Nuclear Astrophysics

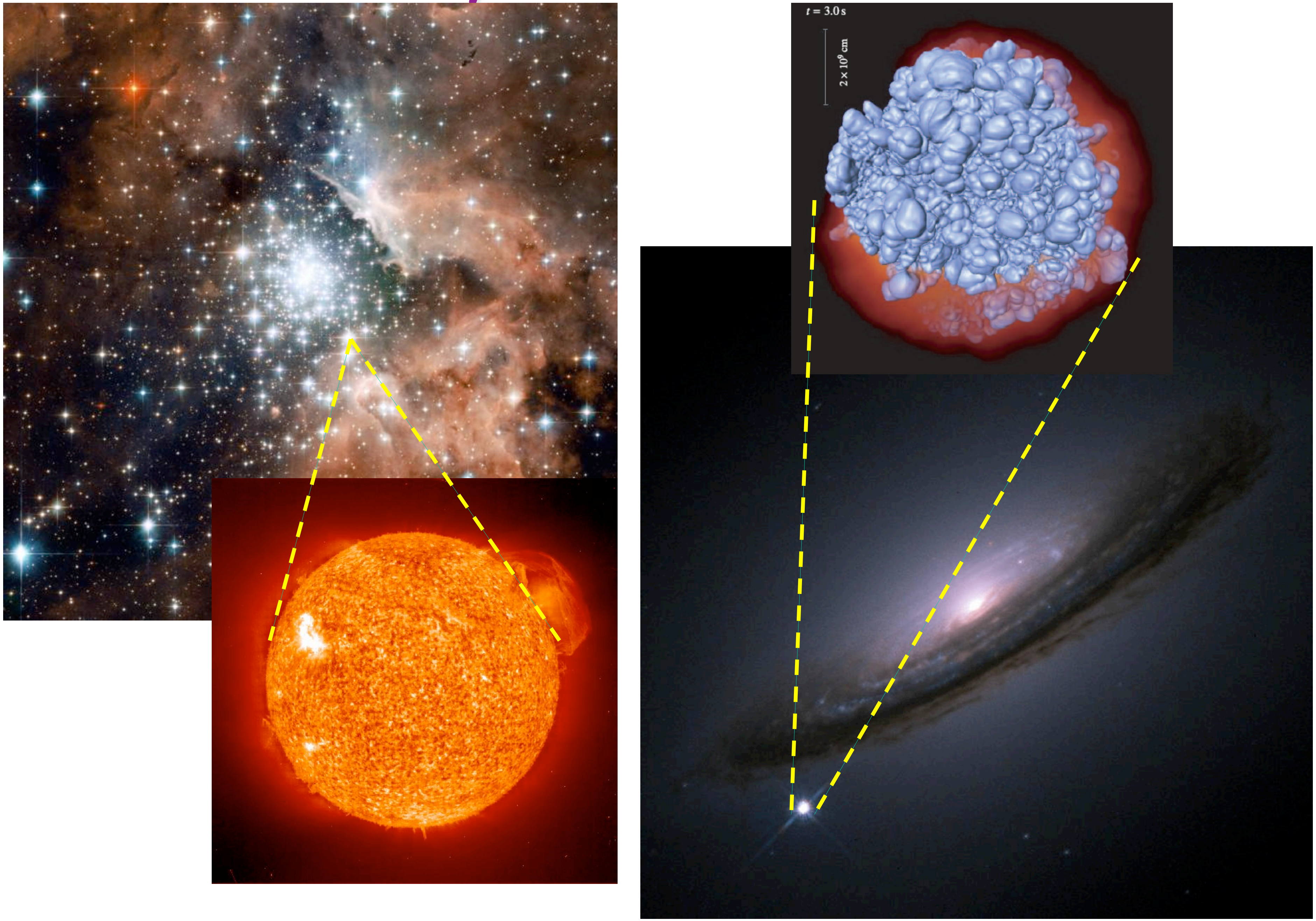
- Observing Nuclei in Cosmic Sites -

by Roland Diehl
MPE Garching

Outline

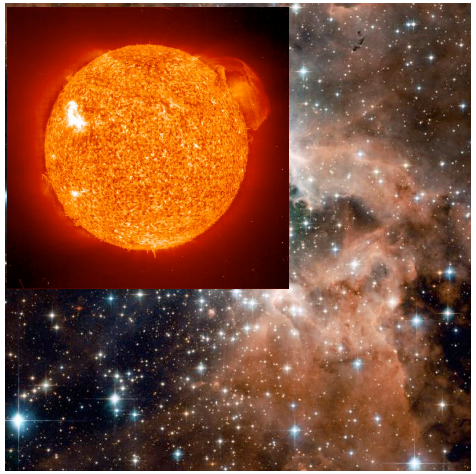
- ☆ Theme of my lecture, the context, the role of astronomy
- ☆ How cosmic messengers of nuclear-physics impacts are obtained
- ☆ What we learned from "astronomical constraints"

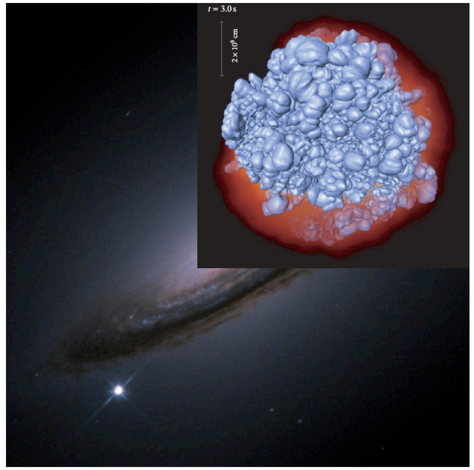
Nuclear Physics in Cosmic Sources



Astrophysics and Nuclear Physics

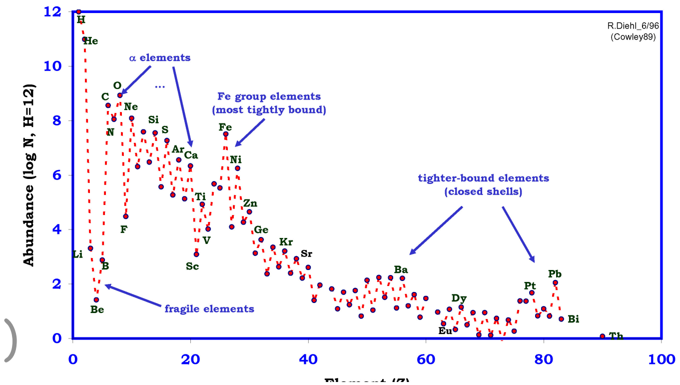
- Nuclear Physics in Cosmic Environments – where is it relevant?





☆ Nuclear Energy Release
  - Structure of Stars
  - Dynamics of Explosions

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

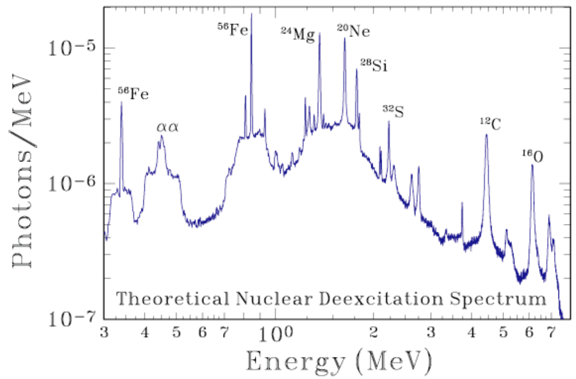


☆ Characteristic Nuclear Radiation
  - Nuclear Excitation (Emission/Absorption Lines)
  - Radioactive Decay

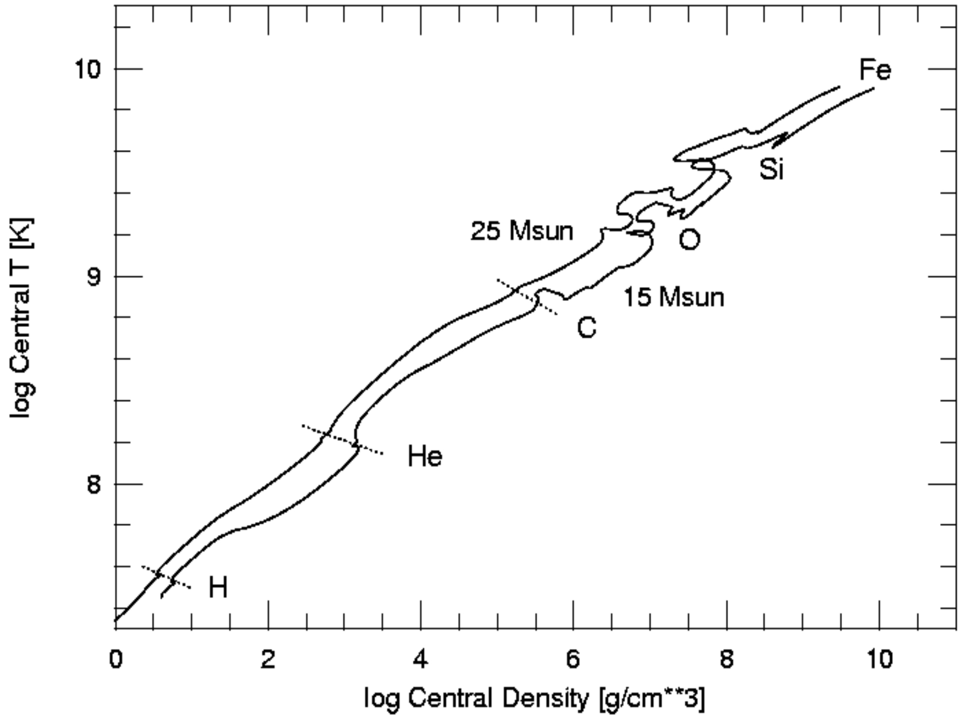
=>

☞ **Nature of Cosmic Sources, Cosmic Processes**

☞ **Search for New Phenomena**



What is a massive star?



Stars are gravitationally confined thermonuclear reactors

Each time one runs out of one kind of fuel, contraction and heating ensue, unless degeneracy is encountered.

For a star over 8 $M_\odot$ contraction and heating continue until a Fe core is made

Gravitational collapse ensues, after no energy-providing fuel is left

courtesy SEWoosley

Astrophysics and Nuclear Physics

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  - ☆ Nuclear Energy Release
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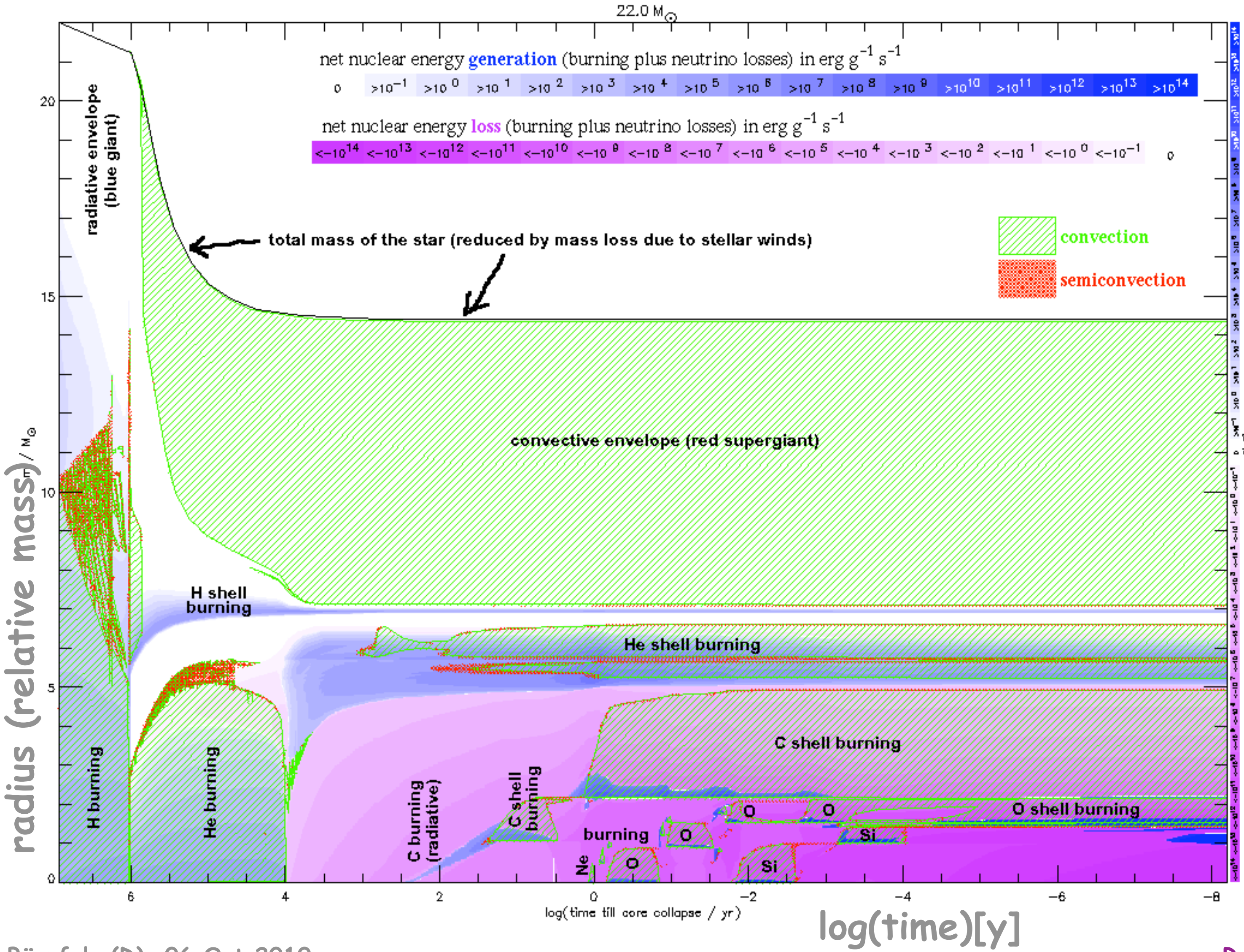

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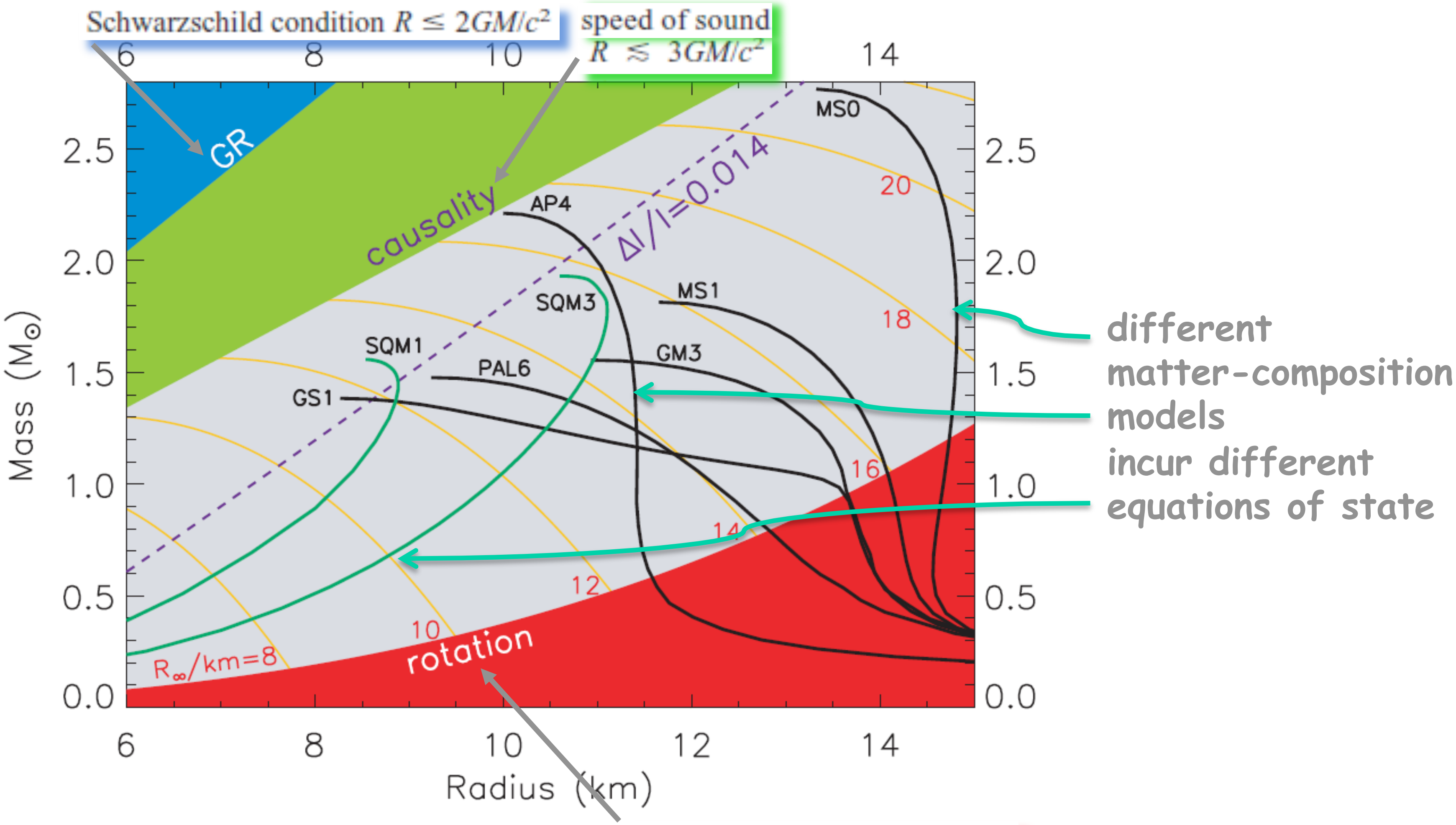
Astrophysics and Nuclear Physics

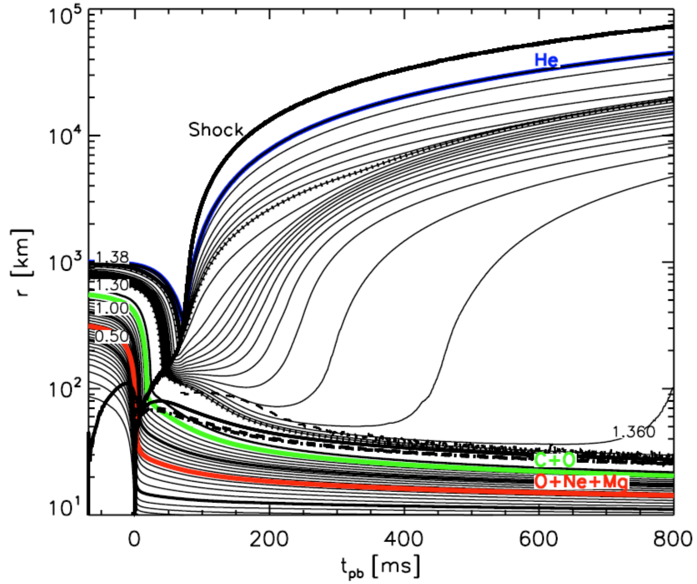
- Nuclear Physics in Cosmic Environments – where is it relevant?
  - ☞ Structure of Neutron Stars
    → Mass-Radius Relation ←→ Composition & State of High-Density Matter

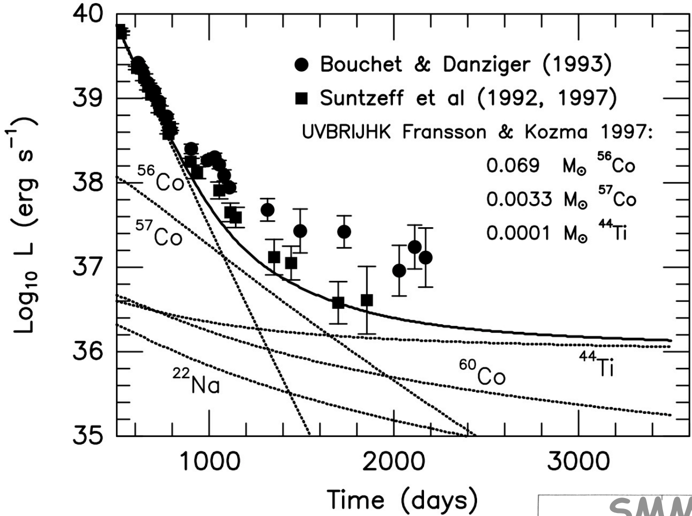


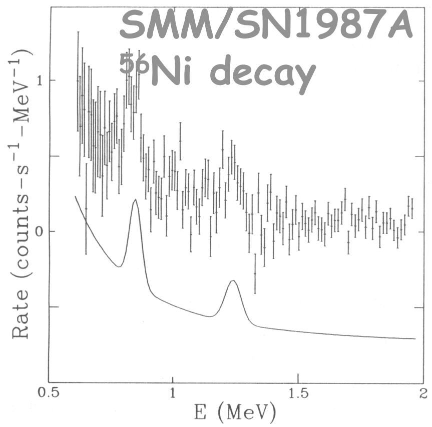
$$\nu_K = (2\pi)^{-1}\sqrt{GM/R^3} = 1833(M/M_\odot)^{1/2}(10\ \mathrm{km}/R)^{3/2}\ \mathrm{Hz}$$

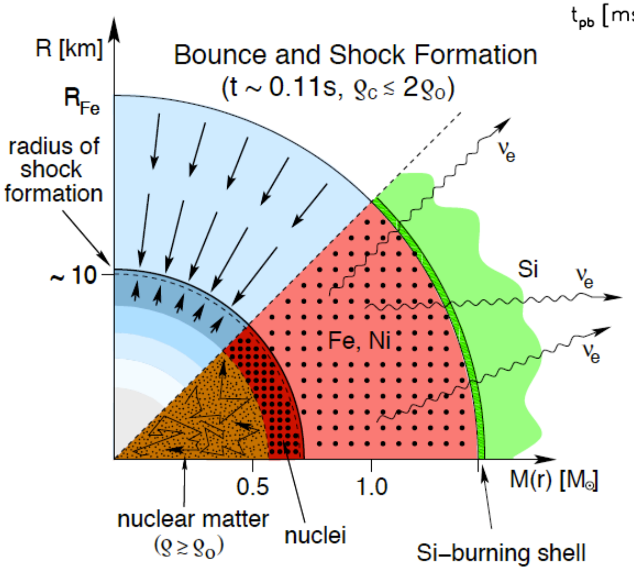
Astrophysics and Nuclear Physics

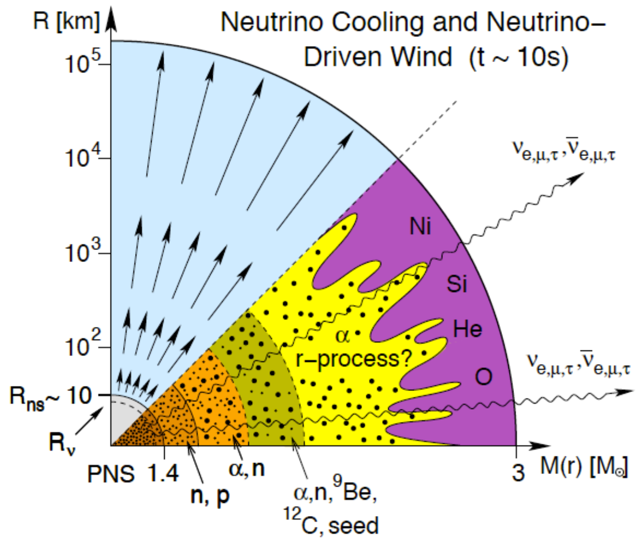
- Nuclear Physics in Cosmic Environments – where is it relevant?
  - ☆ Nuclear Energy Conversions
    - – Dynamics of Explosions











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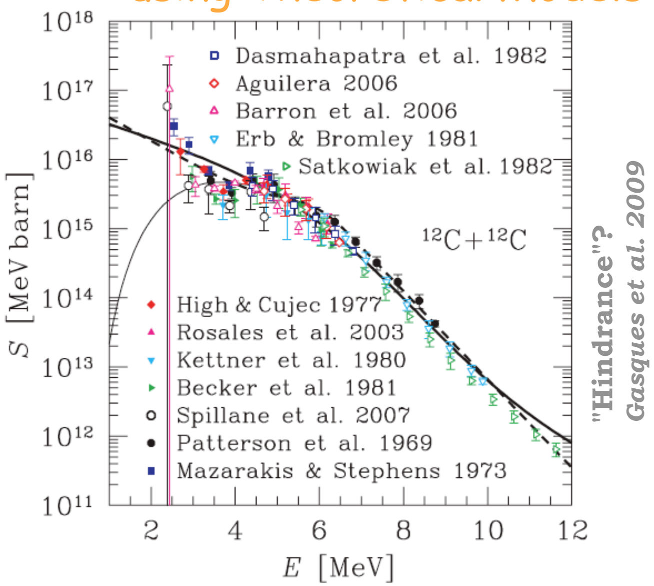
Example: C Fusion ($^{12}C+^{12}C$)

