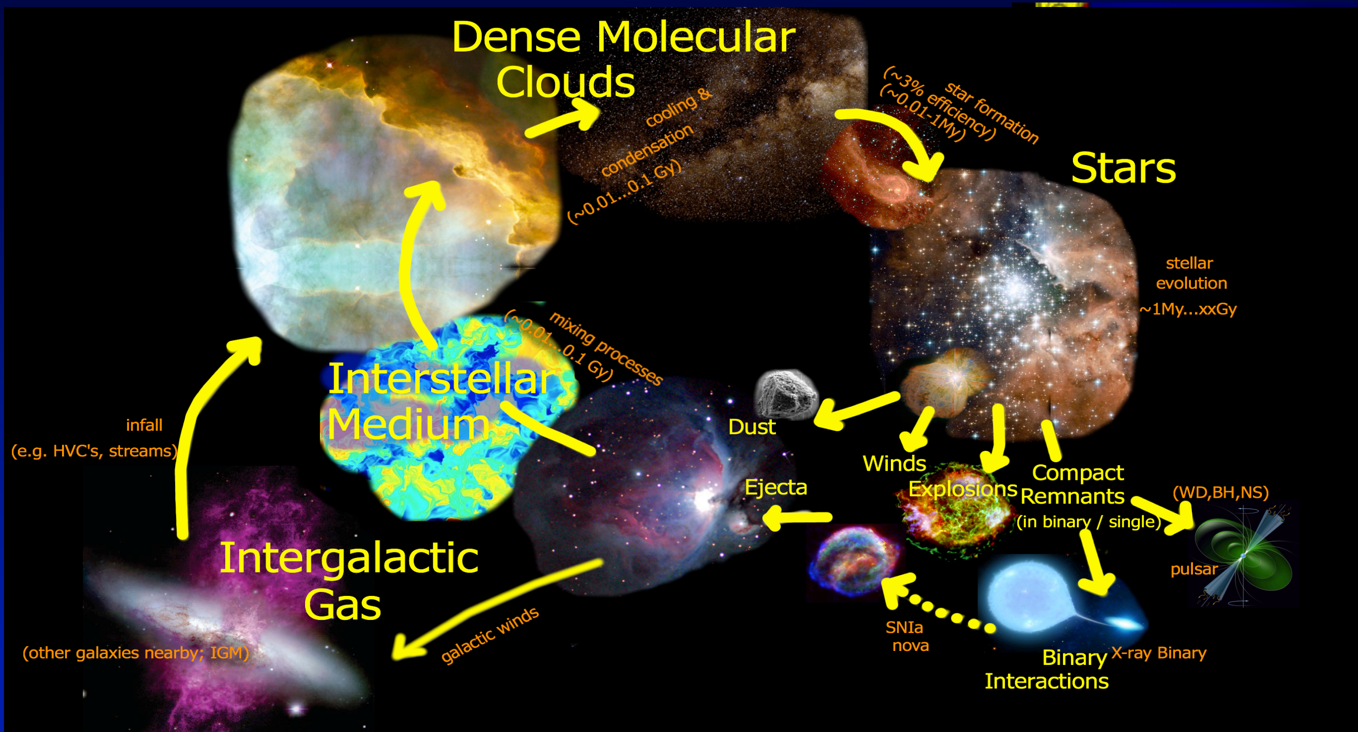
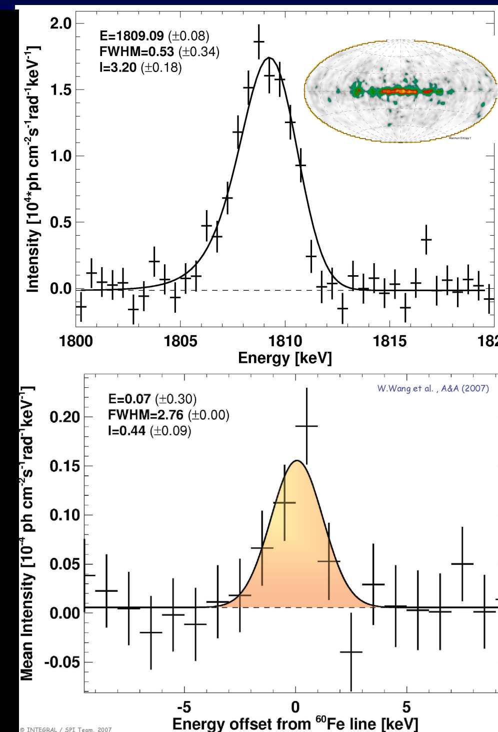
Gamma-Ray Astronomy (& nuclear astrophysics)





by Roland Diehl (MPE Garching, Germany)

Themes:

- ☆ Supernova Interiors
- ☆ Massive Star Nucleosynthesis
- ☆ ISM Around Massive Stars
- ☆ (Annihilating Positrons)
- ☆ Gamma-Ray Telescopes

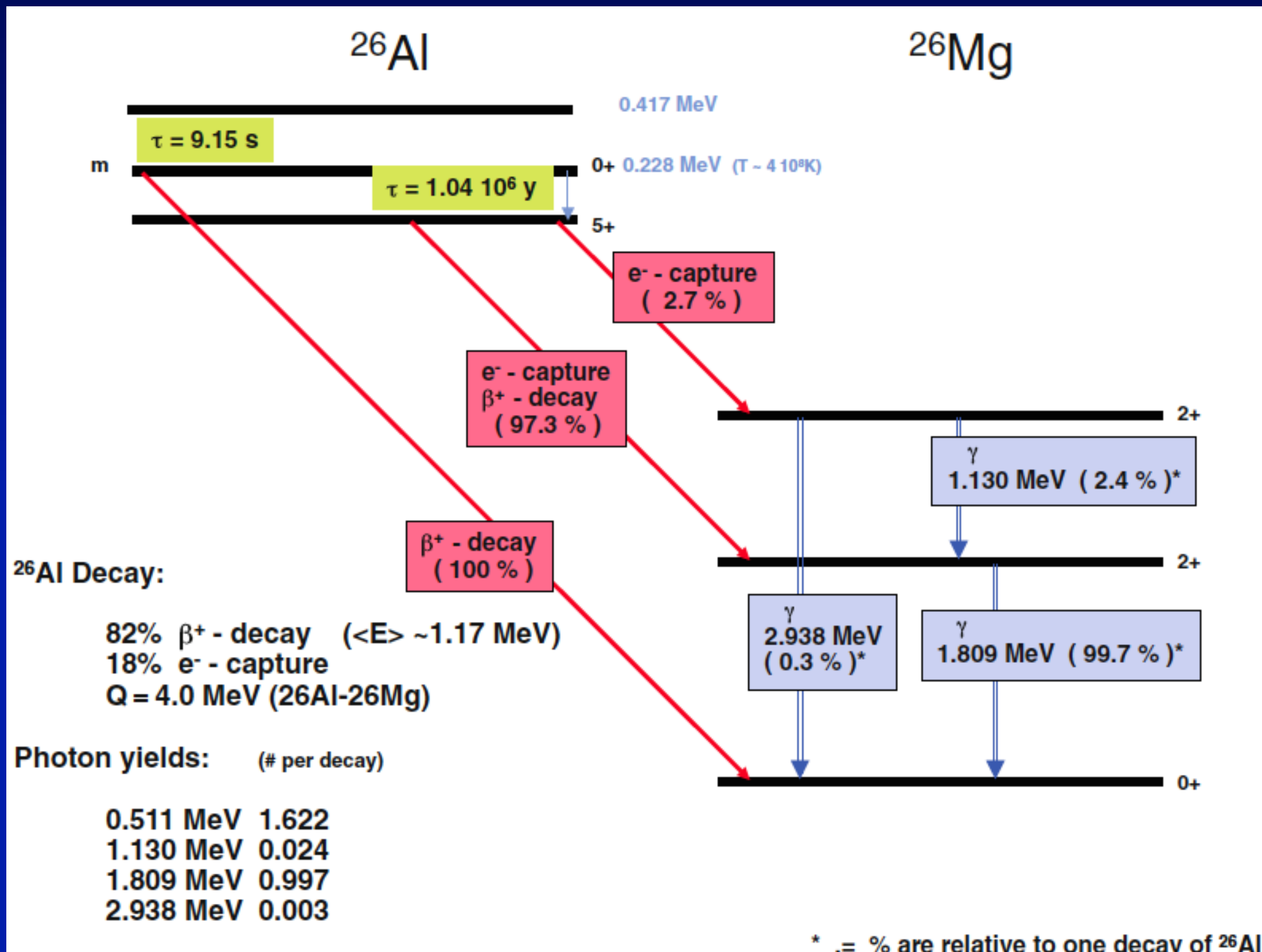
Gamma-Ray Lines and their Messages

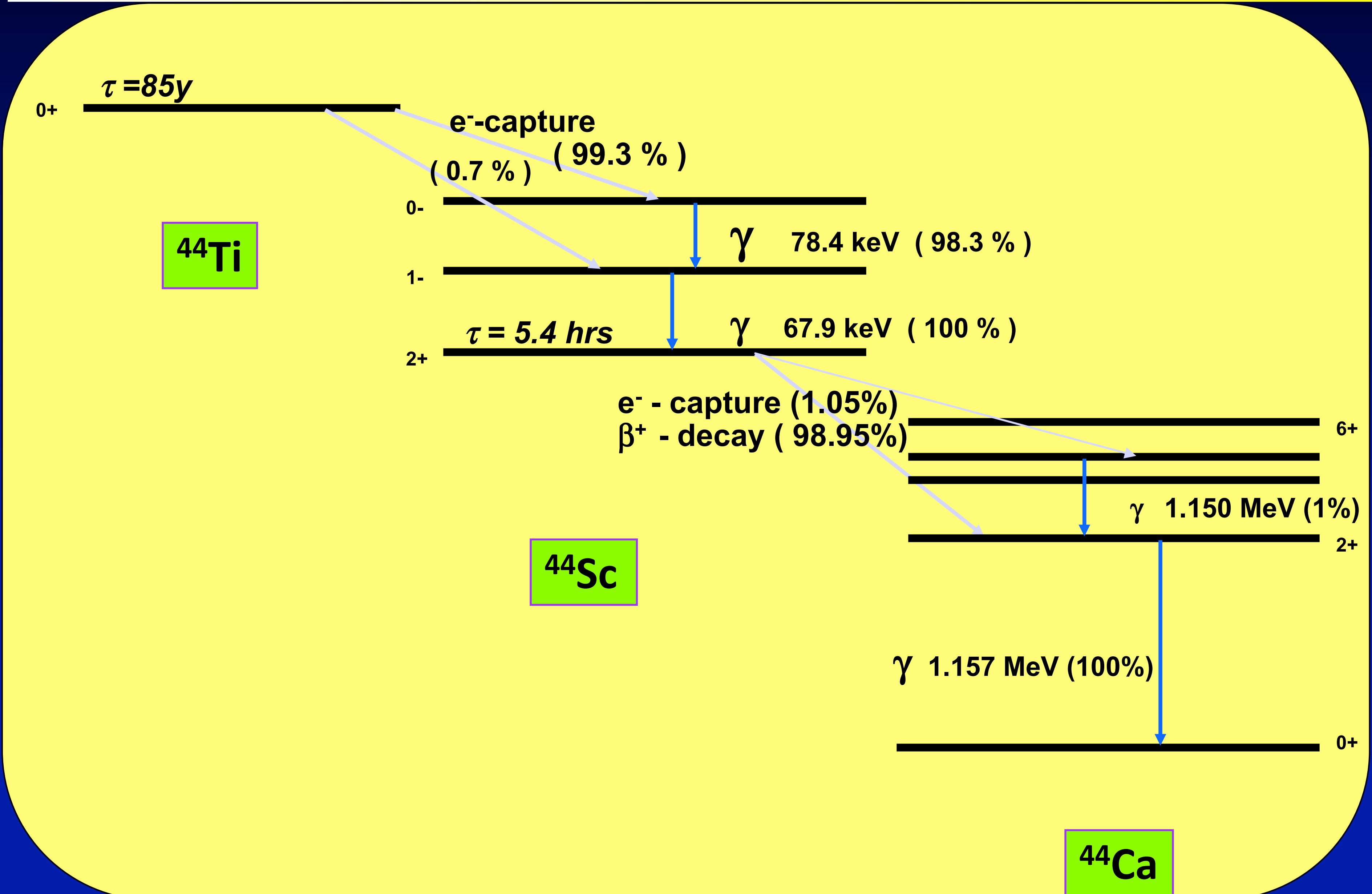
- Radioactive Trace Isotopes are Nucleosynthesis By-Products
- For Gamma-ray Spectroscopy We Need:
  - ☞ Decay Time > Source Dilution Time
  - ☞ Yields > Instrumental Sensitivities

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)	
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478	individual object/event
^{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	cumulative from many events
^{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	

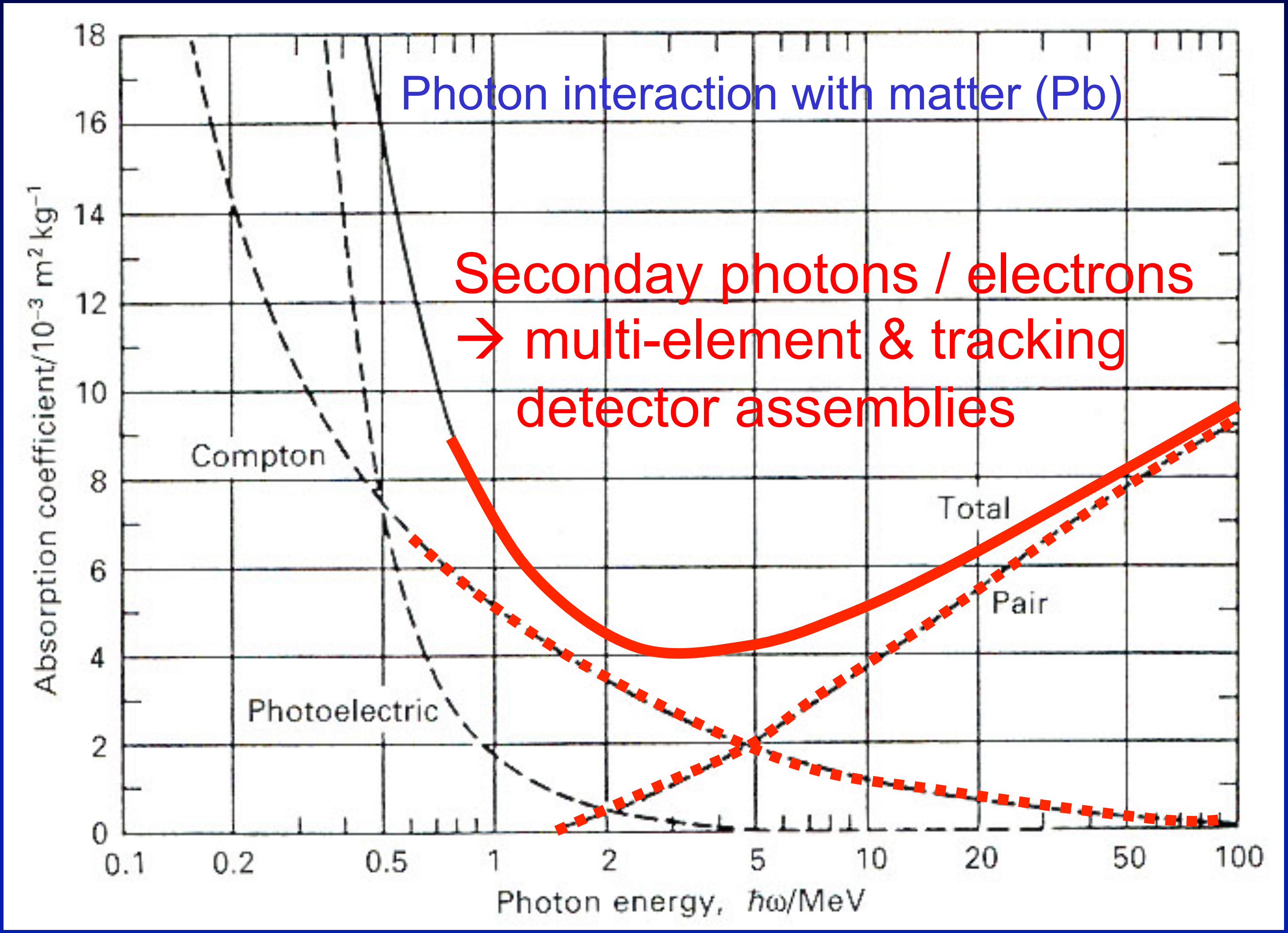
Cosmic Radioactivities: Example

☞ Long Lifetime due to large angular-momentum state differences




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

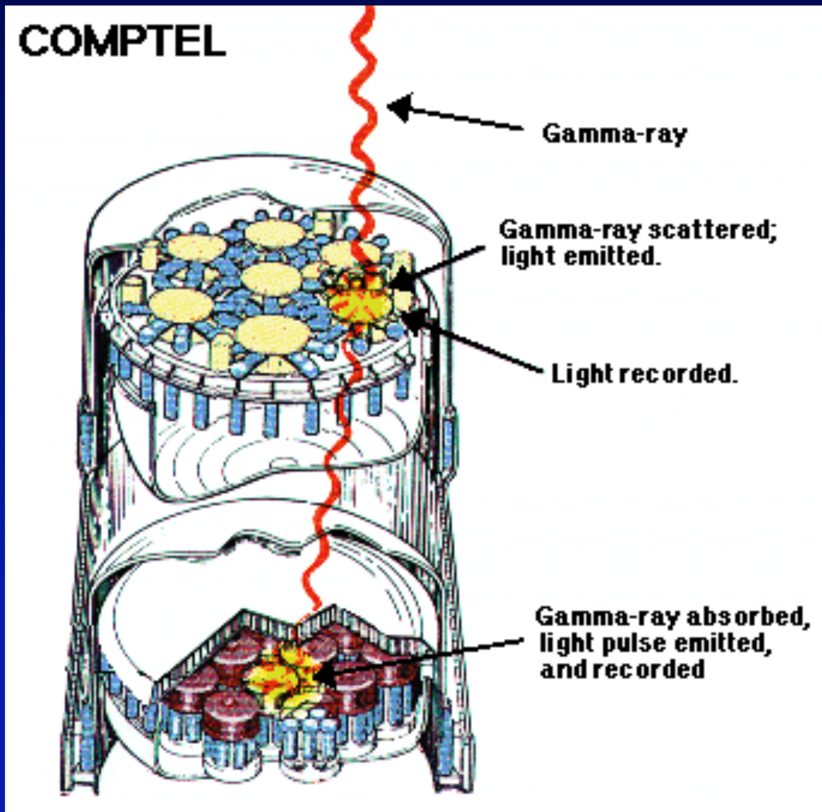
Astronomical Gamma-Ray Telescopes:
Interaction of HE Photons with Matter

