Gamma-Ray Spectroscopy and White Dwarfs

- A contribution to celebrate Margarita Hernanz's Birthday –

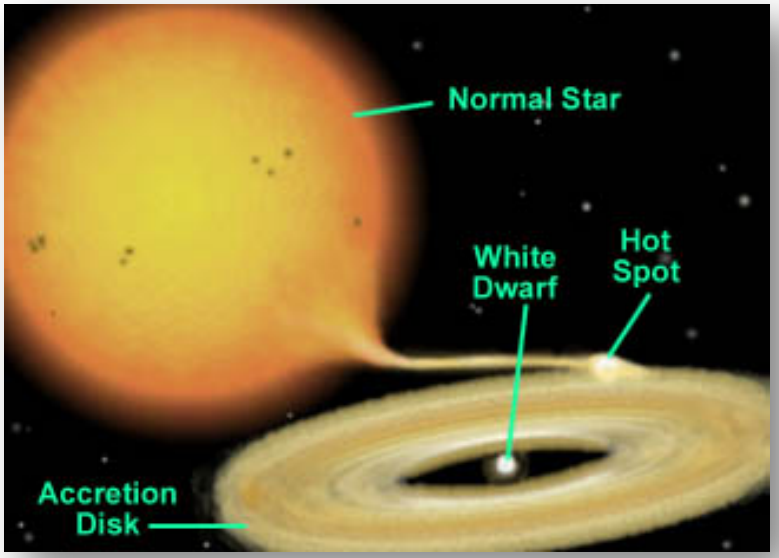
Roland Diehl

Contents

- Astrophysics theory: WDs and gamma-ray lines?
- COMPTEL results: Lines from WDs?
- Novae and gamma-ray lines
- WDs and SNIa: Gamma-ray lines!

White Dwarfs and Gamma-Ray Lines?

Candidate astrophysical processes:



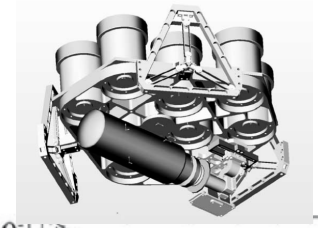
- WD accretion flows
  → LECRs?
  Neutron capture?
  → 2223 keV

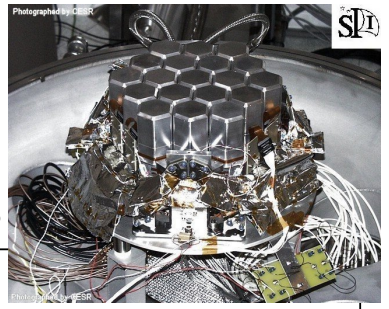
- nova nucleosynthesis
  → several radioactive isotopes
  → 511 keV, 478 keV, 1275 keV, 1809 keV

- WDs in supernovae type Ia
  → ^{56}Ni decay chain
  → 158/812/847/1238 keV

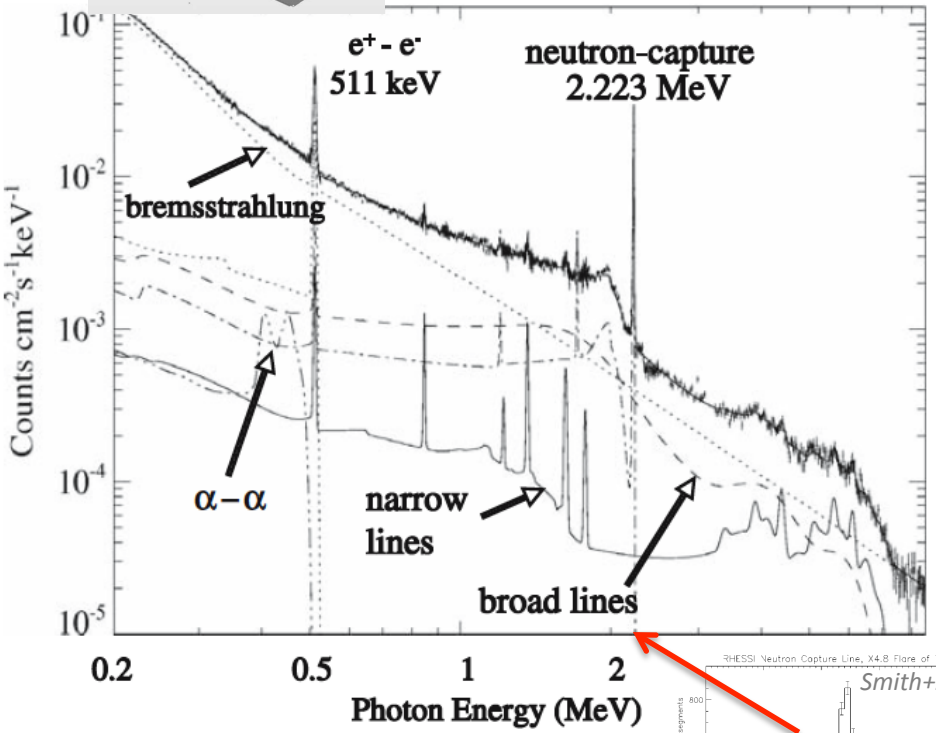
Solar Flares

- 28 Oct 2003 flare: RHESSI, INTEGRAL/SPI

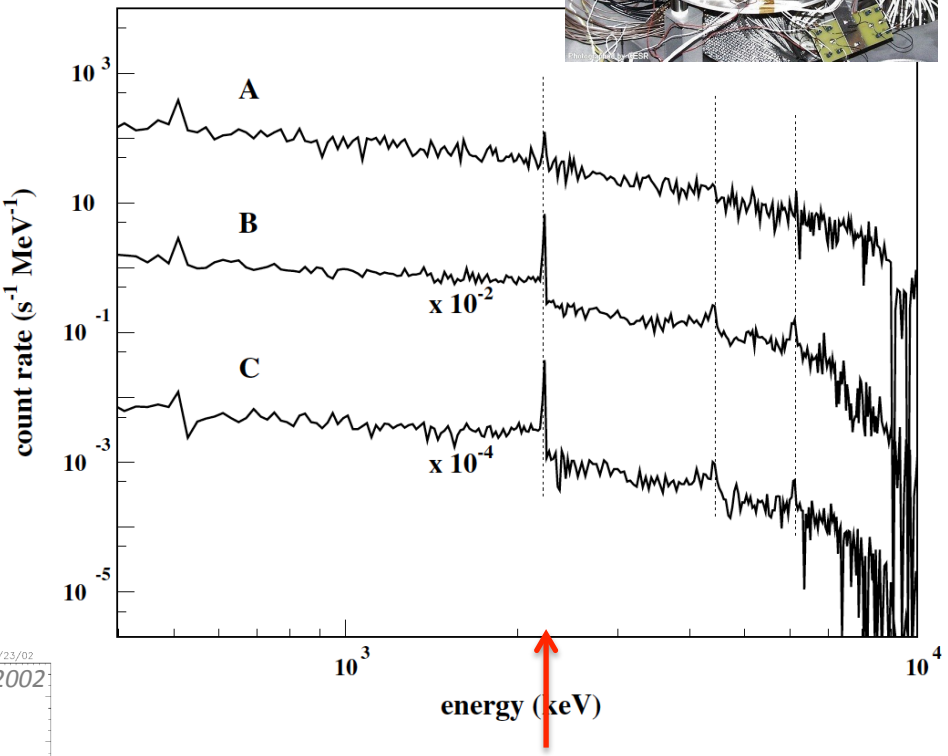




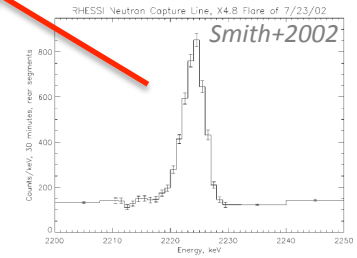
Dennis+2007



Kiener+2008

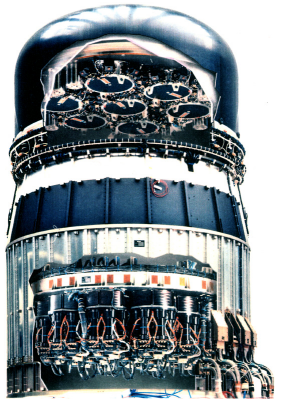


Smith+2002



2.23 MeV γ-rays from Neutron Capture

- All-sky search with COMPTEL (CGRO)



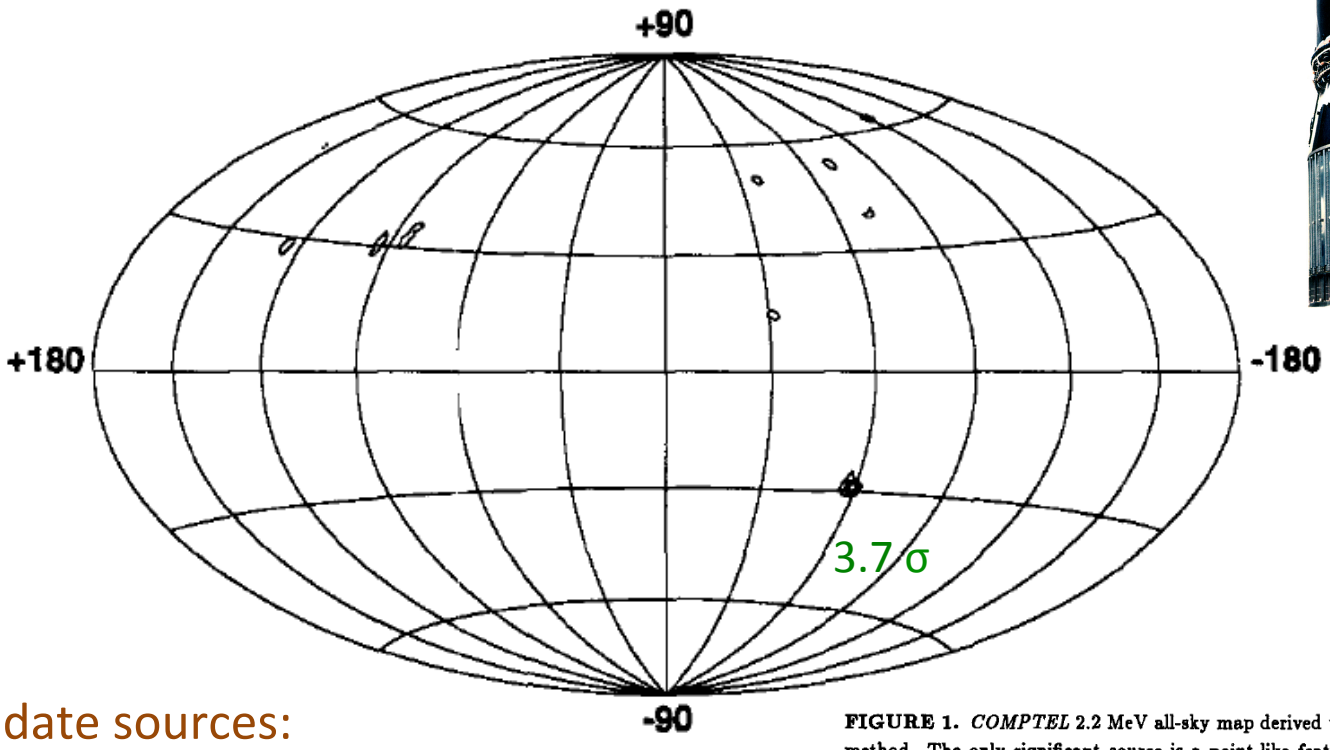


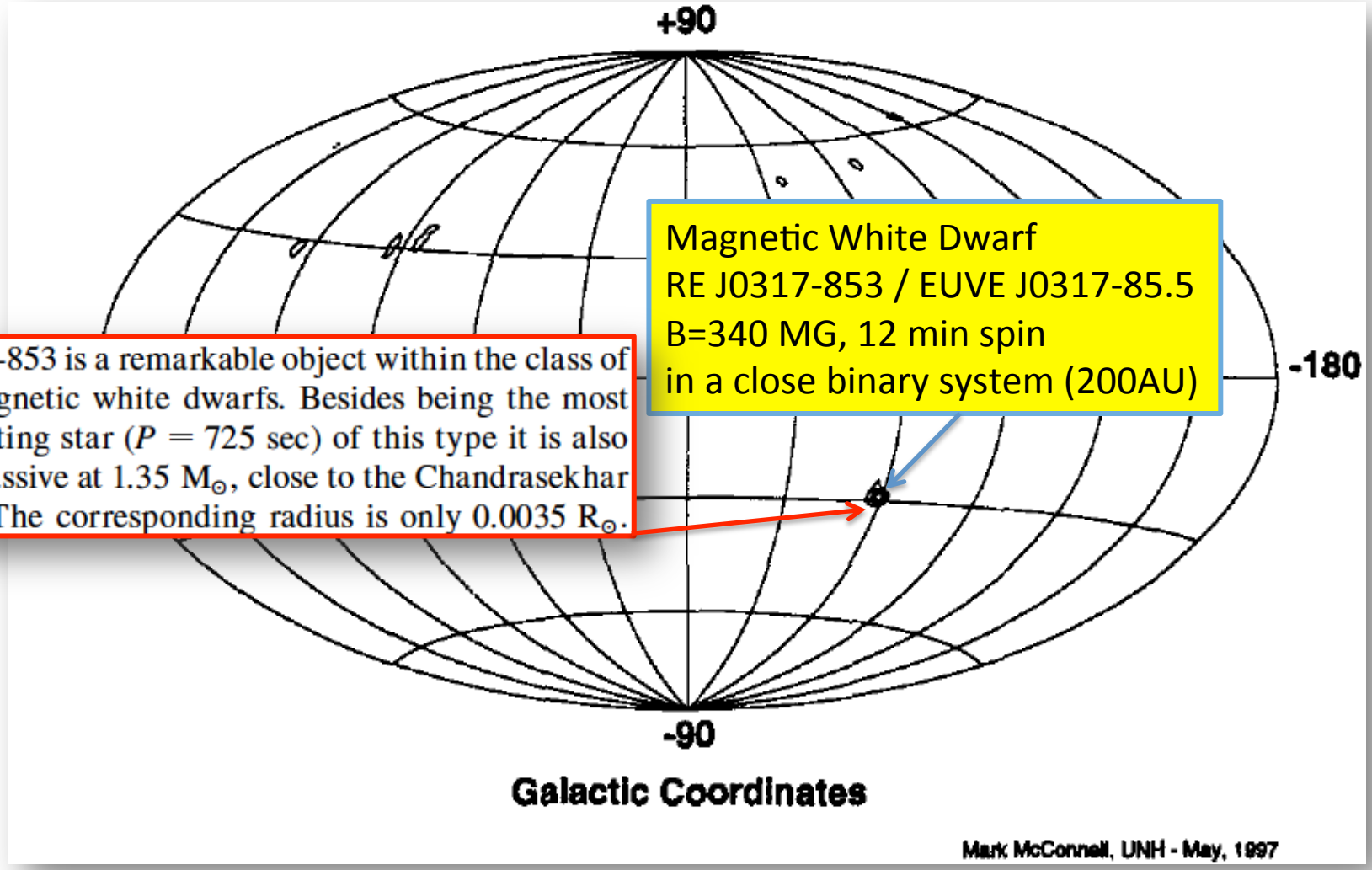
FIGURE 1. *COMPTEL* 2.2 MeV all-sky map derived using a maximum entropy imaging method. The only significant source is a point-like feature near $(\ell, b) = (300°, -30°)$, for which there is no obvious counterpart. This map appears nearly identical to a maximum likelihood map having a likelihood threshold value of 15.
Mark McConnell, UNH - May, 1997

- candidate sources:
  - Sun/flares (known!)
  - Stellar flares
  - Neutron star atmosphere (→ red shifted)
  - Accretion flow near compact stars (WD, NS, BH)

Neutron capture

$^1H(n,\gamma)^2D$ → 2223.42 keV line

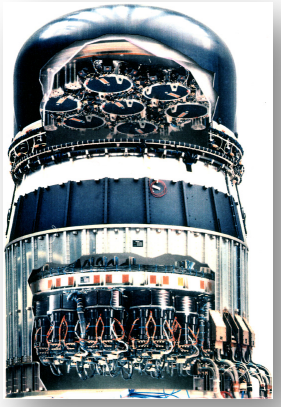
– COMPTEL all-sky search

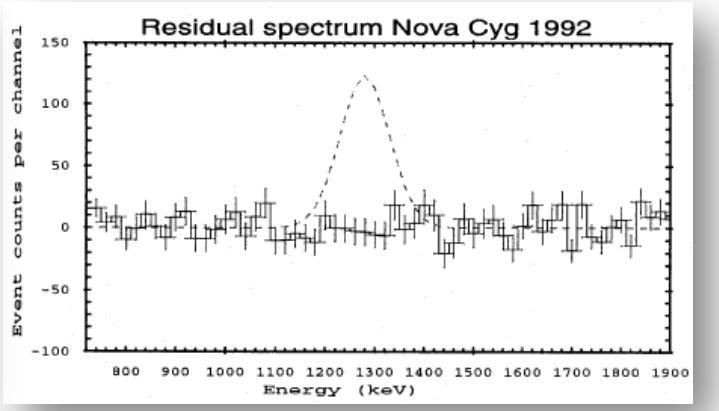


Searching for radioactivity from ^{22}Na

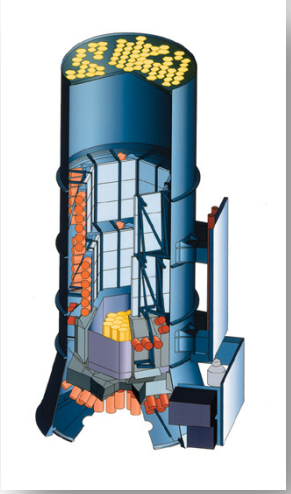
- PhD Leising 1987, search with SMM (w Mike Harris+)
- Models by Starrfield+, Hernanz+, … → how much ejecta?