☆ The Importance of Low-Energy Nuclear Resonances

☞ S-Factor Extrapolation using Theoretical Models

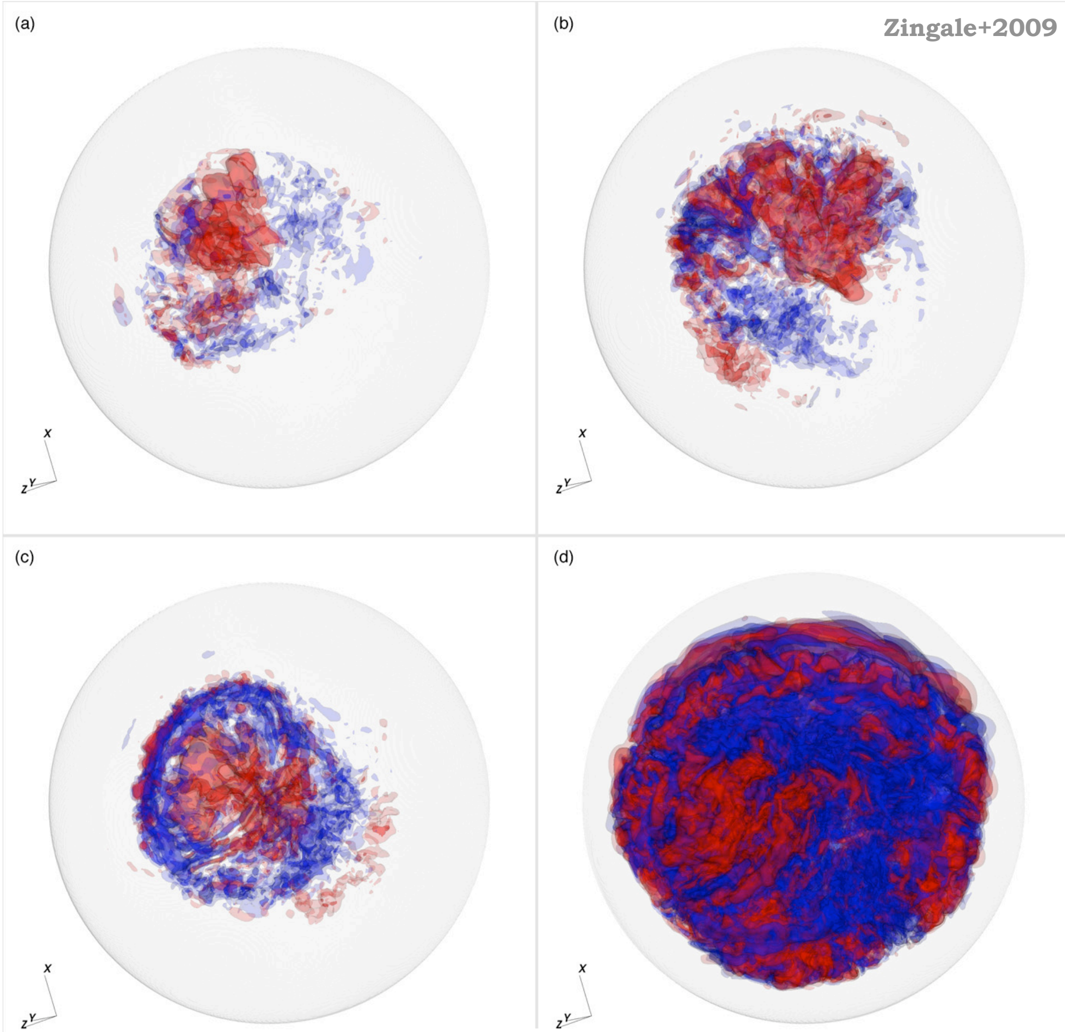


☆ Ignition of SNIa

☞ multi-point ignition towards runaway after 10^4y 'smoldering'

☞ reaction rate vs. T,ρ

Simulations of CO-WD Last Stage Before Runaway



(a) 800 s; (b) 3200 s; (c) 3420 s; (d) 7131.79 s

Astrophysics and Nuclear Physics

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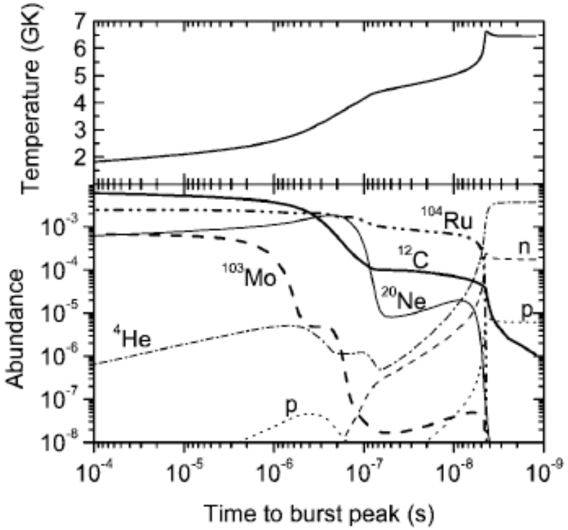
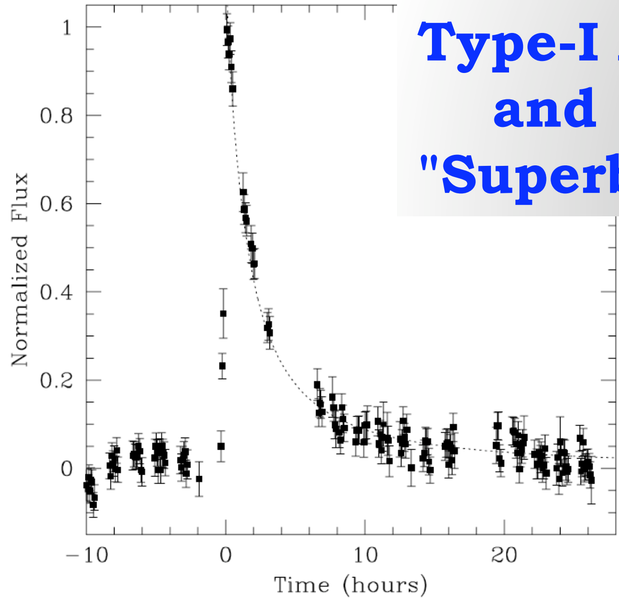
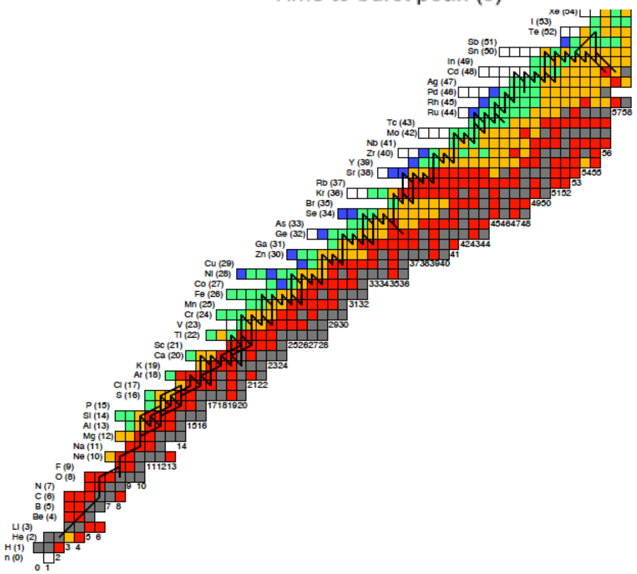
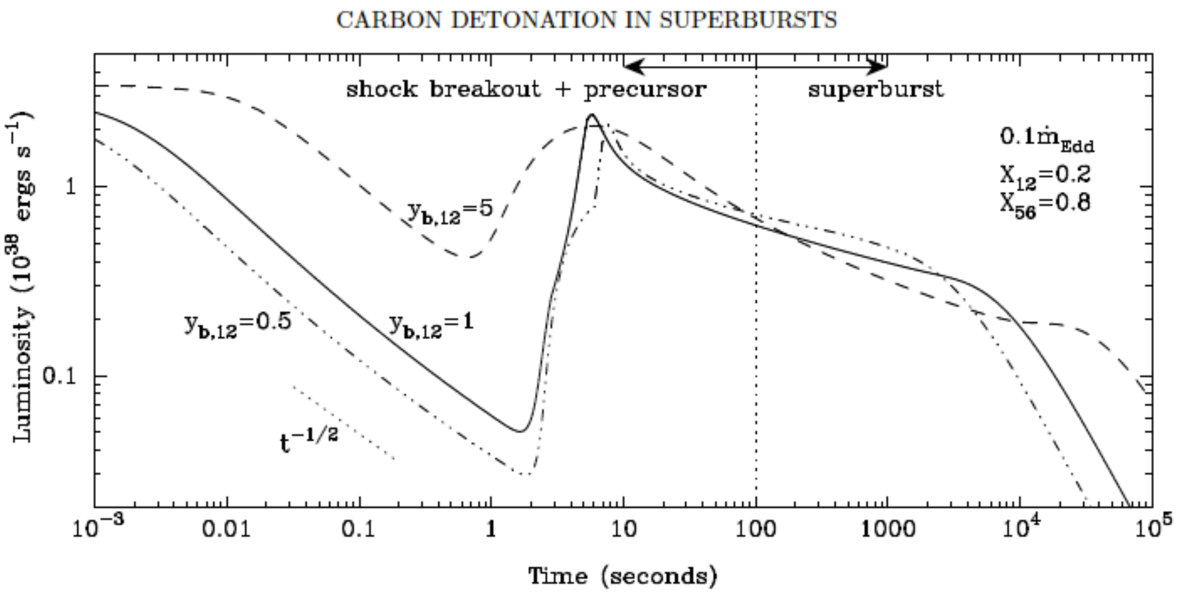
  - ☆ Nuclear Energy Release
    - – Dynamics of Explosions

Type-I X-ray Bursters and "Superbursts"





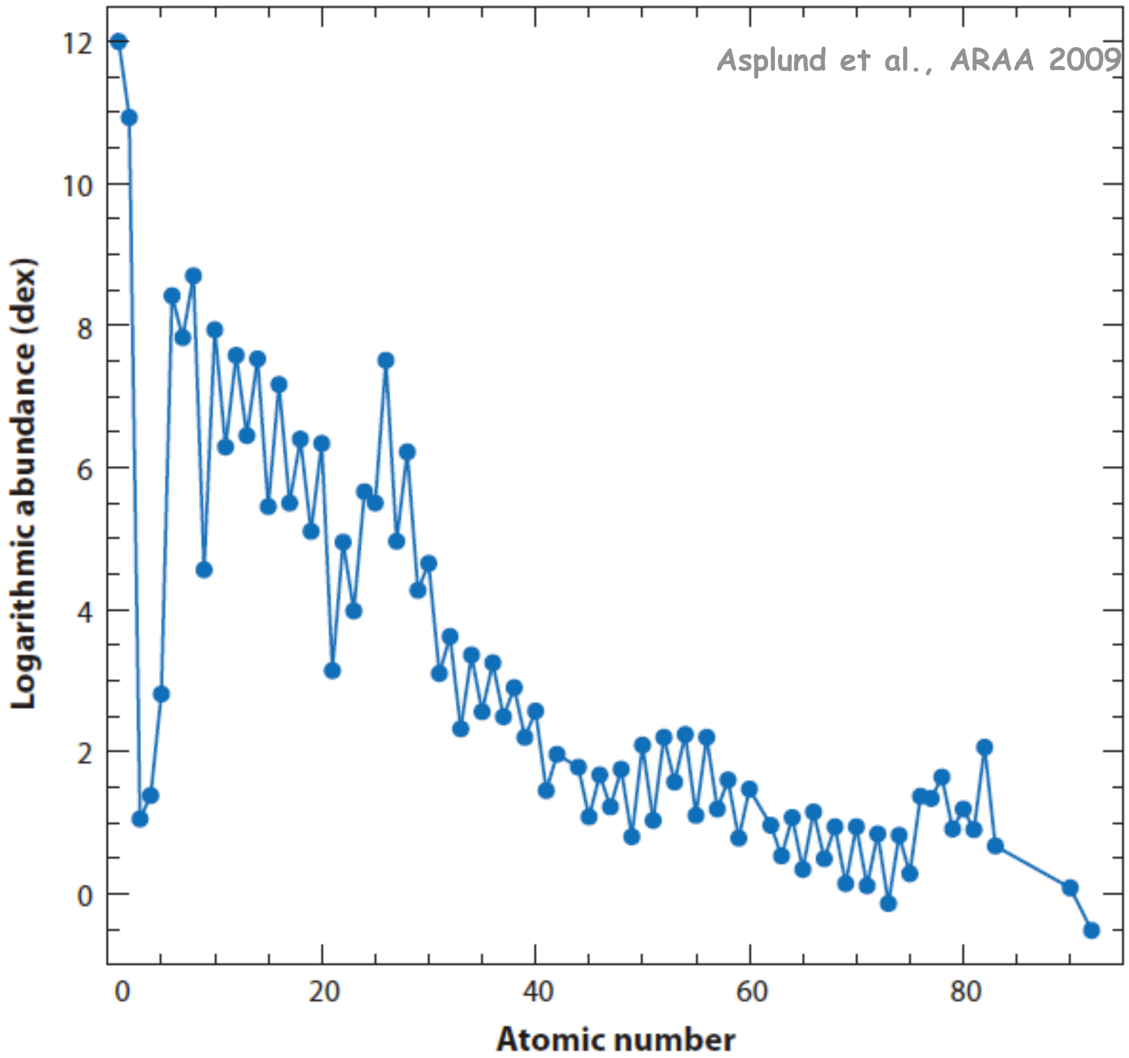




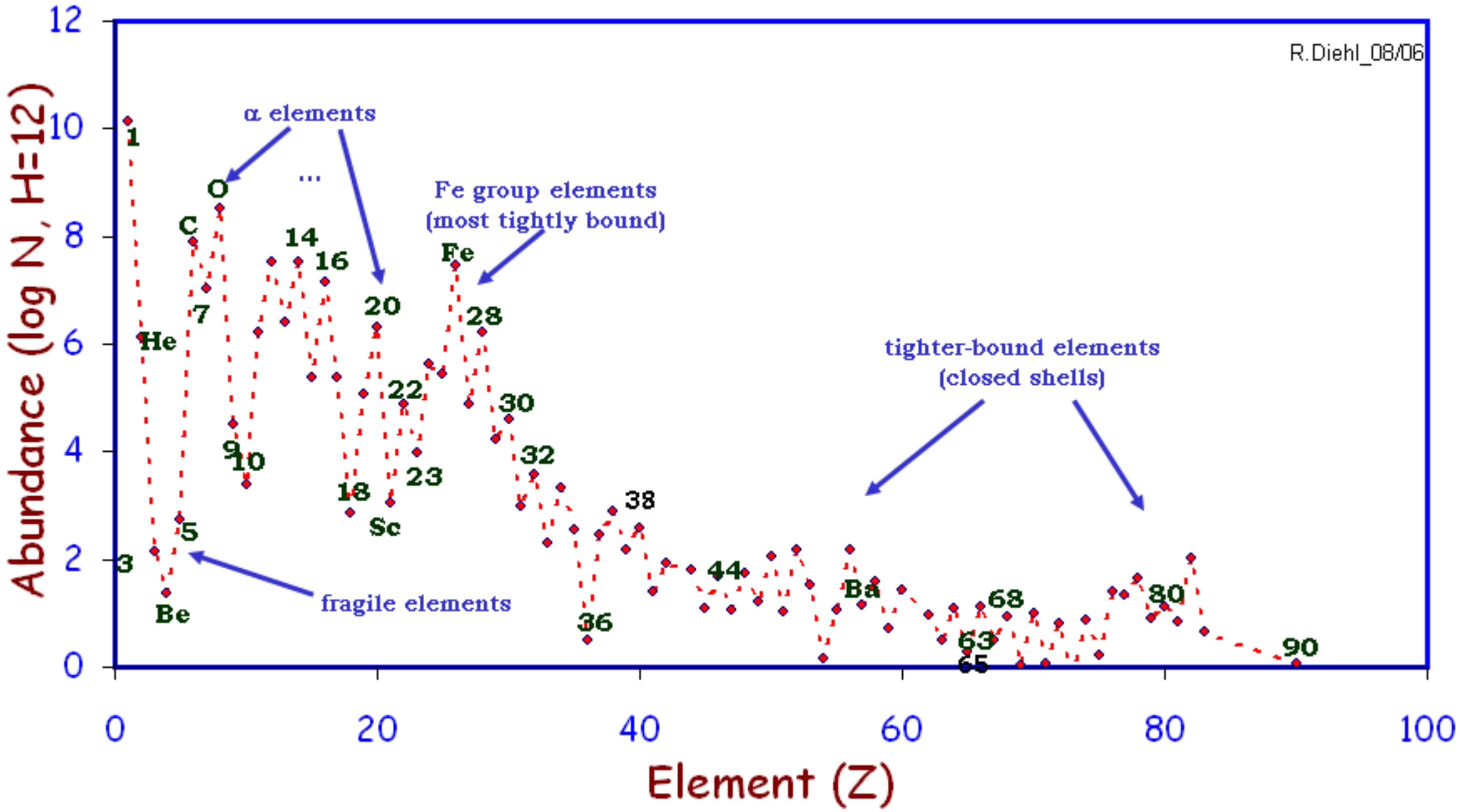
The Quest: Origin of the Elements

☆ What is the Origin of the Variety of Cosmic Elements...

- ☞ at its presently-observed variety (here: solar)
- ☞ with abundances spanning 12 orders of magnitude,
- ☞ ... and revealing remarkable sub-structure



Abundances: An Astronomical Measurement

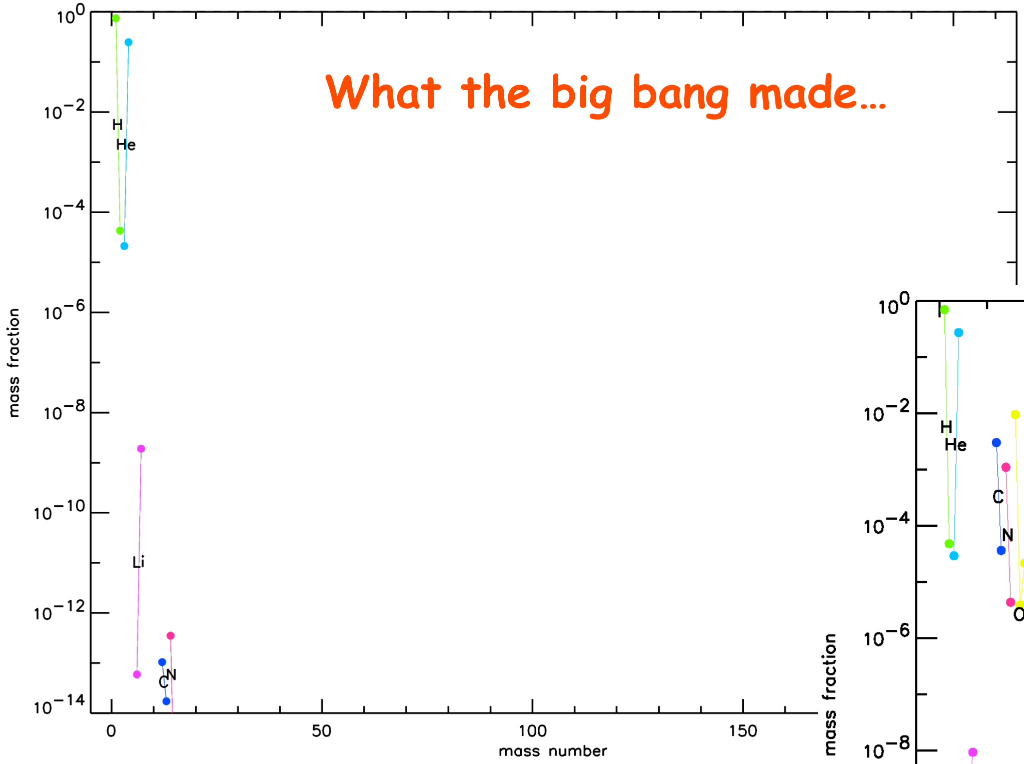


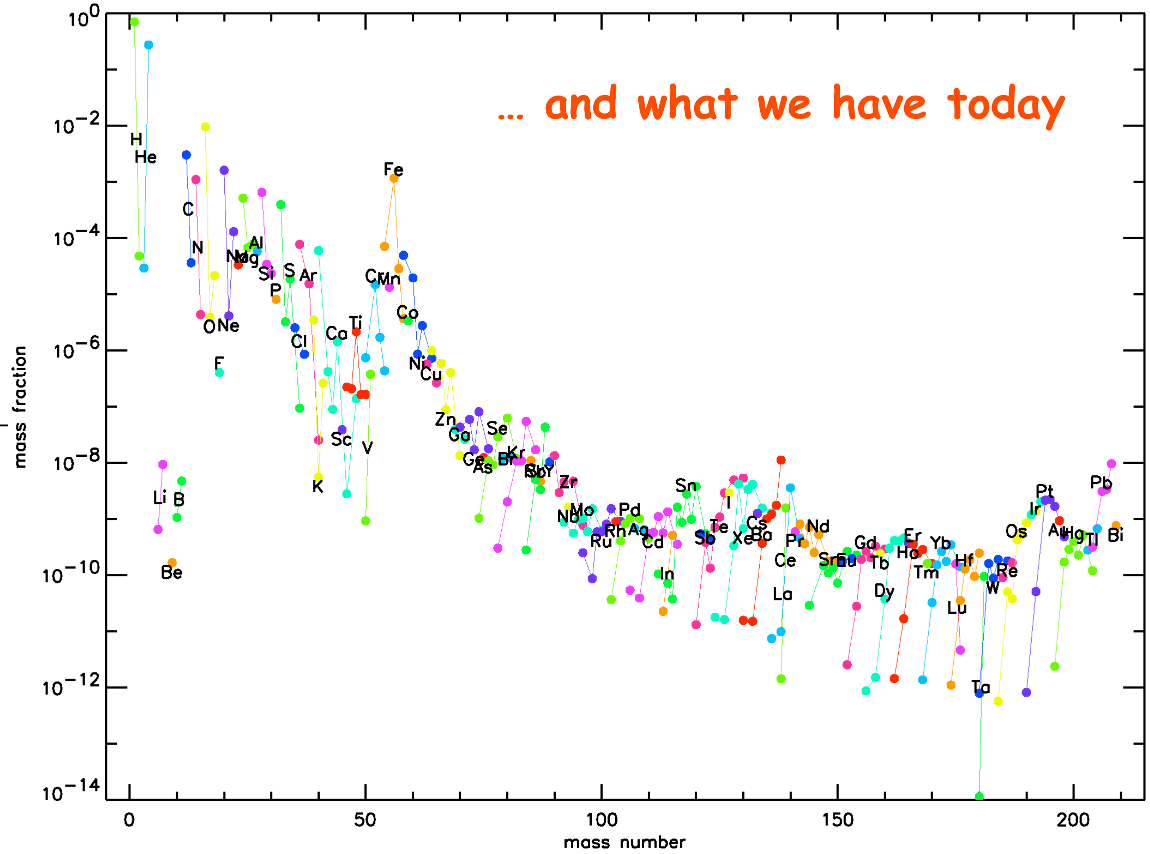
☆ Relevance of Knowledge about Cosmic Abundances:

- ☞ Constraints for Nucleosynthesis
  - Nuclear Reactions in Cosmic Environments
  - *Astrophysical Conditions in Nuclear-Burning Sites*
- ☞ Constraints for Evolutionary Processes in the Universe
  - Formation of Stars and Stellar Assemblies...*Galaxies*
  - Enrichment of Cosmic Gas Supplies with Nucleosynthesis Products