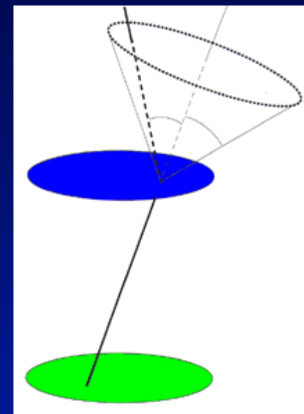


-> Secondary Particles … → e.m. cascade

Compton Telescopes

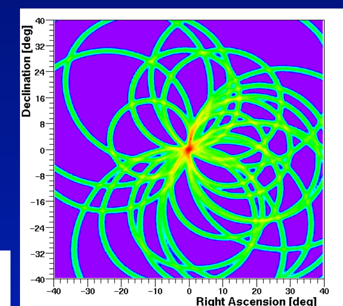
Measure Compton Scattering: Detectors in Coincidence

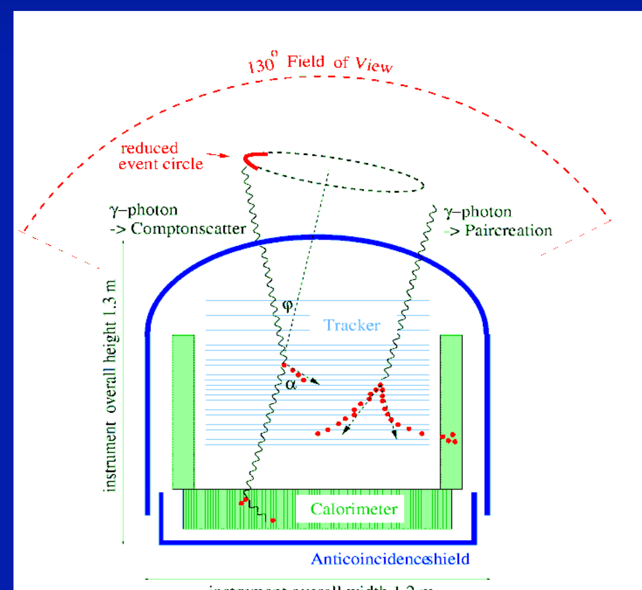




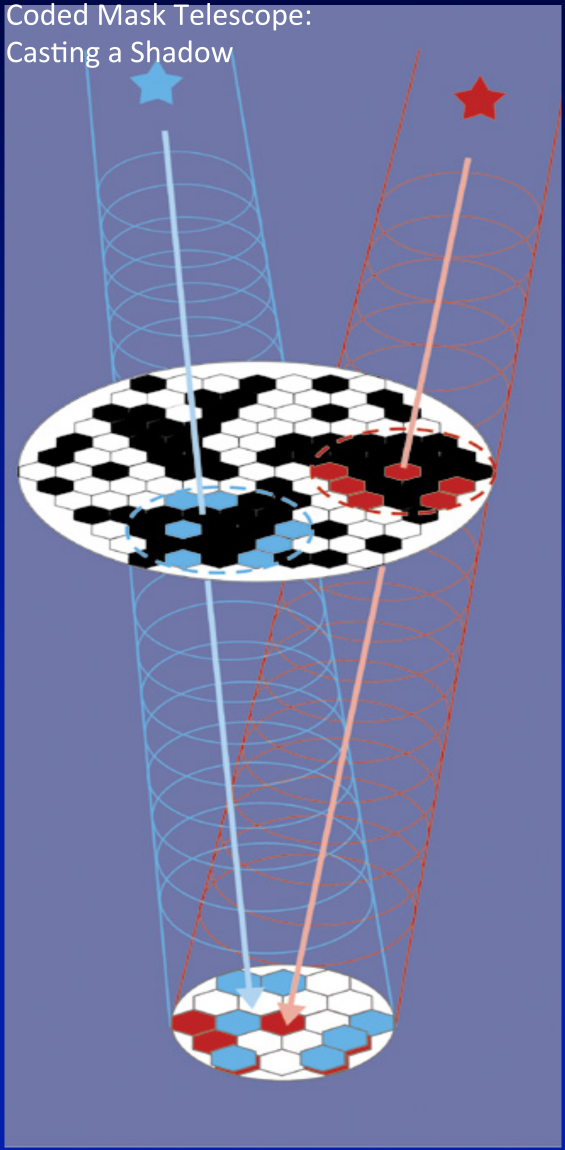
$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

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





INTEGRAL Cosmic Photon Measurements: The SPI Ge γ-Spectrometer



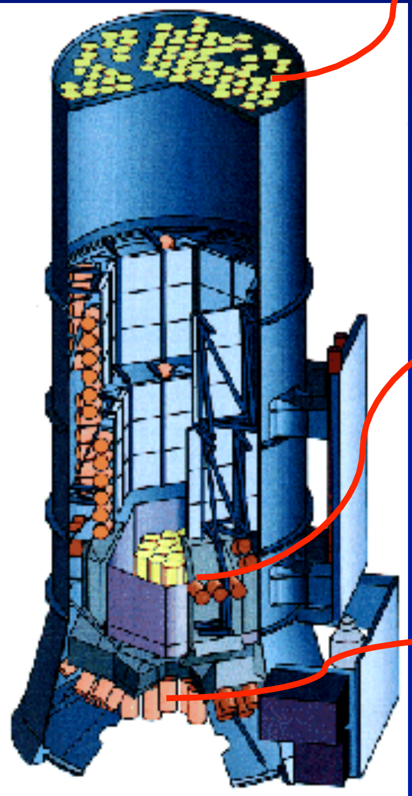
Coded-Mask Telescope

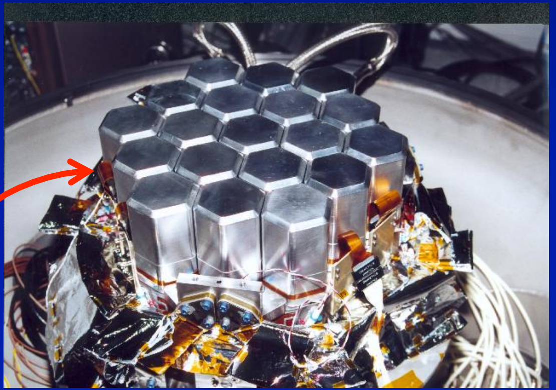
Energy Range 15-8000 keV

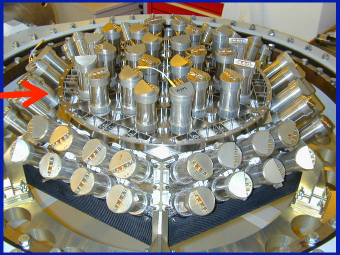
Energy Resolution ~2.2 keV @ 662 keV

Spatial Precision 2.6° / ~2 arcmin

Field-of-View 16x16°

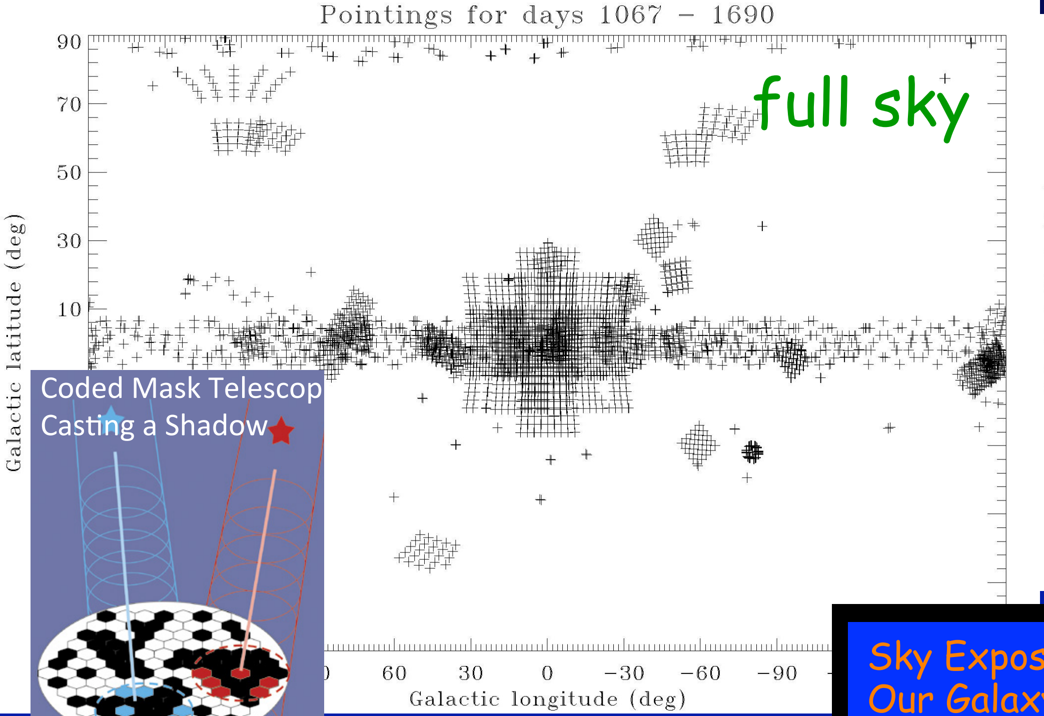




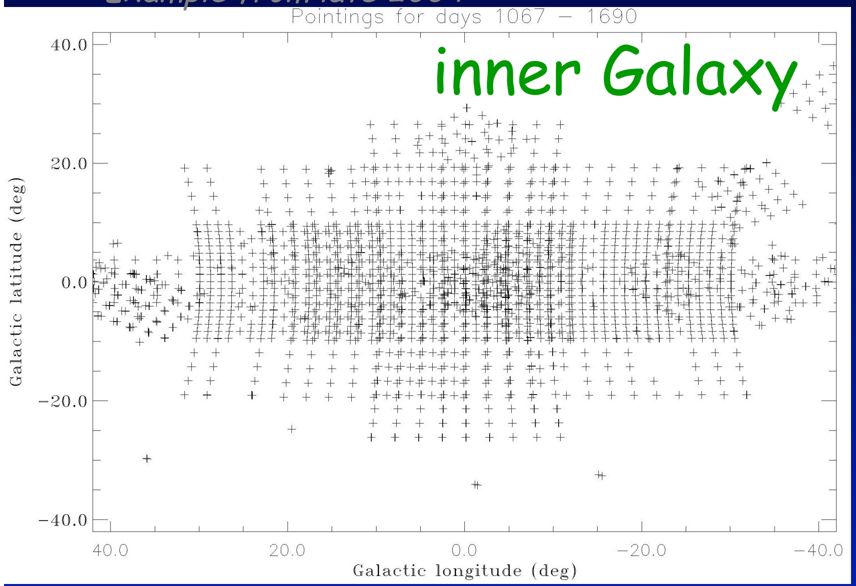


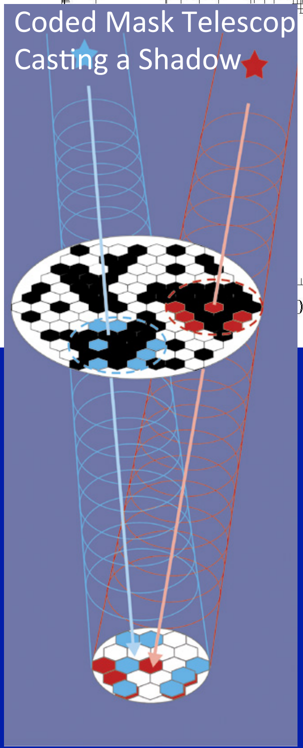
A Sky Survey with INTEGRAL's Coded-Mask Telescopes

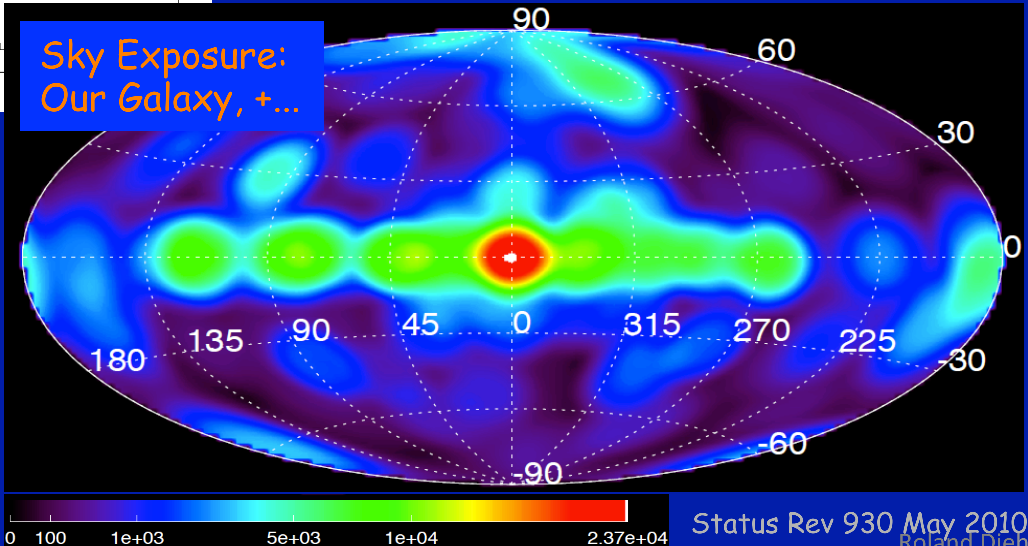
☆ "Dither Patterns" Scattered over the Sky → changing shadowgrams