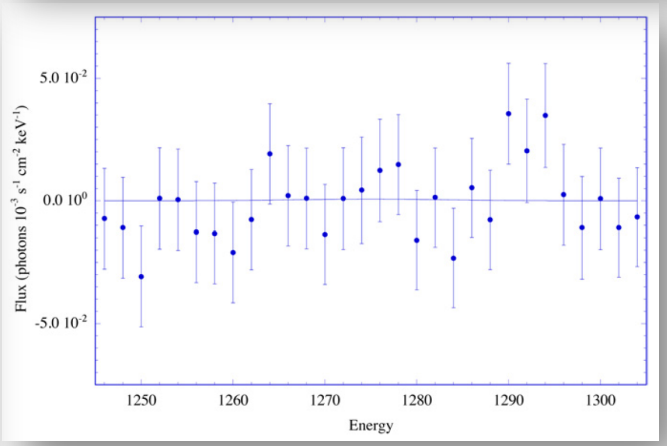
- COMPTEL search
  by Anatoly Iyudin+ 1991+





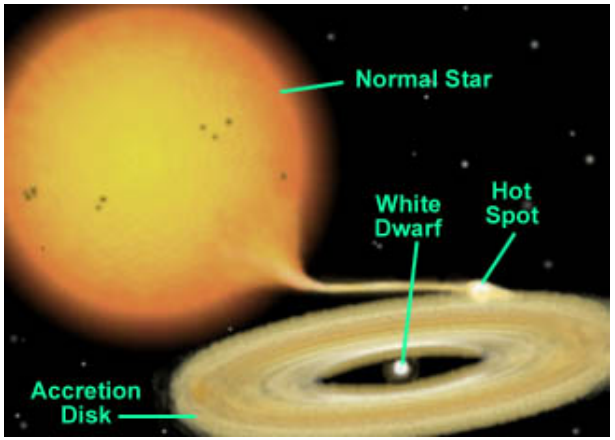
- INTEGRAL/SPI search
  by Pierre Jean+ 2002+

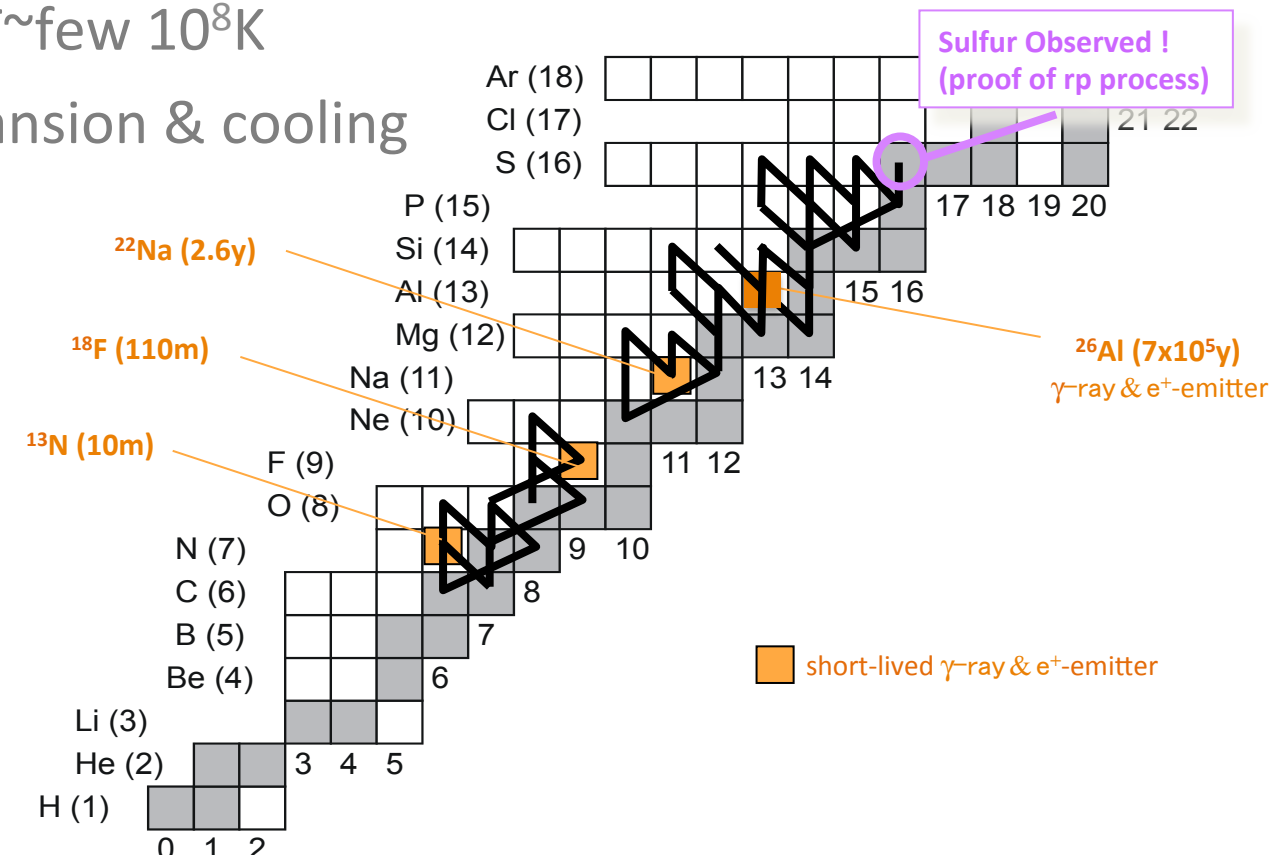




Nova Nucleosynthesis

- H-burning in a runaway on WD surface
  - Accretion of H from companion star $\dot{M} \sim 10^{-8} M_{\odot} y^{-1}$
  - H ignition → T~few 10^8K
  - envelope expansion & cooling





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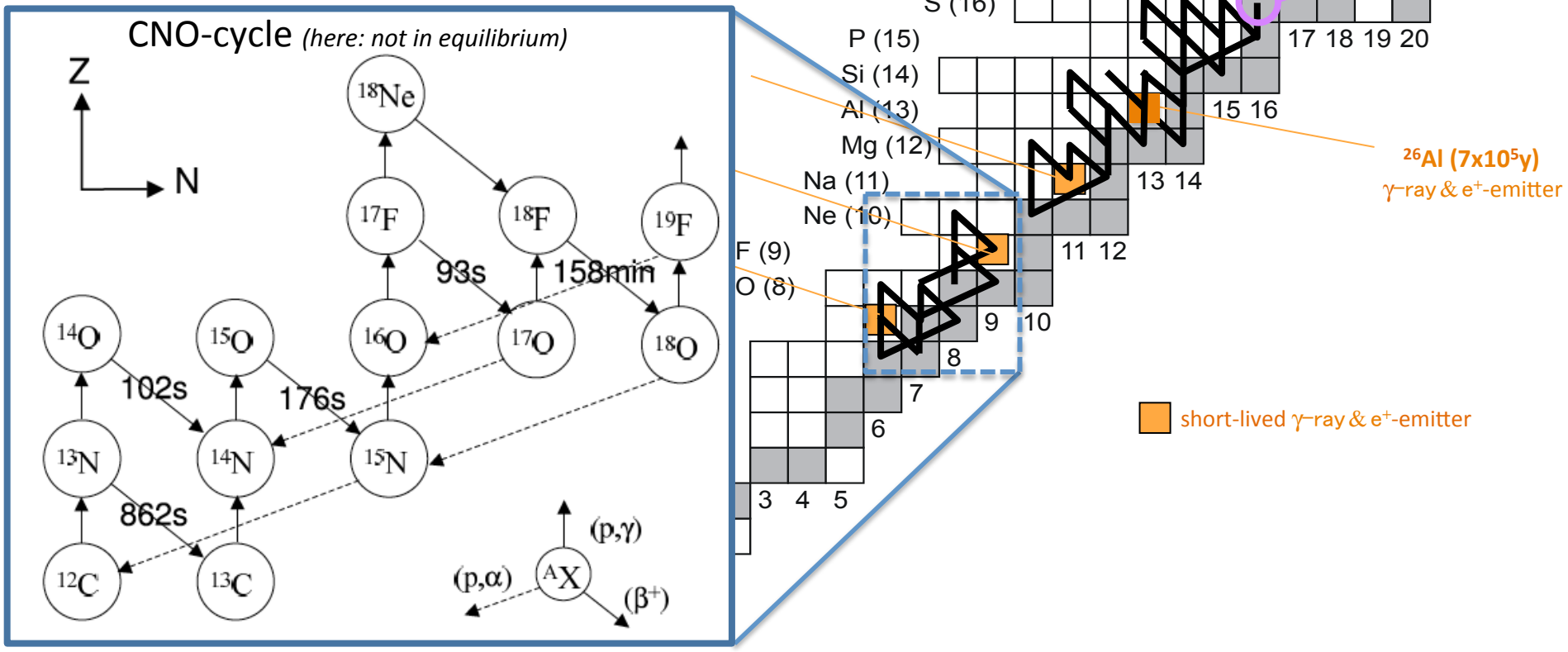
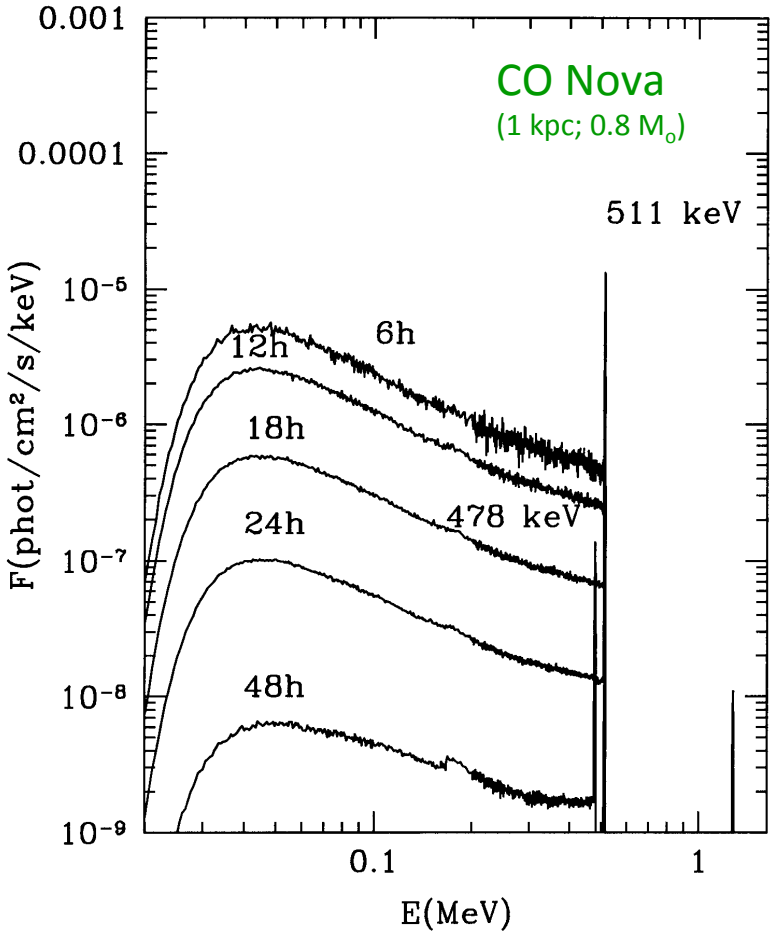
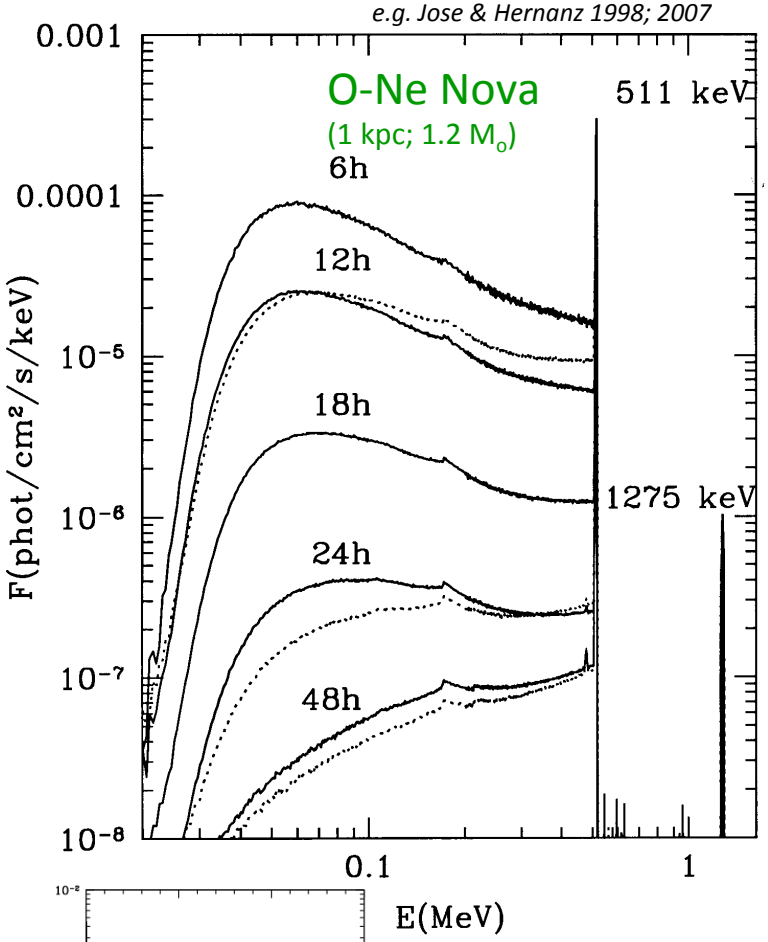
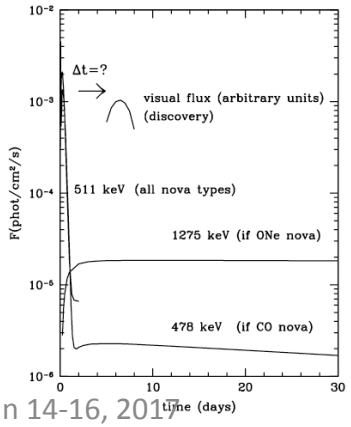


Nova Diagnostics Prospect with Nuclear Lines



e.g. Jose & Hernanz 1998; 2007

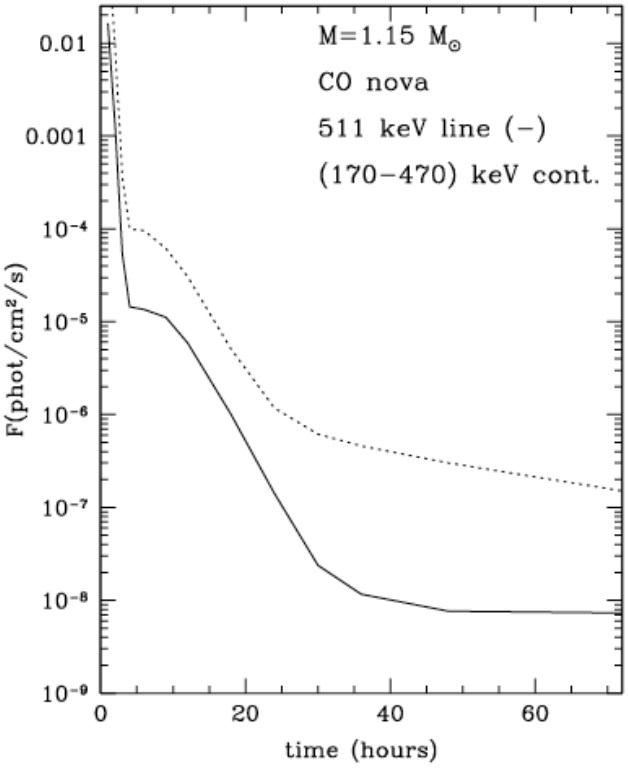




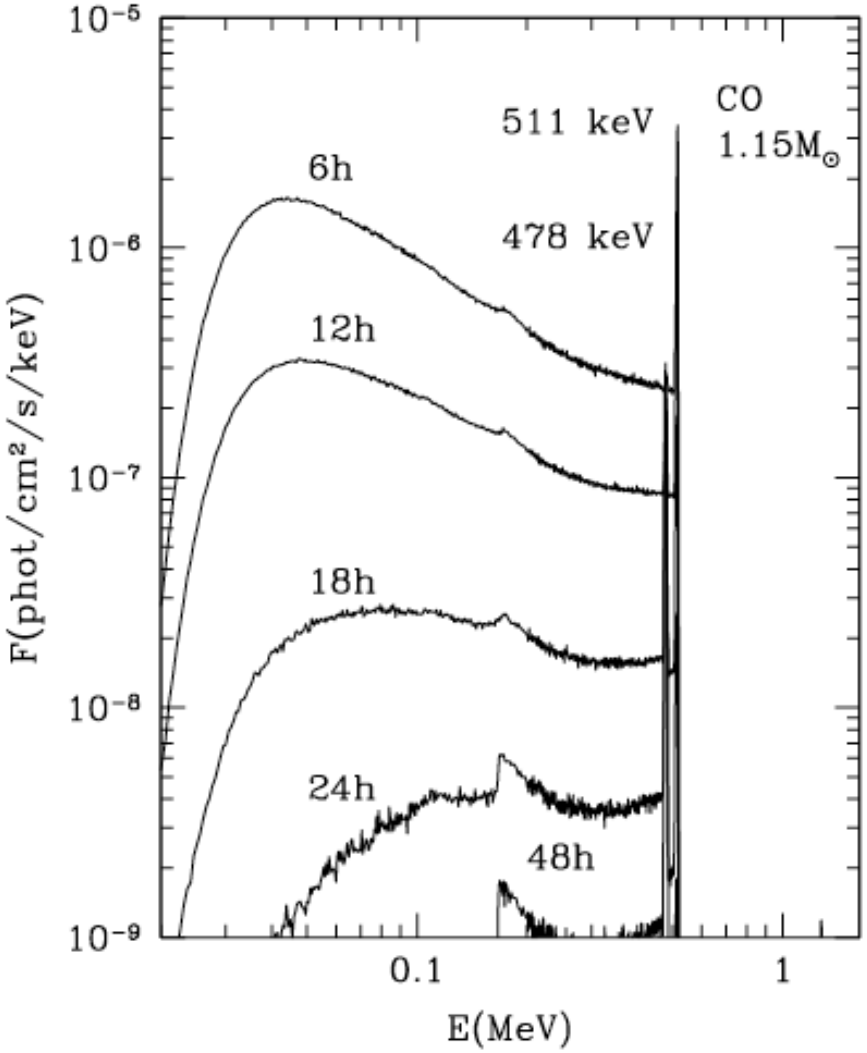
- Brief flash due to e^+ annihilations, with 511 keV line and β^+ decay continuum *(before optical nova!)*
- ^{7}Be radioactivity (CO novae)
- ^{22}Na radioactivity (O-Ne novae)