Cosmic Chemical Evolution

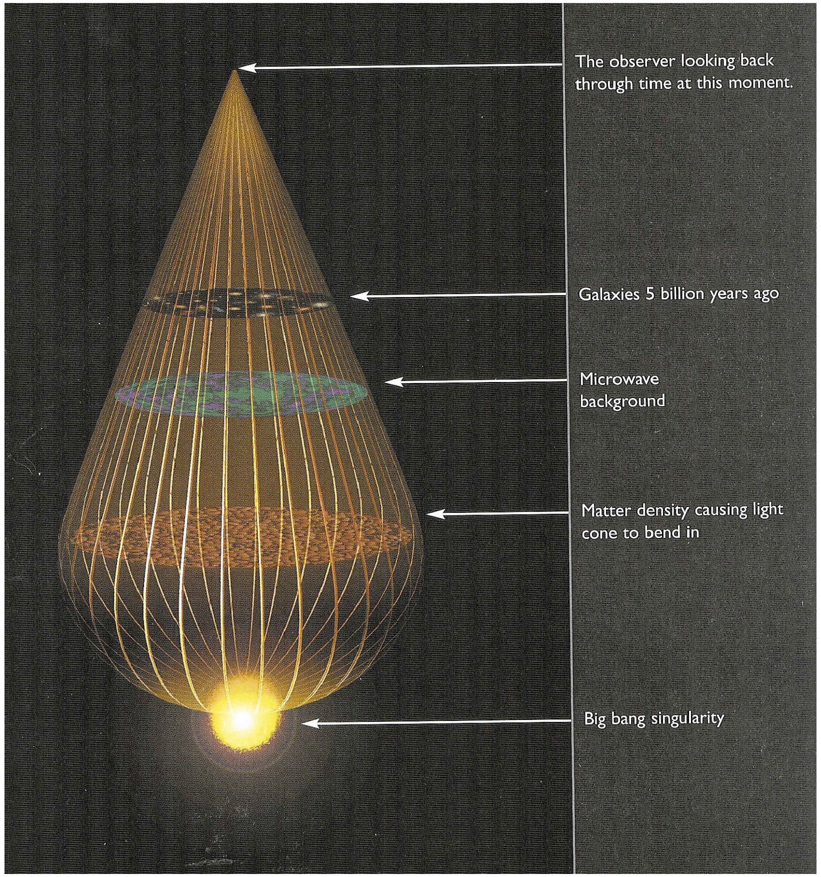
courtesy Alex Heger



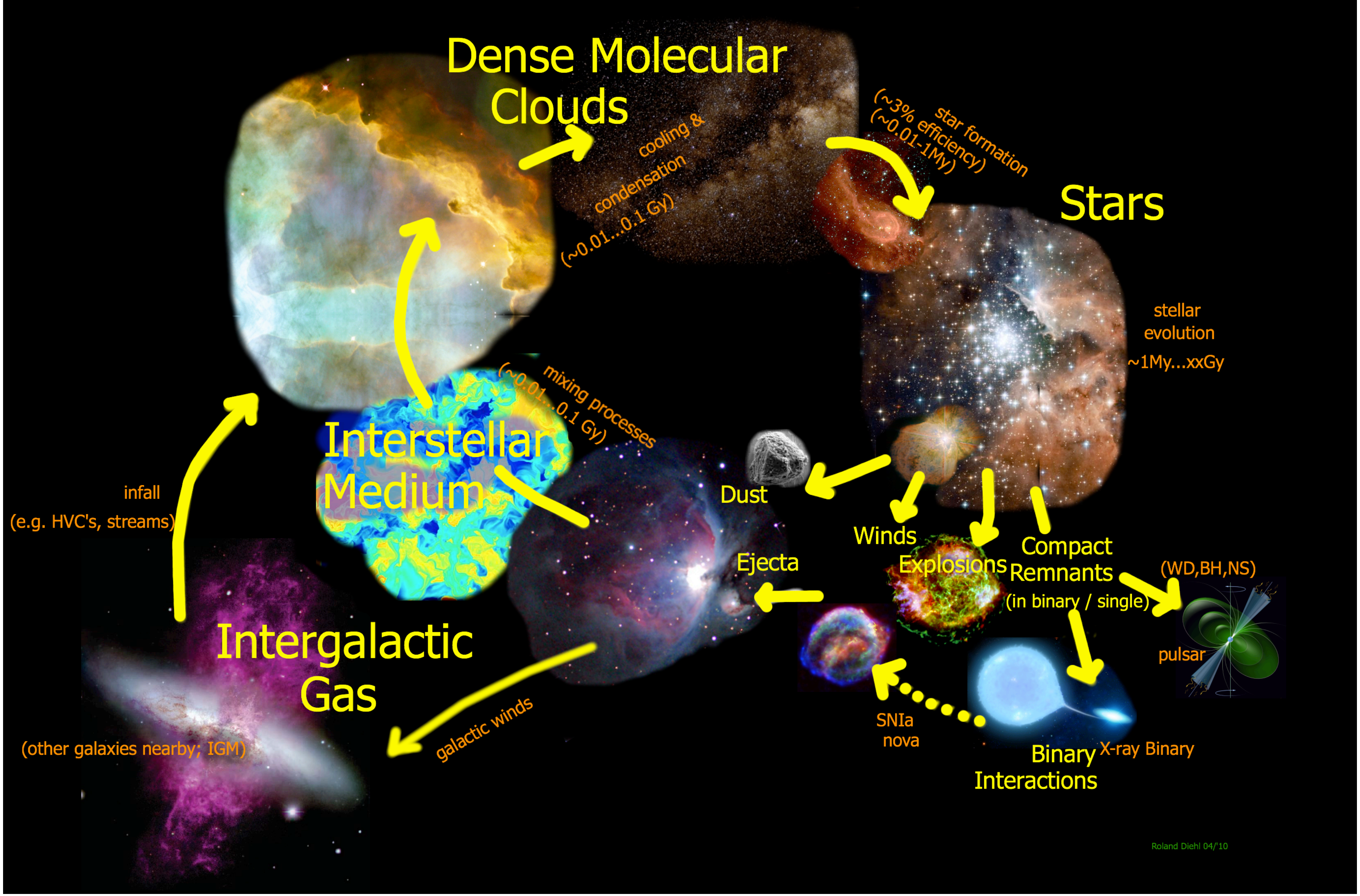


Cosmic Nucleosynthesis

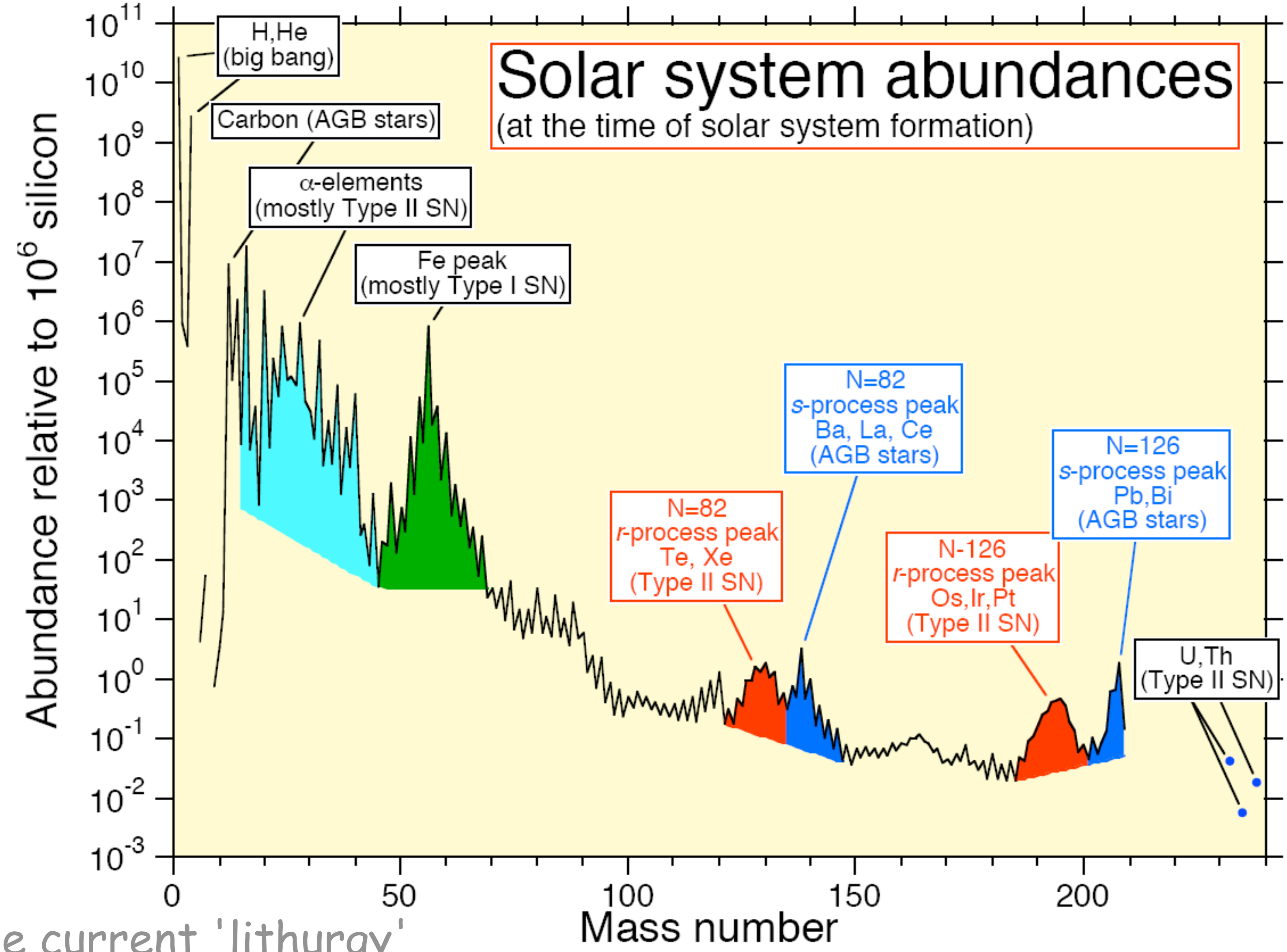
- Big Bang Nucleosynthesis
  - ☆ Extrapolations of Metallicity Evolution Data
  - ☆ Cosmological-Model Consistency Validation z~1000
- First Stars: z~20
  - ☆ Gamma-Ray Bursts
  - ☆ Quasar Absorption Lines
  - ☆ Abnormal Metal-Poor Stars
- Early Stellar Generations z~3...0.1
  - ☆ High-Redshift Galaxies' Metallicities
  - ☆ Metal-Poor Stars
  - ☆ Intergalactic Gas (WHIM, Clusters)
  - ☆ SNIa, GRBs
- Current Nucleosynthesis
  - ☆ Nucleosynthesis Sources (Massive Stars, Supernovae, Novae)
  - ☆ Recent Stellar Generations, ISM



Cosmic Cycles of Matter



One of the Key Tools of Astrophysics:
Where do specific atomic nuclei and their abundance originate?



☆ ... the current 'lithurgy'
-> how much do we understand?

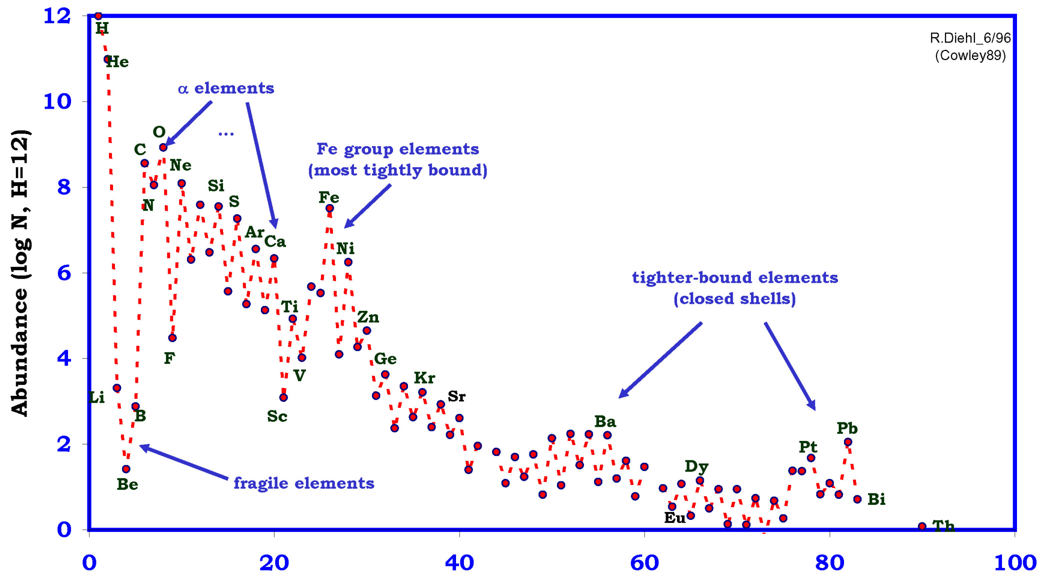
Courtesy: Andy Davis

Astrophysics and Nuclear Physics

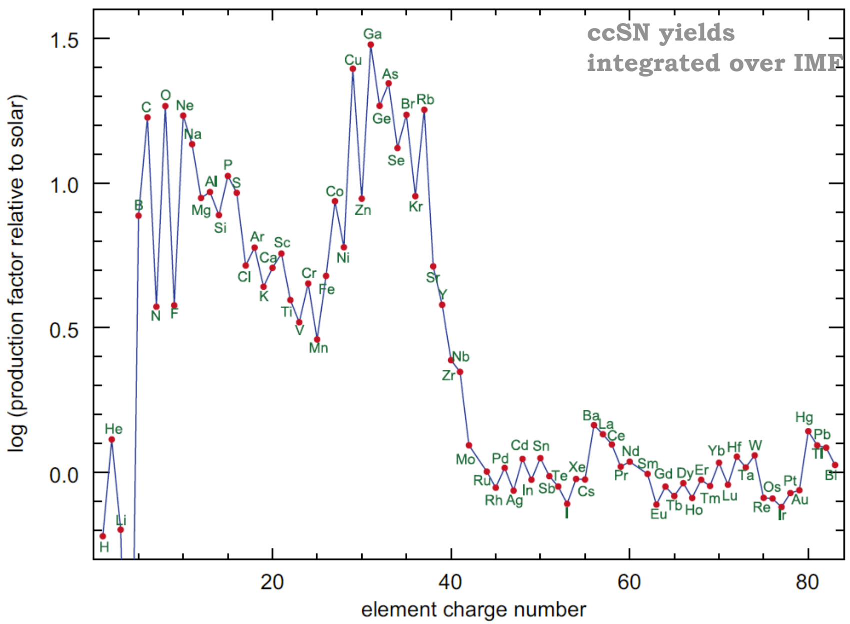
- Nuclear Physics in Cosmic Environments - where is it relevant?

☆ Nuclear Energy Release
  - Structure of Stars
  - Dynamics of Explosions

☆ Nucleosynthesis
  - Elemental Abundances in Stars and Gas
  - Radioactive Isotopes



S.E. Woosley, A. Heger / Physics Reports 442 (2007) 269–283



Astrophysics and Nuclear Physics

- Nuclear Physics in Cosmic Environments – where is it relevant?

☆ Characteristic Nuclear Radiation

- – Nuclear Excitation Lines
- – Radioactive Decay

☞ Relativistic Particle Acceleration → CRs

- – Solar Flares
- – Interstellar Shocks
- – AGN

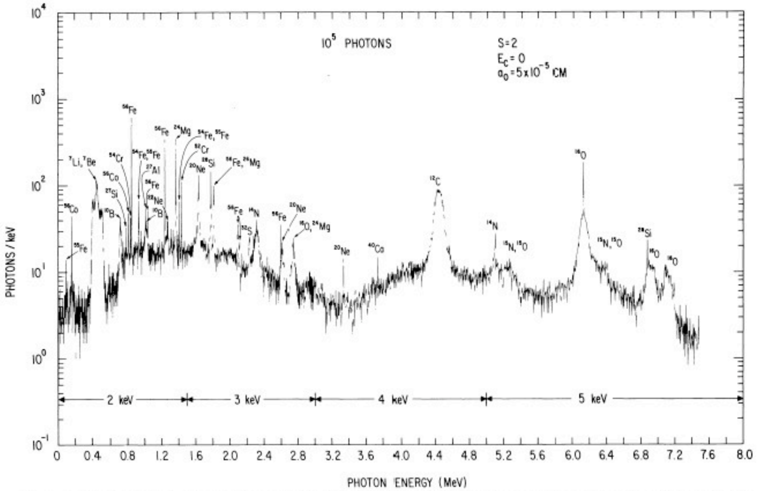
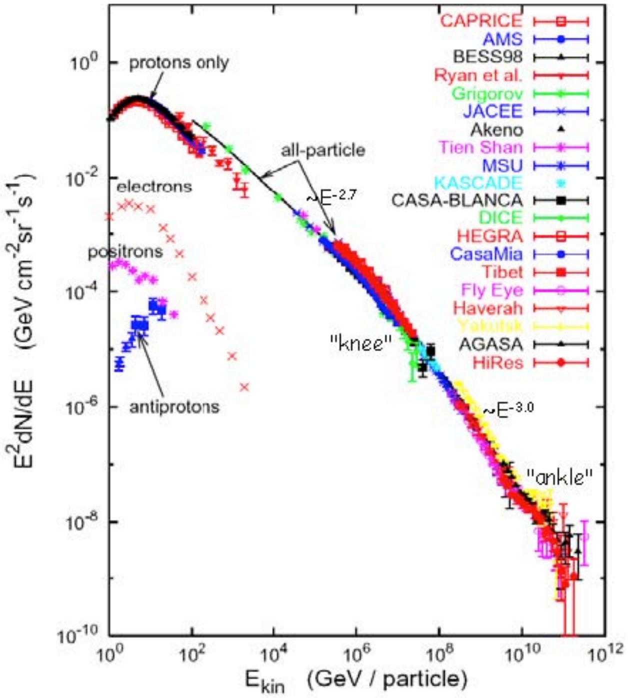
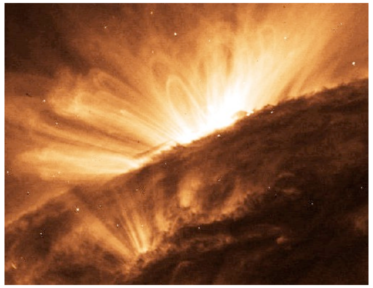
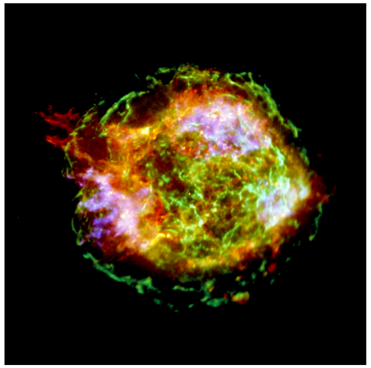
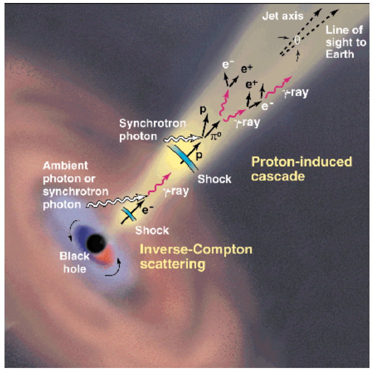


Fig. 18.—Monte Carlo simulated γ-ray spectrum for energetic particles and ambient medium having solar compositions; s and E_c are the spectral parameters of the energetic particles, and a_0 is the characteristic radius of the interstellar grain distribution.

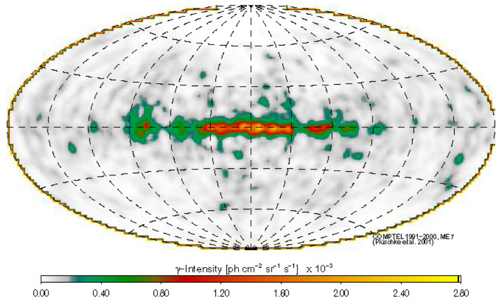








☞ Current Nucleosynthesis Source Locations



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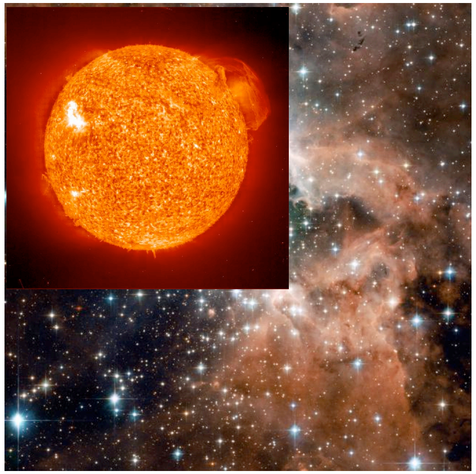

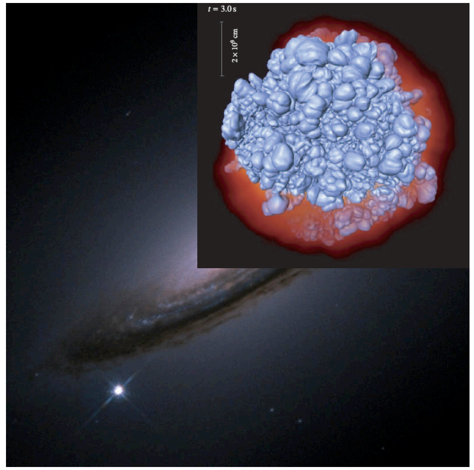

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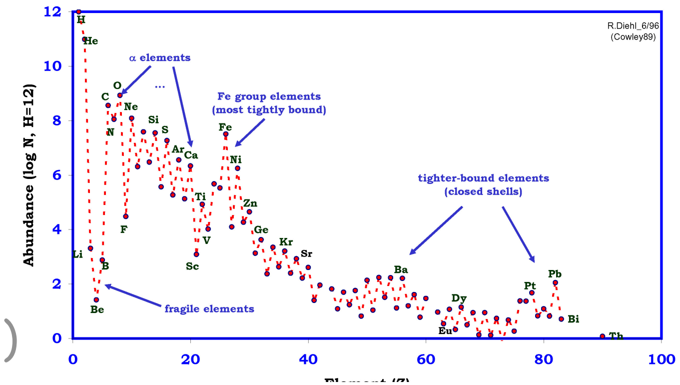

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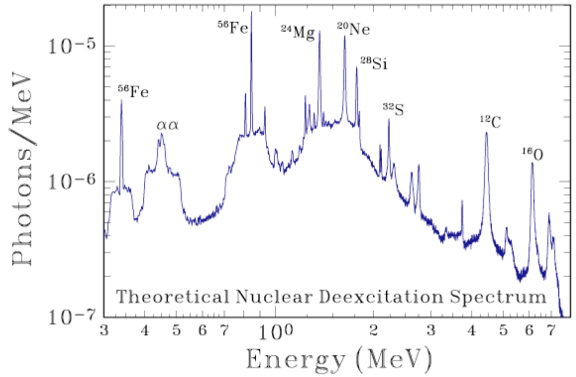
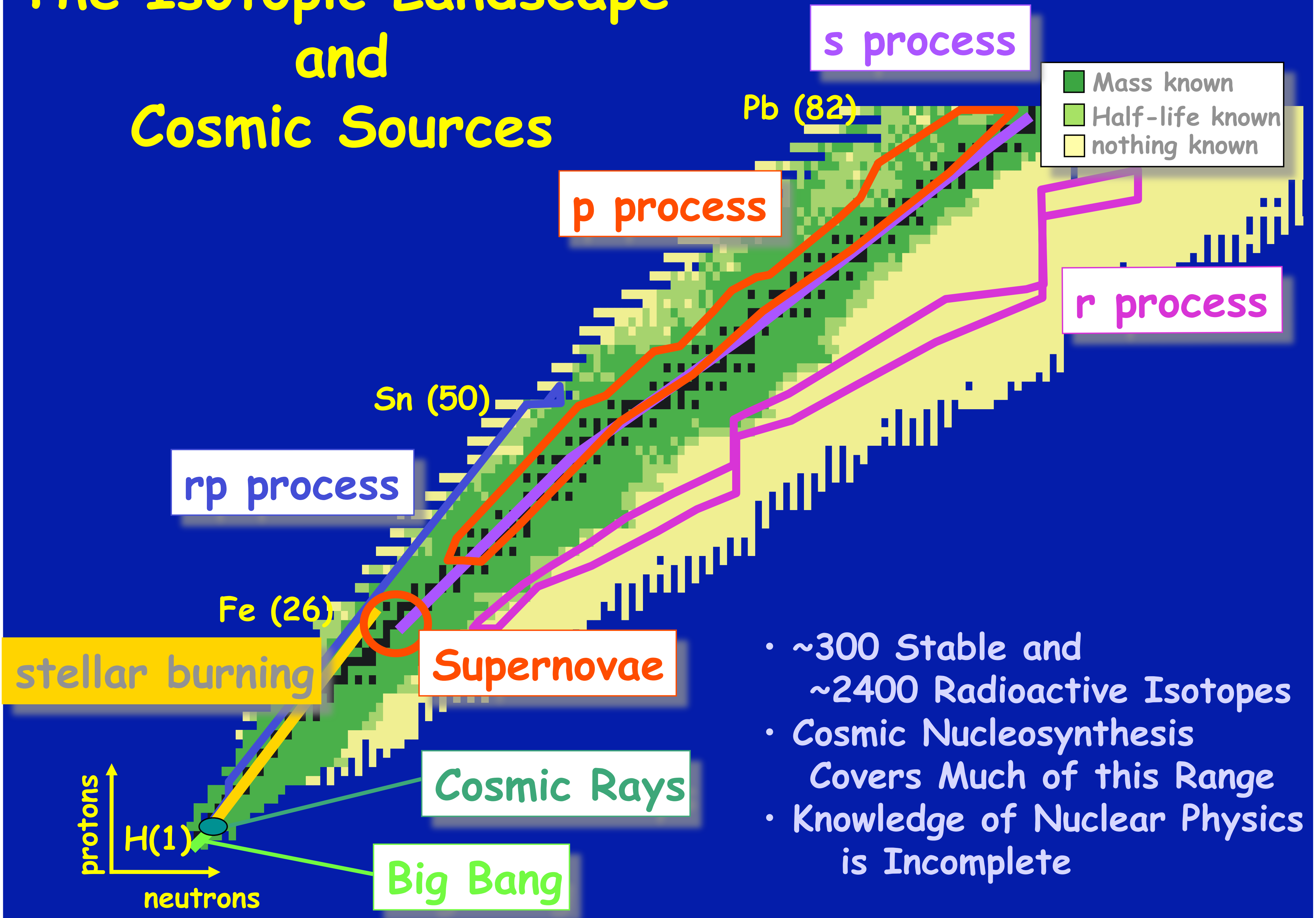
☞ **Nature of Cosmic Sources, Cosmic Processes**

☞ **Search for New Phenomena**



The Isotopic Landscape and Cosmic Sources



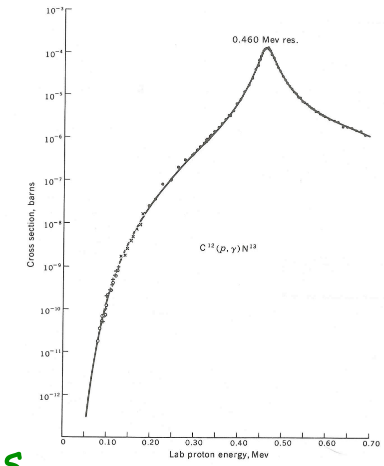
- ~300 Stable and ~2400 Radioactive Isotopes
- Cosmic Nucleosynthesis Covers Much of this Range
- Knowledge of Nuclear Physics is Incomplete

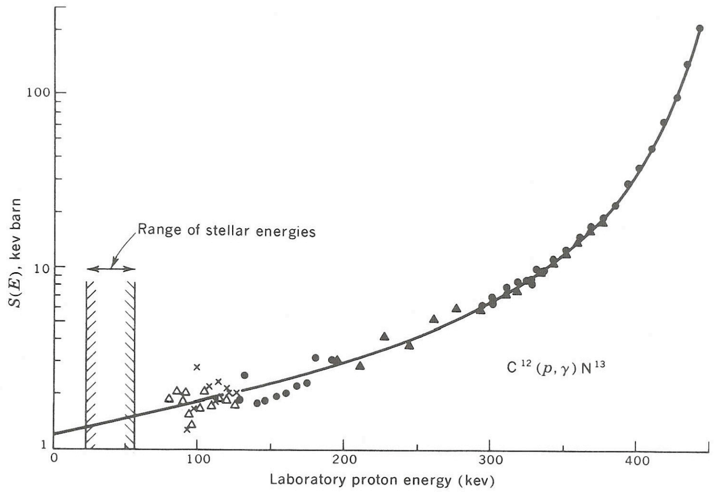
Nuclear Reactions in Cosmic Environments

☆ Tunneling Reactions of Thermal-Particle Populations

☞"Astrophysical S-Factor"

