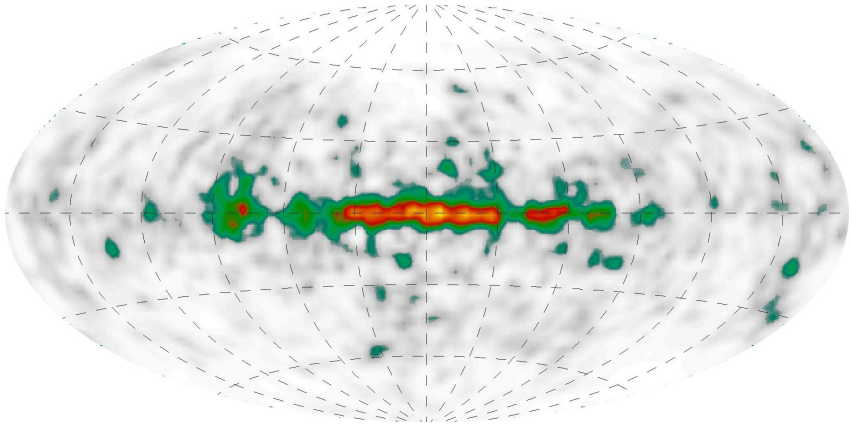
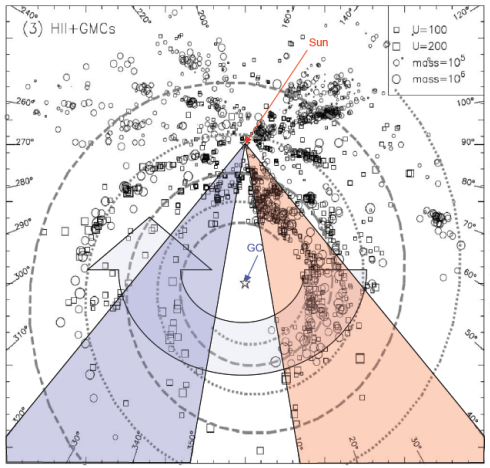
New Insights from Cosmic Gamma-Rays

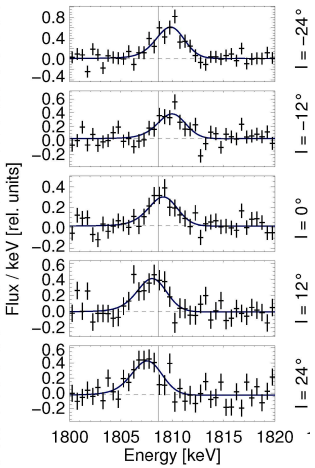
Roland Diehl (MPE Garching, Germany)

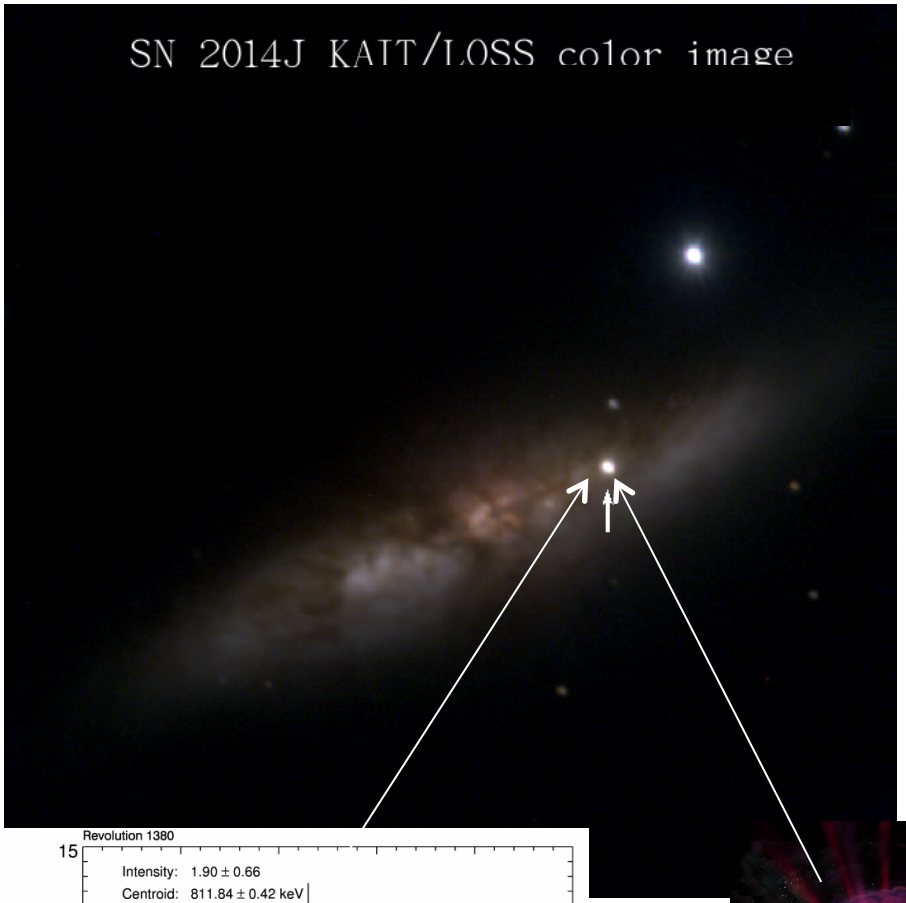
with
Martin Krause, Karsten Kretschmer,
Thomas Siegert, Jochen Greiner, Xiaoling Zhang (MPE)
and many others at other institutions

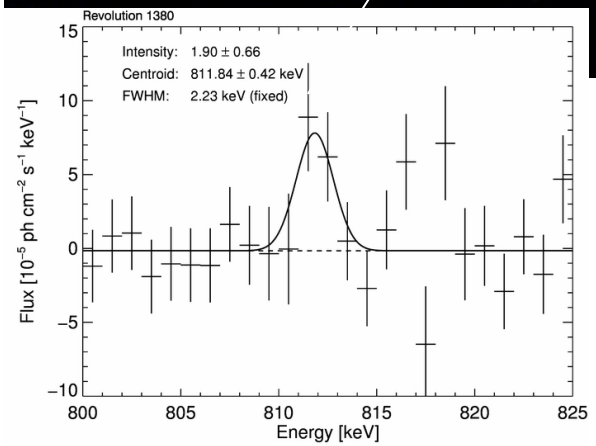
Supernovae, Massive Stars, & ISM

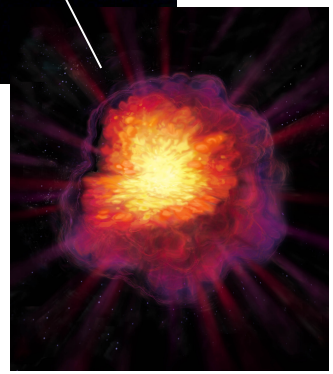




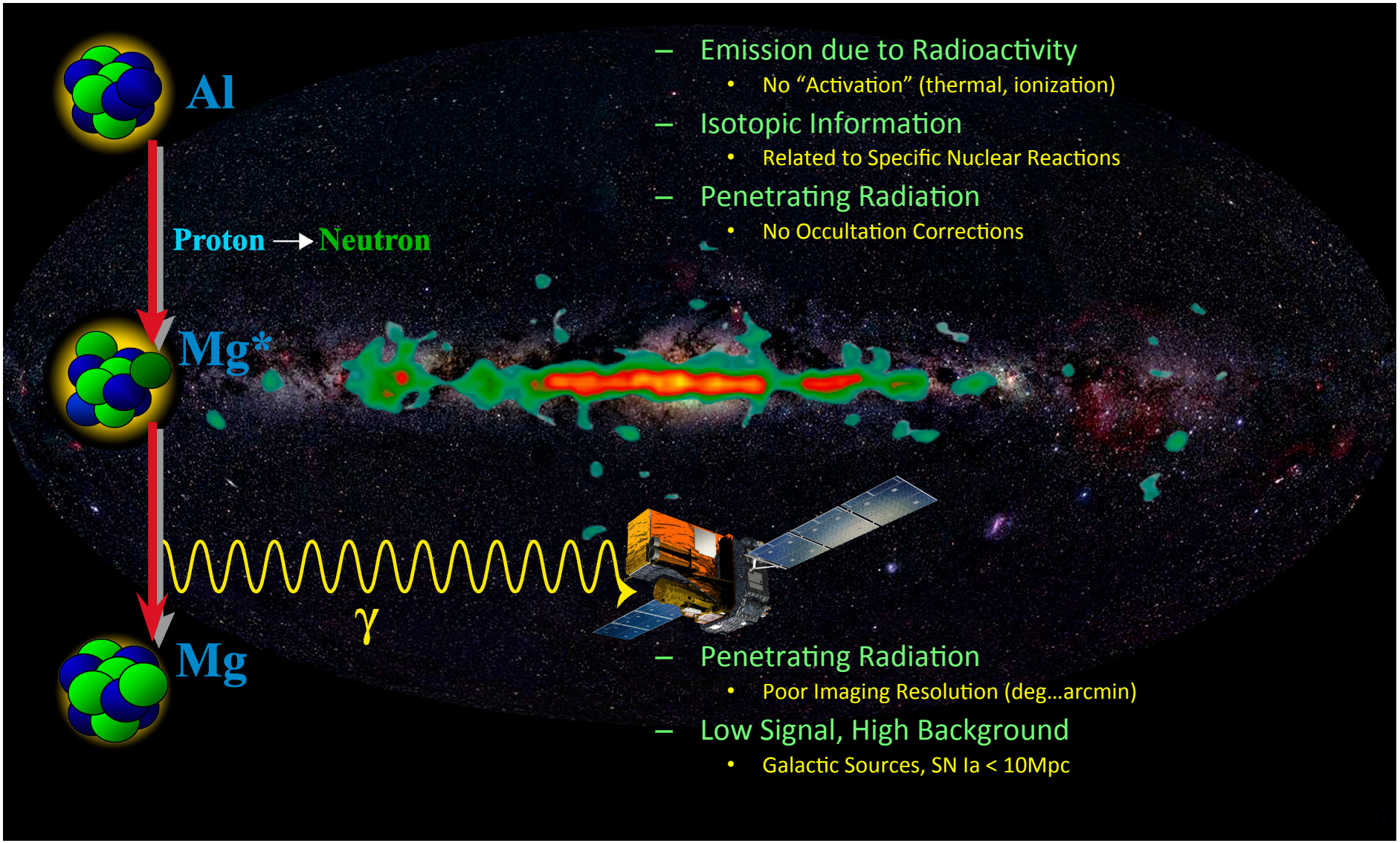








Gamma-Rays from Radioactivity: Key Points



- Emission due to Radioactivity
  - No "Activation" (thermal, ionization)
- Isotopic Information
  - Related to Specific Nuclear Reactions
- Penetrating Radiation
  - No Occultation Corrections

- Penetrating Radiation
  - Poor Imaging Resolution (deg…arcmin)
- Low Signal, High Background
  - Galactic Sources, SN Ia < 10Mpc

Radioactivity Gamma-Ray Lines and their Messages

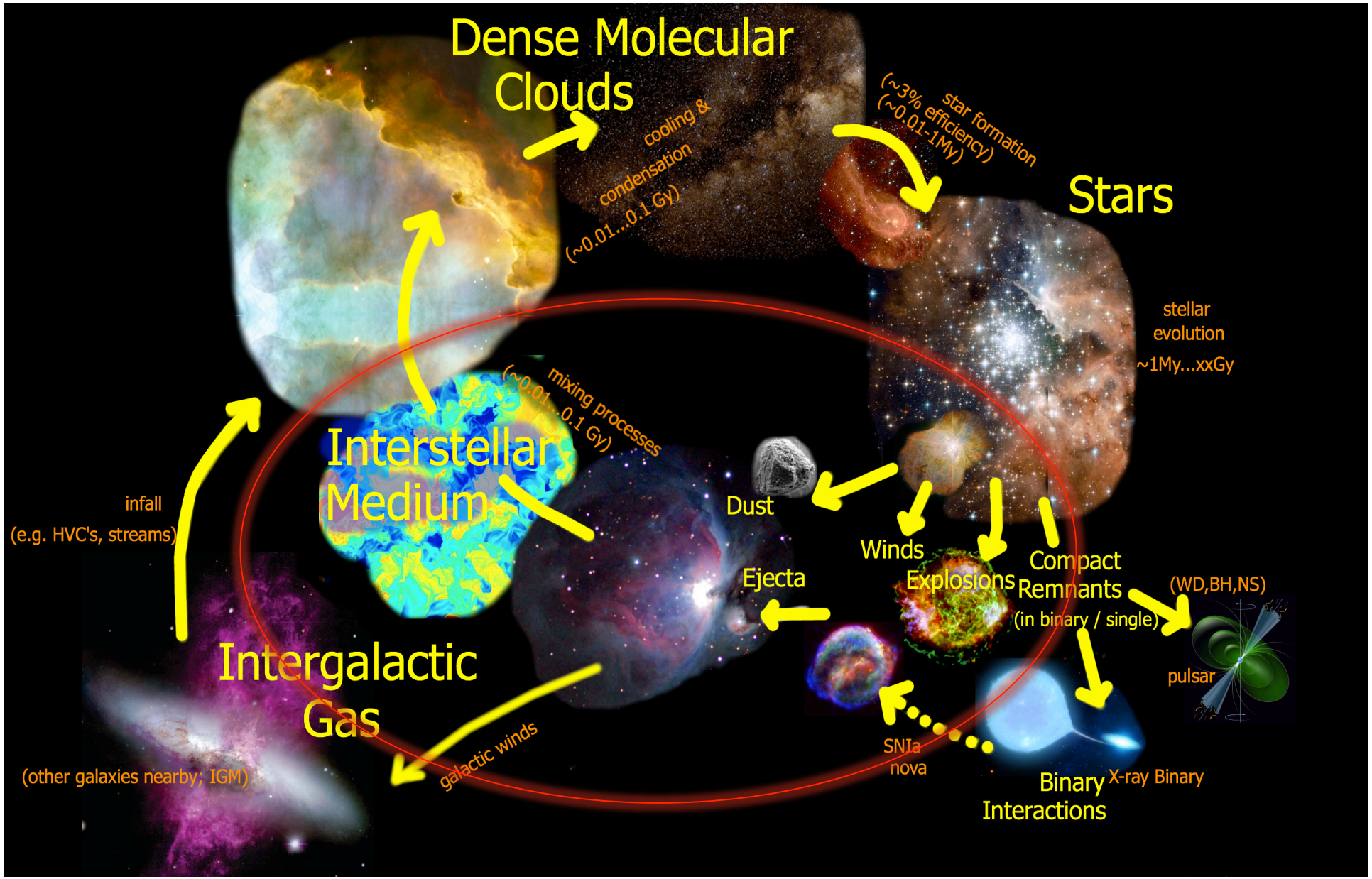
- Radioactive Trace Isotopes are Nucleosynthesis By-Products
- For Gamma-ray Spectroscopy We Need:
  - Decay Time > Source Dilution Time
  - Yields > Instrumental Sensitivities

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	85 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	3.8 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

individual object/event

cumulative from many events

Cosmic Radioactivities: → Production and Re-Cycling of Nuclei



Nuclear Gamma-Ray Line Telescopes / Missions

– Compton Gamma-Ray Observatory

1991-2000

NASA

– INTEGRAL Observatory

2002-(2018+)

ESA

– Earlier Balloone-Borne Experiments

– HEAO-C

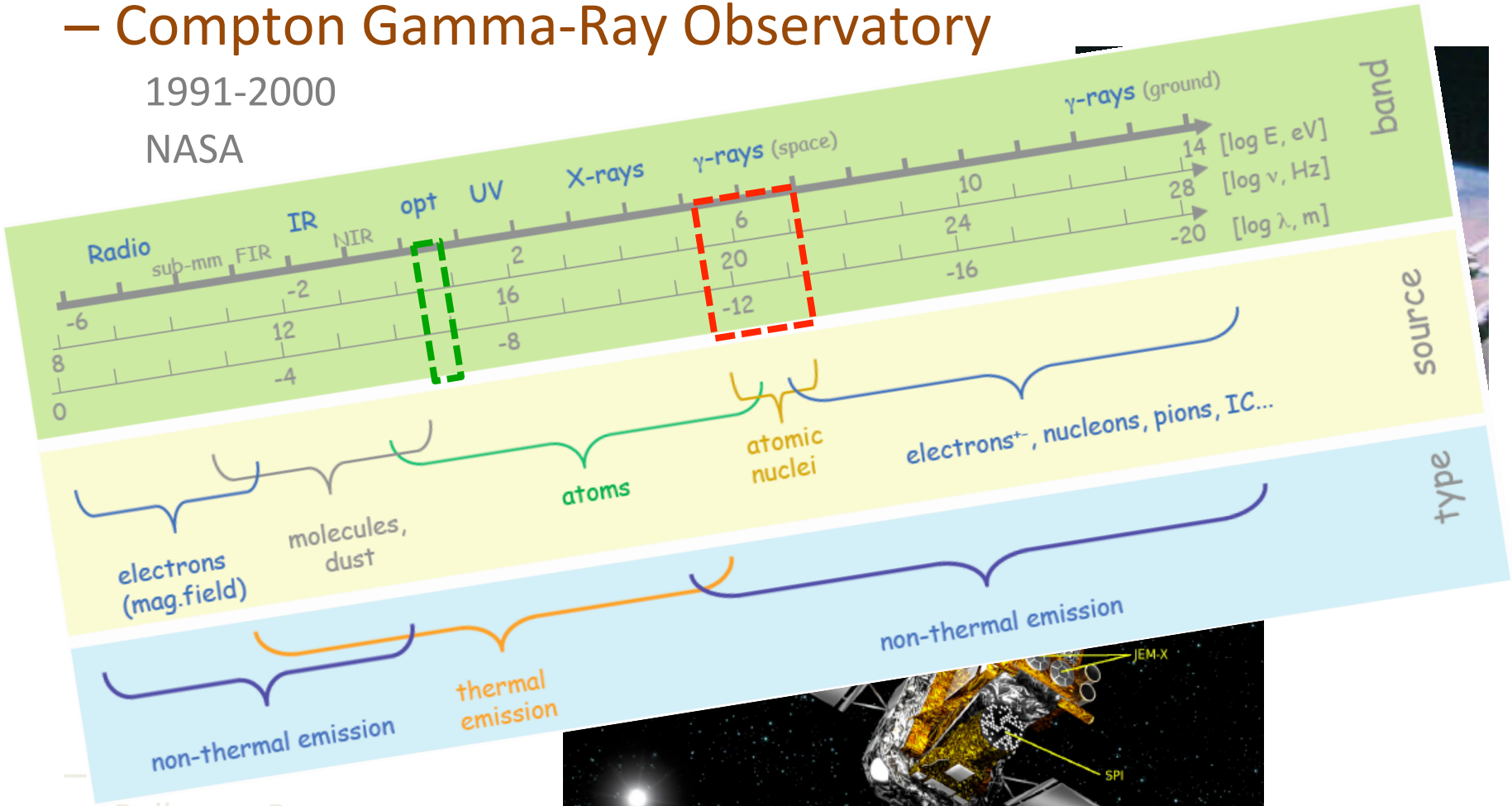
1978

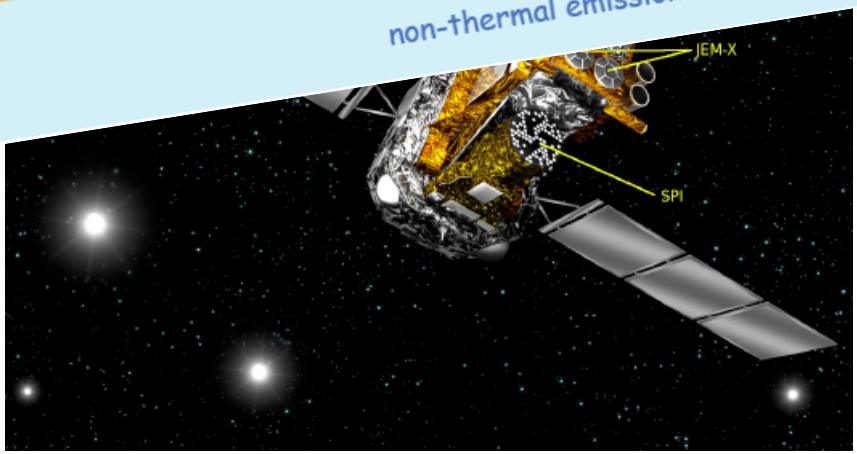
Nuclear Gamma-Ray Line Telescopes / Missions

– Compton Gamma-Ray Observatory

1991-2000

NASA



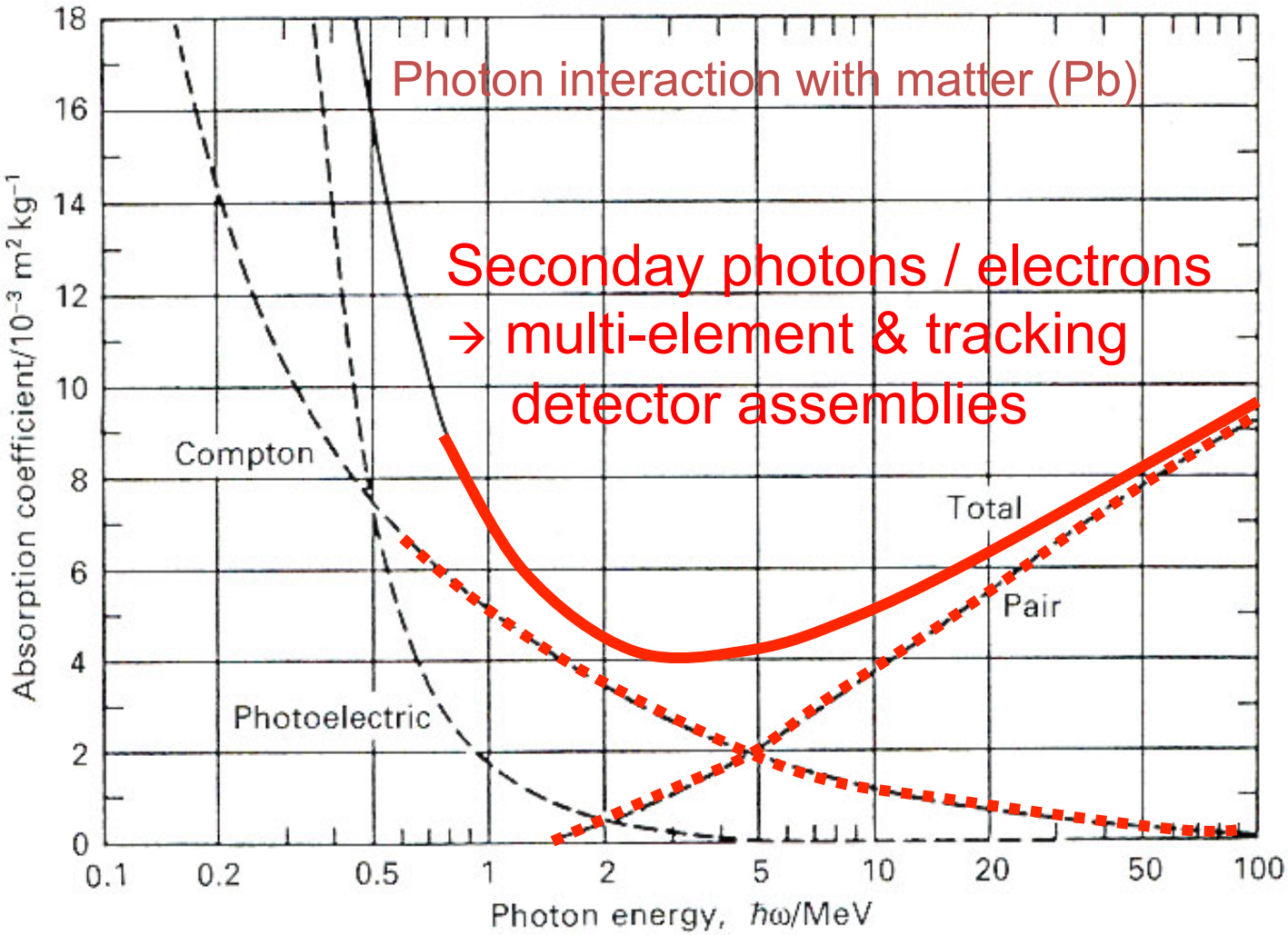


– Balloone-Borne Experiments

– HEAO-C

1978

Astronomical Gamma-Ray Telescopes:
Interaction of High-Energy Photons with Matter



-> Secondary Particles … → e.m. cascade

Compton Telescopes

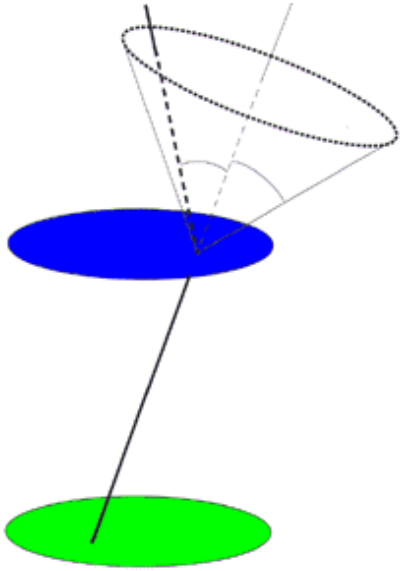
Measure Compton Scattering:

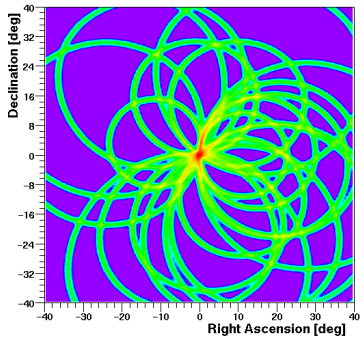
2 Detectors in Coincidence

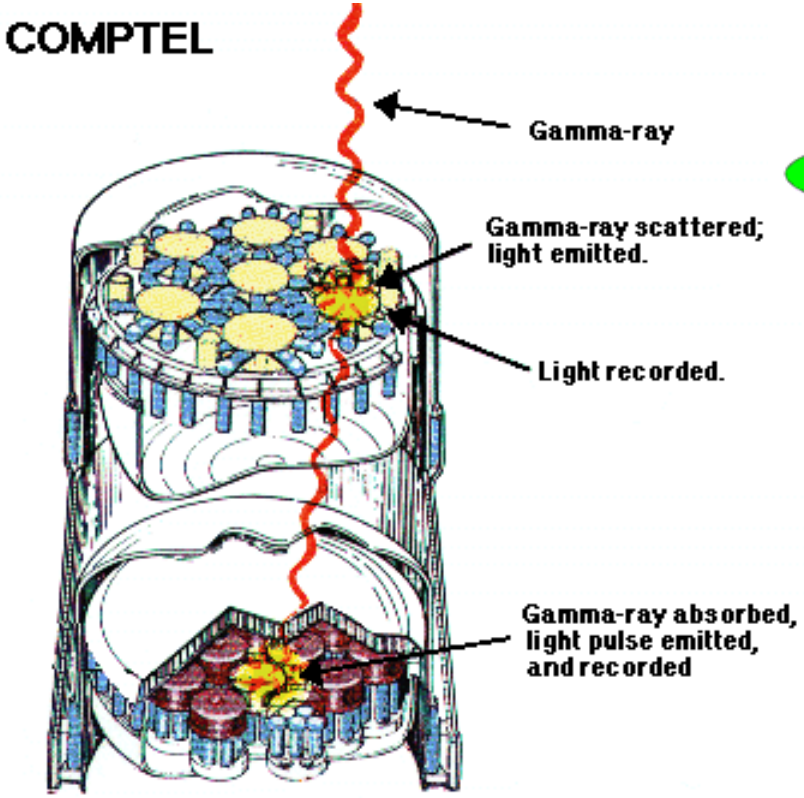
Compton scatter → e-
Scattered photon energy
Scattering geometry

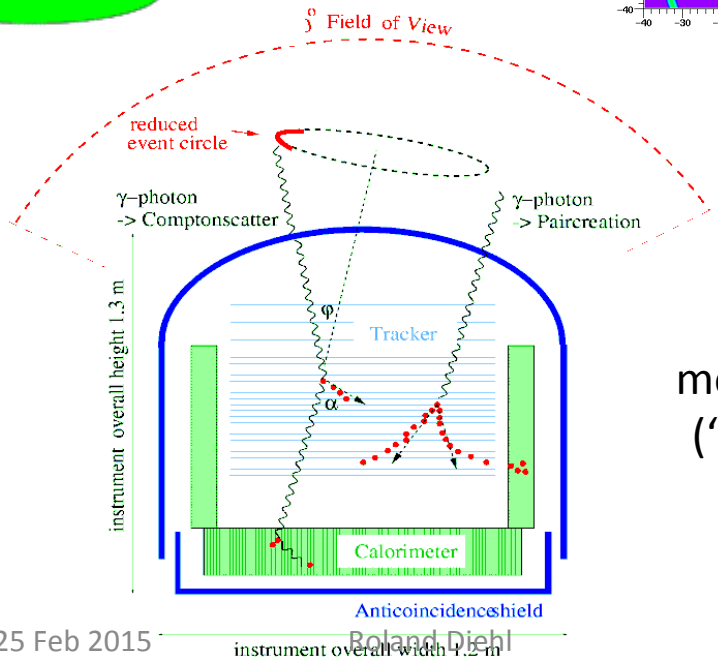
$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

$$\varphi_{geometric} = \arccos\left\{1 + m_e c^2 \left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma - \Delta E}\right)\right\}$$



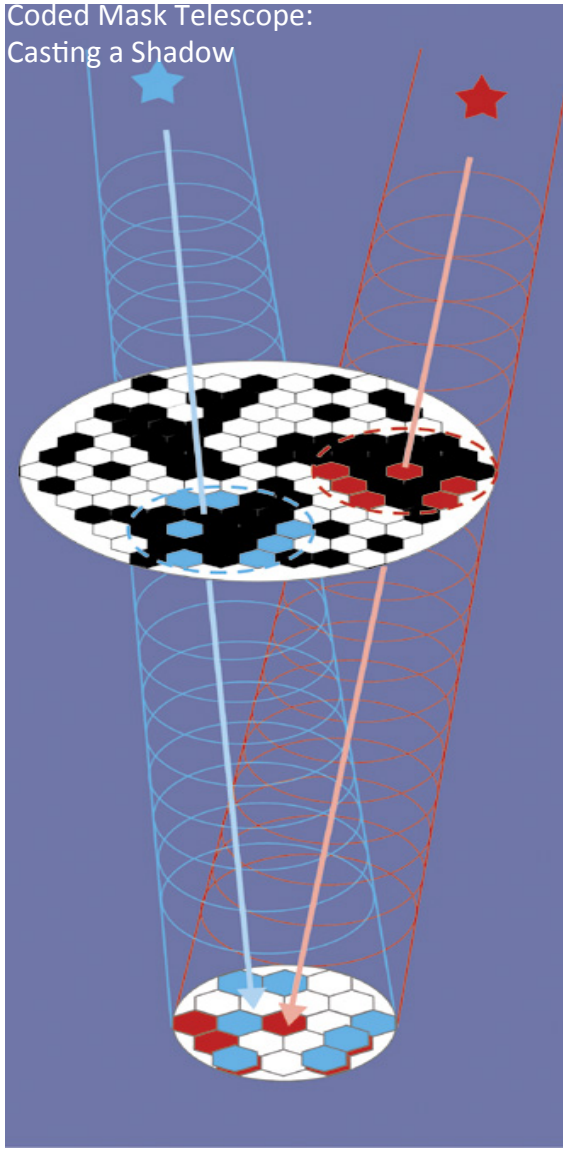






modern version
('GRIPS' et al.)
Greiner+2013

INTEGRAL Cosmic Photon Measurements: The SPI Ge γ-Spectrometer



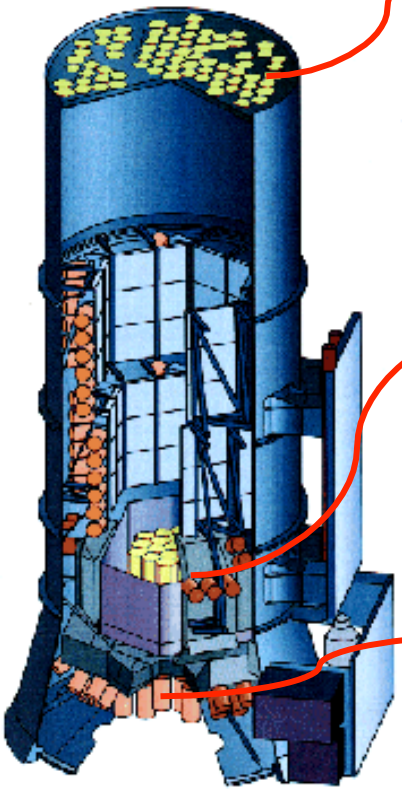
Coded-Mask Telescope

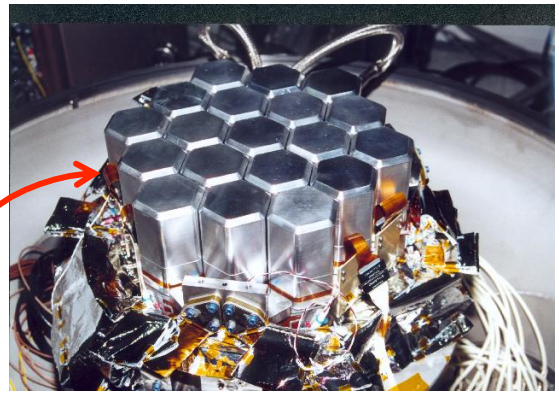
Energy Range 15-8000 keV

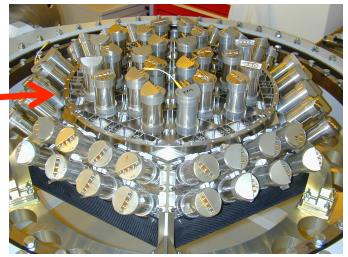
Energy Resolution ~2.2 keV @ 662 keV

Spatial Precision 2.6° / ~2 arcmin

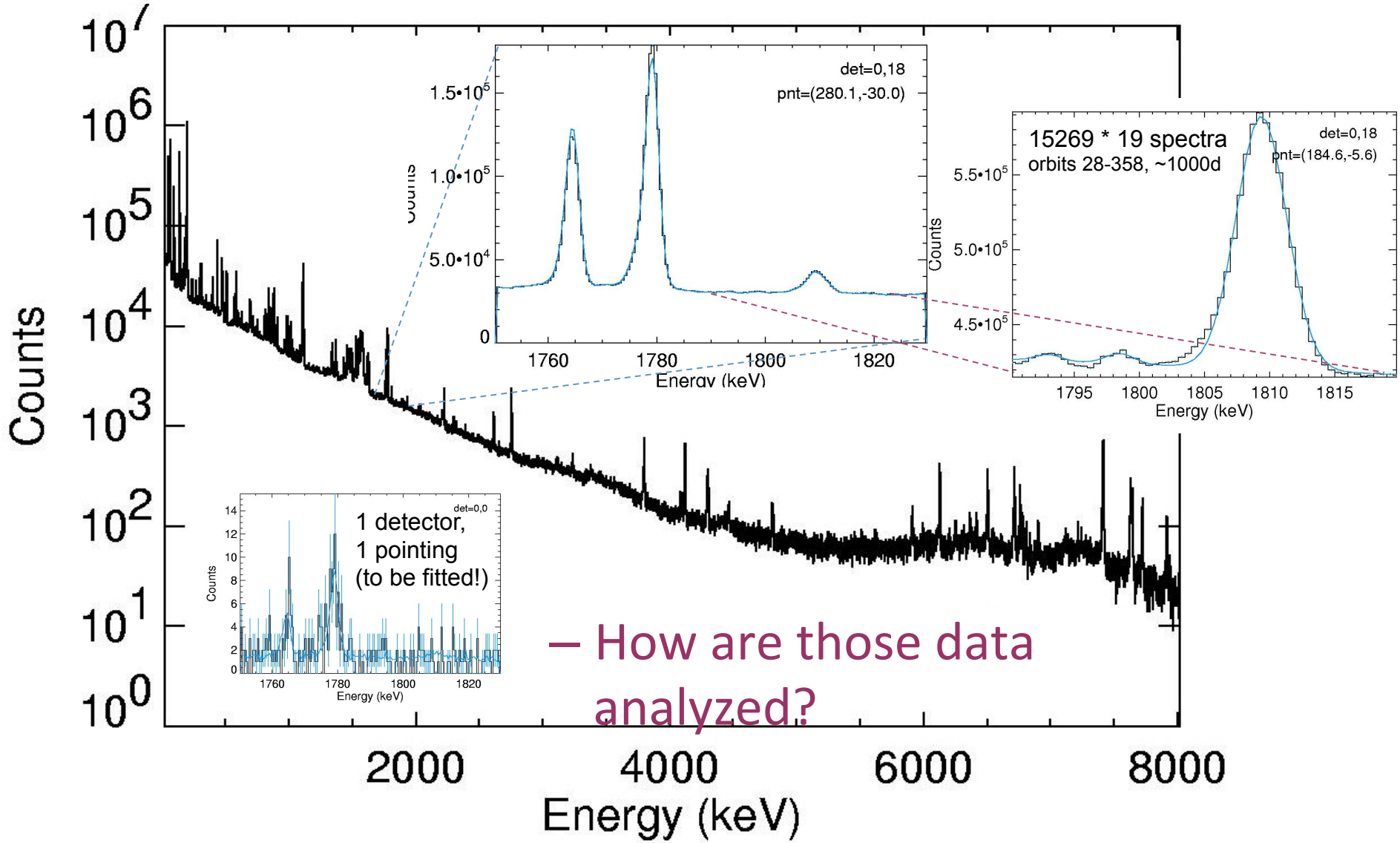
Field-of-View 16x16°





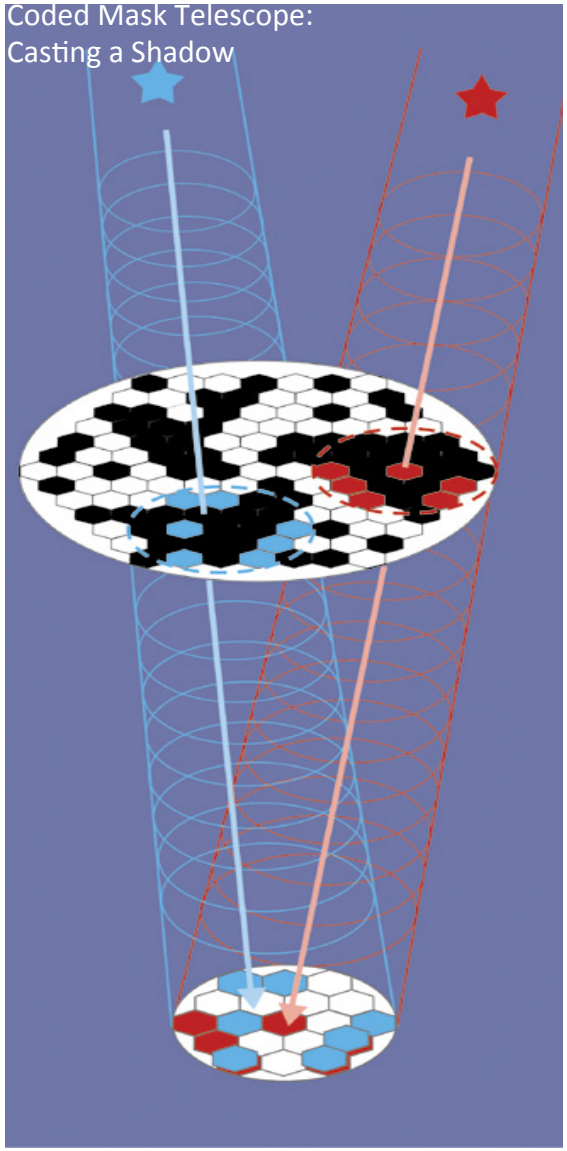


Energy Spectra: Characteristic Examples



– How are those data analyzed?

