Nucleosynthesis in Massive Stars and Supernovae

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Nuclear Physics in Astrophysics; Nucleosynthesis

Nucleosynthesis in Stars, in Supernovae

Cosmic Enrichment with 'Metals'

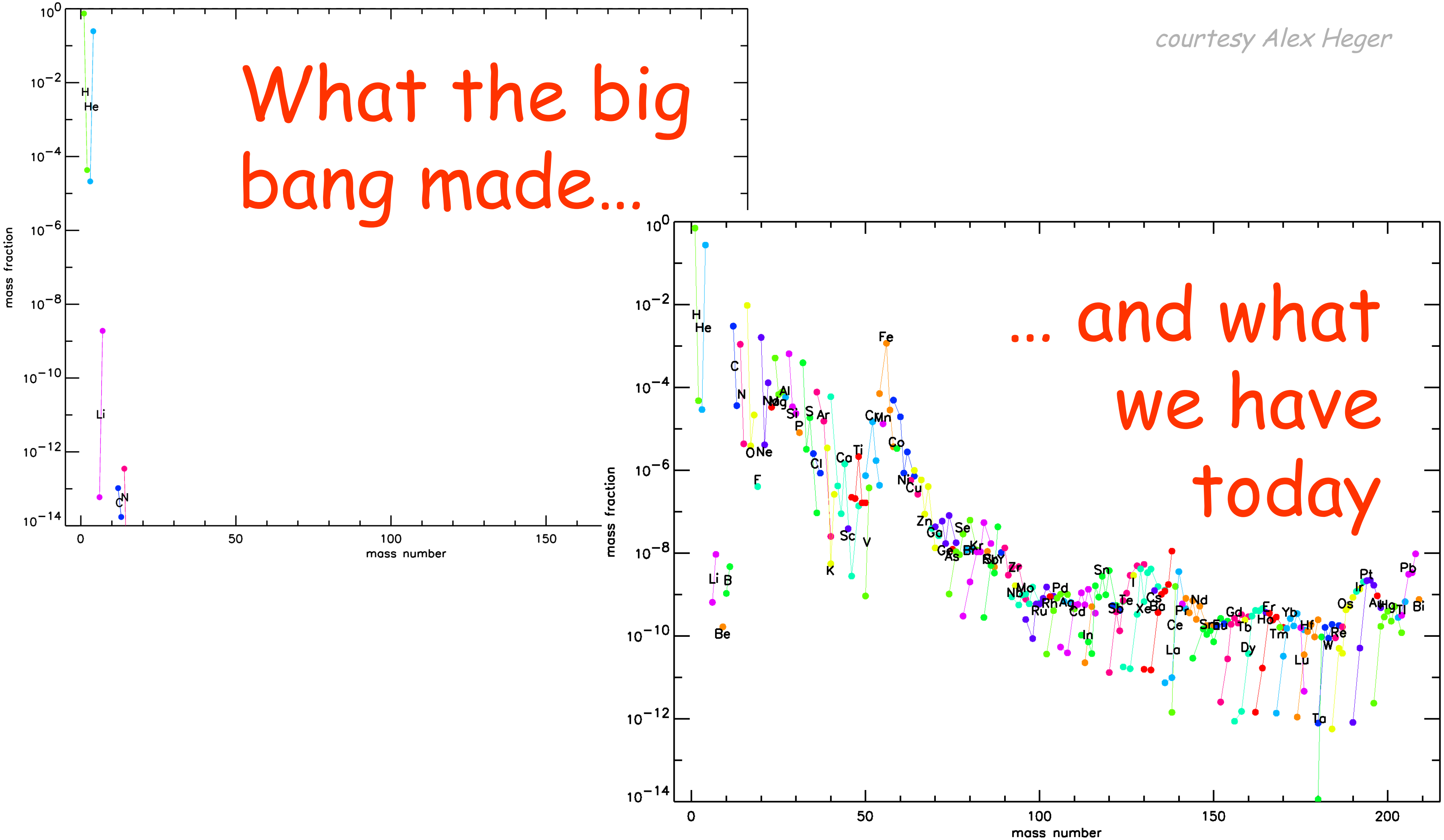
→ How γ-ray Telescopes Contribute

Compositional Evolution of the Universe

courtesy Alex Heger

What the big bang made…

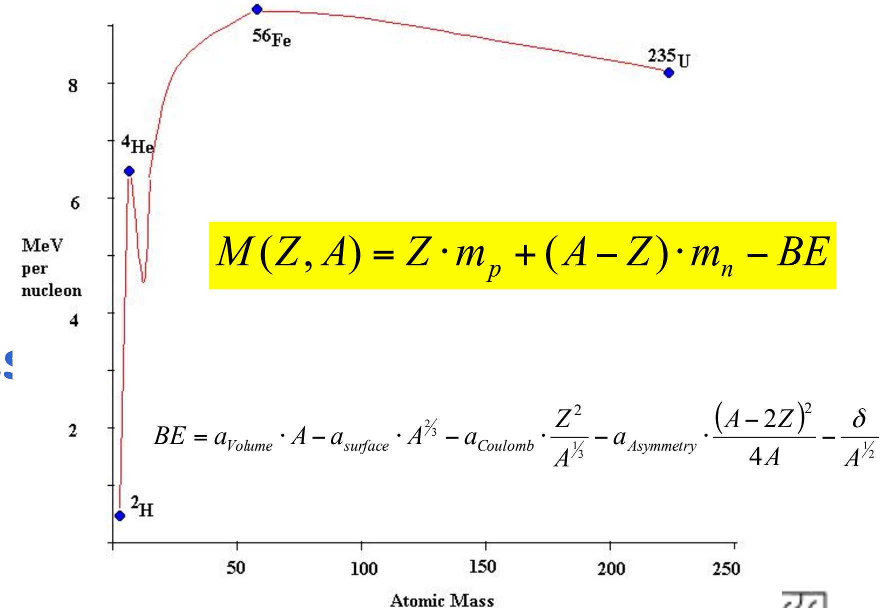
… and what we have today



Roland Diehl

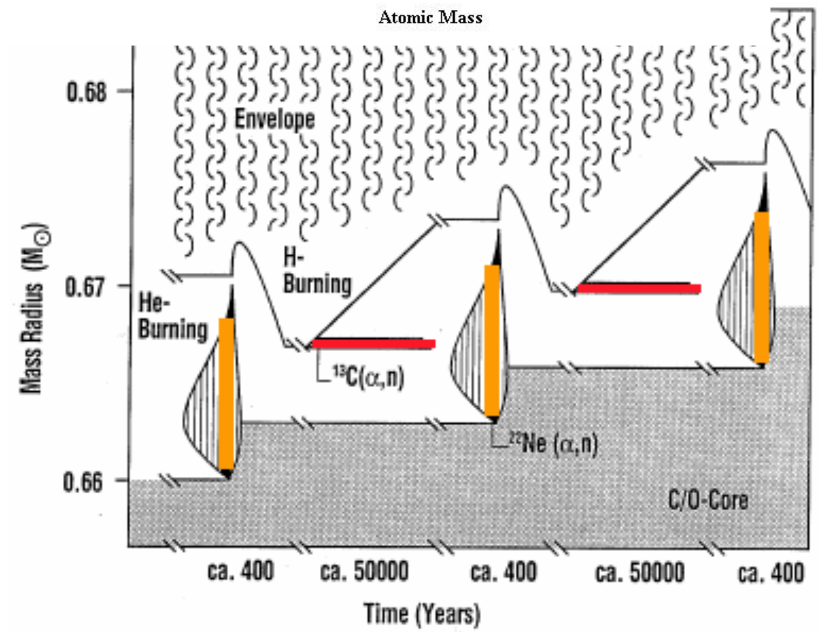
Nuclear Reactions in Cosmic Sites

- Nuclear Reaction Paths and their Efficiencies are driven by:
  - ☆ The Binding Energies / Stabilities of Isotopes (mostly unstable!)
  - ☆ The Abundance & Energies of Isotopes as set within the Cosmic Sites



$$M(Z,A) = Z \cdot m_p + (A - Z) \cdot m_n - BE$$

$$BE = a_{Volume} \cdot A - a_{surface} \cdot A^{2/3} - a_{Coulomb} \cdot \frac{Z^2}{A^{1/3}} - a_{Asymmetry} \cdot \frac{(A-2Z)^2}{4A} - \frac{\delta}{A^{1/2}}$$



Nuclear Reactions in Cosmic Environments

☆ **Tunneling Reactions of Thermal-Particle Populations**

☞ "Astrophysical S-Factor"

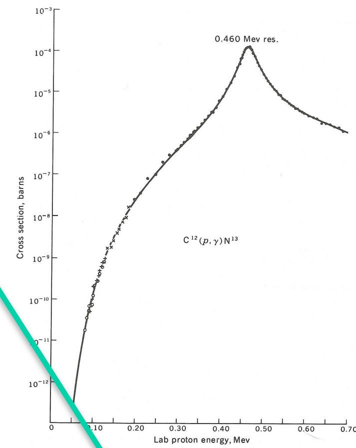
$$\sigma(E) = \frac{1}{E} \cdot e^{-2\pi\eta} \cdot S(E)$$

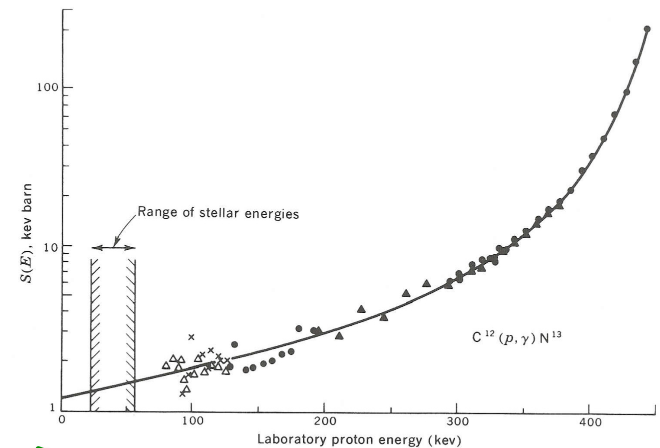
- isolate nuclear properties from tunneling & geometry

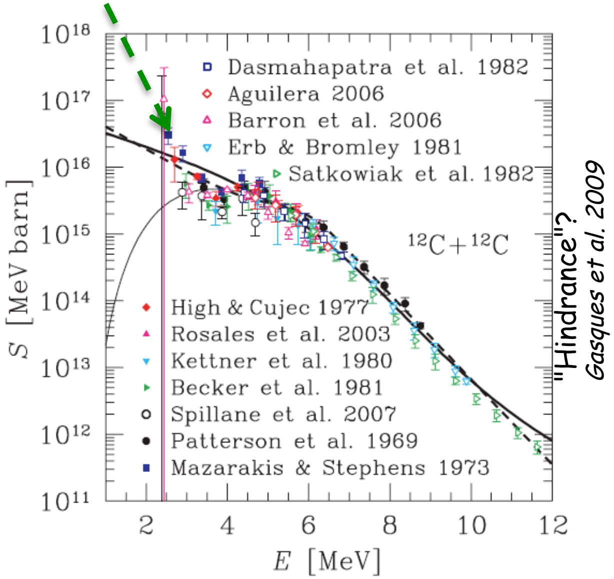
☞ "Gamov Peak" at ~30 keV

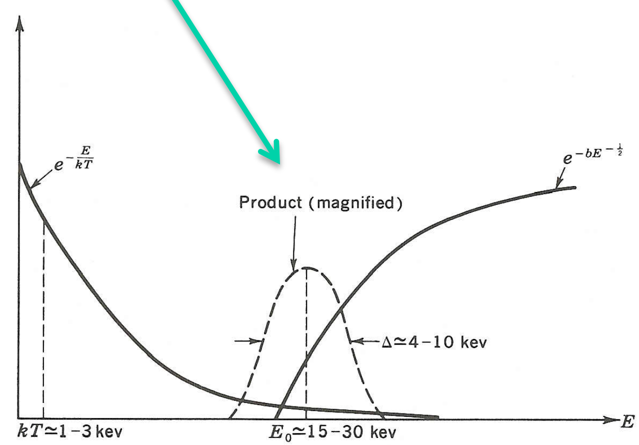
- (still) difficult to measure at nuclear lab facilities

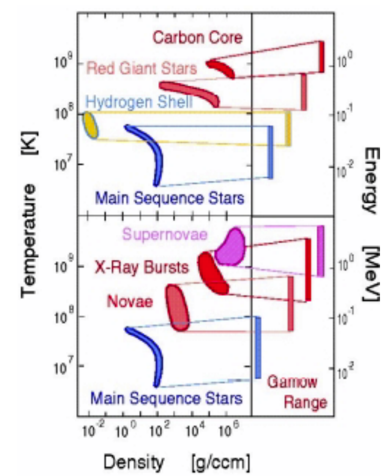
$$\langle \sigma \cdot v \rangle = \left(\frac{8}{\pi \cdot \mu} \right)^{1/2} \cdot \left(\frac{1}{kT} \right)^{3/2} \cdot \int_0^\infty E \cdot \sigma(E) \cdot e^{\frac{-E}{kT}} \cdot dE$$







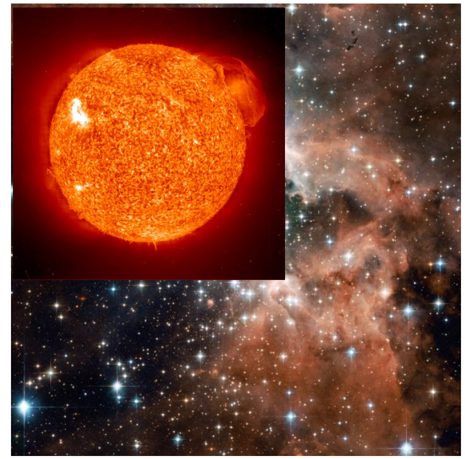


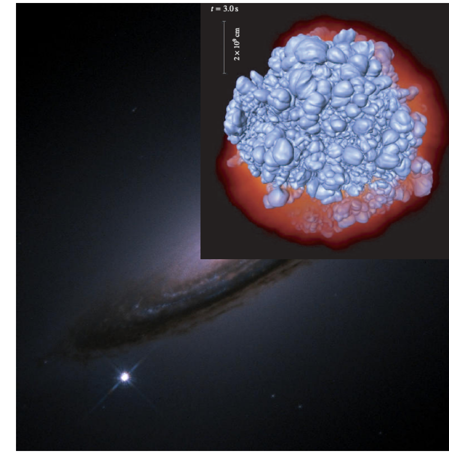


Nuclear Fusion Energy: Where is it Relevant?

☆ **Nuclear Energy Release**

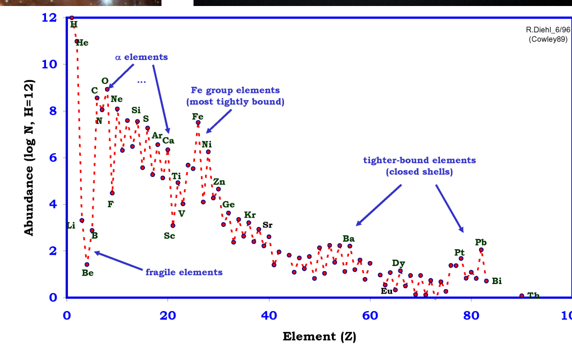
- Structure of Stars
- Dynamics of Explosions





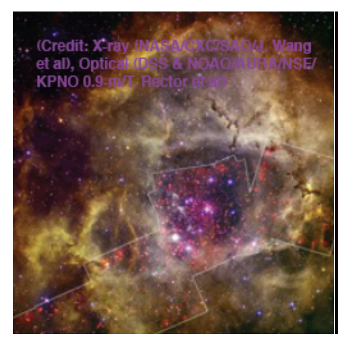
☆ **Nucleosynthesis**

- Elemental Abundances in Stars and in ISM (SNR), IGM
- Radioactive Isotopes



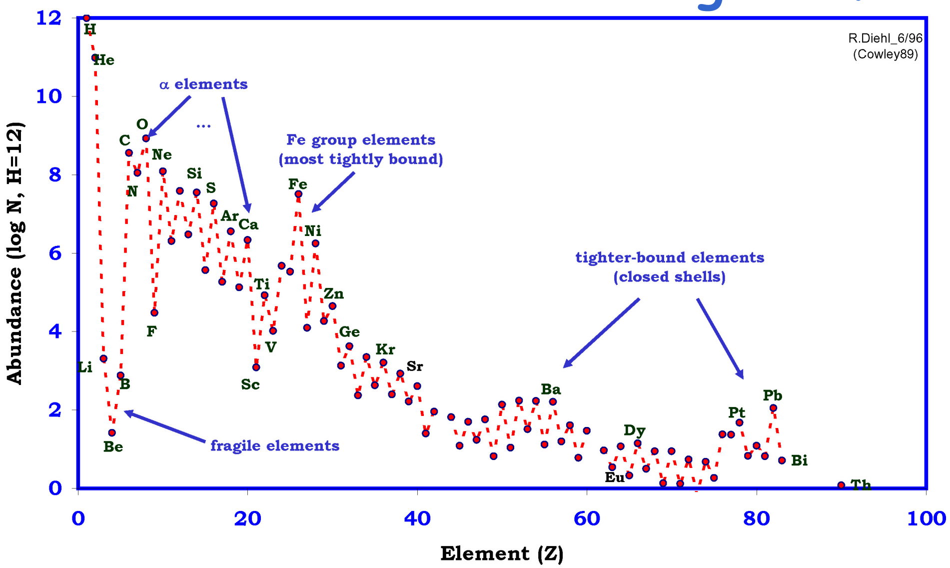
☆ **Large-Scale Impacts of SN Explosions**

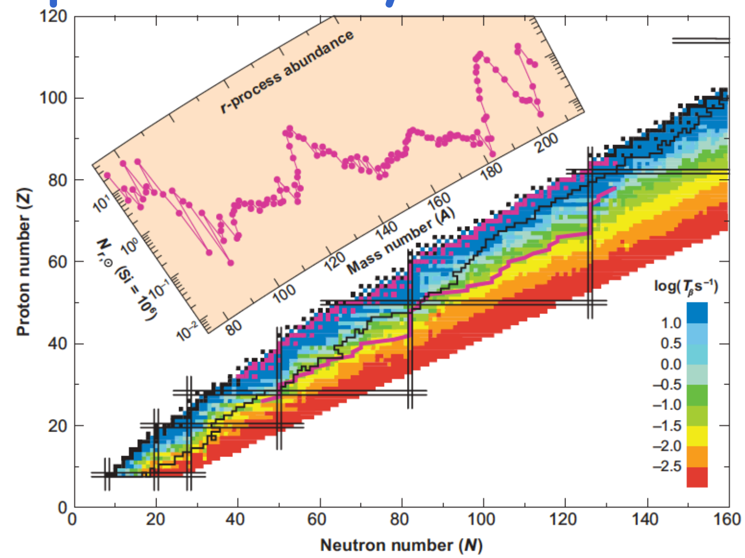
- Feedback → ISM Morphology, SFR
- Galaxy Evolution, Winds, ...IGM



Nuclear Physics & Astrophysics

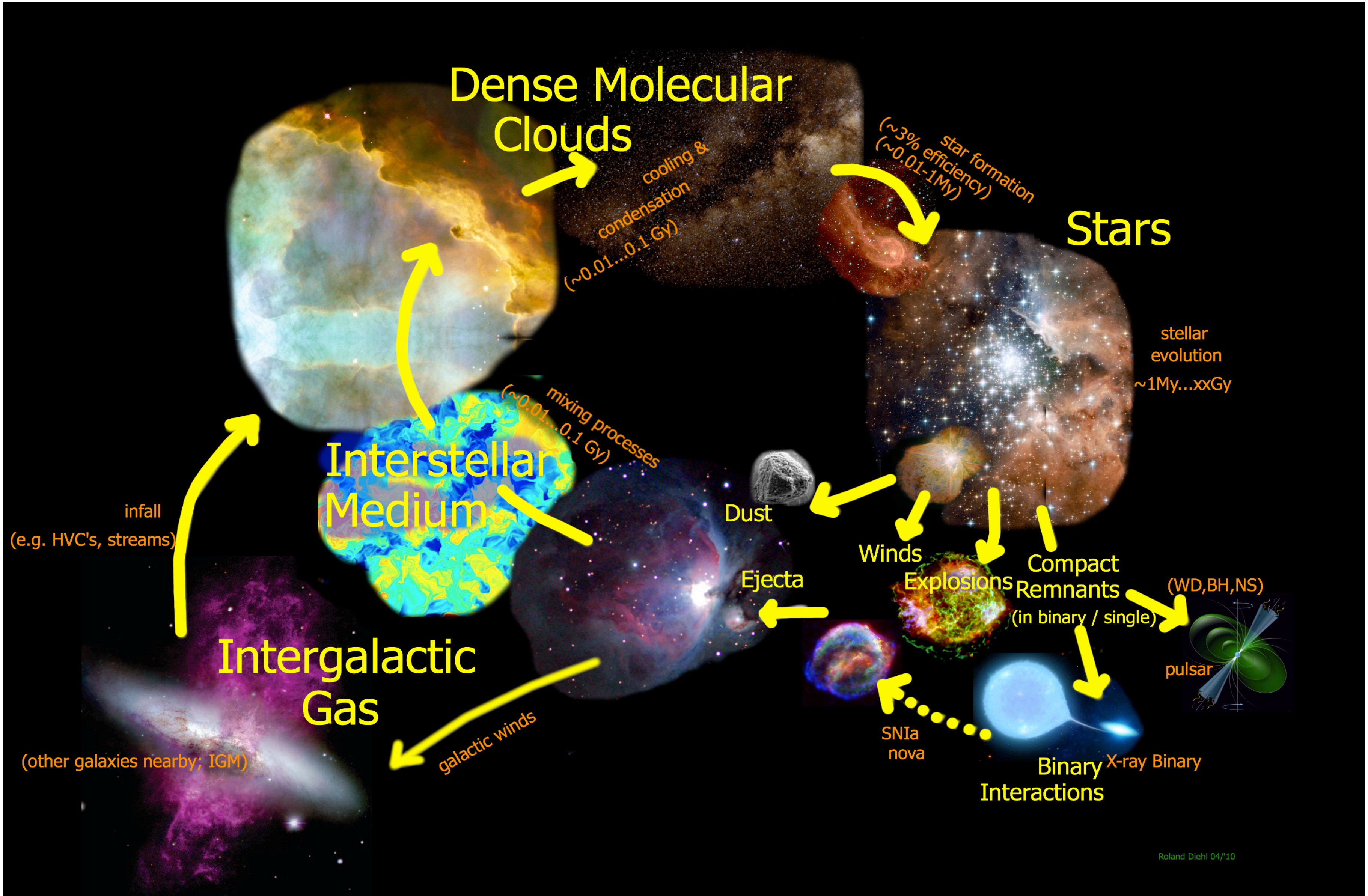
- Nuclear Reaction Paths and Efficiencies are driven by:
  - ☆ The Binding Energies / Stabilities of Isotopes (mostly unstable!)
  - ☆ The Abundance & Energies of Isotopes as Set by the Cosmic Site



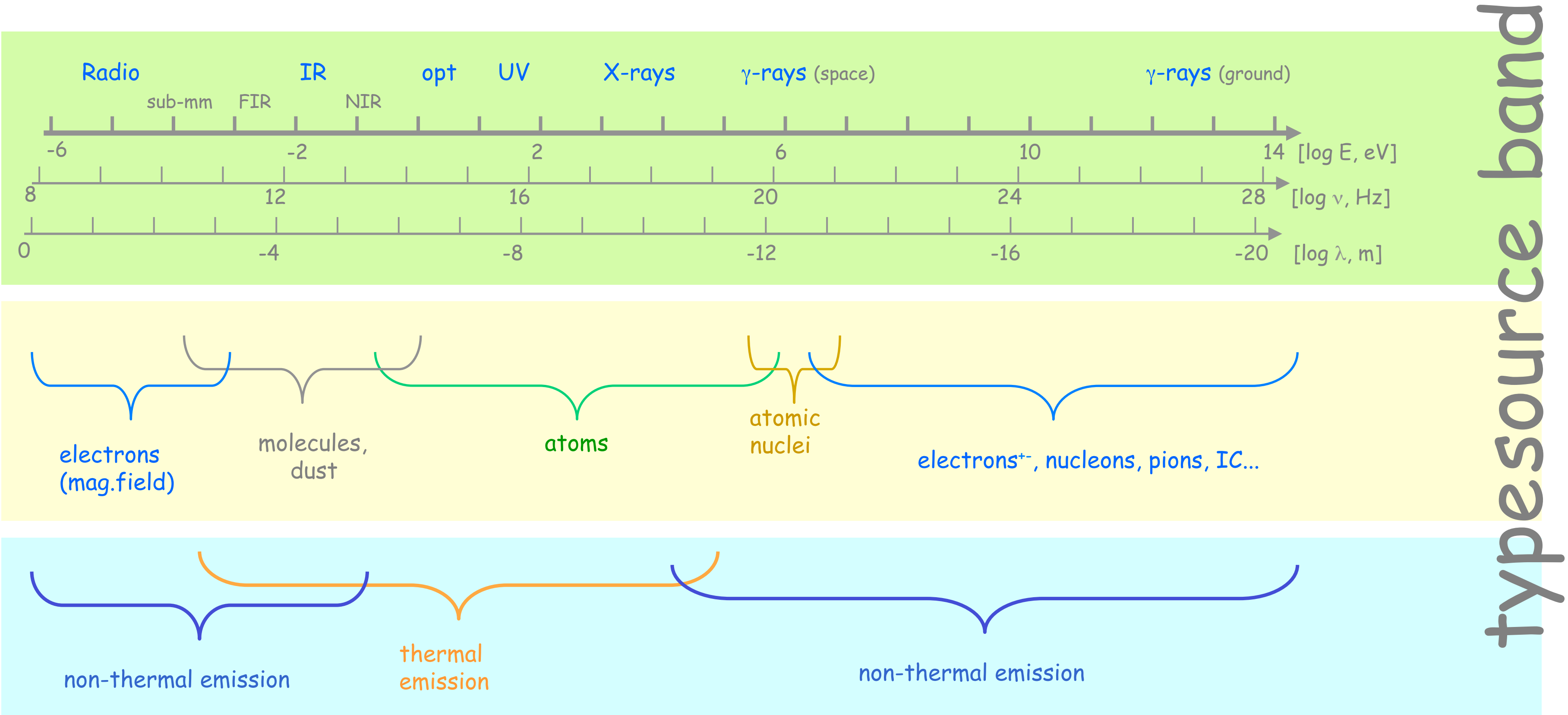


- The Cosmic Abundance Pattern Shows these Effects:
  - ☆ Local Abundance Maximum around Fe
  - ☆ Local Abundance Maxima for α-Multiples
  - ☆ Double-Peaked Abundance Maxima for r- and s-Process

