# Insights from Cosmic Gamma-Rays


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with
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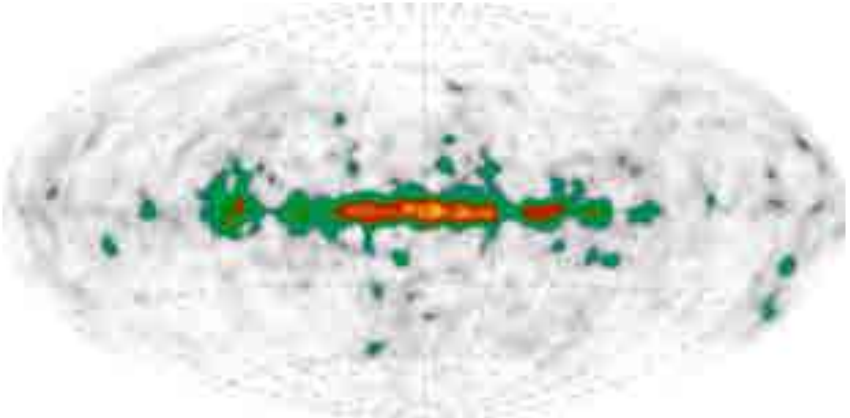
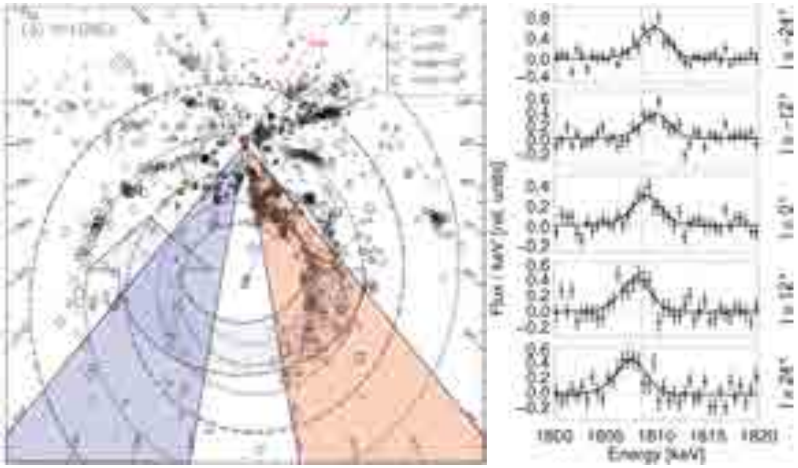
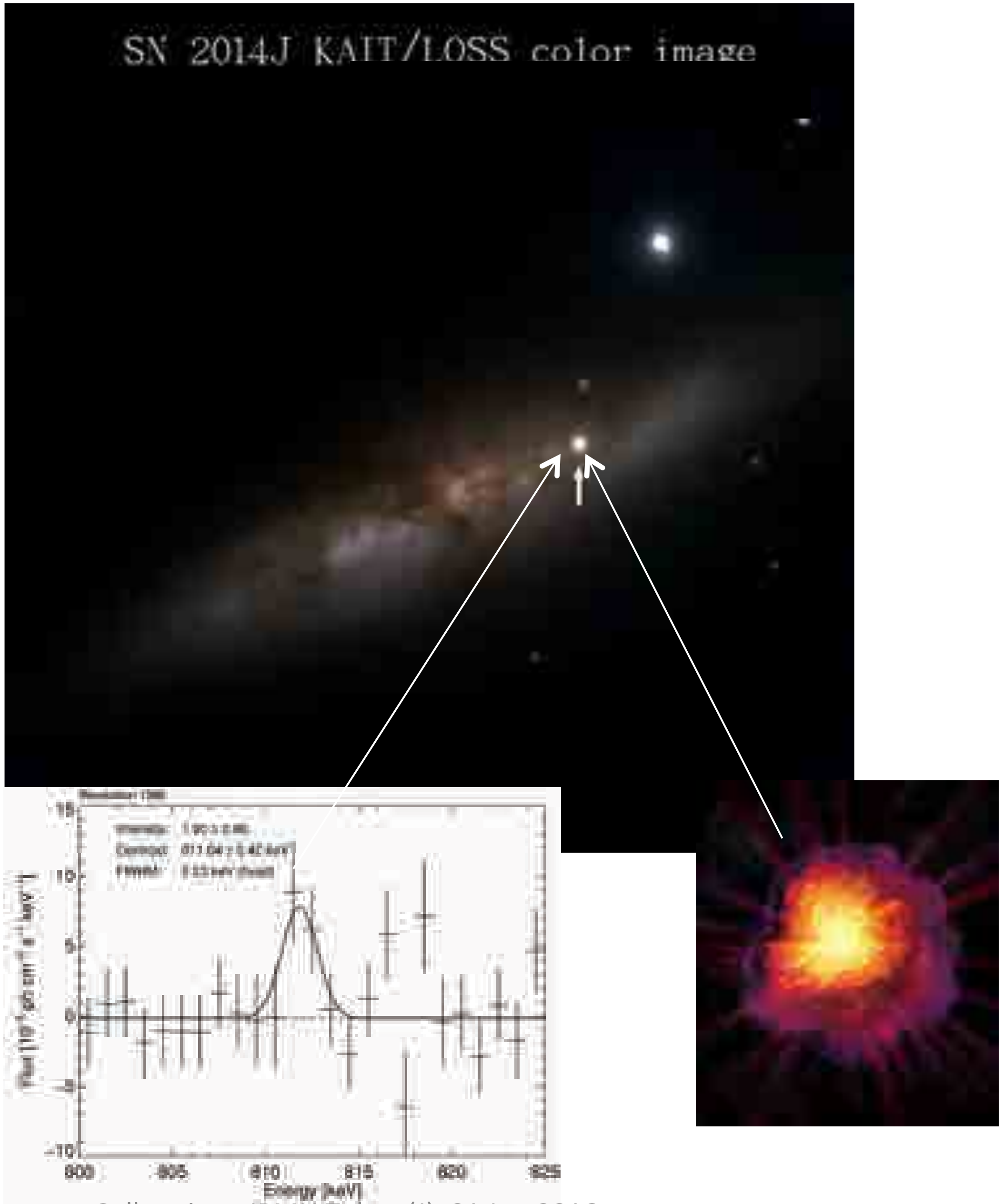
and  many others at other institutions


*Supernovae, Massive Stars, & Positrons*





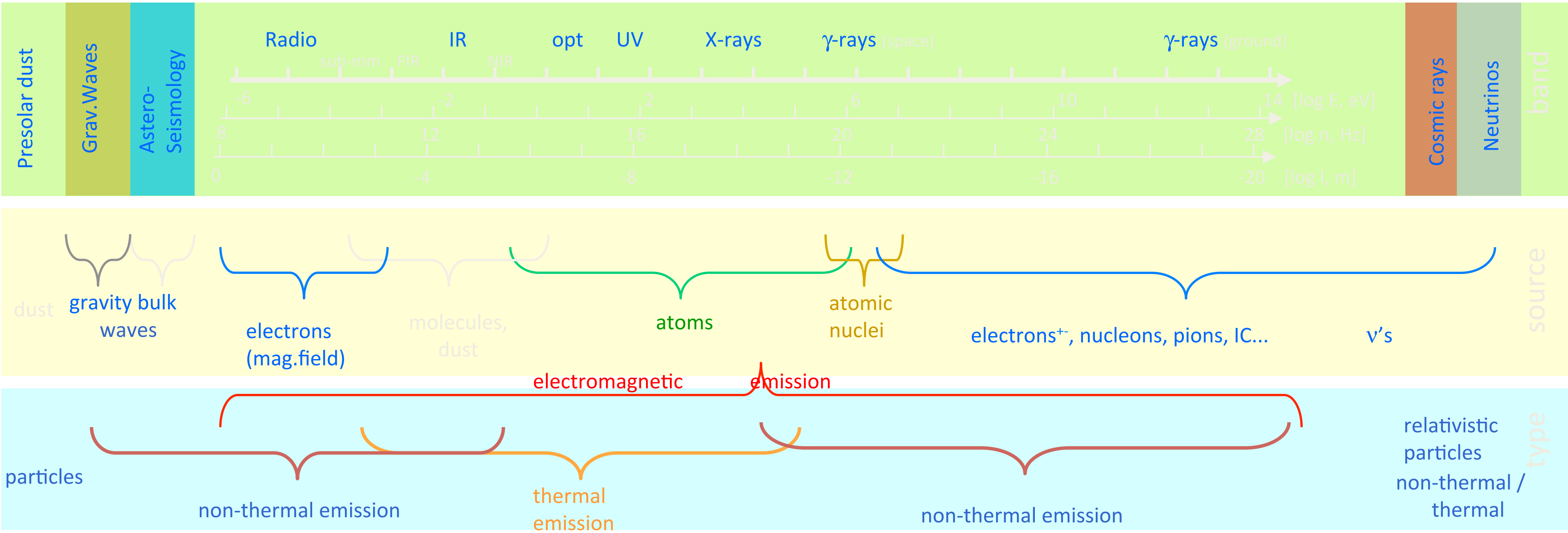



# Contents

- Gamma-ray line emissions
    - Short-lived radioactivities
    - Long-lived radioactivities
    - Positrons from $\beta^+$ decays

- Specific sources
    - Supernova explosions
    - Massive star clusters
    - Microquasars

# Astronomy : Which Astrophysical Messenger?




## – Astronomy with gamma ray photons →

- High-energy processes (>keV…interaction energy)
- Hot Plasma
- Relativistic Particles
- Nucleosynthesis

# Gamma-Ray Lines and their Messages

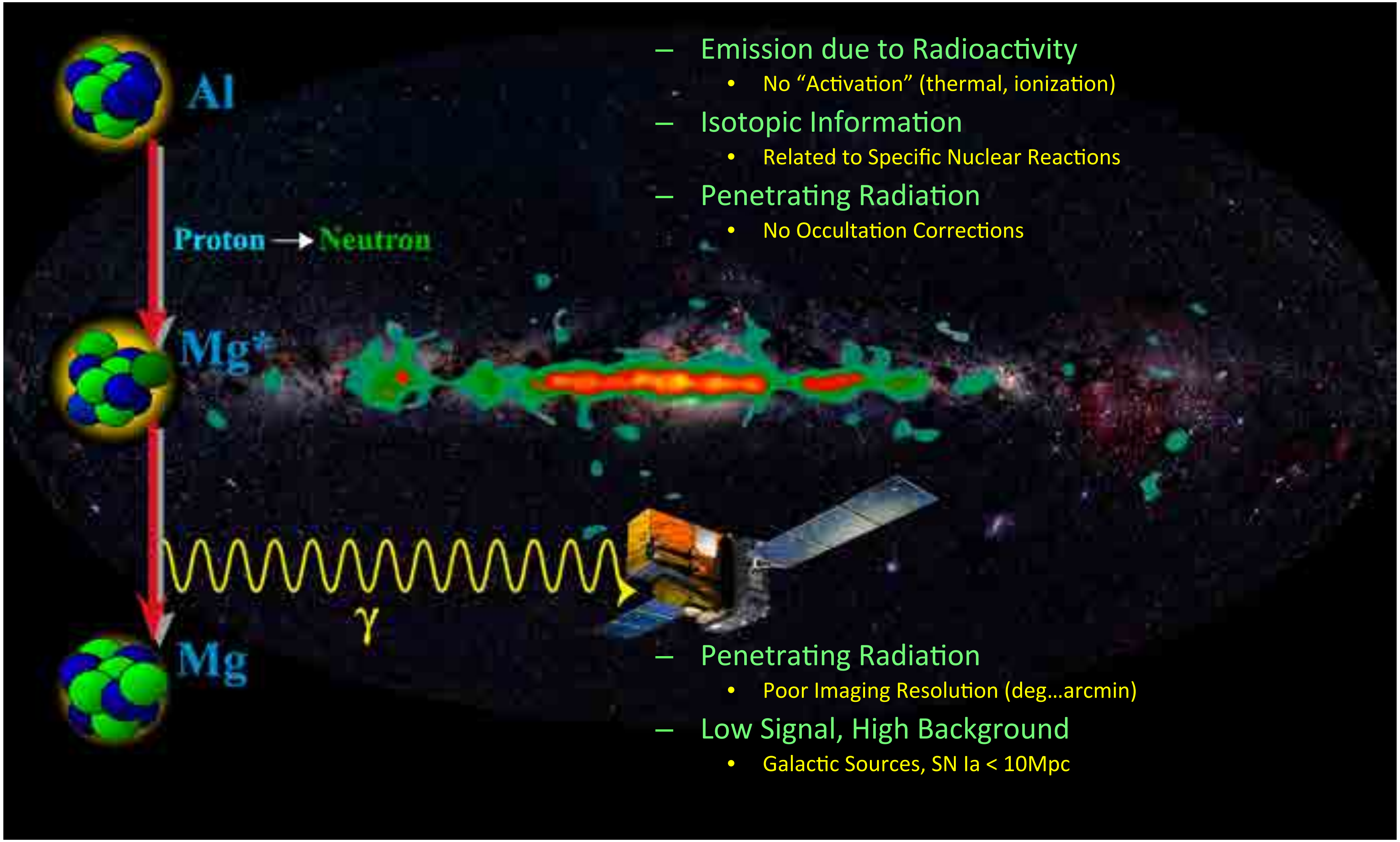
- Radioactive Trace Isotopes are Nucleosynthesis By-Products
- For Gamma-ray Spectroscopy We Need:
  - Decay Time > Source Dilution Time
  - Yields > Instrumental Sensitivities

| 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

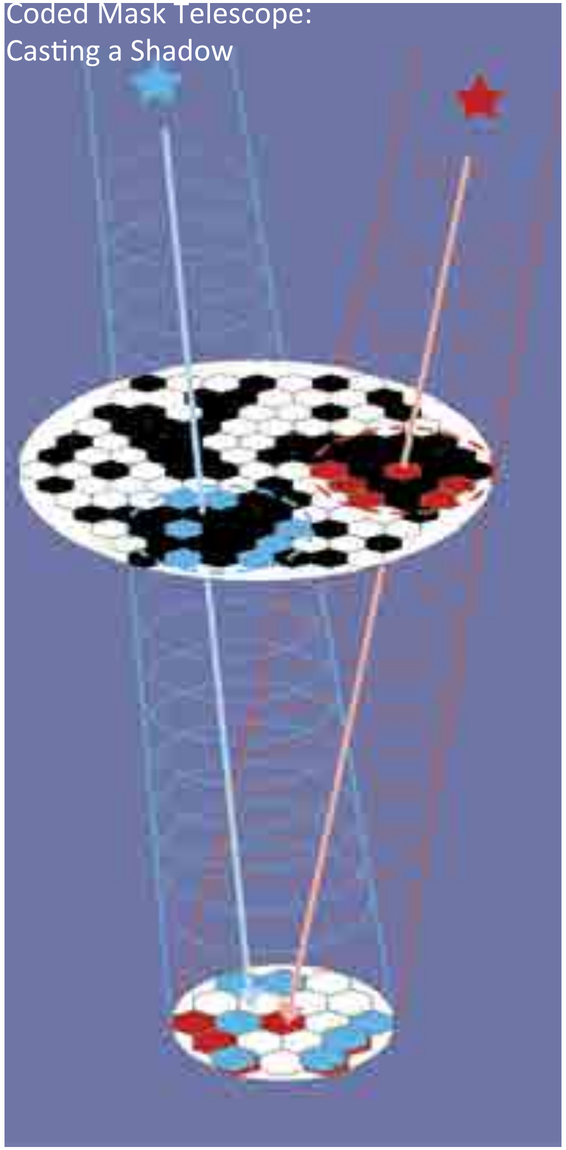
# Gamma-Rays from Radioactivity: Key Points




– 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

# INTEGRAL Cosmic Photon Measurements: The SPI Ge $\gamma$-Spectrometer



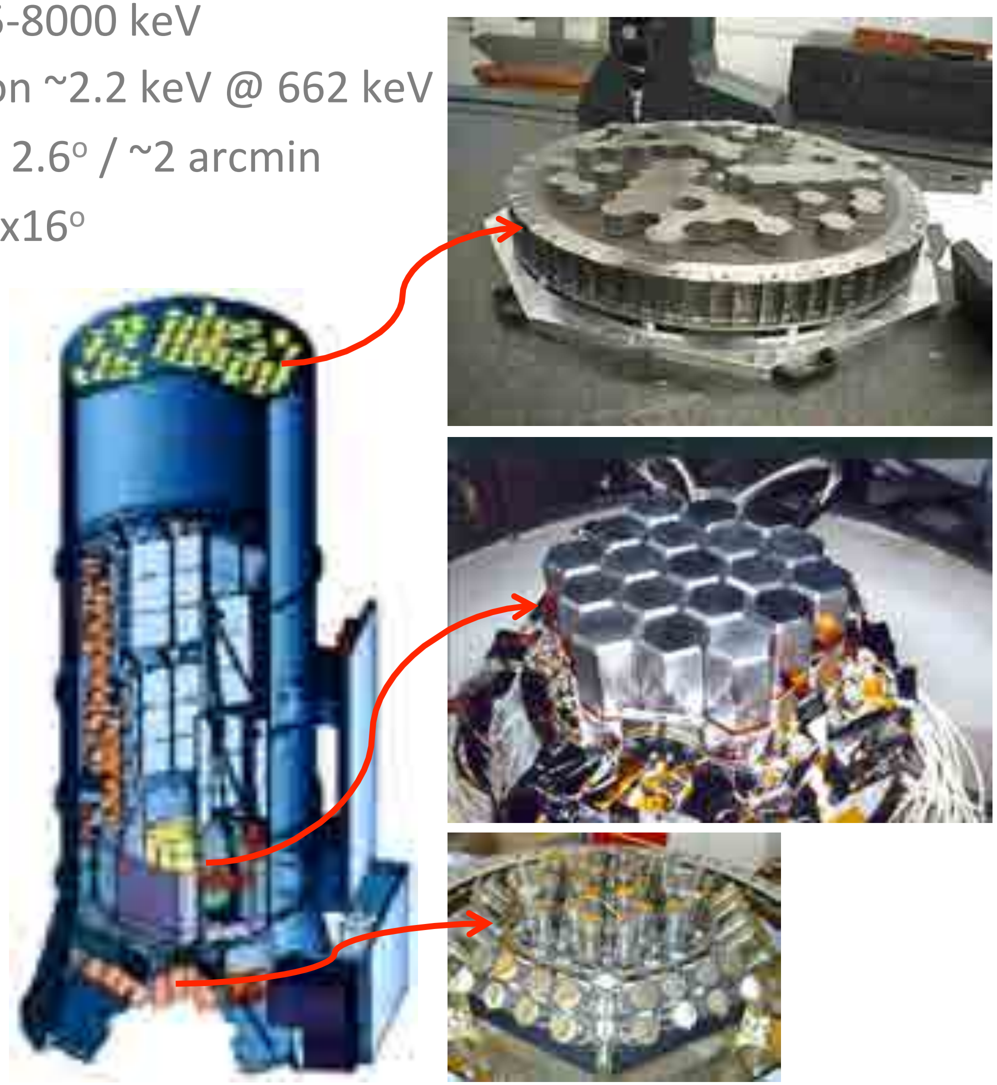

Coded-Mask Telescope

Energy Range 15-8000 keV

Energy Resolution ~2.2 keV @ 662 keV

Spatial Precision 2.6° / ~2 arcmin

Field-of-View 16x16°



# - guiding questions -

## Contents

- Gamma-ray line emissions
  - Short-lived radioactivities
  - Long-lived radioactivities
  - Positrons from $\beta^+$ decays
- Specific sources
  - Supernova explosions
  - Massive star clusters
  - Microquasars

☞ ***Supernova Explosions, and how they unfold and release new nuclei***

☞ ***Using nuclear emission as a tool for astrophysics related to the cycle of matter***

☞ ***High energy sources can make it difficult to disentangle nuclear contributions***

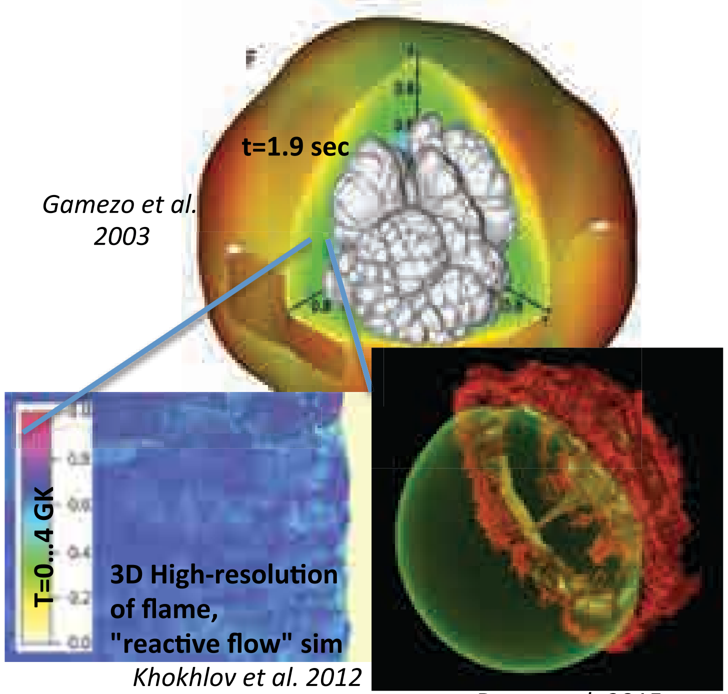
# Supernovae

# SNe Ia: Understanding & Main Issues

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

☆ Issues:

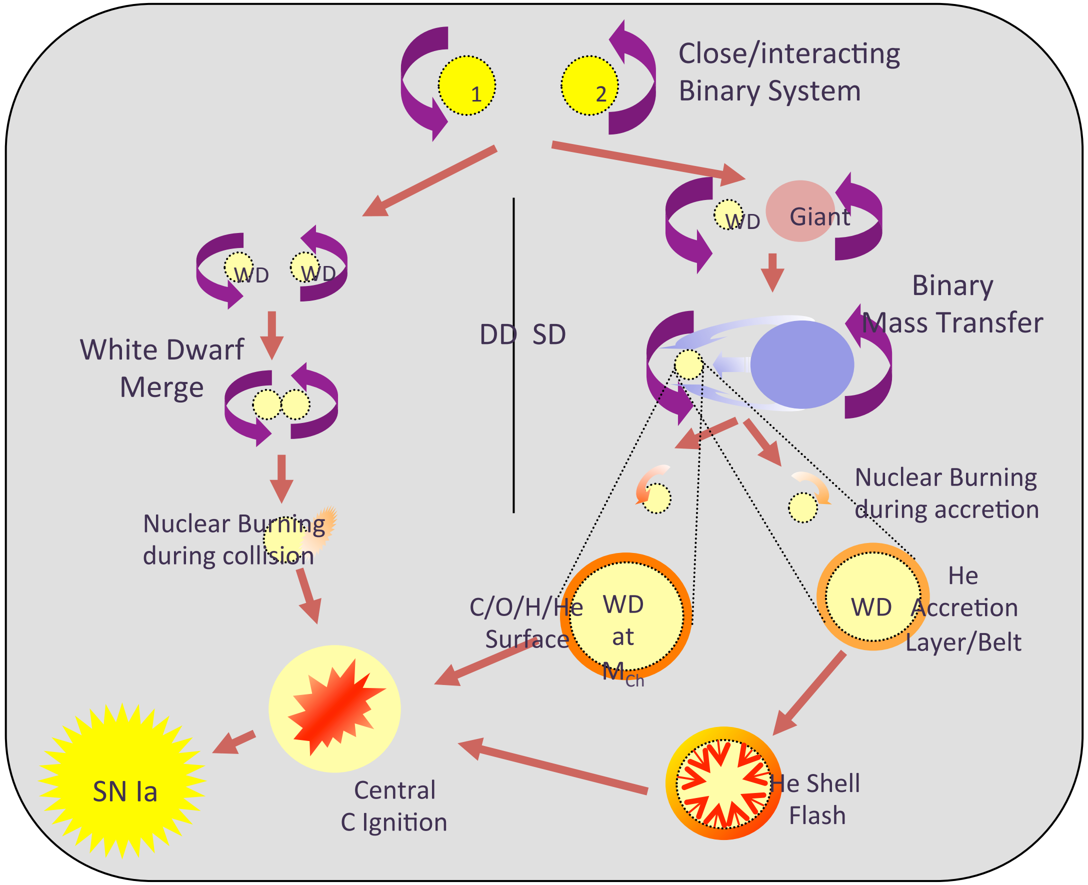
Flame propagation




*Gamezo et al. 2003*

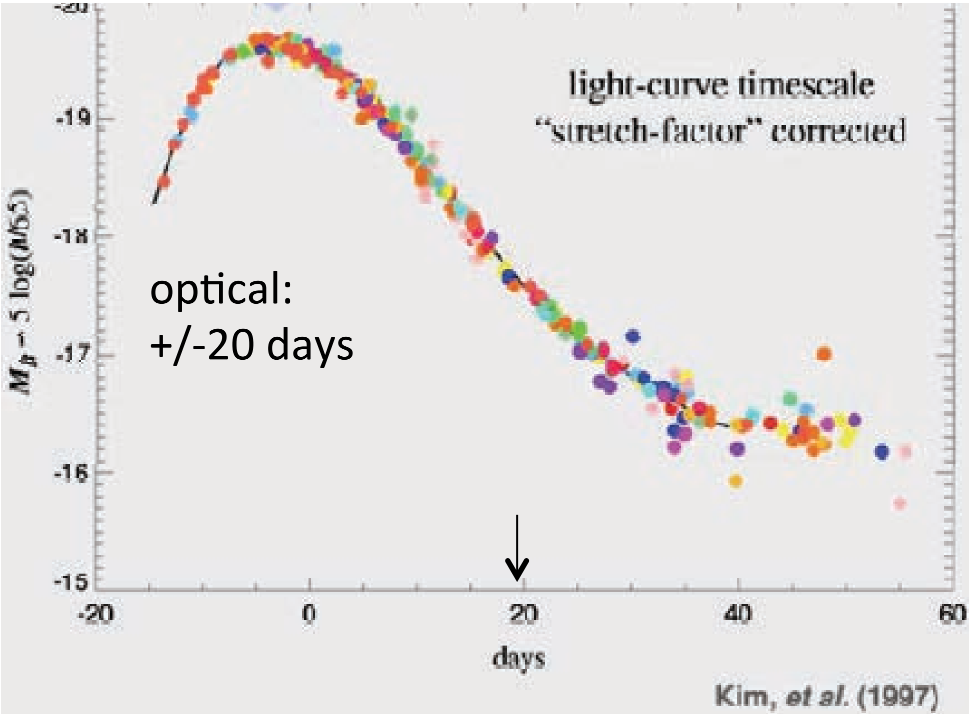
*Khokhlov et al. 2012*

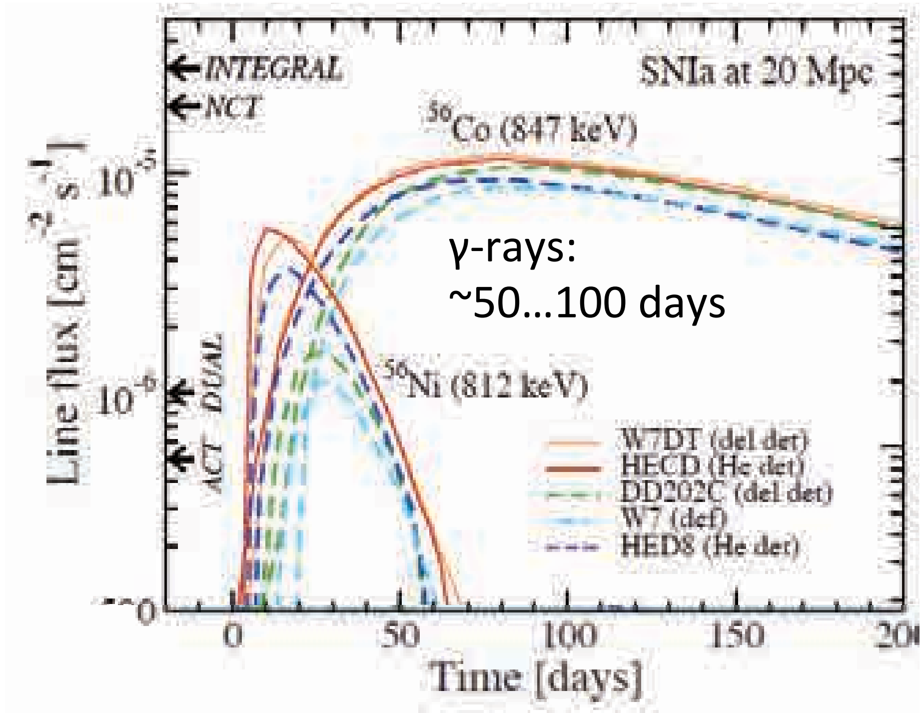
*Daan et al. 2015*




☞ Progenitor diversity?