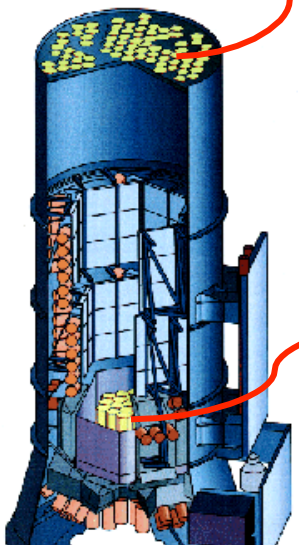
INTEGRAL Cosmic Photon Measurements: The SPI Ge γ-Spectrometer

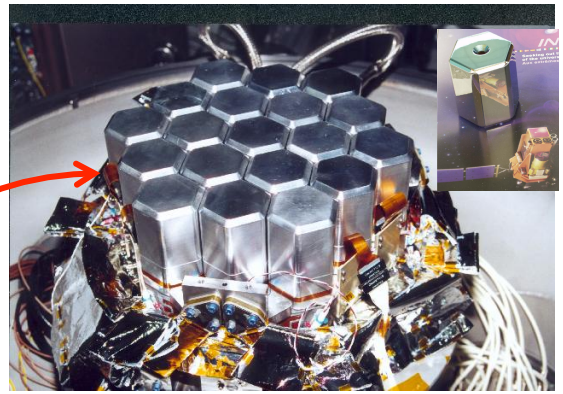


Coded-Mask Telescope

→ Change aspect of src every ~30 min

→ Detect shadowgram of source counts in set of spectra





Energy Range
15-8000 keV

Energy Resolution
~2.2 keV @ 662 keV

Spatial Precision
2.6° / ~2 arcmin

Field-of-View 16x16°

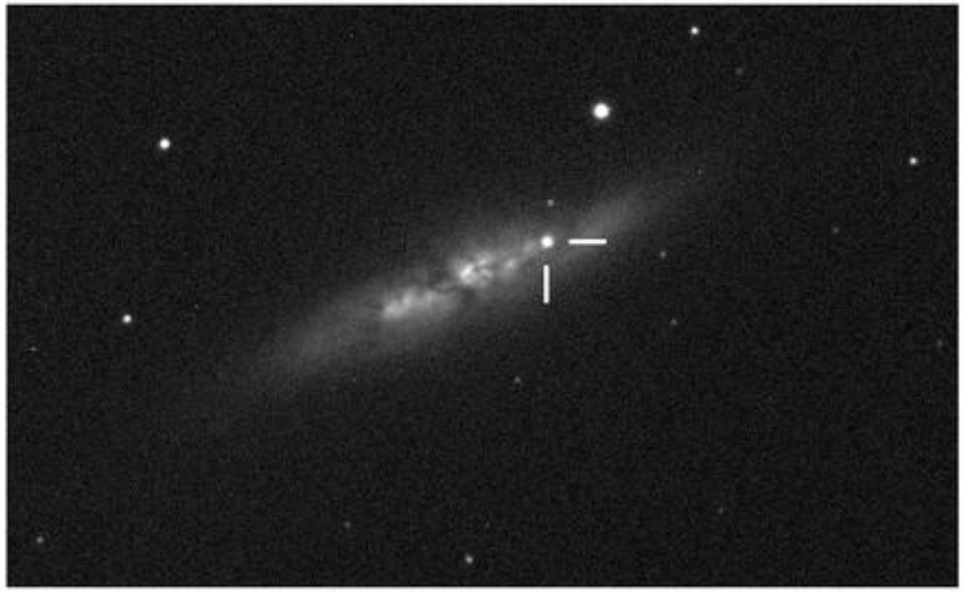
$$d_k = \sum_j R_{jk} \sum_{i=1}^{N_I} \theta_i M_{ij} + \sum_{i=N_I+1}^{N_I+N_B} \theta_i . B_{jk}$$

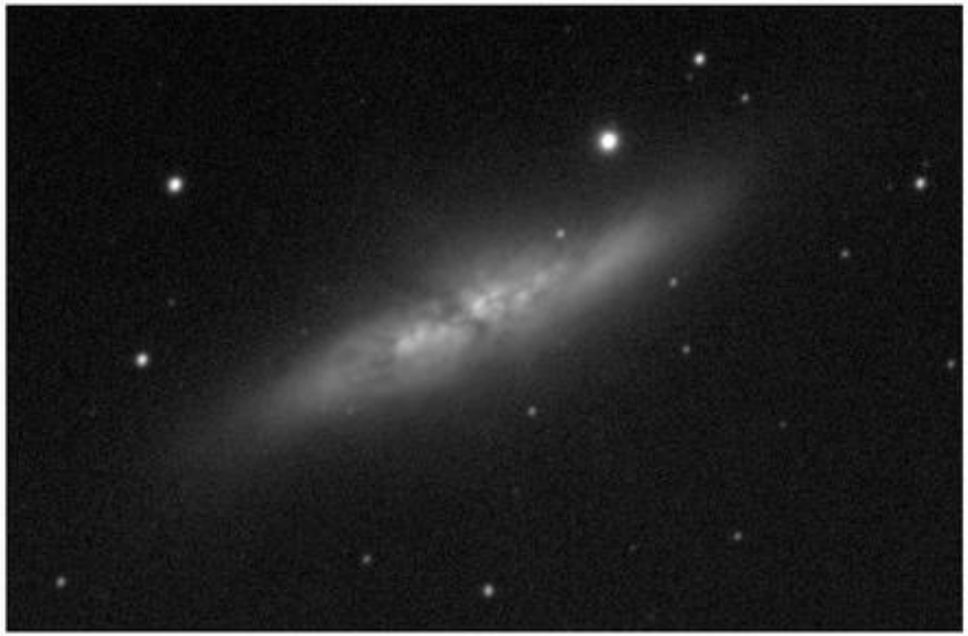
k=energy, detector, time

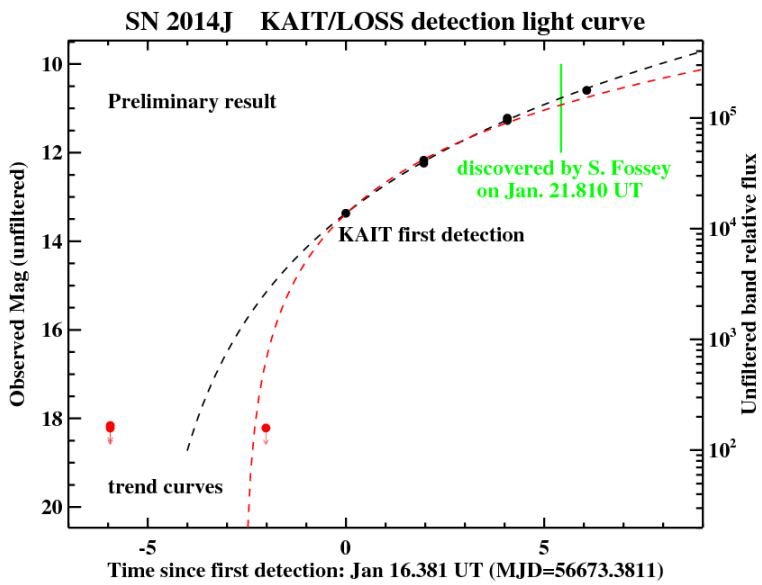
→ analyze typically ~10^5 spectra

SN2014J

- In M82
  (Starburst Galaxy)
  - Discovered 22 Jan 2014
    Cao et al. ATel # 5786
  - Likely Explosion Date:
    14 Jan 2014 (14.75 +/-0.3d)
  - Distance 3.3….3.53 Mpc,
    l=141.41°, b=40.56°

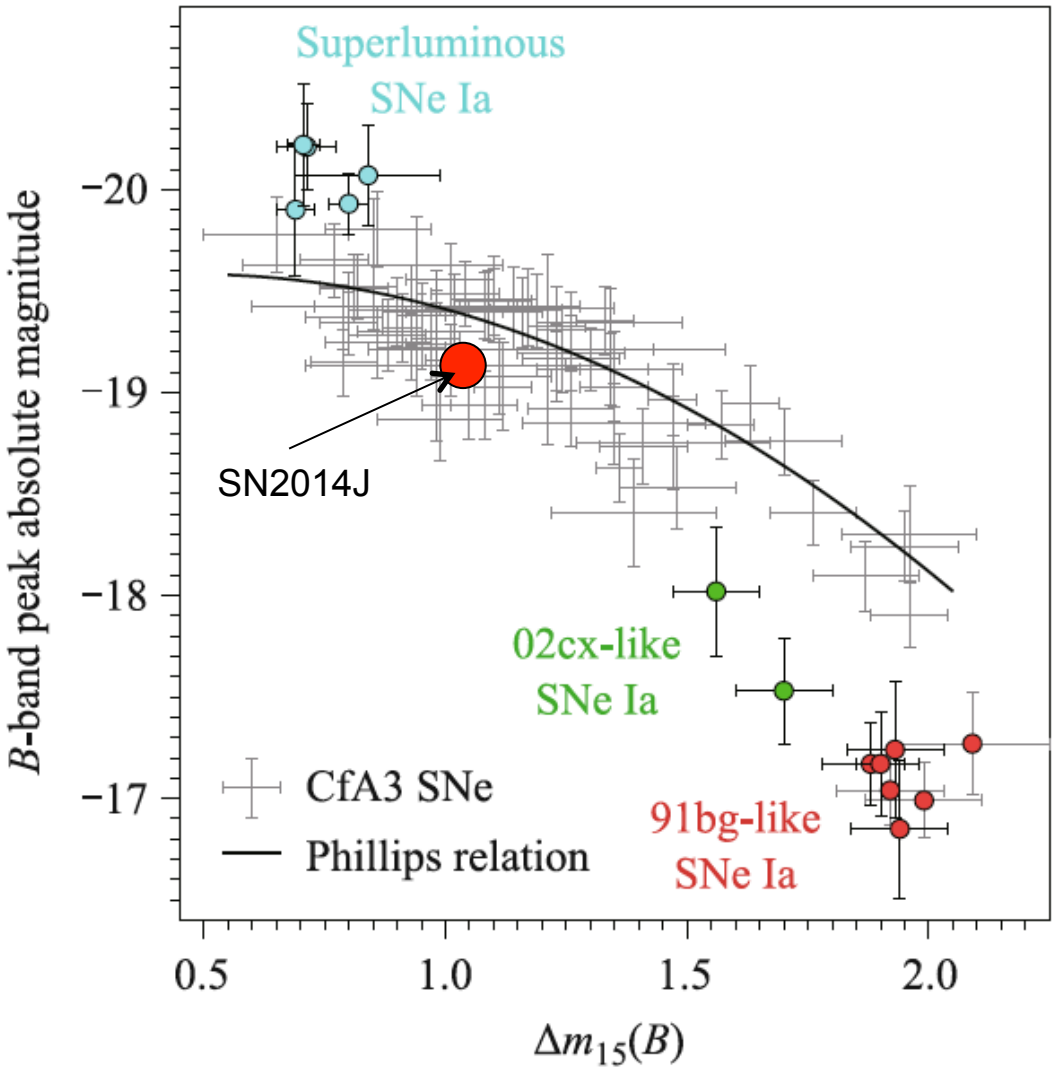






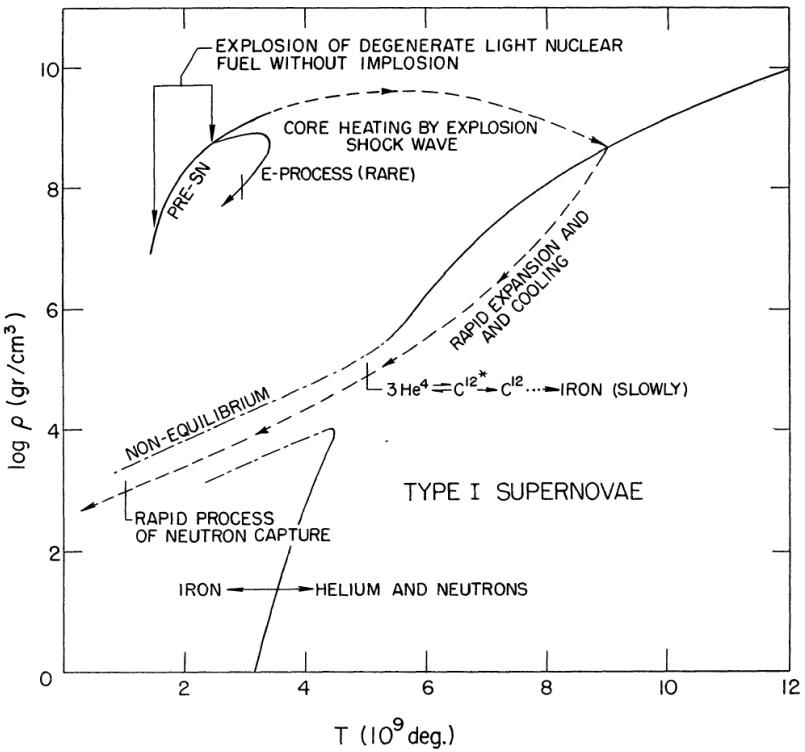
SN2014J

- SN2014J appears to be “normal”



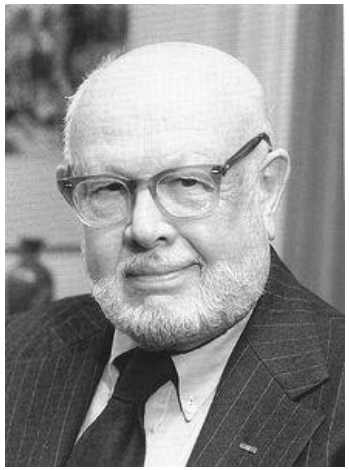
What is a Supernova?

- Release of Nuclear Binding Energy
  - ^{56}Fe: 8.8 MeV/nucl; (13α+4n): 6.6 MeV/nucl
    - » 2.2 MeV/nucl, = 1 10^{18} erg/g > 10^{51} erg/$M_\odot$
- Explosiveness of Stellar Matter:
  - Implosion of iron-group composition → explosive light nuclei → SNII
  - Light nuclei under degenerate conditions → SNI → C,O White Dwarf!



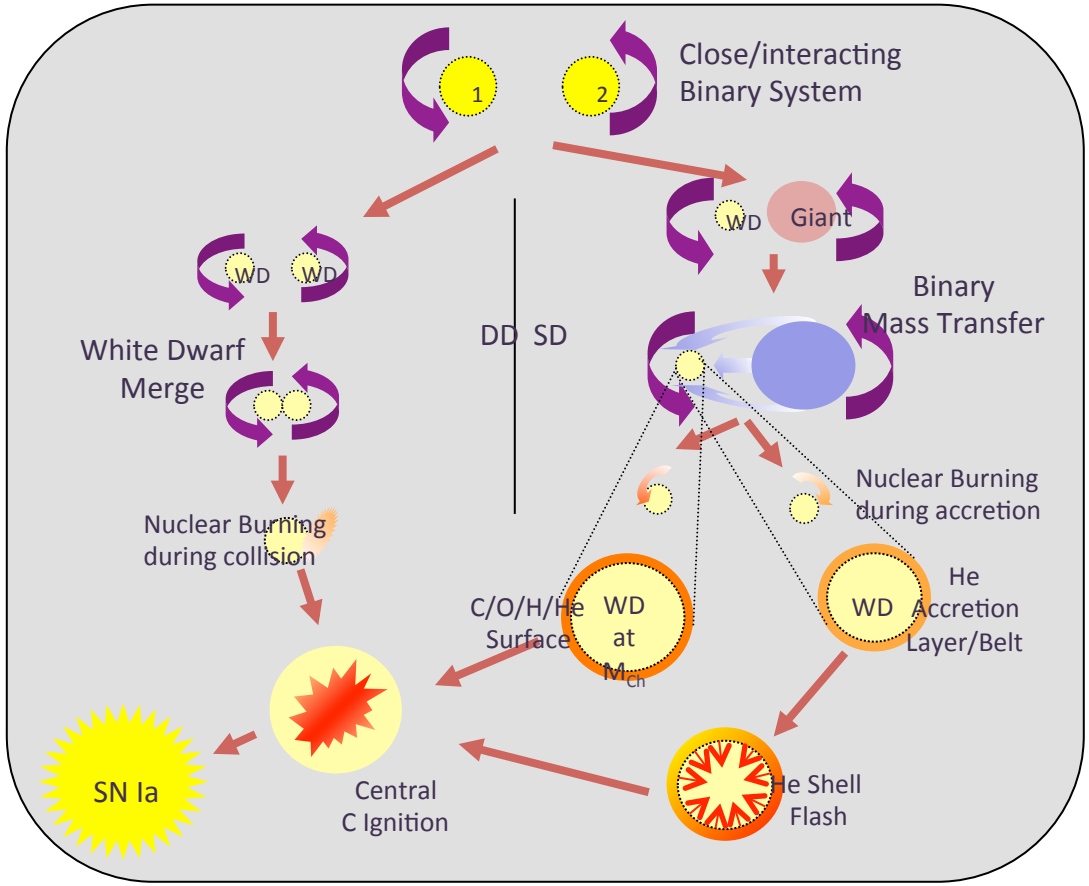
NUCLEOSYNTHESIS IN SUPERNOVAE

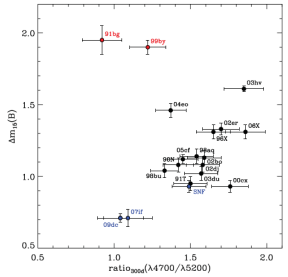
F. HOYLE
St. John's College, Cambridge, and California Institute of Technology
AND
WILLIAM A. FOWLER
California Institute of Technology
Received May 21, 1960

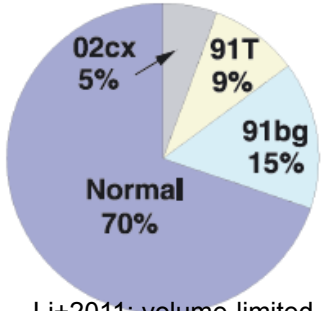


Understanding SNIa: Main Issues

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

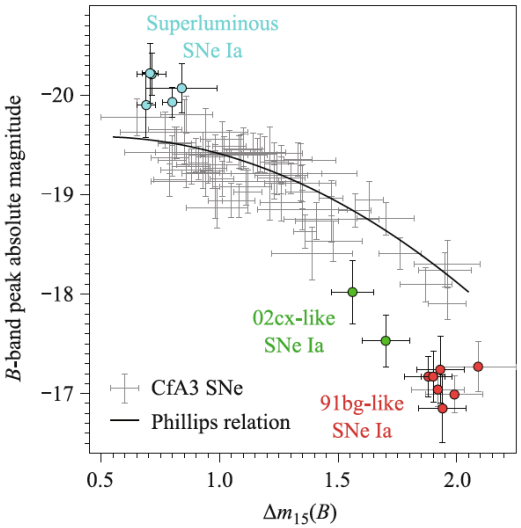




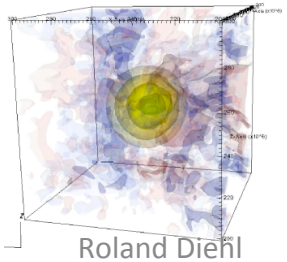


Li+2011; volume-limited

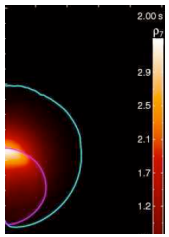
outliers?



ignition?



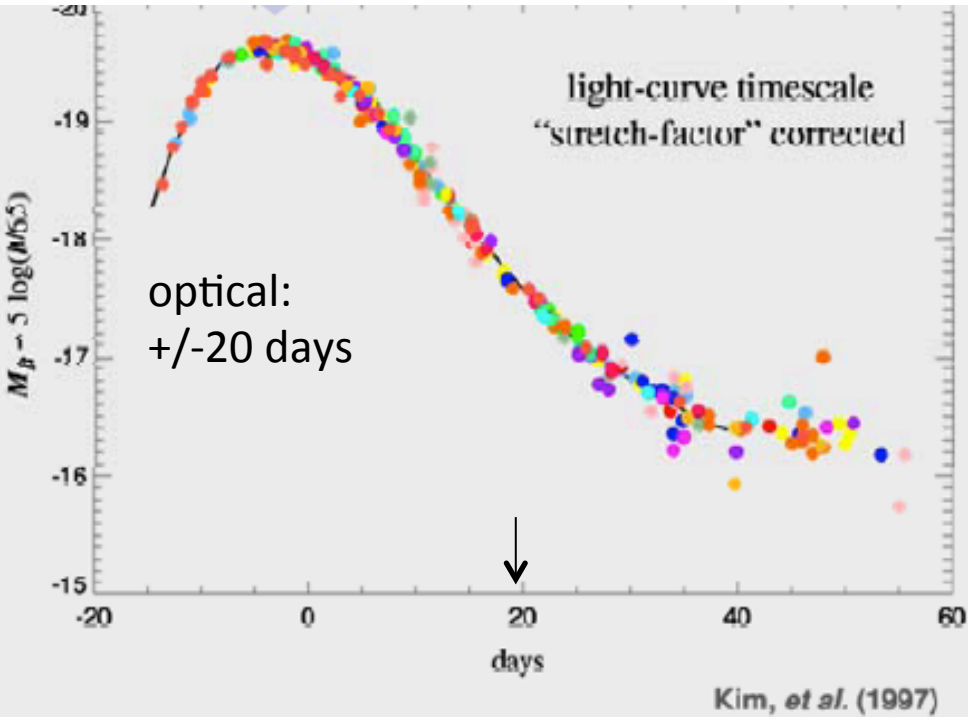
Roland Diehl

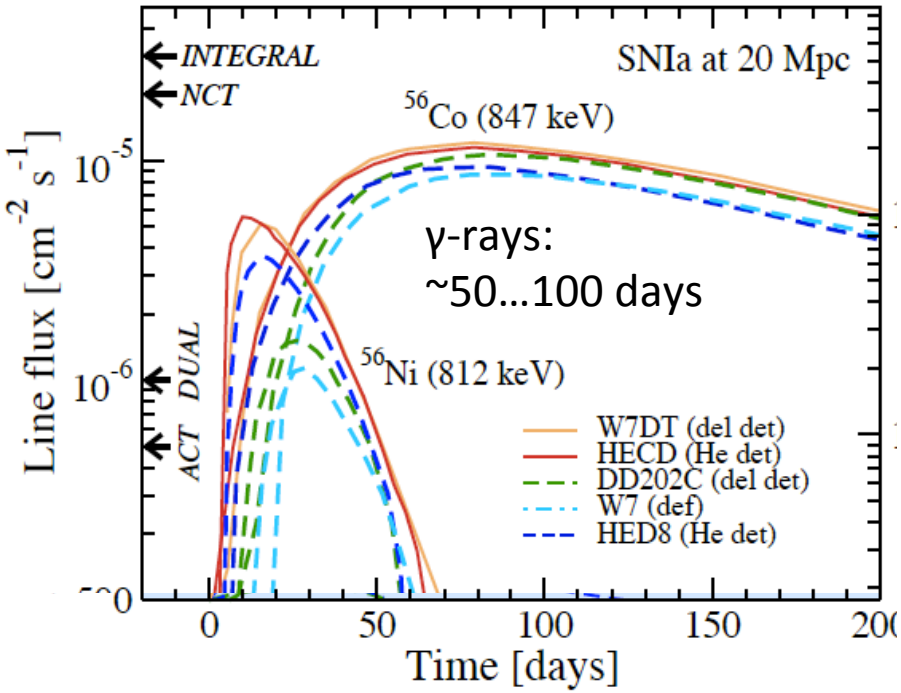


flame
propagation?

☞ Progenitor diversity?

SNIa Light: Radioactivity Gamma-Rays Make Optical Emission



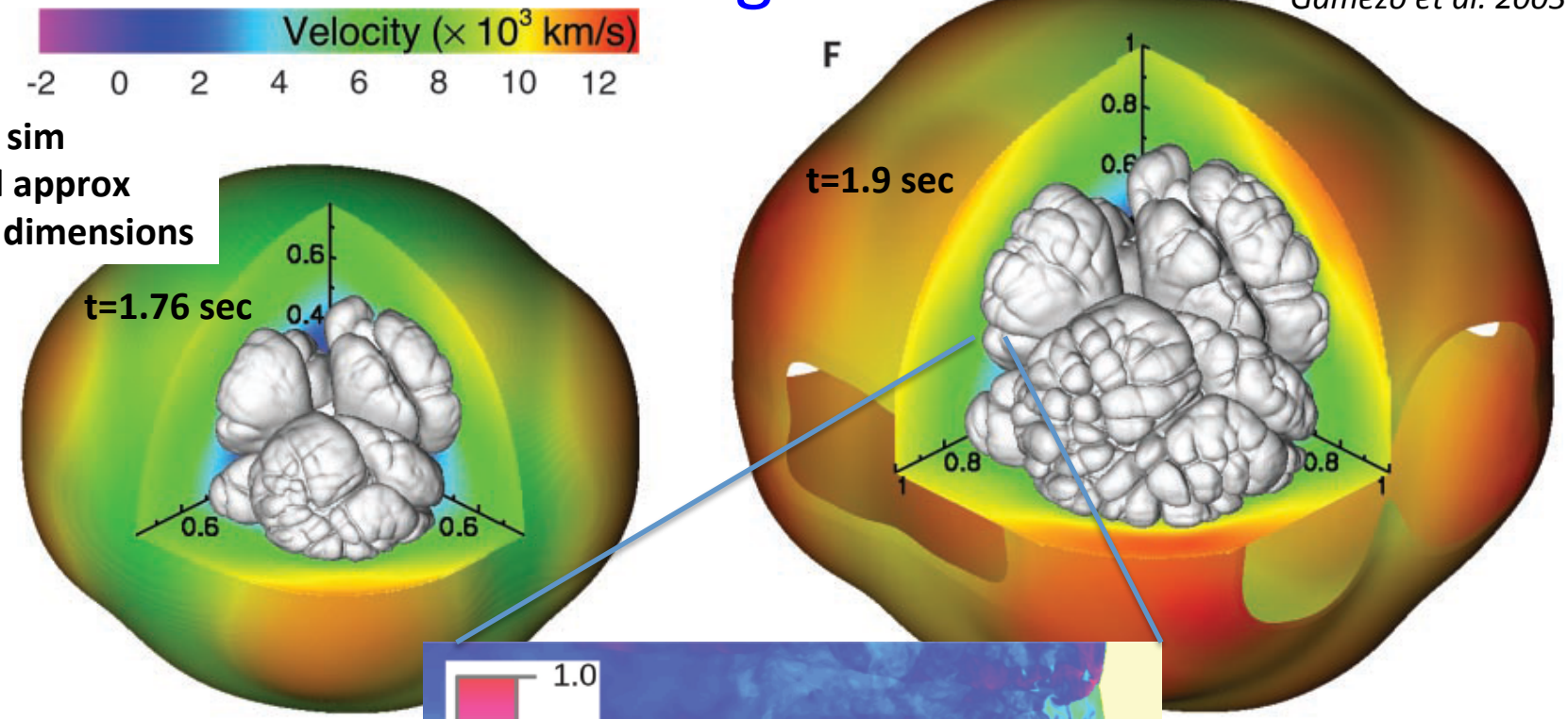


- ^{56}Ni decay gamma-rays and e^+ are initially fully absorbed (→ light), and leak out later

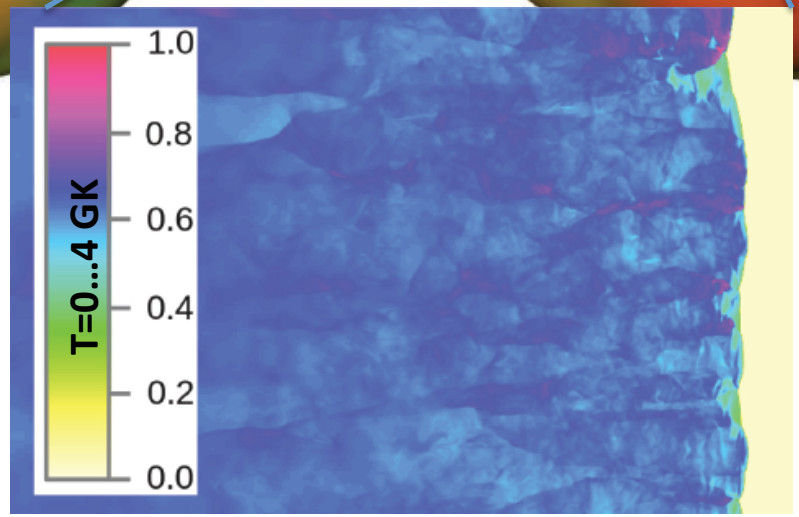
SNIa Flame Simulations

→ plume-like & far-reaching flame surface

Gamezo et al. 2003



3D Hydro sim
w subgrid approx
for flame dimensions



3D High-resolution
of flame,
"reactive flow" sim

Khokhlov et al. 2012

SN type Ia: How the Flame Proceeds

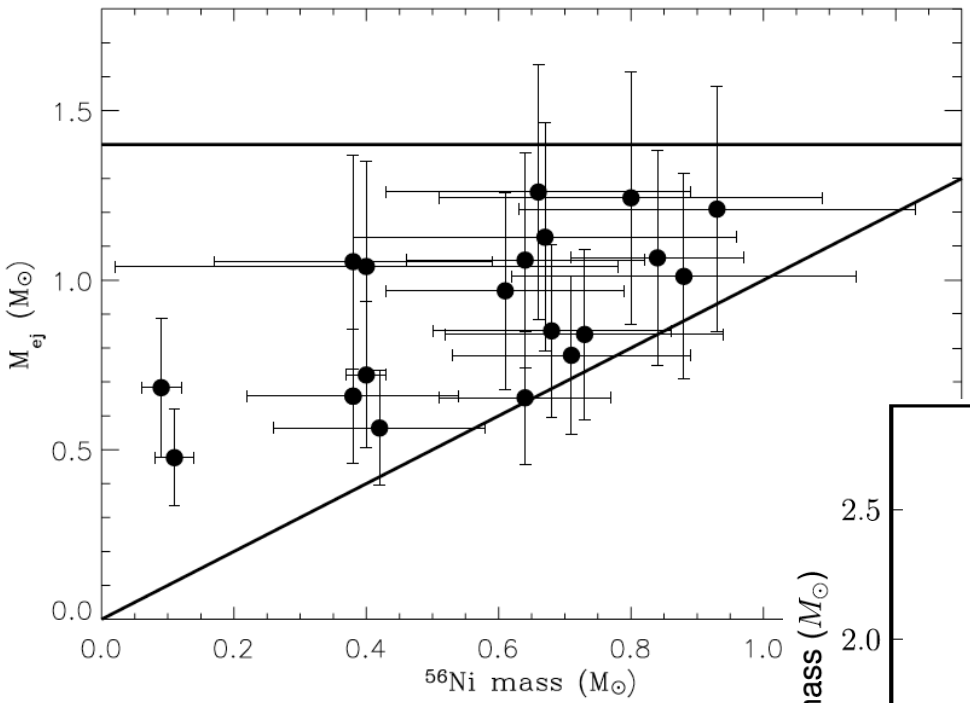
– Physical Processes:
  - Nuclear energy release, electron heat conduction
  - Rayleight-Taylor instabilities wrinkle burning front
  - Magnetic fields may quench turbulence

– Open Issues
  - Large scale plumes?
  - Mixing throughout the White Dwarf star?
  - Preconditioned WD structure?

SNIa Nucleosynthesis

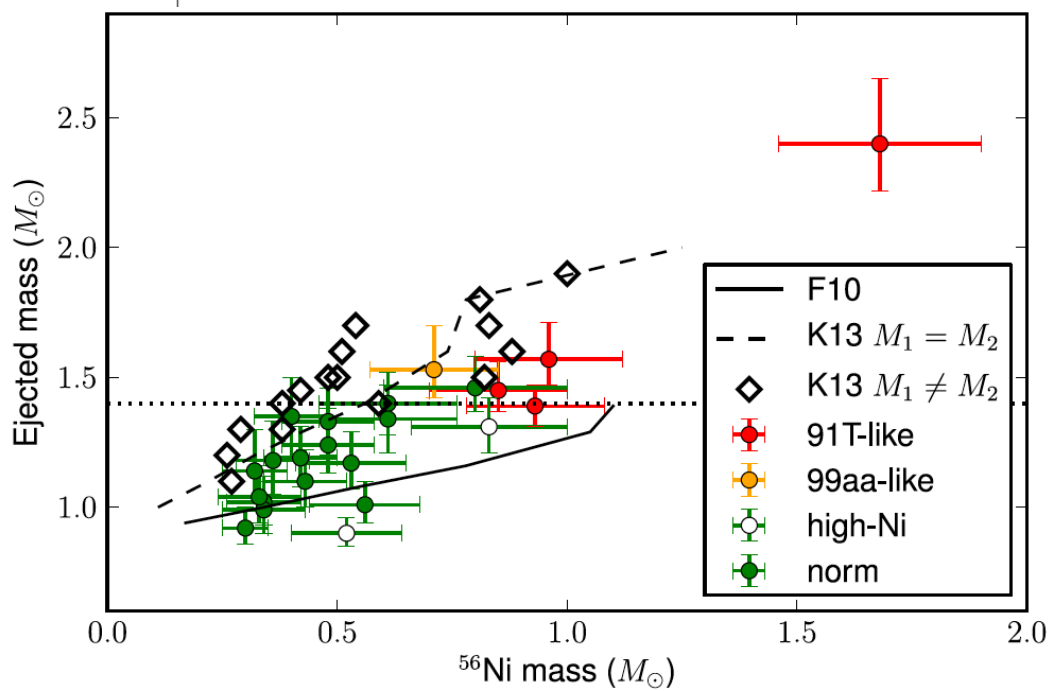
- Major amounts of ^{56}Ni

Stritzinger et al. 2006



- Inferrred from SN light indirectly
  - *Assumption: ~ spherical SN with ^{56}Ni in central region*

Scalzo et al. 2014



Gamma-Ray Lines from SN Ia

The gamma-ray luminosity of a typical type I supernova remnant has been calculated by assuming that the origin of the optical luminosity is due to the energy of the radioactive decay of Ni^{56}. It is expected that Ni^{56} is the most abundant nucleus resulting from silicon burning in the supernova shock conditions. The requisite mass of Ni^{56} (0.14 $M_\odot$) gives rise to gamma-ray lines with energies near 1 MeV that should be detectable in young supernova remnants at distances up to a few Mpc. Future detectors aboard satellites should be able to detect events at the rate of about two observable events per year. A few supernova remnants in the Galaxy should be observable at all times in lines following the decay of Ti^{44}.

