



**γ -ray nucleosynthesis :
results from the
INTErnational Gamma Ray Astrophysics Laboratory**

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Elements synthesized in stars

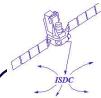
- Abundance analysis → knowledge of the processes occurring in stars.

Advantage of radioactive nuclei

- Witnesses of recent nucleosynthesis
- γ -rays not absorbed by interstellar matter (attenuation length \sim few g cm $^{-2}$)

Requirements

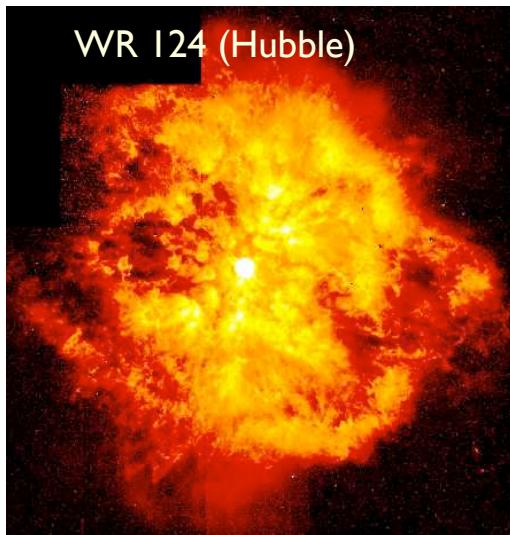
- Nucleus must be abundant
- Must be rapidly ejected into interstellar medium



Massive stars

Wolf-Rayet stars

($M_{\text{init}} > \sim 30 M_{\odot}$)



Supernovae

($M_{\text{init}} > \sim 12 M_{\odot}$)

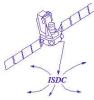


- Strong winds: 10^{-5} - $10^{-6} M_{\odot}/y$
- Ashes from H / He burning



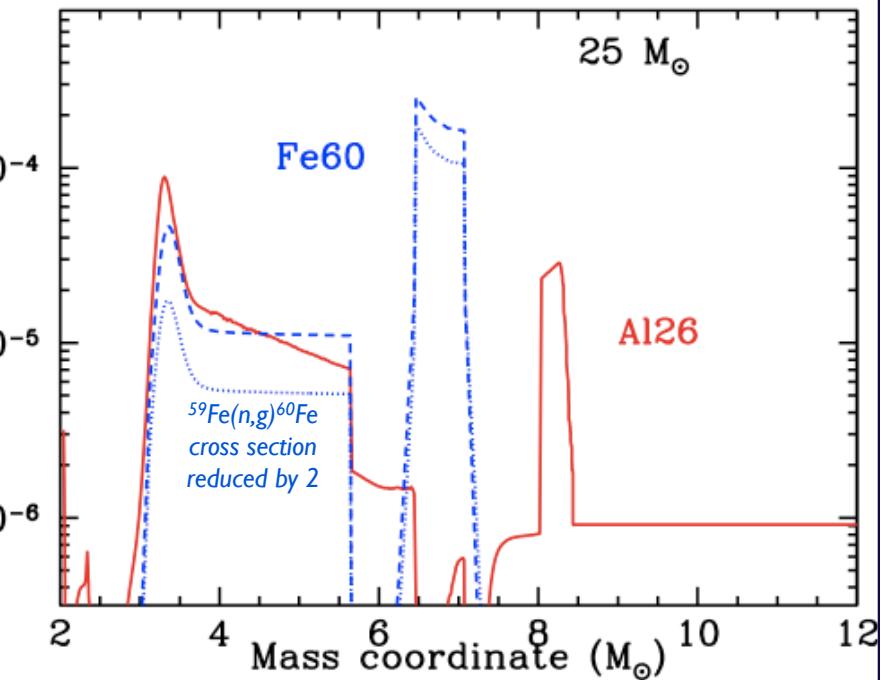
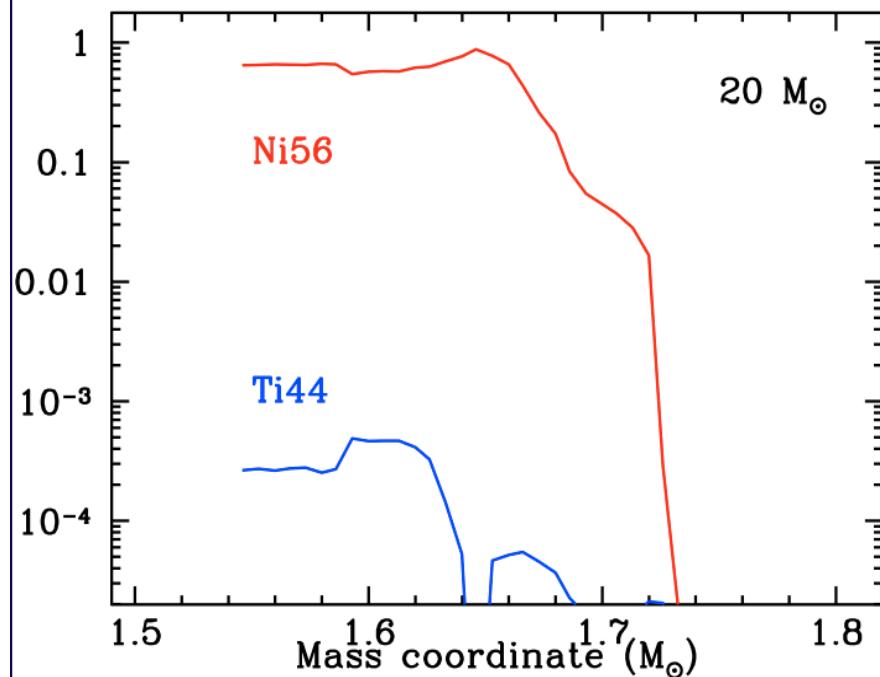
- $\sim 3/\text{century}$ in the Galaxy
- Ashes from all nucleosynthesis phases

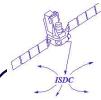




Abundance profiles

Prantzos 2004 (models from Rauscher et al 2002)

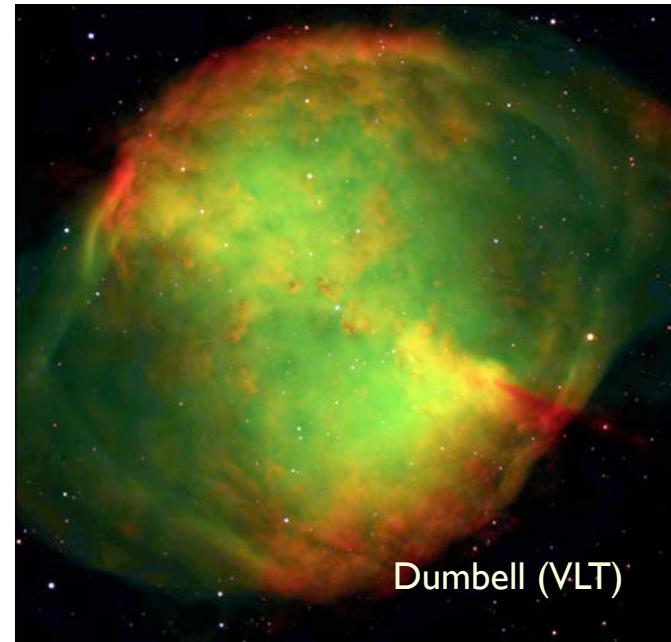
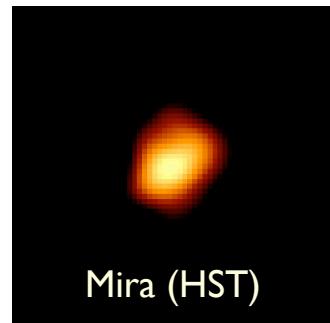




Low-mass stars

Asymptotic Giant Branch stars

($0.8 \text{ M}_\odot < \sim \text{M}_{\text{init}} < \sim 9 \text{ M}_\odot$)