CO Nova Gamma-ray Line Emission

- updates in ^{18}F yields (downward revision) since 1998…2007

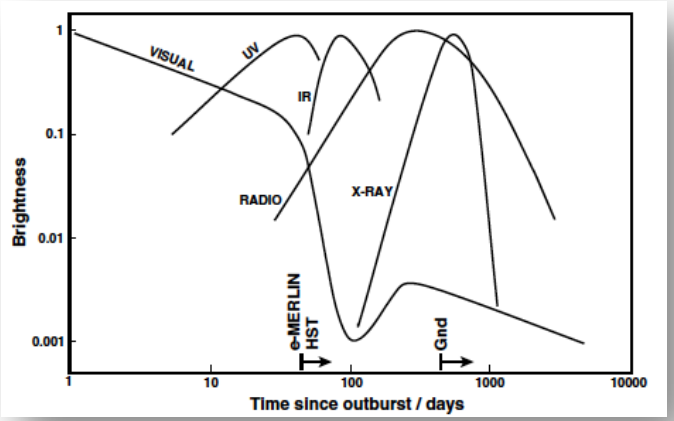


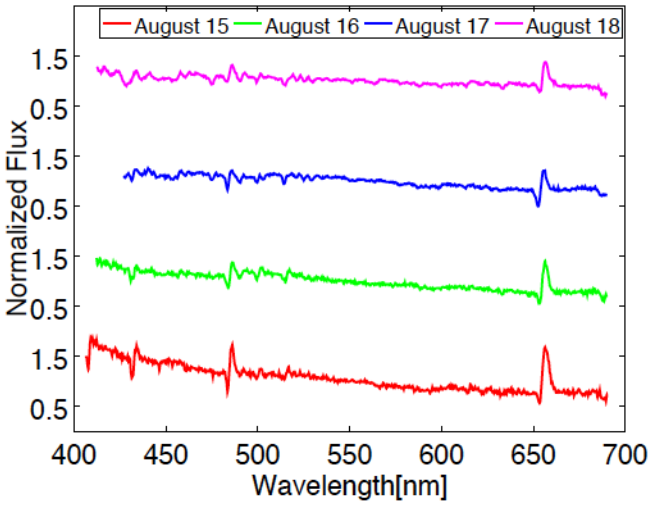
Hernanz+ 2013; 2017

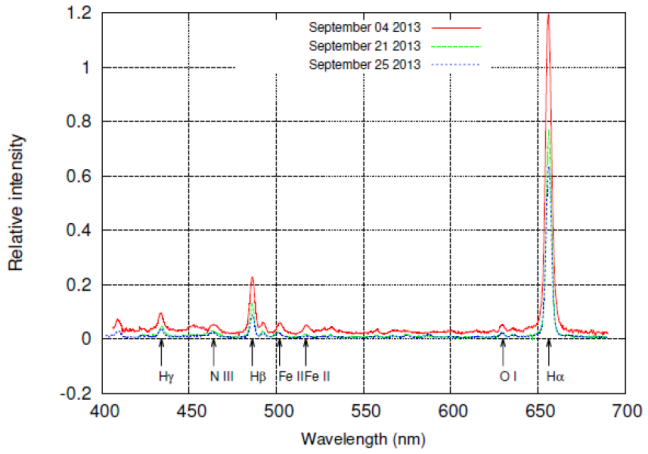


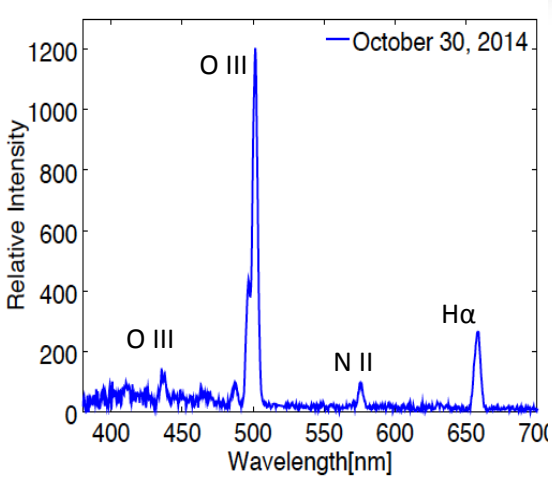
Nova Spectra

- Observe expanding H envelope, as it cools
  - example: Nova Del 2013
    - » discovered 13 Aug
    - » early spectra: P Cyg profiles H
    - » nebular spectra: CNO lines







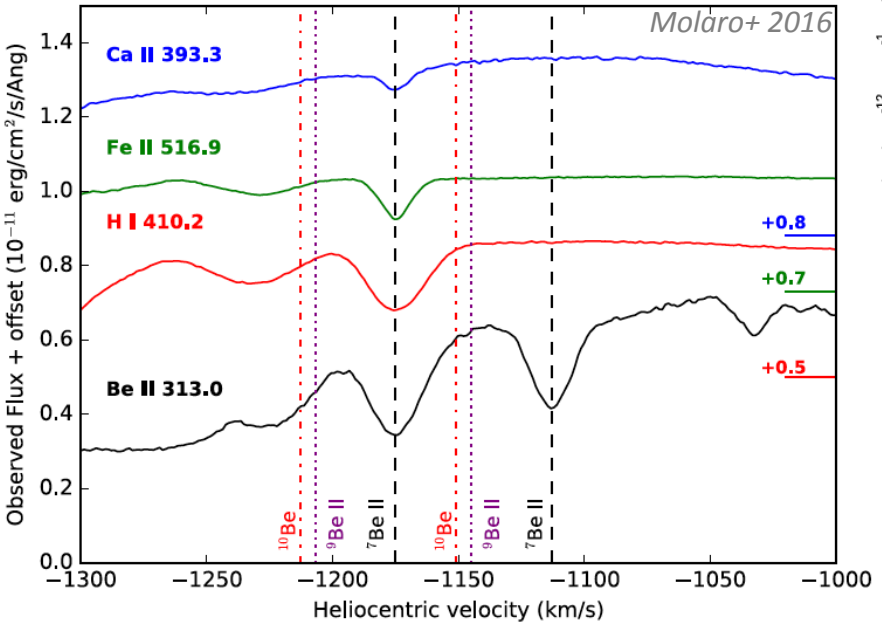


Li nucleosynthesis in a nova?

$$^{7}Li \xrightarrow{EC;\tau\approx 77d} {}^{7}Be + 478keV$$

- Li, Be spectral features seen in three nova outbursts
  - kinematic calibration
  - characteristic doublets

Nova Sgr 2015 (V5668 Sgr)

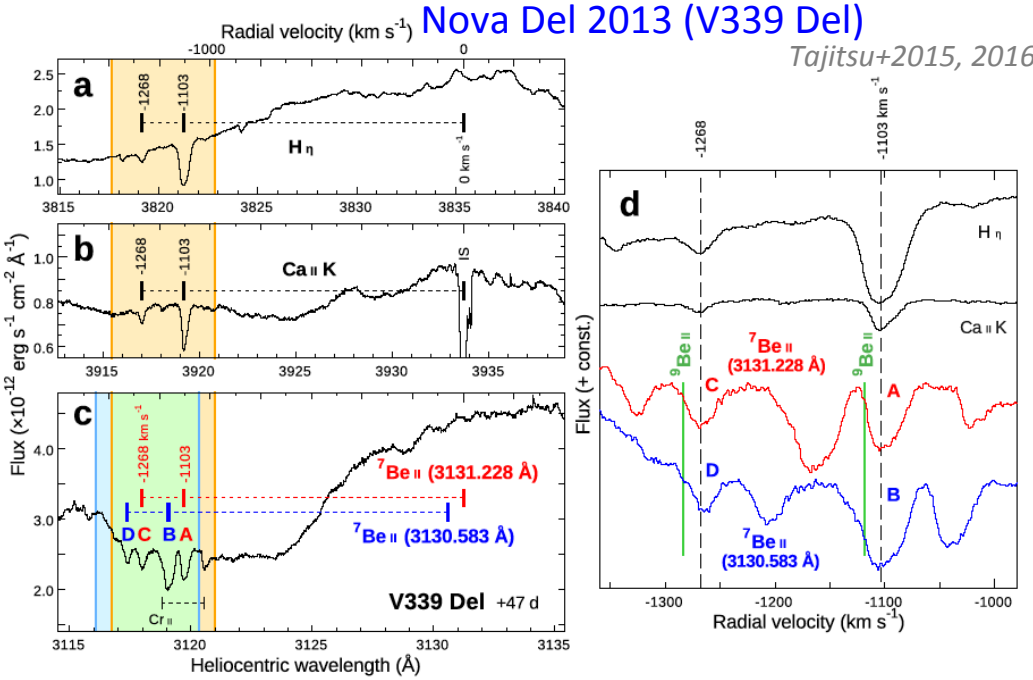


$$M_{\mathrm{Li}} \approx 7 \times 10^{-9} \mathrm{M}\odot$$

"new Li problem"? (A. Coc, yesterday)

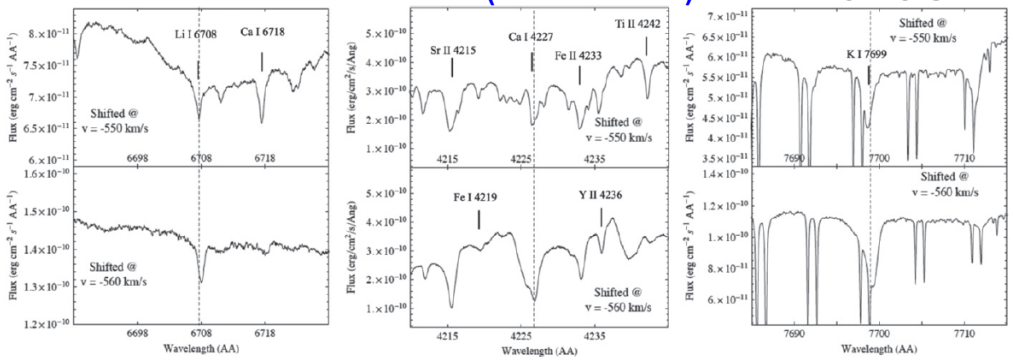
Nova Del 2013 (V339 Del)

Tajitsu+2015, 2016



Nova Cen 2013 (V1369 Cen)

Izzo+ 2015

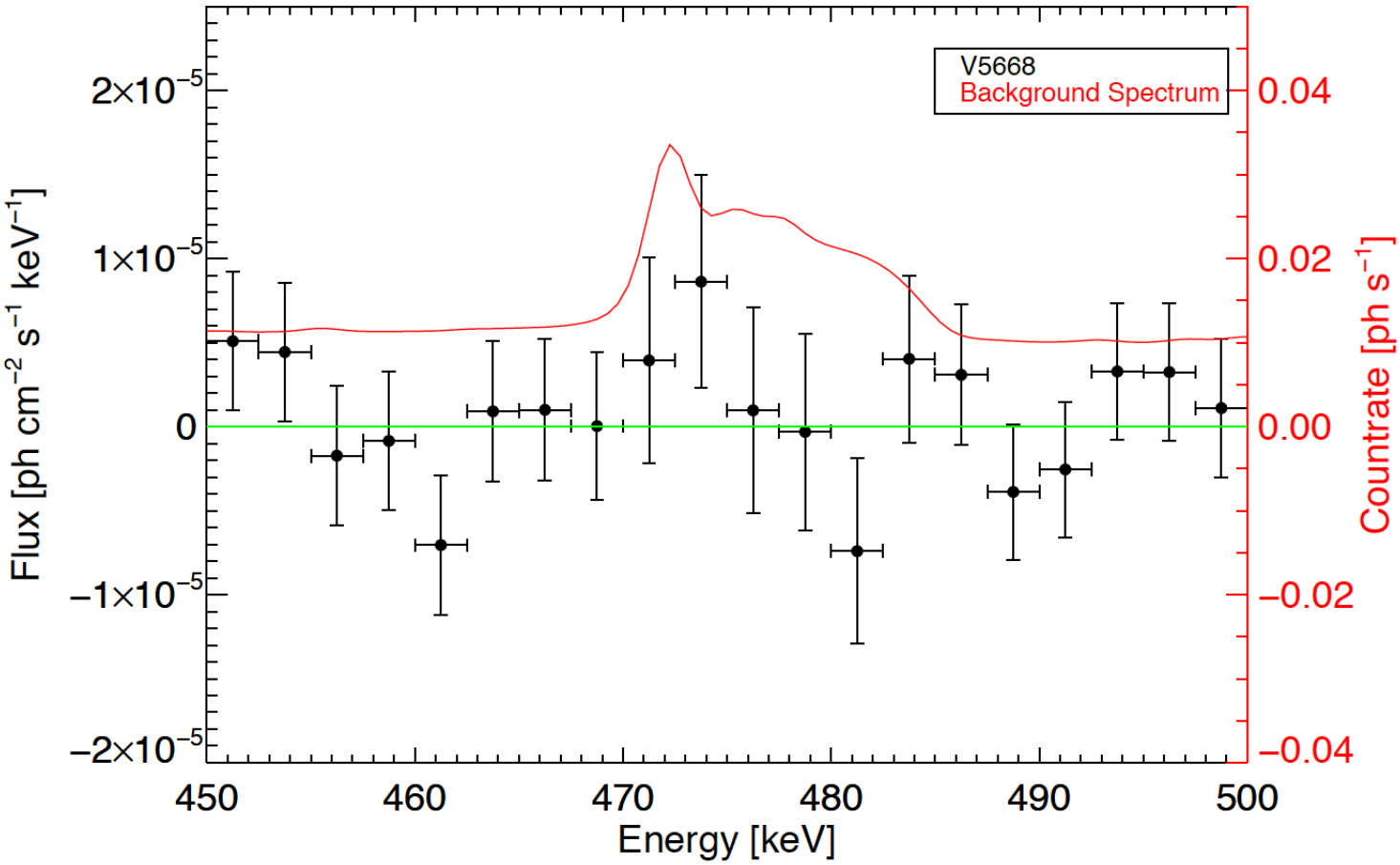


using Na doublet to calibrate kinematics

Line limits on nova from SPI/INTEGRAL

- Nova Sgr 2015 (V5668), opt max 21 Mar 2015

Siegert+, in prep./2017



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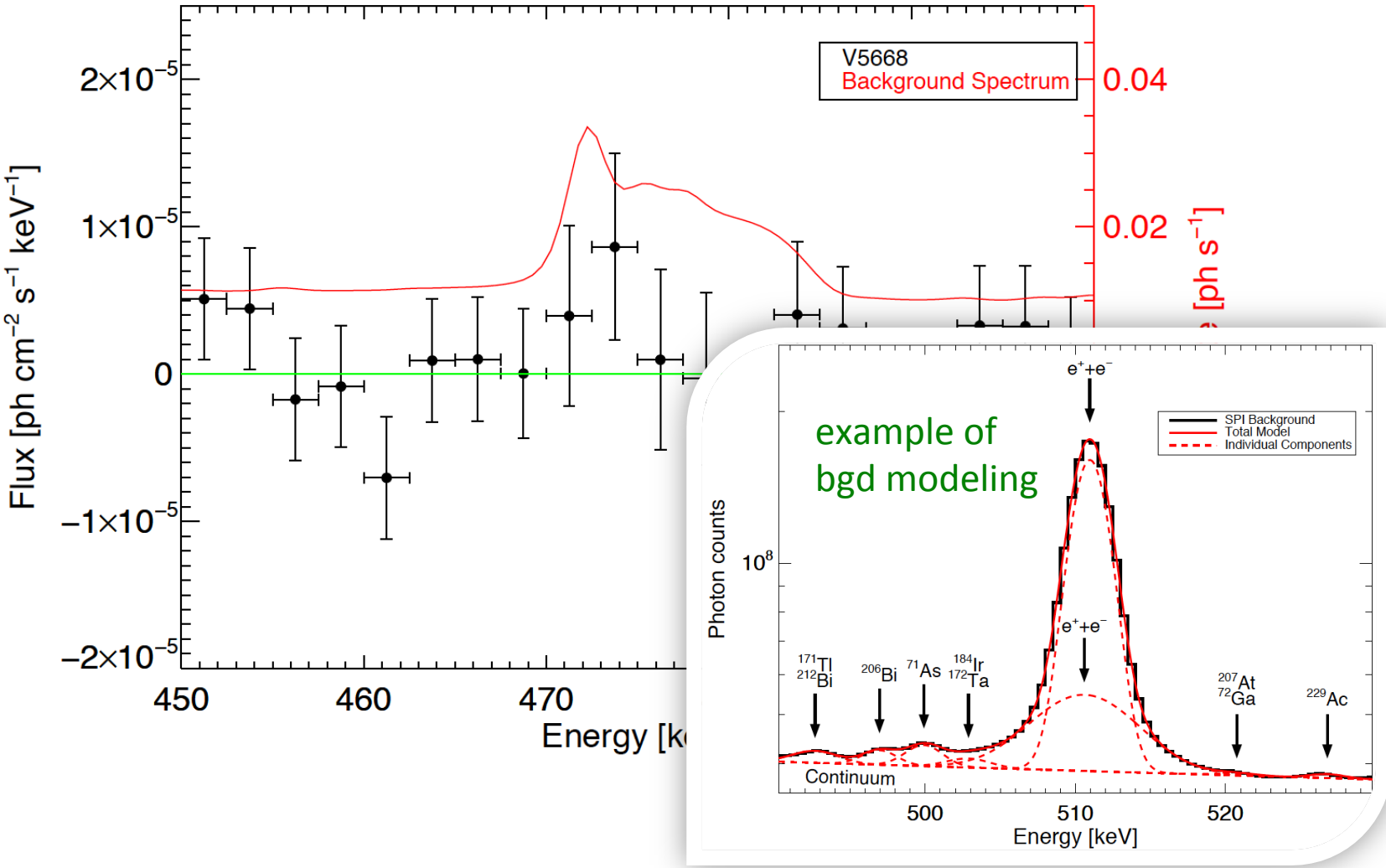
Siegert+, in prep./2017