THE ASTROPHYSICAL JOURNAL, Vol. 155, January 1969

GAMMA-RAY LINES FROM YOUNG SUPERNOVA REMNANTS

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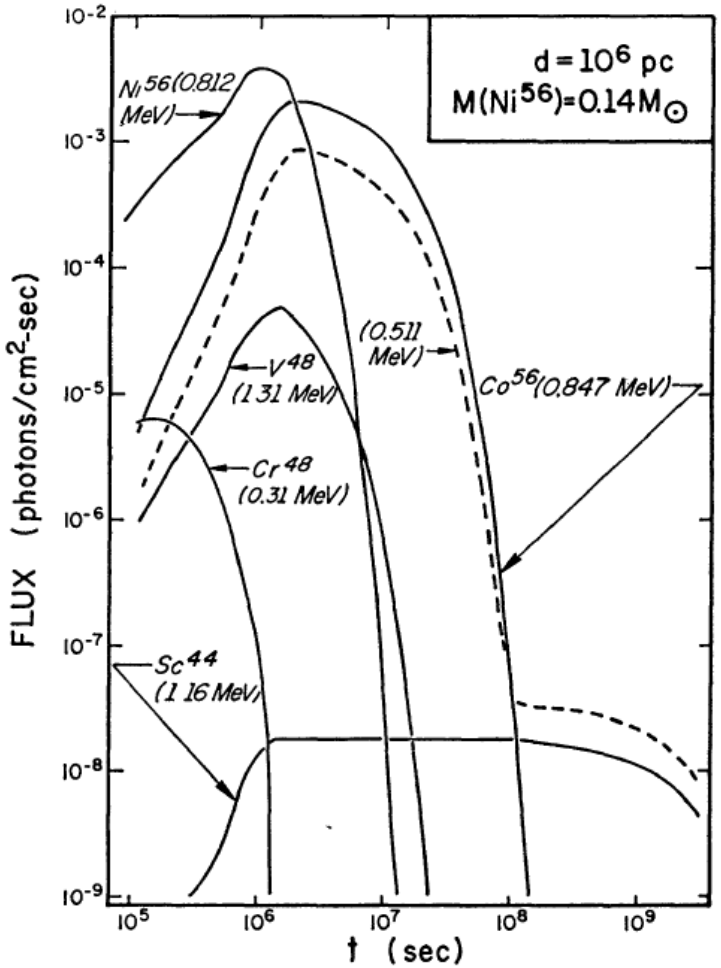
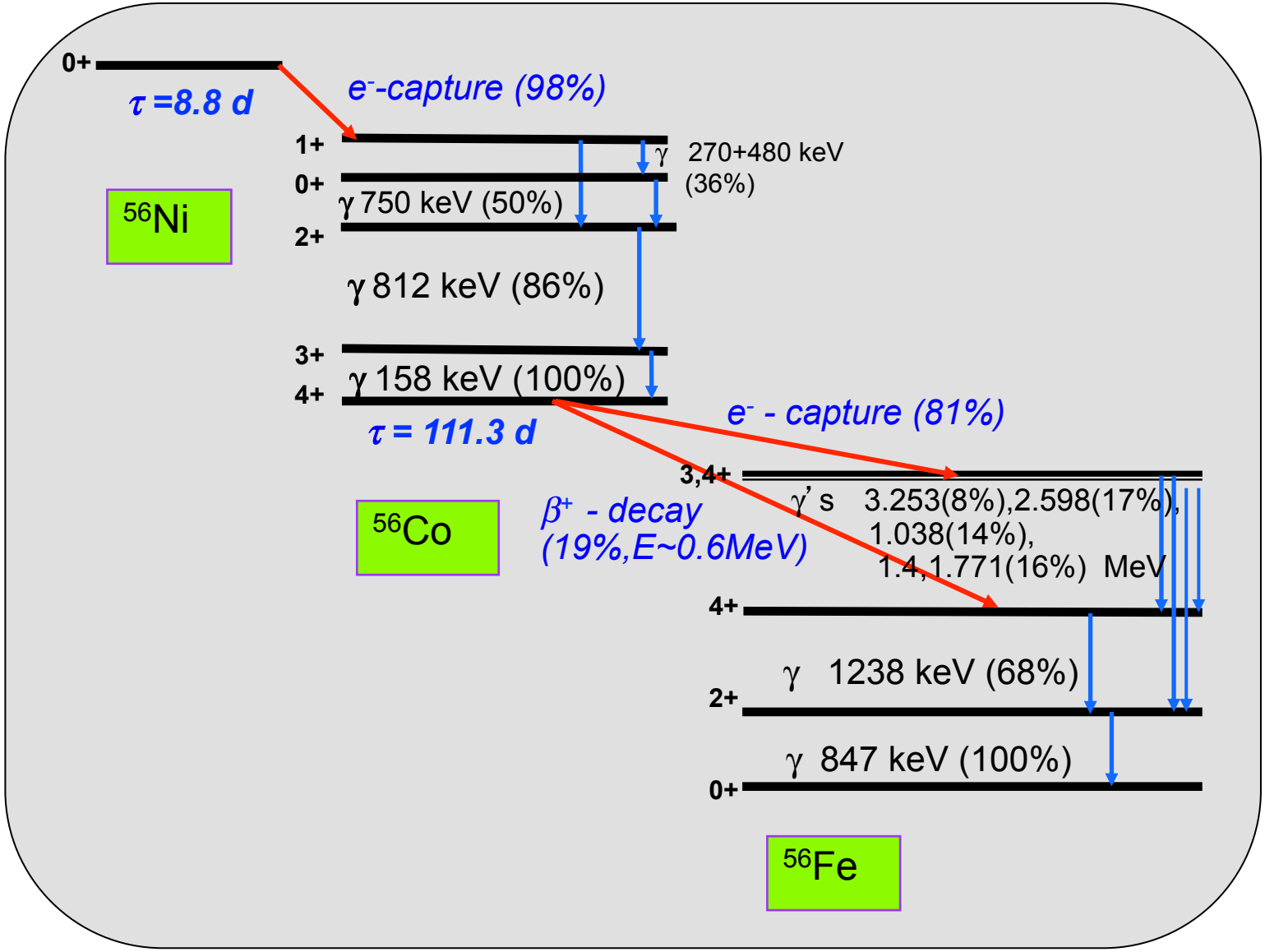
AND

GERALD J. FISHMAN
Rice University, Houston, Texas

Received May 20, 1968; revised June 24, 1968



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

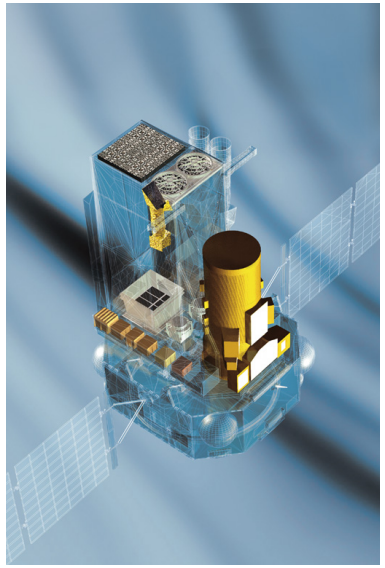
- 

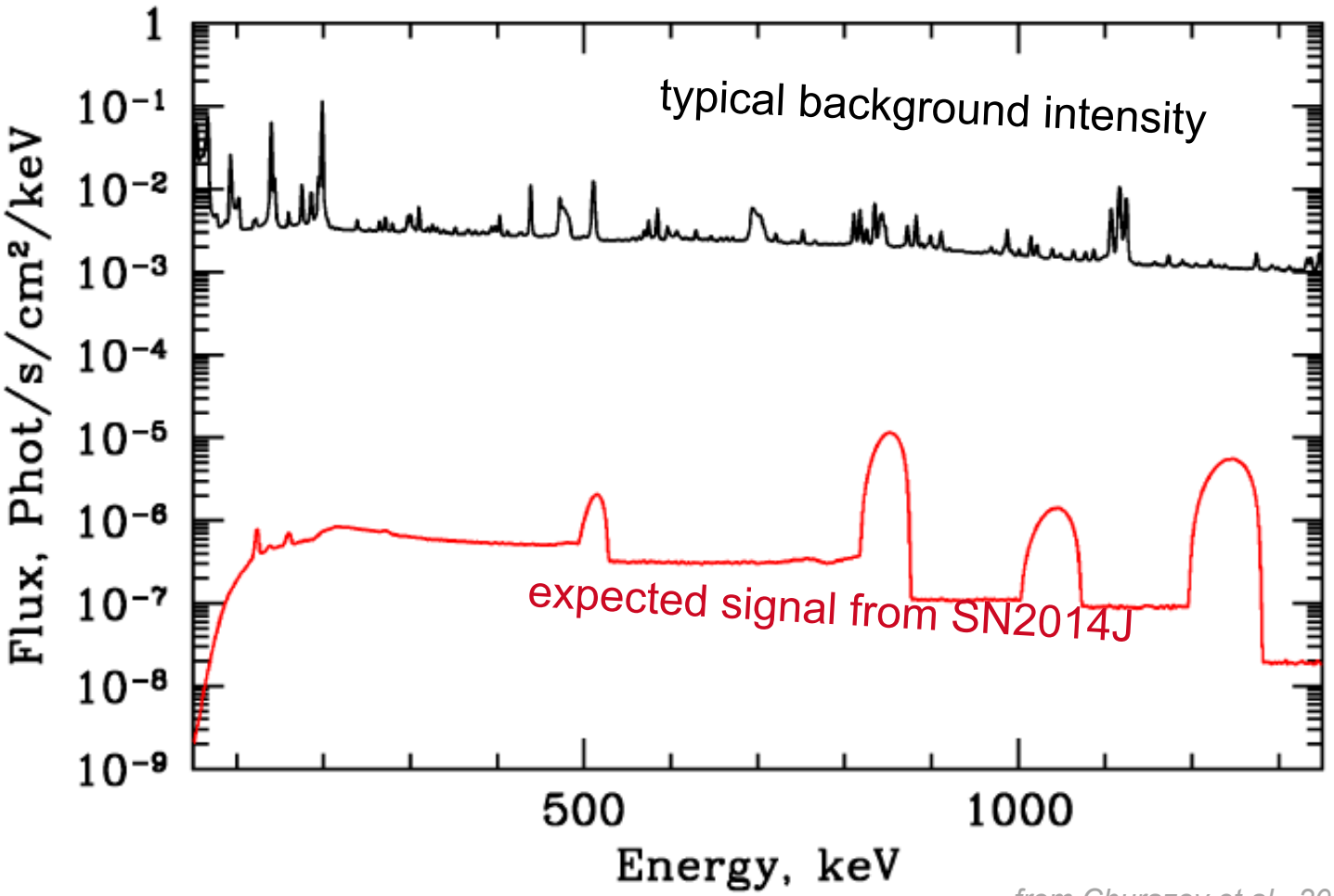
- Nuclear BE release $0.6M_{\odot}$ C,O→^{56}Ni: ~1.1 10^{51} erg (>2*BE_{WD})

The Challenge of Finding SN2014J Gamma-Rays

– Current Gamma-Ray Telescopes Have Large Intrinsic Background

- Cosmic Ray Activation of Spacecraft and Instrument





from Churazov et al., 2014

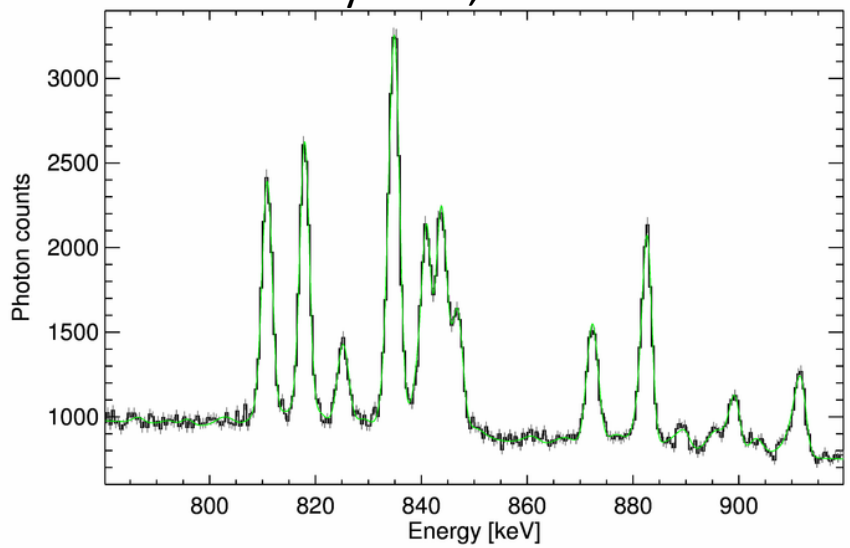
SN2014J Data Analysis

new – Background modeling from detailed mission data spectroscopy
→ exploit physics of lines → consistent high-resolution model

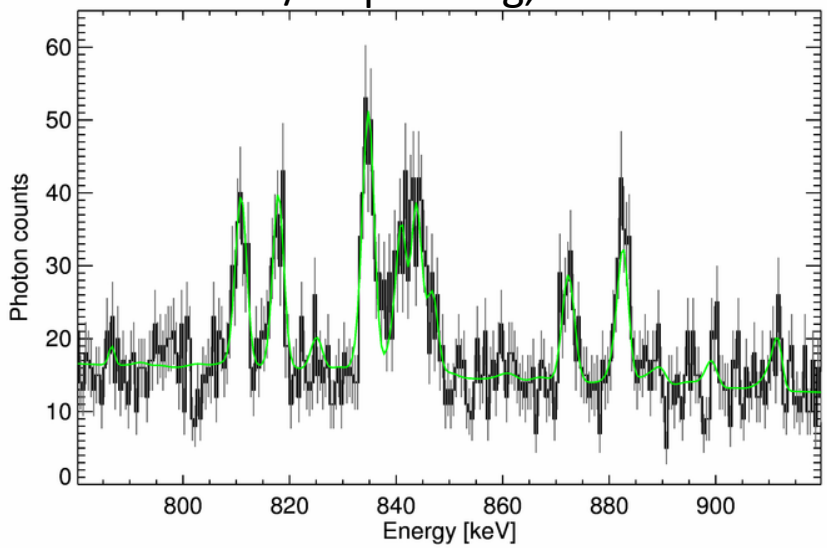
T Siegert, thesis TUM (2013)

- Integrate data over 3 days
- Fit spectra in detail (continuum, lines, steps…)
- Fix spectral-shape and detector ratio parameters *(←physics!)*
- Normalize the spectral-feature template per pointing, and apply individual-detector responses *(degradation & annealing!)*

One 3-day orbit, one detector



One 1/2h pointing, one detector



SN2014J Data Analysis

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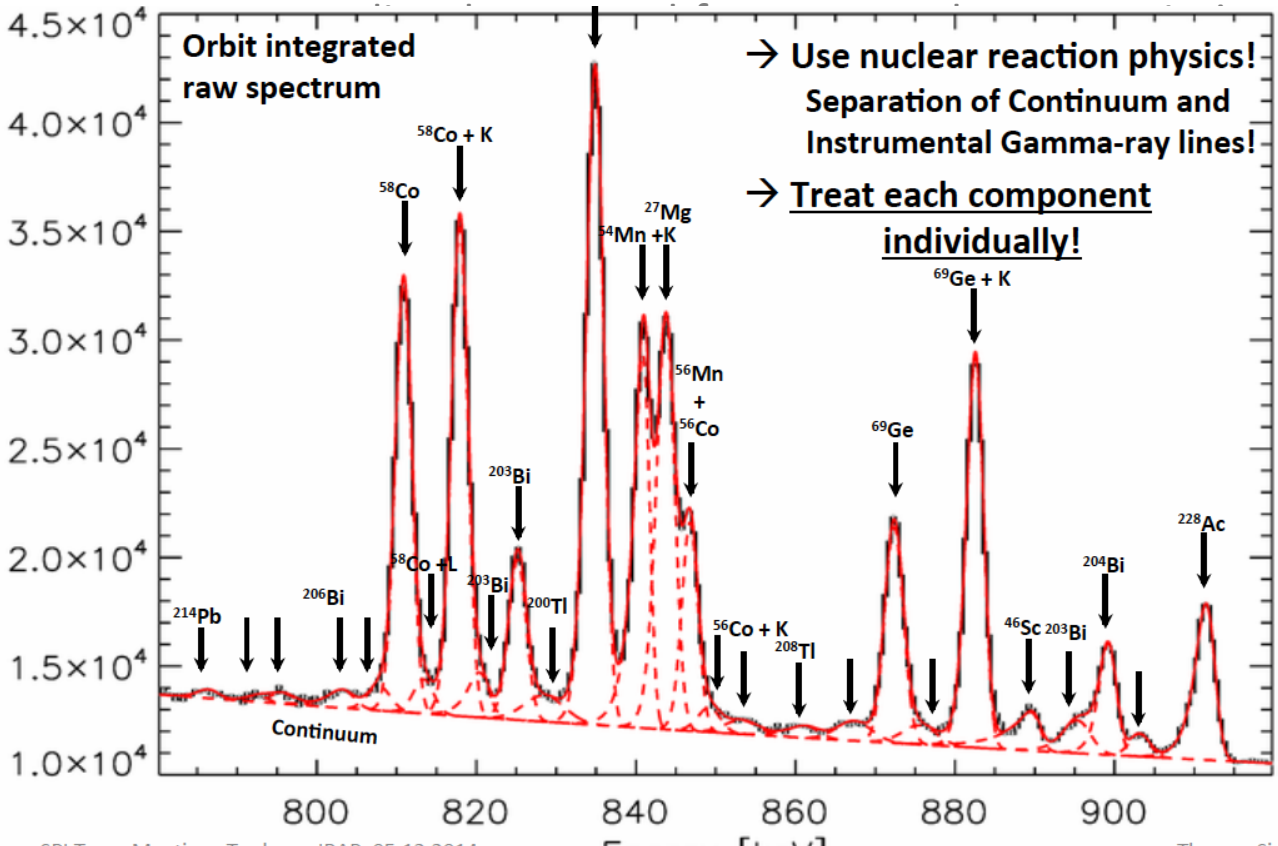
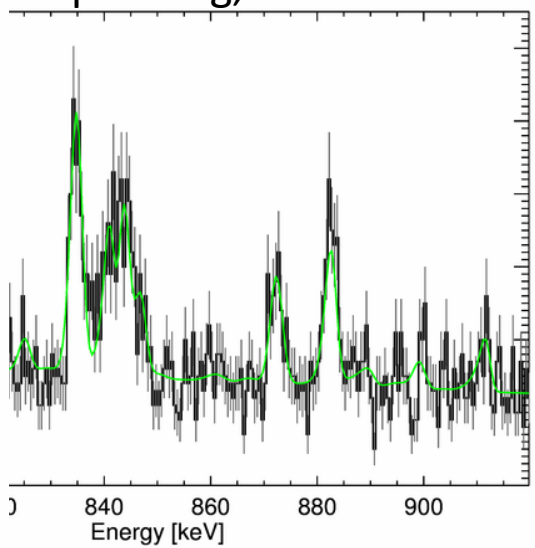


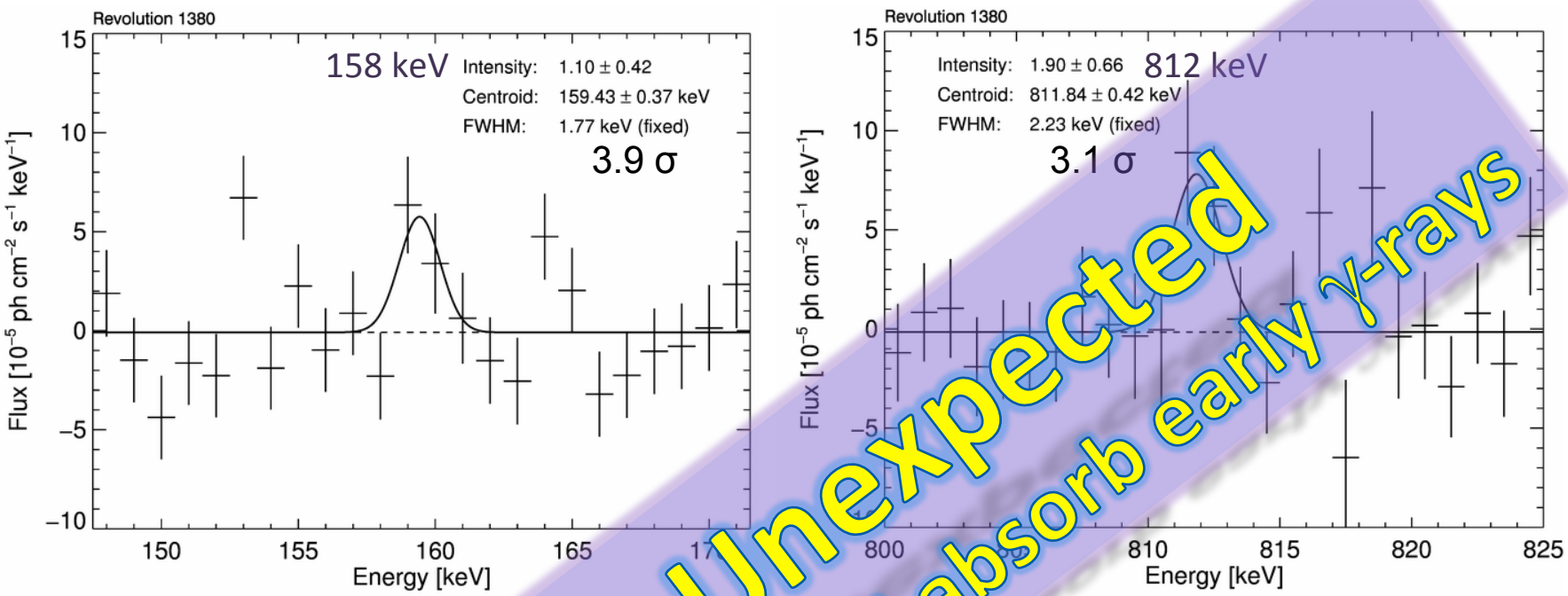
gradation & annealing!)

2h pointing, one detector



SN2014J: Early ^{56}Ni

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

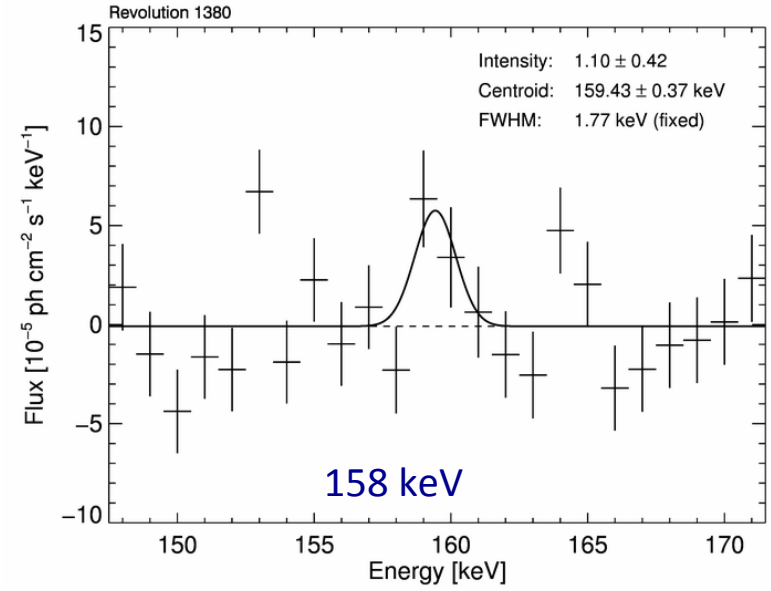


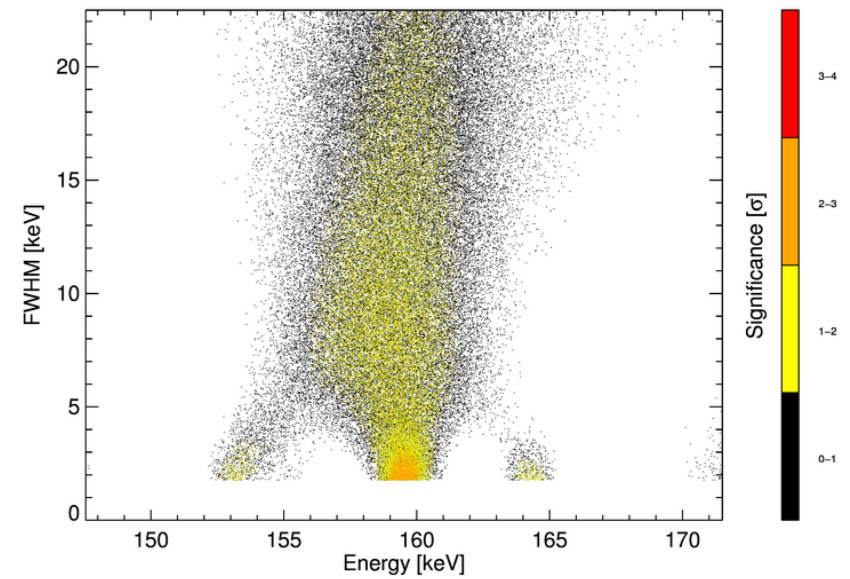
Unexpected

SN should absorb early γ-rays

  - 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 (backscattered explosion): ~0.06 $M_\odot$

Line Uncertainties: Search and method biases



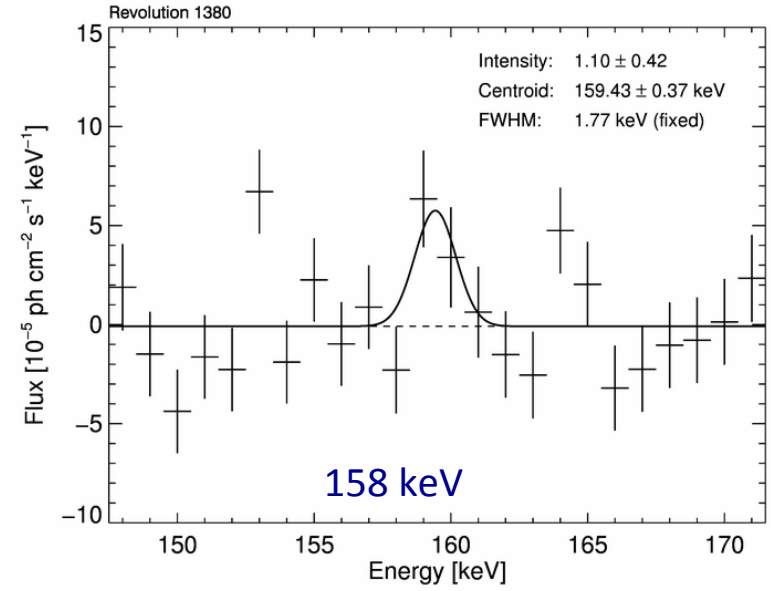


- Random Search: Try to Fit a Line (Centroid,Intensity, Width)

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

☞ Narrow line, ~unshifted

Line Uncertainties: Search and method biases



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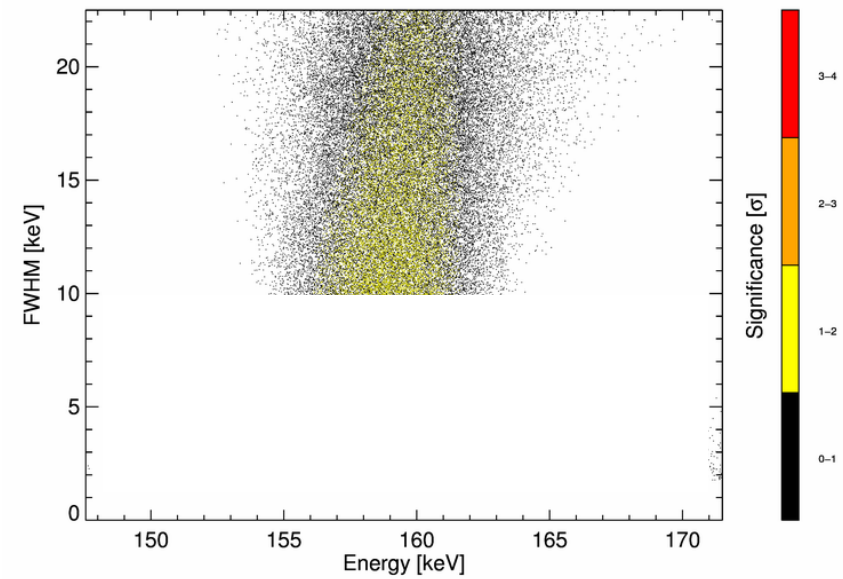


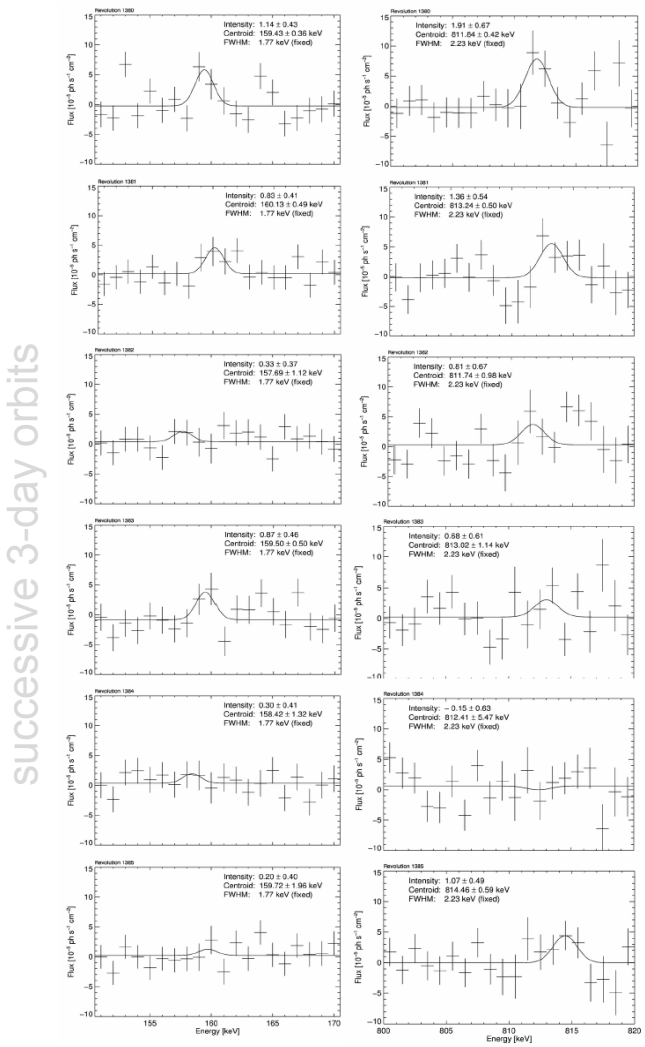
☞ Narrow line, ~unshifted

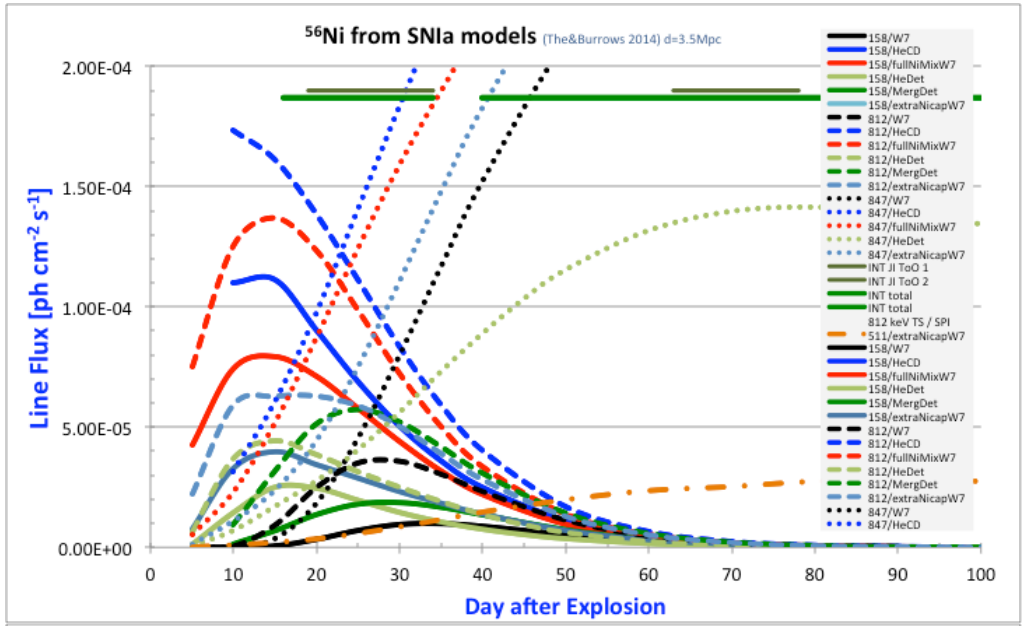
? or ?

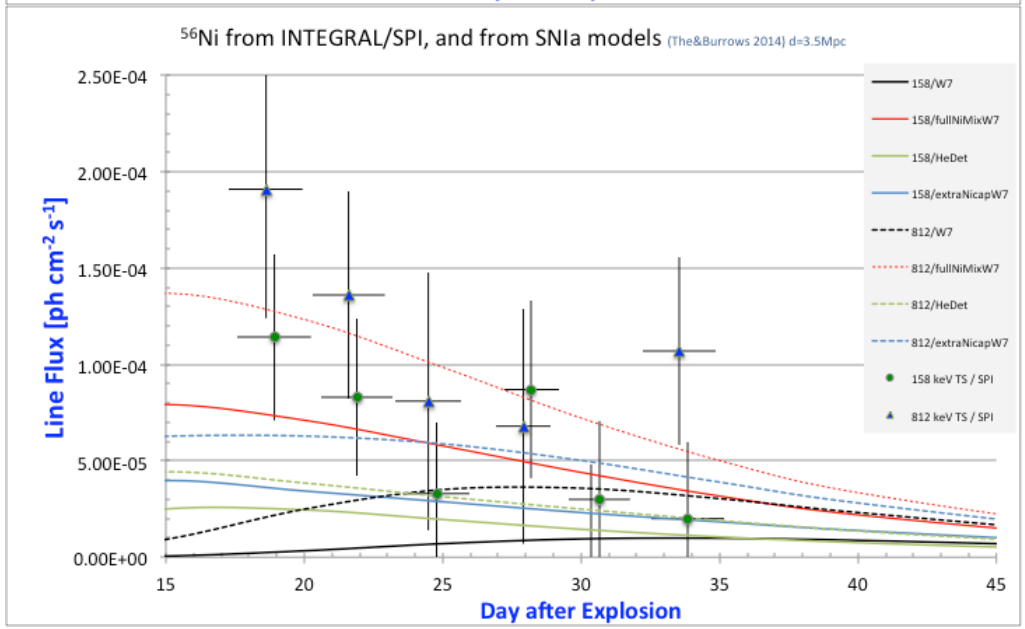
☞ Broad & redshifted line

SN2014J: Early ^{56}Ni-decay

- Spectral evolution:

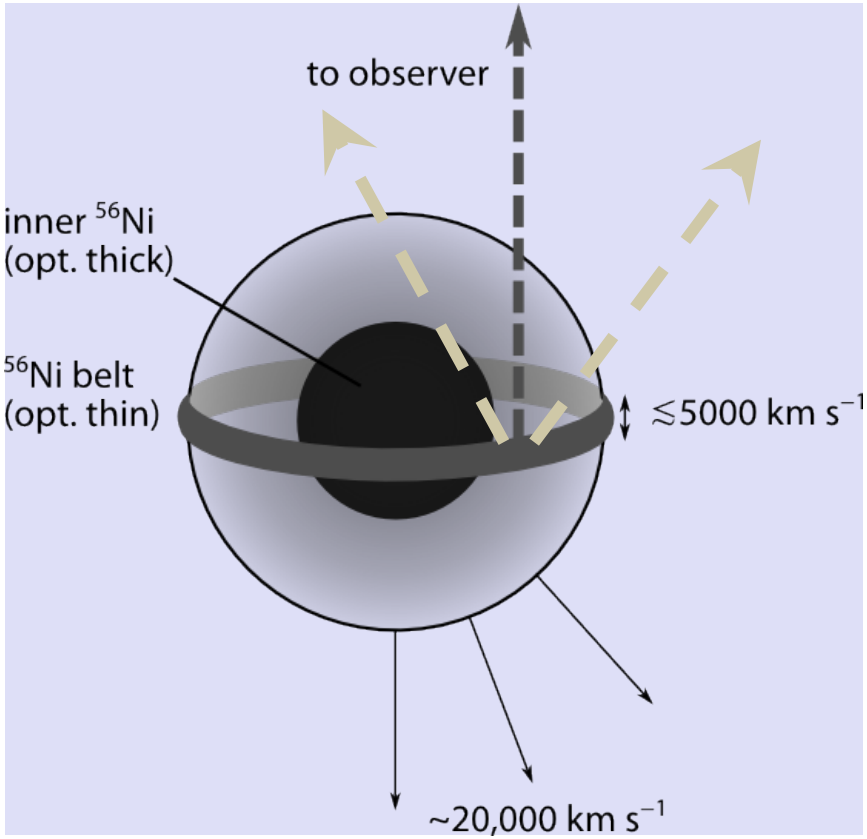






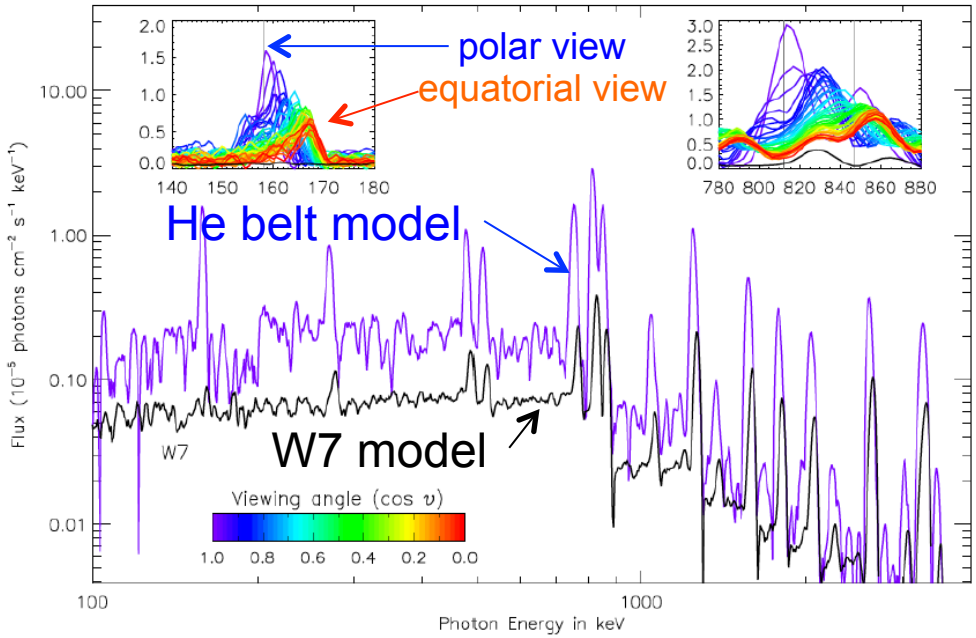
SN2014J: An unusual explosion?