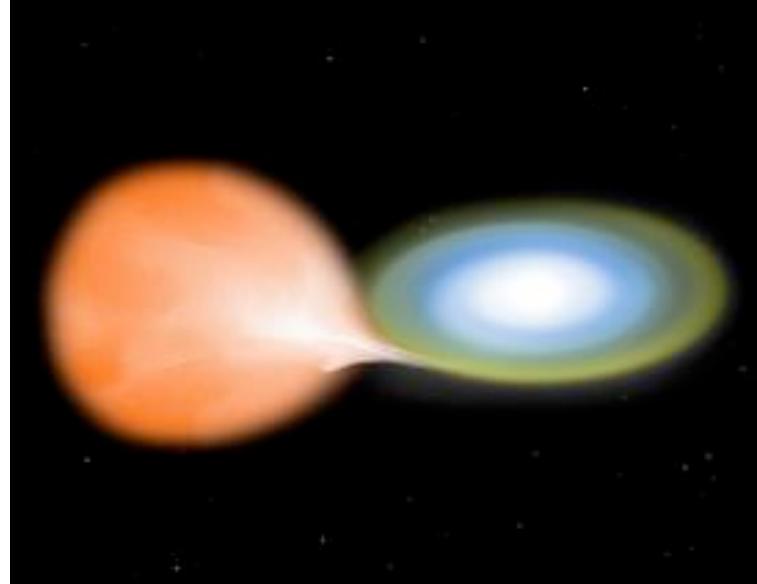
- Strong winds: up to $10^{-4} \text{ M}_\odot/\text{y}$
- Ashes from H / He burning

^{26}Al



Binary systems

Red Giant
filling
its Roche lobe



White Dwarf
accreting
matter

Slow accretion on a massive WD → thermonuclear runaways

= **Nova** (~35/y in Galaxy, but only ~4 observed)

^{7}Be , ^{22}Na , ^{26}Al



Astrophysical γ -ray lines

Decay chain	½ life time	Line energies keV (branching ratios)	Sites
${}^7\text{Be} \rightarrow {}^7\text{Li}$	53.3 d	477.6 (10.5%)	Novae
${}^{22}\text{Na} \rightarrow {}^{22}\text{Ne}$	2.6 y	1274.5 (99.9%)	Novae
${}^{26}\text{Al} \rightarrow {}^{26}\text{Mg}$	0.74 My	1129.7 (2.4%), 1808.6 (99.7%)	WR, SN, AGB, Novae
${}^{44}\text{Ti} \rightarrow {}^{44}\text{Sc}$ ${}^{44}\text{Sc} \rightarrow {}^{44}\text{Ca}$	60 y 3.9 h	67.9 (94.4%), 78.3 (96.2%) 1157.0 (99.9%)	SN
${}^{56}\text{Ni} \rightarrow {}^{56}\text{Co}$ ${}^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$	6.1 d 77.3 d	158.4 (98.8%), 750.0 (49.5%), 811.9 (86.0%) 846.8 (99.9%), 1238.3 (66.1%), 2598.5 (17.0%)	SN
${}^{57}\text{Ni} \rightarrow {}^{57}\text{Co}$ ${}^{57}\text{Co} \rightarrow {}^{57}\text{Fe}$	35.6 h 272.8 d	127.2 (16.7%), 1377.6 (81.7%), 1919.5 (12.3%) 14.4 (9.2%), 122.1 (85.6%), 136.5 (10.7%)	SN
${}^{59}\text{Fe} \rightarrow {}^{59}\text{Co}$	44.5 d	192.4 (3.1%), 1099.3 (56.5%), 1291.6 (43.2%)	SN
${}^{60}\text{Fe} \rightarrow {}^{60}\text{Co}$ ${}^{60}\text{Co} \rightarrow {}^{60}\text{Ni}$	1.5 My 5.3 y	58.6 1173.2 (100%), 1332.5 (100%)	SN
$e^+ + e^-$	0.1-10 My	511	

in red : e^+ emitter

in blue : detected lines



INTEGRAL : the instruments

The imager IBIS

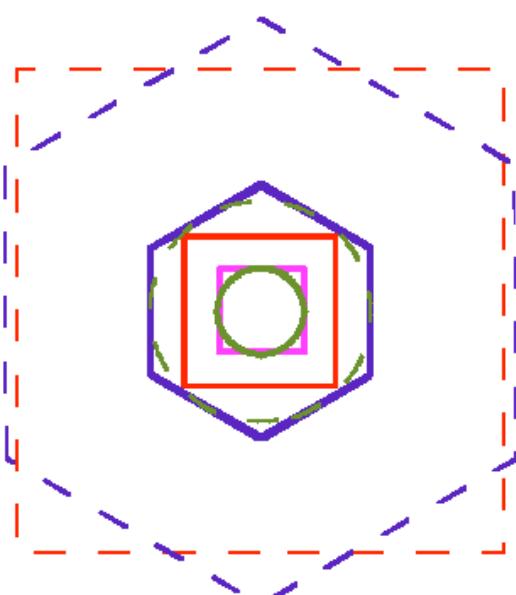
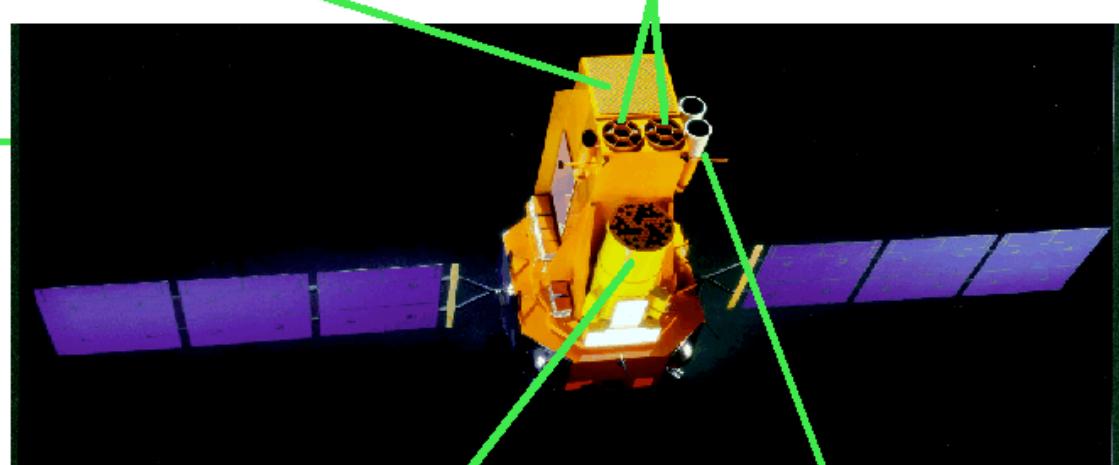
- ISGRI (CdTe, semiconductor): 8 x 2048 pixels
- PIC-SIT (CsI, scintillation crystal): 8 x 512 pixels
- 15 keV → 10 MeV
 - with 9% res. @ 100 keV
- FOV: 9°x9° (fully) - 29°x29° (partial)
 - with 12' resolution

The X-ray imager JEM-X

- 3 keV → 35 keV
 - with 8% res. @ 25 keV
- FOV: 4.8°Ø (fully) - 13.2°Ø (partial)
 - with 3' resolution

The optical camera OMC

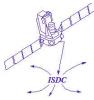
- 5 cm aperture, CCD 1024x1024
- V filter, $m_V=18.2$ mag (100s, 3 σ)
- FOV: 5°x5° with 17.6" resolution



The spectrometer SPI

- Ge, 19 detectors
- 20 keV → 8 MeV
 - with 0.23% res. @ 1.33 MeV
- FOV: 13.2°x13.2° (fully, side-side)
 - 30°x30° (zero response, corner-corner)
- with 2.5° resolution