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

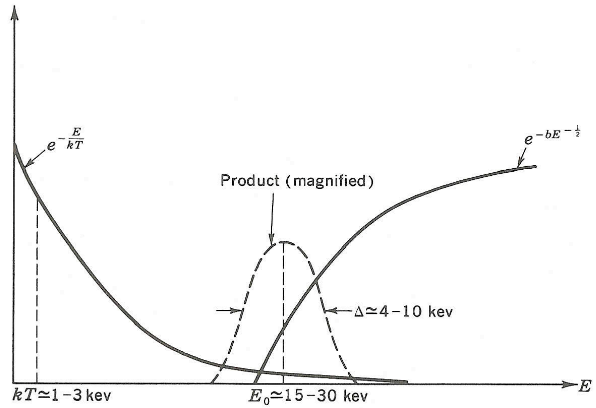


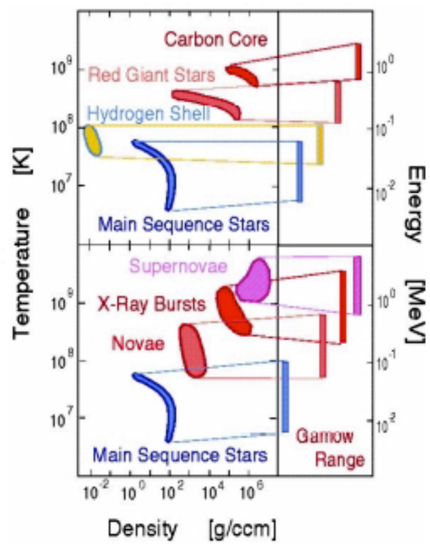


- isolate nuclear properties from tunneling & geometry

☞"Gamov Peak" at ~30 keV

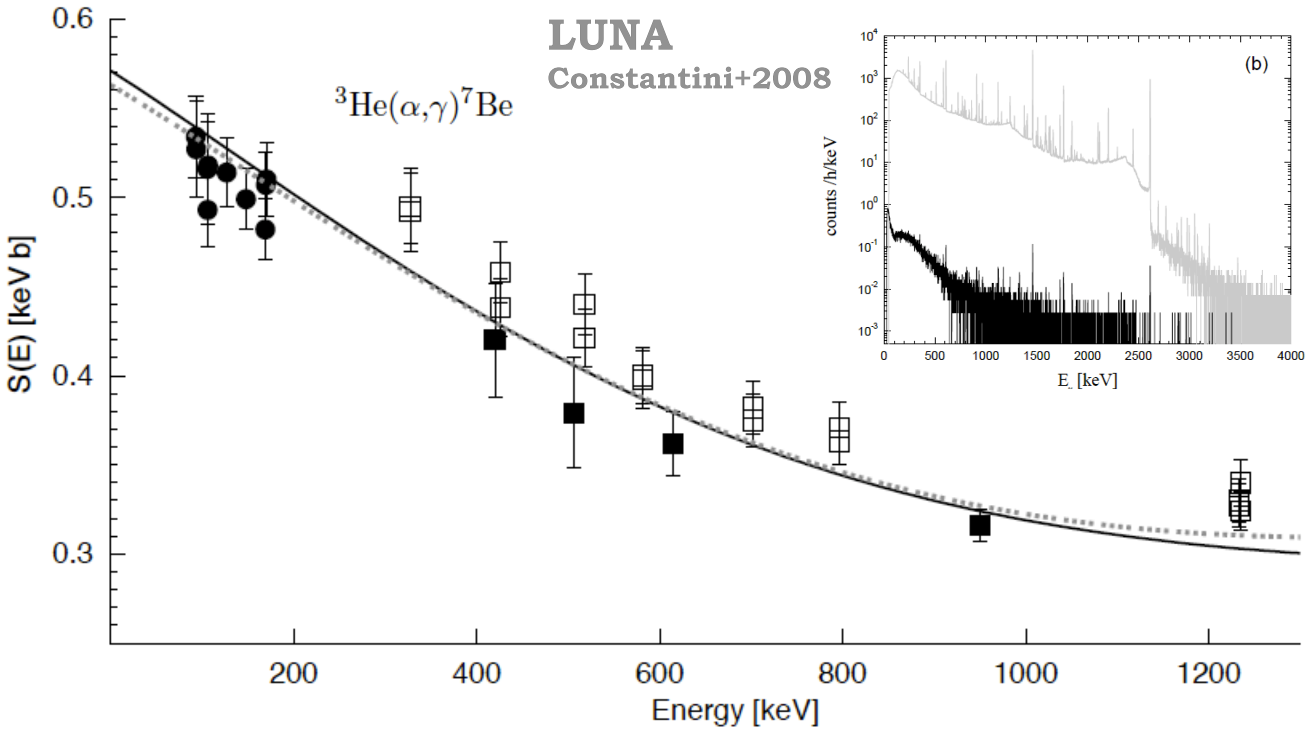
$$\langle \sigma \cdot v \rangle = \left(\frac{8}{\pi \cdot \mu}\right)^{1/2} \cdot \left(\frac{1}{kT}\right)^{3/2} \cdot \int_0^\infty E \cdot \sigma(E) \cdot e^{\frac{-E}{kT}} \cdot dE$$

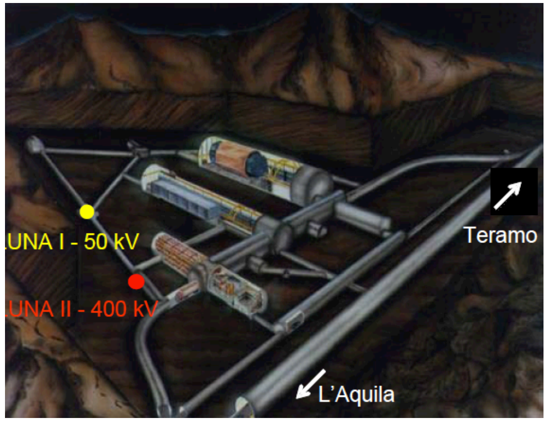


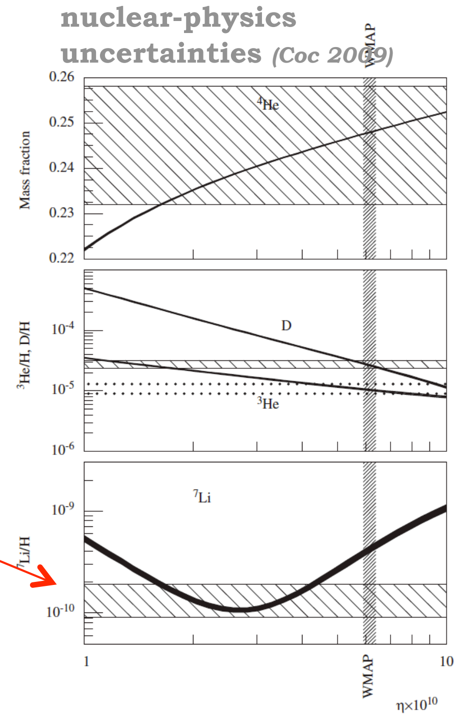


- (still) difficult to measure at nuclear lab facilities

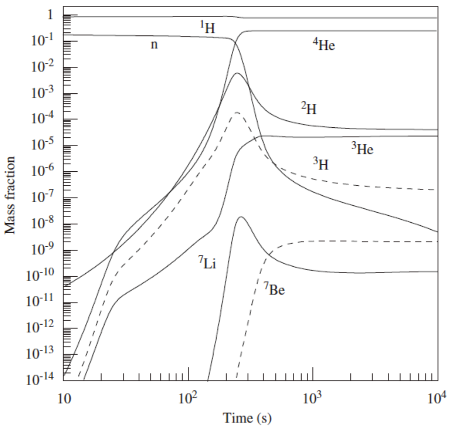
Example: Measuring H-Burning Reactions

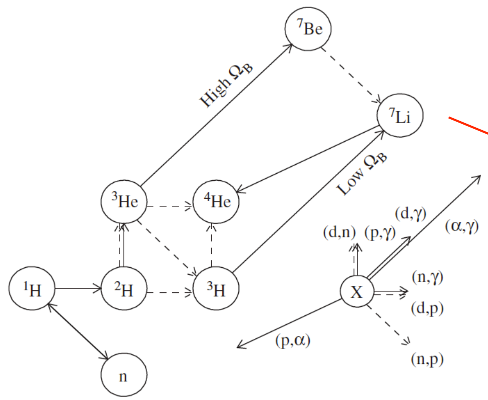






☞ Measurements at ~100 keV -> BBN





☞ Extrapolations for Solar Energies -> Solar ν's

Key Nuclear-Physics Questions

- ☆ What is the Nature of the Nuclear Force, as it Binds Known Nuclei?
- ☆ What is the Origin of Simple Patterns found in Nuclear Structure?
- ☆ What is the Composition and Structure of Neutron Stars?
- ☆ What is the Origin of Cosmic Elements?
- ☆ What are the Nuclear Reactions that Drive the Evolution of Stars and Stellar Explosions?

☞ *adapted from Dean, PT 2007*

Astrophysics and Nuclear Physics

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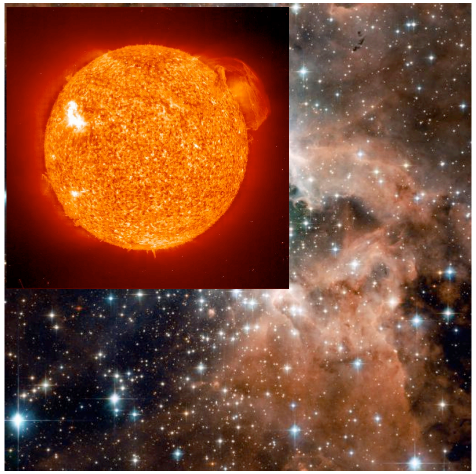

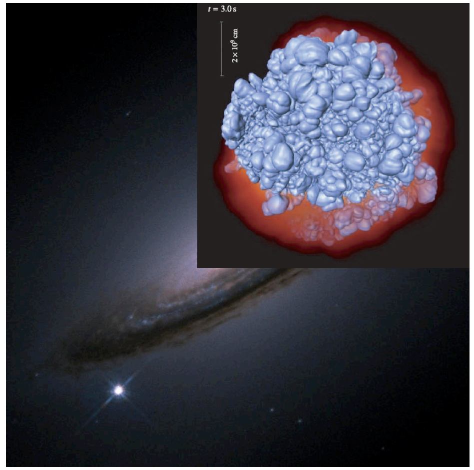

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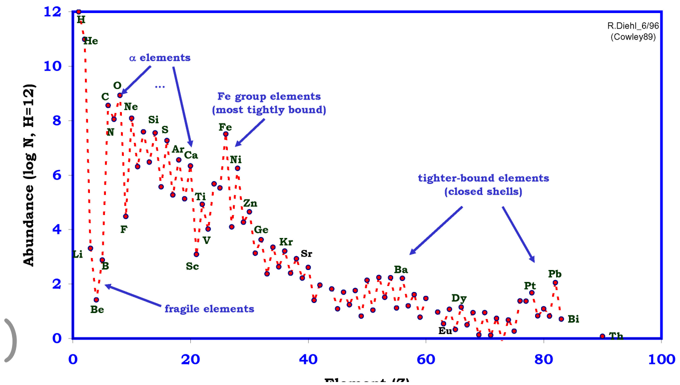

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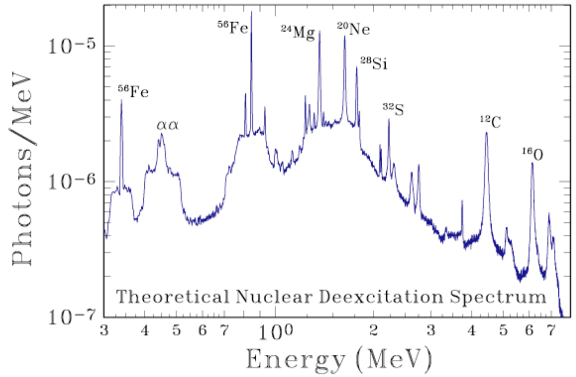

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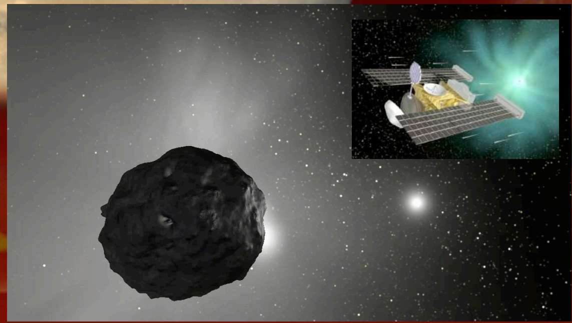
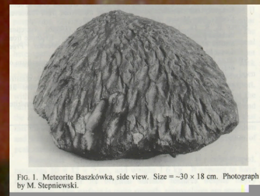
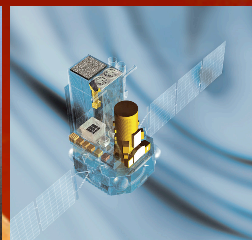
Messengers from Cosmic Objects & Processes

- **Material Samples**
  - Meteorites
  - Cosmic Rays
  - Neutrinos

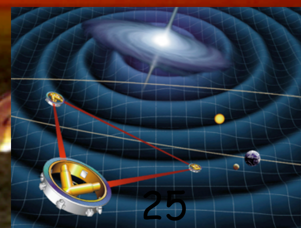




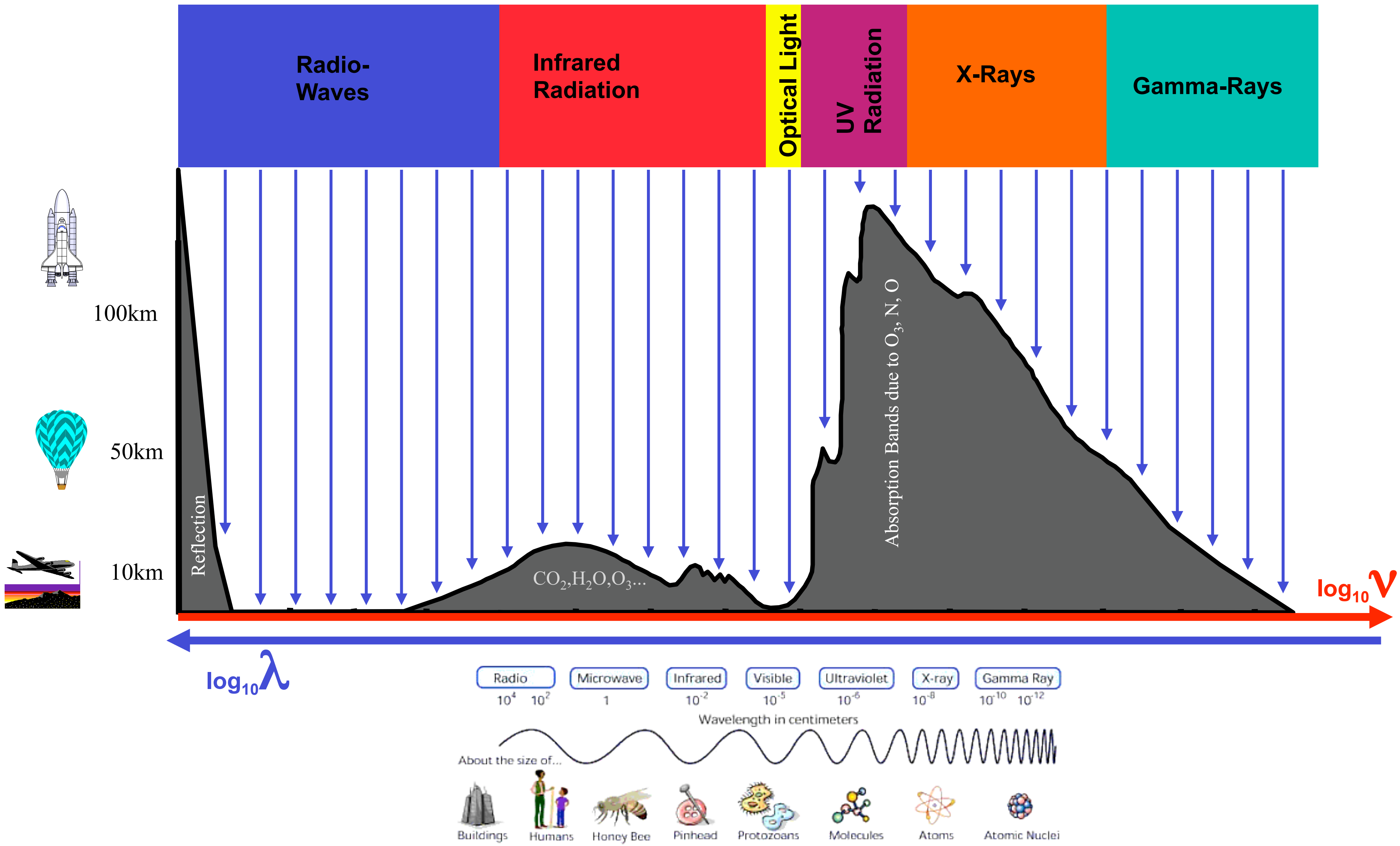
- **Electromagnetic Radiation**
  - Radio / sum-mm / IR / optical / UV / X-rays / Gamma-Rays



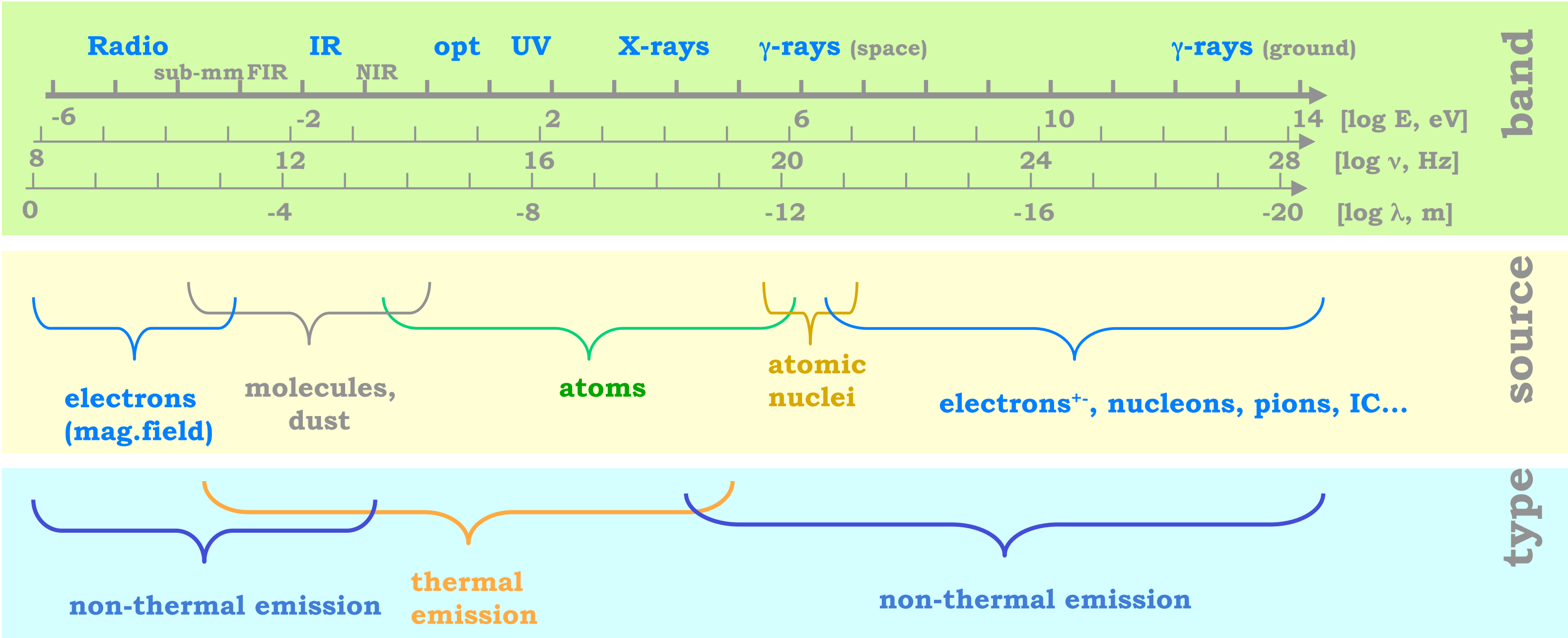
- **others**
  - Gravitational Waves



Astronomical Observations throughout the e.m. Spectrum



Astronomy across the Electromagnetic Spectrum

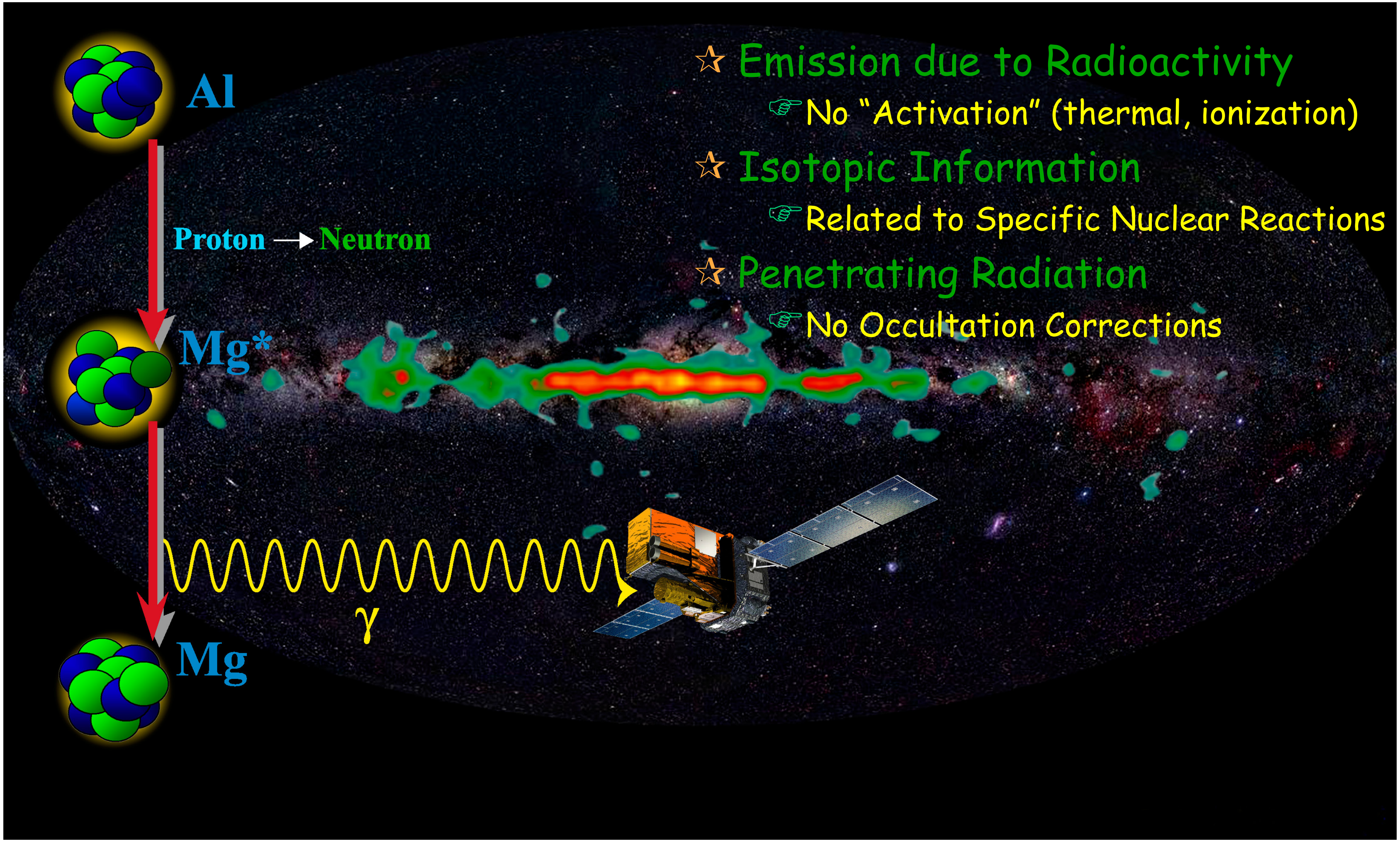


☆ "Nuclear" Astronomy:

- ☞ Diagnostics of high-energy processes MeV...100 MeV
- ☞ Nucleosynthesis Probe
- ☞ Unique / Direct / Complementary
  - Intensity not dependent on ionization states, temperature
  - No attenuation/occultation issues

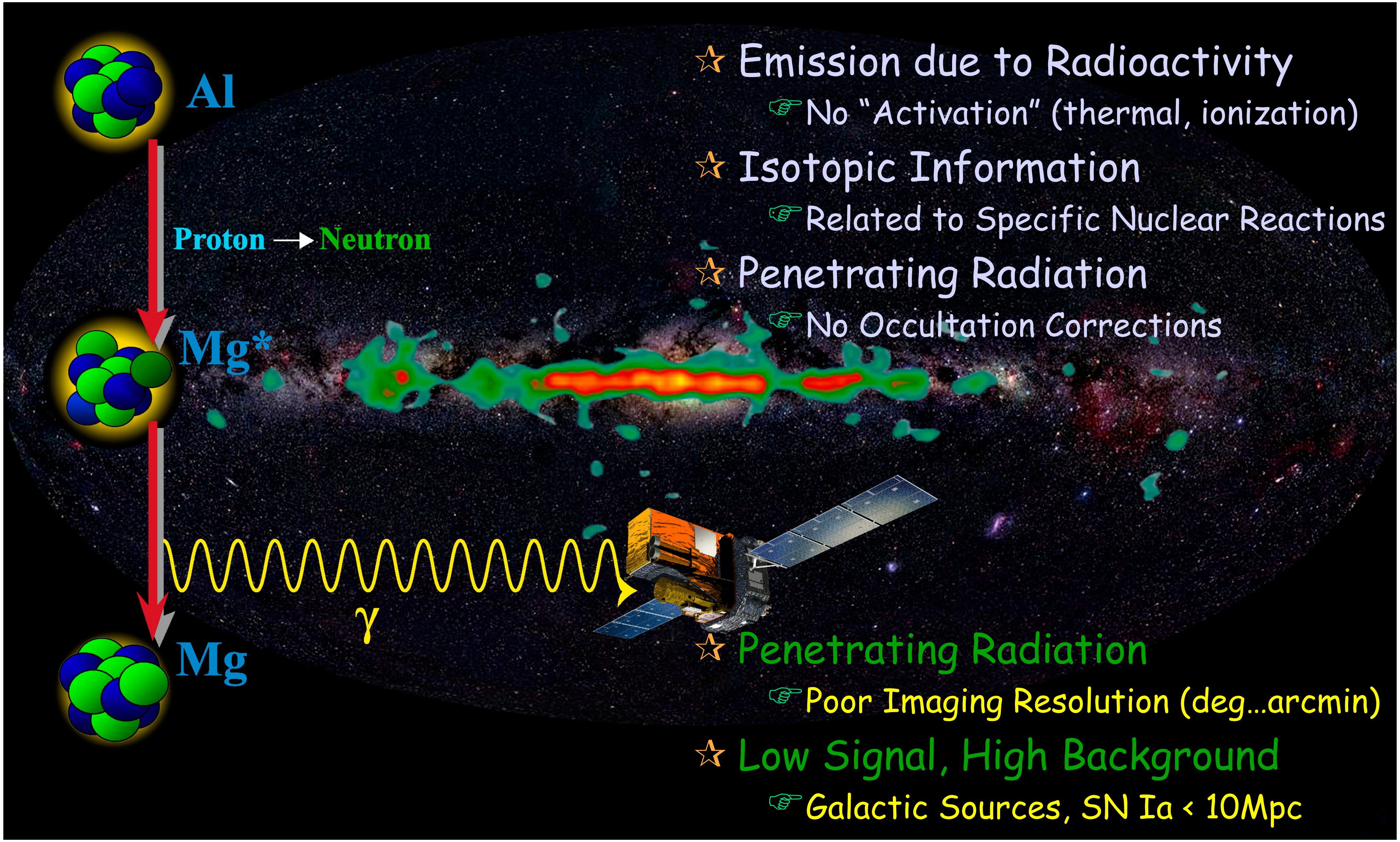
Gamma-Rays for Cosmic-Isotope Measurements