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

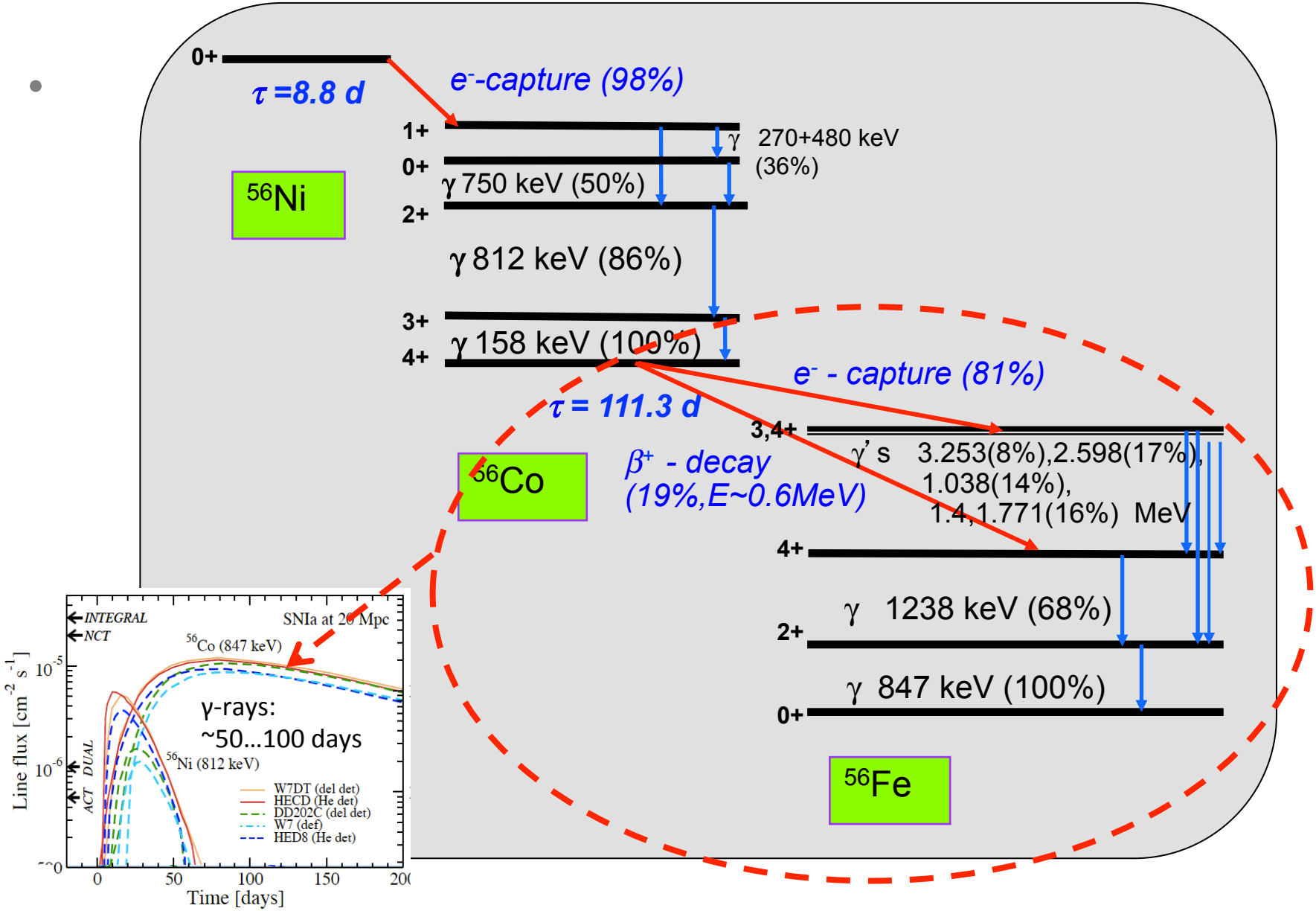


Simulating how an exploding belt of accreted He would be observed in gamma-rays:
Polar viewing → unshifted lines
Equatorial viewing → blue shift

Markus Kromer

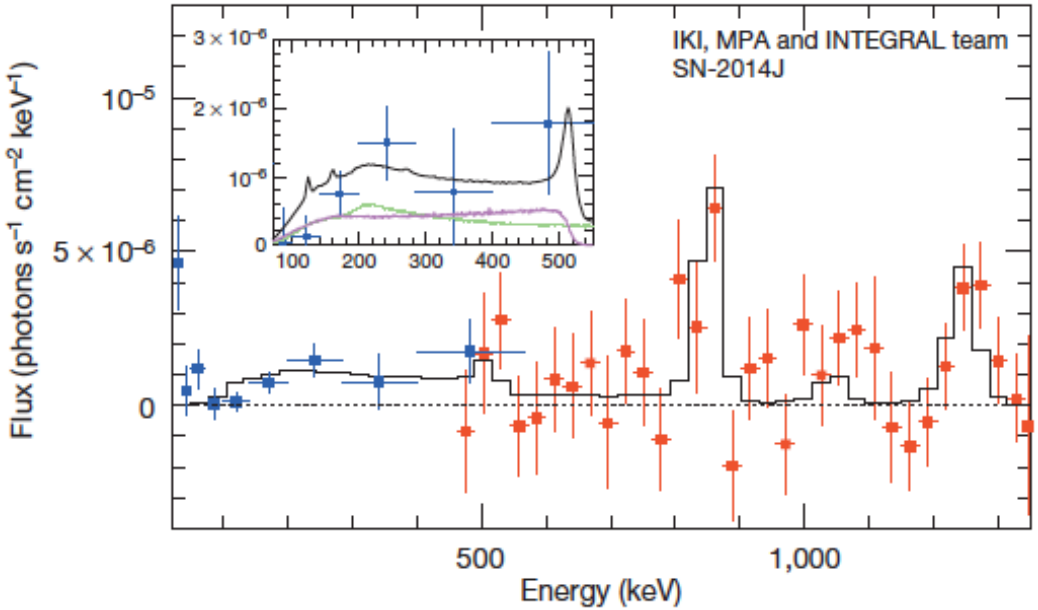


^{56}Ni Radioactivity Decay Chain and Gamma-Rays



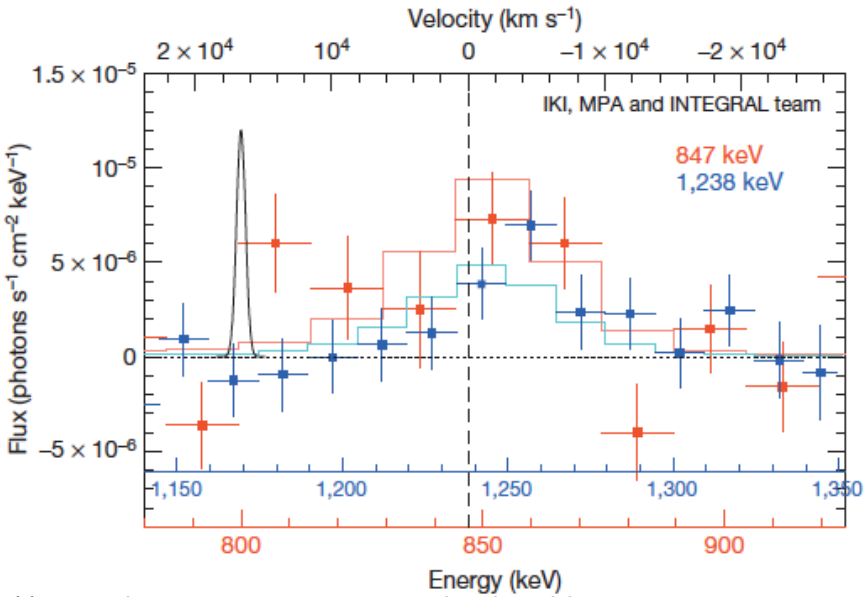
SN2014J data Jan – Jun 2014: ^{56}Co lines

– Detection of 847 and 1238 keV lines from ^{56}Co decay at days 50-100



– Confirm SNIa model

– Significantly Doppler-broadened



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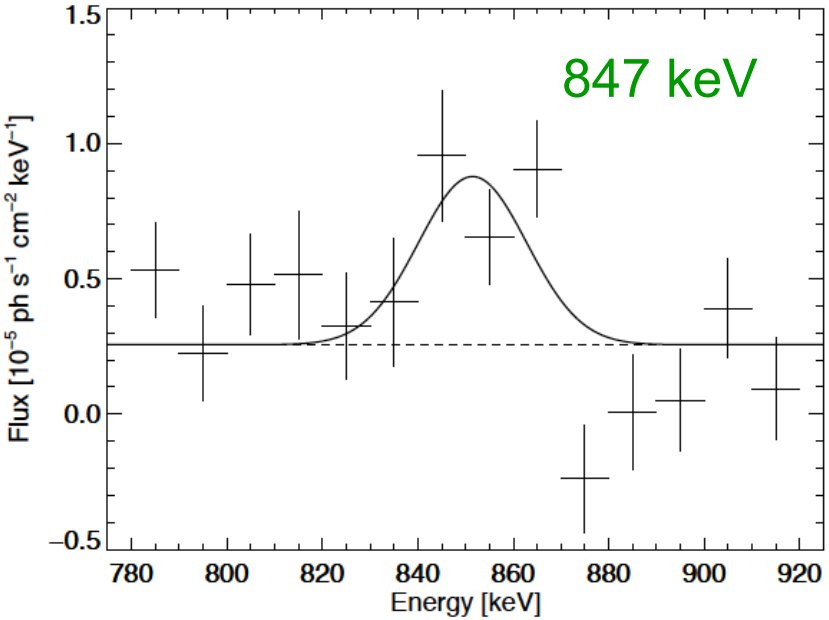
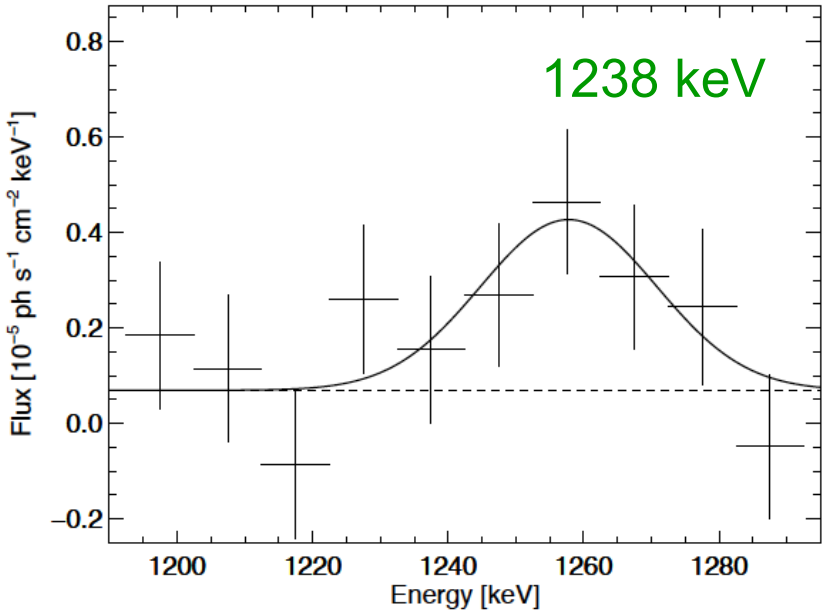


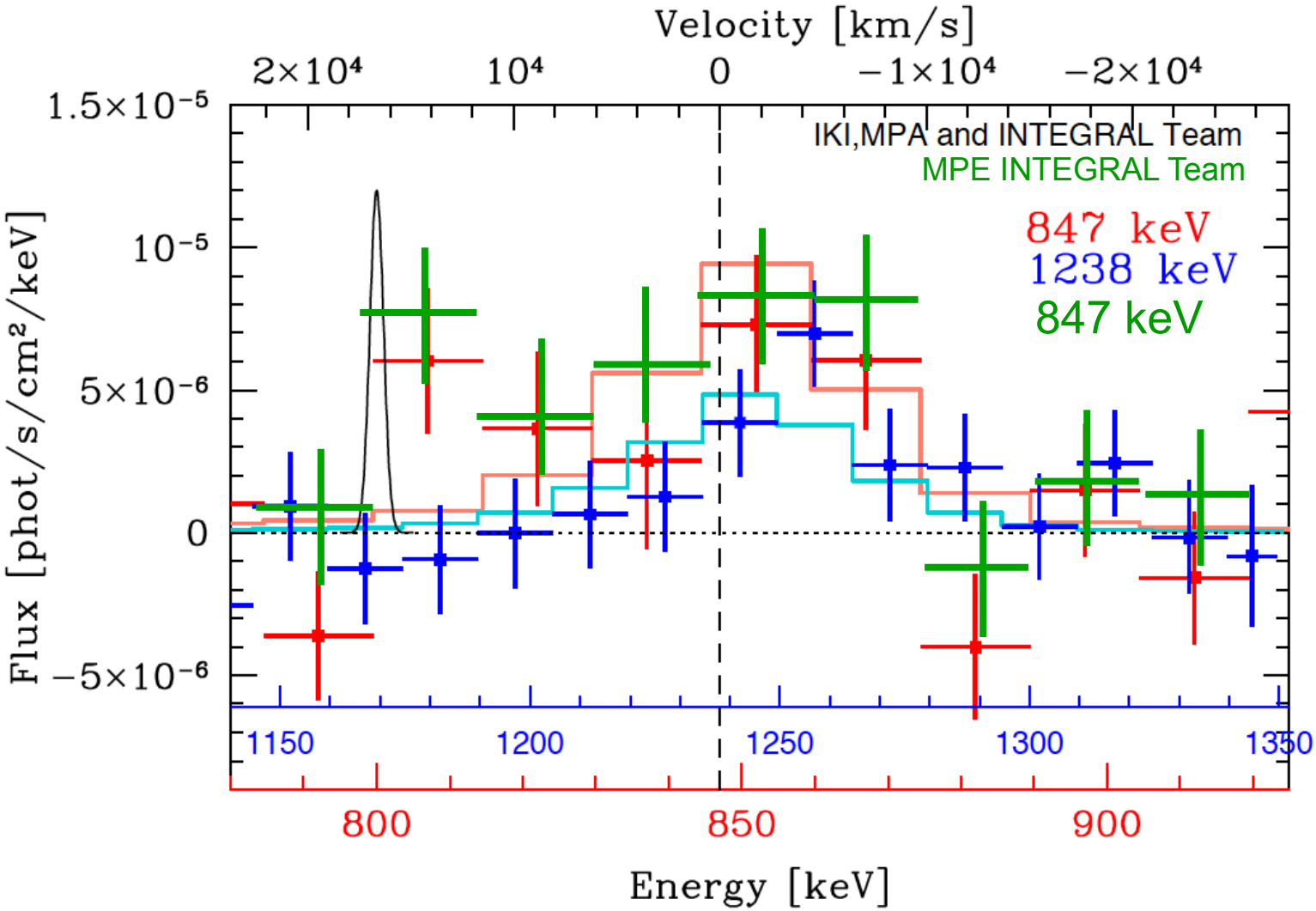


– Significantly Doppler-broadened

- *Diehl et al., A&A (2015), days 17-134*
- ~ as reported by *Churazov et al. 2014*

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

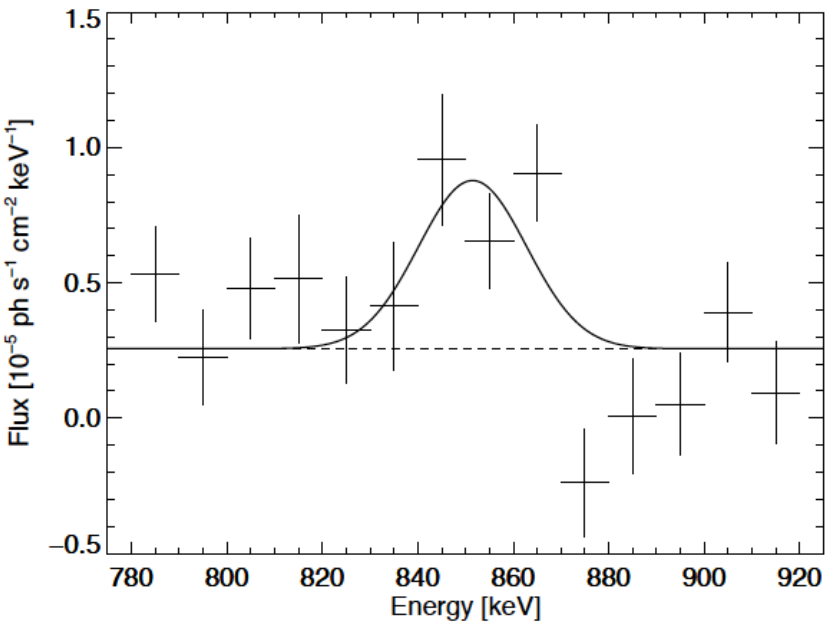
- INTEGRAL Obs from 31 Jan till 26 Jun 2014

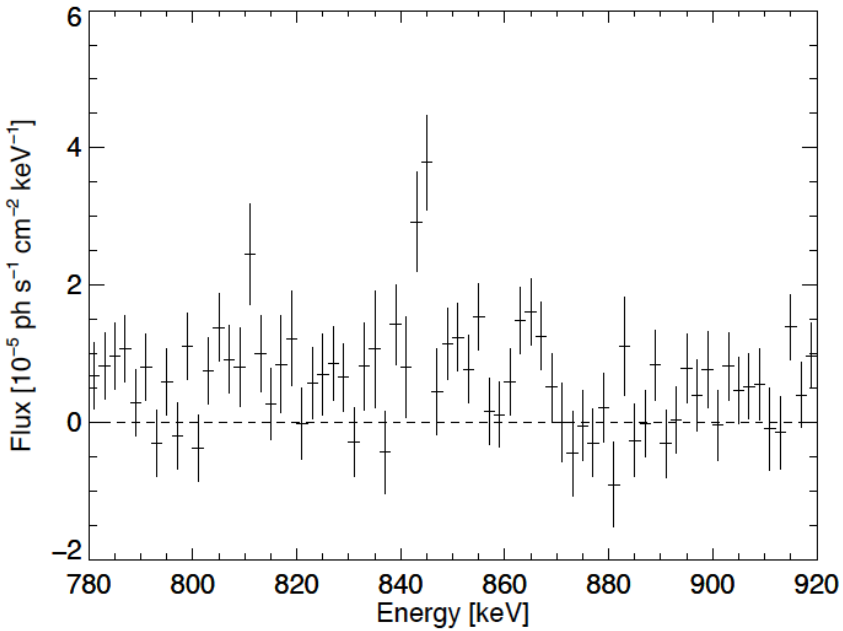


SN2014J data Jan – Jun 2014: ^{56}Co lines

– The 847 keV line from ^{56}Co decay

- Different spectral binning





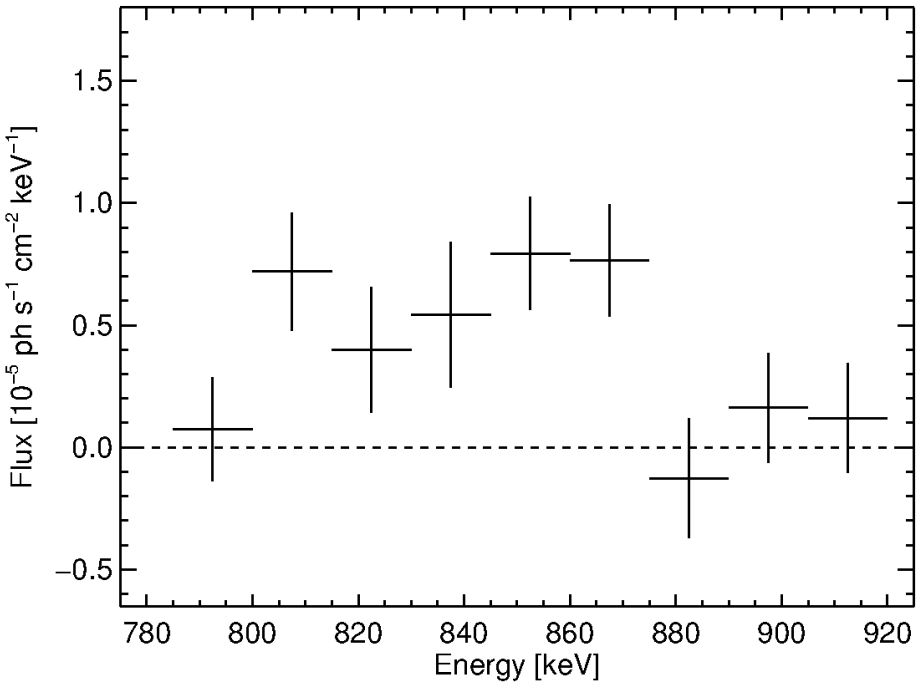
→ Structured spectrum – all from the broadened 847 keV line?

- *Diehl et al. 2015*

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

– The 847 keV line from ^{56}Co decay

– Different spectral binning

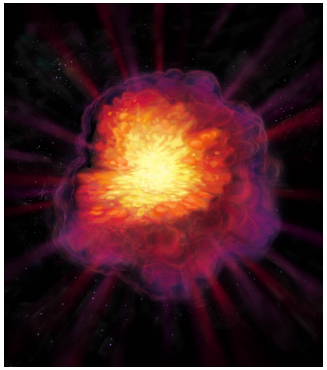


→ Structured spectrum – all from the broadened 847 keV line?

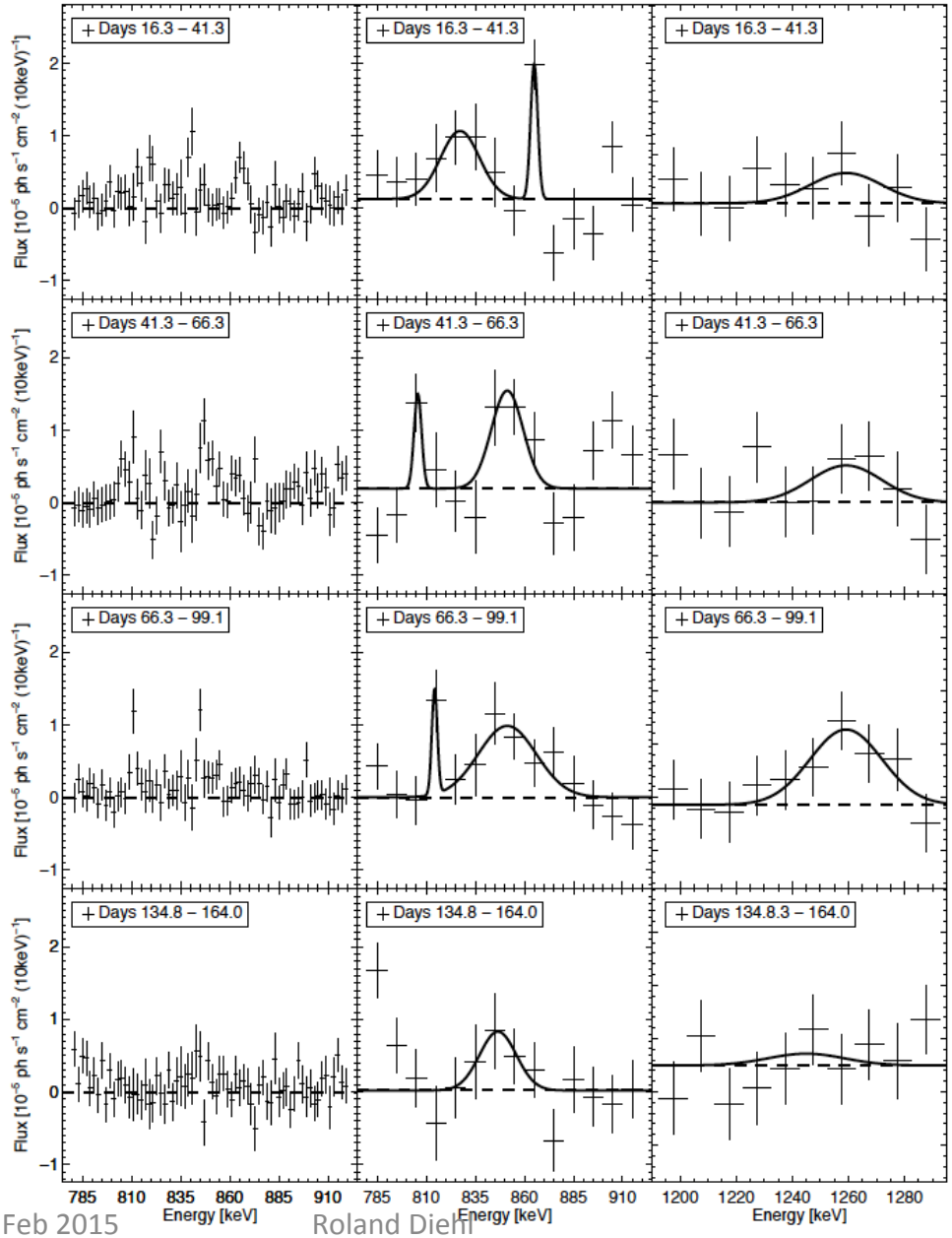
- *Diehl et al. 2015*

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

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



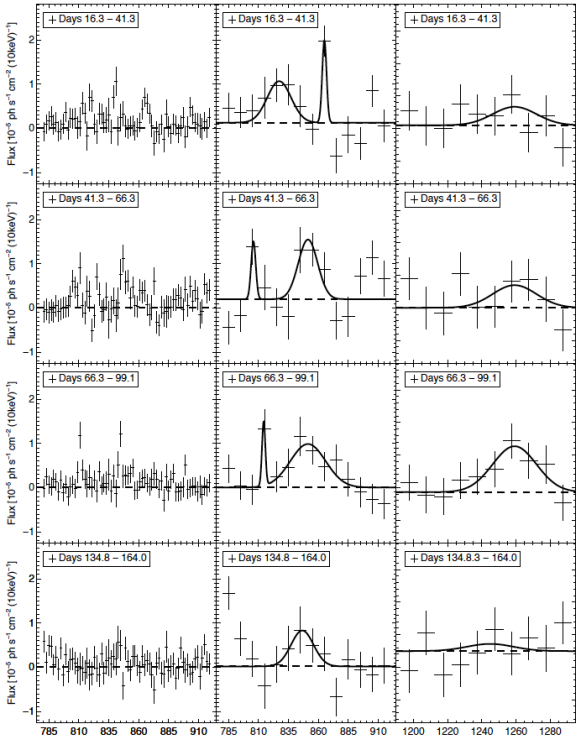
- Structured and evolving spectrum
  - all from broadened ^{56}Co decay lines?



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

Time history of ^{56}Co line emergence

- At high spectral resolution, the appearance of the Co lines shows up more irregular than a 1D model would suggest
- The line as seen in the transparent phase is in (mild) contradiction with the emission at earlier (semi-transparent) epochs



Epoch	$\chi^2_{\rm best}$ (d.o.f.)	$\chi^2_{\rm alltimes}$ (σ)	$\chi^2_{\rm from4thepoch}$ (σ)
1	12.62 (6)	42.05 (4.28)	42.93 (4.36)
2	17.77 (6)	27.48 (1.73)	29.35 (2.04)
3	5.77 (6)	15.37 (1.71)	15.79 (1.78)
4	24.78 (9)	25.54 (0.41)	– (–)

Epoch	$\chi^2_{\rm best}$ (d.o.f.)	$\chi^2_{\rm alltimes}$ (σ)	$\chi^2_{\rm from4thepoch}$ (σ)
1	48.36 (62)	66.85 (3.04)	66.82 (3.03)
2	66.90 (62)	77.73 (1.92)	76.58 (1.72)
3	43.22 (62)	60.95 (2.94)	58.81 (2.65)
4	50.66 (65)	51.18 (0.29)	– (–)

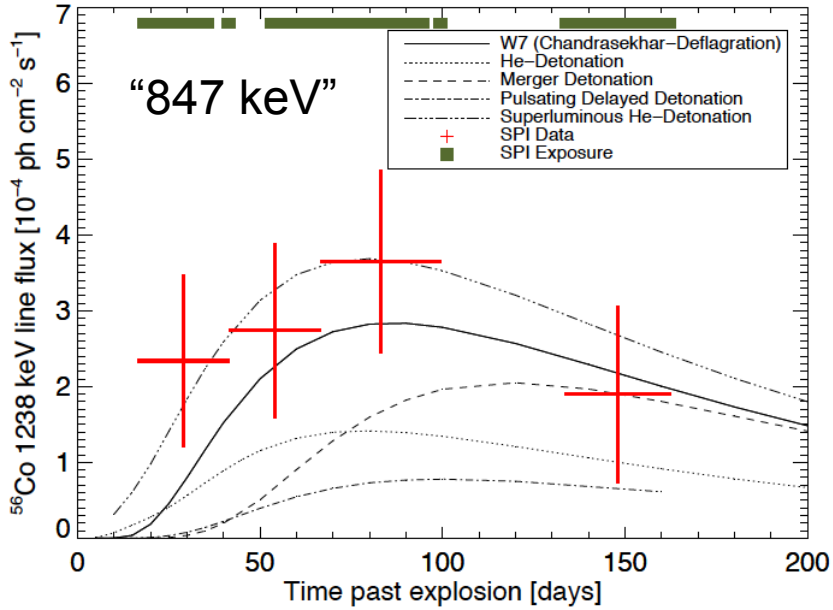
Notes. For each of the four observation epochs, we list the χ^2-values of the best fit (Col. 2; Gaussian with adapted centroid and width), then the intensity-fitted shape of the line as determined in the time-integrated results (Fig. 2) (Col. 3), and finally (Col. 4) the intensity-fitted line shape of the last epoch. The degrees of freedom of the fits are given in Col. 2 in brackets. The discrepancy of the thus-adopted line shape in each of the epochs is given in sigma units in brackets in Cols. 3, 4. The lefthand table gives the results for the 10 keV bin data (center column in Fig. 4), the righthand table gives the results for the 2 keV bin data (left column in Fig. 4)

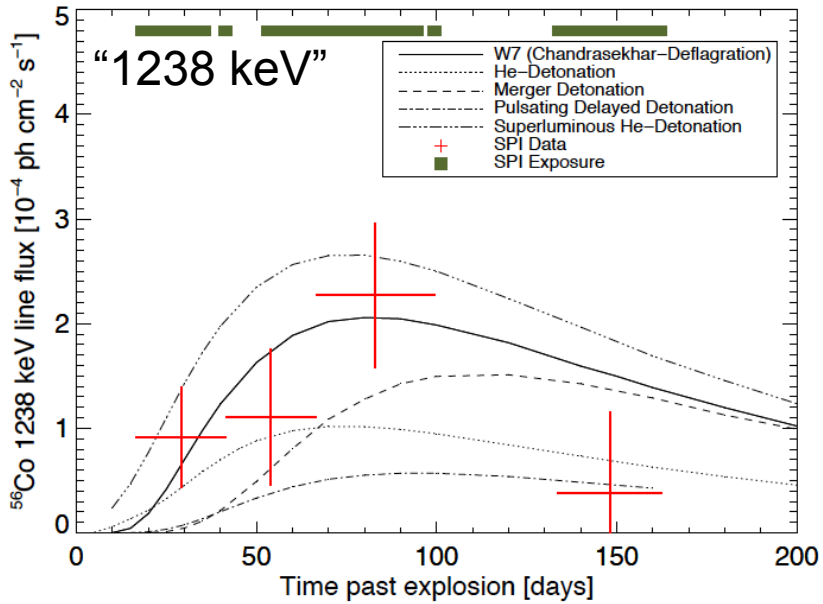
SN2014J data Jan – Jun 2014: ^{56}Co lines

- Brightness evolution of the ^{56}Co decay lines →
- Consistent brightness evolution of both lines
  - Ratio ~0.62 +/-0.28 (0.68)
- Plausible kinematics

time	bulk	spread
16.3–41.3	-6920±1480	5060±1330
41.3–66.3	1600±1720	3940±1260
66.3-99.1	1600±1600	7250±1560
134.8-164.0	-80±1870	4570±1840

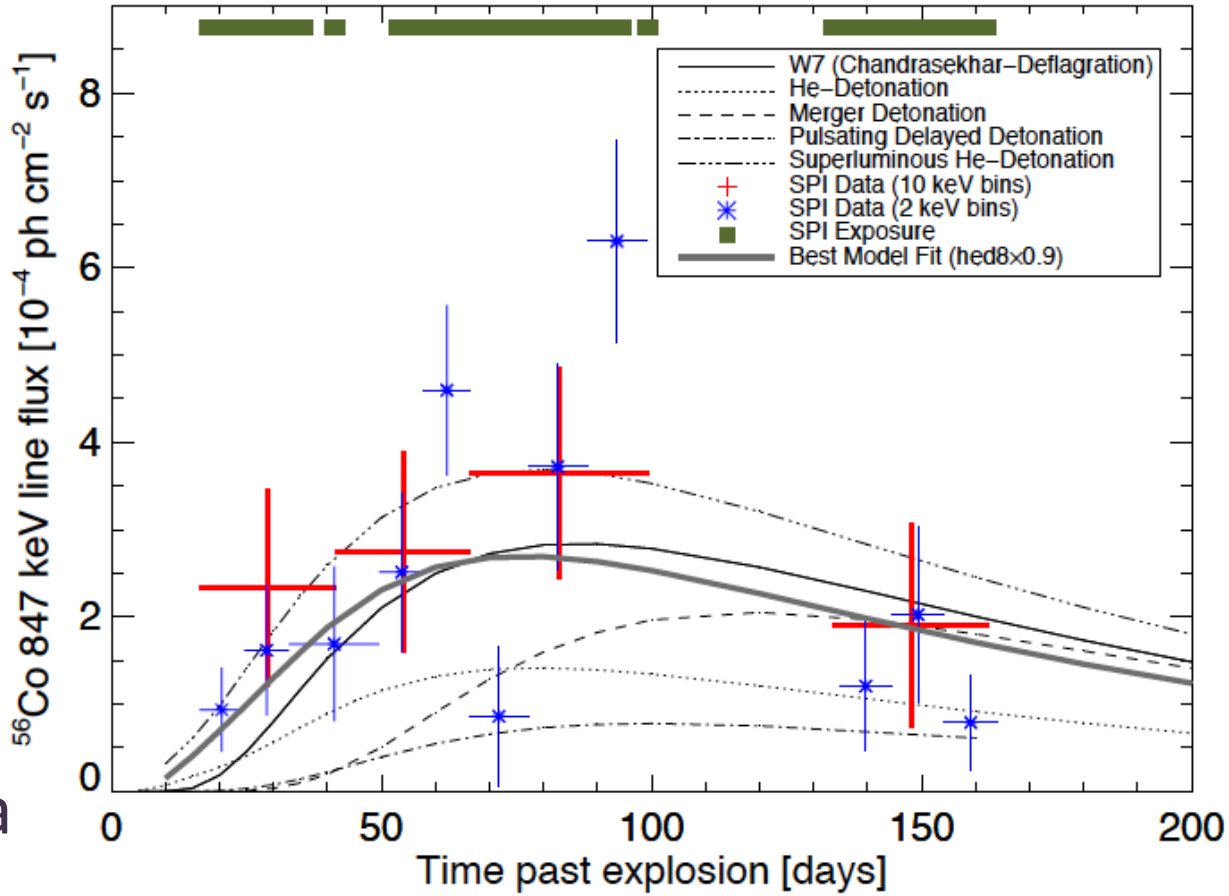
- ~Consistent with many plausible models
- *Choice of spectral "line emission" assignments may affect details*





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

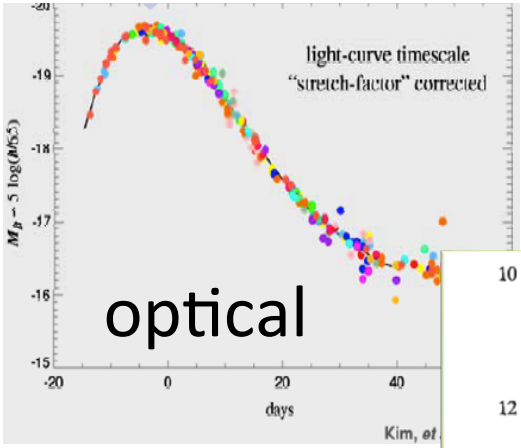
- ^{56}Ni mass (fitted): 0.49 +/-0.09 $M_\odot$

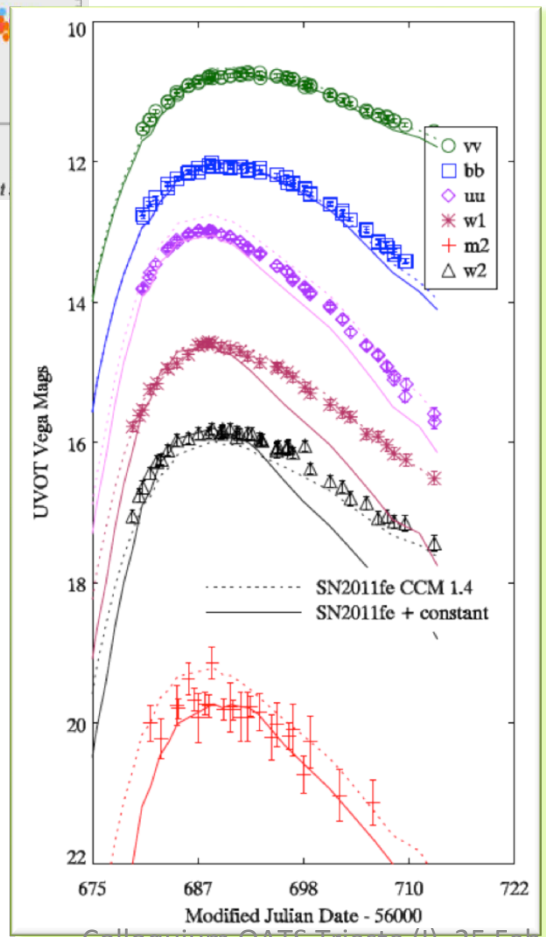
(cmp from bol. Light → 0.42 +/-0.05 $M_\odot$

