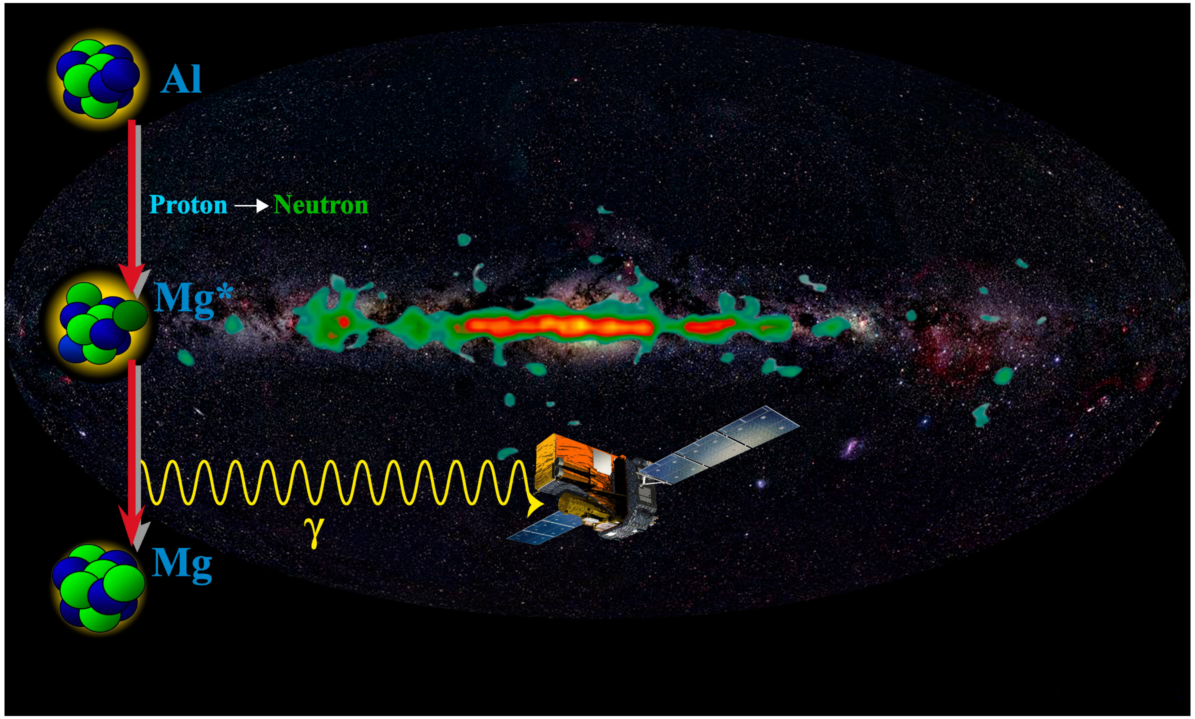
Nuclear Astrophysics

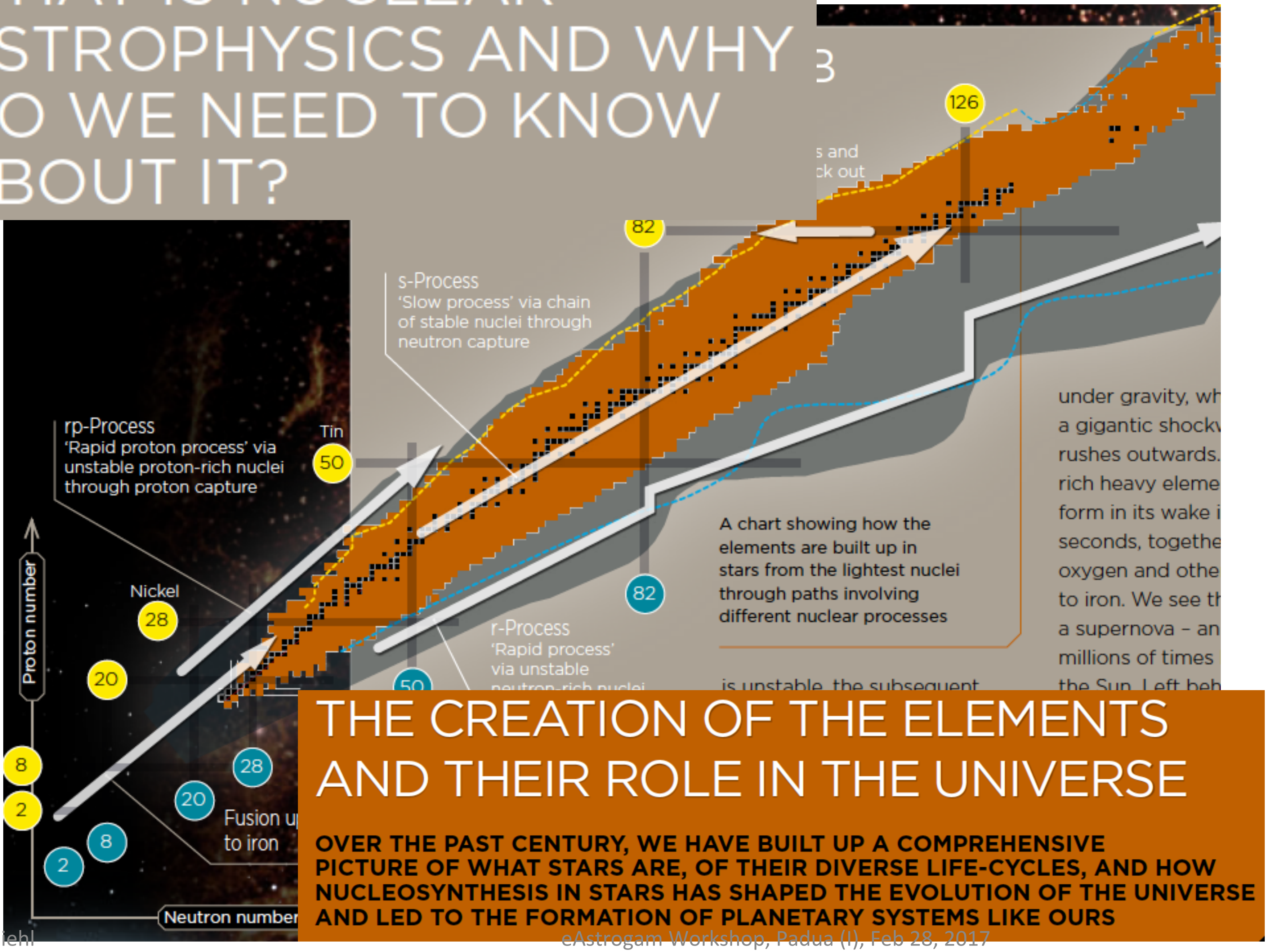
(INTEGRAL Spectroscopy and eAstrogam)

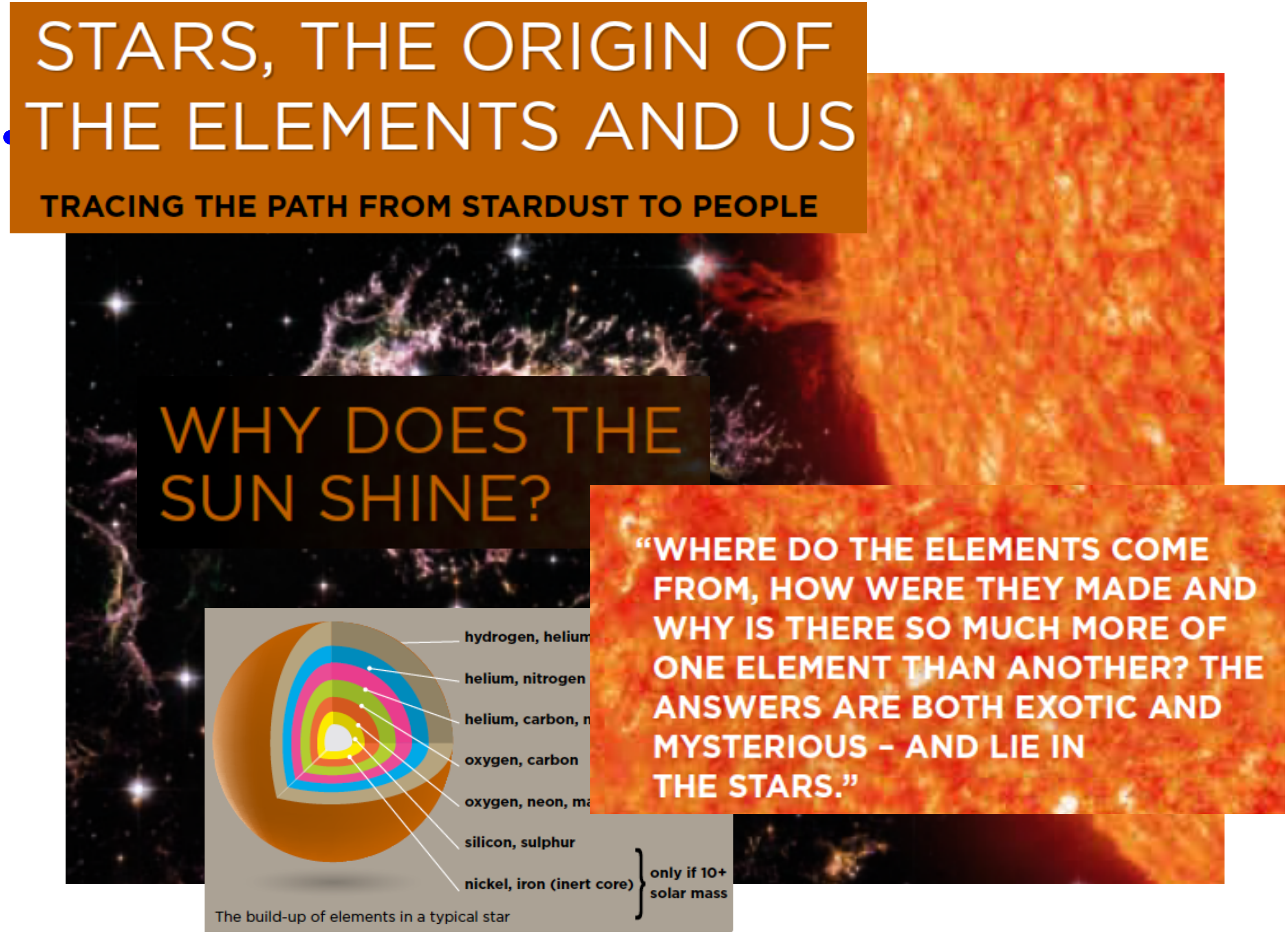


Roland Diehl

(MPE Garching, Germany)

WHAT IS NUCLEAR ASTROPHYSICS AND WHY DO WE NEED TO KNOW ABOUT IT?



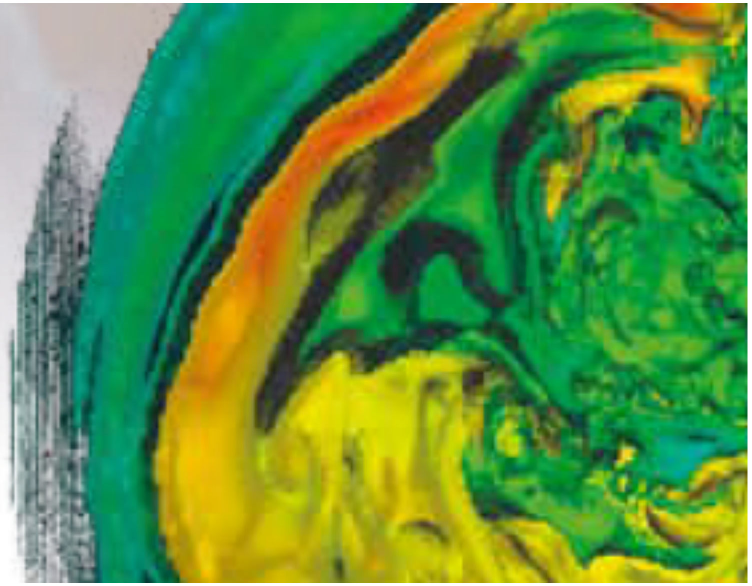


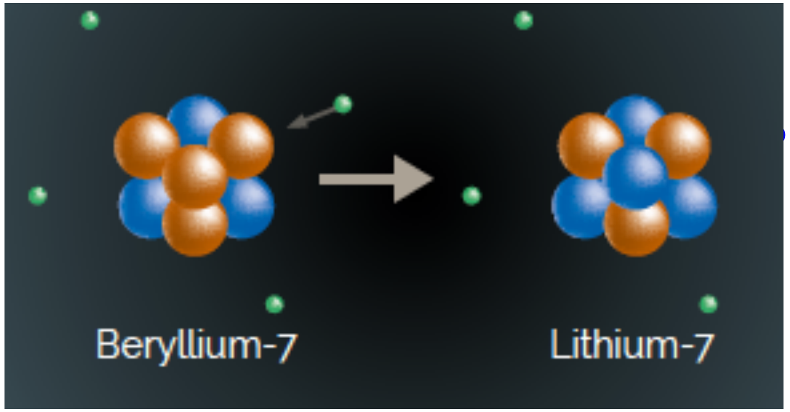
STARS, THE ORIGIN OF THE ELEMENTS AND US
TRACING THE PATH FROM STARDUST TO PEOPLE
WHY DOES THE SUN SHINE?
"WHERE DO THE ELEMENTS COME FROM, HOW WERE THEY MADE AND WHY IS THERE SO MUCH MORE OF ONE ELEMENT THAN ANOTHER? THE ANSWERS ARE BOTH EXOTIC AND MYSTERIOUS – AND LIE IN THE STARS."
hydrogen, helium
helium, nitrogen
helium, carbon,
oxygen, carbon
oxygen, neon,
silicon, sulphur
nickel, iron (inert core)
only if 10+ solar mass
The build-up of elements in a typical star

THE MYSTERIES TO UNCOVER

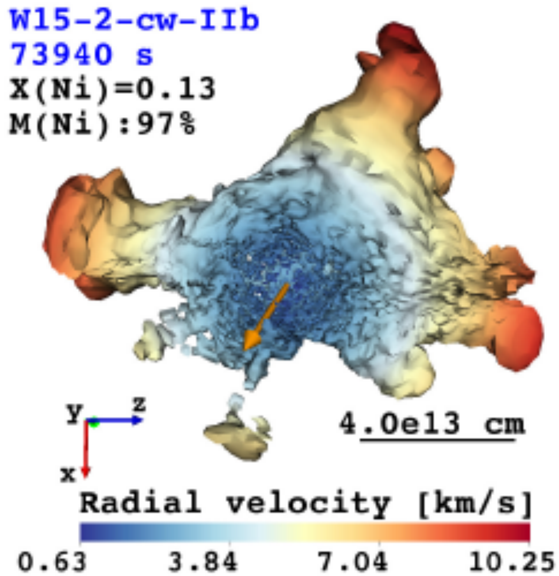
ADVANCED STAGES OF NUCLEAR BURNING

There is a huge dearth of information about the reaction paths leading to the heavier elements. They require much better theoretical models of nuclear structure and stability, to be supported by new experimental measurements using both stable and radioactive nuclear beams to investigate the complex variety of pertinent reactions and their outcomes.





.... a wide range...



Science Questions in Nuclear Astrophysics

- Where do isotopes originate?
- How does nuclear fusion shape stars?
- How do supernovae explode?
- How do novae and Type-I X-ray bursters work?
- Nucleosynthesis in extremes: big bang; BH vicinity;

- How are cosmic rays accelerated & propagated?
- Extremes of matter: BH vicinity; compact-star collisions; jet environments

Gamma-Ray Lines and their Messages

- Radioactive Trace Isotopes are Nucleosynthesis By-Products

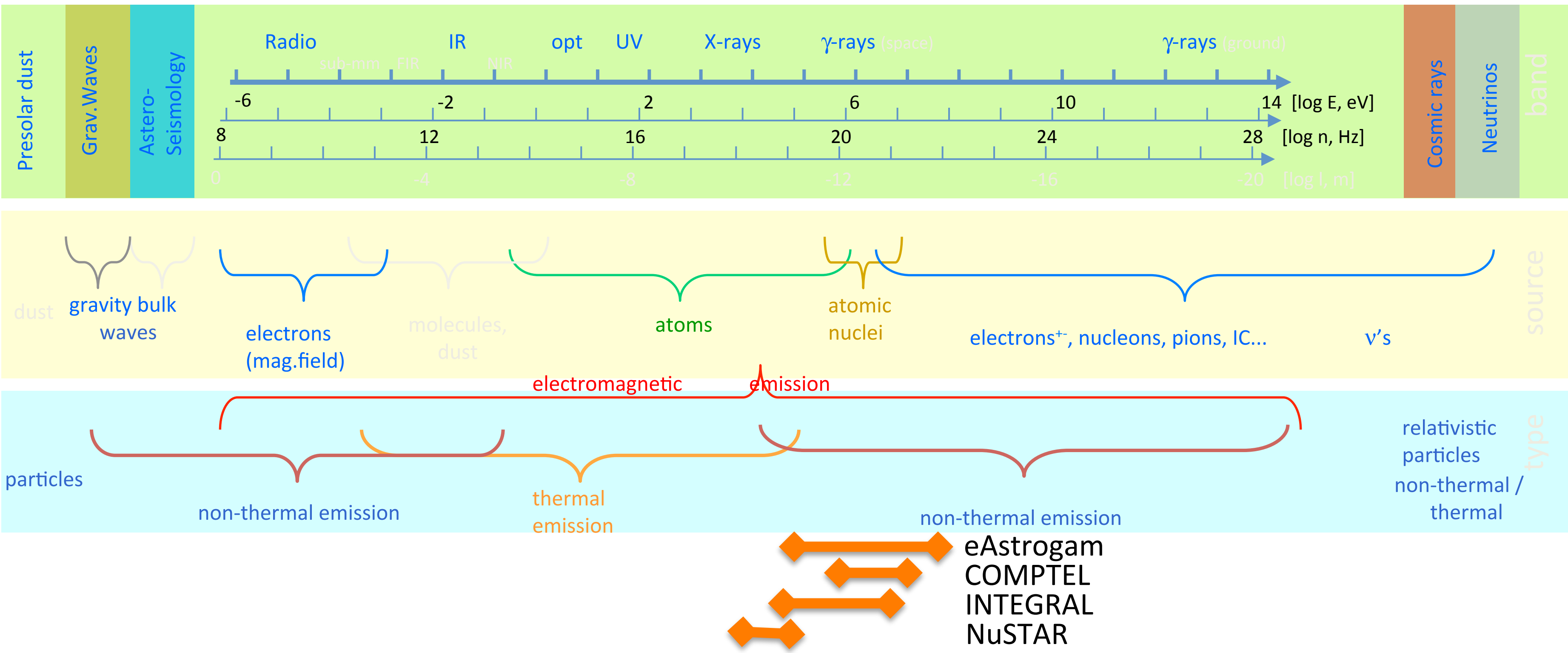
Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	^{7}Be → ^{7}Li*	478
^{56}Ni	111 d	^{56}Ni → ^{56}Co* → ^{56}Fe*+e^{+}	158, 812; 847, 1238
^{57}Ni	390 d	^{57}Co→ ^{57}Fe*	122
^{22}Na	3.8 y	^{22}Na → ^{22}Ne* + e^{+}	1275
^{44}Ti	85 y	^{44}Ti→^{44}Sc*→^{44}Ca*+e^{+}	78, 68; 1157
^{26}Al	1.04 10^{6}y	^{26}Al → ^{26}Mg* + e^{+}	1809
^{60}Fe	3.8 10^{6}y	^{60}Fe → ^{60}Co* → ^{60}Ni*	59, 1173, 1332
e^{+}	…. 10^{5}y	e^{+}+e^{-} → Ps → $\gamma\gamma$..	511, <511

individual object/event (^{7}Be – ^{44}Ti)

cumulative from many events (^{26}Al – e^{+})

- For Gamma-ray Spectroscopy We Need:
  - Decay Time > Source Dilution Time (→ no < days lifetimes)
  - Yields > Instrumental Sensitivities (→ no elements > Fe)

Astronomical windows for nuclear physics



- Nuclear processes (i.e. atomic nuclei de/excitations): 0.05 – 16 MeV
- Nucleosynthesis presolar grains
- Nuclear processes (spallation CRs (near Earth)
- Nucleosynthesis neutrinos (Sun;...)
- Chemical evolution abundances in stars, ISM, ... opt, sub-mm, X-rays
- ...

Nuclear Gamma-Ray Line Telescopes / Missions

– Compton Gamma-Ray Observatory

1991-2000

NASA

– INTEGRAL Observatory

2002-(2018+)

ESA

- NuSTAR

2012-

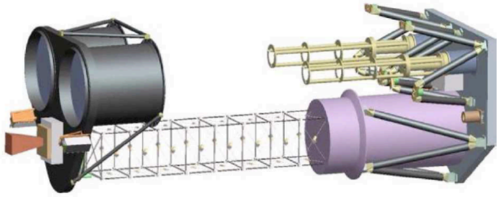
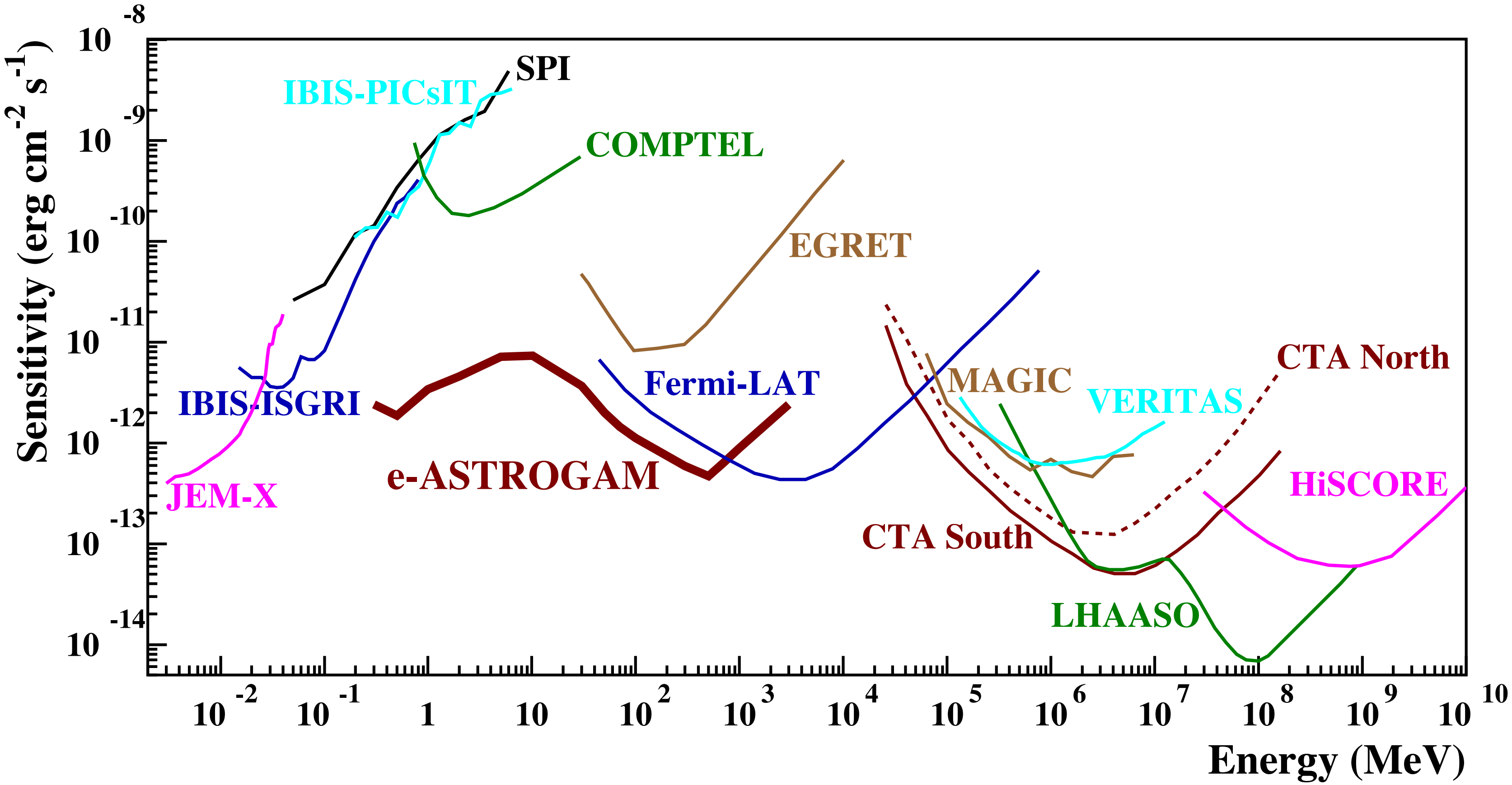


Fig. 1. NuSTAR telescopes in deployed configuration

Explorations in the 0.1...100 MeV Domain



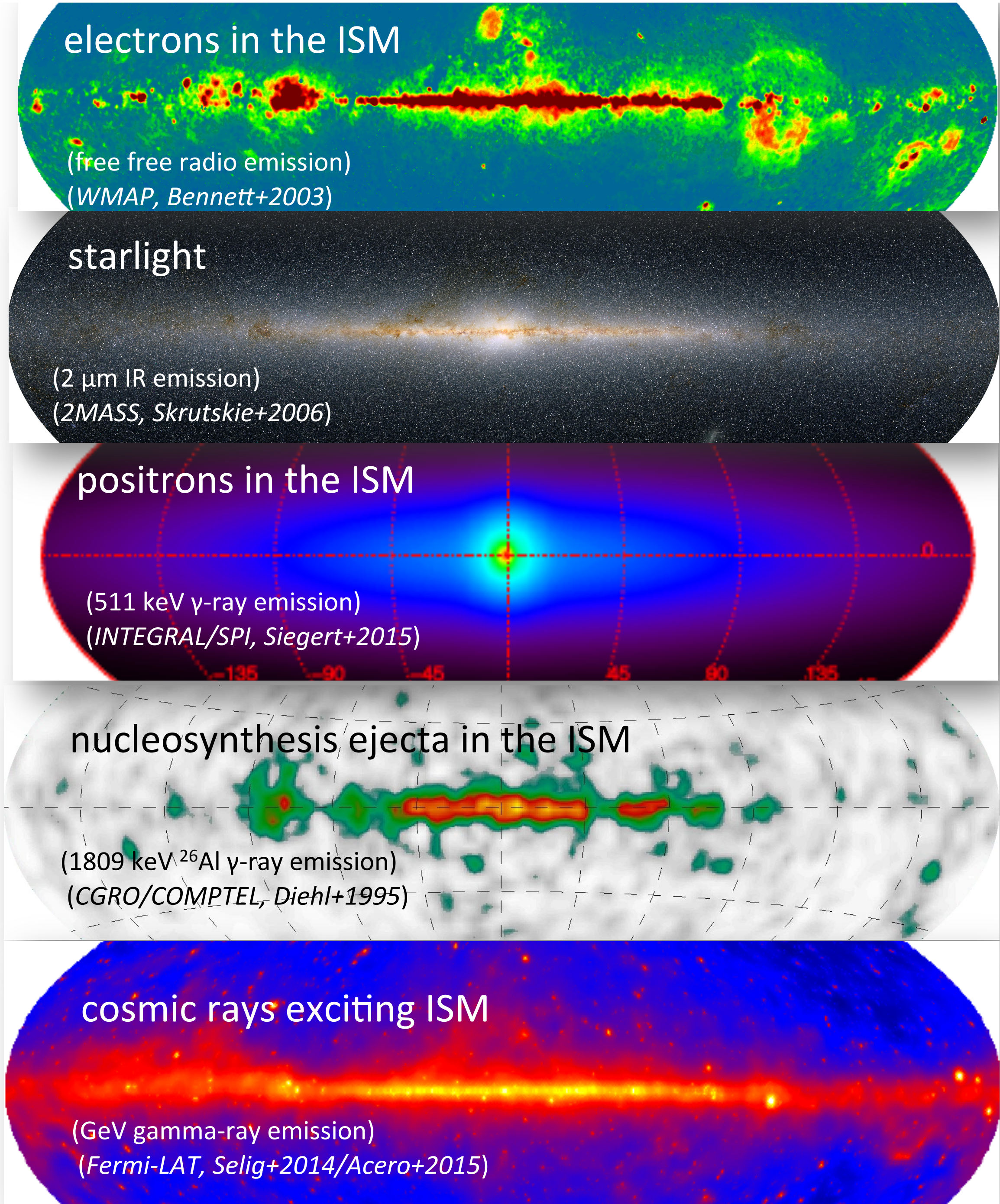
- Instrument sensitivities ~few 10^{-5} ph cm^{-2} s^{-1} (10^{6}s)
- Achieved line sensitivity in RoI's: <10^{-5} ph cm^{-2} s^{-1}

Diffuse Gamma-Ray Line Emissions

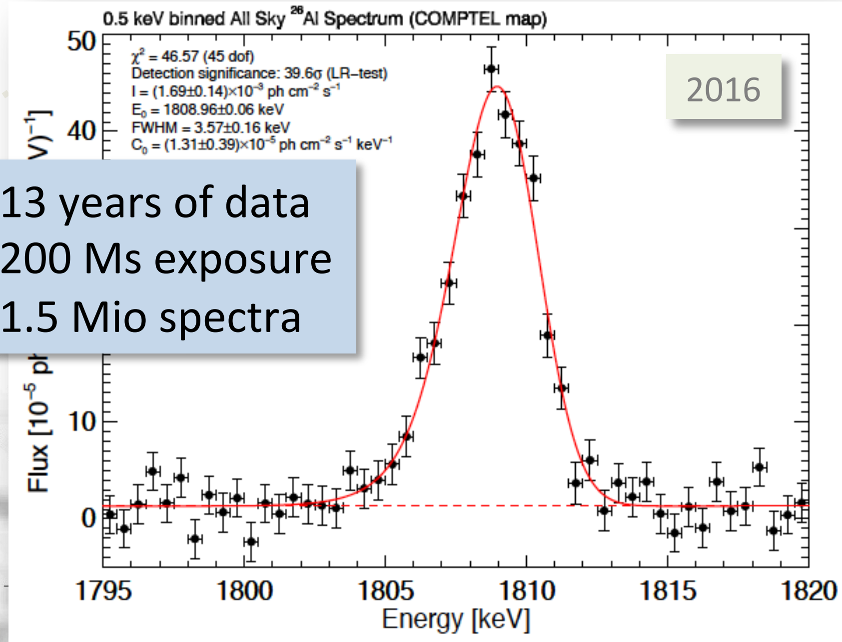
- Radioactivities
- Positrons

Special Messengers: ^{26}Al Radioactivity, Positrons

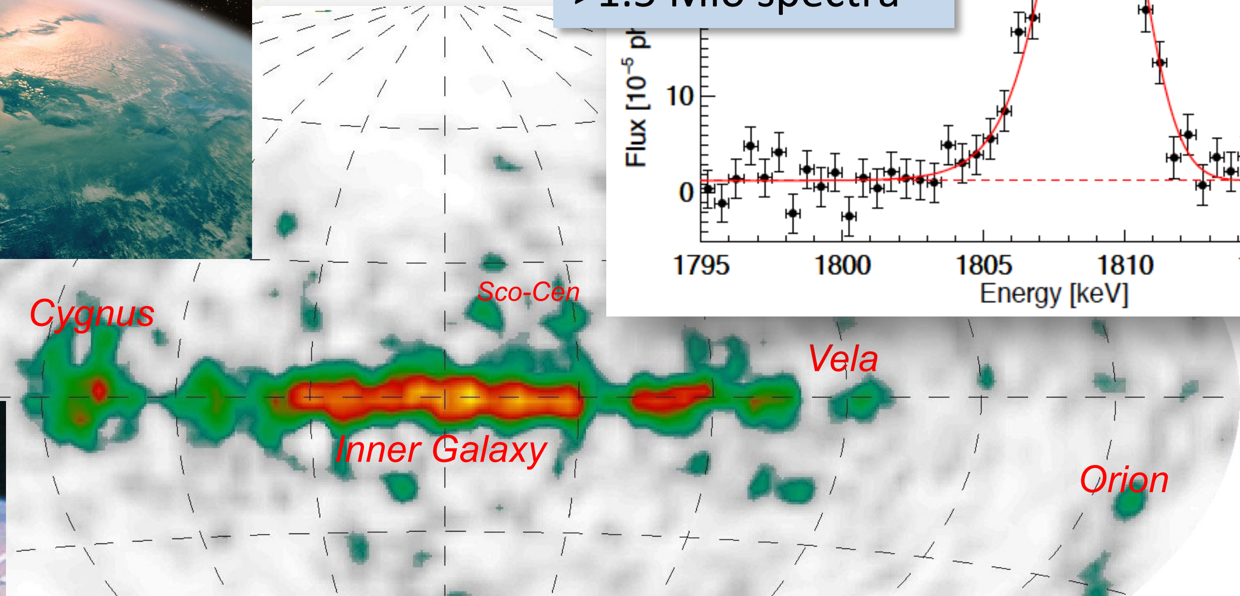
- Radioactivity provides a clock
- ^{26}Al radioactivity traces nucleosynthesis ejecta over ~few Myrs
- Such γ-ray emission is independent of density, ionisation states, …
- Positrons produce a characteristic spectrum upon annihilation → e^+ in the ISM