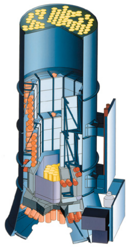
Special Characteristics:



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

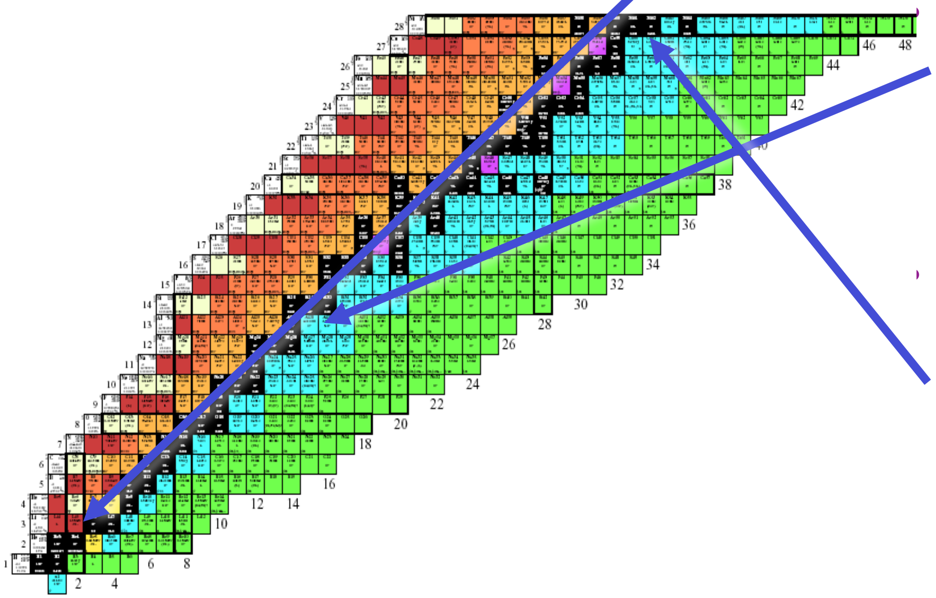
Gamma-Rays for Cosmic-Isotope Measurements
Special Characteristics:





Nucleosynthesis Study with Gamma-Rays
-> Physics / Processes at/inside the Nucleosynthesis Site

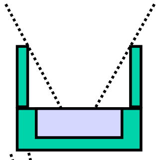
Isotope	Mean Lifetime	Decay Chain	γ-Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^{*}$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^{*} \rightarrow {}^{56}Fe^{*}+e^{+}$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^{*}$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+}$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^{*} \rightarrow {}^{44}Ca^{*}+e^{+}$	78, 68; 1157
^{26}Al	1.04 10^{6}y	$^{26}Al \rightarrow {}^{26}Mg^{*} + e^{+}$	1809
^{60}Fe	2.0 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

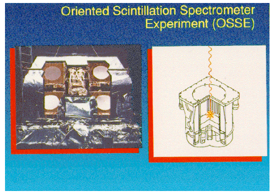


- 511 keV, ^{7}Be -> Novae
  -> p-Captures, β^{+} Decays
  -> ^{19}F Production...
- ^{26}Al -> Reaction Path Details in Stars/ SNe, ν-Process
  -> Metal/Fe Ratio, Si/Fe
- ^{44}Ti, ^{56}Ni -> Most Stable Isotopes ^{56}Ni/ ^{4}He, Freeze-Out of NSE
  -> Metal/Fe Ratio, Heavies/Fe

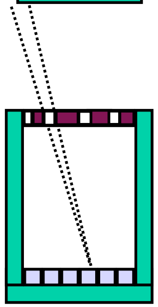
Gamma-Ray Astronomy: Instruments

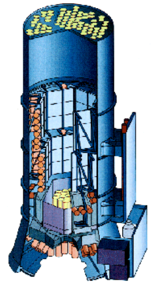
Photon Counters and Telescopes



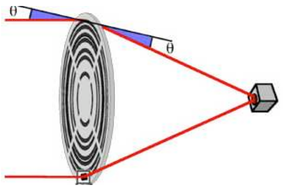


- **Simple Detector (& Collimator)**
  (e.g. HEAO-C, SMM, CGRO-OSSE)
  Spatial Resolution (=Aperture) Defined Through Shield

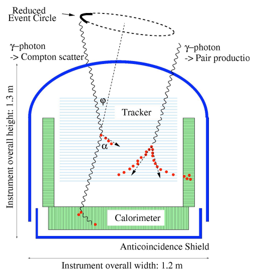


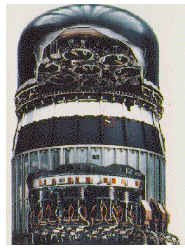


- **Coded Mask Telescopes**
  (Shadowing Mask & Detector Array)
  (e.g. SIGMA, INTEGRAL)
  Spatial Resolution Defined by Mask & Detector Elements Sizes



- **Focussing Telescopes**
  (Laue Lens & Detector Array)
  (CLAIRE, MAX)
  Spatial Resolution Defined by Lens Diffraction & Distance





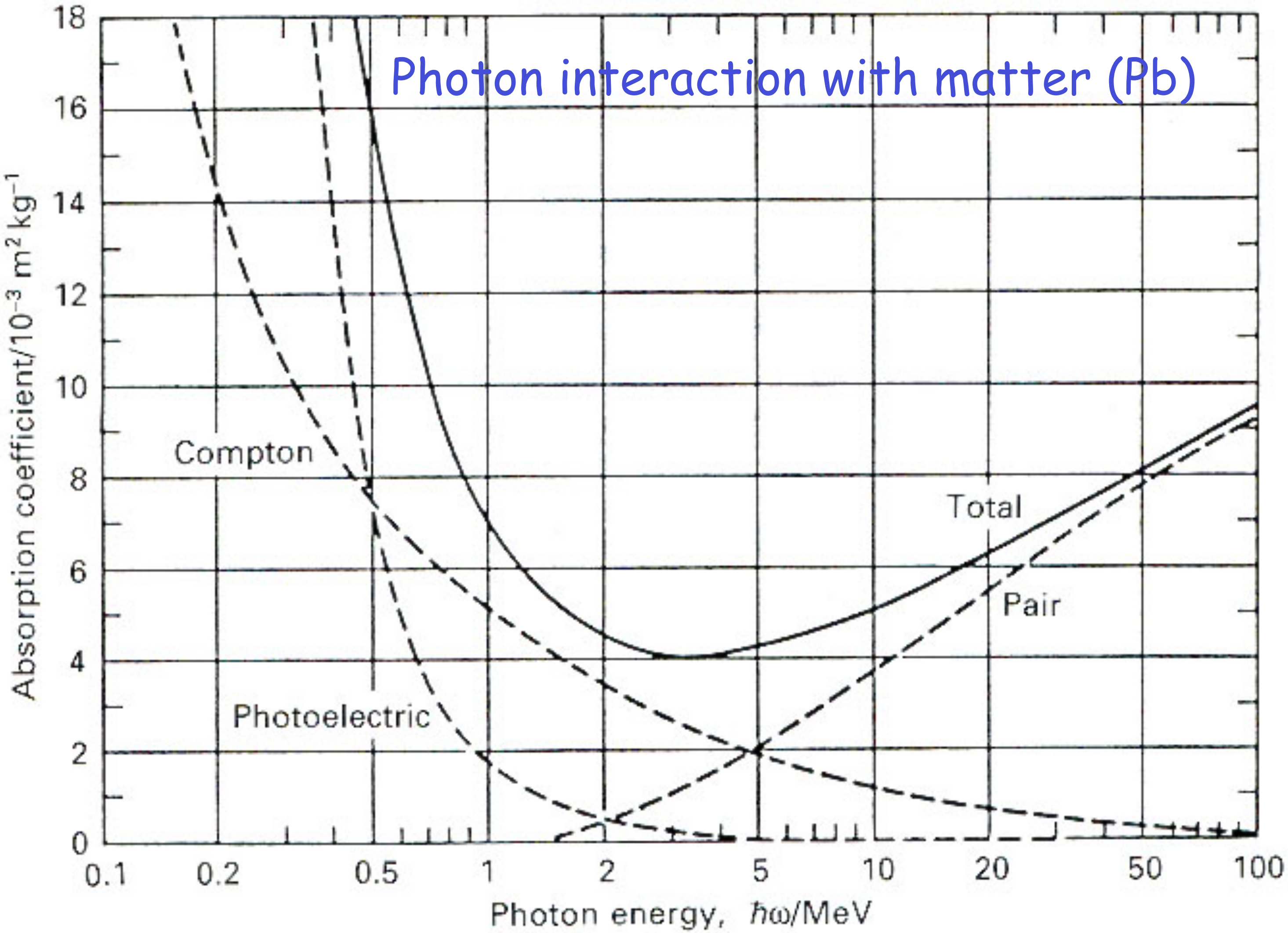
- **Compton Telescopes**
  (Coincidence-Setup of Position-Sensitive Detectors)
  (e.g. CGRO-COMPTEL, LXeGRiT, MEGA, GRIPS)
  Spatial Resolution Defined by Detectors' Spatial Resolution

Achieved Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution ≥ deg

Limitation: Overwhelming Instrumental Background

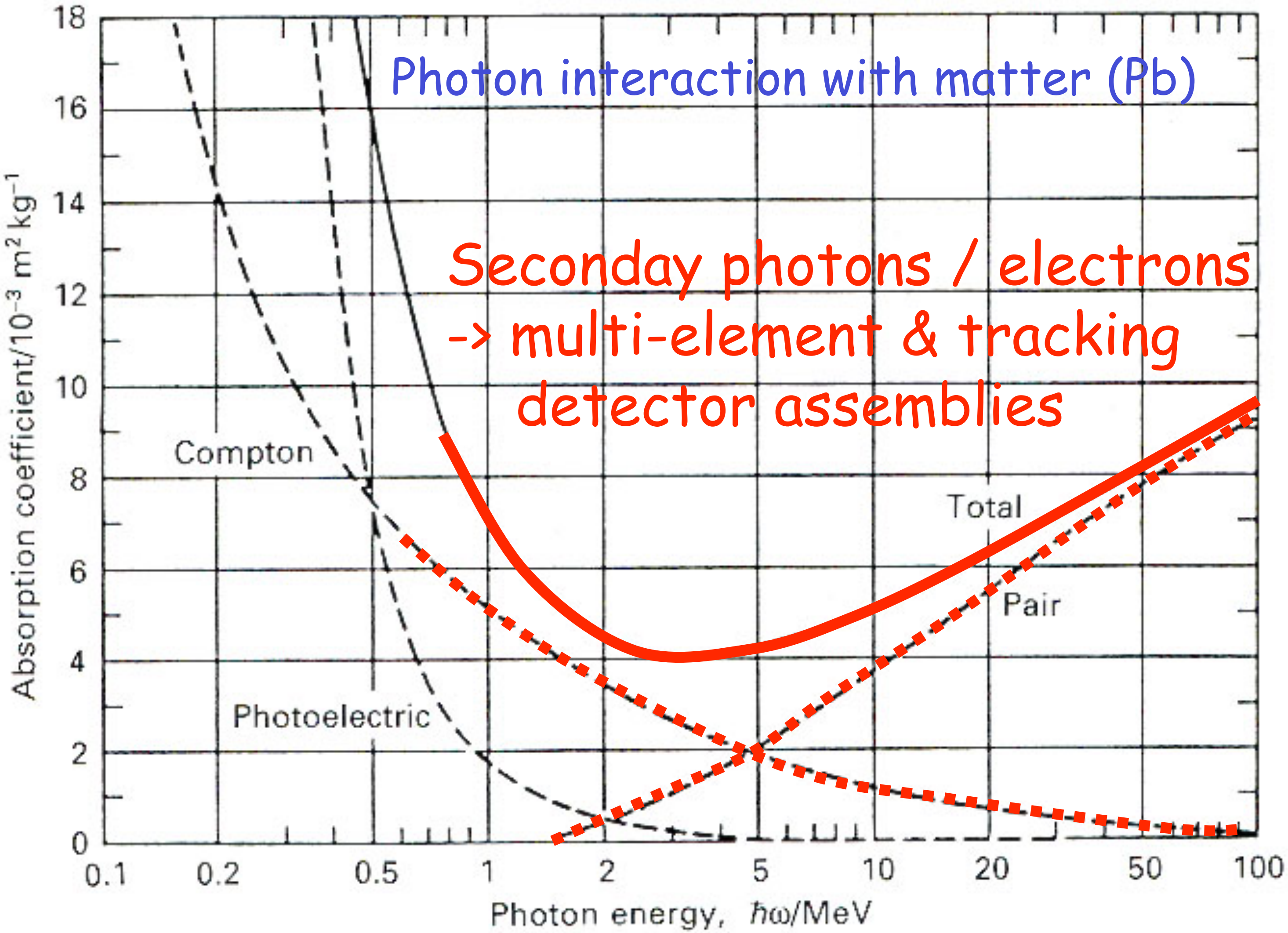
→ Need Discriminating (& Imaging) Information per Event

Gamma-Ray Astronomical Telescopes:
Interaction of HE photons with matter



Roland Diehl

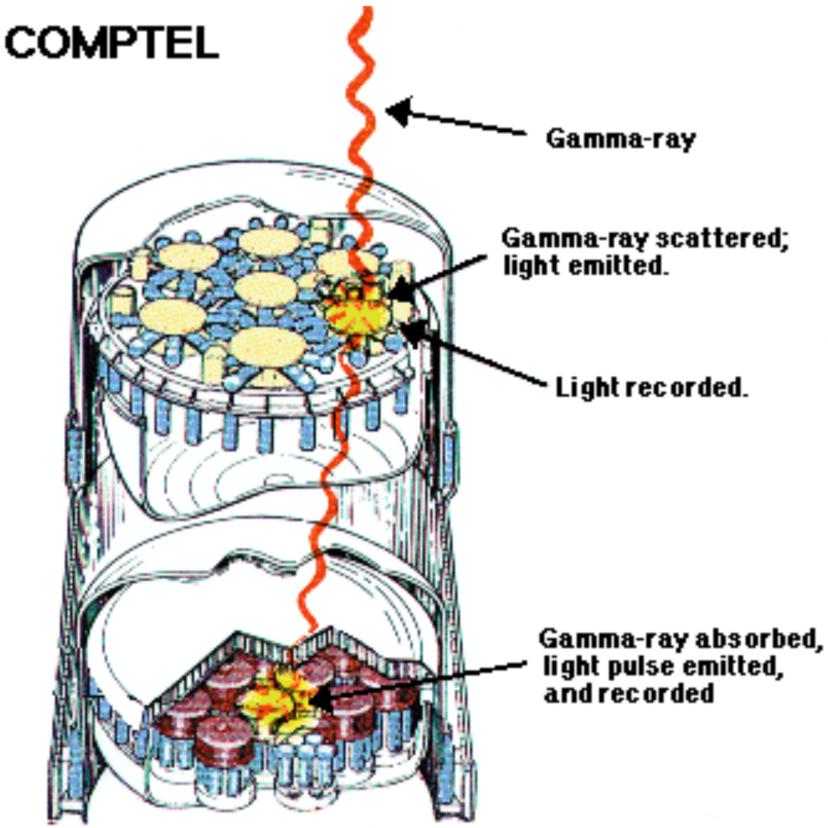
Gamma-Ray Astronomical Telescopes:
Interaction of HE photons with matter

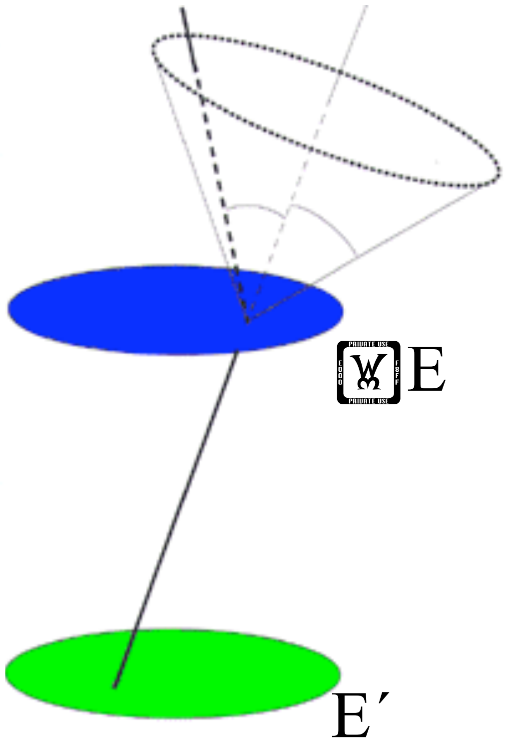


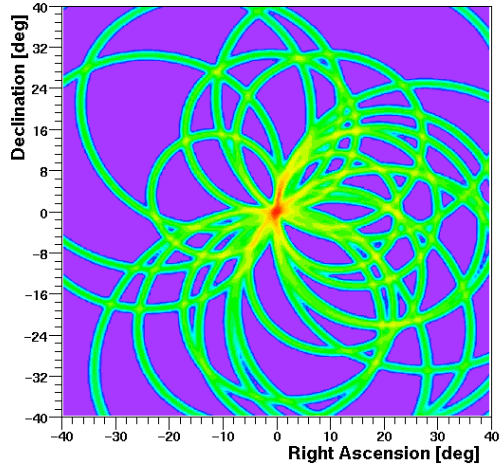
-> Secondary Particles … -> e.m. cascade

The Imaging Compton Telescope

Compton Scattering: A Coincidence Technique



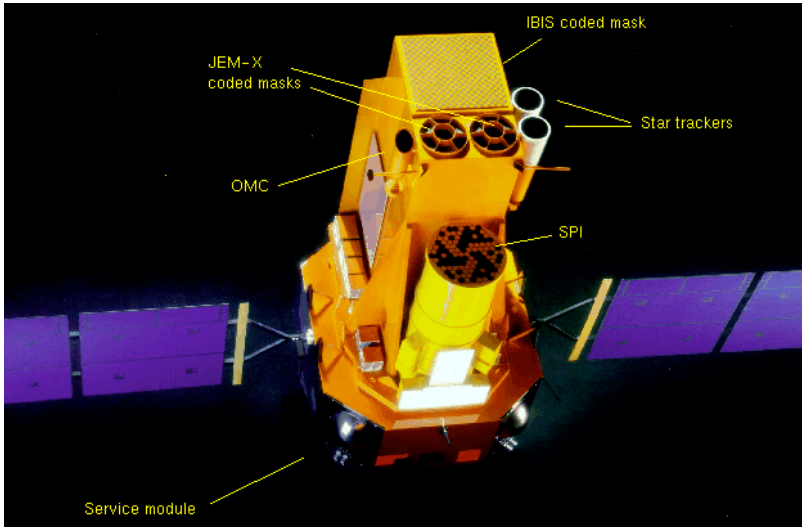




$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

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

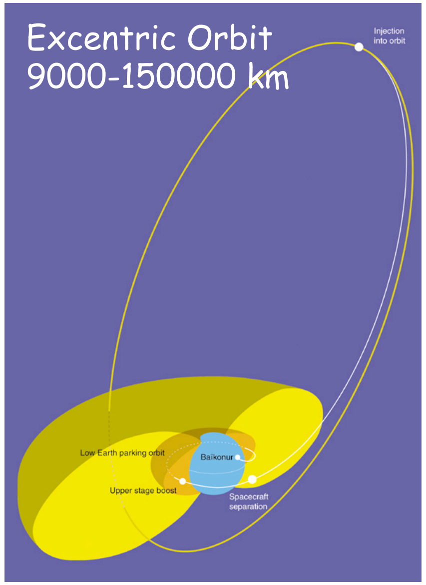
INTEGRAL: Ge γ-Spectrometry in Space!

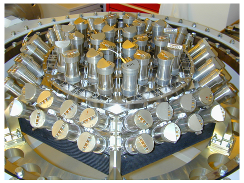


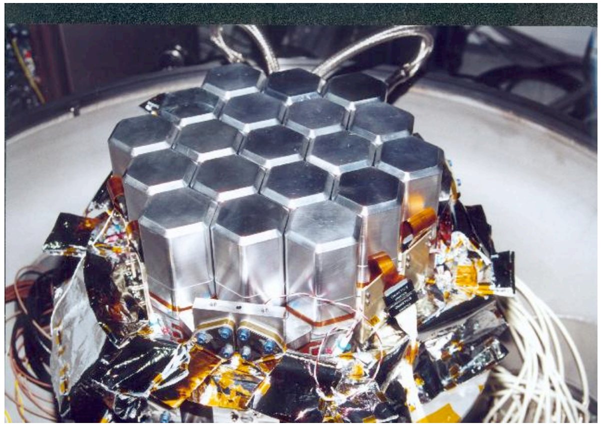
17 October 2002:
06:41 Launch from Baikonur / Kasachstan

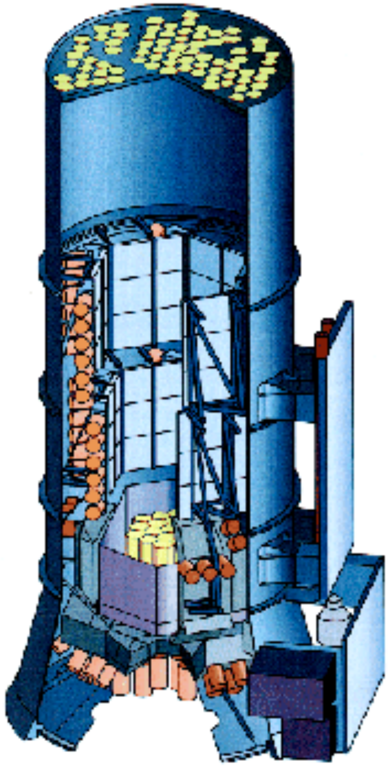
Summer 2008:
Healthy Spacecraft & Instruments
Mission Operations till 2012+

SPI: Coded-Mask Telescope 15-8000 keV
Energy Resolution ~2.2 keV @ 662 keV
Spatial Precision 2.6° / ~2 arcmin
Field-of-View 16x16°