How Stars Shape Galaxies



Astronomy across the Electromagnetic Spectrum



☆ "Nuclear" Astronomy:

- Diagnostics of high-energy processes MeV...100 MeV; Non-Thermal Emission
- Radiation Characteristics for Astronomy:
  - Intensity not dependent on ionization states, temperature
  - No attenuation/occultation issues

Radioisotope 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 → ^{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	89 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 → γγ..	511, <511

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

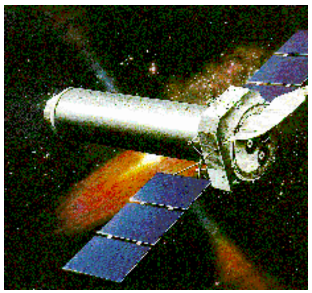
cumulative from many events (^{26}Al to e^{+})

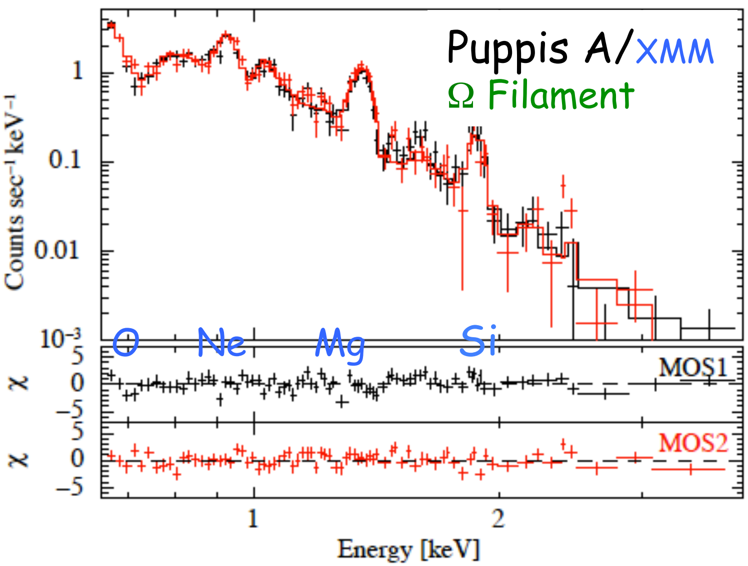
Observe Ejecta from Nucleosynthesis Sources

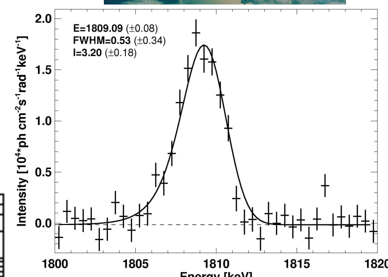
☆ In-Situ Measurement of Nucleosynthesis Ejecta in (current-universe) Sources

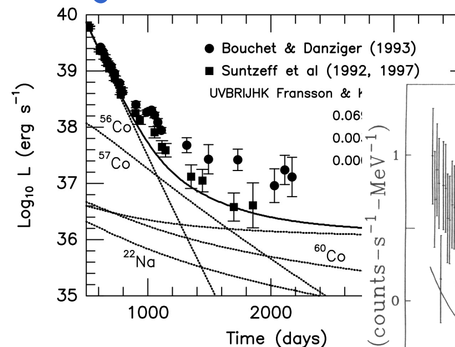
» More Detail Accessible

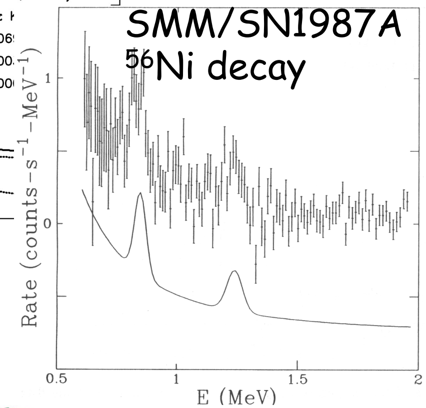
» Test our Models

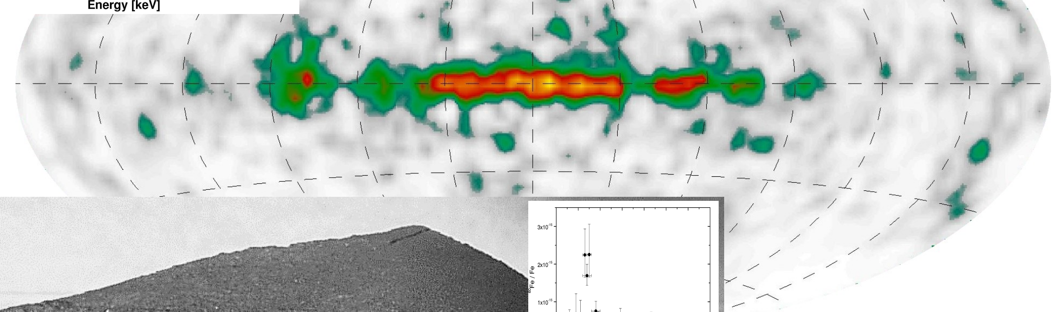












Knie et al. 2004

The "γ-ray" Window

☆ Nucleosynthesis Can Be "Observed" in Many Messengers

- ☞ejected radioactivities → decay gamma rays
- ☞ejected matter → X-ray lines in SNR
- ☞ejected matter → presolar grains, formed in SNR, captured in meteorites
- ☞SN light curves → OIRUV emission from re-processed radioactivity
- ☞atoms in ISM → absorption spectroscopy of diffuse ISM gas phase
- ☞dust and molecules in ISM/MCs → radio spectra of molecules formed in MCs
- ☞atoms in photospheres of stars → ejecta recycled through ISM in new stars
- ☞... (and similar for extragalactic nucleosynthesis)

☆ Gamma-Ray Specials:

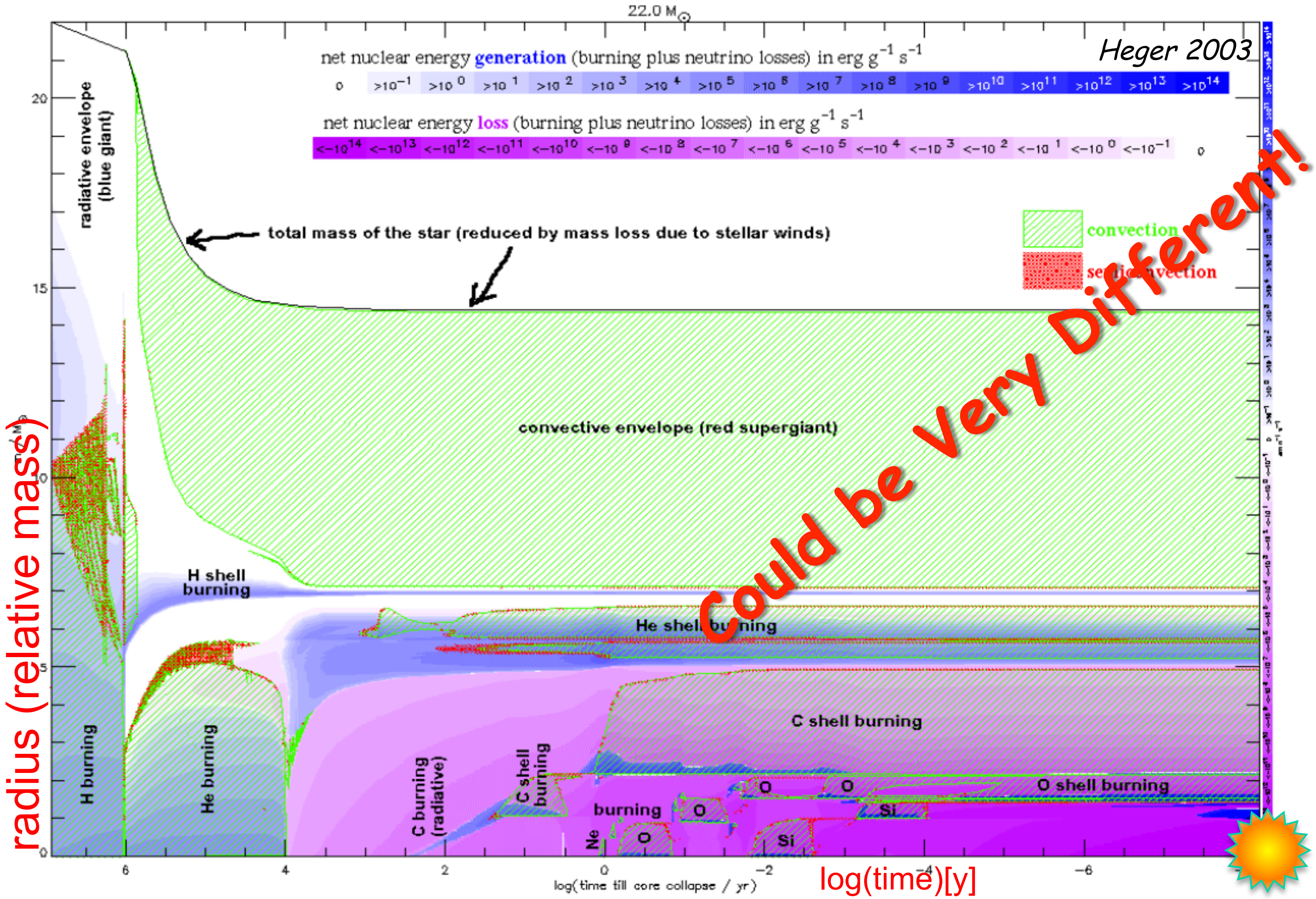
- ☞NO model or theory of transport and fractionation and branching involved
- ☞Can thus complement all other messengers, helping to "calibrate" the various biases or uncertainties in reprocessing of primary nucleosynthesis products

- **The Issues of Nucleosynthesis Sources**

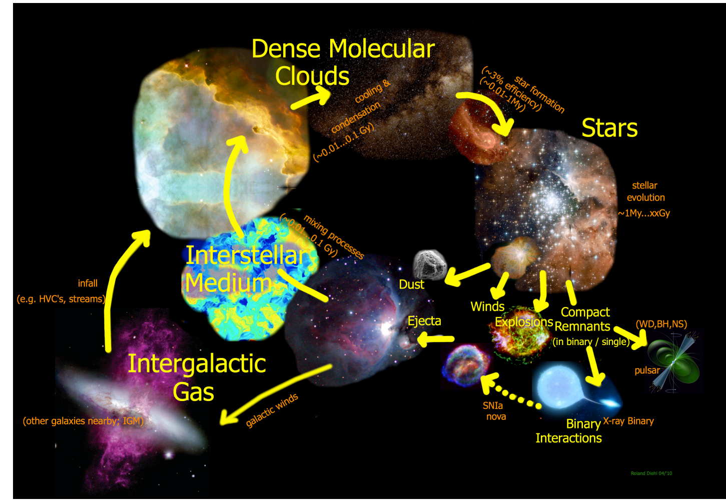
  (and why we would benefit from gamma-ray measurements)

Following Stellar Evolution

☆ The "Kippenhahn" Diagram:



Massive-Star Interiors

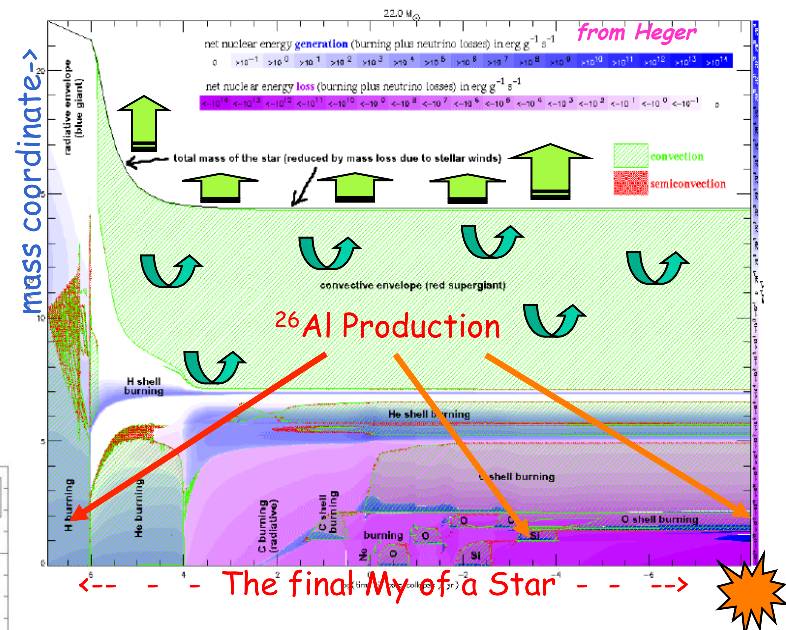


☆ Massive Stars are:

- ☞ Key Producers of Cosmic 'Metals'
- ☞ Key Agents for Cosmic Evolution in Galaxies

☆ How does the Interior Structure Evolve in Late Stages?

- ☞ Which "Shells" are Active?
- ☞ Which Nuclei are Produced? (ejected?)
- ☞ What are the Time Scales?
- ☞ How does all this Depend on Rotation?
- ☞ How does all this Depend on Metallicity?

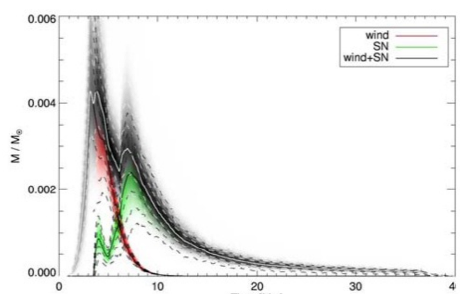


Main Sources of ^{44}Ti, ^{26}Al, ^{60}Fe

☆ How Important are Binary Interactions?

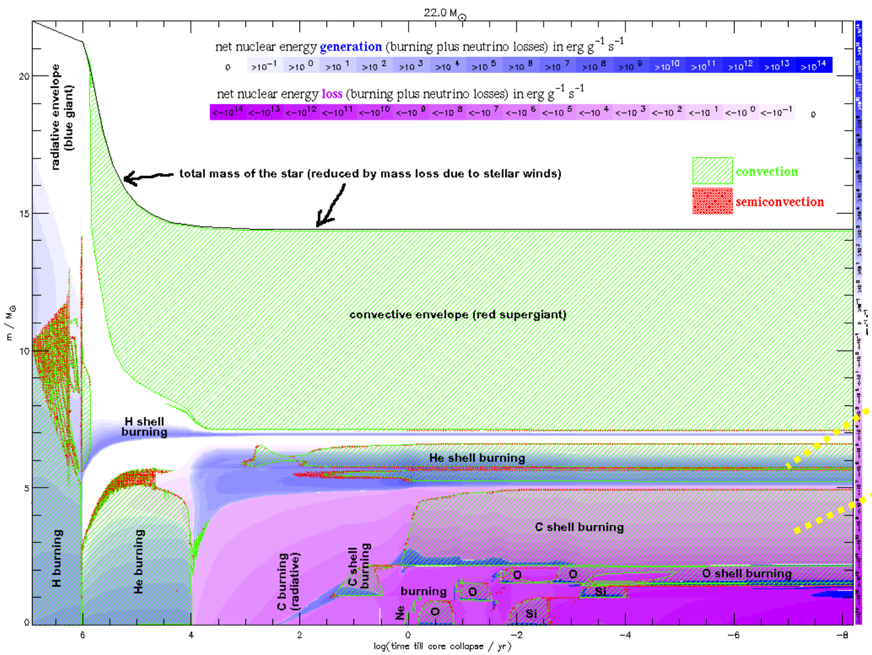
☆ Exploit γ-rays from

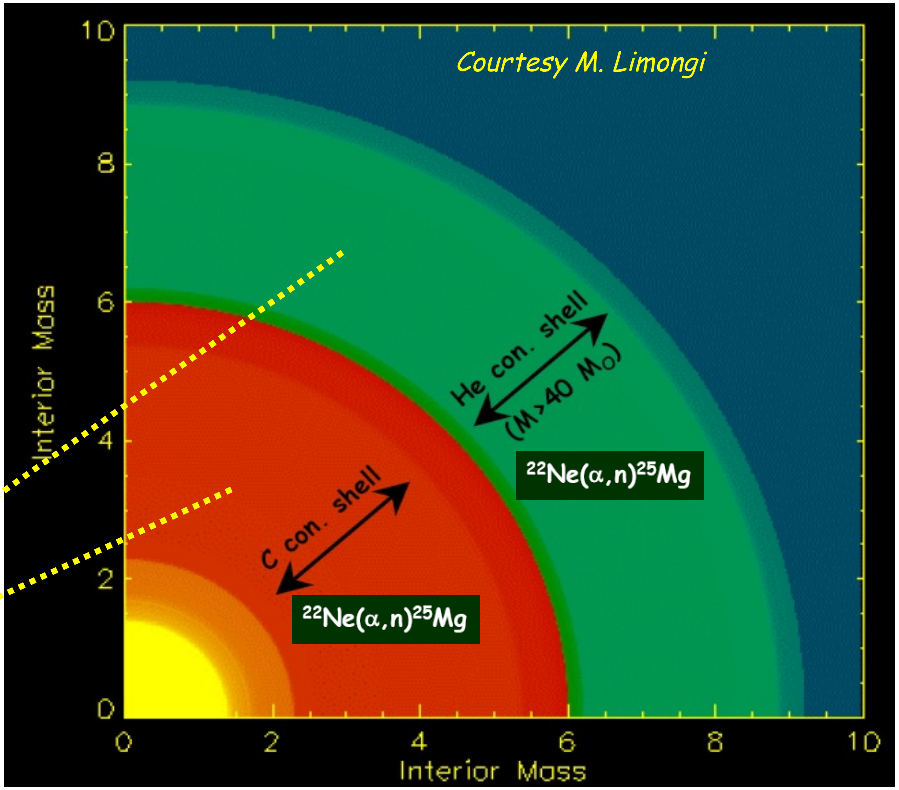
- ☞ Radioactive Products from Different Phases
- ☞ Wind Interactions



^{60}Fe Production in Stars

- ☆ No Production during ANY Central-Burning Phase
- ☆ Need Convection plus n Source

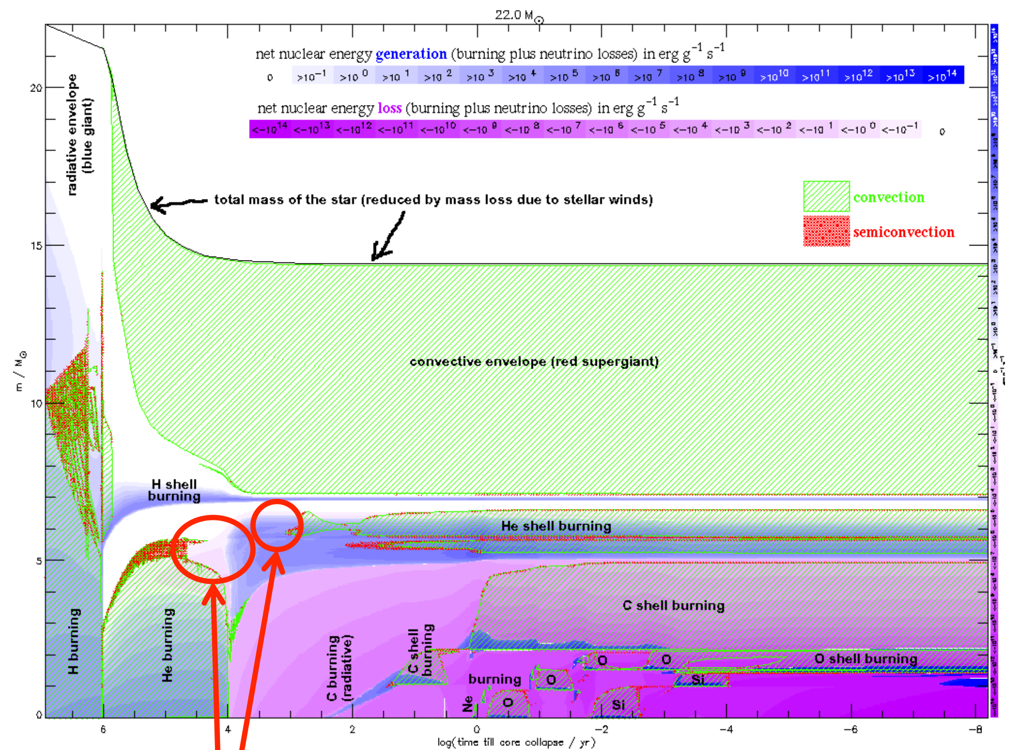


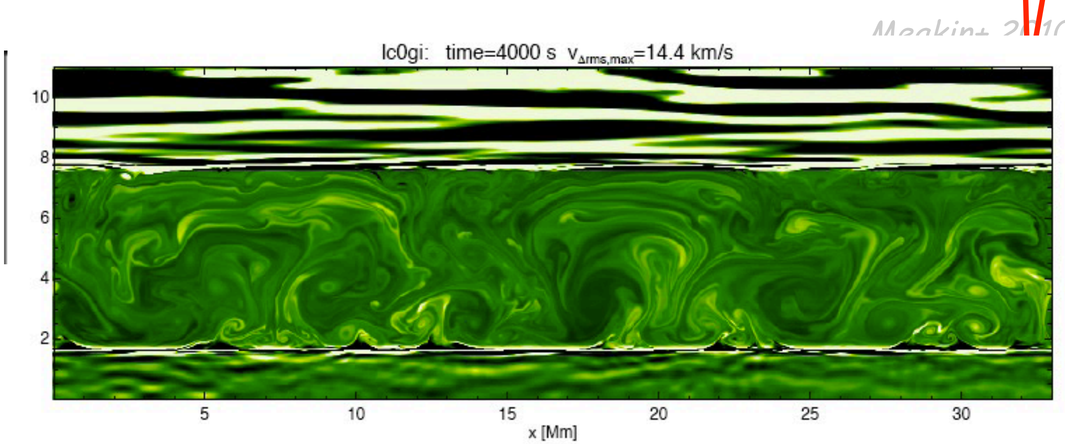


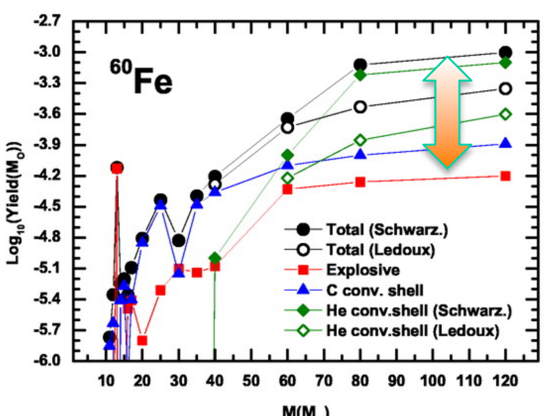
- ☆ Explosive-Burning Contributions Neglegable
- ☆ Ejection by Supernova Explosion

Massive-Star Structure: Convection Issues

- ☆ How Does Convective Zone Transit into Stable (radiative) Zone?
- ☆ 3D Simulations Illustrate
  - ☞ The Inadequacy of "Mixing-Length" Modeling
  - ☞ Details of "Semiconvection", "Overshooting" and other Empirical Corrections
  - ☞ How e.g. Stellar Rotation Leads to 3D Mixing Processes



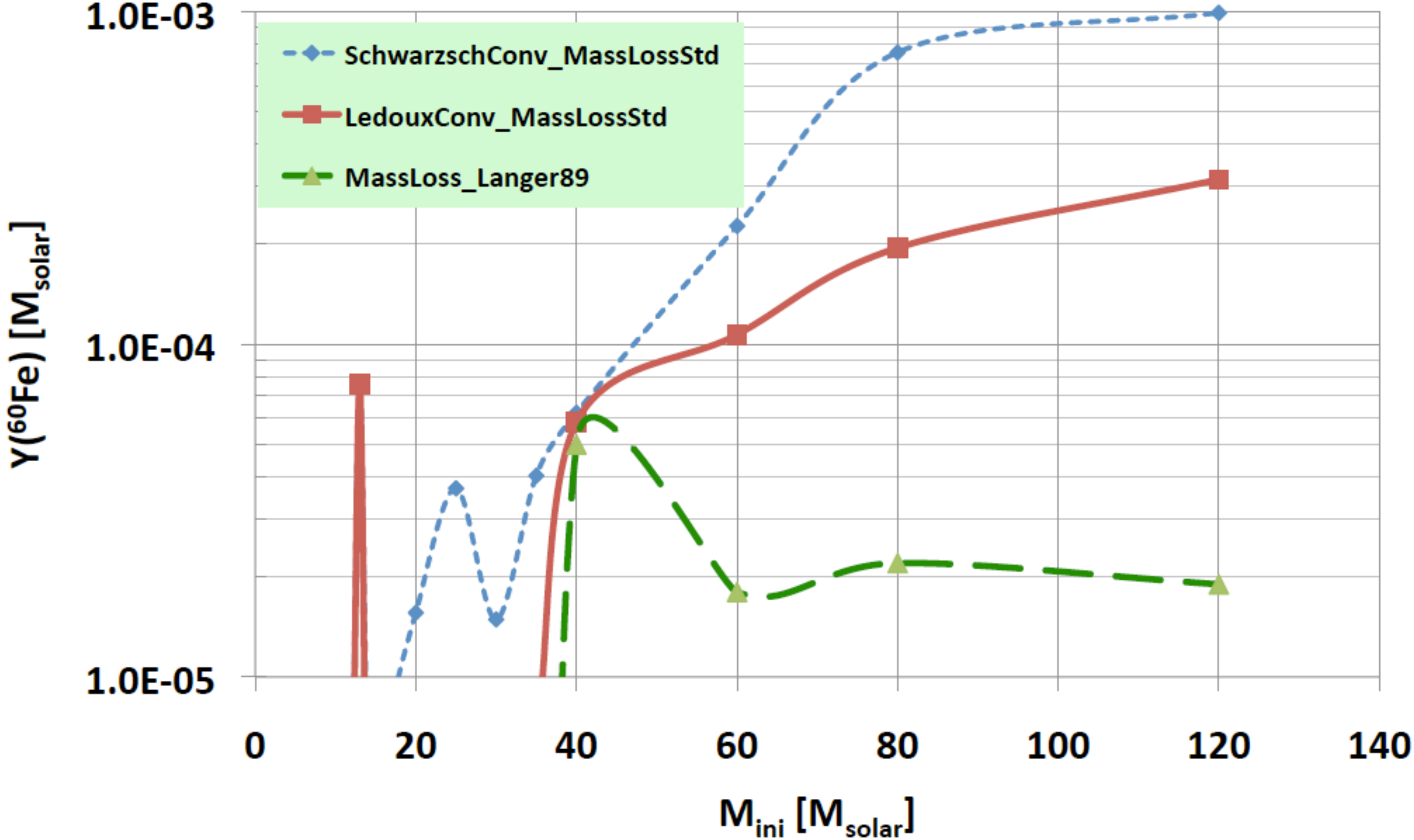




☞ Affects Isotopic Yields (e.g. ^{60}Fe)