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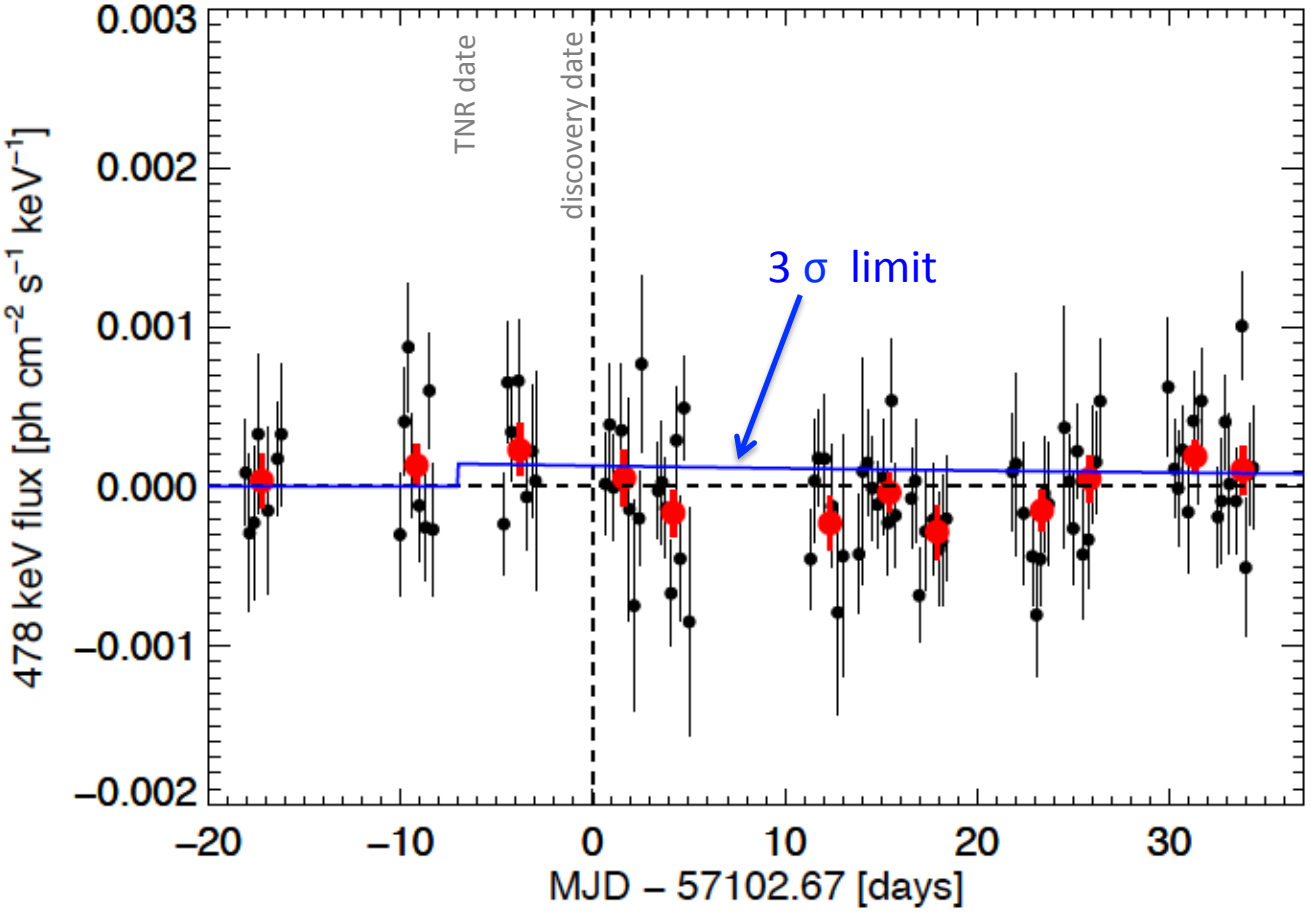
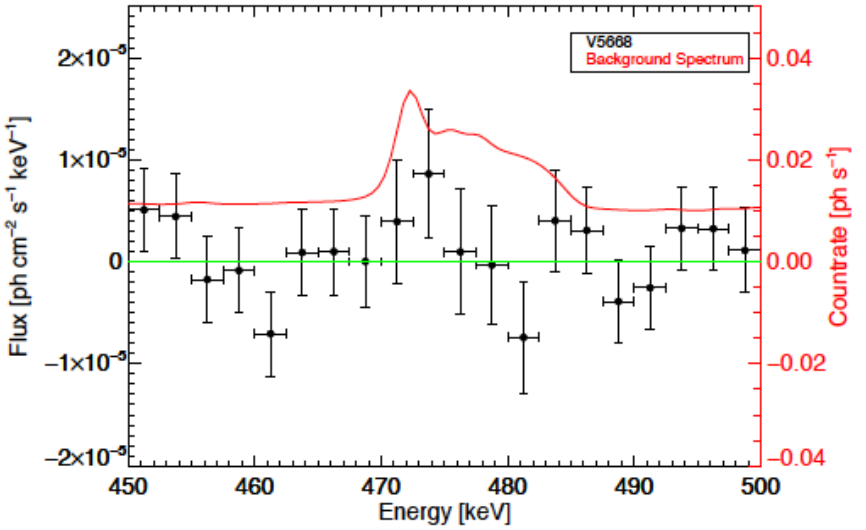


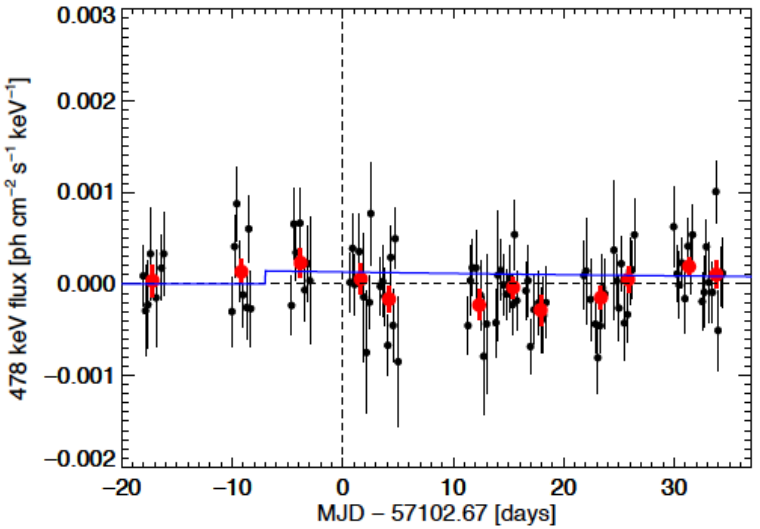
Li nucleosynthesis in a nova?

Siegert+, in prep (2017)

- Search in INTEGRAL/SPI Ge detector data:
  - no γ-ray signal from ^{7}Be
    - spectrum
    - fitted light curve



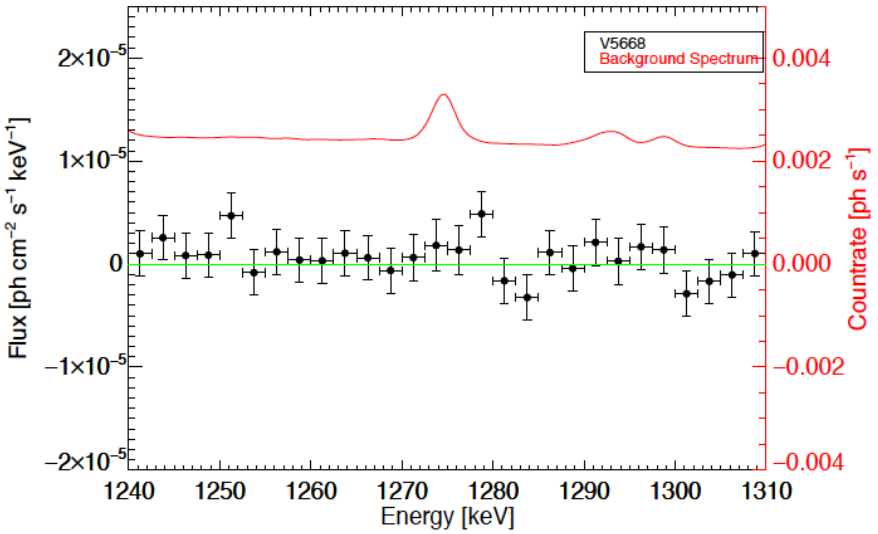
$$M_{3\sigma}^{^{7}\mathrm{Be}} < 4.8\times10^{-9}\left(\frac{d}{\mathrm{kpc}}\right)^{2} M_{\odot}$$

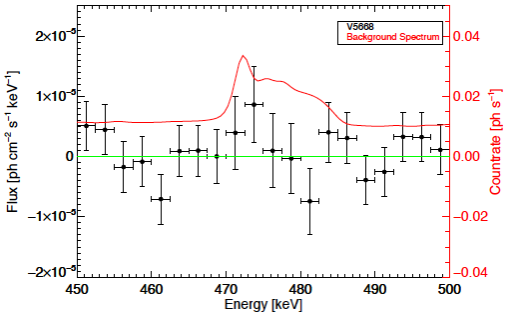


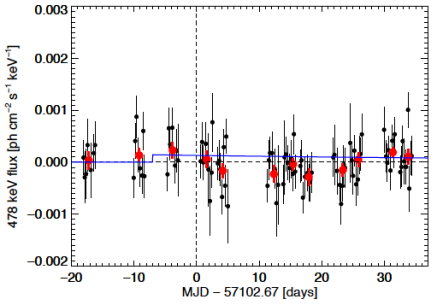
- limit value consistent with estimates from optical spectra
  - » uncertainties in distance, ejecta mass, …

Nucleosynthesis gamma-ray lines from a nova?

- Search in INTEGRAL/SPI Ge detector data:

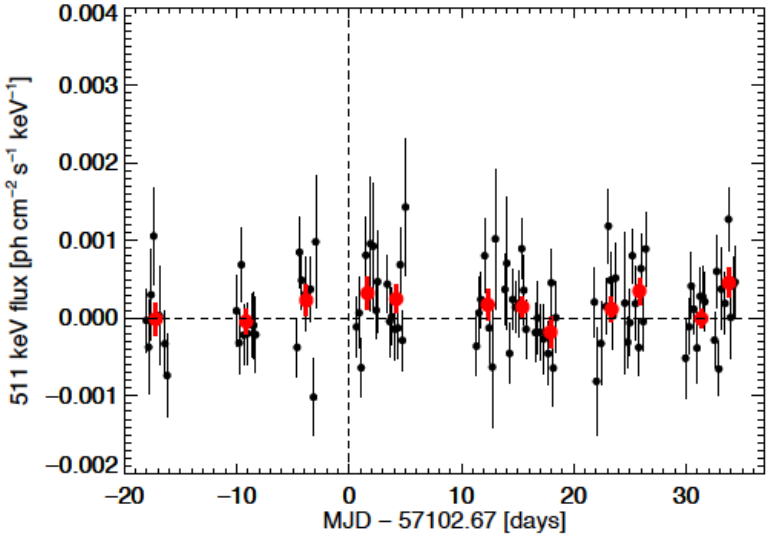






$$M_{3\sigma}^{^{7}\mathrm{Be}} < 4.8\times10^{-9}\left(\frac{d}{\mathrm{kpc}}\right)^2 M_\odot$$

$$M_{3\sigma}^{^{22}\mathrm{Na}} < 2.4\times10^{-8}\left(\frac{d}{\mathrm{kpc}}\right)^2 M_\odot$$



	Flux (spectrum)	Mass (spectrum)	Mass (light curve)
^{7}Be	$< 8.2\times10^{-5}$	$< 4.8\times10^{-9}(d/\mathrm{kpc})^2$	$< 6.4\times10^{-9}(d/\mathrm{kpc})^2$
^{22}Na	$< 7.6\times10^{-5}$	$< 2.4\times10^{-8}(d/\mathrm{kpc})^2$	-
	Flux (spectrum)	Annihilation rate	
$e^+ + e^- \rightarrow 2\gamma$	$< 17\times10^{-5}$	$< 4\times10^{40}$	
	From spectrum	From light curve	
Distance	> 1.1	> 1.2	

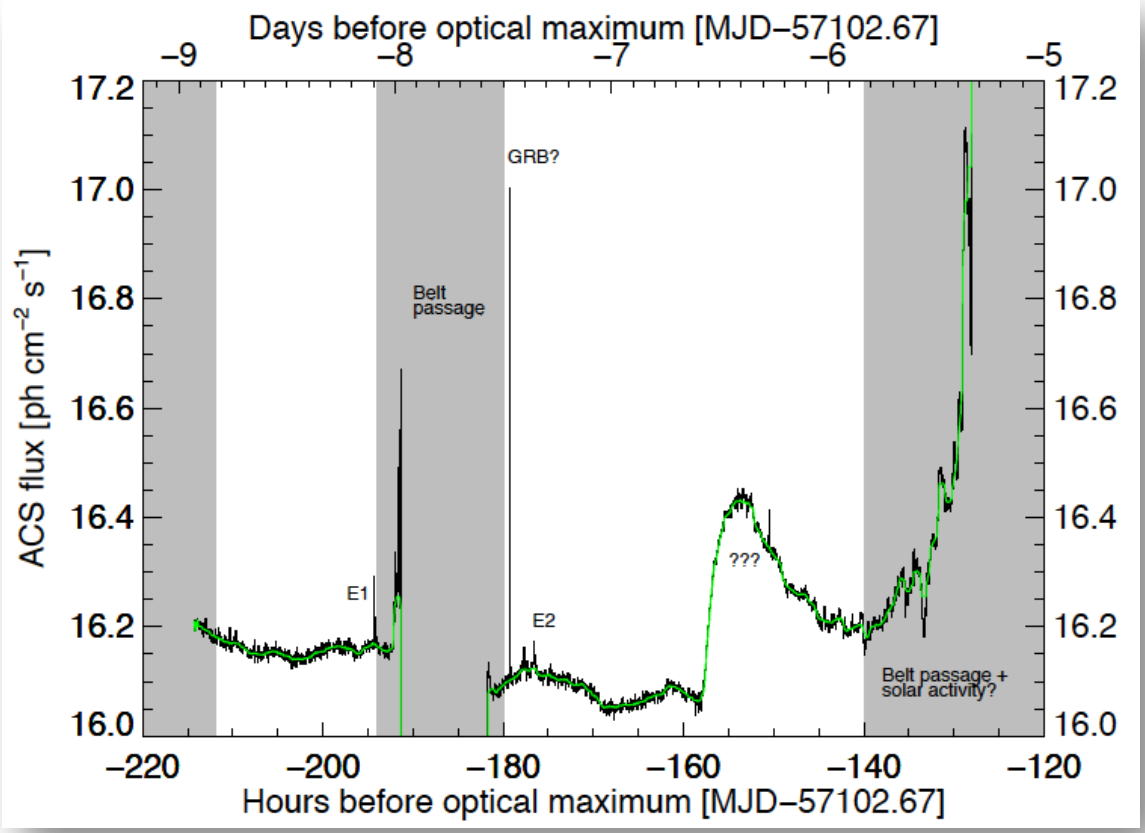
Siegert+, in prep./2017

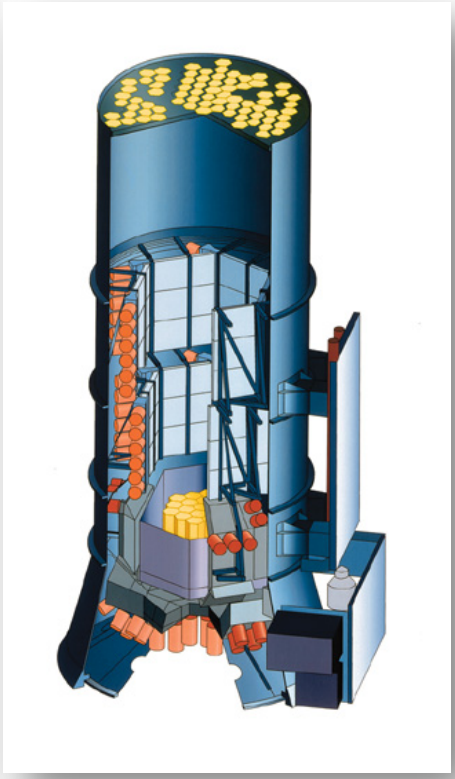
Pre-nova flash from β^+ decays?

- Searching the INTEGRAL/SPI database in SPI ACS

Siegert+, in prep./2017

  - Nova V5668 Sgr:



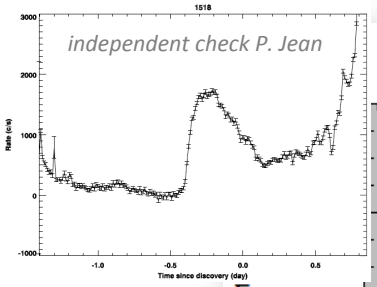


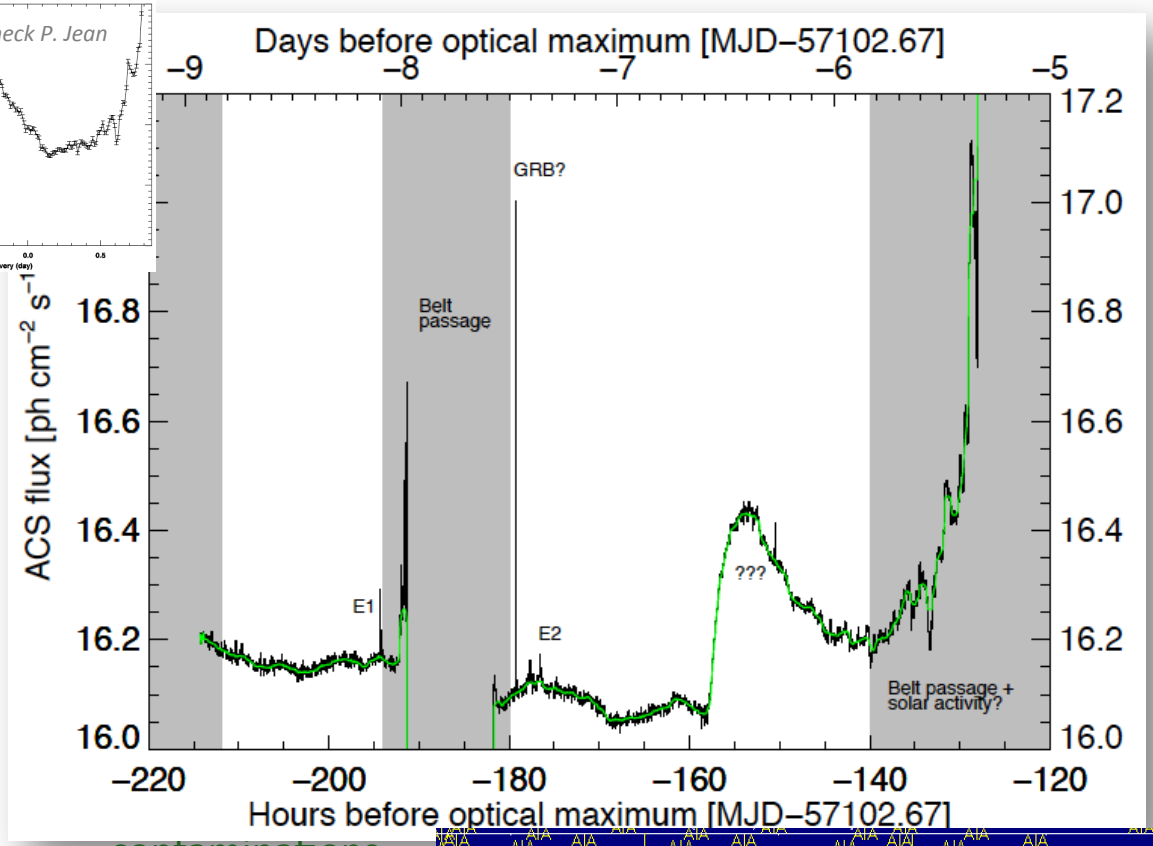
  - Rate of SPI's summed 91 BGO anticoincidence detectors (A_{eff} 0.7m^2, E>75 keV)

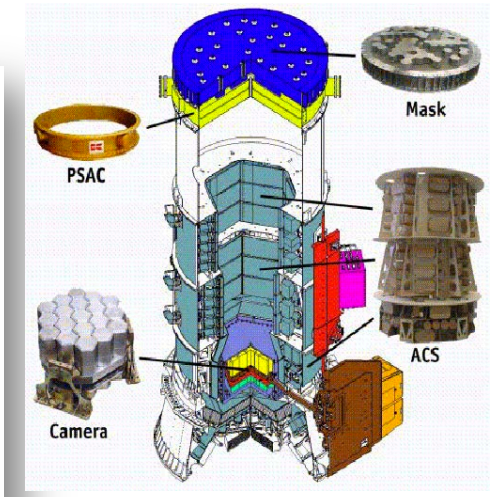
Pre-nova flash from β^+ decays?

