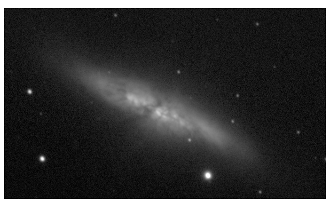
^{56}Co gamma-ray lines from type Ia supernova (SN2014J) with INTEGRAL

Eugene Churazov

(IKI, MPA)



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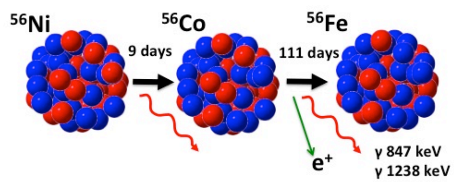

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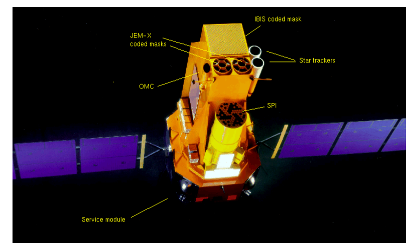

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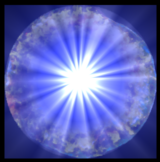
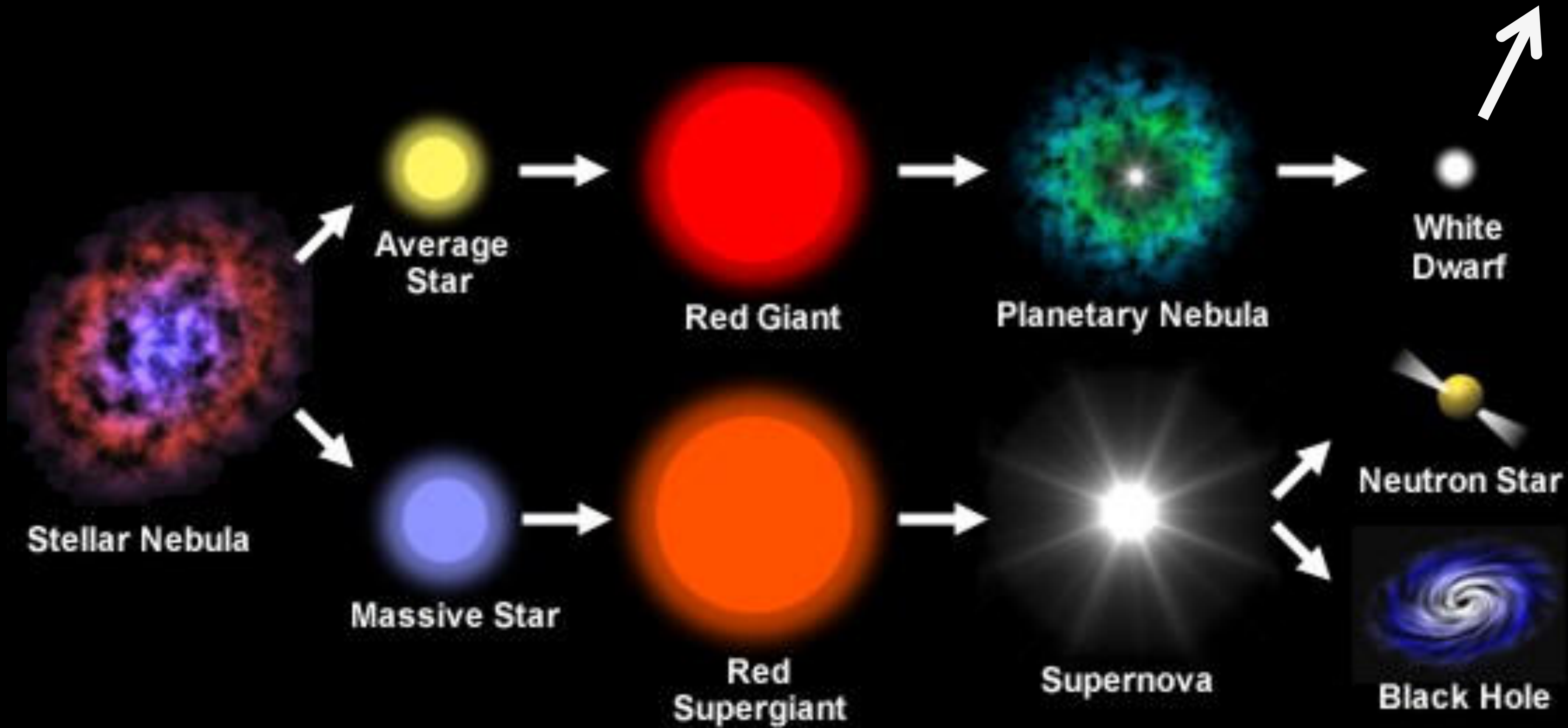
R. Sunyaev R., J.Isern, J.Knödlseder, P.Jean, F.Lebrun, N.Chugai, S.Grebenev, E.Bravo, S.Sazonov, M.Renaud, E.Kuulkers

Stellar evolution

Supernova

Type Ia
SN2014J





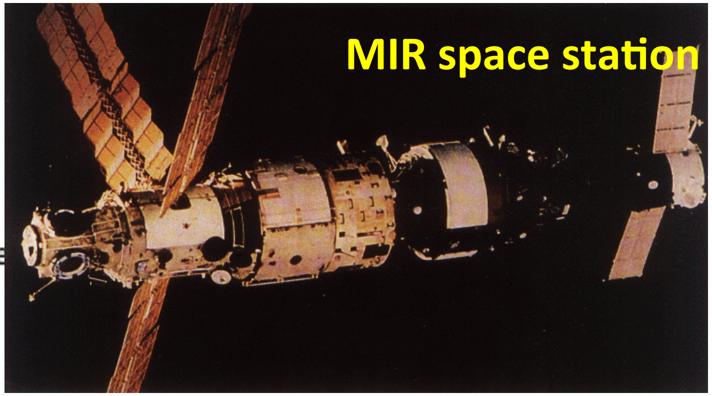
Type II
SN1987A

Nearest SN during space era
(with gamma-ray observatory in space)

Supernova Type II : SN1987A in LMC (55 kpc)
(Core Collapse, Massive Star)

Supernova Type Ia : SN2014J in M82 (3.5 Mpc)
(Thermonuclear explosion of WD, Low Mass Star)

SN1987A type Ii in Large Magellanic Cloud



Letters to Nature

Nature **330**, 227-229 (19 November 1987) | doi:10.1038/330227a0; Accepte

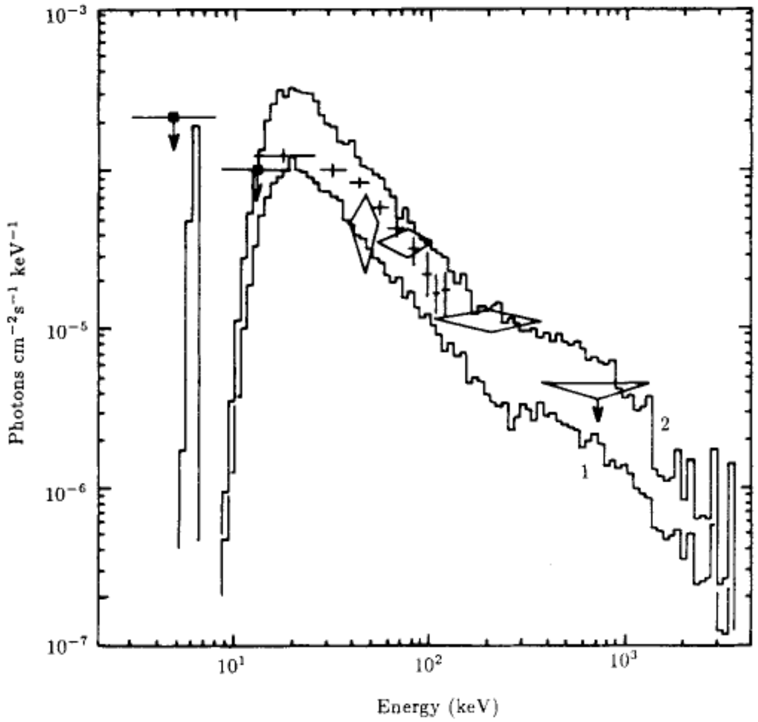
Discovery of hard X-ray emission from supernova 1987A

R. Sunyaev*, A. Kaniovsky*, V. Efremov*, M. Gilfanov*, E. Churazov*, S. Grebenev*, A. Kuznetsov*, A. Melioranskiy*, N. Yamburenko*, S. Yunin*, D. Stepanov*, I. Chulkov*, N. Pappe*, M. Boyarskiy*, E. Gavrilova*, V. Loznikov*, A. Prudkoglyad*, V. Rodin*, C. Reppin†, W. Pietsch†, J. Engelhauser†, J. Trümper†, W. Voges†, E. Kendziorra‡, M. Bezler†, R. Staubert†, A. C. Brinkman§, J. Heise§, W. A. Mels§, R. Jager§, G. K. Skinner||, O. Al-Emam||, T. G. Patterson|| & A. P. Willmore||

1. *Space Research Institute, USSR Academy of Sciences, Moscow, USSR
2. †Max-Planck-Institut für Physik und Astrophysik, Institut für Extraterrestrische Physik, 8046 Garching, FRG
3. ‡Astronomisches Institut der Universität Tübingen, 7400 Tübingen, FRG
4. §Space Research Laboratory, Utrecht, The Netherlands
5. ||Department of Space Research, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

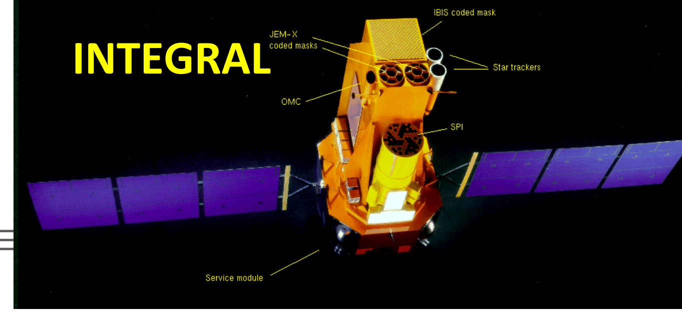
We report the discovery of hard X-rays from the region of the supernova SN1987A in the Large Magellanic Cloud. The observations were made from the Mir-Kvant observatory 'Röntgen'. Hard X-rays were first observed on 10 August 1987

▲ Top



Core Collapse of a massive (20 M_{sun}) star

SN2014J type Ia in M82



LETTER

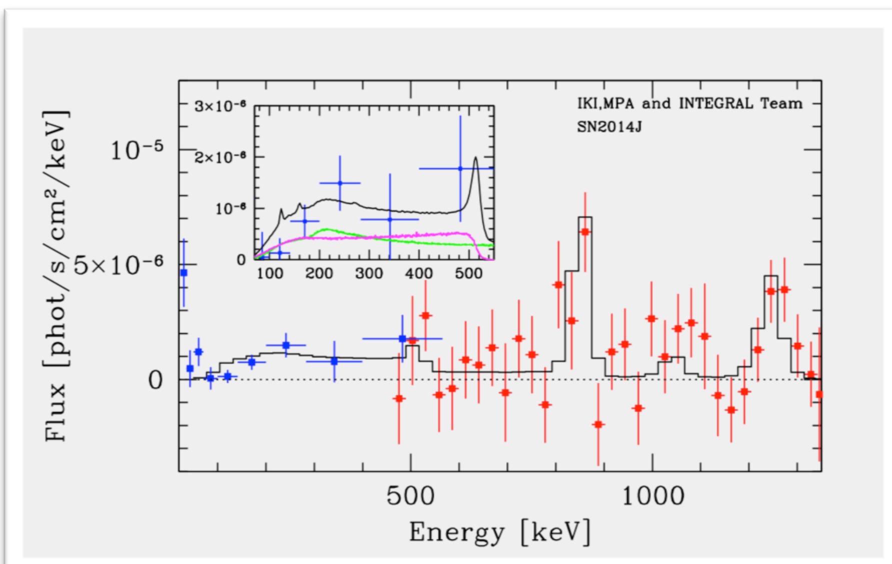
28 August 2014

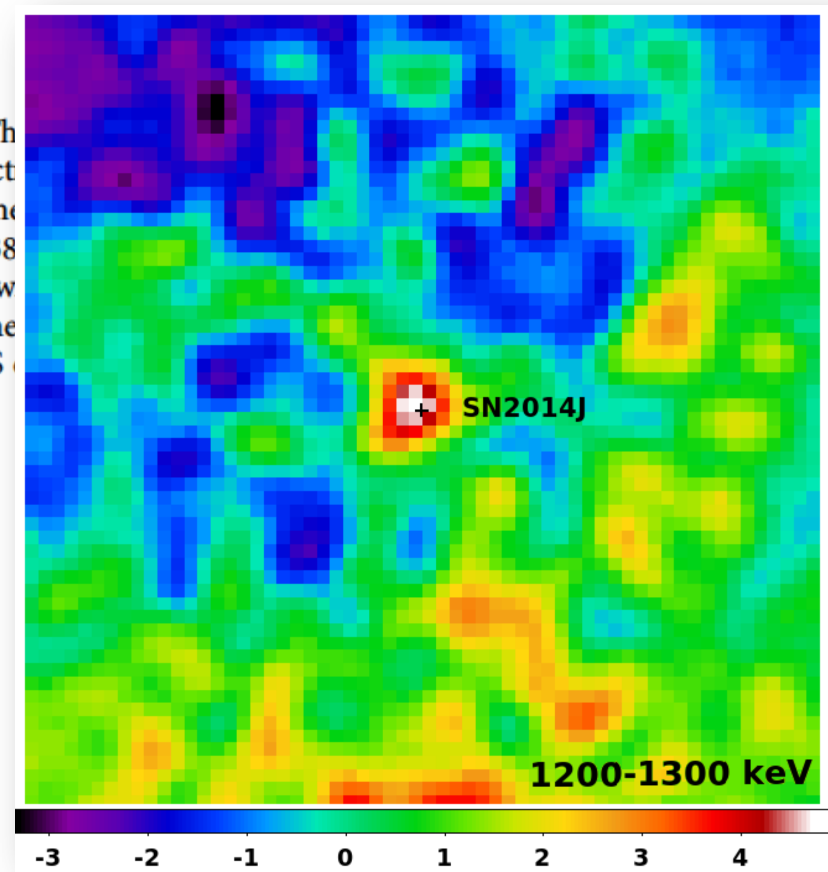
doi:10.1038/nature13672

Cobalt-56 γ-ray emission lines from the type Ia supernova 2014J

E. Churazov[1,2], R. Sunyaev[1,2], J. Isern[3], J. Knödlseder[4,5], P. Jean[4,5], F. Lebrun[6], N. Chugai[7], S. Grebenev[1], E. Bravo[8], S. Sazonov[1,9] & M. Renaud[10]

A type Ia supernova is thought to be a thermonuclear explosion of either a single carbon–oxygen white dwarf or a pair of merging white dwarfs. The explosion fuses a large amount of radioactive ^{56}Ni (refs 1–3). After the explosion, the decay chain from ^{56}Ni to ^{56}Co to





SN2014J

Discovery:
21 January 2014, Steve Fossey, UCL

Explosion date:
Jan 14.75 UT (Zheng et al., 2014)

M82 (Cigar Galaxy)