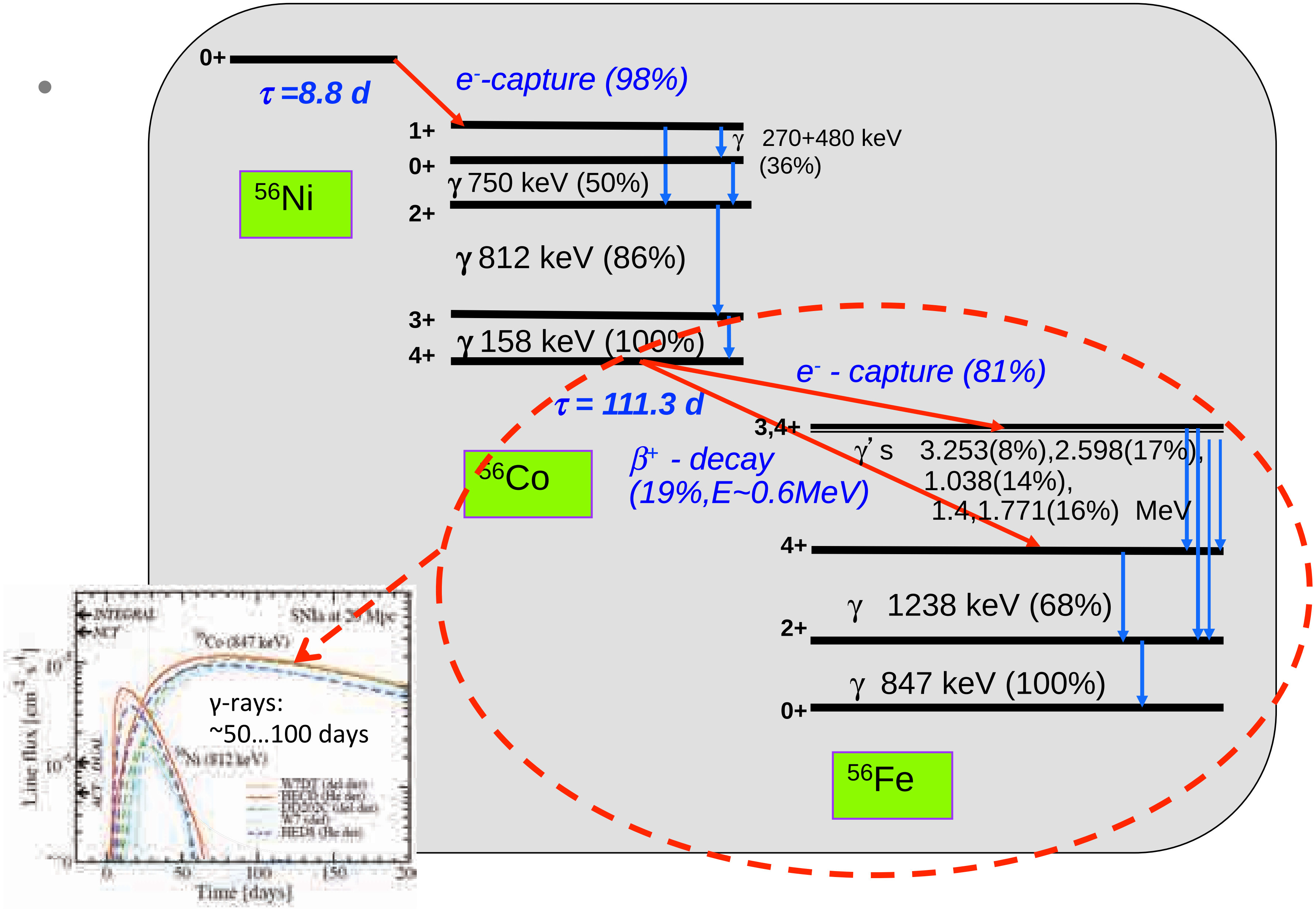
# SNIa Light: Radioactivity Gamma-Rays Make Optical Emission



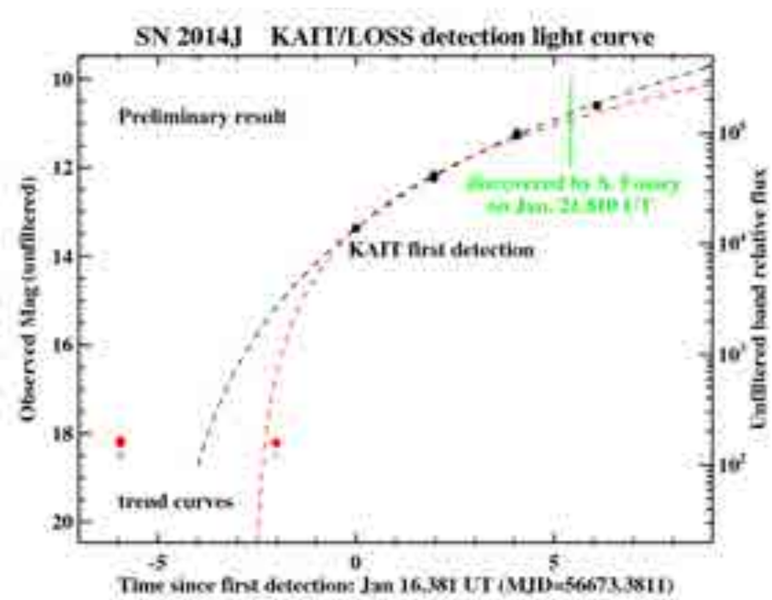

- $^{56}$Ni decay gamma-rays and $e^+$ are initially fully absorbed (→ supernova light from this 'bolometer'), and leak out later

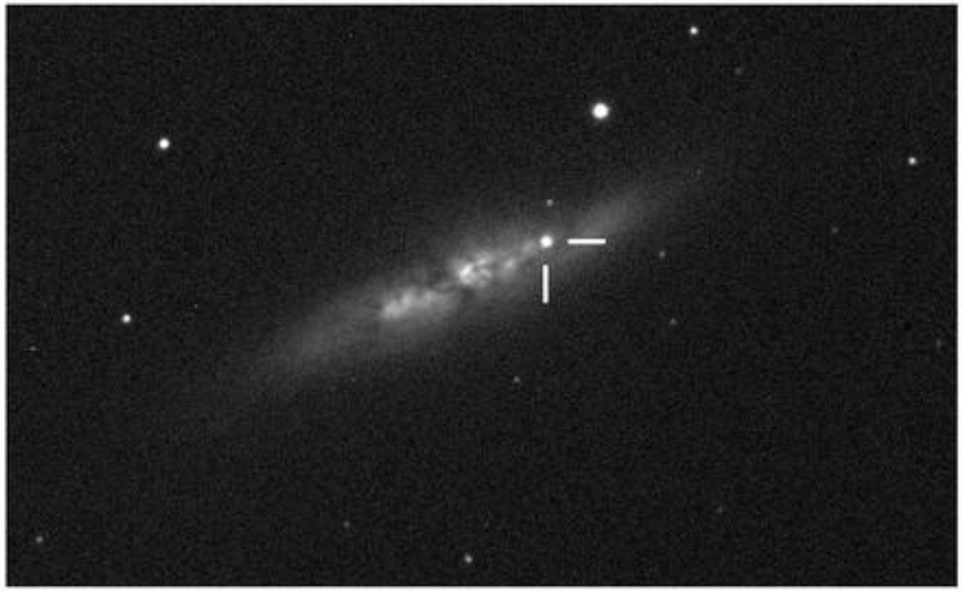
# $^{56}$Ni Radioactivity Decay Chain and Gamma-Rays

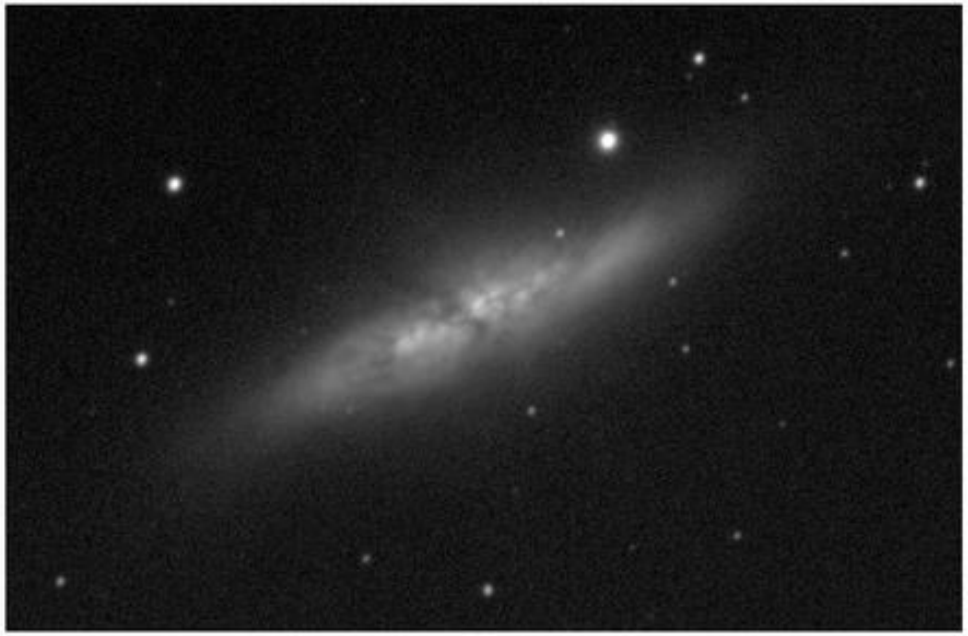


# SN2014J

- In M82
  (Starburst Galaxy)
  - Discovered 22 Jan 2014
  - Likely Explosion Date:
    14 Jan 2014 (14.75 +/-0.3d)
  - Distance 3.3….3.53 Mpc,
    l=141.41°, b=40.56°
  - Closest SN Ia in 40 y!

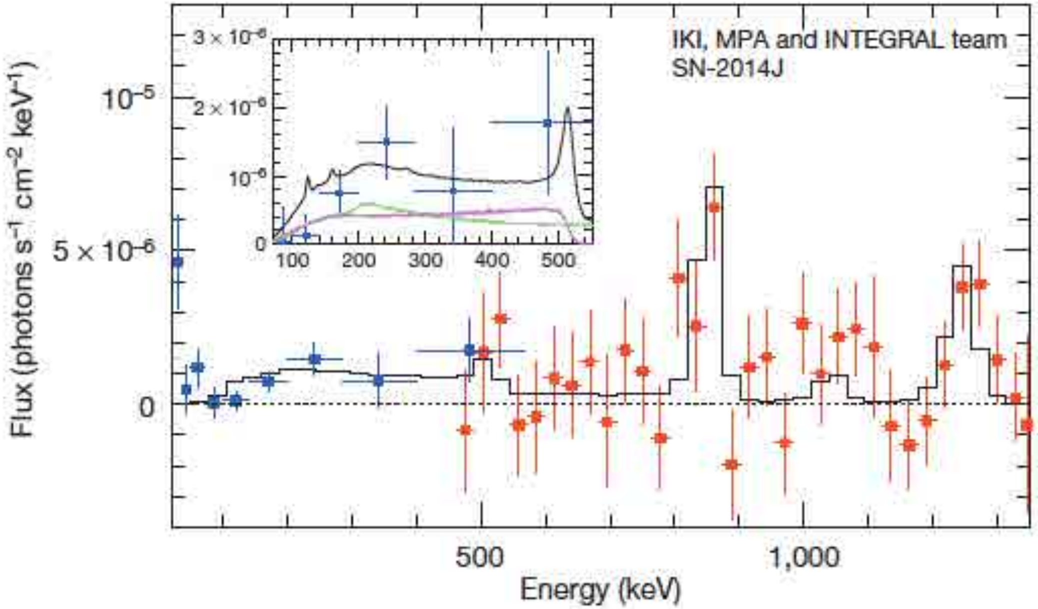


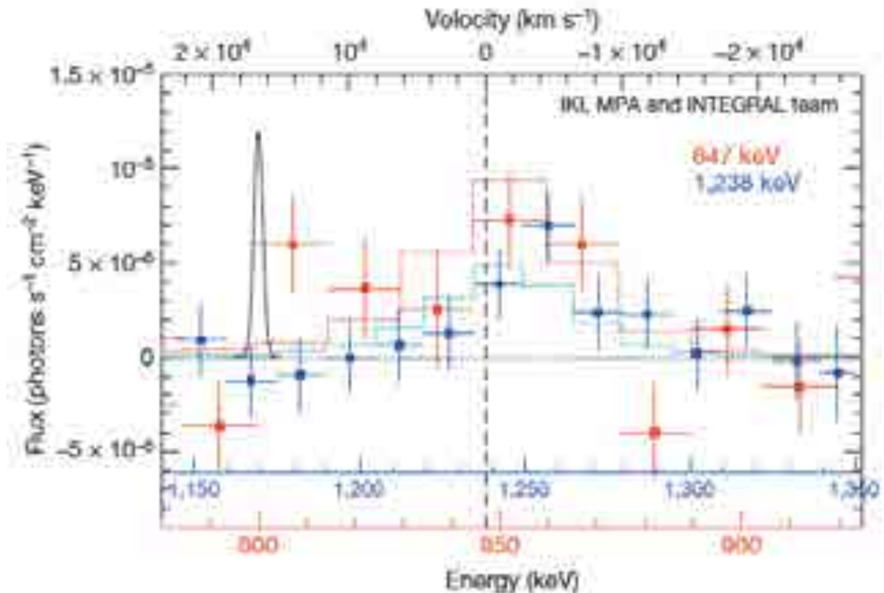





# SN2014J data Jan – Jun 2014: $^{56}$Co lines

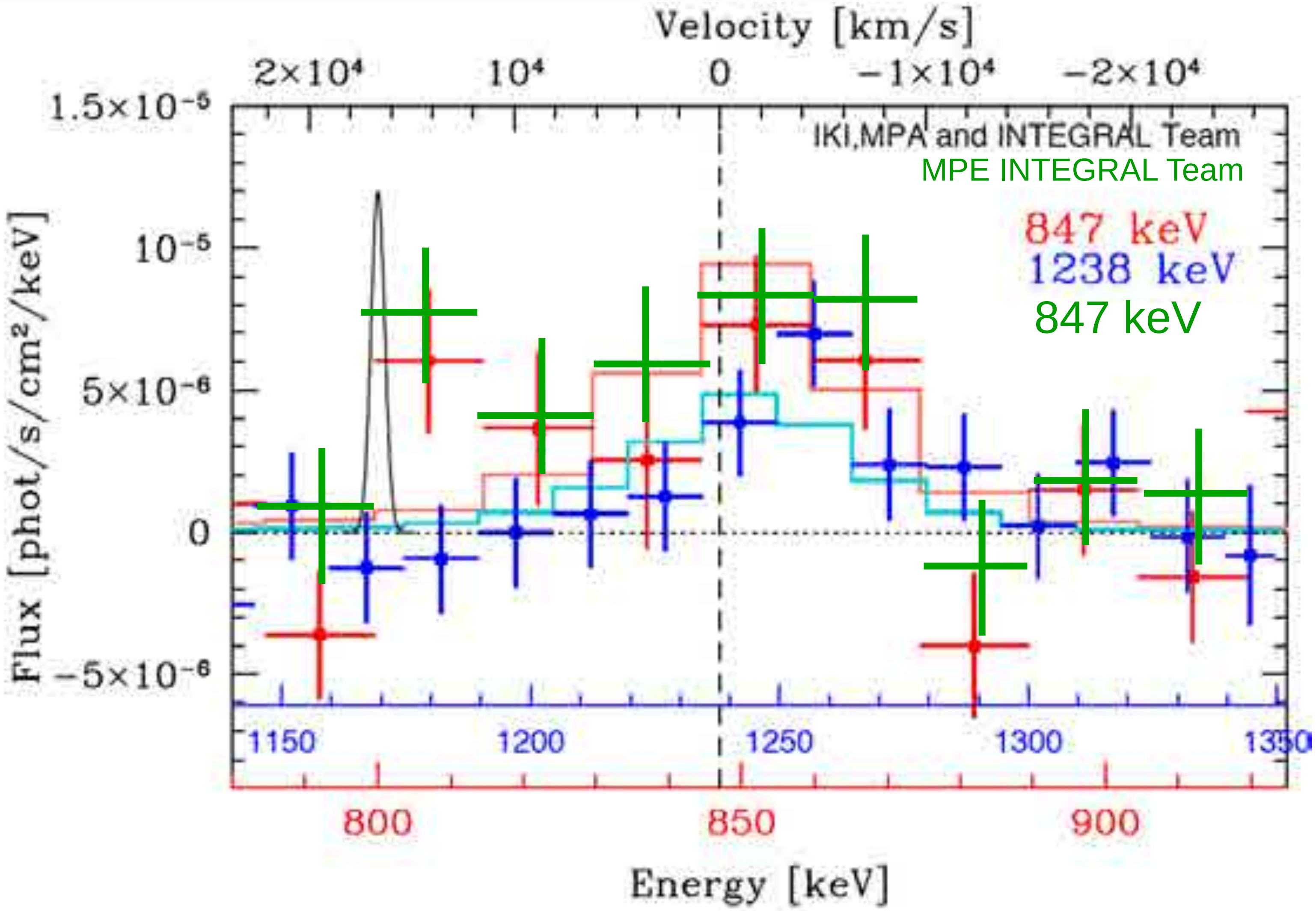
- Detection of 847 and 1238 keV lines from $^{56}$Co decay at days 50-100
- Confirm SNIa model
- Significantly Doppler-broadened
  - *Churazov et al., Nat, 2014*



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

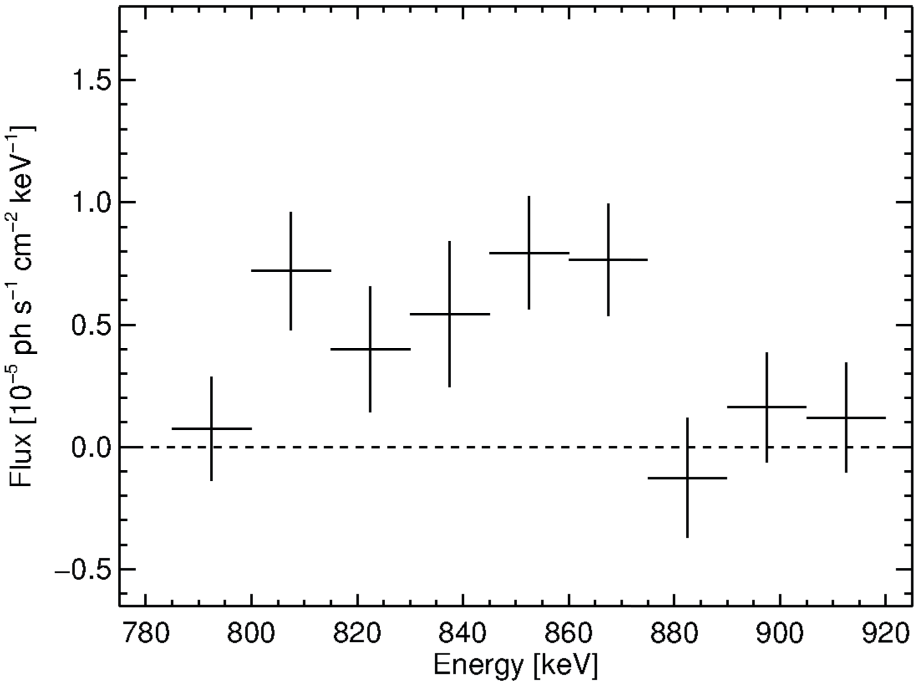
- INTEGRAL Obs from 31 Jan till 26 Jun 2014



