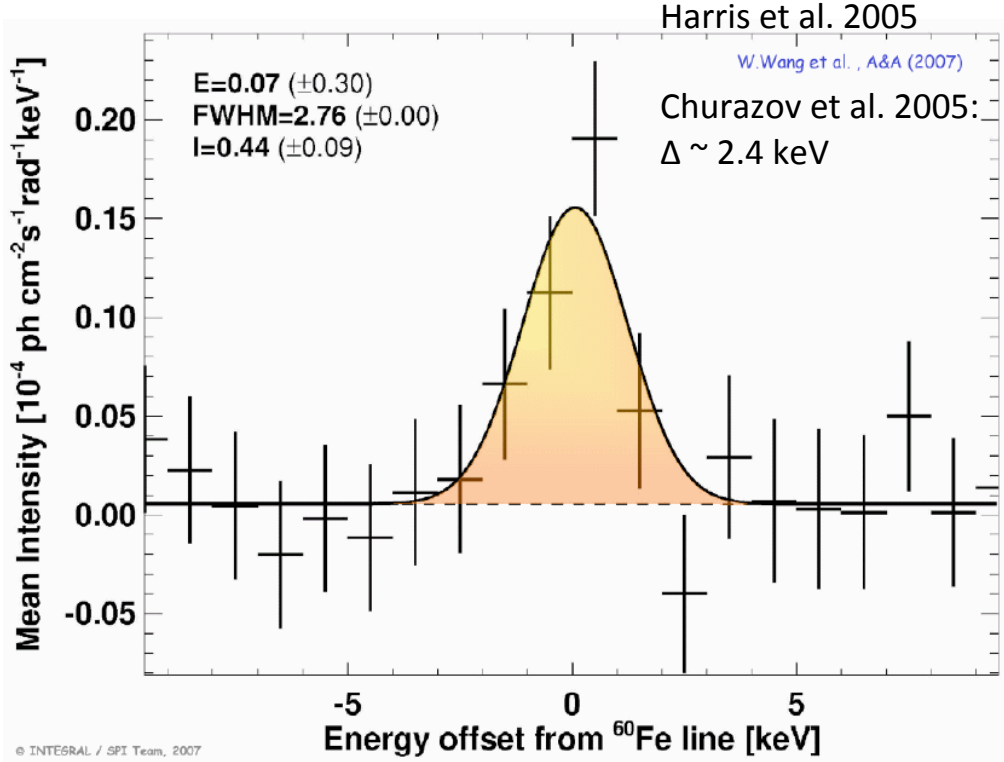


^{26}Al & ^{60}Fe

Coproduced in massive stars: Static He-shell burning s-process (the explosion only ejects!)



RHESSI: Smith 2005
INTEGRAL/SPI
Harris et al. 2005



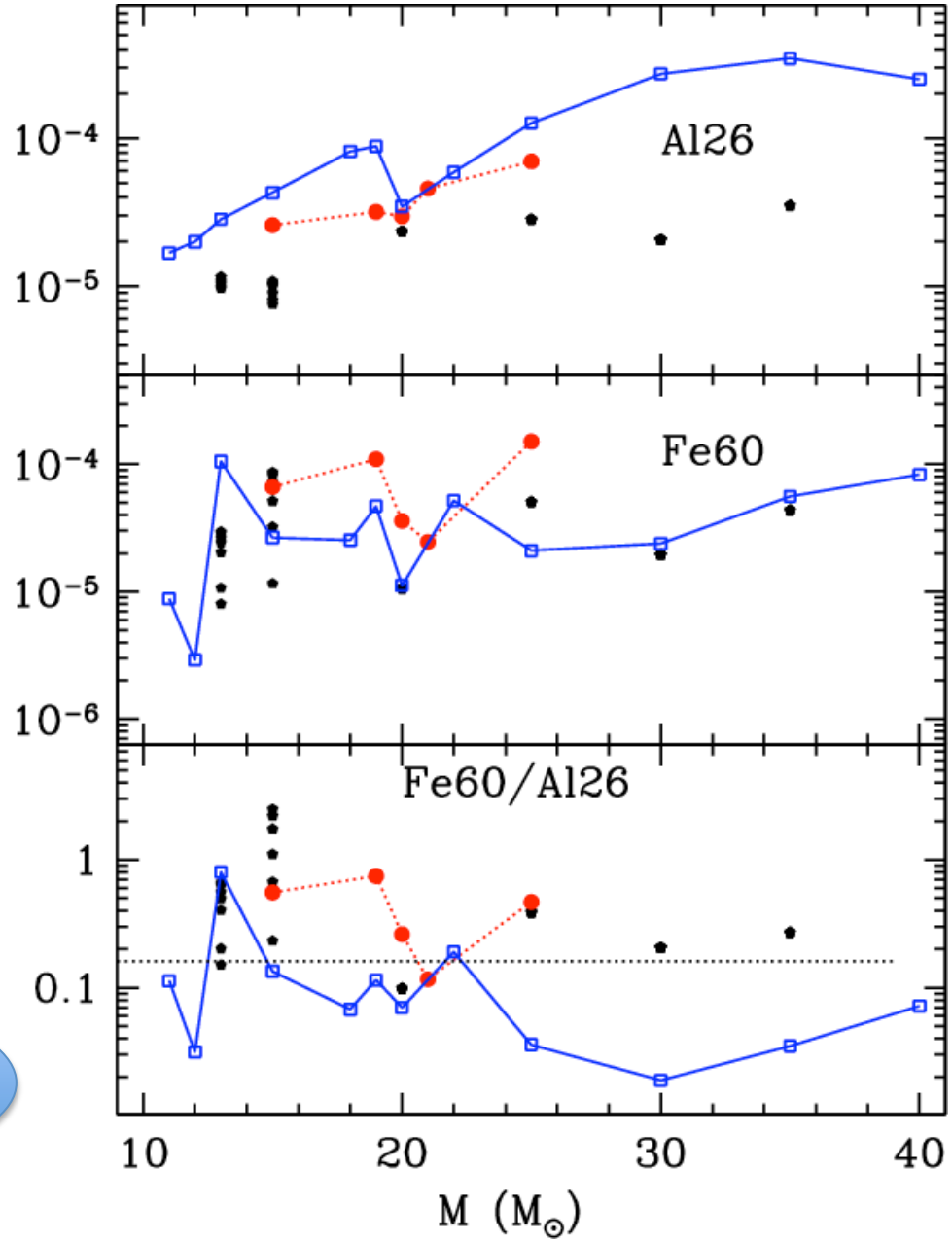
Churazov et al. 2005:
Δ ~ 2.4 keV

Clarisse Tur (MSU)

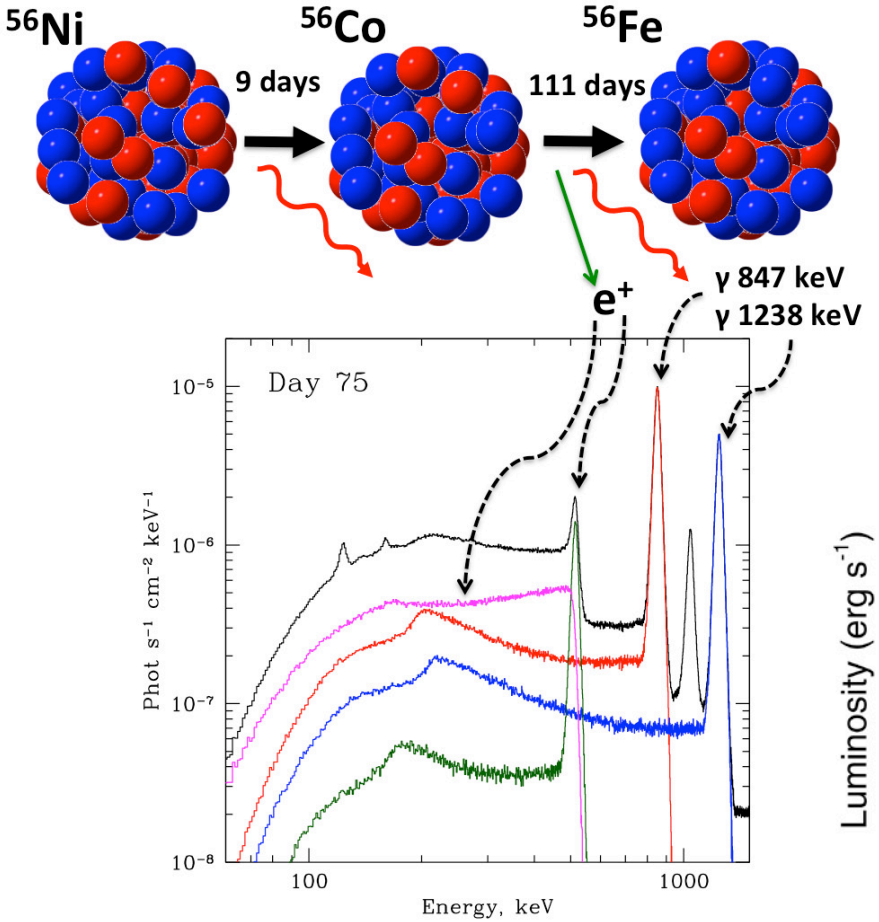
$^{59}Fe(n,\gamma)^{60}Fe(n,\gamma)^{61}Fe$
Reaction rate uncertainties
➔ yield uncertainties
Mass loss

$^{26}Al/^{60}Fe$ flux ratio
~ 10-20% ✔

Diagnostic
for SNII/Nova
decomposition



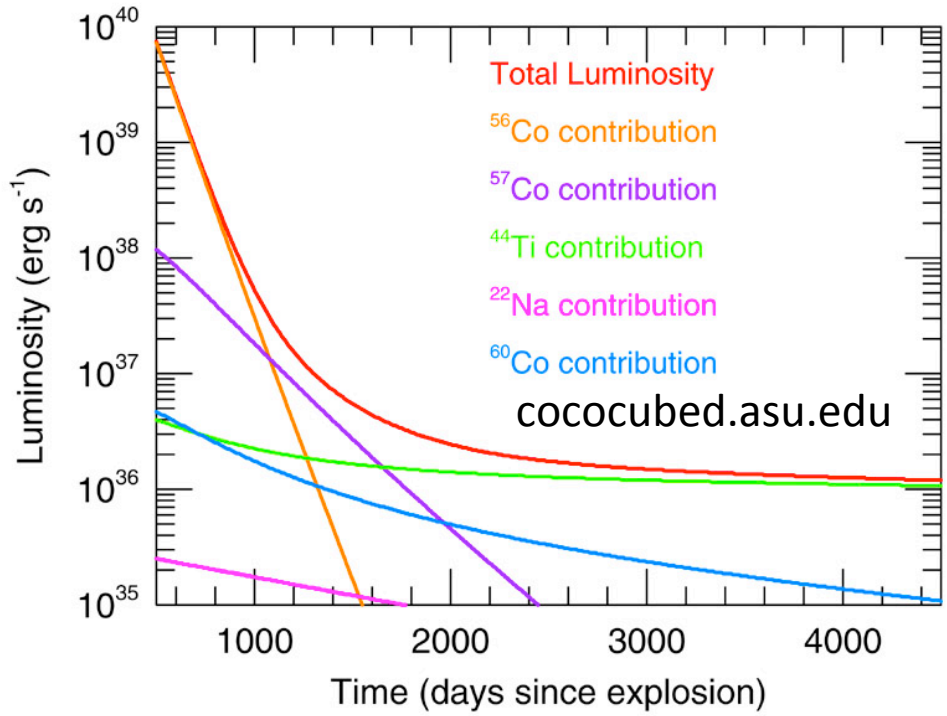
We need a map



Radioactivities

keep the SN lights on !