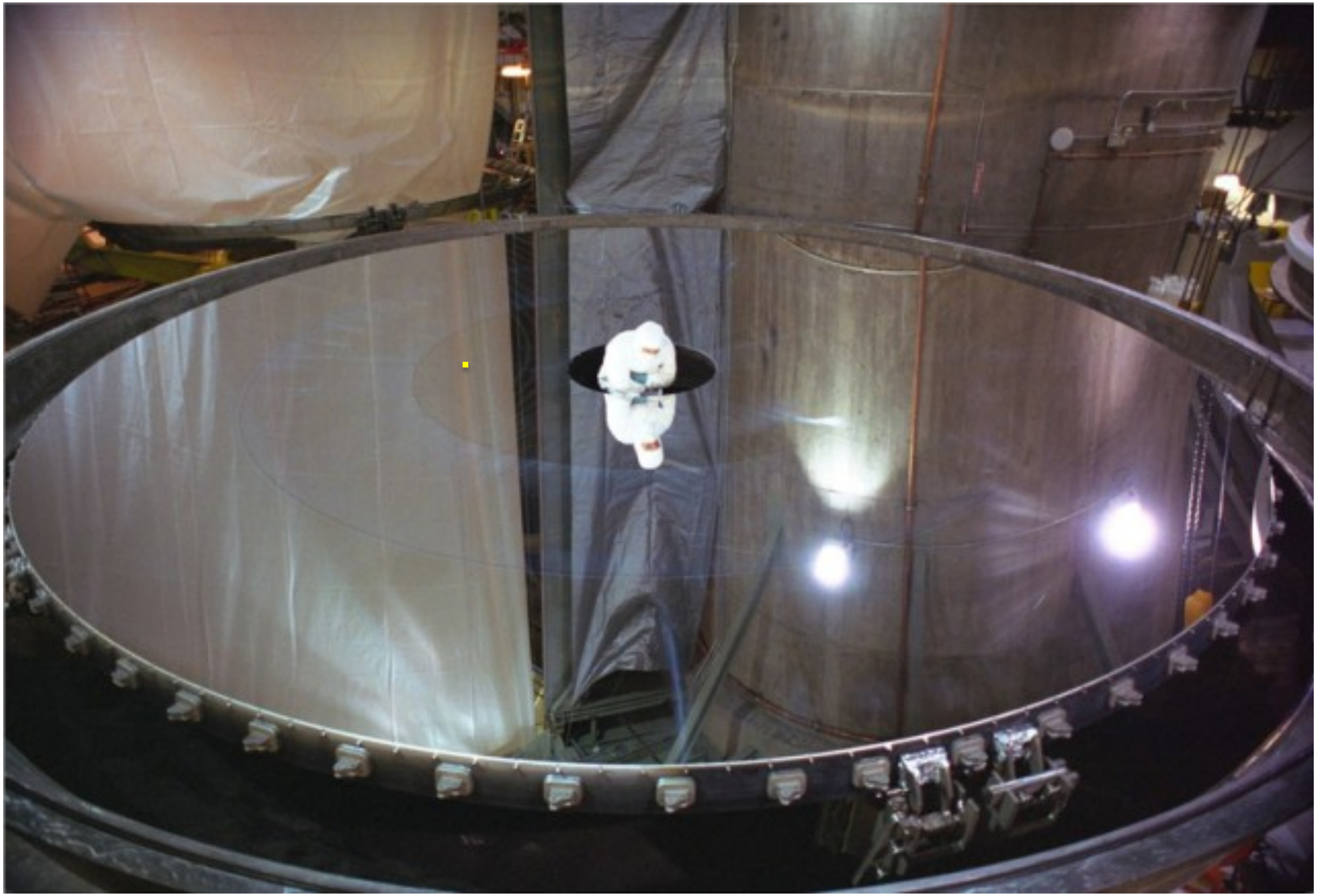
Karachentsev, Kashibadze, (2006):
3.53±0.26 Mpc

Progenitor & interaction with ISM & X-rays:
HST – no (Graur+, Kelly+)
Chandra – no (Nielsen+, Margutti+)
EVN, eMerlin – no (Perez-Torres+)

Extinction:
A_V~1.7-2.5
1.85 (Amanullah+)

Best chance to detect gamma-rays

Why for gamma-rays we need nearby SN Ia?



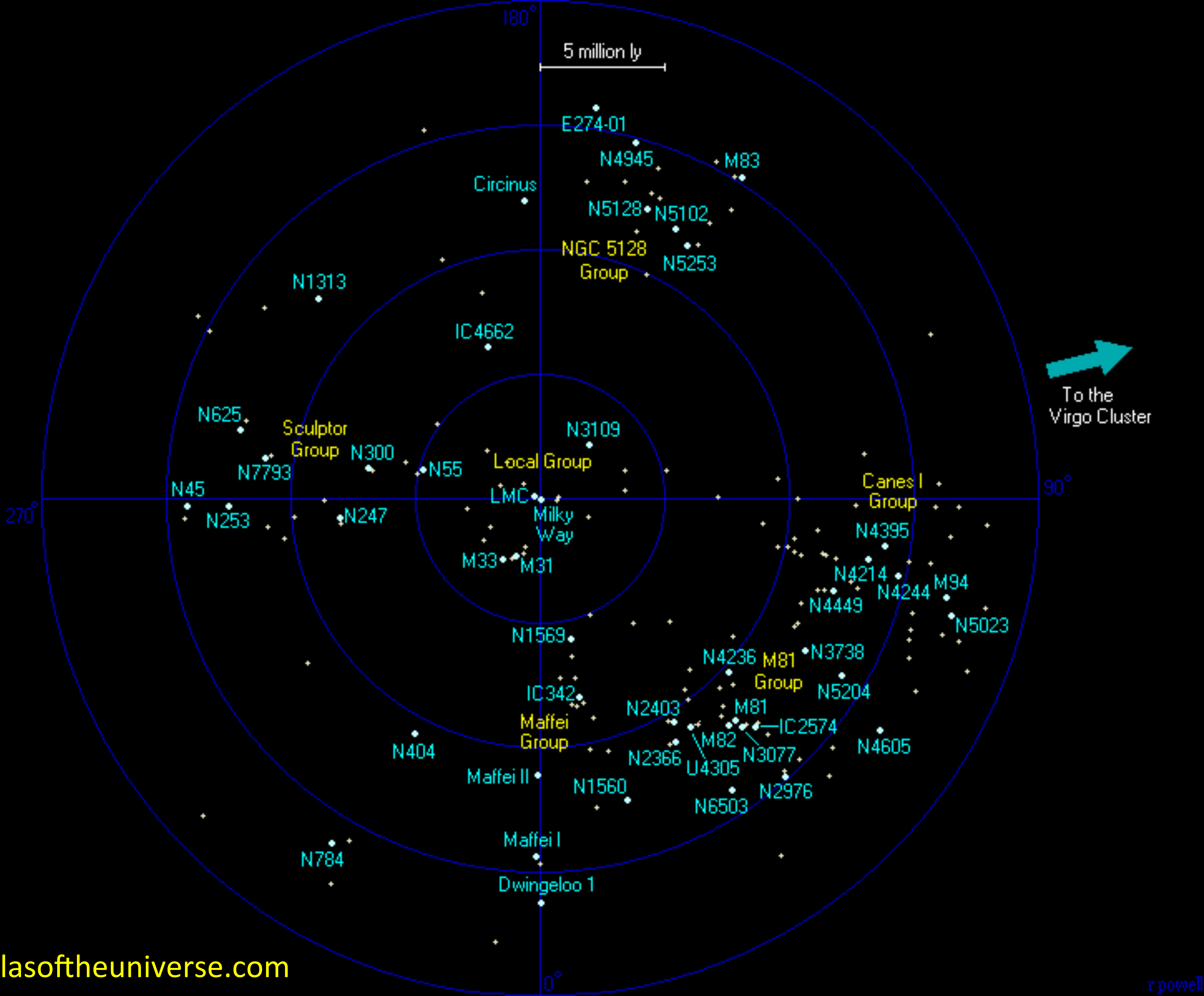
Is SN2014J "really nearby"?

"The nearest SNIa during last 3 decades (.. SN1986G)"
"The nearest SNIa over the least 40 years (.. SN1972E)"
"The nearest SNIa in many decades"
"The nearest detected SNIa over the last 410 years (since Kepler SN)."

3.5 Mpc (Karachentsev, Kashibadze, 2006)
3.3 Mpc (Foley et al., 2014)

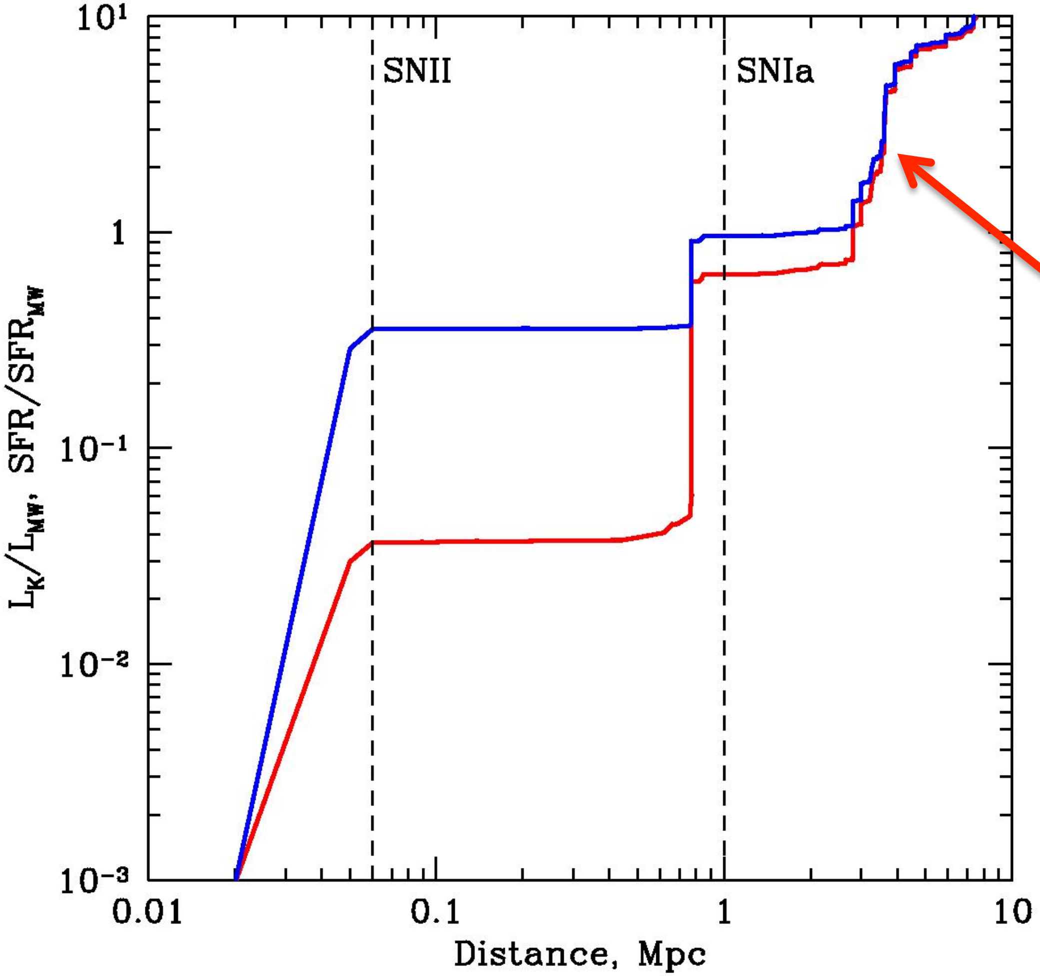
SN1604A <6 kpc
SN1972E 3.6 Mpc
SN1986G 3.7 Mpc
SN2011fe 6.4 Mpc

Milky Way: ~1 SNIa per century



www.atlasoftheuniverse.com

Stellar mass around Milky Way M(<R)

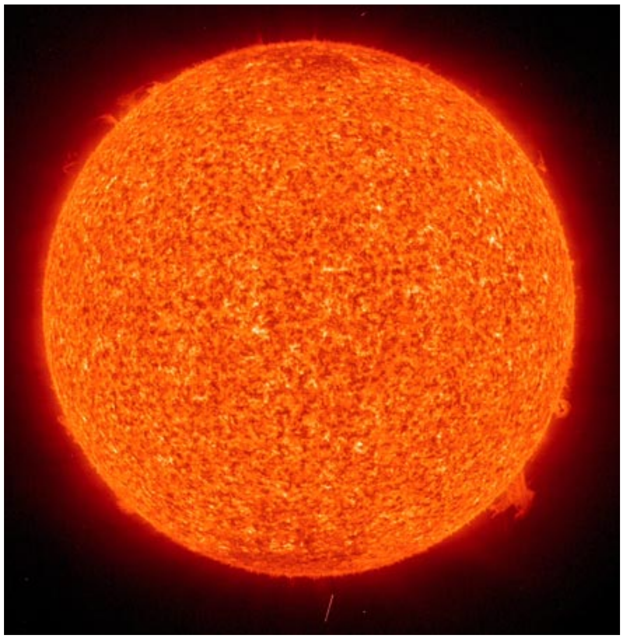


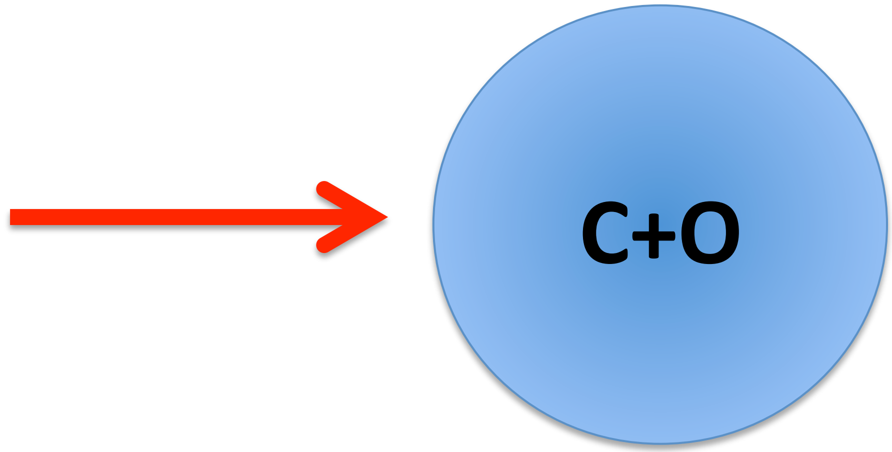
1 per 25 years

(using catalog of local galaxies from Karachentsev's sample)