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

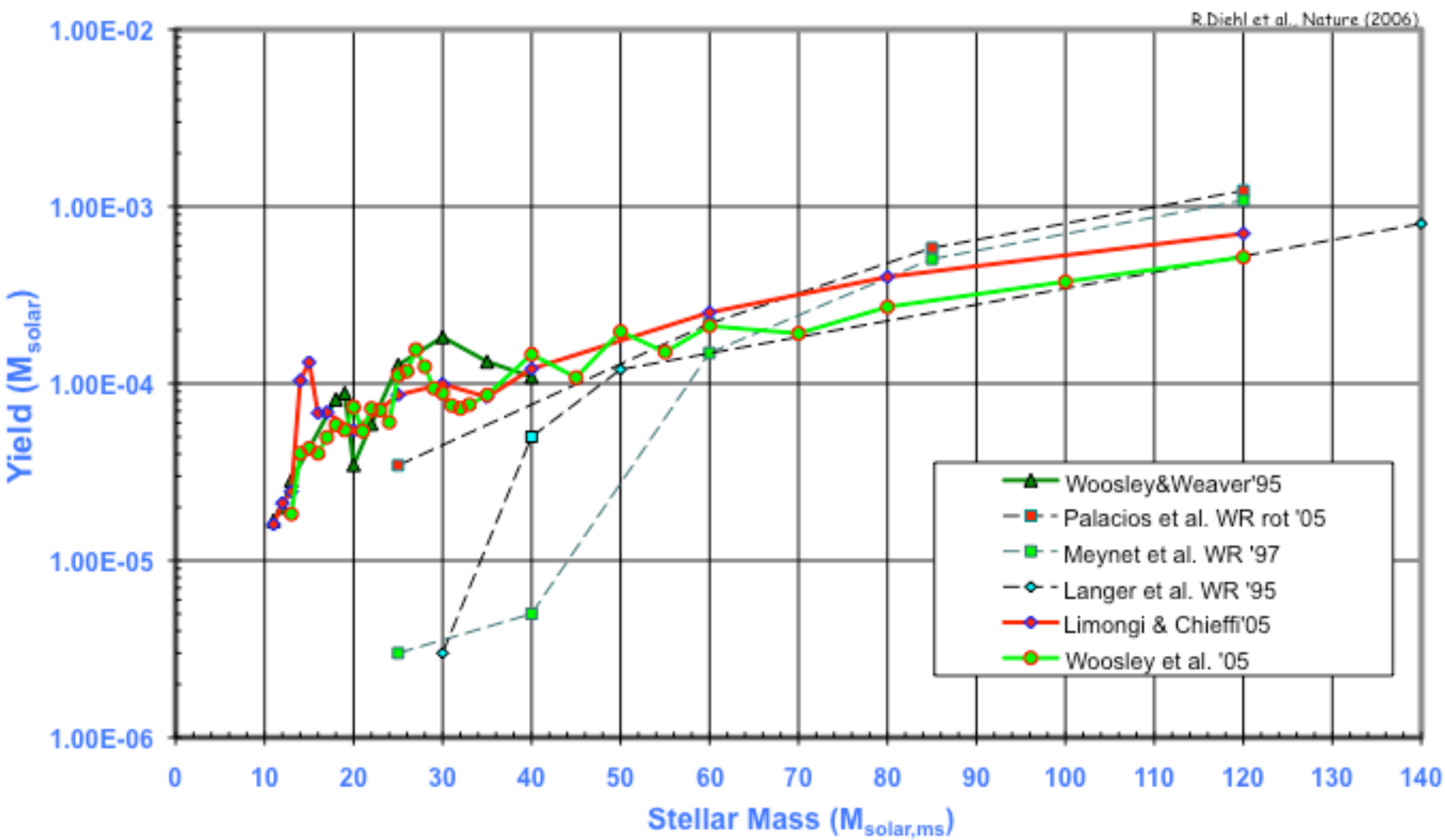
☆ Model Parameters Have Major Impact on Total Yield



Nucleosynthesis Yields: ^{26}Al

- The Summary of Much Experimental and Theoretical Efforts (Nucl.Reactions, Stars, SNe):

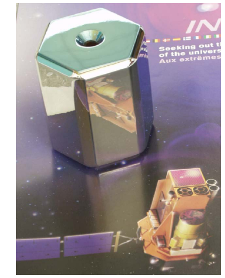
☆

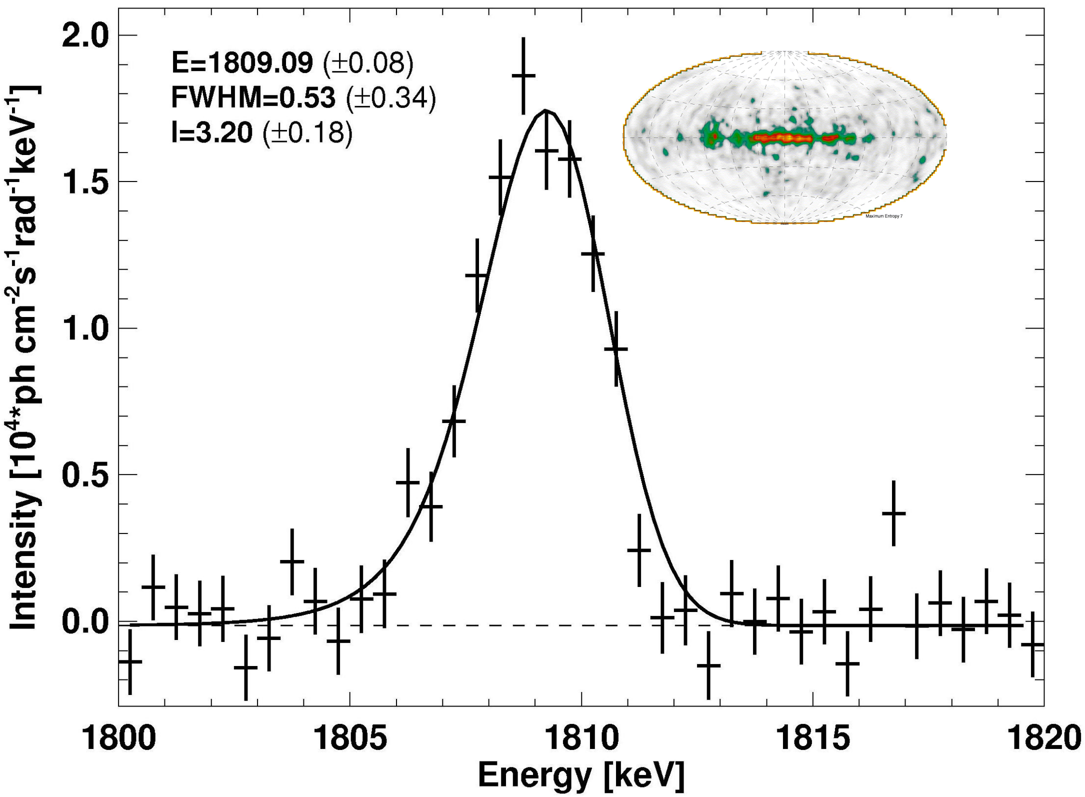


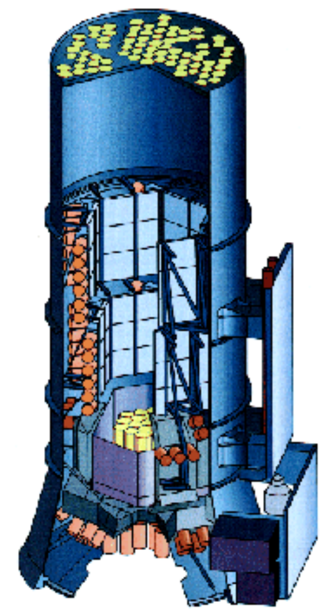
^{26}Al γ-rays with SPI

☆ **SPI Observations / INTEGRAL →**

- ☞ Confirm Spatial Map & Flux from COMPTEL
- ☞ Add Spectroscopy





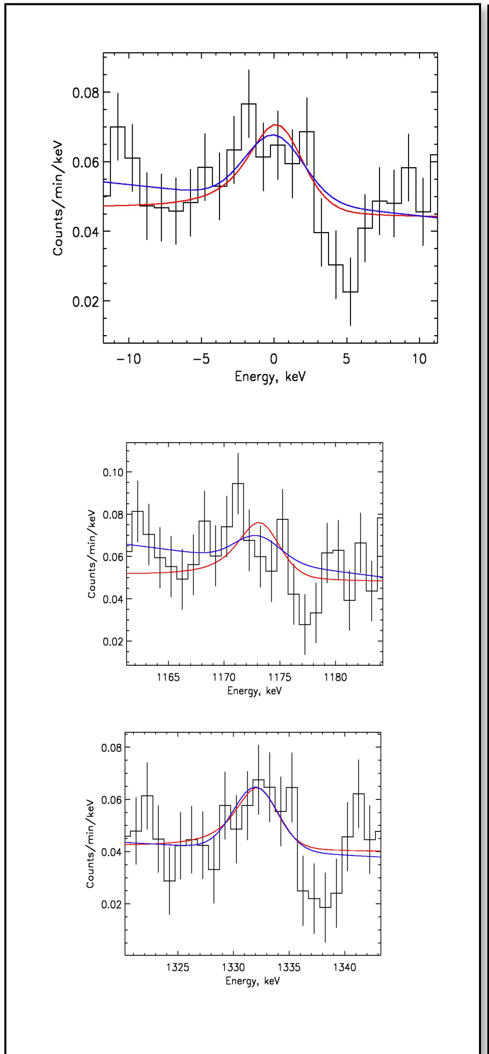


-> Data up to mid 2006; → W.Wang et al., (2008)

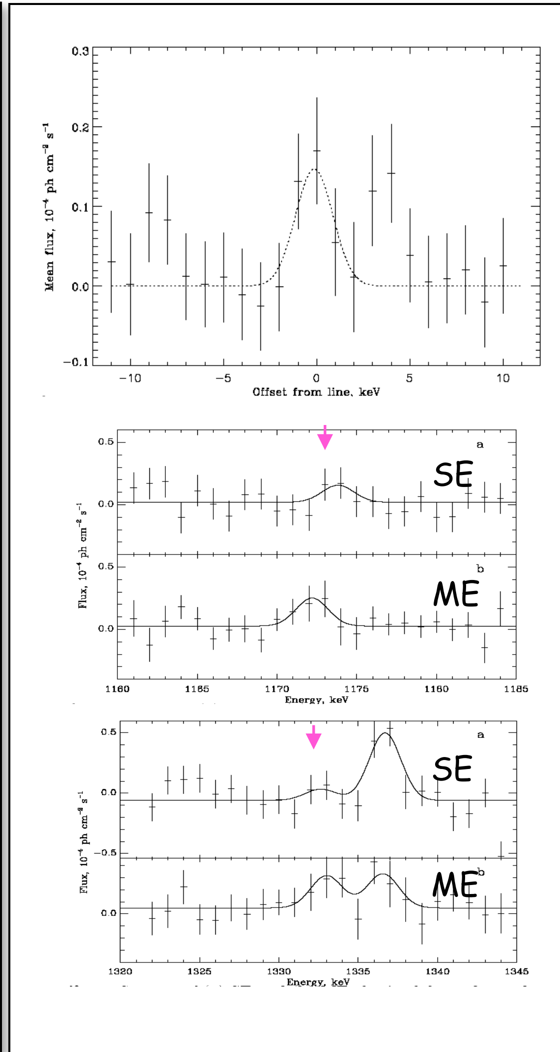
Line Width Probability Distribution by K.Kretschmer

Gamma-Ray Measurements of Galactic ^{60}Fe

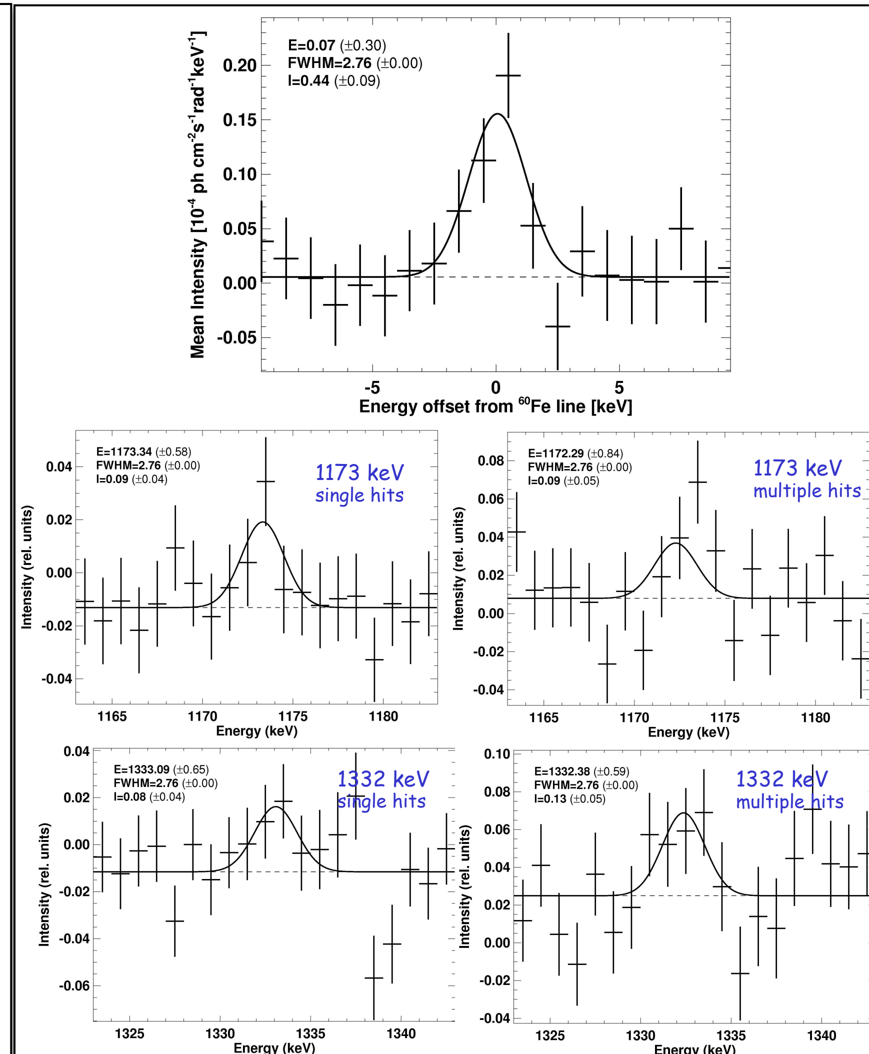
RHESSI(2005)



INTEGRAL/SPI 2005

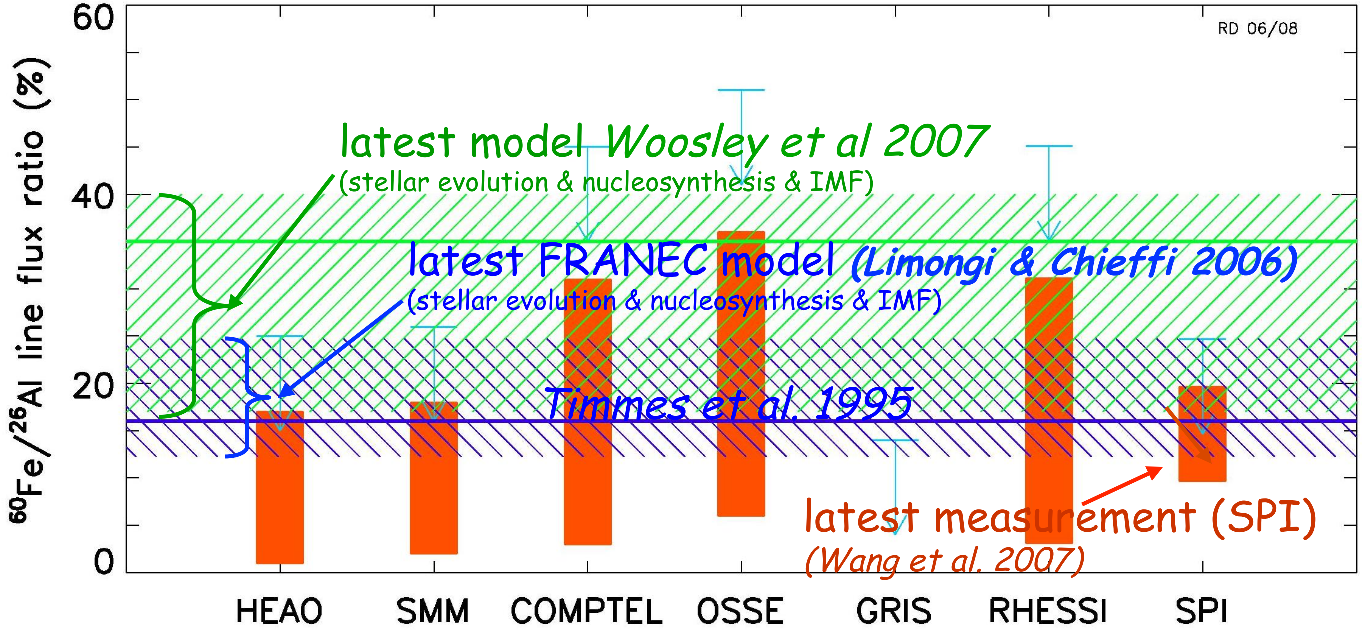


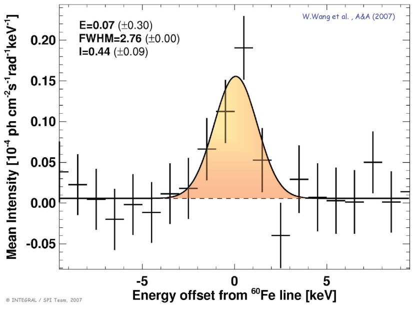
INTEGRAL/SPI 2007



^{60}Fe from Massive Stars: Observations vs. Theory

- ☆ **Measuring an ISOTOPE RATIO $^{60}Fe/^{26}Al$**
  - ☞ Independent of Source Number Density and Distances etc.
  - ☞ Diagnostics of Nucleosynthesis in Burning Shells
- ☆ **Current Model Agrees with Measured $^{60}Fe/^{26}Al$ γ-Ray Intensity Ratio**

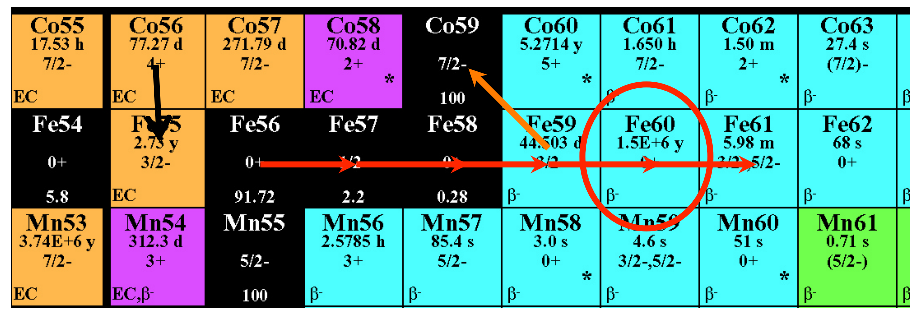


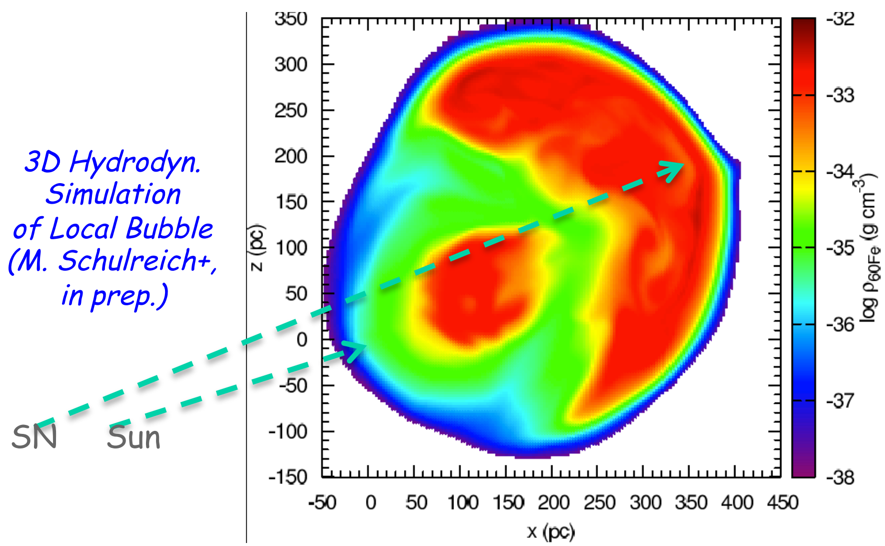


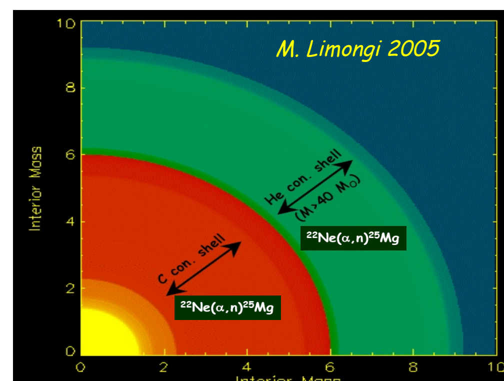
- ☞ **Uncertainties are Substantial in Several Areas:**
  - ☞ Stellar Models?
  - ☞ Nuclear Physics?
  - ☞ Gamma-Ray ^{60}Fe Signal Origin?