^{254}Cf (B^{2}FH: 1957) ➔ ^{56}Ni



$$^{56}\mathrm{Co} + e^- \rightarrow {}^{56}\mathrm{Fe}^* + \nu_e$$
$$^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}^* + e^+ + \nu_e$$
$$^{56}\mathrm{Fe}^* \rightarrow {}^{56}\mathrm{Co} + \gamma$$
$$E_\gamma = 847\,\mathrm{keV}(100\%),\ 1238\,\mathrm{keV}(67\%),$$

But $L(t) \neq L_{radiogenic}(t)$

Delayed power model (Clayton92)
Time-dependent ionization

Diagnosing SNIa models with MC Transport simulations

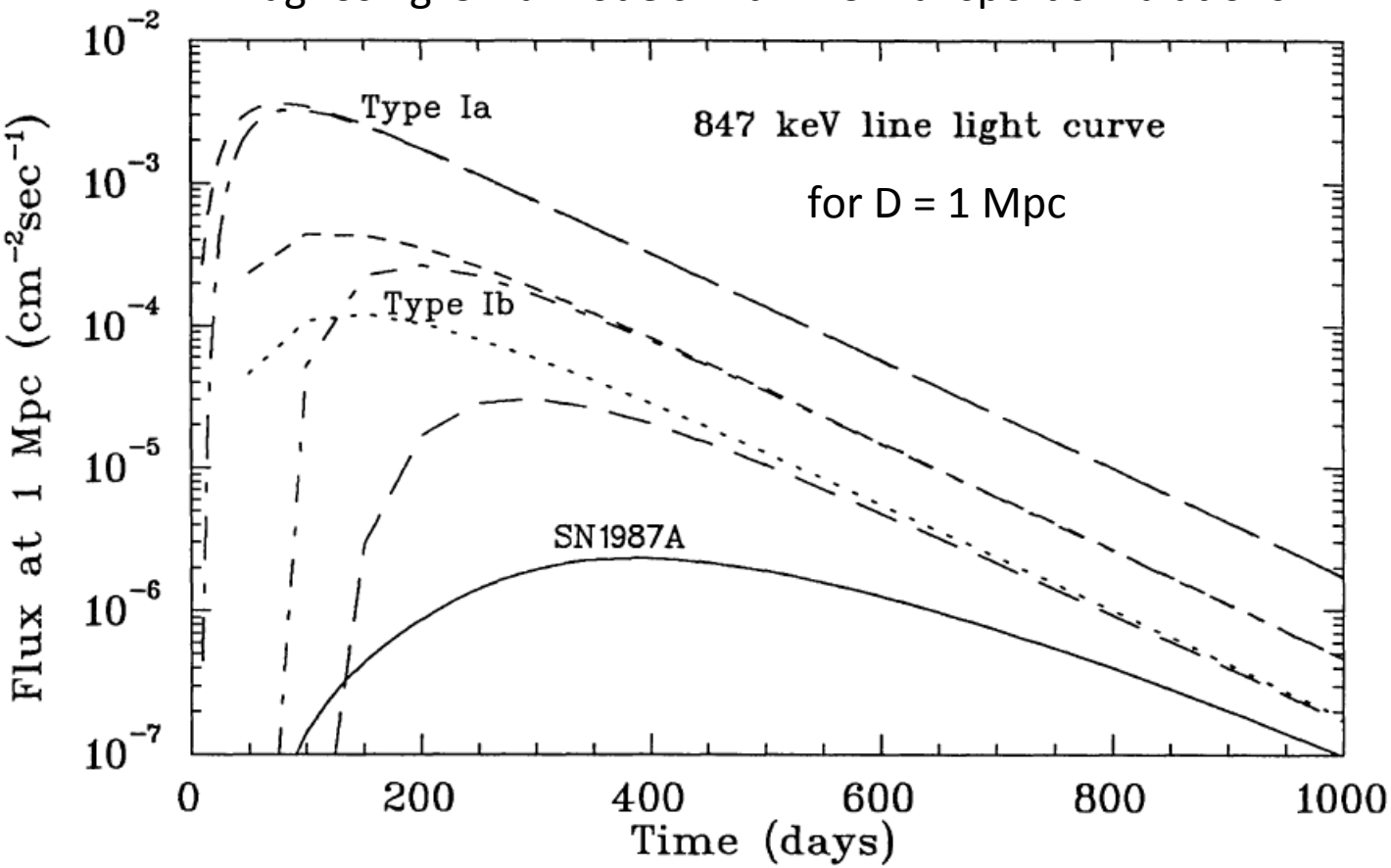
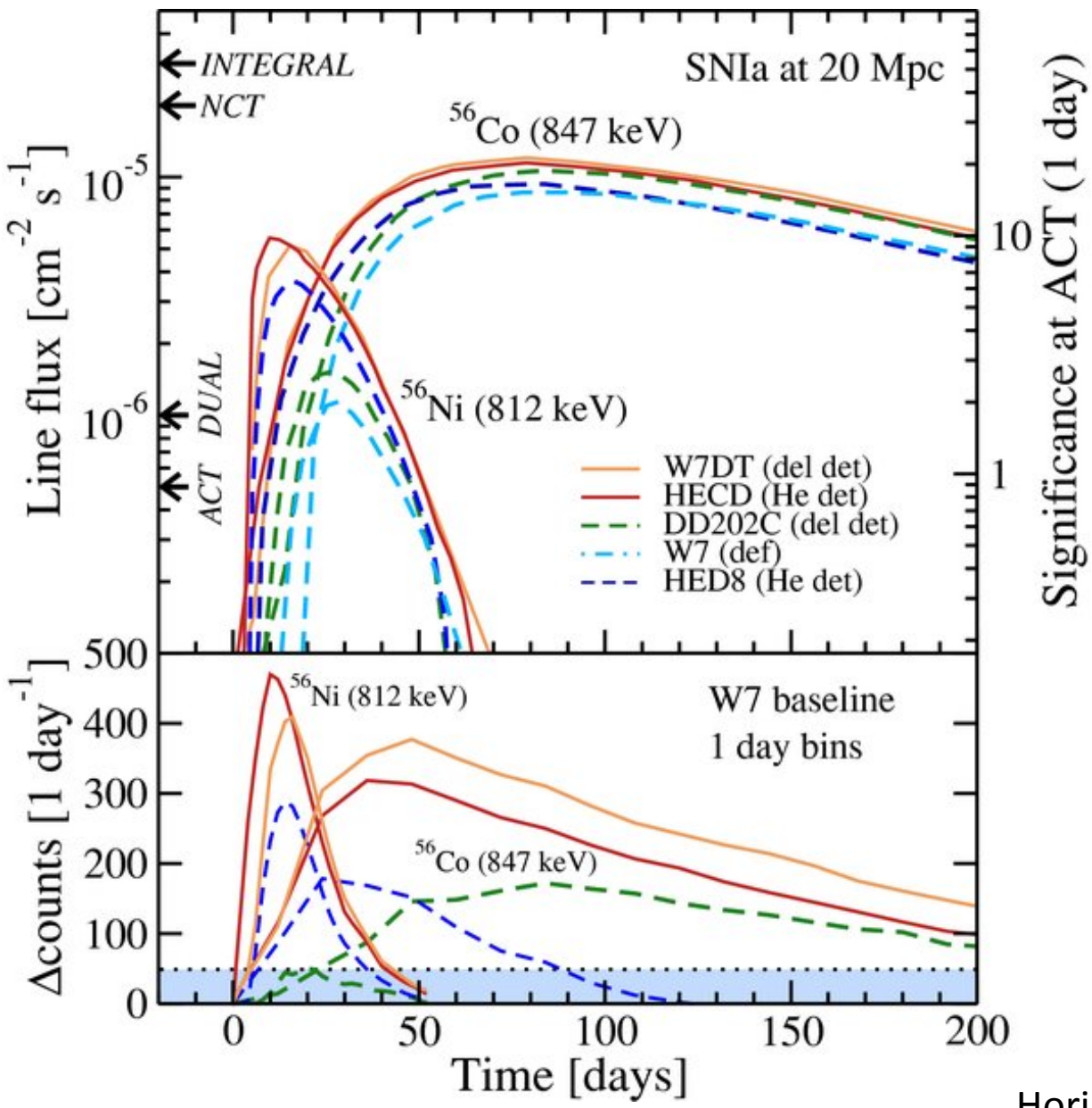