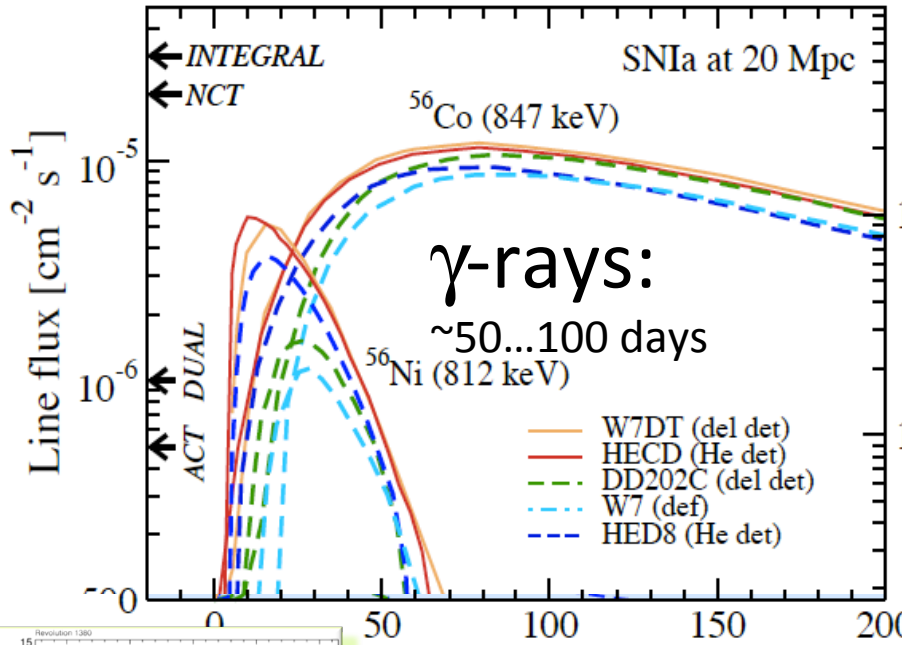
- *Diehl et al., A&A 2015*

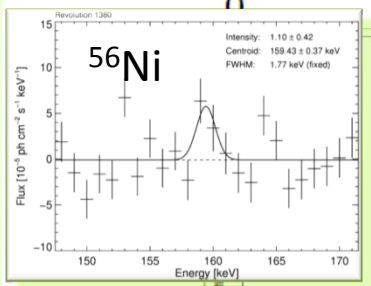
SNIa Light: Radioactivity Gamma-Rays Make Optical Emission

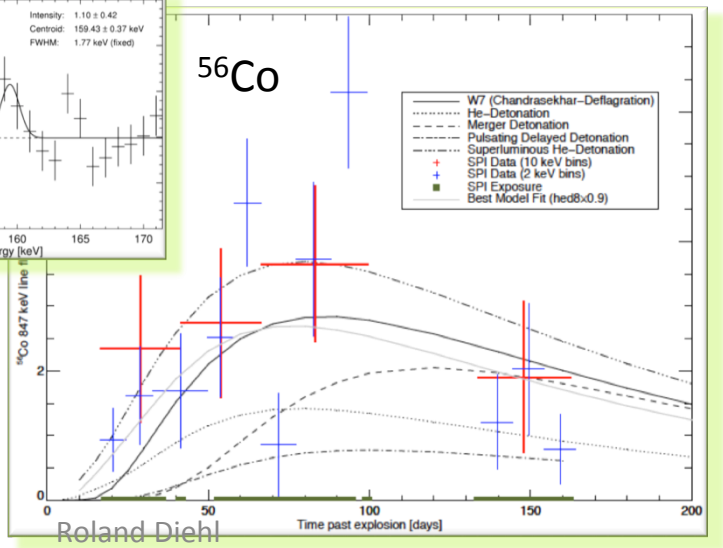
→ SN2014J in multi-wavelength data ✔











SN2014J: a unique opportunity

- Multiple observing windows
- Proximity → Detailed observational constraints

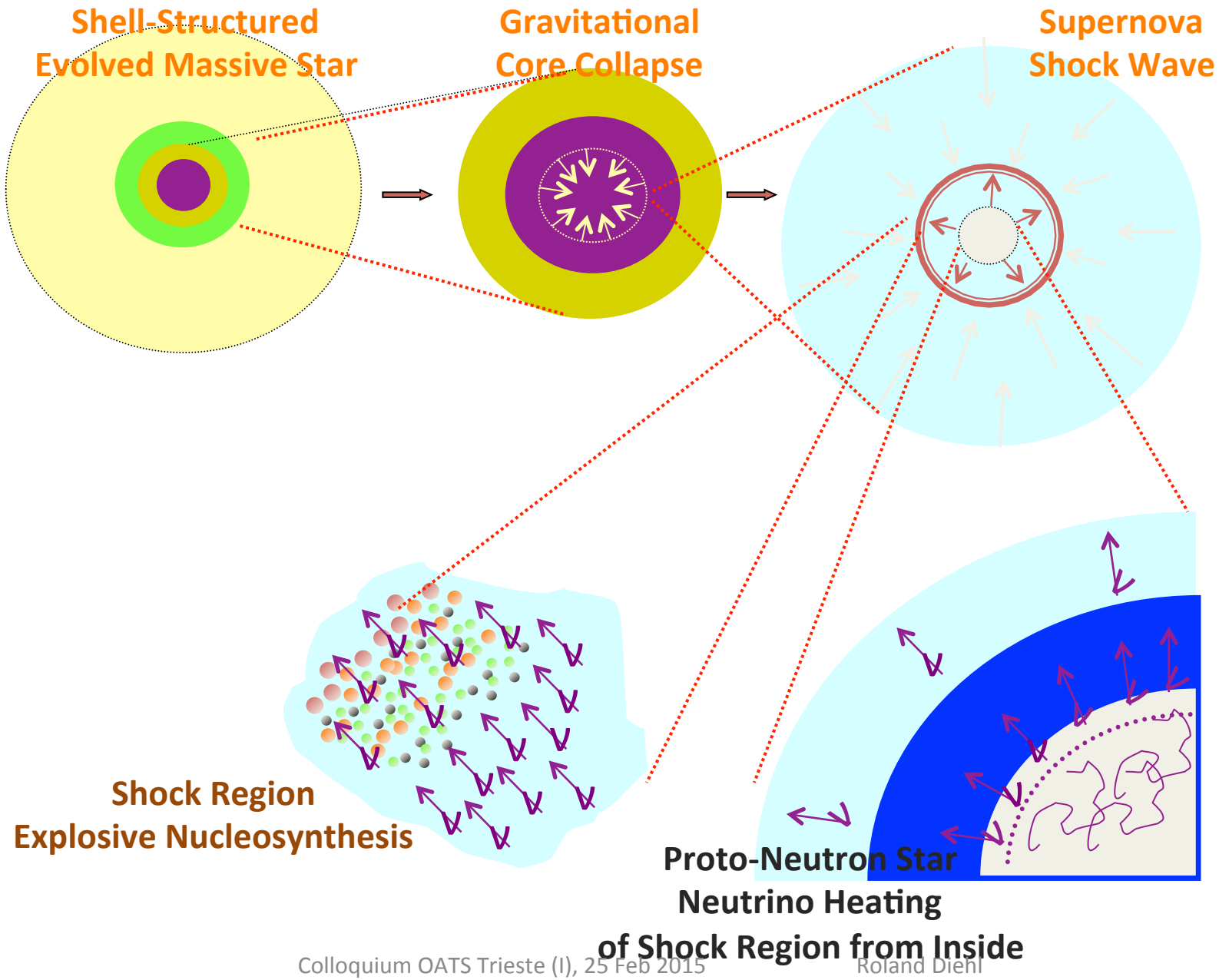
→Understand this supernova Ia and its origin?

  - Anomalies in light evolution with time
  - Polarization
  - Search for companion
  - Search for progenitor
  - …

Supernovae

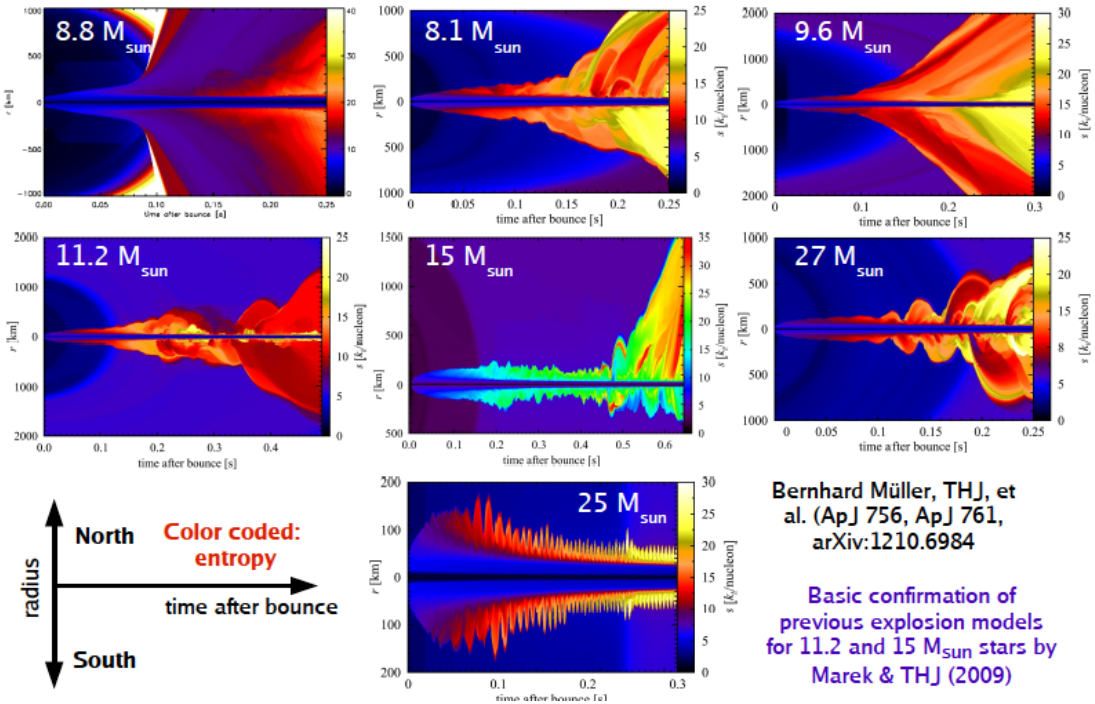
- Core Collapse

Nucleosynthesis in CC-Supernova Models



Core-Collapses: Supernova Explosions (?)

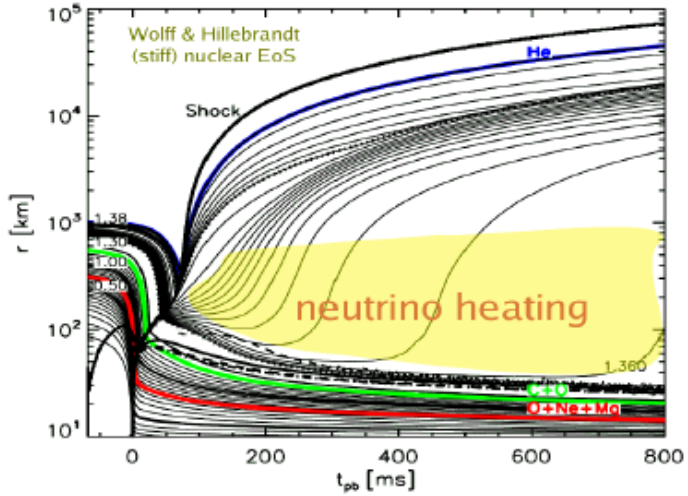
- 1D Simulations → SNe (EC) from ~8-10 $M_\odot$ Stars
- 2D Simulations → SNe across 10-25 $M_\odot$ Stars by x Groups
  - SASI, n's, G modes → 3D-effects
- 3D Simulations → ???



Bernhard Müller, THJ, et al. (ApJ 756, ApJ 761, arXiv:1210.6984

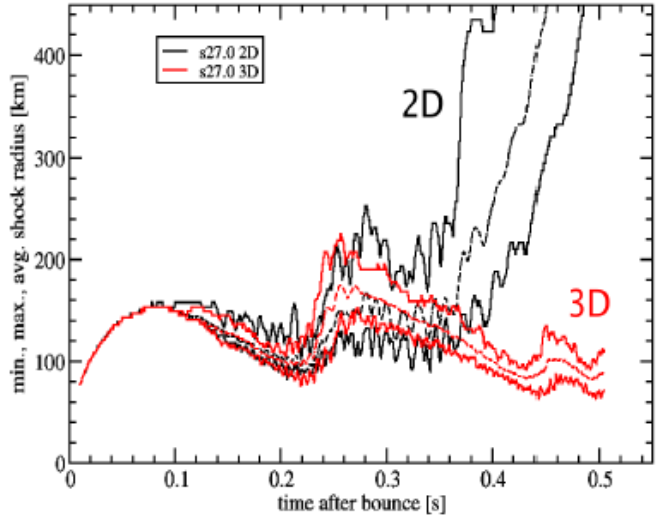
Basic confirmation of previous explosion models for 11.2 and 15 M_{sun} stars by Marek & THJ (2009)

"Electron-capture supernovae"
or "ONeMg core supernovae"

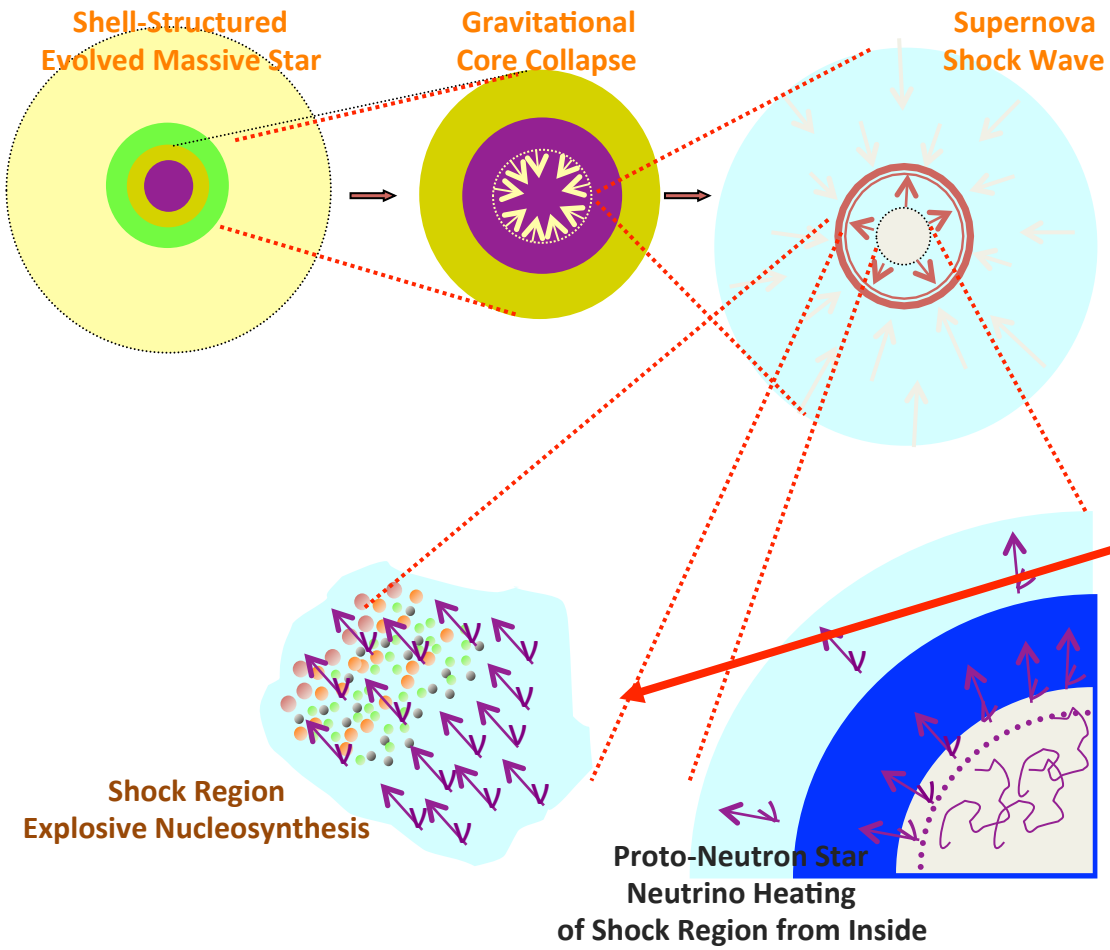


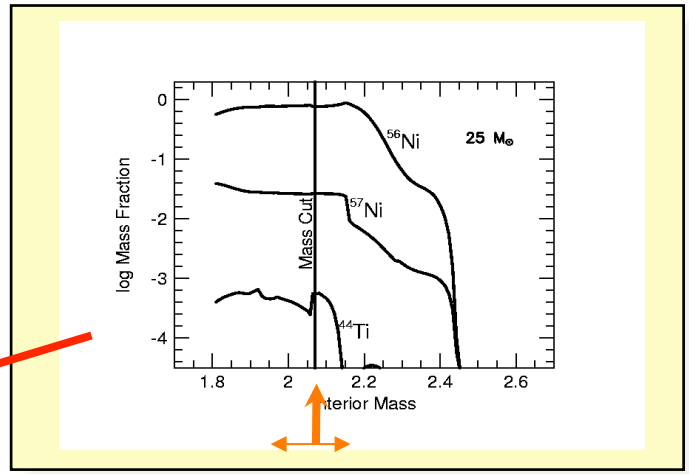
Kitaura et al., A&A 450 (2006) 345; Janka et al., A&A 485 (2008) 199

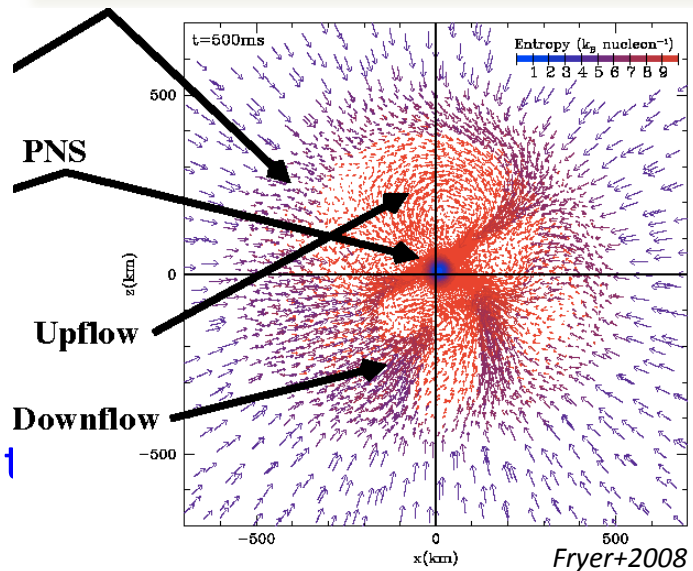
Fischer et al. 2010



Nucleosynthesis in CC-Supernova Models and ^{44}Ti





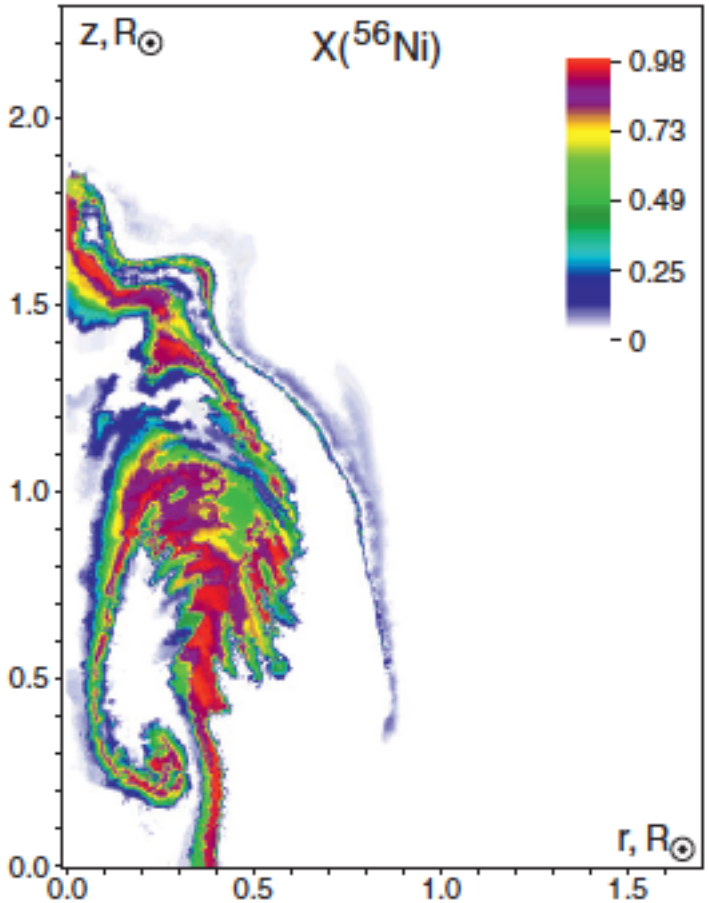


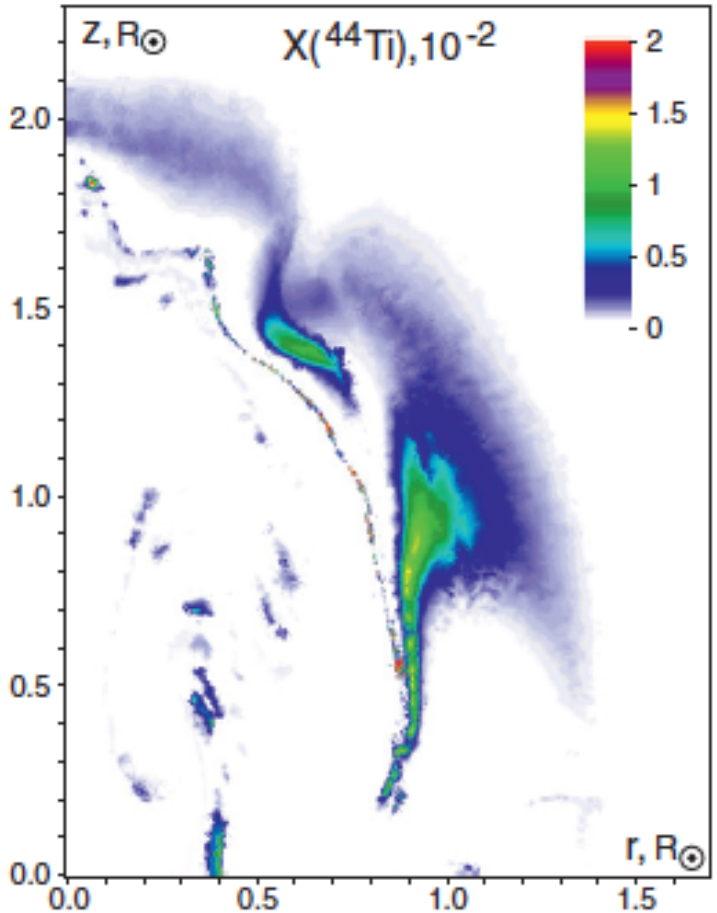
Fryer+2008

- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out
  => Unique Probe (+Ni Isotopes)

Asymmetric Supernova Explosions

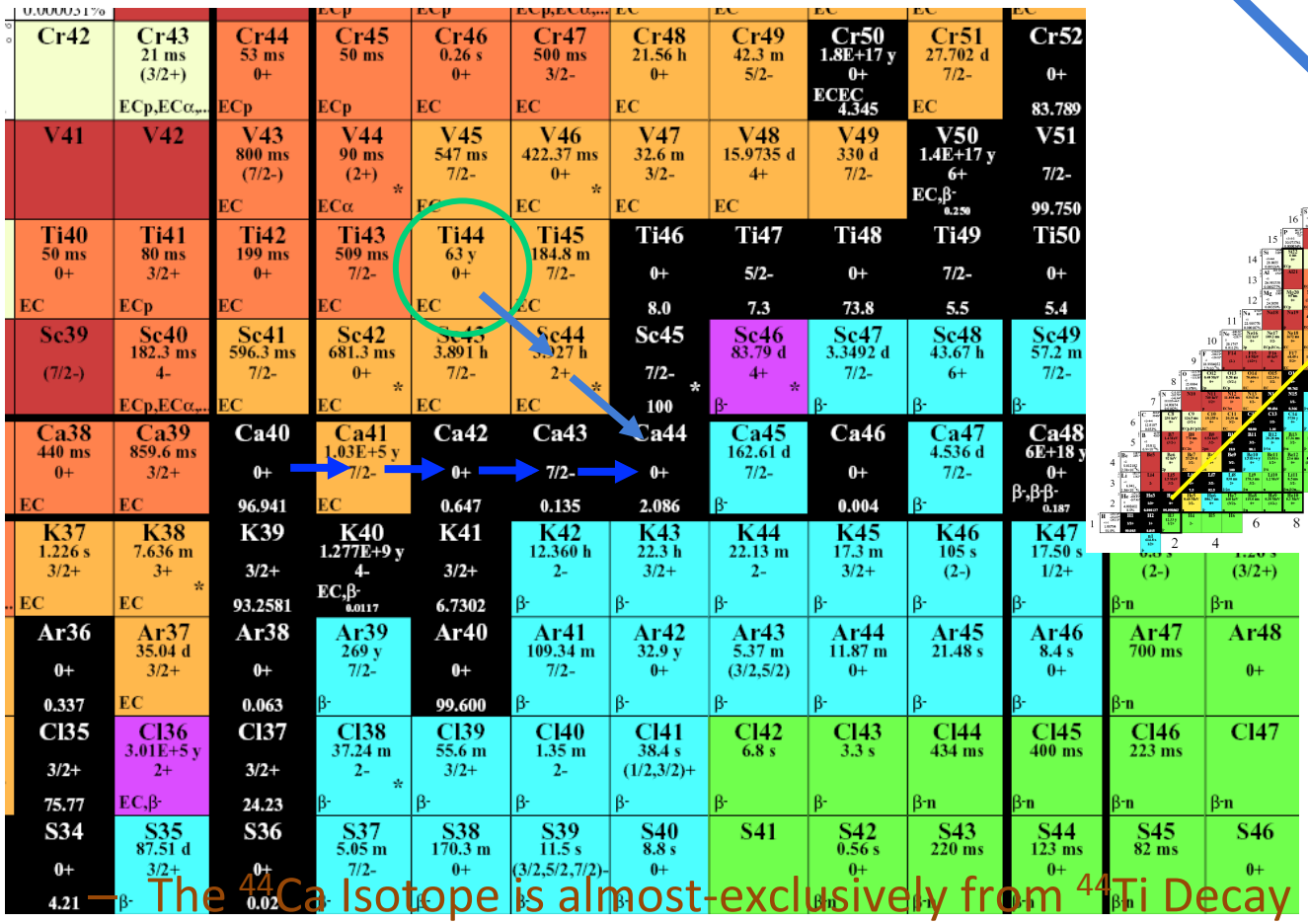
- Stellar Rotation likely incurs asymmetries at SN time
  - *Nagataki et al. 1998; Maeda et al. 2002; Popov et al. 2014*





Nucleosynthesis around ^{44}Ti

– ^{44}Ti is the first unstable nucleus on the "a line"

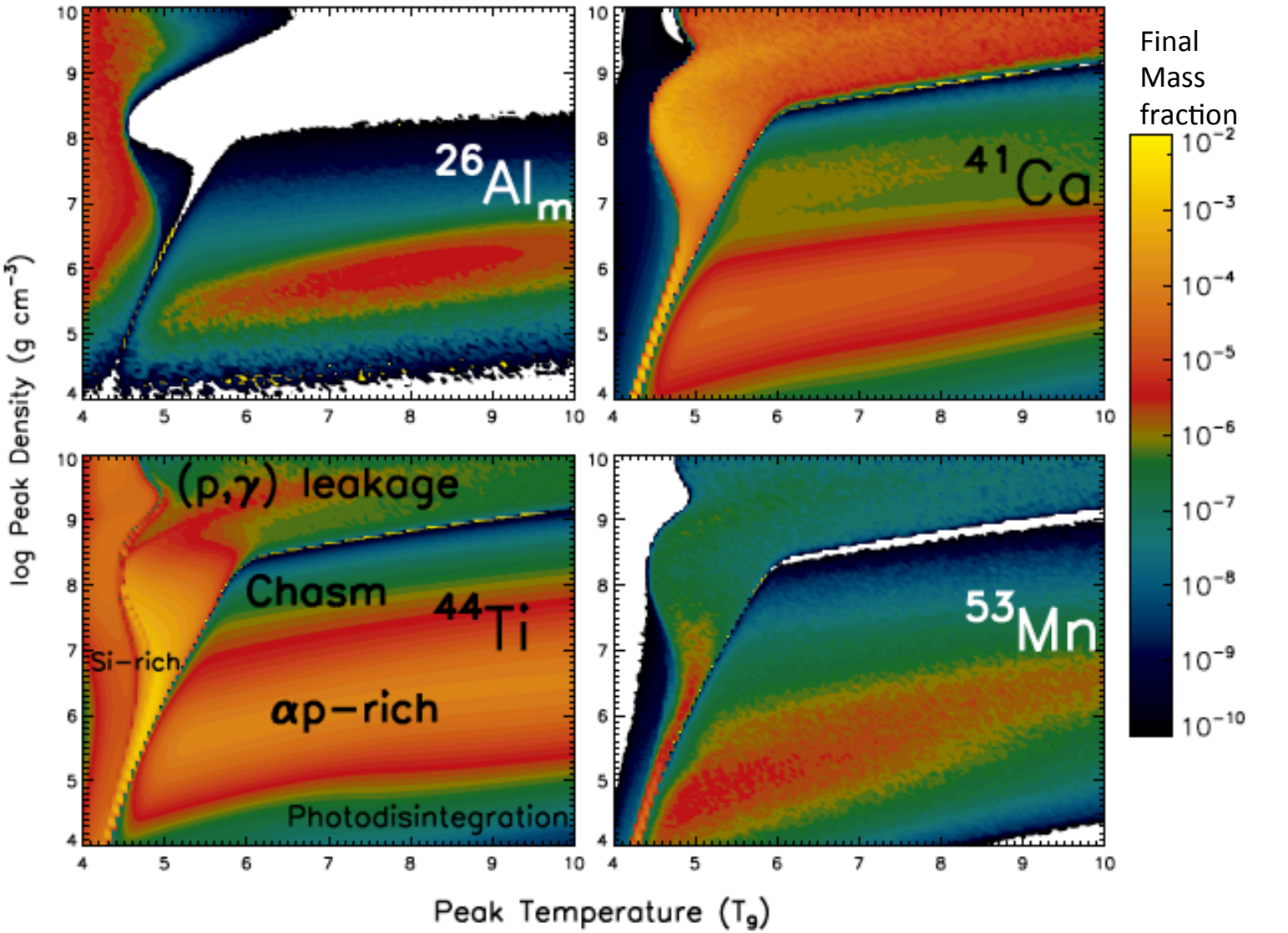


– The ^{44}Ca Isotope is almost-exclusively from ^{44}Ti Decay

- some minor admixture from s-process of ^{40}Ca

Nucleosynthesis in cc-SN Density/Temperature Regimes

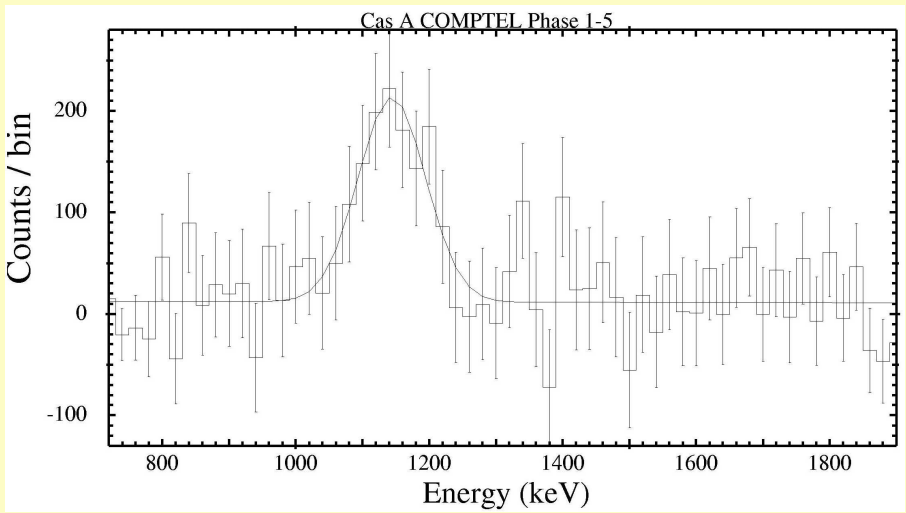
NuGrid collaboration (Magkotsios et al., ApJ 2011)



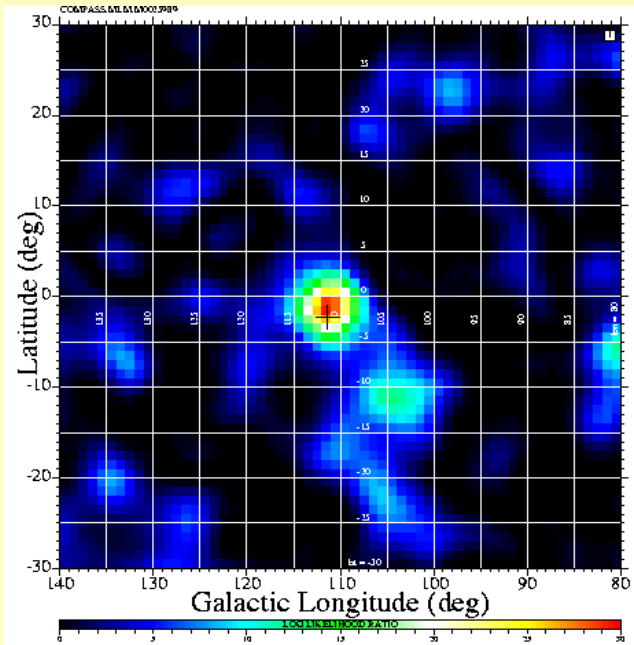
"For each region only certain reactions affect the yields of ^{44}Ti"

Discovery of ^{44}Ti in Core Collapse Supernova Cas A

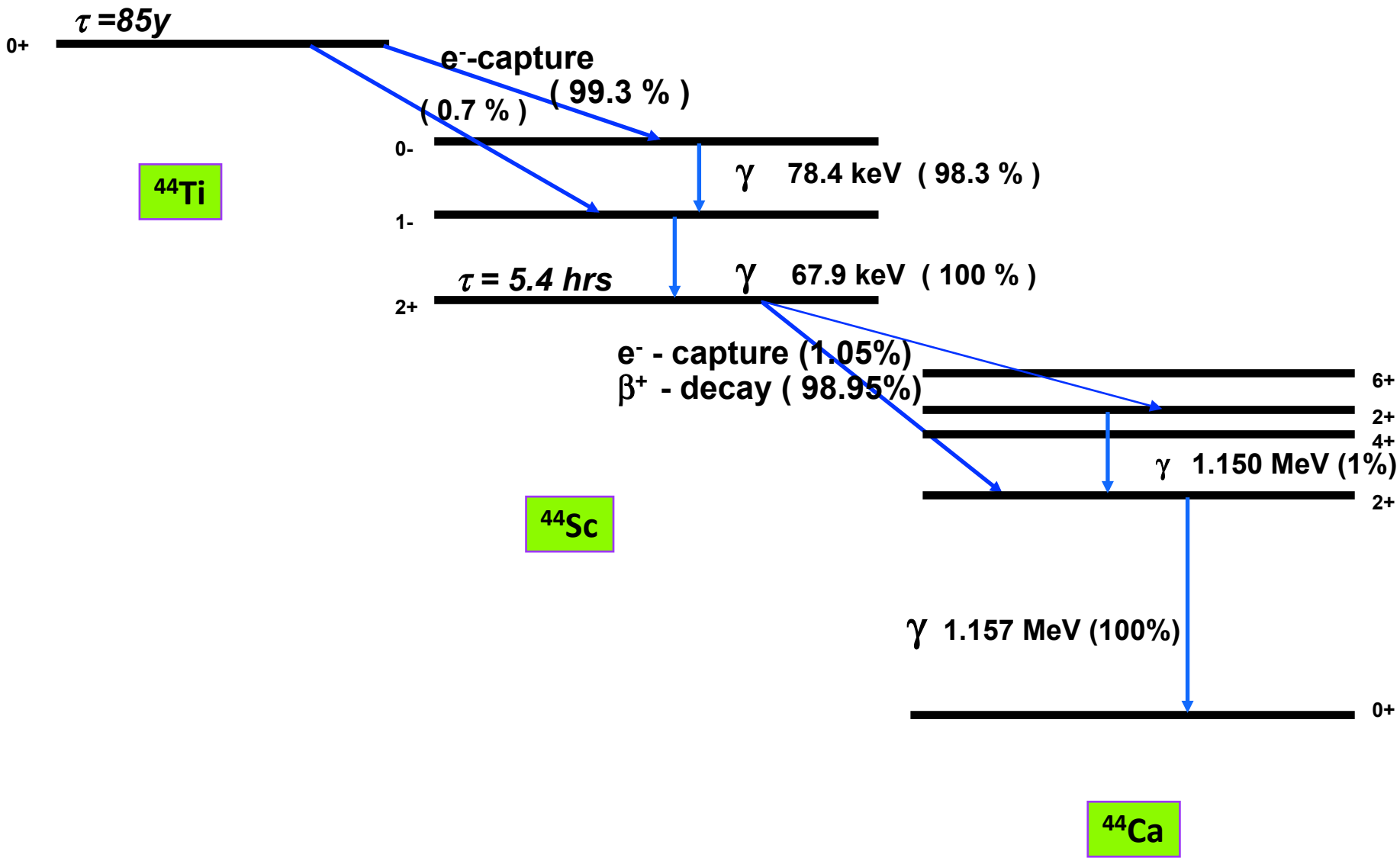
- 1.157 MeV ^{44}Ti Line Detection (6σ) by COMPTEL