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



>13 years of data
>200 Ms exposure
>1.5 Mio spectra



Nucleosynthesis from Massive-Star Groups in the Current Galaxy:

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

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

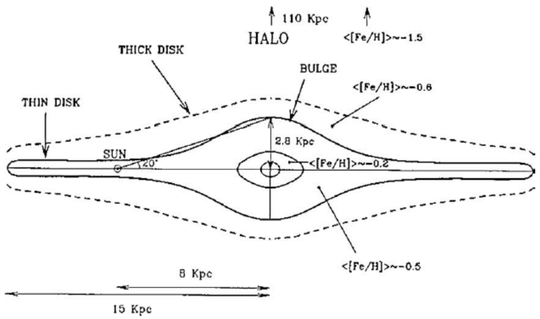
→ Diehl et al., Nature 2006
*→ Diehl et al., A&A 2010**
*→ Diehl et al., in prep. (2017)**

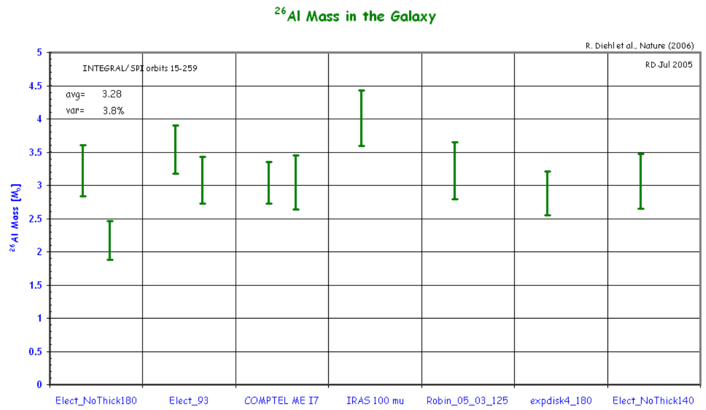
Measured Gamma-Ray Flux*

**) better account for foreground emission*

Galaxy Geometry

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

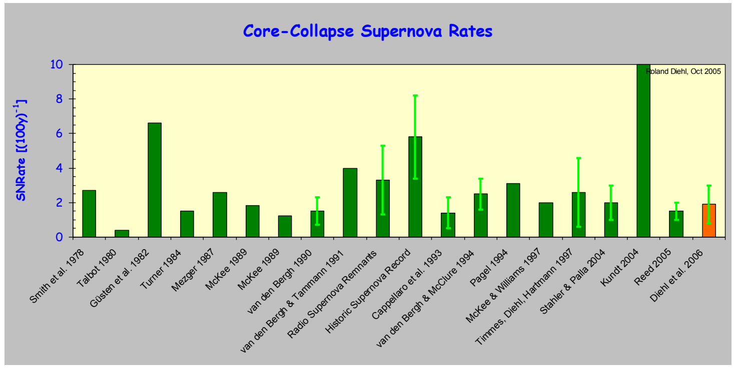


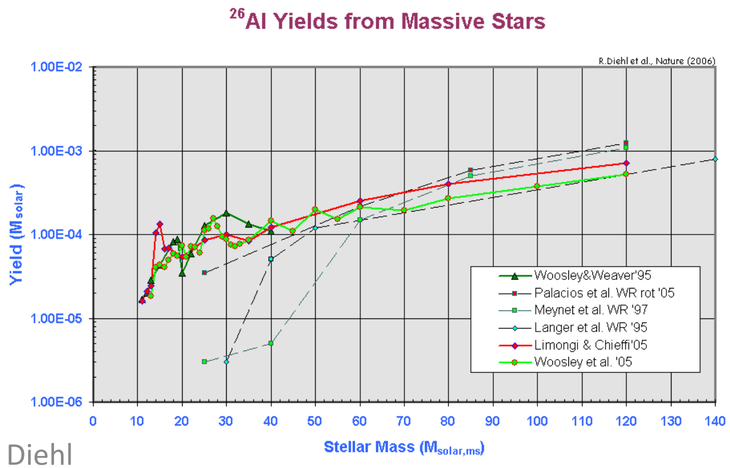


Stellar Mass Distribution,

^{26}Al Yields per Star

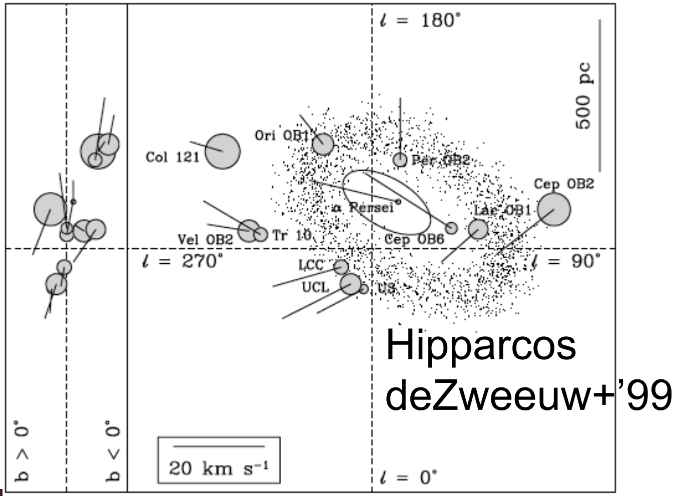
✓ cc-SN Rate = 1.3 (± 0.4) per Century





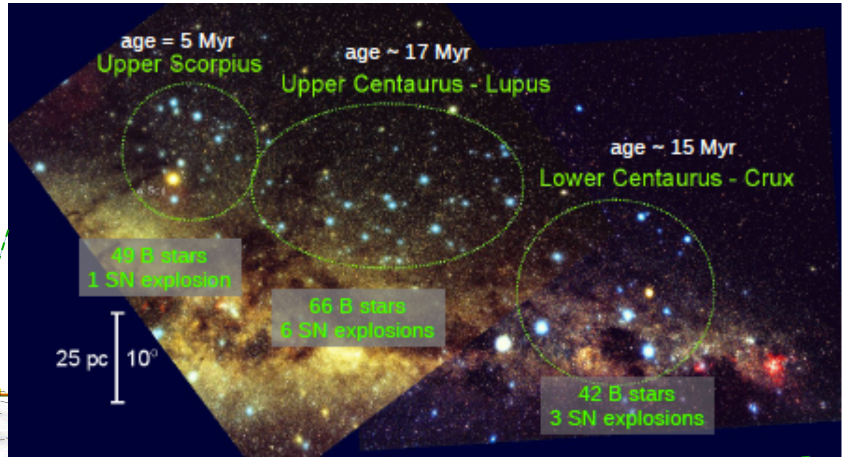
✓ Star Formation Rate = 2.8 $M_\odot$/yr

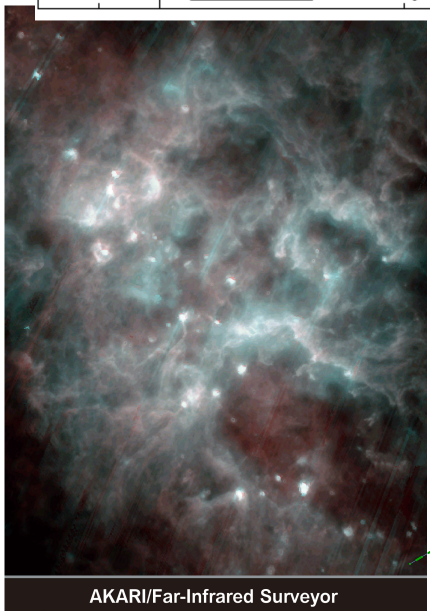
Resolving ^{26}Al Emission from Specific Groups of Stars

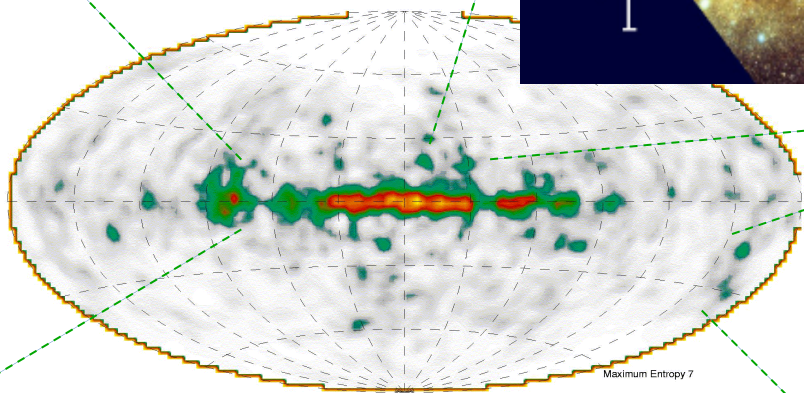


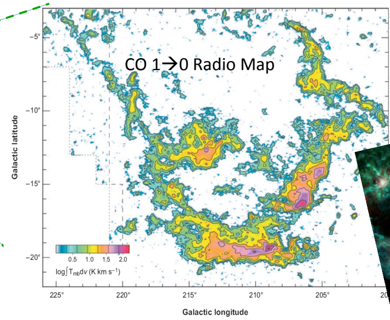
Nearby and/or rich Groups of Stars:

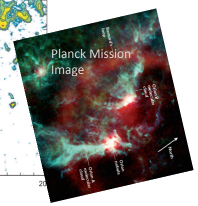
Test our Models for Consistency







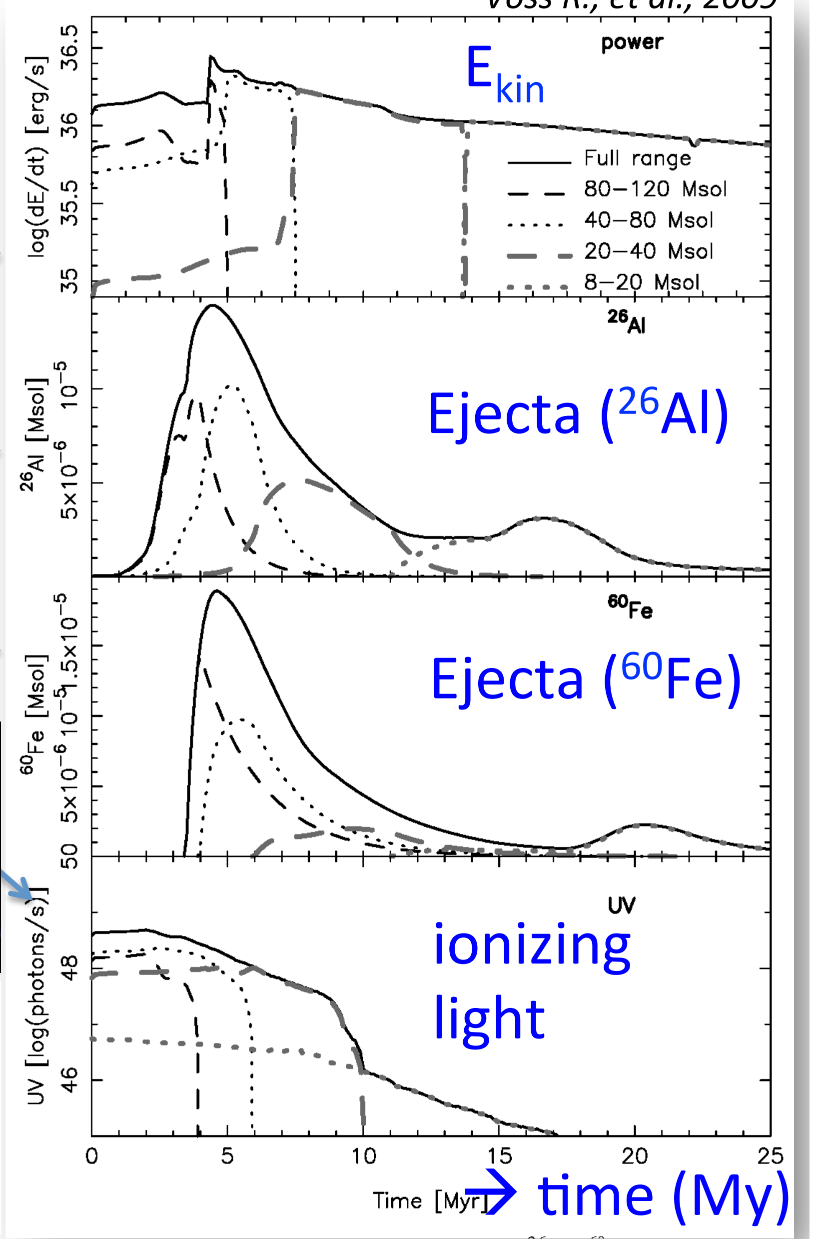


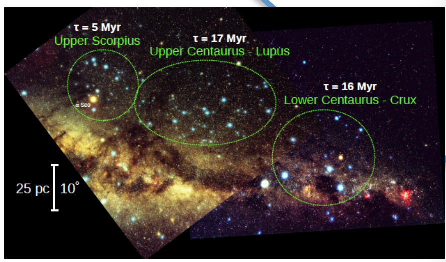


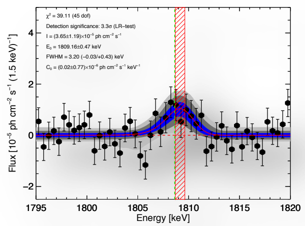
Massive-Star Groups

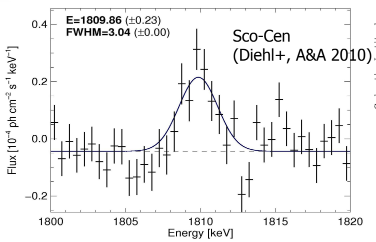
- The "outputs" of massive stars and their supernovae:
  - Winds and Explosions
  - Nucleosynthesis Ejecta
  - Ionizing Radiation
- Observational constraints from:
  - Star Counts
  - ISM Cavities
  - Free-Electron Emission
  - Radioactive Ejecta

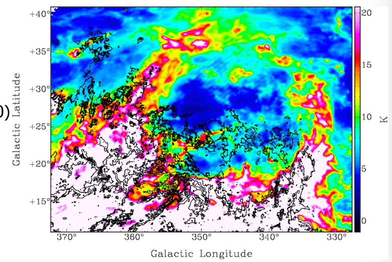
Voss R., et al., 2009





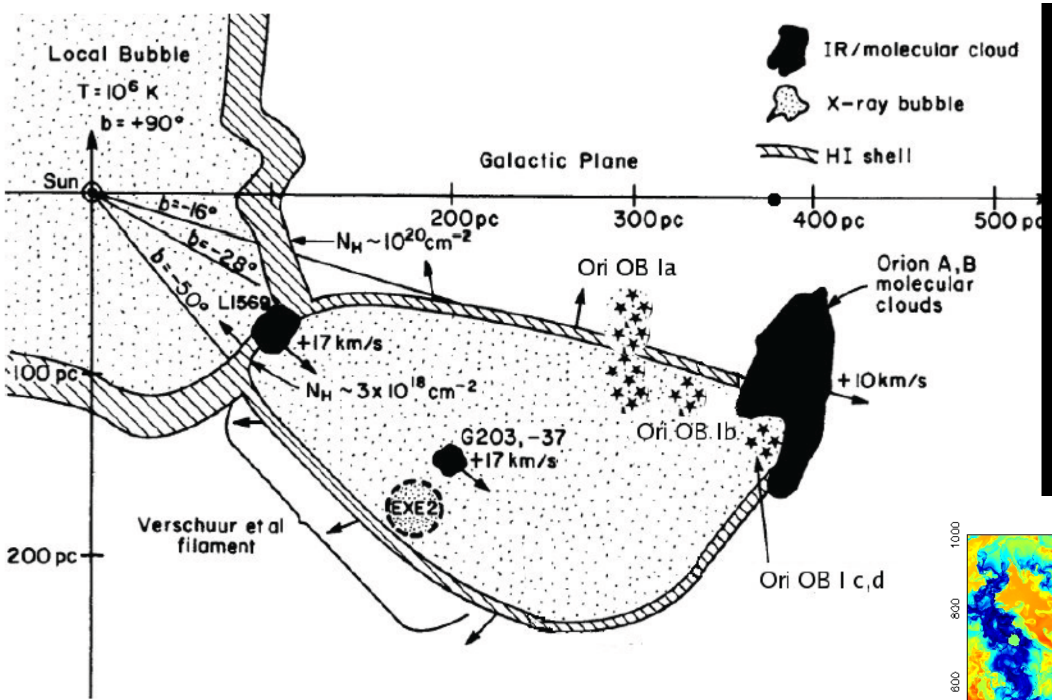


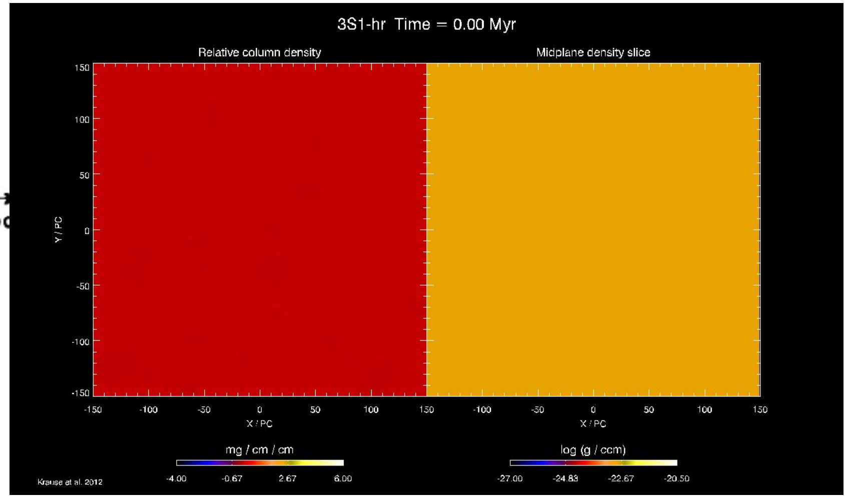


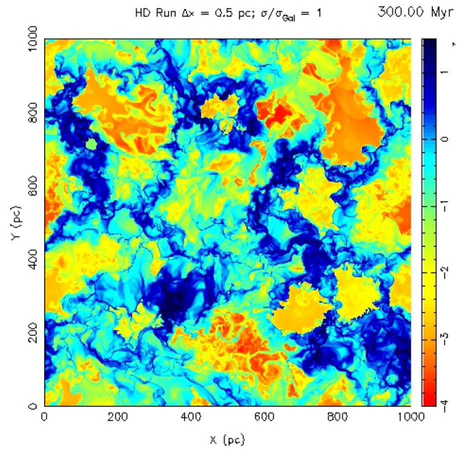


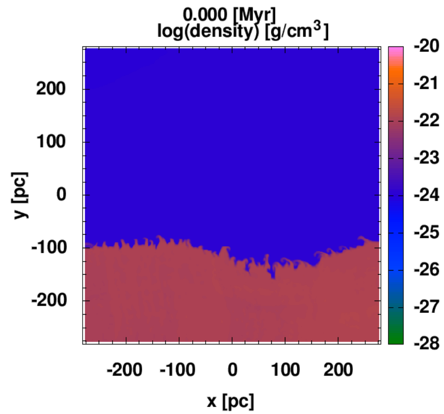
Nucleosynthesis Ejecta and the Dynamics of Interstellar Medium

- ISM is Highly-Dynamic ←→ "Feedback" → Ejecta in (Super-)Bubbles
  - λλλ Study of Regions in Detail (Cygnus, Orion, Scorpius-Centaurus, Carina)







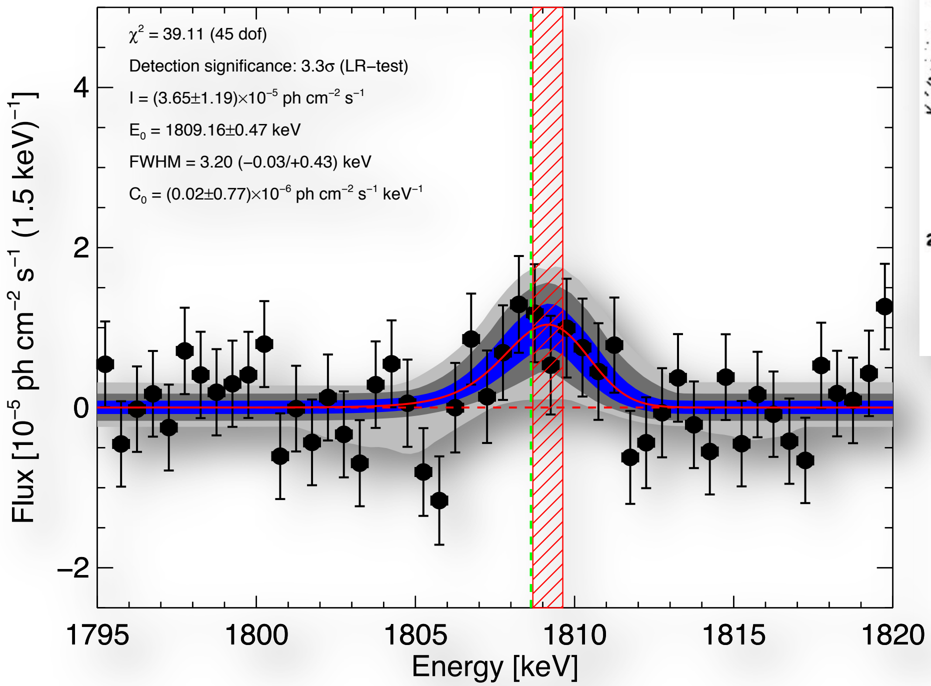


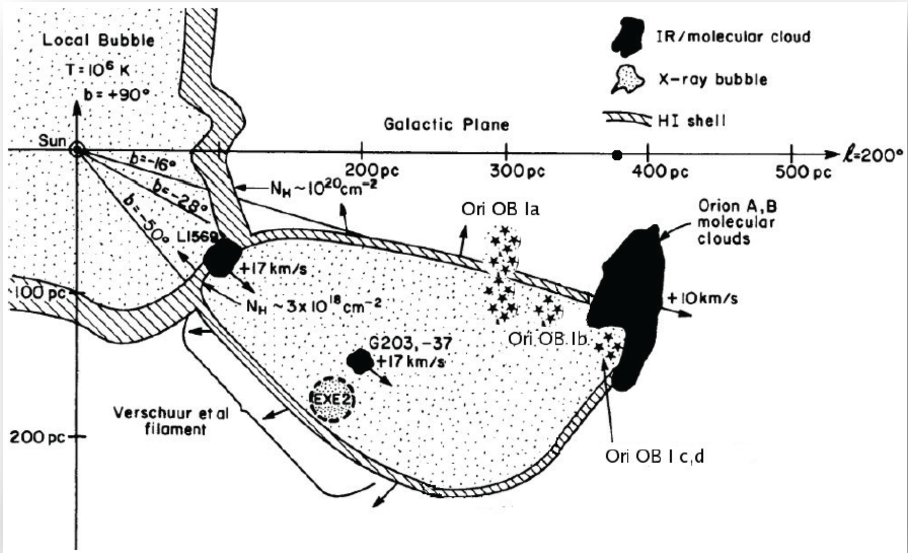
» *Krause+ 2013ff, Fierlinger et al. 2*

^{26}Al in Orion

- Just now detected with SPI/INTEGRAL: challenging

Siegert & Diehl (2016), arxiv 1609.08817

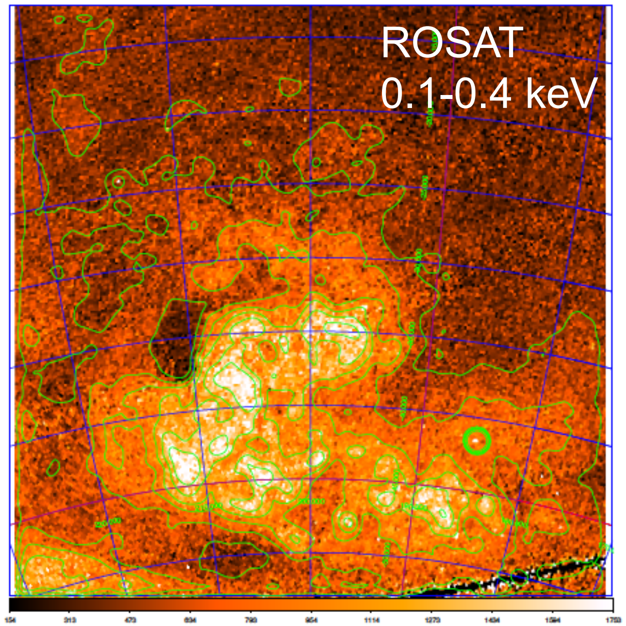


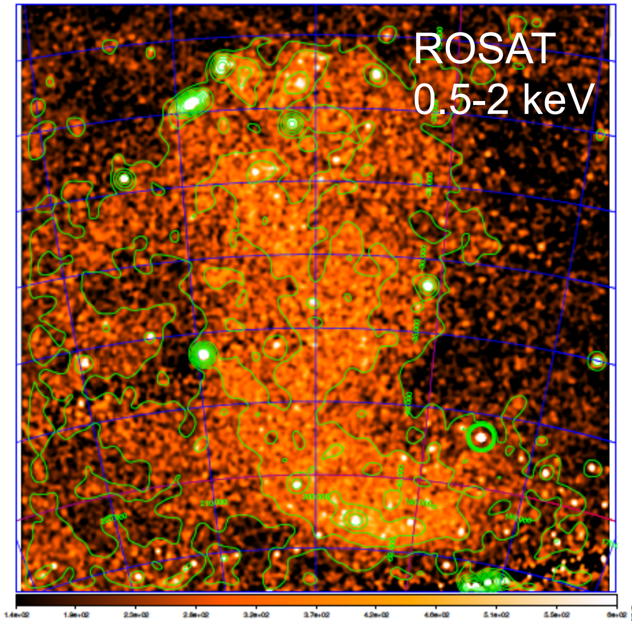


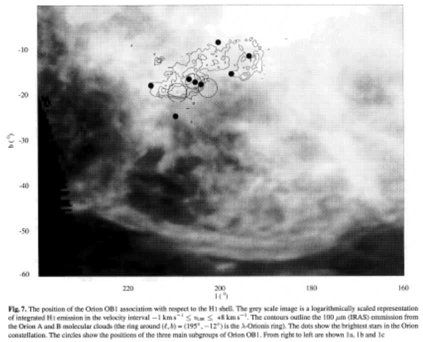
→ Ejecta kinematics?? ← blue shift; velocity broadening?