The startrackers
determine the attitude
of the spacecraft

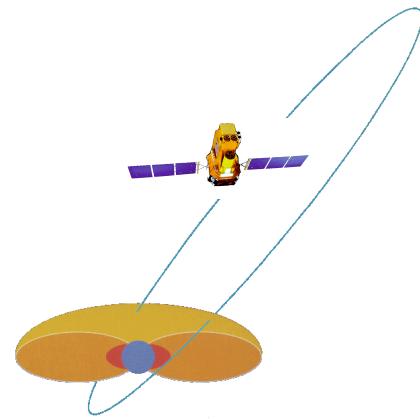
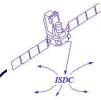


INTEGRAL : the instruments



The Spectrometer SPI

- 19 Ge detectors
- 20 keV → 8 MeV
with 0.23 % res. @ 1.33 MeV
- Field of View:
 - 13.2° x 13.2° (fully)
 - 30° x 30° (zero response)
with 2.5° resolution



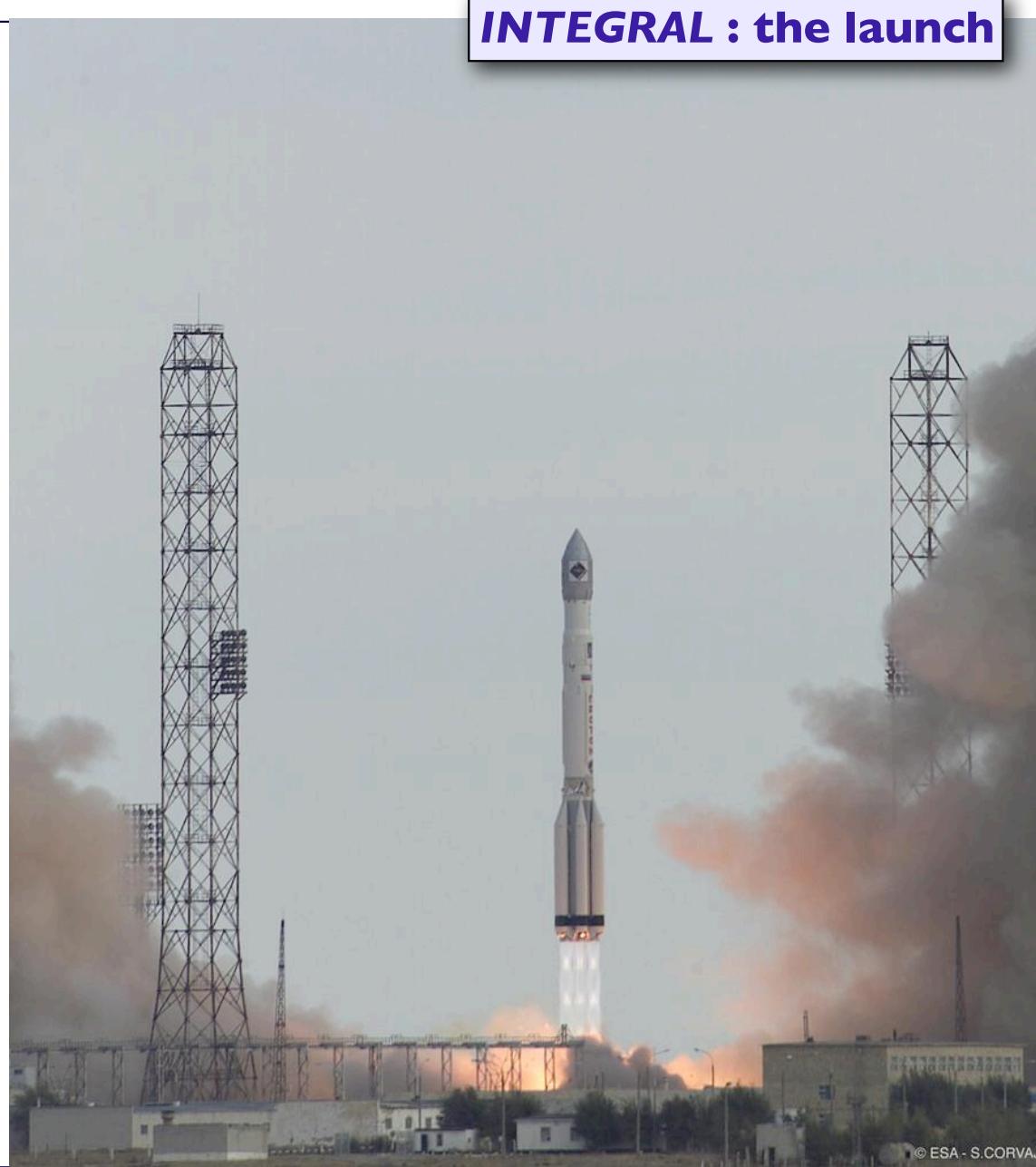
Perigee: ~9000 km

Apogee: ~150000 km

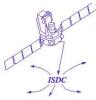
Period : ~72 h

- **Scientific data** processed and checked at the ISDC/Geneva Observatory
- **Successful mission :** extended up to at least 2012

INTEGRAL : the launch

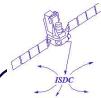


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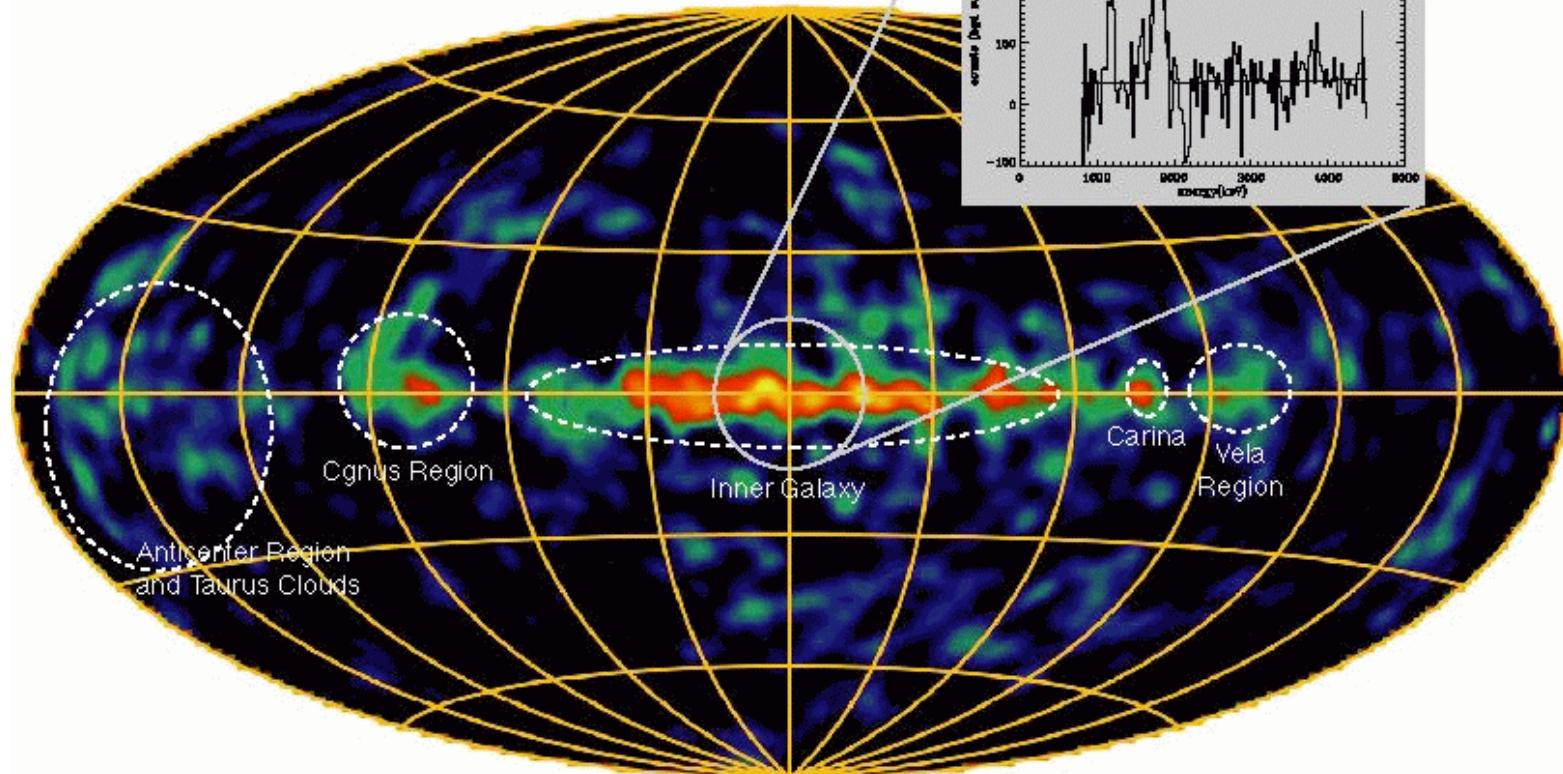
Observations