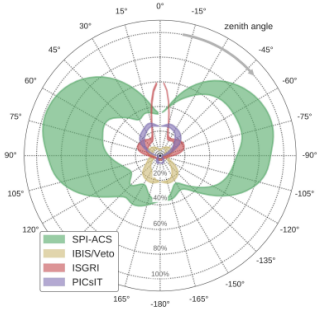
- Searching the INTEGRAL/SPI database in SPI ACS
  - Nova V5668 Sgr:

Siegert+, in prep./2017



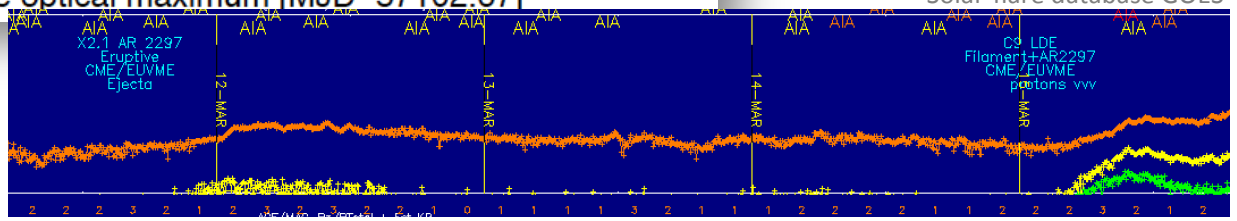






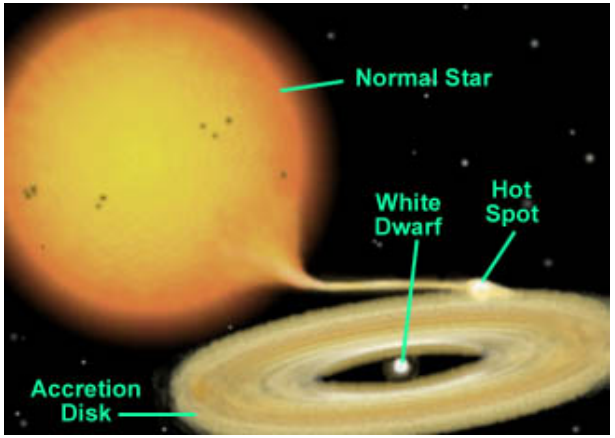
contaminations
& directionality

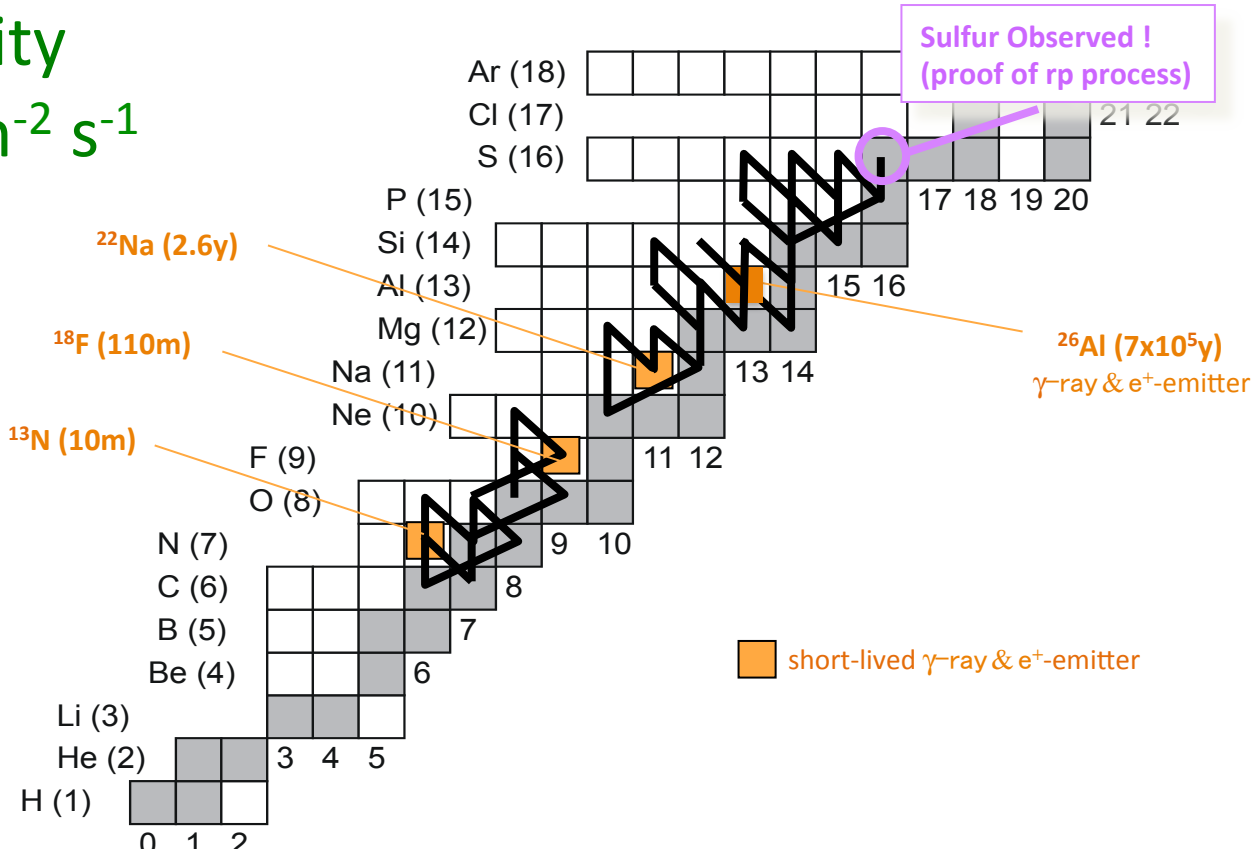
Solar-flare database GOES



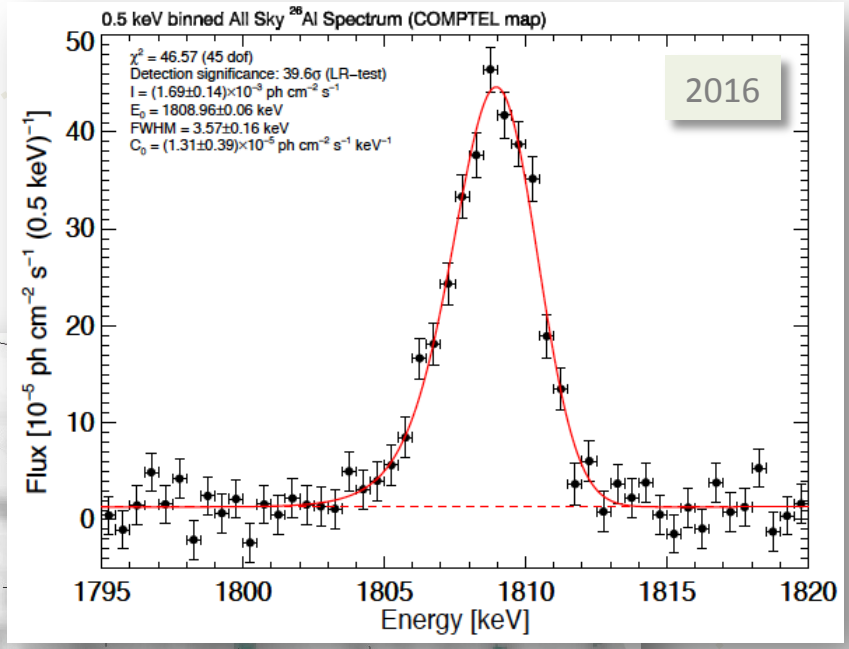
Nova radioactivity: Awaiting a nearby nova

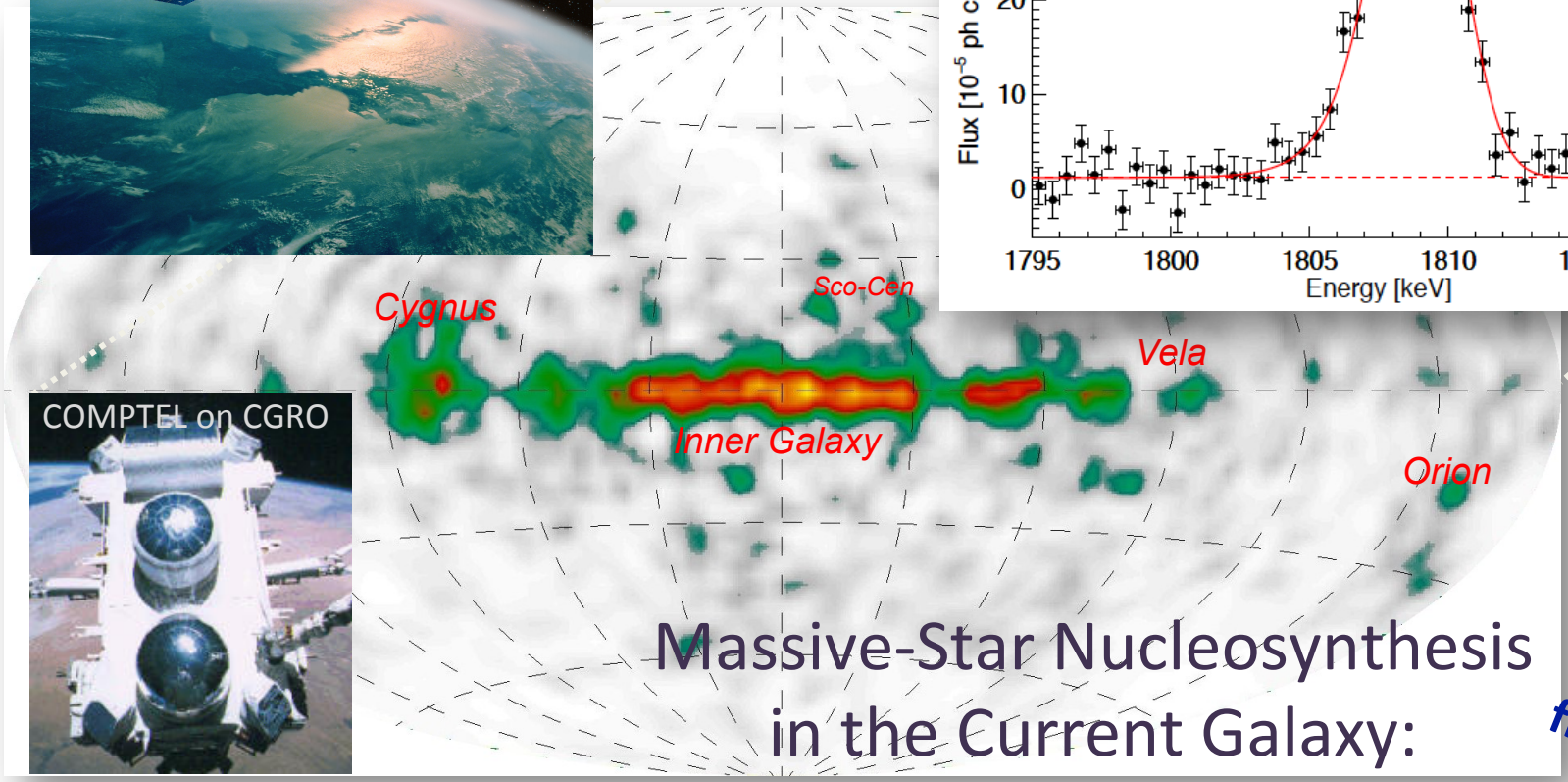
- SPI's large field of view could catch early flash
- ^{7}Be line intensity may be enhanced wrt models
  - Optical lines suggest $M_{\mathrm{Li}} \approx 7 \times 10^{-9} \mathrm{M}\odot$ SPI sensitivity $M_{3\sigma}^{^{7}\mathrm{Be}} < 4.8 \times 10^{-9} \left(\frac{d}{\mathrm{kpc}}\right)^{2} M_{\odot}$
- SPI line sensitivity
  ~few 10^{-5} ph cm^{-2} s^{-1}





^{26}Al in our Galaxy: γ-ray Image and Spectrum



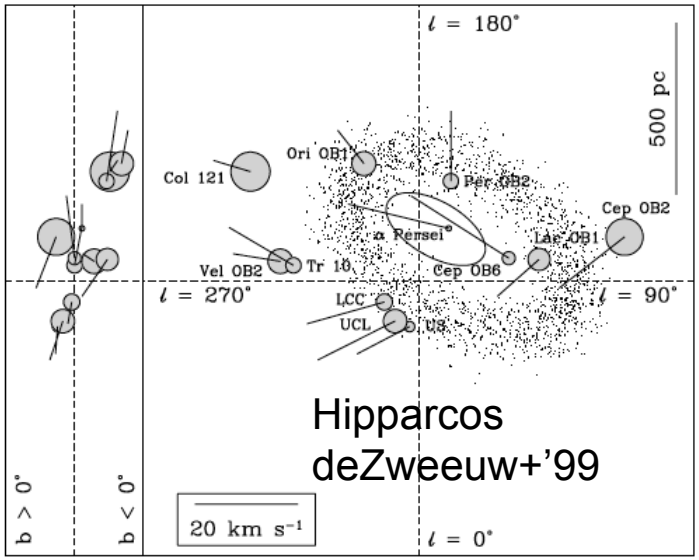


Massive-Star Nucleosynthesis in the Current Galaxy:

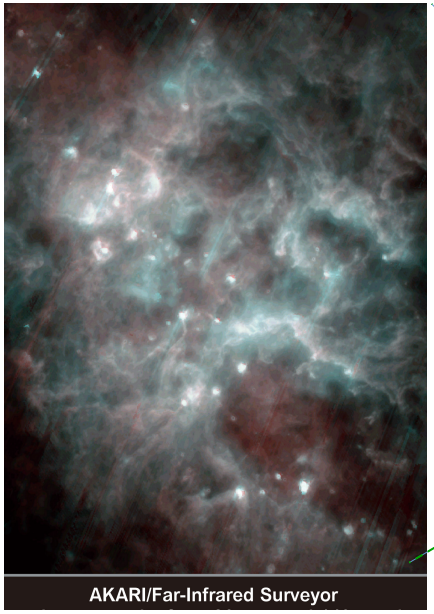
Current Enrichment (~My) from ^{26}Al γ-rays

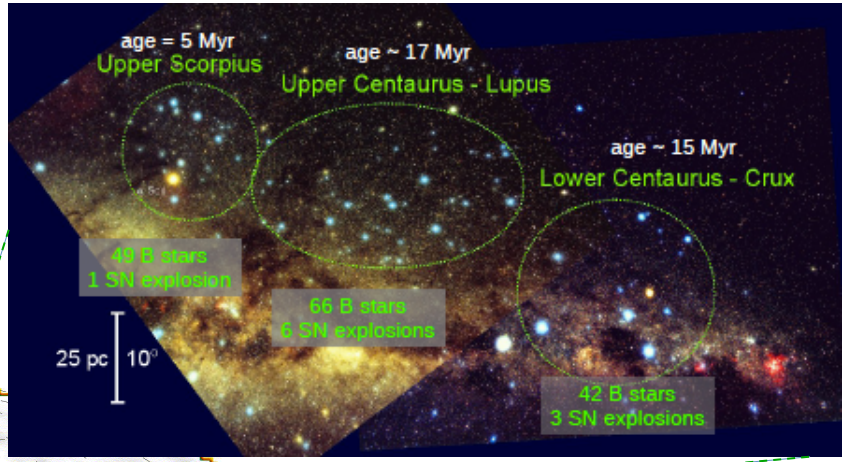
plus some from novae

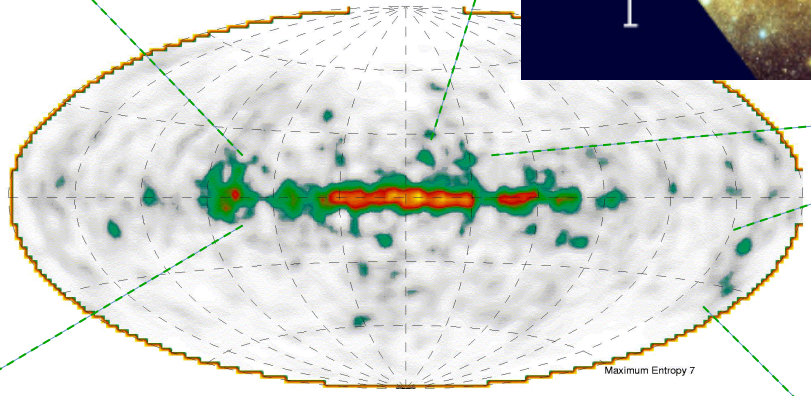
Resolving ^{26}Al Emission from Specific Groups of Stars

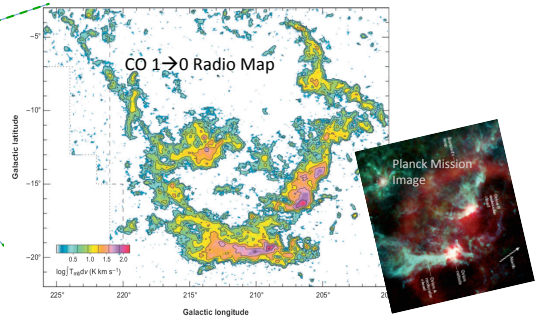


Hipparcos
deZweeuw+'99









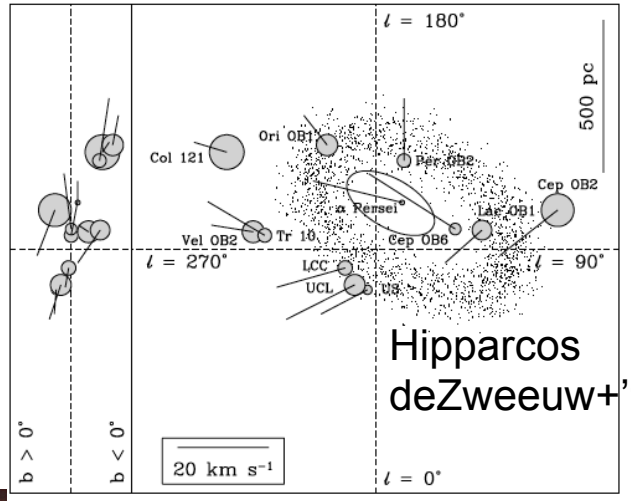
Resolving ^{26}Al Emission from Specific Groups of Stars