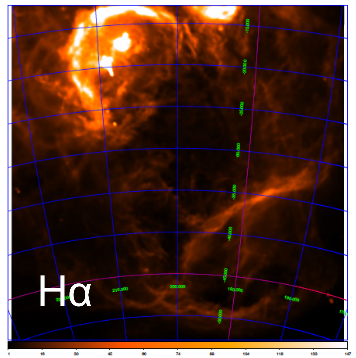
Understanding the Eridanus Superbubble

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

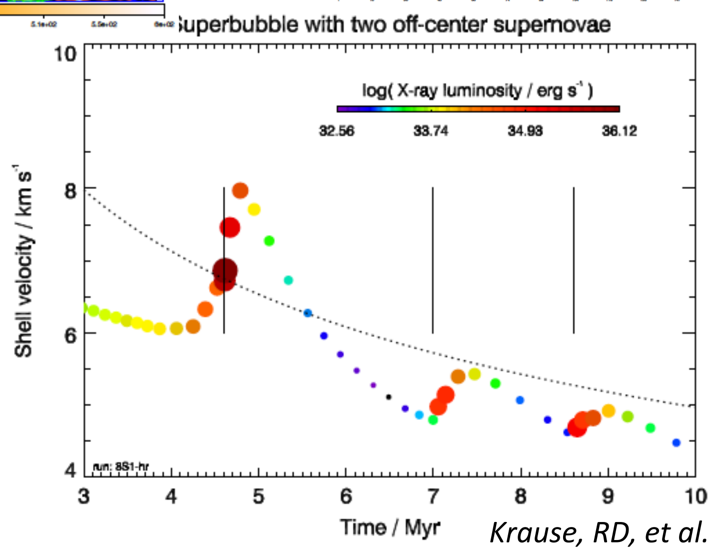








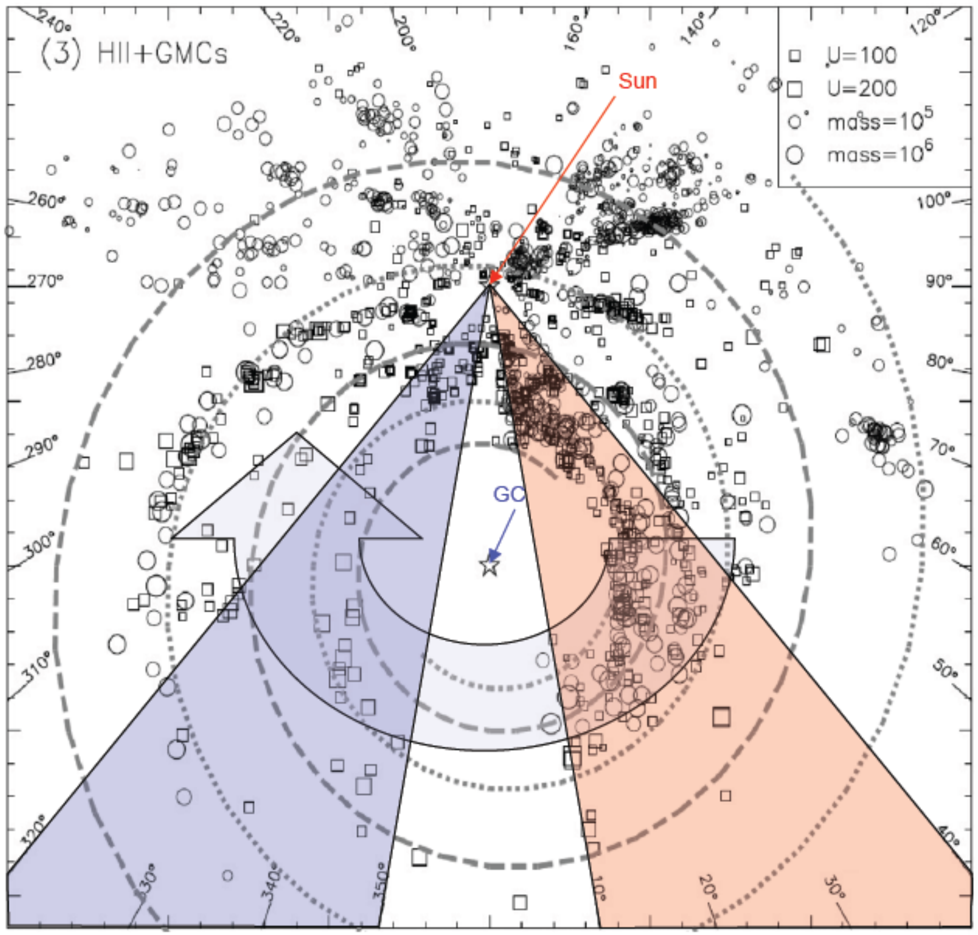
  - Temporal X-ray brightenings after SN energy injections
  - spatial oscillations

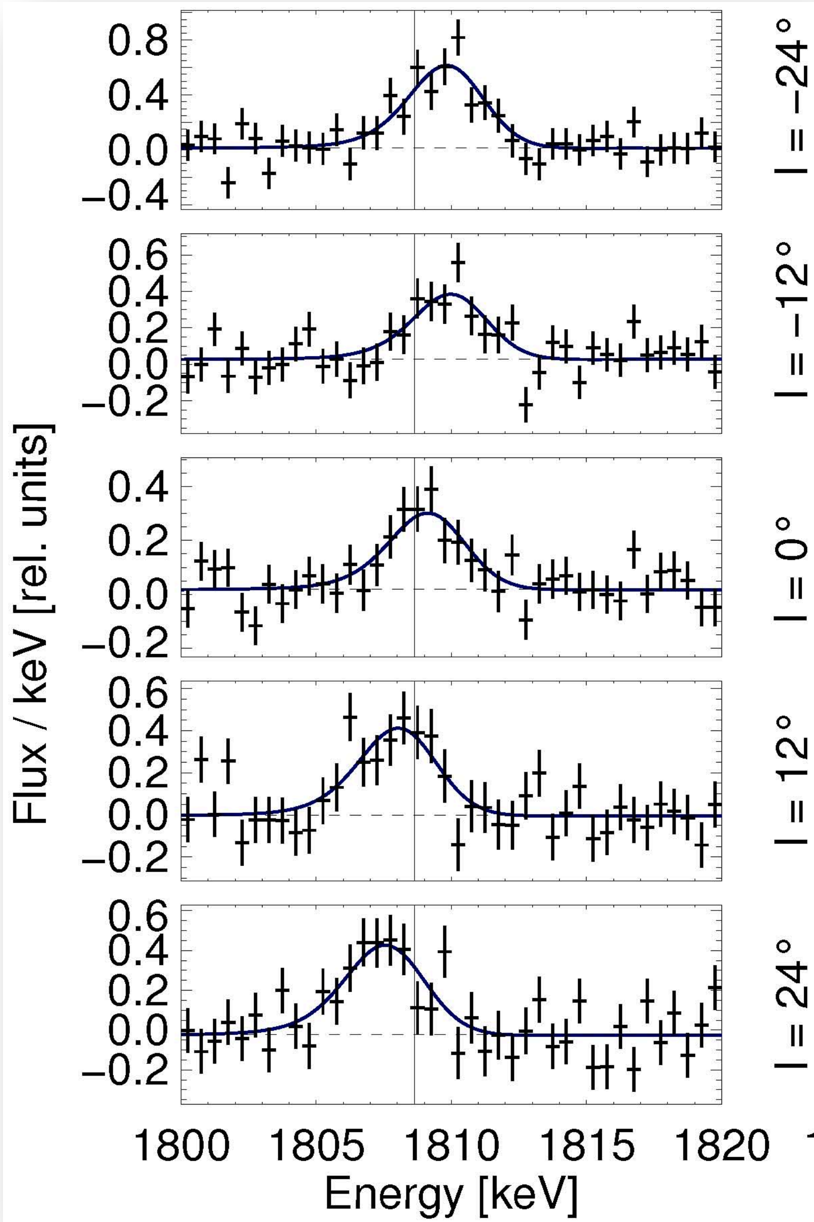


Krause, RD, et al. 2015

Galaxy-scale aspects of feedback: ^{26}Al γ-rays

- Large-scale Galactic rotation

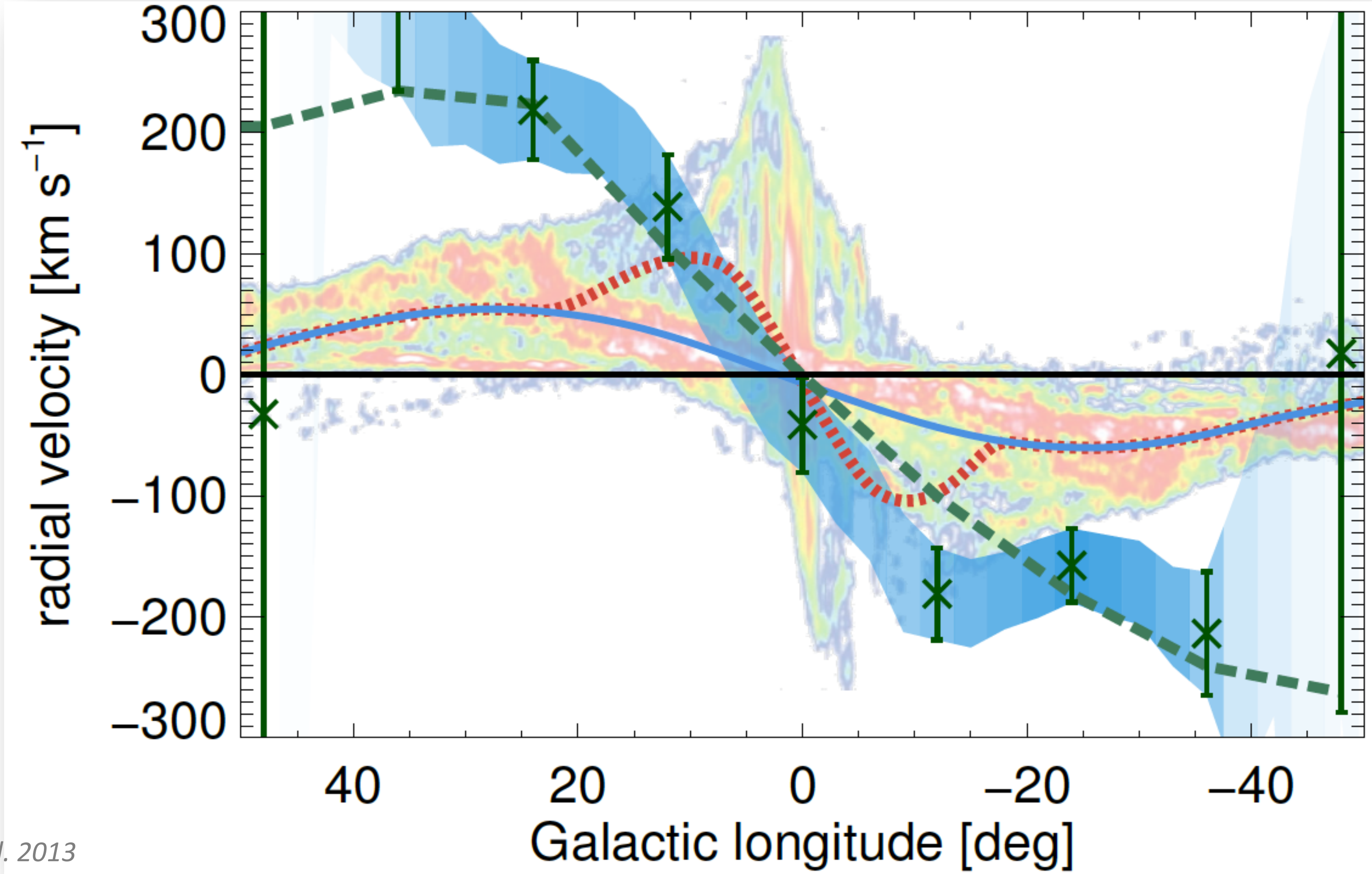




Kretschmer et al., A&A (2013)

using longitude-velocity diagrams

- excess velocity seen for massive-star ejecta!



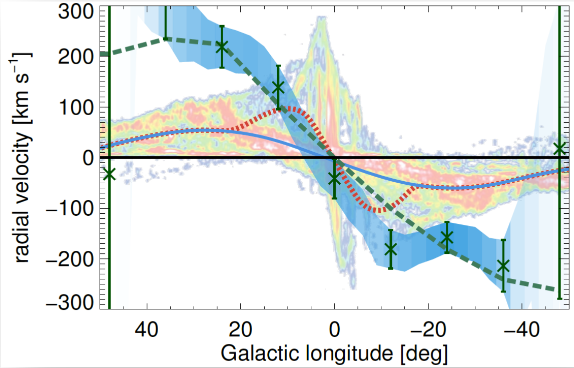
Kretschmer, Diehl, et al. 2013

Kinematics of massive star ejecta in the Milky Way as traced by ^{26}Al

Karsten Kretschmer[1,2], Roland Diehl[2,3], Martin Krause[2,3], Andreas Burkert[4,3,2], Katharina Fierlinger[3,4], Ortwin Gerhard[2], Jochen Greiner[2,3], and Wei Wang[5]

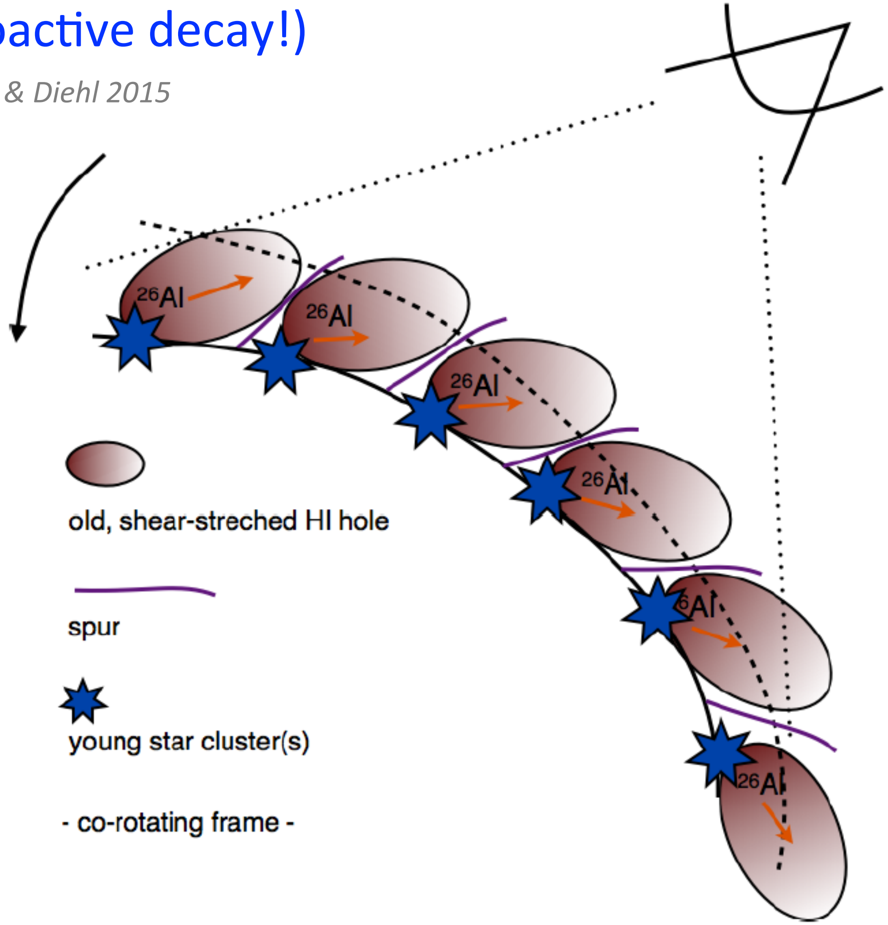
Superbubbles and HI Holes

- ^{26}Al ejecta flow into forward-extended (inter-arm) cavities → 200 km/s extra velocity



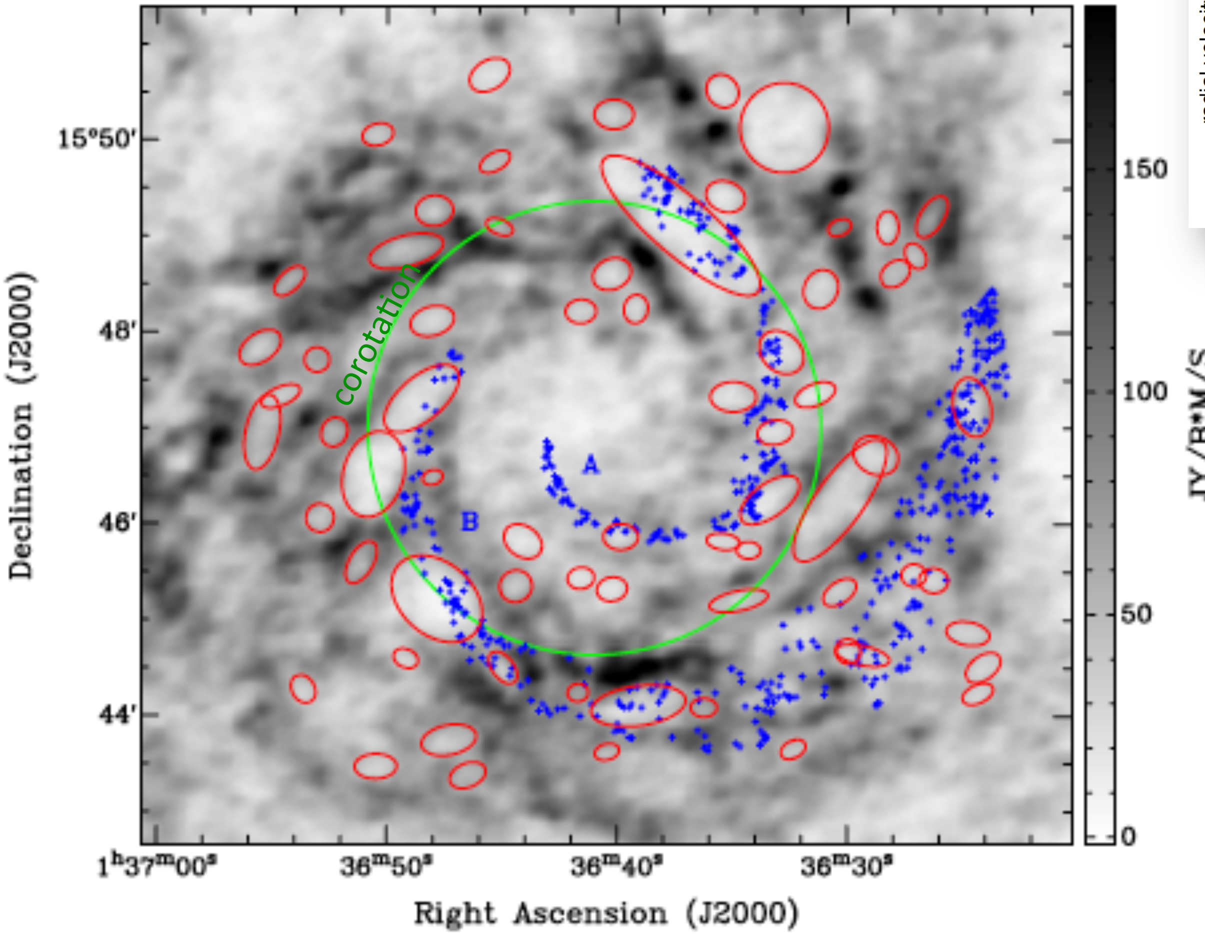
(radioactive decay!)

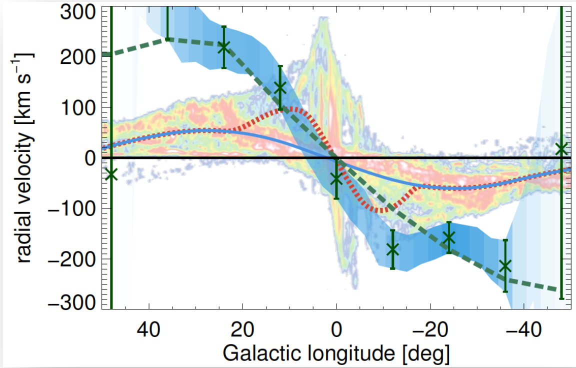
Krause & Diehl 2015



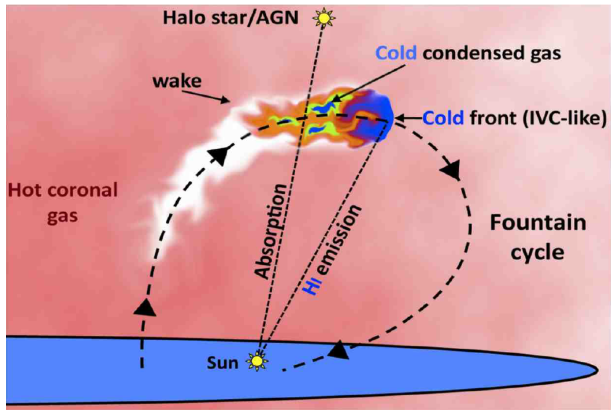
Superbubbles, HI Holes, Halo Clouds…

- ^{26}Al (=SN-Ejecta) are predominantly streaming into large superbubbles

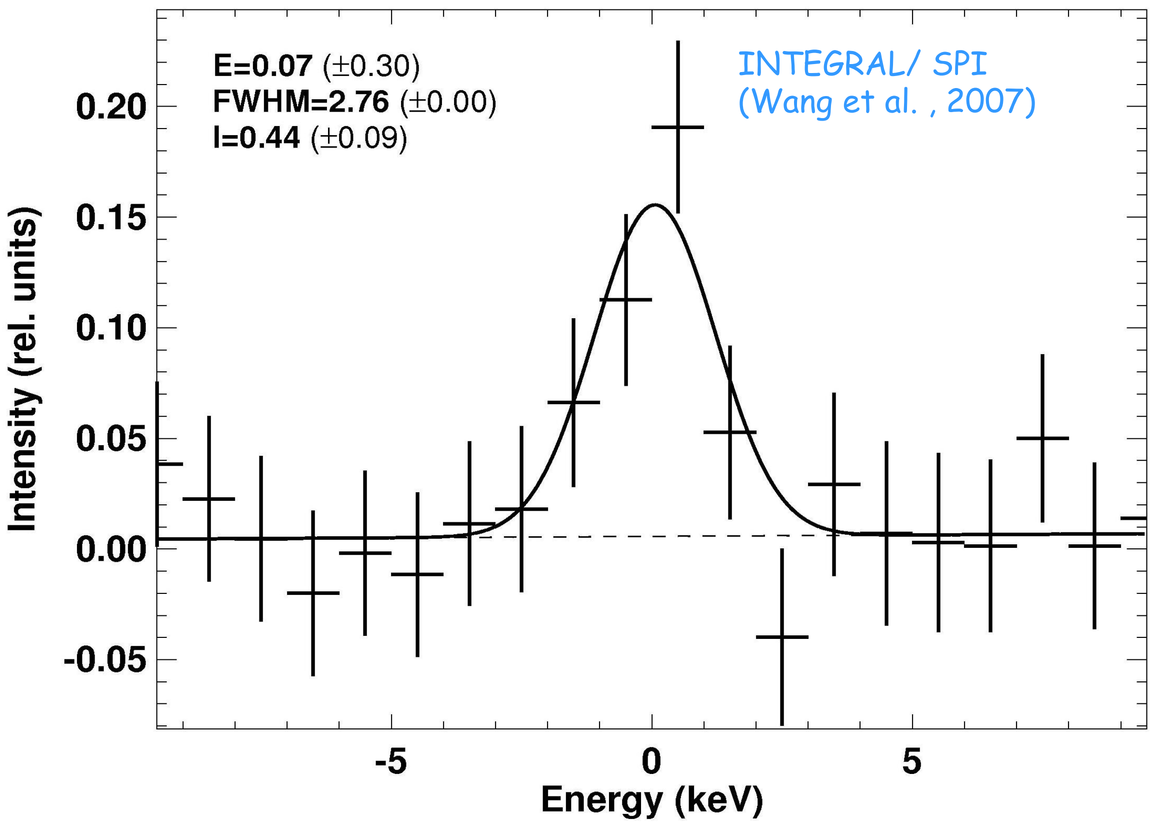


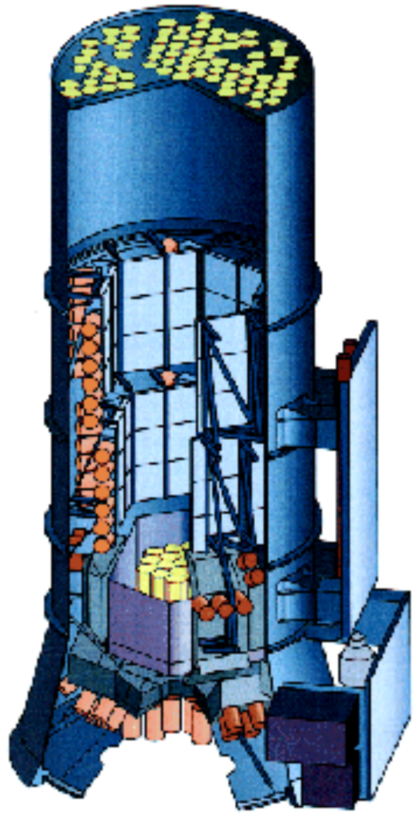


Fraternali+2015



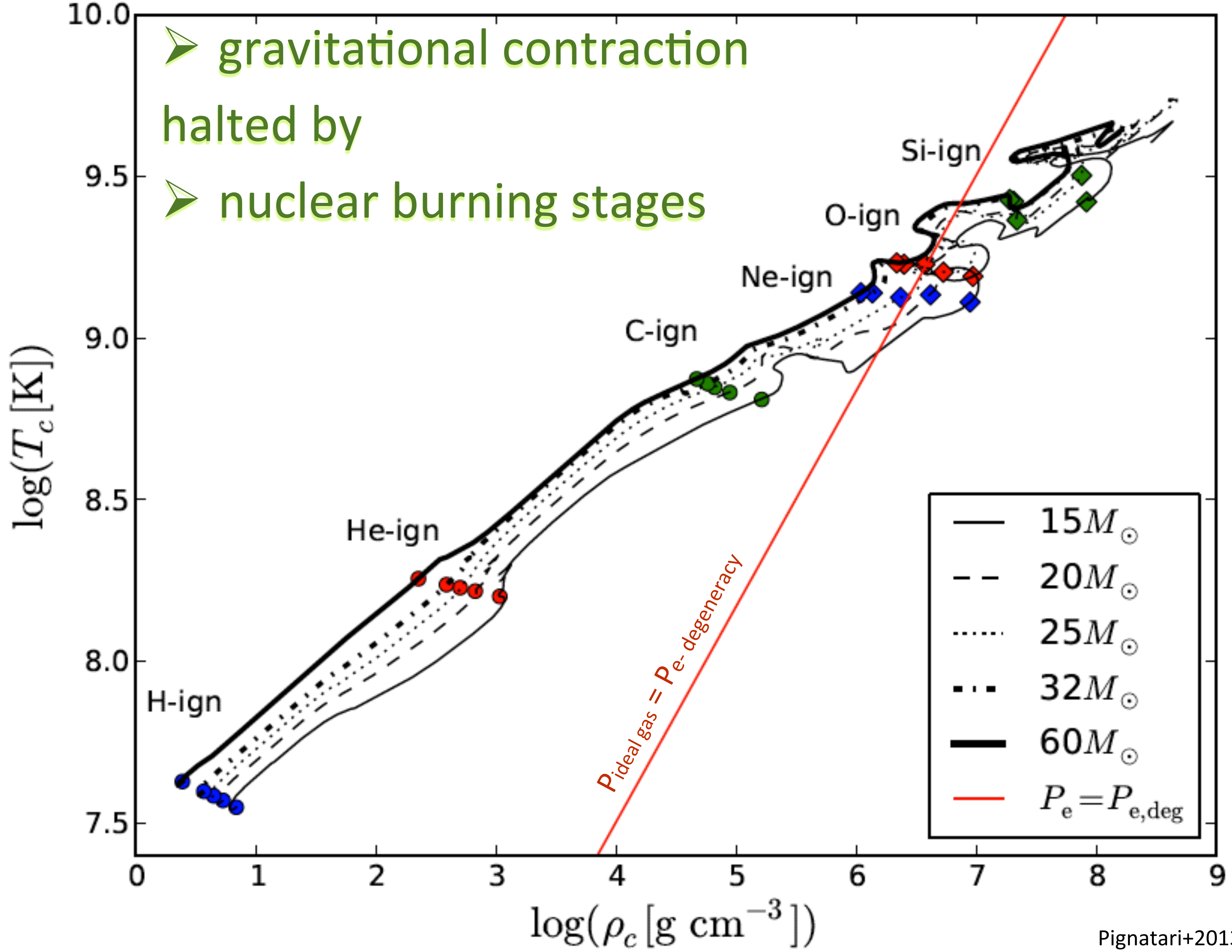
^{60}Fe Emission is Seen from the Galaxy





– Gamma-ray Signal Now Beyond 'Hints'/'Limits' (5s)
– ^{60}Fe/^{26}Al Emission Ratio ~15%

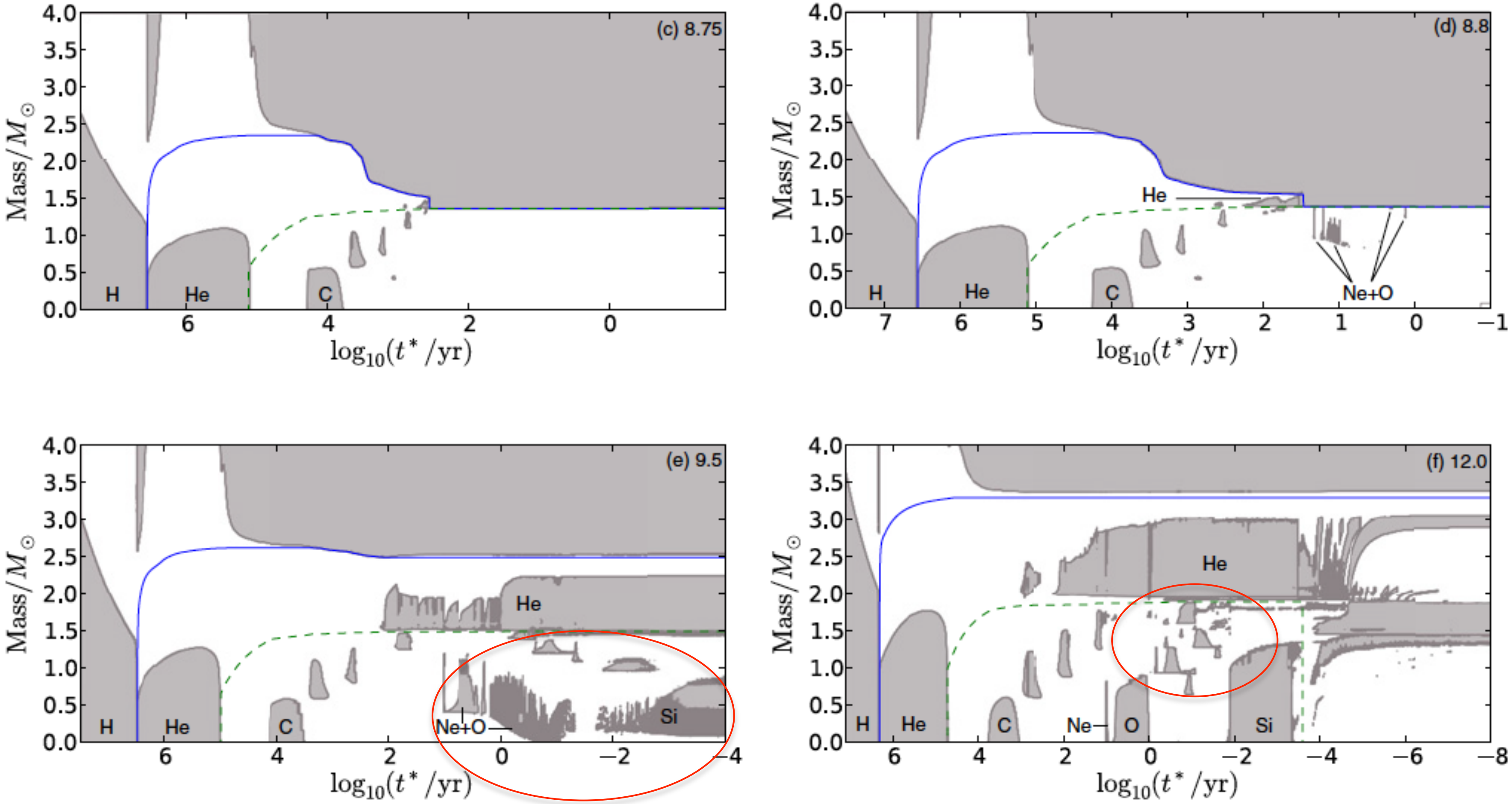
Massive Stars:
Gravitationally-confined fusion reactors