- ^{26}Al
- ^{60}Fe
- ^{44}Ti
- $e^+ + e^-$



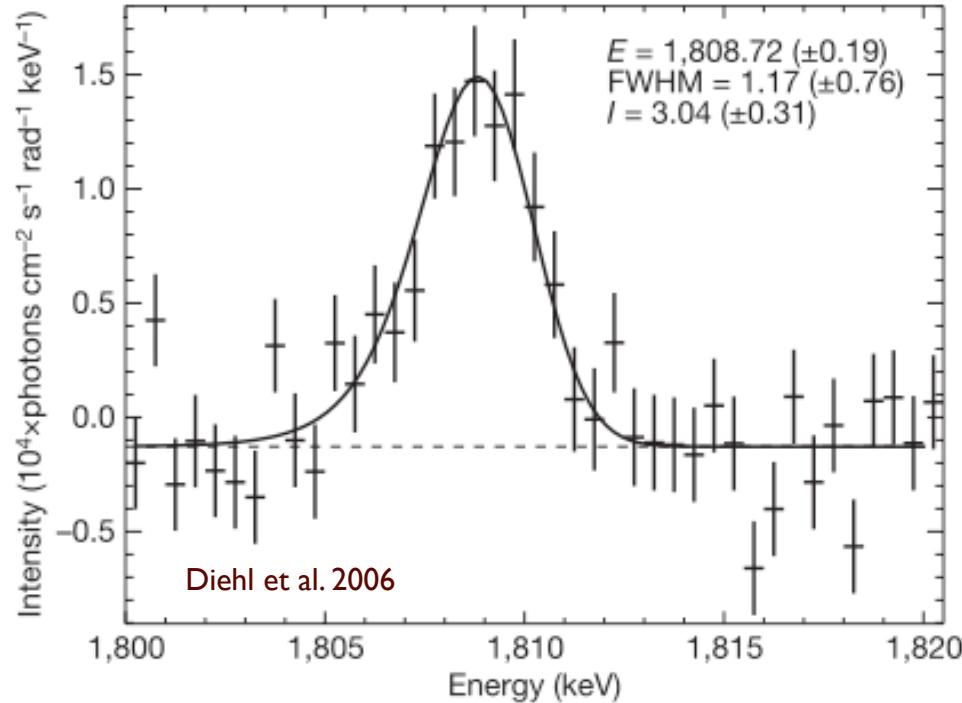
Expected distribution of the diffuse ^{26}Al in the Galaxy:

^{26}Al all-sky map from CGRO-Comptel





Galactic ^{26}Al diffuse emission



**Predicted masses of
 ^{26}Al ejected by stars**

WR
SN
AGB [$1 - 5 M_{\odot}$]
[$5 - 8 M_{\odot}$]
Novae
Total

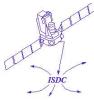
<i>per star</i>	<i>in Galaxy</i>
$\sim 2000 \times 10^{-7} M_{\odot}$	$1.2 M_{\odot}$
$\sim 300 \times 10^{-7} M_{\odot}$	$0.9 M_{\odot}$
$2 \times 10^{-7} M_{\odot}$	$0.1 M_{\odot}$
$40 \times 10^{-7} M_{\odot}$	$0.1 M_{\odot}$
$0.2 \times 10^{-7} M_{\odot}$	$0.2 M_{\odot}$
<hr/>	
	$2.5 M_{\odot}$

INTEGRAL/SPI

1.5 years of data

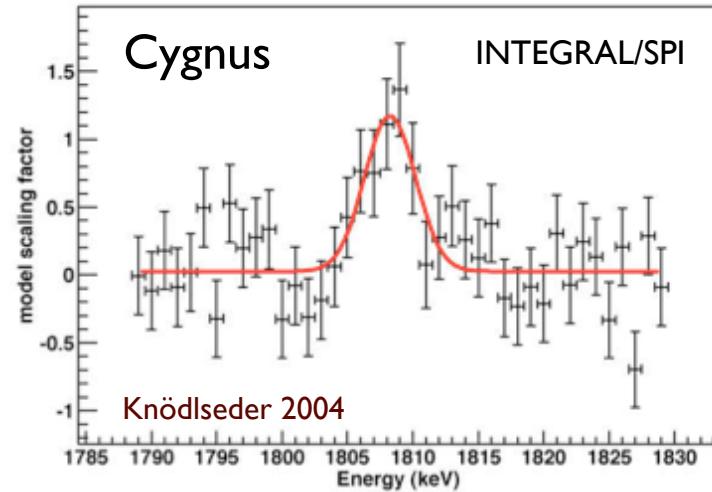
$$\hookrightarrow M_{\text{gal}}(^{26}\text{Al}) = (2.8 \pm 0.8) M_{\odot}$$

$\rightarrow 1.9 \pm 1.1$ core collapse
SNe per century

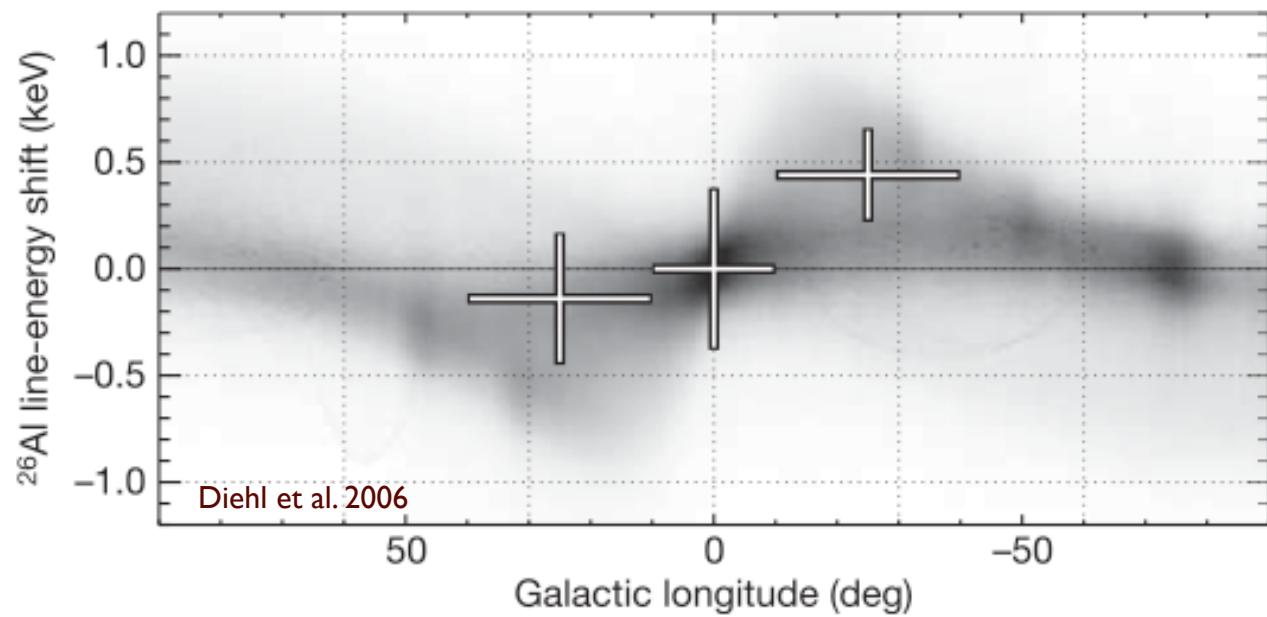


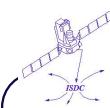
Galactic ^{26}Al diffuse emission

- ^{26}Al in the **Cygnus region** (young stellar associations); factor of 2 more than expected