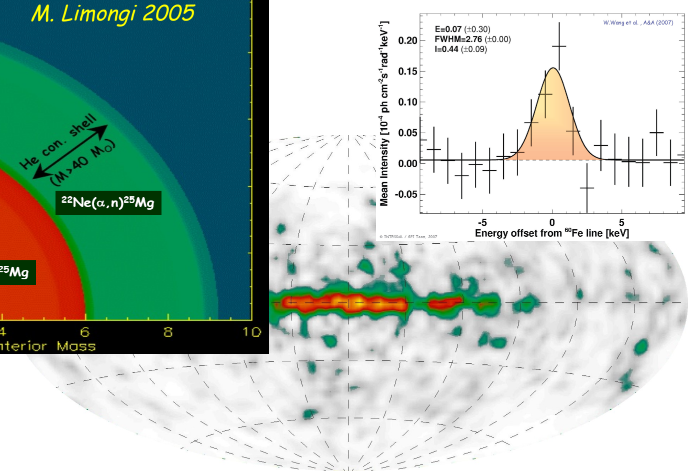
Measuring SN Ejecta Directly

- ^{60}Fe Origins
  - ☆ Clearly Seen in Oceanfloor Sample (and Galaxy-wide)
  - ☆ Origin Reflects Nuclear Physics (β decay, n capture)
  - ☆ Massive-Star Envelope Models are Uncertain (Shell Burning & Mixing)
  - ☆ SN Ejecta Transport at ~10pc Scale is Uncertain



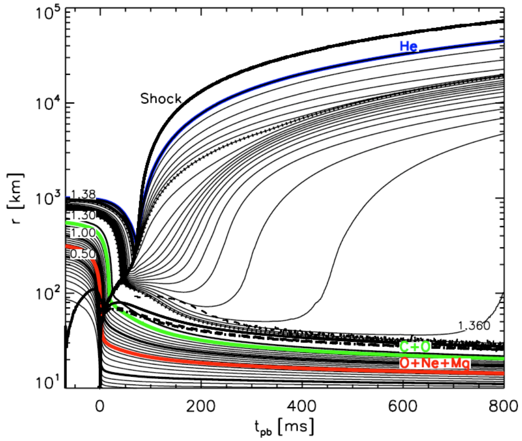


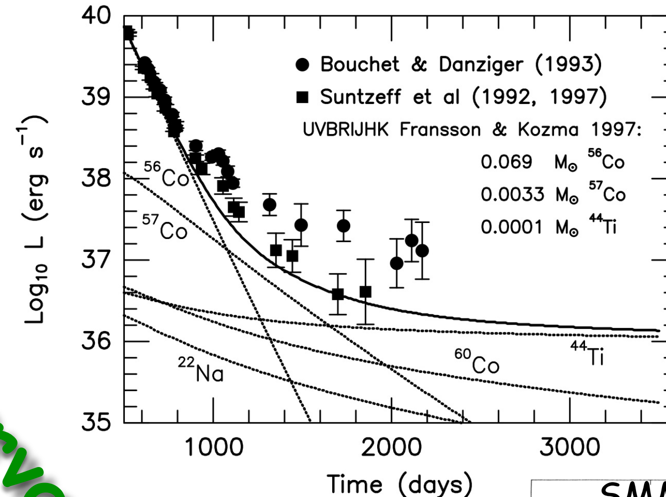




Aspects of a Core-Collapse Supernova

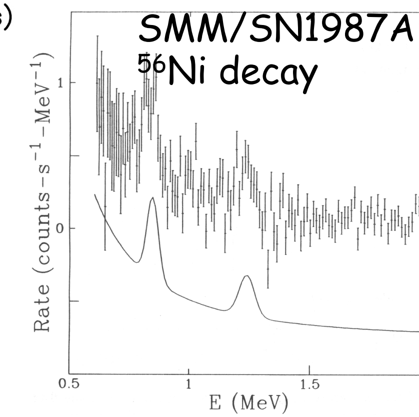
- Nuclear Energy Conversions +...
  - ☆ Dynamics of Explosions
  - ☆ Structure of Stars

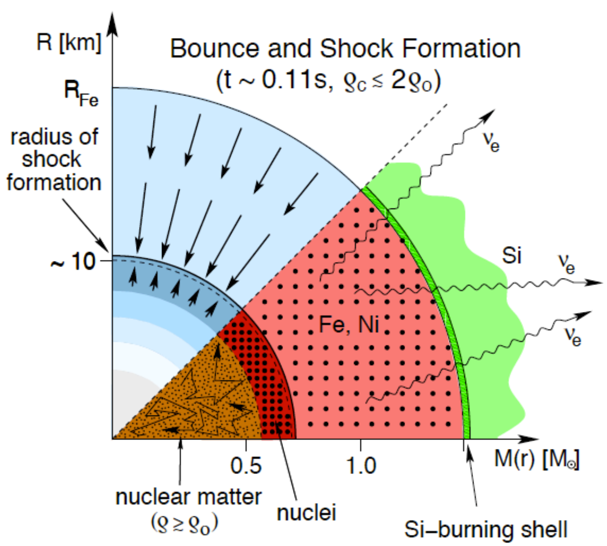


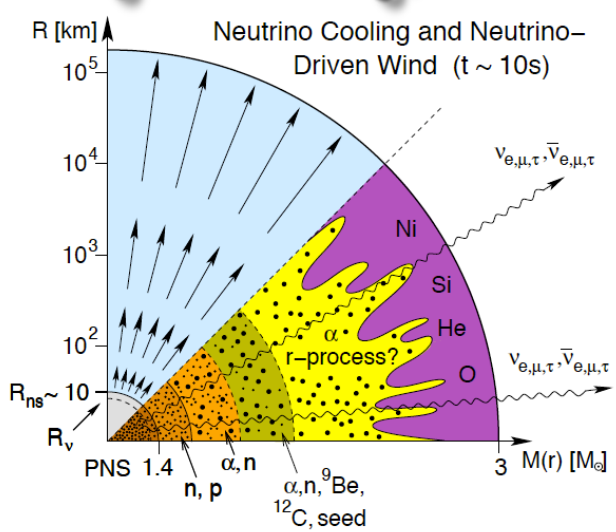


Observations

Models

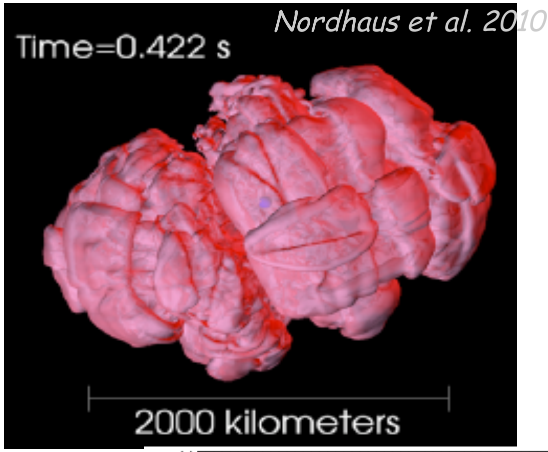


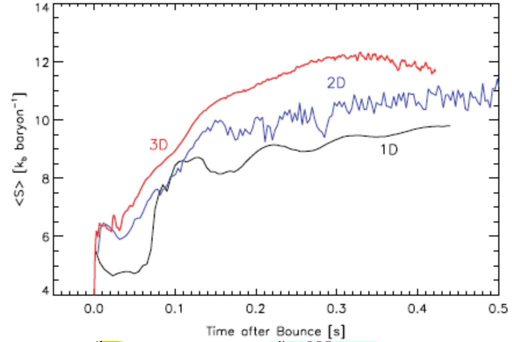




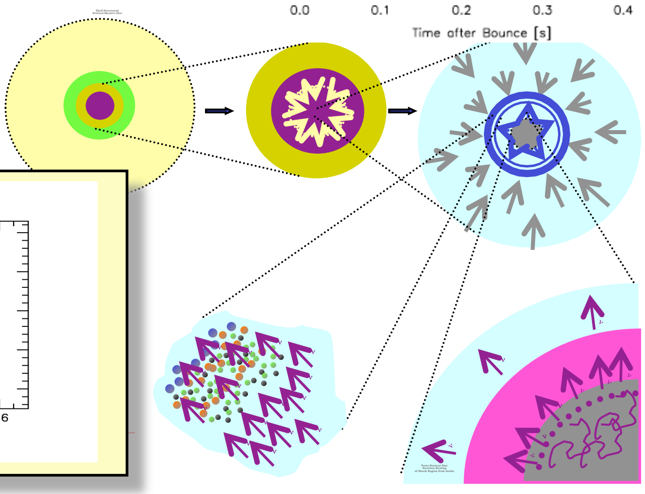
How Do Core-Collapse Supernovae Explode?

- ☆ **What are the relevant Processes in the Inner Supernova?**
  - ☞ What triggers the Explosion???
  - ☞ ν Energy Deposits alone Insufficient?
  - ☞ Late Acoustic Modes / SASI a 2D Artifact?
  - ☞ Which Nucleosynthesis Conditions Prevail?
  - ☞ Where is the Separation between Ejecta and Fallback & Compact Remnant?
  - ☞ What is the Role of Asymmetries/Rotation?

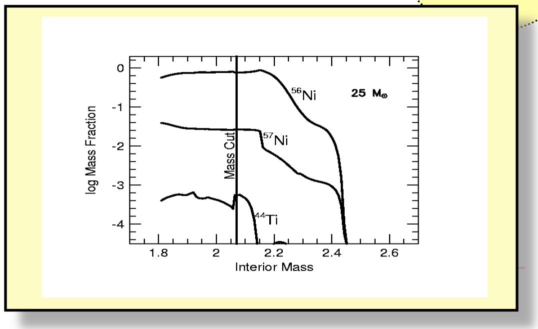




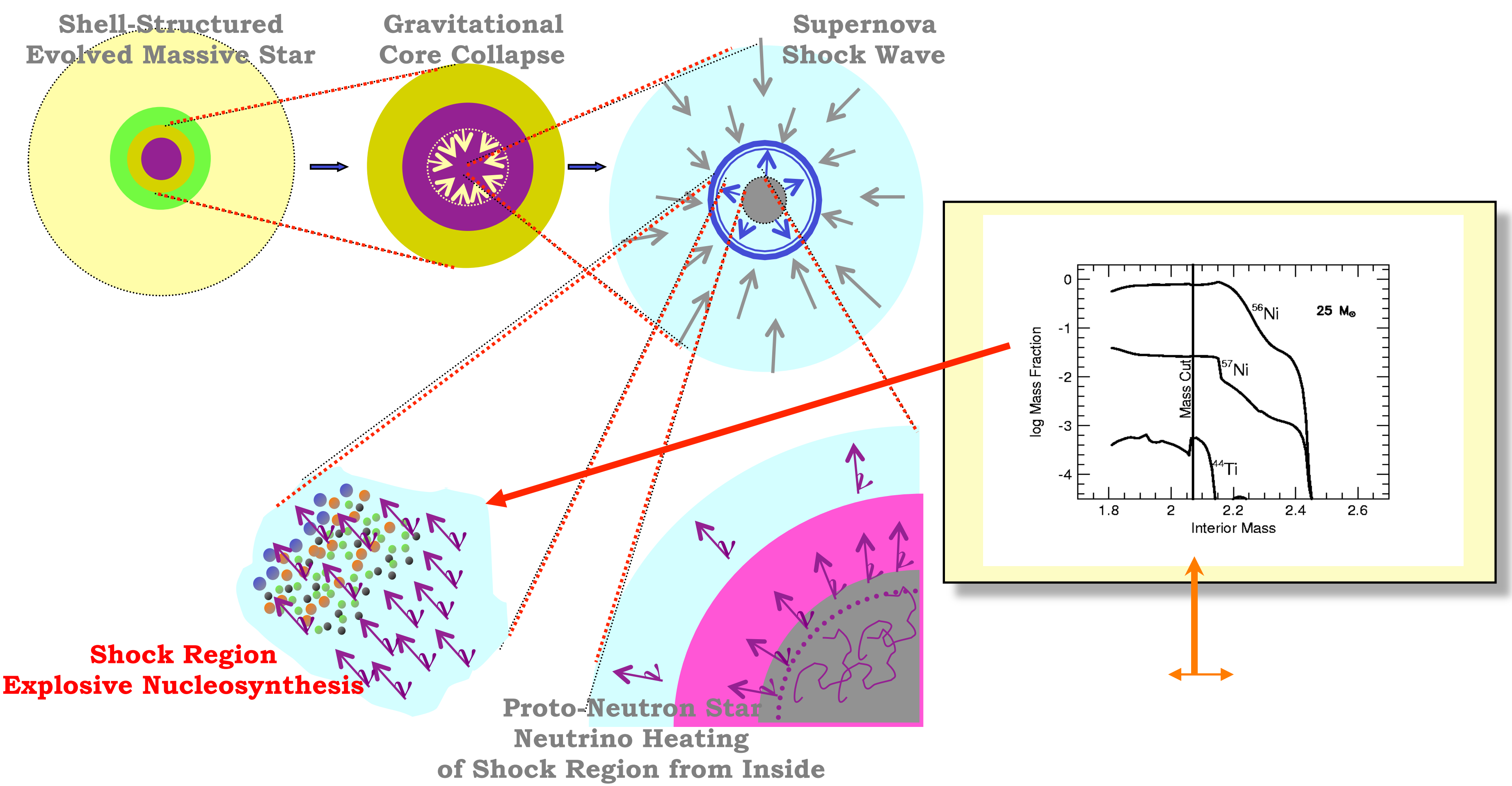
- ☆ **How are Core-Collapse Supernovae related to their Variants?**
  - ☞ Faint SNe
  - ☞ Hypernovae
  - ☞ Long GRBs



- ☆ **Exploit Radioactivities from Inner Supernova**



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

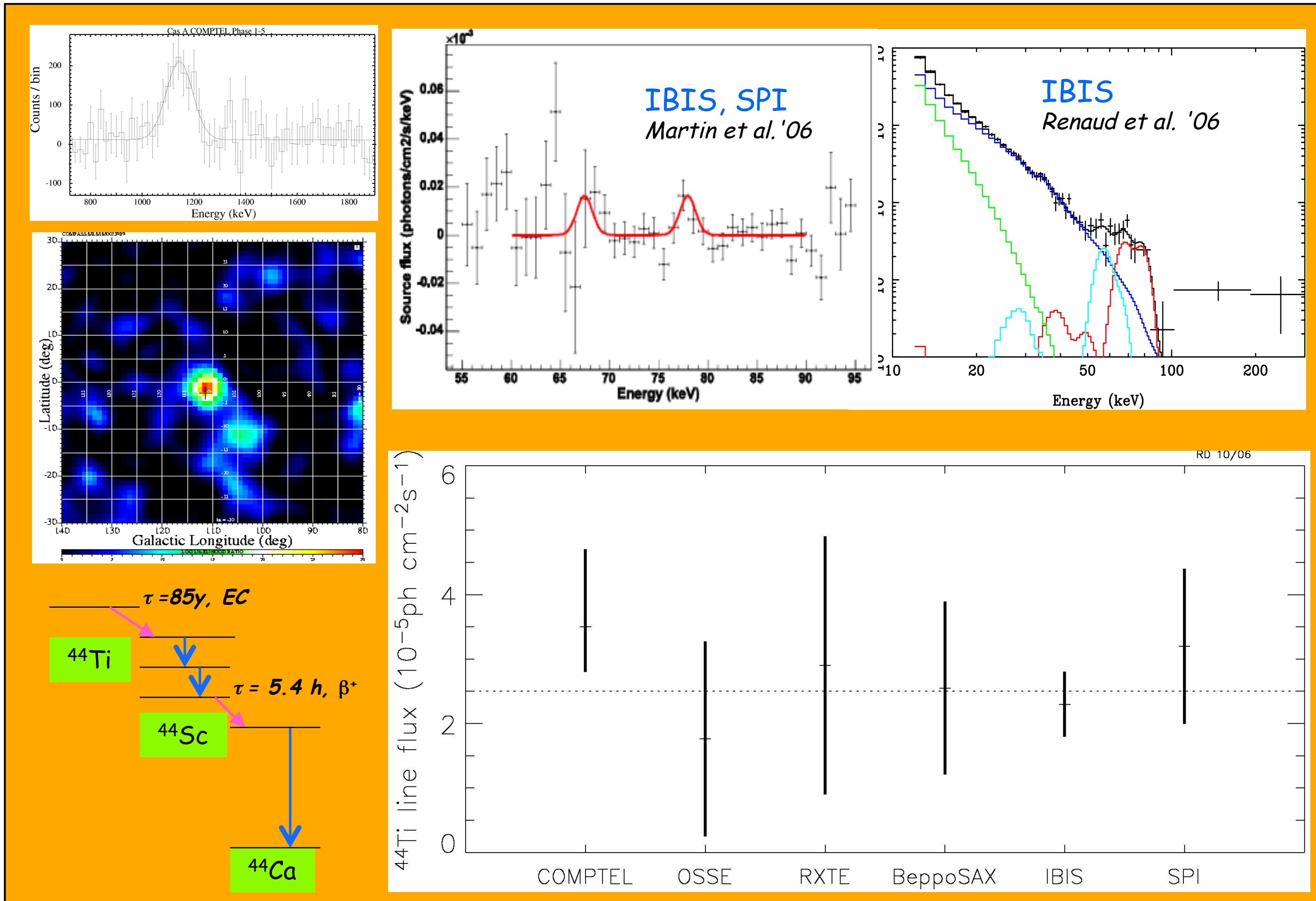


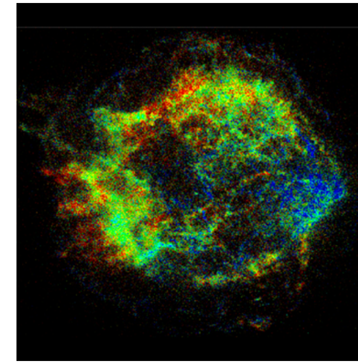
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out,
  => Unique Probe (+Ni Isotopes)

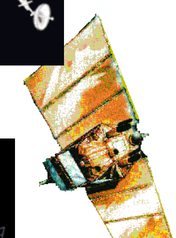
^{44}Ti γ-rays from Cas A

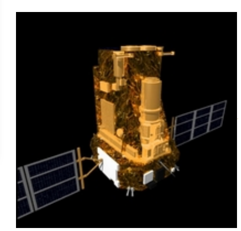
τ=85y (Ahmad et al. 2006)

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





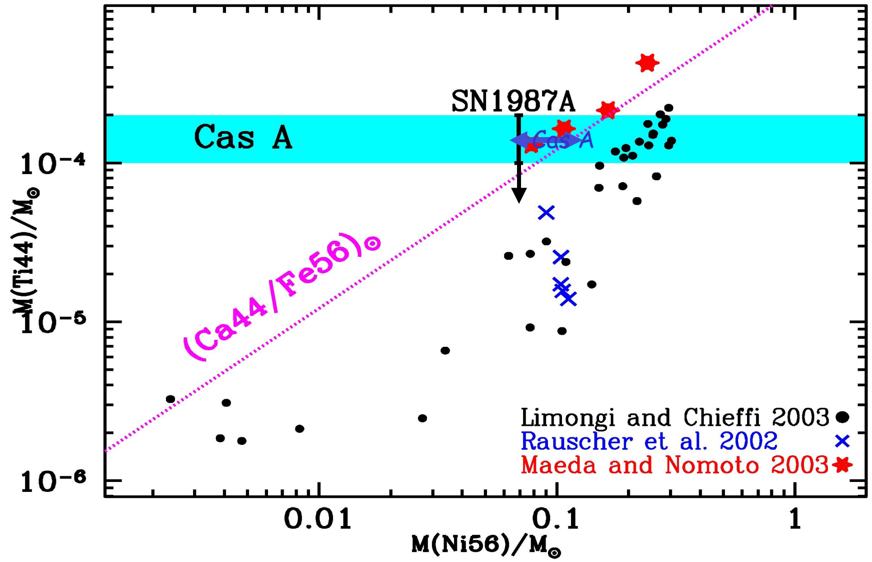




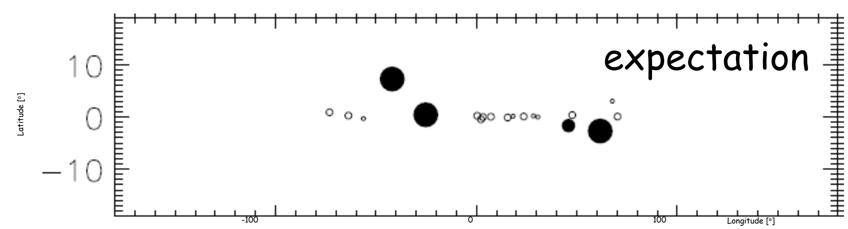
^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} $M_\odot$

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

- ^{44}Ti vs. ^{56}Ni: Models compared to
  - Solar ^{44}Ca/^{56}Fe
  - SN1987A & Cas A
  - Only Non-Spherical Models Seem to Reproduce Observed ^{56}Ni/^{44}Ti Ratios

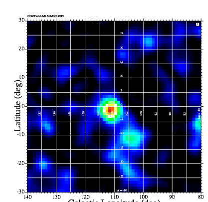


- Sky Regions with Most Massive Stars are ^{44}Ti Source-Free (COMPTEL, INTEGRAL)



- ***^{44}Ti is from Rare Events??***

- *The et al. 2006*

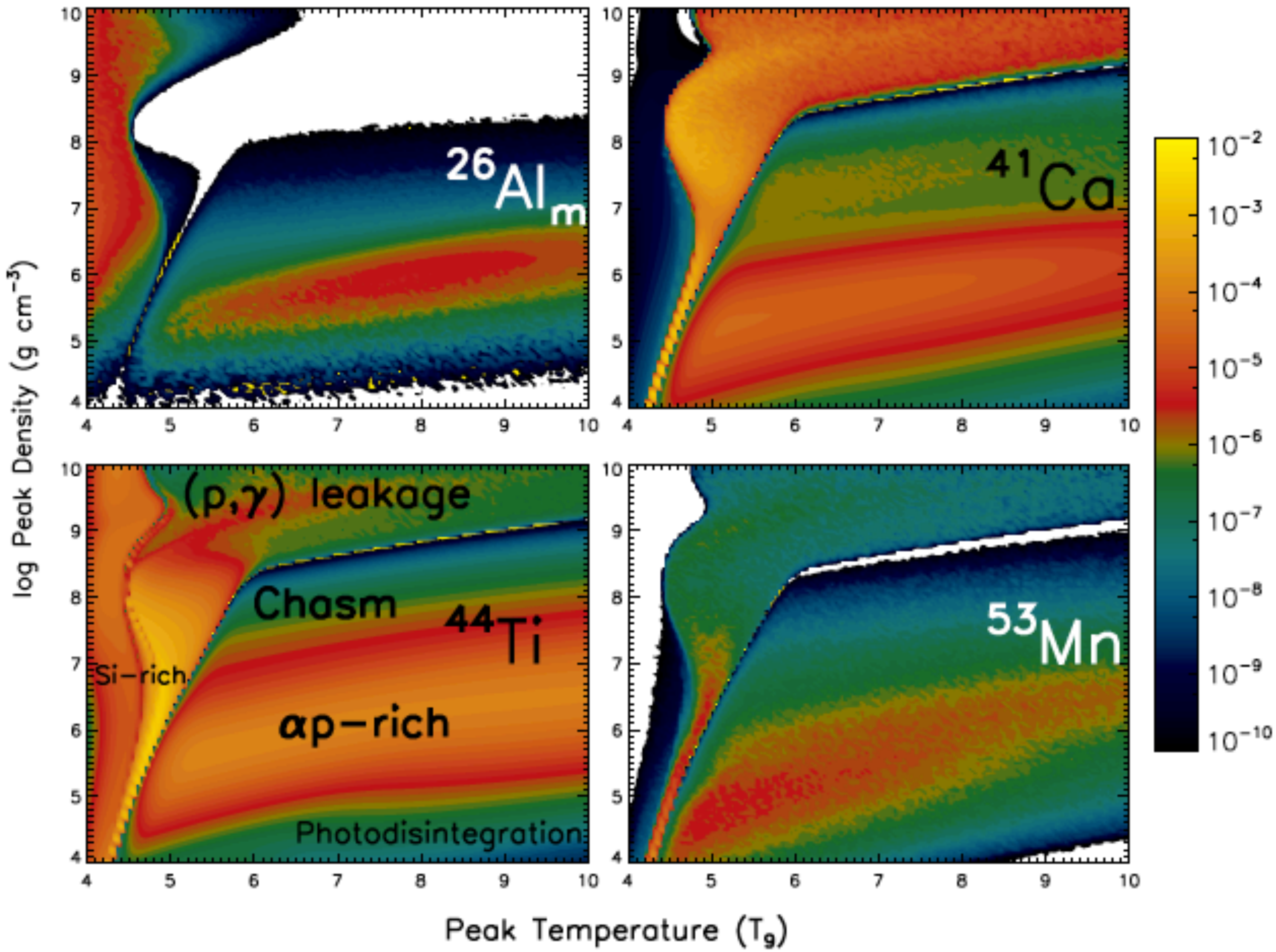


Cas A is the ONLY Source Seen in our Galaxy

(Iyudin et al 1994)

^{44}Ti Synthesis in cc-SNe

NuGrid collaboration (Magkotsios et al., ApJ 2011)



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

^{44}Ti Ejecta Velocities

- ☆ **High-Energy Line Not Seen with SPI**
  - ☞ Velocity-Broadened, → Dissappearing in Bgd
- ☆ **Estimate Doppler Broadening:**
  - ☞ Astrophysical Line Width >3.2 keV -> 500 km s^{-1} (lower v limit)
  - ☞ *Martin et al. 2009*
- ☆ **^{44}Ti Ejecta from Turbulent Zones Well Outside Mass Cut**
- ☆ **NuStar Mission will (?) Map ^{44}Ti Clumps**

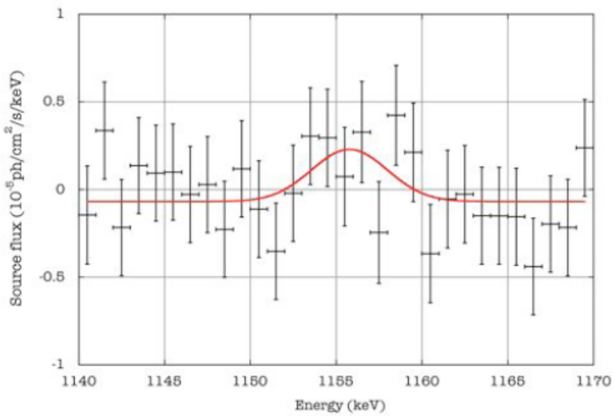
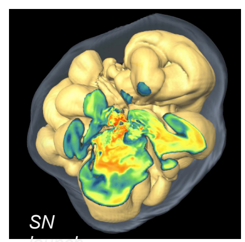
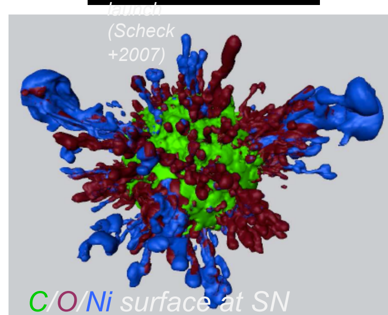


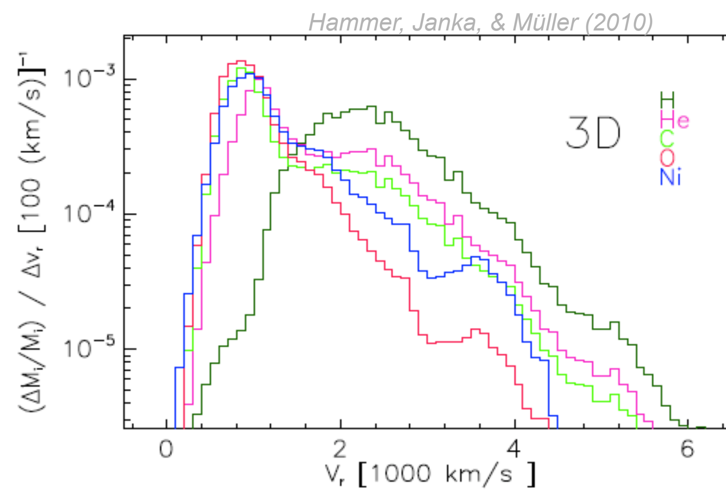
Fig. 4. Cassiopeia A spectrum at 1157.0 keV combining SE and ME2; red solid curve is the fit of a Gaussian shape.