Pignatari+2013

Late burning stages

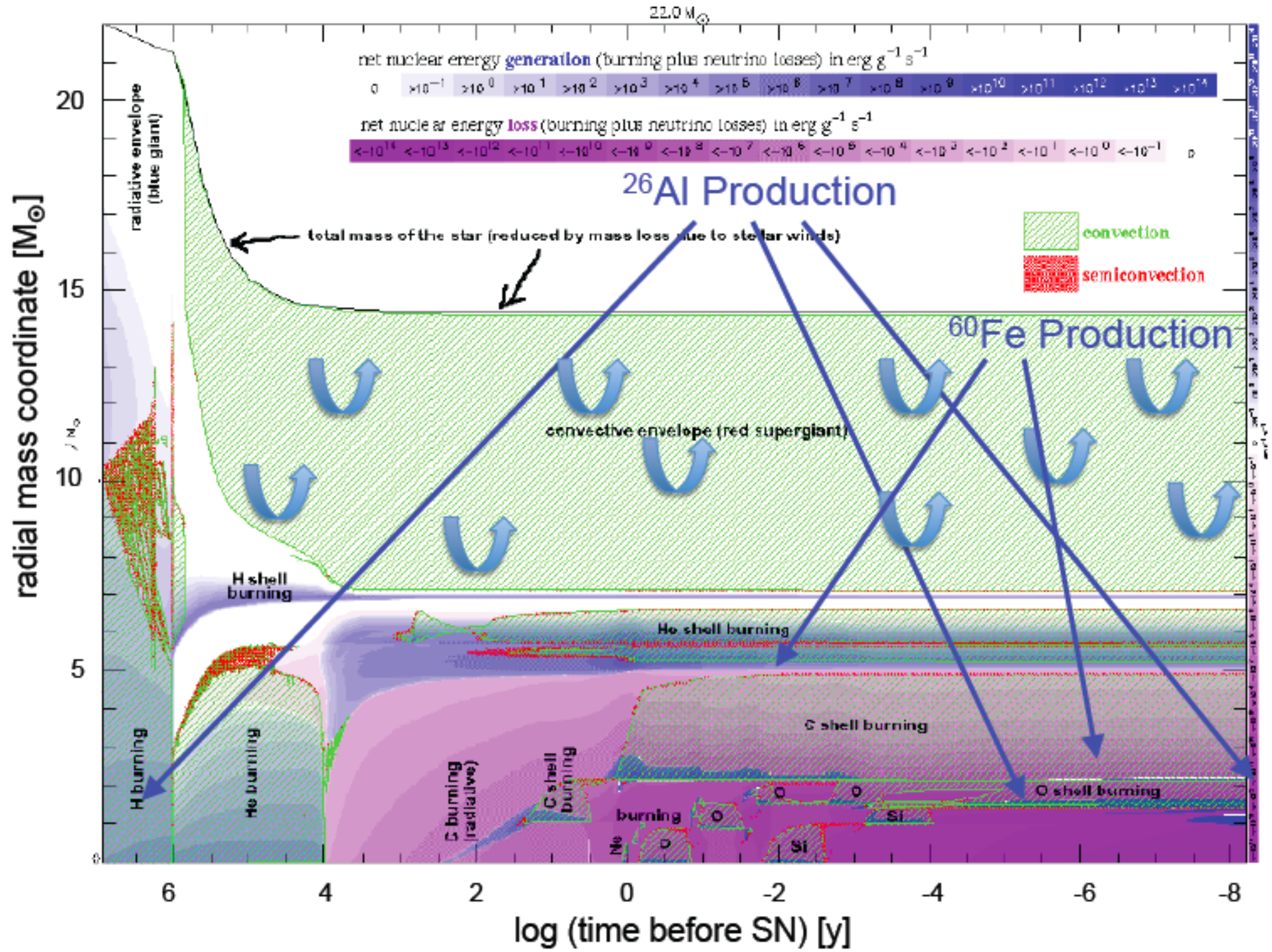
Jones+ 2013



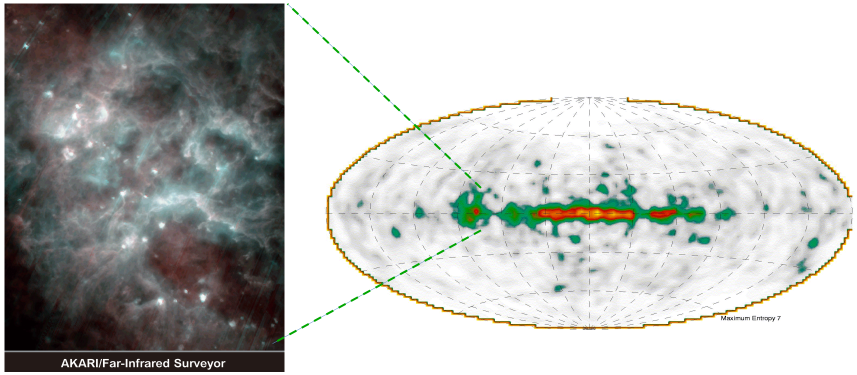
- Shell burning stages are intermittent
- Shell ignition may propagate down to core, or not

Massive-Star Structure Diagnostics: $^{60}Fe/^{26}Al$ Ratio

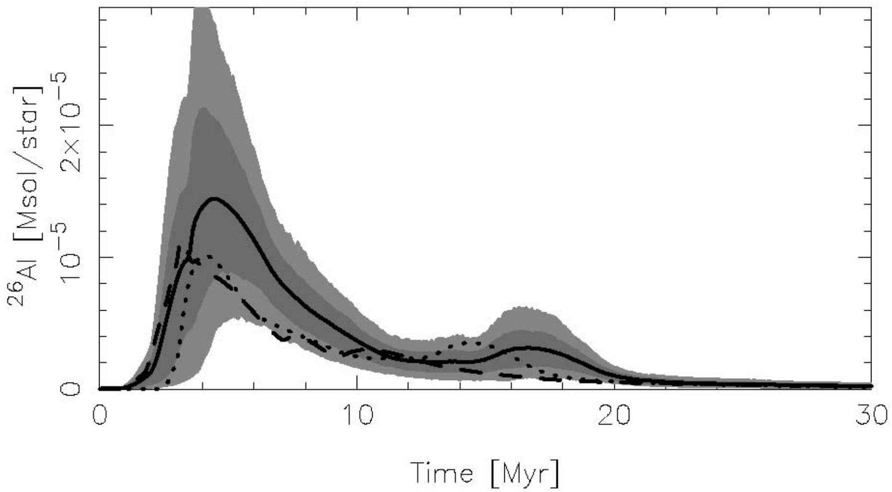
- Two Isotopes from Same Source Type → Eliminate Astronomical Bias
- Production-
  Site Detail
  (adapted from Heger)

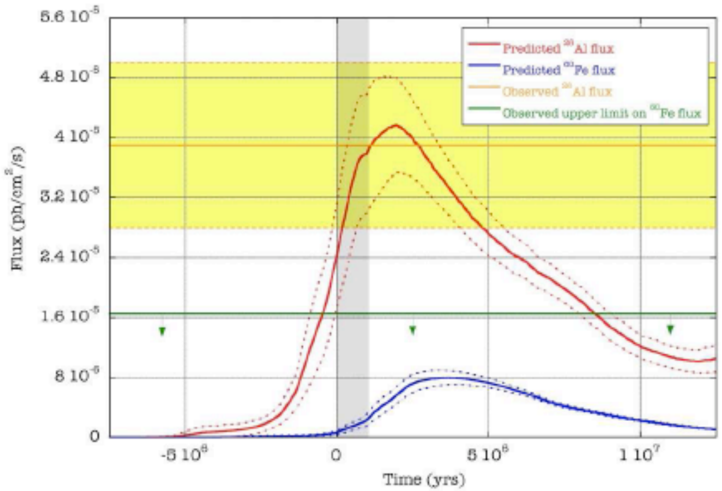


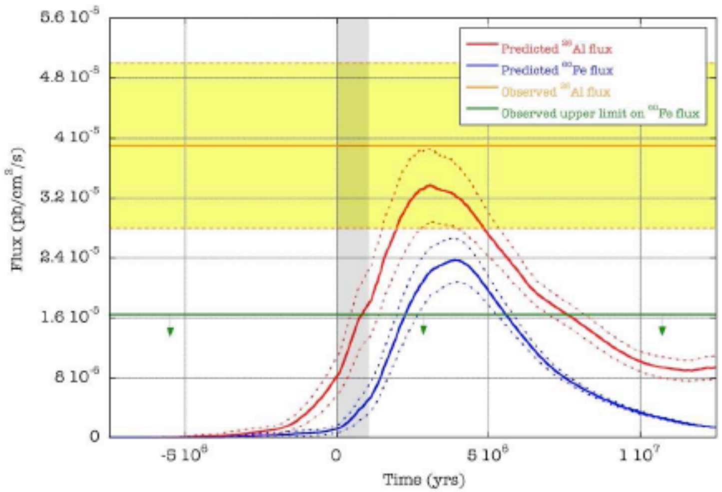
Testing our Models: Cygnus at its Specific Age and Metallicity



- Population Synthesis Application to Cygnus Region
    - Models for Solar Metallicity ~OK
    - If Lower Metallicity: Underprediction?
    - *Martin+ 2010*



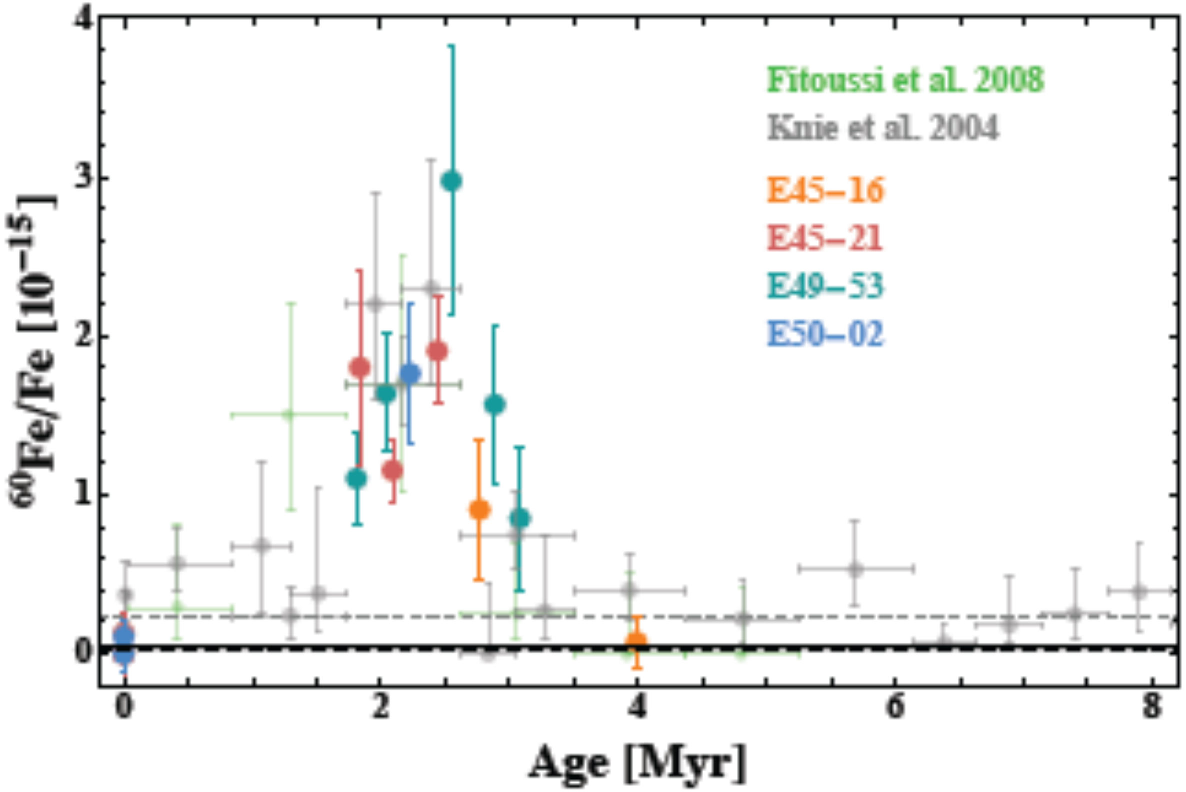




SN Ejecta Nearby: Transport in ISM

- ^{60}Fe Clearly Seen in Oceanfloor (and Lunar) Samples from SN ~2-3 My ago
  - Compare oceancrust and sediments *(Feige2014)*

Knie et al. 2004; Fitousi et al. 2008; Feige 2014; Fimiani et al. 2015



^{60}Fe on Earth: The Origins

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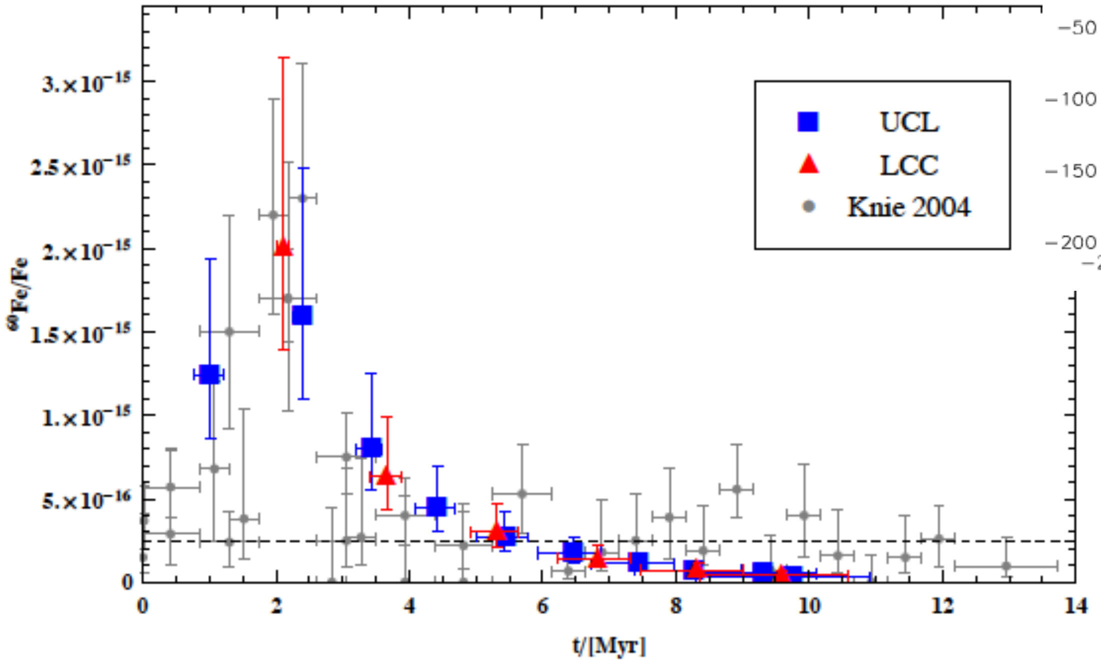
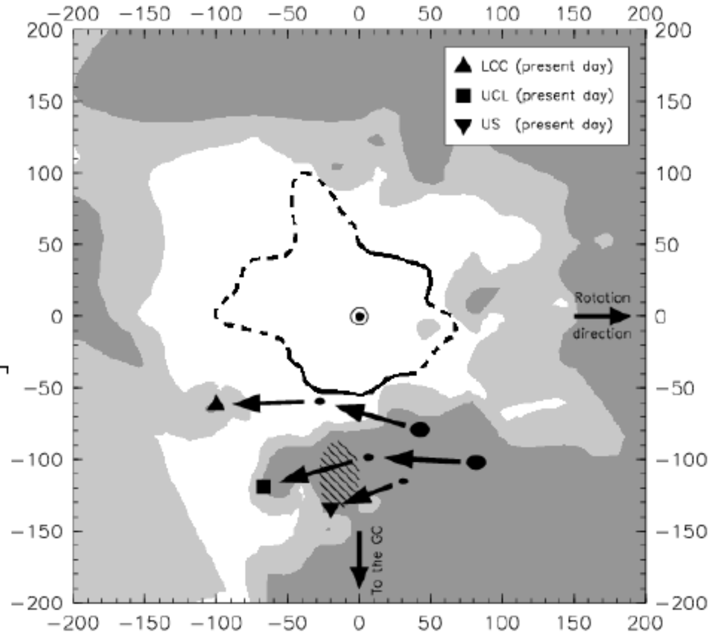
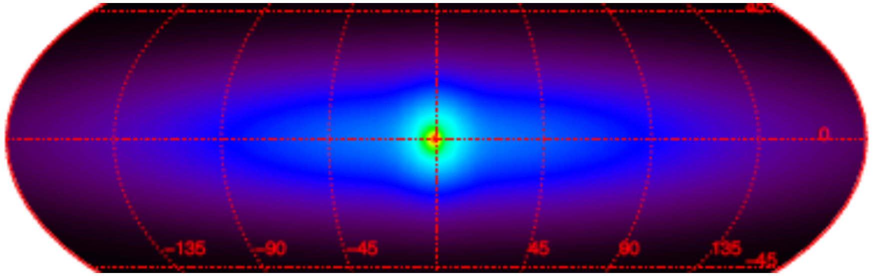


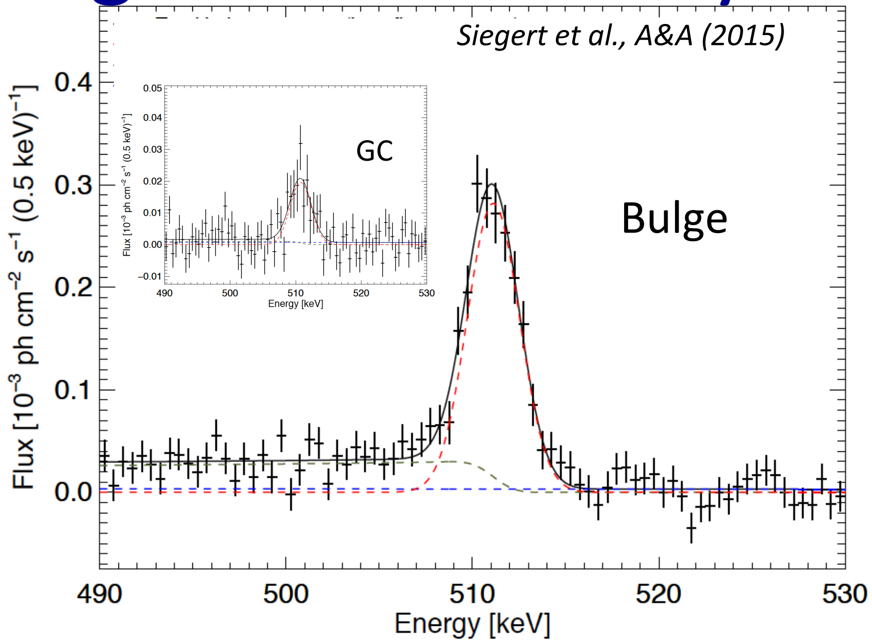


The computed data (UCL: blue, LCC: red) plotted over the ^{60}Fe measurements (black points) with an ISM density of $n = 1$ atom/cm^3.

Feige; *The connection between the Local Bubble and the ^{60}Fe anomaly in the deep sea hydrogenetic ferromanganese crust*, Magisterarbeit, Universität Wien, 2010

Positrons annihilate throughout the Galaxy

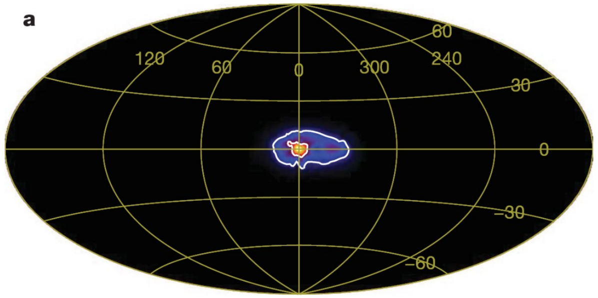




Why is only the bulge so bright?

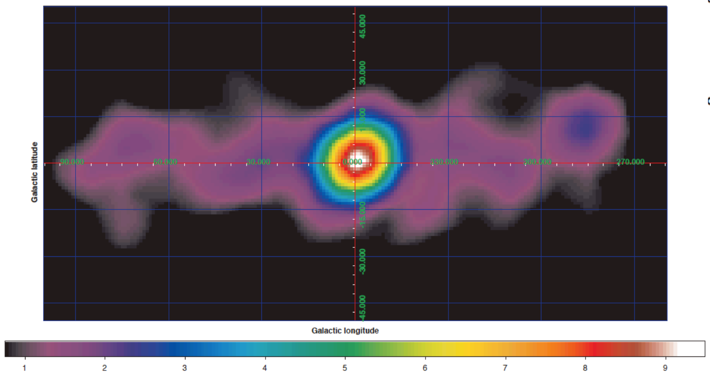
- Earlier imaging results:

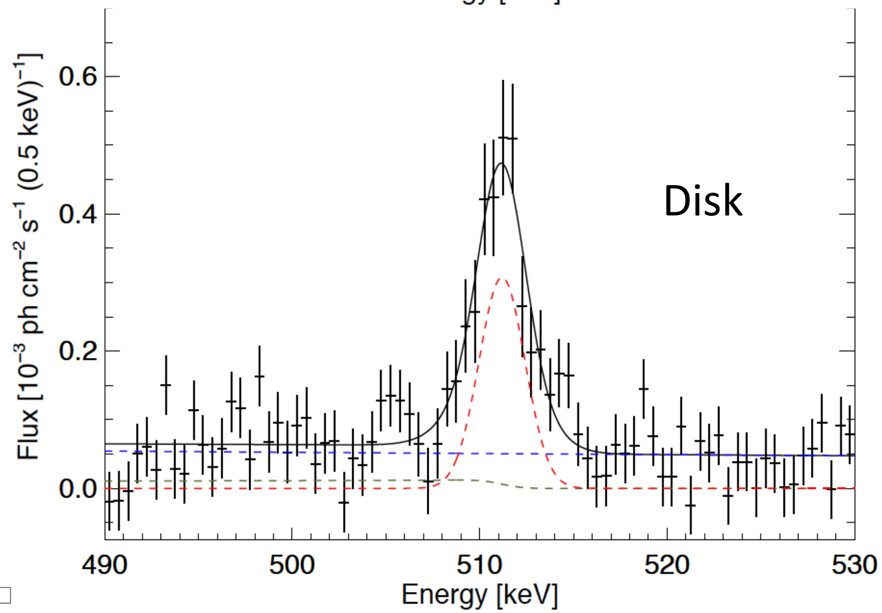
a



asymmetric, XRBs?

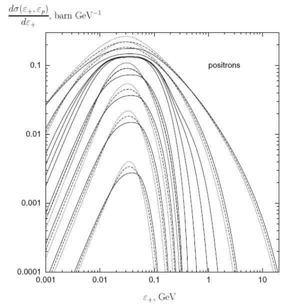
» Slightly offset & extended





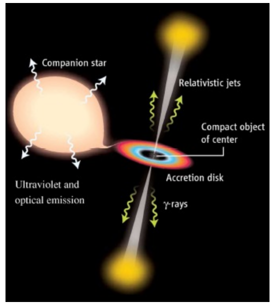
The Sources of Positrons throughout the Galaxy

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



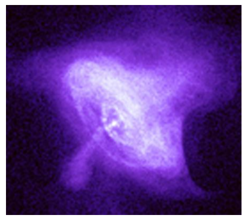
- Pairs from Hot Plasma
  - Sources: Accreting Binaries
  - Positron Energies: ~MeV

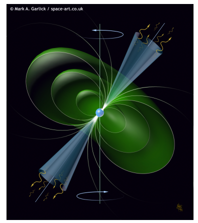
  T>100 keV (E_{thr}=1.02 MeV)



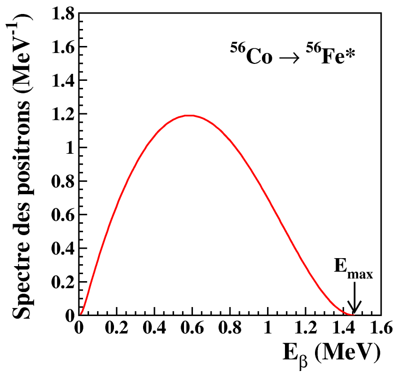
- Pairs from Strong Magnetic Fields
  - Sources: Pulsars, Magnetars
  - Positron Energies: ~MeV…GeV

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





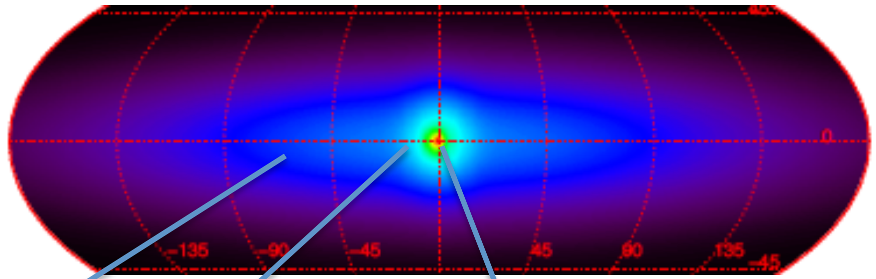
- Radioactive Nuclei
  - Sources: Supernovae, Novae, Cosmic Rays & ISM
  - Positron Energies: ~MeV

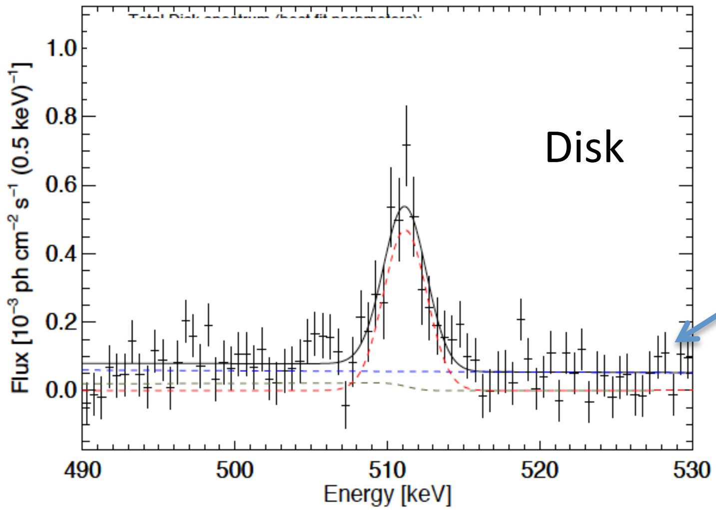


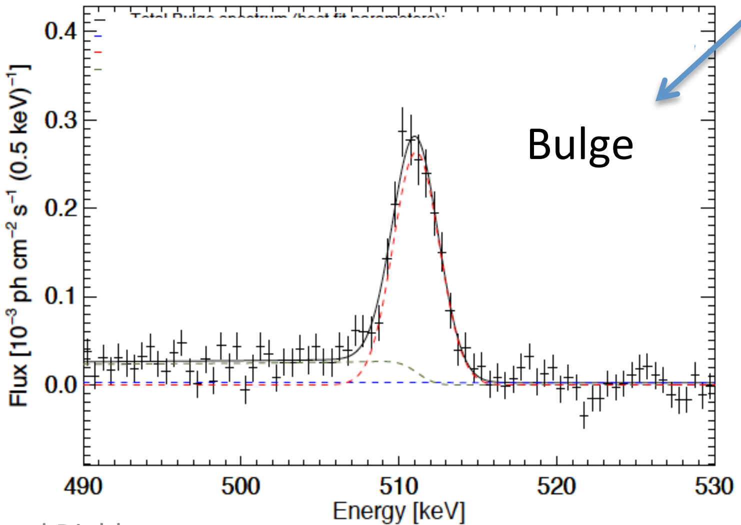
Insights from spectral details?

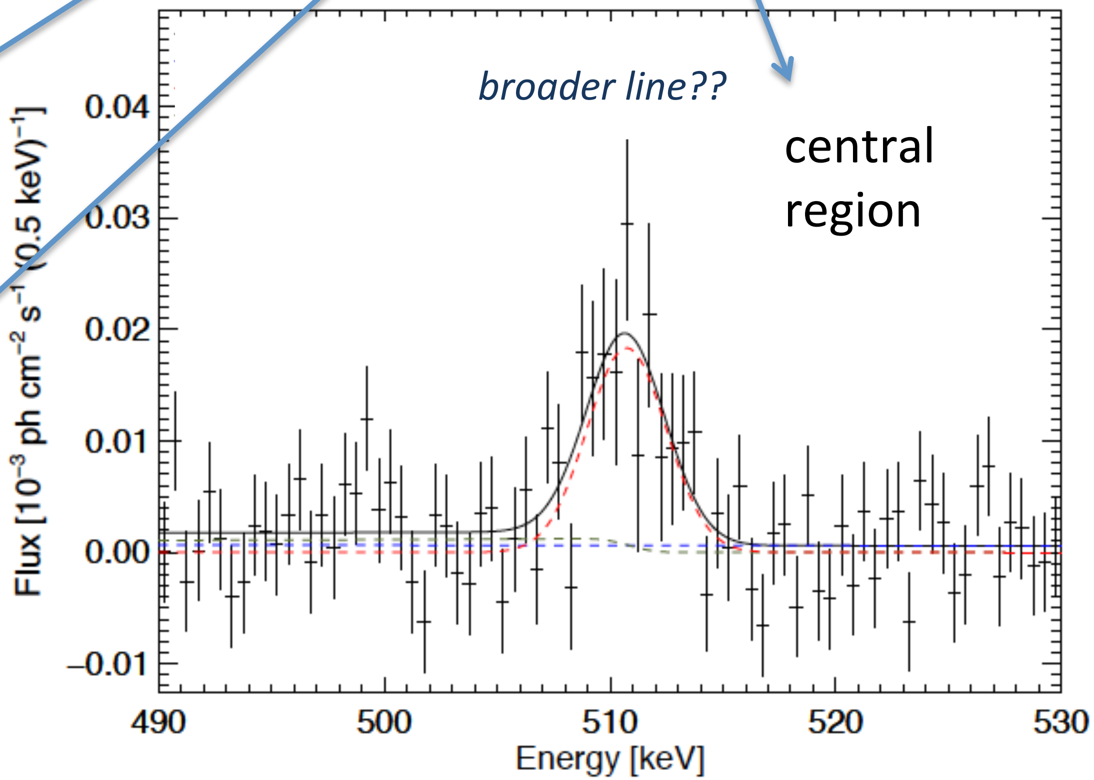
– Derive/discriminate spectra from different regions

Siegert et al. (2015)