A. Iyudin et al., A&A 1994; ESA-SP 382 1997



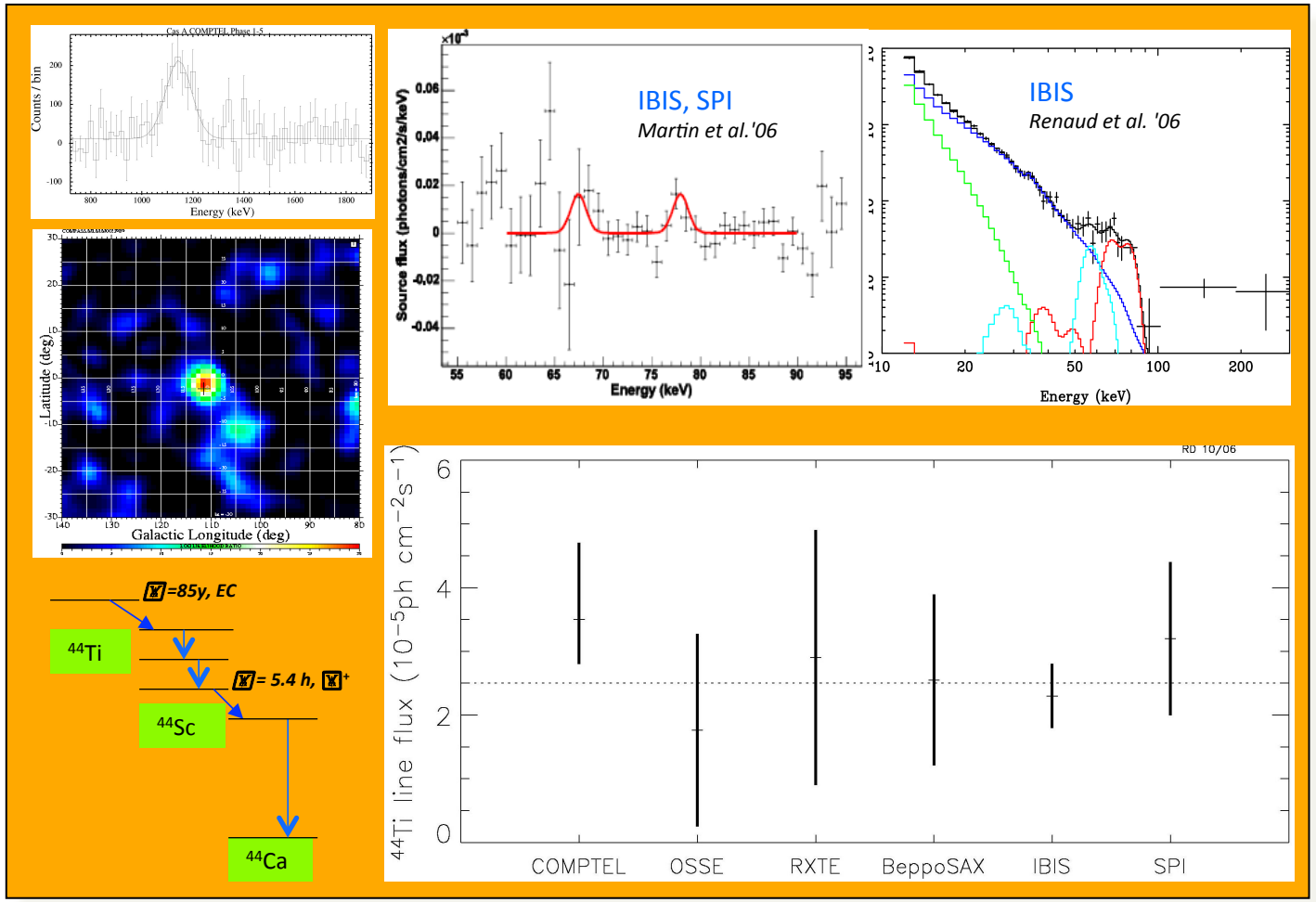
- Line Flux 4.2 (±0.9) 10^{-5} ph cm^{-2} s^{-1}

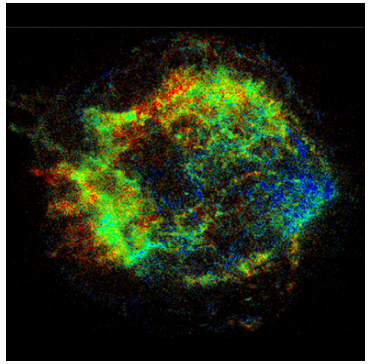

τ =85y
0+
e⁻-capture
(99.3 %)
(0.7 %)
0-
44Ti
γ 78.4 keV (98.3 %)
1-
τ = 5.4 hrs
γ 67.9 keV (100 %)
2+
e⁻ - capture (1.05%)
β⁺ - decay (98.95%)
6+
2+
4+
γ 1.150 MeV (1%)
2+
44Sc
γ 1.157 MeV (100%)
0+
44Ca

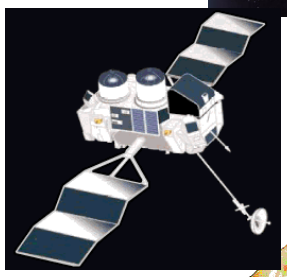
^{44}Ti γ-rays from Cas A

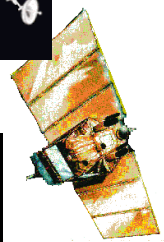
t=85y (Ahmad et al. 2006)

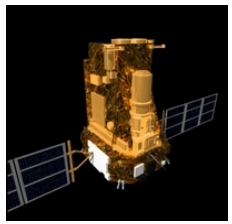
89 y	**^{44}Ti→^{44}Sc*→^{44}Ca*+e^{+}**	**78, 68; 1157**











^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} $M_{\odot}$

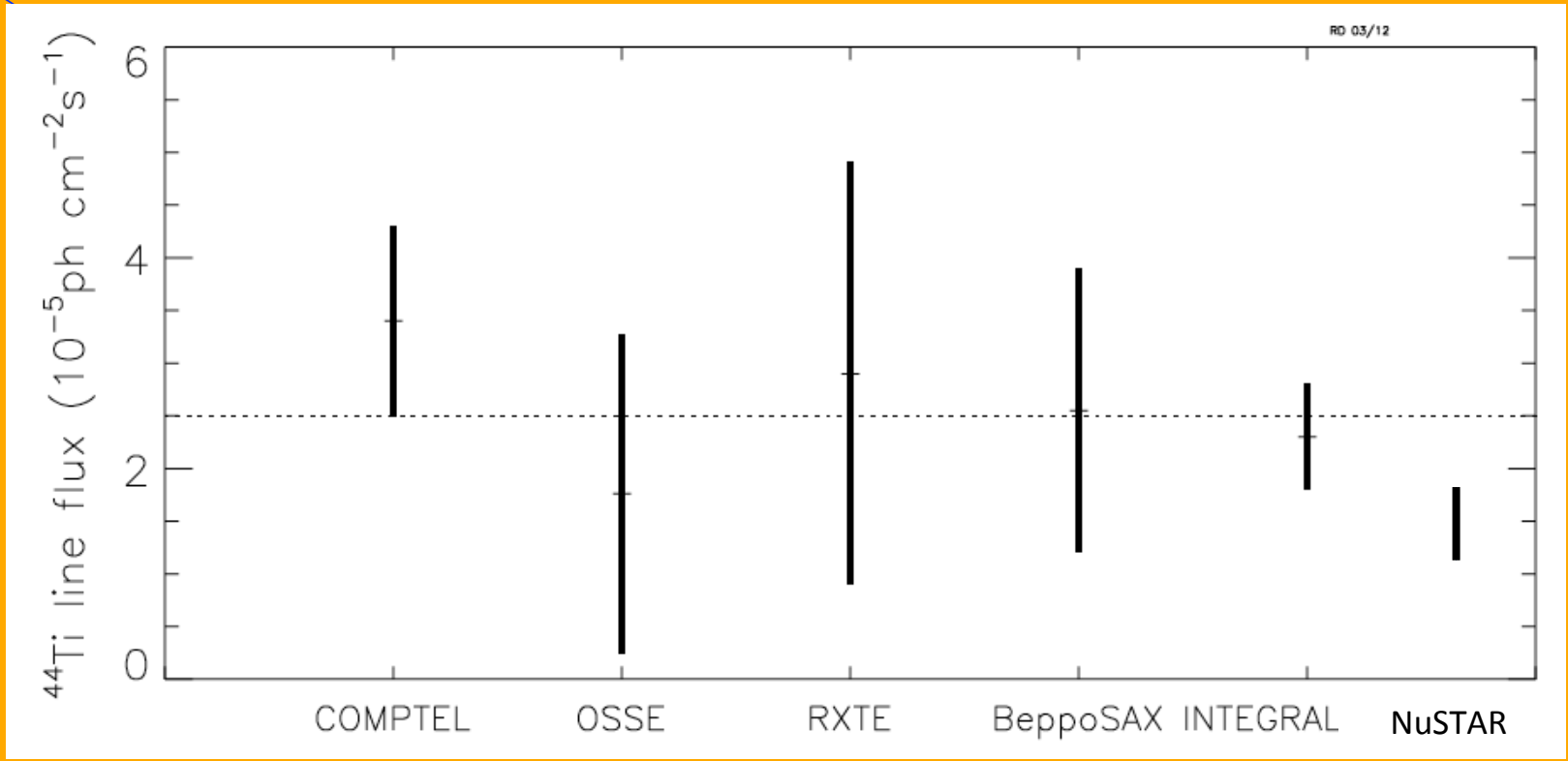
^{44}Ti γ-rays from Cas A

t=85y (Ahmad et al. 2006)

89 y	**^{44}Ti→^{44}Sc*→^{44}Ca*+e^{+}**	**78, 68; 1157**

τ=85y, EC

^{44}Ti

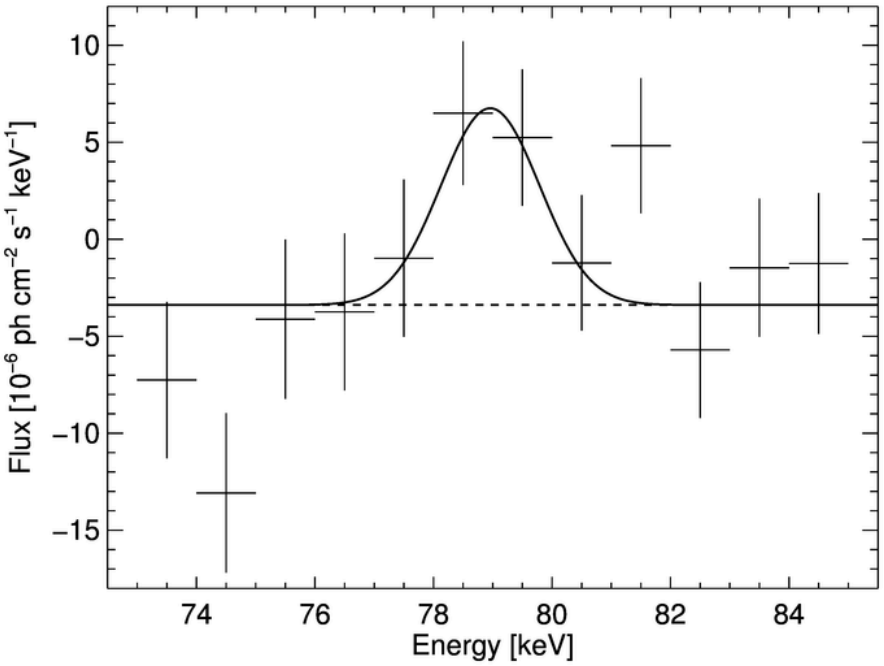


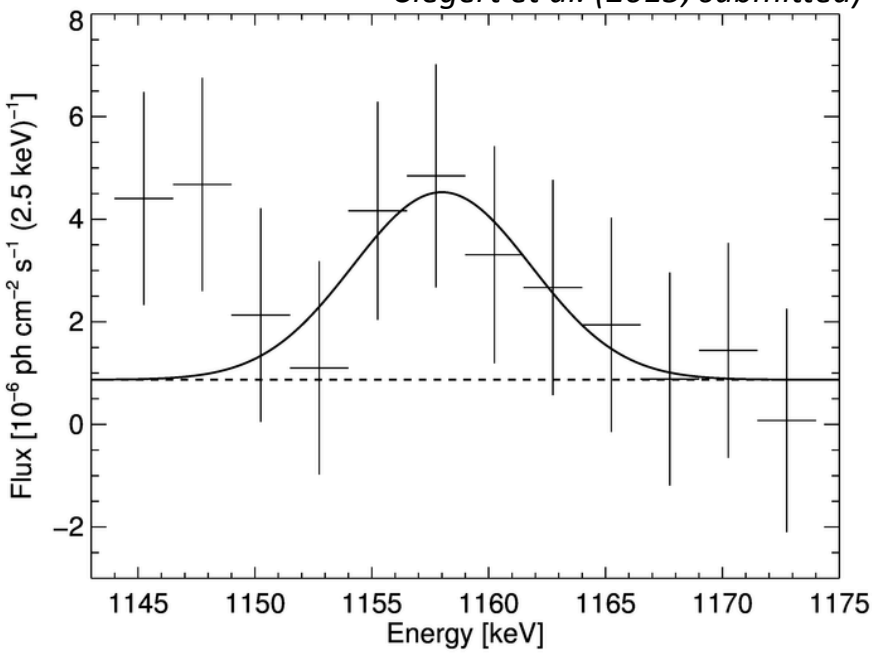
↳ ^{44}Ti Ejected Mass ~1.23 ±0.25 10^{-4} $M_{\odot}$

SPI Re-Analysis of Cas A for ^{44}Ti

- Using cumulative data from >12 years, and a new instrumental-background treatment
- Find 78 keV and 1157 keV line emission

Siegert et al. (2015; submitted)



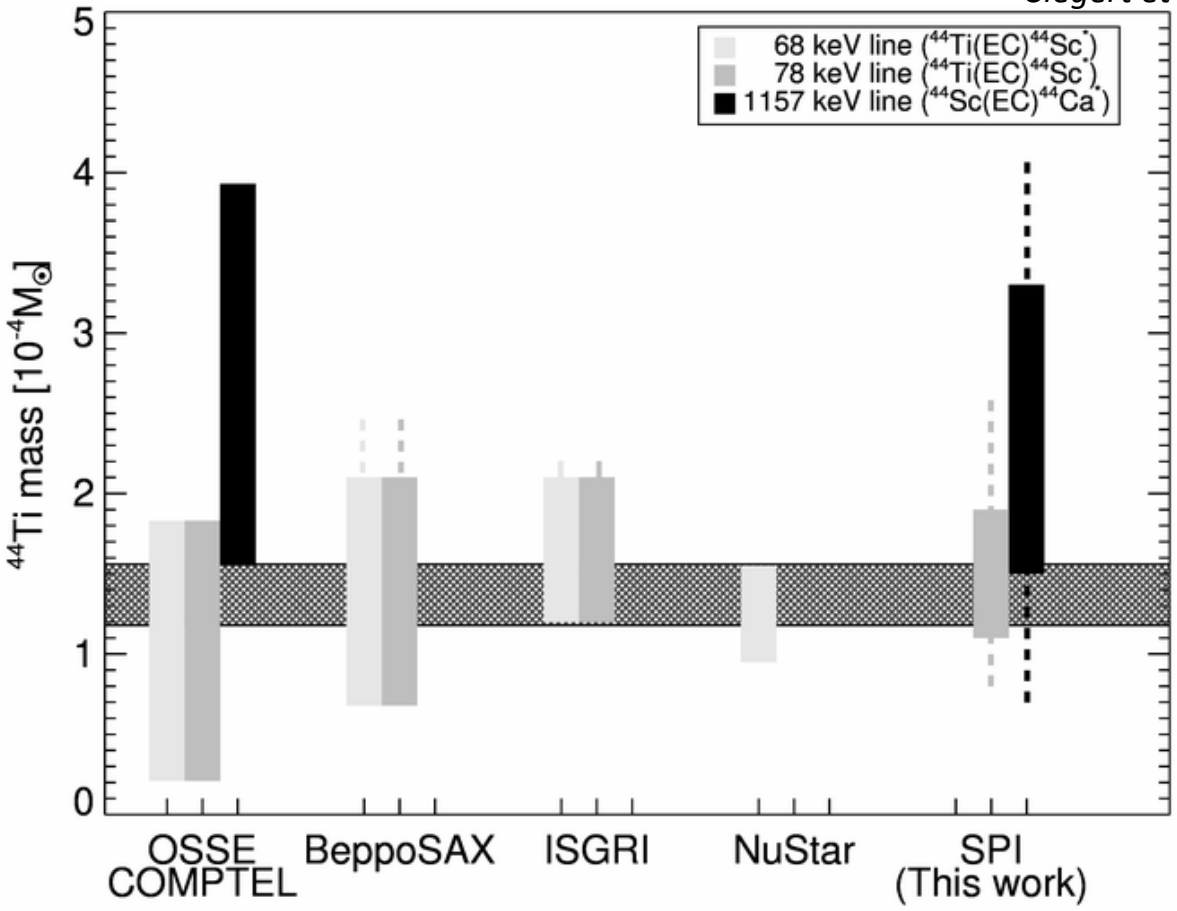


- Doppler broadening: 4300±1600 / 2200±1600 km s^{-1} (78, 1157 keV)

^{44}Ti from Cas A

- Consistency checks:
  - Different instruments / detector systematics?

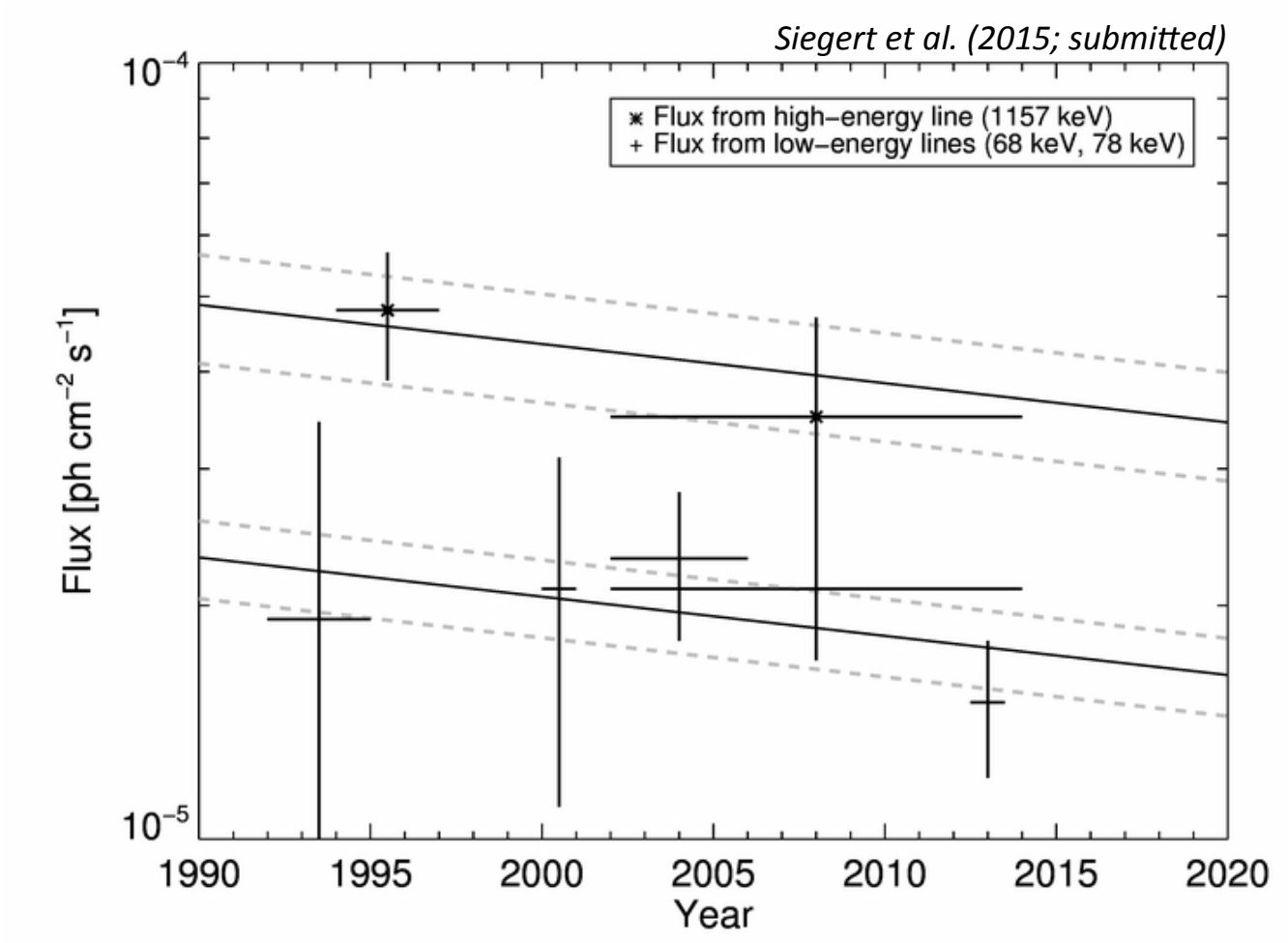
Siegert et al. (2015; submitted)



  - ^{44}Ti mass = (1.37 ± 0.19) 10^{-4} $M_\odot$

^{44}Ti from Cas A

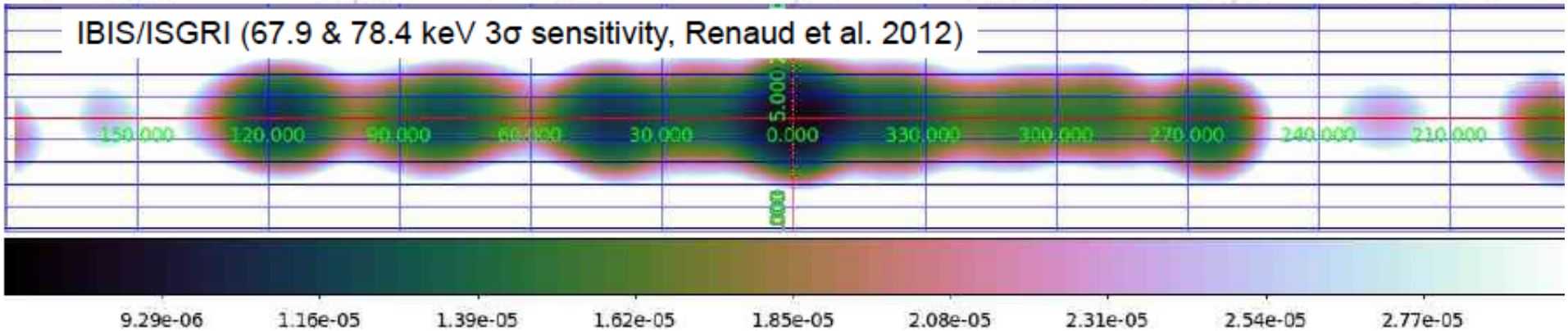
- Consistency checks:
  - Decay time; ^{44}Sc/^{44}Ca systematics?

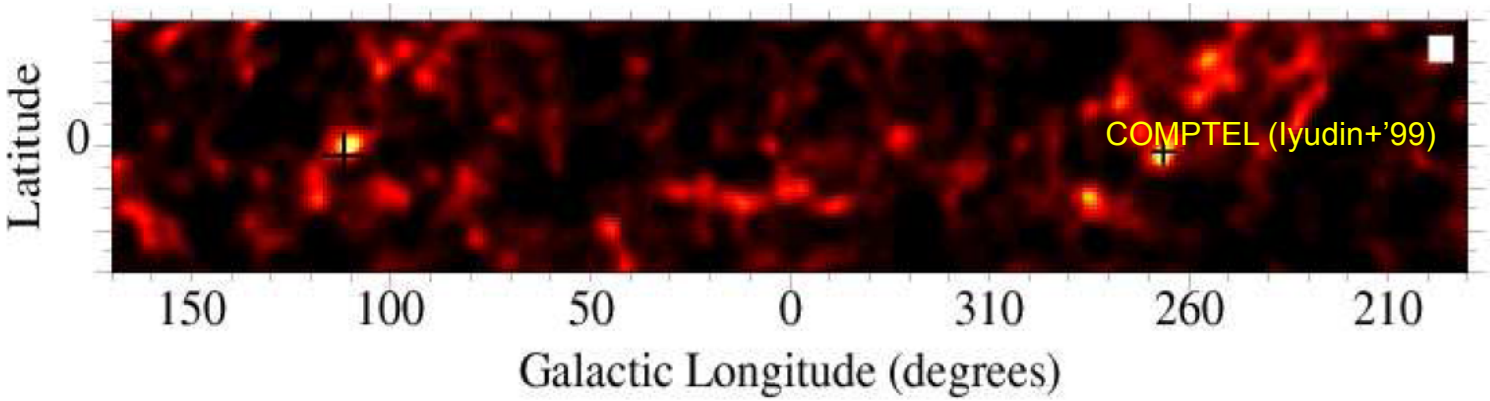


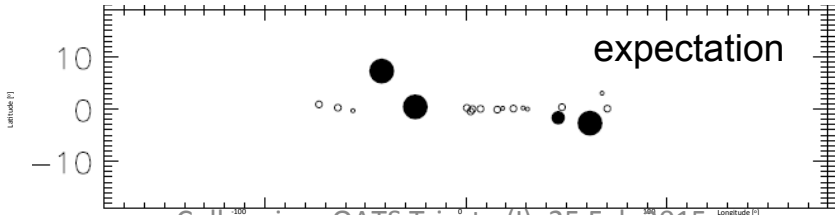
  - Contribution from LECRs and nuclear de-excitation?

Are Core Collapse Supernovae ^{44}Ti Sources?

- ☆ Cas A is the ONLY Source Seen in our Galaxy
- ☆ Sky Regions with Most Massive Stars (inner Galaxy) are ^{44}Ti Source-Free
- ☆ We expect to see > a few of such sources!

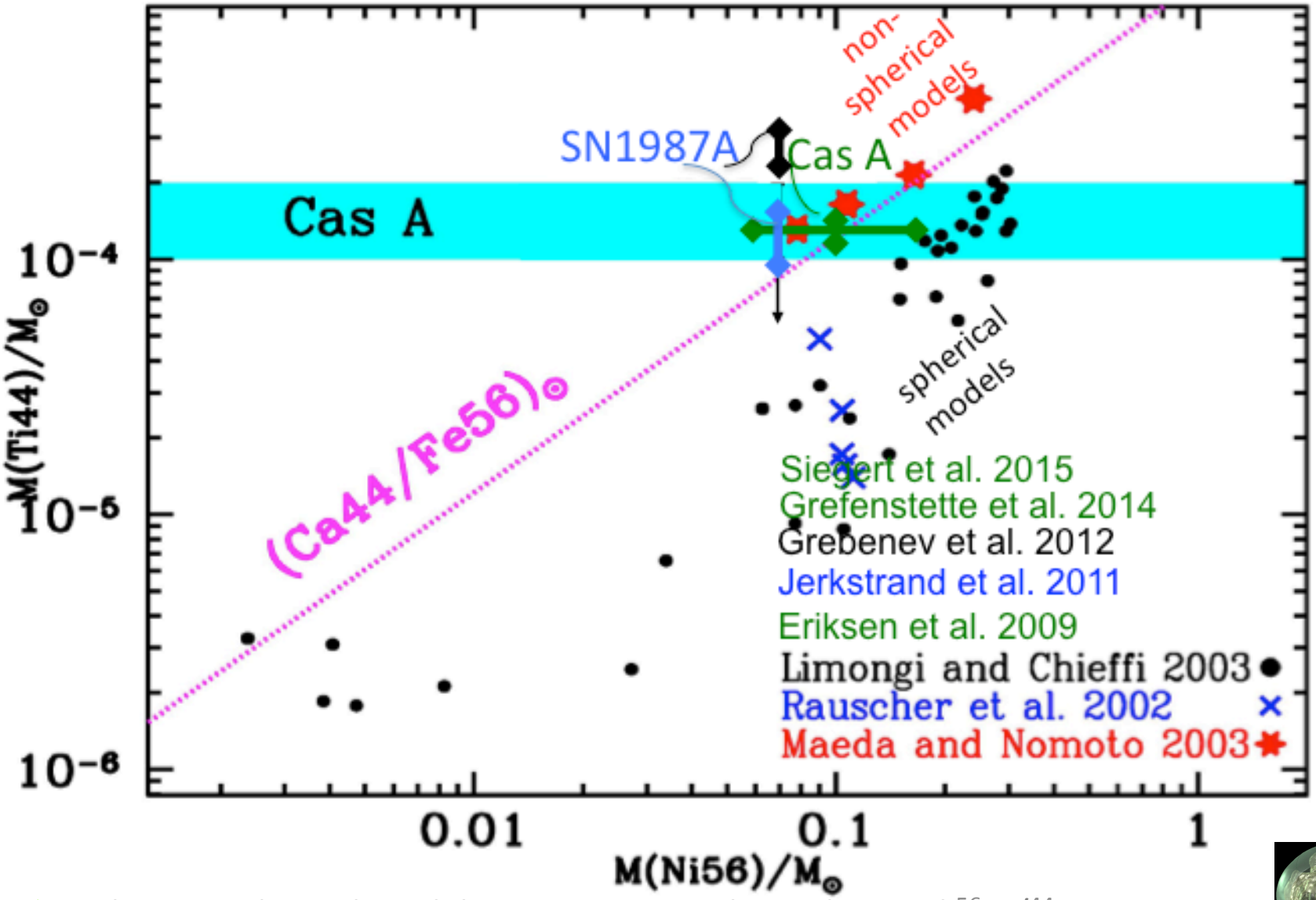


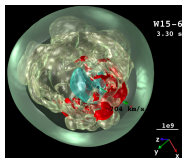




The et al. 2006

“Abnormal” Core Collapse Supernovae as ^{44}Ca (=^{44}Ti) Sources?



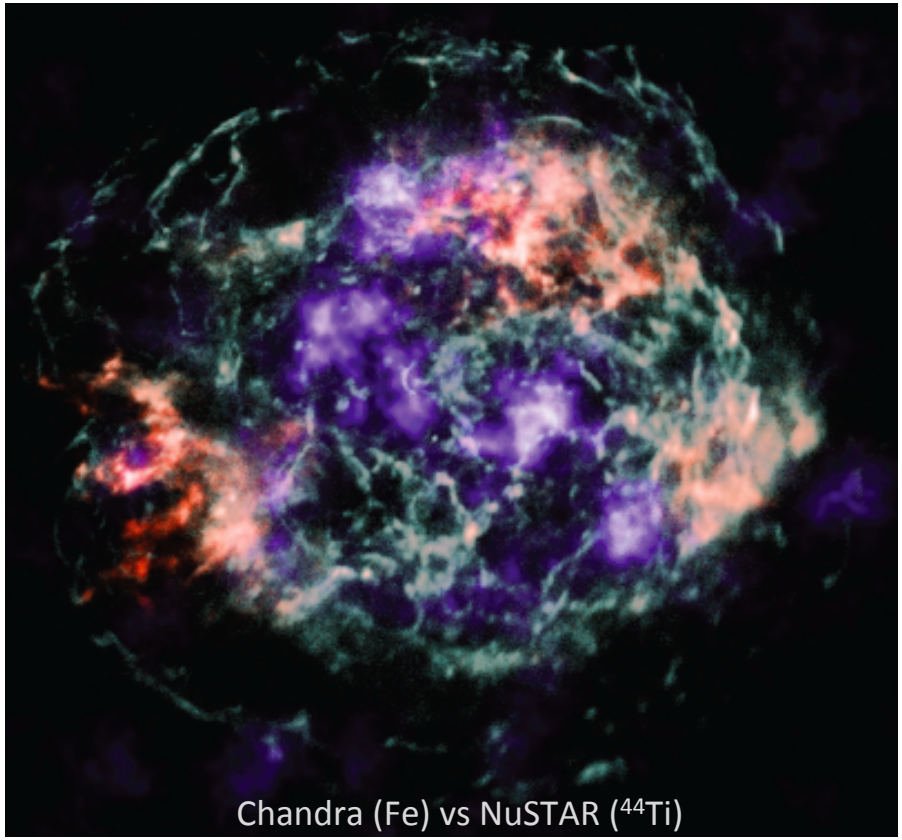


- ⇨ Only Non-Spherical Models Seem to Reproduce Observed ^{56}Ni/^{44}Ti Ratios
- ⇨ *The et al. 2006*

NuSTAR and ^{44}Ti

– Imaging in hard X-rays (3-79 keV) → ^{44}Ti lines at 68,78 keV

- Cas A: first mapping of radioactivity in a SNR

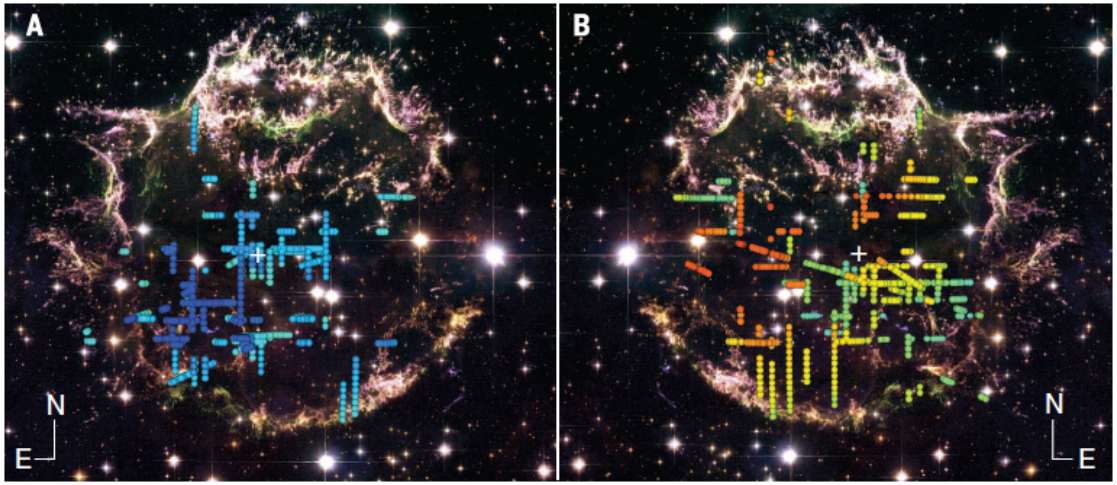


– Both ^{44}Ti lines detected clearly
– line redshift 0.5 keV
→ 2000 km/s redshift asymmetry
– Image differs from Fe!!
– ^{44}Ti flux consistent with earlier measurements
– Doppler broadening: (5350 ±1610) km s^{-1}

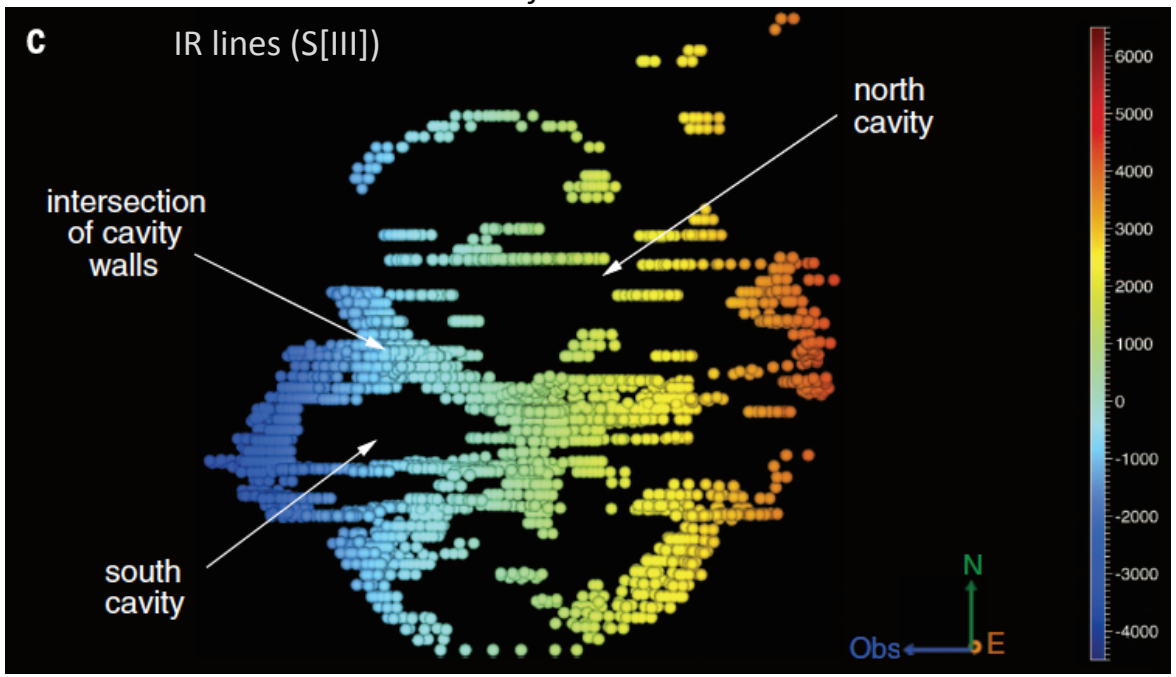
Grefenstette et al. 2014

Inner Unshocked Ejecta of Cas A in IR

– S[III] imaged from thermal deexciations at 907,953 nm



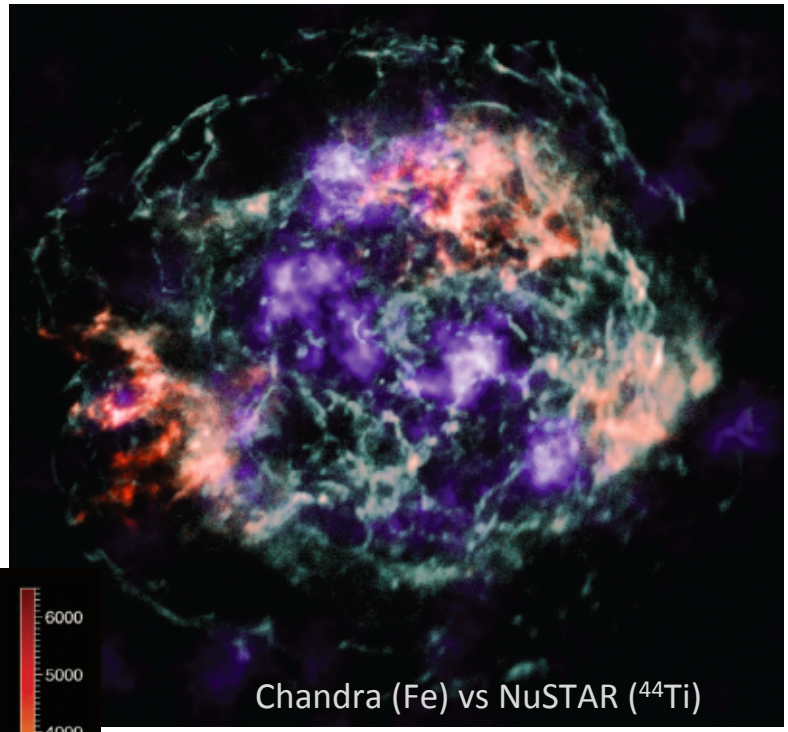
Milisavljevich & Fesen 2015



Few, large cavities blown by ^{56}Ni

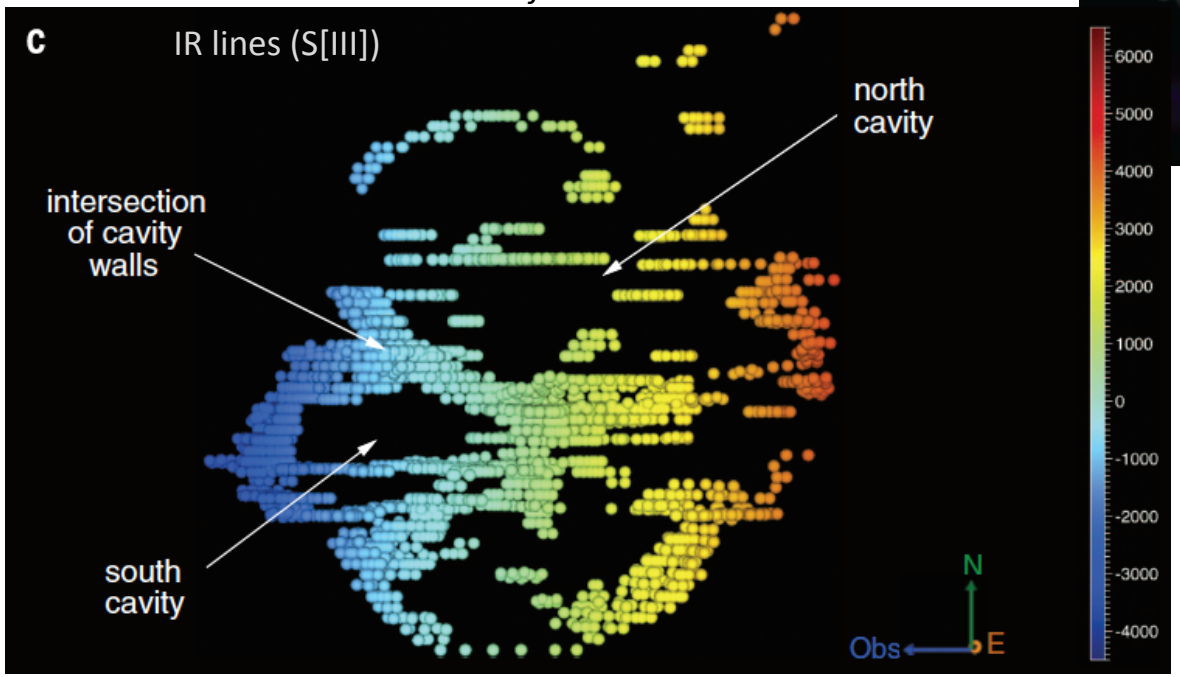
Inner Ejecta of Cas A

- ^{44}Ti imaged from radioactivity
- Fe imaged by X-ray recombination lines
- S[III] imaged from thermal deexciations at 907,953 nm