Milky Way: ~1 SNIa per century

WD = End-product of stellar evolution for $M<8\ M_{Sun}$



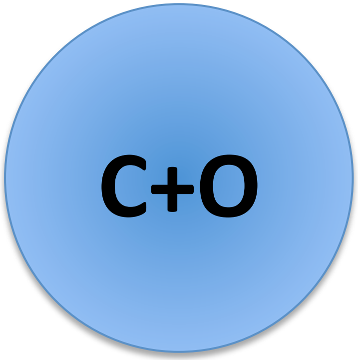


Radius ~ 10 000 km
Mass ~ 0.5 Msun
Carbon+Oxygen

WD is supported by the pressure of degenerate electron gas

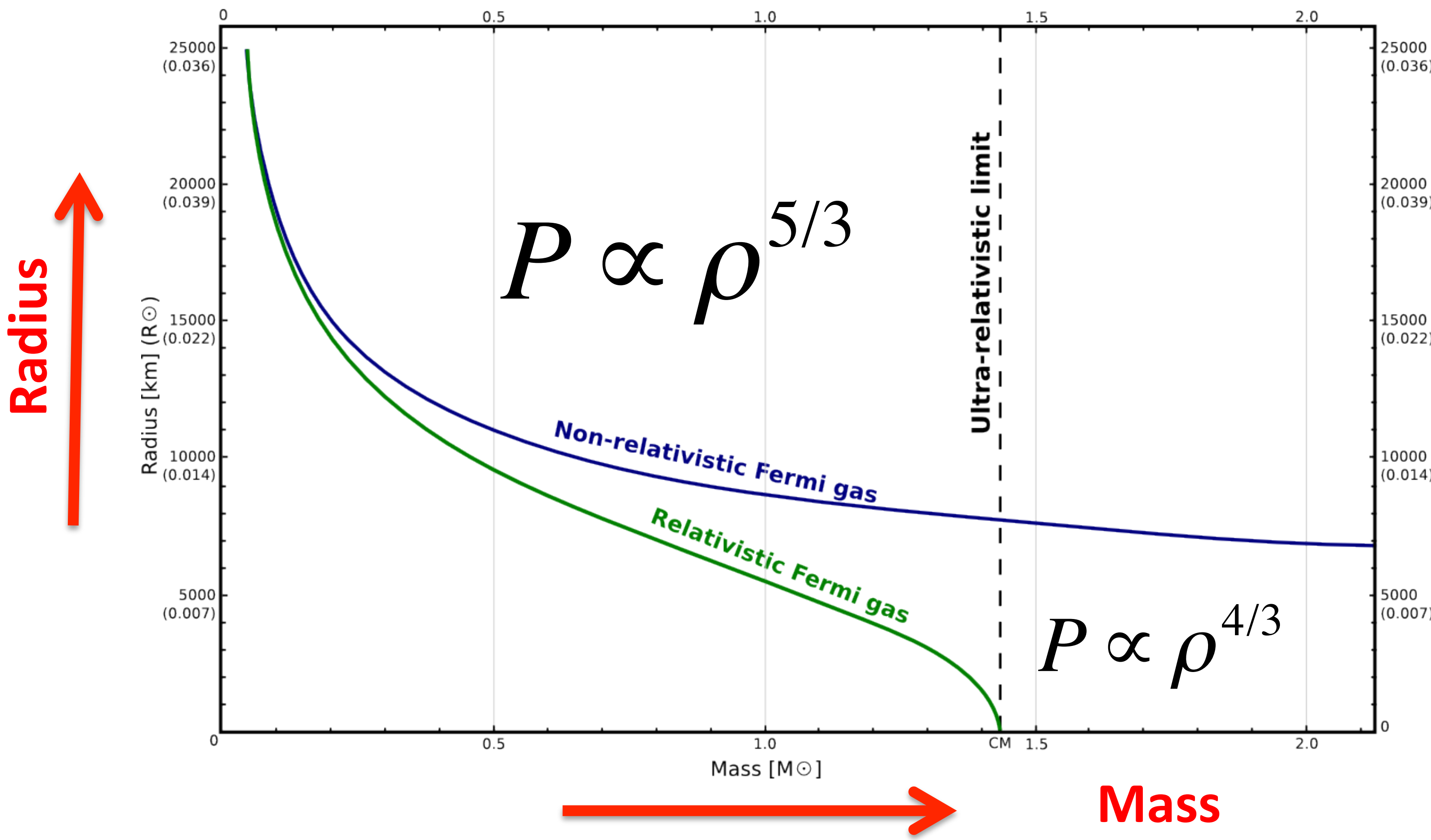
Typical initial mass M_1~0.5 M_{Sun}
Maximal mass M_{Ch}~1.4 M_{sun} -- Chandrasekhar limit

Chandrasekhar Limit



$$\Delta p \Delta x \sim \hbar$$

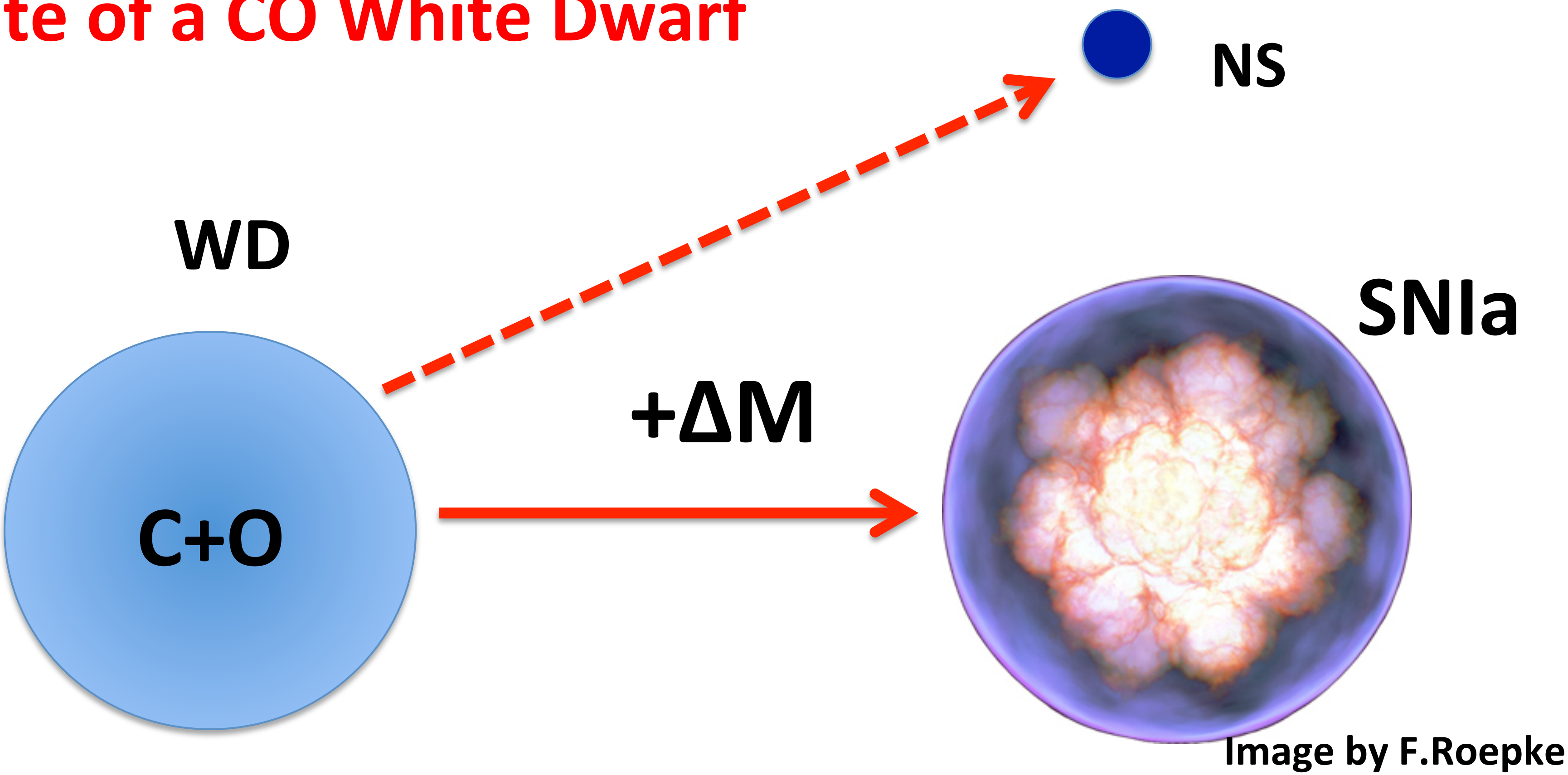
$$\Delta x \propto \rho^{-1/3}$$



$$P \propto \rho^{5/3}$$

$$P \propto \rho^{4/3}$$

Fate of a CO White Dwarf



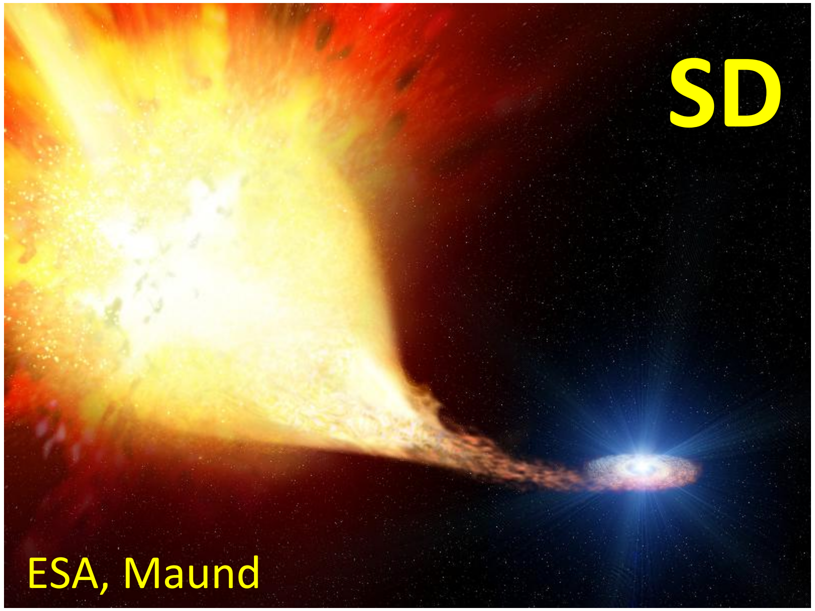
1. Relativistic electrons
2. WD shrinks
3. Burning of CO starts
4. Detonation and Fusion of ^{56}Ni