☞ *Example from late 2004*



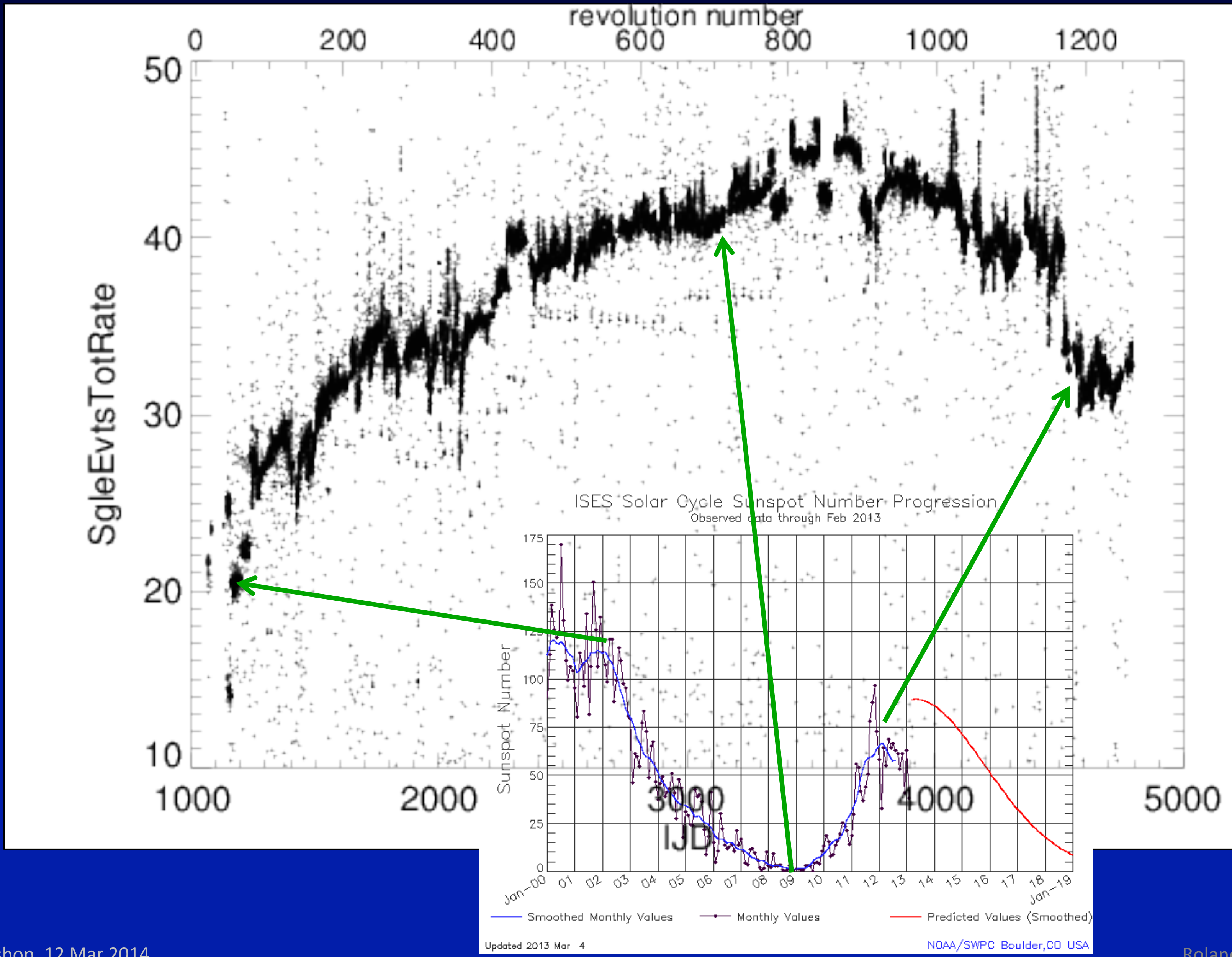




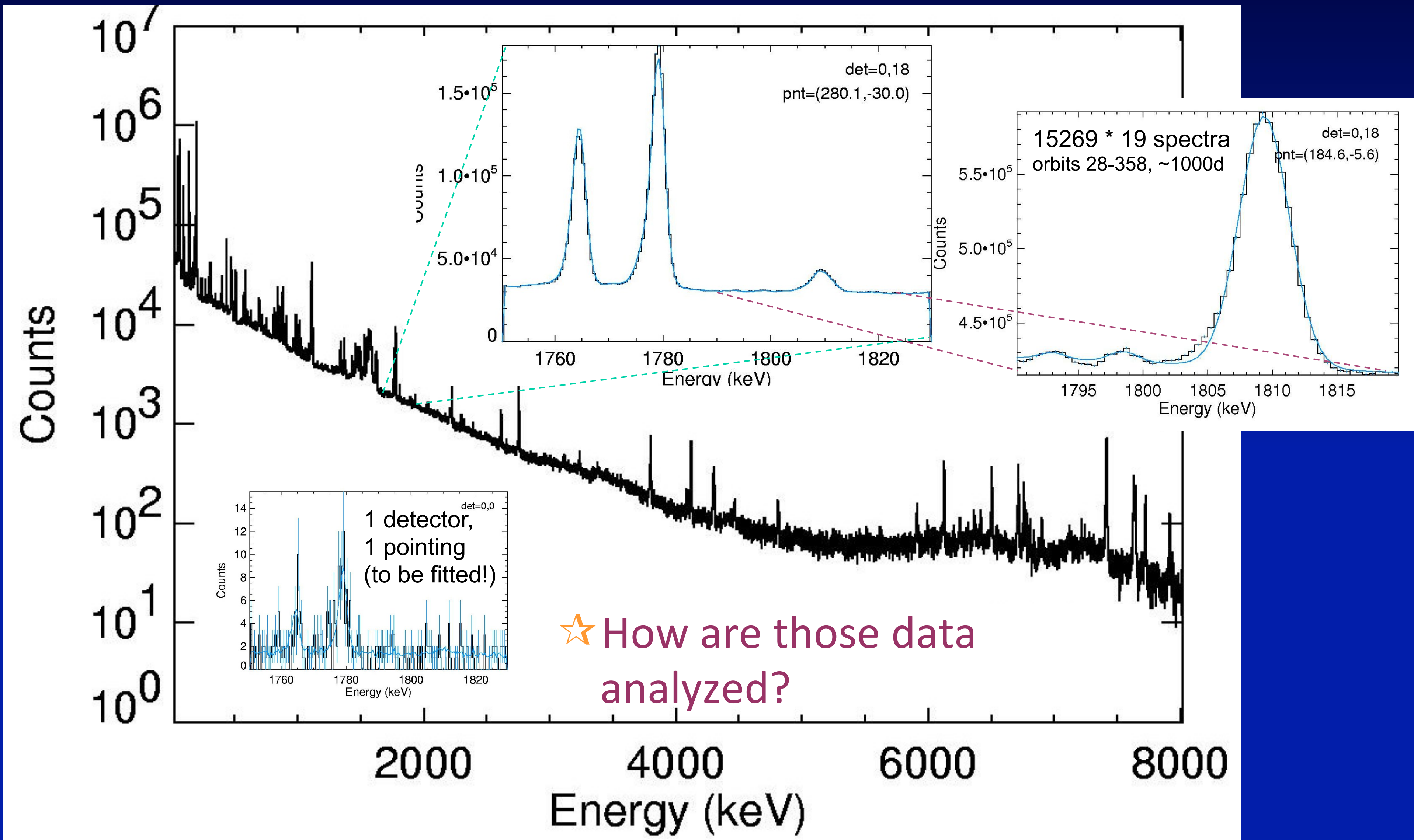
Status Rev 930 May 2010

SPI Count Rate History 2002 - 2013

▪

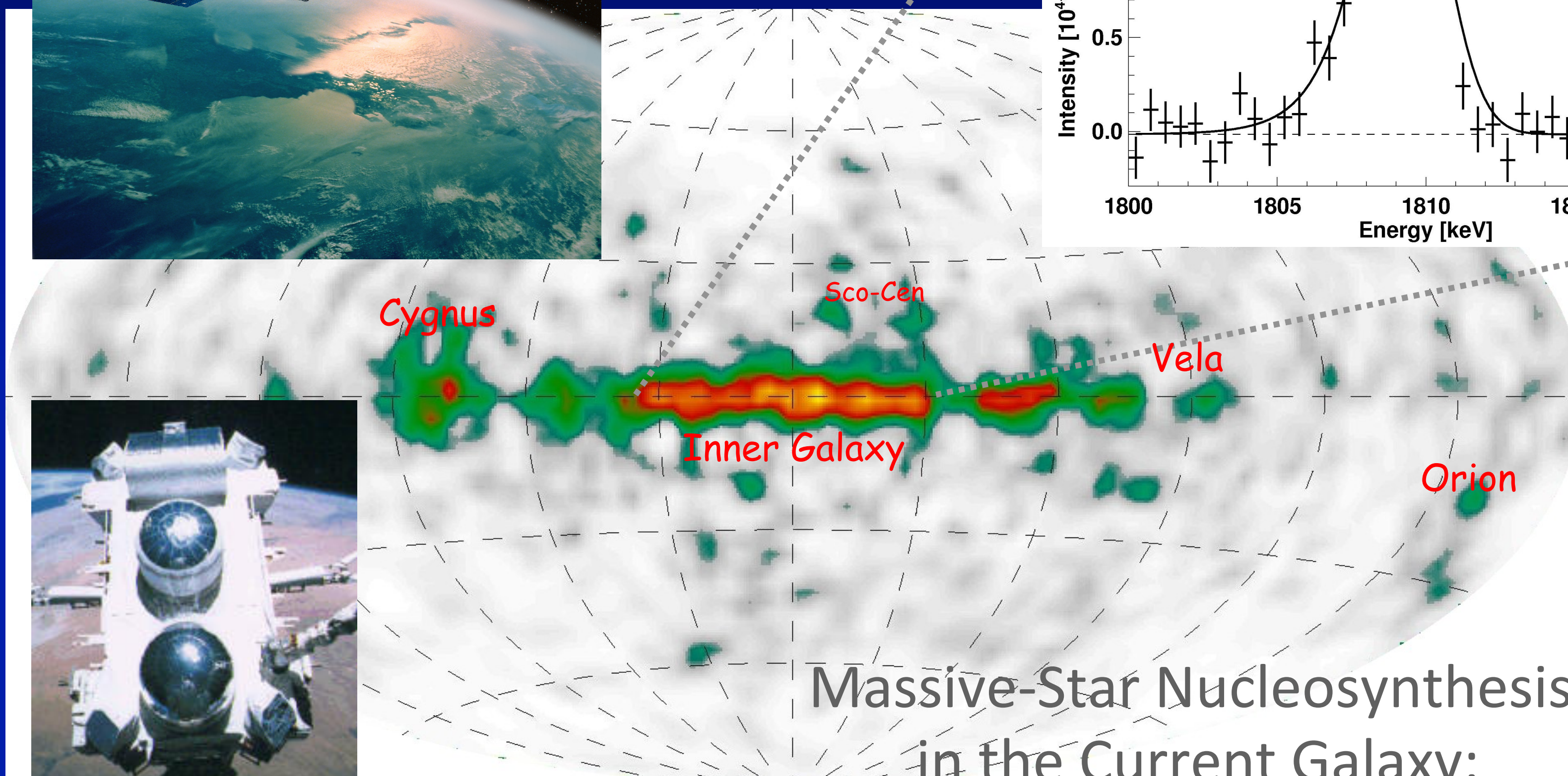


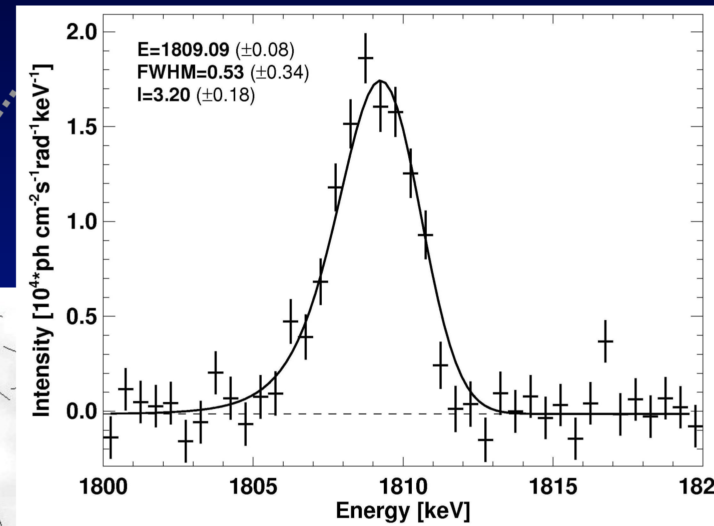
Energy Spectra: Characteristic Examples



☆ How are those data analyzed?

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





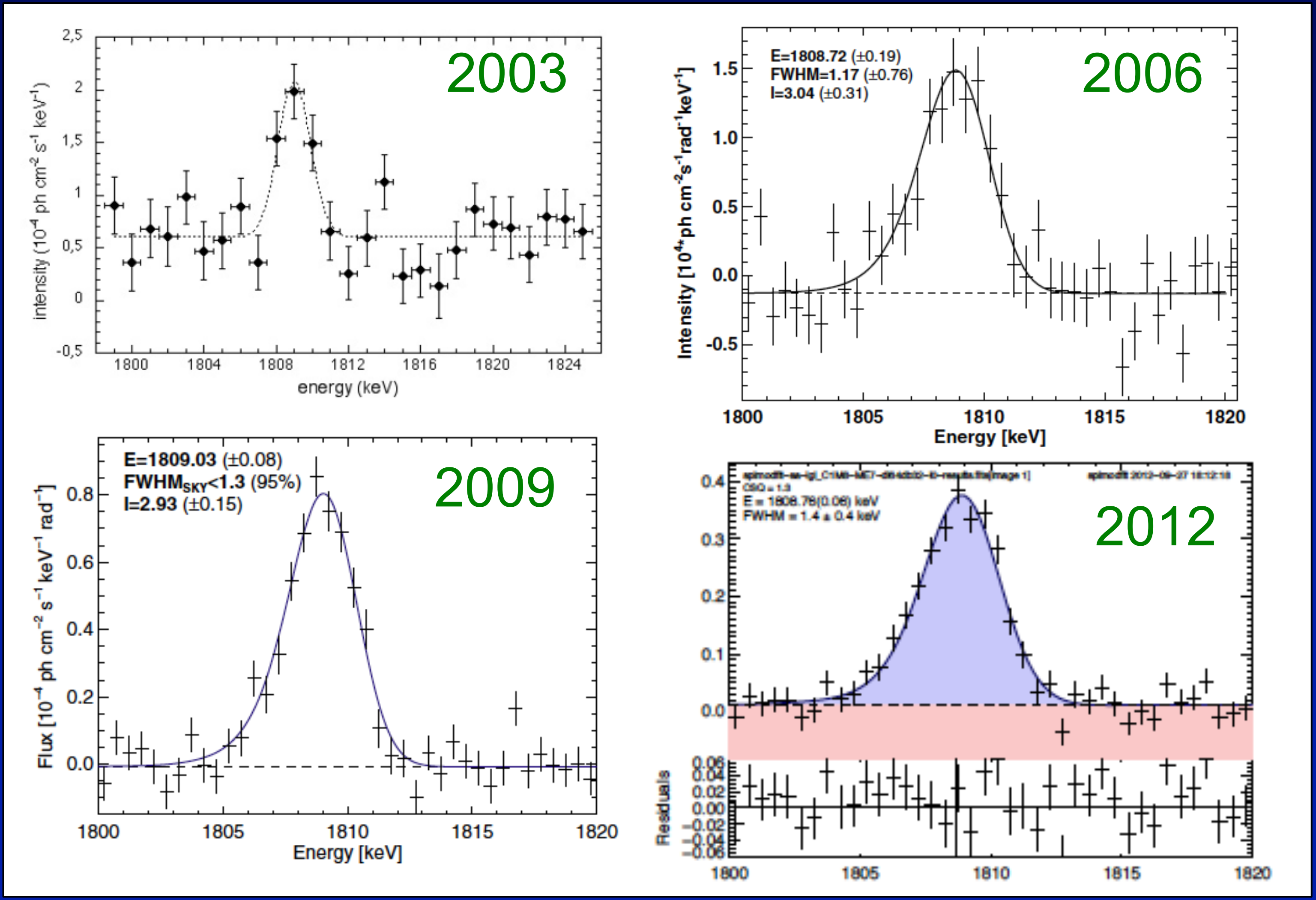
Massive-Star Nucleosynthesis in the Current Galaxy:

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

Measuring the ^{26}Al Gamma-Ray Line from the Galaxy

- Increasing Exposure (Oct 2002…. Today)

→

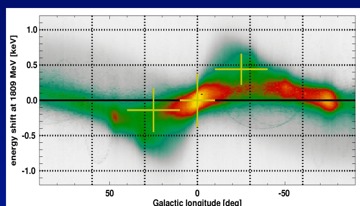


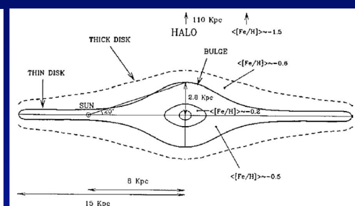
Using the ^{26}Al Line to Characterize the Galaxy

☆ Measured Gamma-Ray Flux

☆ Galaxy Geometry

} ➢ ^{26}**Al Mass in Galaxy**
= 2.25 (±0.65) $M_\odot$





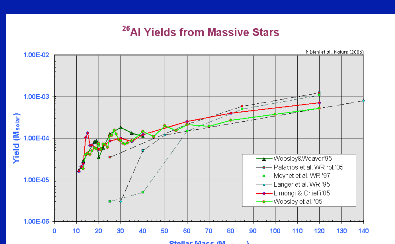
✓ cc-SN Rate = 1.5 (± 0.9) per Century

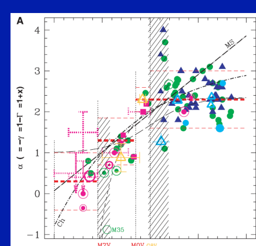
☆ ^{26}Al Yields per Star

☆ Stellar Mass Distribution

}

✓ SFR = 3.1 $M_\odot$/yr





☆ Gas Mass in Galaxy

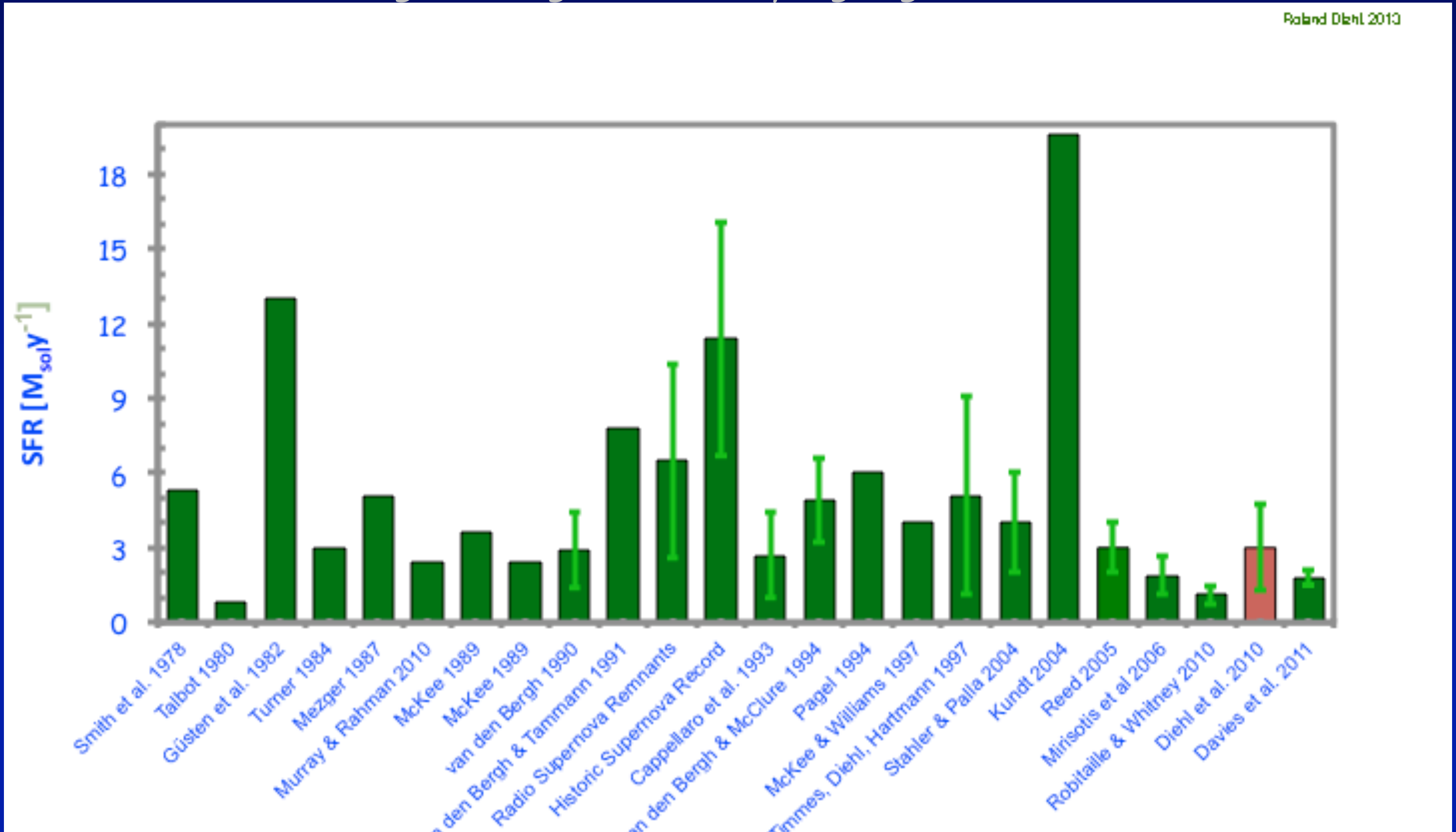
☞ M_{ISM} ~5 10^9 $M_\odot$

} ✓ **Al Isotopic Ratio = 6 10^{-6}**

The Galactic Star Formation Rate

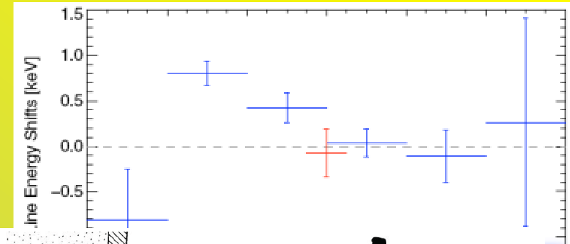
☞ Overall Rate ~2..3 $M_\odot$/yr (1.9 +/-0.4 $M_\odot$/yr, Chomiuk&Povich 2012)