Grefenstette et al. 2014

Milisavljevich & Fesen 2015

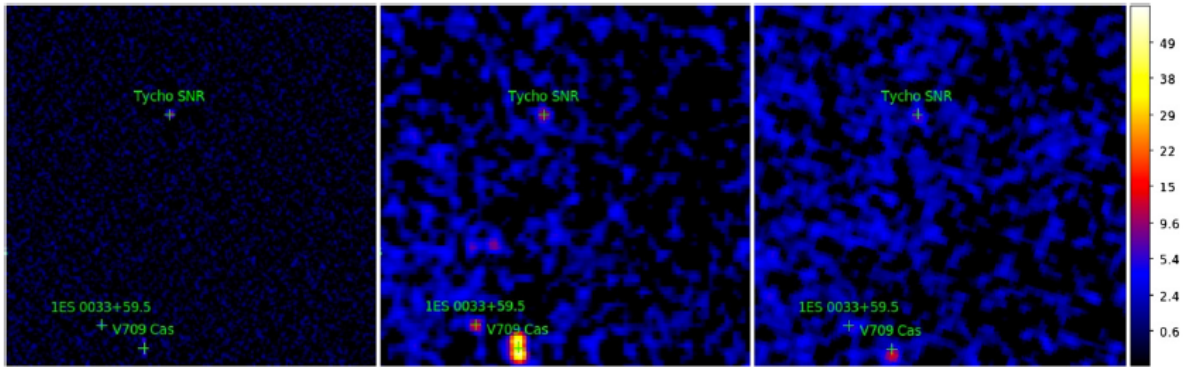


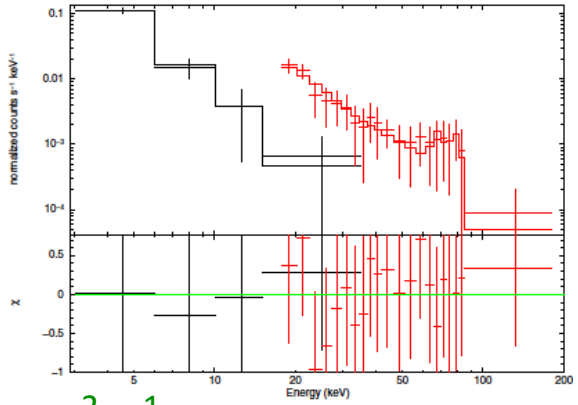
Few large cavities blown by ^{56}Ni

Not all ejecta shocked yet

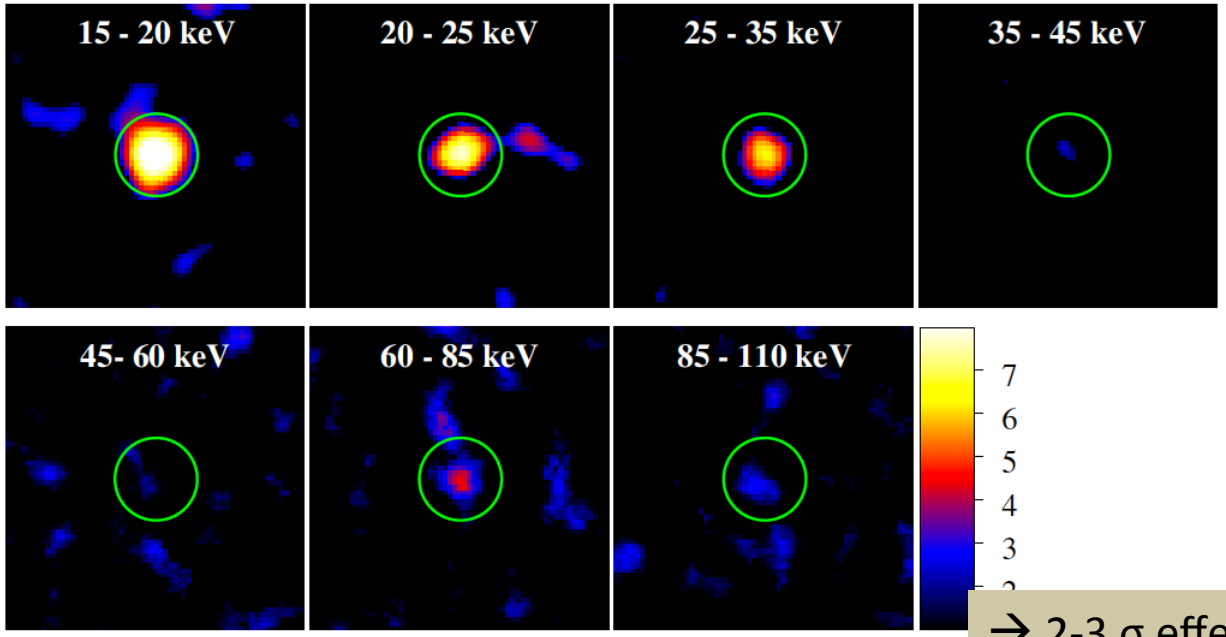
SN Type Ia as Sources of ^{44}Ti?

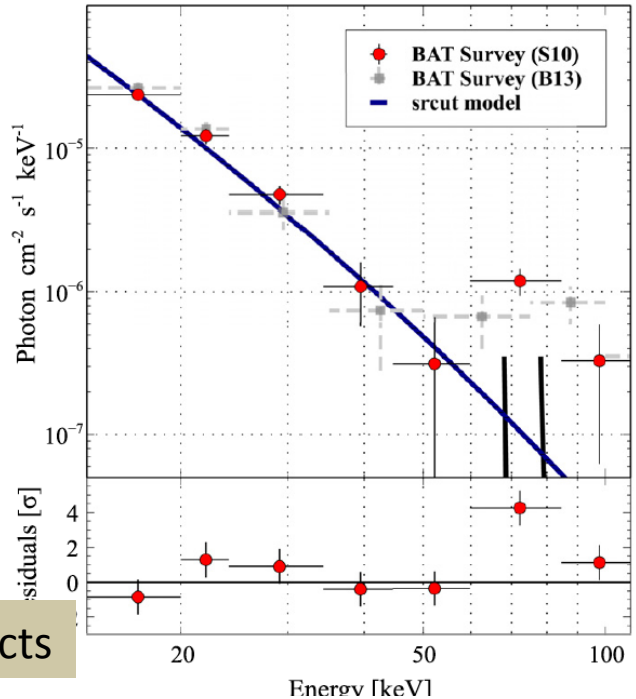
- Images vs. Energy:
  - INTEGRAL/IBIS, Wang & Li 2014 → ~1.5 10^{-5} ph cm^{-2} s^{-1}





  - SWIFT/BAT, Troja et al. 2014 → ~1.4 10^{-5} ph cm^{-2} s^{-1}





→ 2-3 σ effects

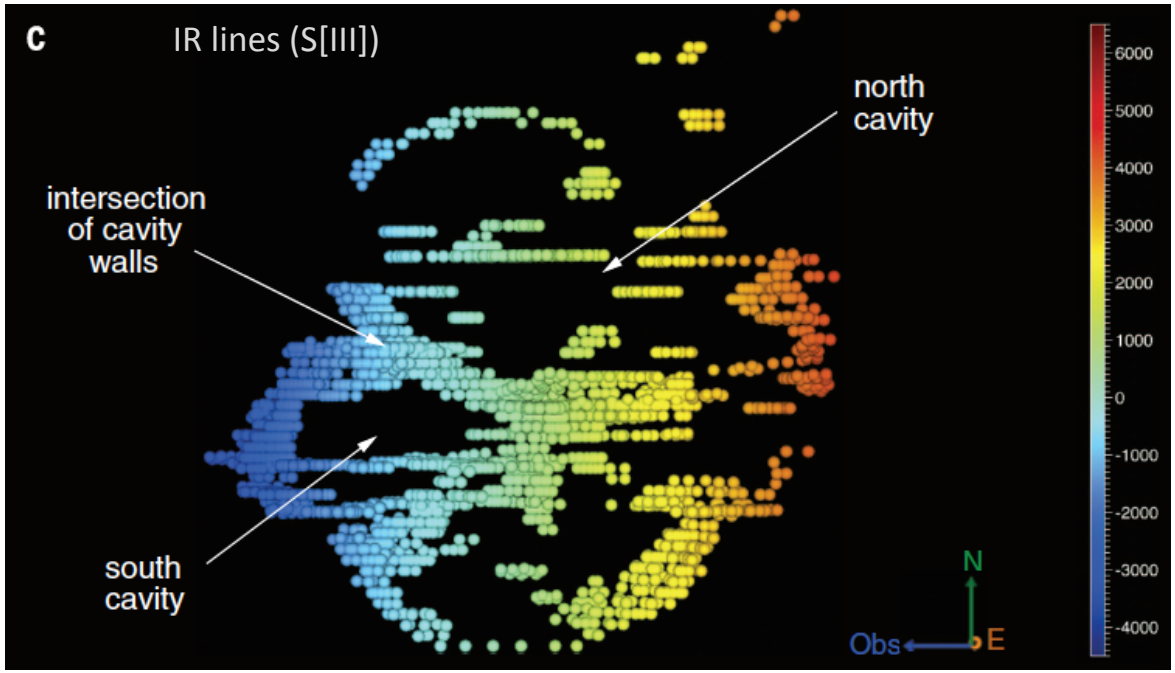
Inner Ejecta Shaping by ^{56}Ni Decay

– ^{56}Ni energy input compressed non-radioactive materials

– Formation of bubbles around ^{56}Ni-rich ejecta

– Cas A: Only very few bubbles → ^{56}Ni in few major clumps

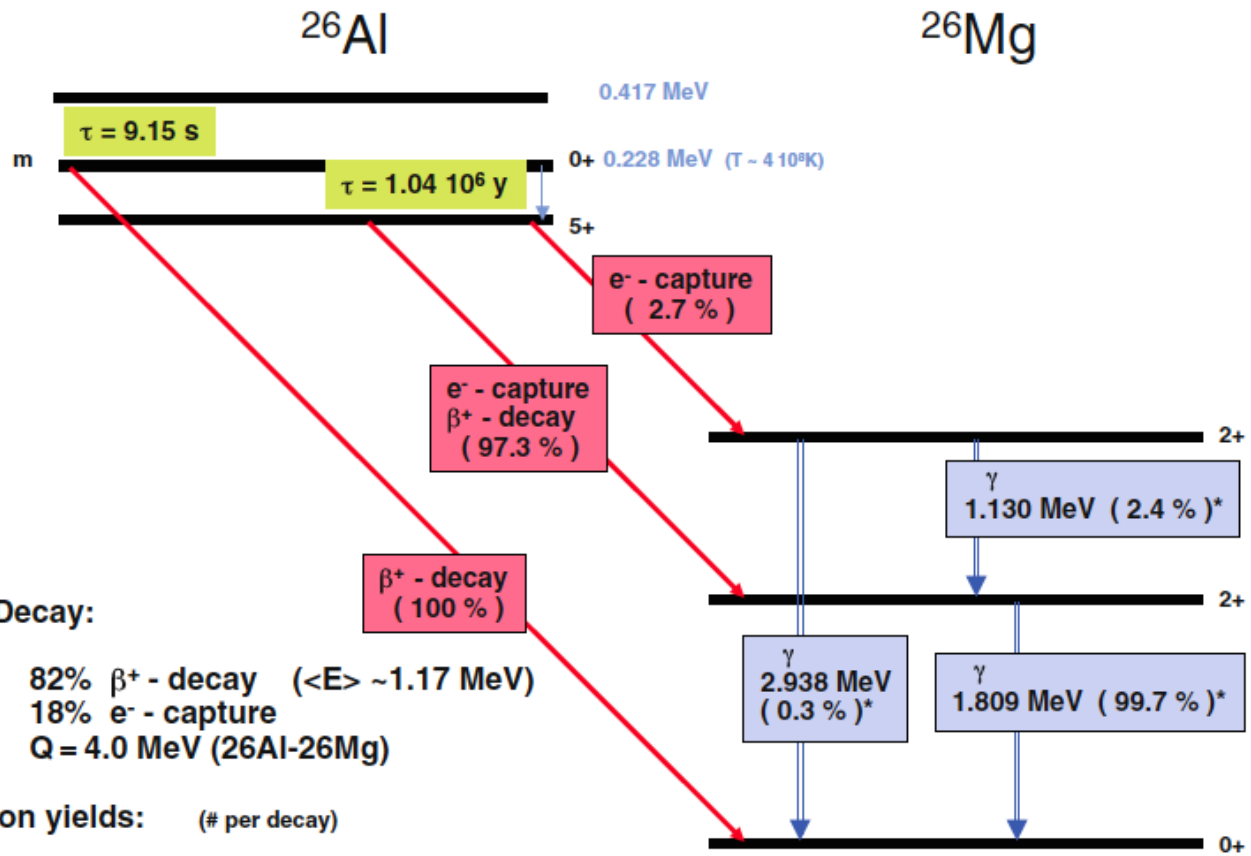
Milisavljevich & Fesen 2015



– Could this also shape SNIa explosions (SN2014J)??

» few major ejecta clumps? → distinguished gamma-ray line features?

^{26}Al



^{26}Al Decay:

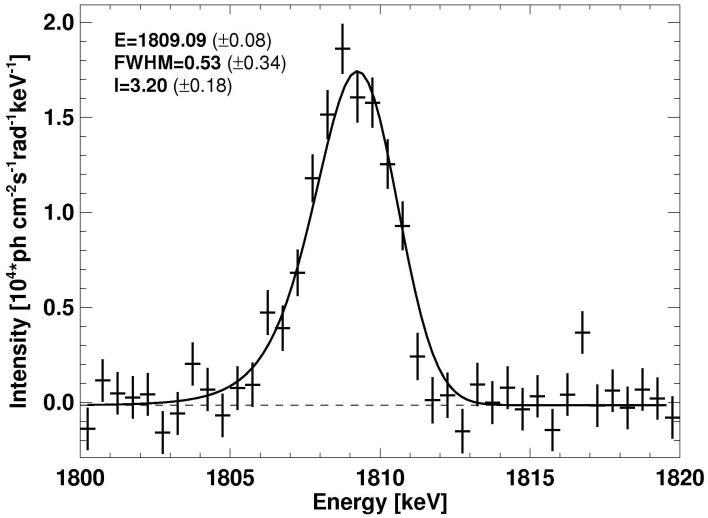
82% β^+ - decay (<E> ~1.17 MeV)
18% e^- - capture
Q = 4.0 MeV (26Al-26Mg)

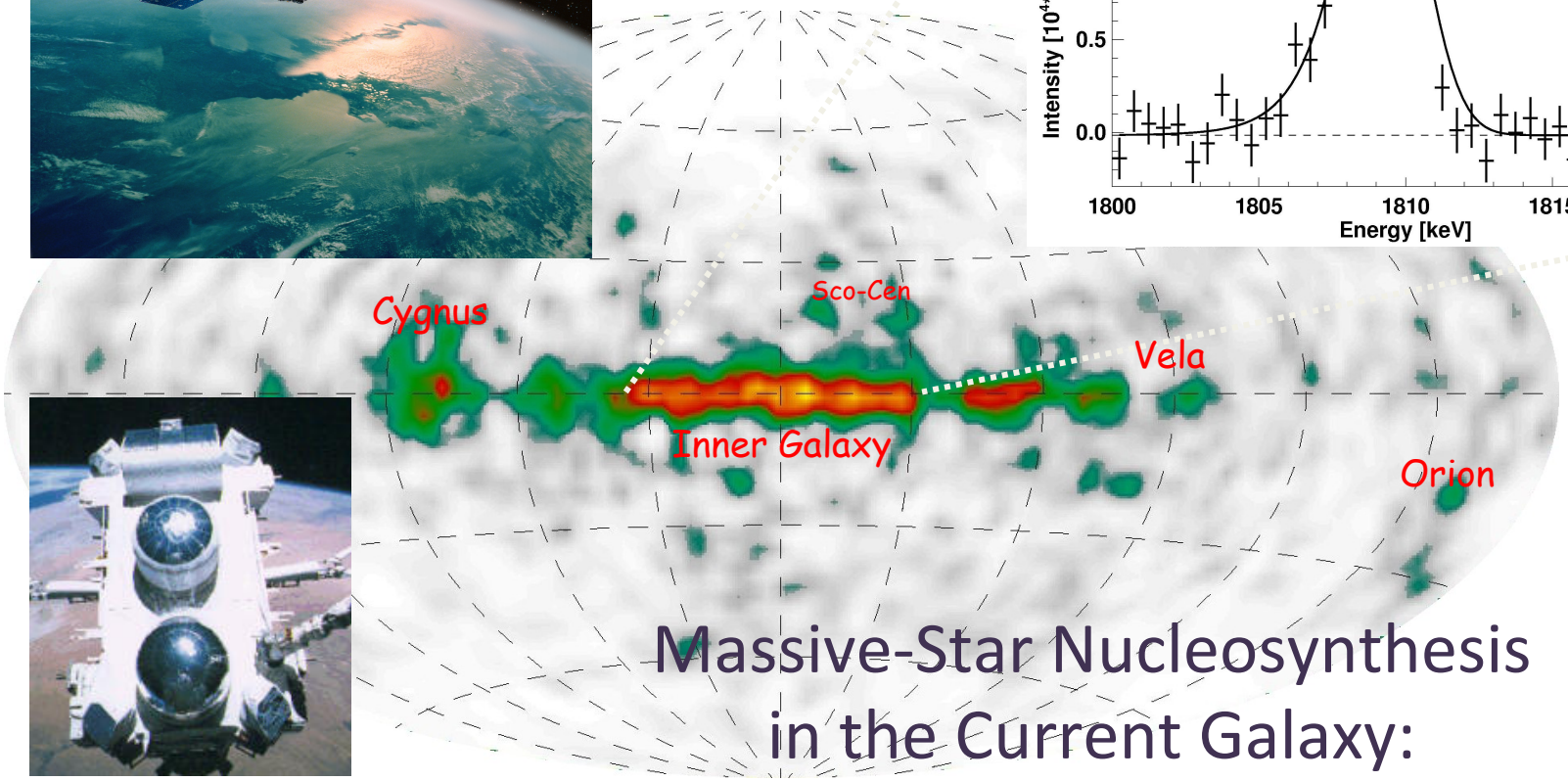
Photon yields: (# per decay)

0.511 MeV	1.622
1.130 MeV	0.024
1.809 MeV	0.997
2.938 MeV	0.003

* .= % are relative to one decay of ^{26}Al

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



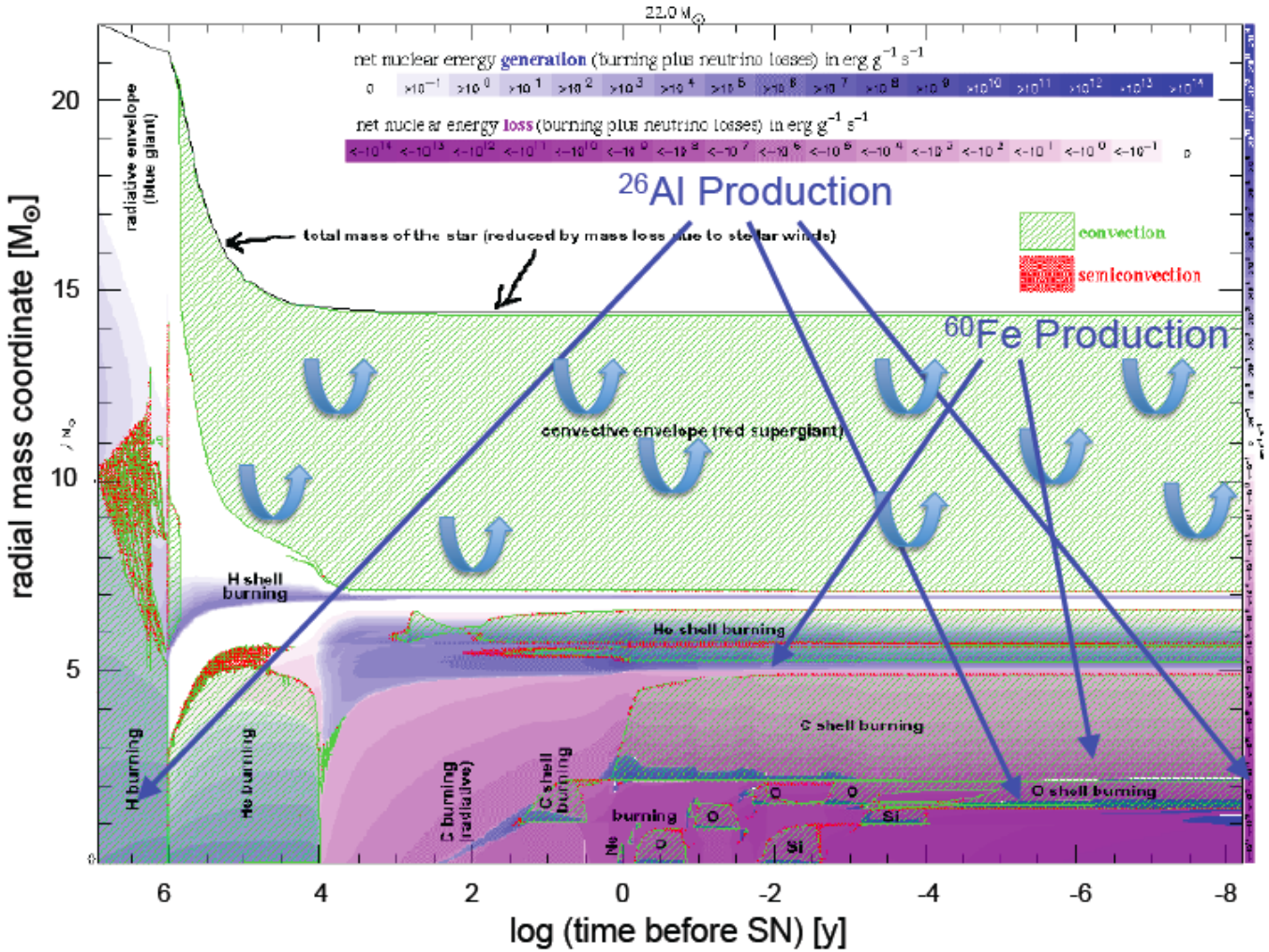


Massive-Star Nucleosynthesis in the Current Galaxy:

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

Radioactivities from massive stars: ^{60}Fe, ^{26}Al

- Production-Site Detail
  (adapted from Heger)
  - *Hydrostatic fusion*
  - *WR wind release*
  - *Explosive fusion*
  - *Explosive release*

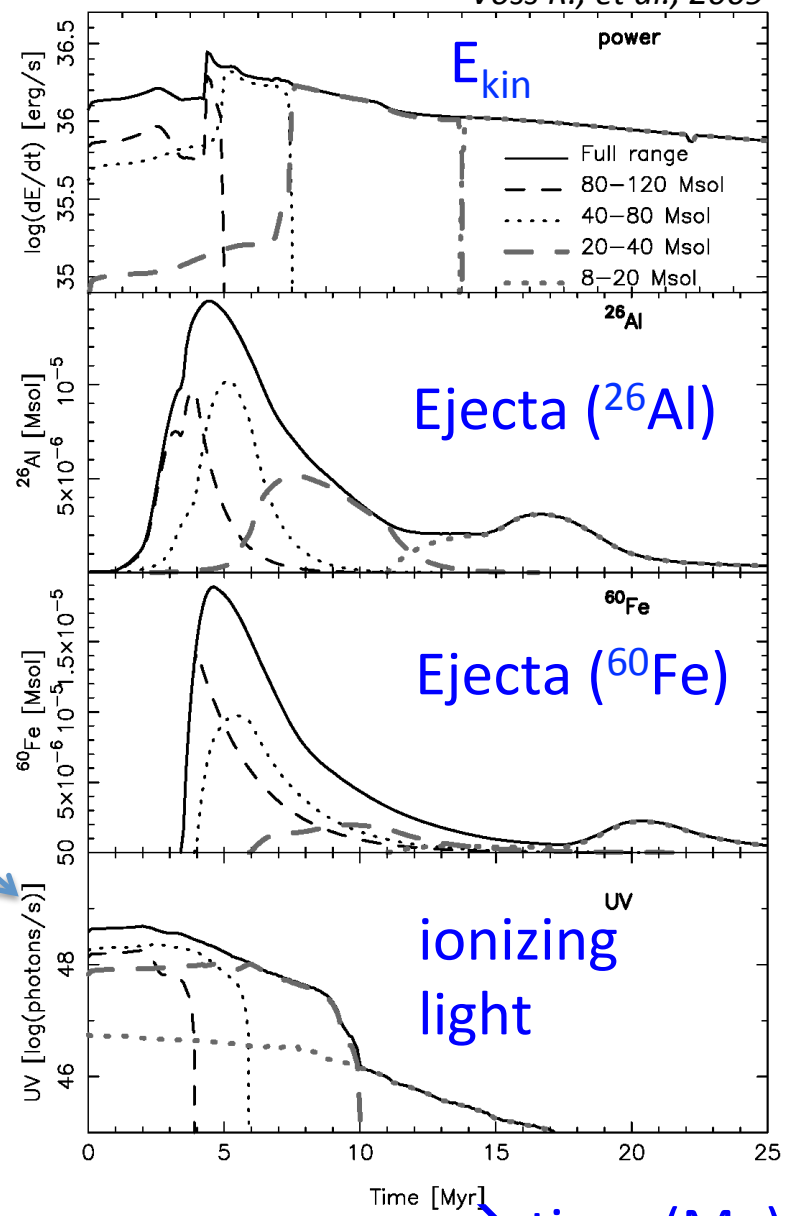


Massive-Star Groups

- We study the "outputs" of massive stars and their supernovae
  - Winds and Explosions
  - Nucleosynthesis Ejecta
  - Ionizing Radiation

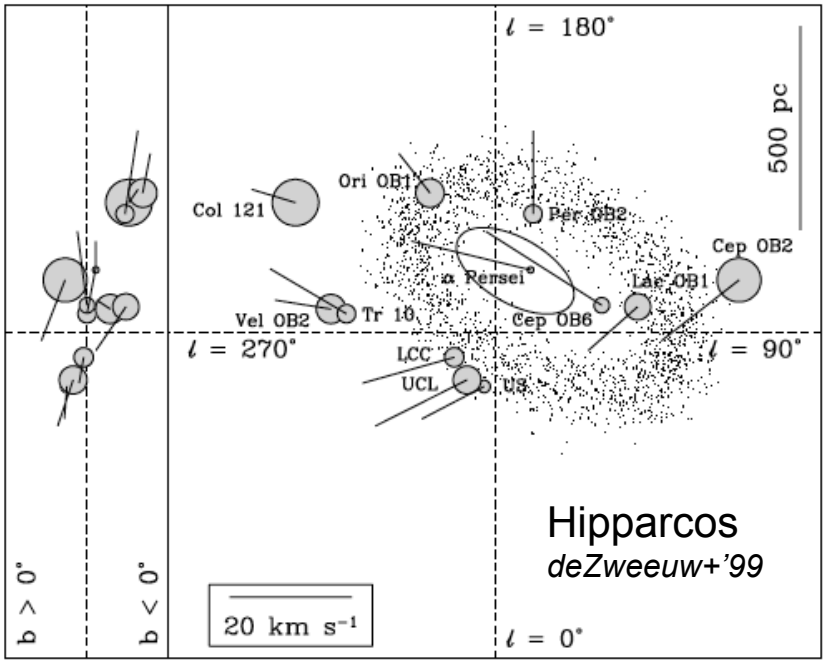
- We get observational constraints from
  - Star Counts
  - ISM Cavities
  - Free-Electron Emission
  - Radioactive Ejecta

Voss R., et al., 2009



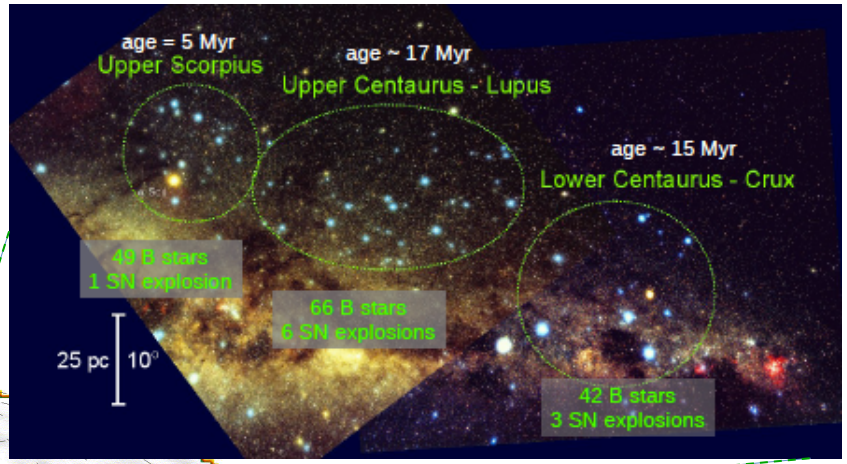
→ time (My)

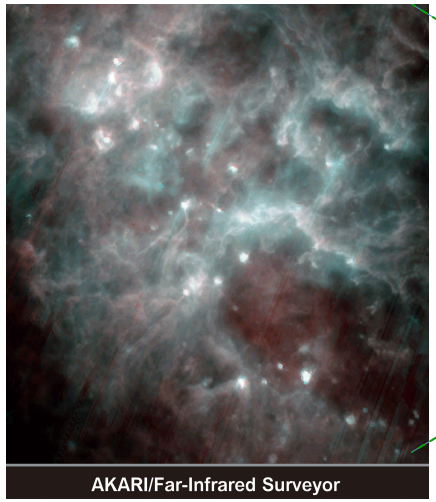
Examples of Nearby Massive-Star Groups

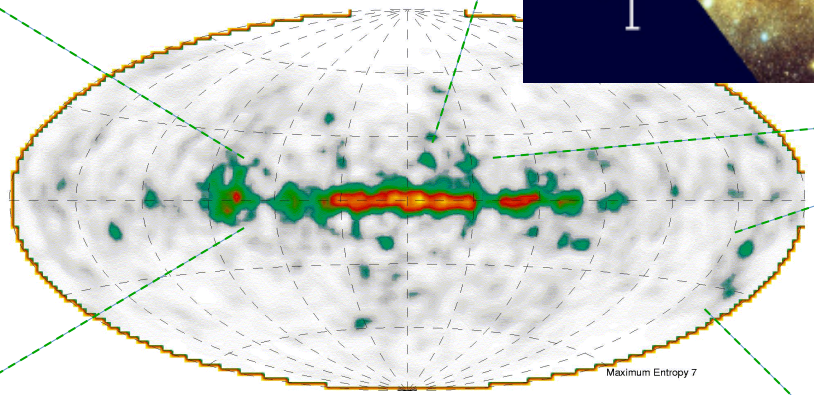


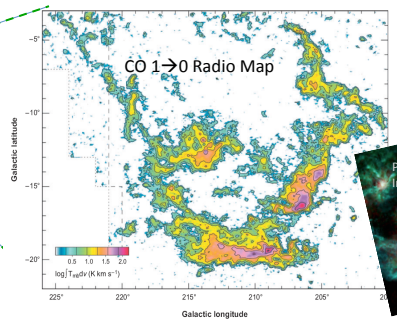
Opportunities to test our model for consistency

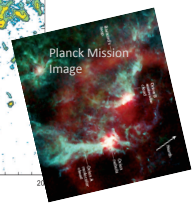
- ^{26}Al ejecta, stars, shells/bubbles







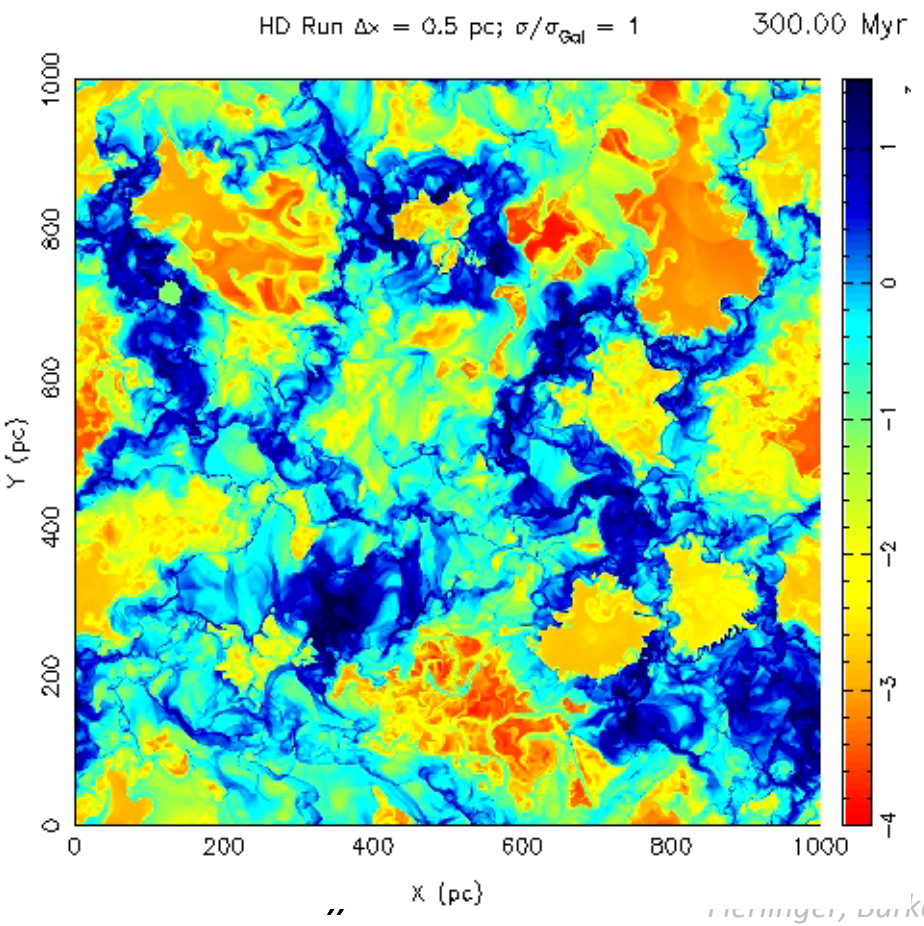


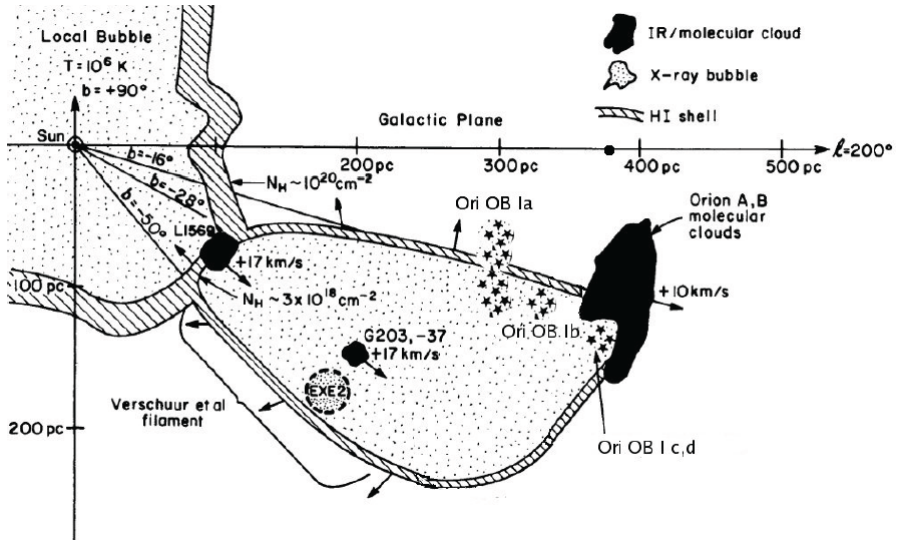


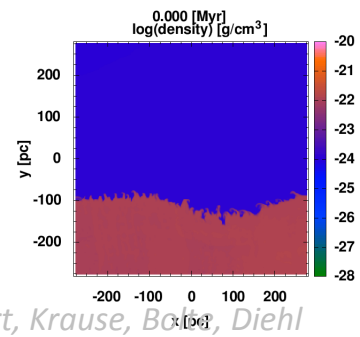
Orion: Nucleosynthesis Ejecta and Dynamics of Interstellar Medium

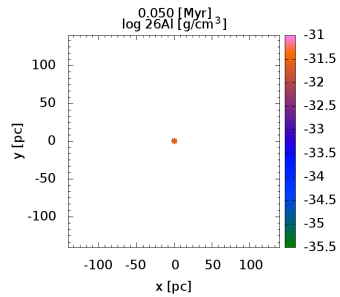
INTEGRAL Data are Being collected!