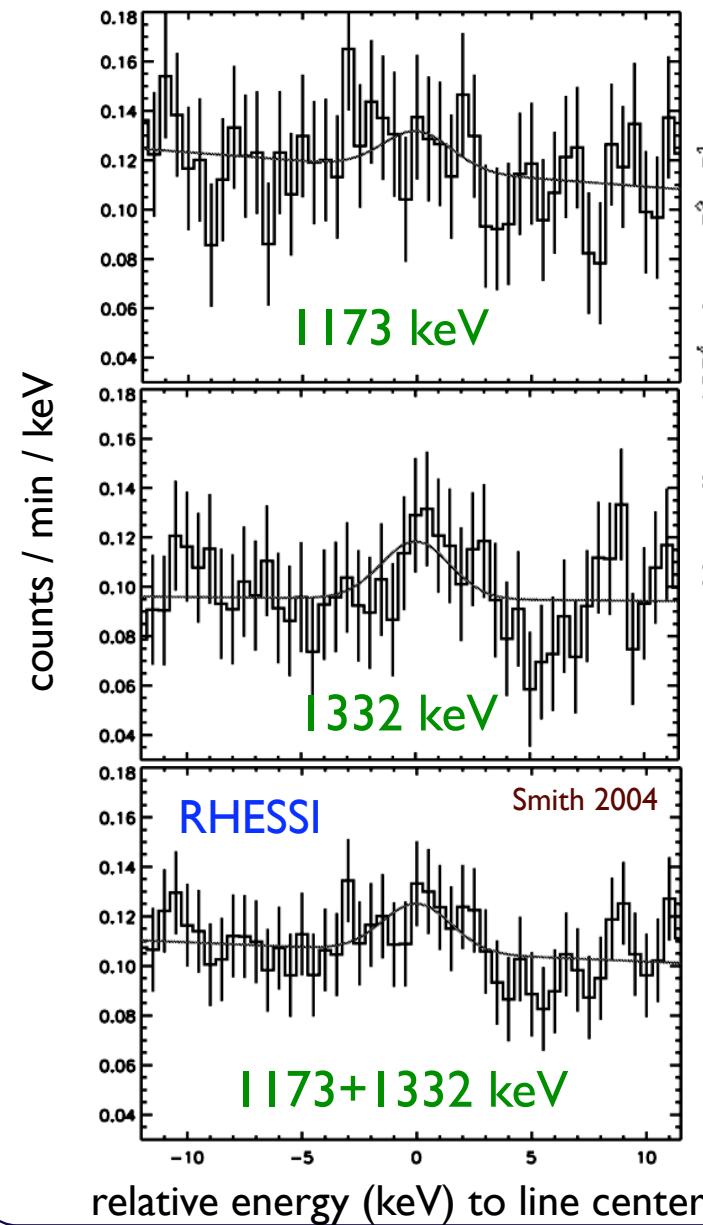


- ^{26}Al traces **Galactic rotation** ($v \sim 200$ km/s)

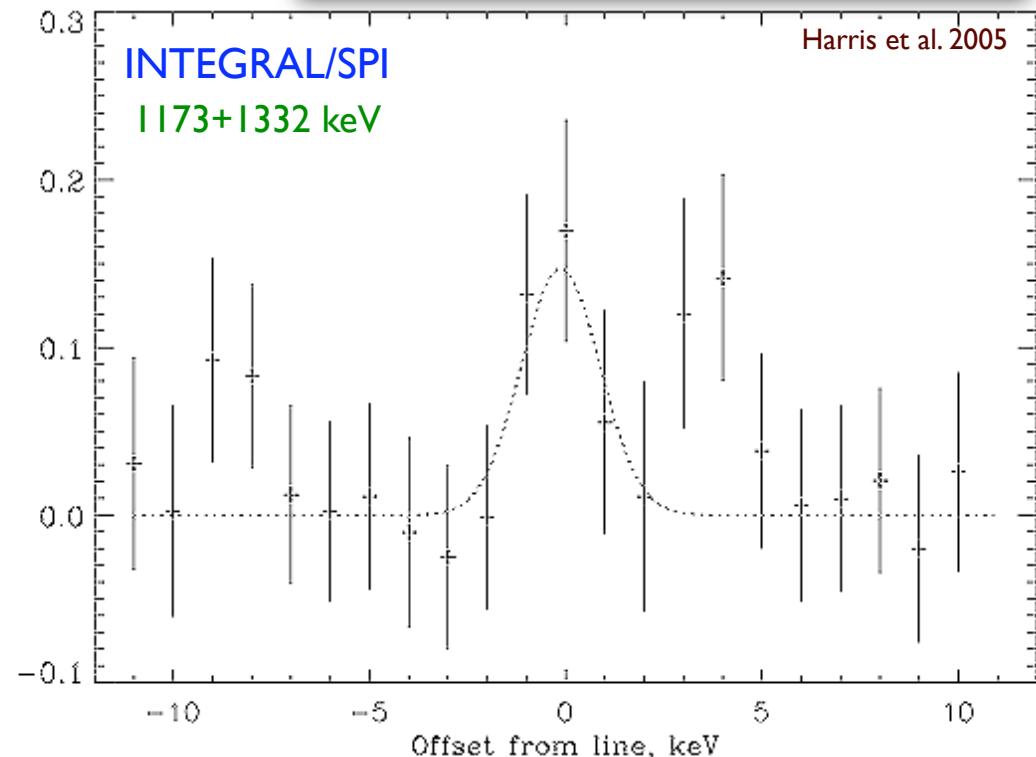




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Galactic ^{60}Fe diffuse emission