(Scheck +2007)



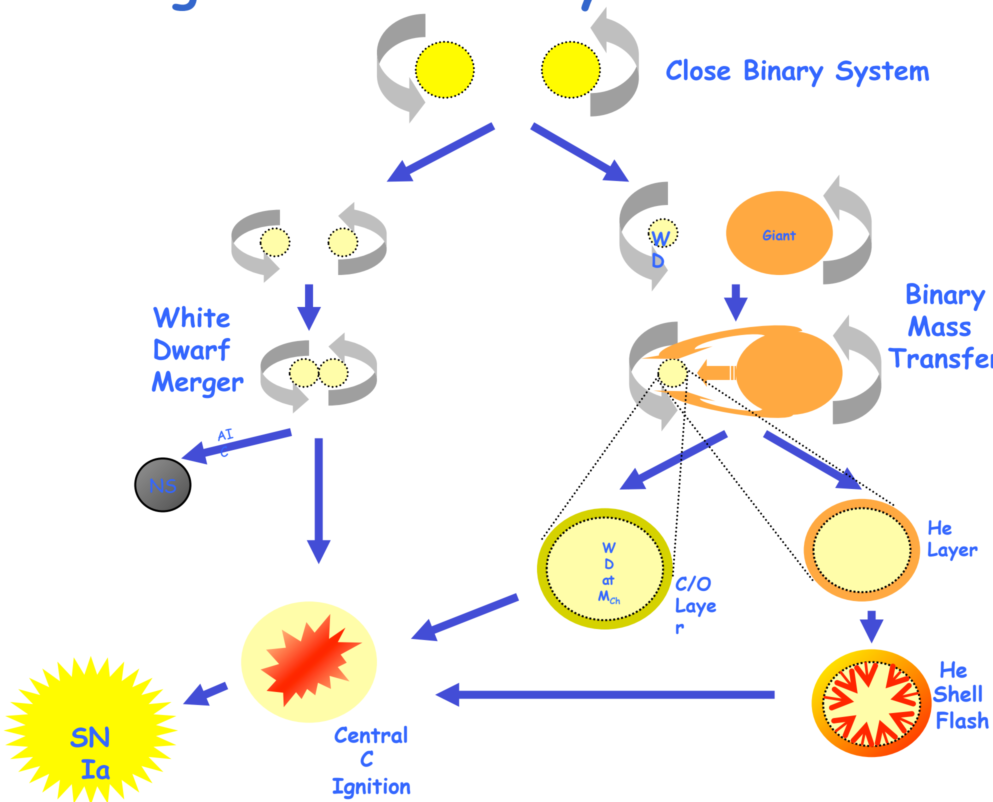
shock breakout (t~9000 sec)

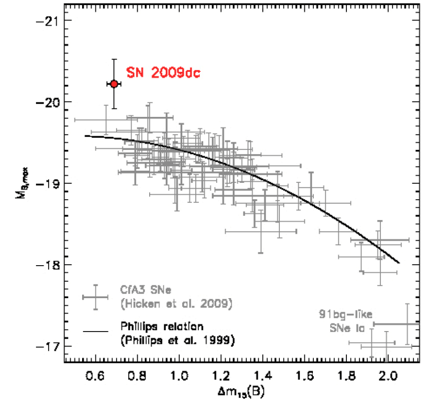


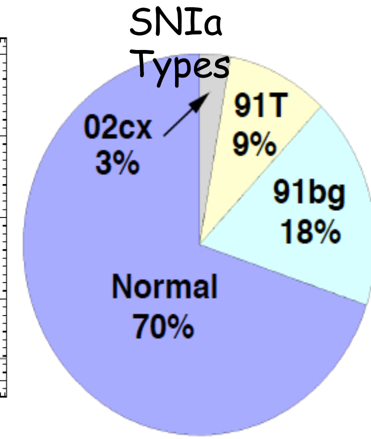
11+: X-ray Imaging

SNIa

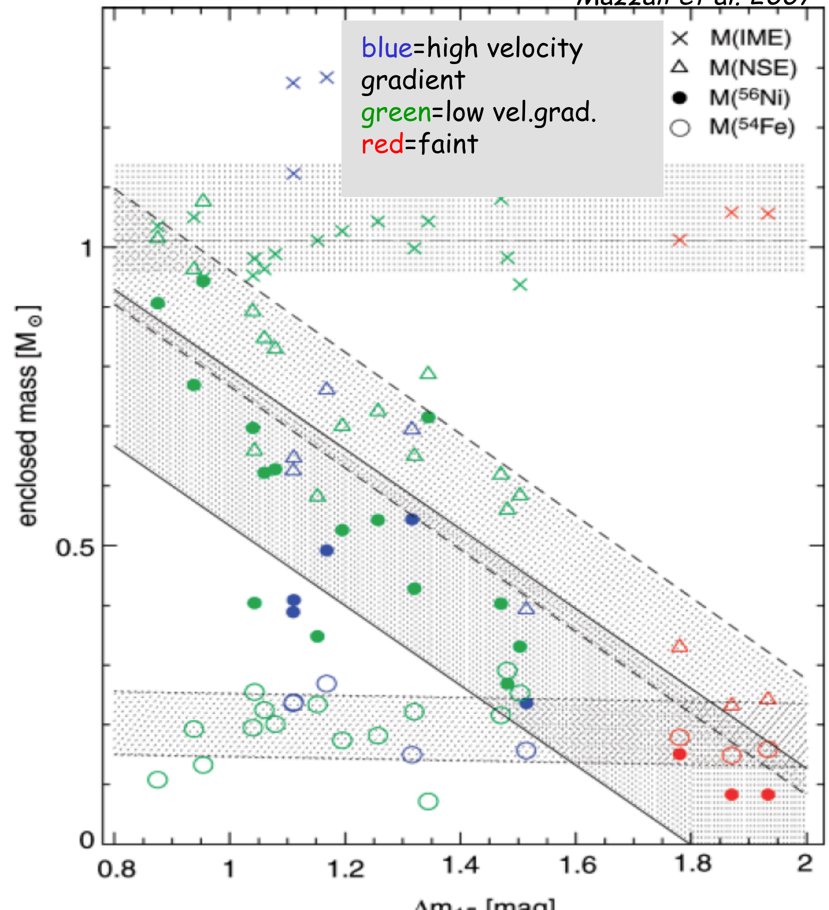
- **SNIa Diversity becomes a Reality**
  - ☆ Progenitor Diversity?



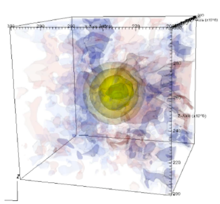


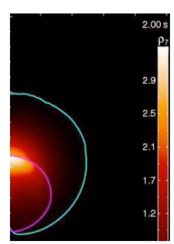


Mazzali et al. 2007



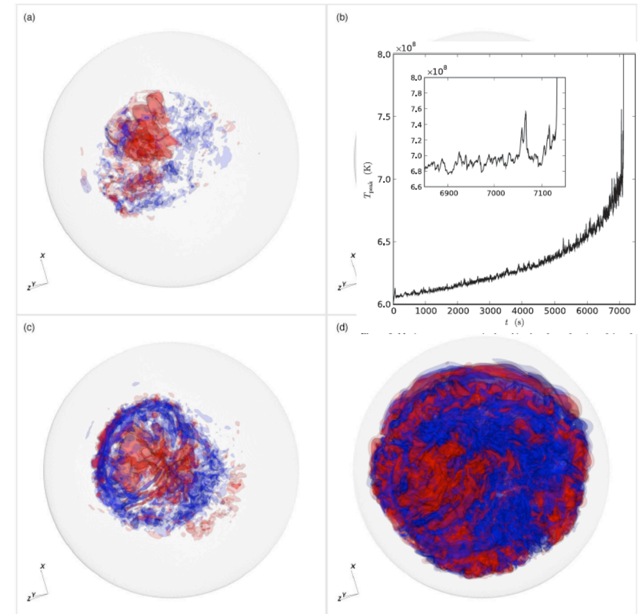
- ☆ Ignition Physics?

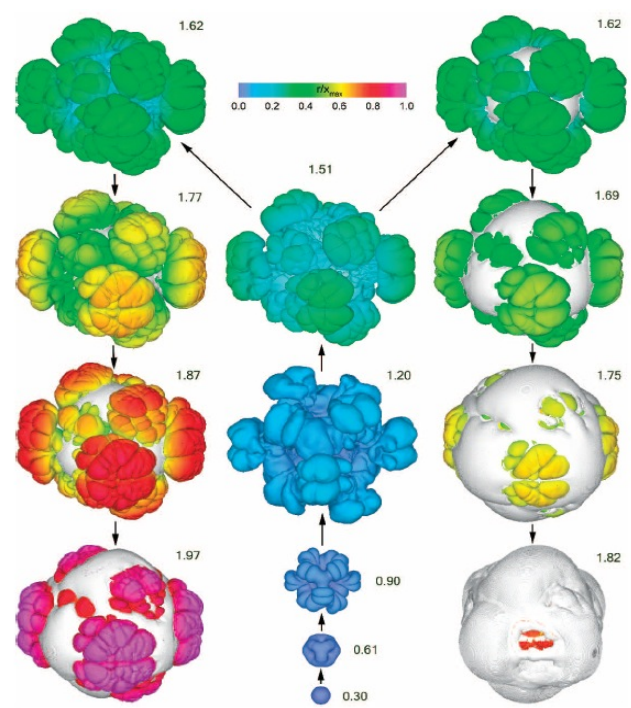




SNIa Model Issues

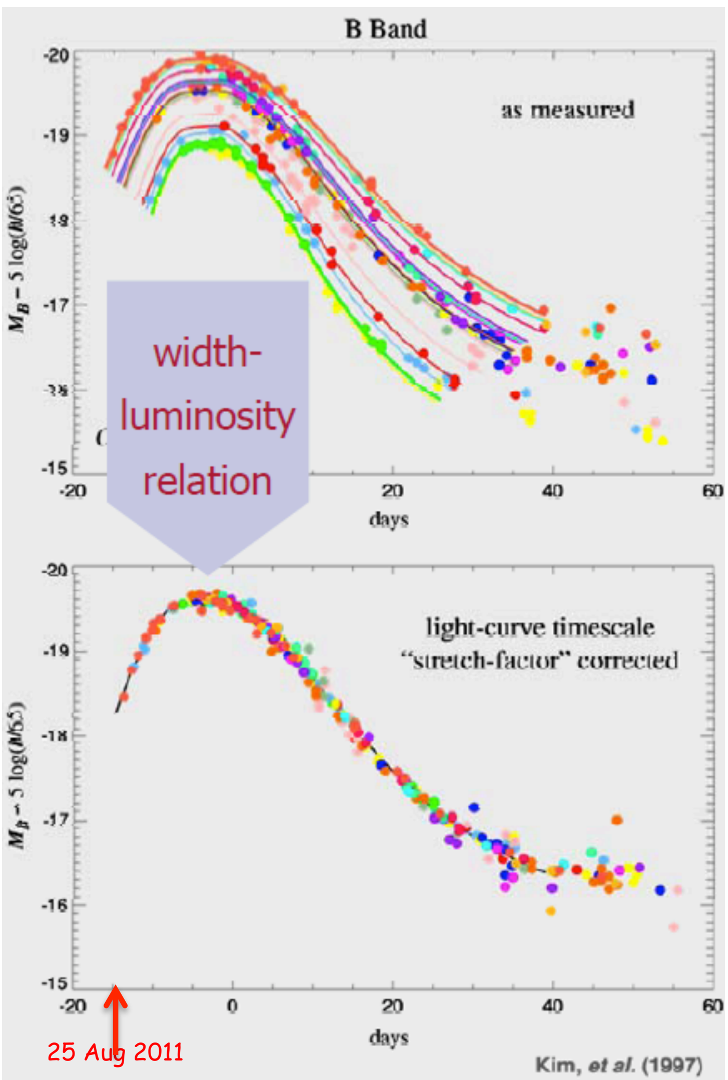
- **Ignition of the Runaway**
  - ☆ Smoldering
    - ☞ How Long (SSSources)
  - ☆ Central or Distributed?
  - ☆ by He Flash?
- **Propagation of the Flame in WD**
  - ☆ Detonation (supersonic flame):
    - ☞ Unlikely (only Fe-Group Elements); Use as "extreme reference case"
  - ☆ Deflagration: v_{flame} ~size & time scale of turbulence
    (Rayleigh-Taylor, Kelvin-Helmholtz, Landau Darrius)
  - ☆ Laminar:
    - ☞ Unlikely: WD Expansion -> Fizzles; Possibly 'preparing the SN' (pulsational models)
- ...

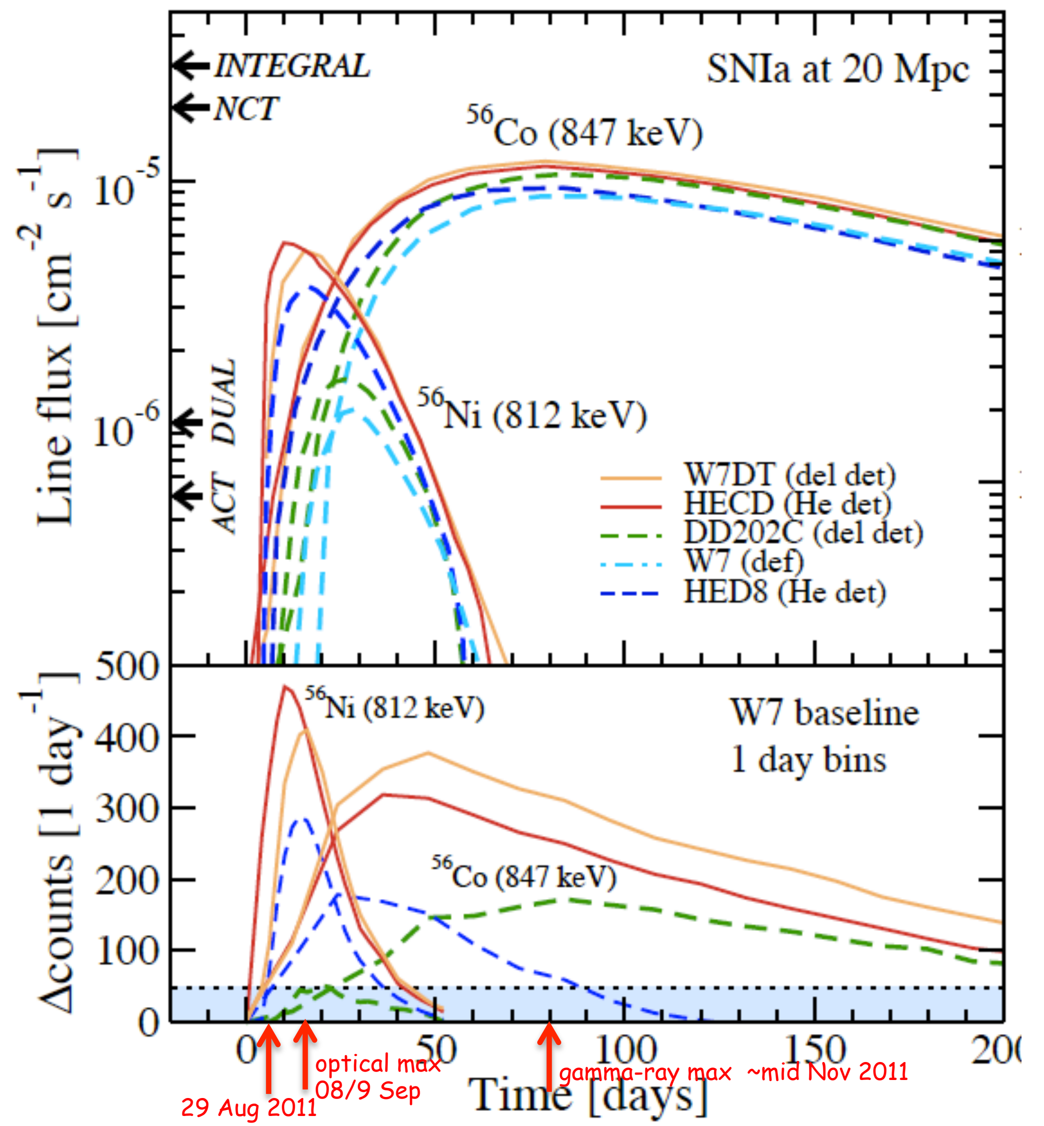




SNIa Models and Radioacivity Gamma-Rays

- SN 2011fe in M101 is a Chance to Gamma-Calibrate SNIa Models (d~6.4 Mpc)
  - ☆ Phillips Relation, Light Transport Codes from Gamma to X/UV/OPT/IR



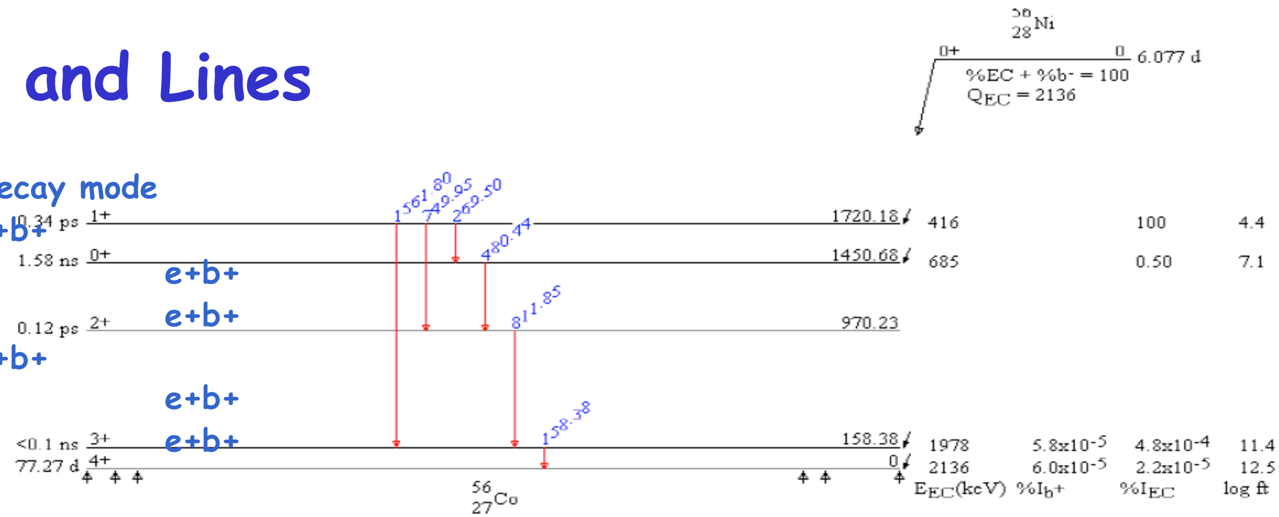


^{56}Ni Decay

- **Decay Properties and Lines**

$T_{1/2}$= 6.077 d

Eγ (keV)	Iγ (%)	Decay mode
158.38 3	98.8 10	e+b+
269.50 2	36.5 8	e+b+
480.44 2	36.5 8	e+b+
749.95 3	49.5 12	e+b+
811.85 3	86.0 9	e+b+
1561.80 5	14.0 6	e+b+



$T_{1/2}$= 77.27 d

Eγ (keV)

158.38 3 98.8

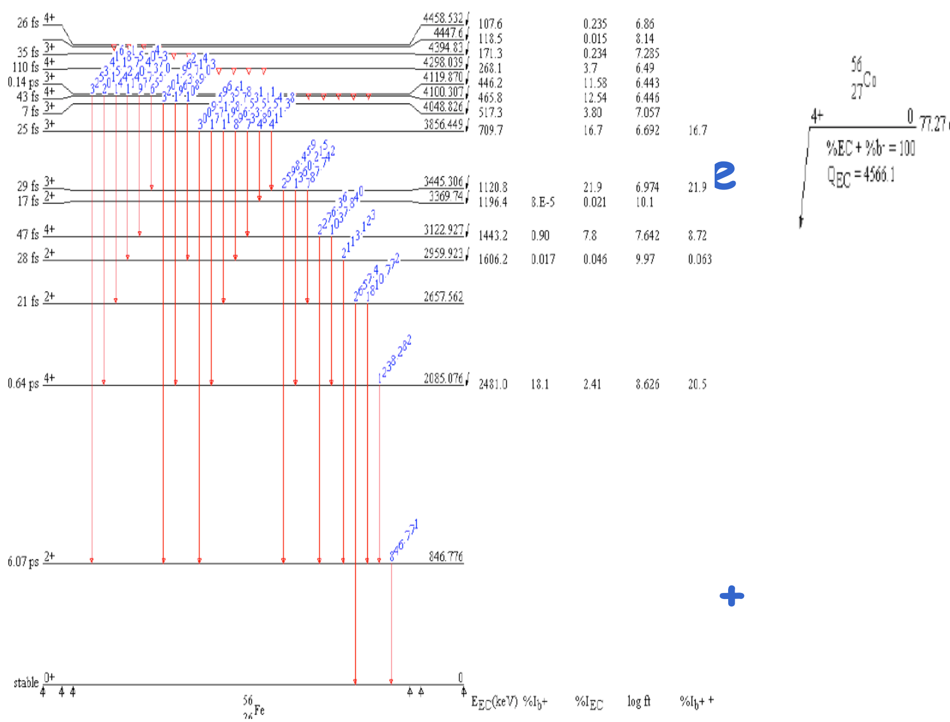
269.50 2 36.5

480.44 2 36.5

749.95 3 49.5

811.85 3 86.0

1561.80 5



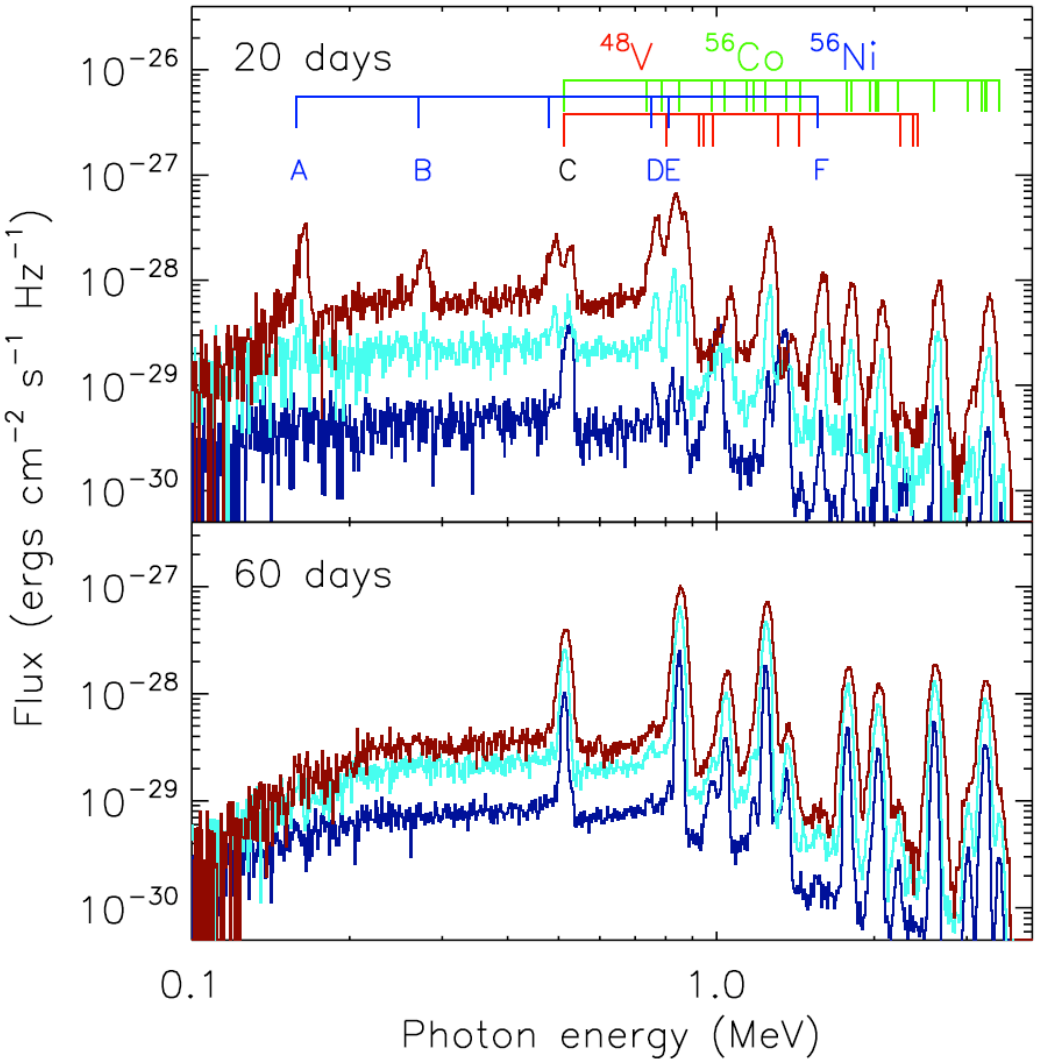
e

+

SNIa Models: Diagnostics from γ-ray Spectra

☞ Gamma-Ray Spectra

» for sub-Ch Model Variants *Kromer et al. 2010*



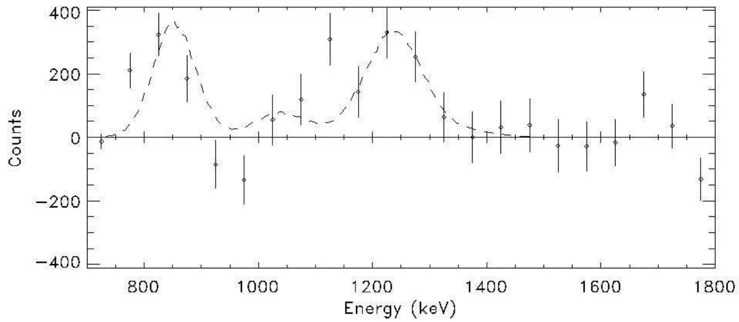
Identifier	Photon Energy (MeV)	Source
A	0.158	^{56}Ni
B	0.270	^{56}Ni
C	0.511	Annihilation of positrons from ^{56}Co and ^{48}V
D	0.750	^{56}Ni
E	0.812	^{56}Ni
F	1.562	^{56}Ni

Lines are Broad (~10...30 keV)

Line Ratios Change Significantly

Roland Diehl

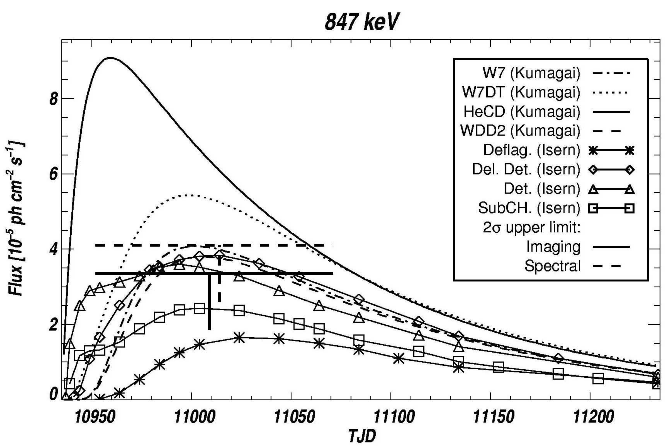
"Calibration" of Thermonuclear Supernovae



(Morris et al. 1995;1997)

❍ SN 1991T

- Peculiar & Super-Bright; d~17Mpc
- Indication of ^{56}Co Lines (COMPTEL) -> M_{Ni}~0.6-3.3 M_o



(Georgii et al. 1999)