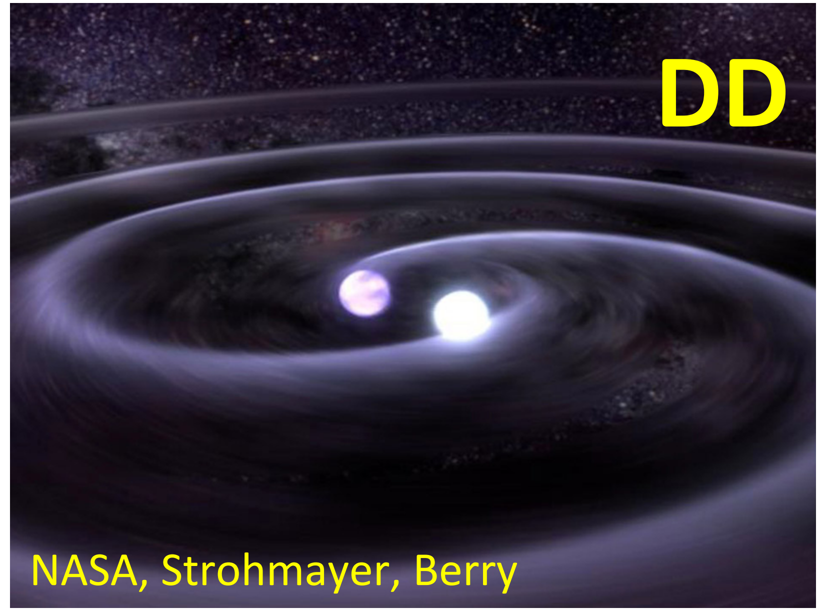
C,O→ Si, Ca, Ni

0.6-0.8 MeV/nucleon

Velocity ~ 10^4 km/s

Growing mass of WD





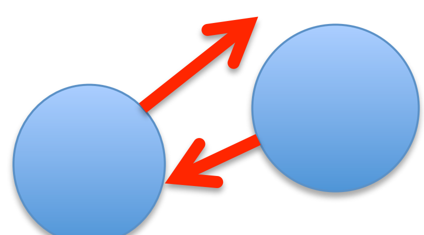
WD+ΔM

Whelan & Iben 1974

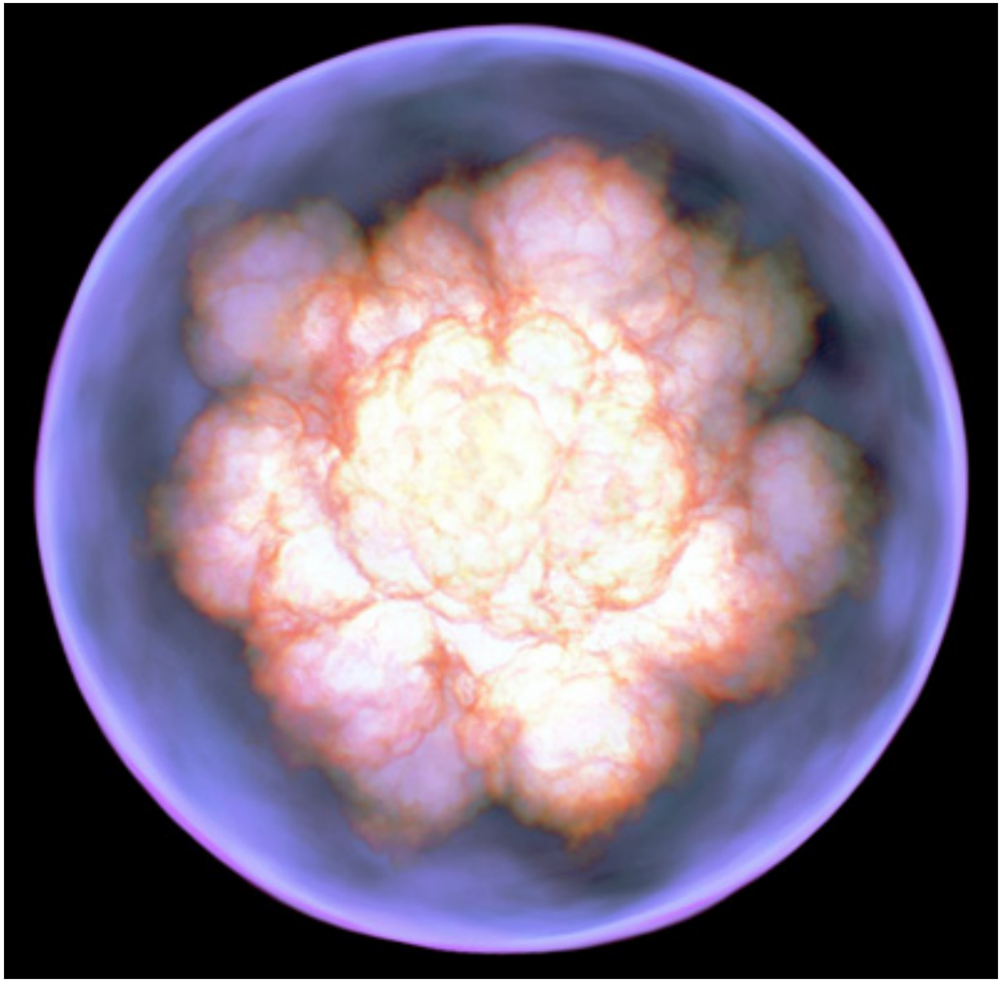
WD+WD

Iben & Tutukov 1984
Webbink 1984

DD’
Kushnir et al., 2013



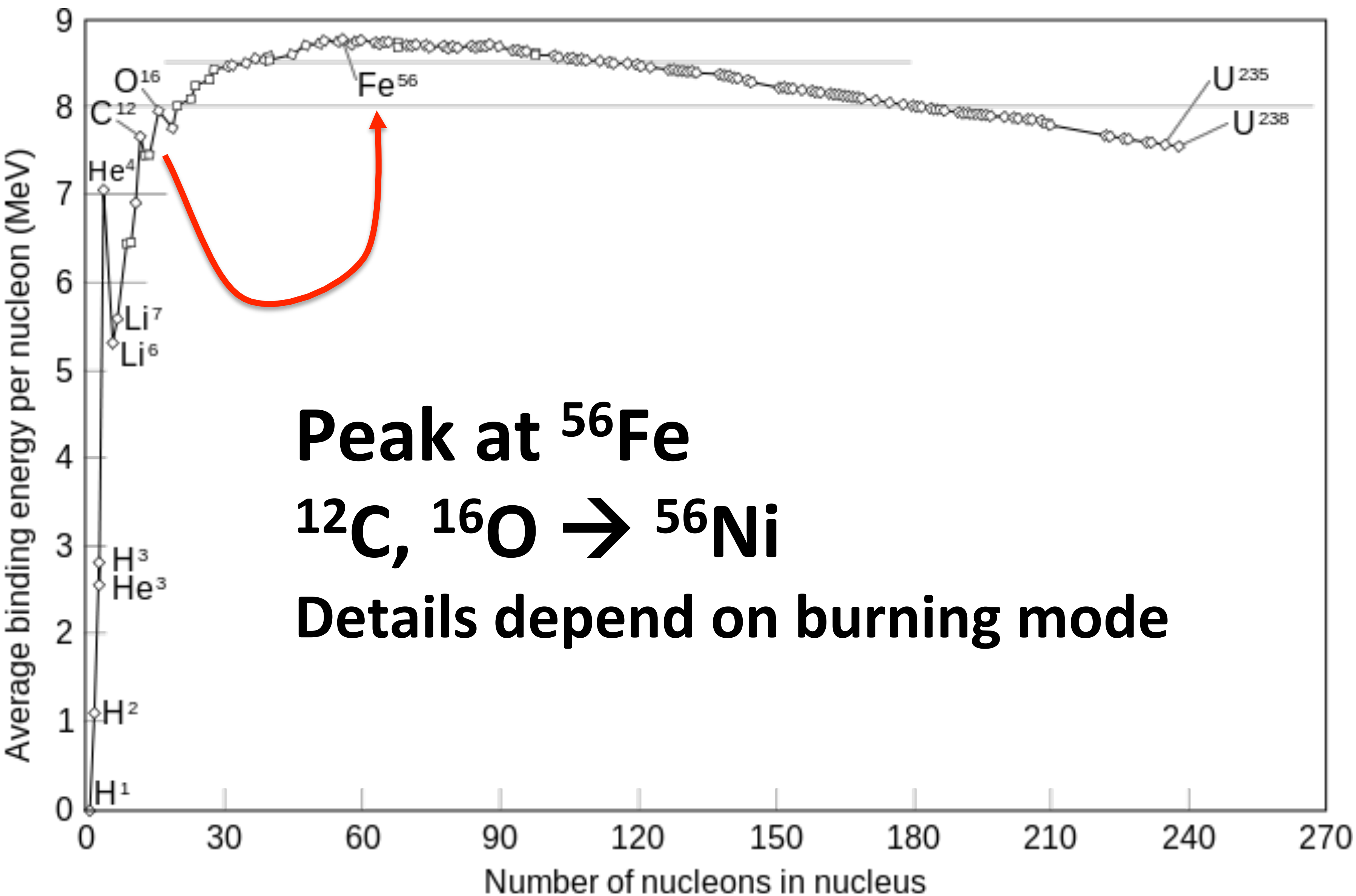
C+O burning in WD



1. What ignites WD?
   approaching M_{Ch}
   collision or shock waves?

2. Burning mode?
   Deflagration
   Detonation
   Deflagration+Detonation

Binding energy per nucleon

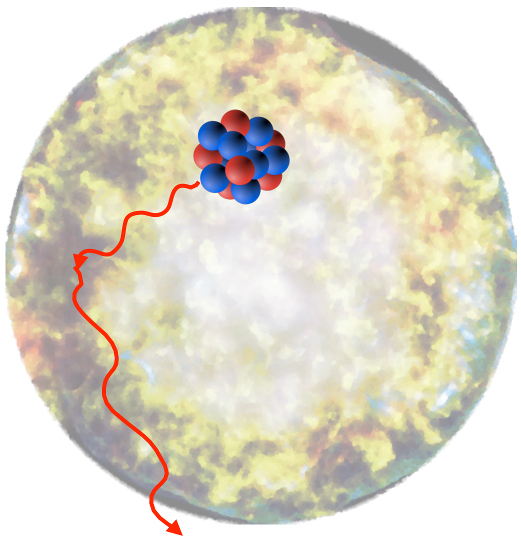


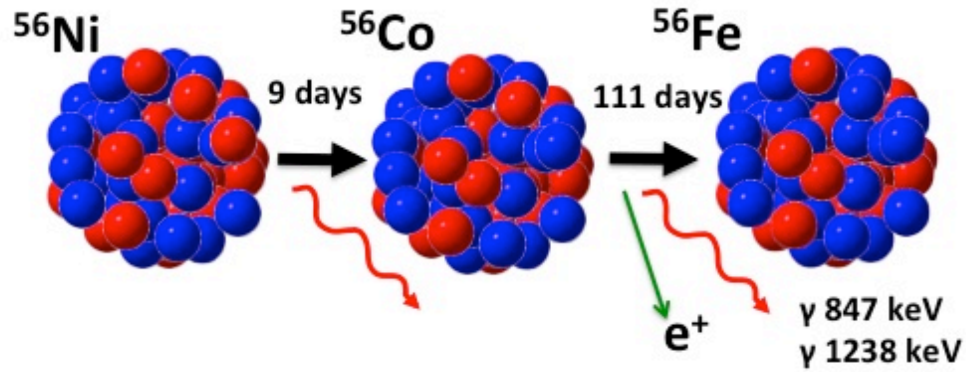
Peak at ^{56}Fe

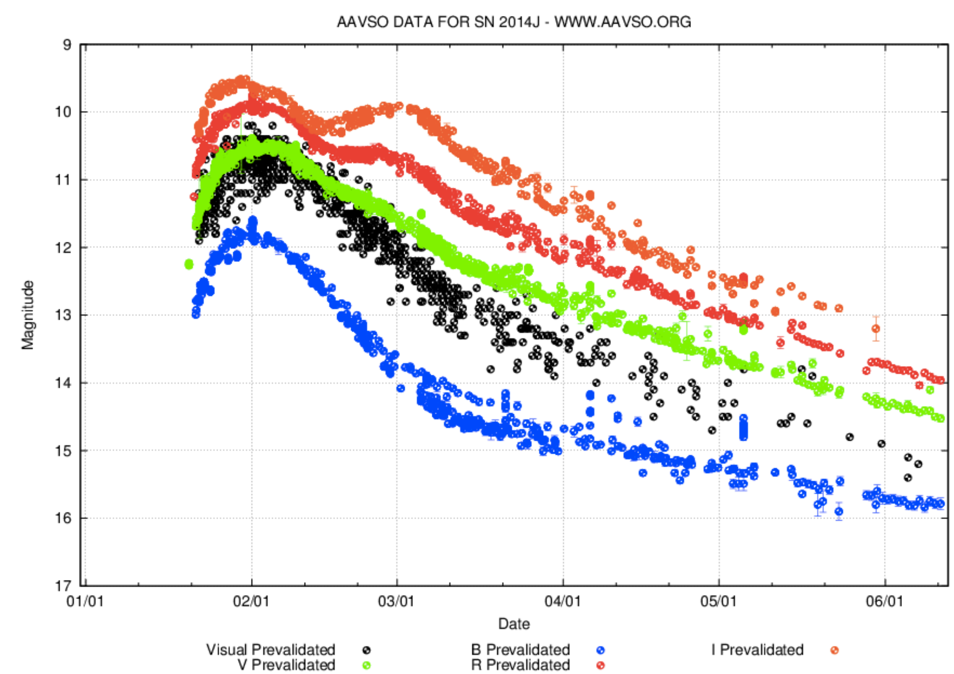
^{12}C, ^{16}O → ^{56}Ni

Details depend on burning mode

Why we see supernovae after the explosion?

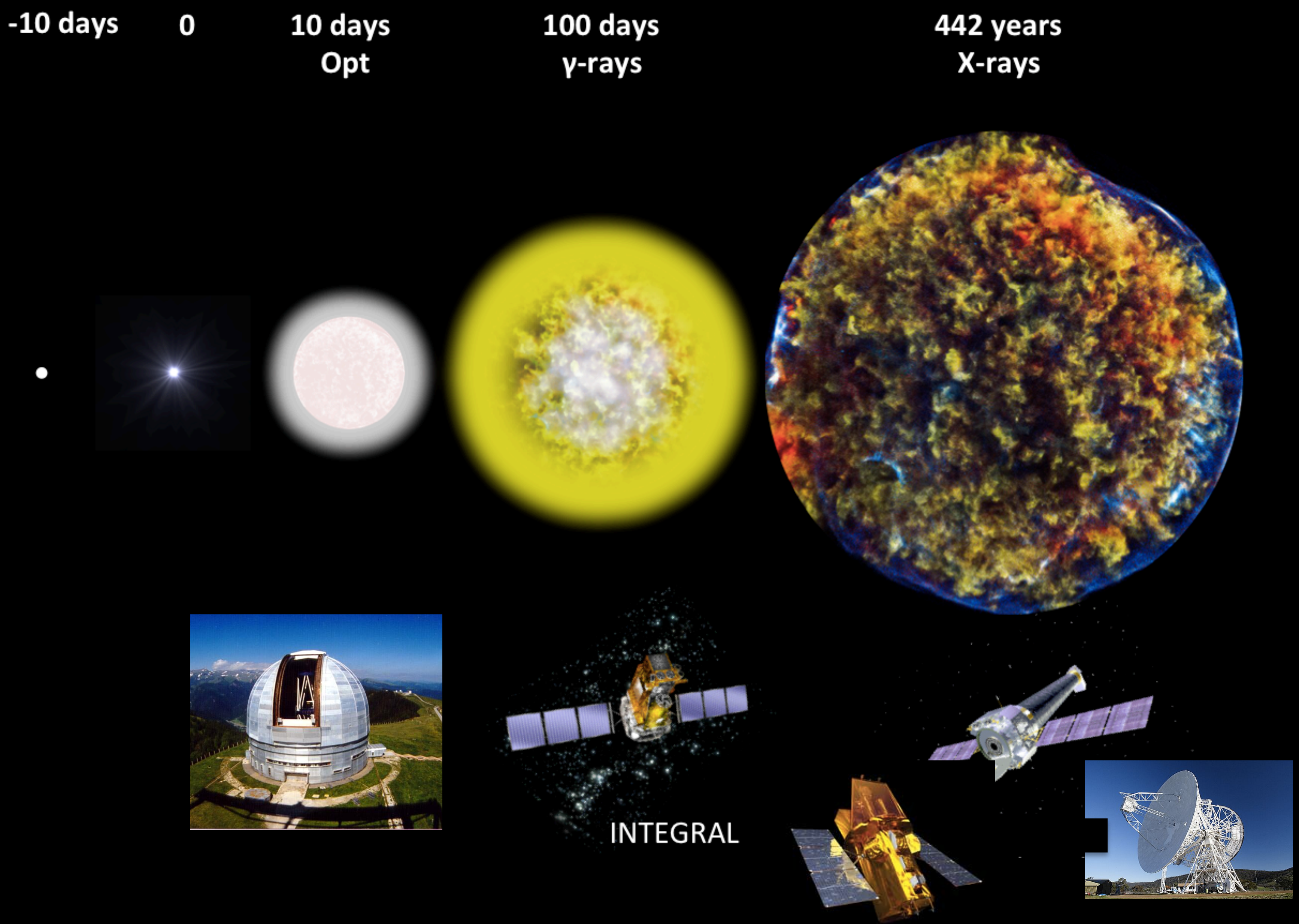






1. Direct gamma-photons
2. Reprocessed emission (optical band)

$$\tau \propto t^{-2}$$

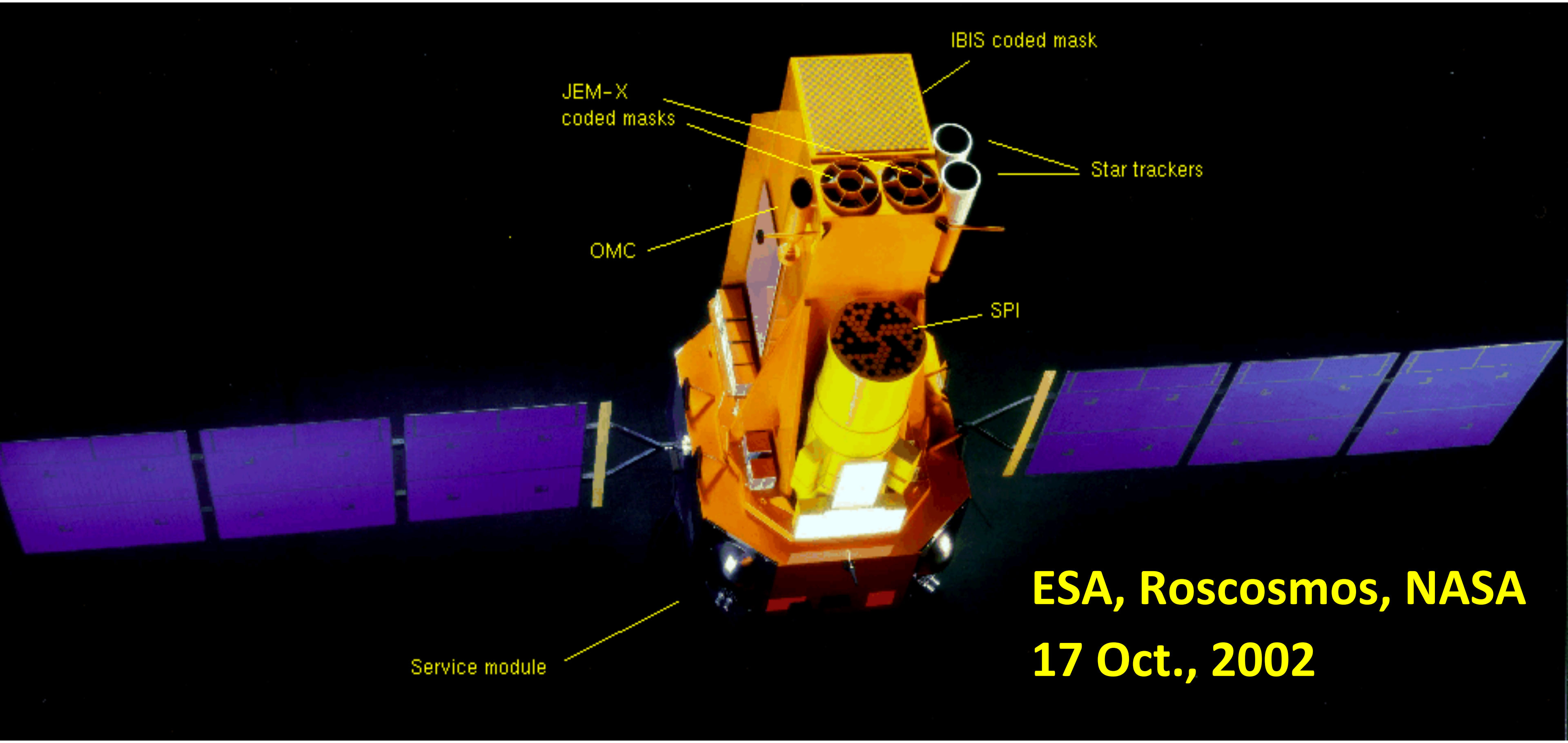

-10 days
0
10 days
Opt
100 days
γ-rays
442 years
X-rays
INTEGRAL

Three elements from standard physics

1) Chandrasekhar limit → 1.4 M_{sun}
2) Synthesis of C,O to Ni → 0.6-0.8 MeV/nucleon
3) Decay of Ni,Co → Fe few MeV per decay