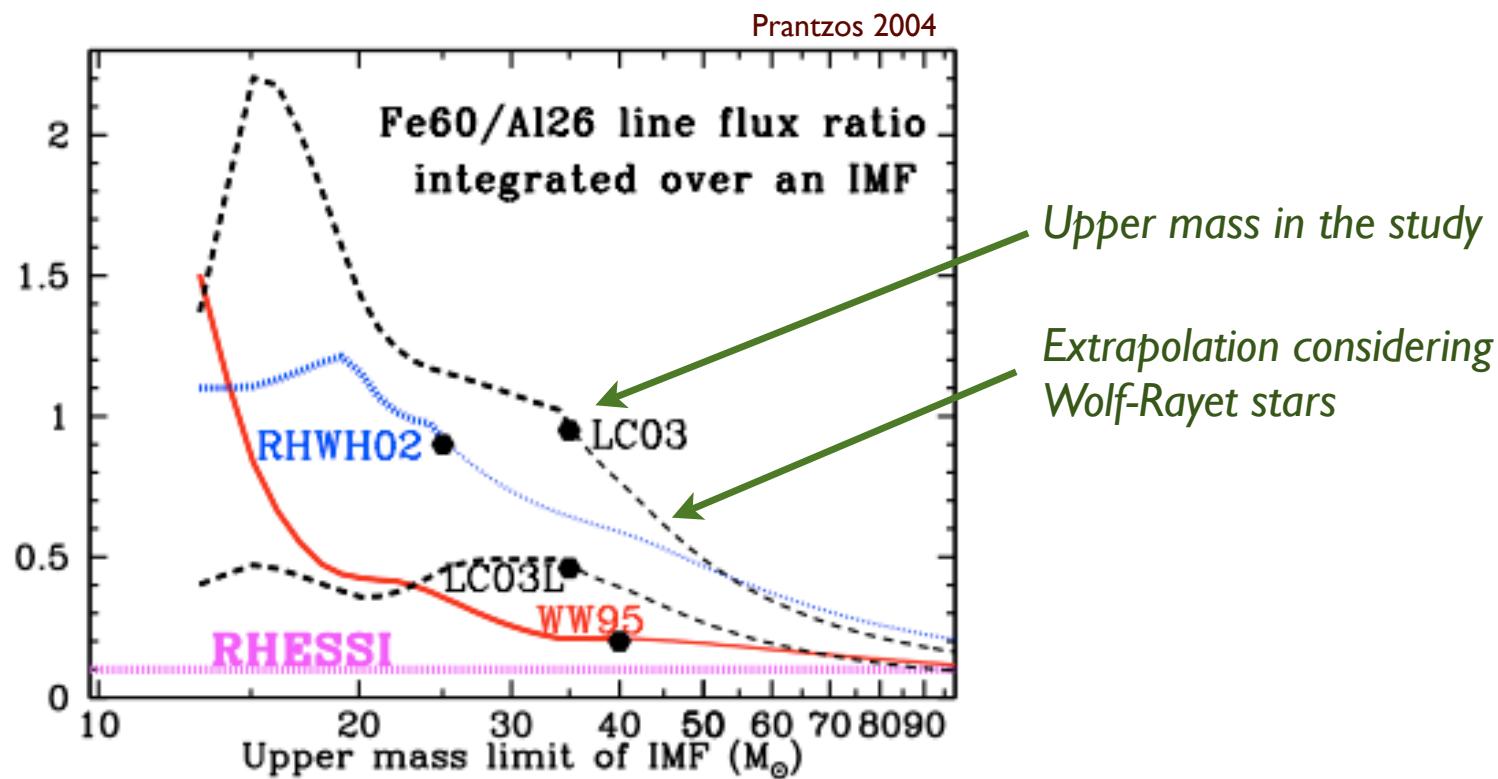


$$^{60}\text{Fe}/^{26}\text{Al} = 0.11 \pm 0.03$$

→ Needs extra source(s) of ^{26}Al
other than core collapse SN

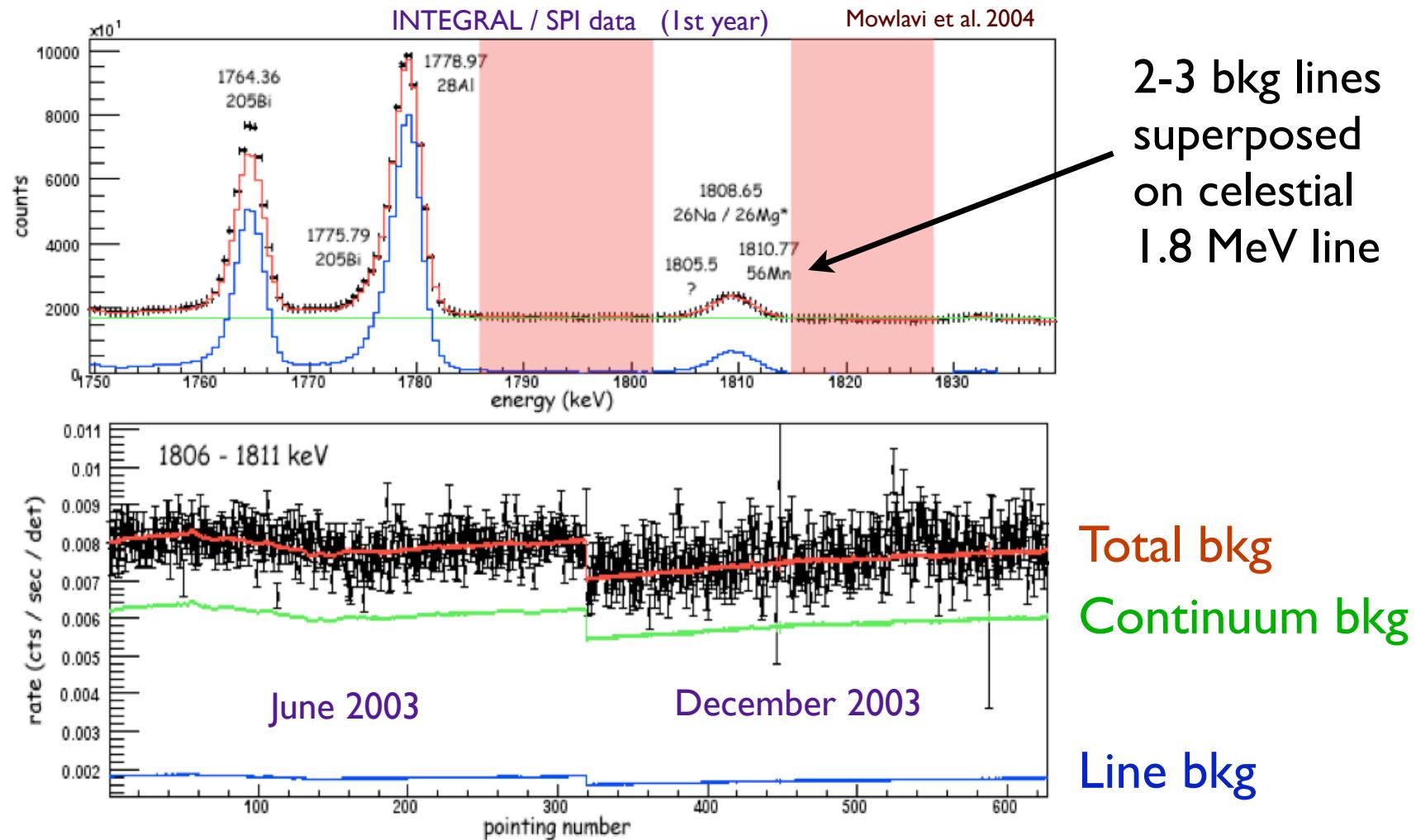


When taking also Wolf-Rayet stars as a source of ^{26}Al ...