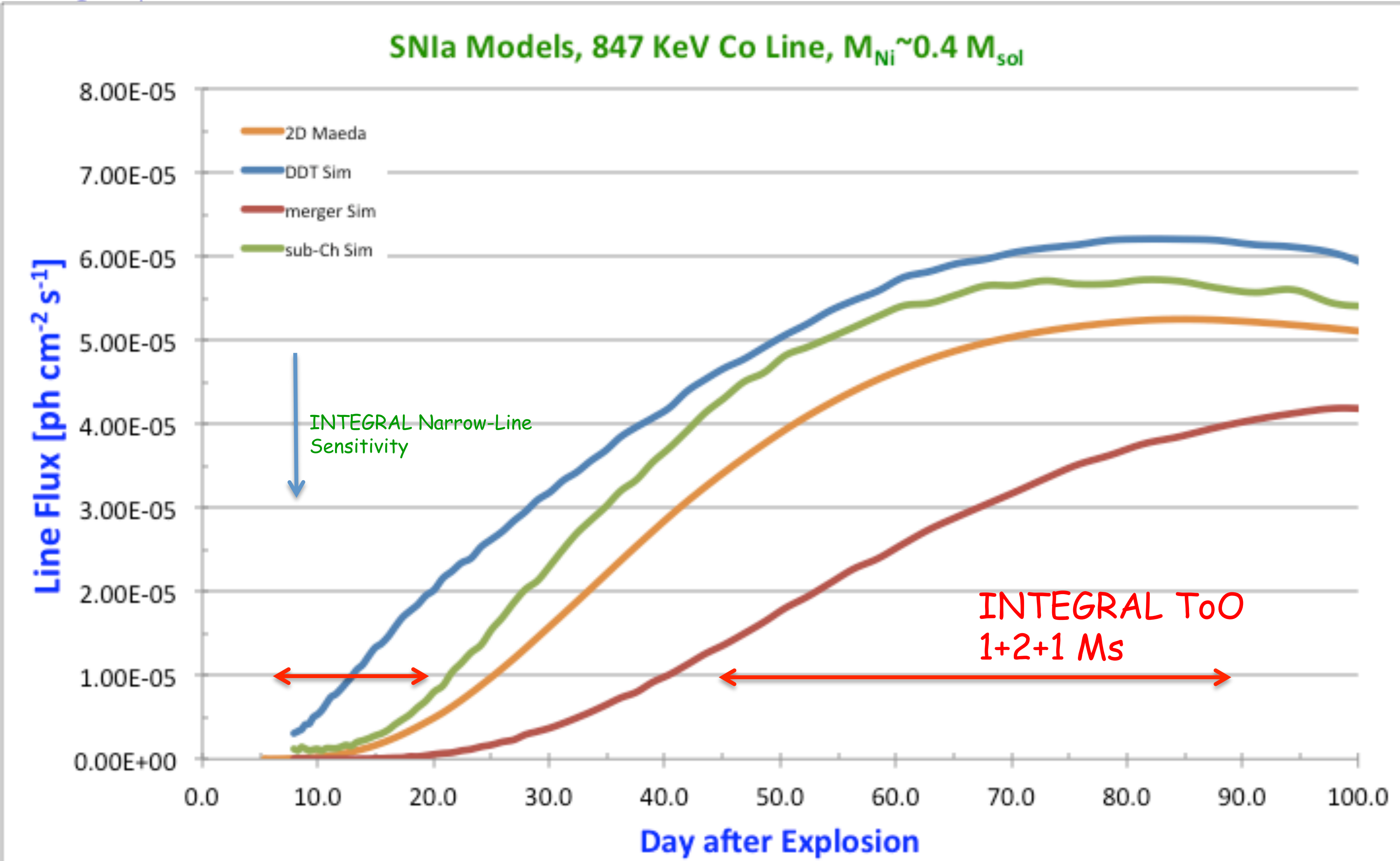
❍ SN1998bu

- Unusually-high Reddening; d~8-12 Mpc
- Limits on Lines (OSSE; COMPTEL)
  Constrain Models:
  No He Cap Detonator(s)

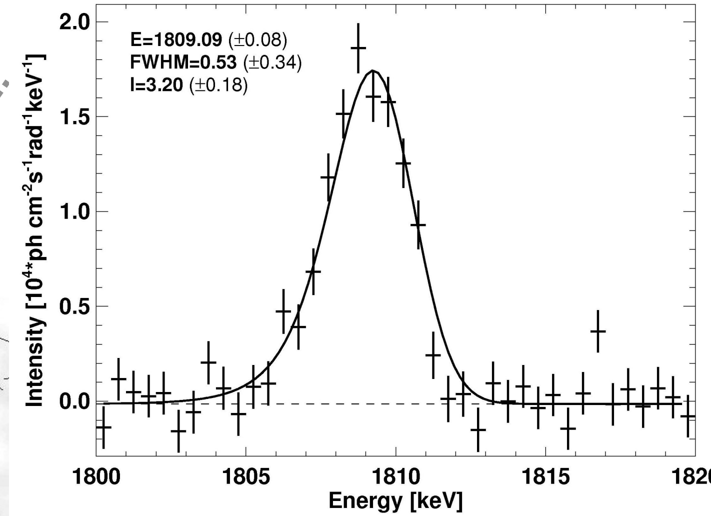
- **Instrumental Sensitivity Requires d < 10 Mpc**
- **Two "Opportunities" Both "Unusual"**
- **Accuracy Insufficient for Real ^{56}Ni Mass Constraints**

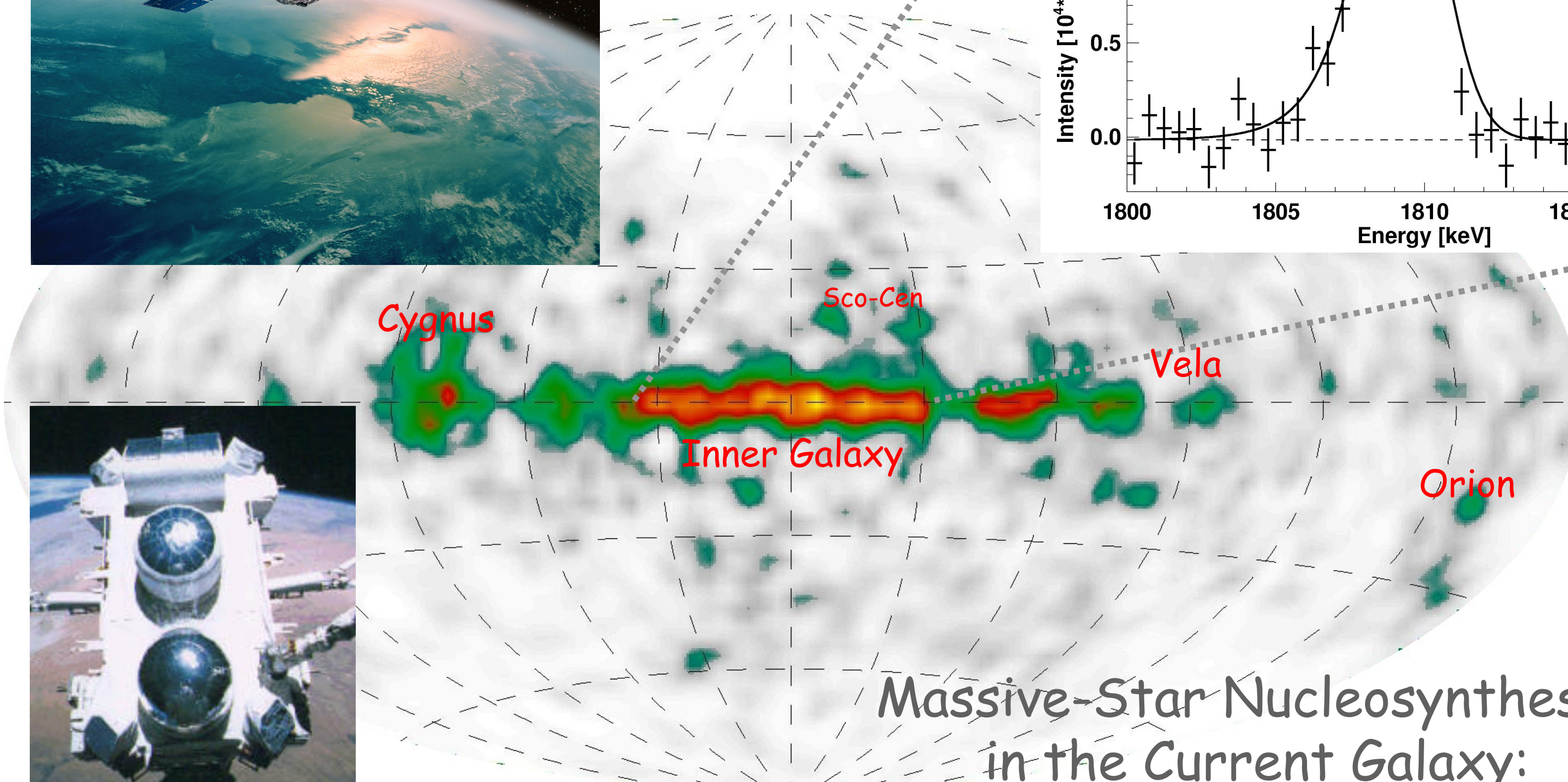
SNIa Models and Gamma-Rays: SN2011fe @6.4 Mpc

- The ^{60}Co Gamma-Ray Intensity Peaks at ~50...90 Days after



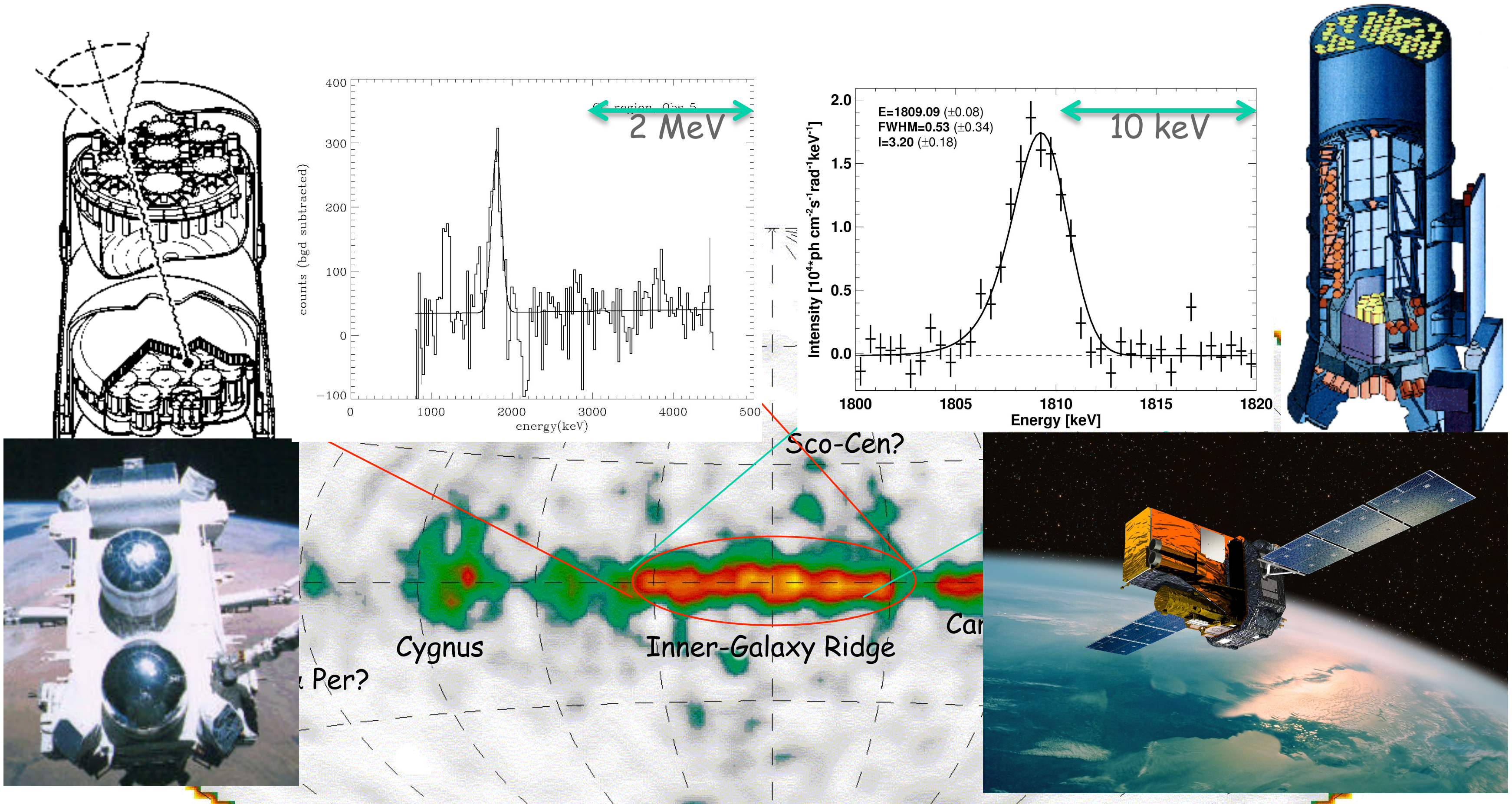
^{26}Al in our Galaxy: γ-ray Image and Spectrum





Massive-Star Nucleosynthesis
in the Current Galaxy:
Exploiting the Message from ^{26}Al γ-rays

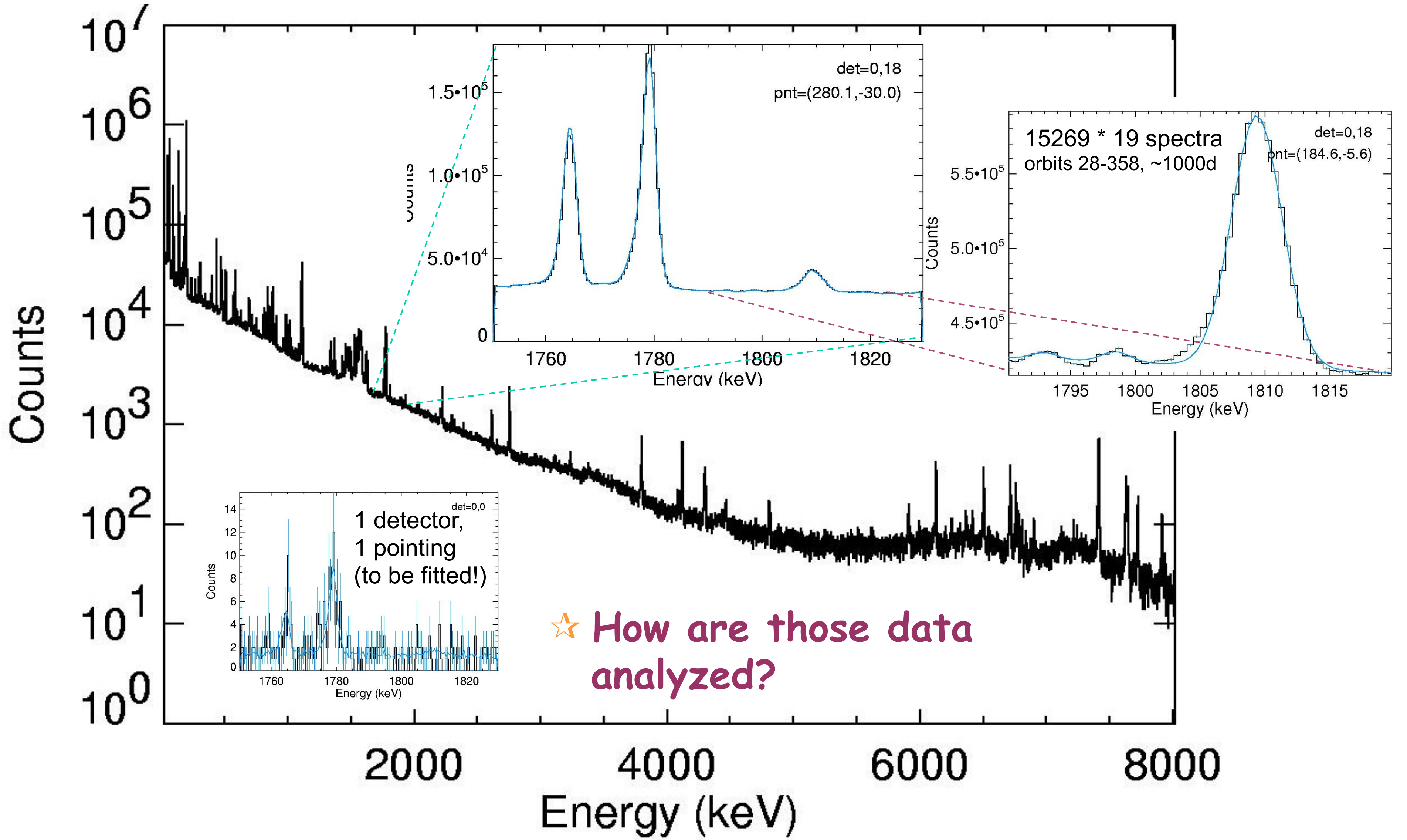
CGRO (<2000) / INTEGRAL (>2002) Spectroscopy



COMPTEL's δE~200 keV
(-> $v_{Doppler}$>25000km/s needed ☹)

INTEGRAL's δE~3 keV
(-> $v_{Doppler}$>100km/s needed ☺)

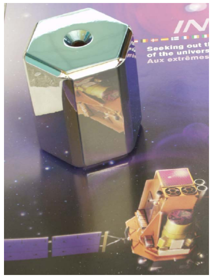
Energy Spectra: Characteristic Examples

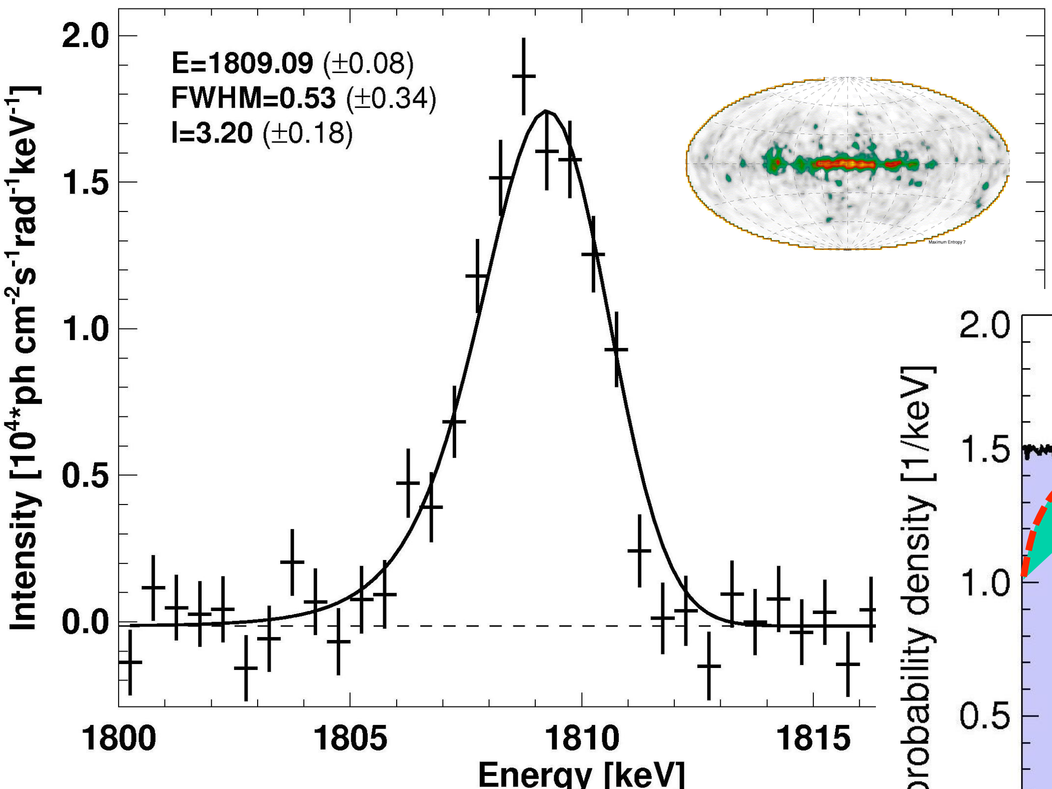


☆ How are those data analyzed?

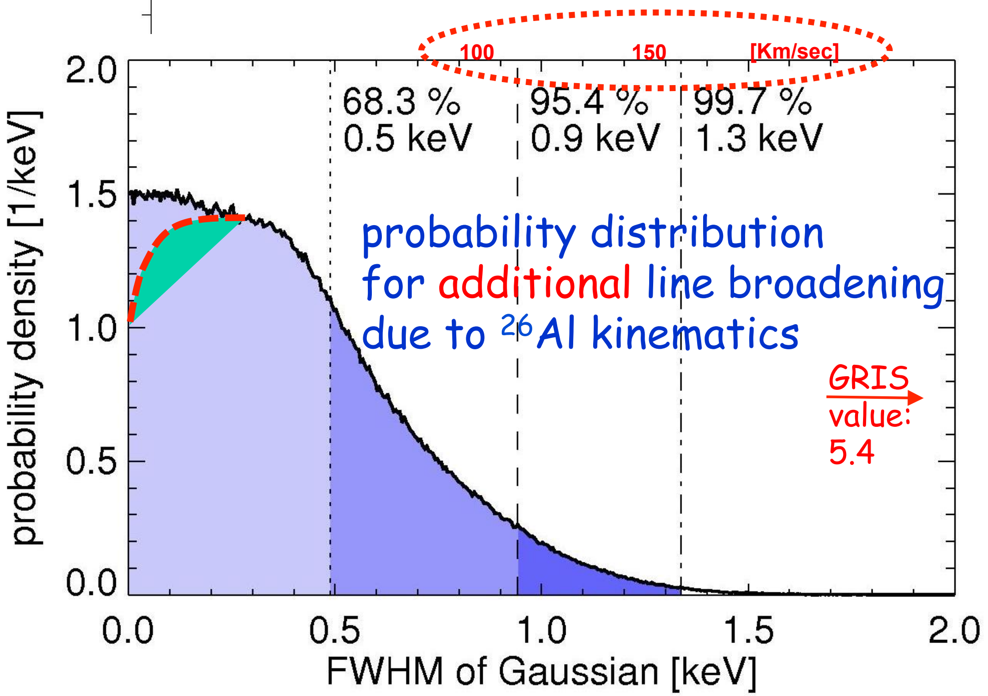
Spectroscopy with γ-rays

☆ **SPI High-Resolution Spectroscopy Pushed the Velocity Contraints Towards the Astrophysically-Meaningful ISM Velocity Range**





- Galaxy-integrated ^{26}Al Line is "Narrow"
  (~instrumental width+)
  - ☞ SPI: ~0.4 keV, <1.3 keV
  - ☞ ISM velocities 25…150 km s^{-1}



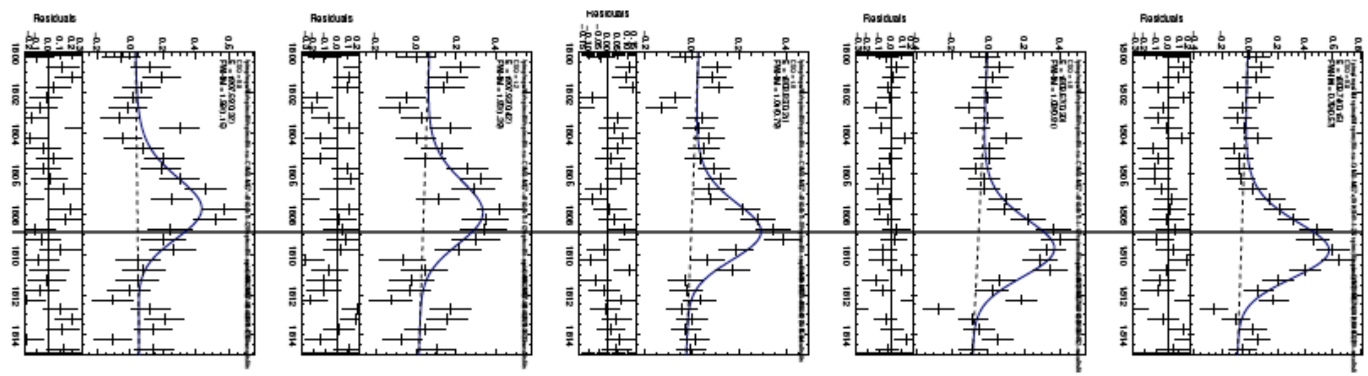
-> Data up to mid 2006; → W.Wang et al., (2008)

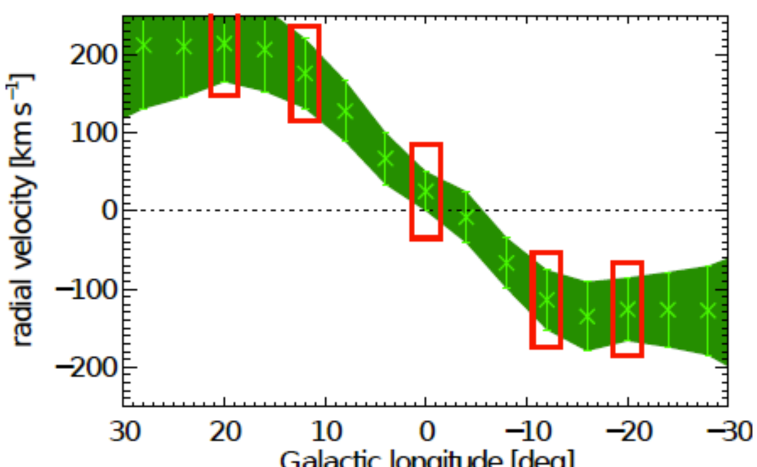
Line Width Probability Distribution by K.Kretschmer

^{26}Al Kinematics

- Mapping ^{26}Al-enriched gas in inner Galaxy with INTEGRAL:
  - 2.7° FWHM 'Beam'

☆ Integrate ^{26}Al Line in Δl Bins → Centroid → Galactic Rotation





- fit sky maps to INTEGRAL data → spectrum
- spectral fit → line centroid
- scan region of interest along Galactic plane

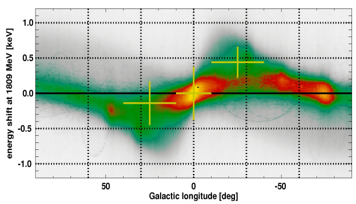
Using the ^{26}Al Line to Characterize the Galaxy