1) Optical depth of the ejecta
2) Velocity of expansion
3) Ni mass and flux in gamma-lines

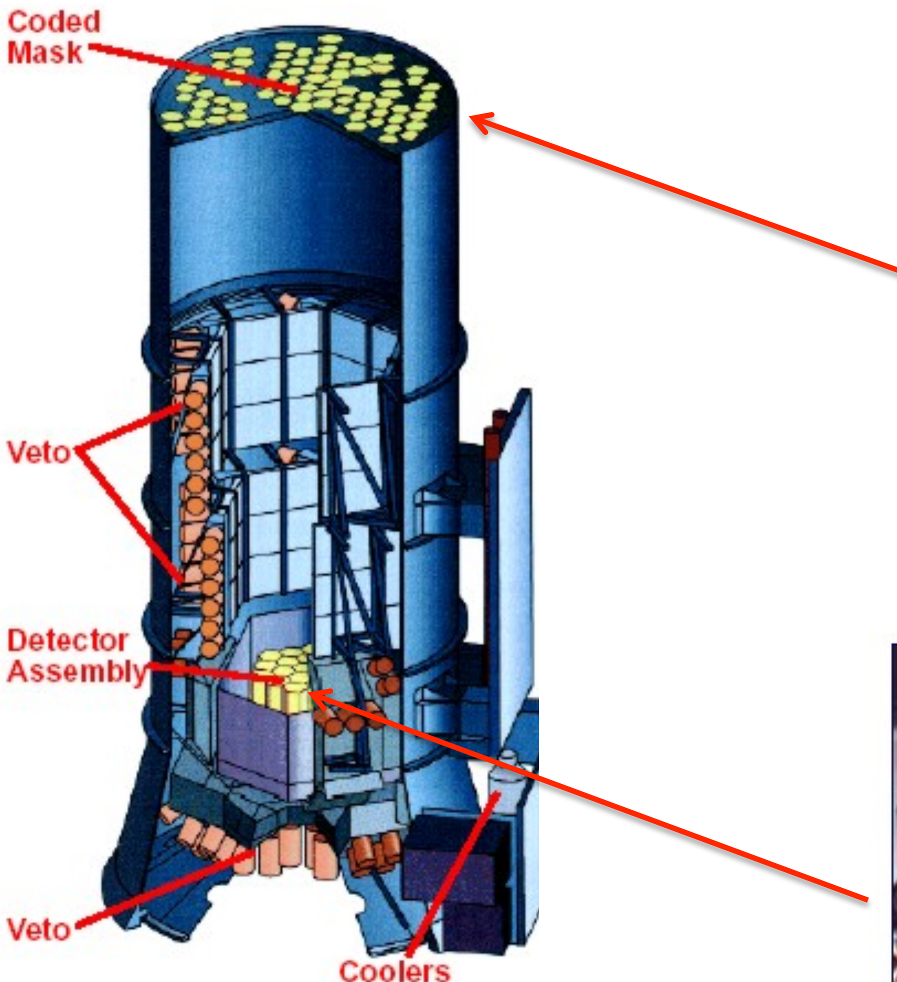
INTEGRAL Observatory



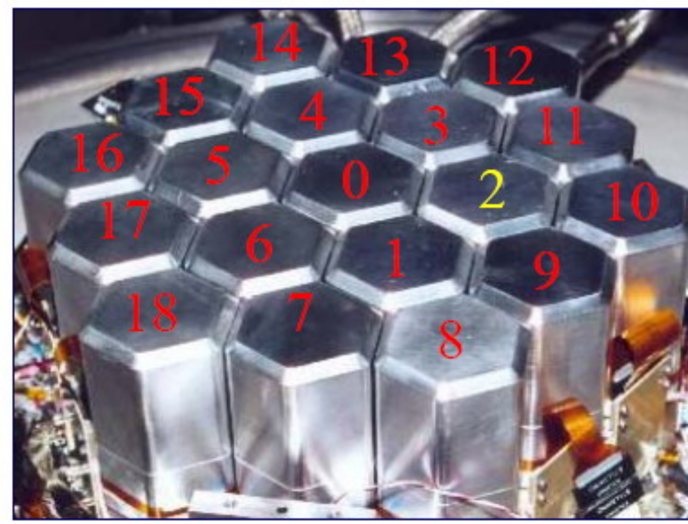
Energy range : 20 keV – 8 MeV
Angular resolution: 10'-1°

Observing periods:
17-35, 50-100, 132-…

INTEGRAL/SPI



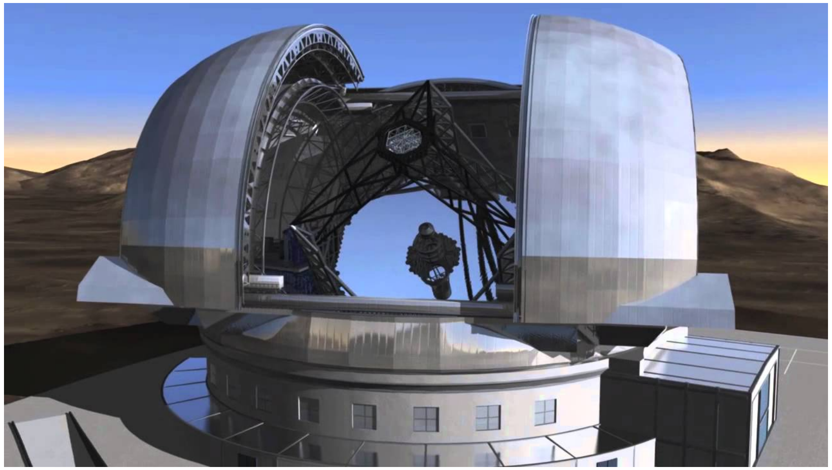
Tungsten mask

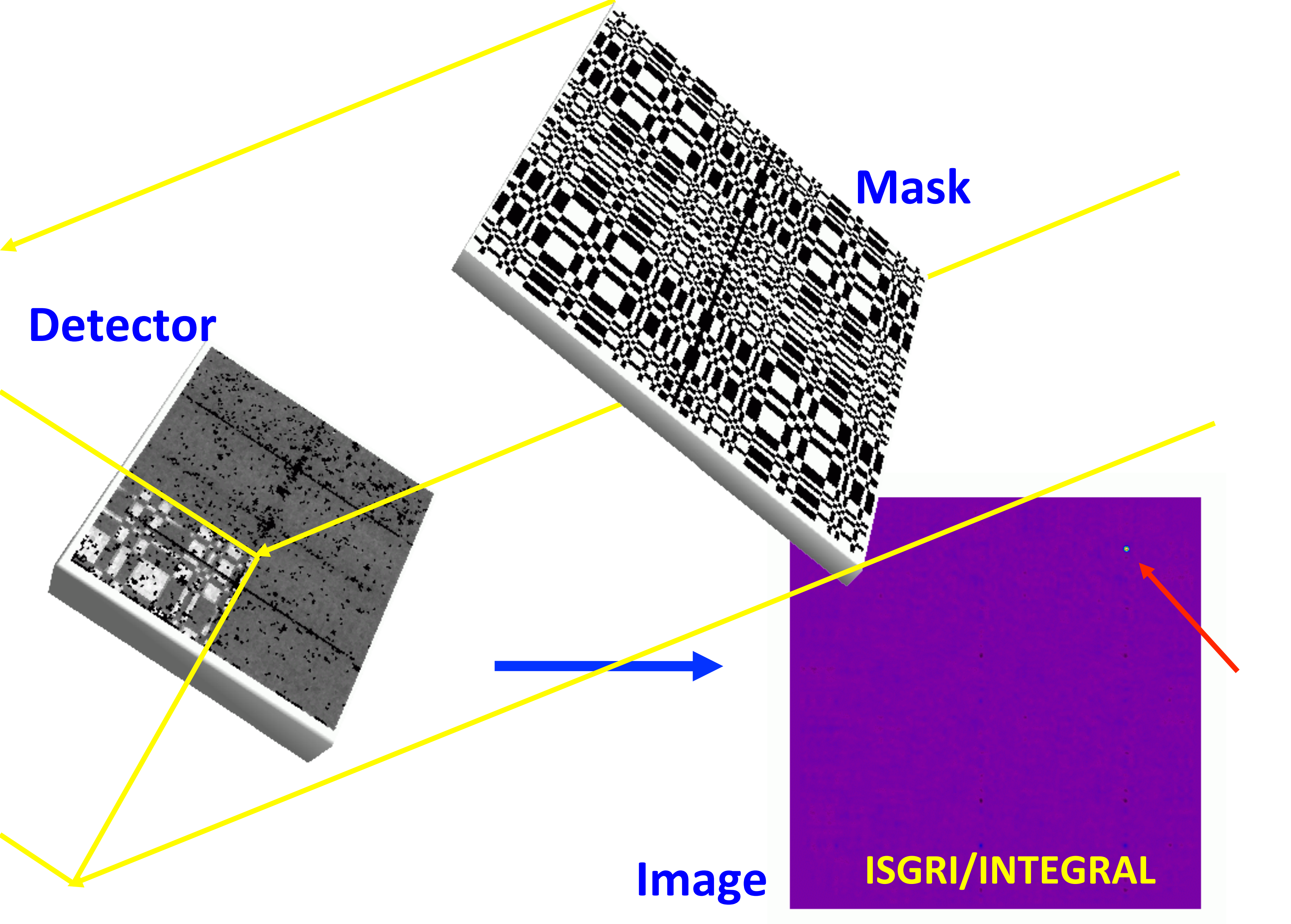


Resolution: ~2 keV @ 511 keV

Area: ~70 cm^2

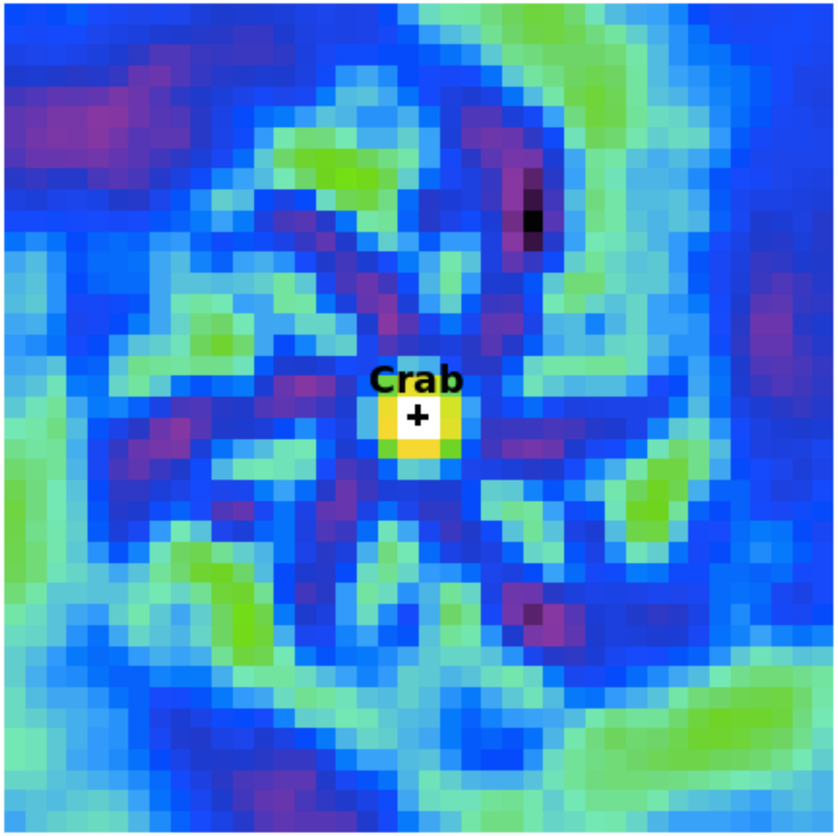
No focusing optics at energies above 79.1 keV