# 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?

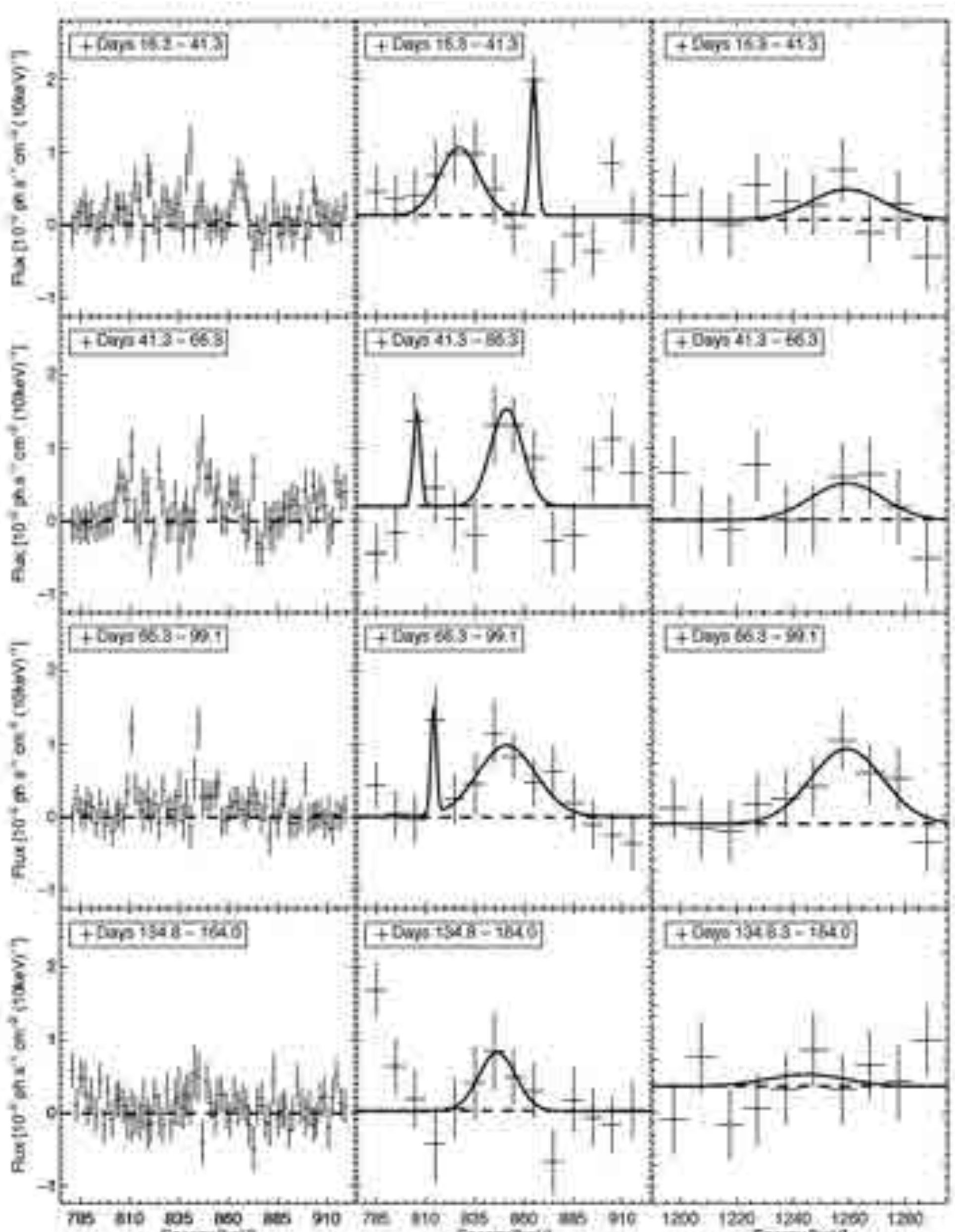
- *Diehl et al. 2015*

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

- The $^{56}$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)*

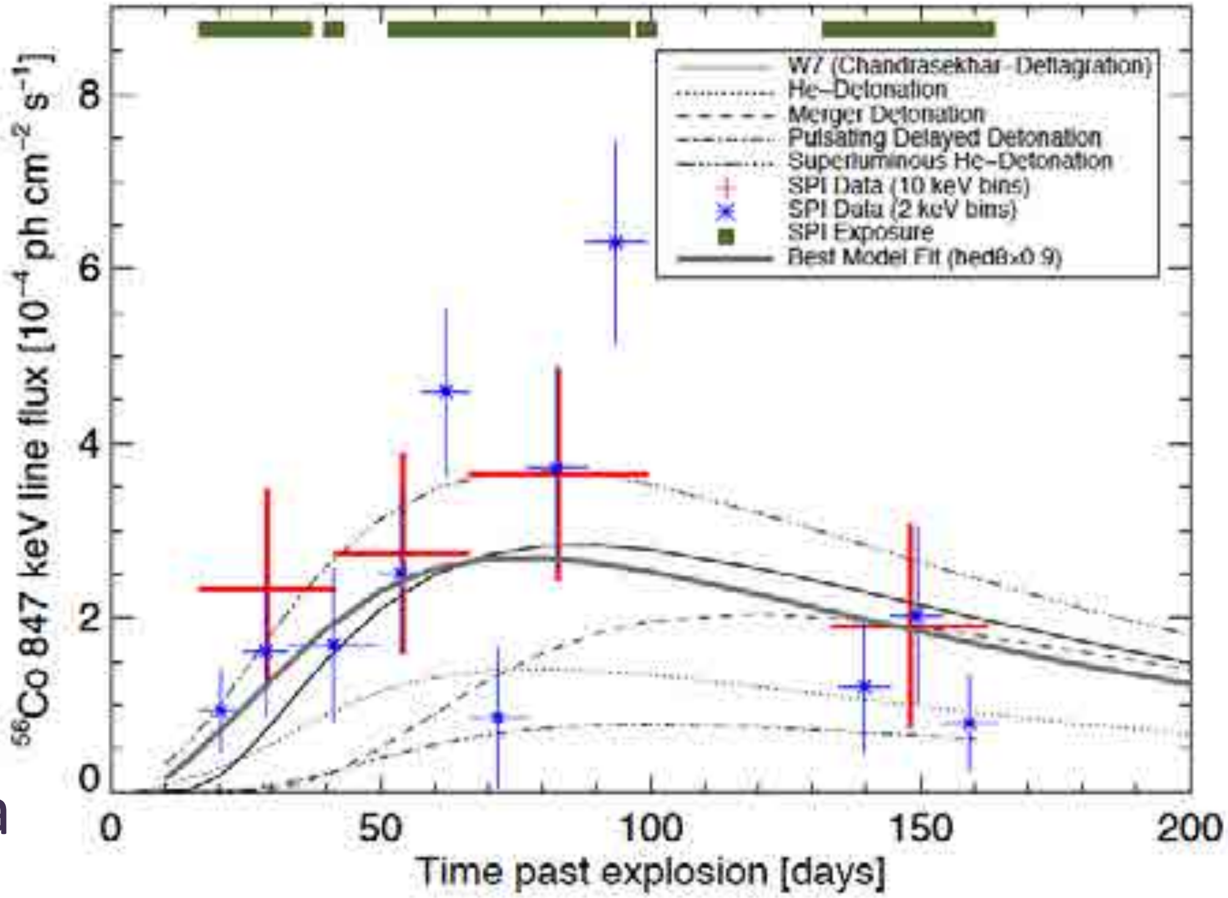


# SN2014J data Jan – Jun 2014: 847 keV $^{56}$Co line

– Choice of spectral “line emission” assignments

– Structured brightness evolution

→ Compare high/low res data to models

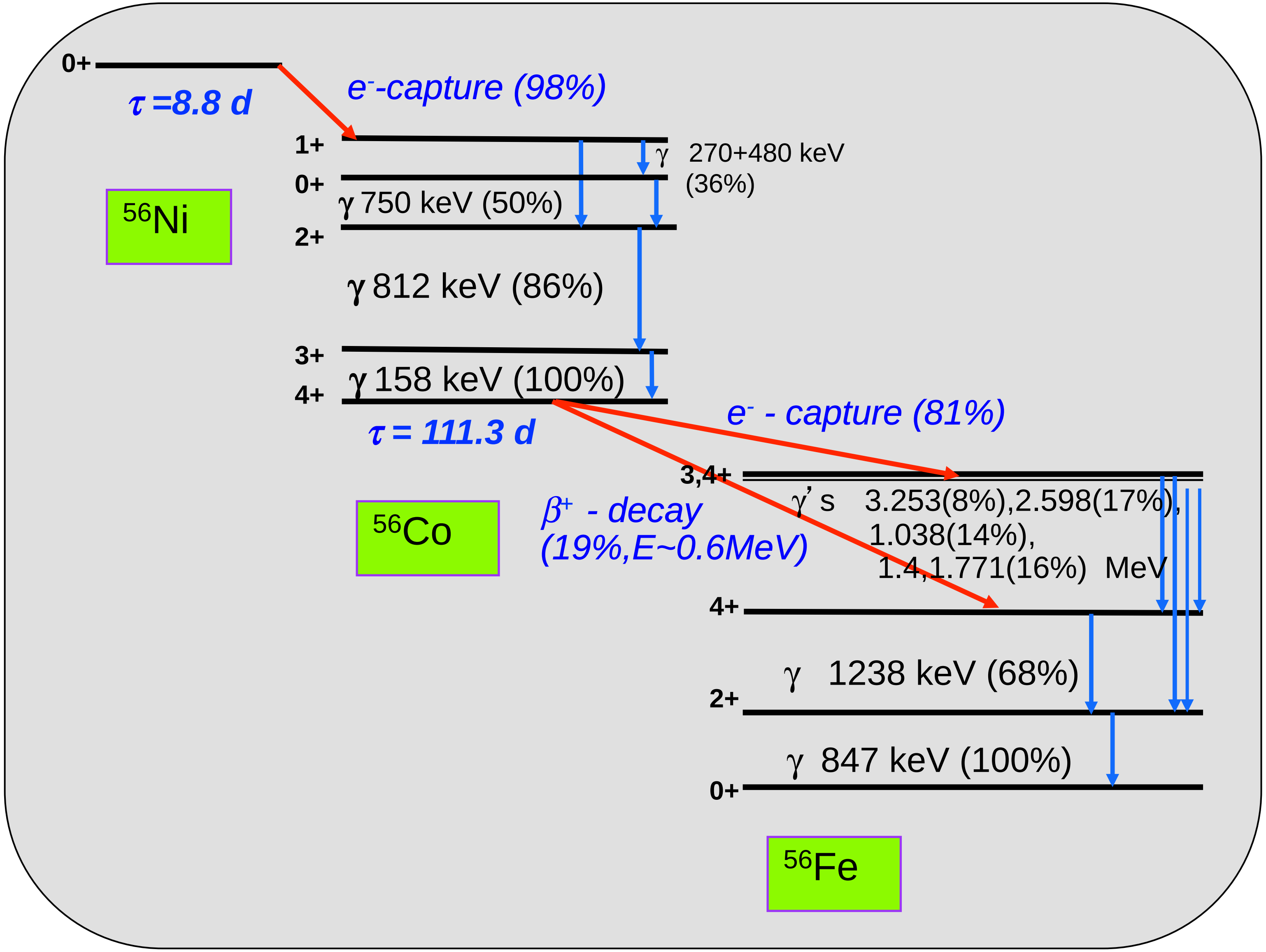



– $^{56}$Ni mass (fitted): 0.49 $_{+/-0.09}$ $M_\odot$

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

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

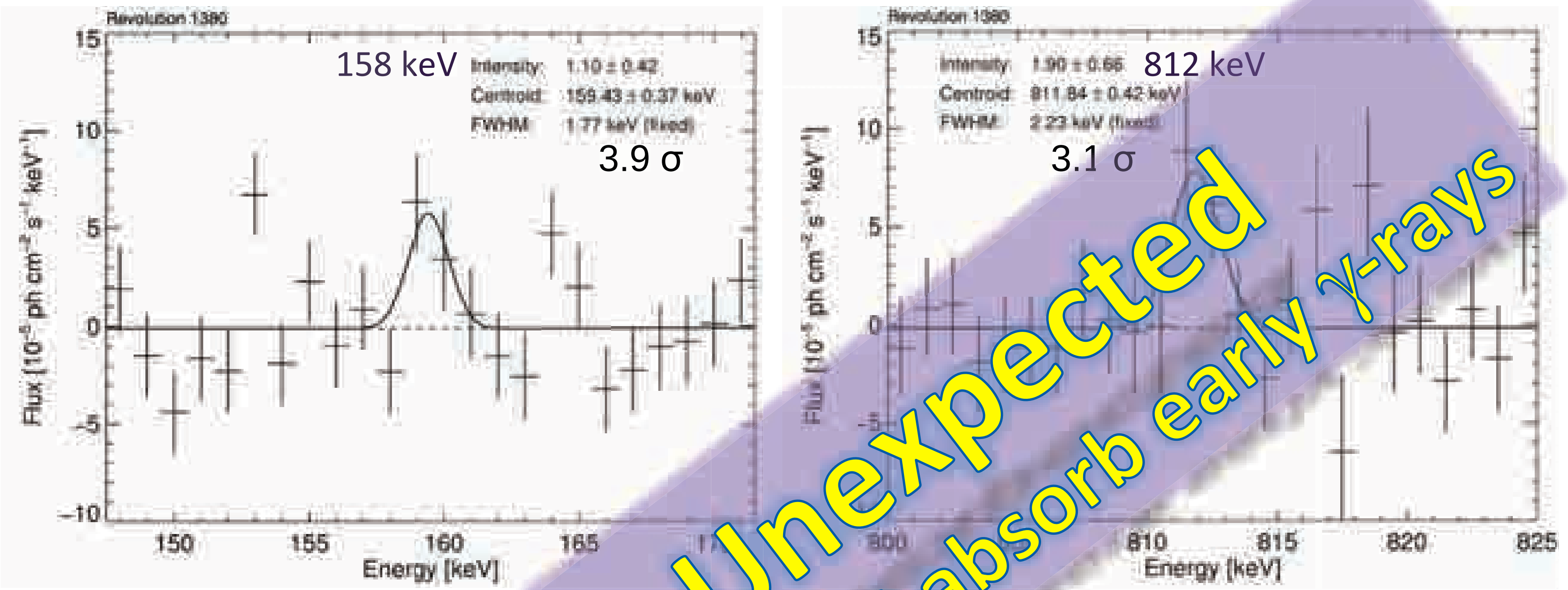
# $^{56}$Ni Radioactivity Decay Chain and Gamma-Rays

- 


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

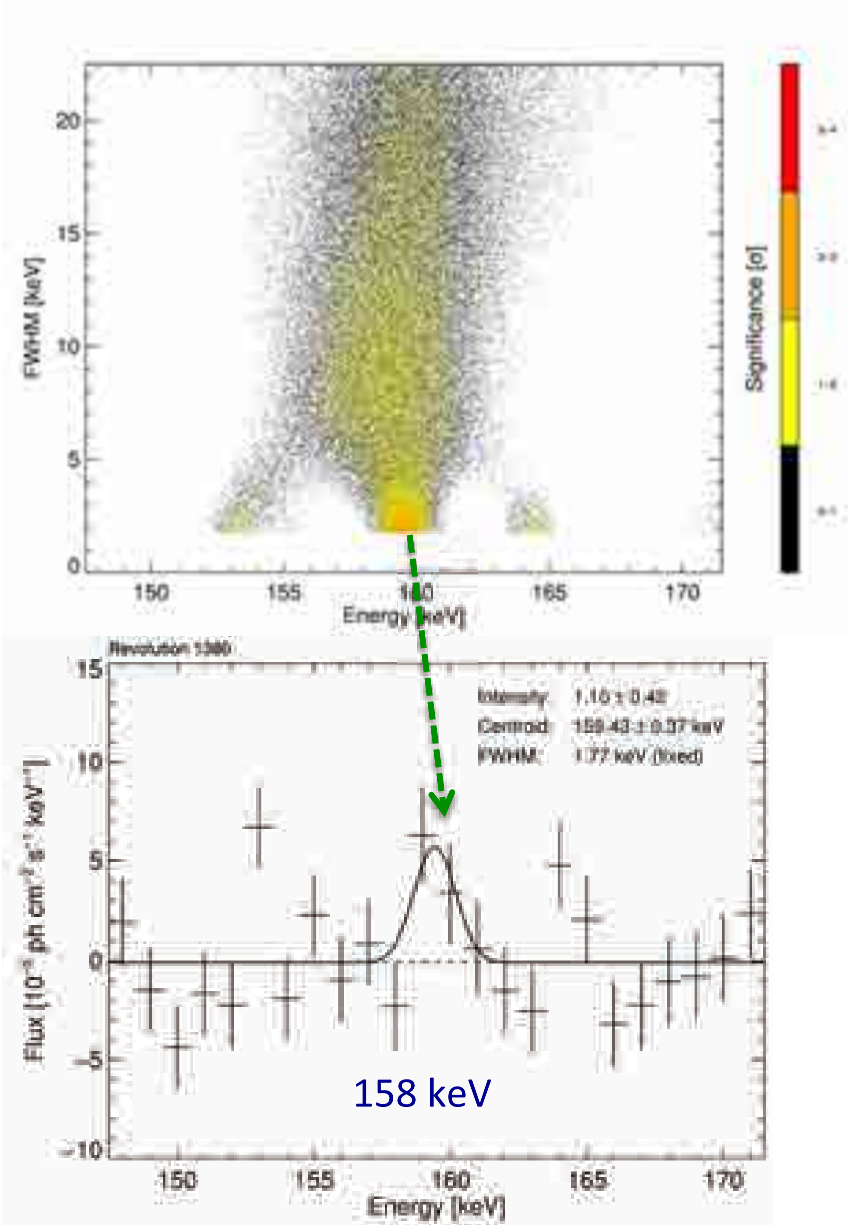
# SN2014J: Early $^{56}$Ni

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




  - 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 (backscale to explosion): ~0.06 $M_\odot$

# Line Uncertainties: Search and method biases

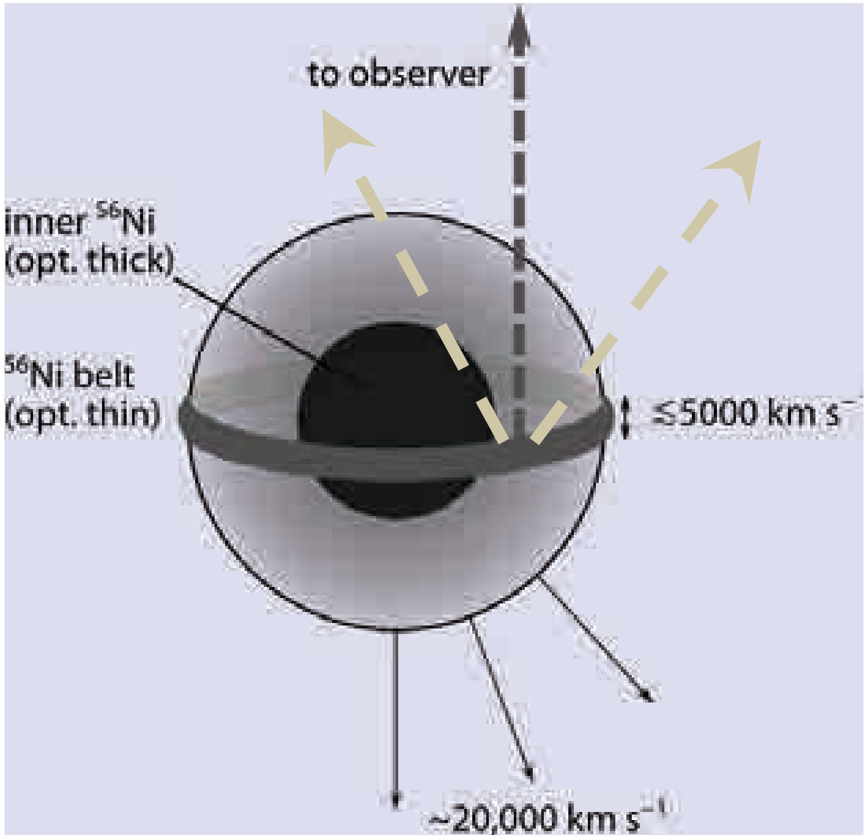



- Random Search: Try to Fit a Line (Centroid,Intensity, Width)

☞Narrow line, ~unshifted as most-likely solution

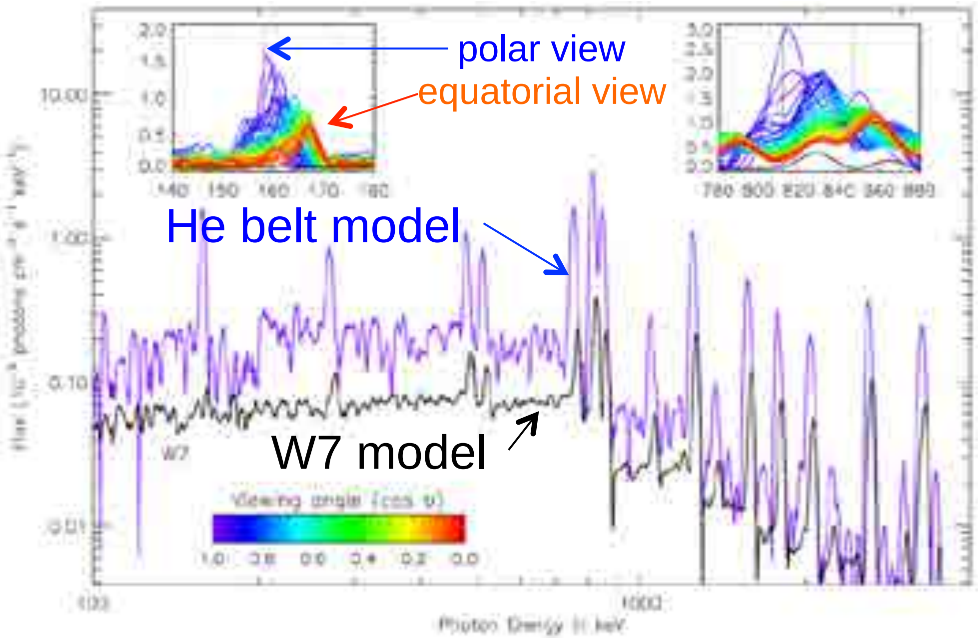
# SN2014J: An unusual (triggered) explosion?

- 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*

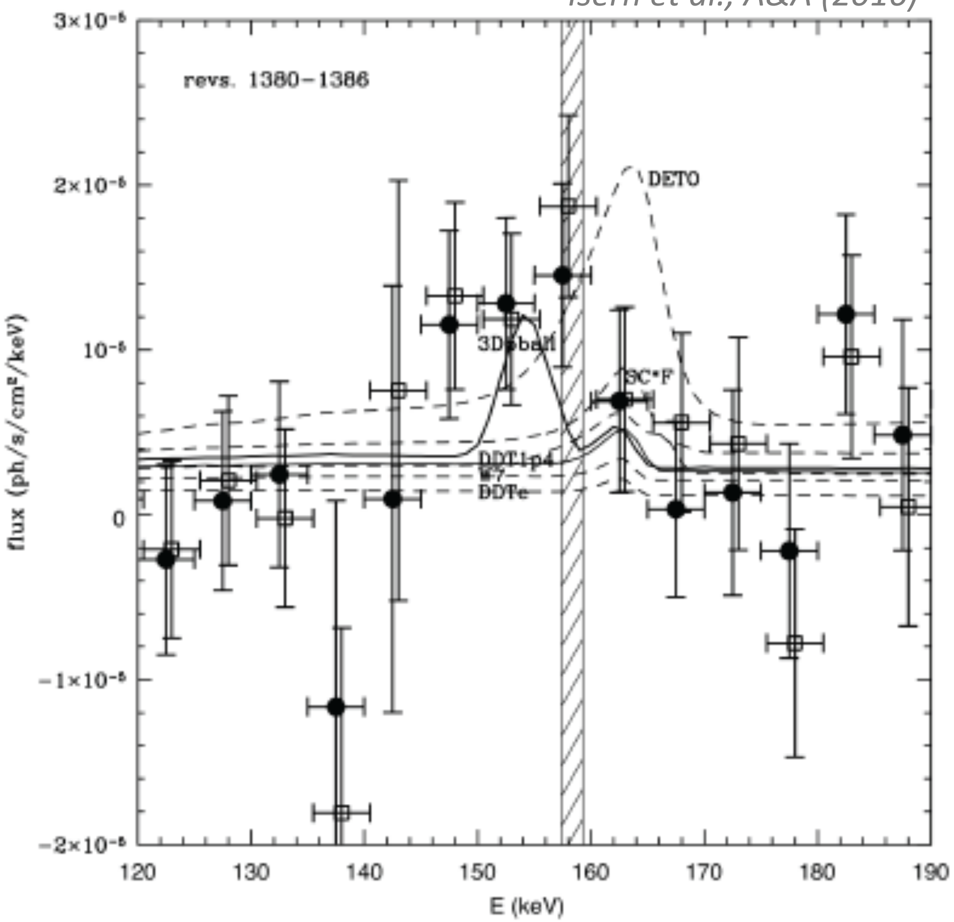


# SN2014J: Early $^{56}$Ni (τ~8.8d)

## Spectra from the SN at ~20 days after explosion

Isern et al., A&A (2016)

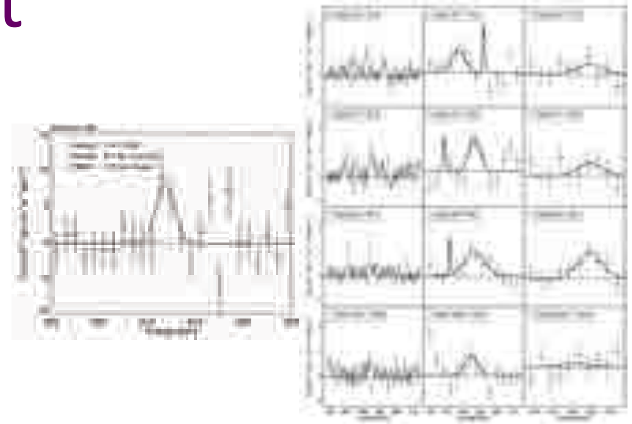
- Detection of ~158 keV emission also in broad-bin analysis



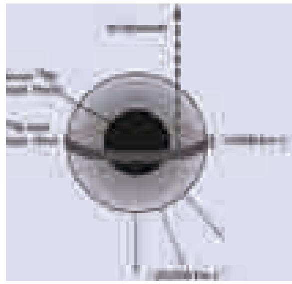

- An underlying broad, red-shifted line as well??
- $^{56}$Ni mass estimate (backscaled to explosion): ~0.08 $M_\odot$

# Summary SN Ia Gamma-Rays

- $^{56}$Ni source of supernova type Ia light seen in γ-rays for the first time
  - Lines at 847 and 1238 keV from $^{56}$Co: late, and broad
  - Lines at 158 and 812 keV from $^{56}$Ni: early, narrow