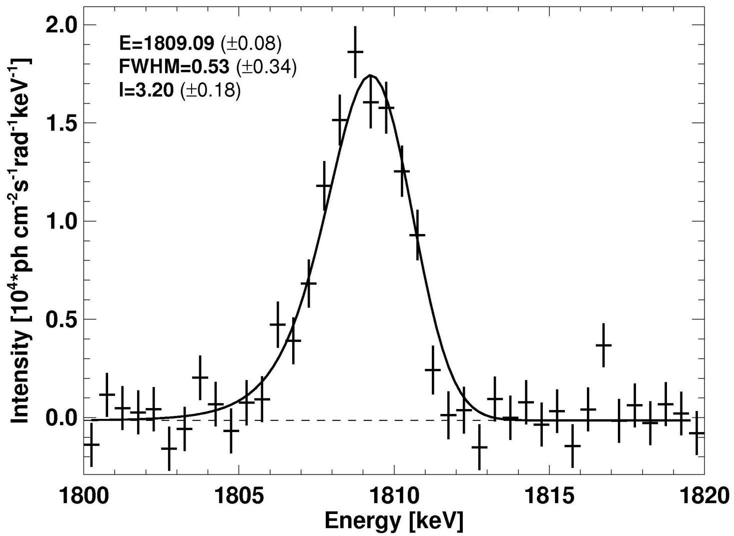


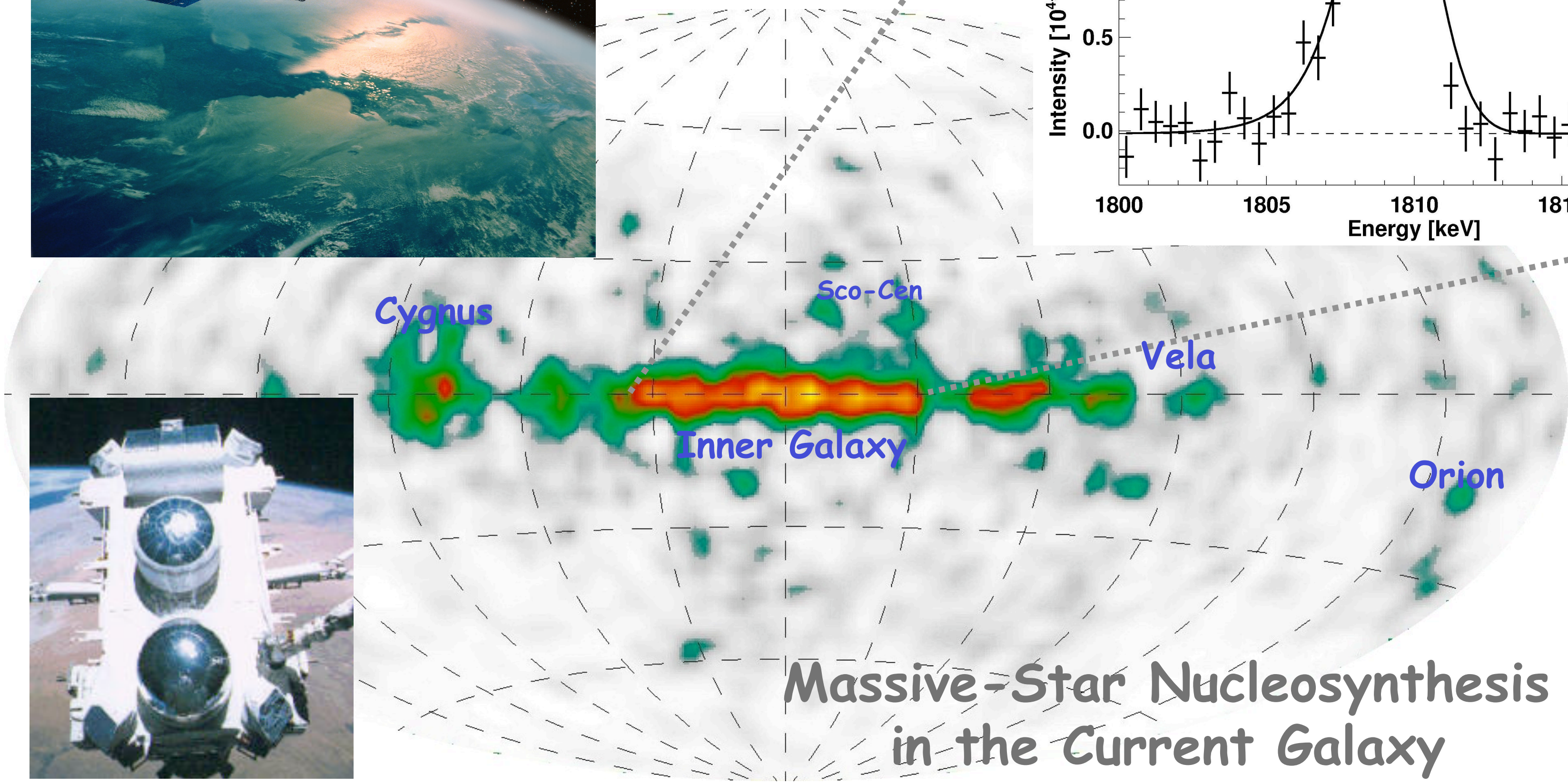




Achievements:

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



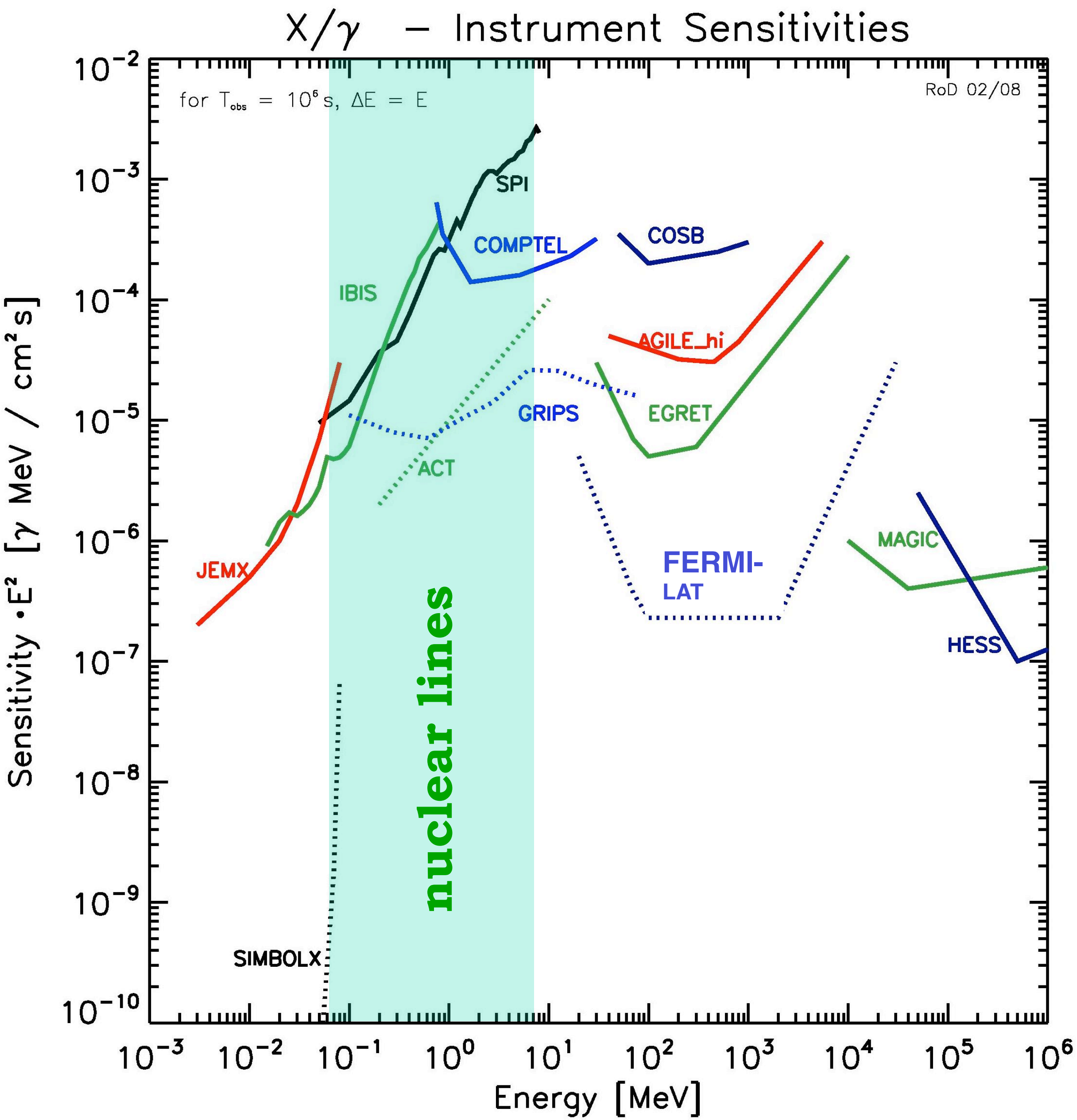


Massive-Star Nucleosynthesis in the Current Galaxy

Roland Diehl

Capabilities for Nuclear Astronomy

- ☆ Experimental Technology 'Waterscheds'
  - ☞ near ~100 keV: Fading Mirror Performance
  - ☞ below ~100 MeV: Fading Tracking Detector Efficiency
  - ☞ the Nuclear Energy Range is Difficult
    - CR-> Radioactivities



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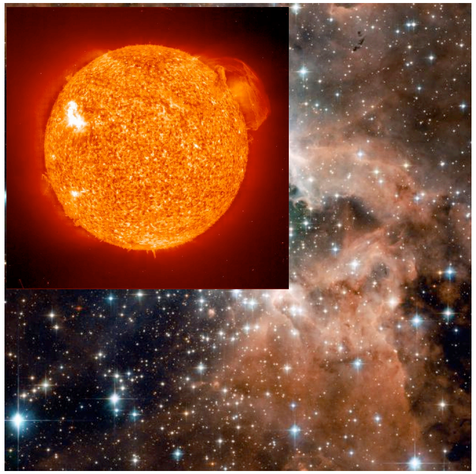
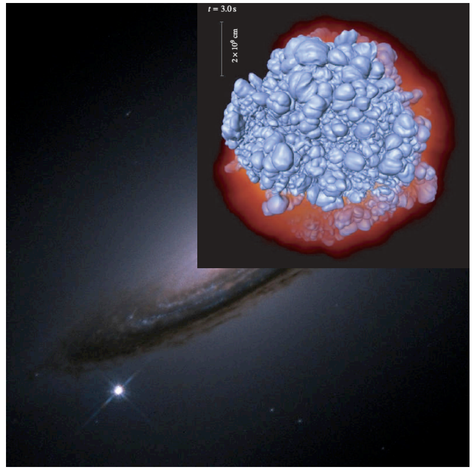
What Did We Achieve?

☆ Comments on Science Results, and How They Have Been Obtained

Astrophysics and Nuclear Physics

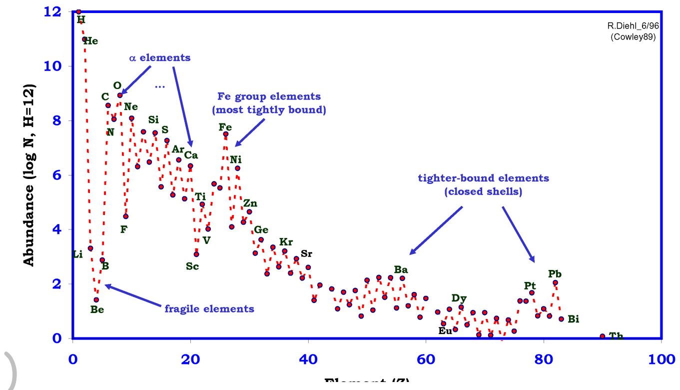
- Nuclear Physics in Cosmic Environments – where is it relevant?



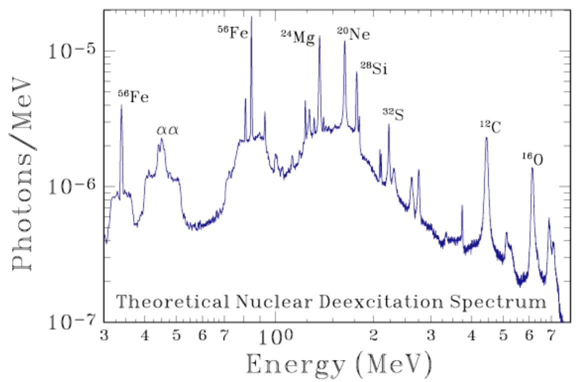


☆ Nuclear Energy Release
- Structure of Stars
- Dynamics of Explosions

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



☆ Characteristic Nuclear Radiation
- Nuclear Excitation (Emission/Absorption Lines)
- Radioactive Decay



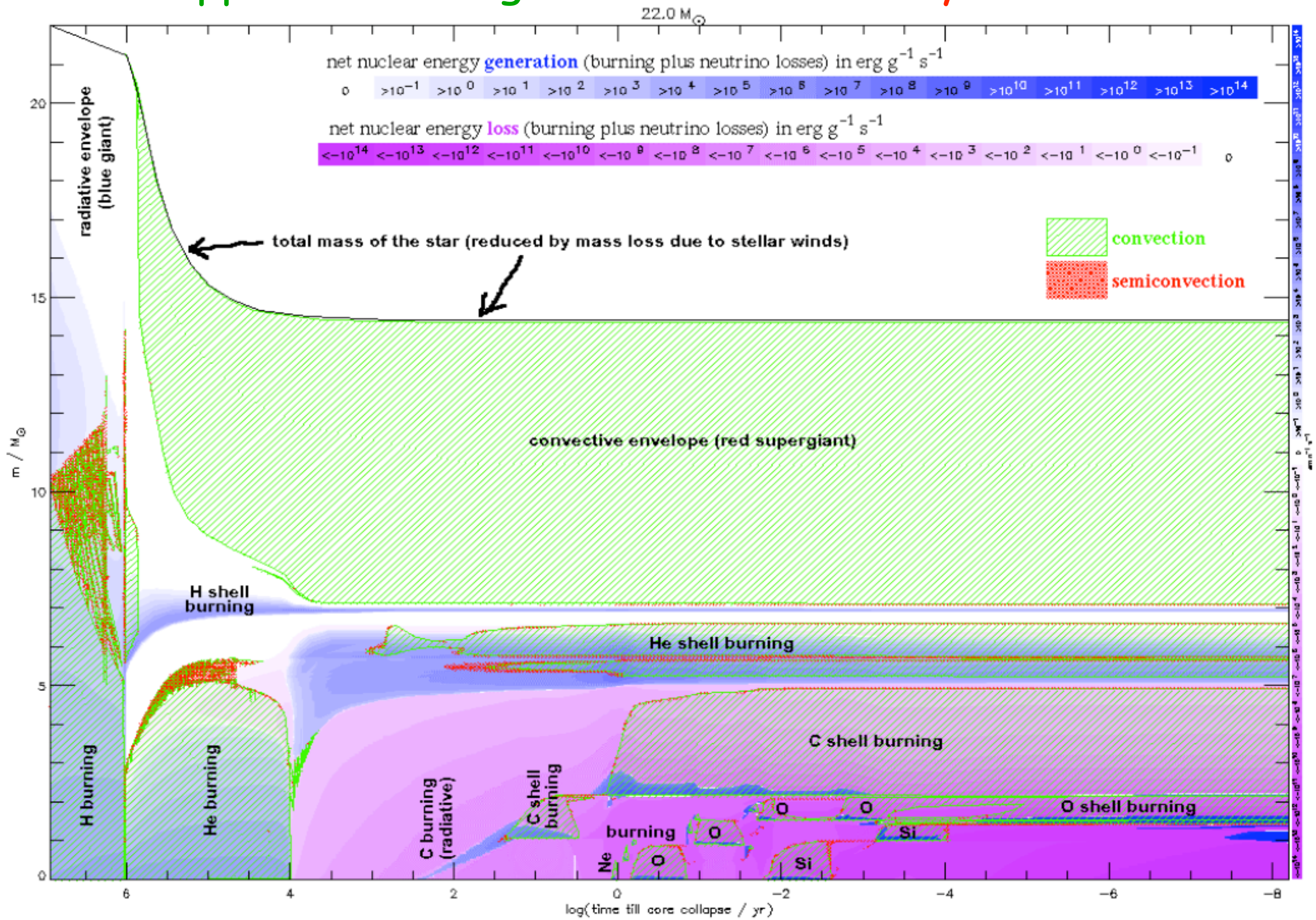
=>

☞ Nature of Cosmic Sources, Cosmic Processes
☞ Search for New Phenomena

Following Stellar Evolution

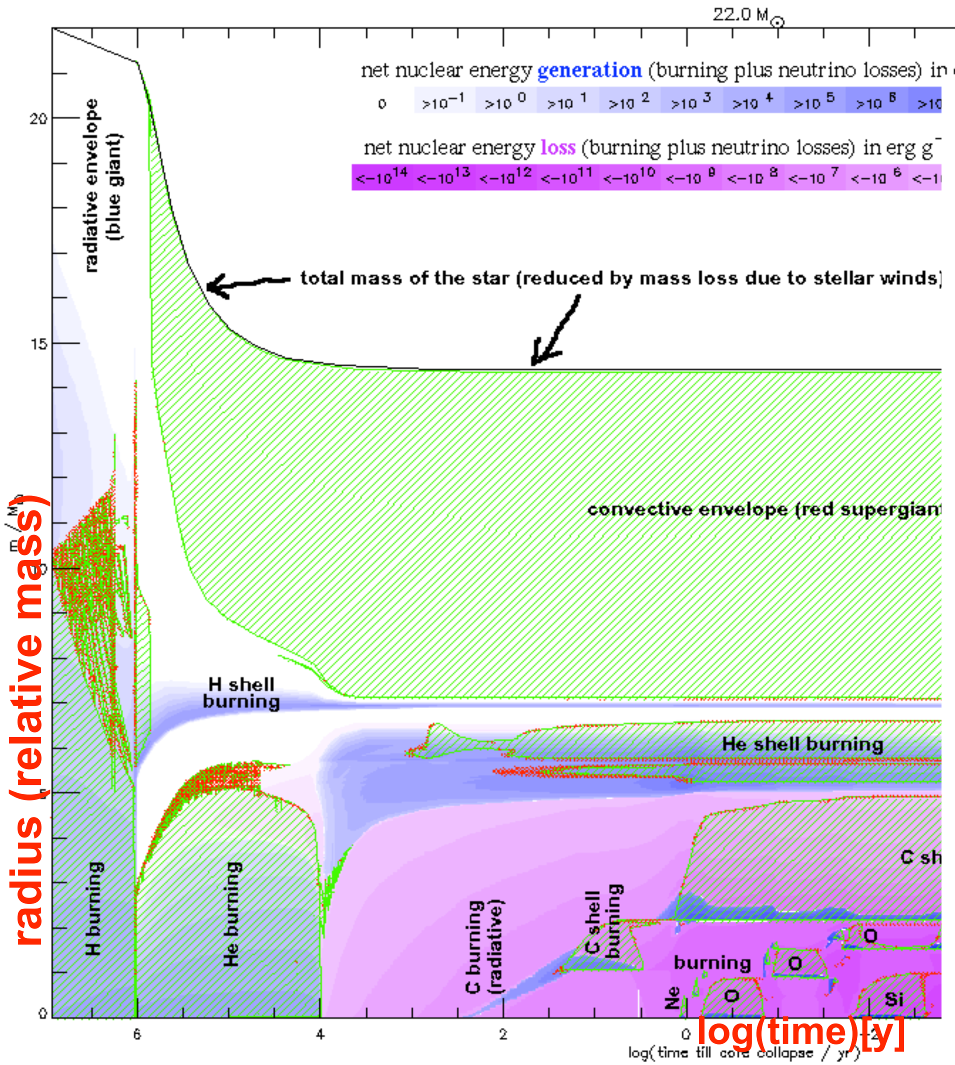
Rauscher; Heger 2003

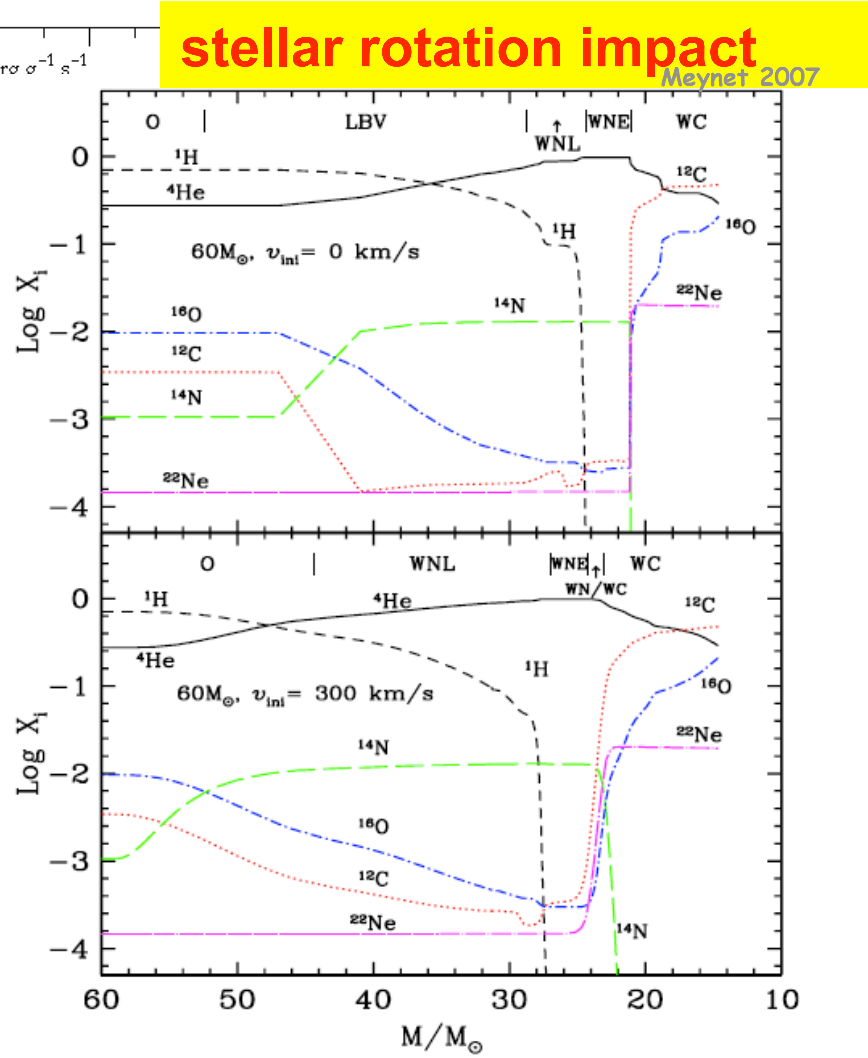
- ☆ The "Kippenhahn" Diagram: Could be Very Different!



Stellar Structure Complexities

☆ Stellar Rotation Incurs Structural Changes!





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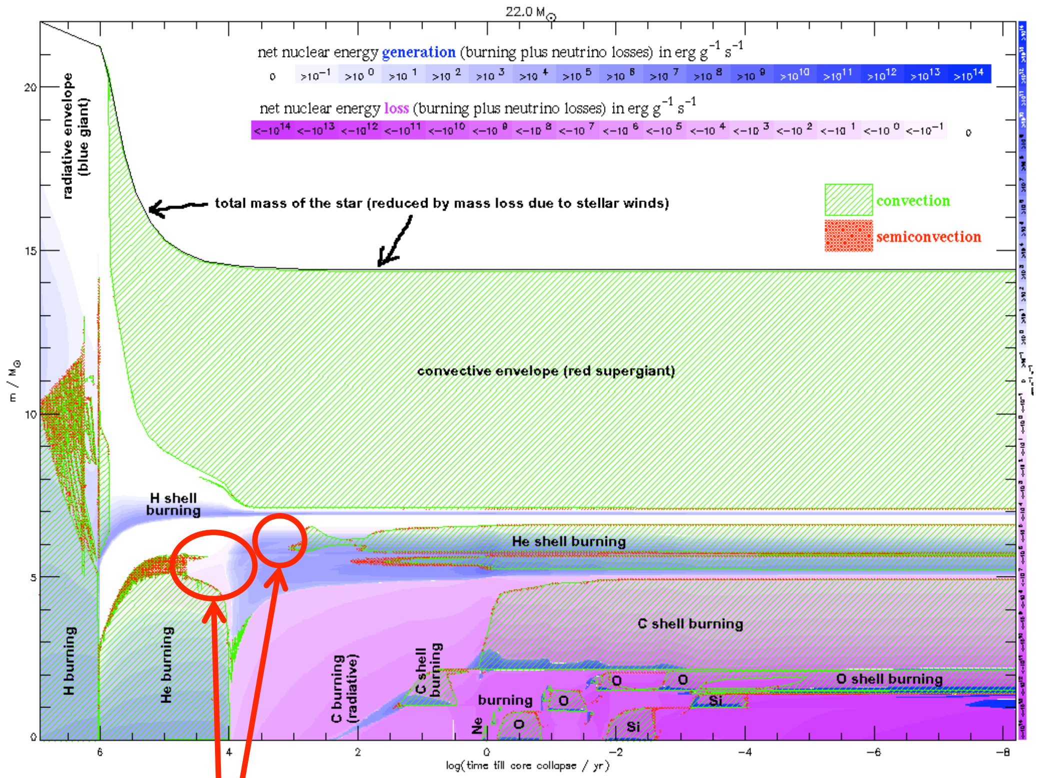
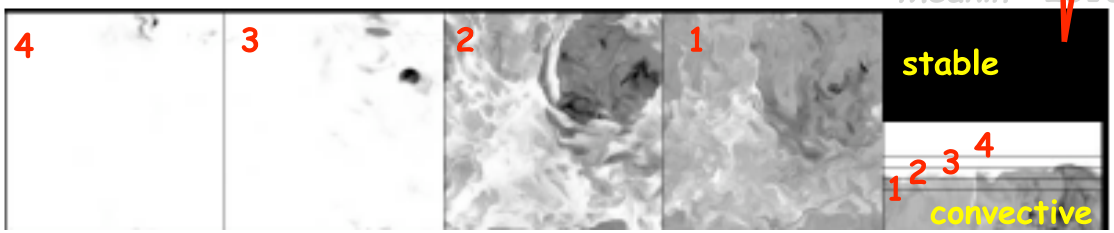
Massive-Star Structure: Issues

☆ How Does Convective Zone Transit into Stable (radiative) Zone?