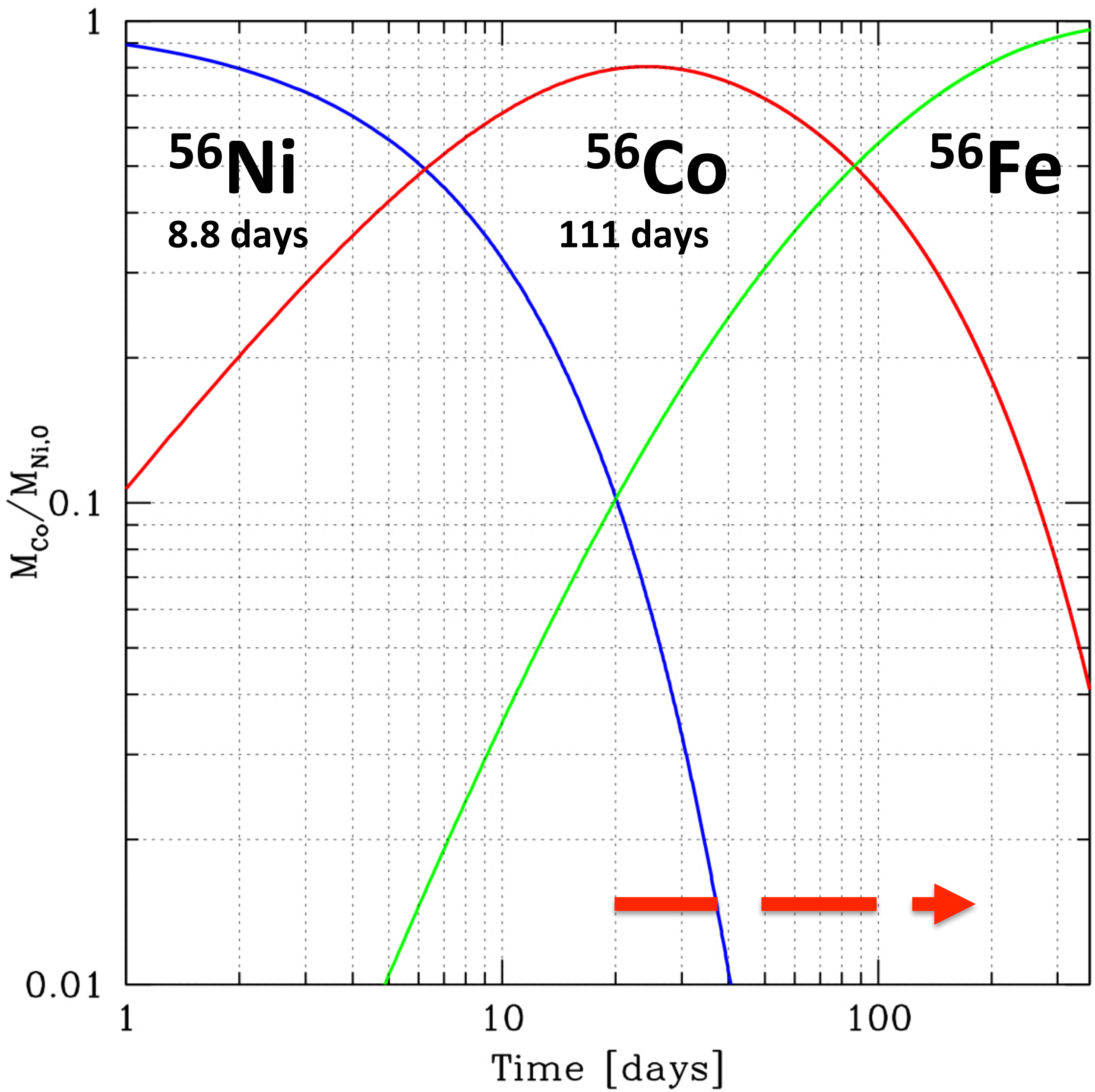


Mask
Detector
Image
ISGRI/INTEGRAL

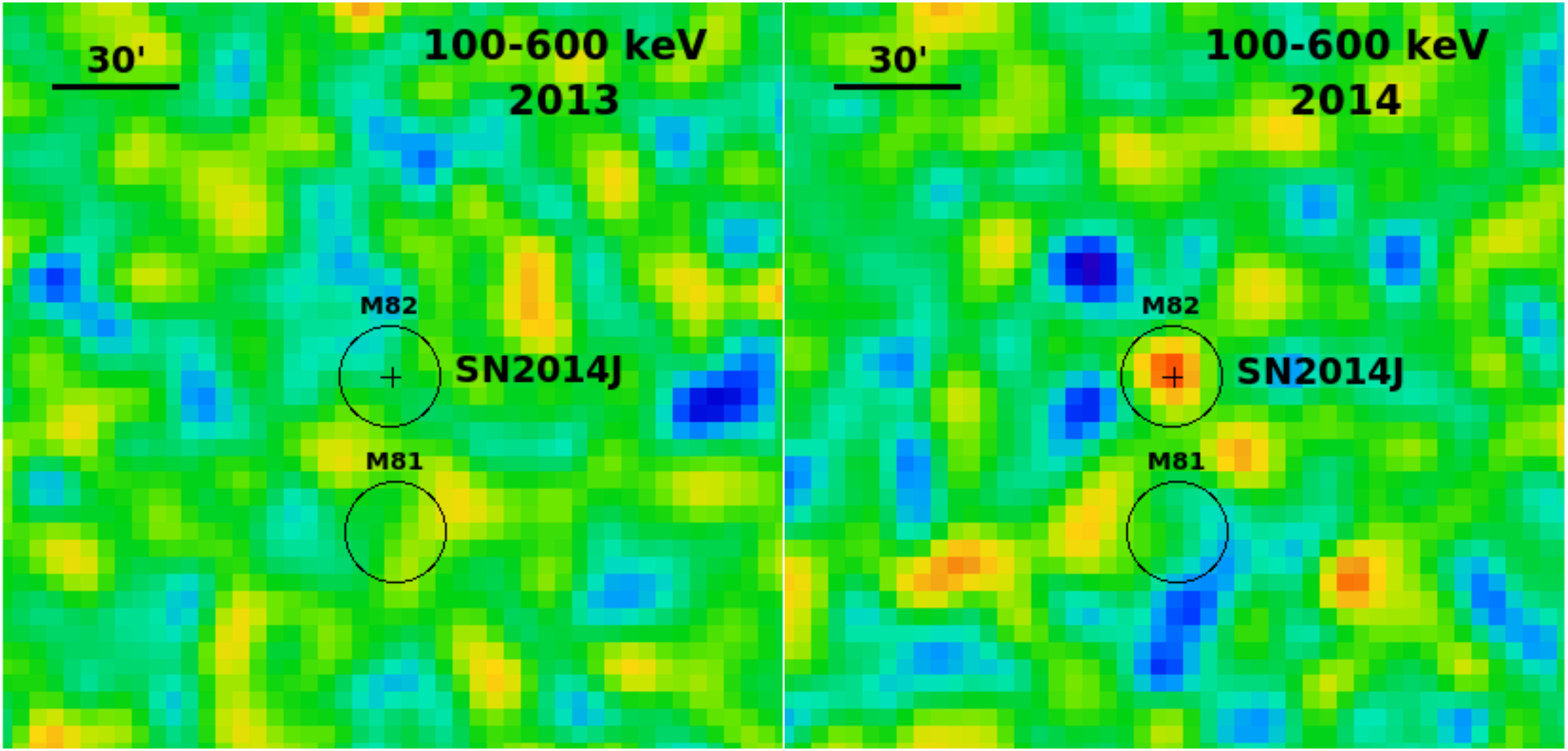
Crab Nebula Image with SPI



Evolution of Ni and Co mass: $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$



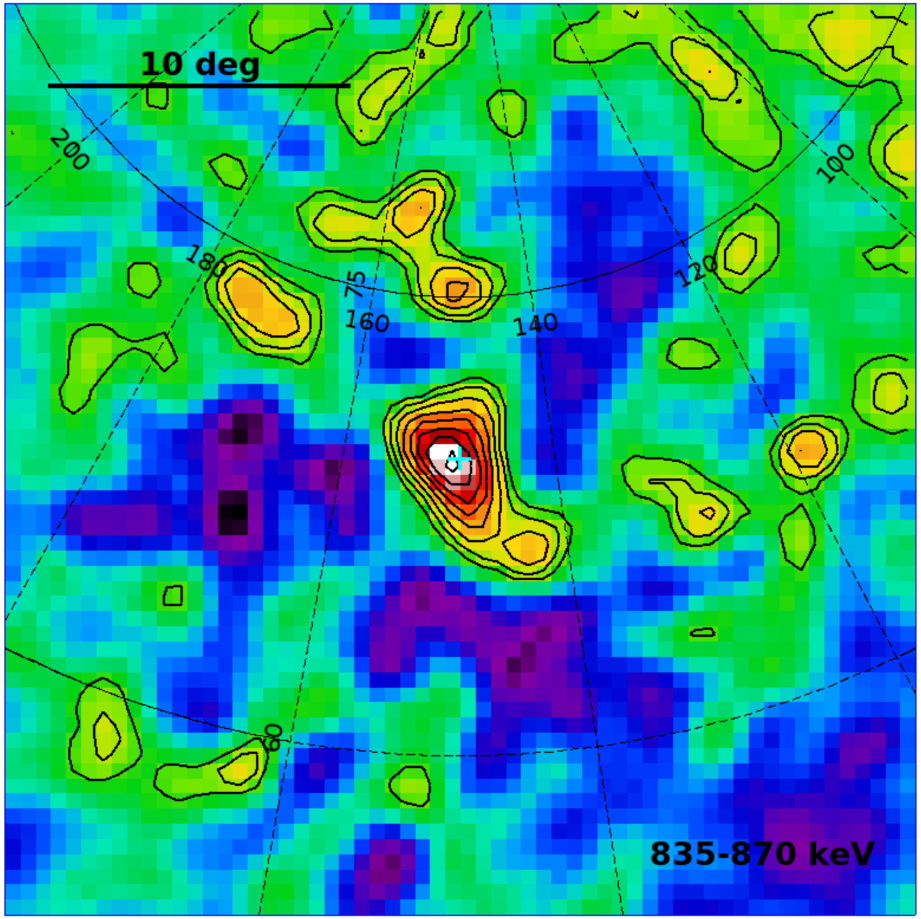
M82 before after the explosion SN2014J (100-600 keV)



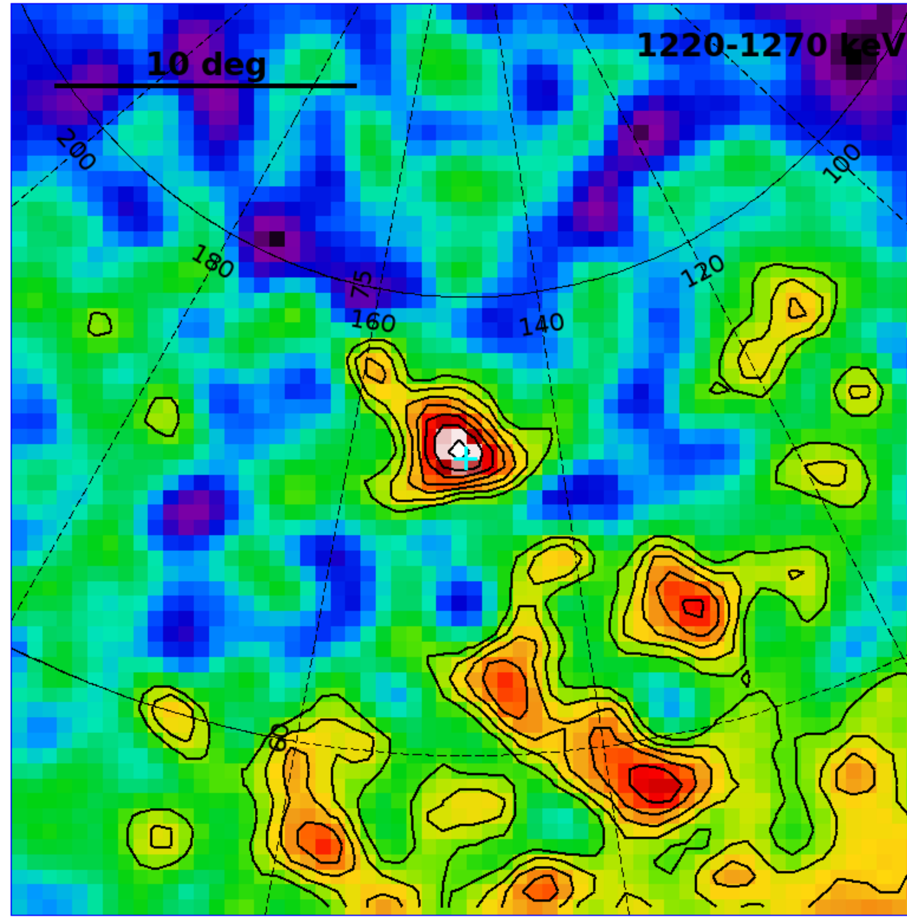
3.7σ

Before **After**

Images in narrow bands around prominent ^{56}Co lines

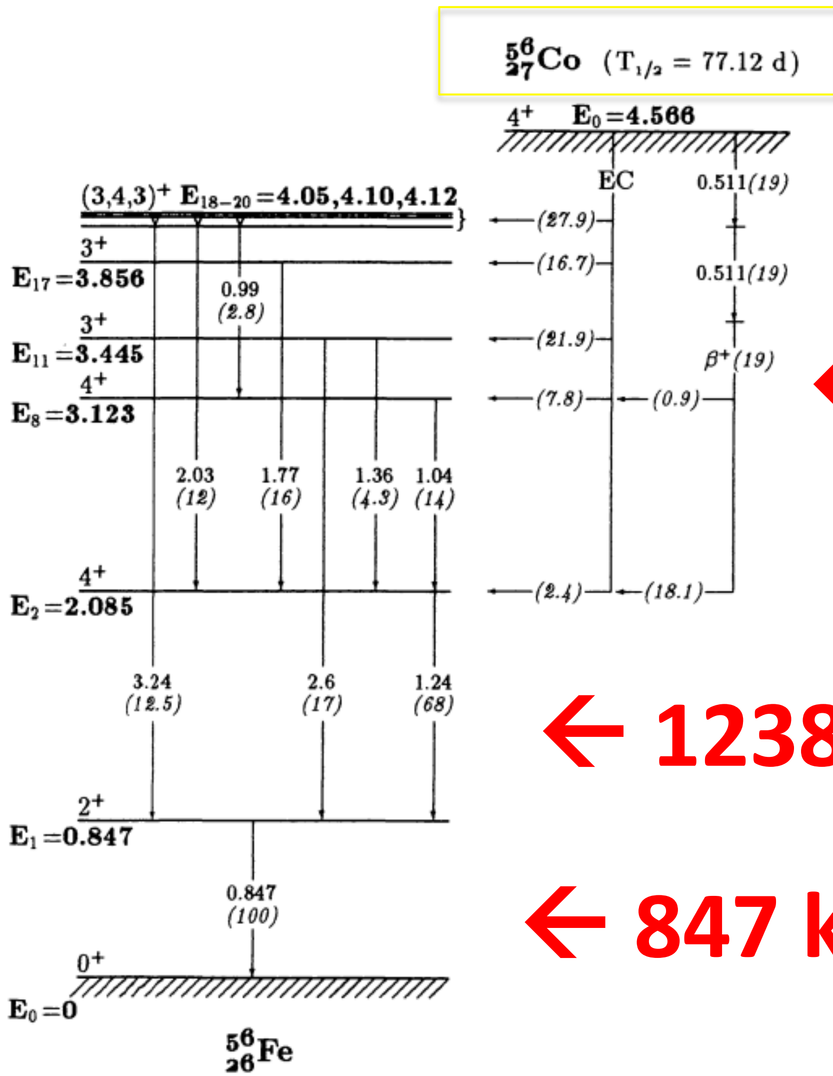


4.7σ



4.3σ

Gamma-ray Lines due to $^{56}Co \rightarrow ^{56}Fe$



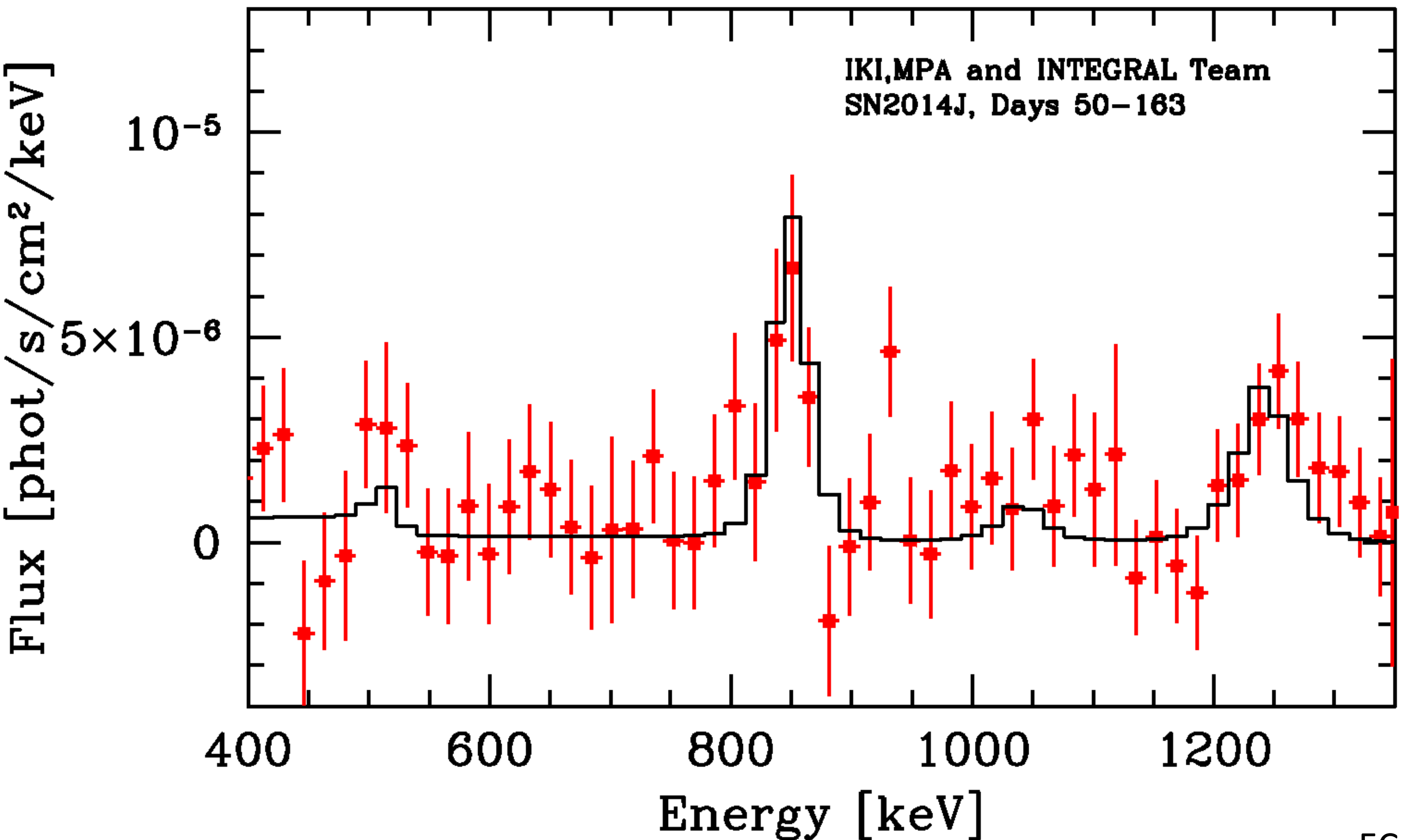
← e^+, 19%

← 1238 keV, 68%

← 847 keV, 100%

From Nadyozhin, 94

Spectrum of SN2014J (50+ days)