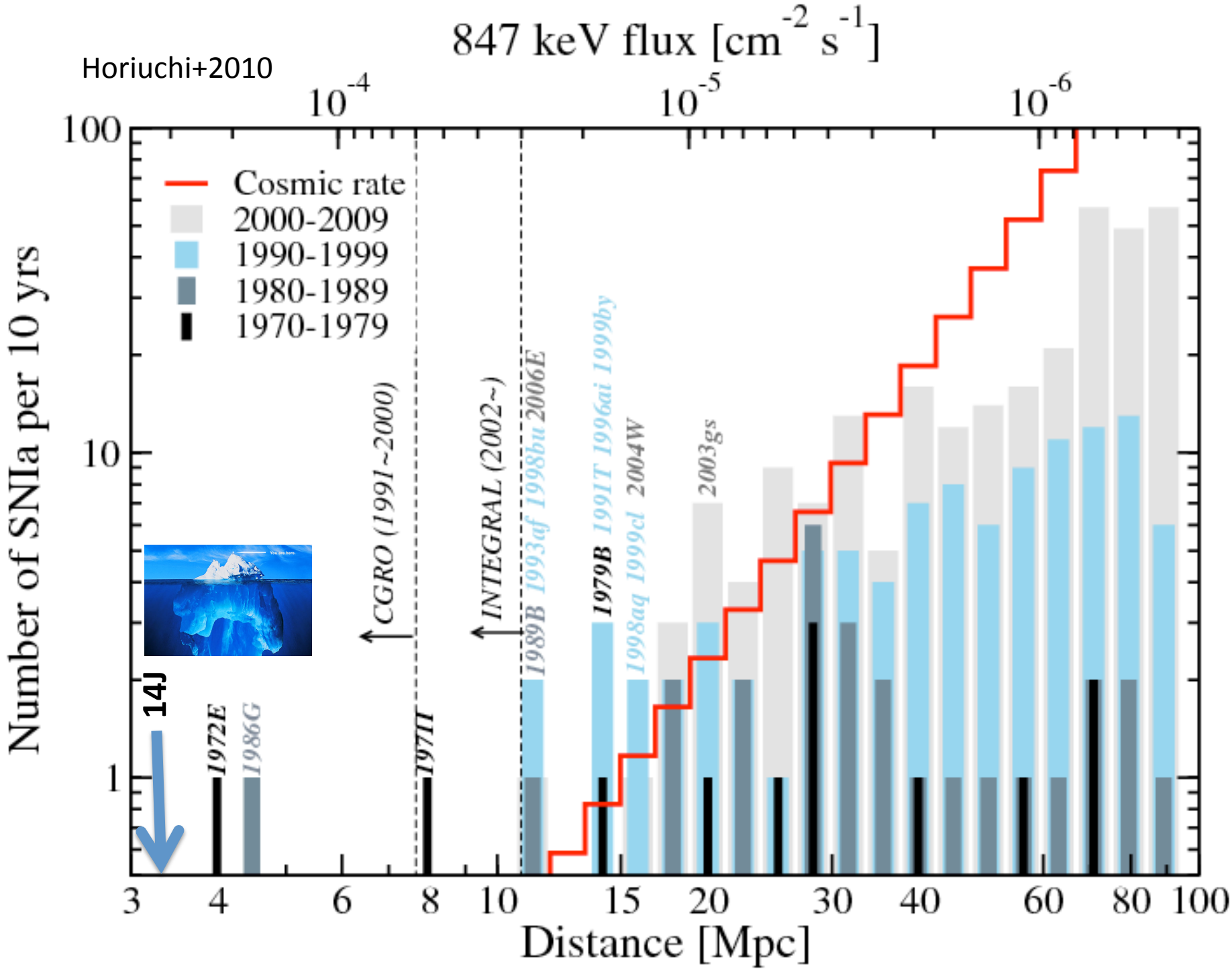
Figure 1. The 847 keV Gamma line light curves of different types of supernovae at distance of 1 Mpc: (Ia) W7; (Ib) WR6C upper and WR4A lower; (SN1987A for Type II) W10hmm. Brighter branches of W7, WR6C, and WR4A are fully mixed counterparts of those models.

The, Clayton, Burrows 1991

Diagnosing SNIa models



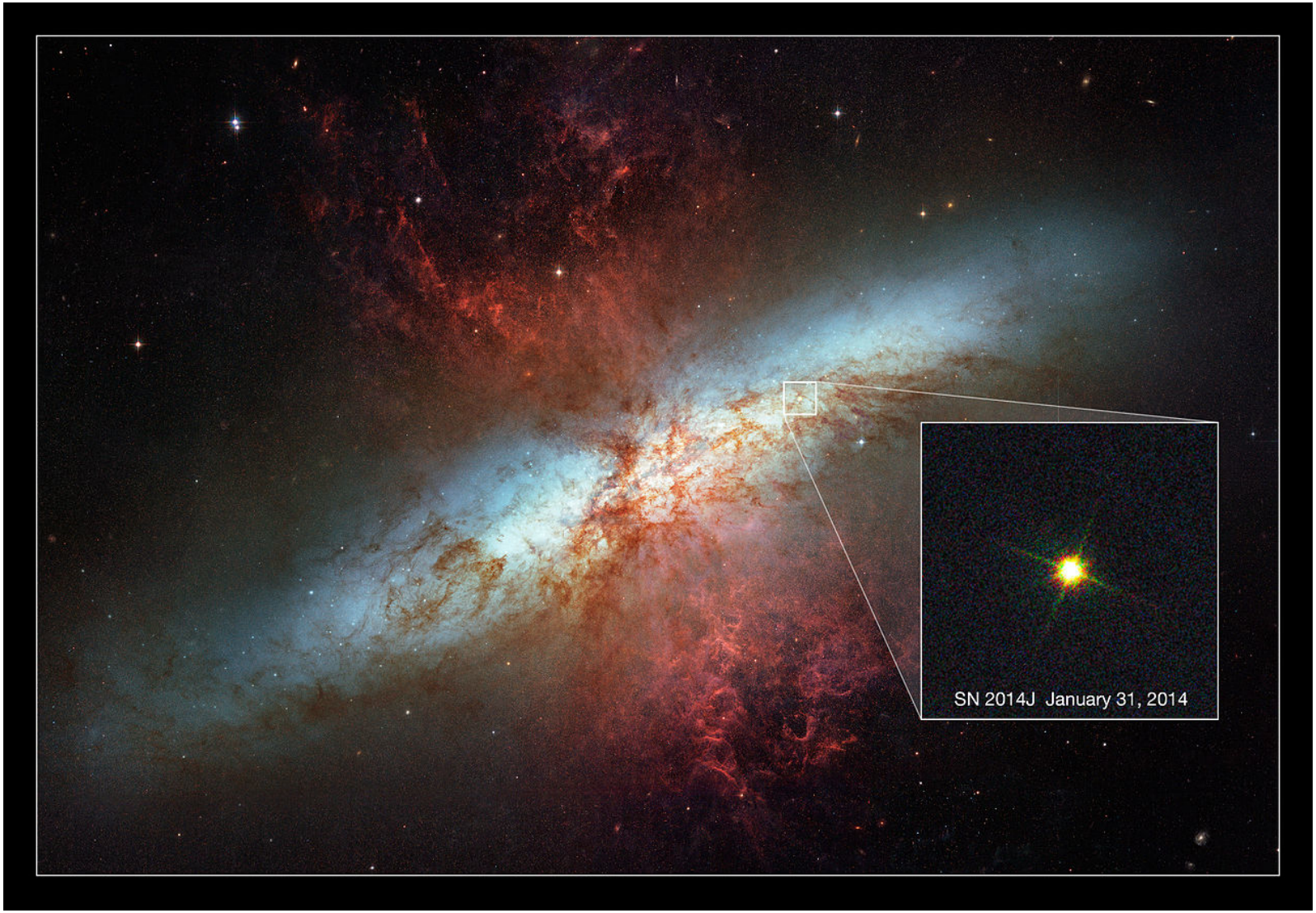
Horiuchi+2010


Horiuchi+2010
847 keV flux [cm^{-2} s^{-1}]
10^{-4}
10^{-5}
10^{-6}
Cosmic rate
2000-2009
1990-1999
1980-1989
1970-1979
Number of SNIa per 10 yrs
100
10
1
CGRO (1991~2000)
INTEGRAL (2002~)
14J
1972E
1986G
1977I
1989B 1993af 1998bu 2006E
1979B 1991T 1996ai 1999by
1998aq 1999cl 2004W
2003gs
3
4
6
8
10
15
20
30
40
60
80
100
Distance [Mpc]

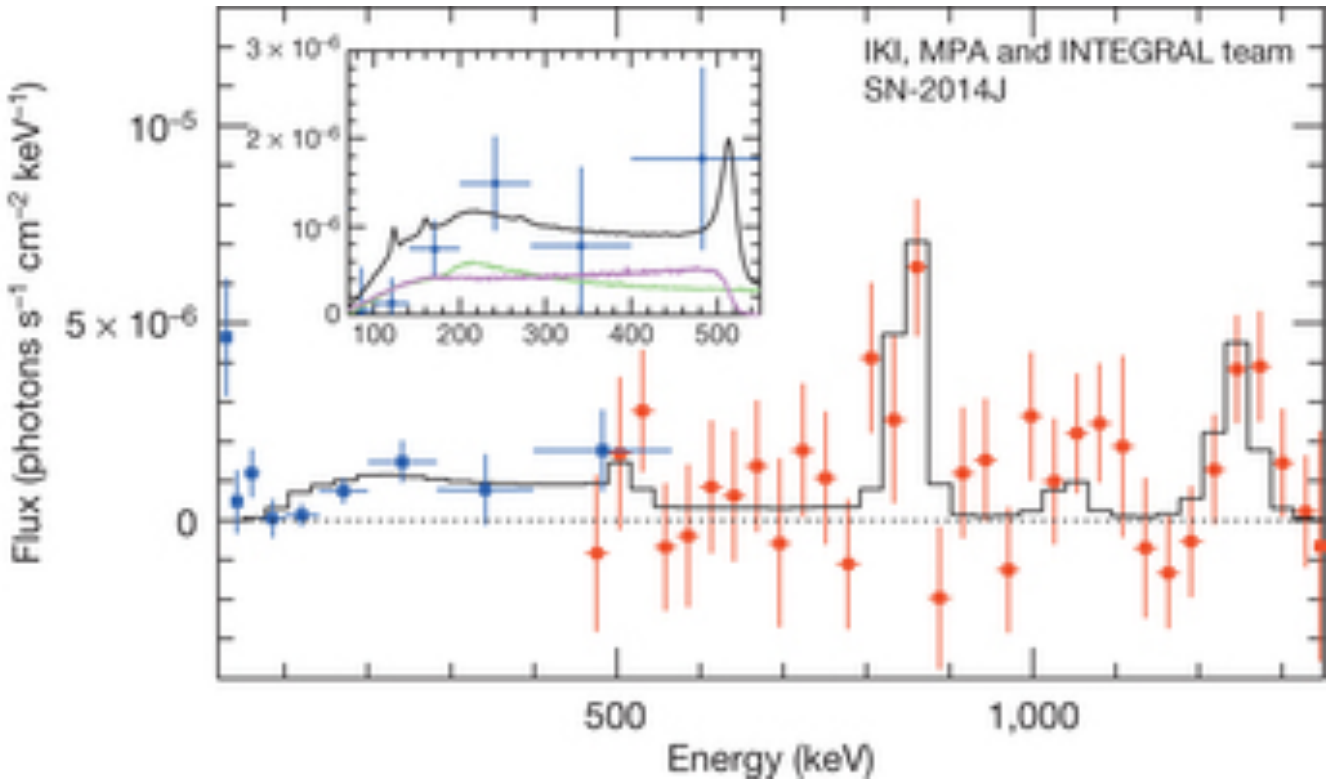
Nearest recent SNIa: SN2014J in M82 at D ~ 3.5 Mpc

- discovered by Steve Fossey, of University College London -

:

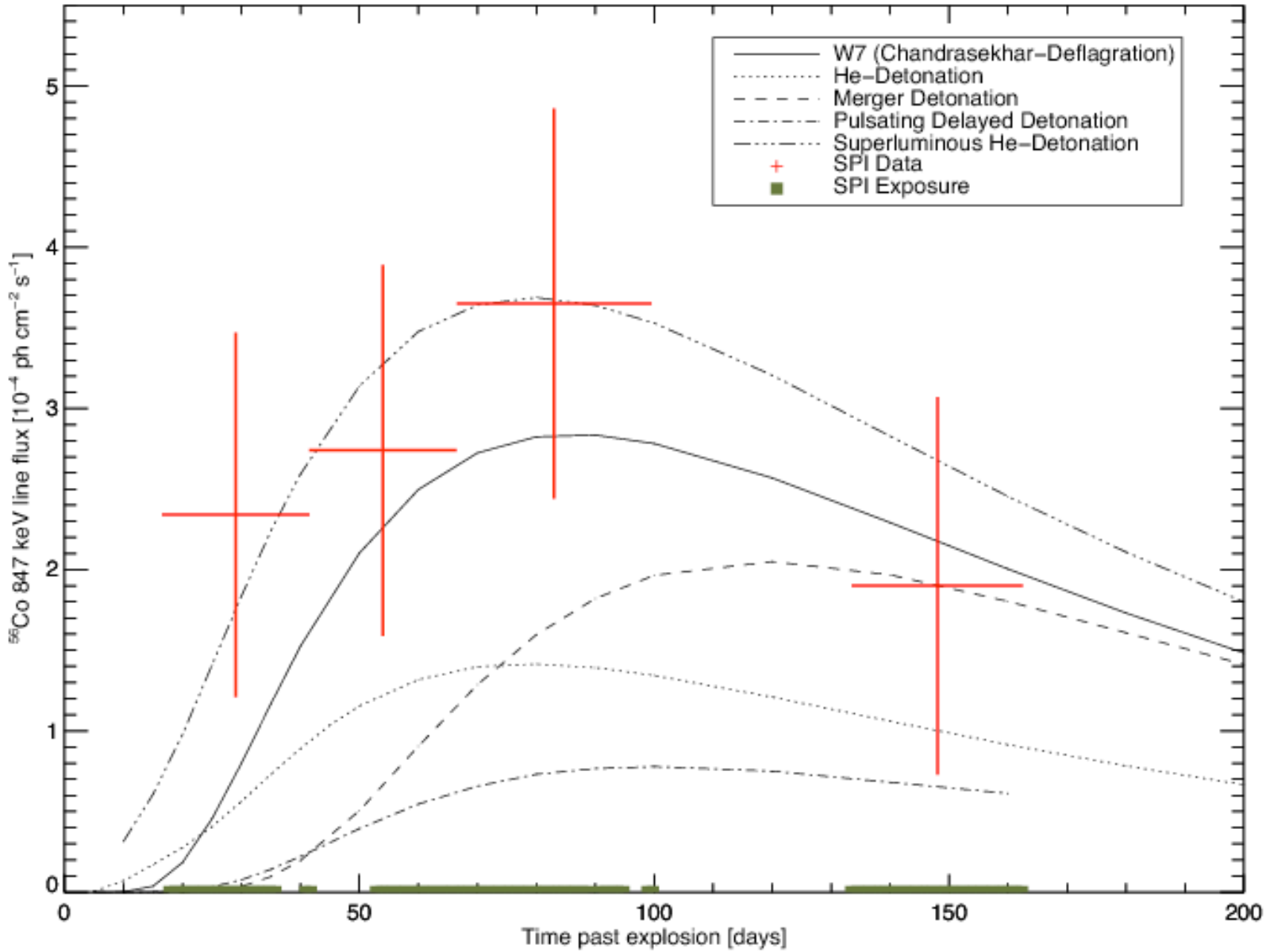


Eugene Churazov, MPA: 2014, Nature; Siegert & Diehl 15; Isern+16

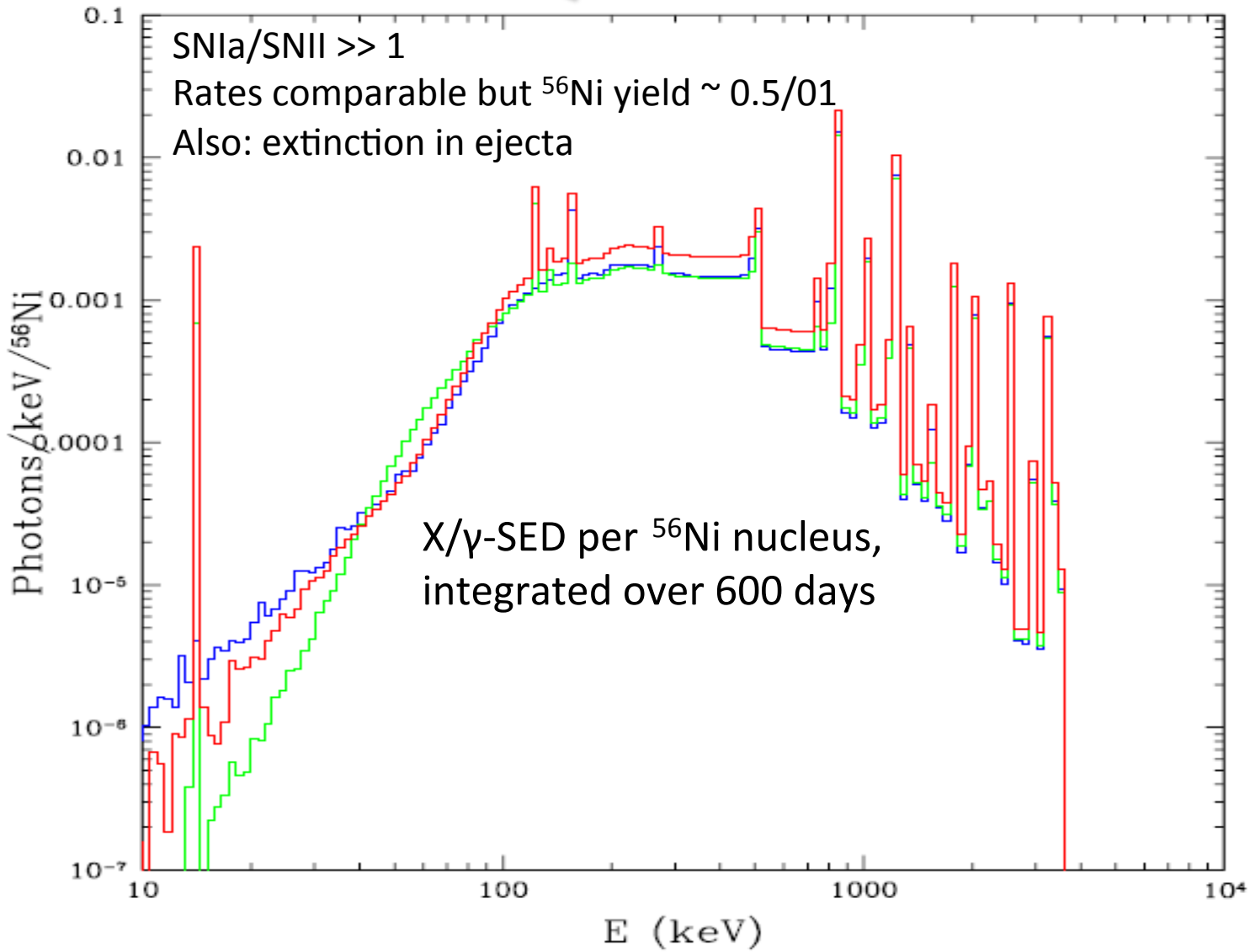


- F(^{56}Co), observed with INTEGRAL, imply 0.6 $M_\odot$ of ^{56}Ni.
- Line broadening: v ~10000 km/s.
- e+ (^{56}Co) annihilation makes significant contribution to the continuum below 511 keV.
- Data are consistent with canonical 1D models: delayed detonation or for a near-Chandrasekhar mass WD. Pure detonation or sub-Chandrasekhar models are excluded.