Prominent Groups of Massive Stars:

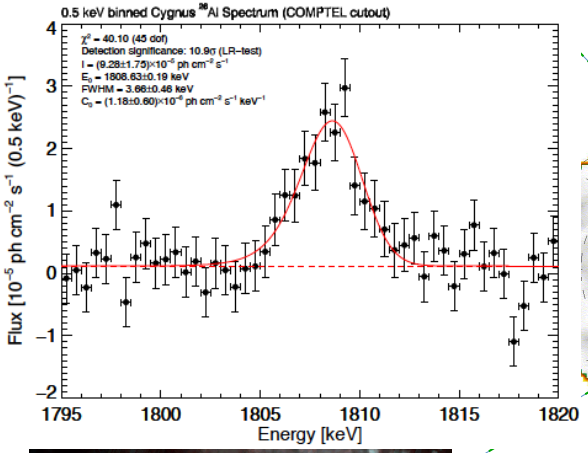
Test our Models for Consistency

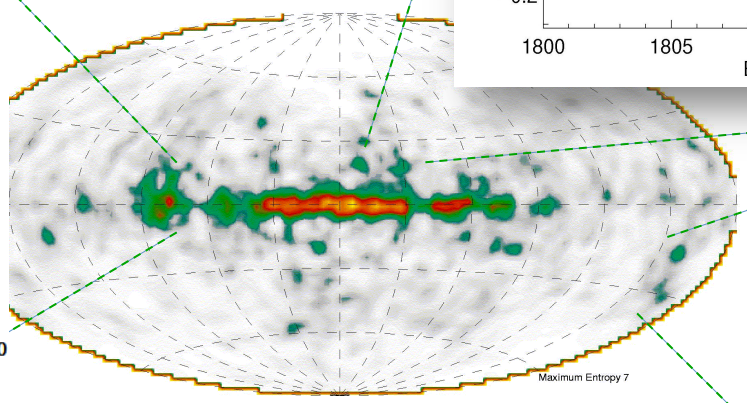
Separate WR-Wind from SN yields

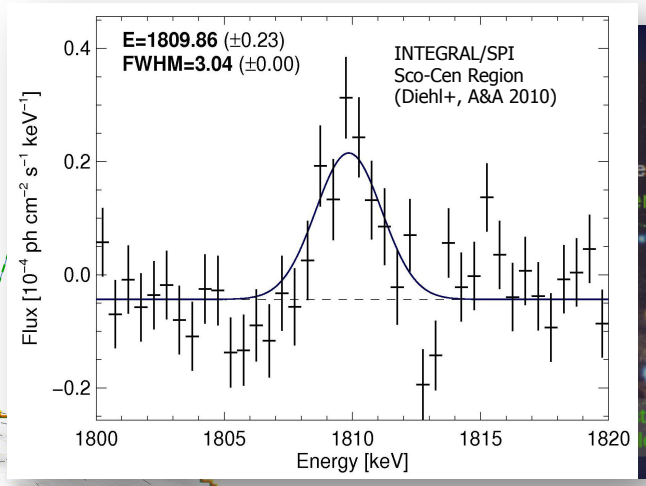
Measure ejecta kinematics

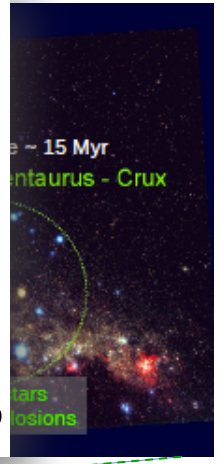


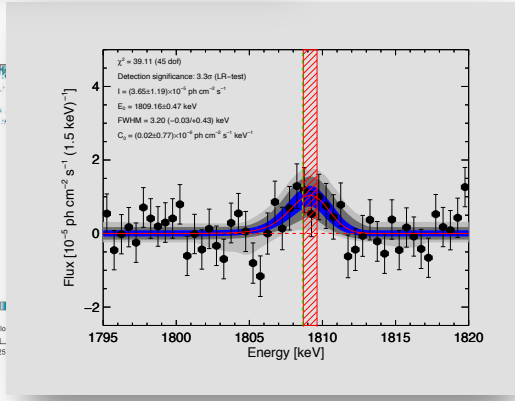
Hipparcos
deZweeuw+'99











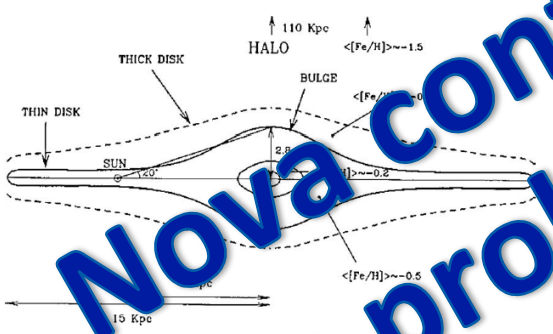
Using the ^{26}Al Line to Characterize the Galaxy's SN Activity

→ *Diehl et al., Nature 2006*
→ *Diehl et al., A&A 2010**
→ *Diehl et al., in prep. (2017)**

Measured Gamma-Ray Flux*

*) *better account for foreground emission*

Galaxy Geometry

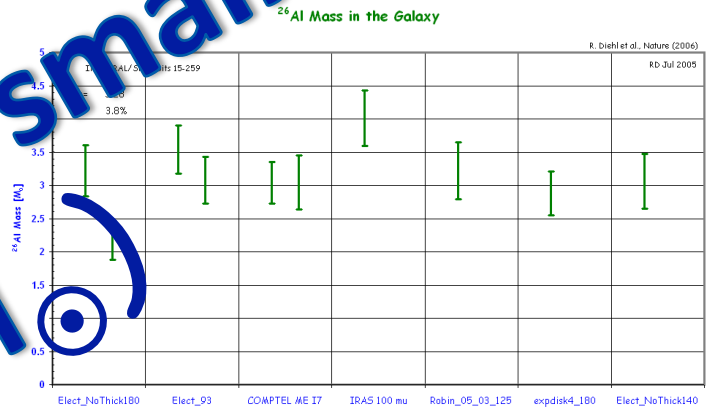


^{26}Al Yields per Star

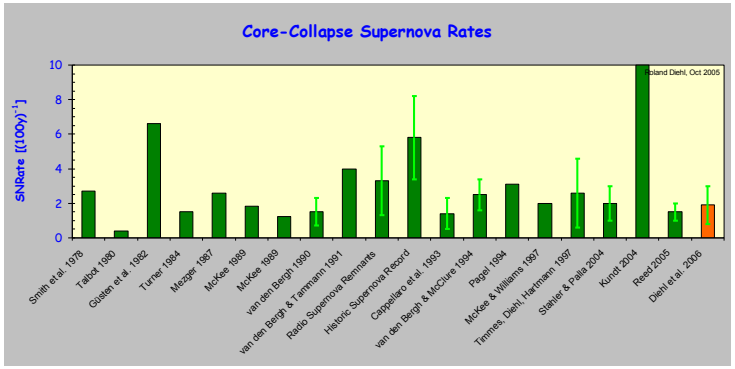
Stellar Mass Distribution

Nova contributions are probably small (<0.5 $M_\odot$)

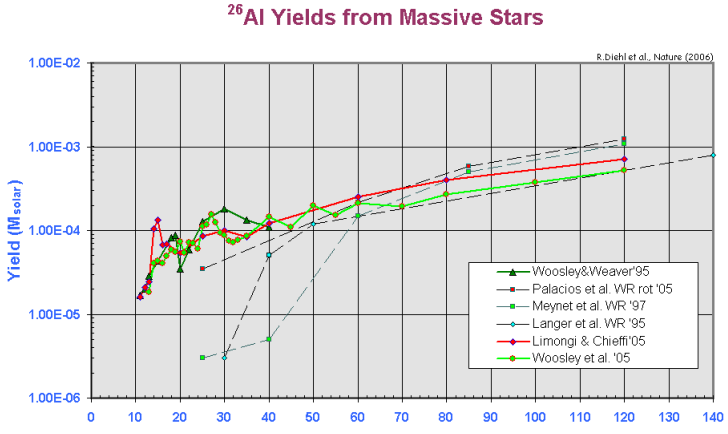
✓ ^{26}Al Mass in Galaxy = 2.0 (±0.3) $M_\odot$



✓ cc-SN Rate = 1.3 (± 0.4) per Century



✓ Star Formation Rate = 2.8 $M_\odot$/yr

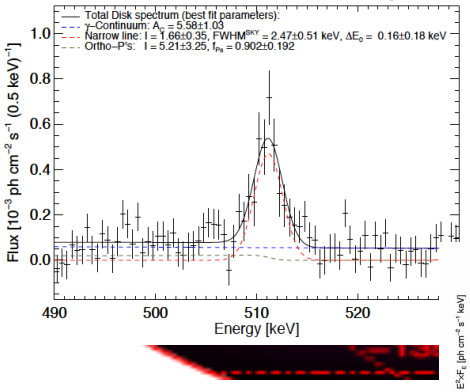


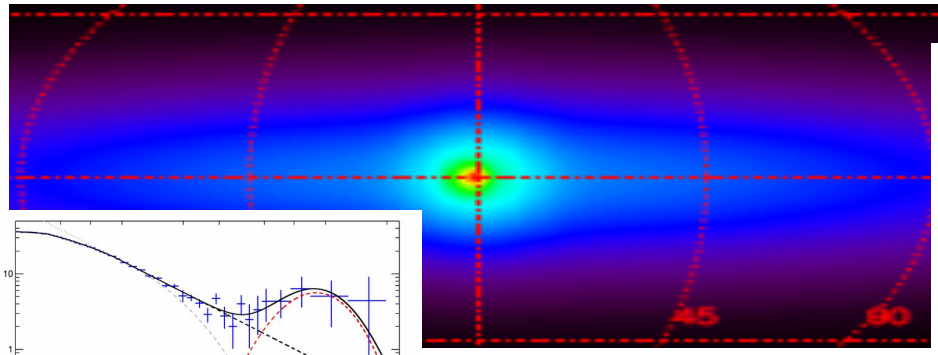
Understanding the 511 keV Line Emission

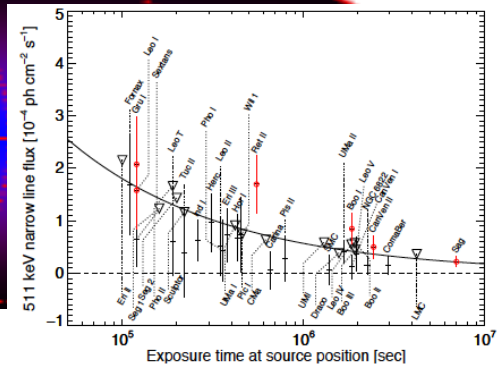
After 12 y of measurements and various different analyses

- *Knödlseder+ 2005, Jean+ 2005, Weidenspointner+ 2008, Bouchet+ 2011, Skinner et al. 2013, 2015a,b, Siegert+ 2016a,b*

- None of the plausible candidate sources produces morphology
- The centroid appears offset by ~1 deg towards 4th quadrant
- The disk (now) appears quite extended → e^+ outflows?
- Only ^{26}Al has been established as a e^+ source/injector
- Dark matter contributions are unlikely/small
- Positron injection and annihilation probably are 'decoupled'
- Injections from pulsars, microquasars (!), SNe, …, **novae**, … all are plausible. How then the bulge enhancement?



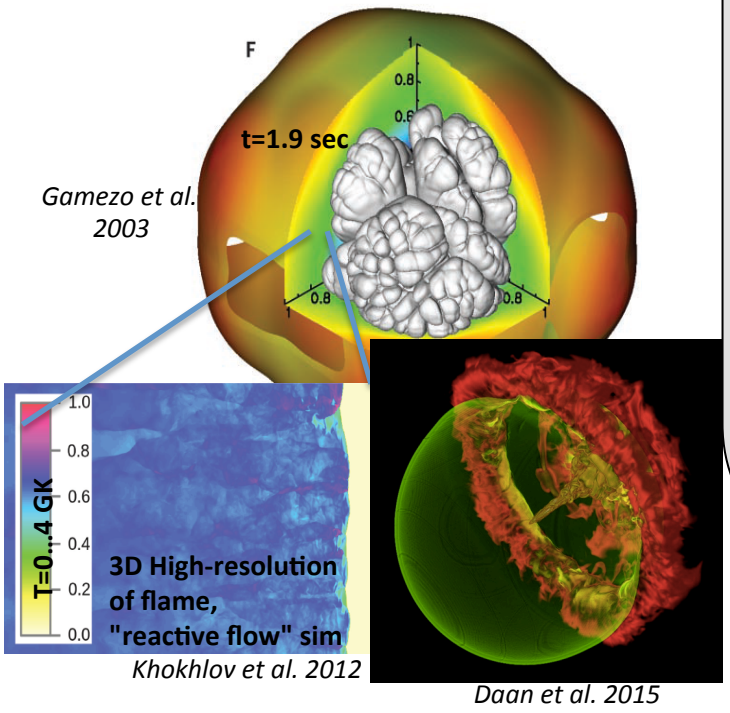




SNe Ia: WDs in action. But HOW?

- ☆ Consensus:
  Explosion of a CO WD (C fusion)
- ☆ Issues:

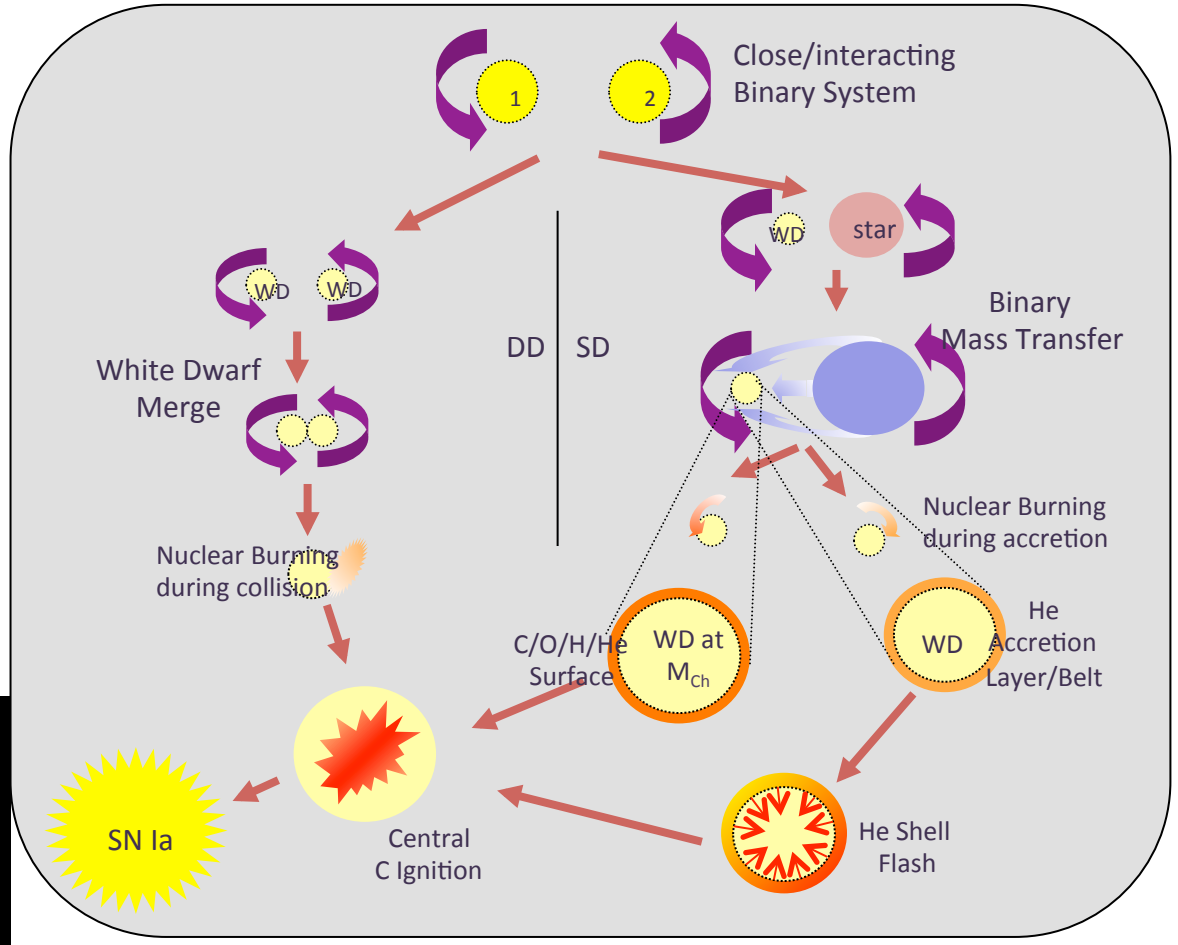
  Flame
  propagation



Gamezo et al. 2003

Khokhlov et al. 2012

Daan et al. 2015

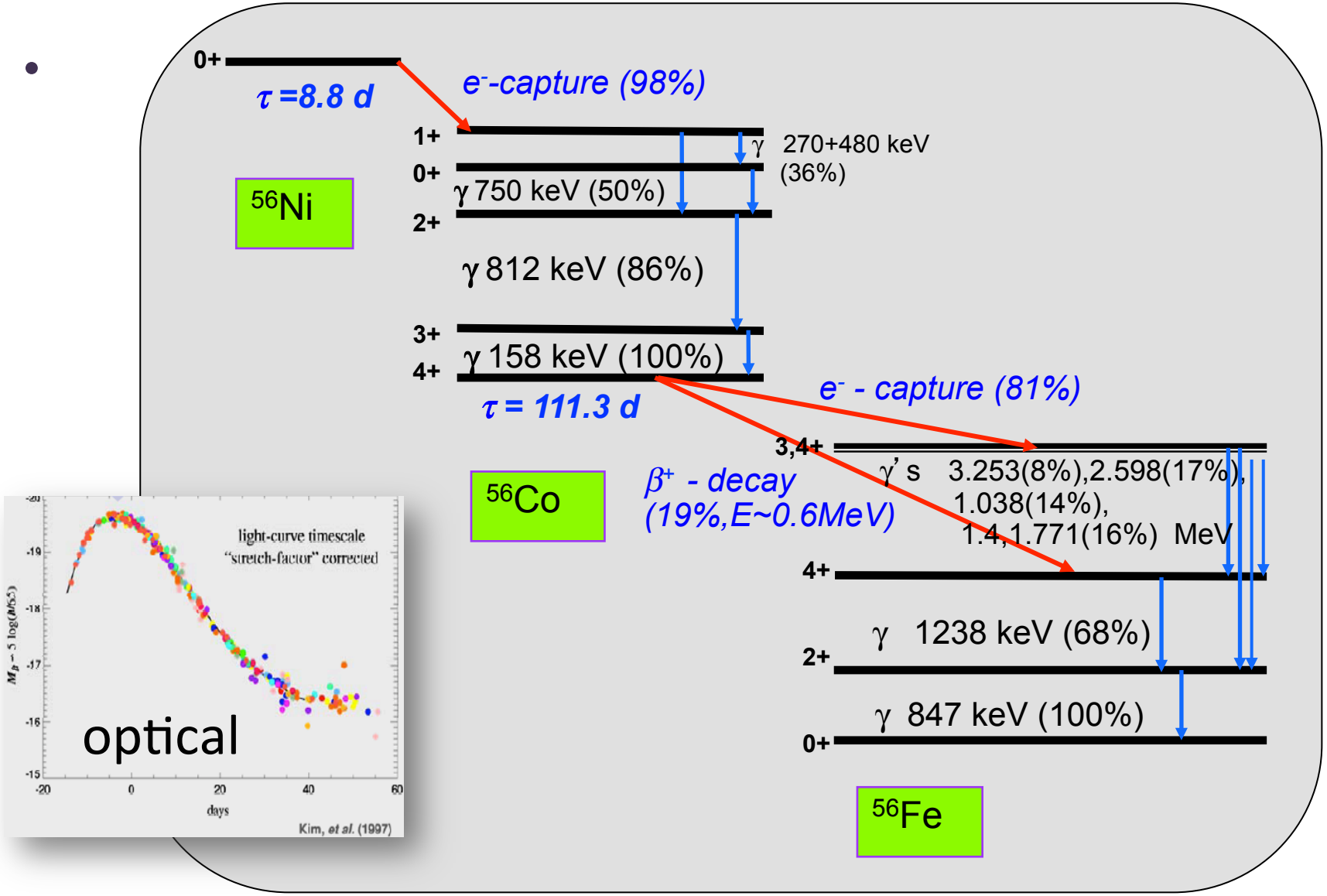


"we don't understand SN Ia"
(Domingo Garcia-Senz, yesterday)

☞ Progenitor diversity?