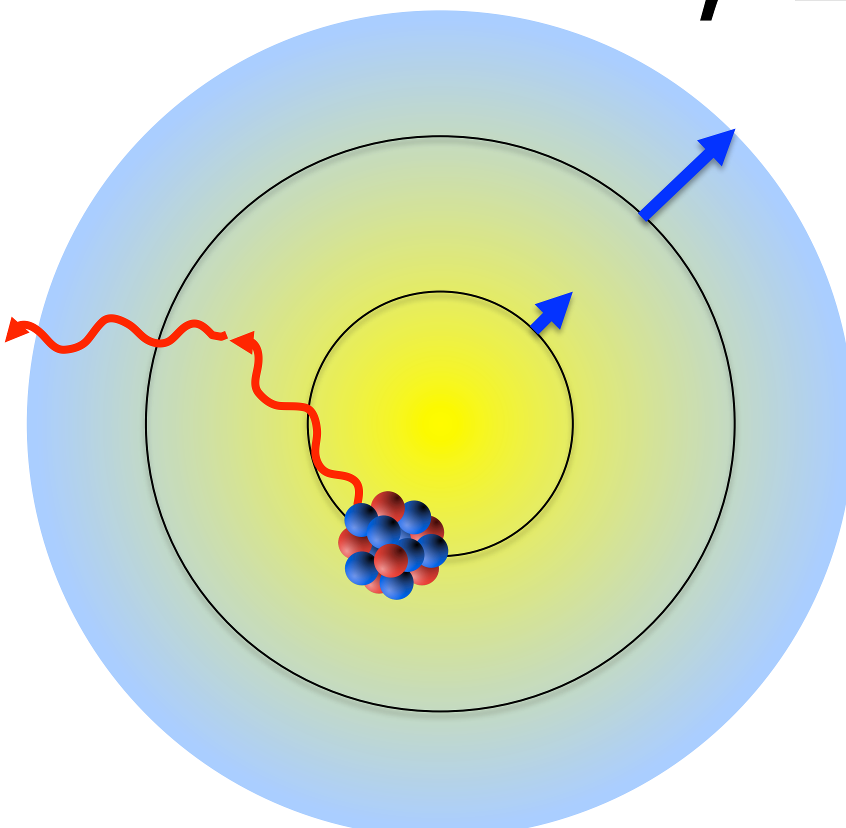


EC+,14b

Homologous expansion
Uniform composition
Exponential distribution

3PAR model

$$r = \upsilon t$$



58% - Iron group
21% - Si
21% - S

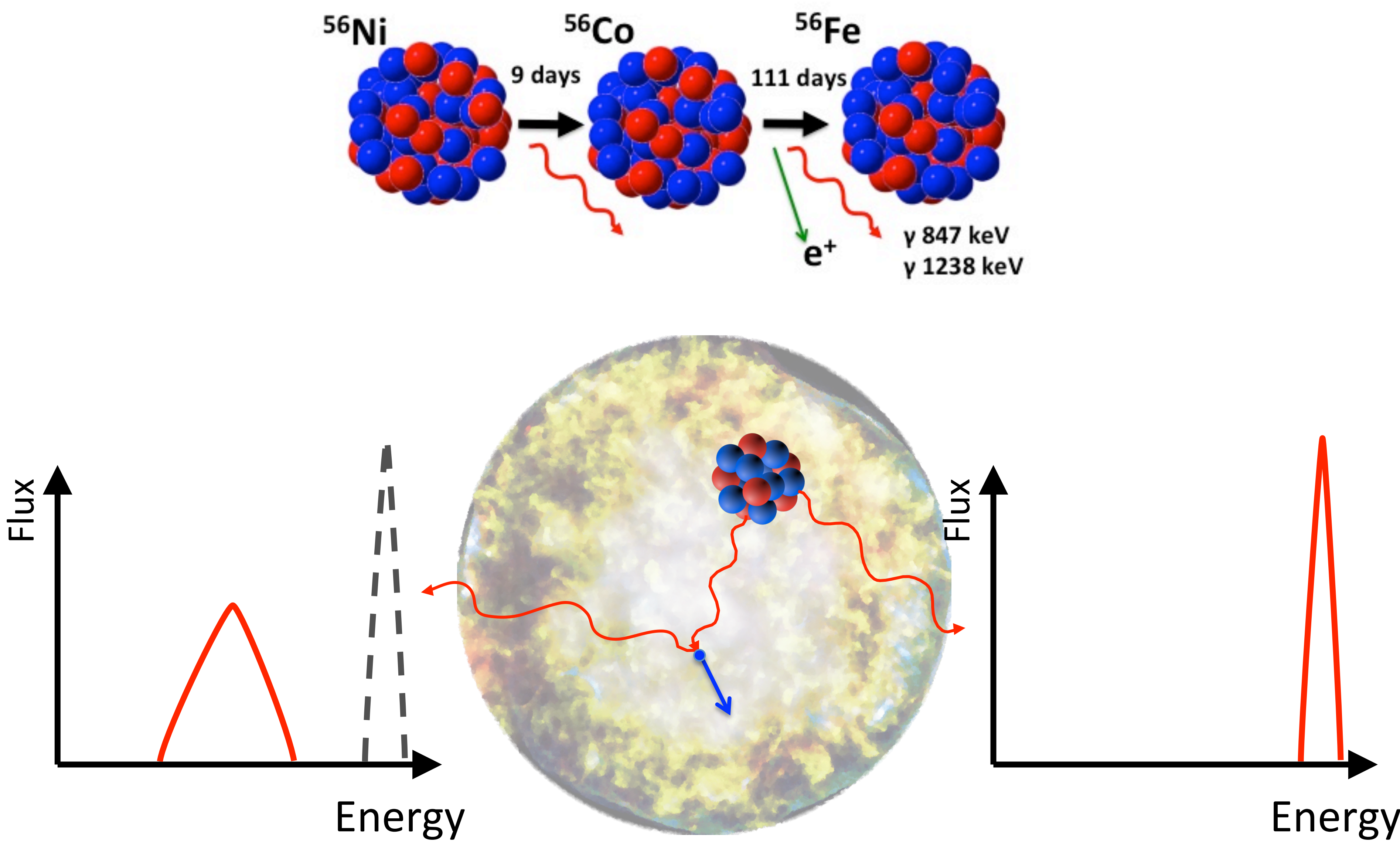
$$\rho \propto e^{-\upsilon/V_e}$$

Dwarkadas & Chevalier 1998

$$M_{Ni}, M_{Ejecta}, V_e$$

$$V_e = \sqrt{\frac{E_K}{6M_{Ejecta}}}$$

Calculating expected gamma-ray spectra

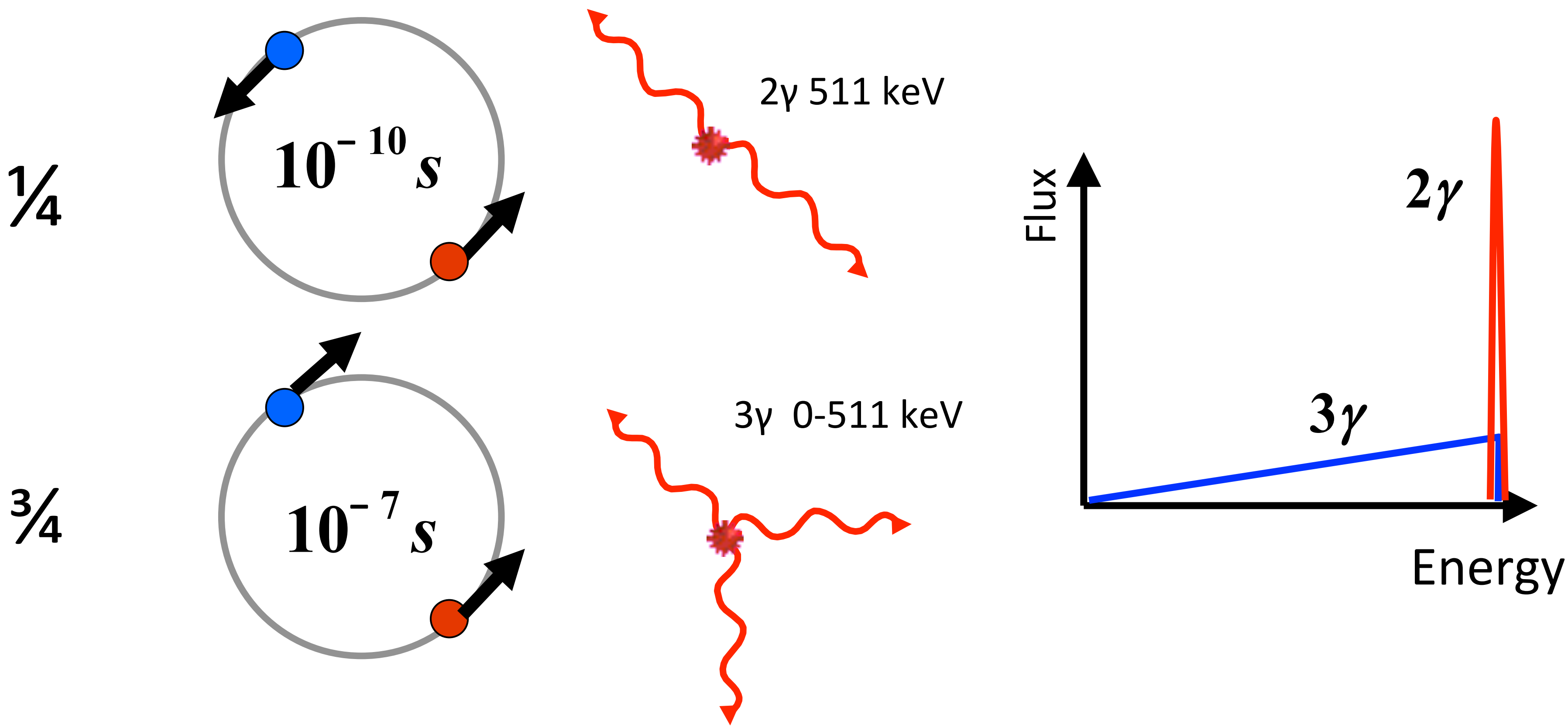


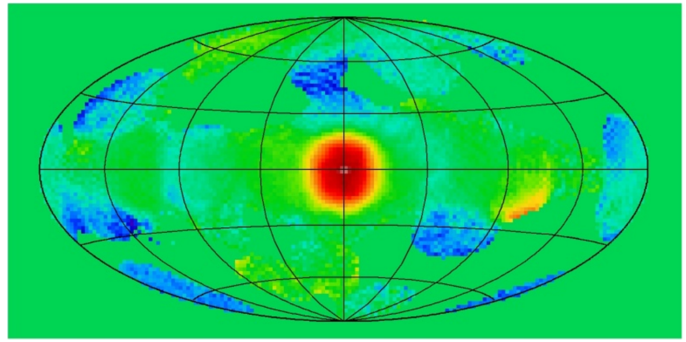
Fate of positrons (19% of decays)

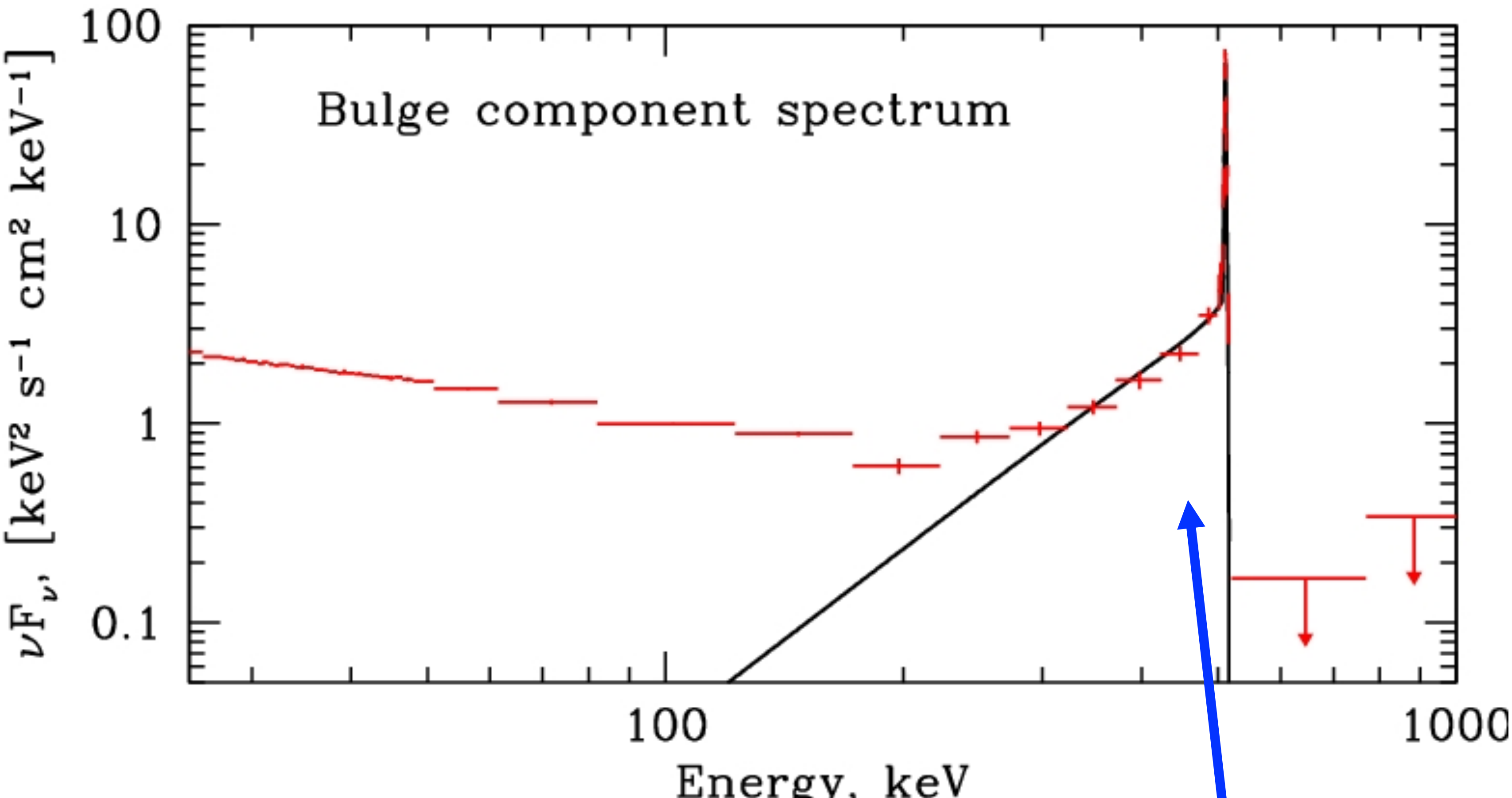
Positron has initial kinetic energy ~600 keV