SN2014J Diehl et al 2015: INTEGRAL/SPI

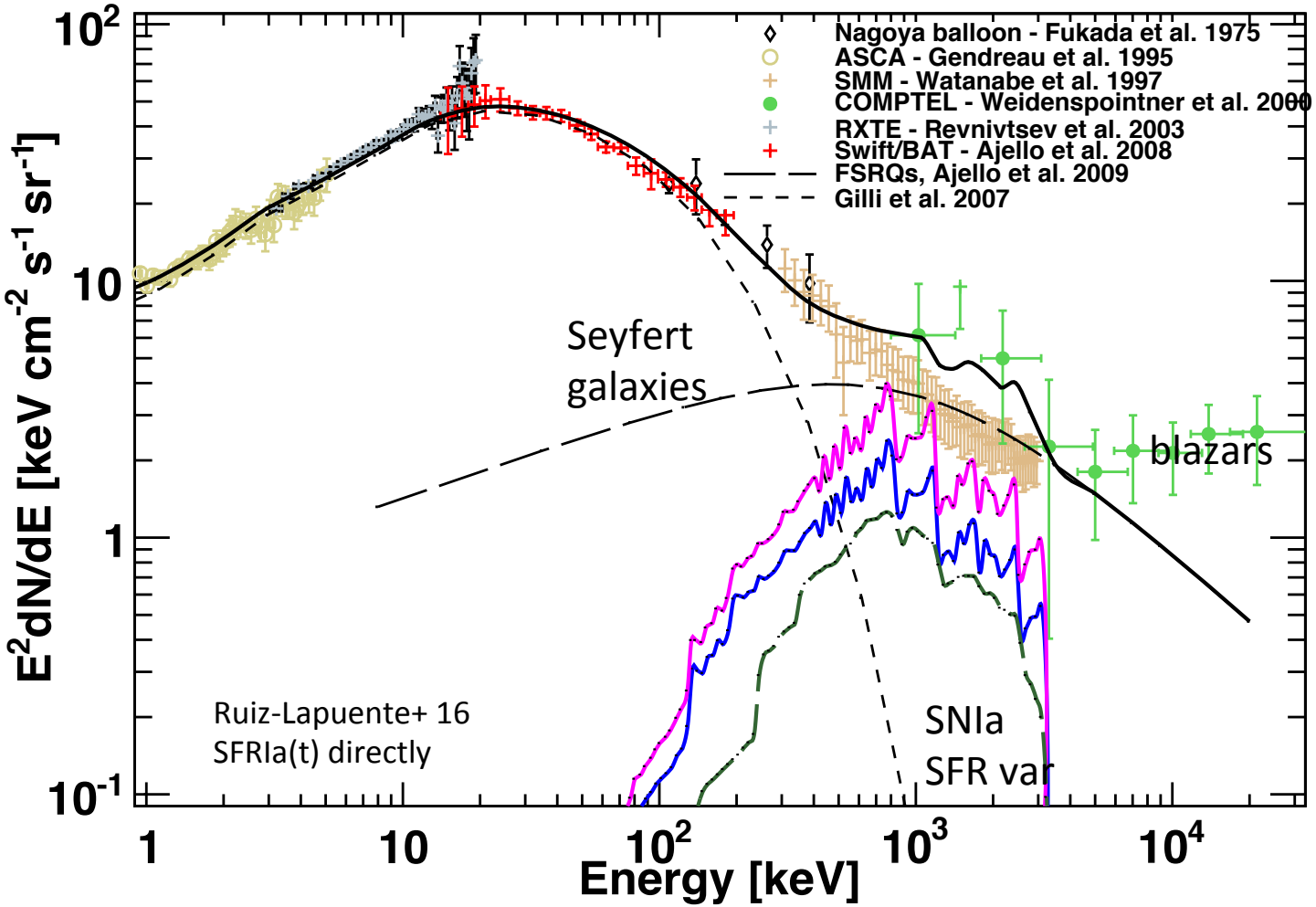


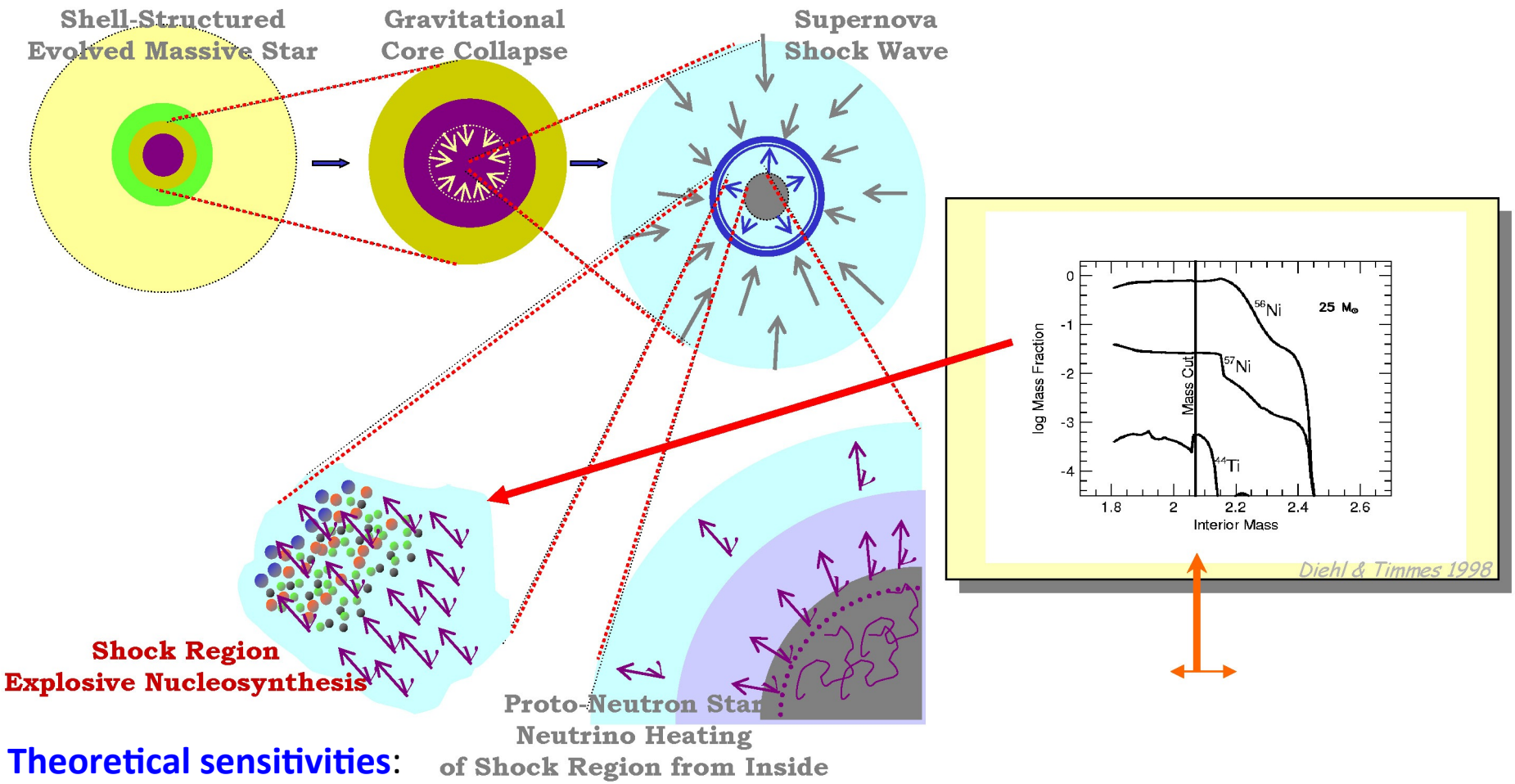
Time integrated escape SED



Edges in

The Cosmic Gamma-Ray Background



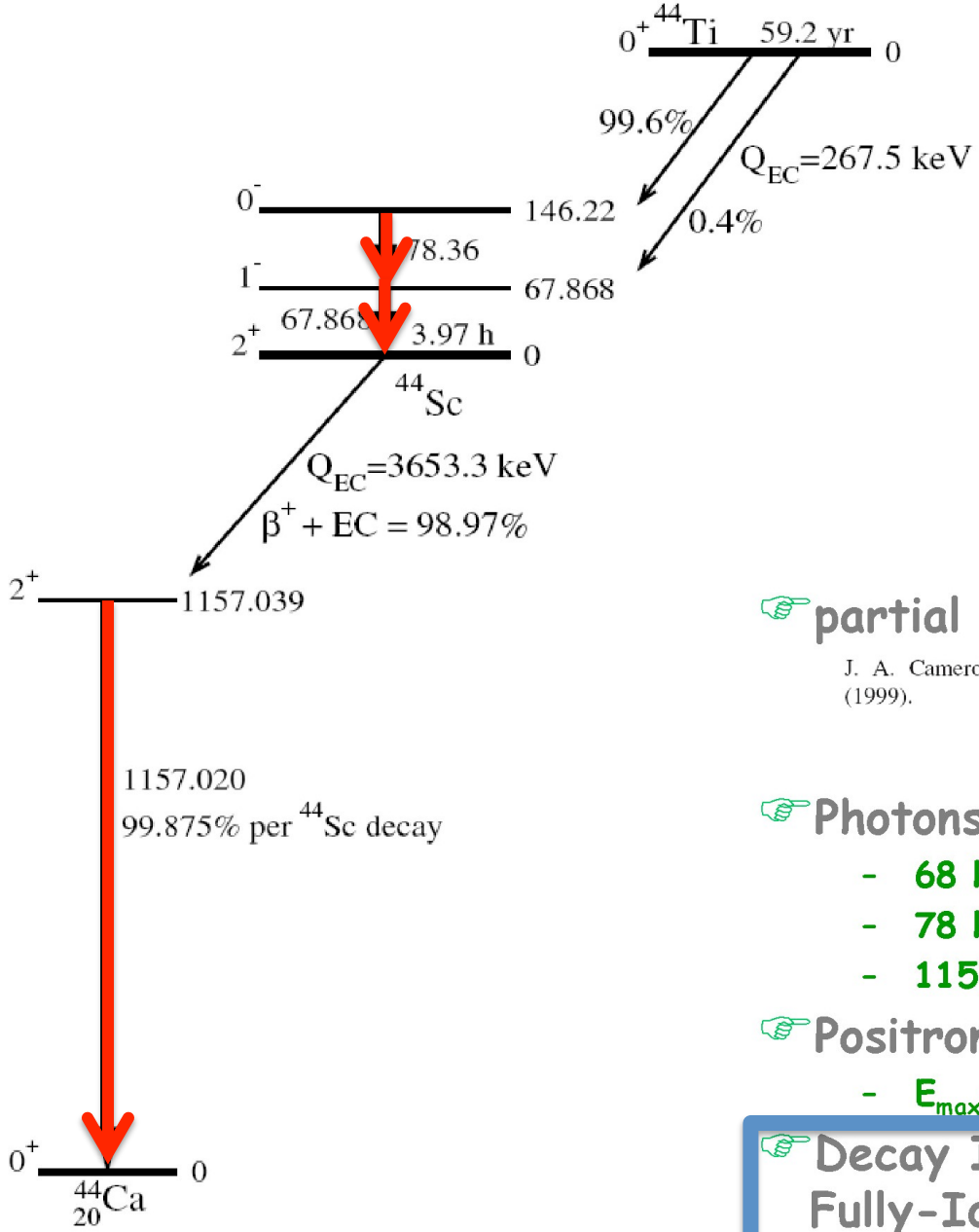


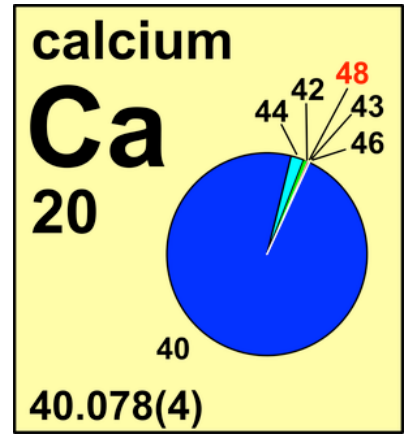
Theoretical sensitivities:

- V_{ejecta} ➔ Thermodynamic trajectory (E_{kin})
- Fall back (M_{cut}), and M_*, z_* - Progenitor
- Explosion anisotropies and inhomogeneities

Expected ccSNe Yields ~ $10^{-5} – 10^{-4}$ $M_\odot$

Expected SNIa Yields ↓ (W7) but in some (rare) cases (Double Det sub-Chandra) ↑ 10^{-3} $M_\odot$



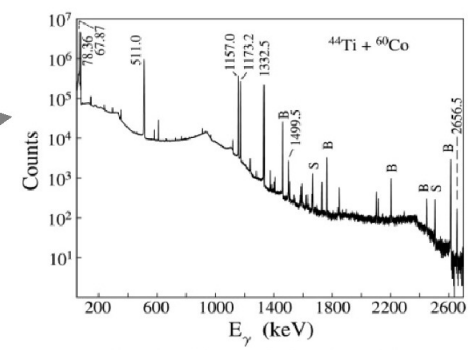


$^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca$

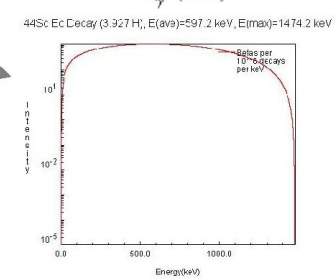
- partial level schemes and ^{44}Ti decay

J. A. Cameron and B. Singh, Nucl. Data Sheets **88**, 299 (1999).

- Photons:
  - 68 keV 100%
  - 78 keV 99.6%
  - 1157 keV 99.9%

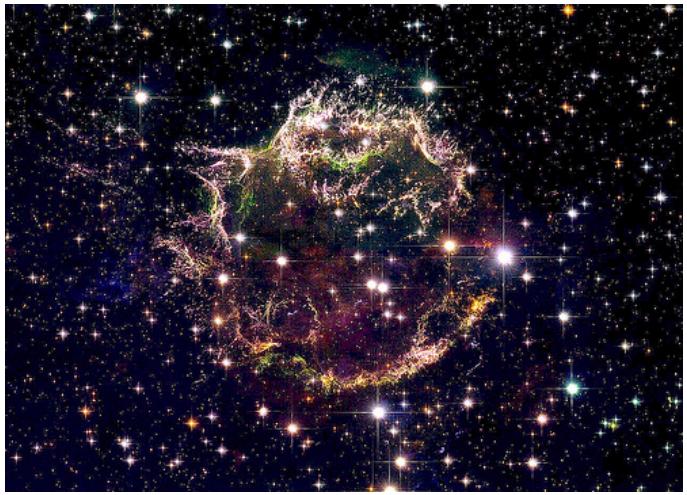


- Positrons
  - E_{max}=1.47 MeV 98%



- Decay Inhibited for Fully-Ionized ^{44}Ti (EC!)