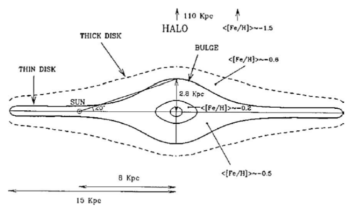
-> Diehl et al., Nature 2006

☆ Measured Gamma-Ray Flux

☆ Galaxy Geometry

} ➢ ^{26}Al Mass in Galaxy = 2.8 (±0.8) $M_\odot$





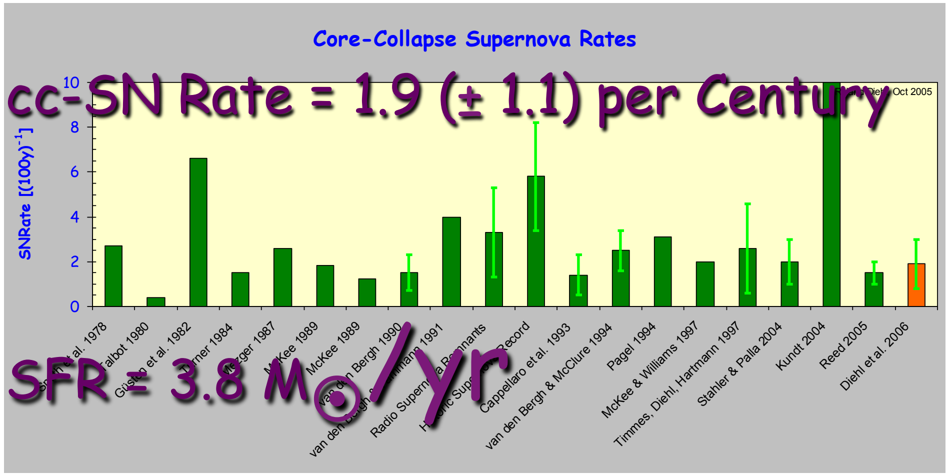
☆ ^{26}Al Yields per Star

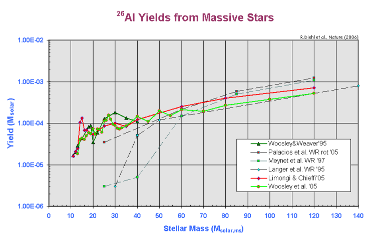
☆ Stellar Mass Distribution

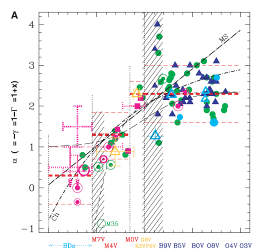
}

✓ cc-SN Rate = 1.9 (± 1.1) per Century

✓ SFR = 3.8 $M_\odot$/yr

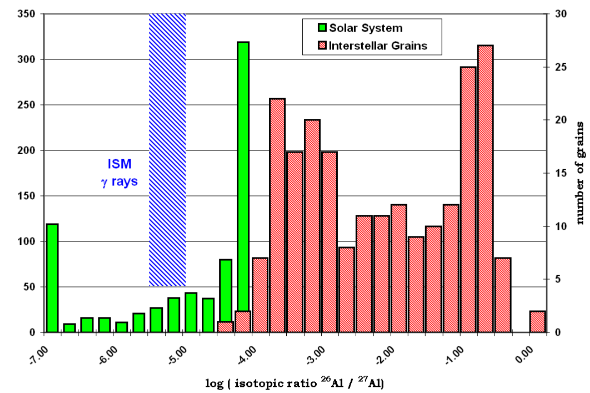






☆ Gas Mass in Galaxy

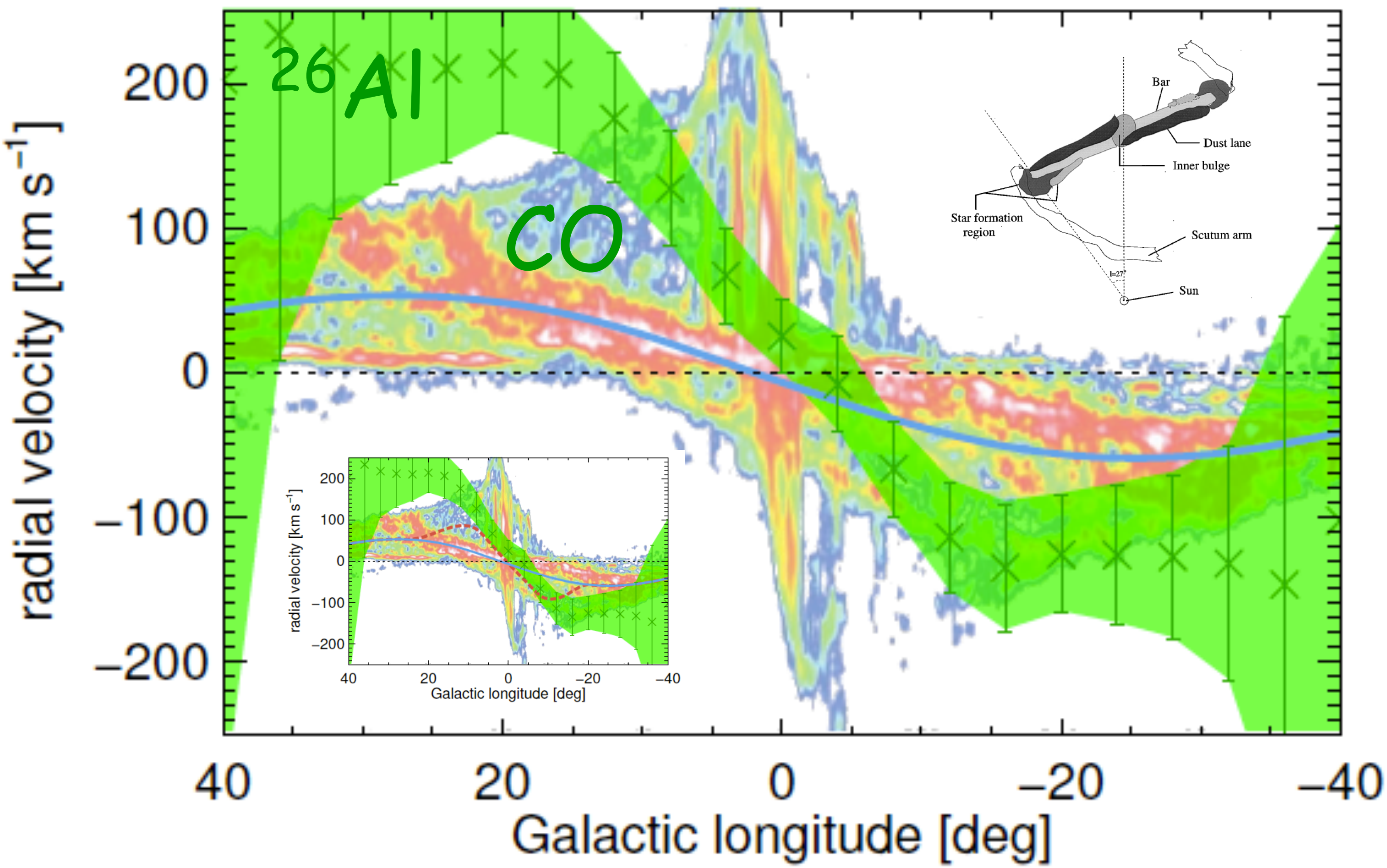
} ✓ Al Isotopic Ratio = 8.4 10^{-6}



ISM Kinematics along the Galactic Bar

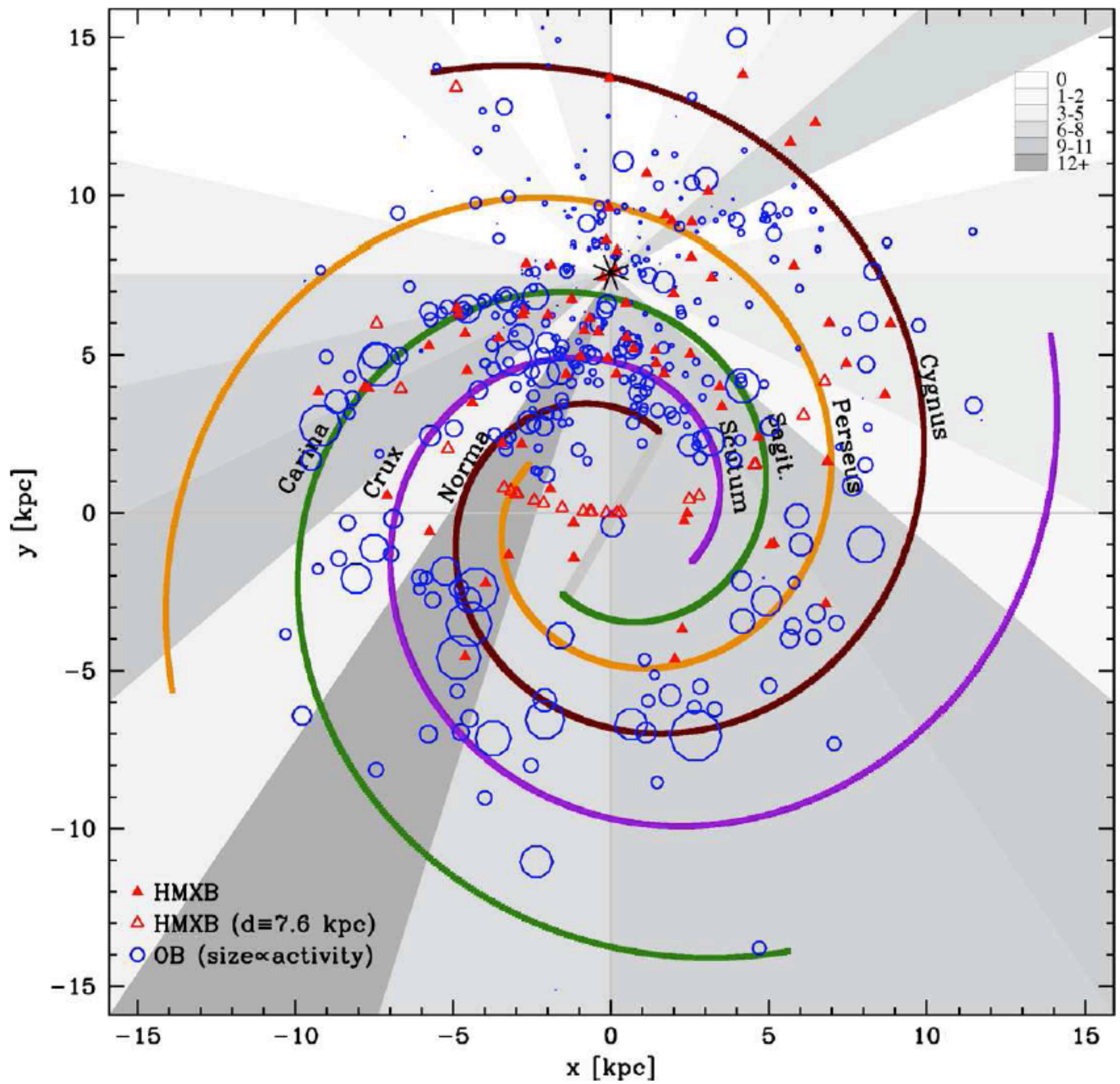
☆ Hot ISM as Traced by ^{26}Al Appears at Higher Velocities

Kretschmer et al., in prep. / 2012

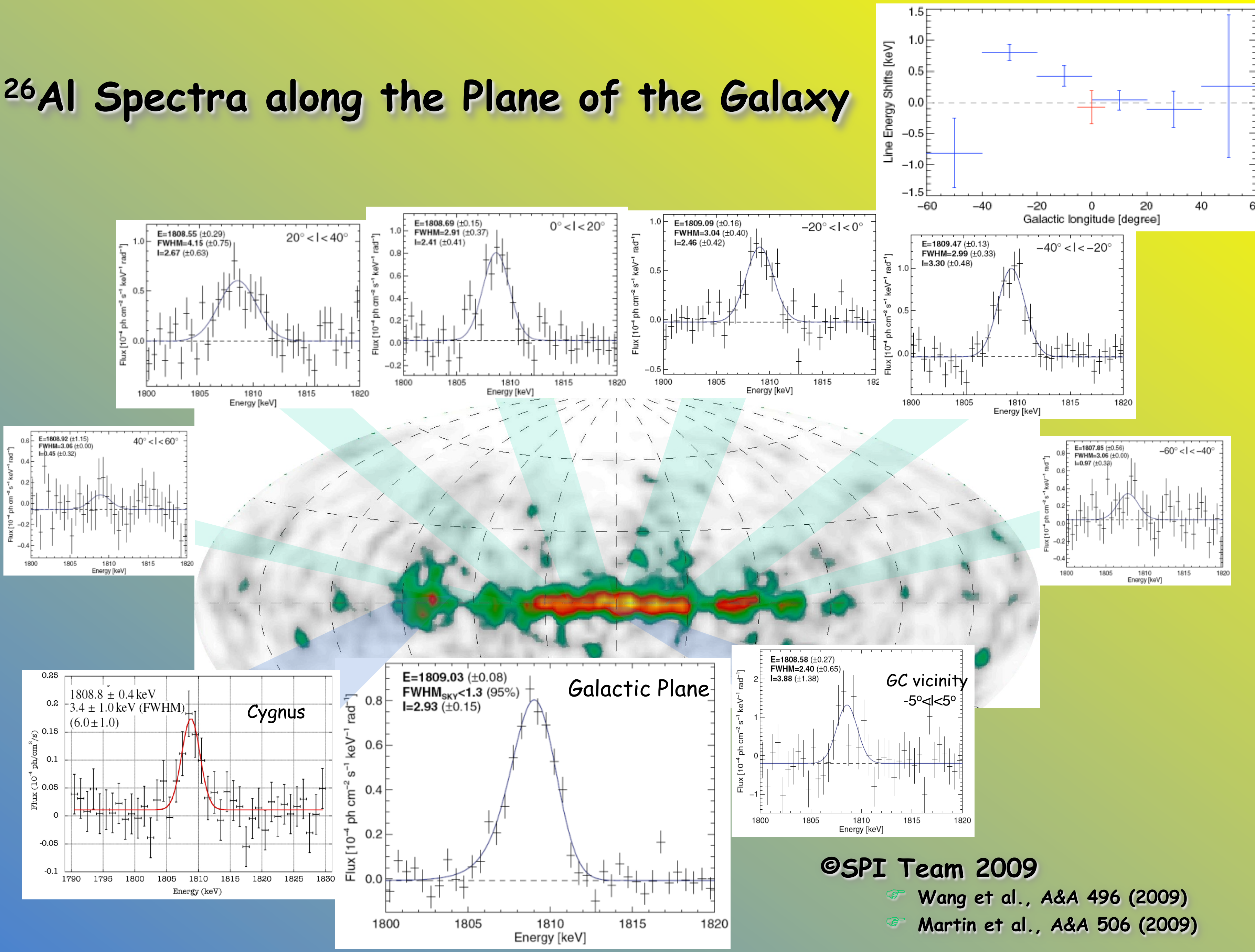


Where are the Candidate Sources?

- ☆ OB Associations, Massive Binaries, ...
  - ☞ We Need to Account for Incomplete Knowledge:
    - Biases in Time
    - Biases in Radiation
    - Biases in Space



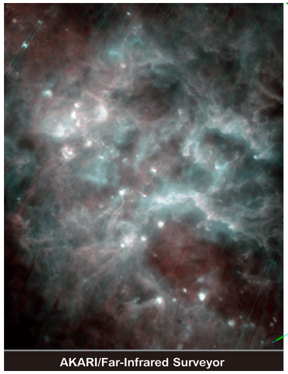
^{26}Al Spectra along the Plane of the Galaxy

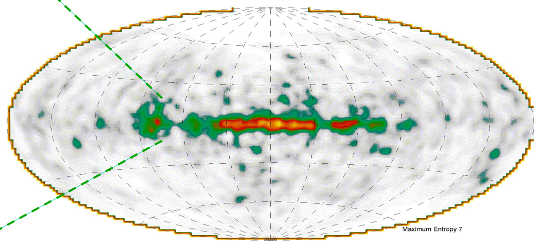


©SPI Team 2009

- Wang et al., A&A 496 (2009)
- Martin et al., A&A 506 (2009)

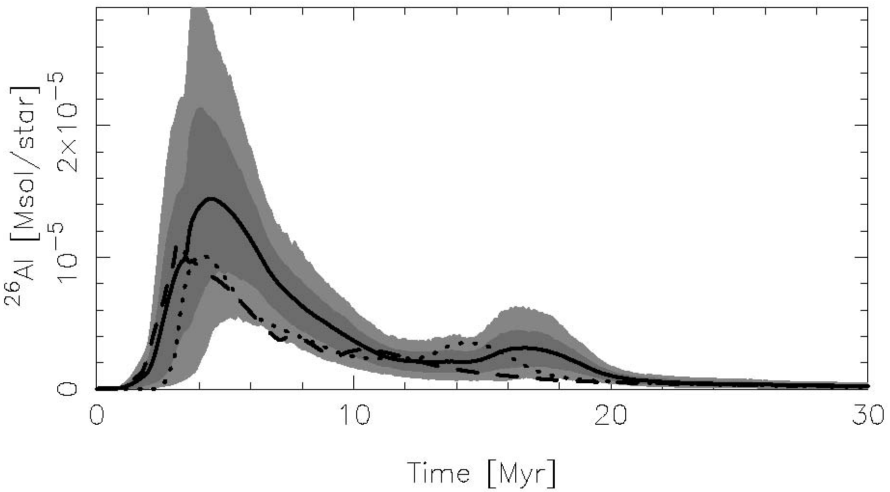
Testing our Models: Cygnus at its Specific Age

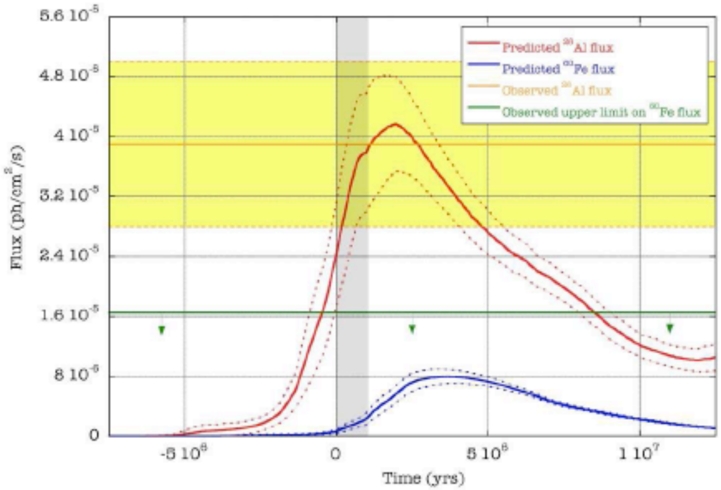


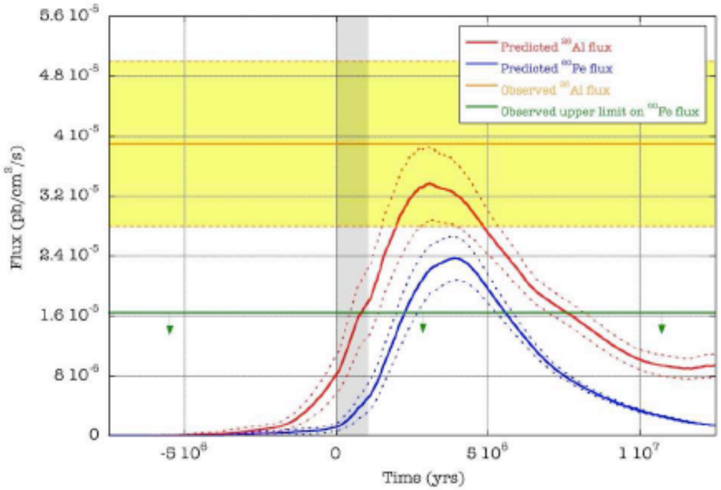


☆ **Population Synthesis: Application to Cygnus Region**

- ☞ Models for Solar Metallicity ~OK
- ☞ If Lower Metallicity: Underprediction?
- ☞ *Martin+ 2010*

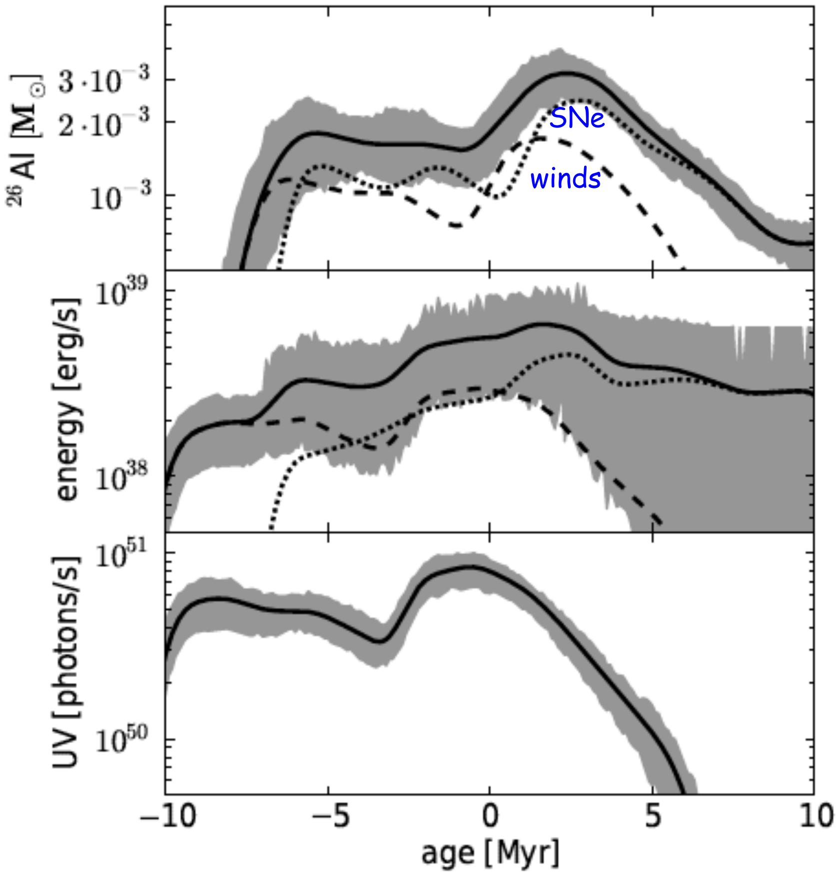






The Carina Region

- ☆ Comparing Model Predictions to Observations:
  - ☞ *Voss et al. 2011*



Plüschke+2001; Martin+ 2011:

^{26}Al Gamma-Rays 1-2 10^{-5} ph cm^{-2} s^{-1}

→ 4…9 10^{-3} $M_\odot$ of ^{26}Al

Smith & Brooks 2007:

Stellar-Wind Energy ~ 2 10^{38} erg s^{-1}

No SNe

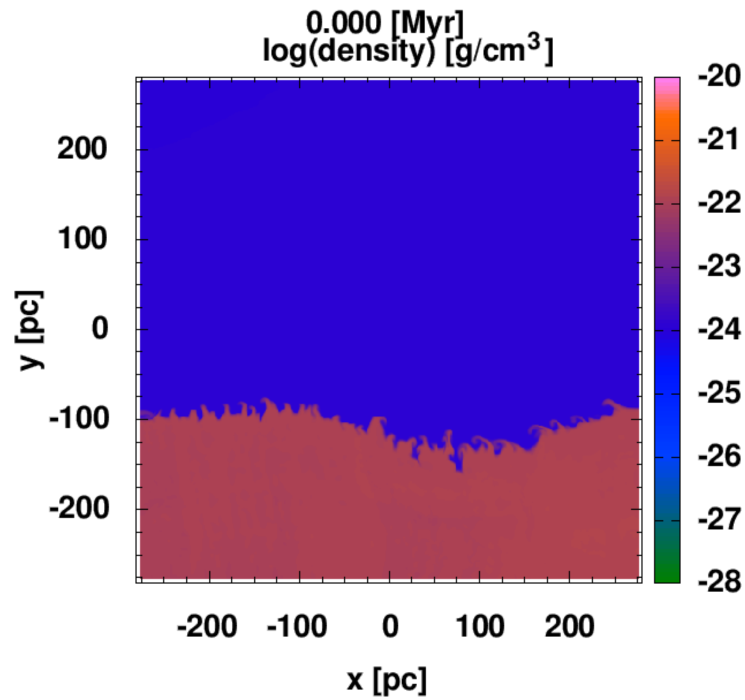
Smith & Brooks 2007:

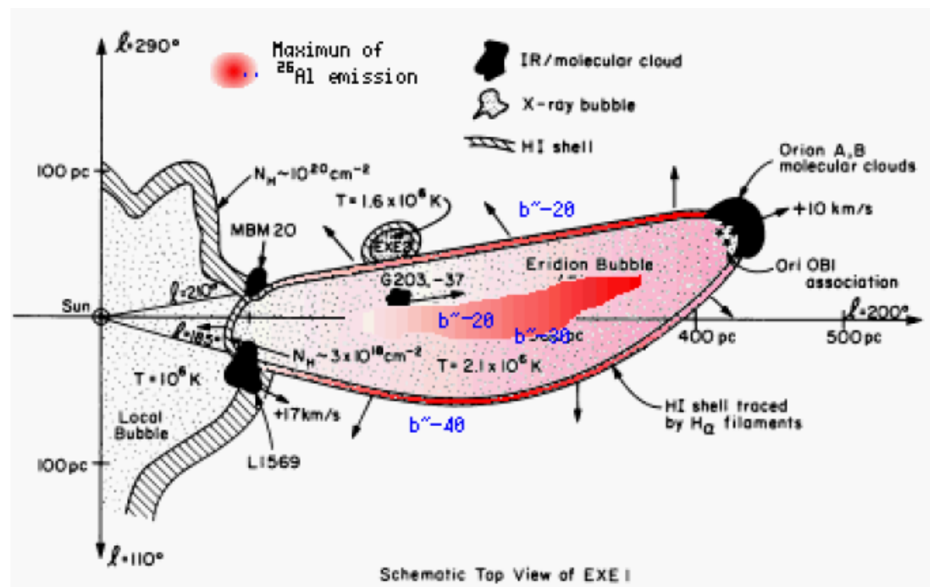
Ionizing Photons → Rate ~ 2 10^{51} s^{-1}