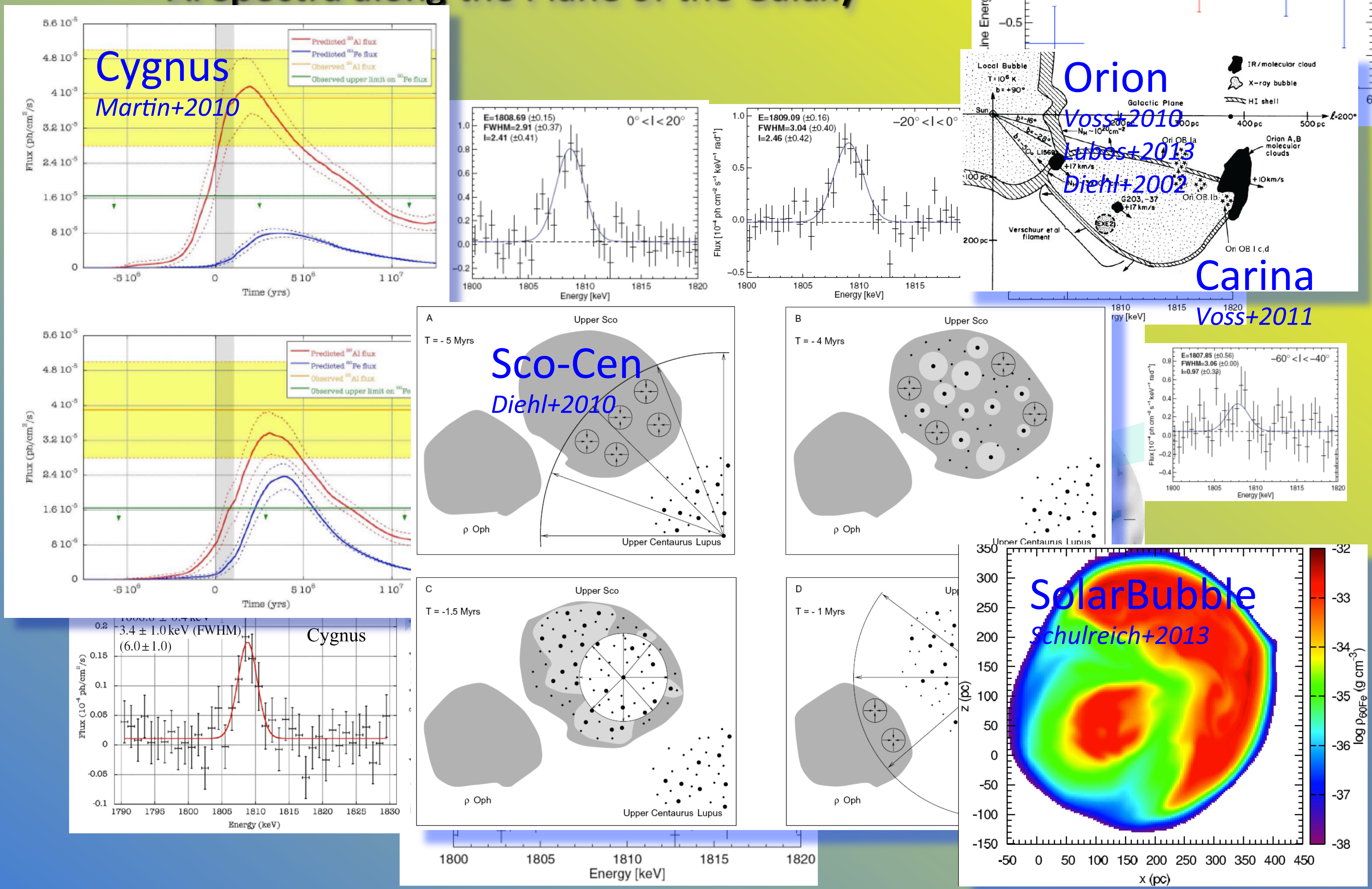
- Various methods, different biases
  - *Extragalactic/galactic; sampling region; IMF; models*



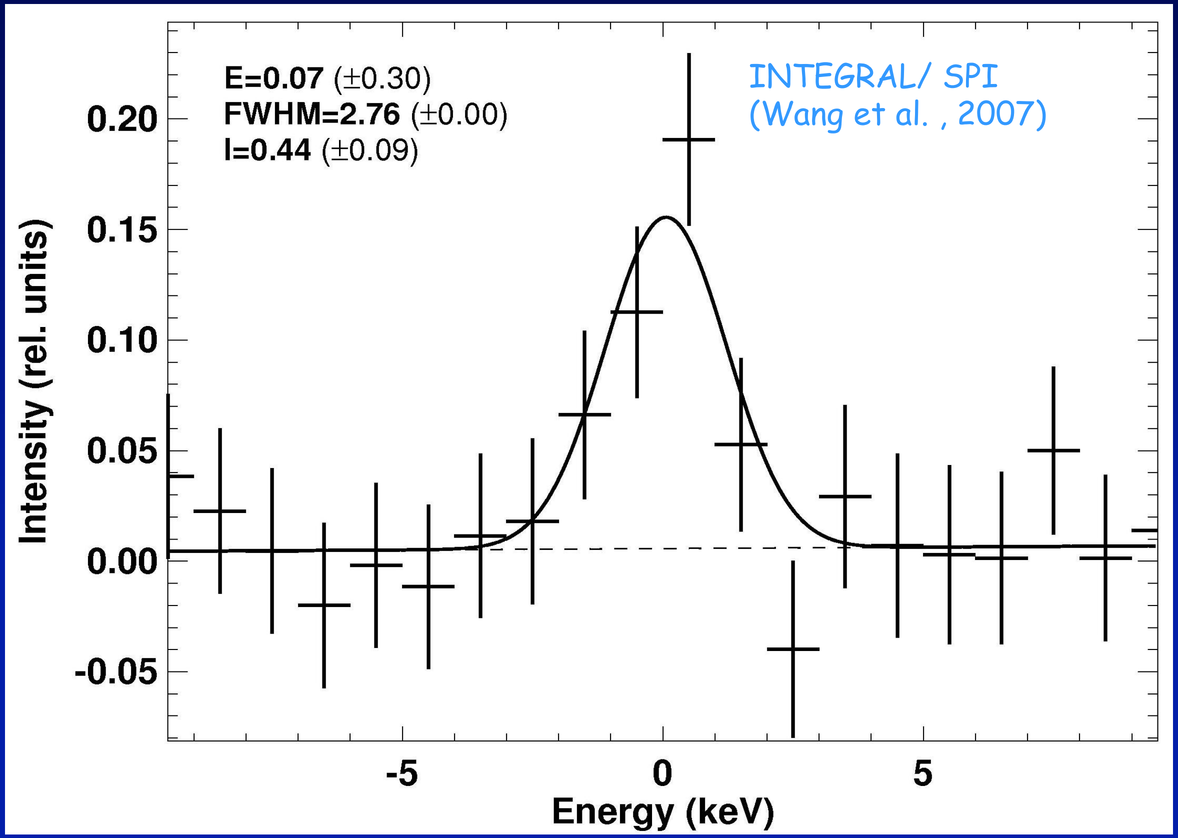
...from SN statistics in other galaxies; ionization; dust; star counts; nucleosynthesis – opt…radio..IR..γ-rays

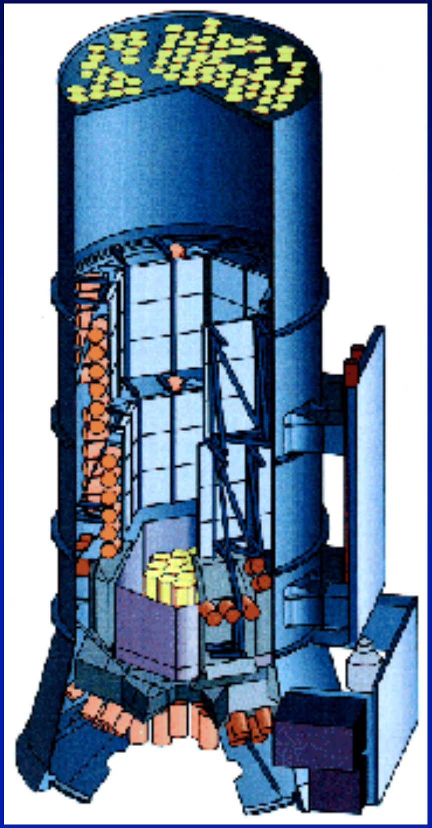
^{26}Al Spectra along the Plane of the Galaxy





^{60}Fe Emission is Seen from the Galaxy

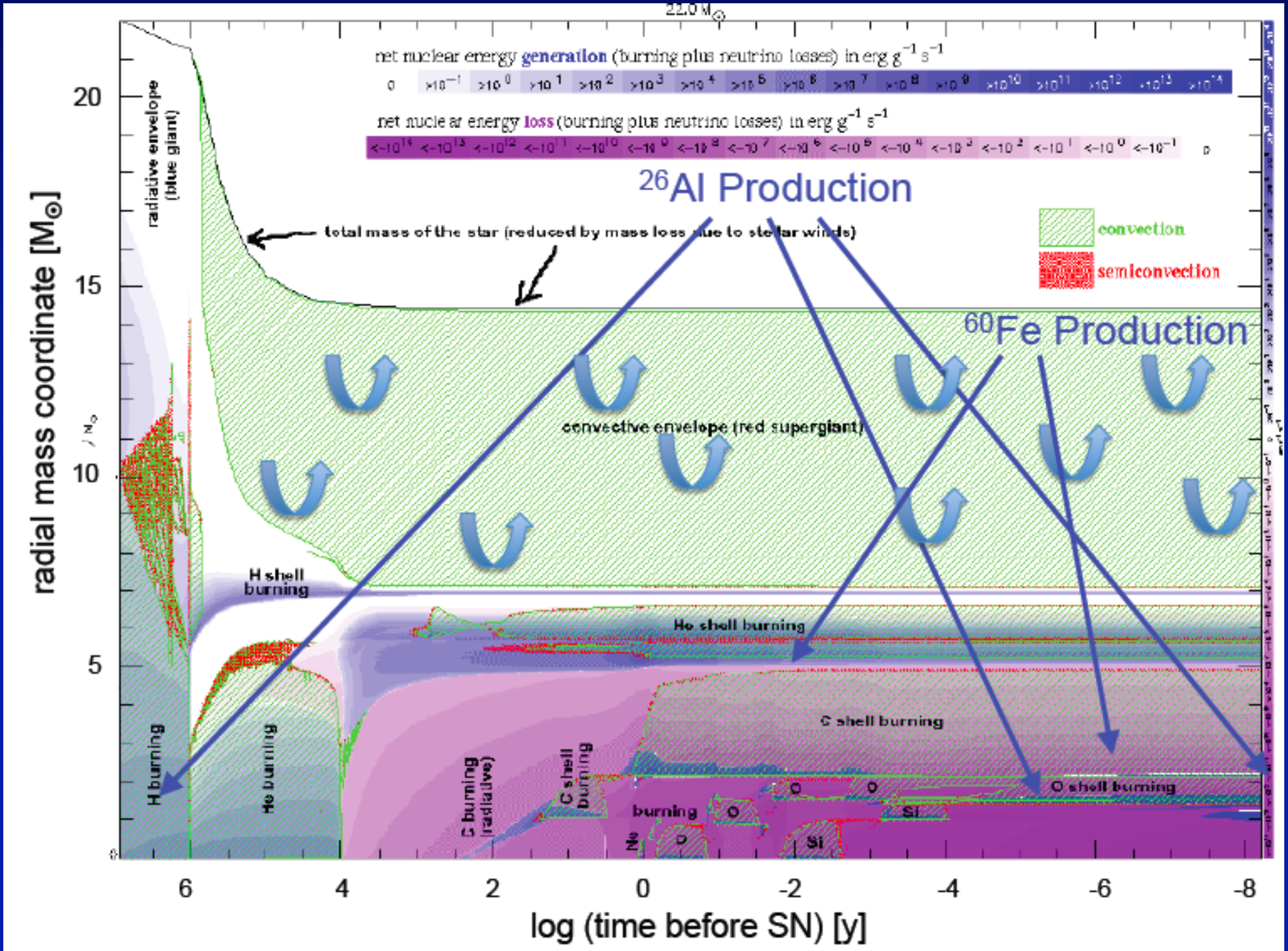




- ☆ Gamma-ray Signal Now Beyond 'Hints'/'Limits' (5σ)
- ☆ ^{60}Fe/^{26}Al Emission Ratio ~15%

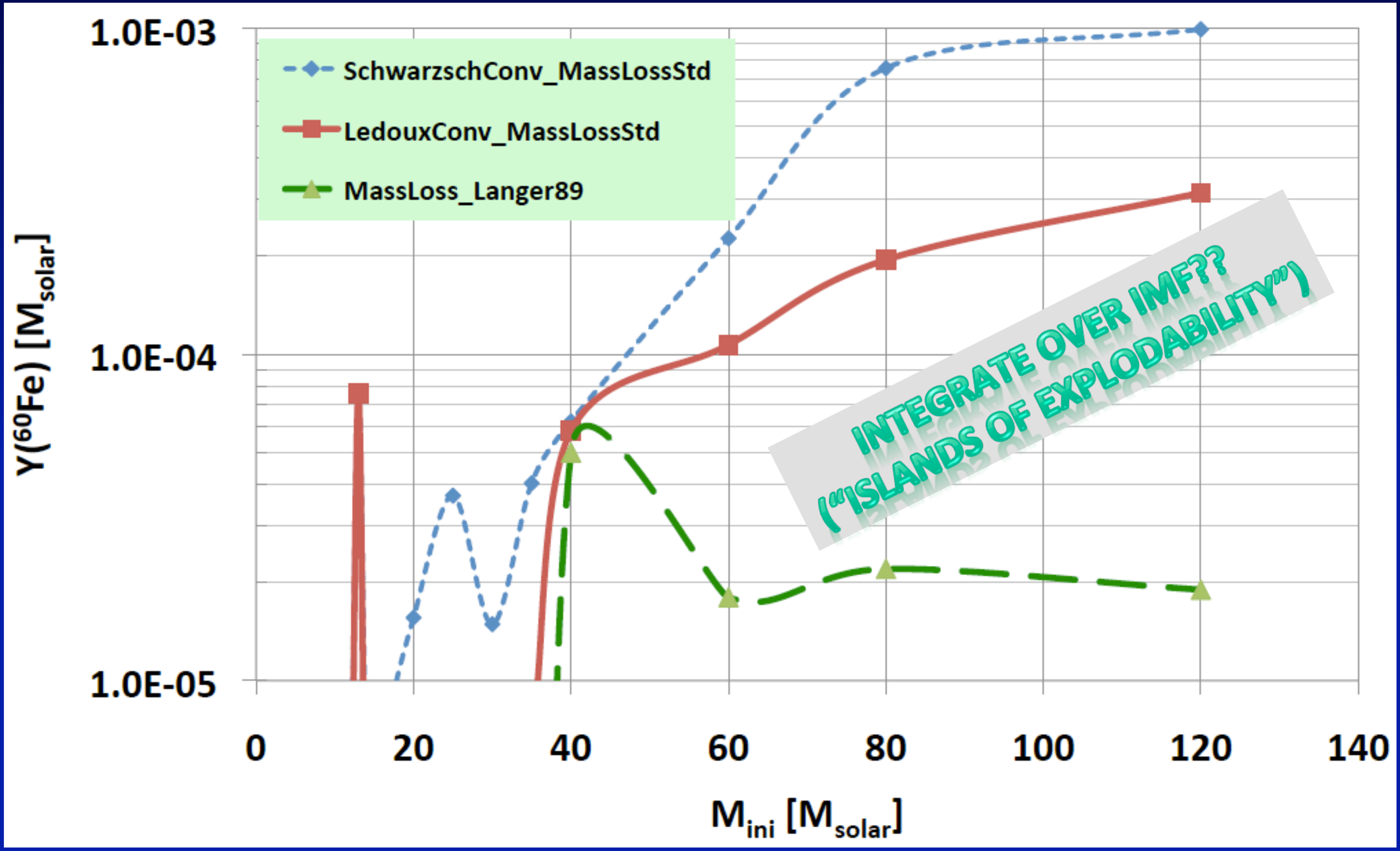
Massive-Star Structure Diagnostics: $^{60}Fe/^{26}Al$ Ratio