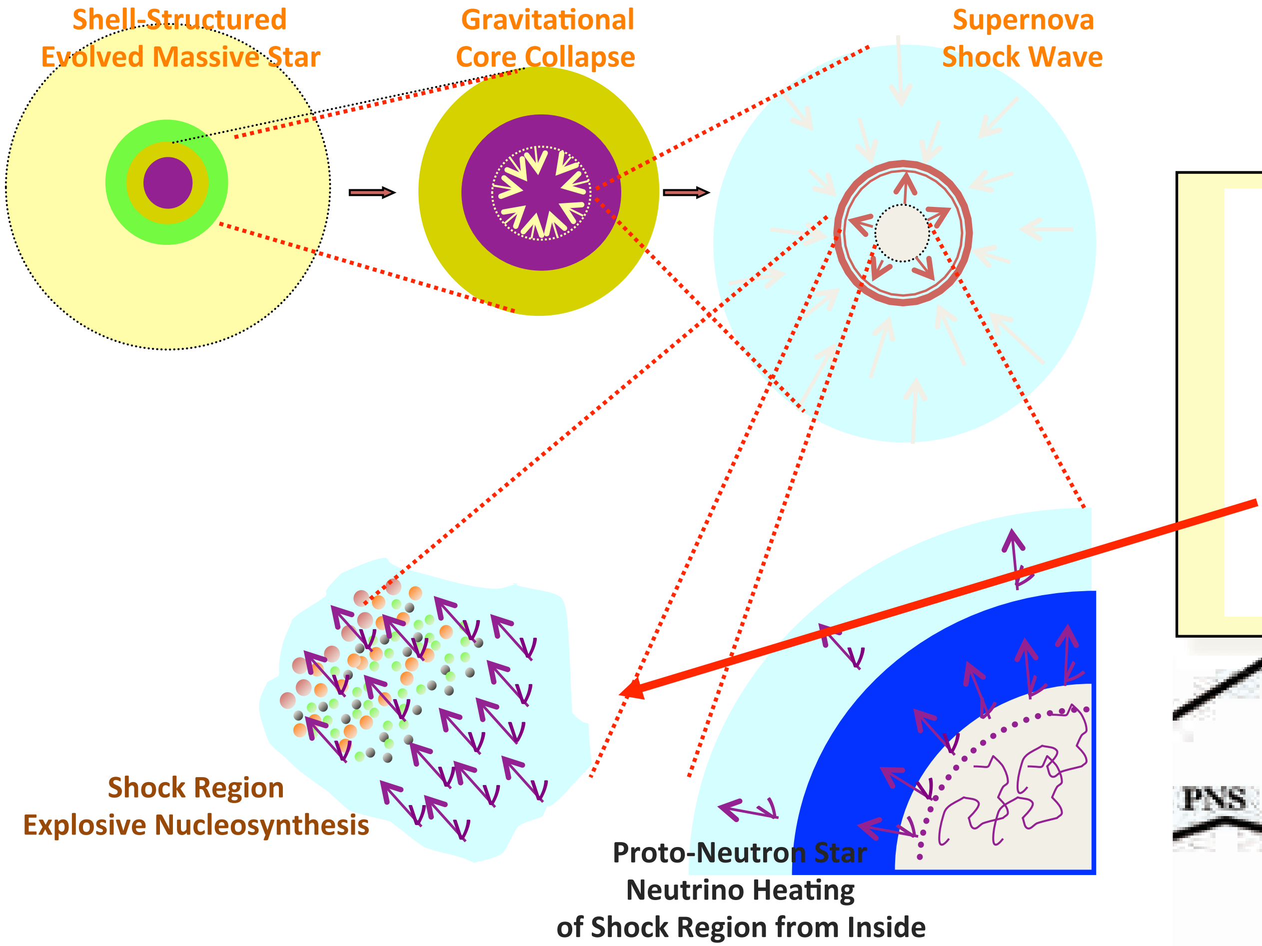


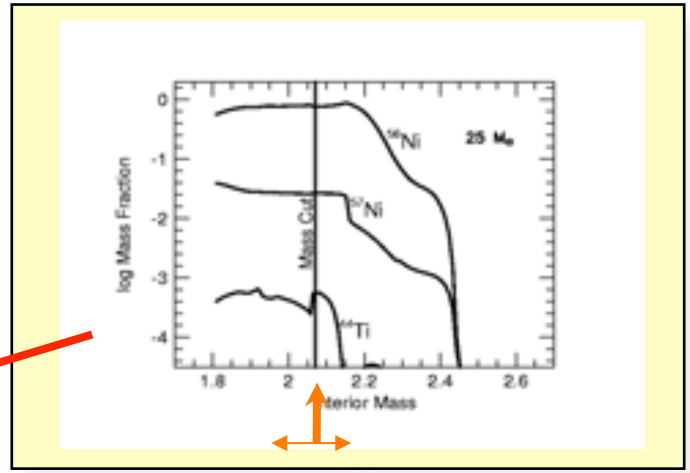
- Basic model confirmed:
  - 0.5 M of $^{56}$Ni produced, SN expansion kinematics

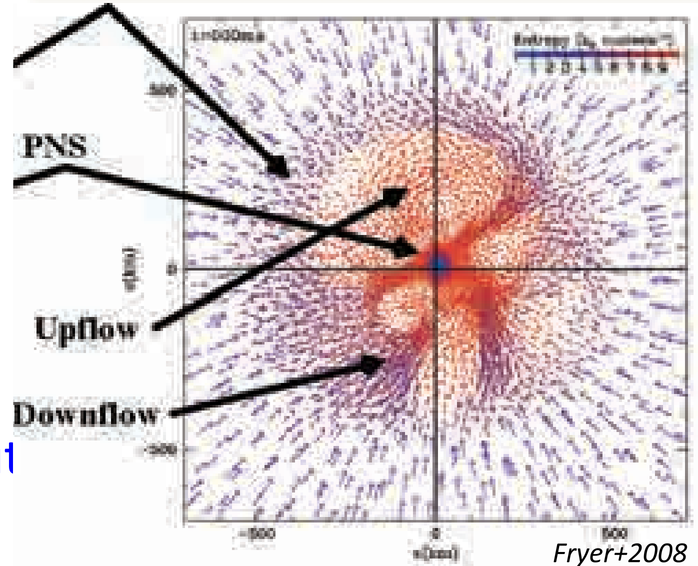


- Puzzles and Challenges:
  - Some $^{56}$Ni apparently near surface → surface trigger explosion??
  - Irregular $^{56}$Co appearance → γ-ray sight lines / Ni clumps??

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




*Fryer+2008*

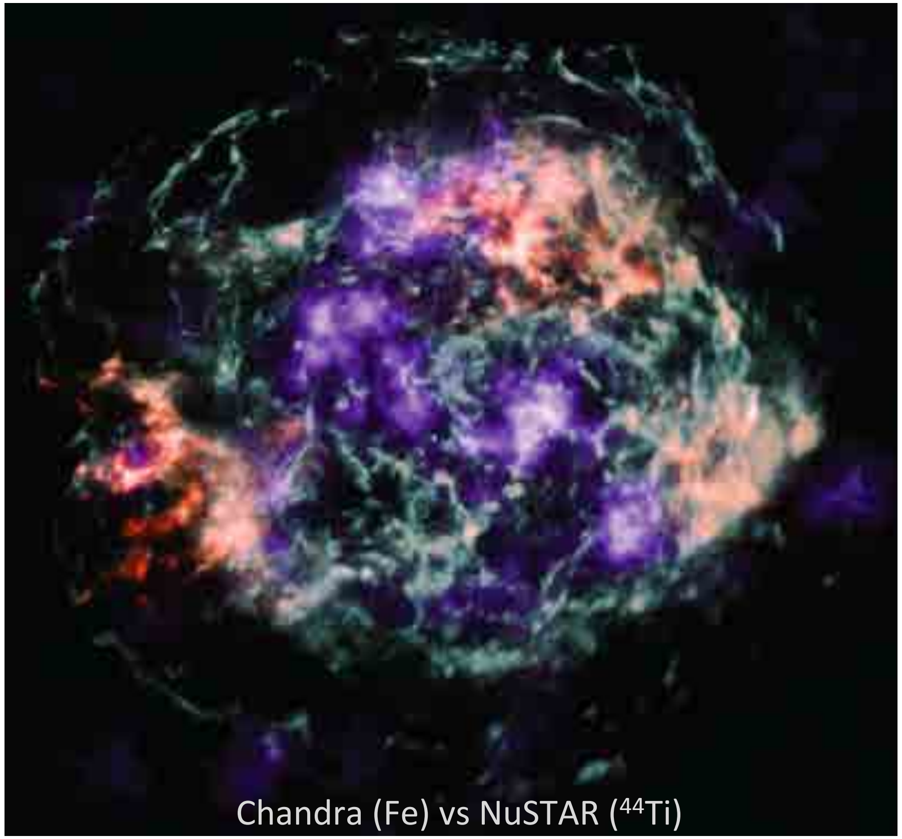
- $^{44}$Ti Produced at r < $10^3$ km from $\alpha$-rich Freeze-Out

  => Unique Probe (+Ni Isotopes)

# NuSTAR and $^{44}$Ti in Cas A

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

- Cas A: first mapping of radioactivity in a SNR



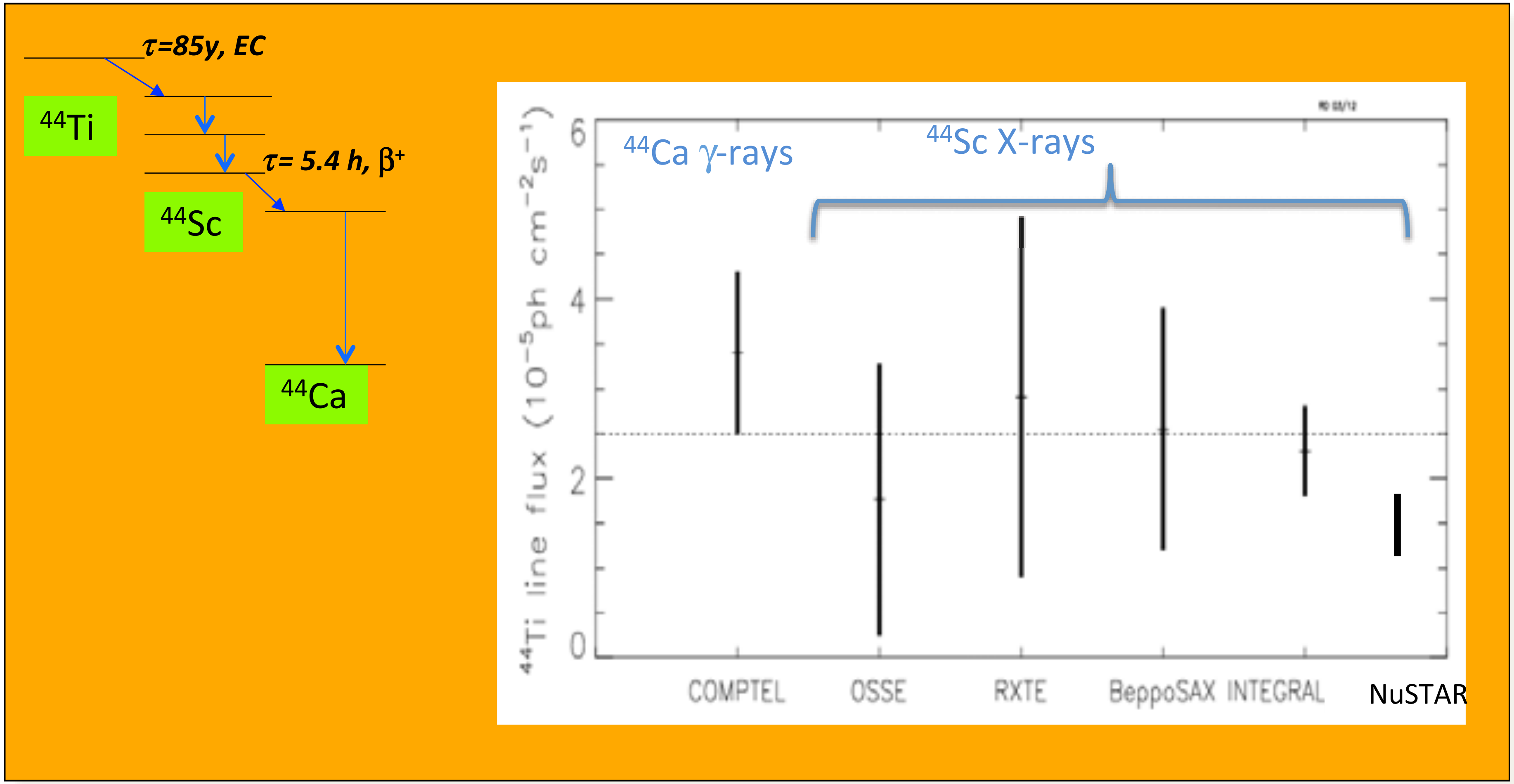

*Grefenstette et al. 2014*

  – 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$^{-1}$

# $^{44}$Ti γ-rays from Cas A

**t=85y** (Ahmad et al. 2006)

| | | |
|---|---|---|
| 89 y | $^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^{**}e$ | 78, 68; 1157 |

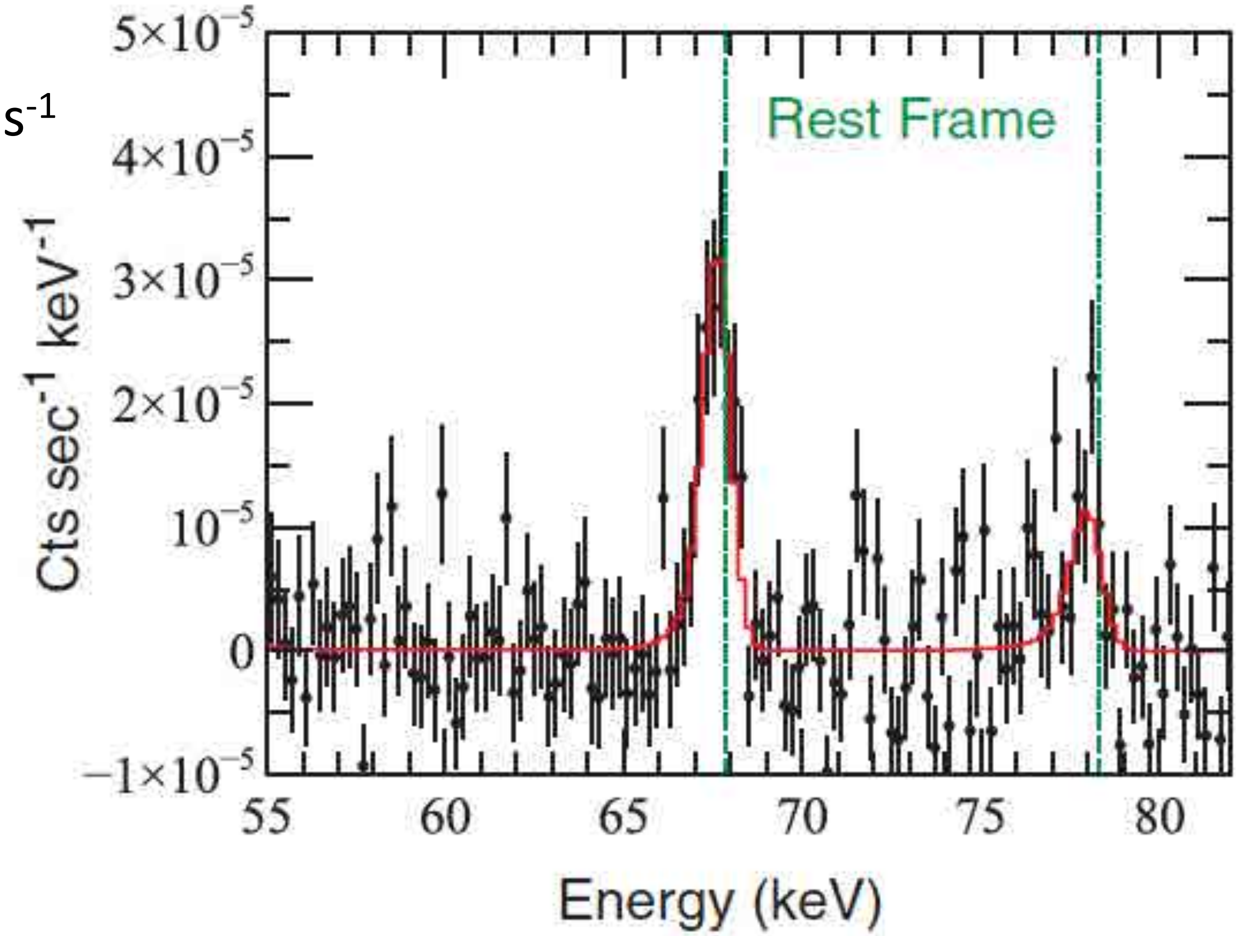



↳ $^{44}$Ti Ejected Mass ~1.23 ±0.25 $10^{-4}$ $M_\odot$

# NuSTAR and $^{44}$Ti

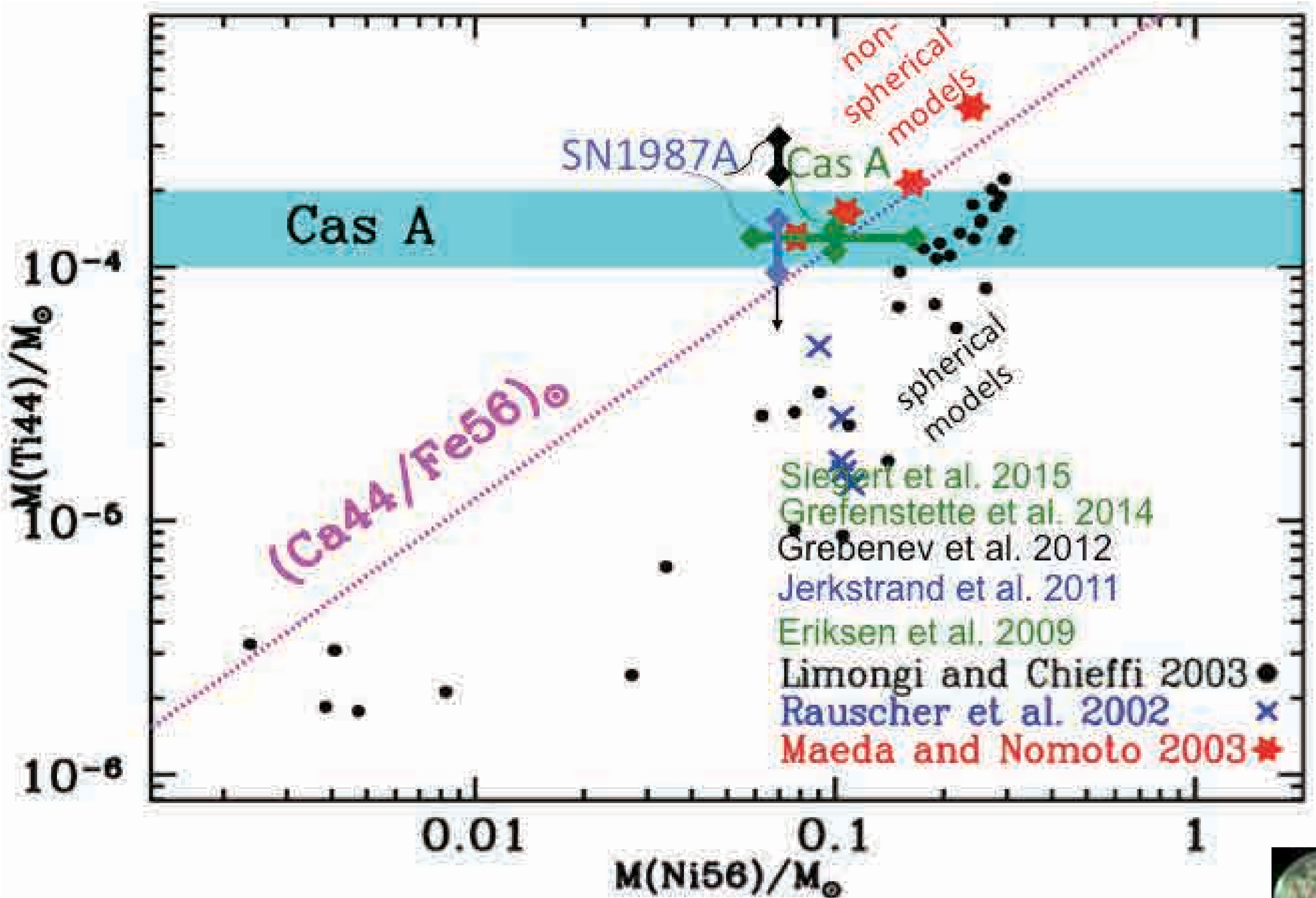
Measuring SN1987A in hard X-rays (3-79 keV) (no image: 'point src' for NuSTAR)
→ $^{44}$Ti lines at 68,78 keV

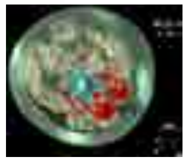
- Flux:
  3.5 (±0.7) $10^{-5}$ ph $cm^{-2}$ $s^{-1}$
  → 1.5 $10^{-4}$ $M_\odot$
- Line width
  → ejecta velocity
  ~4000 km $s^{-1}$
- Confirm earlier indications for redshift of new-nuclei ejecta
  (~700 (±0.400) km $s^{-1}$)
  → SN asymmetry




*S. Boggs et al., Sci (2015)*

# "Abnormal" Core Collapse Supernovae as $^{44}$Ca (=$^{44}$Ti) Sources?



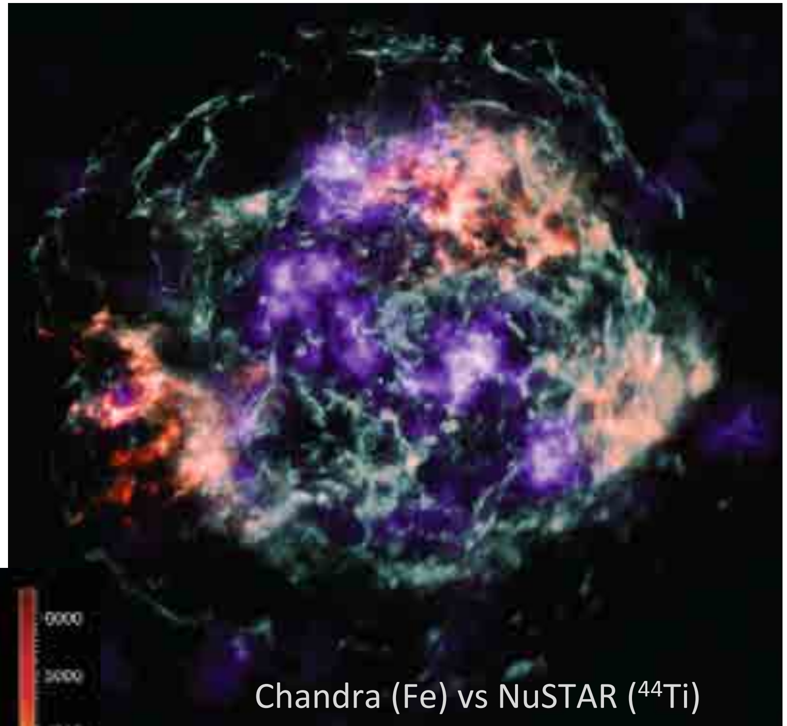



⇨ Only Non-Spherical Models Seem to Reproduce Observed $^{56}$Ni/$^{44}$Ti Ratios