"SD excluded (obs); DD excluded (theory)"
(Mike Sharaz, yesterday)

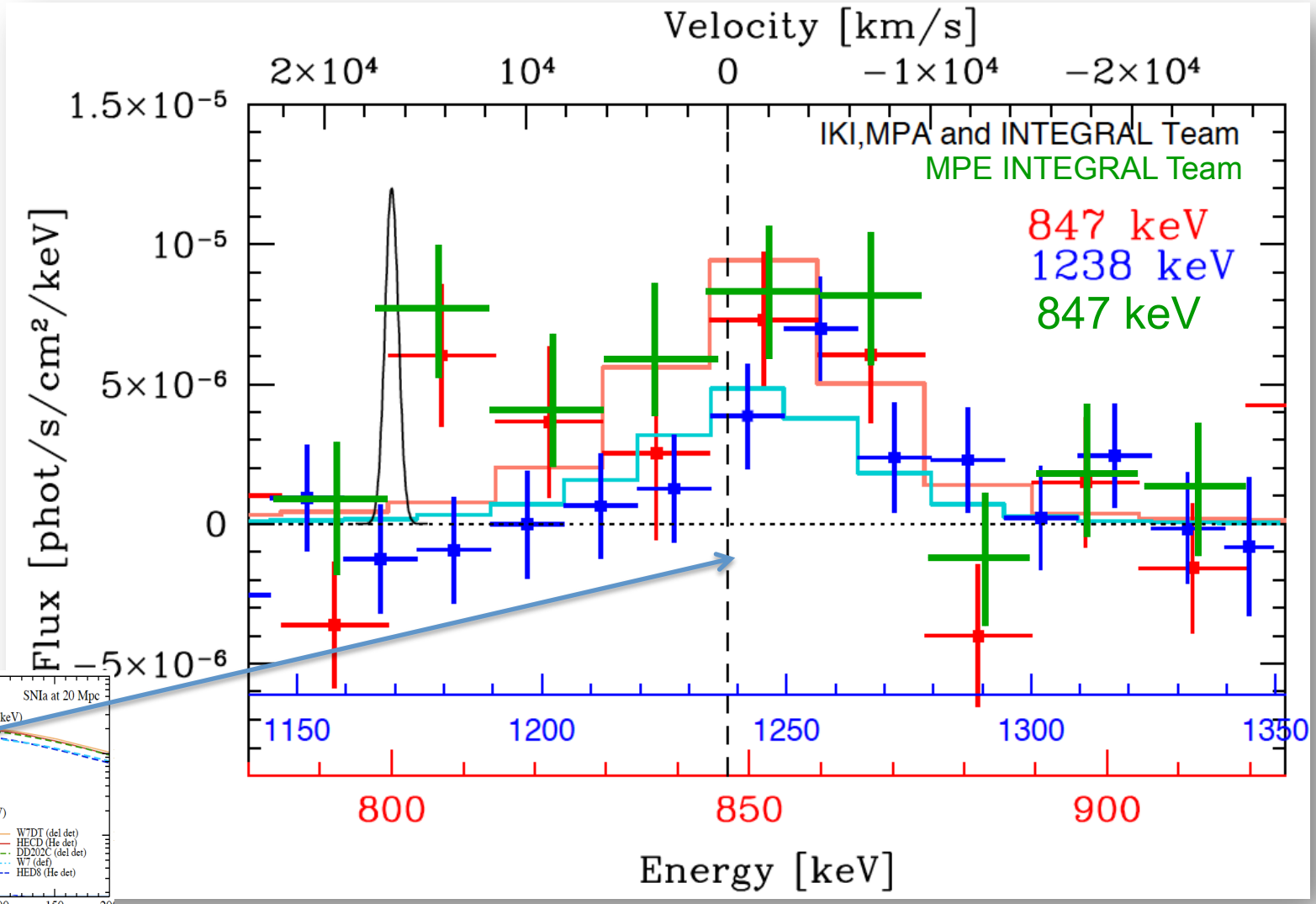
^{56}Ni Radioactivity Decay Chain and Gamma-Rays

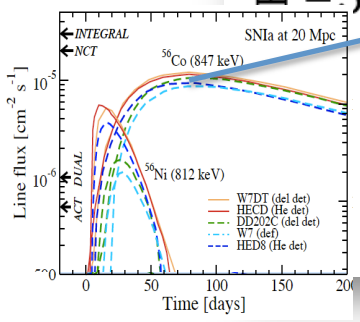


- Nuclear BE release 0.6$M_\odot$ C,O→^{56}Ni: ~1.1 10^{51} erg (>2*BE_{WD})

Longterm Data: Broad Lines from ^{56}Co!

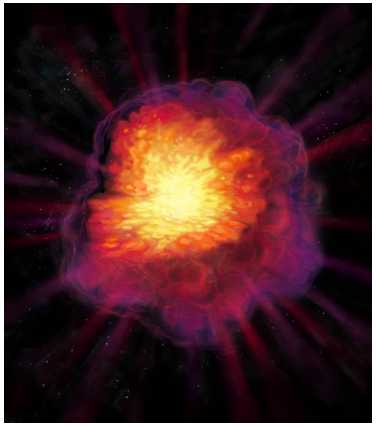
- INTEGRAL Obs from 31 Jan till 26 Jun 2014





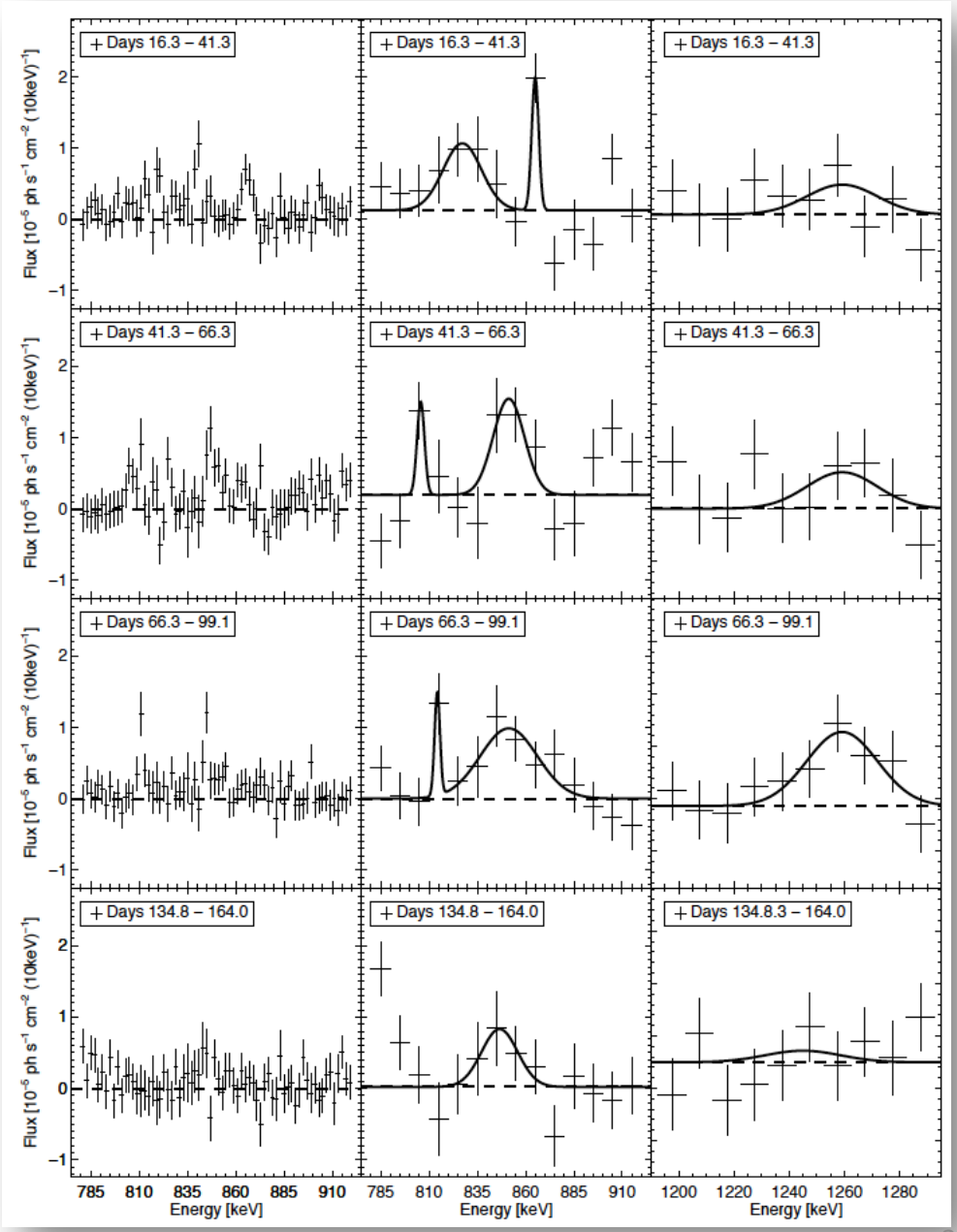
SN2014J data Jan – Jun 2014: ^{56}Co lines

- The ^{56}Co decay lines
- Different spectral binning
- Different epochs



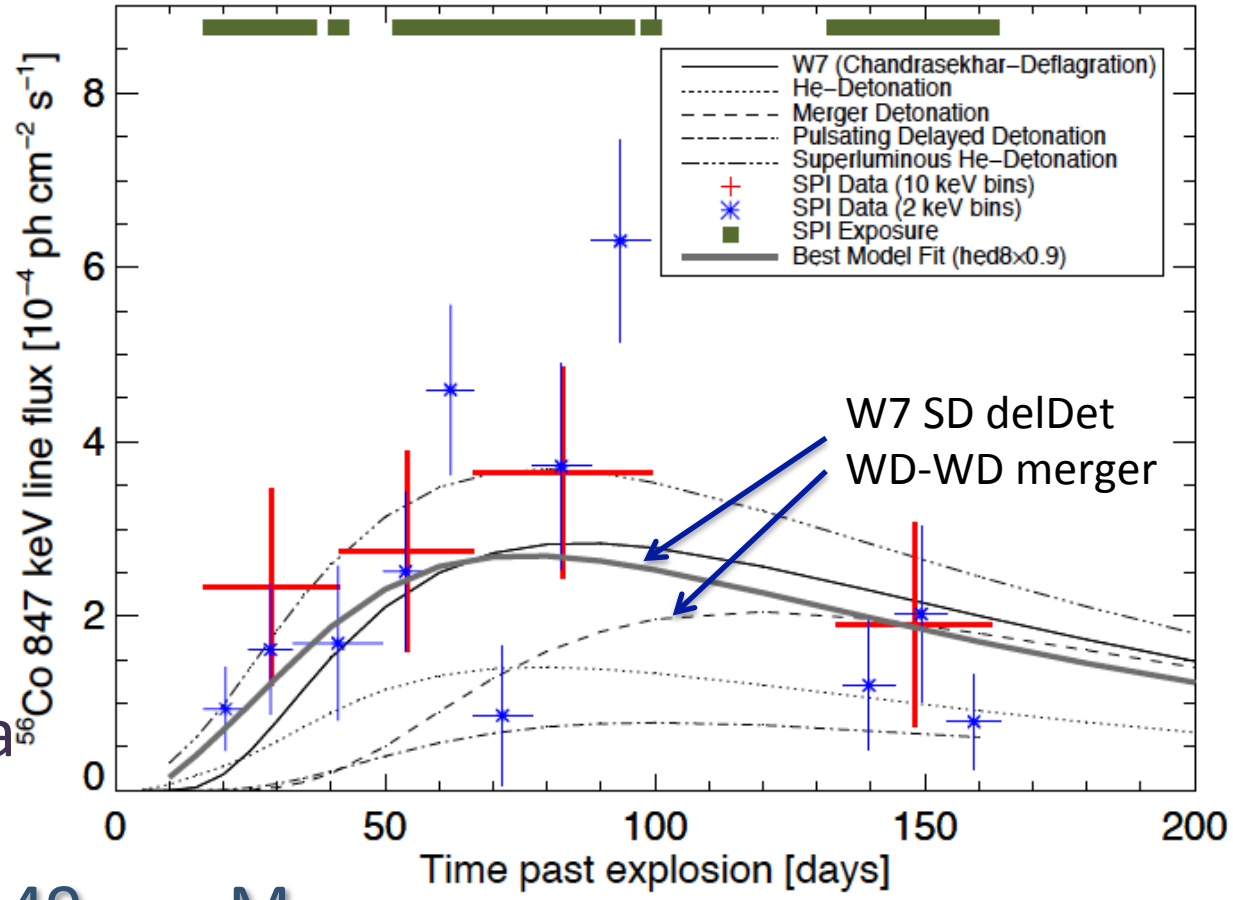
→ Observe a structured and evolving spectrum

- expected: gradual appearance of broadened ^{56}Co lines
  - *Diehl et al., A&A (2015)*



SN2014J data Jan – Jun 2014: 847 keV ^{56}Co line

- Choice of spectral "line emission" assignments
- Structured brightness evolution



→Compare high/low res data to models

- ^{56}Ni mass (fitted): 0.49 +/-0.09 $M_\odot$

(cmp from bol. Light → 0.42 +/-0.05 $M_\odot$

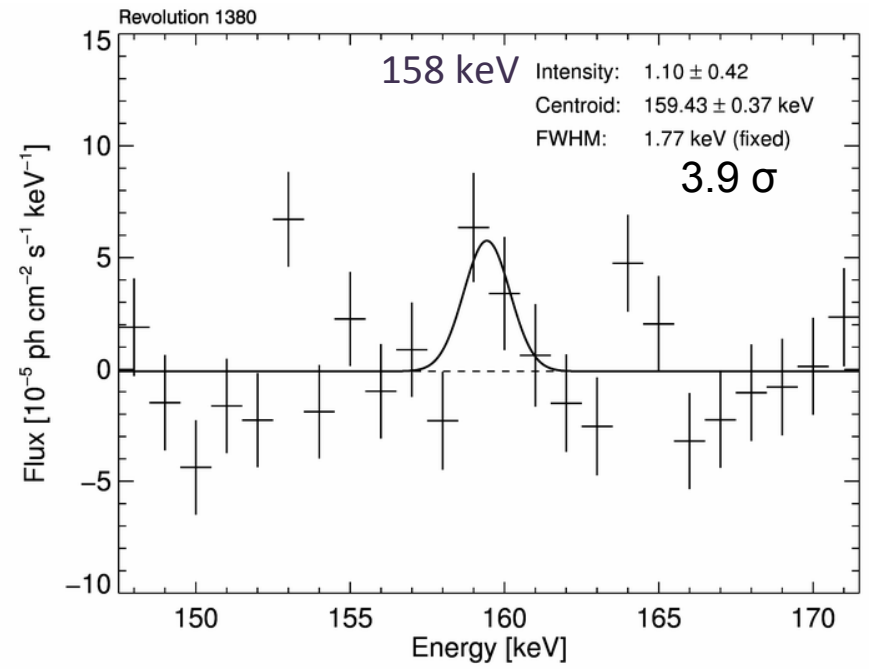
from models → 0.5 +/-0.3 $M_\odot$

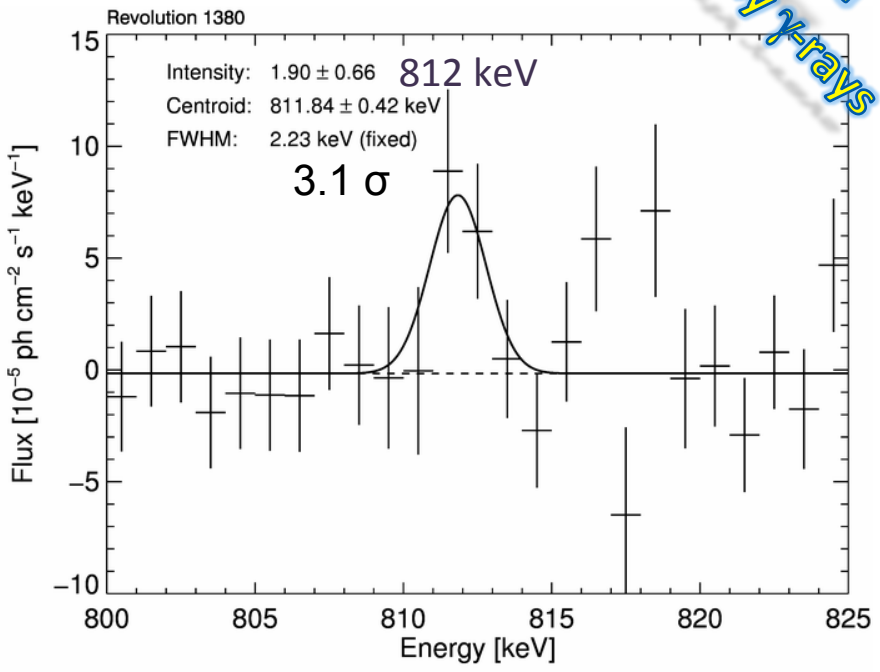
- *Diehl et al., A&A 2015*

SN2014J: Early ^{56}Ni

Unexpected
SN should absorb early γ-rays

- Spectra from the SN position
  - Clear detections of the two strongest lines expected from ^{56}Ni with the INTEGRAL Spectrometer 'SPI'