1) Positron slows down

2) Captures electron via charge exchange and forms positronium atom



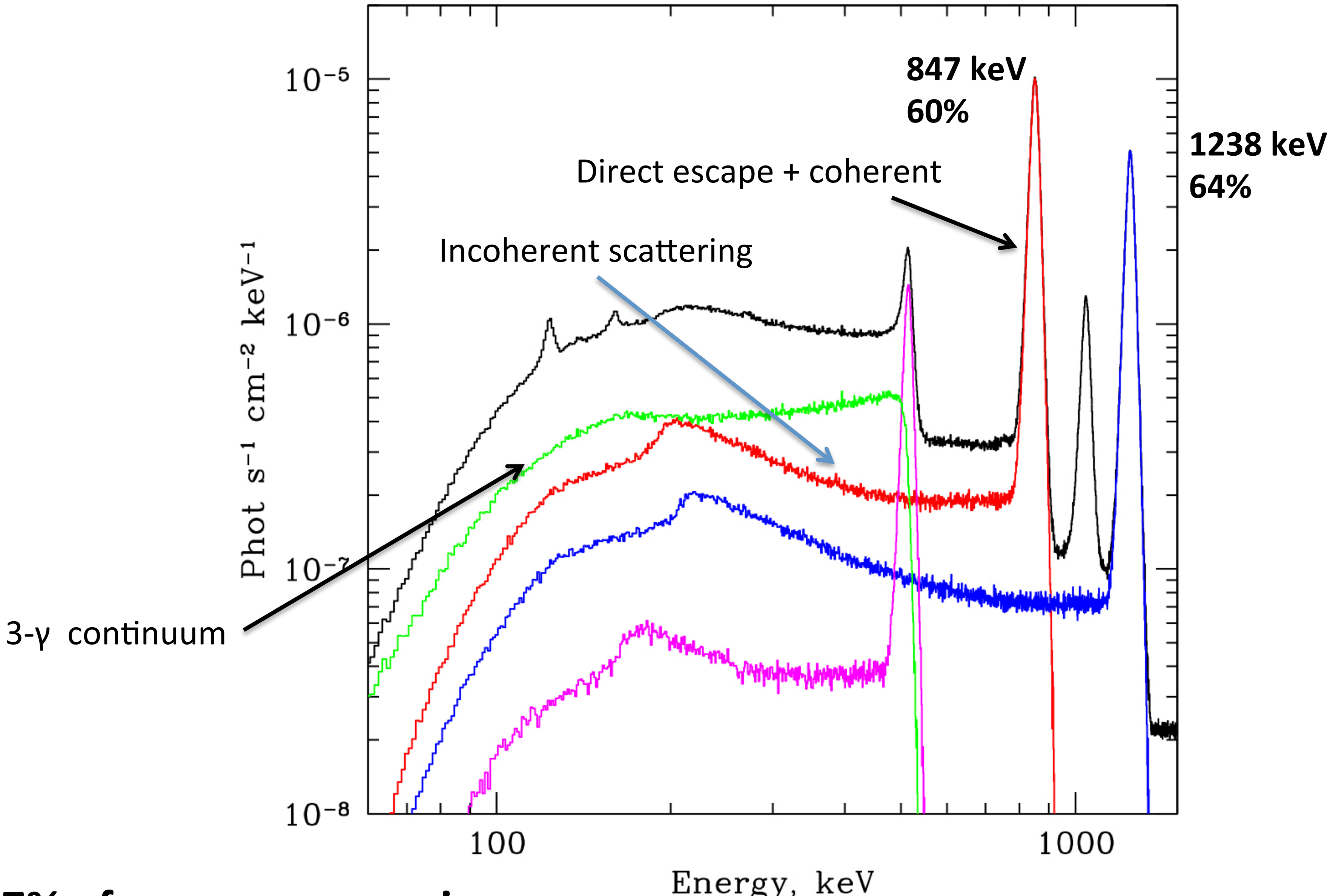




EC et al, 2005, 2011

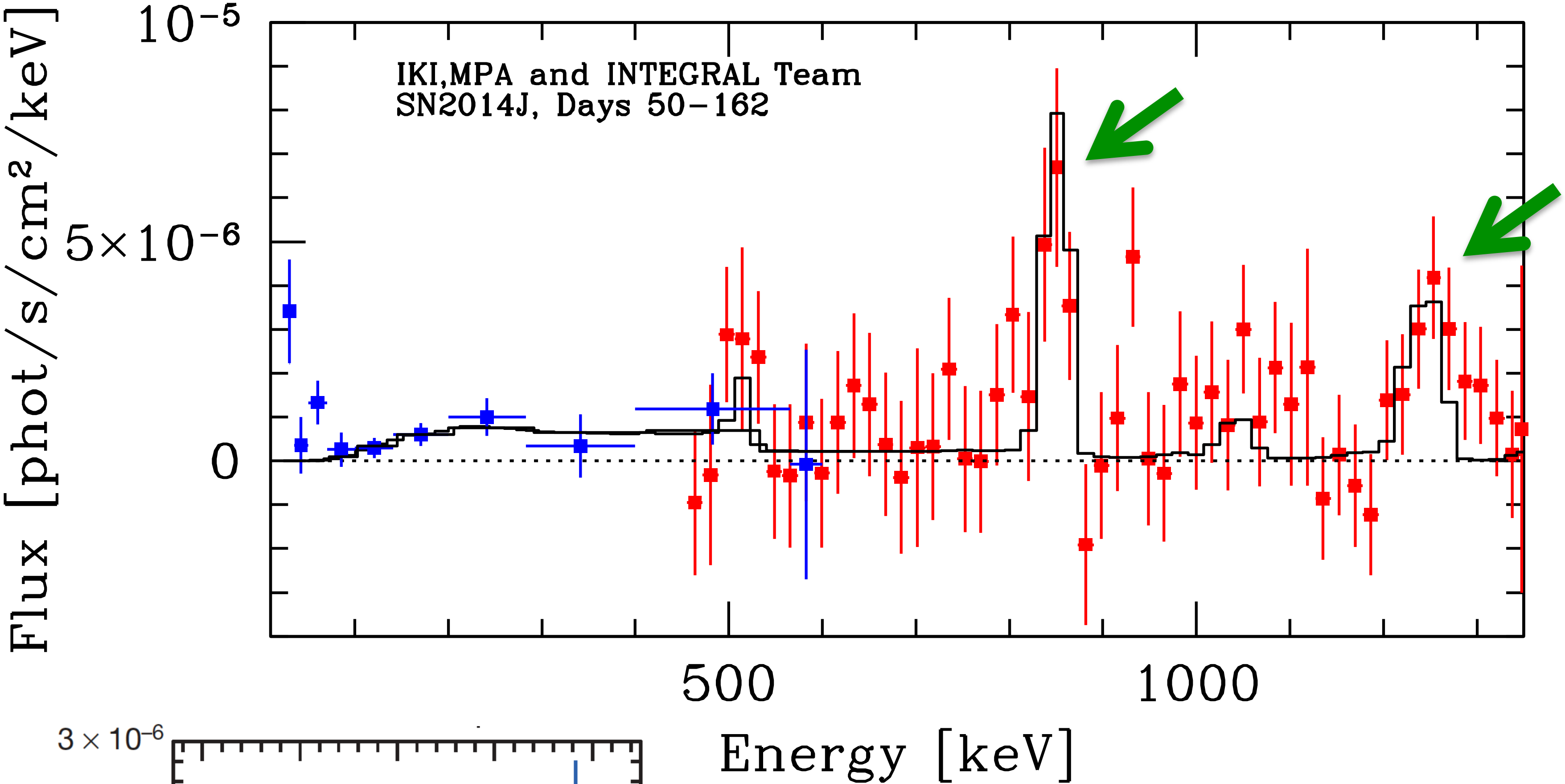
Positron annihilation

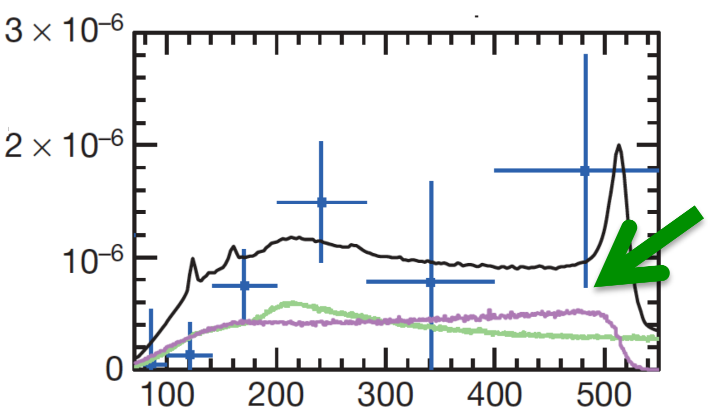
Typical emergent spectrum (day 75 since the explosion)



77% of energy escapes in gamma-rays

Broad band SN2014J spectrum (847 and 1238 keV lines + continnum below 511 keV)





Positrons provide ~50% of continuum

847 and 1238 keV lines at day 75

Parameter	847 keV line	1238 keV line
Flux, 10^{-4} phot cm^{-2} s^{-1}	2.34±0.74	2.78±0.74
Luminosity, 10^{41} erg s^{-1}	4.7	8.1
V_{shift} (l.o.s. velocity), km s^{-1}	-1900±1600	-4300±1600
Line width (l.o.s. velocity rms), σ_V, km s^{-1}	3600±1300	4700±1400

At day 75:

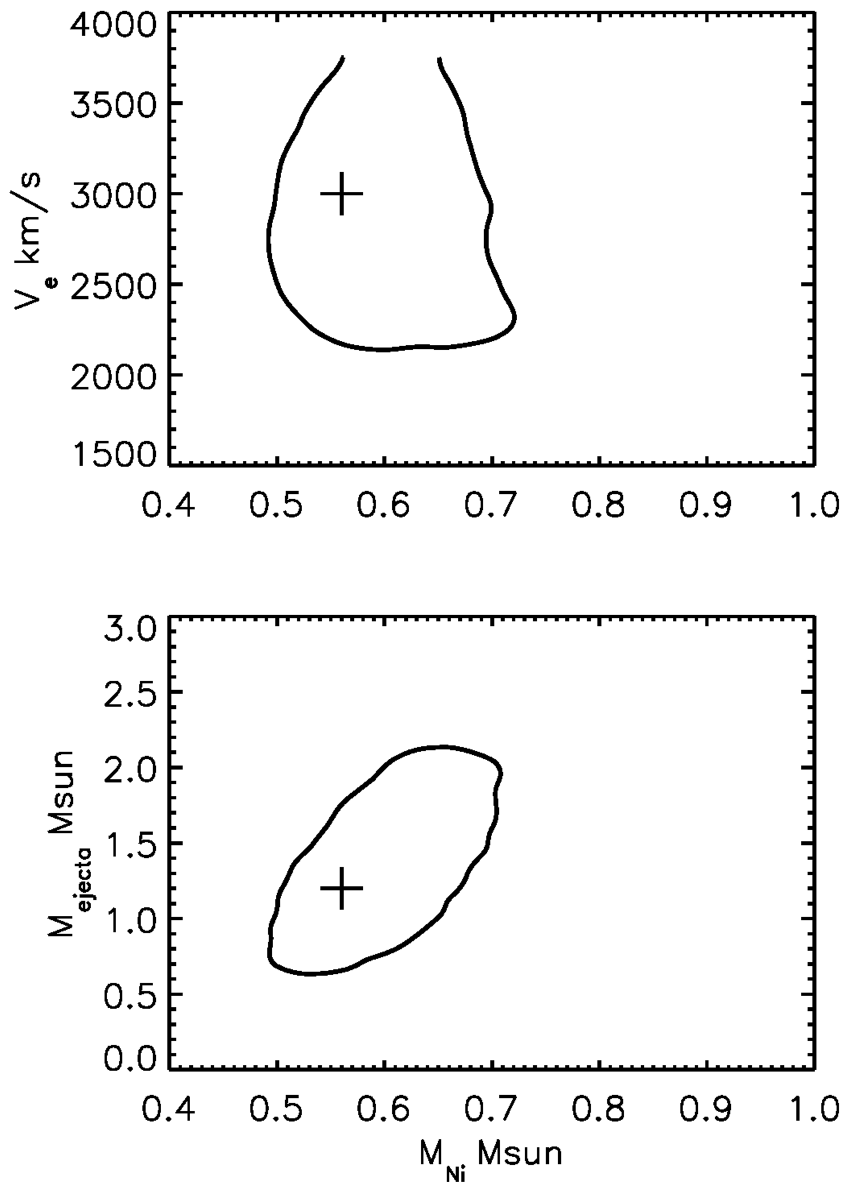
77% of gamma-rays escape

23% + kinetic energy of positrons thermalize

~3x10^{42} erg/s in Gamma

~1x10^{42} erg/s in Optical band

Best-fitting parameters of the 3PAR model



$$M_{Ni}, M_{Ejecta}, V_e$$

$$M_{Ni} \sim 0.6\, M_{Sun} \quad [\pm 0.1]$$

$$M_{Ejecta} \sim 1.3\, M_{Sun} \quad [\pm 0.7]$$

$$V_e \sim 3000 \text{ km/s} \quad [\pm 1000]$$

SN2014J and canonical models

Model	M_{Ni}, M_{Sun}	M_{Ej}, M_{Sun}	E_K, 10^{51} erg	$\Delta\chi^2$
W7[2]	0.59	1.38	1.24	54.4
DDT1p1	0.54	1.36	1.29	52.5
DD4[30]	0.61	1.39	1.24	52.0
DDT1p4	0.66	1.36	1.35	51.9
3PAR, best-fitting	0.56	1.20	1.3	50.5
3PAR, fiducial	0.70	1.38	1.3	49.3
DDT1p4halo	0.62	1.55	1.3	49.1
HED6[30]	0.26	0.77	0.72	38.2
DETO[29]	1.16	1.38	1.44	12.1

Nomoto+, 1984; Woosley & Weaver, 1991; Hoeflich & Khokhlov, 1996; Bravo+, 2014

Conclusions

- ✔ "Normal" SNIa in gamma-rays (at least after day 50)
- ✔ Gamma-ray lines of ^{56}Co (847 and 1238 keV)
- ✔ 0.6±0.1 M_{sun} of ^{56}Ni
- ✔ V~3000 km/s → Energy per nucleon ~0.6 MeV
- ✔ M_{ejecta}~1.3 M_{Sun}
- ✔ Positronium annihilation in the ejecta

Supernova seen through γ-ray eyes

Observations of γ-ray photons from a type Ia supernova indicate that stellar explosions of this kind get their energy from sudden thermonuclear fusion in the progenitor star. SEE LETTER P.406

ROBERT P. KIRSHNER

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Upsetting the conventional wisdom is always a joy in science. You can get prizes for that. But there is also a deep pleasure in showing decisive evidence on an important physical idea that has been used without proof for decades. The INTEGRAL data establish the thermonuclear explosion mechanism for type Ia supernovae. It is a wonderful result. ■