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



Yield of ^{60}Fe: Sensitive to Model Issues

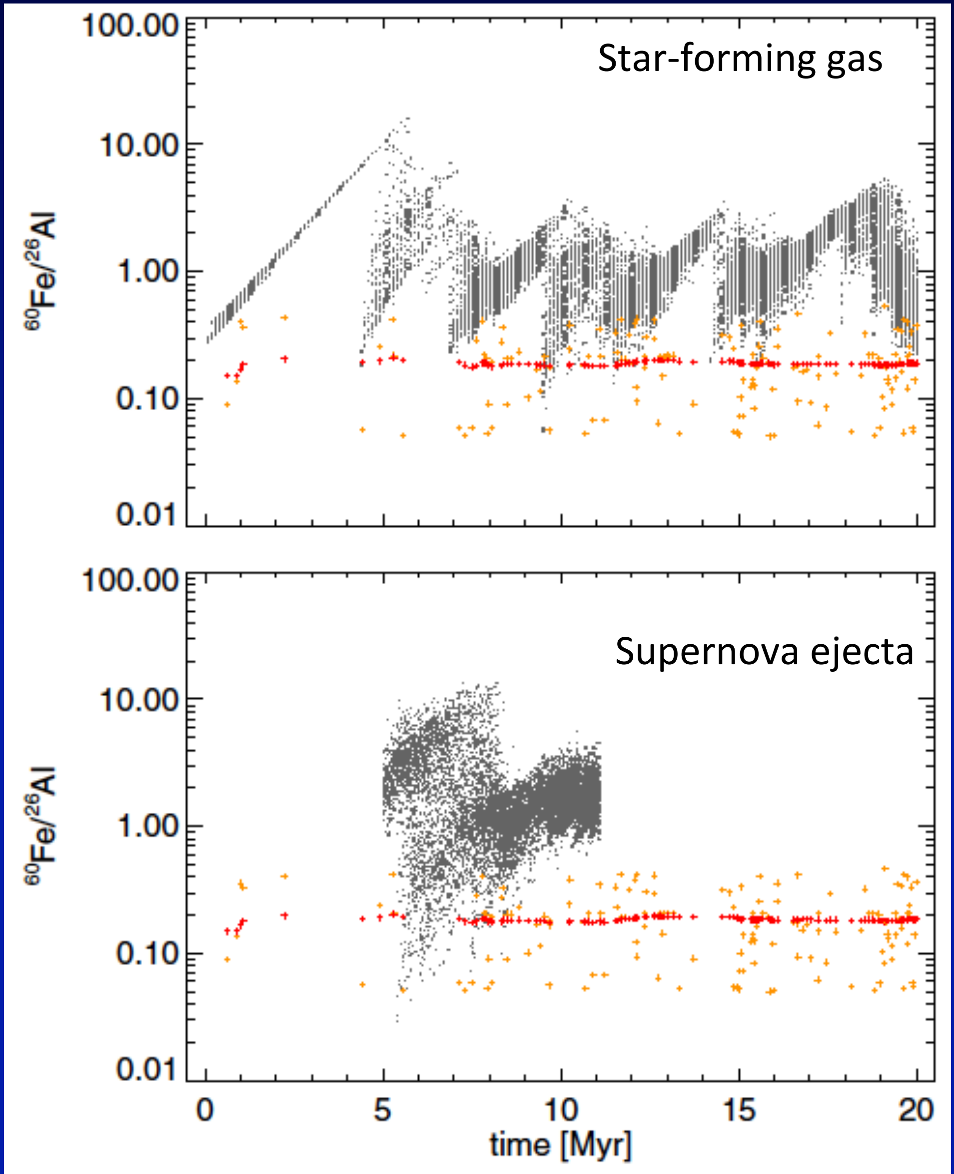
☆ Model Parameters Have Major Impact on Total Yield



$^{60}Fe/^{26}Al$: Expectations from stars as they form and explode

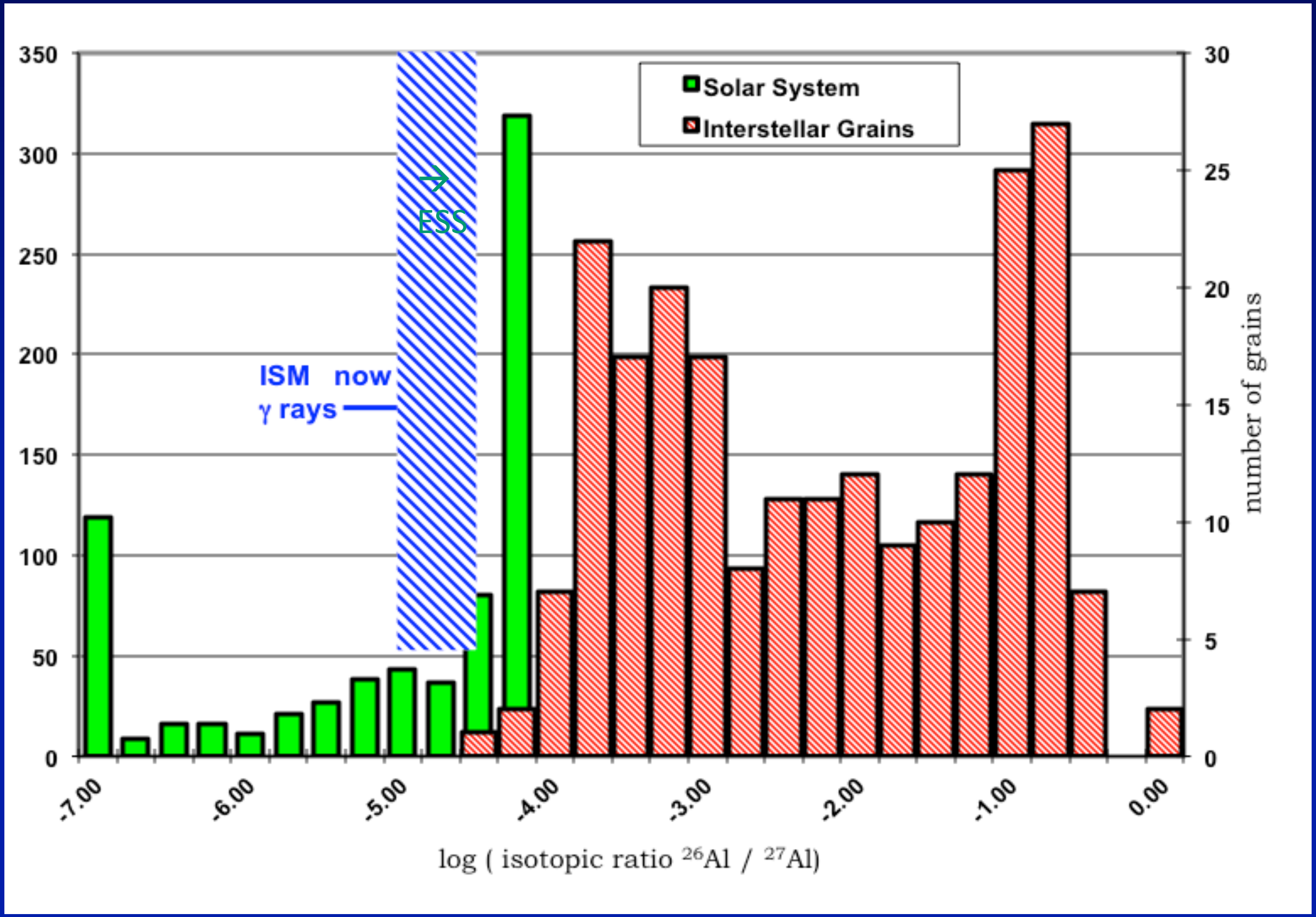
- Hydrodynamical Simulations of a Giant Molecular Cloud's Evolution
  → Stars, SNe, Ejecta Flows and Feedback

  Vasileiadis, Nordlund, and Bizzarro 2013



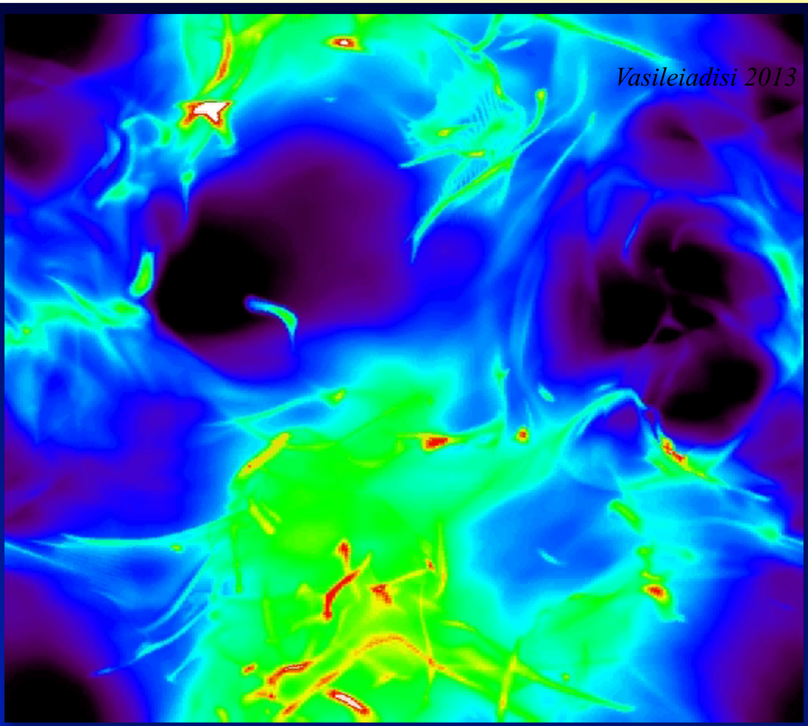
The $^{26}Al/^{27}Al$ Isotope Ratio

- ☆ Current ISM Value Measured from γ-Rays → 6 10^{-6}
  - ☞ evolution $^{27}Al \sim t^2$ (secondary isotope), ^{26}Al steady → 1.5 10^{-5} in ISM at ESS
- ☆ Compare to Meteoritic (=ESS) and Presolar-Grain (sources) values
  - ☞ ESS Meteorites: 5.2 10^{-5}

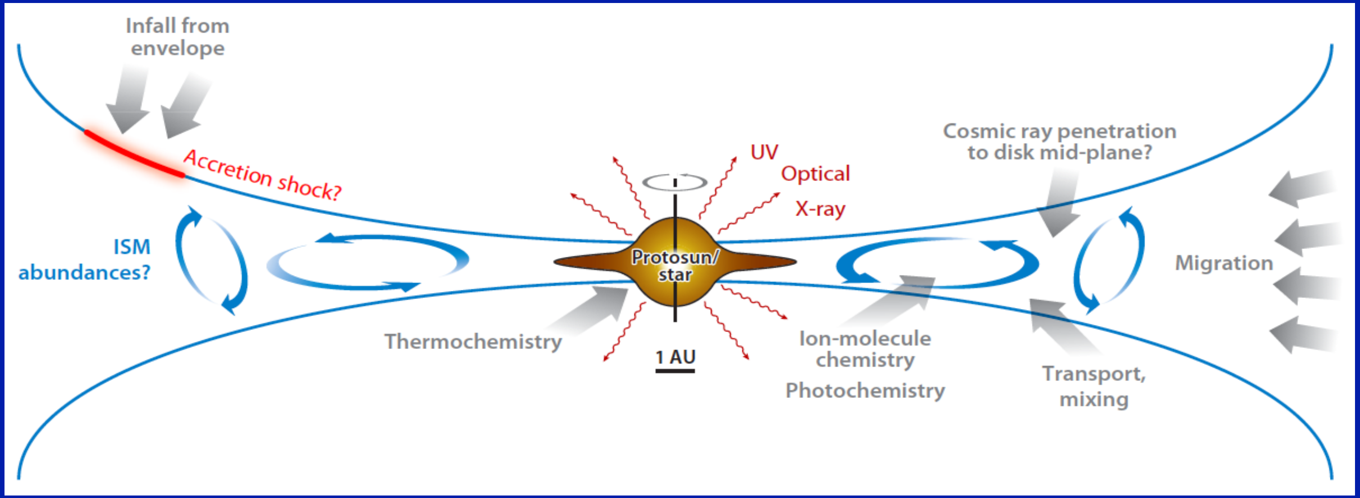


- ☆ Enrichment of ESS?

ISM transport towards a newly-forming star/Sun



- From the dynamic ISM a concentration of gas cools → protostar
- ISM ingestion through rapid disk flow
- Accreting ISM partly forms solids at inner disk edge

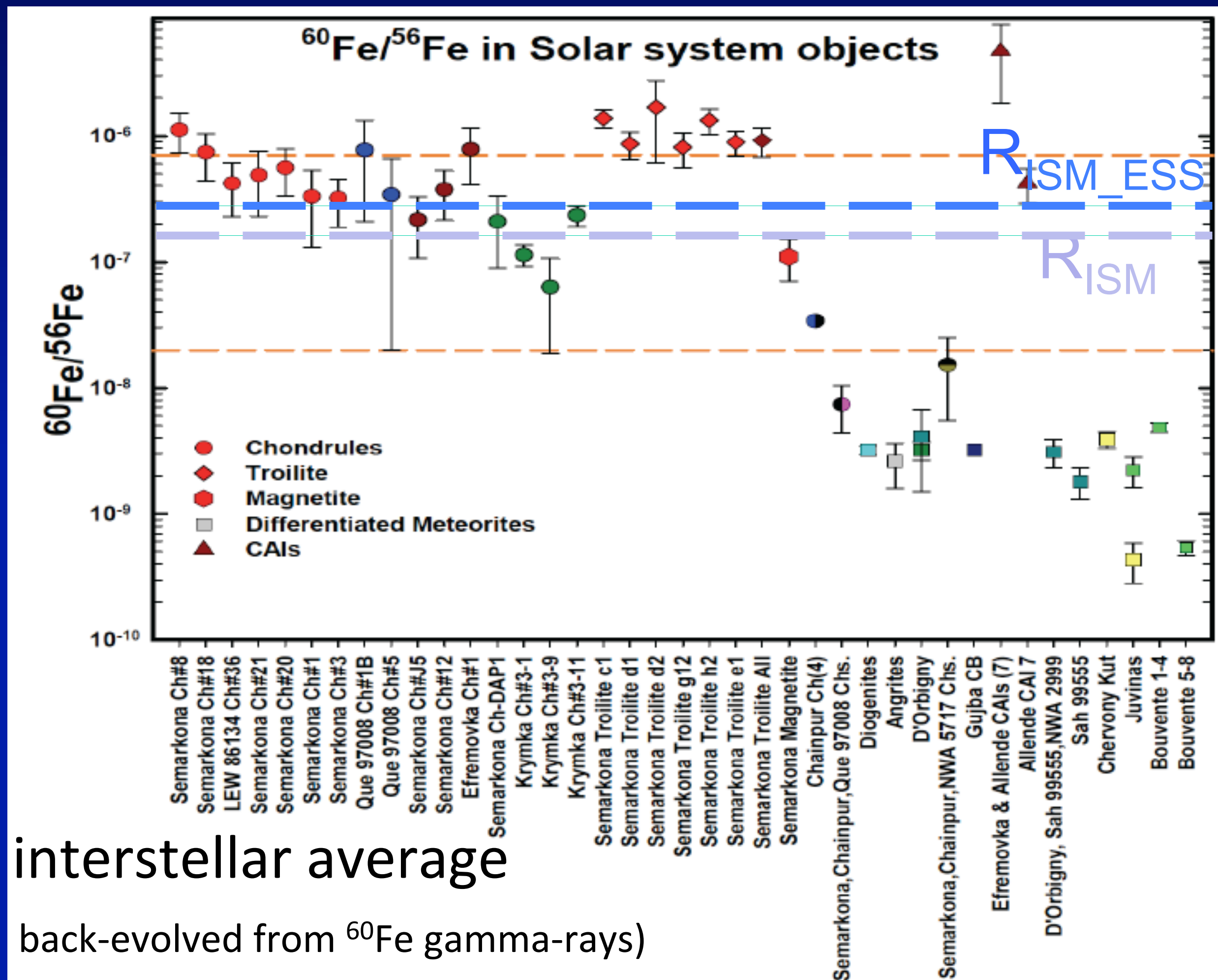


^{60}Fe in the Early Solar System

☆ Measurements from Early Condensated Bodies:

☞ Initial ^{60}Fe/^{56}Fe ratios uncertain between few 10^{-7} and $<10^{-8}$

Mishra+2013



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☆ Could be ~ interstellar average

(R_ISM_ESS, back-evolved from ^{60}Fe gamma-rays)

SN Ejecta Nearby: Transport in ISM

- ^{60}Fe Clearly Seen on Earth
  - ☆ in Oceanfloor Sample (Knie et al.)
  - ☆ in Lunar Samples (Fimiani et al.)
  - ☆ in Sediments (Bishop et al.)

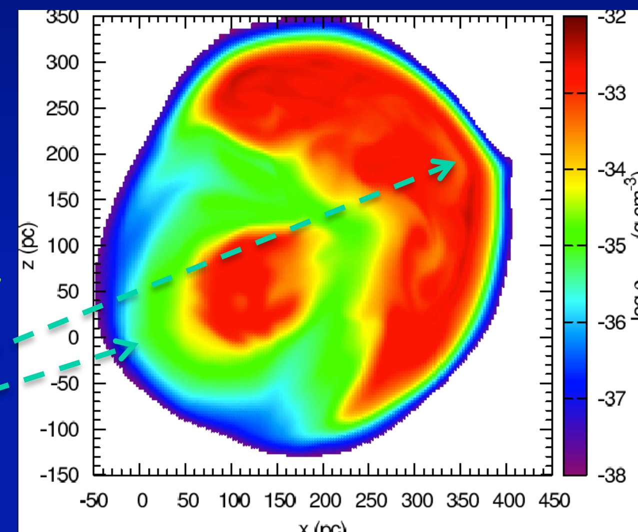
- ^{26}Al → Study ISM Dynamics

→

☆SN Ejecta Transport at ~10pc Scale??