⇨ *The et al. 2006*

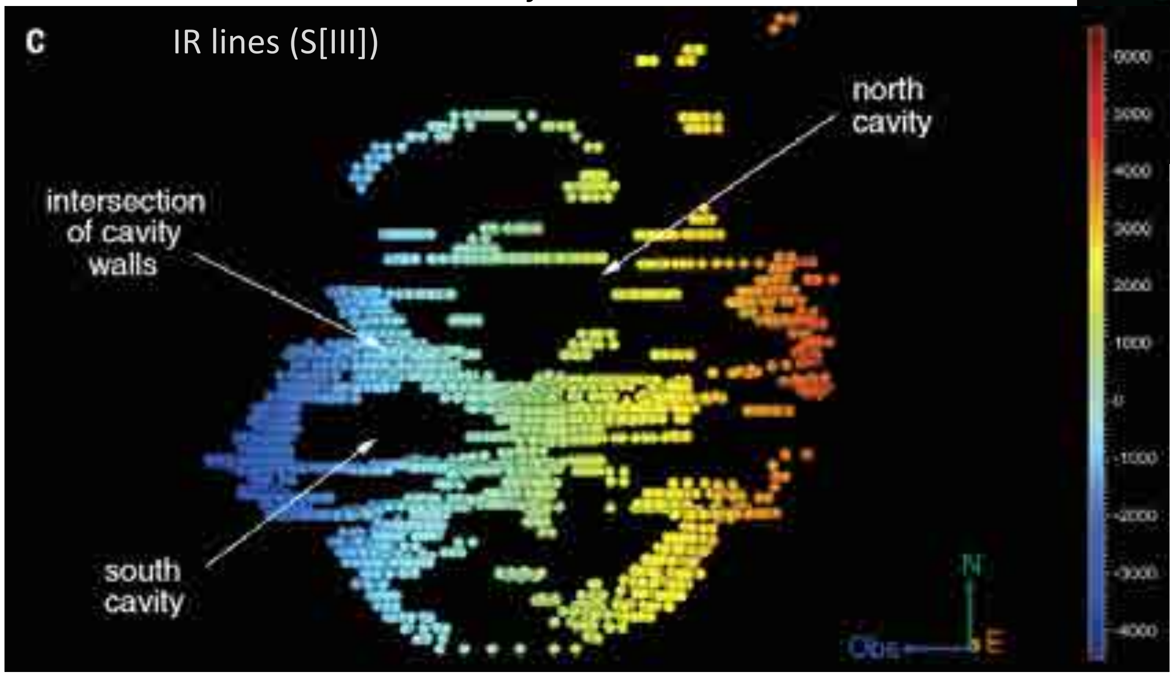
# Inner Ejecta of Cas A

- $^{44}$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*



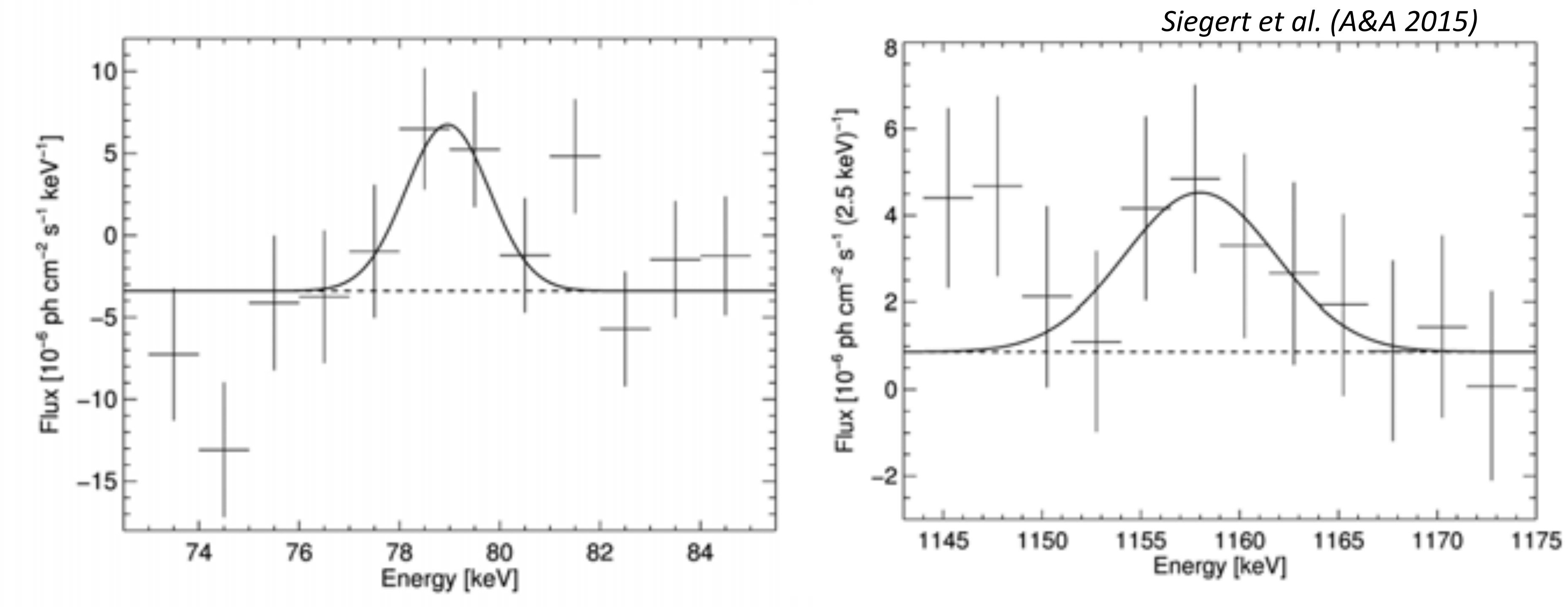

Few large cavities blown by $^{56}$Ni

Not all ejecta shocked yet

# 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

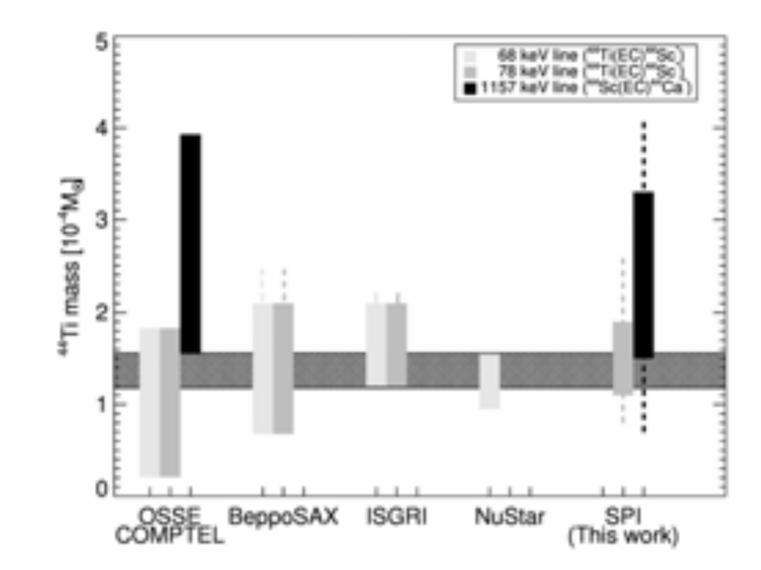
*Siegert et al. (A&A 2015)*

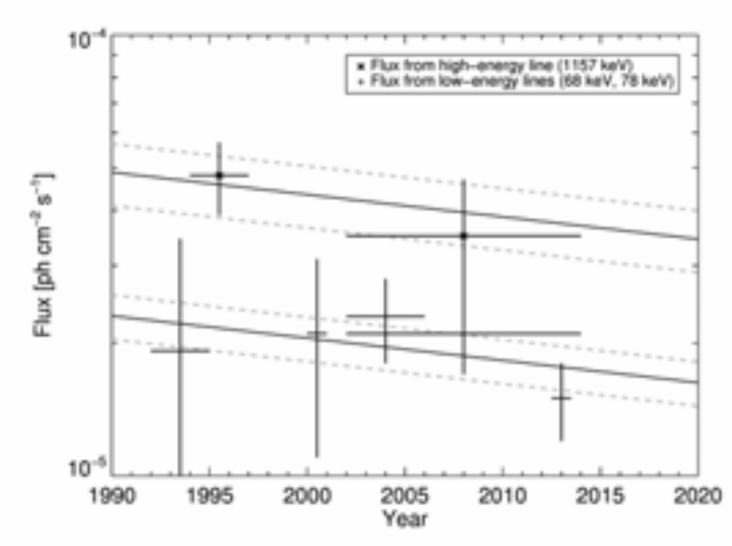



- Doppler broadening: 4300±1600 / 2200±1600 km $s^{-1}$ (78, 1157 keV)

# $^{44}$Ti from Cas A

- **Consolidated Mass Determination:**
  - Different instruments & lines combined




  - $^{44}$Ti mass = (1.37 ± 0.19) $10^{-4}$ $M_\odot$ (all measurements)
  - $^{44}$Ti mass = (1.29 ± 0.15) $10^{-4}$ $M_\odot$ (78 keV line only)
  - $^{44}$Ti mass = (2.72 ± 0.43) $10^{-4}$ $M_\odot$ (1.157 MeV line only)

# $^{44}$Ti from Cas A

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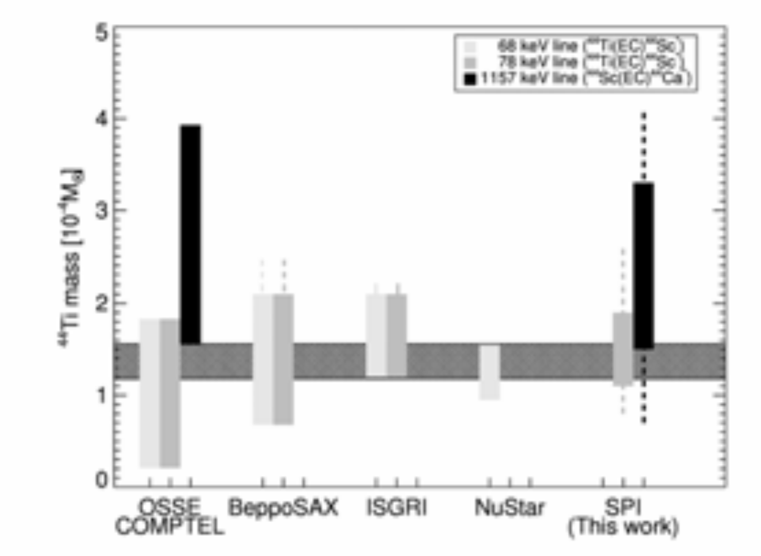
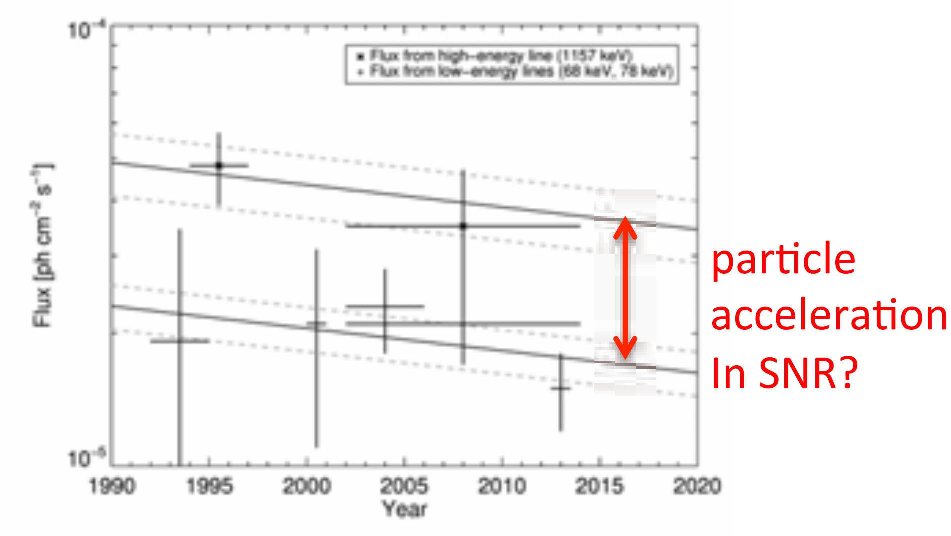
  - Different instruments & lines combined

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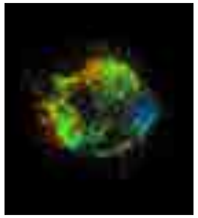
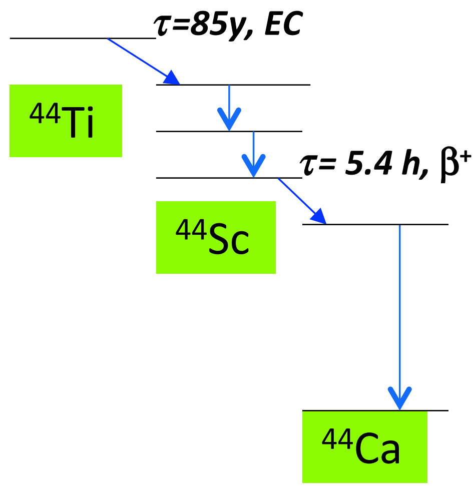
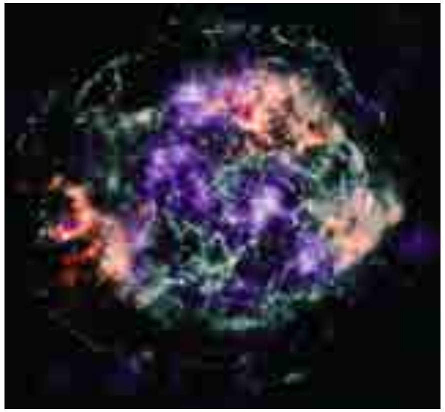


# Summary ccSN Gamma-Rays

- $^{44}$Ti source of late supernova afterglow seen in $\gamma$-rays for Cas A, SN1987a(?)
  - Lines at 68, 78, and 1157 keV from $^{44}$Sc and from $^{44}$Ca
- Basic model confirmed:
  - $^{44}$Ti and $^{56}$Ni coproduced, SN expansion kinematics
- Puzzles and Challenges:
  - Only some $^{56}$Ni bright SNe are $^{44}$Ti bright → strong rotation/3D required?
  - Brighter $^{44}$Ca line appearance → $\gamma$-rays from nuclear deexcitation??

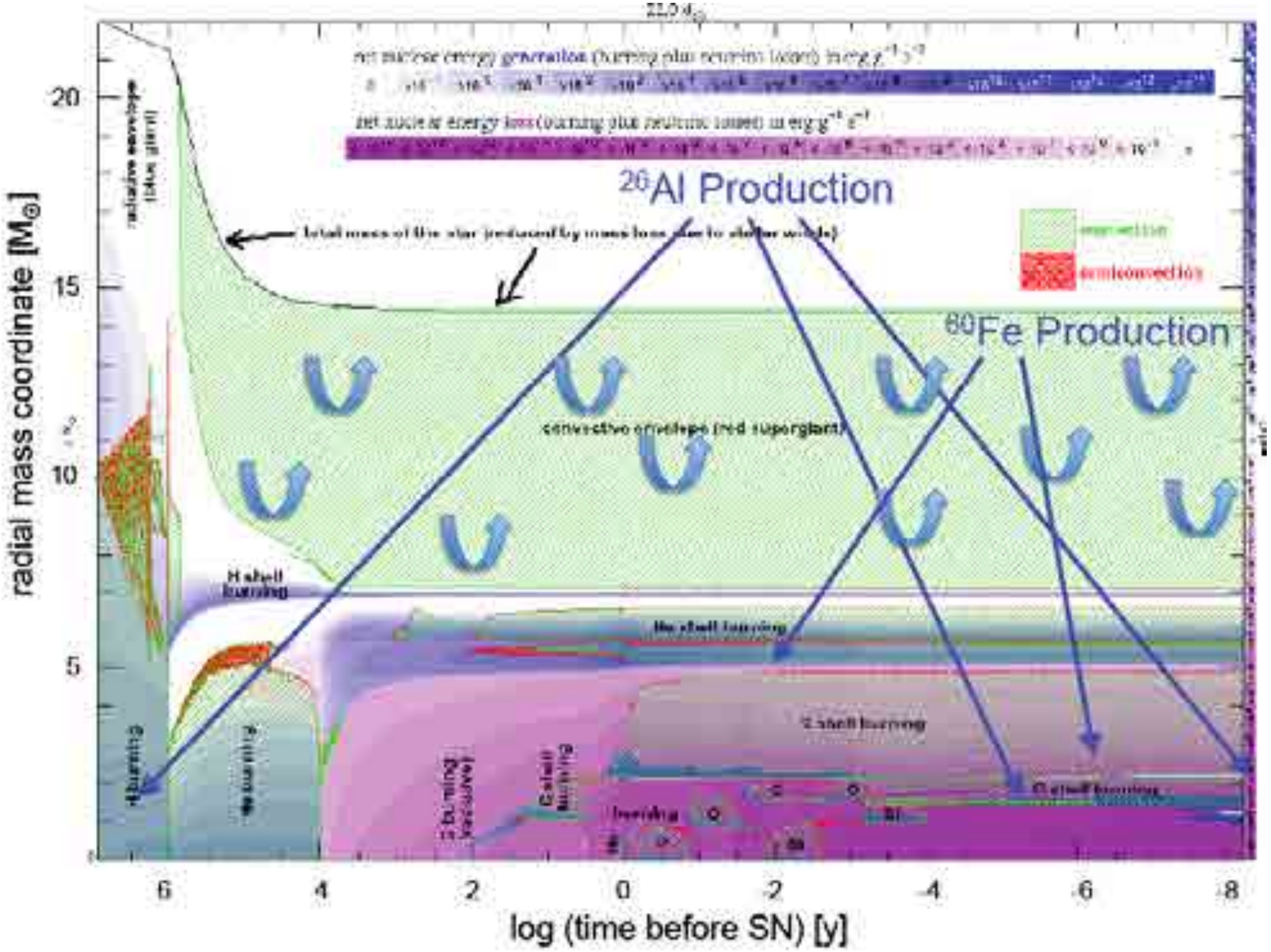


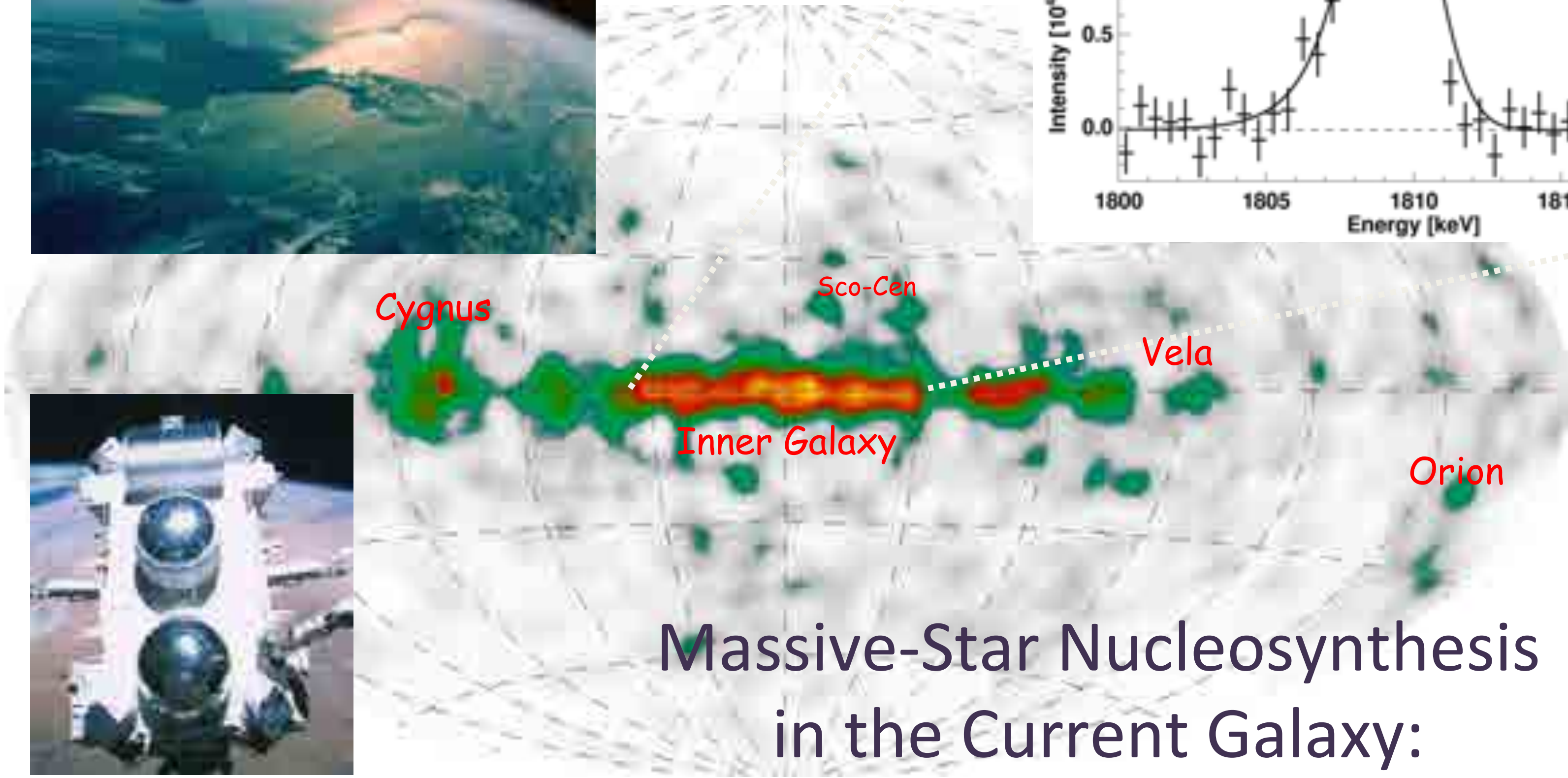
# Stars, Stellar Groups,
# and
# Interstellar Medium & Galactic Structure Aspects

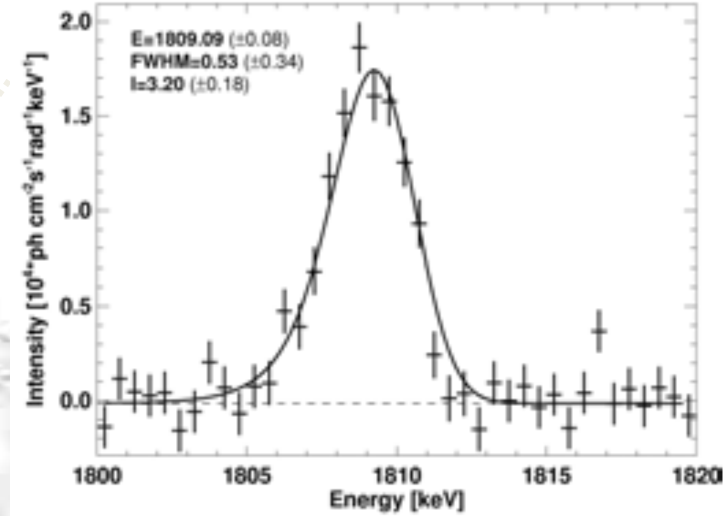
# Radioactivities from massive stars: $^{60}$Fe, $^{26}$Al

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



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

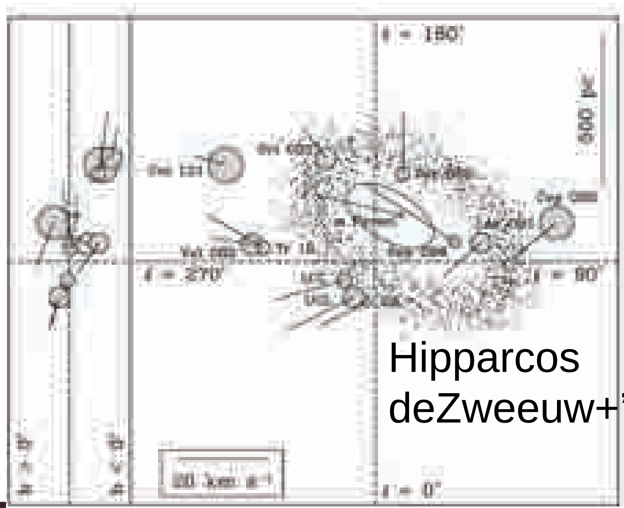



Massive-Star Nucleosynthesis in the Current Galaxy:

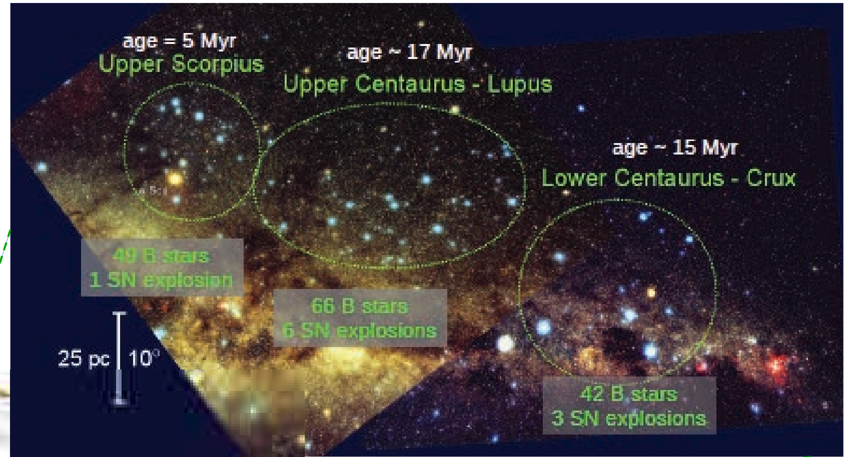
Current Enrichment (~My) from $^{26}$Al γ-rays