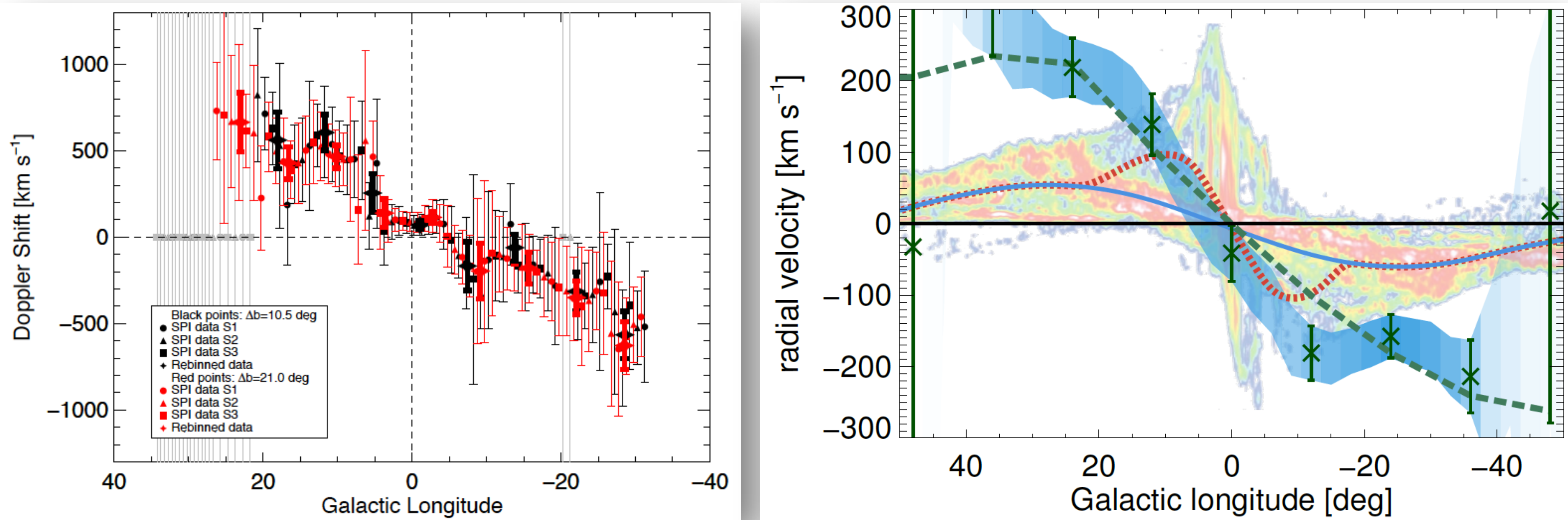






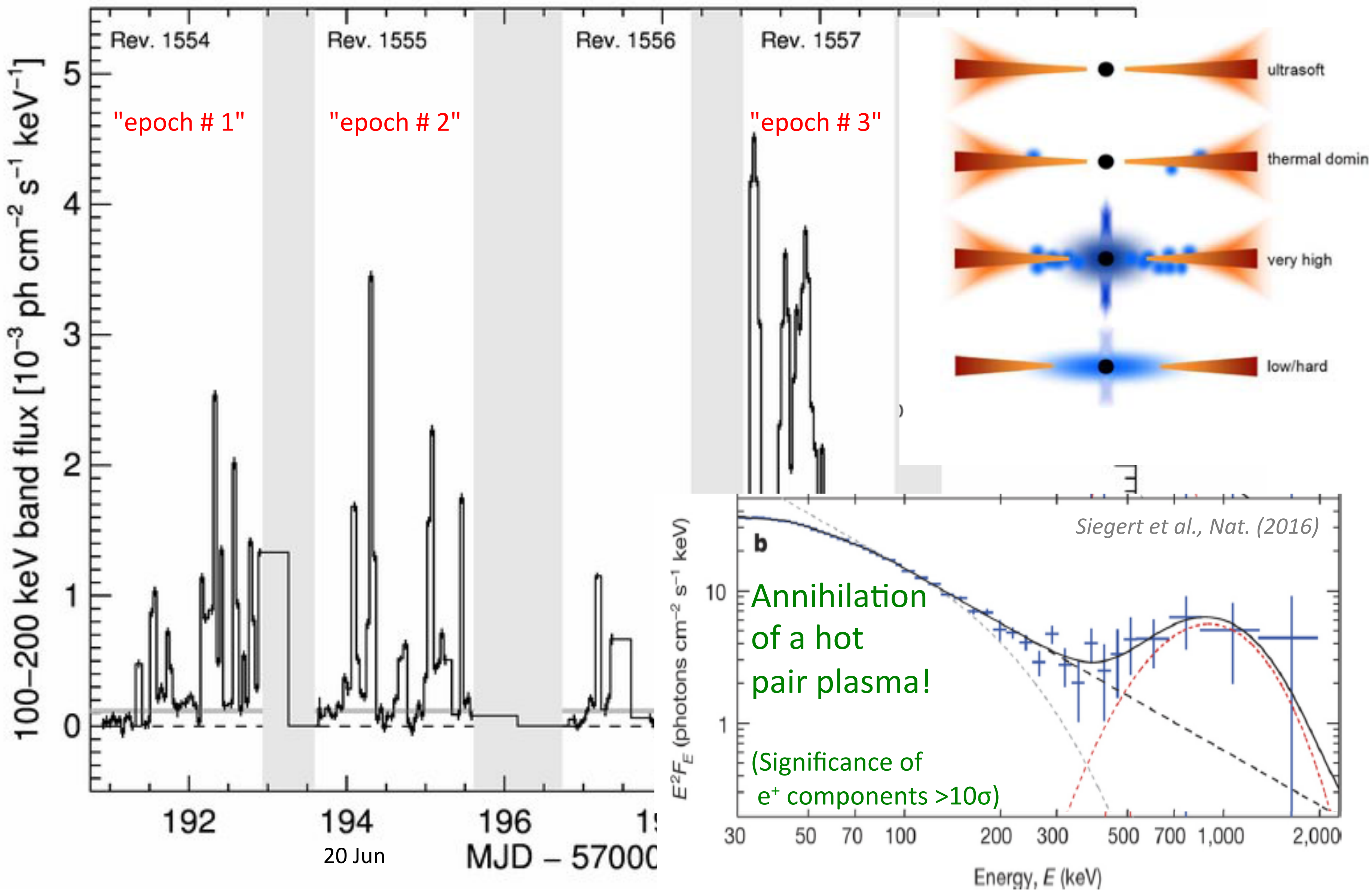
511 keV emission from positron annihilation

- Velocity trends with Galactic longitude:

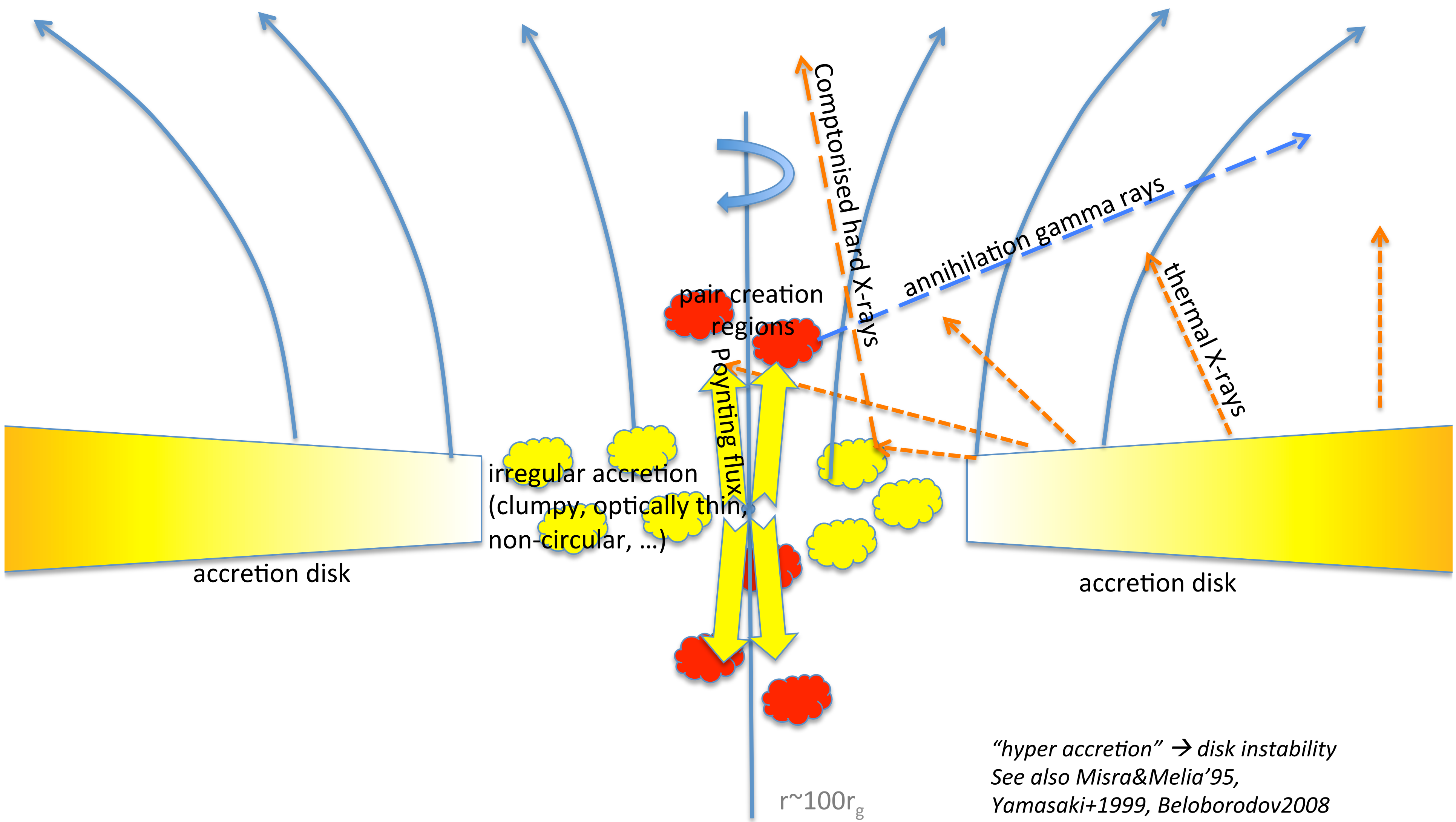


Siegert & Diehl, in prep. (2017)

Flaring Period of V404 Cyg Jun 2015 → e⁺!



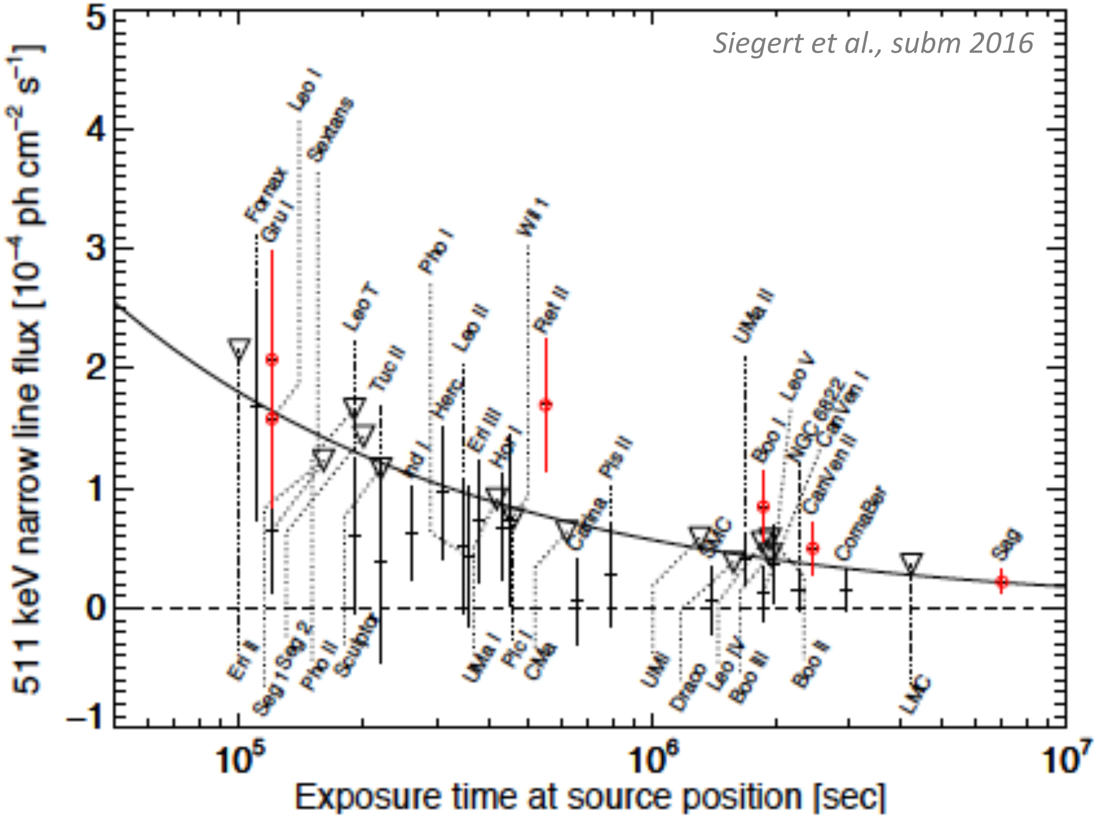
BH accretion: Pair plasma outflow scenario



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

Dark Matter / 511 keV Correlation?

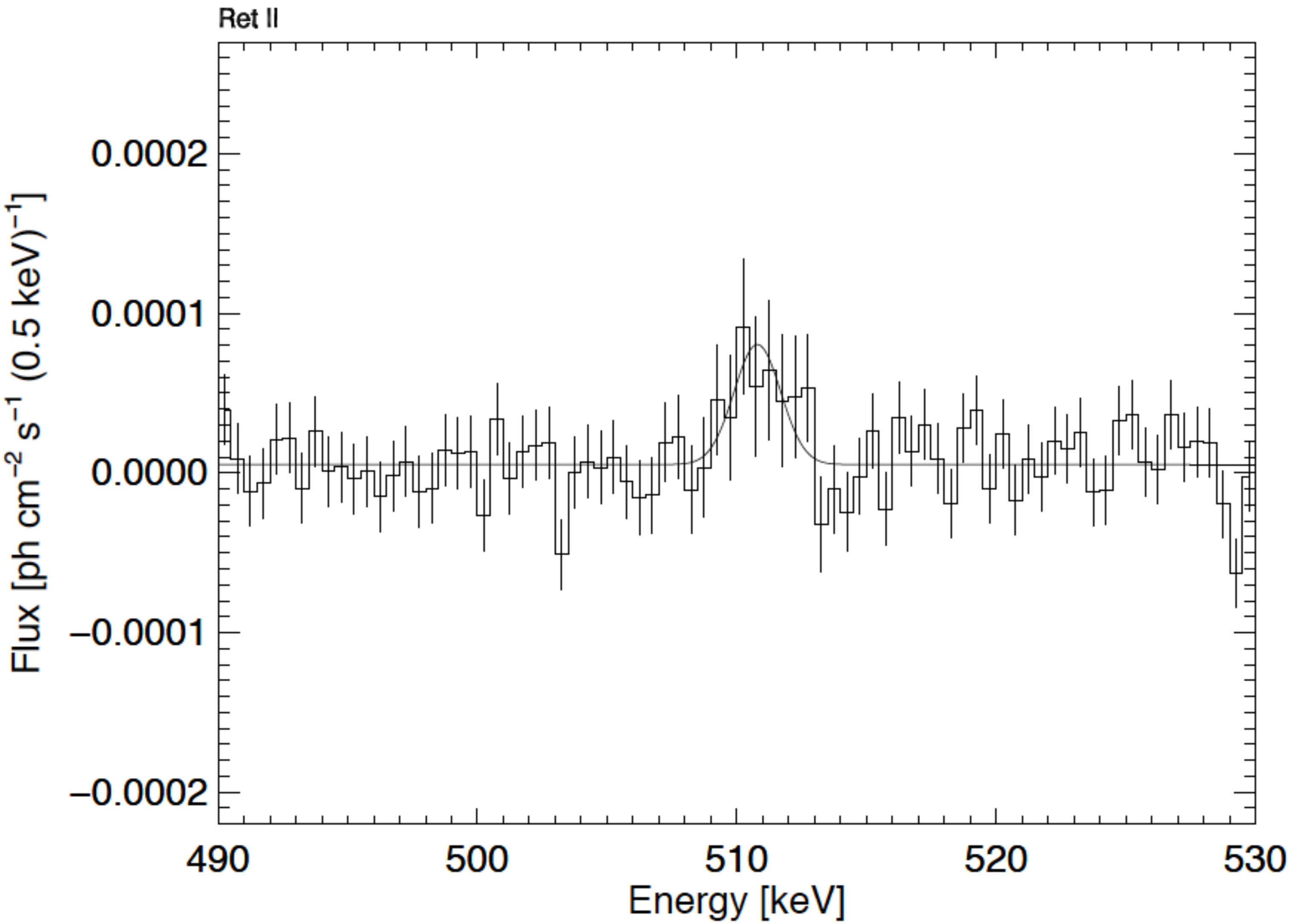
Search for 511 keV emission in nearby dSph galaxies



No significant & consistent detections → DM not a e^+ source

- Ret II 3σ detection! → these are stellar-production e^+

Annihilation gamma rays from Ret II?



- eAstrogam will/must open the extragalactic domain

How Supernovae Explode…

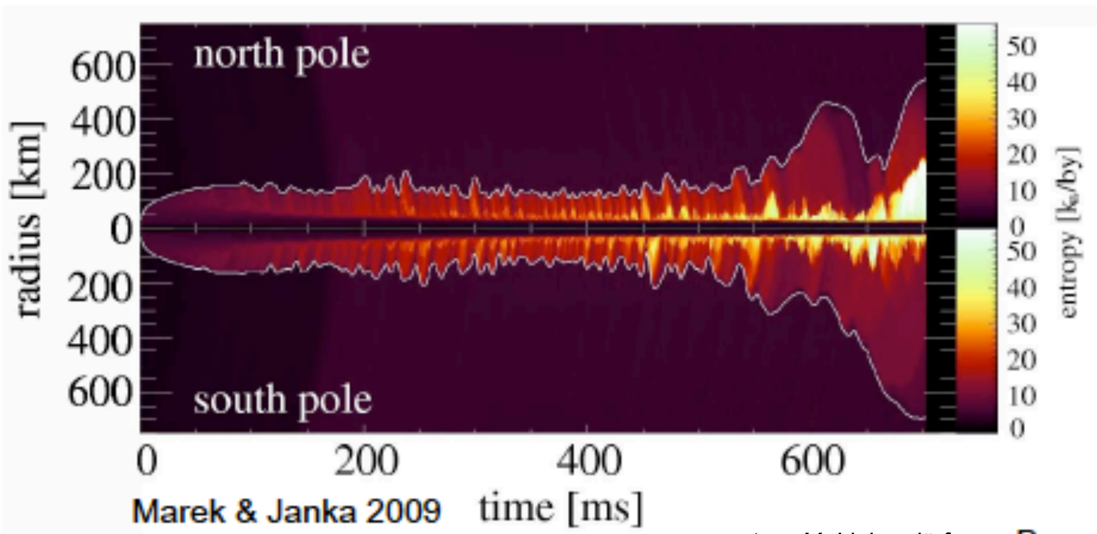
- Core collapse
- Thermonuclear
- SLSNe, PISNe, …

Modelling ccSNe

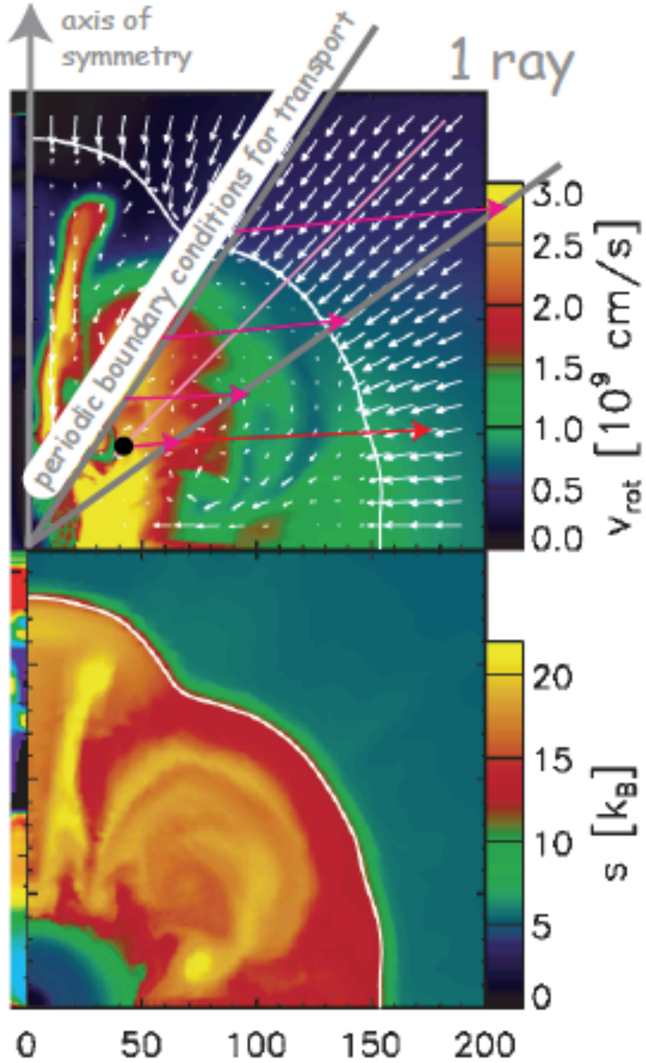
- Neutrino Transport as a Key

Ray-by-ray approach
(still computationally expensive -->
only few runs available)

- Standing Accretion Shock Instability (SASI) perturbs shock radius
- Extended postbounce phase before weak explosion for 11 Ms and 15 Ms models



Marek & Janka 2009

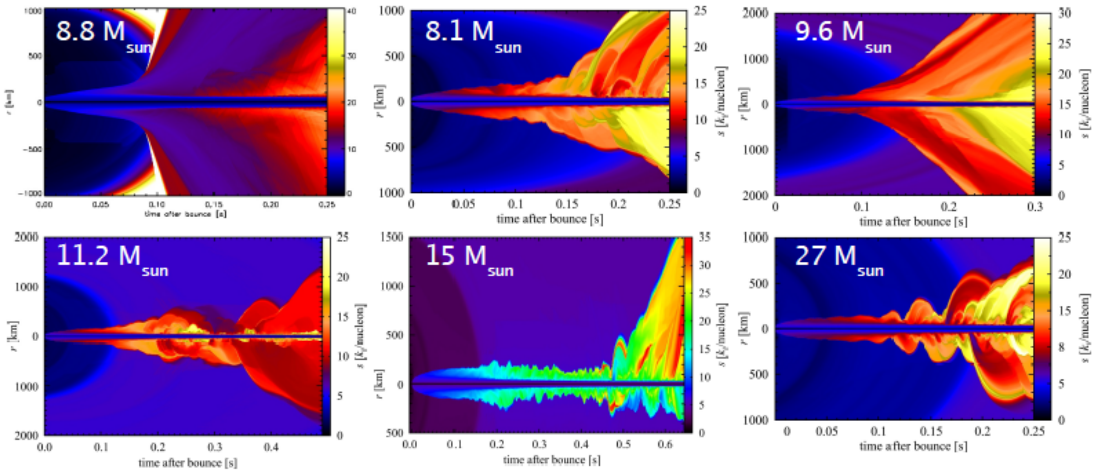


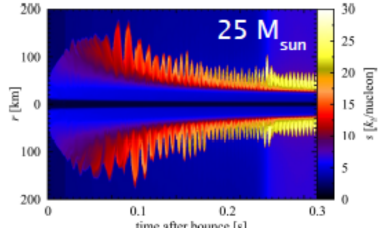
courtesy M. Liebendörfer

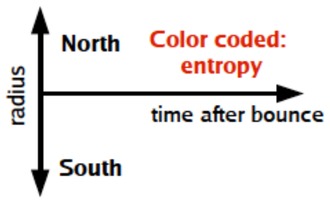
Buras et al. 2003 (s15r at 198 ms)

Core-Collapses: Supernova Explosions (?)

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

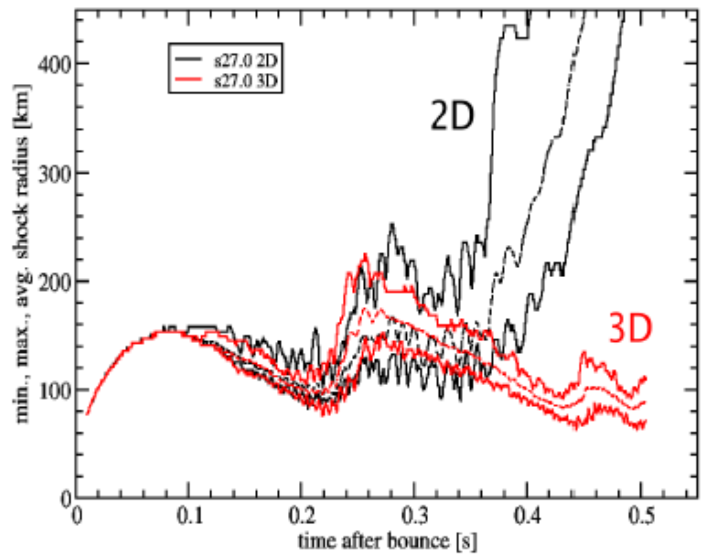






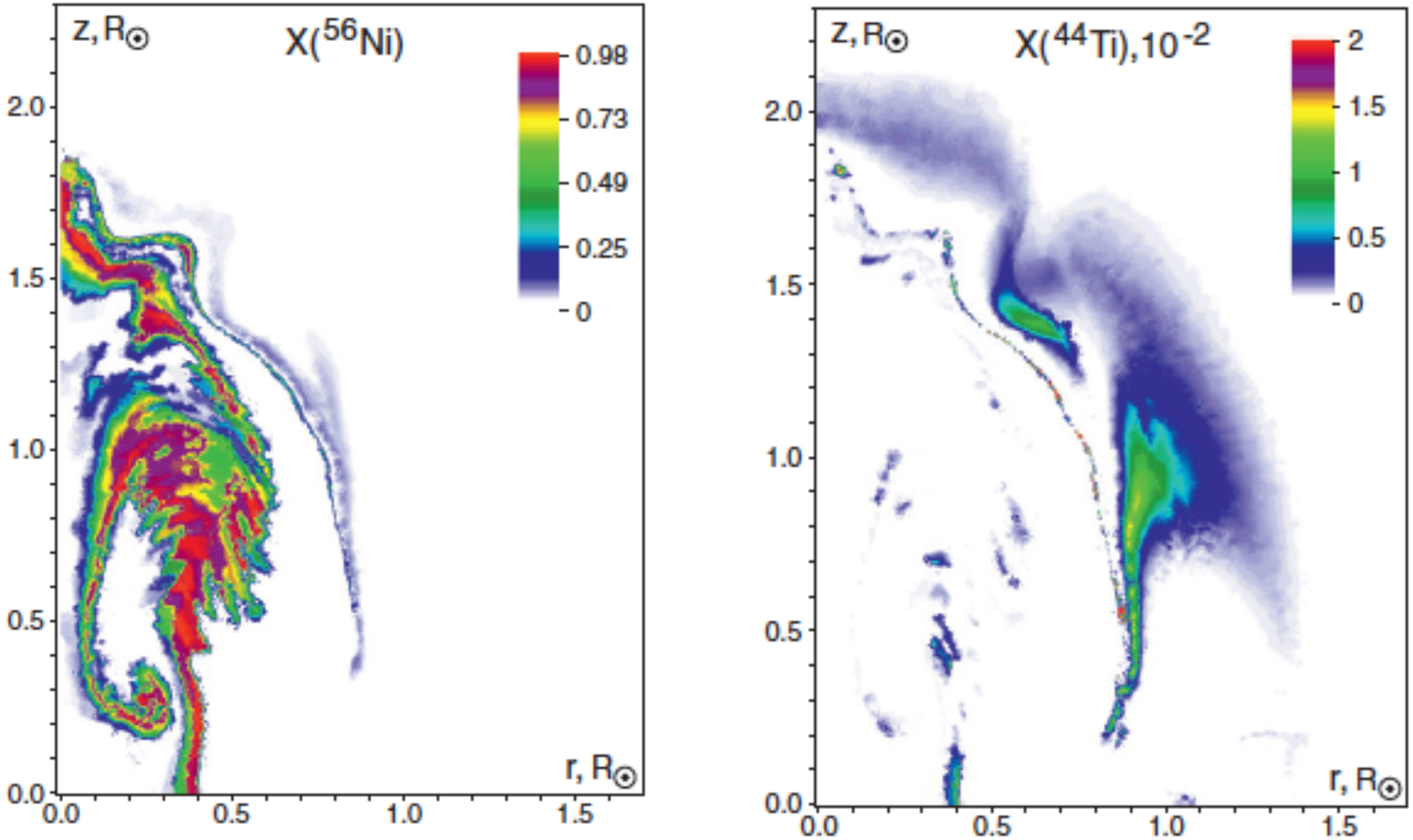
Bernhard Müller, THJ, et al. (ApJ 756, ApJ 761, arXiv:1210.6984

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



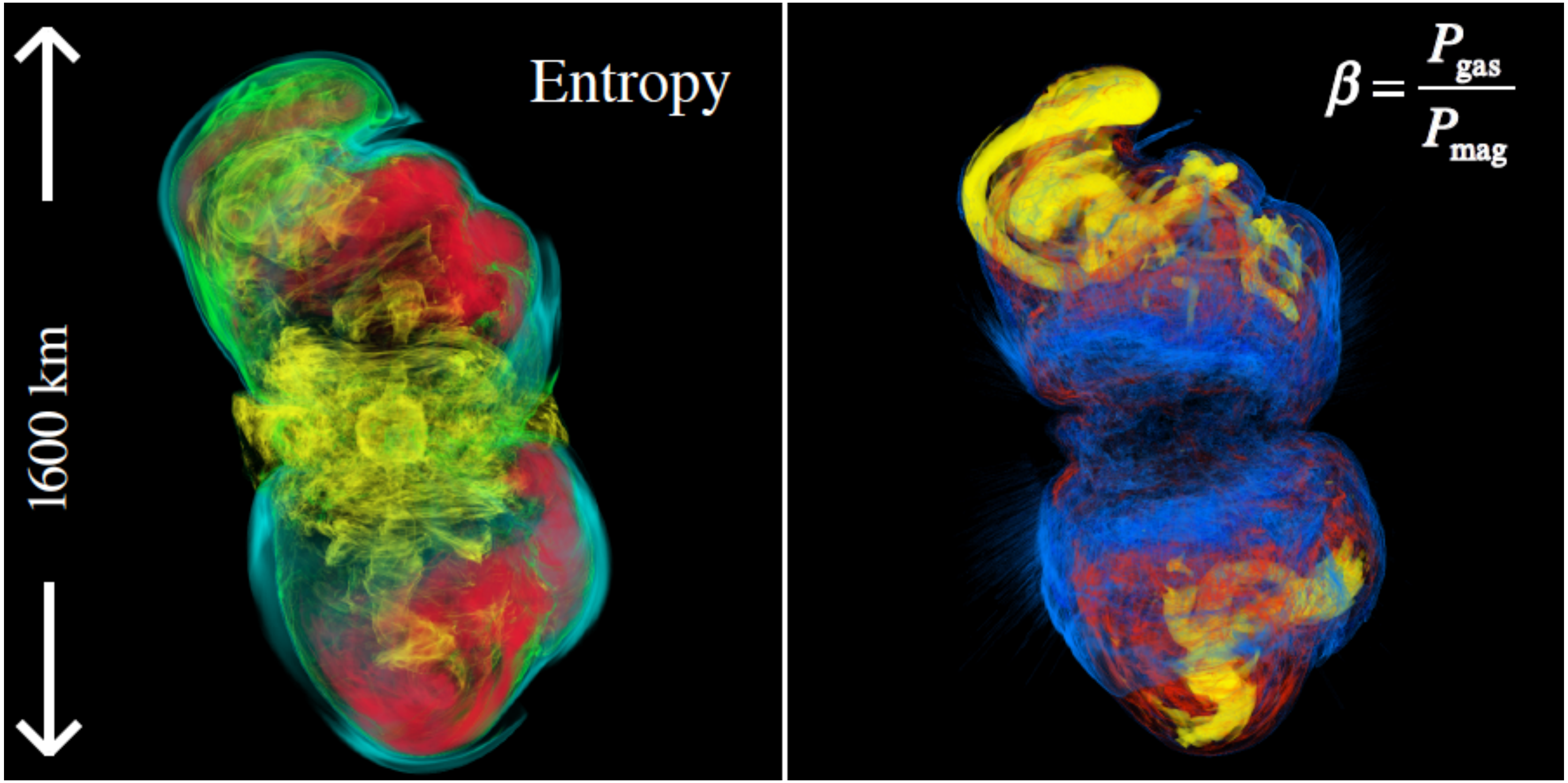
Asymmetric Supernova Explosions

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



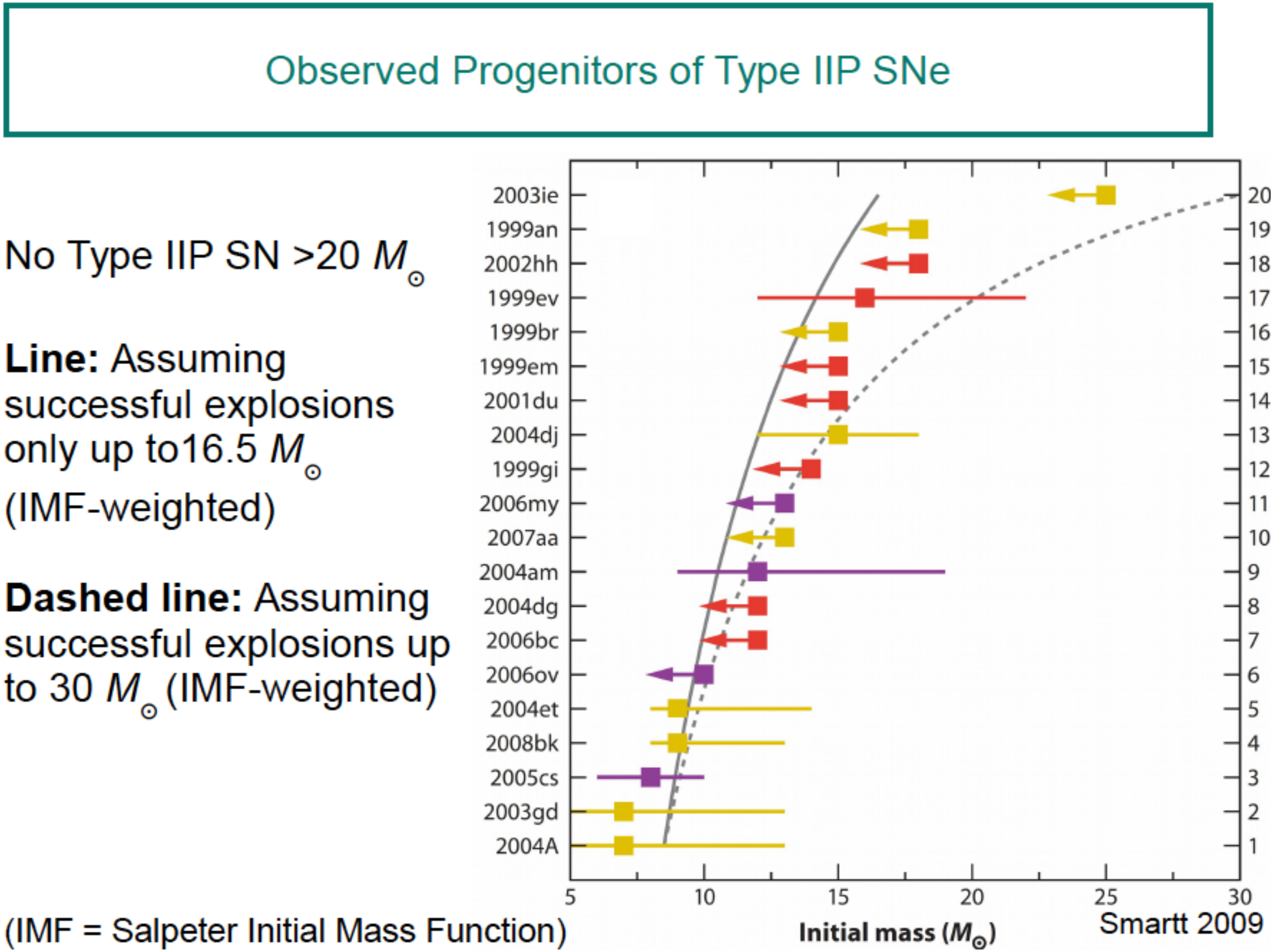
Core Collapse of Magnetized Plasma

- Magnetic Field Compression as Energy Source
  - *Mösta et al. 2014*



- Winding up magnetic fields during core collapse → ejection of inner material

ccSNe: Which mass range of massive stars?