Cas A, T ~ 333 yrs, D ~ 3.3 kpc



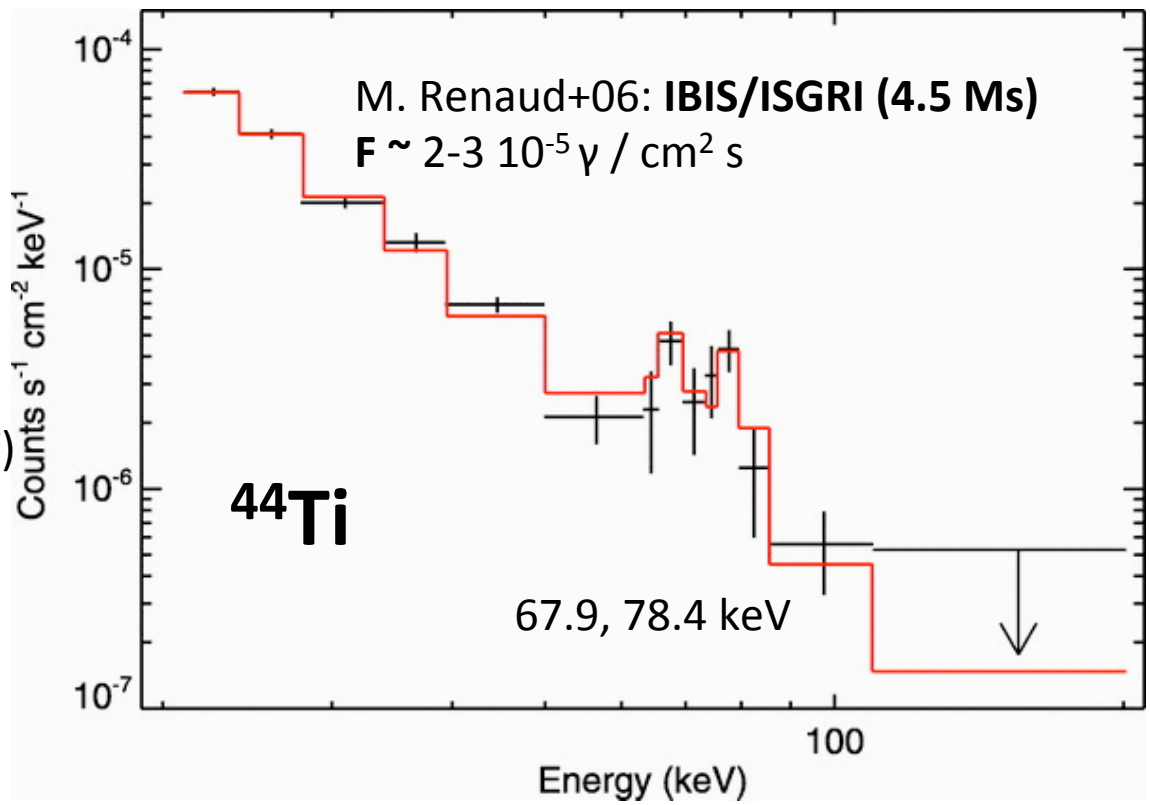
Iyudin+ 1994 **COMPTEL at 1.157 MeV**

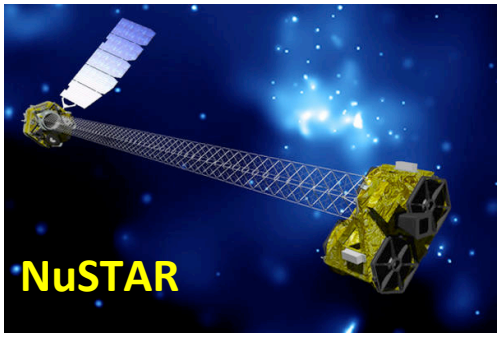
F ~ 2-4 10^{-5} γ / cm² s

T. Siegert+15: **INTEGRAL/SPI**
F ~ 2 +/- 0.4 10^{-5} γ / cm² s @ 78 keV)
F ~ 2 - 5 10^{-5} γ / cm² s @ 1157 keV)

Wang & Li+6: **INTEGRAL/ISGRI-IBIS**
F ~ 2.2 +/- 0.4 10^{-5} γ / cm² s @ 78 keV)

Yield: 1-3 10^{-4} $M_\odot$!

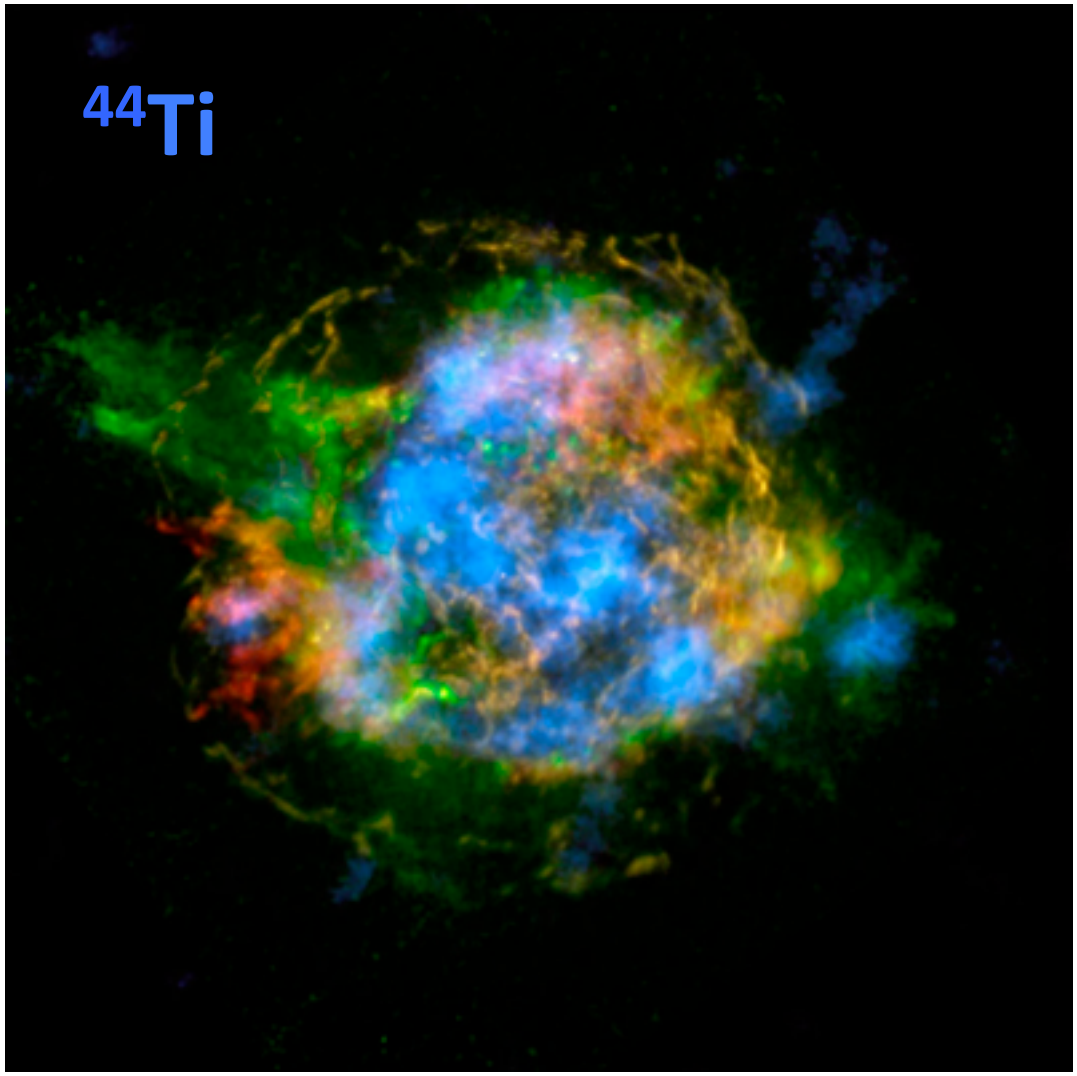


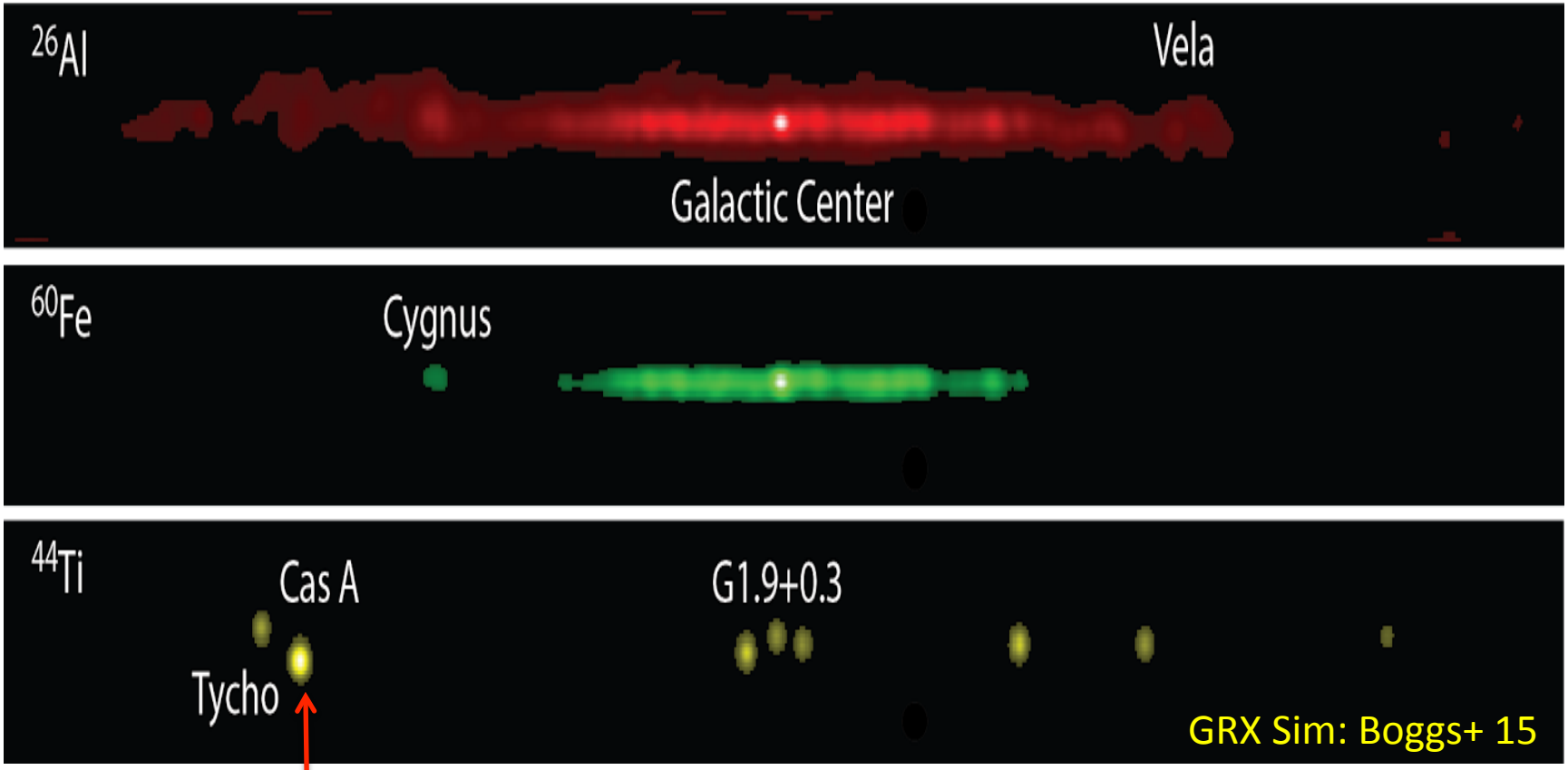


Grefenstette+14 Nature 506,339

Mapping Cas A

Asymmetries, Redshift by 0.5 keV,
F ~ 1-2 10^{-5} γ / cm^2 s





Tsygankov+16, IBS/ISGRI 12 year survey … to 4.8 10^{-6} γ/cm^2 s ~ 5 X CGRO/COMPTEL