- ☞ Empirically, "Overshoot" and "Semiconvection" Parametrizations Used
- ☞ 3D simulations Show Significant Transition Zone



Meakin+ 2010

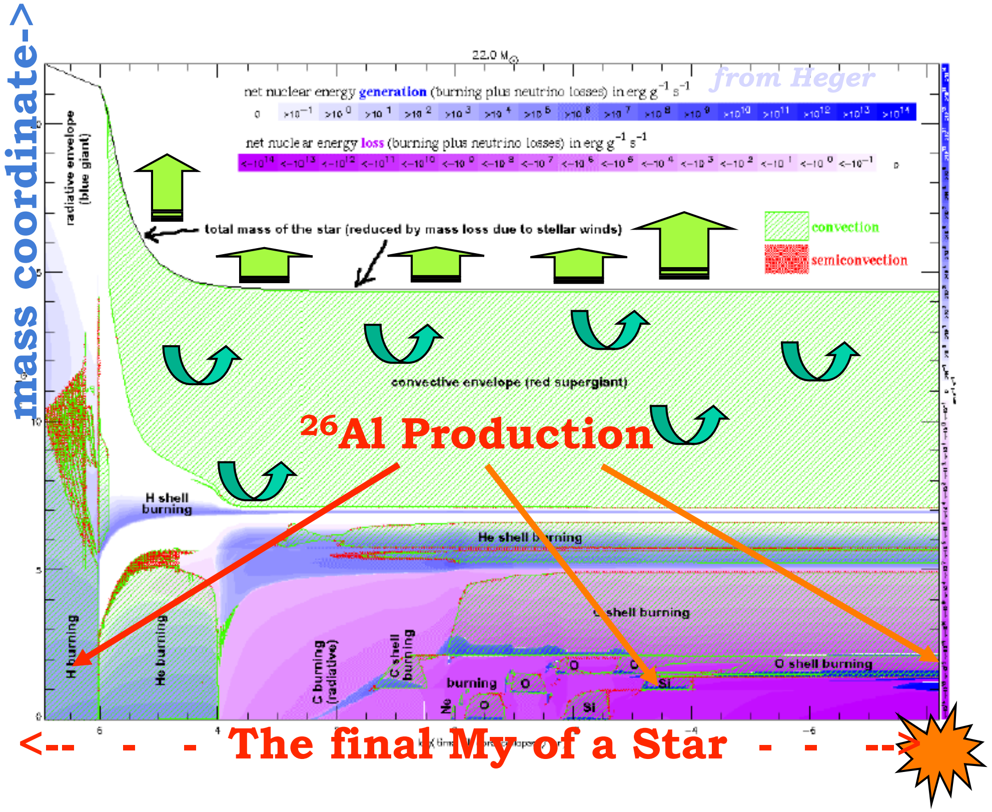


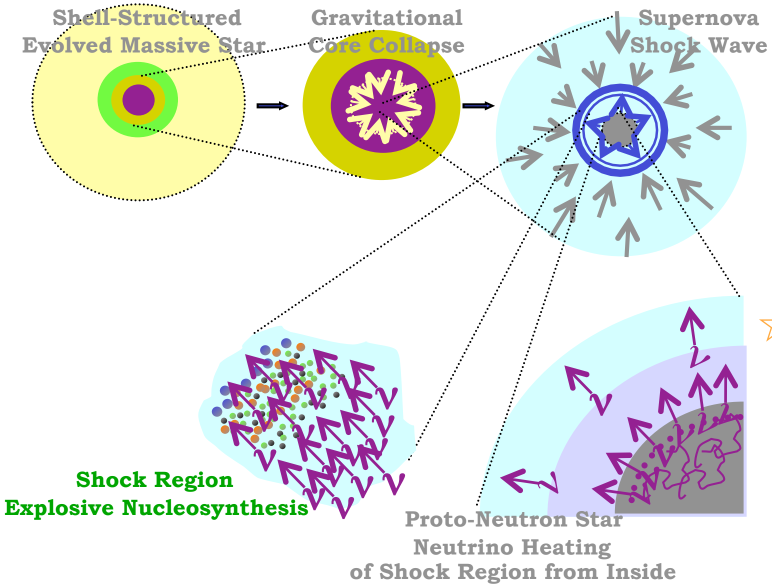
Synthesis of ^{26}Al in Stars and Supernovae

☆ Massive Star Burning

☞ Physics:

- Stellar Evolution Phases
- Mass Loss
- Convection & Mixing
- Intermittent Nuclear-Burning Phases





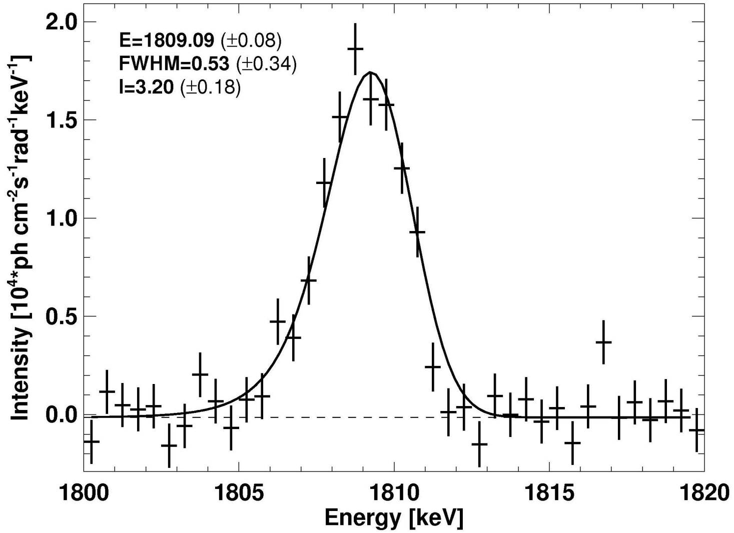
☆ Supernova Explosive Nucleosynthesis

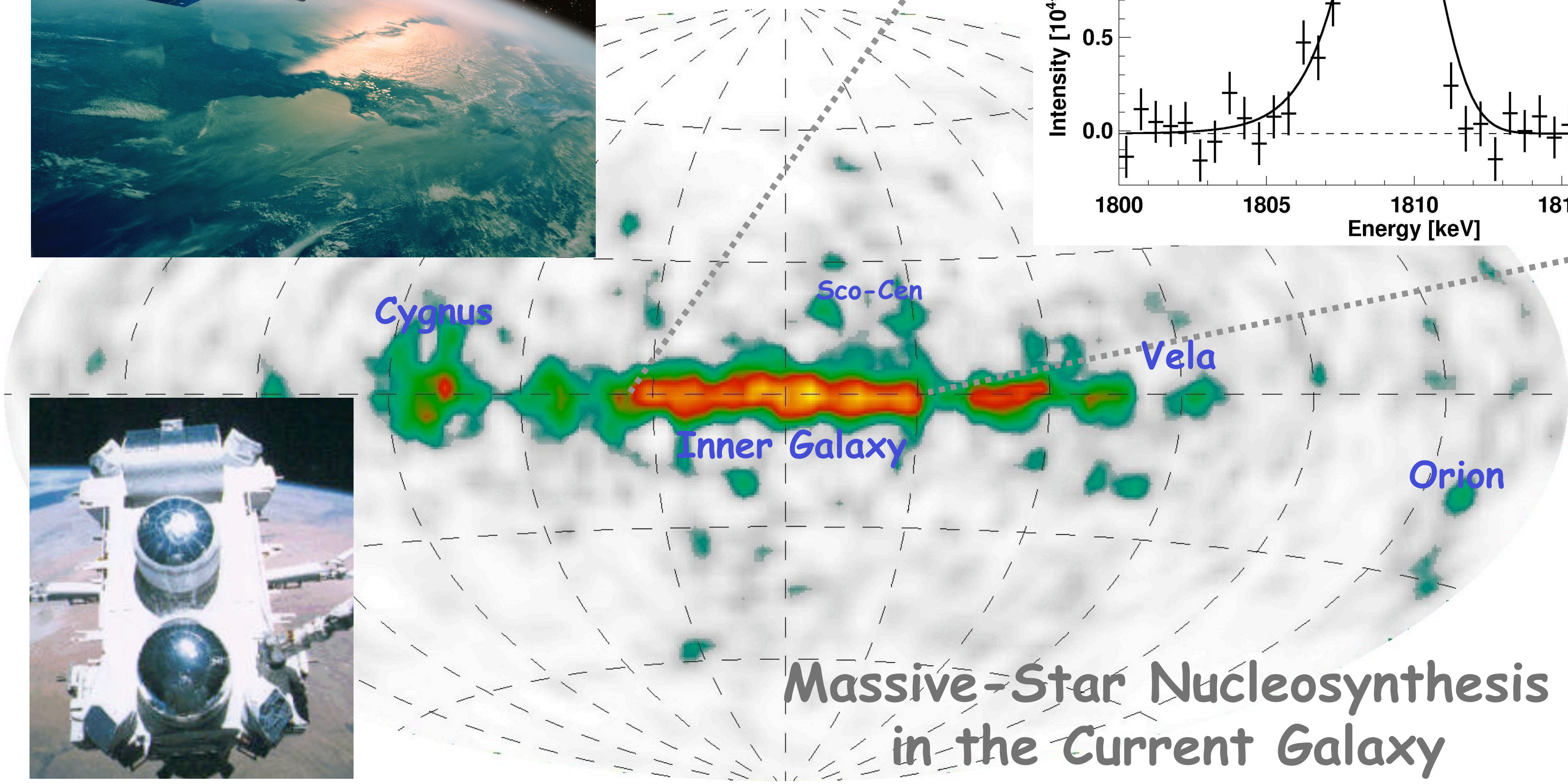
☆ Physics:

☞ Explosion Trigger

☞ Shock Structure and Mixing

^{26}Al in our Galaxy: Ejecta from Massive Stars





Massive-Star Nucleosynthesis
in the Current Galaxy

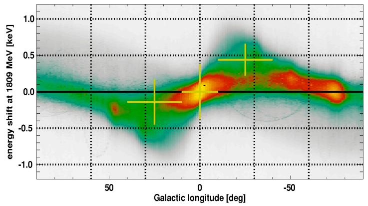
Using the ^{26}Al Line to Characterize the Galaxy

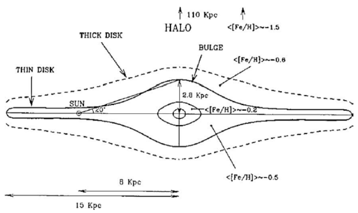
-> Diehl et al., Nature 2006

☆ Measured Gamma-Ray Flux

☆ Galaxy Geometry

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



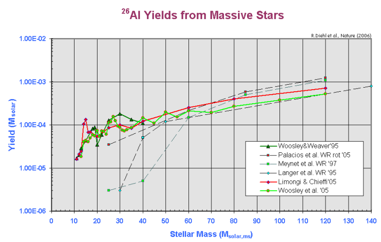


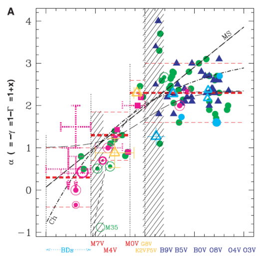
☆ ^{26}Al Yields per Star

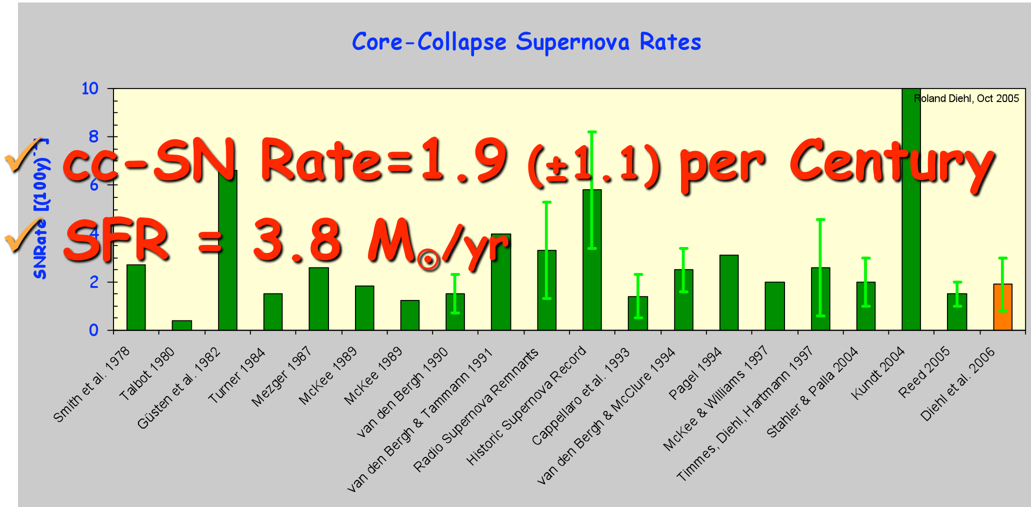
☆ Stellar Mass Distribution

} ✓ cc-SN Rate=1.9 (±1.1) per Century

✓ SFR = 3.8 $M_\odot$/yr

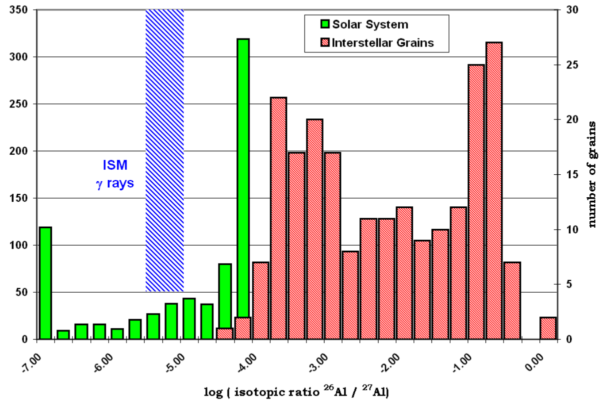




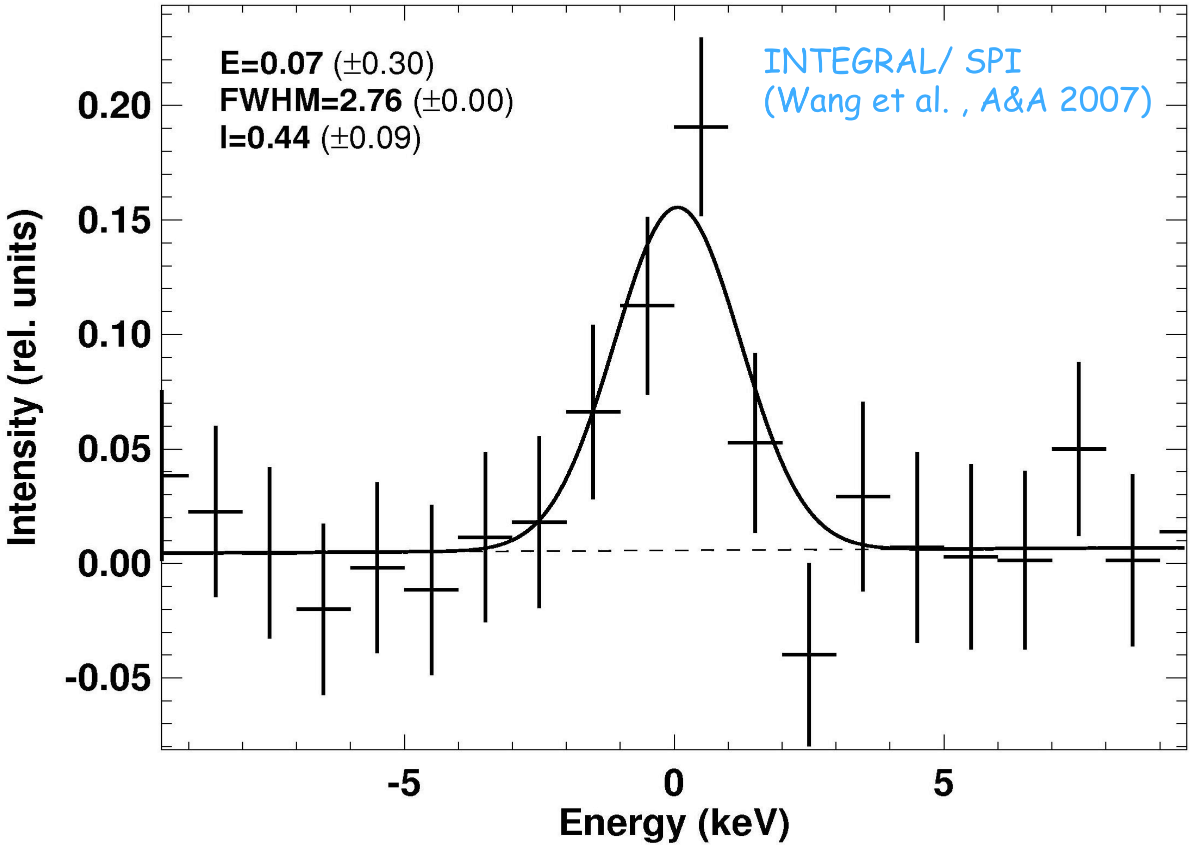


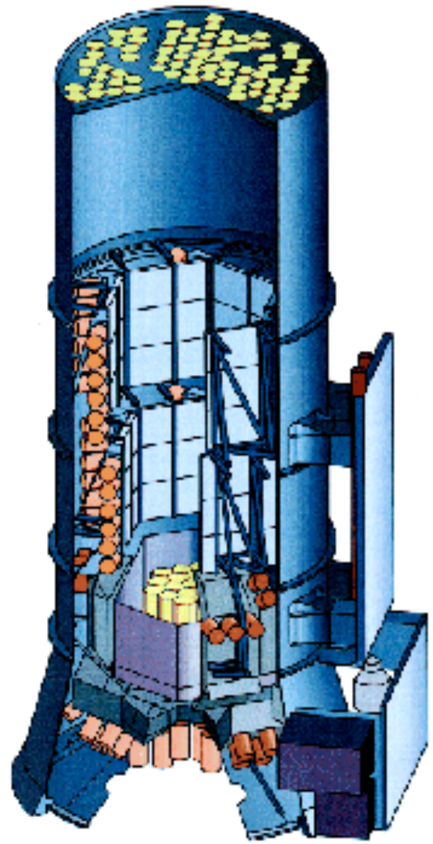
☆ Gas Mass in Galaxy

} ✓ Al Isotopic Ratio = 8.4 10^{-6}



^{60}Fe Emission is Seen from the Galaxy





☆ Gamma-ray Signal Now Beyond 'Hints'/'Limits' (5σ)

☞ ^{60}Fe/^{26}Al Emission Ratio ~15%

^{60}Fe: Why is it Interesting?

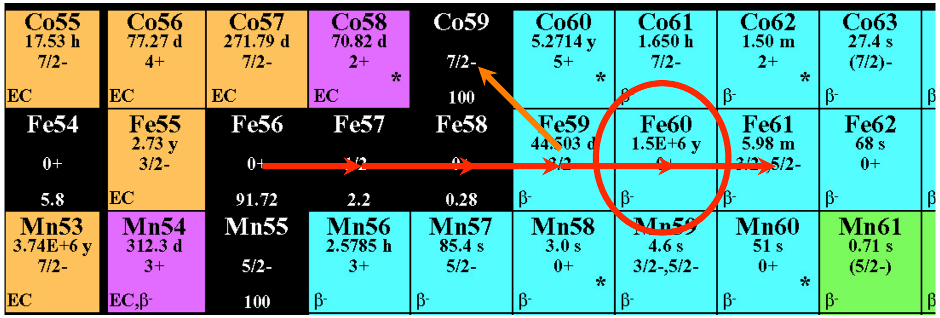
3.8 10^6y	^{60}Fe → ^{60}Co* → ^{60}Ni*	59, 1173, 1332

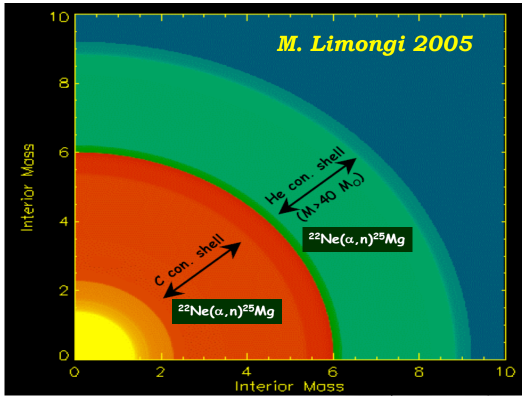
☆ ^{60}Fe is Produced through Successive Neutron Captures
- ☞ n Capture Astrophysics...(->s-Process...)

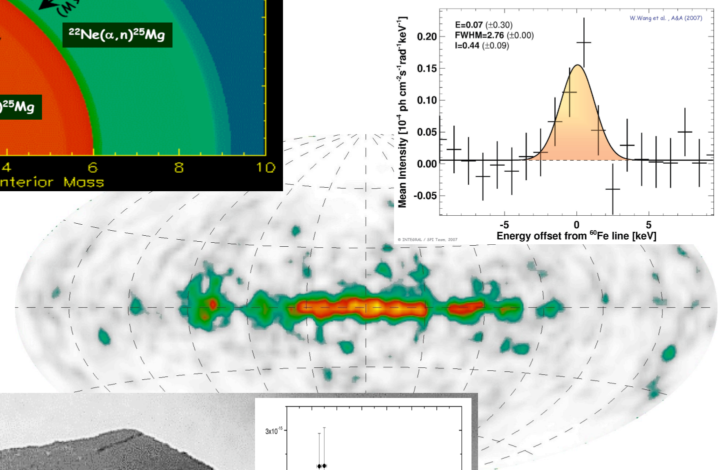
☆ Massive Stars are Likely Sources of ^{60}Fe
- ☞ ... the MAIN Agents of Cosmic Evolution

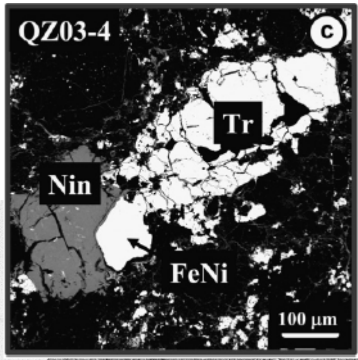
☆ ^{60}Fe has been Detected in
- ☞ a Pacific-Ocean Crust
- ☞ Solar-System Meteorites
- ☞ the Interstellar Medium

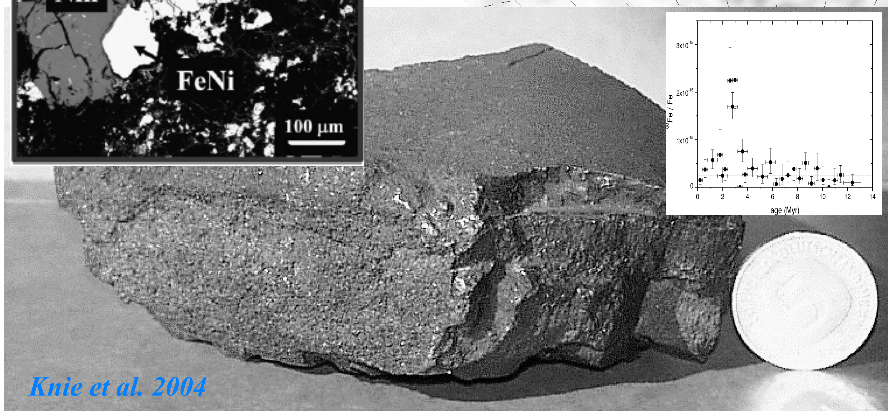
☞ Radioactive Dating of Different Astrophysical Events!