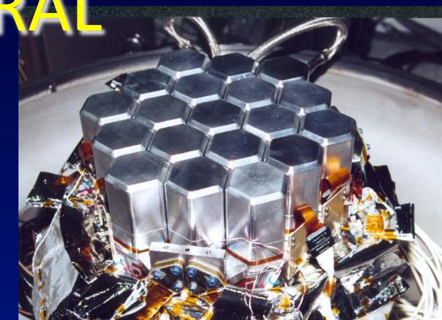
3D Hydrodyn. Simulation of Local Bubble (M. Schulreich+, in prep.)

SN Sun



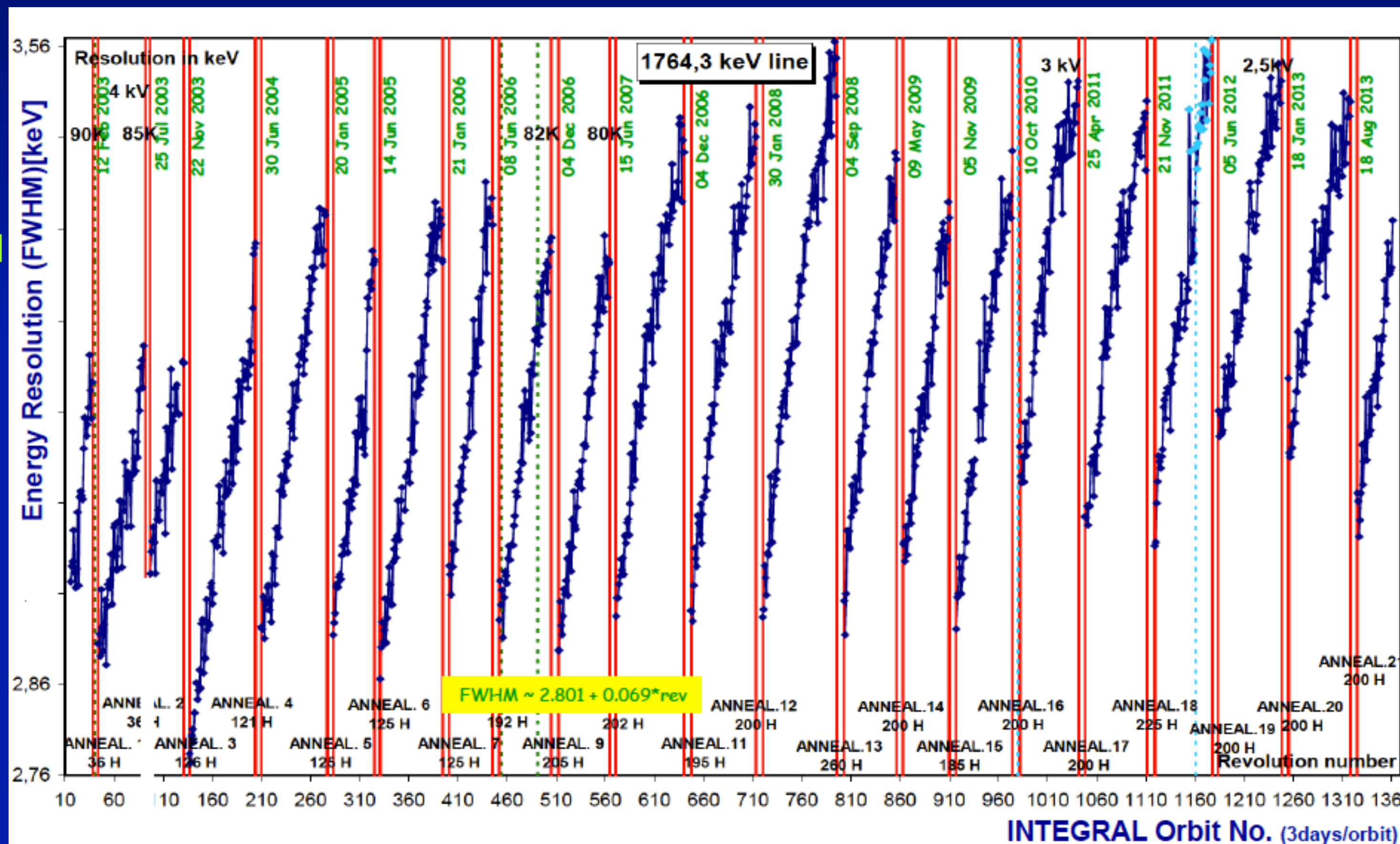
High-Resolution Gamma-Ray Spectroscopy Maintained in Space: SPI on INTEGRAL

- Cosmic-Ray Irradiation
  - → Degradation of Charge Collection
    - ☆ ~2% per Orbit, ~20% in 6 Months (@1 MeV)
- Annealings: ~100-200 hrs at 105°C, few hrs at 90K



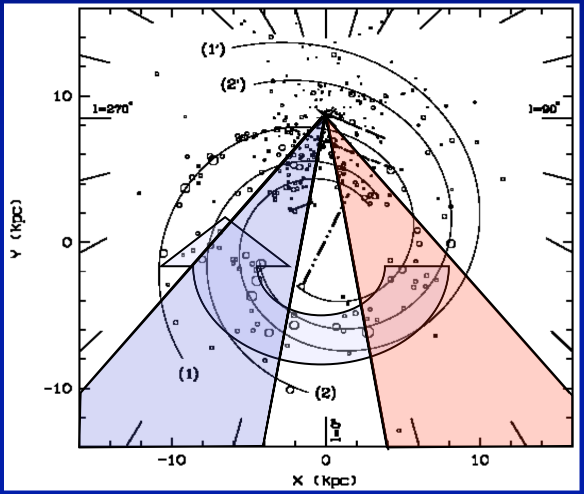
✓21 Annealings Successfully Completed (up to end 2013)

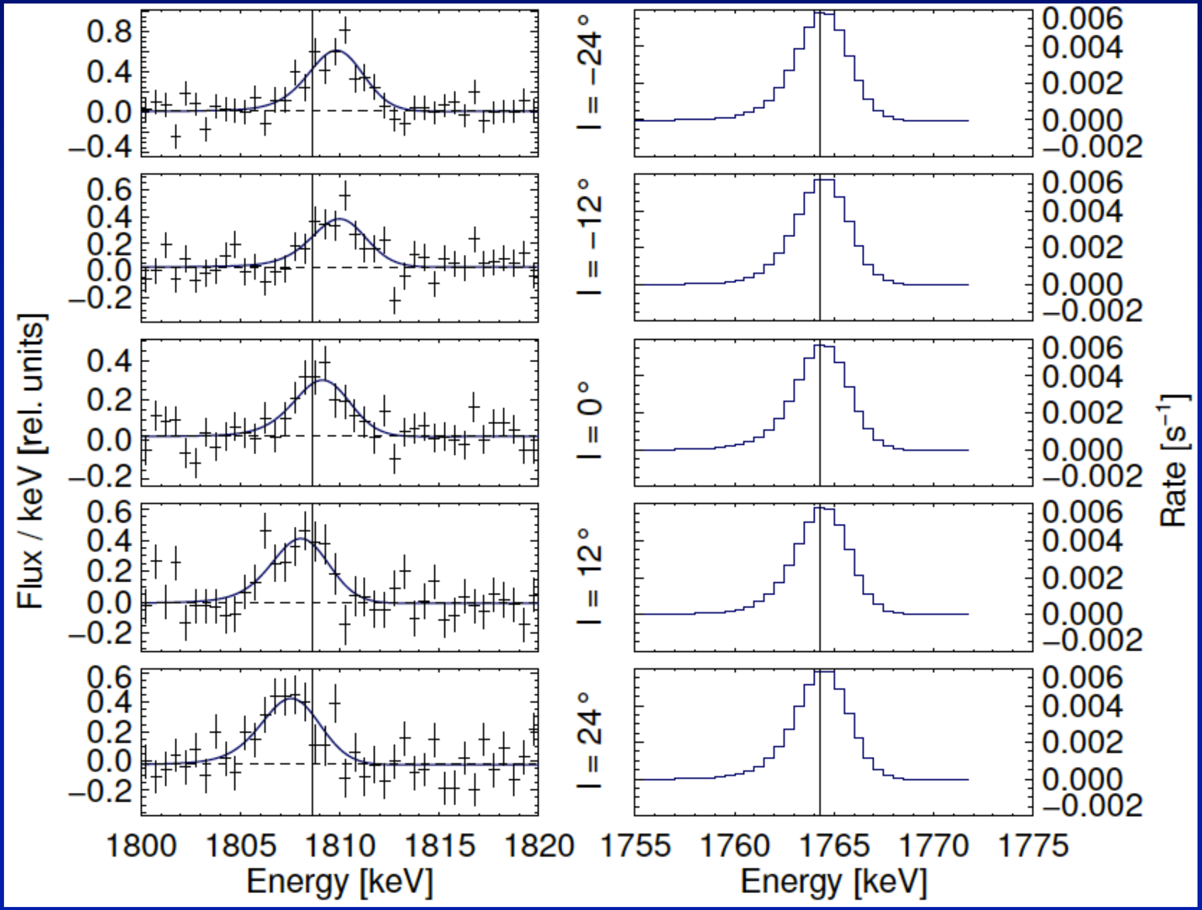
✓15 of 19 Detectors Operational with Fine Resolution



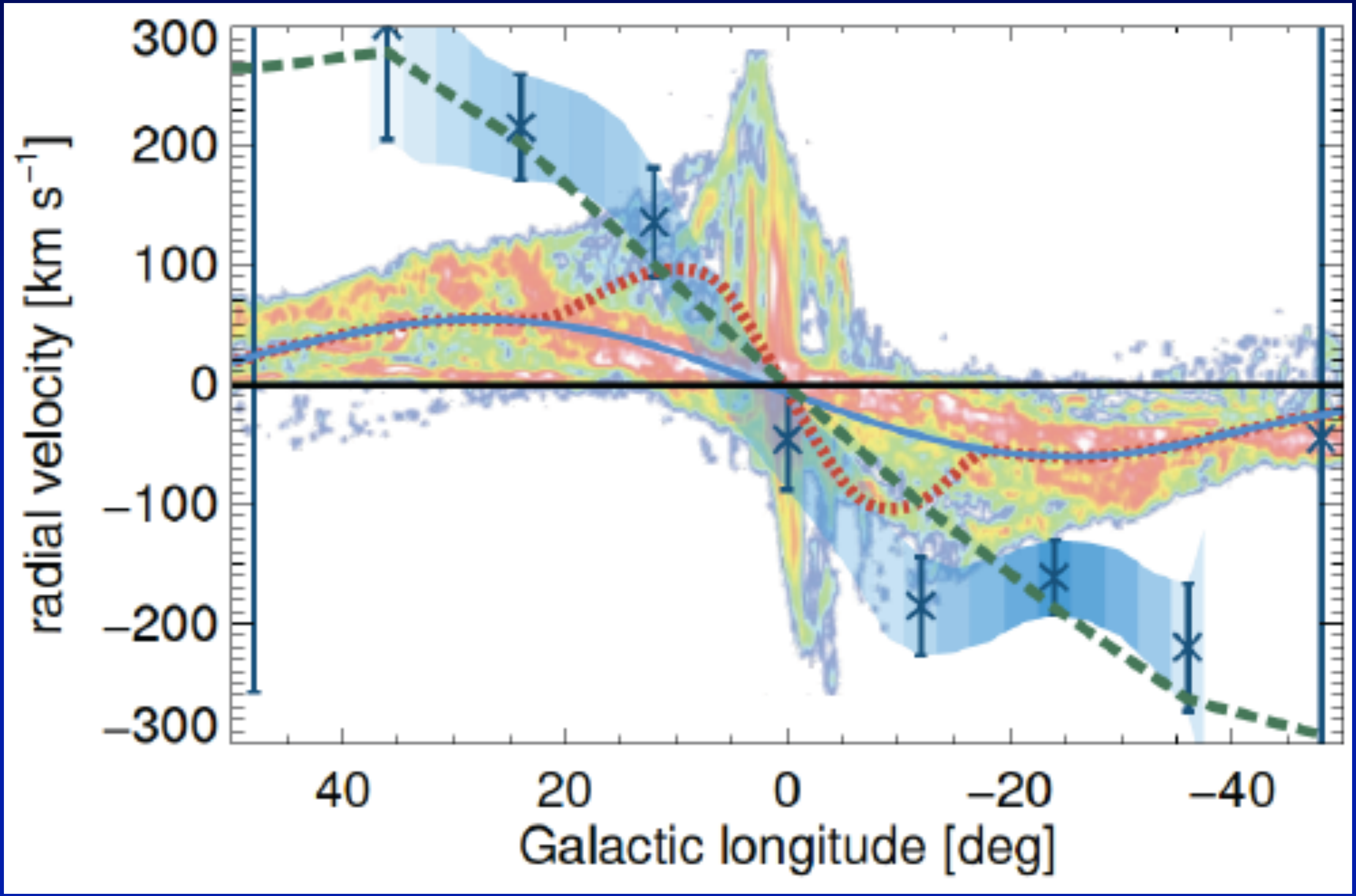
Spatially-Resolved Spectroscopy

- Analyze Line Shape and Position for Different Directions
  - ☆ Galactic Rotation





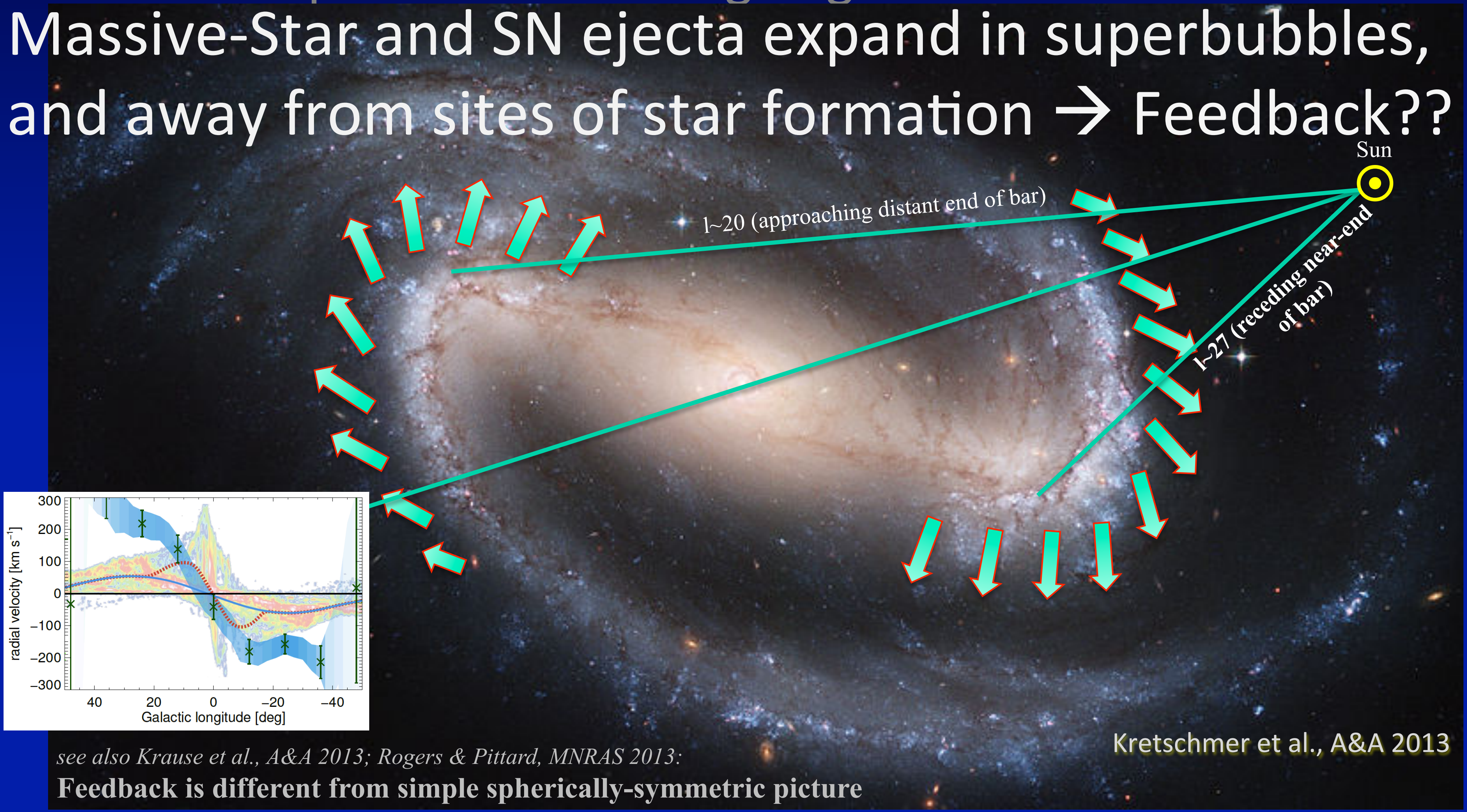
^{26}Al in the Inner Galaxy: Excess Gas Velocities Seen in ^{26}Al



How Massive-Star Feedback Occurs…

- ^{26}Al Kinematics → Large-scale preference for outflow towards spiral-arm's leading edges

Massive-Star and SN ejecta expand in superbubbles, and away from sites of star formation → Feedback??