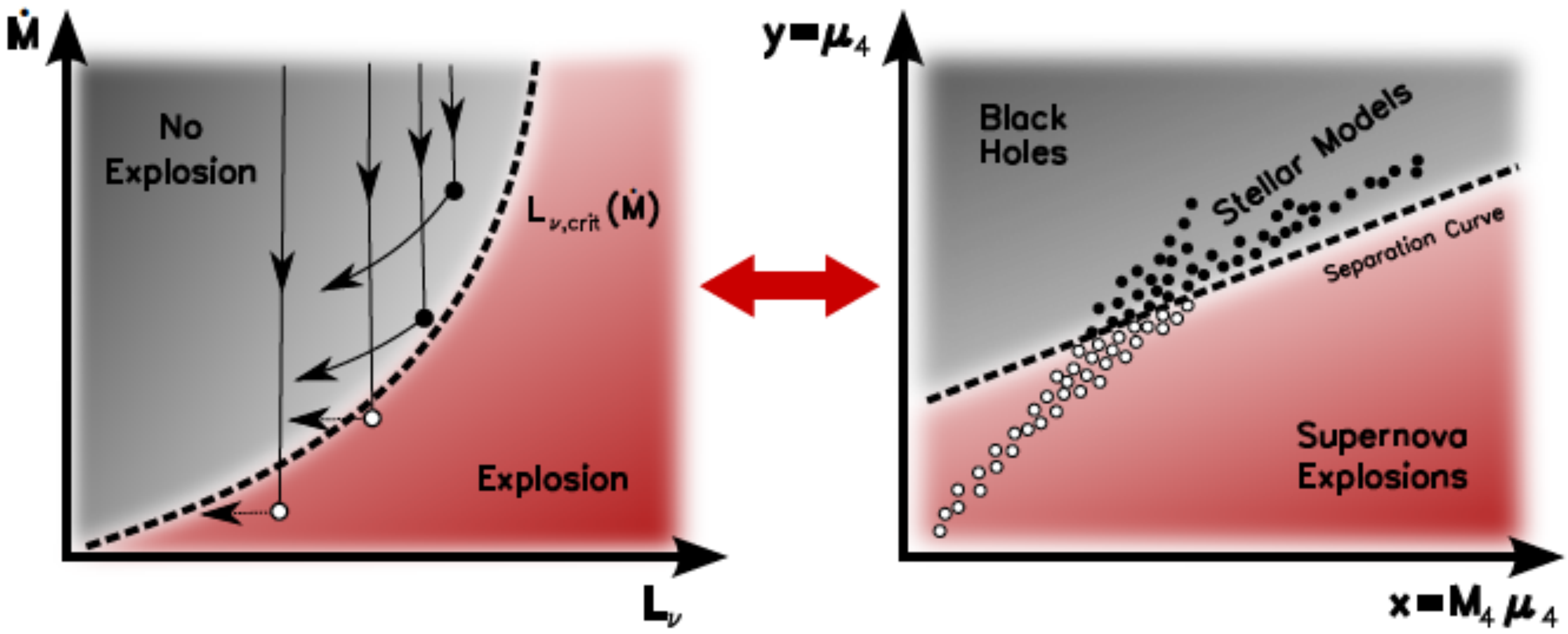
- No Type IIP SN >20 $M_\odot$
- **Line:** Assuming successful explosions only up to16.5 $M_\odot$ (IMF-weighted)
- **Dashed line:** Assuming successful explosions up to 30 $M_\odot$ (IMF-weighted)

(IMF = Salpeter Initial Mass Function)

Systematics across mass range

→ *T. Ertl et al. 2015*

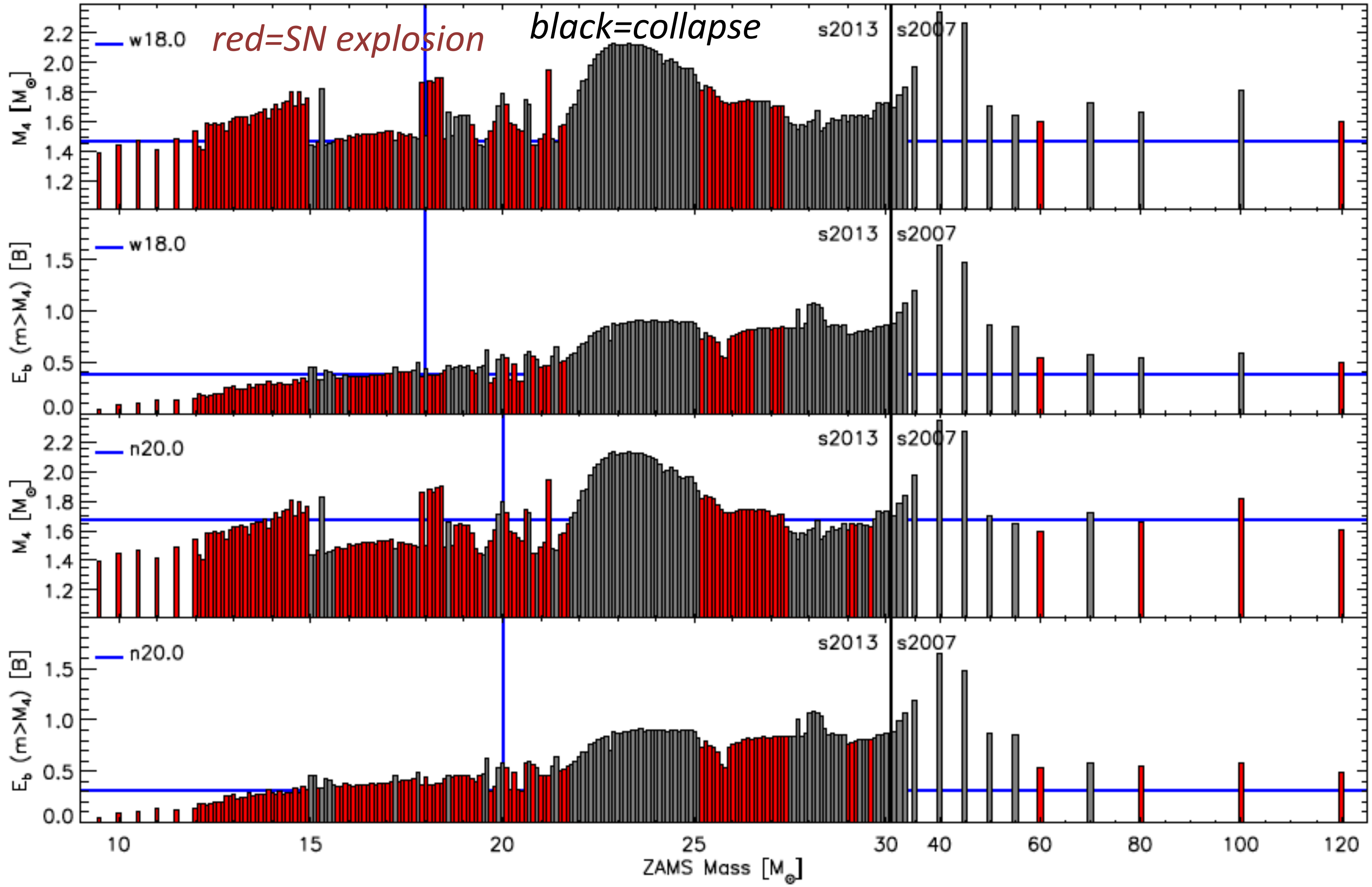
- Parametrization of the explosion process
  - 1D model for time dependent neutrino source
  - Energy deposition (bomb, piston)
- Study outcomes as they differ with progenitor mass



Systematics across mass range

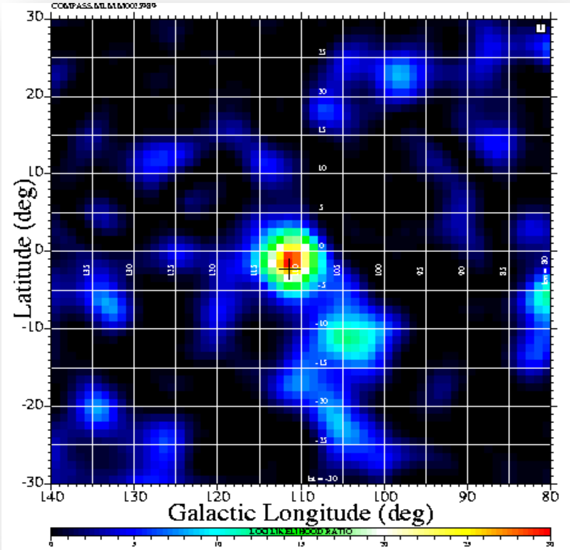
- "Explodability" : understanding systematics

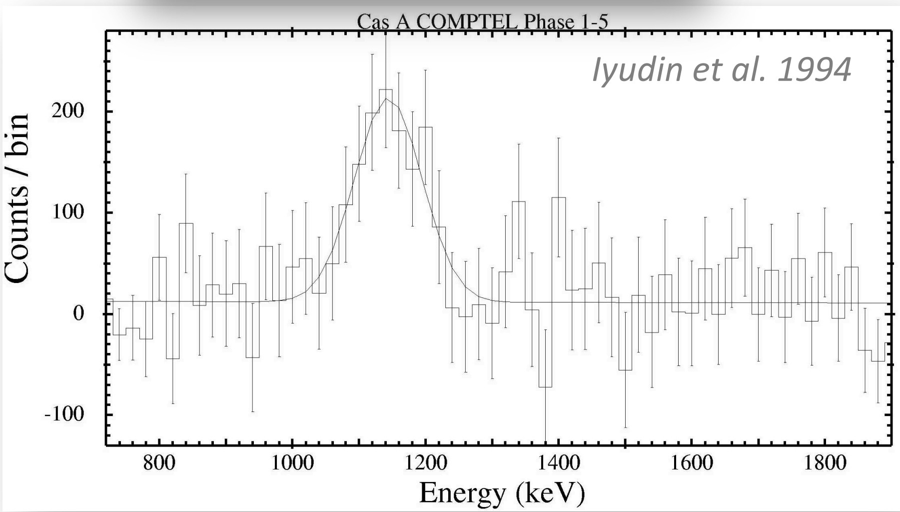
Ertl+ 2015; Sukhbold+2015

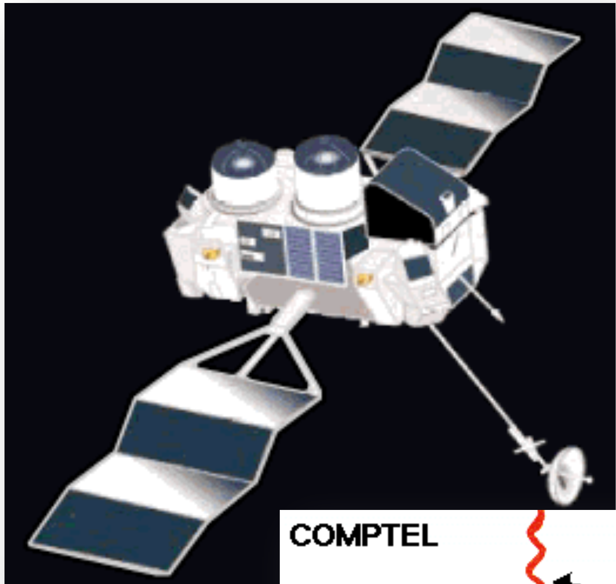


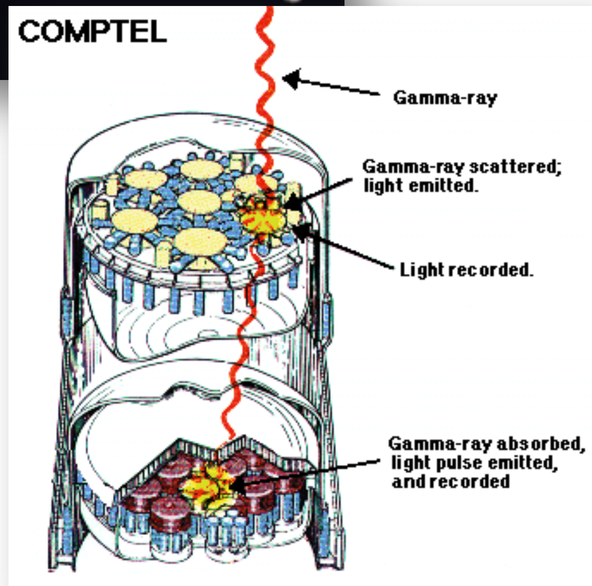
Discovery of ^{44}Ti from Cas A

- COMPTEL on the Compton Gamma Ray Observatory

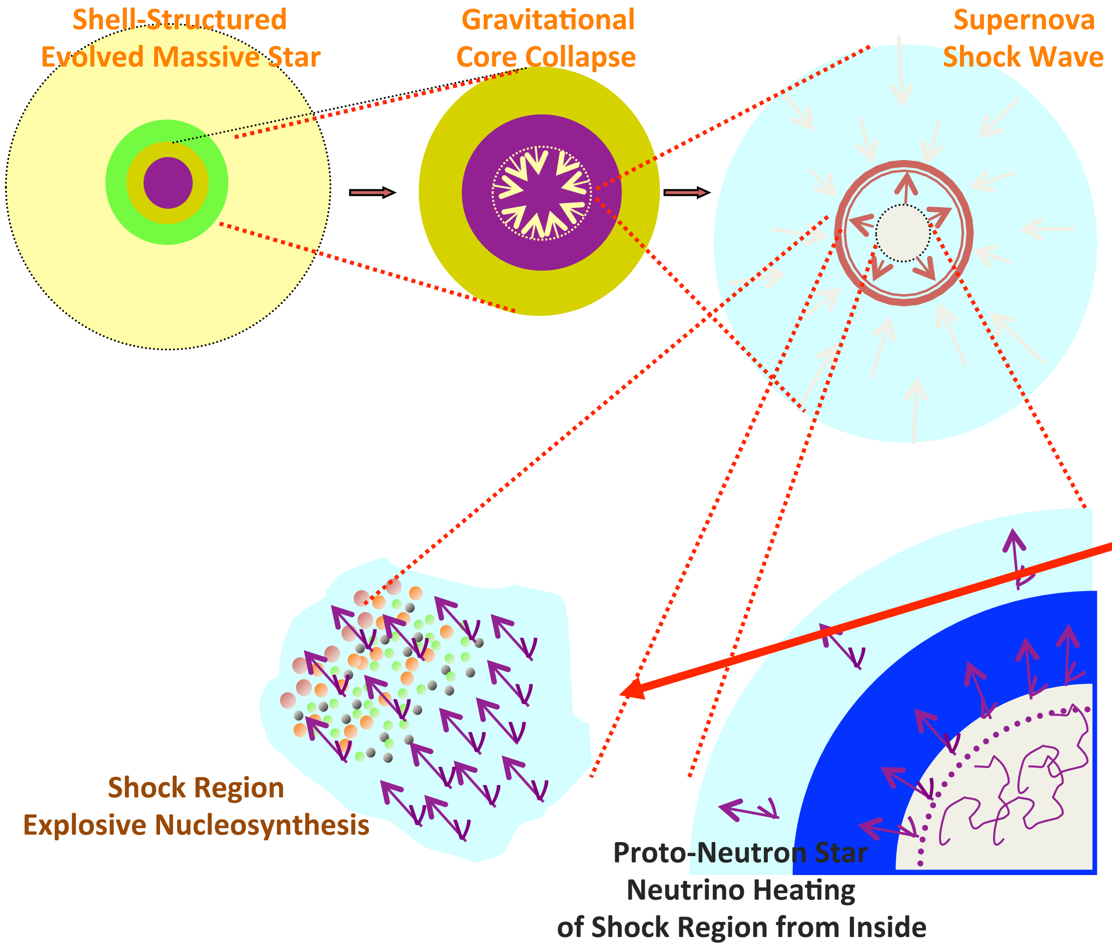


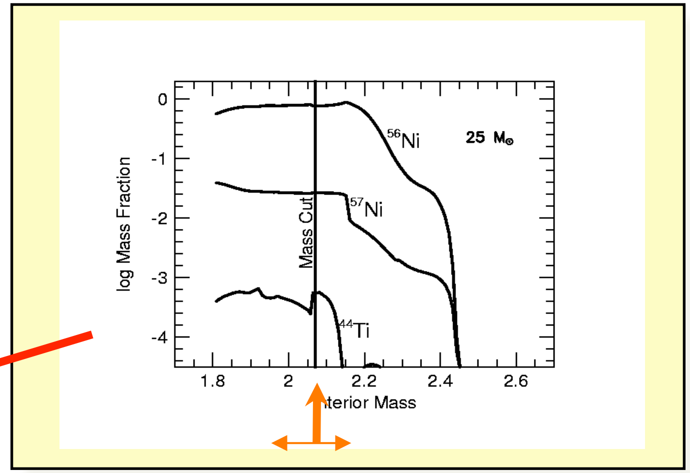


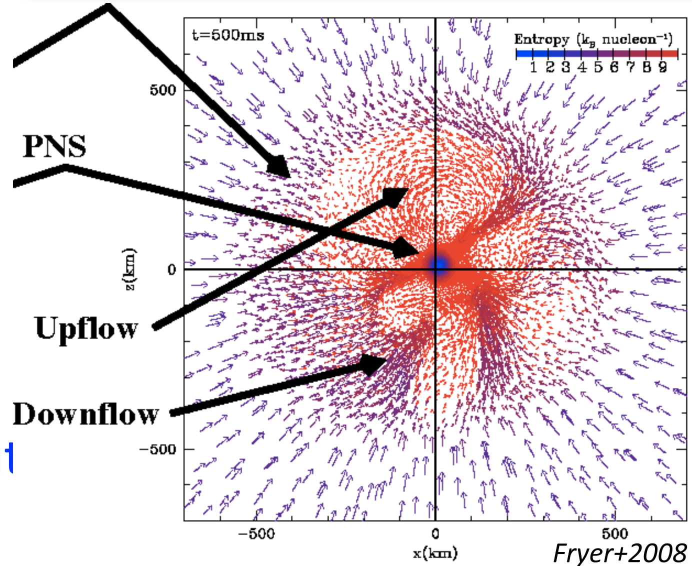




Nucleosynthesis in CC-Supernova Models and ^{44}Ti





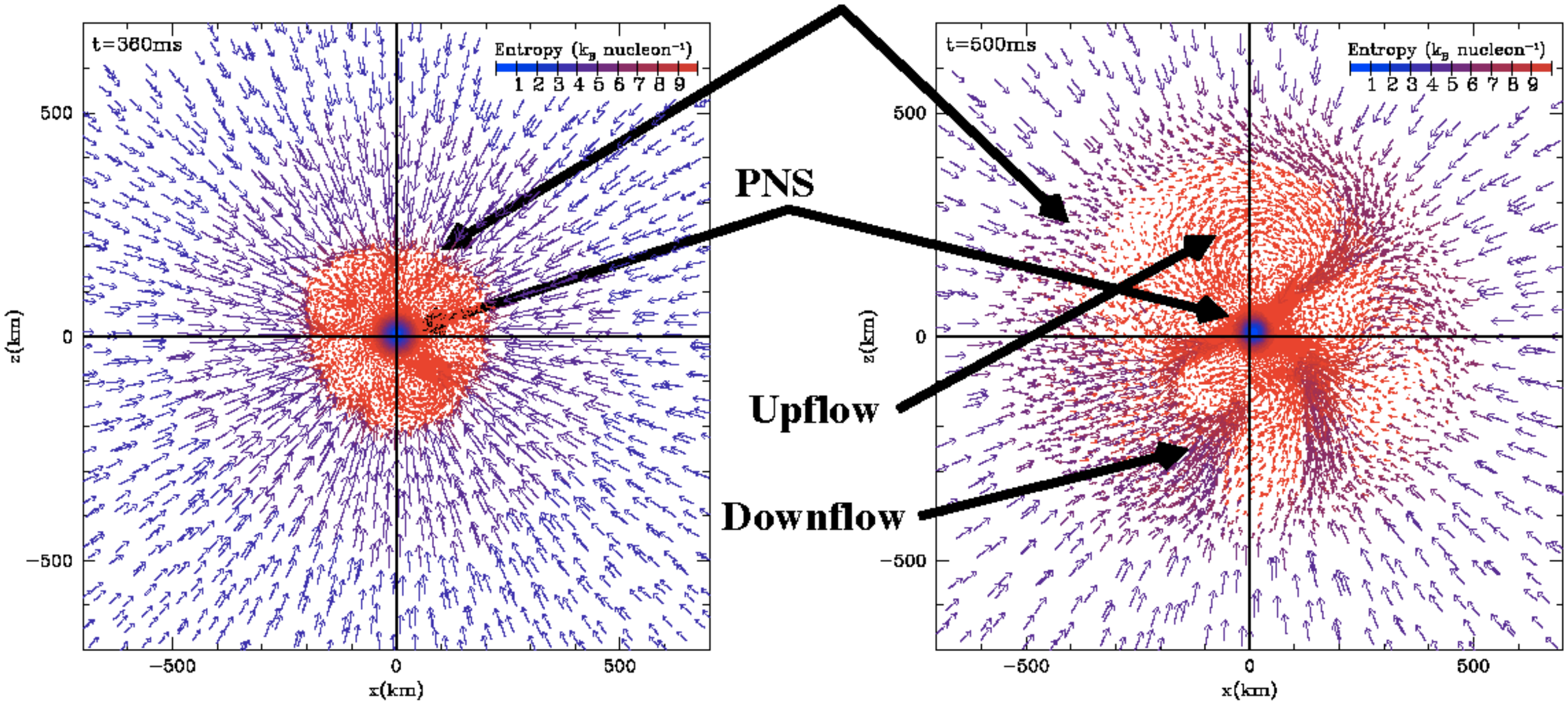


- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out

  => Unique Probe (+Ni Isotopes)

Inner ccSN

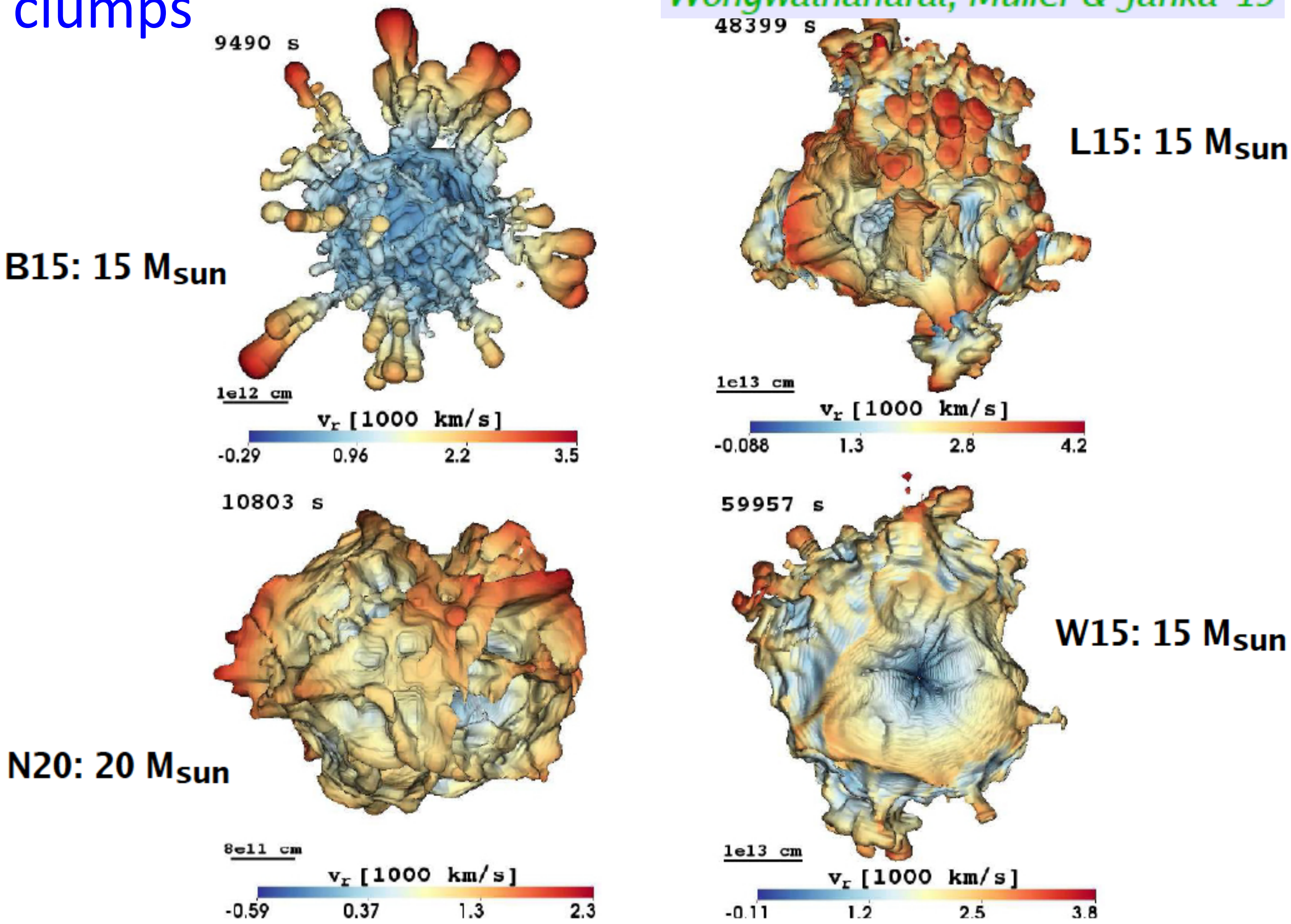
- Complex Inward & Outward Gas Flows



Core-collapse explosions

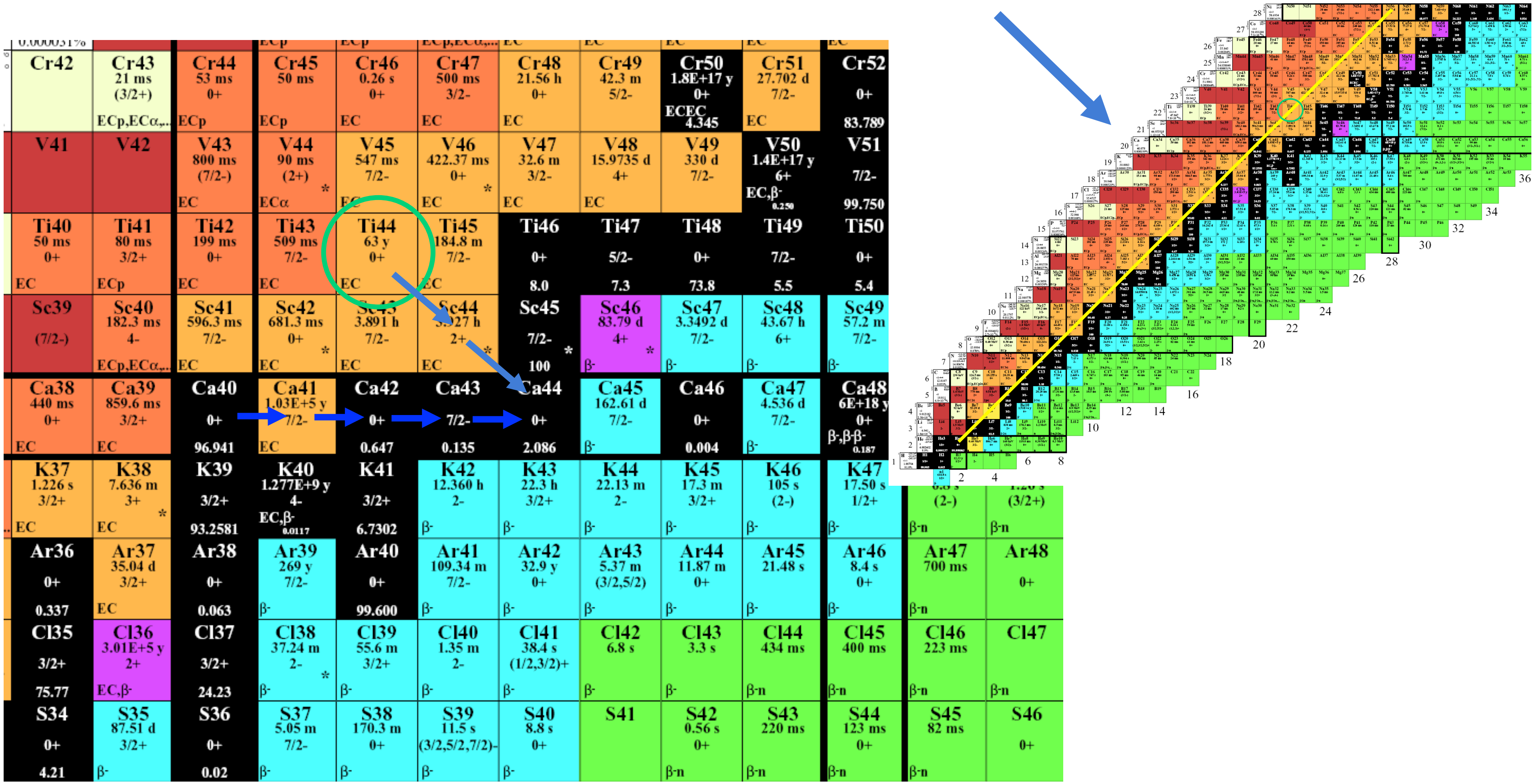
- Inner convective region: asphericities may survive H-He
  → Ni,Ti clumps