- ISM is Highly-Dynamic → Ejecta in (Super-)Bubbles
  - Study Specific Regions in Detail (Cygnus, Orion, Scorpius-Centaurus, Carina)





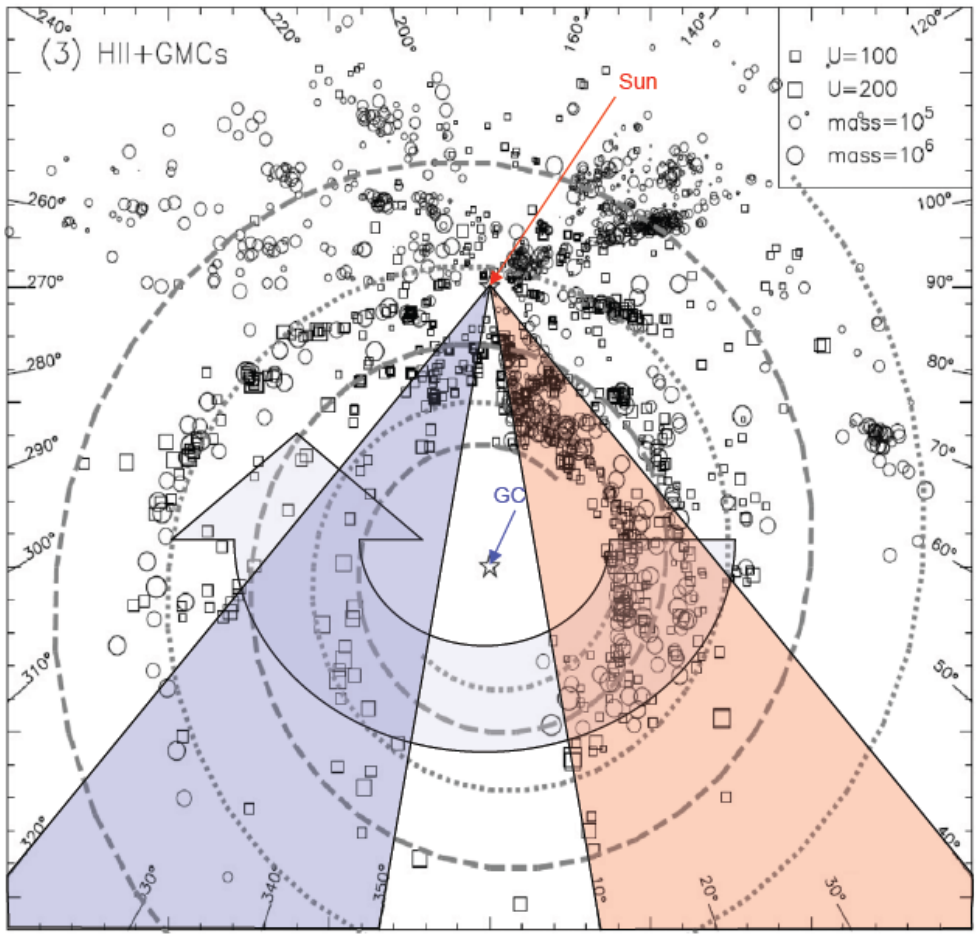


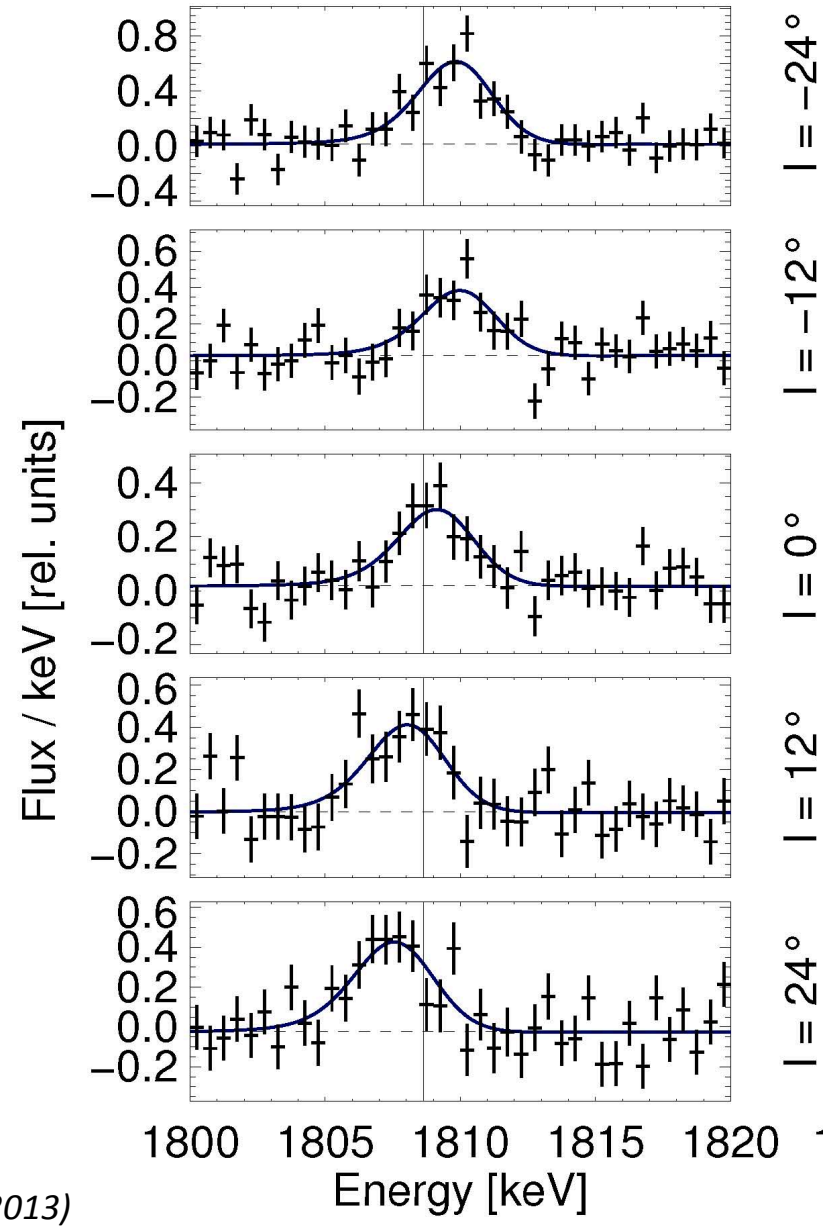


Hernandez, Burkert, Krause, Boehm, Diehl

Views of Objects in our Galaxy: ^{26}Al γ-rays

- Large-scale Galactic rotation

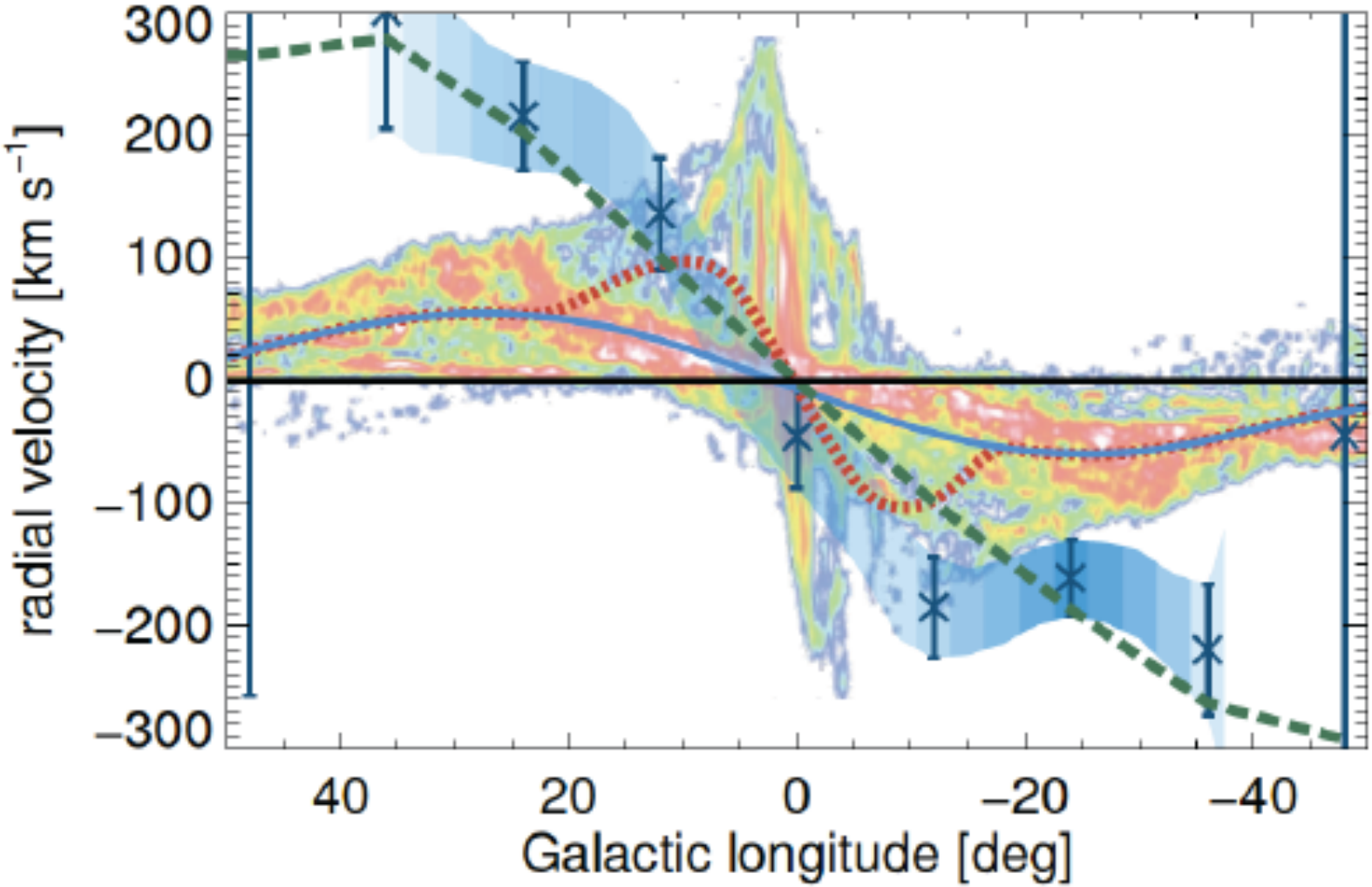




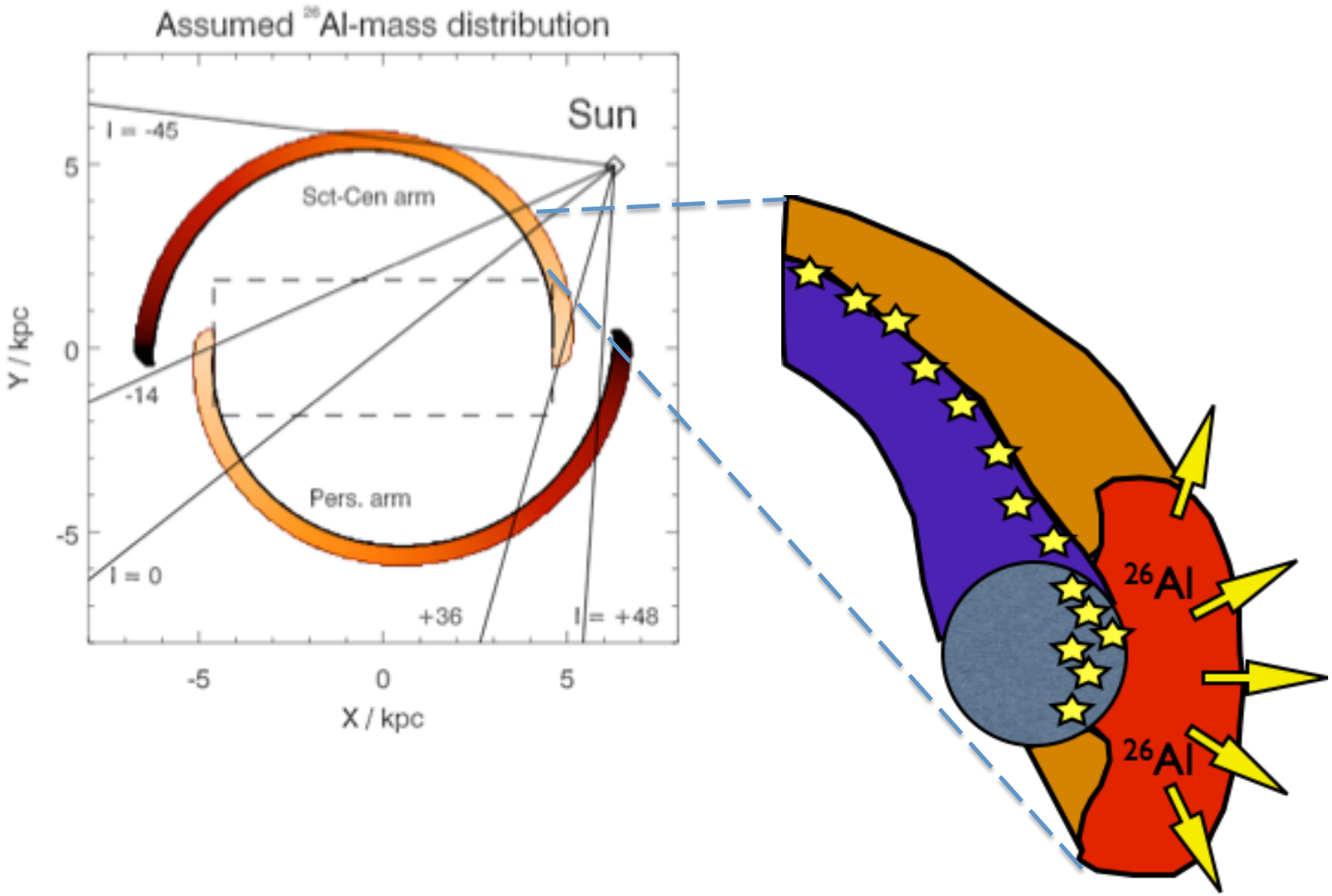
Kretschmer et al., A&A (2013)

The Galactic View: longitude-velocity diagrams

- excess velocity seen for massive-star ejecta!

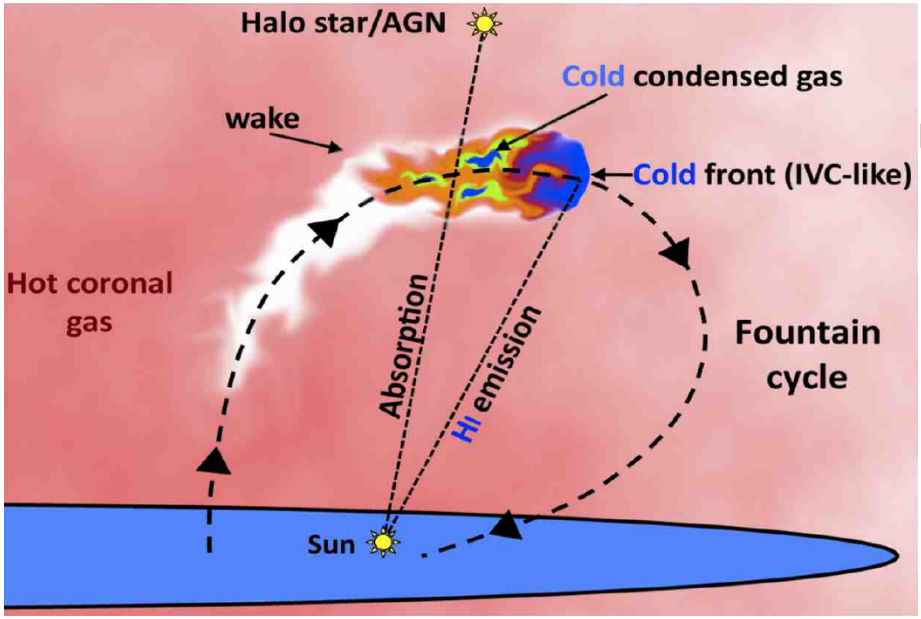


How Massive-Star Feedback Occurs…



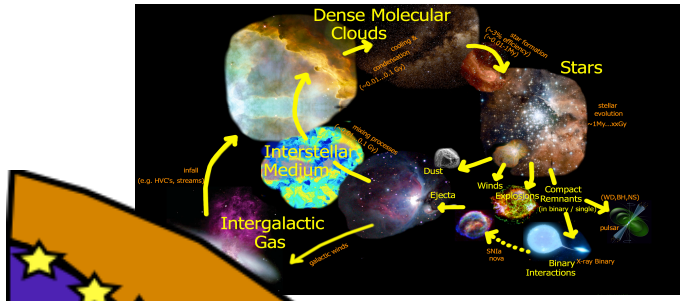
The Cycle of Gas in a Galaxy

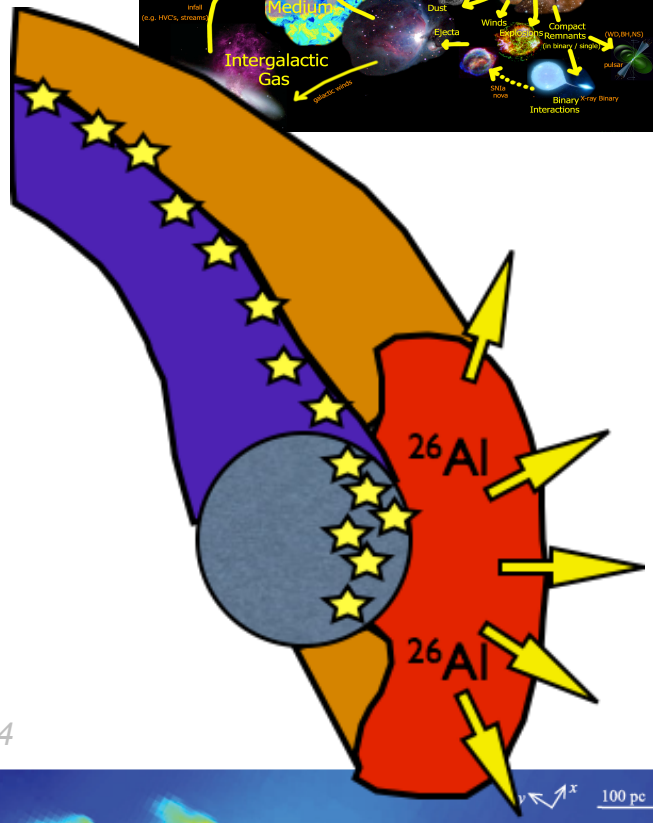
- How the Galaxy's Disk and Halo "communicate"
  - Chimneys around massive-star groups eject gas into halo
  - Constancy of Star Formation Rate



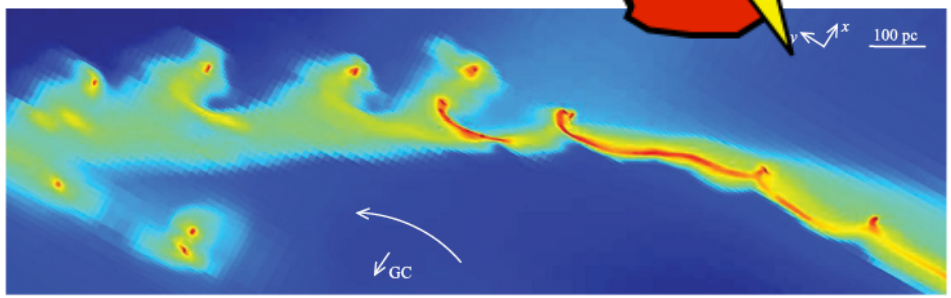
Marasco, Fraternai, & Binney 2011; Fraternali et al. 2013

pletion would be

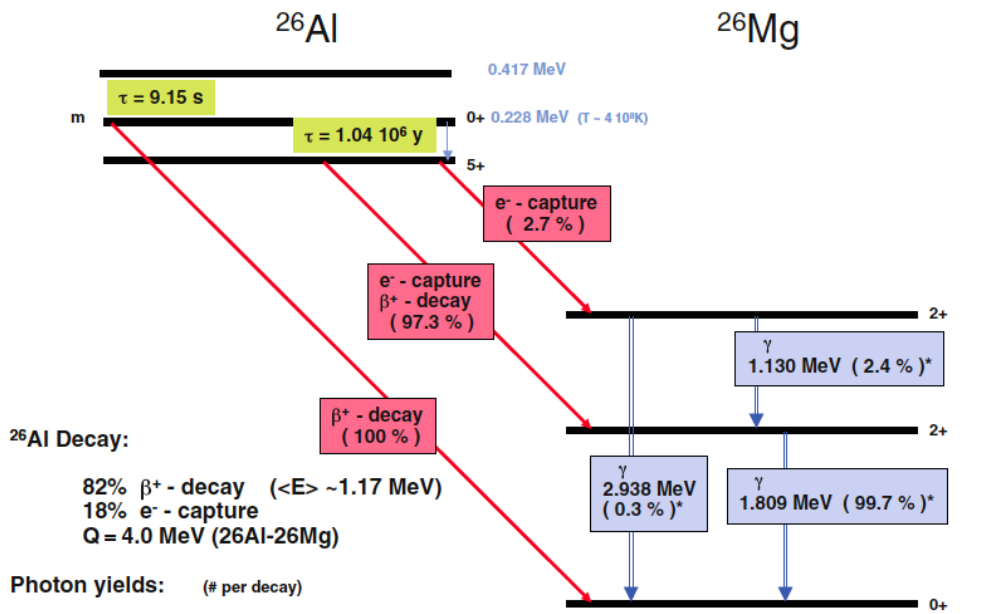




Renaud et al. 2014



^{26}Al



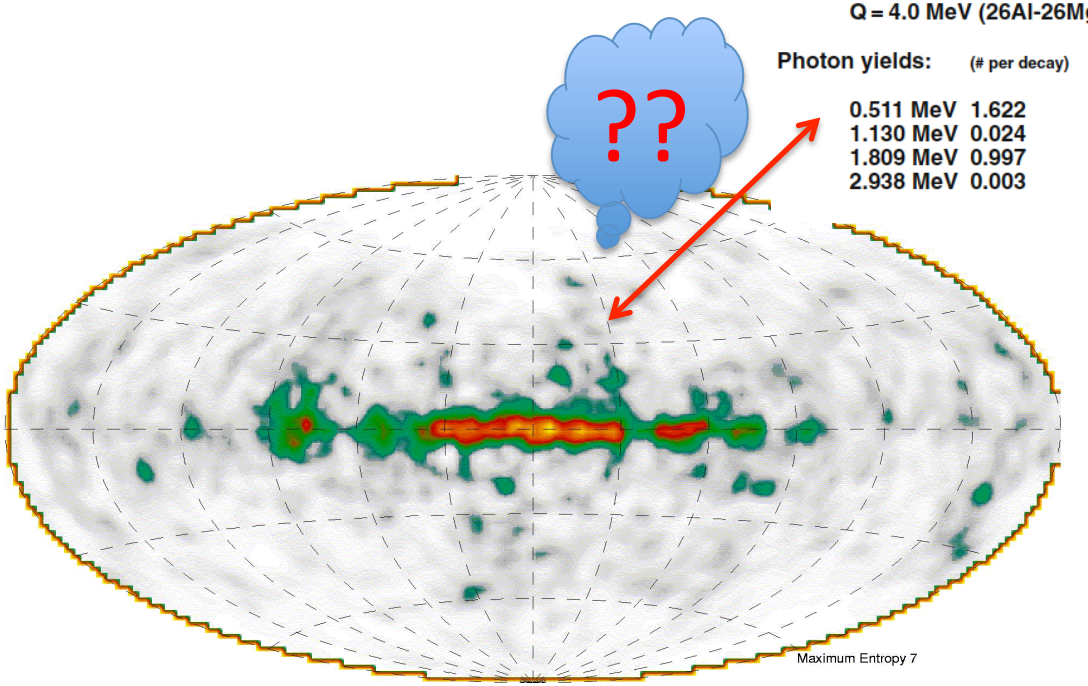
^{26}Al Decay:

82% β^+ - decay (<E> ~1.17 MeV)
18% e^- - capture
Q = 4.0 MeV (26Al-26Mg)

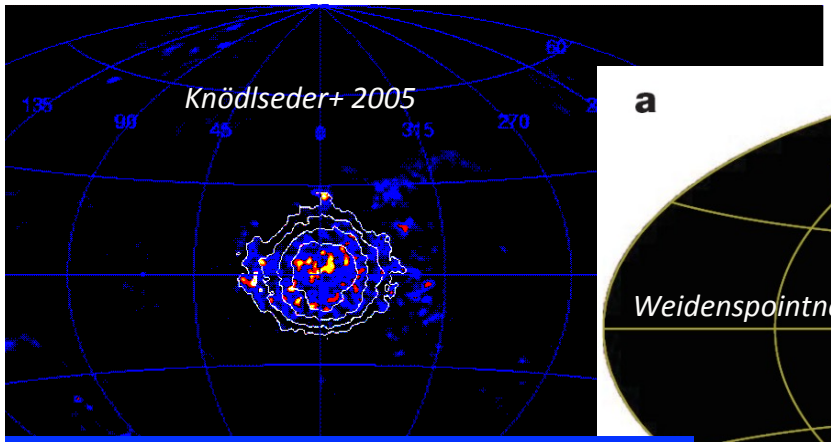
Photon yields: (# per decay)

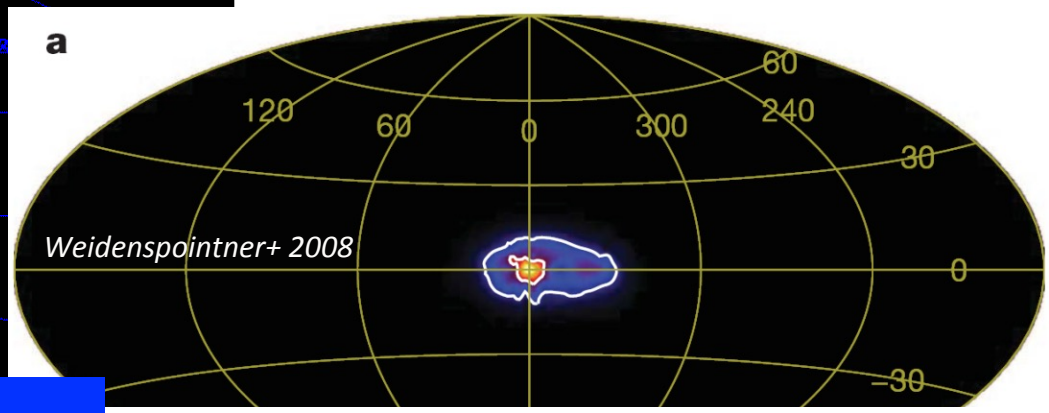
0.511 MeV	1.622
1.130 MeV	0.024
1.809 MeV	0.997
2.938 MeV	0.003

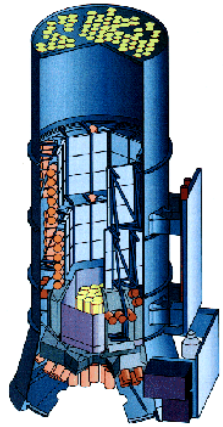
* .= % are relative to one decay of ^{26}Al



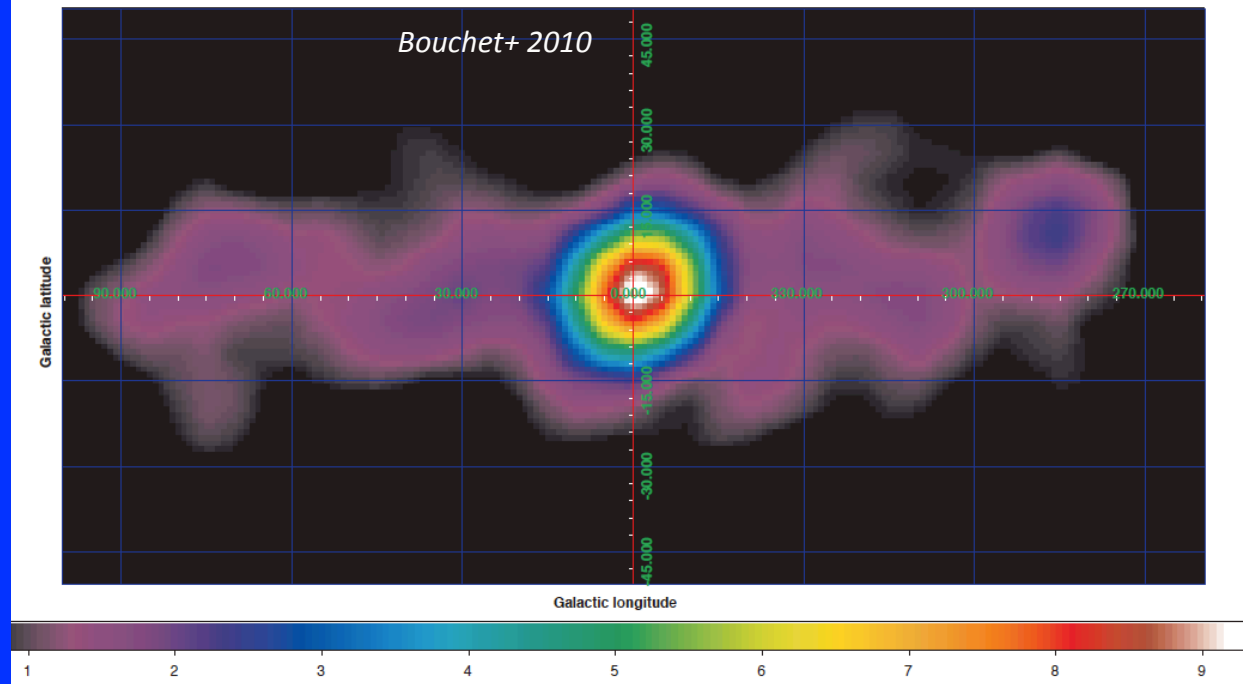
Measuring Galactic Positron Annihilation with SPI







- Annihilation g-rays are dominated by a Bright Inner-Galaxy Component
- The ^{26}Al e+ Produced in the Disk (82%) are a Minor Contribution
- Annihilation g-ray Emission Presents a Puzzle:
  - e+ Sources ?
  - Propagation !!
  - Annihilation



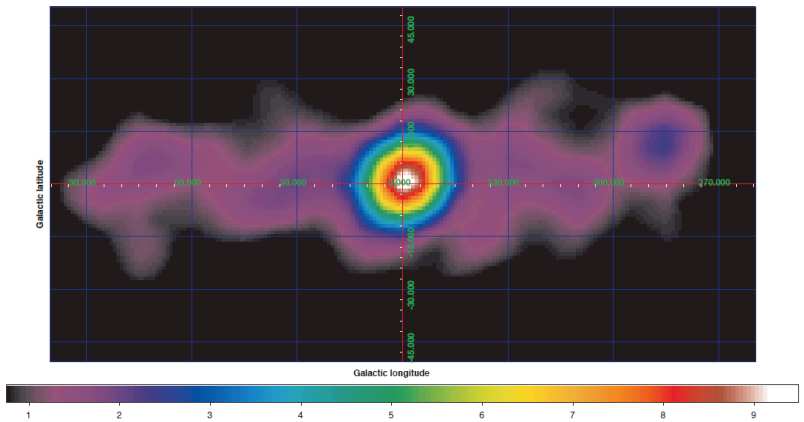
Understanding the 511 keV Line Emission

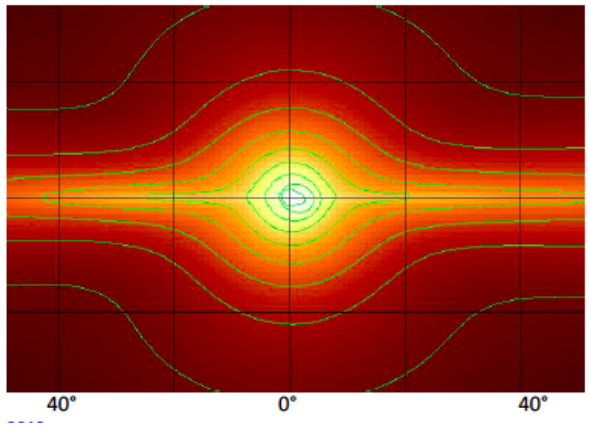
After 10 y of measurements and various different analyses

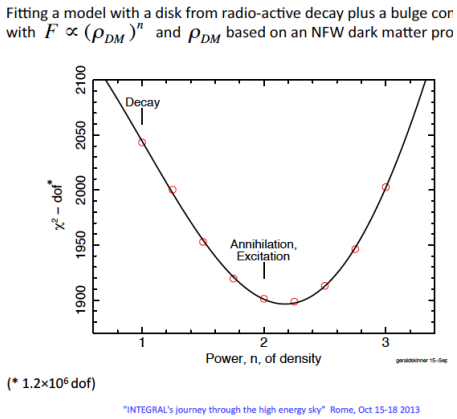
- *Knödlseder+ 2005, Jean+ 2005, Weidenspointner+ 2008, Churazov+ 2011, Bouchet+ 2011, Skinner et al. 2013*

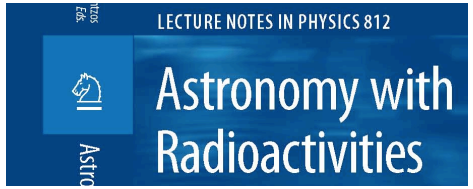
– Surprisingly-bright extended "bulge-like" emission

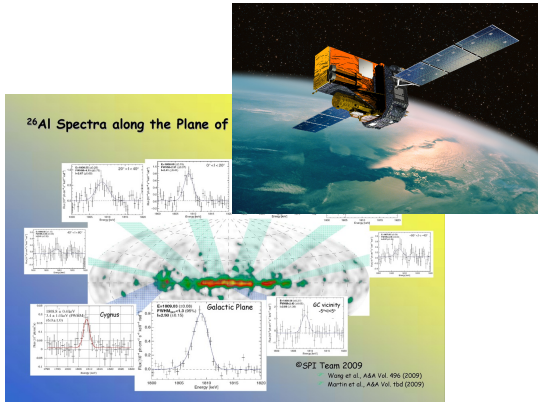
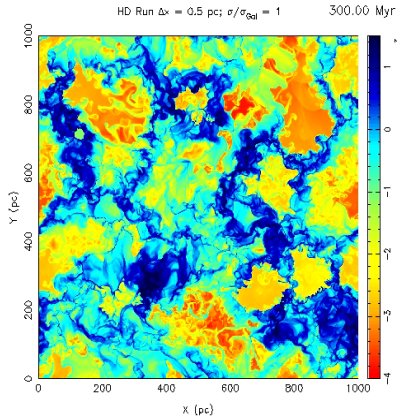
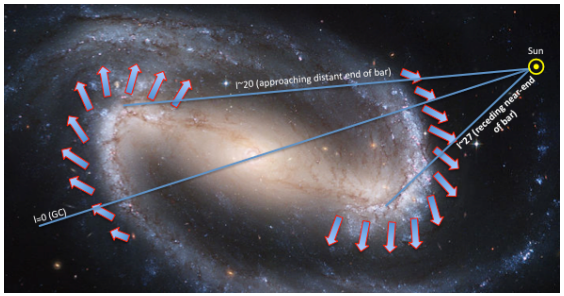
- None of the plausible candidate sources would produce this
- The centroid appears offset by ~1 deg towards 4th quadrant
- Sgr A*(?) appears to contribute 'point-like' emission, but cannot explain the extended bulge
- Dark matter annihilation matches observed "bulge" emission (but why??? There are pulsars, microquasars, SNe, …)









Cosmic Radioactivities Summary

- Radioactivity γ-rays provide a unique / different view
  - Yield constraints for SNe and Novae, Independent of complexity from unfolding of the explosion
  - Radioactivity traces diluted ejecta at late phases
- SNIa ^{56}Ni and how the explosion occurs
  - SN2014J reveals its ^{56}Ni irregularly → Luck happens.
- ccSupernova ^{44}Ti is Sensitive to Asymmetries
  - Only Some SN Eject ^{44}Ti, but then much, and clumpy
- Massive-star shell structure & evolution tests: ^{26}Al, ^{60}Fe
  - ^{26}Al as a tool; next: test groups of specific ages…
  - How much ^{60}Fe from n captures in C and He shells?
- ISM dynamics around massive-star regions: new tools
  - ^{26}Al spreading and kinematics; e^+ transport