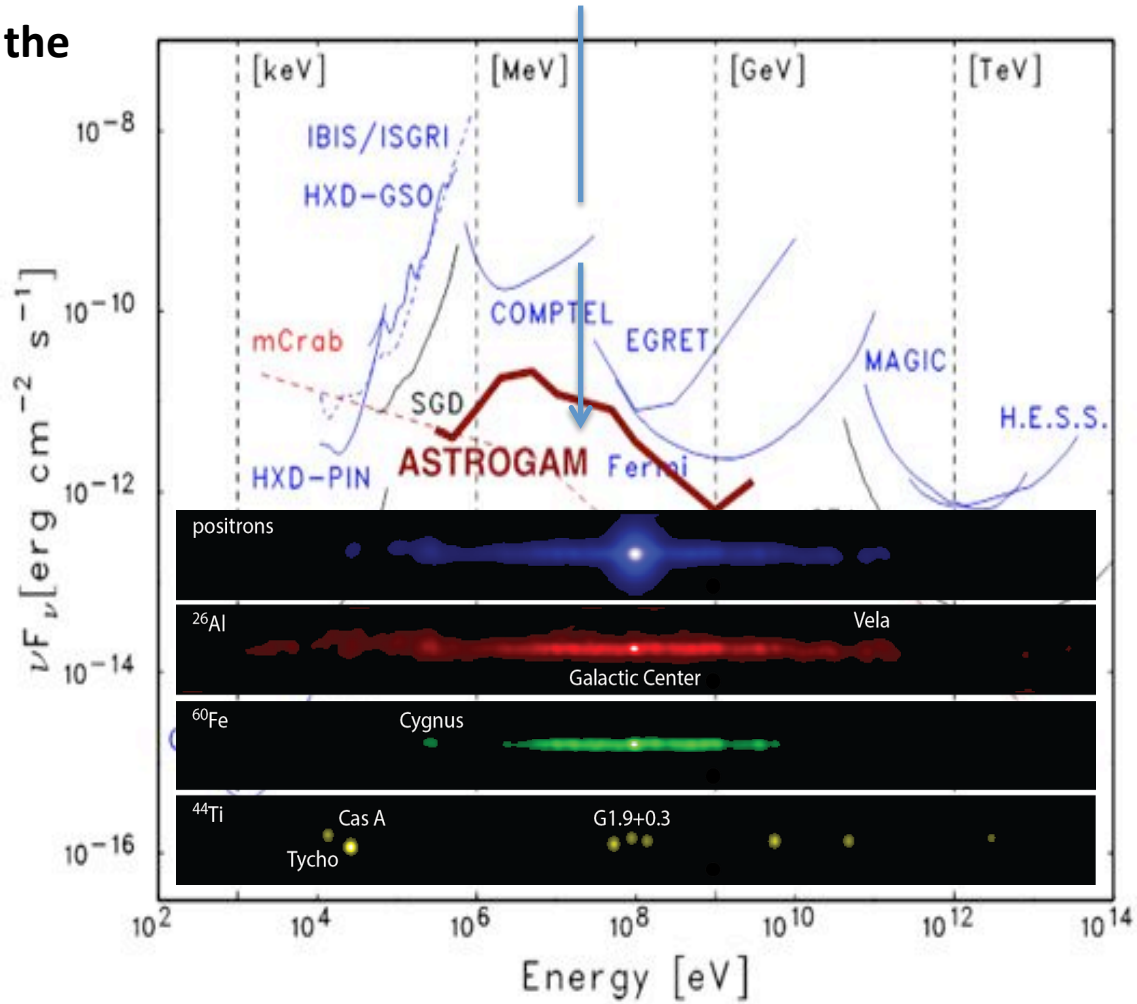
✓ But no other source !!!!

The+ 06: ^{44}Ti sources are rare events with big yields

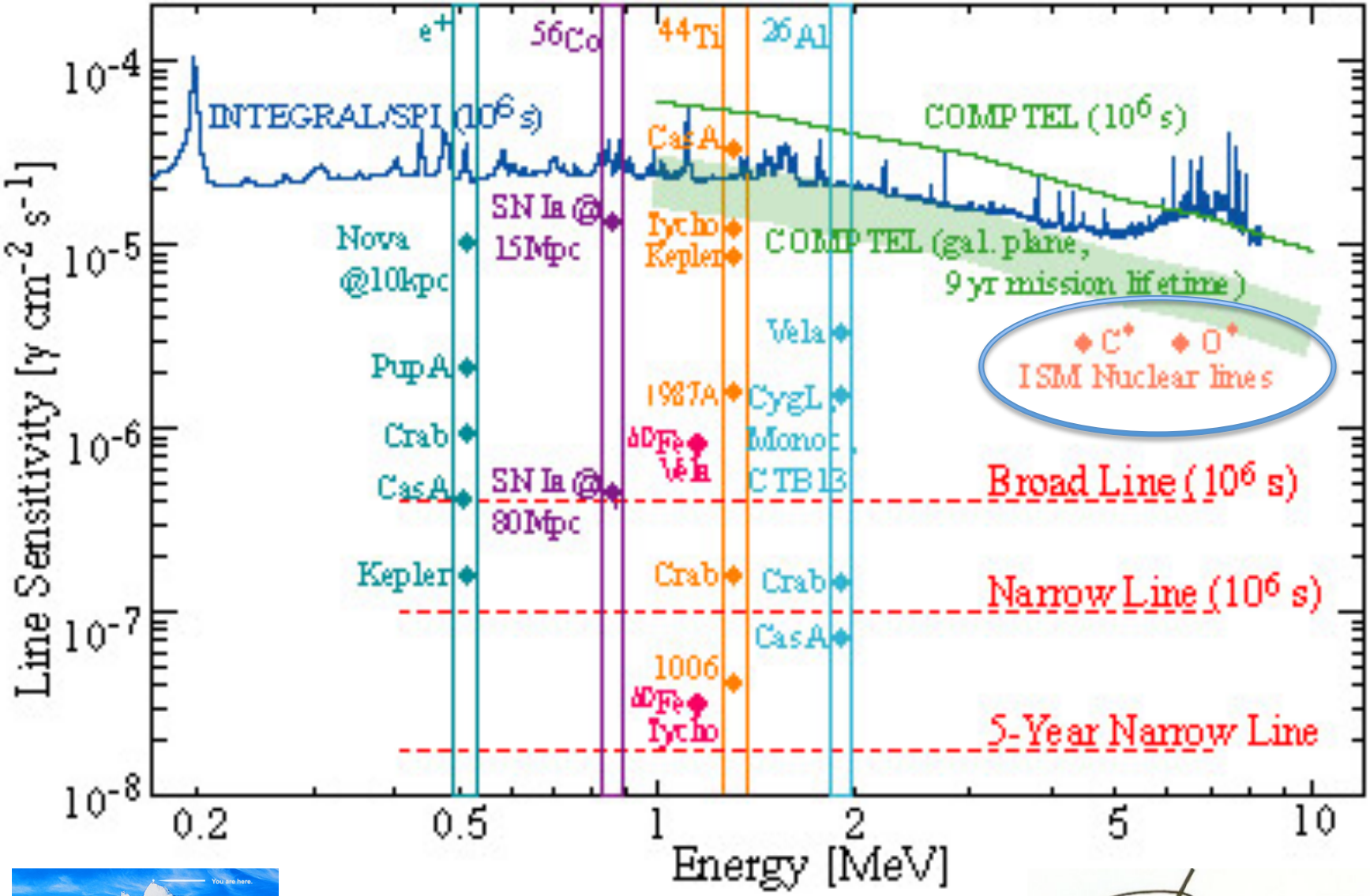
GRX: Boggs+

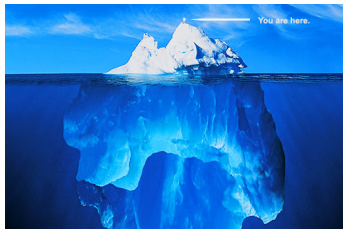
The challenging MeV band has so far only allowed us to sample the tip of the

Atomic- **Nuclear-** Particle-Physics

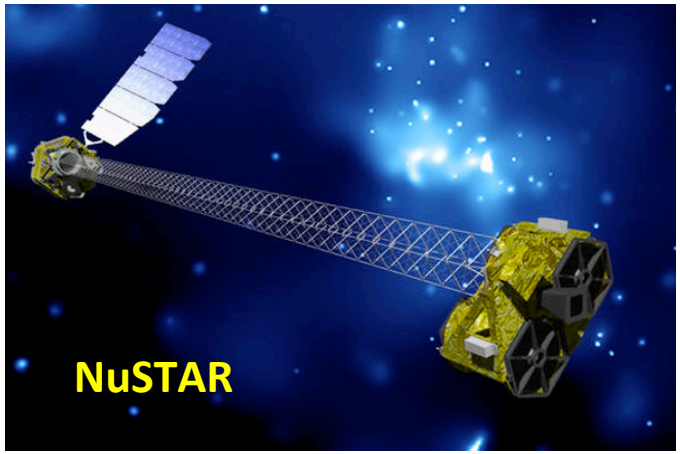


ACT


Line Sensitivity [γ cm^{-2} s^{-1}]
Energy [MeV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.2
0.5
1
2
5
10
e+
56Co
44Ti
26Al
INTEGRAL/SPI (10^6 s)
COMPTEL (10^6 s)
Cas A
SN Ia @ 15Mpc
Tycho
Kepler
COMPTEL (gal. plane, 9 yr mission lifetime)
Nova @10kpc
Vela
Pup A
C+
O+
ISM Nuclear lines
1987A
Cyg L
Crab
Mono
CTB13
Cas A
SN Ia @ 80Mpc
Broad Line (10^6 s)
Kepler
Crab
Crab
Narrow Line (10^6 s)
Cas A
1006
Tycho
5-Year Narrow Line

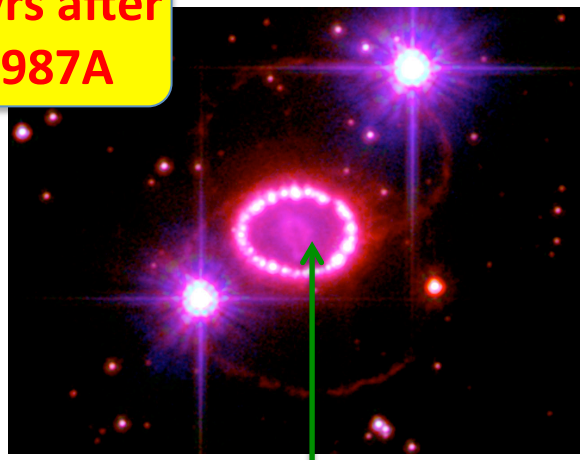

You are here.