  - Intensities:
    (1.14 ±0.43) 10^{-4} ph cm^{-2} s^{-1} (158 keV line)
    and (1.91 ±0.67) 10^{-4} ph cm^{-2} s^{-1} (812 keV line)
  - **^{56}Ni mass estimate** (backscaled to explosion): **~0.06 $M_\odot$**

Diehl+ Science 2014

Another analysis of SN2014J SPI data…

→ a broad
^{56}Ni 158 keV line 😉

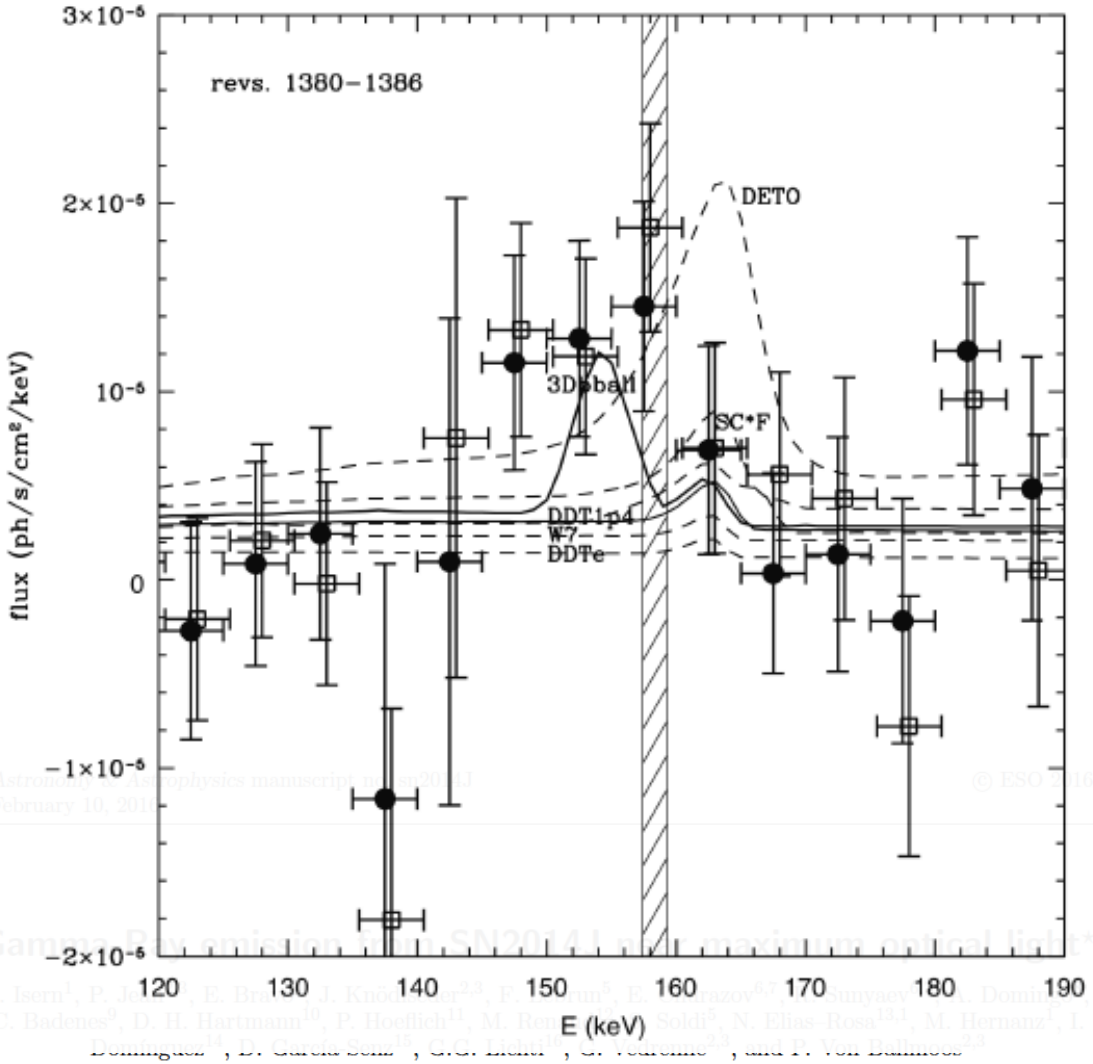
^{56}Ni mass estimate

(backscaled to explosion):

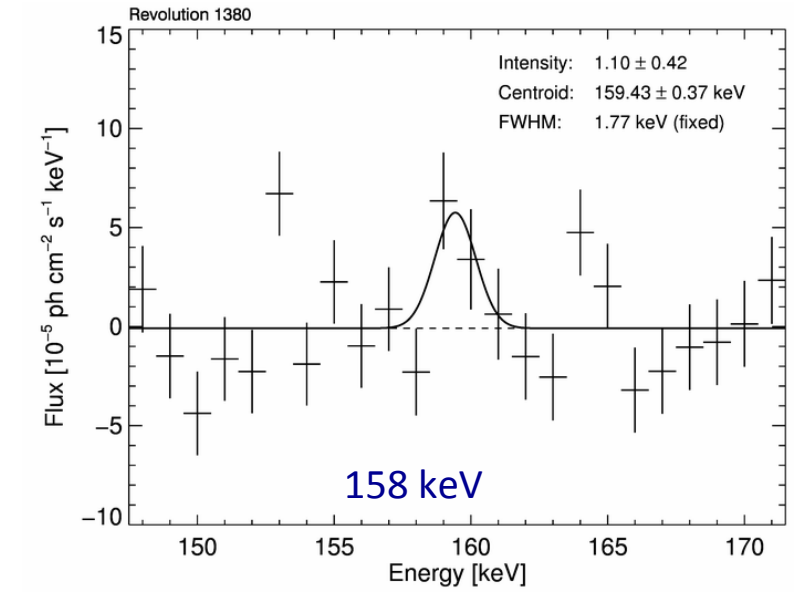
~0.08 $M_\odot$

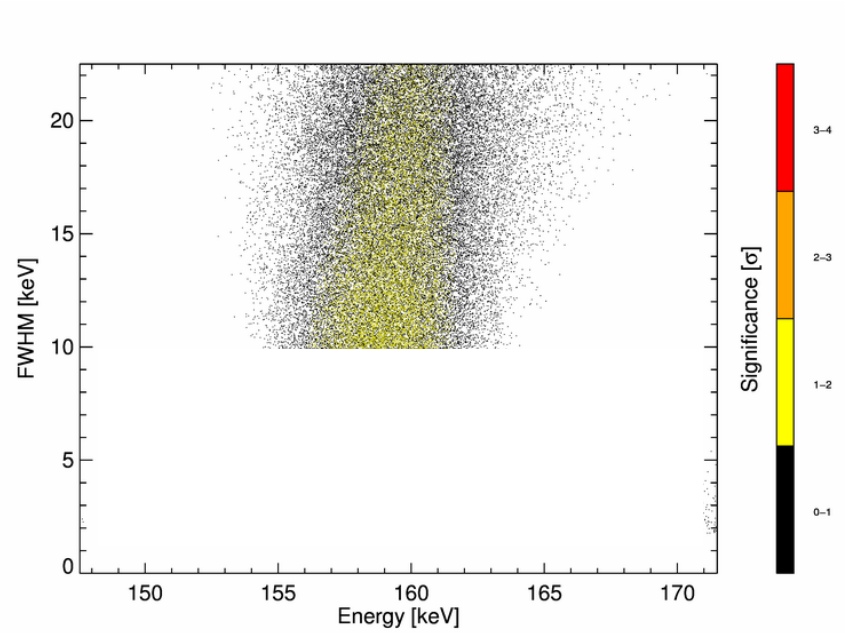
Broad-bin analysis,
convolving SN Ia model spectra
(i.e. model dependent)

Isern+ A&A 2016



Line Uncertainties: Search and method biases





- Random Search: Try to Fit a Line (Centroid,Intensity, Width)

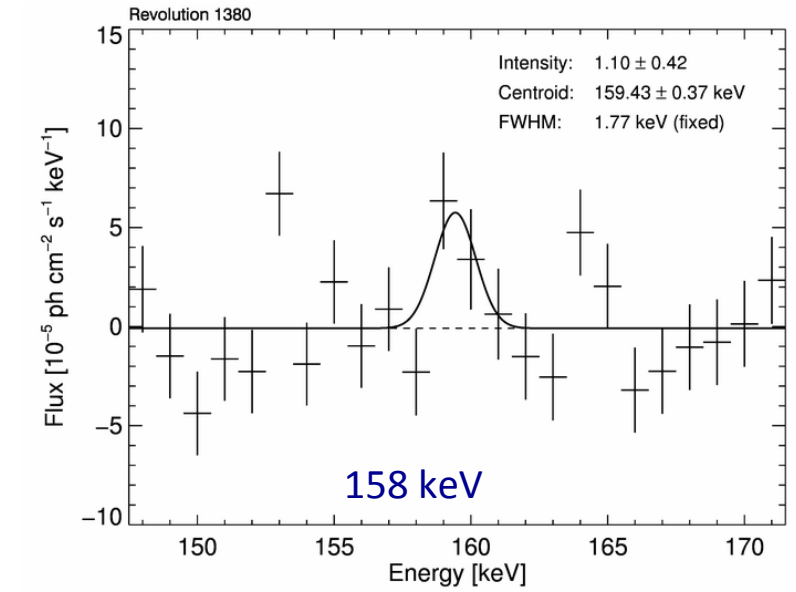
☆ Depending on resolution of the analysis method, and on fitting approach, results may differ

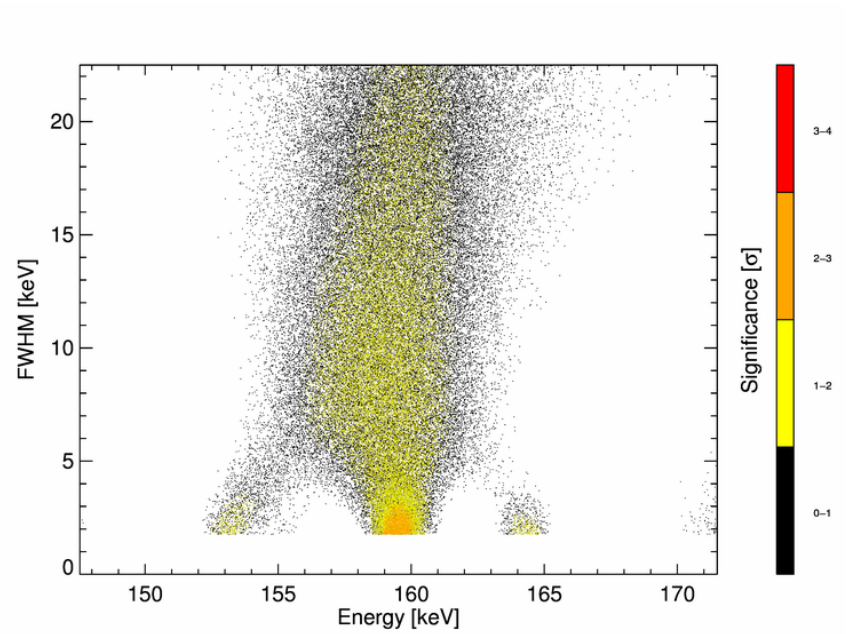
☞ Narrow line, ~unshifted

? or ?

☞ Broad & redshifted line

Line Uncertainties: Search and method biases





- Random Search: Try to Fit a Line (Centroid,Intensity, Width)

☆ Depending on resolution of the analysis method, and on fitting approach, results may differ

☞ Narrow line, ~unshifted, is most likely

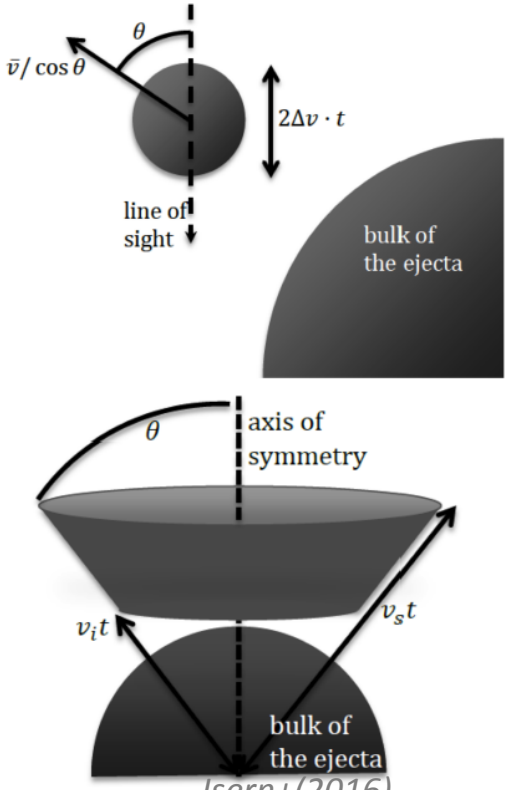
(from data analysis alone; no model)

☞ Underlying broad line cannot be excluded

SN2014J: An unusual explosion?

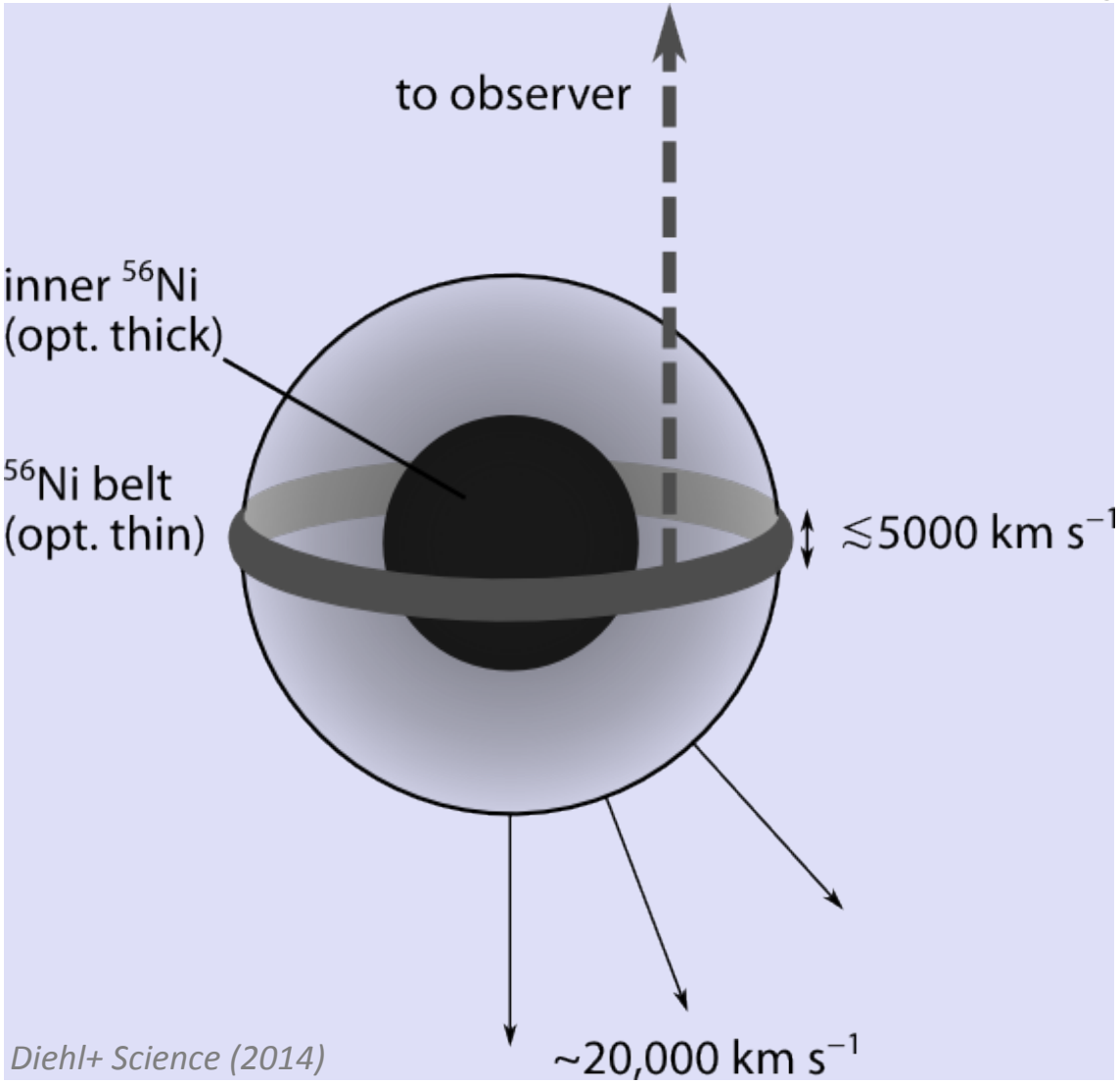
- SN2014J had significant ^{56}Ni near the surface

Possible geometries of outer ^{56}Ni:



Isern+(2016)

A belt of He accreted from the companion star → He explosion, triggering the SNIa explosion of the CO white dwarf ($M<M_{ch}$)



Diehl+ Science (2014)

Summary: White Dwarfs and Gamma-Ray Lines?

– WD accretion flows
→ LECRs / neutron capture
not seen

– nova nucleosynthesis
→ short-lived radioactivity close to detection
→ long-lived radioactivity & e^+ not distinguishable

– WDs in supernovae type Ia
→ DD's: He accretion may be an important ingredient