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

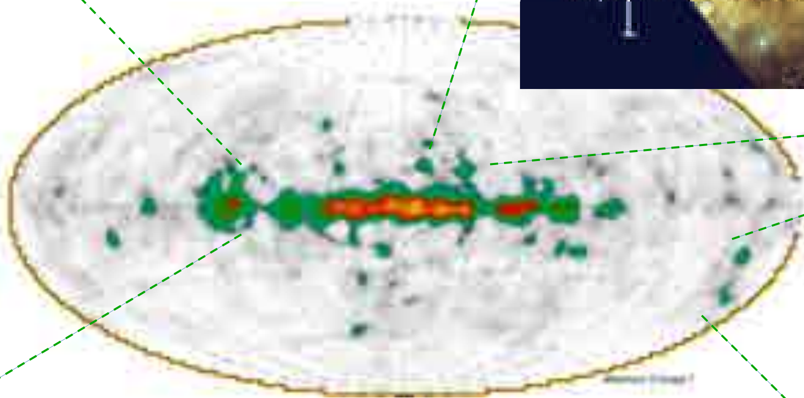


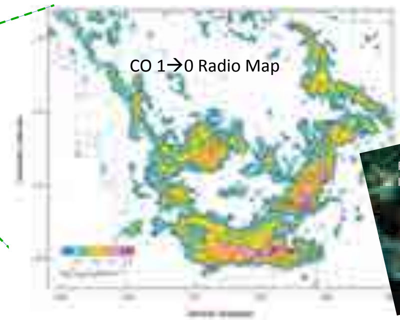

## Nearby and/or rich Groups of Stars:

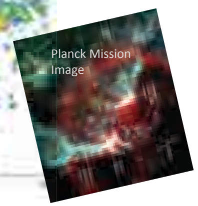
*Test our Models for Consistency*







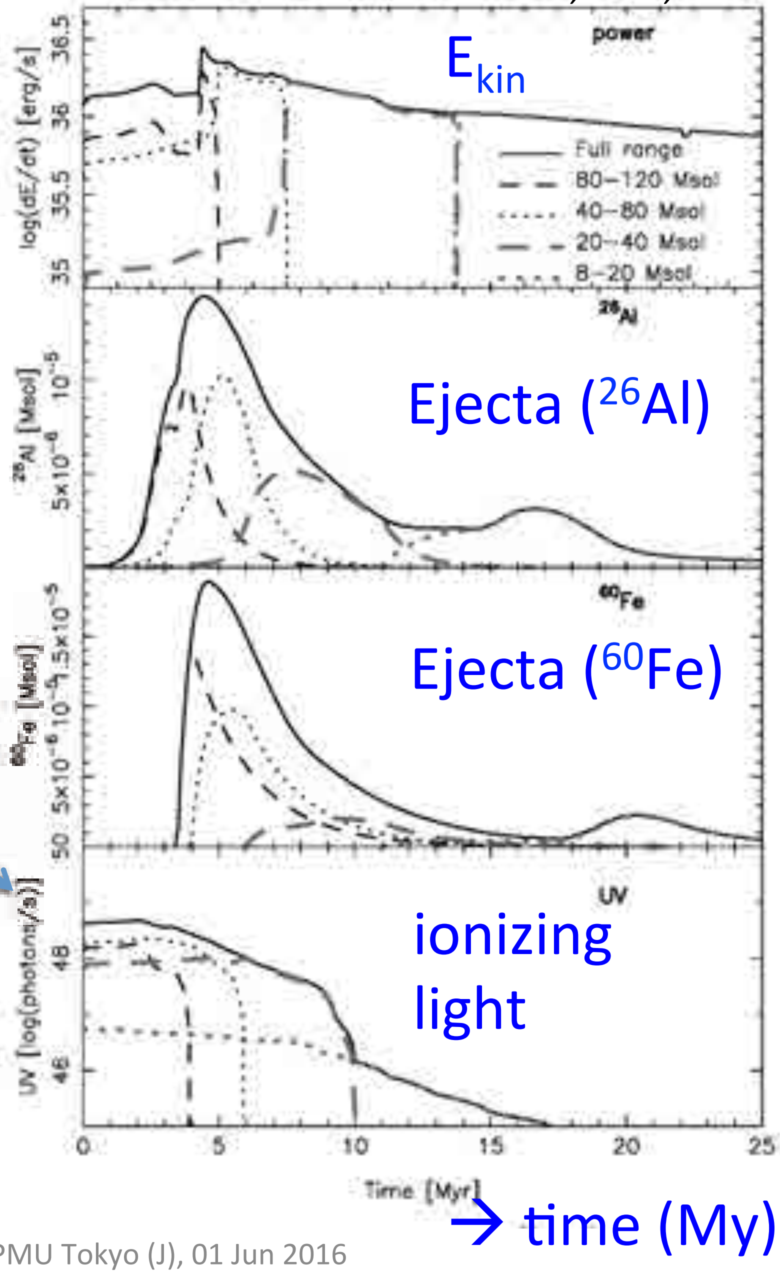


# Massive-Star Groups

- 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

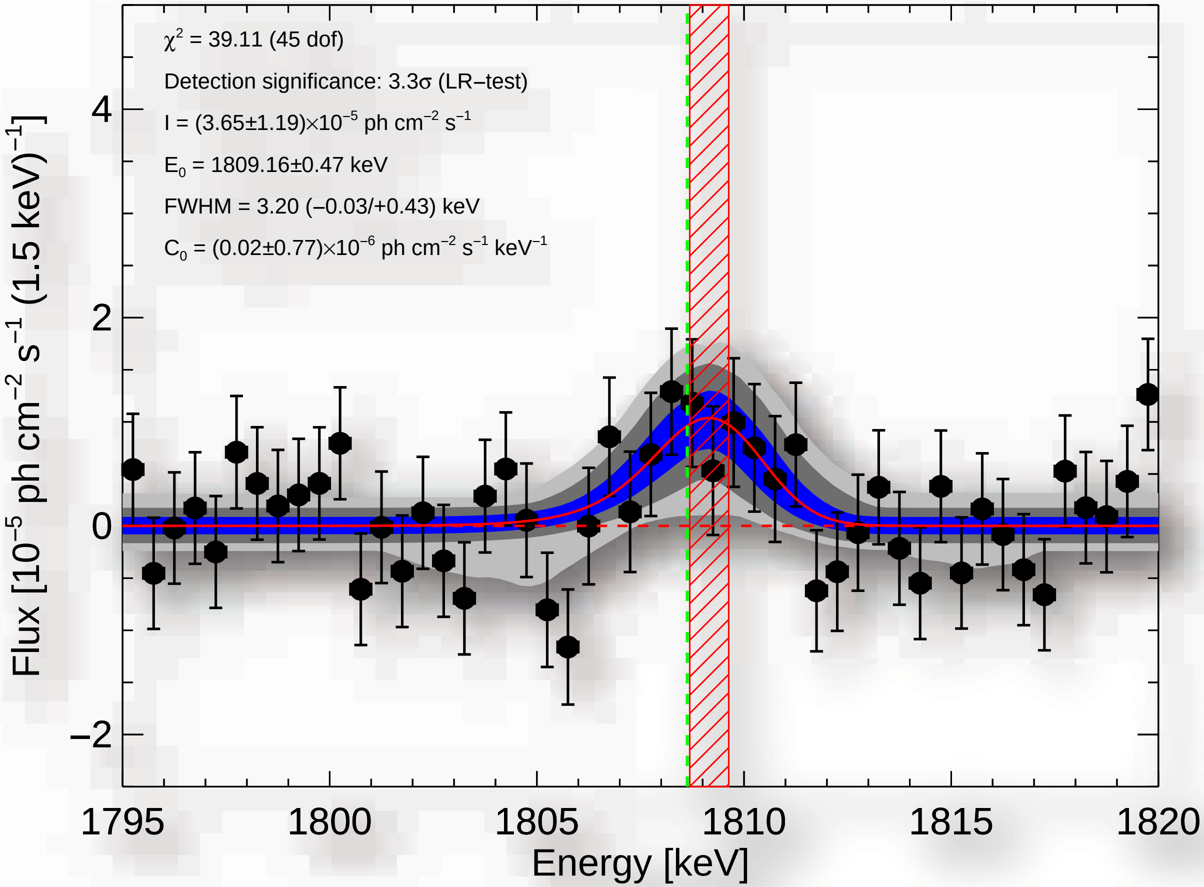
*Voss R., et al., 2009*



# $^{26}$Al in Orion

- Now also detected with SPI/INTEGRAL

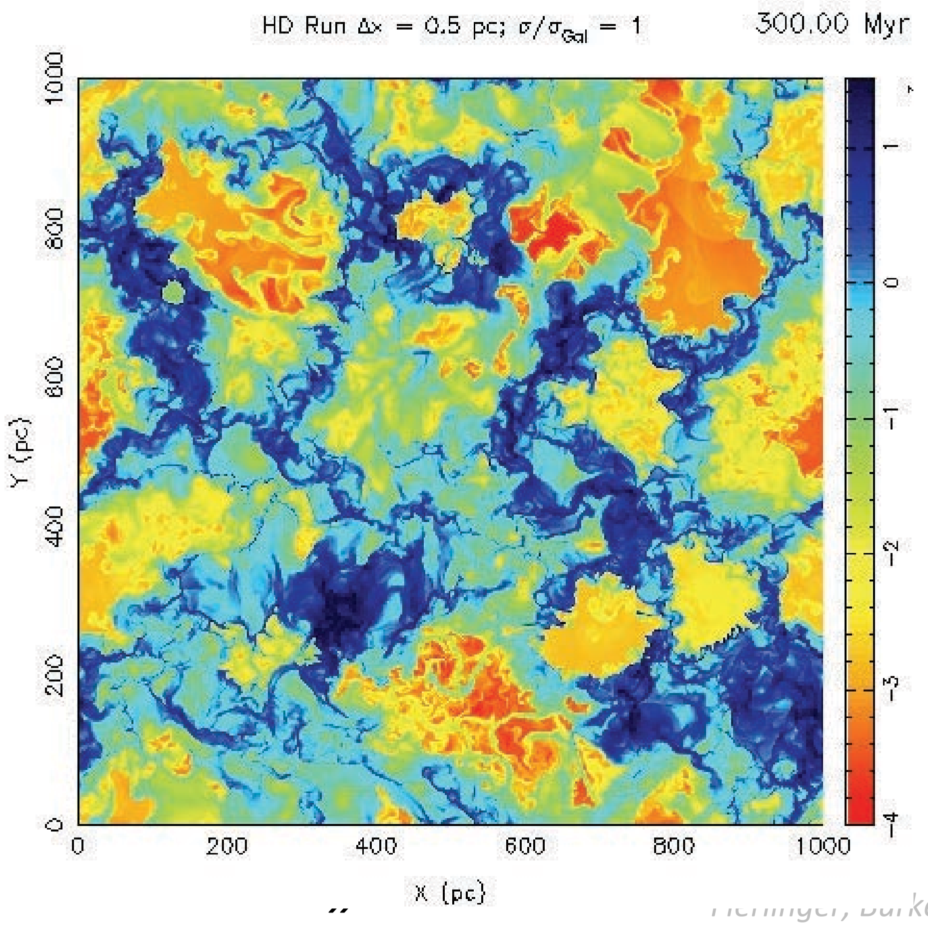
*Siegert+, in preparation*

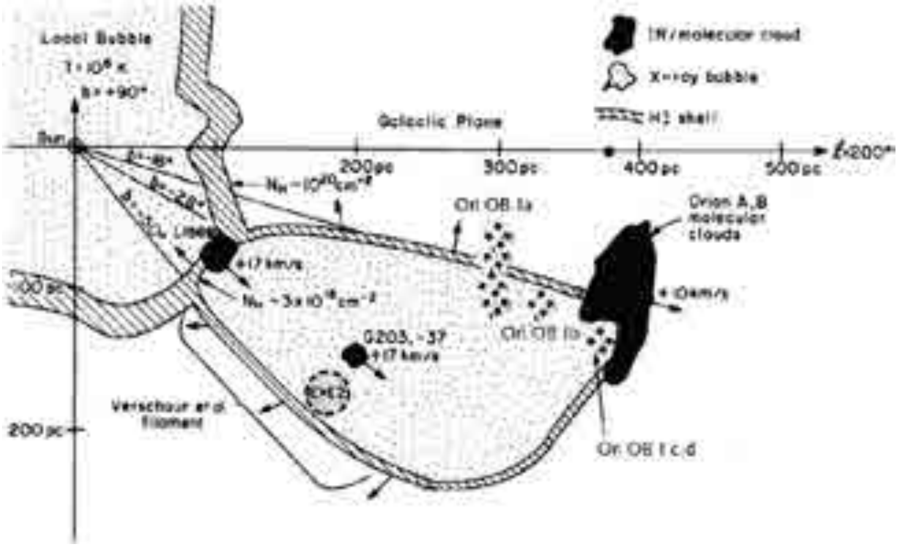


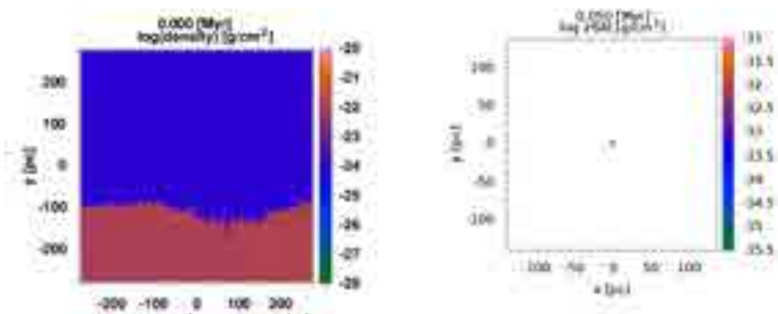
# Orion: Nucleosynthesis Ejecta and Dynamics of Interstellar Medium

INTEGRAL Data are being collected!

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



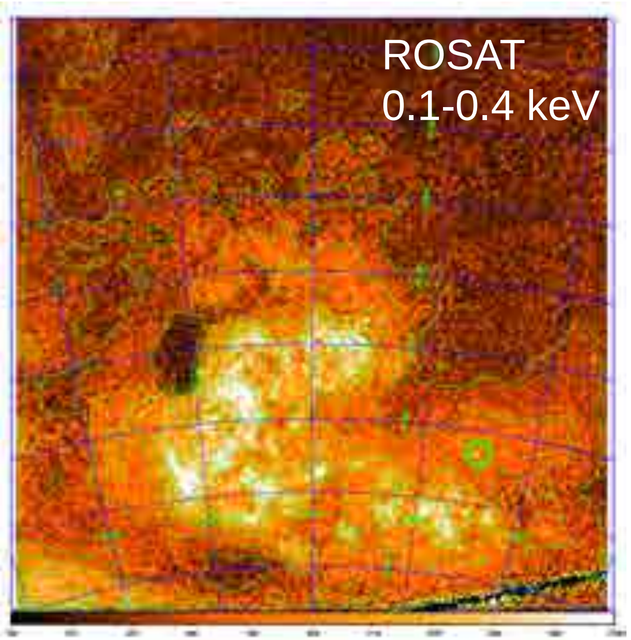



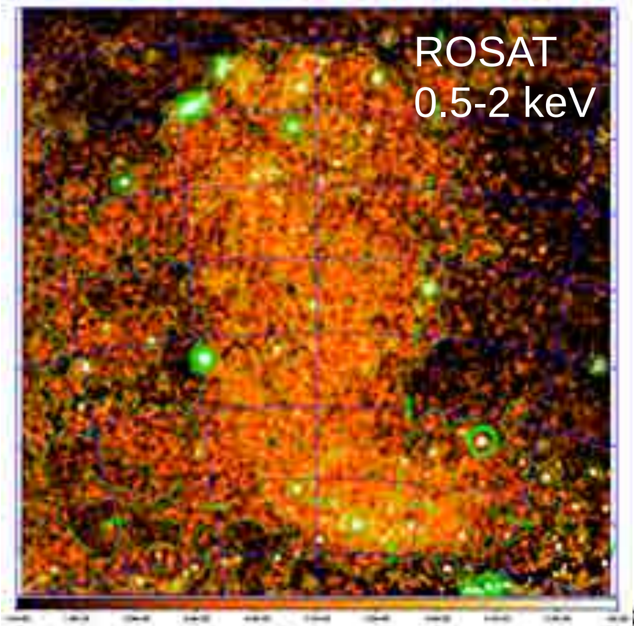



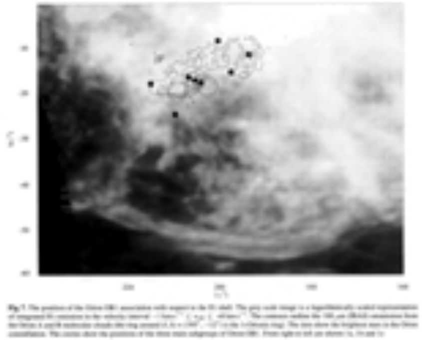
…kert, Krause, Bo…, Diehl

# Understanding the Eridanus Superbubble

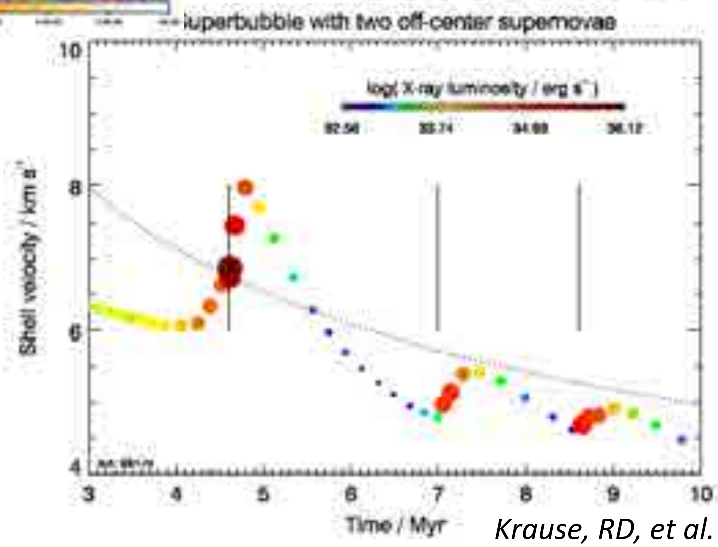
- X-ray Emission, size, $^{26}Al$



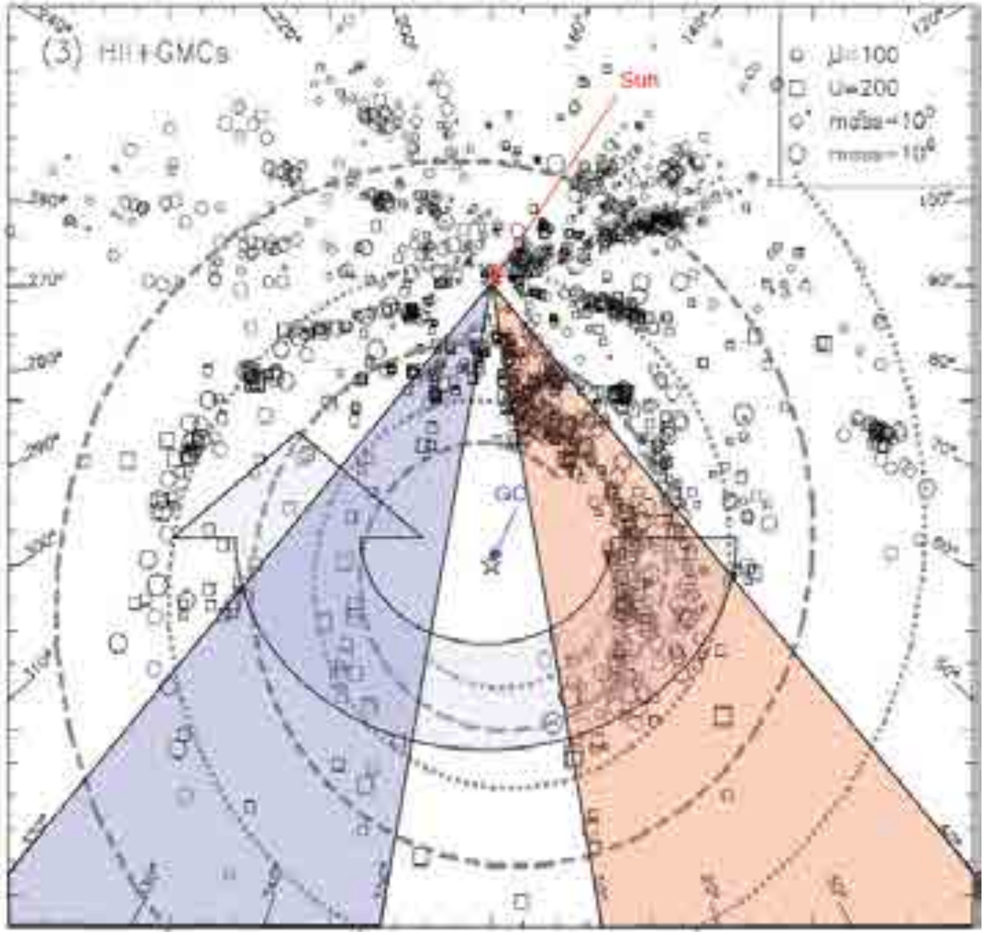

  – Temporal X-ray brightenings after SN energy injections
  – spatial oscillations