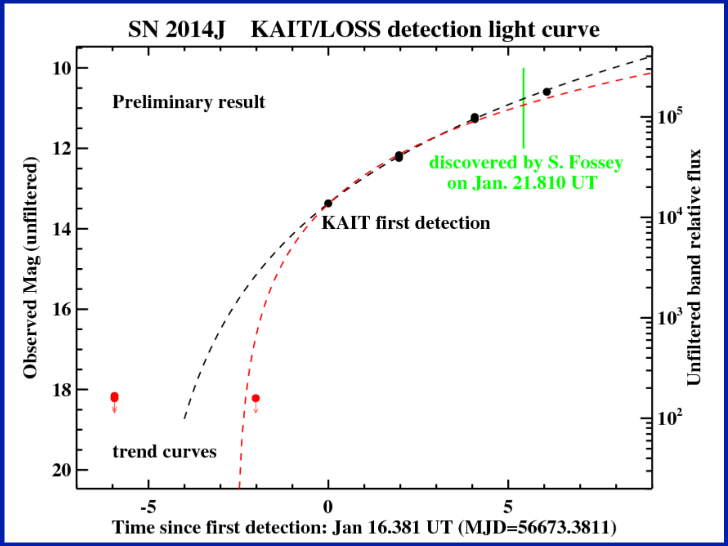


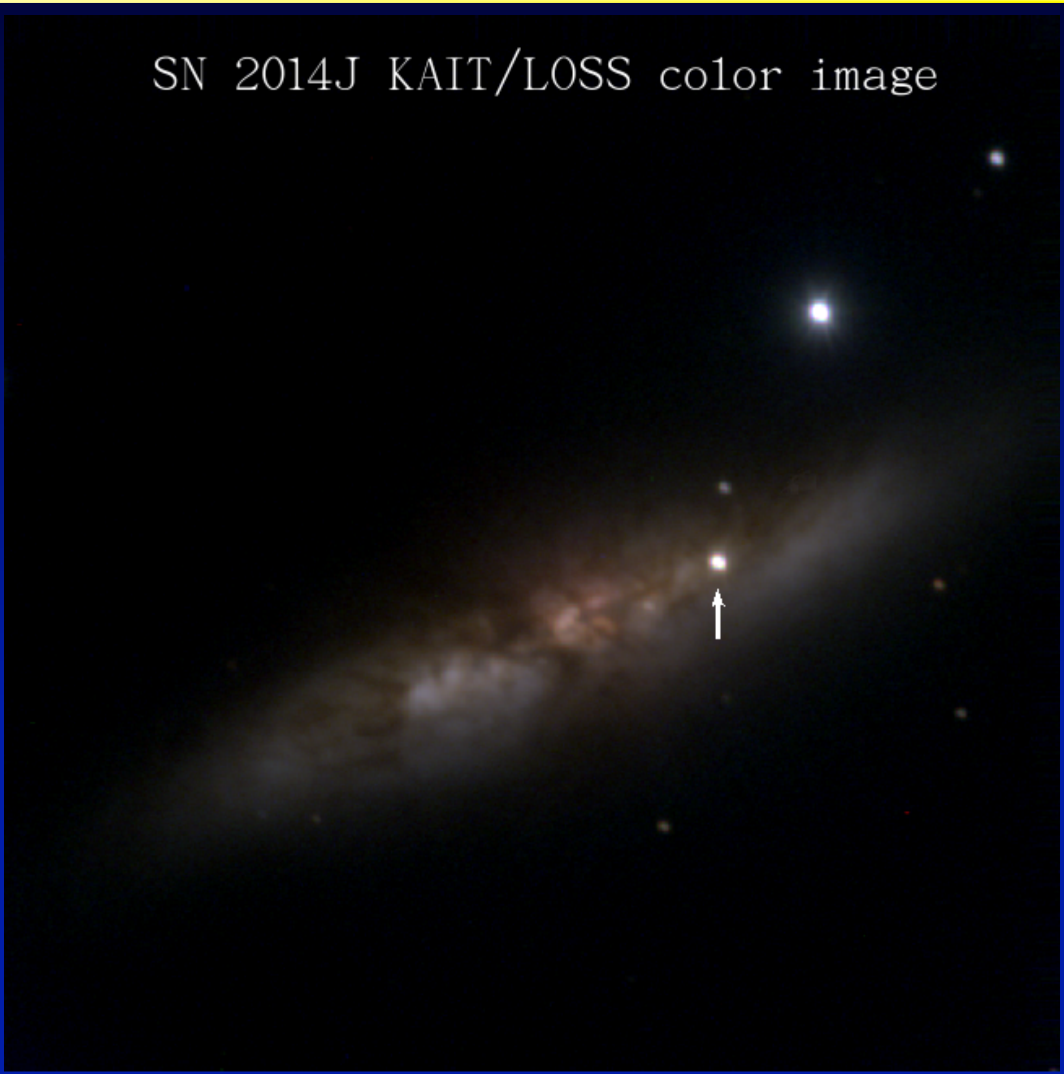
see also Krause et al., A&A 2013; Rogers & Pittard, MNRAS 2013:

Feedback is different from simple spherically-symmetric picture

SN2014J

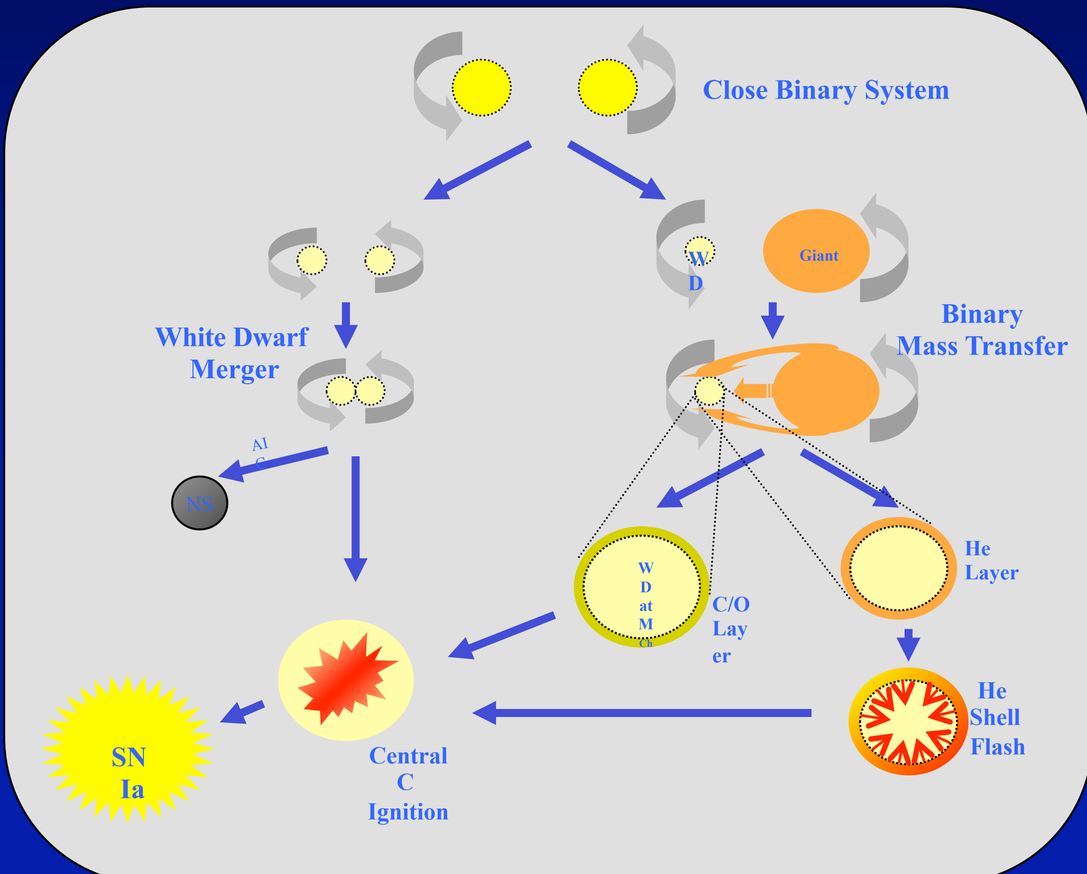
- In M82
  Starburst Galaxy
  - Discovered 22 Jan 2014
    Cao et al. ATel # 5786
  - Likely Explosion Date
    14 Jan 2014
  - Distance 3.53 Mpc,
    l=141.41, b=40.56

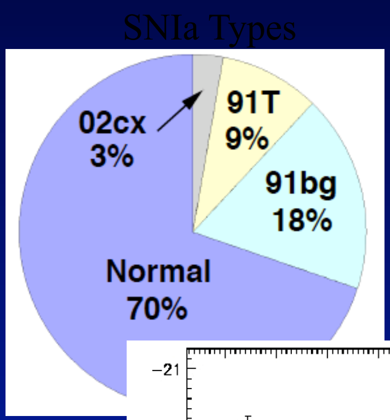




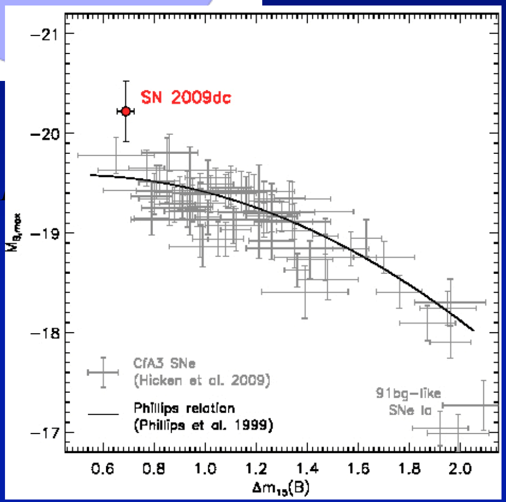
SNIa: Model Issues

☞ Progenitor Diversity?

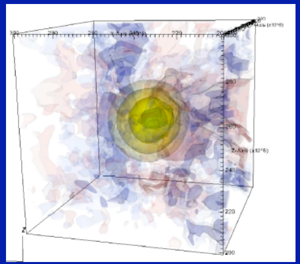




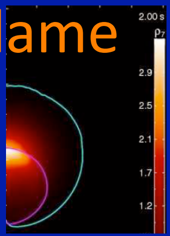
outliers?



Ignition?



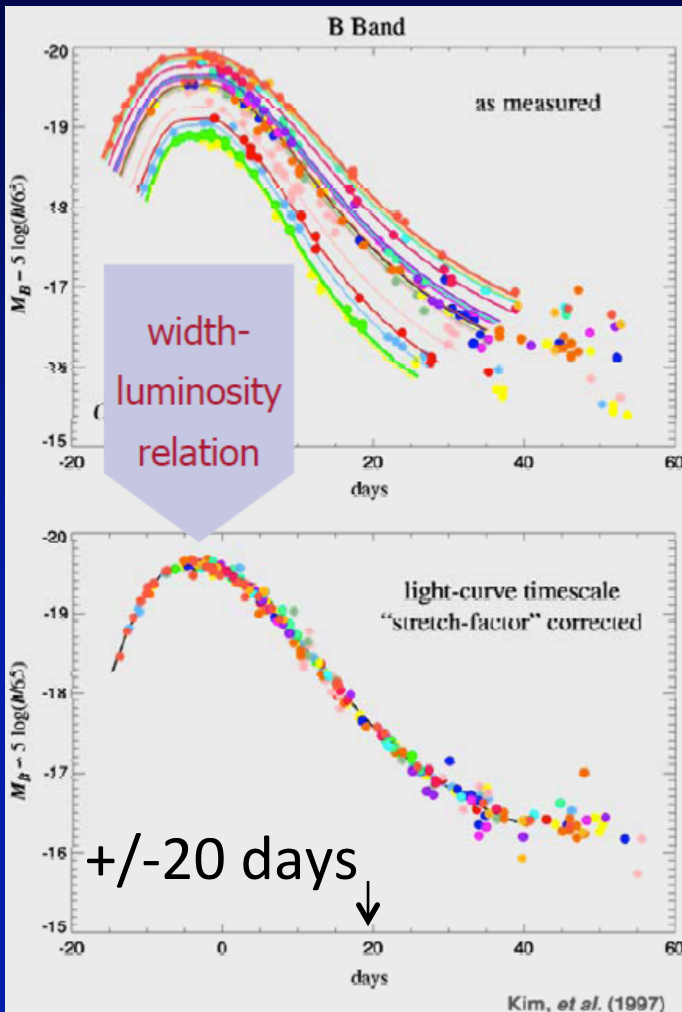
Flame

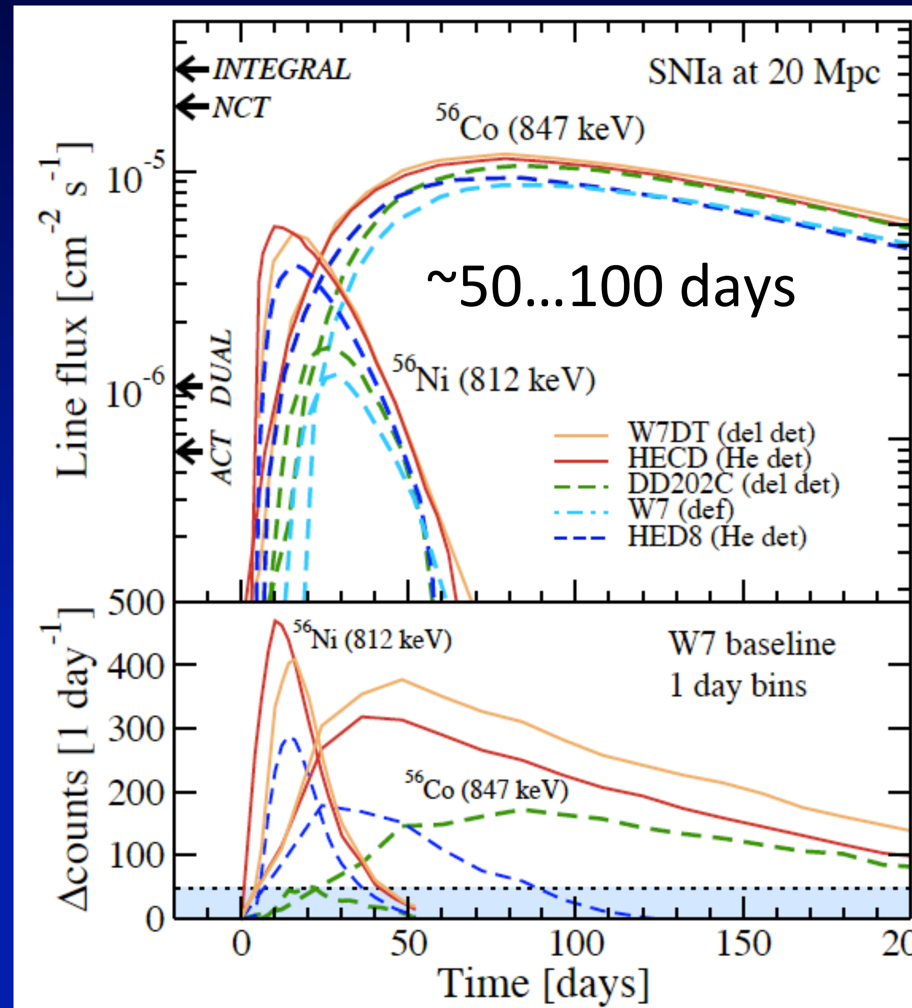


propagation?