Wongwathanarat, Müller & Janka '15



Nucleosynthesis around ^{44}Ti

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

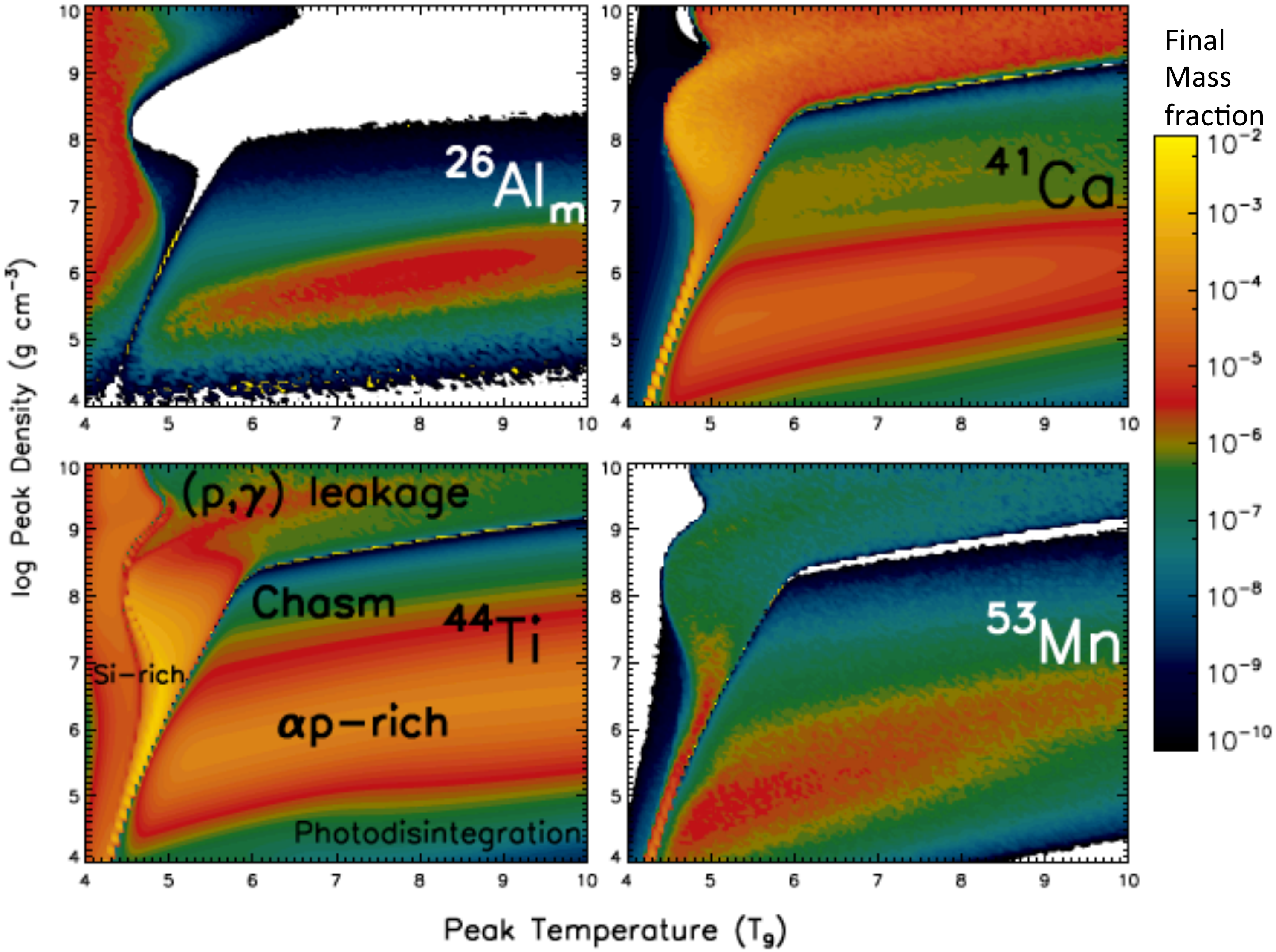


– The ^{44}Ca Isotope is almost-exclusively from ^{44}Ti Decay

- 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"

SN1987A with IBIS on INTEGRAL

- INTEGRAL Line Band Imaging with IBIS *(Grebenev+2012)*
  - Detection (5σ) (6 Ms exposure)

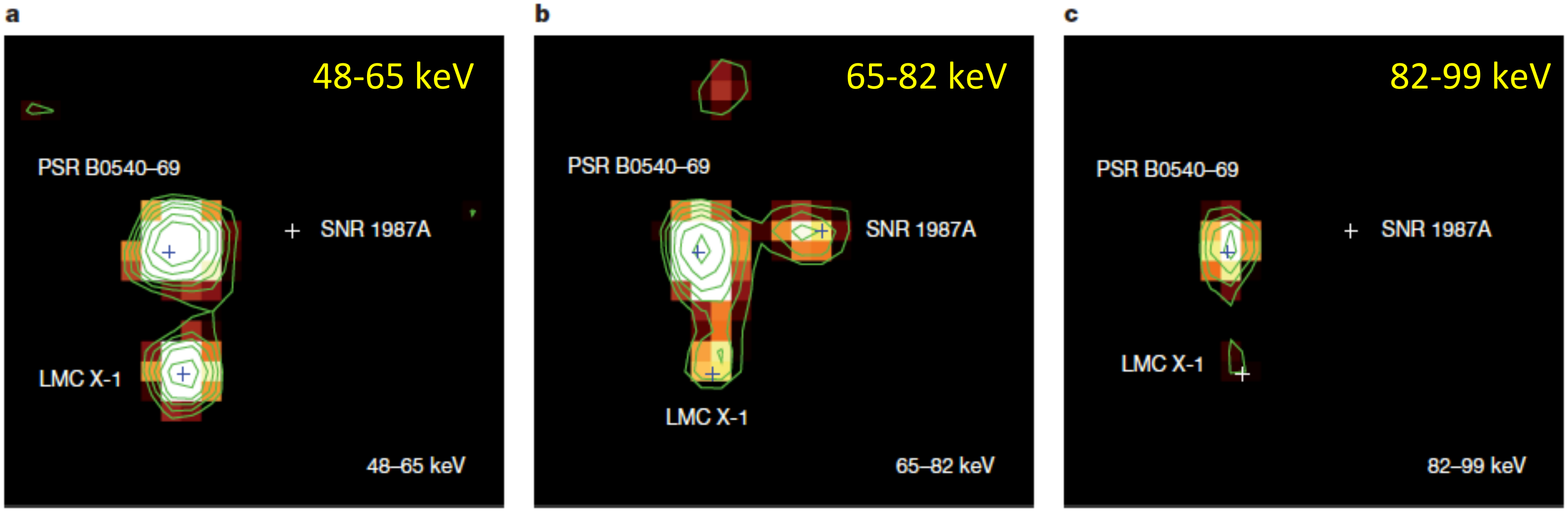


Figure 1 | Hard-X-ray images indicating the detection of ^{44}Ti emission lines from SNR 1987A. **a–c**, Maps of the signal-to-noise ratio (*S/N*) of the 1.5° × 1.5° sky region around SNR 1987A accumulated in three energy bands with the IBIS/ISGRI telescope on board INTEGRAL during observations in 2003–2011 (~6.0 Ms of real exposure or ~4.2 Ms of dead-time-corrected exposure): 48–65 keV (**a**); 65–82 keV (**b**); 82–99 keV (**c**). The maps were reconstructed using standard techniques[27] with contours given at *S/N* levels of 2.7, 3.3, 3.9, 4.5, 5.4 and 6.3. Two well-known sources, PSR B0540–69 and LMC X-1, are seen bright in all three images, but SNR 1987A is confidently detected only in **b**, in the band that contains the 67.9- and 78.4-keV direct-escape lines of radioactive ^{44}Ti decaying inside the ejecta.

↳ Flux 1.7 10^{-5} ph cm^{-2} s^{-1} → 3.5 10^{-4} $M_{\odot}$ of ^{44}Ti

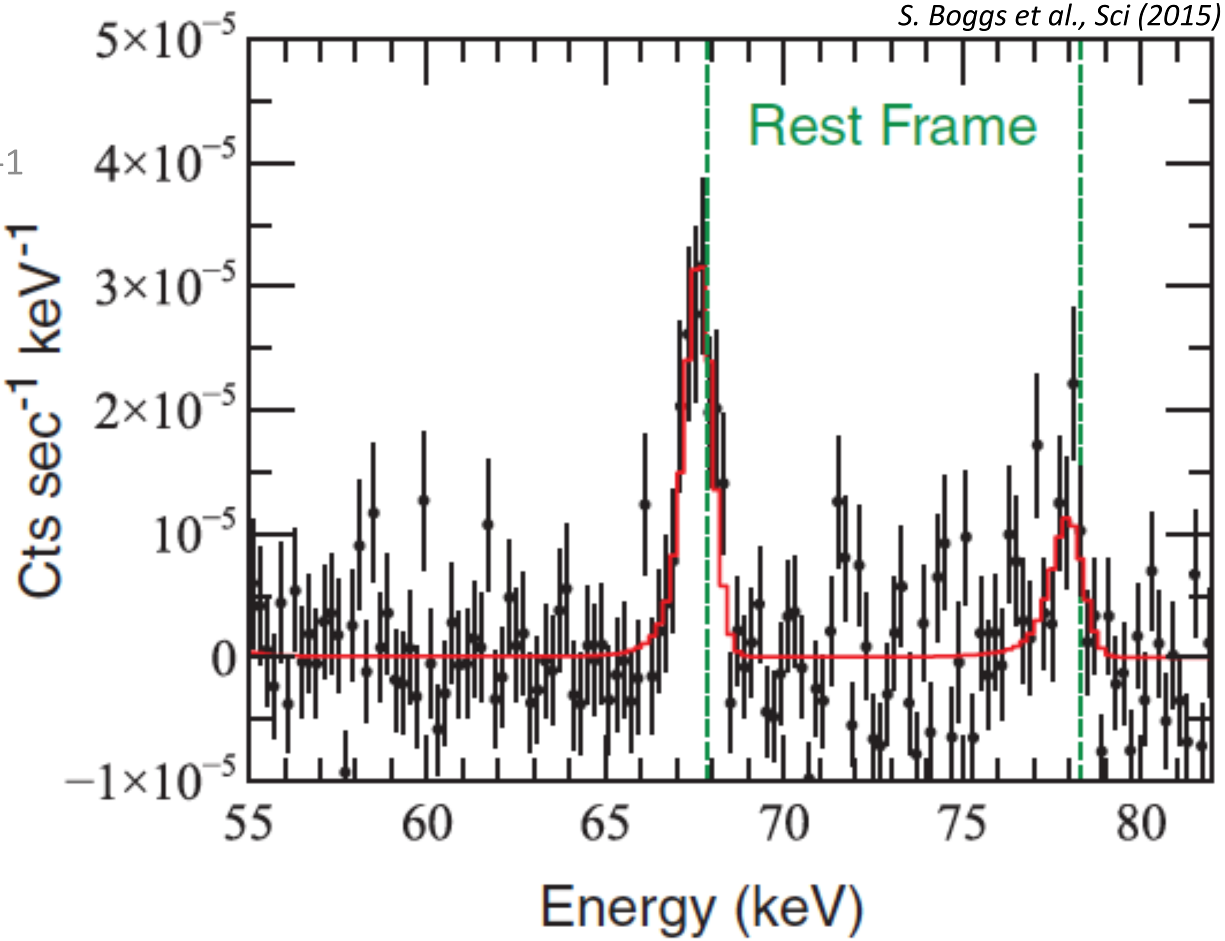
NuSTAR and ^{44}Ti: SN1987A

Measuring hard X-ray lines at 68,78 keV

(no image: 'point src' for NuSTAR)

- 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

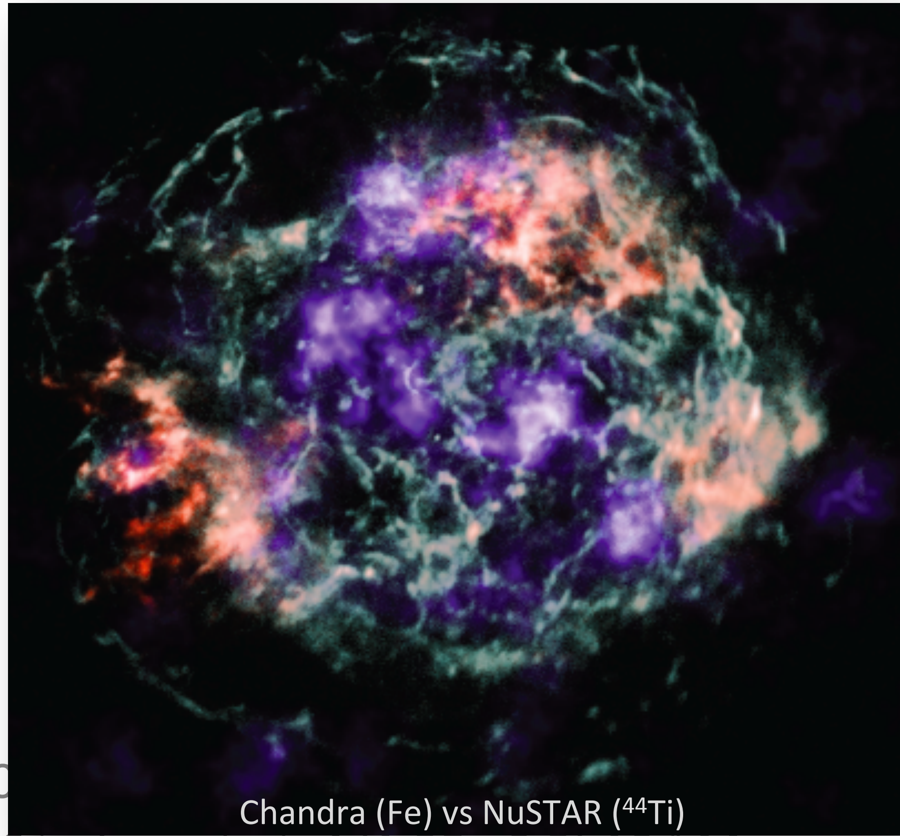
S. Boggs et al., Sci (2015)



NuSTAR measurement of ^{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

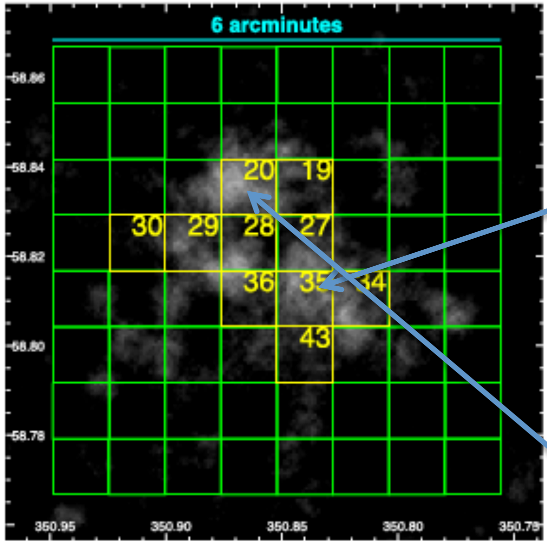
– Flux in 68 keV line: (1.53 ± 0.31) 10^{-5} ph cm^{-2} s^{-1} →(1.25 ±0.3) 10^{-4} $M_\odot$

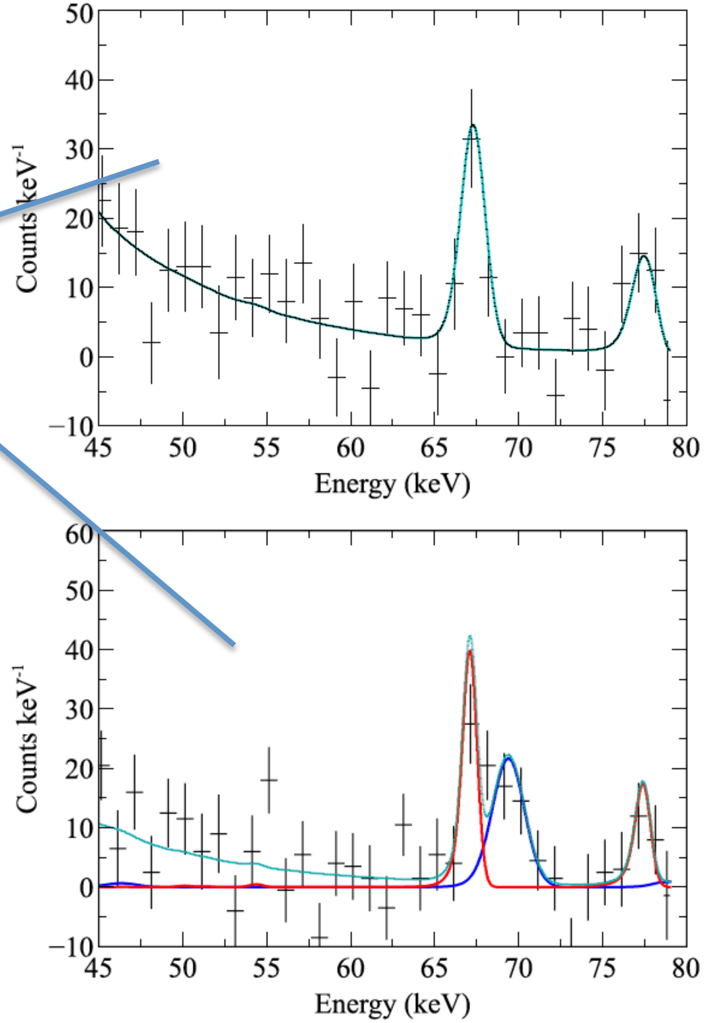
– 2017 update: (1.84 ± 0.25) 10^{-5} ph cm^{-2} s^{-1} →(1.54 ±0.2) 10^{-4} $M_\odot$

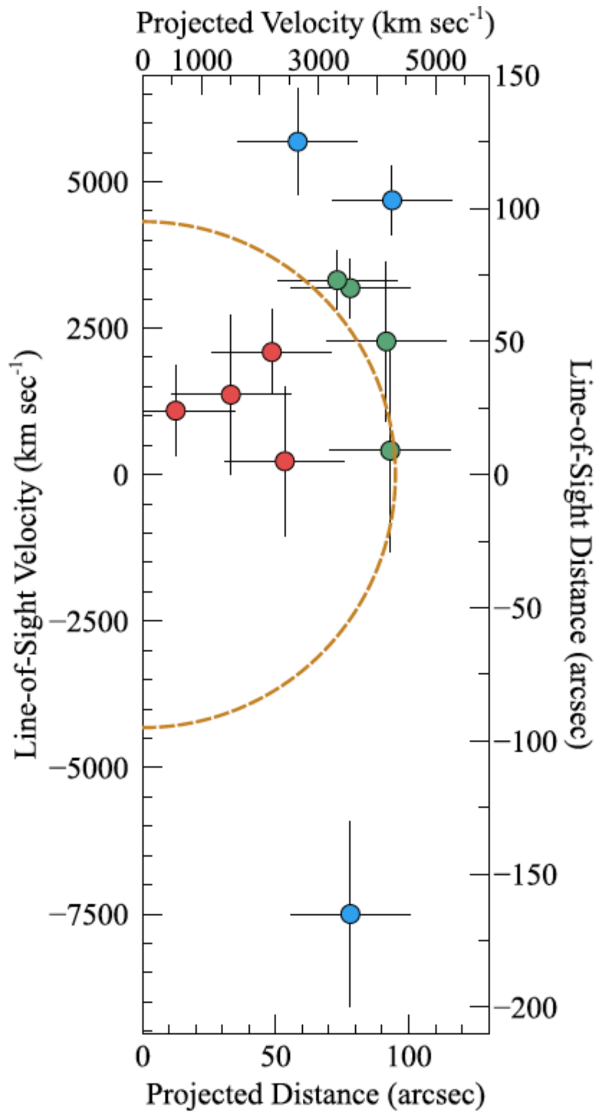
NuSTAR update: ^{44}Ti in Cas A

2.4 Msec NuSTAR campaign
Grefenstette et al. 2017

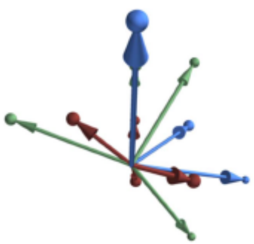
– Imaging resolution allows to spatially resolve Cas A's ^{44}Ti:



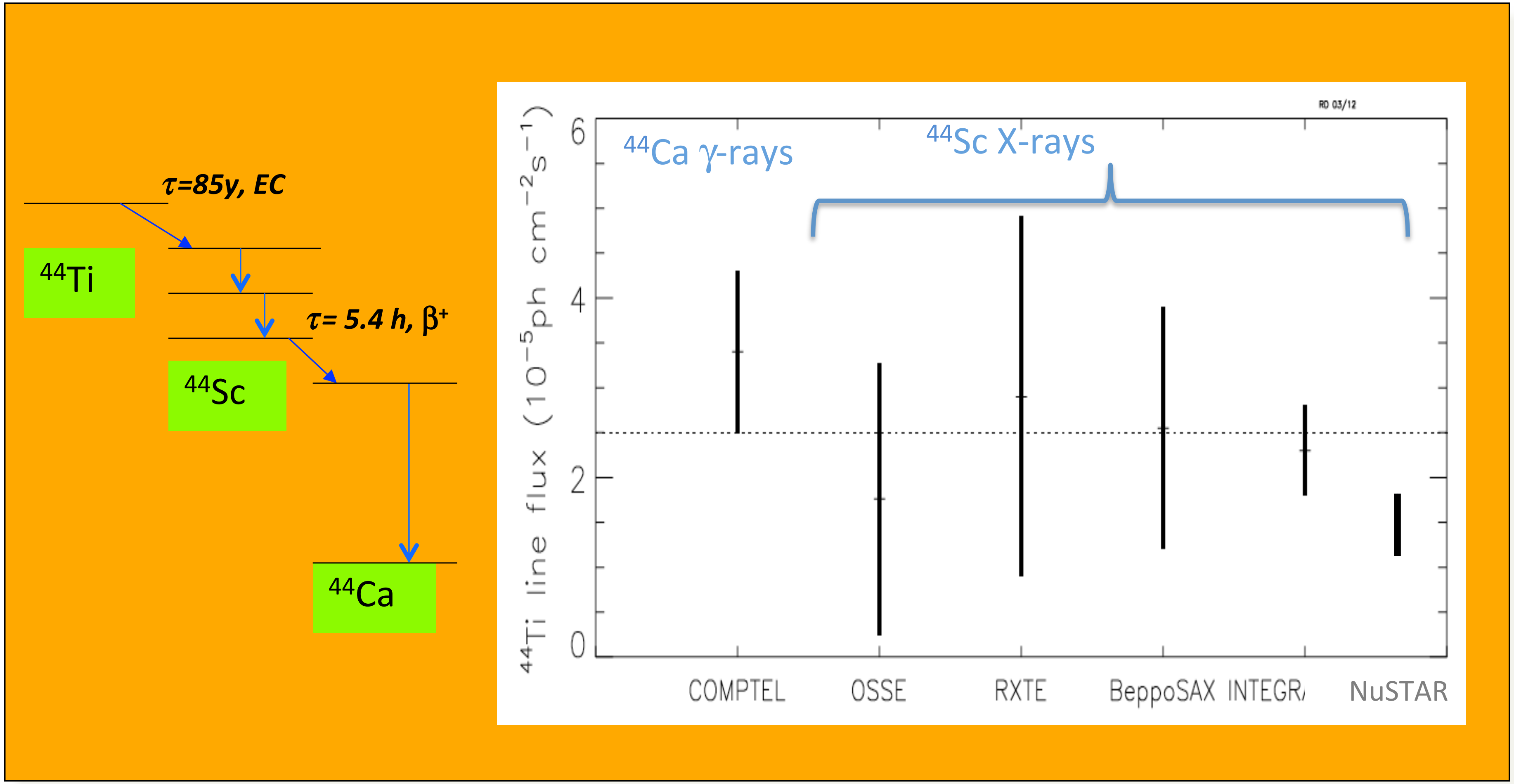




→ motion away
from us,
and in clumps



^{44}Ti γ-rays from Cas A



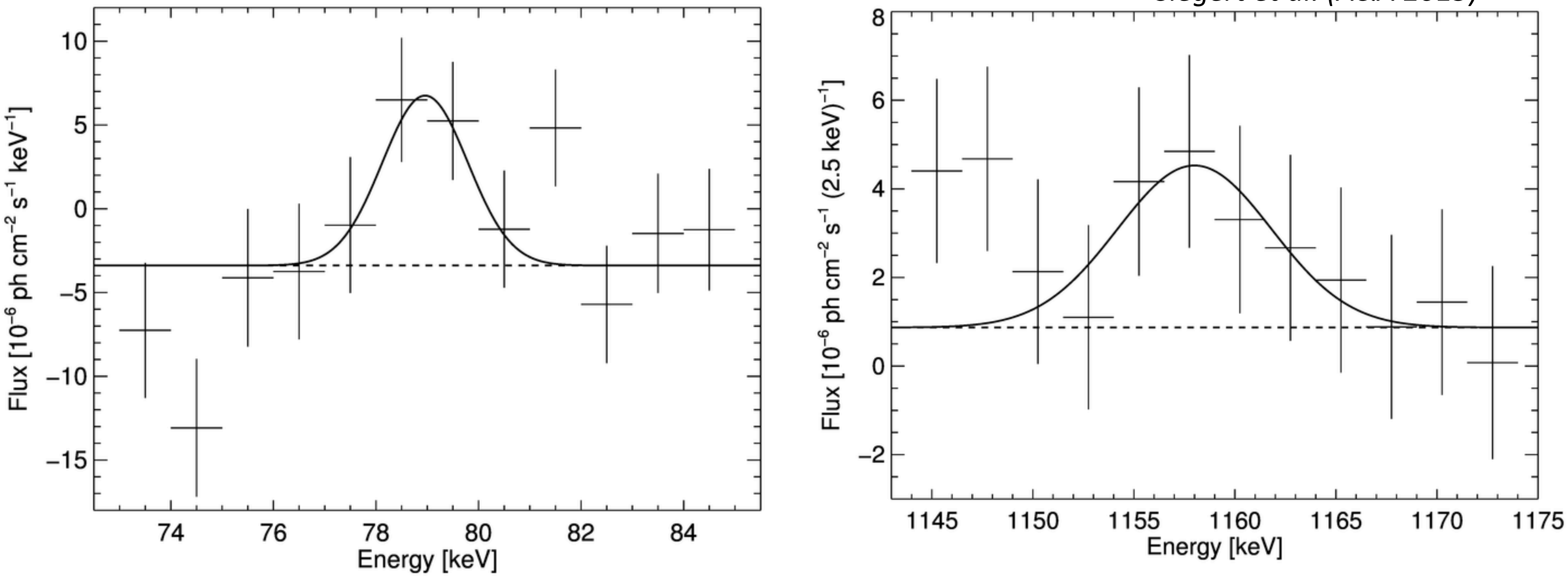
↳ ^{44}Ti Ejected Mass ~1.23 $_{\pm 0.25}$ 10^{-4} $M_\odot$

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

Using cumulative data from >12 years,
and a new instrumental-background treatment

→ We see the 78 keV and 1157 keV line emission

Siegert et al. (A&A 2015)

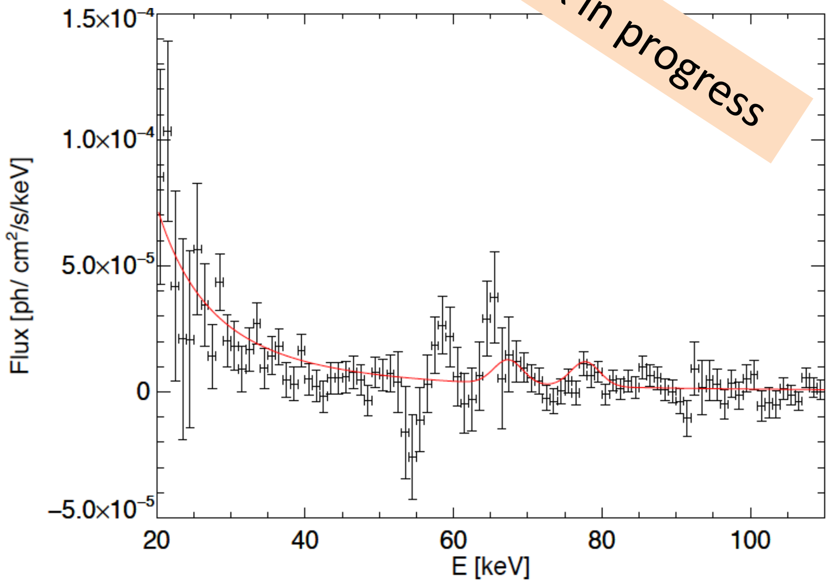


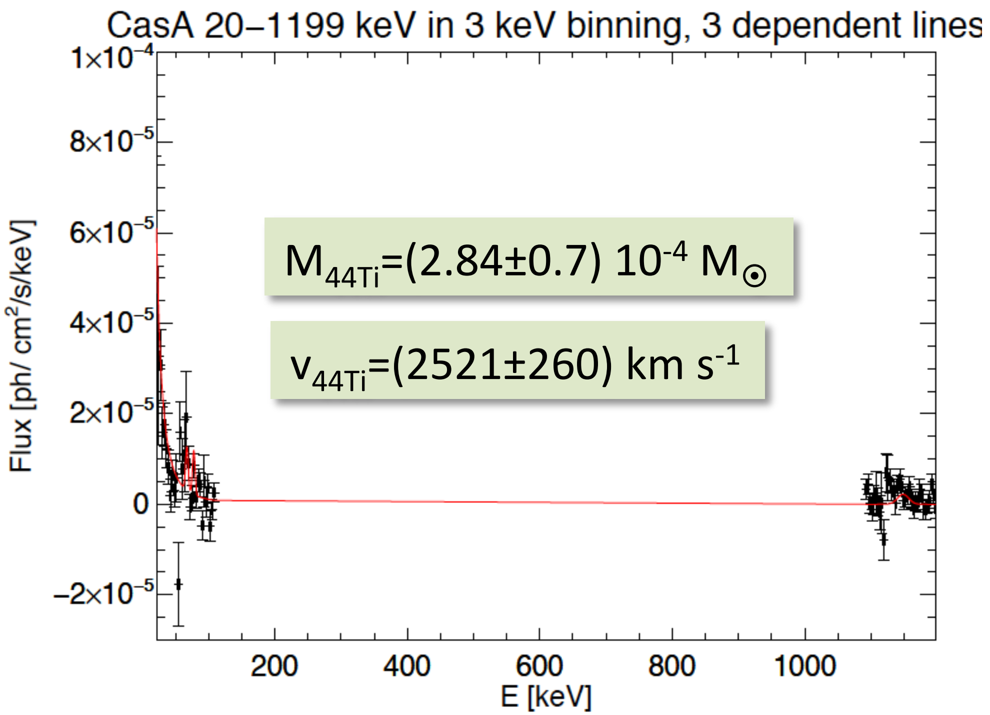
– Doppler broadening: 4300±1600 / 2200±1600 km s^{-1} (78, 1157 keV)