Thank You!

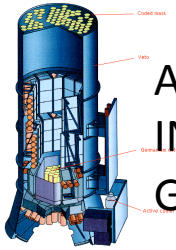


lines are narrow and redshifted with a Doppler velocity of ~700 kilometers per second, probing direct evidence of large-scale asymmetry in the explosion.

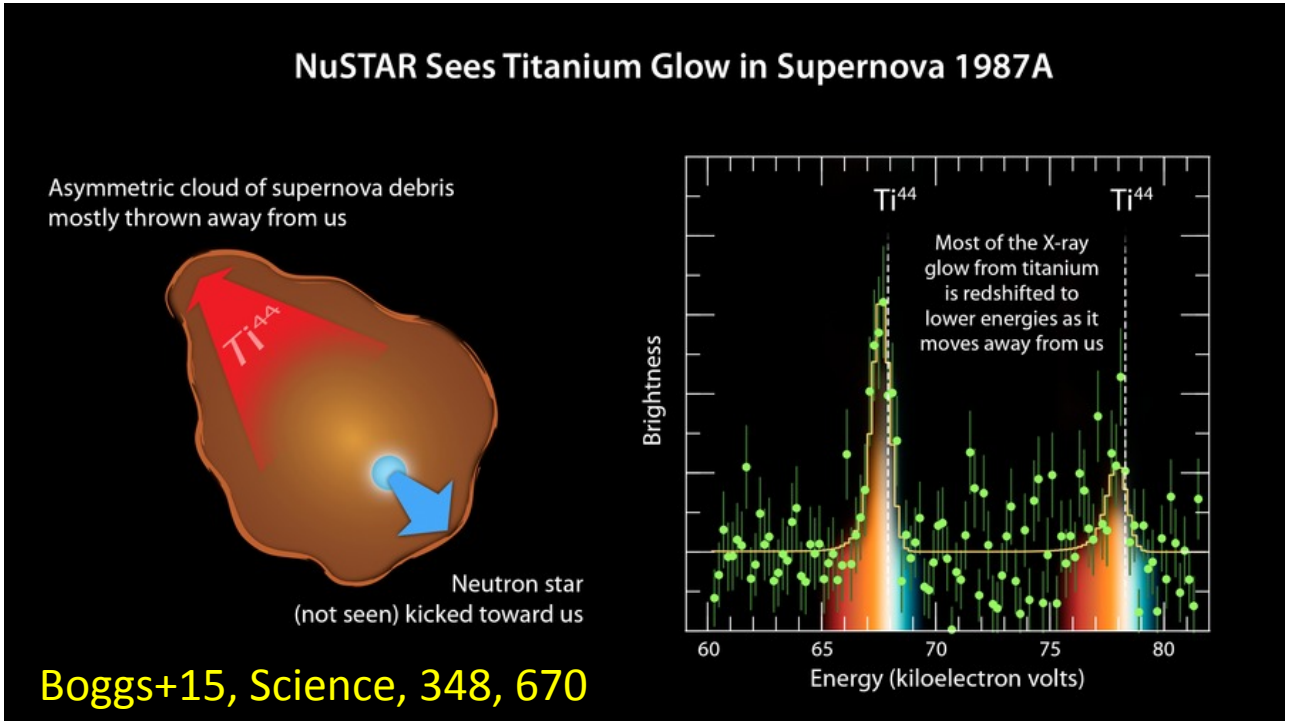
25 yrs after SN1987A



^{44}Ti



Also detected by INTEGRAL Grebenev+ 2012

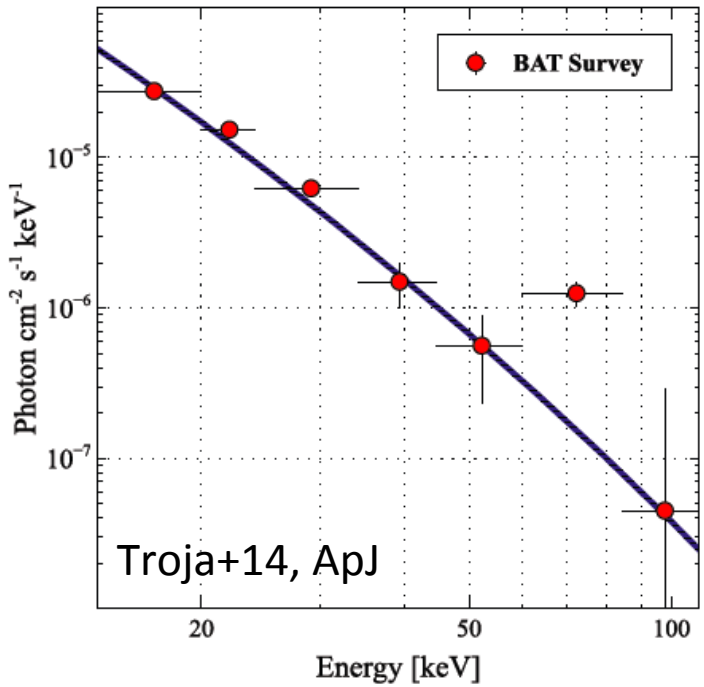


Boggs+15, Science, 348, 670

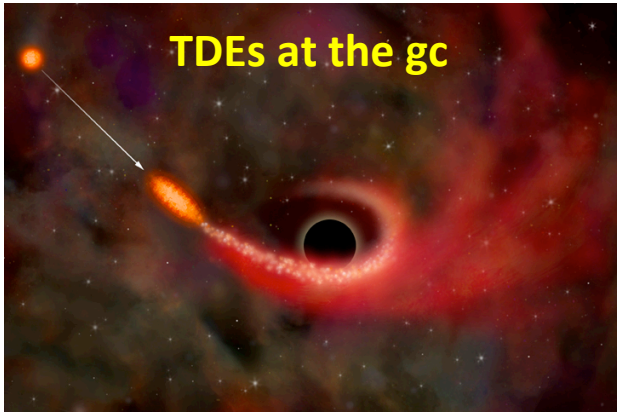
Vivid View of Tycho's Supernova Remnant

Spitzer Space Telescope / Chandra / Calar Alto

NASA/JPL-Caltech/CXC/Calar Alto O. Krause (Max Planck Institute for Astronomy) sig08-016

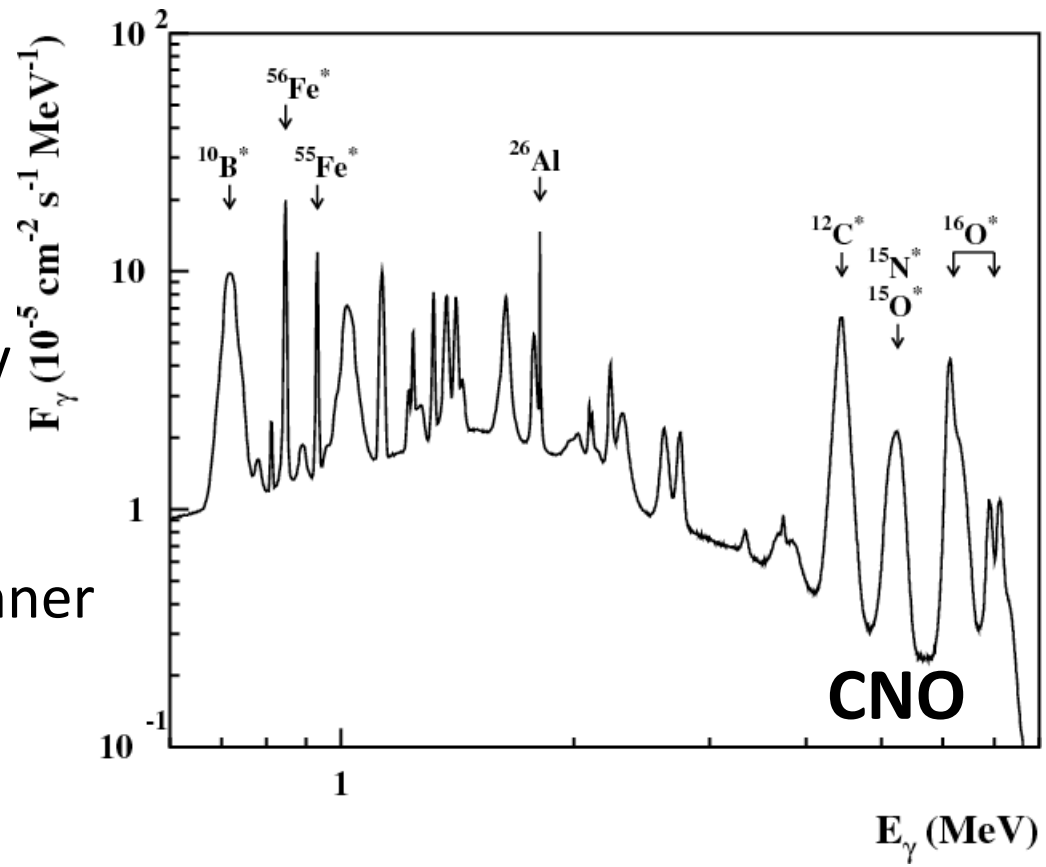


But not confirmed by NuSTAR (Zoglauer+15) and INTEGRAL (Tsygankov +16)



Tidal Disruption Events yield non-rel. protons, which diffuse and excite the ambient medium

Spallation produced long-lived radionuclei can come to rest in ~ 10^4 yrs, producing narrow lines: e.g. $^{26}Mg(p,n)^{26}Al$

Dogiel et al. 2009, A&A 508, 1

Predict a flux at 1.809 MeV of 3.5 10^{-7} γ/cm^2 s
~ 10^{-3} of the observed INTEGRAL/SPI flux in the inner radian (Diehl et al.)