Dynamics of the Interstellar Medium

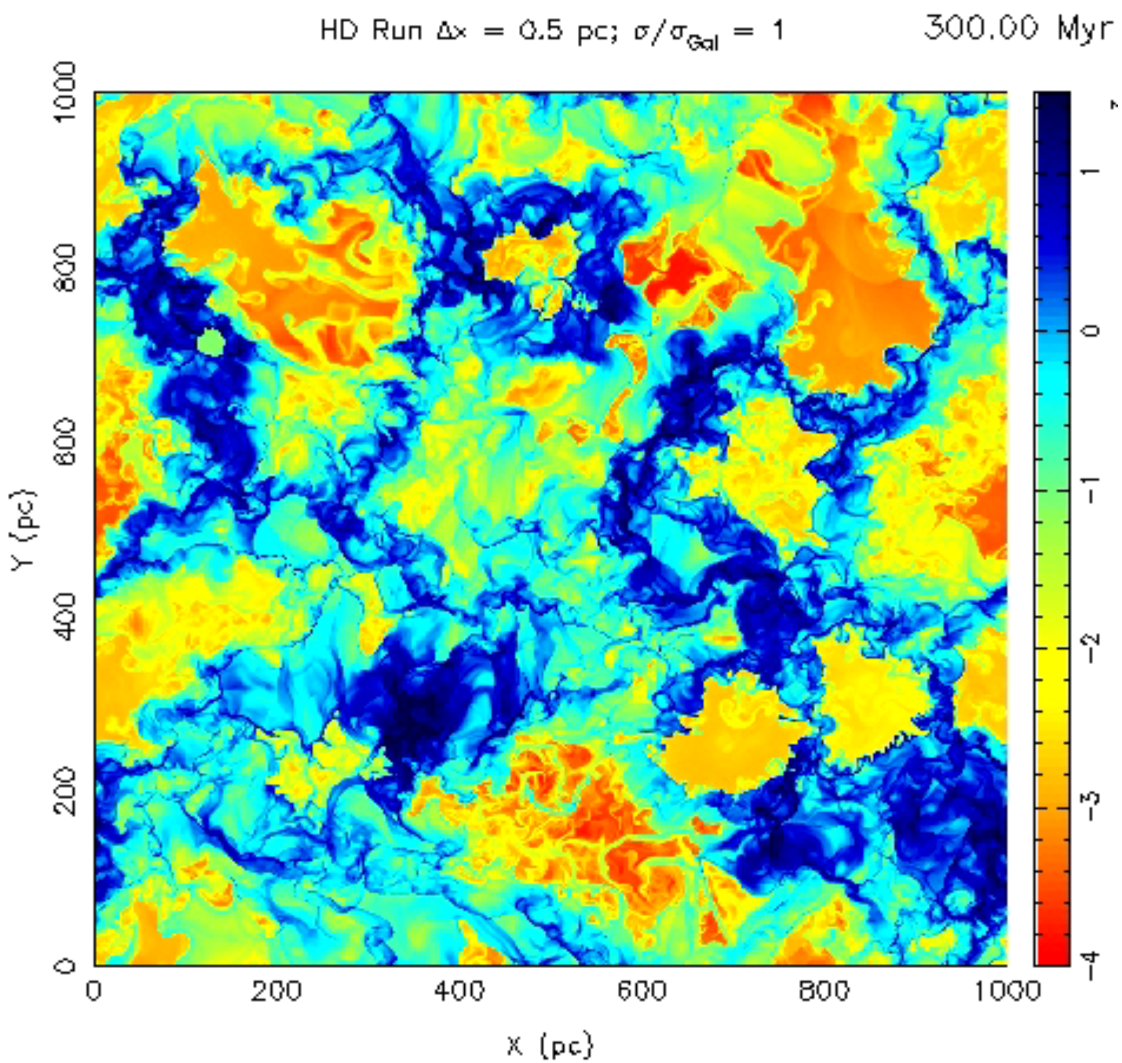
- The Orion Region as Test Case (Laboratory)
  - ☆ Mixing of SN Ejecta into Multi-Phase ISM?
- Simulations:
  - ☆ Trace Evolution of Massive-Star Activity in Parental Cloud

Fierlinger, Burkert, Diehl, et al.



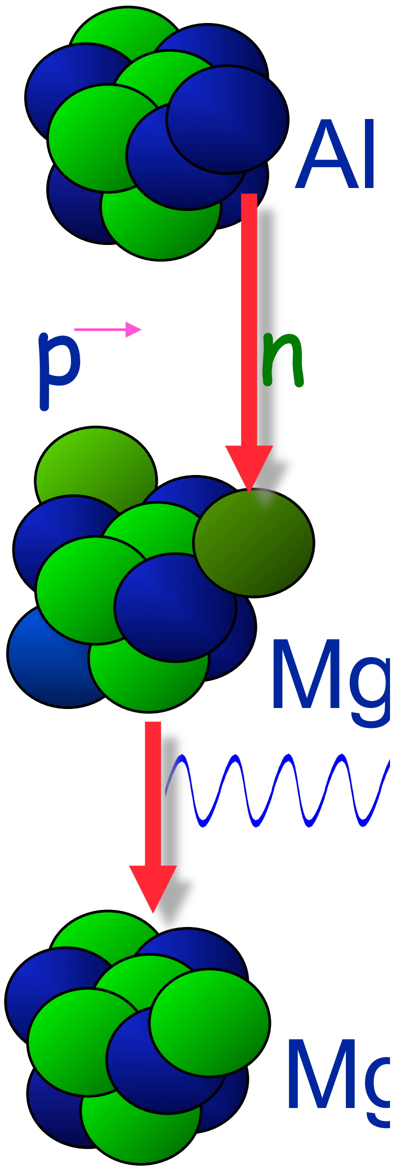


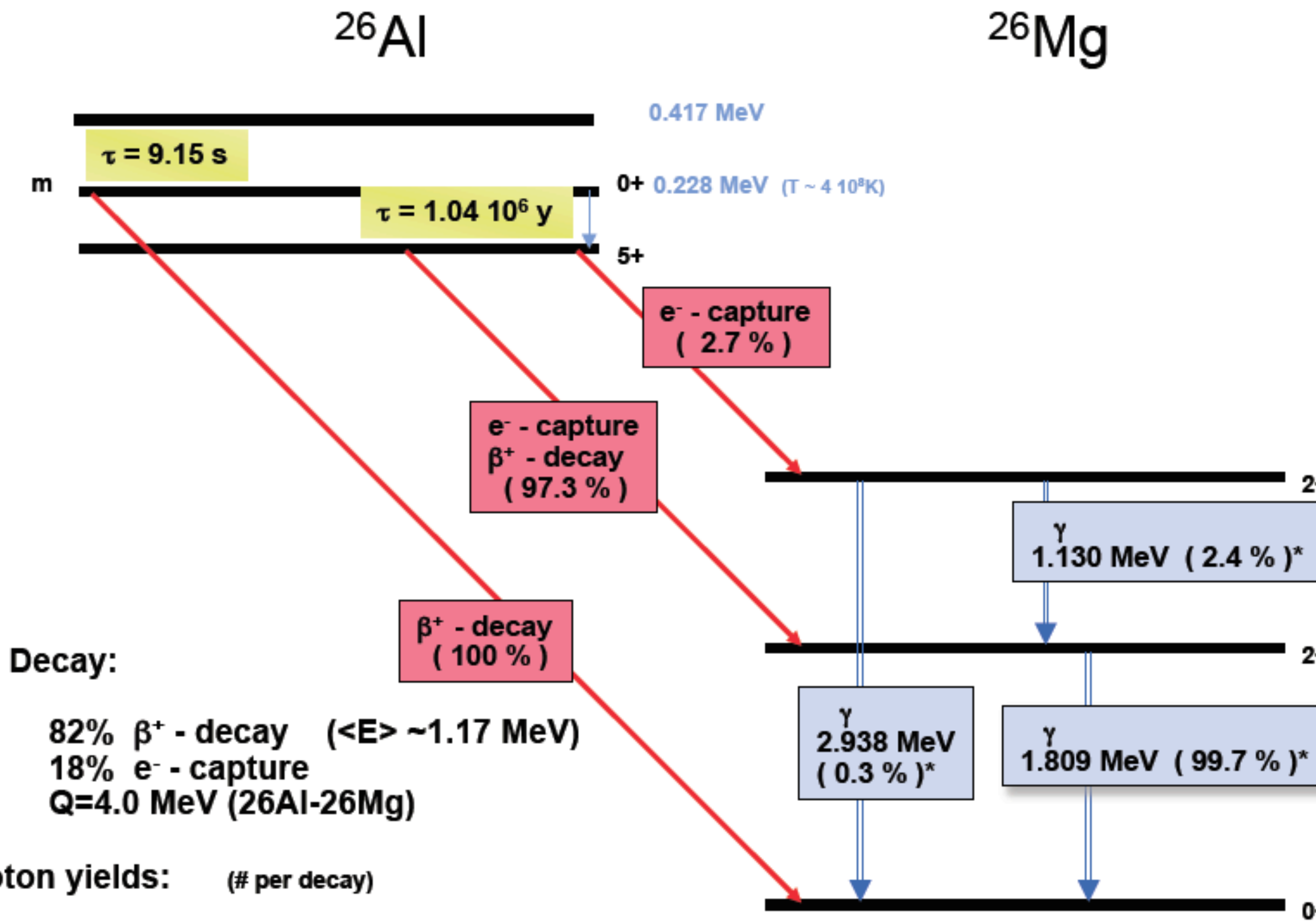
The Dynamic Interstellar Medium



courtesy Miguel de Avillez 2010

^{26}Al Radioactive Decay





^{26}Al Decay:

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

Photon yields: (# per decay)

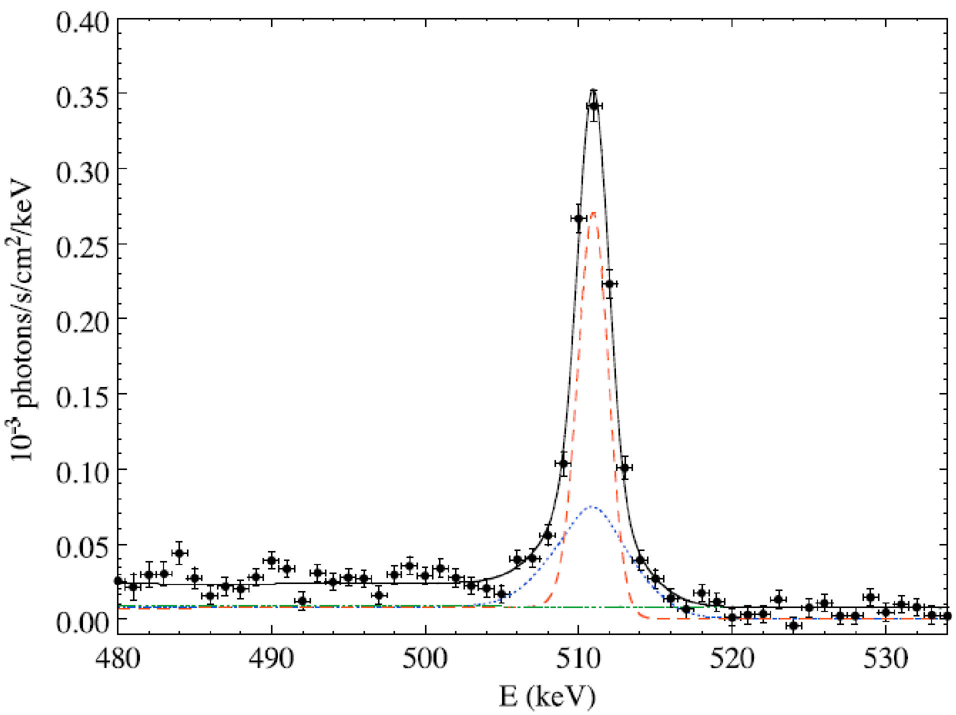
0.511 MeV	1.622
1.130 MeV	0.024
1.809 MeV	0.997
2.938 MeV	0.003

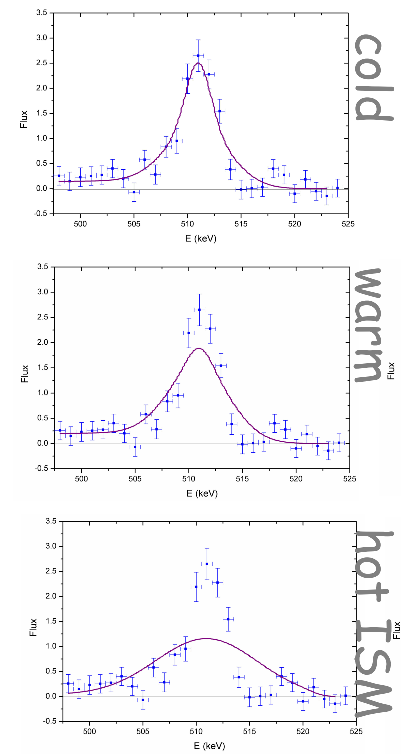
* .= % are relative to one decay of ^{26}Al

Annihilation Conditions and the Line Width

☆ Annihilation Environments:

- ☞ In-Flight -> broad line
- ☞ Hot ISM -> broad line
- ☞ Warm&Cold ISM -> narrow line
- ☞ On Dust Grains -> narrow line

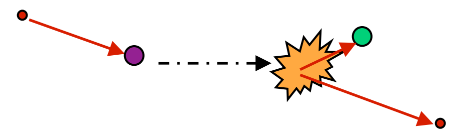




Positron Production Processes

✓ Cosmic-Ray Nuclear Reactions

☆ e.g. $^{12}C(p,pn)^{11}C(\beta^+)$, or $^{16}O(p,\alpha)^{13}N(\beta^+)$



☆ Pion Production in HE Collisions

$$p + p \rightarrow \pi^+ + X$$

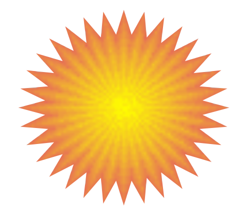
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (\tau = 2{,}6 \cdot 10^{-8}\ s)$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (\tau = 2{,}2 \cdot 10^{-6}\ s)$$

✓ Hot-Plasma Pair Production

☆ 'kT>MeV'-Plasma

$$\gamma + \gamma \rightarrow e^+ + e^-$$

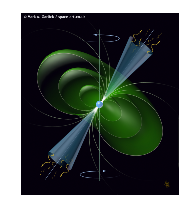


- ☞ Accretion Columns & Disks
- ☞ Jet Bases

✓ E.M.-Cascade Pair Production

☆ Strong Magnetic Fields

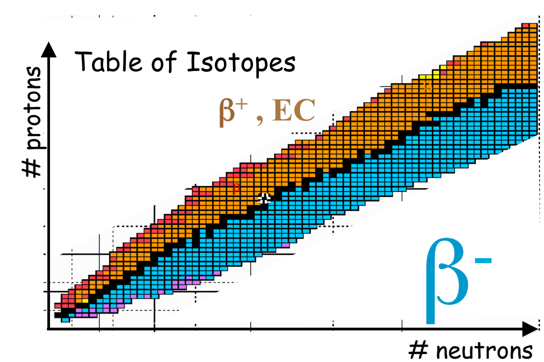
$$\gamma + B \rightarrow e^+ + e^-$$



- ☞ Pulsars
- ☞ Jets

✓ Nucleosynthesis

☆ e.g. $^{56}Ni(\beta^+)$, $^{44}Ti(\beta^+)$, $^{26}Al(\beta^+)$, $^{22}Na(\beta^+)$, $^{13}N(\beta^+)$, $^{14}O(\beta^+)$, $^{15}O(\beta^+)$, $^{18}F(\beta^+)$

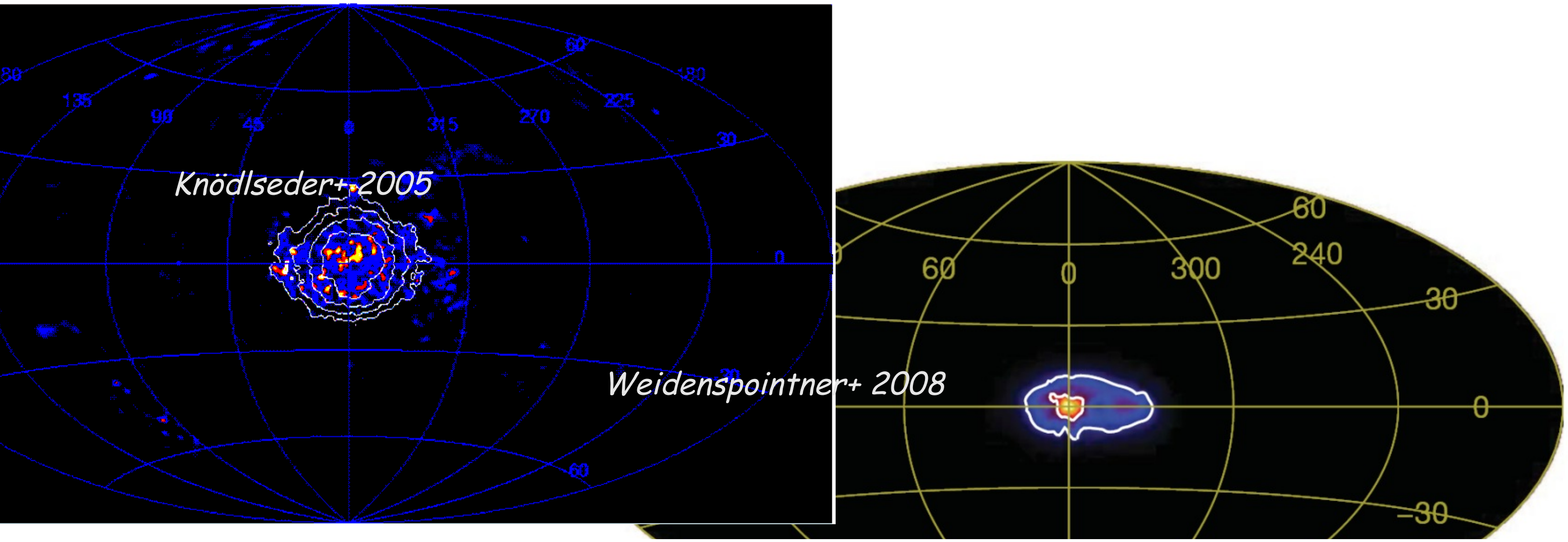


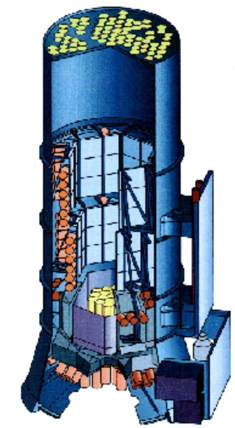
$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \nu_e$$

All Spread-out in Galactic Disk!

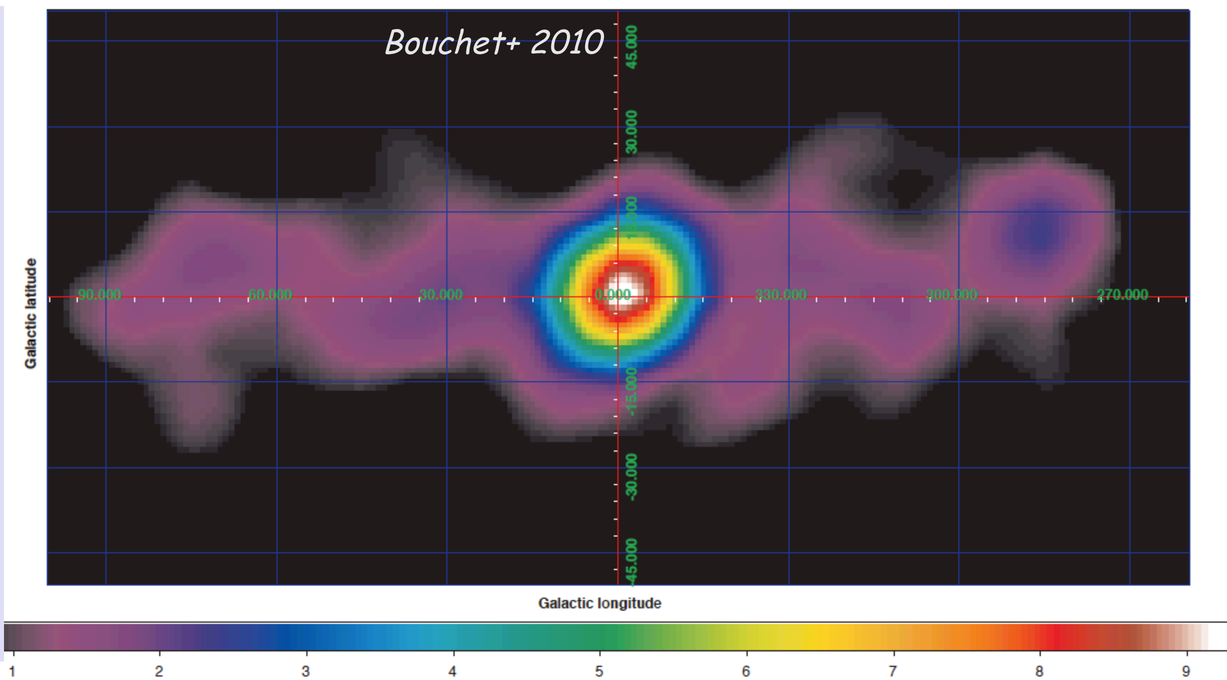
Roland Diehl

The Signature of Annihilating Positrons

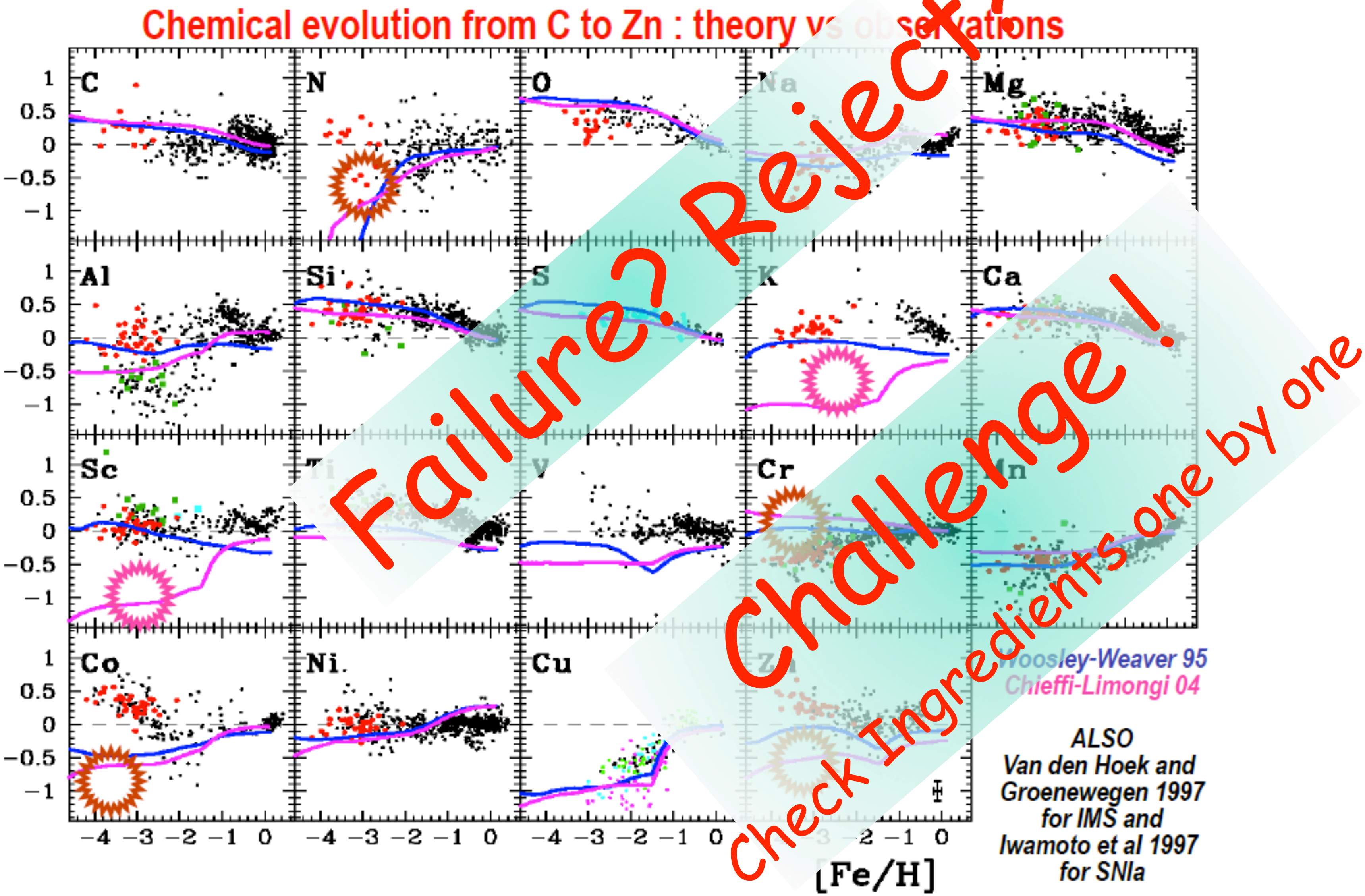




- ☆ Annihilation γ-rays are dominated by a Bright Inner-Galaxy Component
- ☆ The ^{26}Al e+ Produced in the Disk (82%) are a Minor Contribution
- ☆ Annihilation γ-ray Emission Presents a Puzzle:
  - ☞ e+ Sources ?
  - ☞ **Propagation !!**
  - ☞ Annihilation Environments



How Does Our Model Perform?



☆ Galactic Elemental Composition NOT Consistently Reproduced

☞ "the source yields must be wrong"

Open Nucleosynthesis Questions for γ-Telescopes

- ☆ How do Supernova Explosions work? (^{56}Ni mass & dynamics)
- ☆ How does the Structure of Massive Stars Evolve? (60Fe/26Al)
- ☆ What are the Mass Loss Properties of Massive Stars?
- ☆ How did Massive Stars influence the Early Universe & [illegible]s?
- ☆ How is the Composition of White Dwarfs? How do [illegible]gnite?
- ☆ How do White Dwarfs Evolve into SNIa?
- ☆ What are the Sources of Positrons?
- ☆ Is there a HE Signature from Dark [illegible]er?

Gamma Telescopes address all these