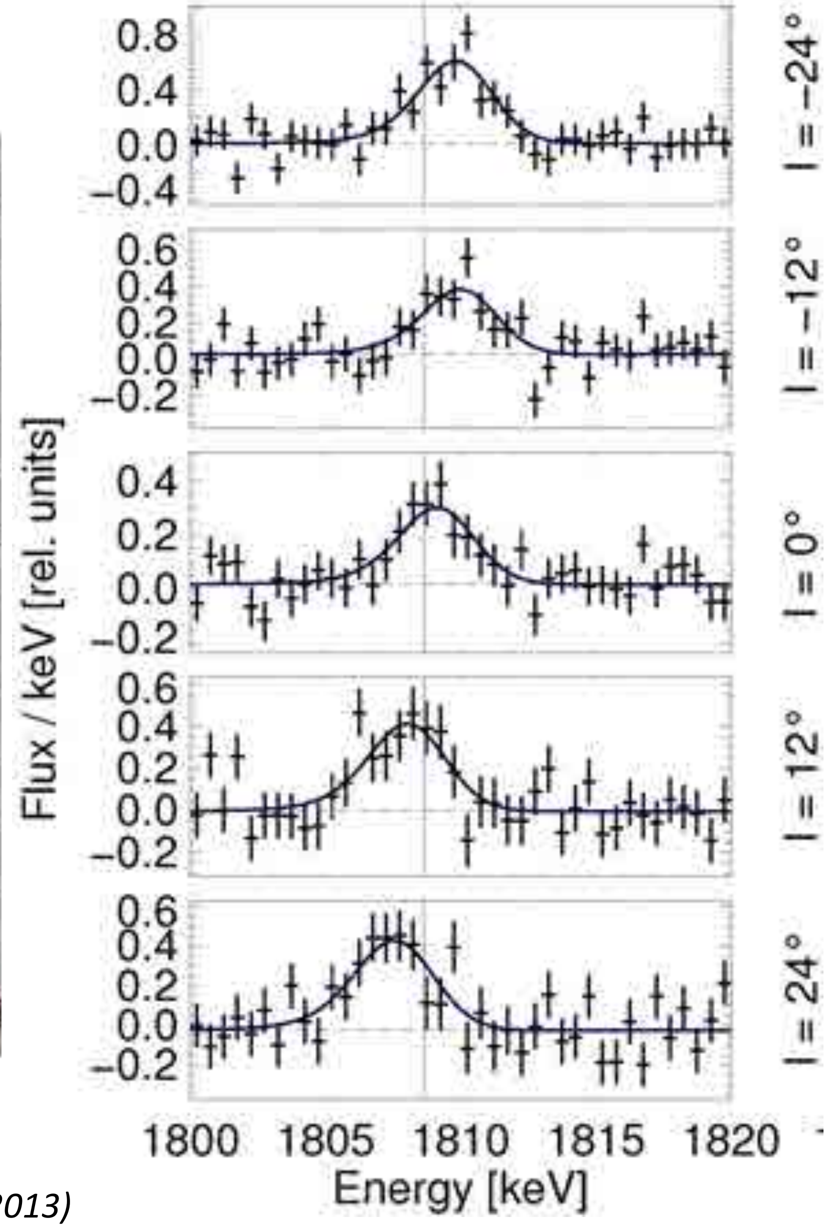



*Krause, RD, et al. 2015*

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

- Large-scale Galactic rotation

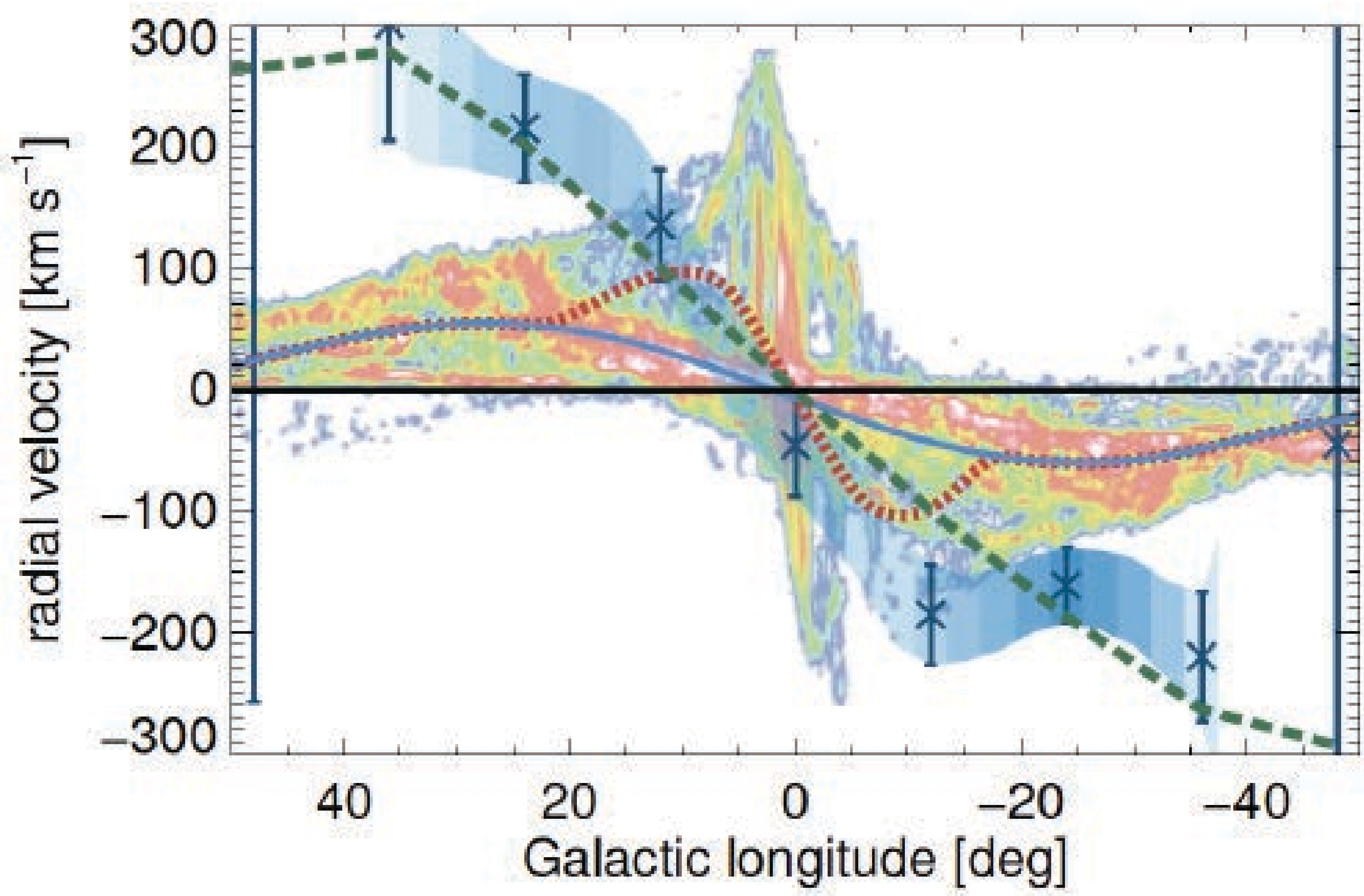


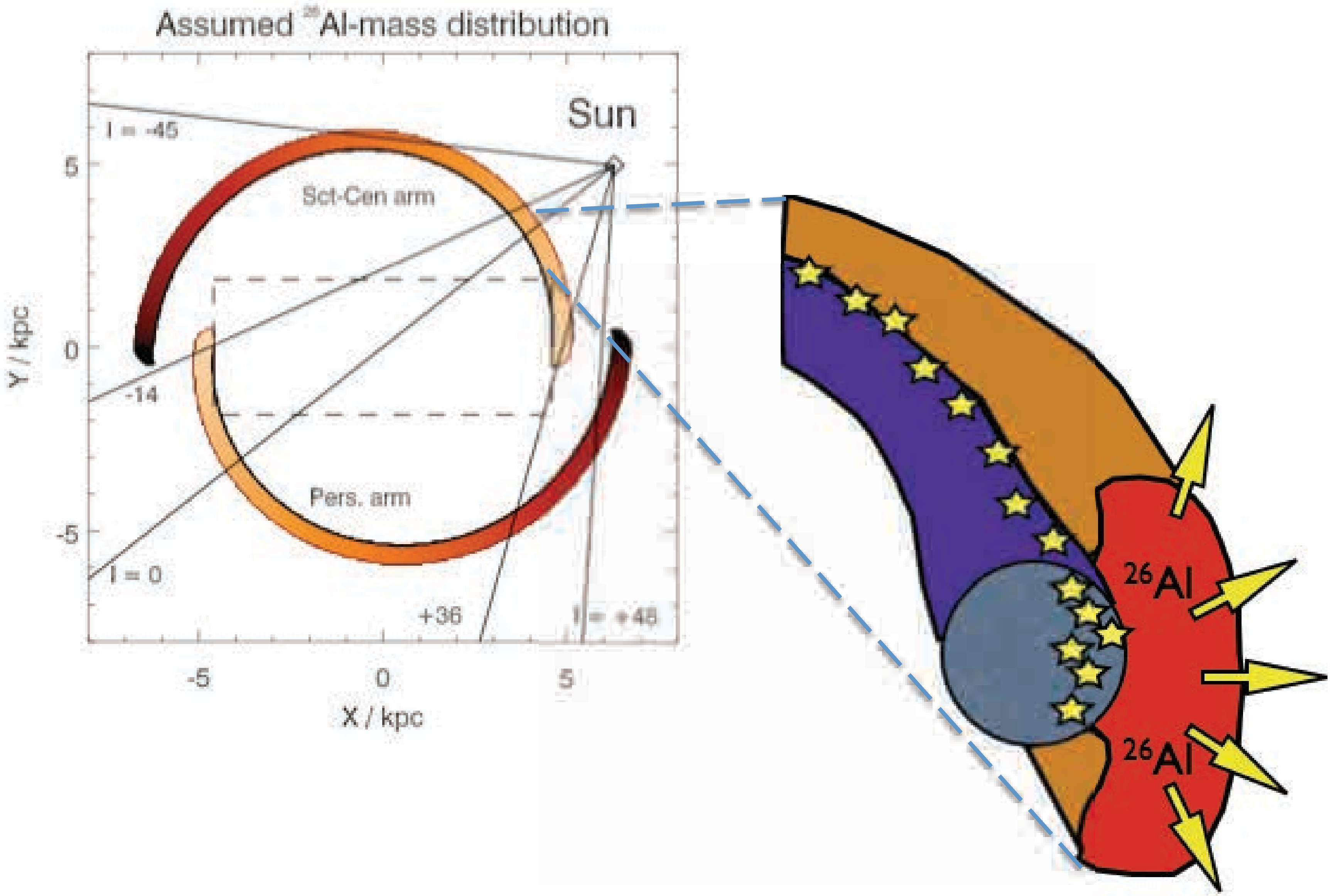

*Kretschmer et al., A&A (2013)*

# The Galactic View: longitude-velocity diagrams

- excess velocity seen for massive-star ejecta!



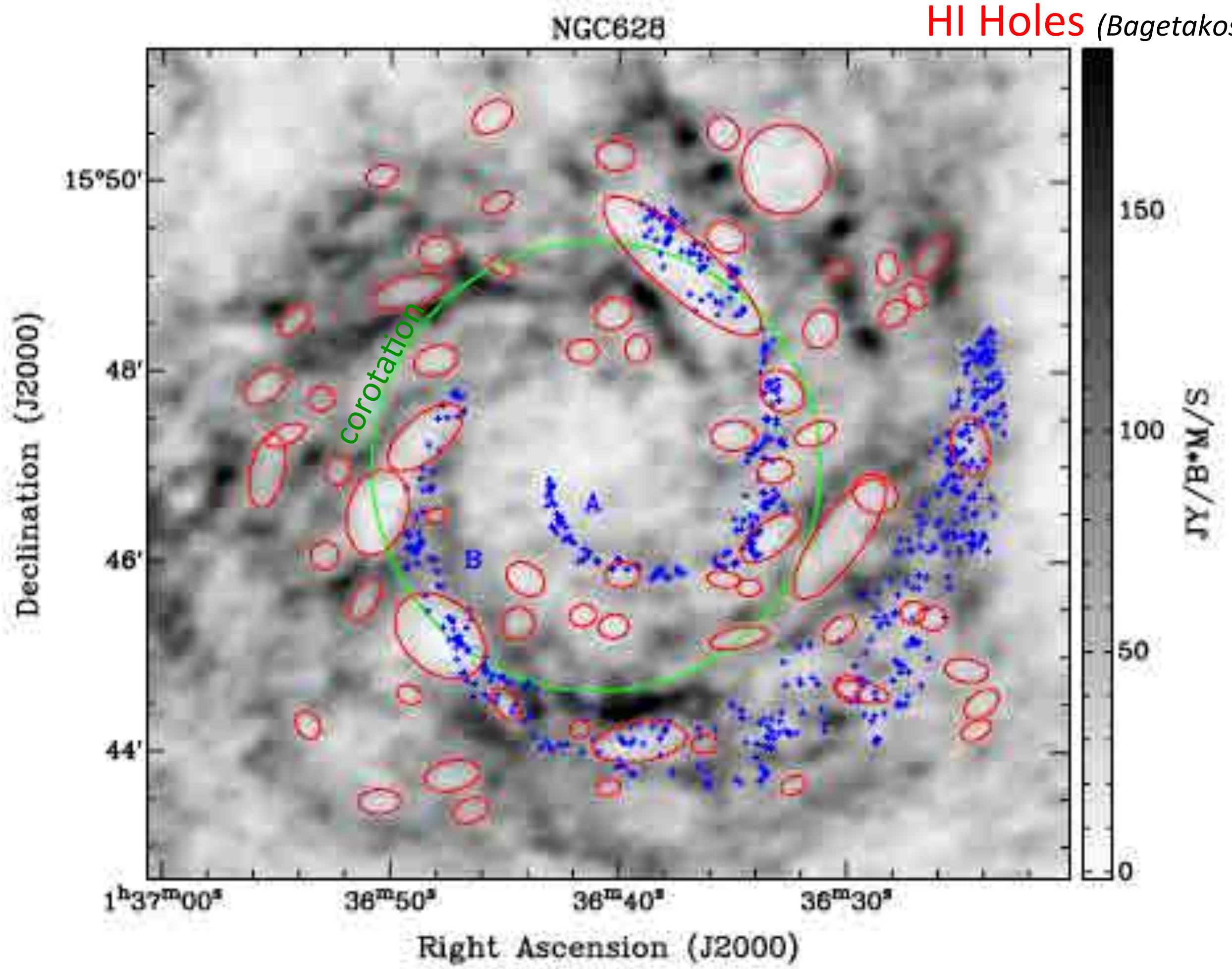
# How Massive-Star Feedback Occurs…

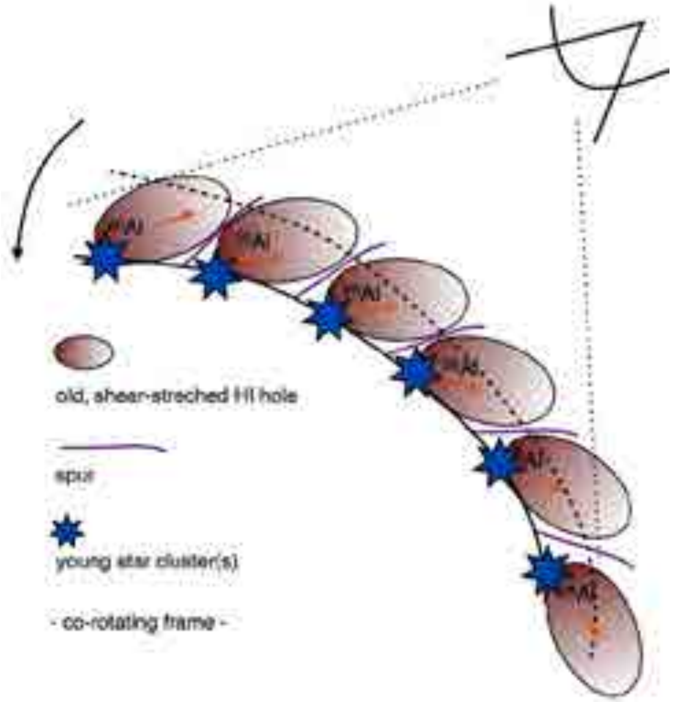


# Superbubbles and HI Holes

- $^{26}$Al Ejecta Streaming into HI Holes Between Arms

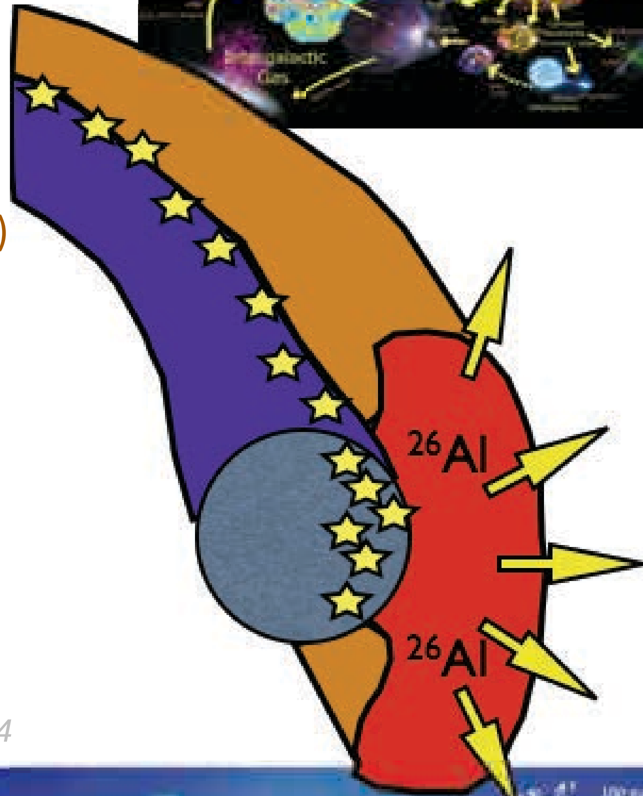
HI Holes *(Bagetakos+2011*

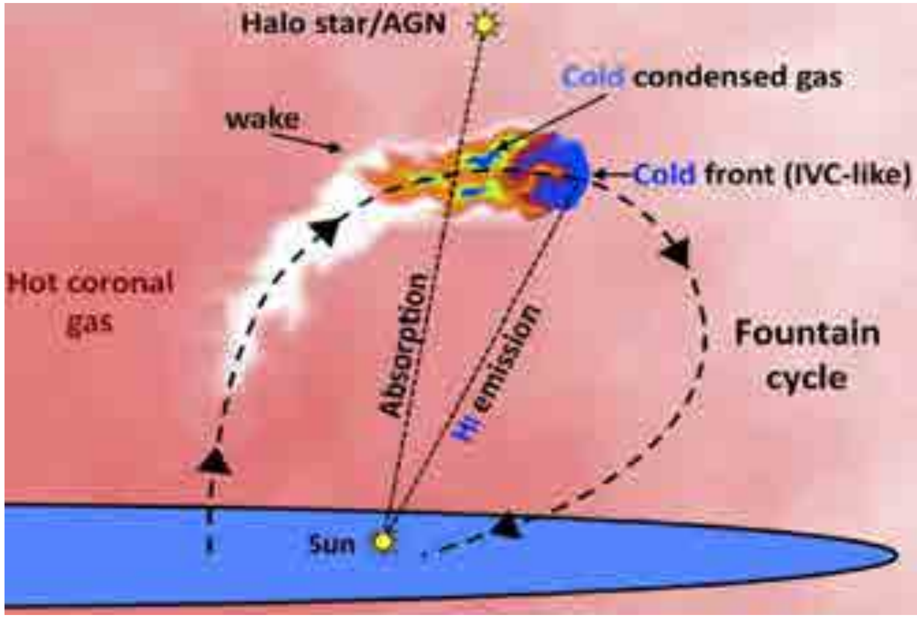


# The Cycle of Gas in a Galaxy

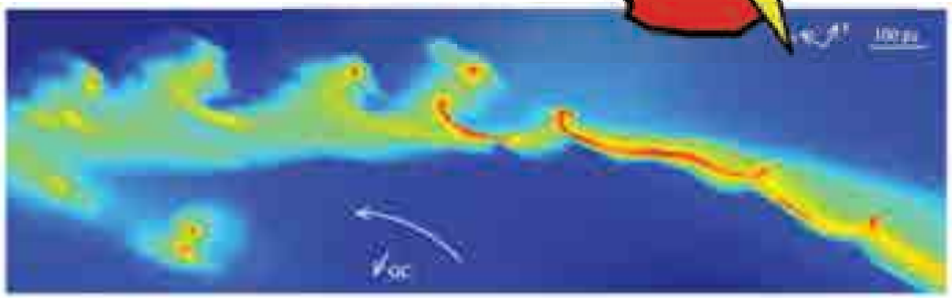
- How the Galaxy's Disk and Halo "communicate"
  - Chimneys around massive-star groups eject gas into halo
  - Constancy of Star Formation Rate over Galaxy-Evolution Times (Depletion would be Fast)

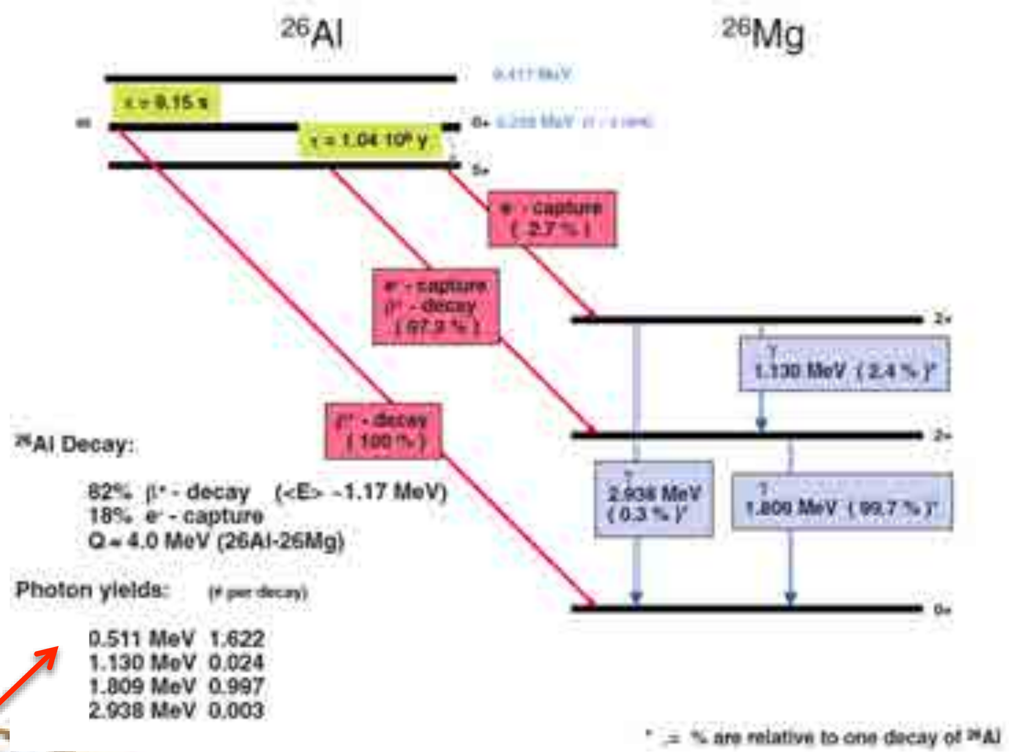




Marasco, Fraternai, & Binney 2011; Fraternali et al. 2013

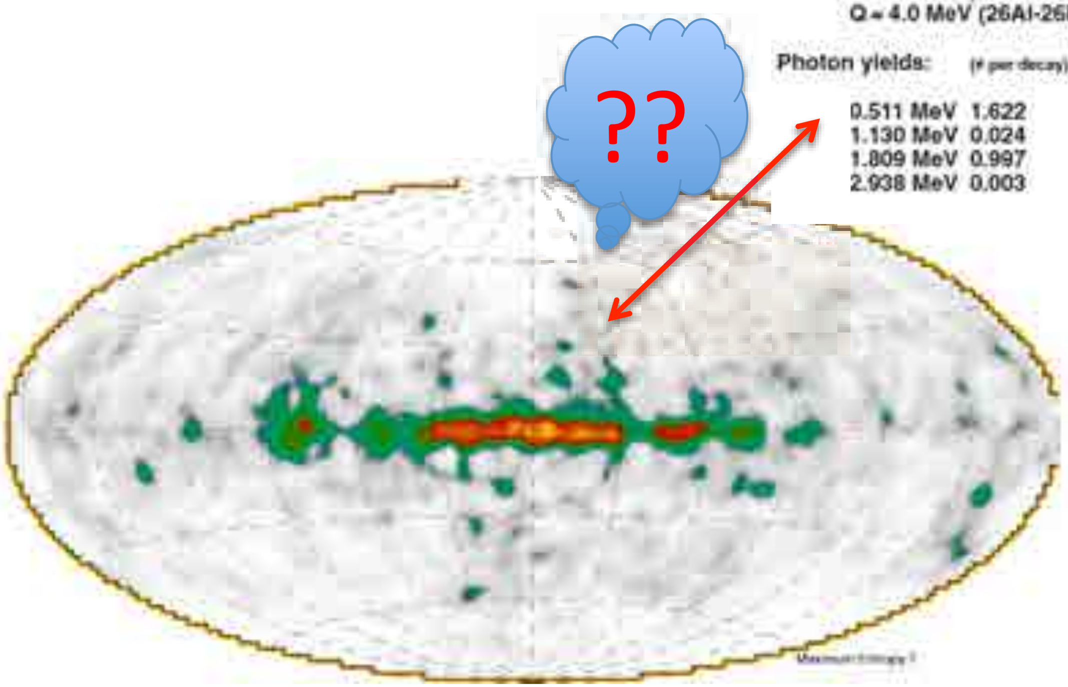
Renaud et al. 2014



# $^{26}$Al



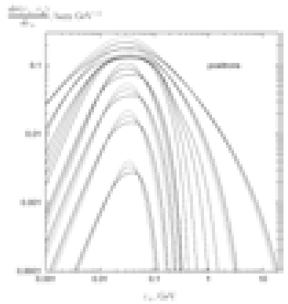
26Al
26Mg
τ = 1.04 10⁶ y
e- - capture
( 2.7 % )
e- - capture
β+ - decay
( 97.3 % )
β+ - decay
( 100 % )
1.130 MeV ( 2.4 % )*
2.938 MeV
( 0.3 % )*
1.809 MeV ( 99.7 % )*
26Al Decay:
82% β+ - decay (<E> ~1.17 MeV)
18% e- - capture
Q = 4.0 MeV (26Al-26Mg)
Photon yields: (# per decay)
0.511 MeV 1.622
1.130 MeV 0.024
1.809 MeV 0.997
2.938 MeV 0.003
* := % are relative to one decay of 26Al

??

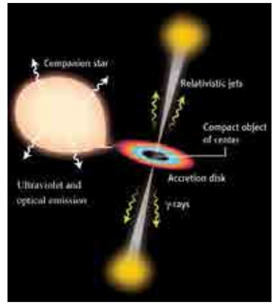
# The Sources of Positrons throughout the Galaxy

- Pion Production
  - Sources: Cosmic Rays & ISM
  - Positron Energies: <E>~30 MeV



- Pairs from Hot Plasma
  - Sources: Accreting Binaries
  - Positron Energies: ~MeV

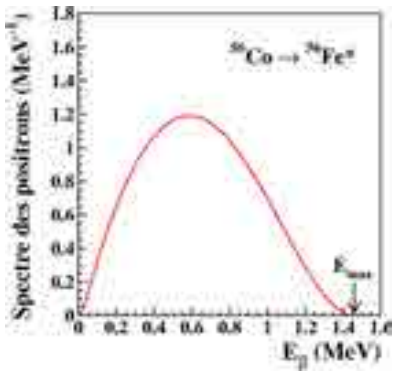
    T>100 keV ($E_{thr}$=1.02 MeV)



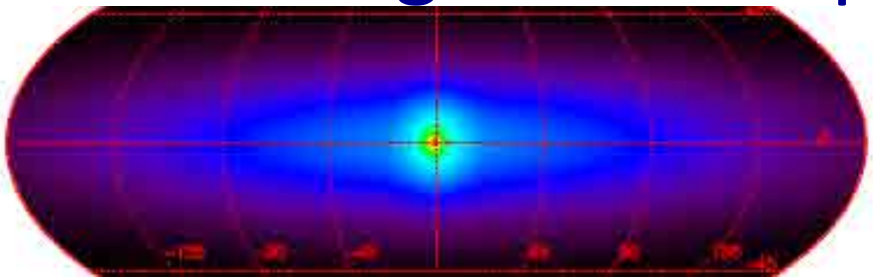

- Pairs from Strong Magnetic Fields
  - Sources: Pulsars, Magnetars
  - Positron Energies: ~MeV…GeV

    ($E_{thr}$=1.02 MeV) (B>$10^{12}$G)

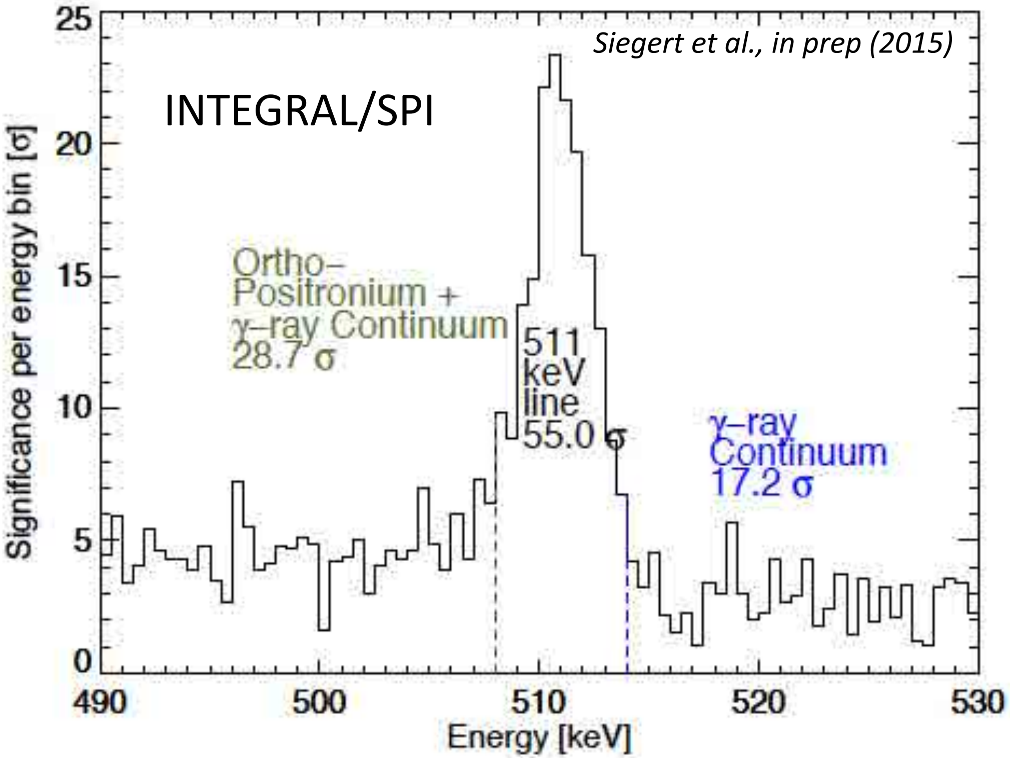
- Radioactive Nuclei
  - Sources: Supernovae, Novae, Cosmic Rays & ISM
  - Positron Energies: ~MeV

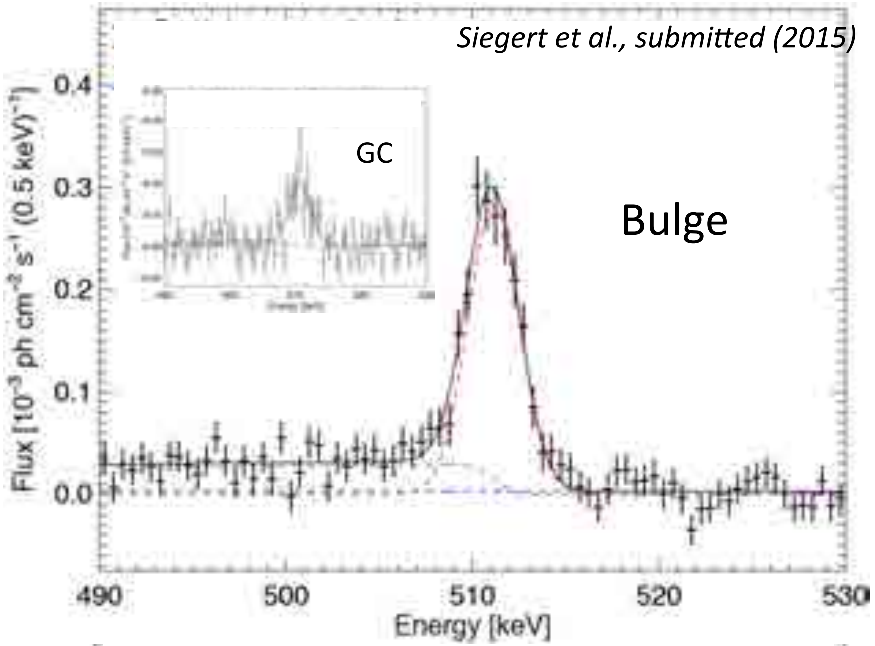


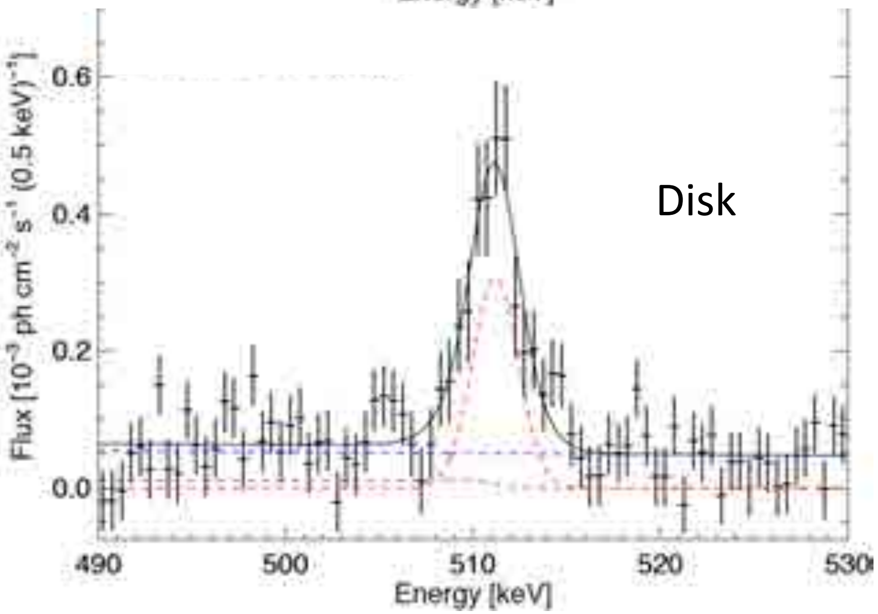
# Insights from spectral details?