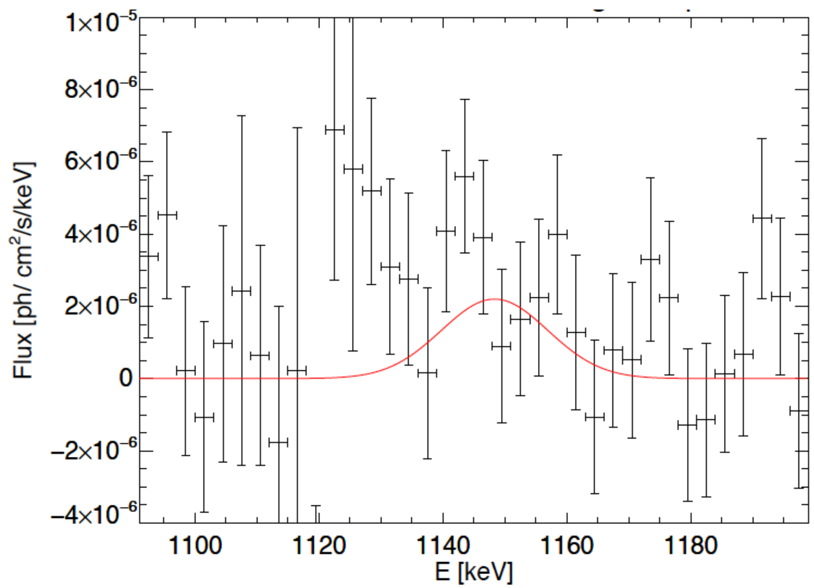
Update: 3-line analysis

- INTEGRAL Deep Exposure Program 2016-2017
  » additionally 2 Msec of Cas A & Tycho region; currently: ~8.6 Ms
- Refined analysis (Weinberger+, preliminary)
  » use templates for blended-lines background features
  » constrain ^{44}Ti through 3-line set (one line amplitude + cont fitted)

work in progress



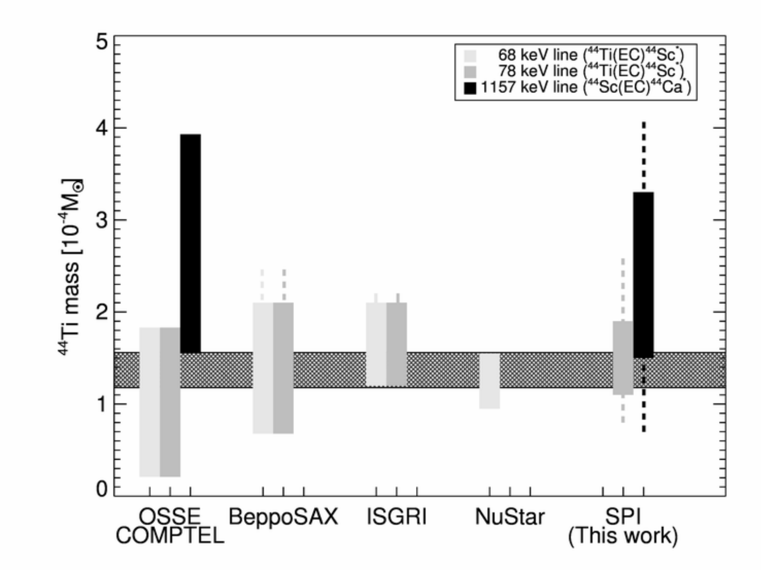


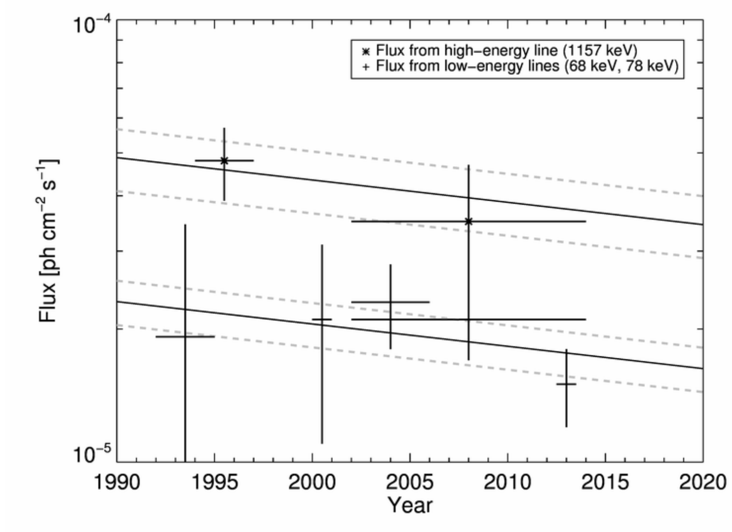


^{44}Ti from Cas A

- Consolidated Mass Determination:
  - Different instruments & lines combined

Siegert et al. 2015



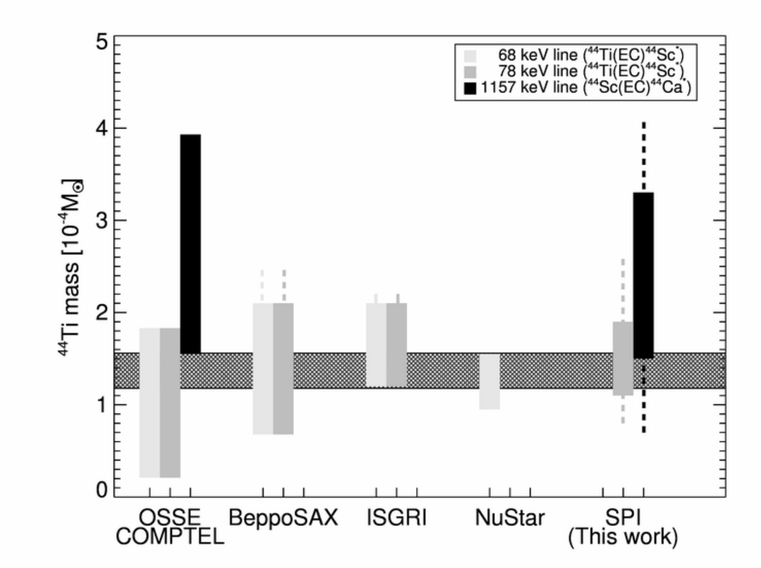


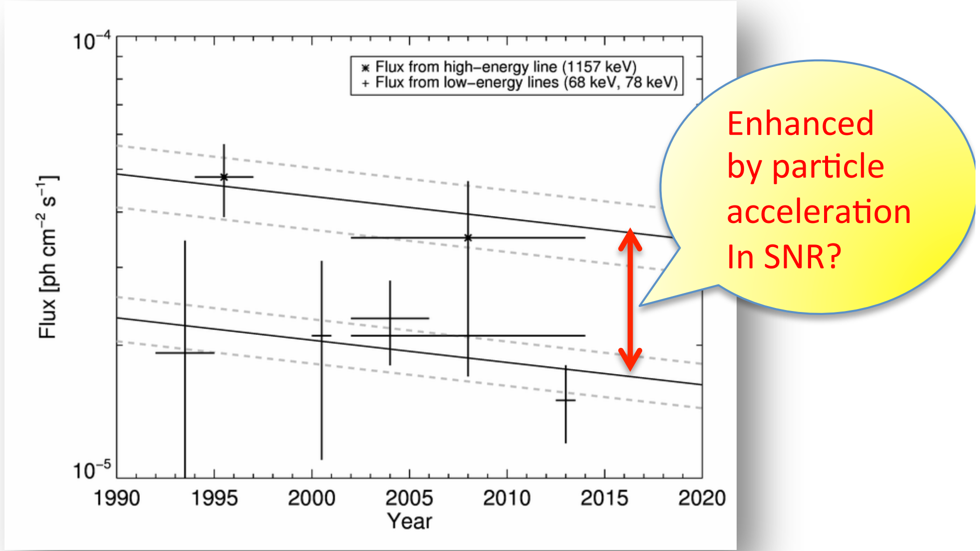
- ^{44}Ti mass = (1.37 ± 0.19) 10^{-4} $M_\odot$ (all measurements)
- ^{44}Ti mass = (1.29 ± 0.15) 10^{-4} $M_\odot$ (78 keV line only)
- ^{44}Ti mass = (2.72 ± 0.43) 10^{-4} $M_\odot$ (1.157 MeV line only)

^{44}Ti from Cas A

- Consolidated Mass Determination:
  - Different instruments & lines combined

Siegert et al. 2015





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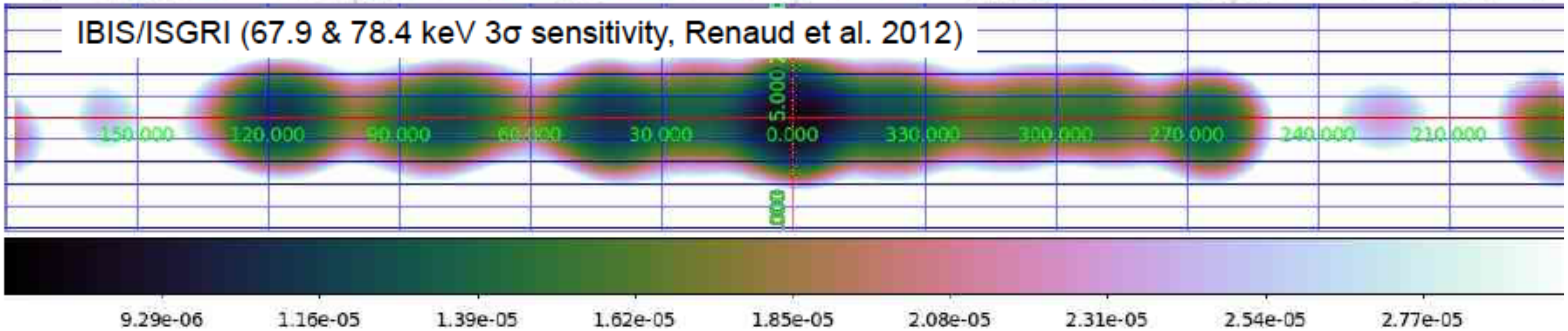
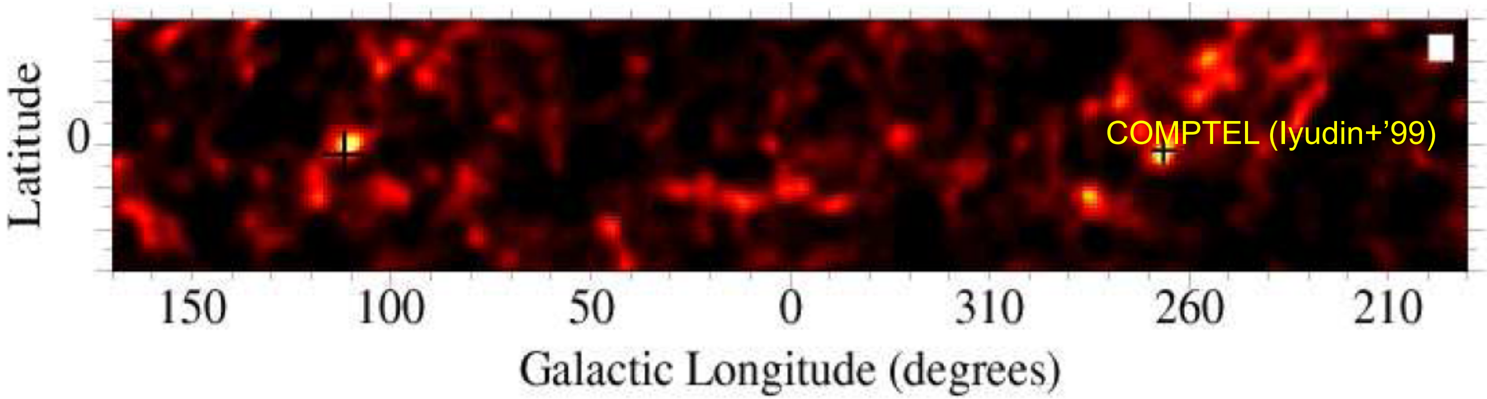
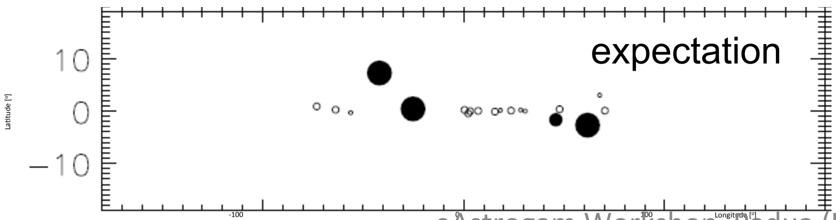
Survey: Are all Core Collapse Supernovae ^{44}Ti Sources?

- ☆ Cas A is the ONLY SNR Seen in our Galaxy – with R_{ccSN}=1.3 (± 0.4) /100y
- ☆ Sky Regions with Most Massive Stars (inner Galaxy) are ^{44}Ti Source-Free
- ☆ We would expect to see > a few of such sources!

see also Tsygankov+2016

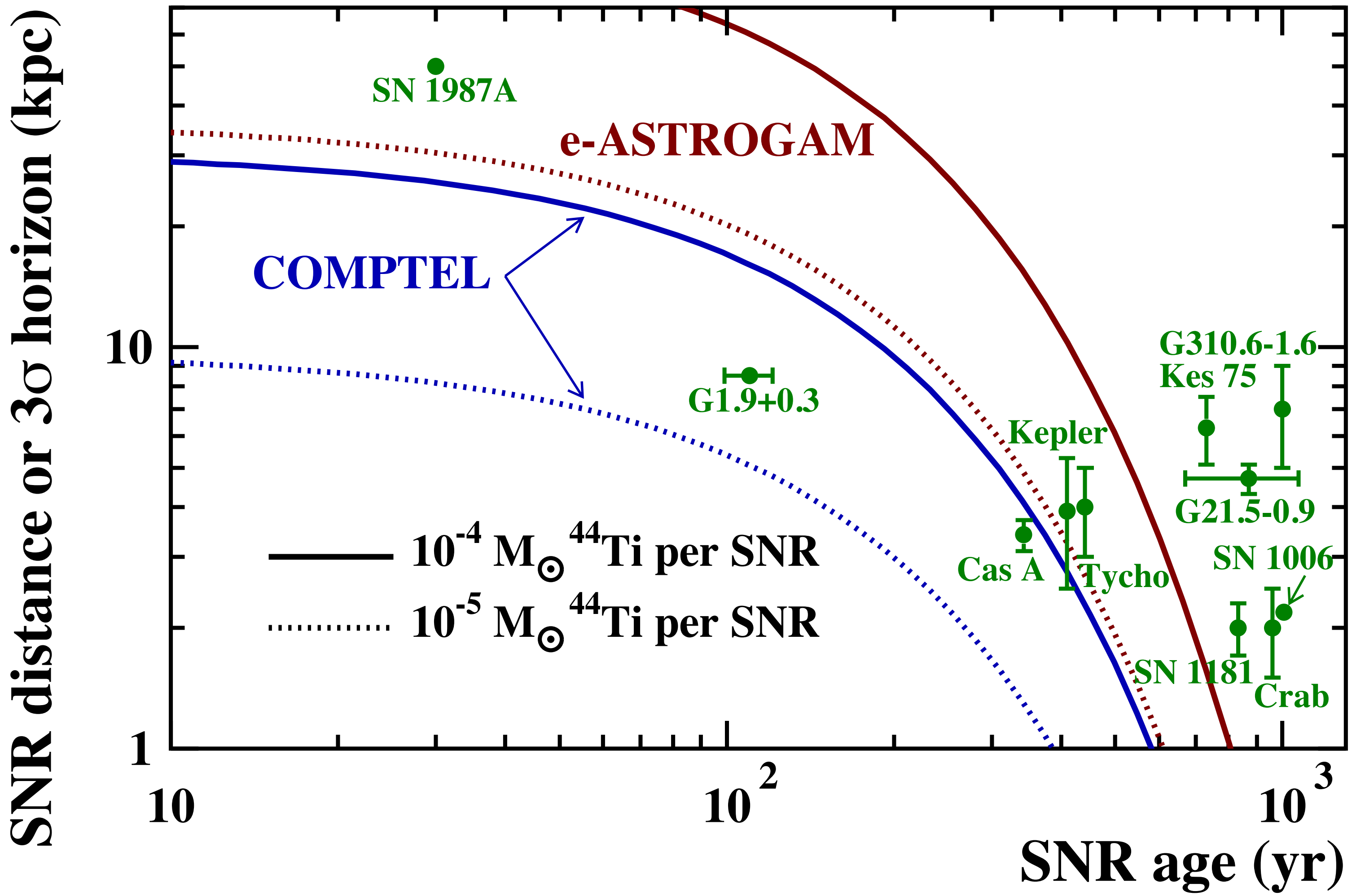






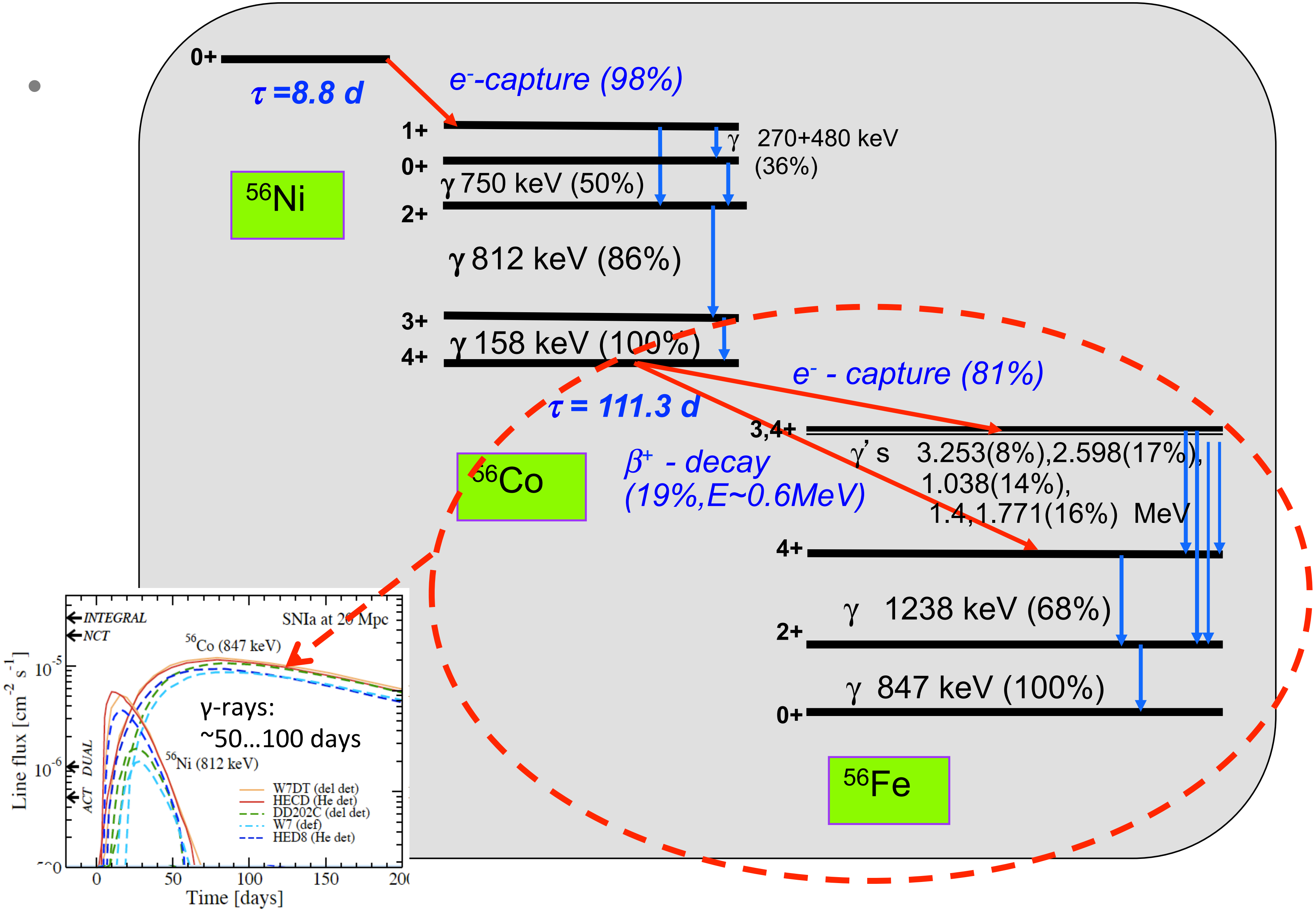
The et al. 2006*; see also Dufour & Kaspi 2013*

Recent SN as candidate ^{44}Ti sources



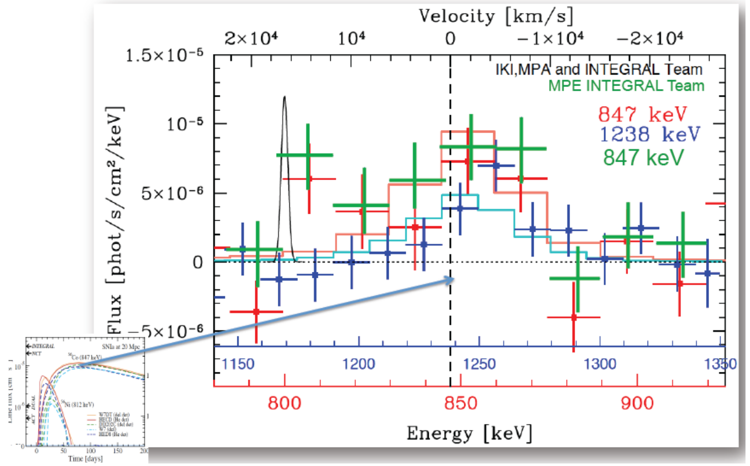
- e-ASTROGAM should detect ~10 young SNR in ^{44}Ti *(The et al. 2006)*

^{56}Ni radioactivity: Decay chain, γ rays, e^+



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

– Doppler broadened ✓



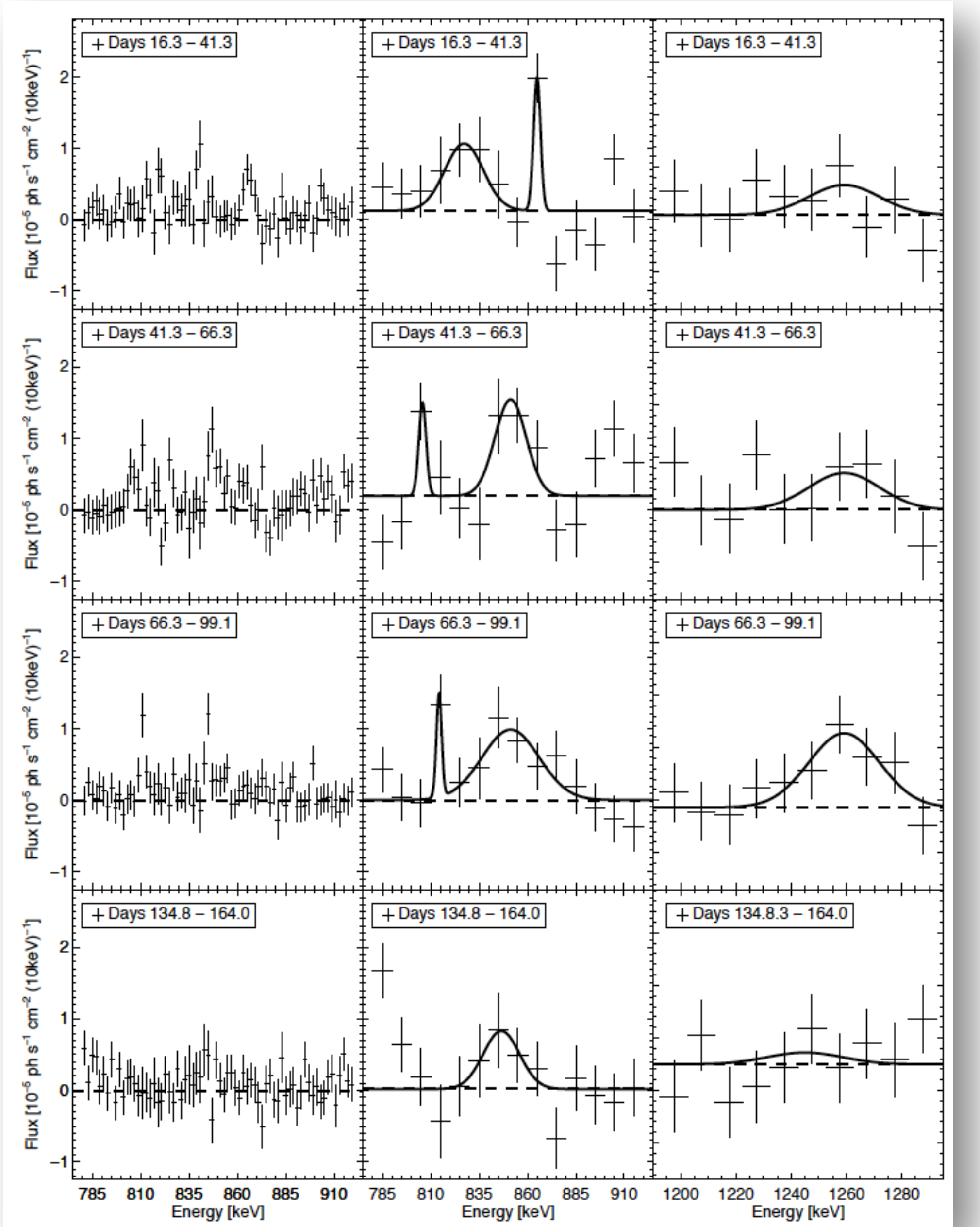
– Split into 4 time bins

– Coarse & fine spectral binning

→ Observe a structured and evolving spectrum

– expected: gradual appearance of broadened ^{56}Co lines

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

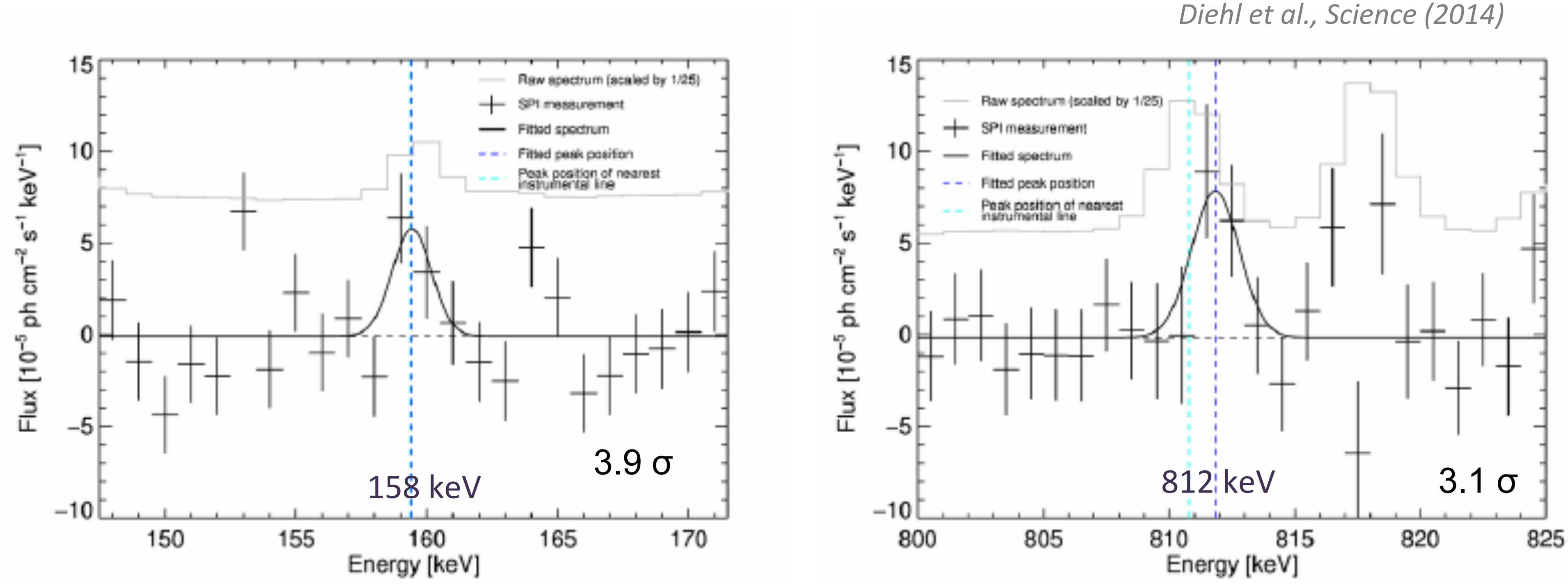


SN2014J: Early ^{56}Ni (τ~8.8d)

Spectra from the SN at ~20 days after explosion

- Clear detections of the two strongest lines expected from ^{56}Ni

Diehl et al., Science (2014)



- 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)
- Corresponding ^{56}Ni mass (backscaled to explosion): ~0.06 $M_{\odot}$

Challenges in Nuclear Astrophysics for eAstrogam

- Radioactivity γ-rays provide a unique / different view
  - Yields for SNe and Novae, emission not dependent on gas state, radioactivity clock
  - INTEGRAL achieved ~10^{-6} ph cm^{-2} s^{-1} → a challenge!
- SNIa ^{56}Ni and how the explosion occurs
  - SN2014J reveals its ^{56}Ni,^{56}Co irregularly → 3D effects?
- ccSupernova ^{44}Ti demonstrates SN asymmetries, 3D effects
  - 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 variety & puzzle; incl μQSOs