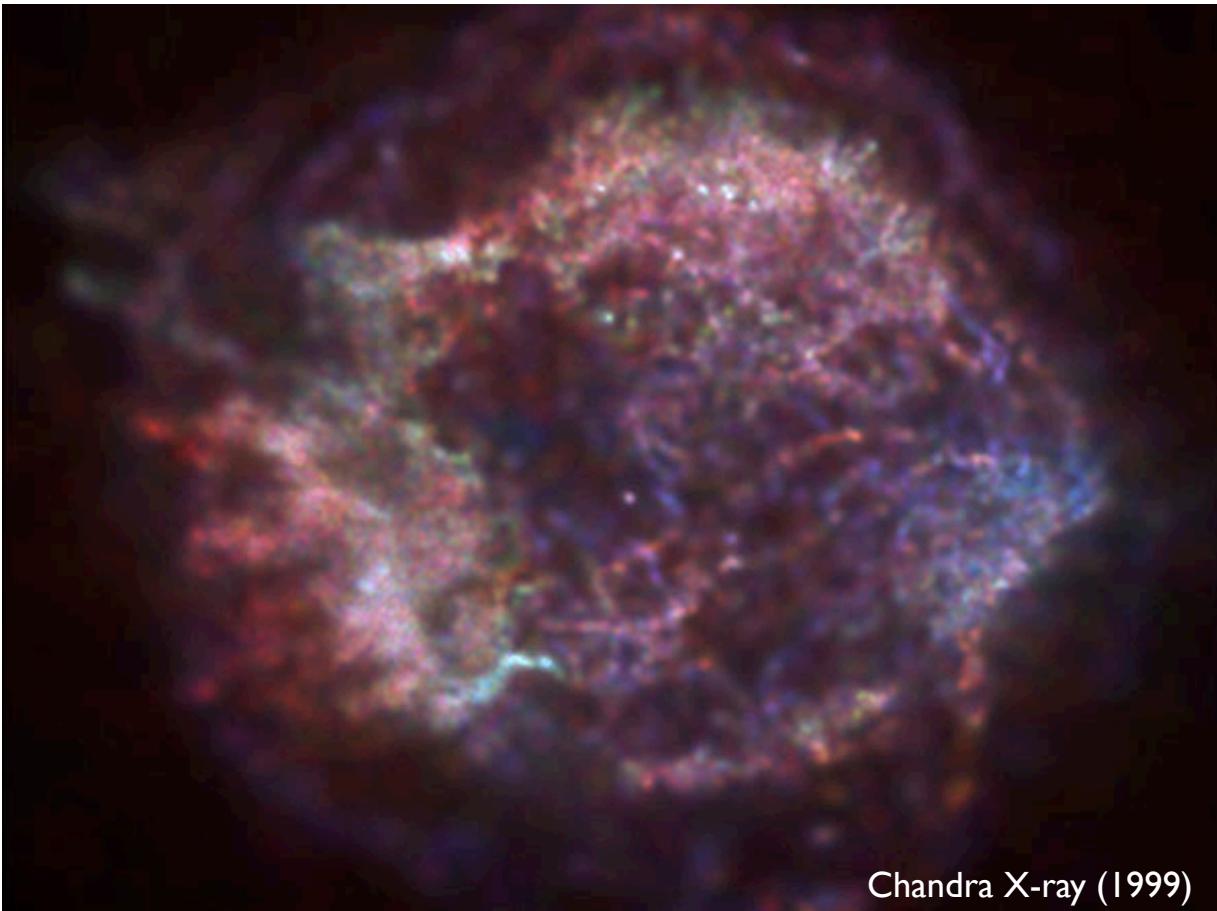


^{26}Al from closest WR star to the Sun ($\Upsilon^2\text{-Velorum}$, 260 pc)?





44Ti from Cas A

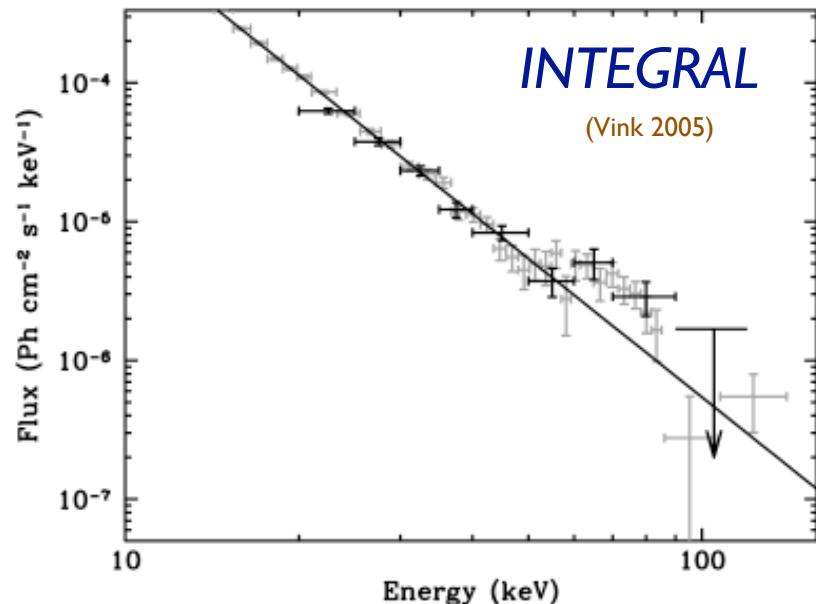
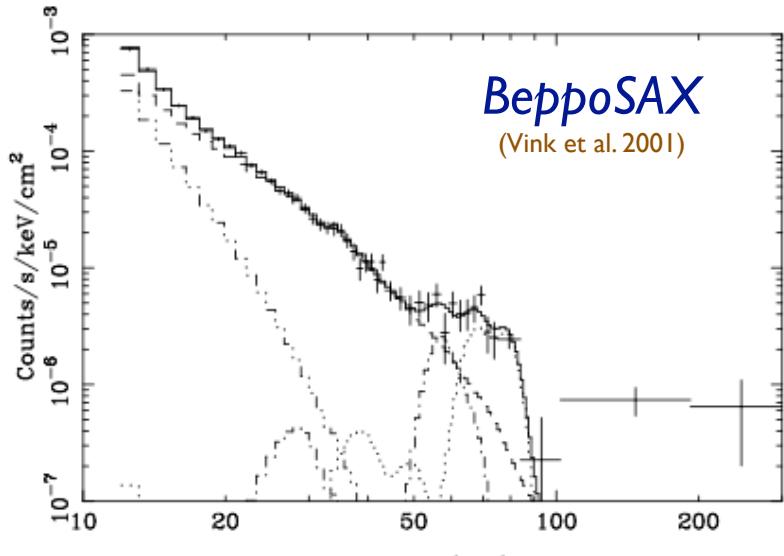


- Exploded in 1667 at ~ 3.4 pc
- $10-15 M_{\odot}$ ejected

- Youngest SN known in Galaxy
- Progenitor: probably WR (SN Ib)



Detection of the **67.9 and 78.4 keV** lines with BeppoSAX



But continuum makes line measurement difficult

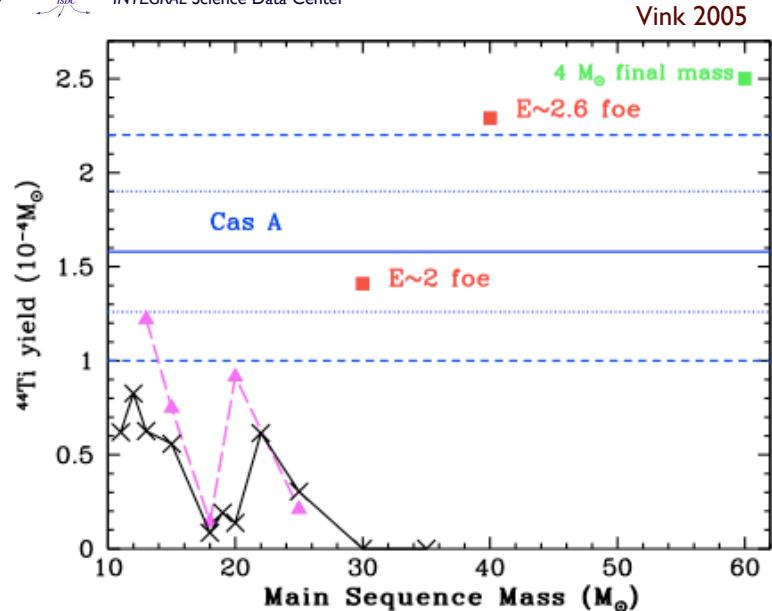
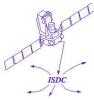
Flux: $(1.9 \pm 0.4) \times 10^{-5}$ ph cm⁻² s⁻¹ if power law continuum
 $(3.2 \pm 0.3) \times 10^{-5}$ ph cm⁻² s⁻¹ if steepening of synchrotron and non-thermal bremsstrahlung

COMPTEL+BeppoSAX averaged results:

$$(2.6 \pm 0.4 \pm 0.5) \times 10^{-5} \text{ ph cm}^{-2} \text{ s}^{-1}$$

statistical error

systematic error due to bkg



$$\rightarrow M(^{44}\text{Ti}) = (1.6 \pm 0.3 \pm 0.3) \times 10^{-4} M_{\odot}$$

Similar to that from SN 1987A

Model predictions too low !