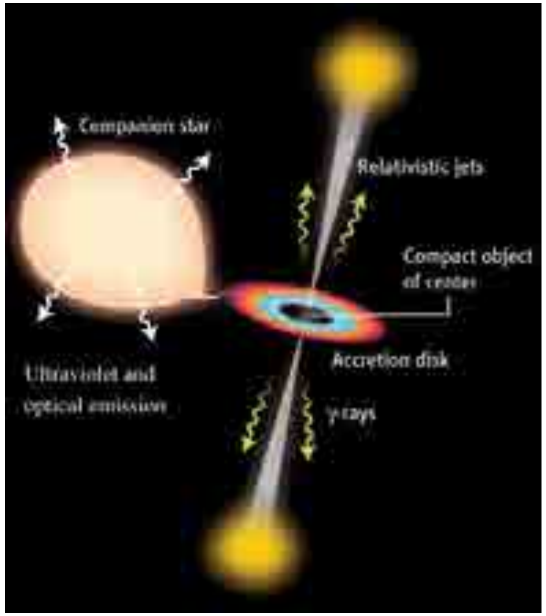
– Derive/discriminate spectra from different regions



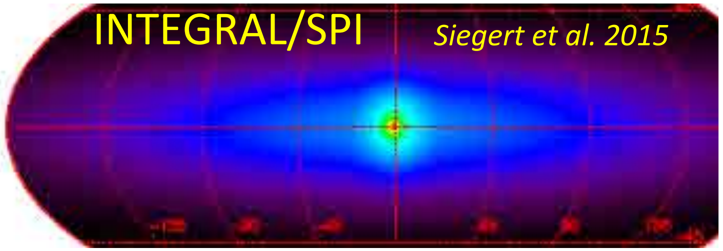



# Microquasars as Sources of Positrons



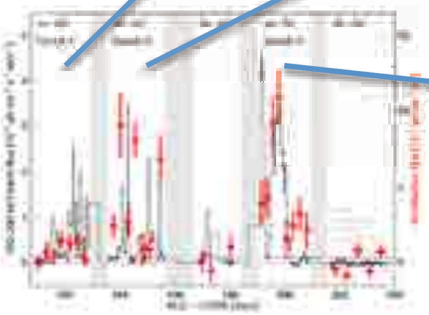

- Pairs from hot plasma in accreting BH binaries
  - Pair creation near compact central $\gamma$-ray source
    - T>100 keV ($E_{thr}$=1.02 MeV), $\tau$~3…5
  - Positron energies: ~MeV
  - Total luminosity:
    - June 2015 flaring average annihilation flux: ~5.4 $10^{-3}$ ph $cm^{-2}$ $s^{-1}$
    - @2.4 kpc → 3.7 $10^{42}$ $e^+$ $s^{-1}$
  - Annihilation fraction uncertain
    - If 50% $e^+$ escape → ~10 such sources required for Galactic ~2..3 $10^{43}$ $e^+$ $s^{-1}$
  - Duty cycle uncertain
    - ~tens of y between flaring periods, flaring for ~weeks
    - duty cycle ~$10^{-3}$?
  - total population of accreting BH binaries:
    - need ~$10^{3..4}$ accreting BH binaries
      (e.g. Sadowski+2008, van Haaften+2015)
    - propagation smoothes out source distribution
    - disk dominated, or centrally enhanced in Galaxy?

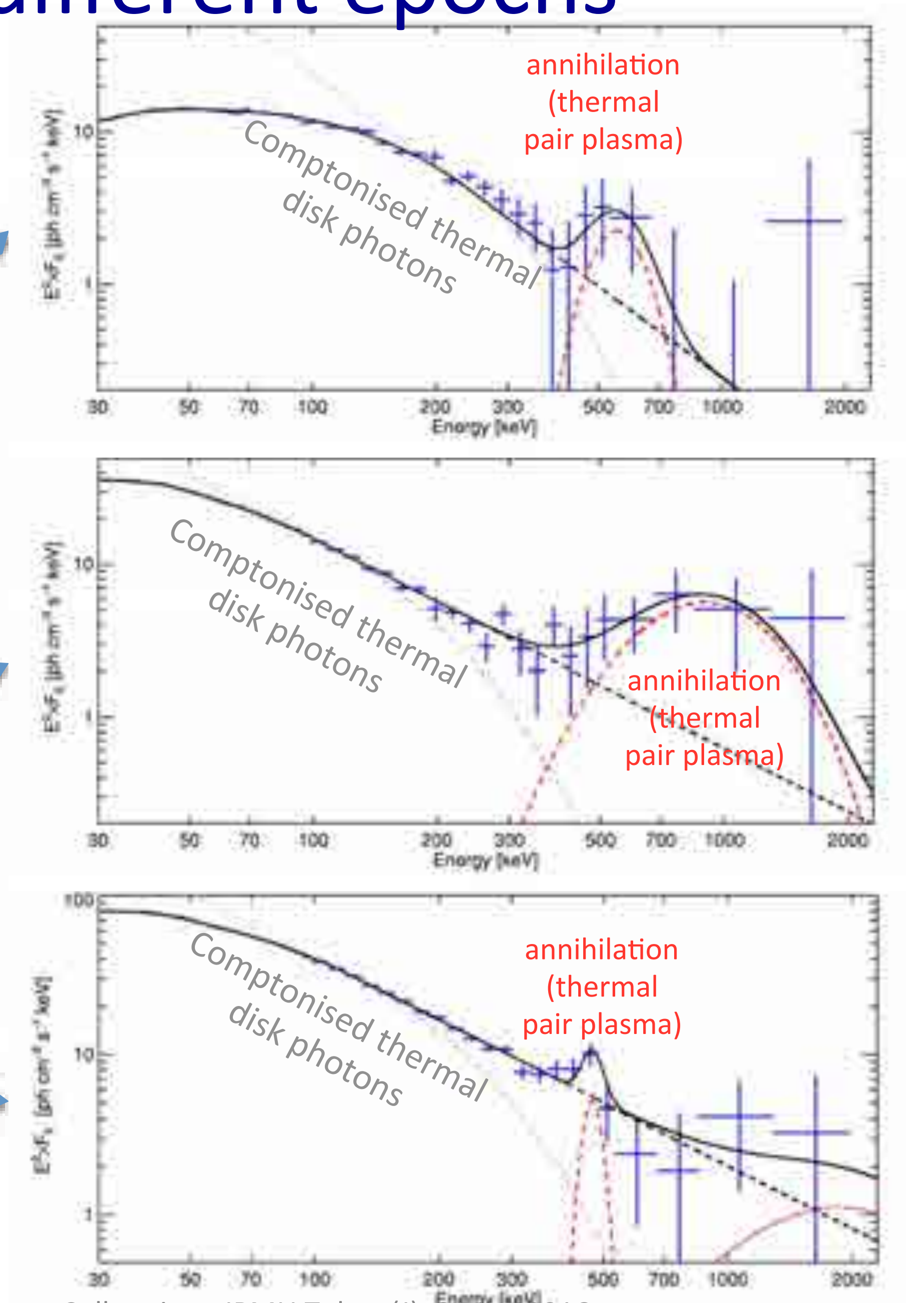


# Spectra for different epochs

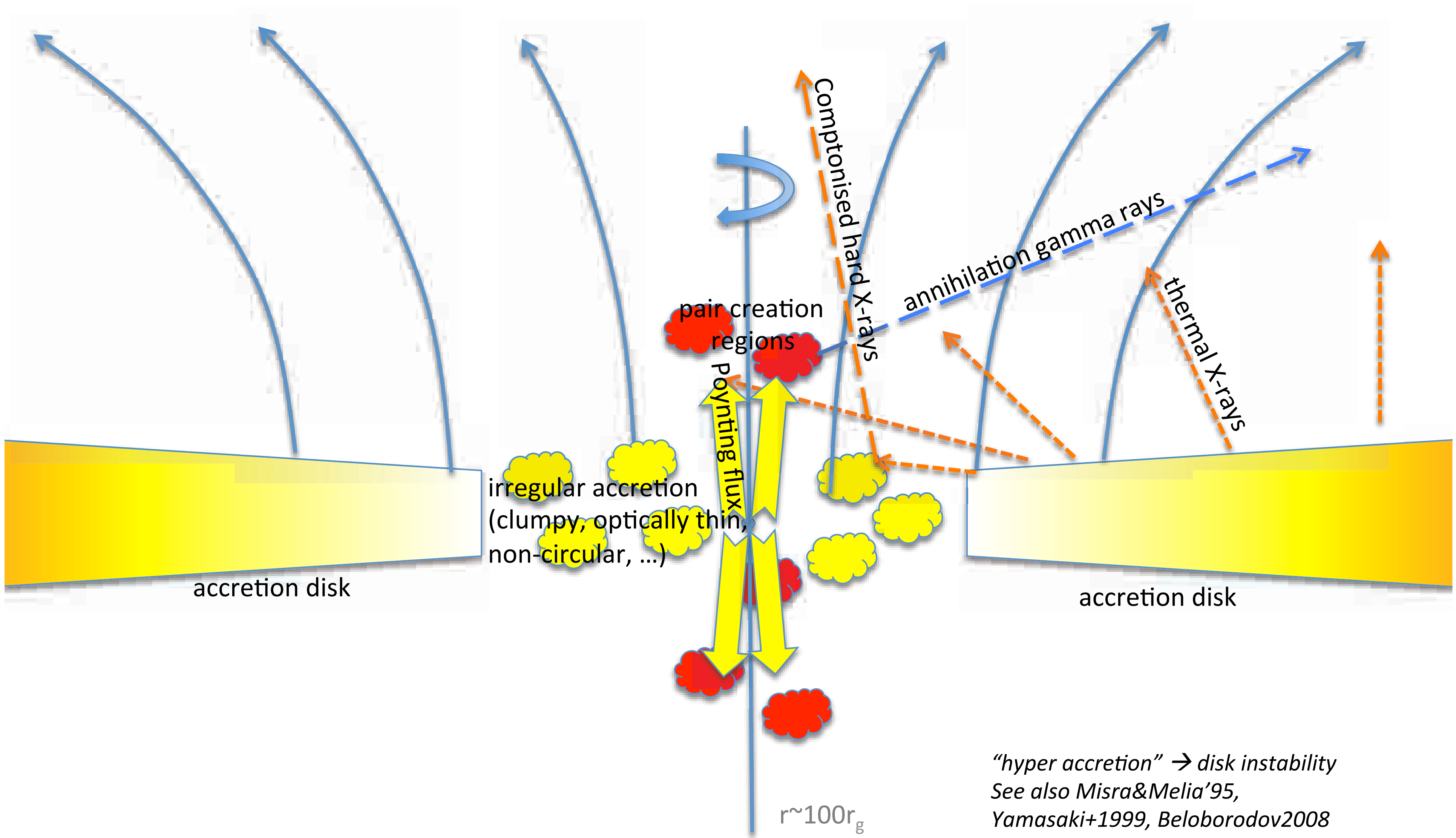
Pair plasma most plausible

$e^+$ components significance $>10\sigma$



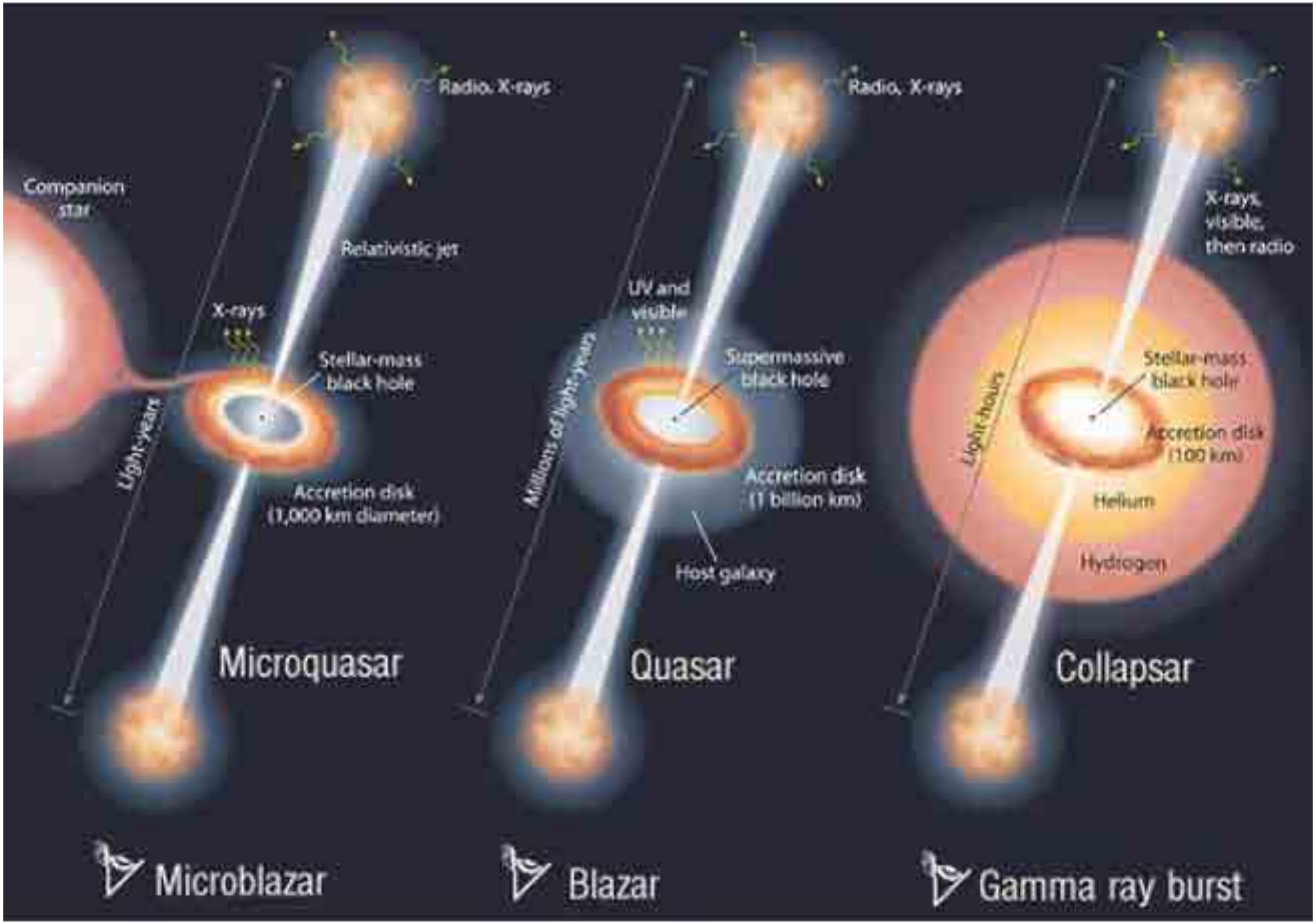


# Pair plasma outflow scenario




*"hyper accretion" → disk instability*
*See also Misra&Melia'95,*
*Yamasaki+1999, Beloborodov2008*

# Broader connections…



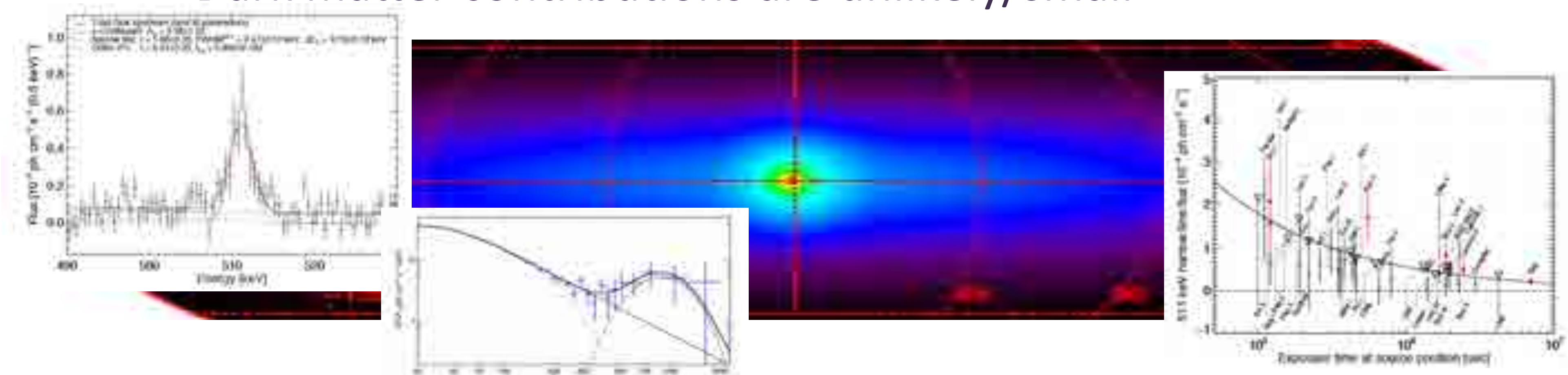
# Understanding the 511 keV Line Emission

*After 12 y of measurements and various different analyses*

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

– Surprisingly-bright extended “bulge-like” emission

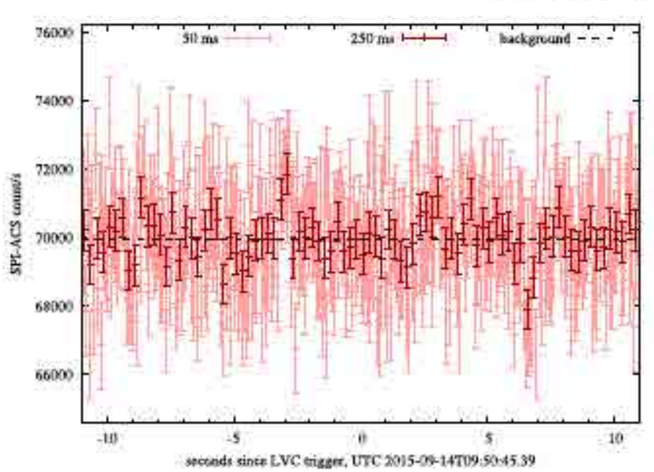
- None of the plausible candidate sources would produce this
- The centroid appears offset by ~1 deg towards 4$^{th}$ quadrant
- Sgr A*(?) appears to contribute ‘point-like’ emission, but cannot explain the extended bulge
- The disk (now) appears quite extended → e$^+$ outflows? (Pulsars, microquasars (!), SNe, …, with bulge enhancement?)
- Dark matter contributions are unlikely/small

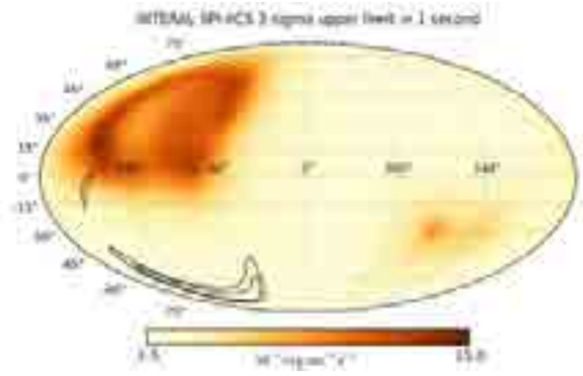


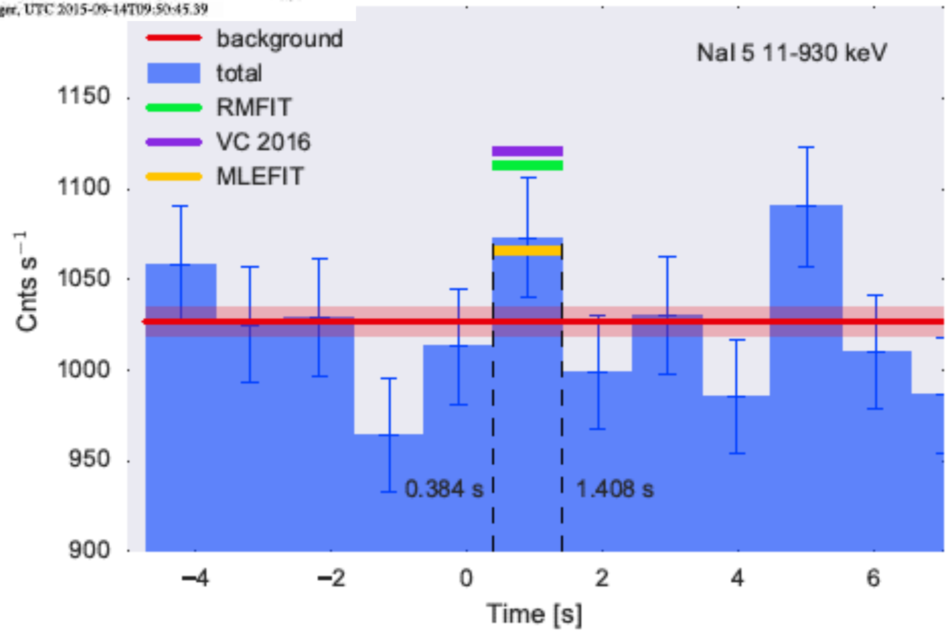
# Gravitational-Wave Counterparts

- SPI ACS is the largest gamma ray detector in space

Example:
GW150904



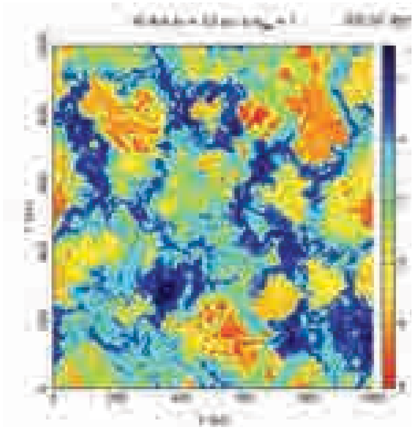





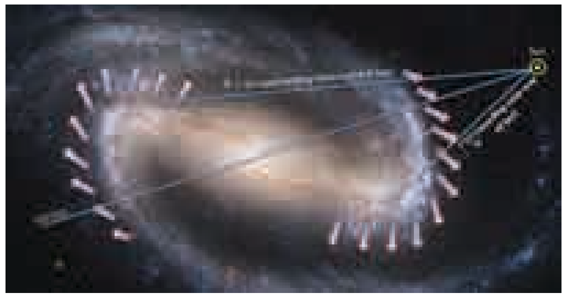

- *Note:*
  Fermi-GBM alert
  of a gamma-ray signal
  is controversial
  - » *Greiner et al. 2016*


# Cosmic Gamma Rays **Summary**

- Radioactivity $\gamma$-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,$^{56}$Co irregularly → 3D effects?



- ccSupernova $^{44}$Ti demonstrates SN 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: understand groups of massive stars (Mys)
  - How much $^{60}$Fe from n captures in C and He shells?



- ISM in the Galaxy: Role of superbubbles; e$^{+}$ sources
  - $^{26}$Al spreads into large (super)bubbles
  - e$^{+}$ sources are a tantalizing variety & puzzle