Roland Diehl

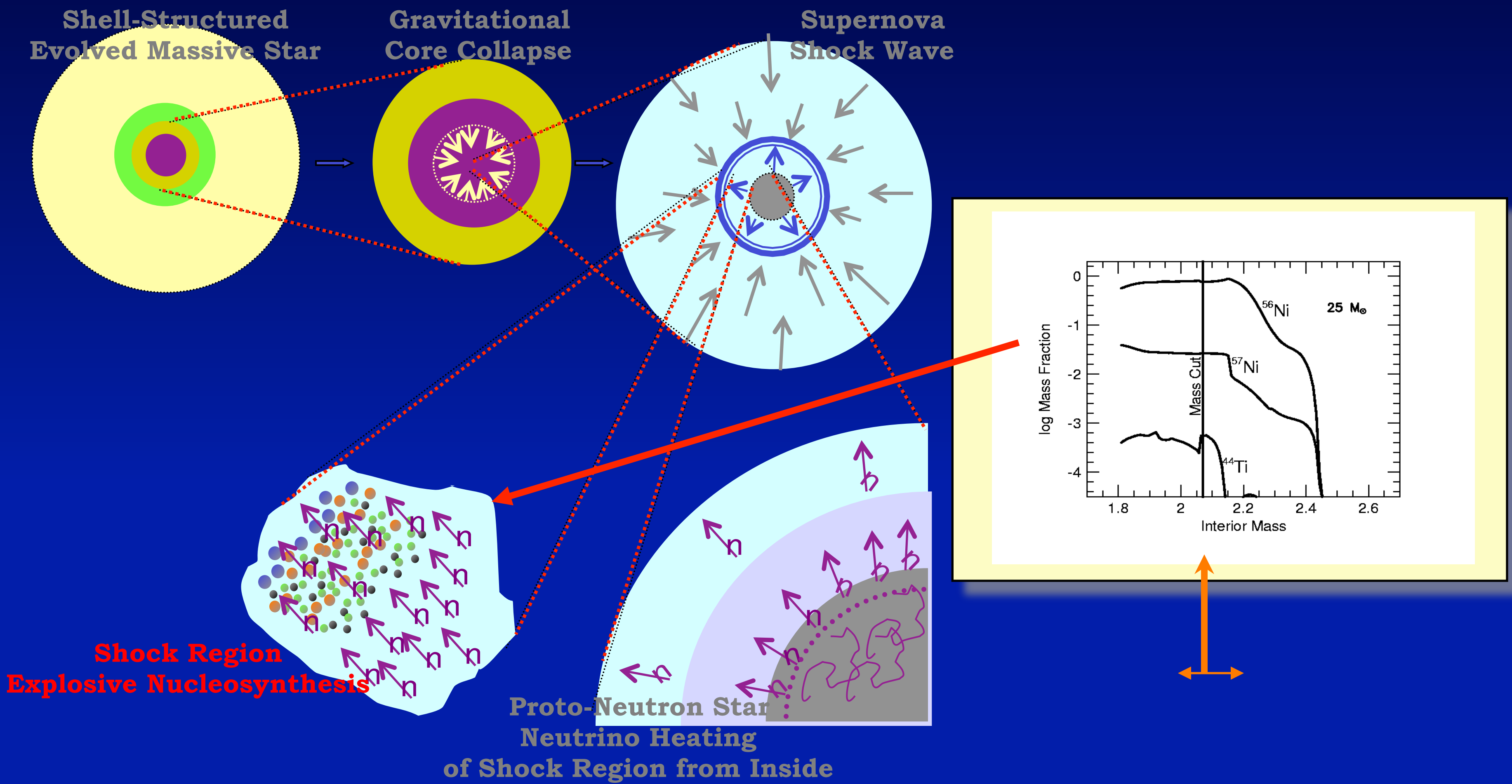
SNIa: Optical Light and Radioacivity Gamma-Rays





- Gamma-Calibrate SNIa Models in Early (10d) and Late (~100d) SNR Evolution
  - ☆ Issues: Phillips Relation, Light Transport Codes from Gamma to X/UV/OPT/IR

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



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

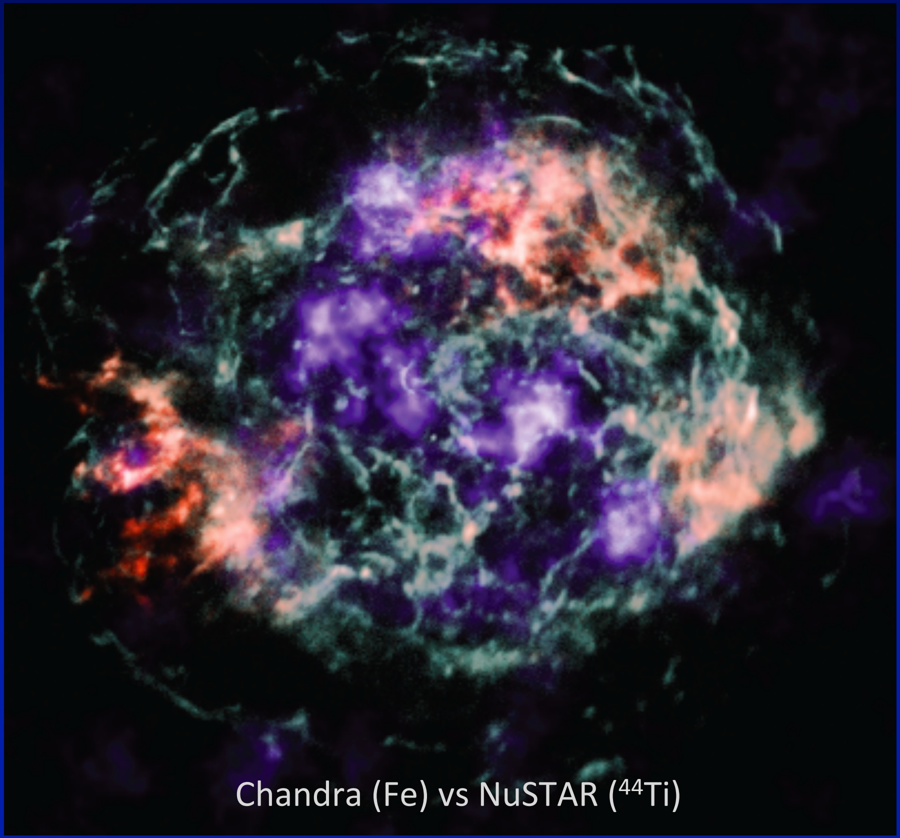
  => Unique Probe (+Ni Isotopes)

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 ever

- 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
- continuum: harder near rim



Chandra (Fe) vs NuSTAR (^{44}Ti)

☞ SN1987A: 6 σ, consistent with INTEGRAL flux (no image)

F Harrison, AG Tübingen Sep 2013
Grefenstette et al., Nat, 2014

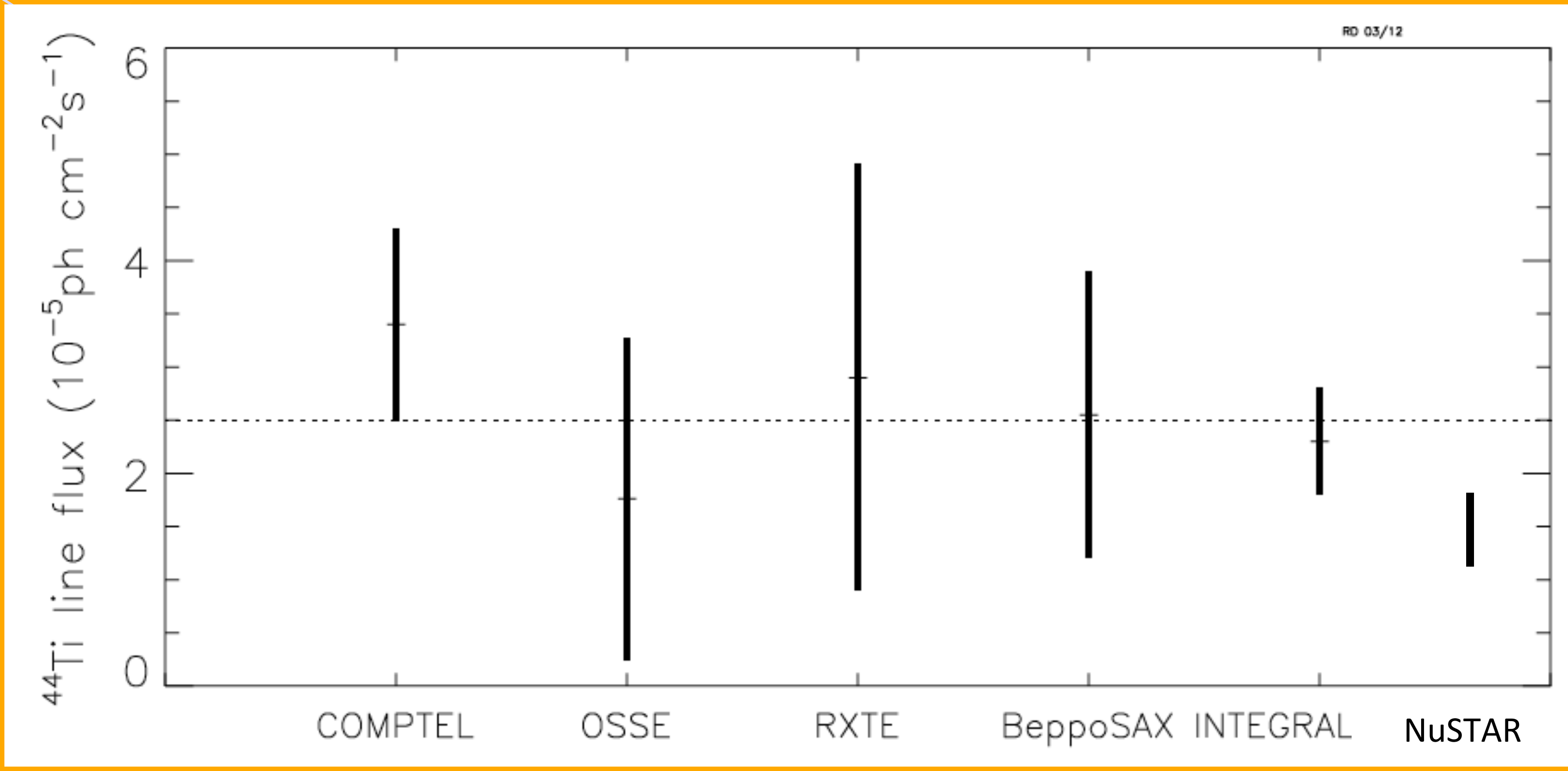
^{44}Ti γ-rays from Cas A

t=85y (Ahmad et al. 2006)

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

[illegible]=85y, EC

^{44}Ti



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

SN1987A with INTEGRAL

- INTEGRAL Line Band Imaging with IBIS *(Grebenev+2012)*
  - ☞ Detection at 5s significance (6 Ms exposure)

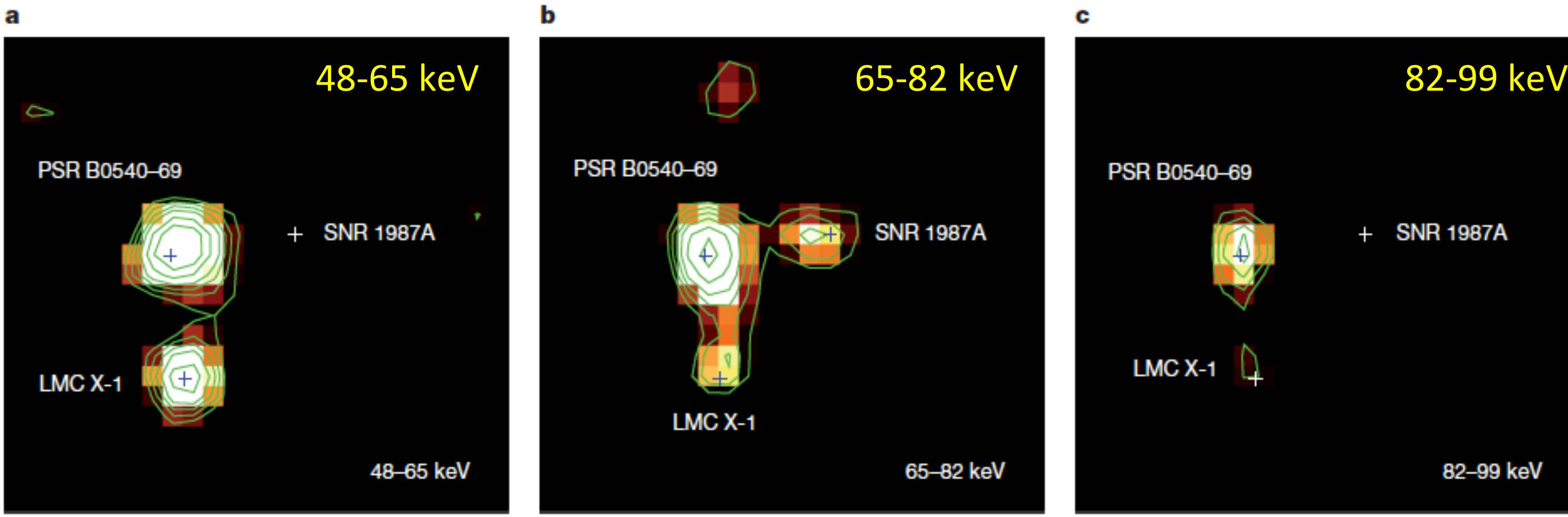
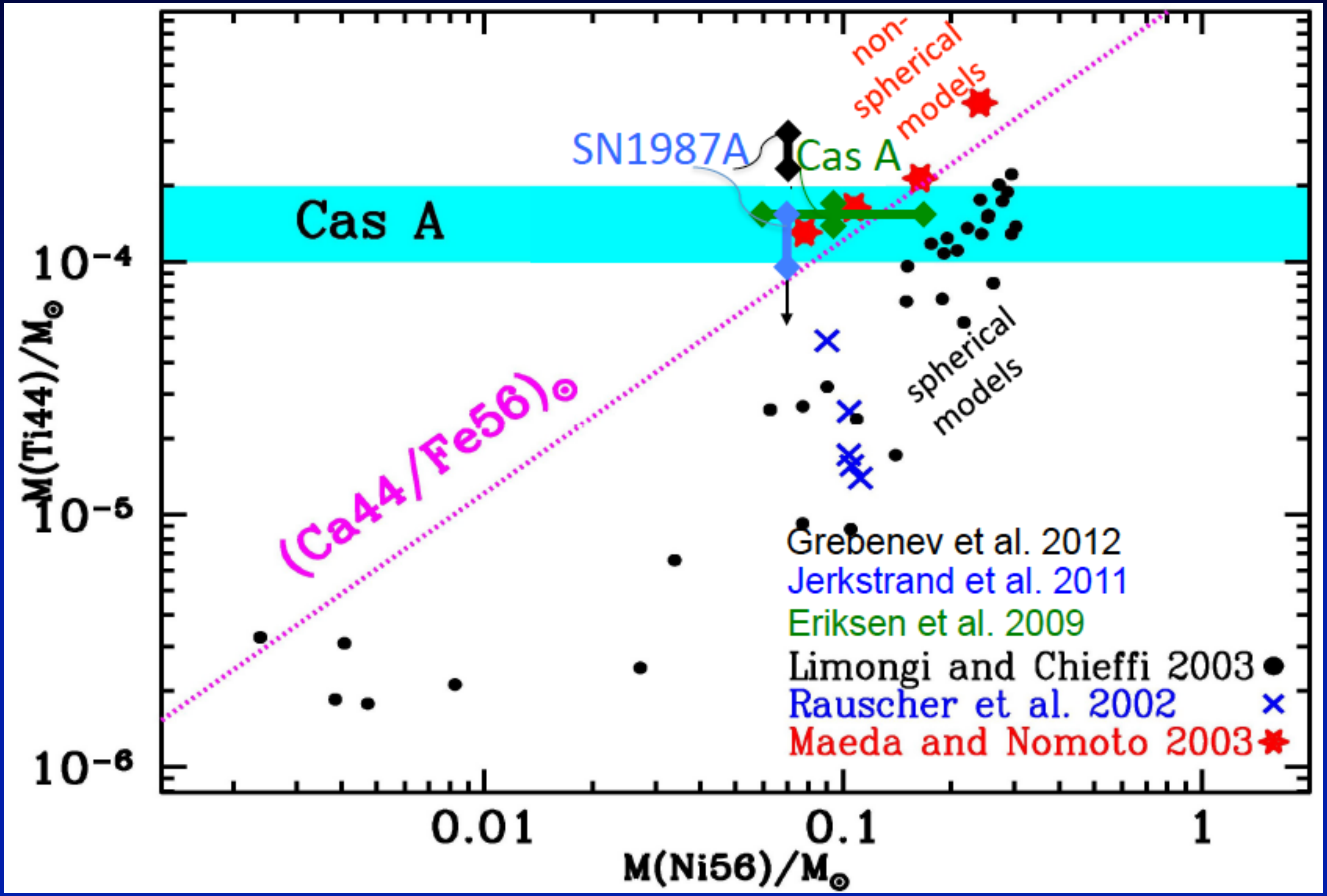


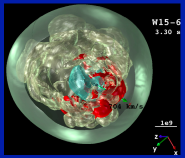
Figure 1 | Hard-X-ray images indicating the detection of ^{44}Ti emission lines from SNR 1987A. a–c, Maps of the signal-to-noise ratio (*S/N*) of the 1.5° × 1.5° sky region around SNR 1987A accumulated in three energy bands with the IBIS/ISGRI telescope on board INTEGRAL during observations in 2003–2011 (~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.

↳ ^{44}Ti Ejected Mass ~3.1 $\pm$0.8 10^{-4} $M_\odot$

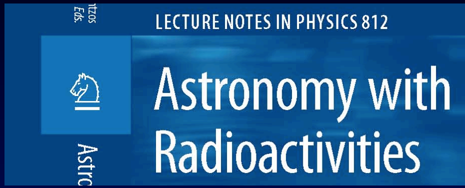
↳ LC Analysis Jerkstrand+2011: ~1…2 10^{-4} $M_\odot$

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

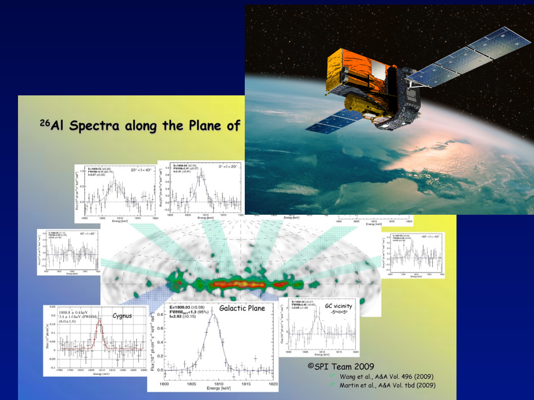




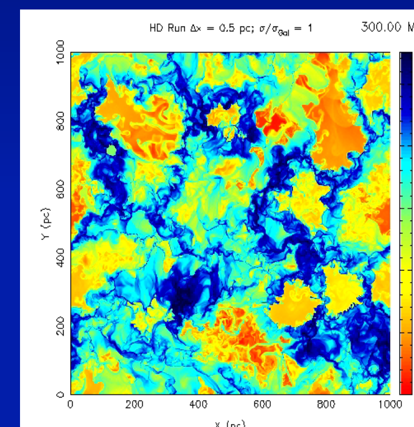
- Only Non-Spherical Models Seem to Reproduce Observed $^{56}Ni/^{44}Ti$ Ratios
- *The et al. 2006*



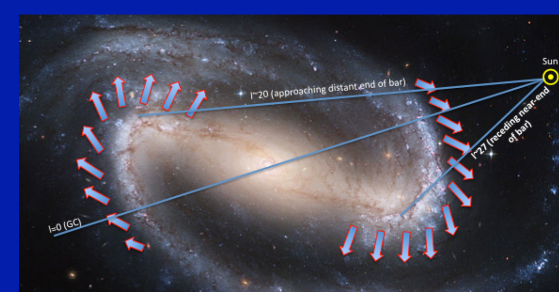
INTEGRAL & Cosmic Radioactivities Summary



- ☆ 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 Nova early β decay & ^{22}Na Calibrations:
  - ☞ SN2014J → Luck happens. Still awaiting a nearby nova.



- ☆ 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