Why ? (cf. Vink 05)

More energetic ?

Kinetic energy derived from SNR's kinematic $\sim 2 \times 10^{51}$ erg
(Laming & Hwang 2003)

Asymmetric SN ?

Ample evidence of asymmetric ejecta expansion (e.g. Hwang et al. 2004)

Higher pre-SN mass loss?

Ejecta mass measured in X-rays quite low, 2-4 M_{\odot}

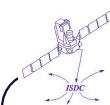
Uncertain yields ?

1-D models, no rotation, no magnetic field, ...

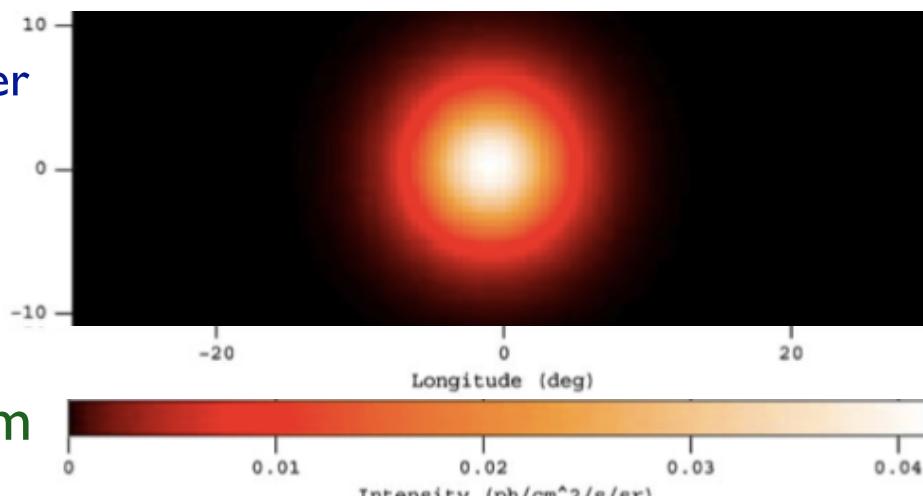
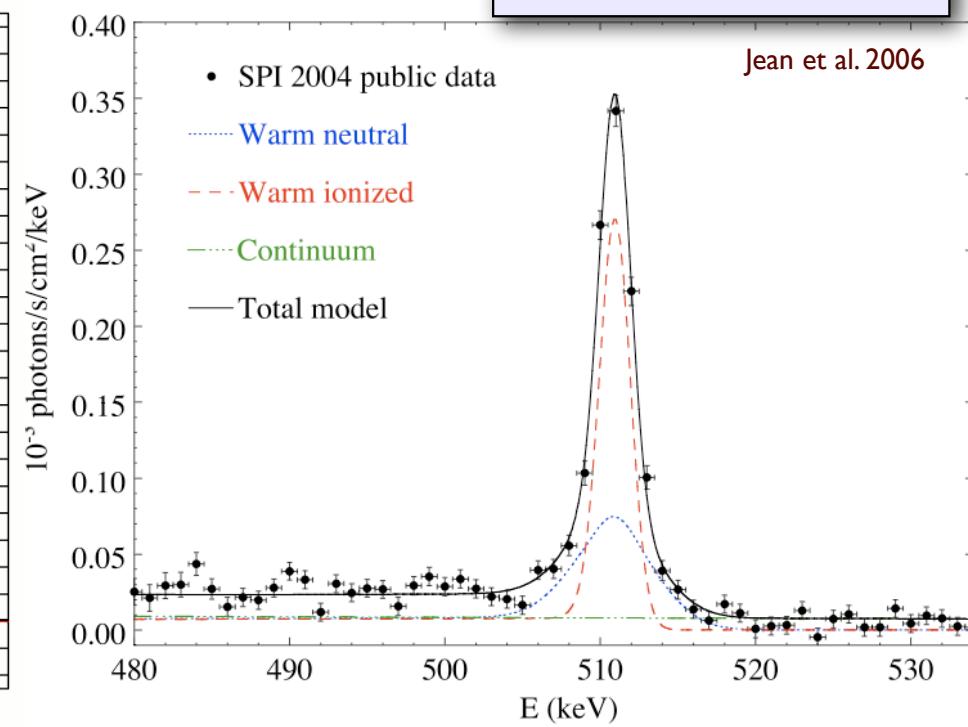
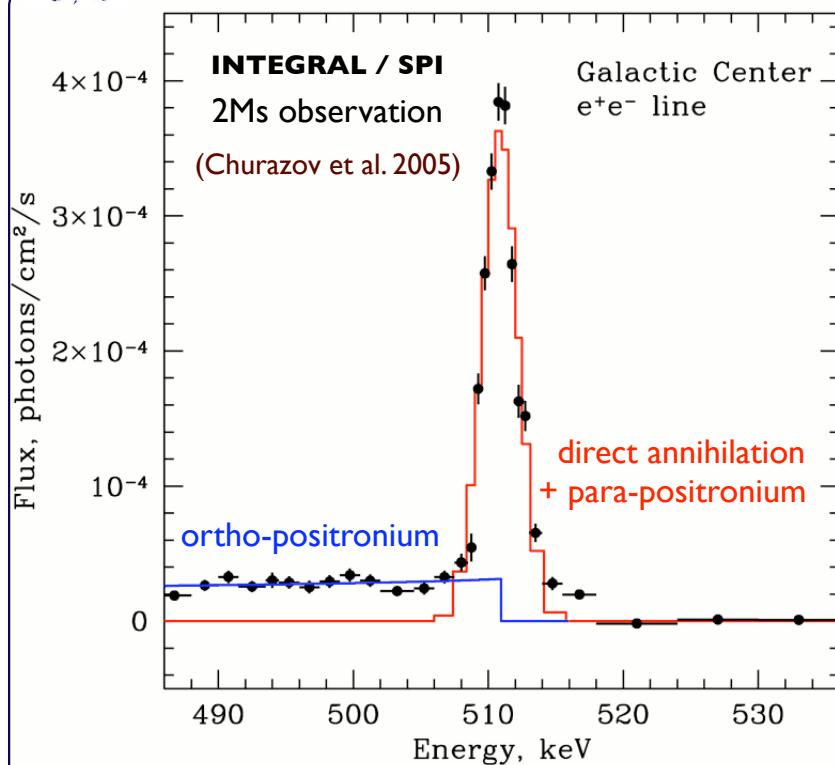
Higher effective ^{44}Ti life-time ?

(If ionized, EC rate drops, Mochizuki et al. 1999, Motizuki & Kumagai 2004)

But X-ray spectroscopy indicates that both Ca and Fe (similar ionization cross sections) are still ionizing

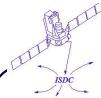


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- Symmetric distribution in Galactic center
- $94 \pm 6\%$ of positrons form positronium before annihilation
- Line shape

→ Constraints on T_{gas} and degree of ionization of interstellar medium



- **511 keV from Galactic disk**

- Recent evidence
- All can be explained from ^{26}Al (surprise)

- **511 keV from Galactic center**

Annihilation of 10^{43} e⁺/sec in small region

- Origin?**
- β^+ -decaying radioactive isotopes (SNIa $\rightarrow 2 \times 10^{42}$ e⁺/sec, but great uncertainties)
 - Decay of Π^+ produced in cosmic ray interactions with interstellar nuclei (should be seen in disk too)
 - High energy processes (pair creation by high-energy photons)
 - Bosonic dark matter annihilation of low-mass particles (1-100 MeV) \rightarrow Check from dwarf galaxies which are dark-matter dominated?

Conservative interpretation: Galaxy's old stellar populations

- SNIa $\rightarrow 2 \times 10^{42}$ e⁺/sec (but great uncertainties)



Conclusions

- INTEGRAL = successful mission
- Challenging results for astrophysicists (and nuclear physicists)
- More results as the mission extends further