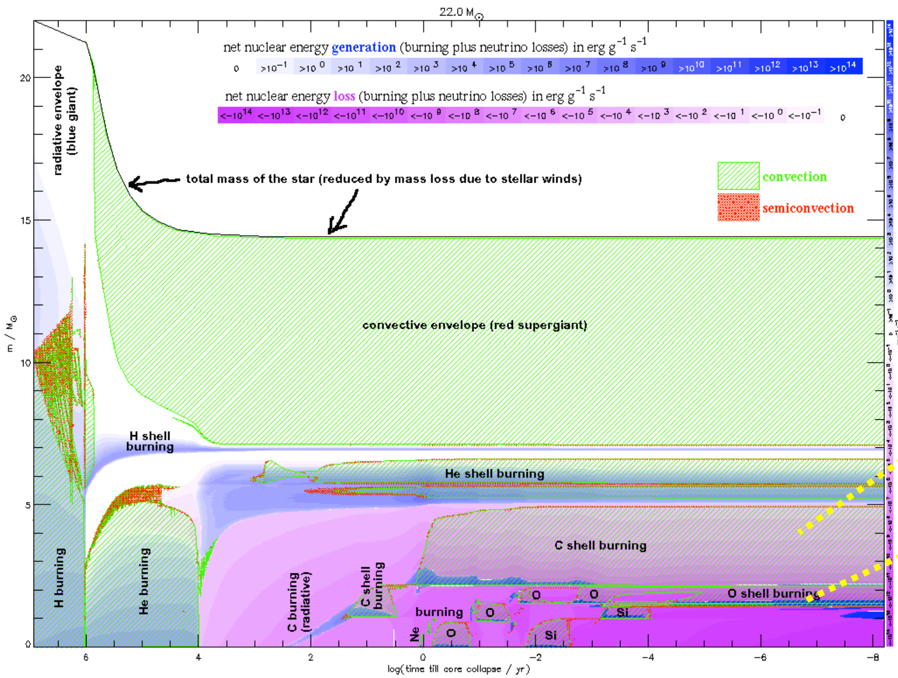


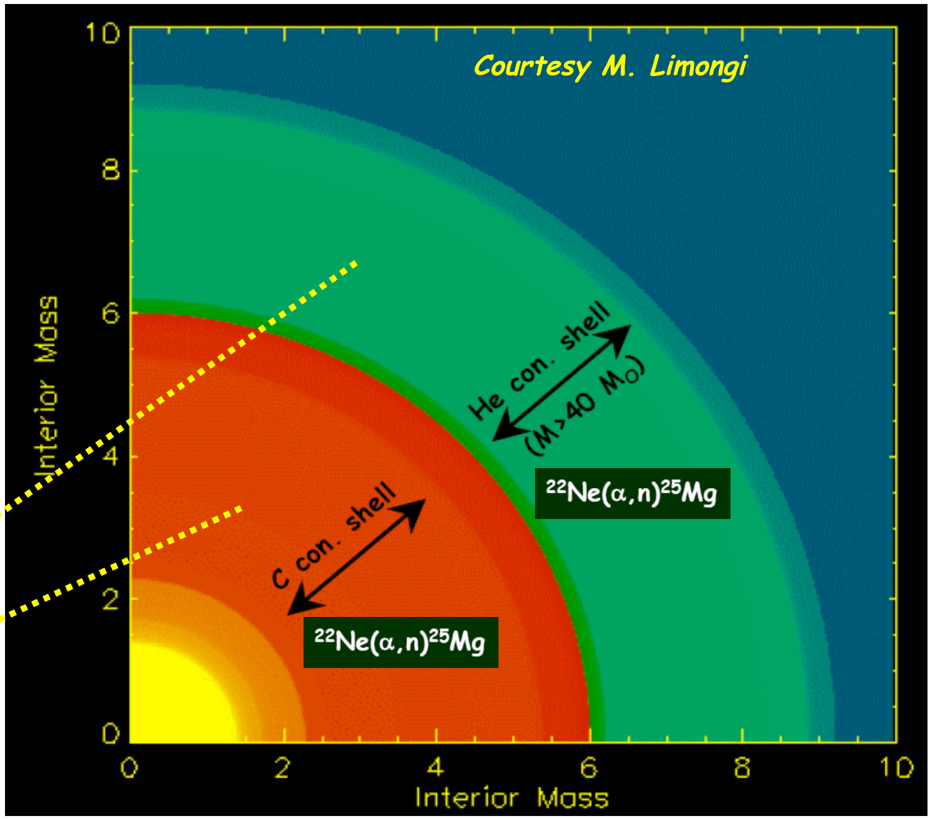
Knie et al. 2004

Roland Diehl

^{60}Fe Production in (^{26}Al-producing) Stars

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

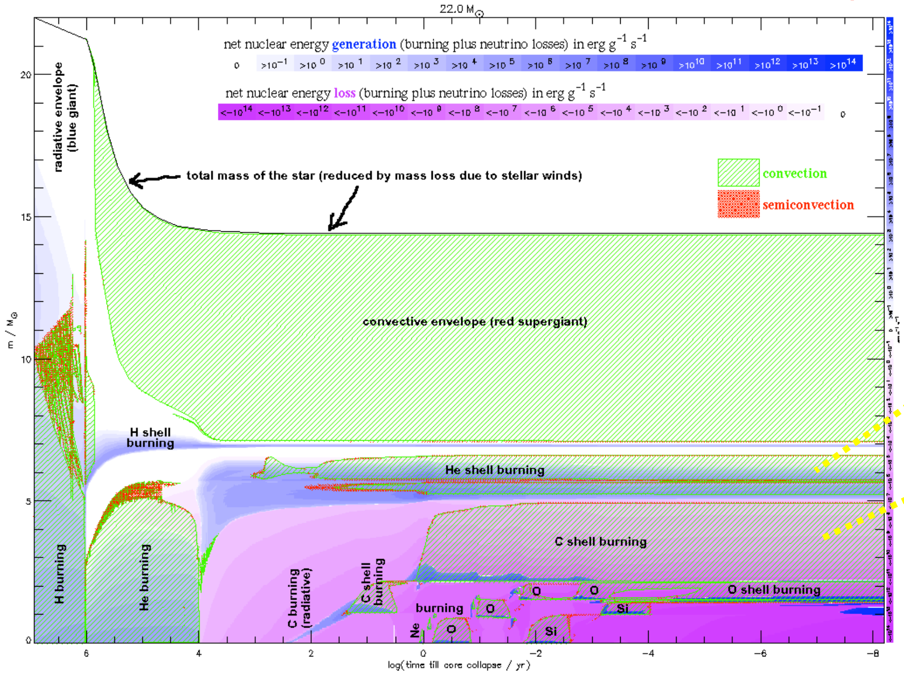


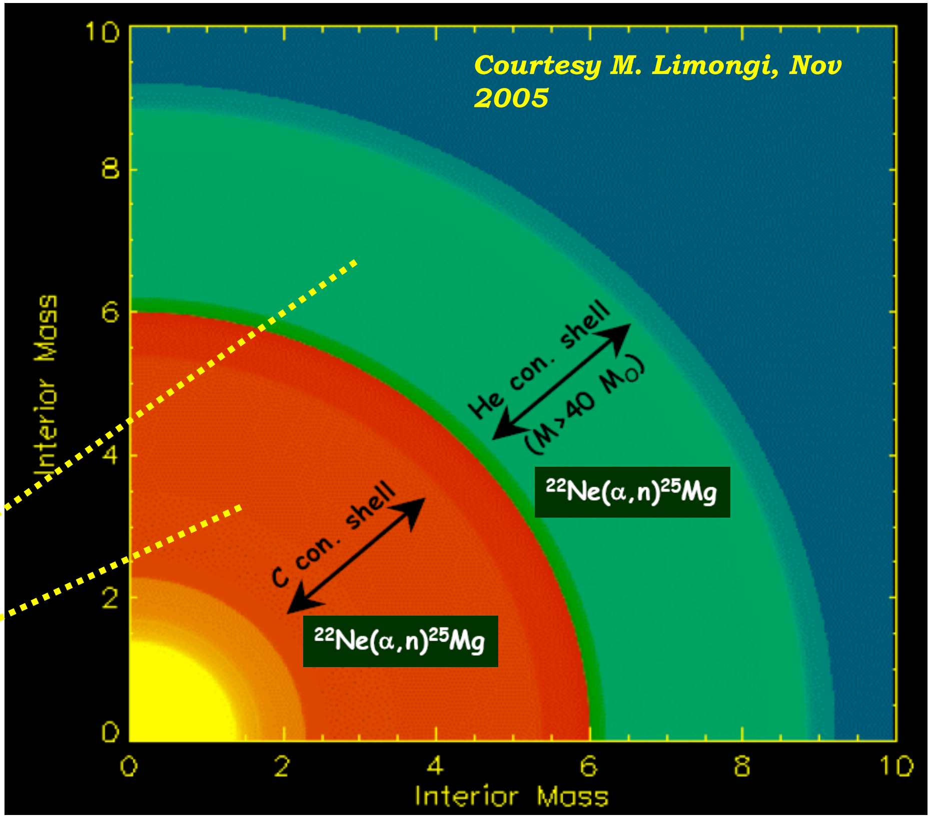


- ☆ Explosive-Burning Contributions Negligable
- ☆ Ejection by Supernova Explosion

^{60}Fe Production in Stars: **Issues for Nucleosynthesis Environment**

- ☆ What are the n Densities from $^{22}Ne(\alpha,n)^{25}Mg$?
- ☆ What are the Temperatures (and gradients) in the Shell? (τ_β)





- ☆ ...and: How Do Other Reactions Shape the Structure of the Star (3α, $^{12}C(\alpha,\gamma)$)

Production of ^{60}Fe and ^{26}Al in Massive-Stars

- ☆ Ratio Differs with Progenitor Mass!

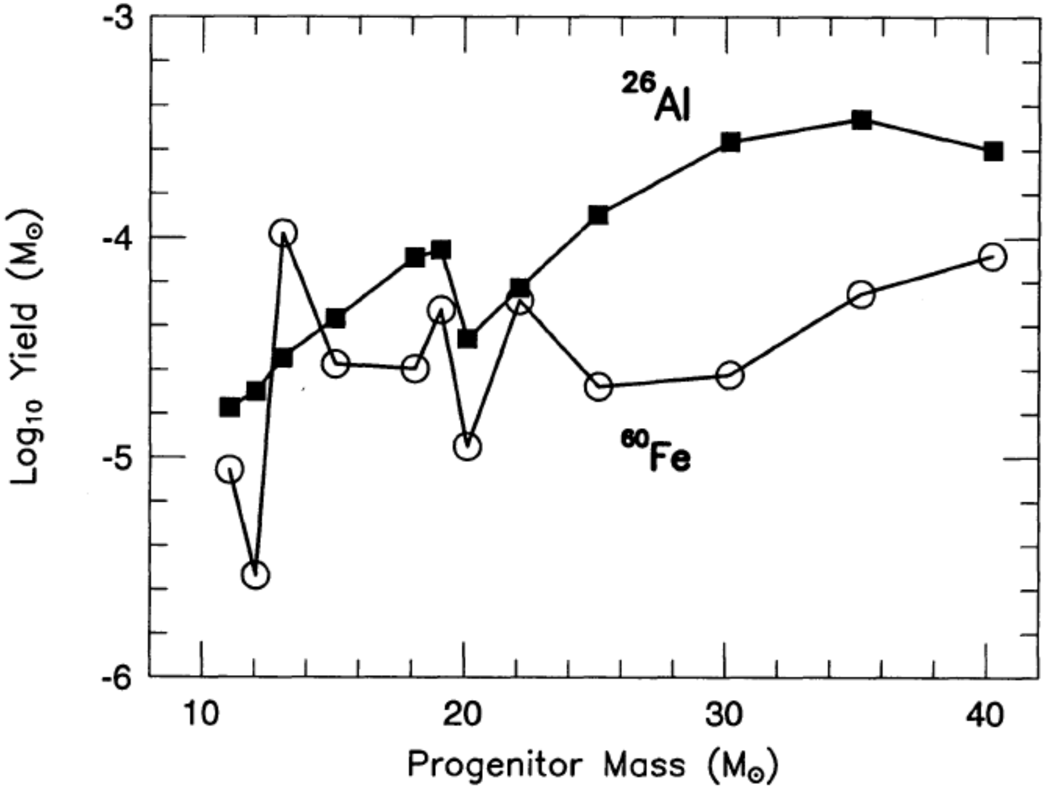
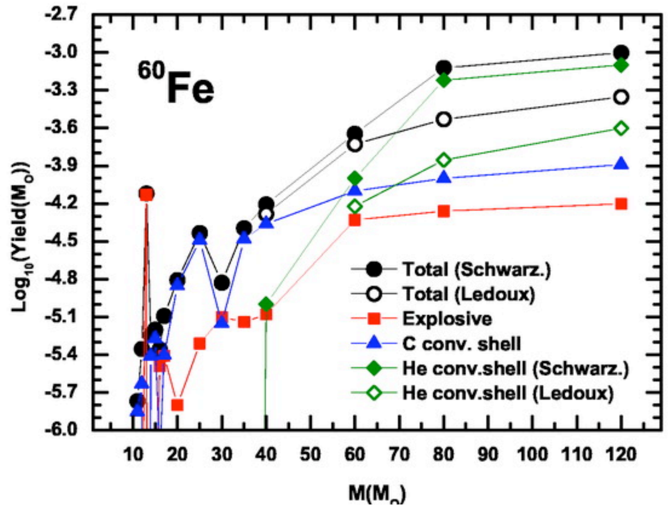
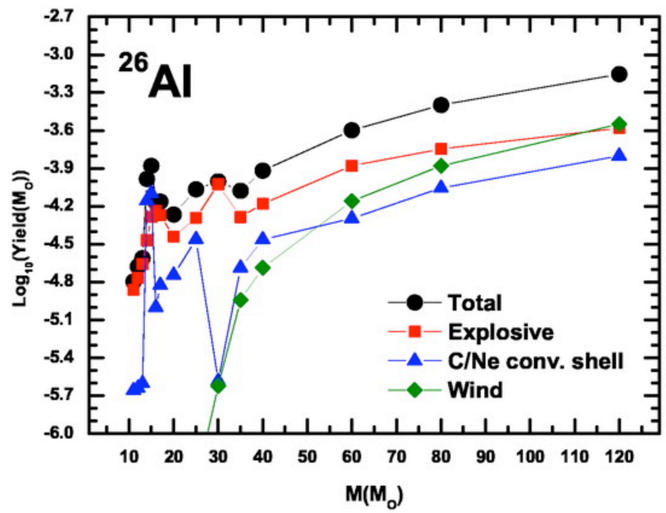


FIG. 3.—Mass of ^{26}Al (*filled squares*) and ^{60}Fe (*open circles*) ejected as a function of the main-sequence progenitor mass.



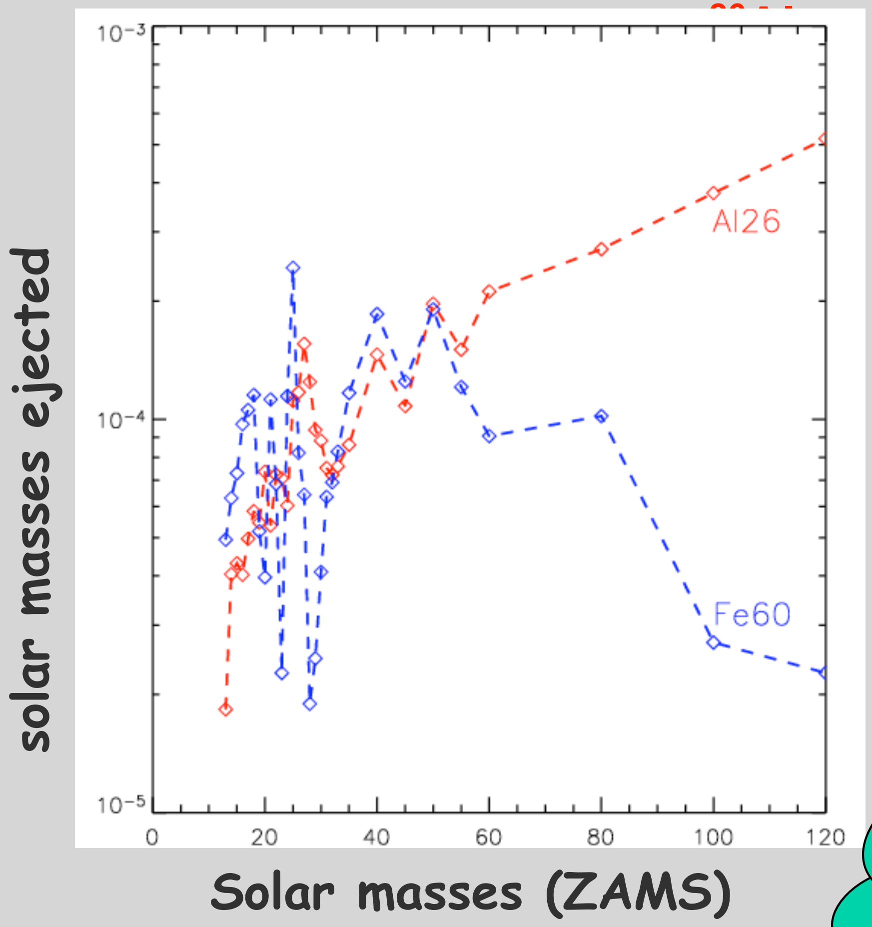


Timmes et al. (1995)

Limongi & Chieffi (2006)

Revised/Updated/New Massive-Star Nucleosynthesis

Woosley & Heger, PRL'07:

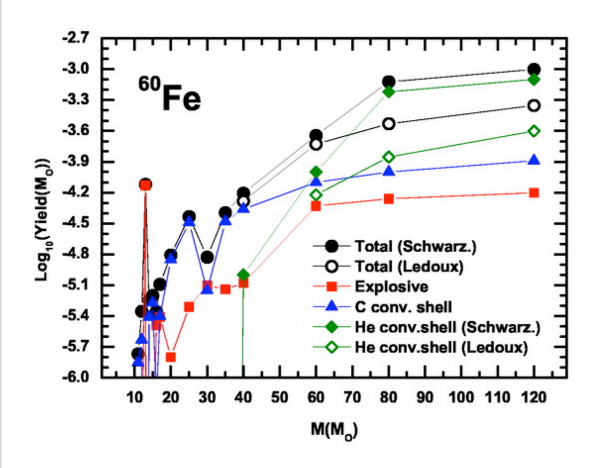


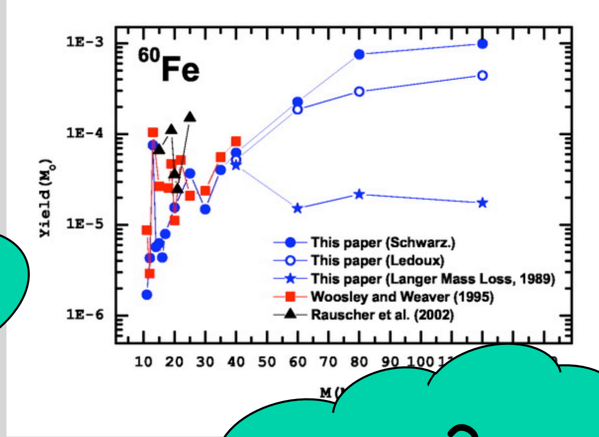
Woosley & Heger 2007:

- ☆ He Core Evolution through SN
- ☆ Including ν Process

Limongi & Chieffi 2006:

- ☆ MS Evolution through SN
- ☆ Test Various Convection & Mixing & Mass Loss Models
- ☆ High-End Masses Very Variable for ^{60}Fe
- ☆ Agree with Gamma-Ray Constraints for Latest Models and M_{upper}=80M





ν process?

Rotation?

IMF, M_{max}?

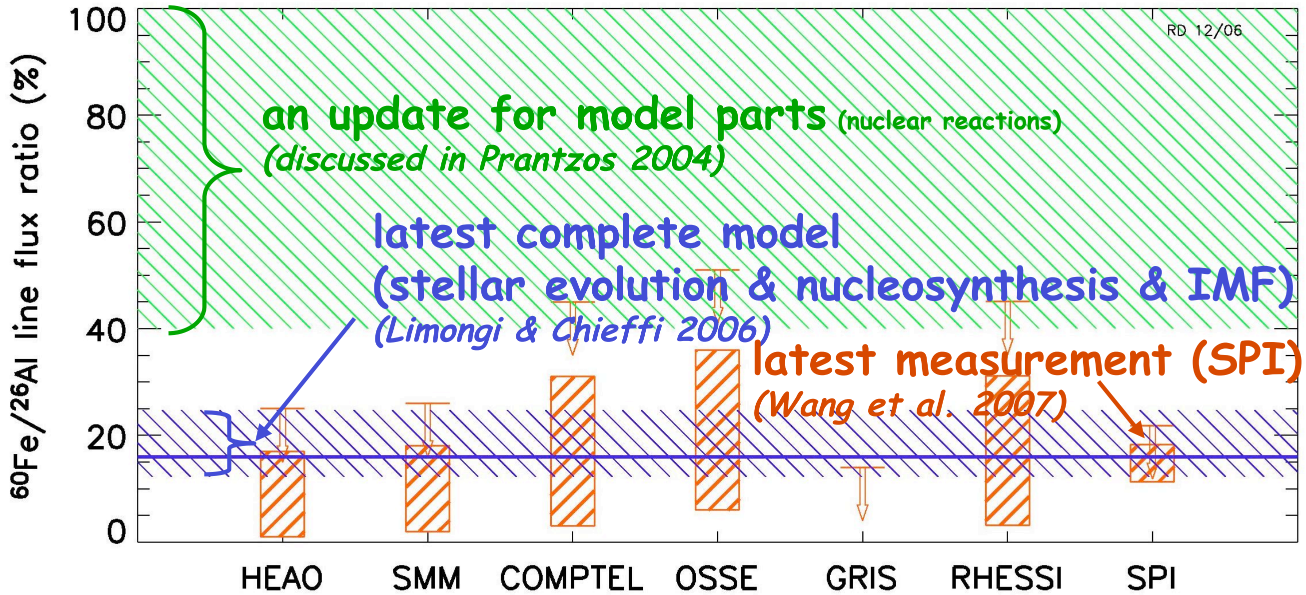
^{60}Fe from Massive Stars: Observations vs. Theory

3.8 10^6y

~~2.0 10^6y~~	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332

☆ How Do Models Agree with Data on ^{60}Fe/^{26}Al γ-Ray Intensity Ratio?

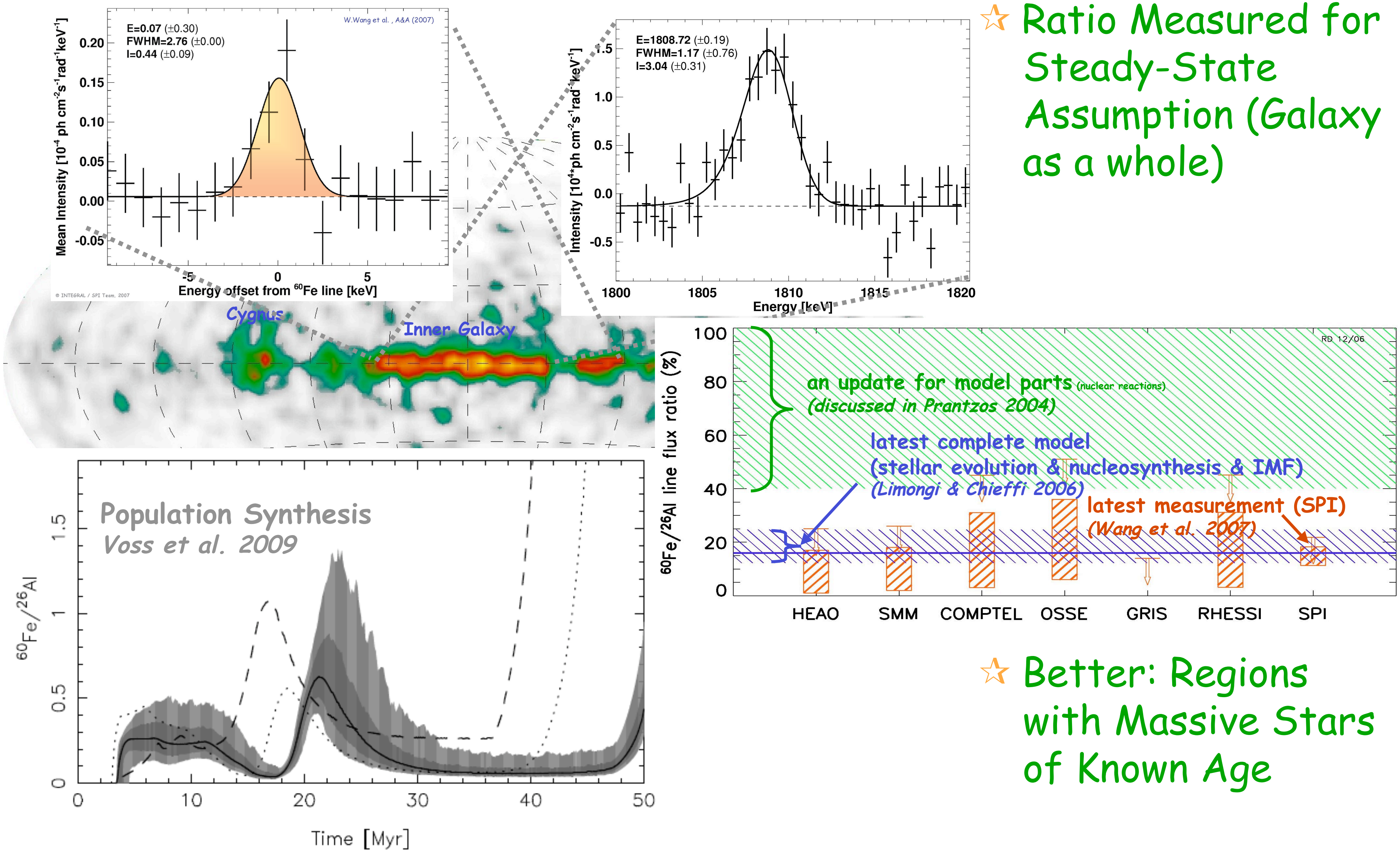
- ☞ Ratio <0.3; Massive Stars?
- ☞ Revised Yields Had Led to Higher Predicted Ratios ~1.0
- ☞ Alternative Stellar Models Agreed with Earliest Ratios



☆ Issues:

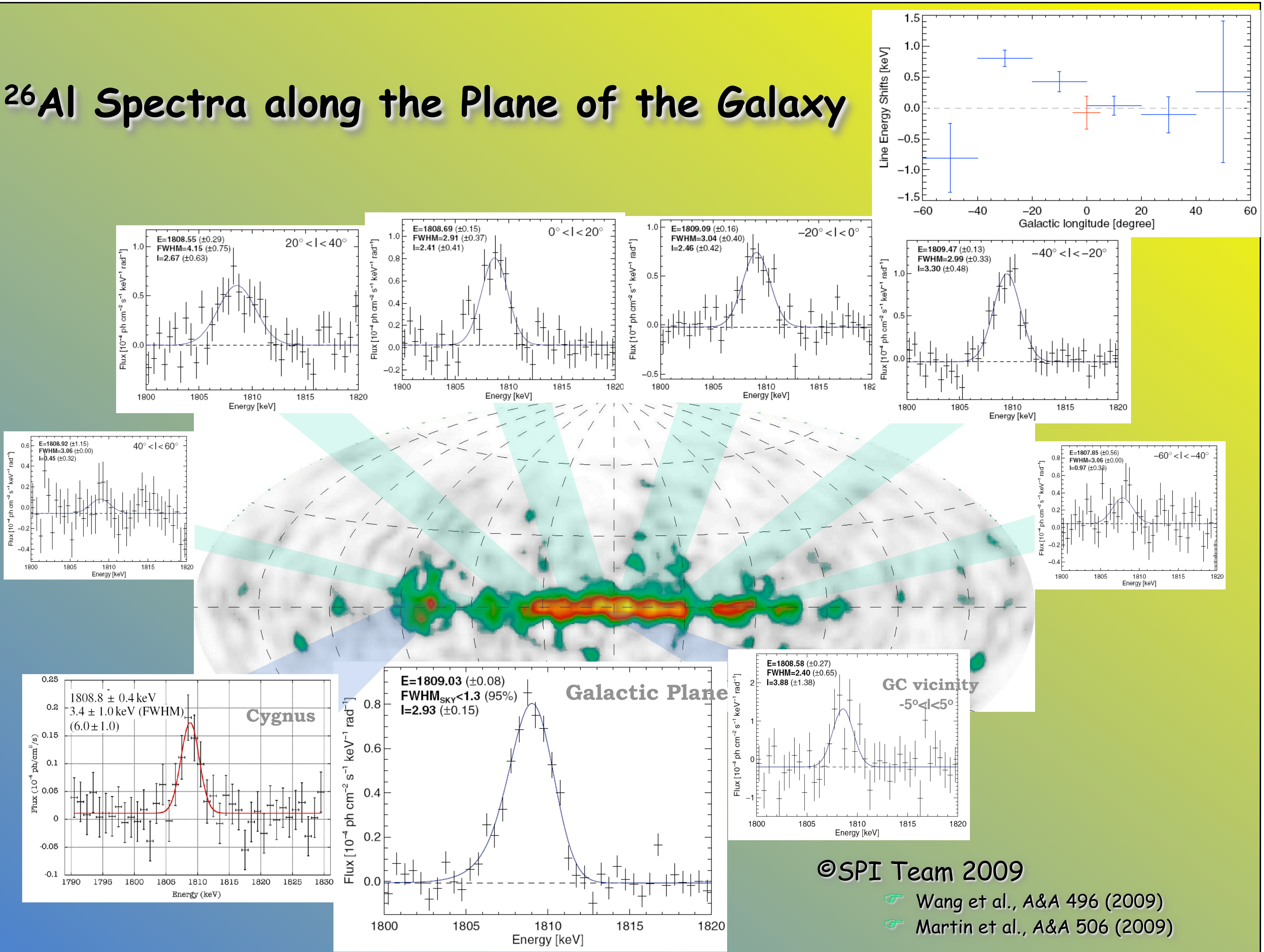
- ☞ Stellar Models
- ☞ Nuclear Physics
- ☞ Gamma-Ray ^{60}Fe Signal (Intensity; Galaxy Regions)

$^{60}Fe/^{26}Al$ Line Ratio Diagnostics



- ☆ Ratio Measured for Steady-State Assumption (Galaxy as a whole)
- ☆ Better: Regions with Massive Stars of Known Age

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

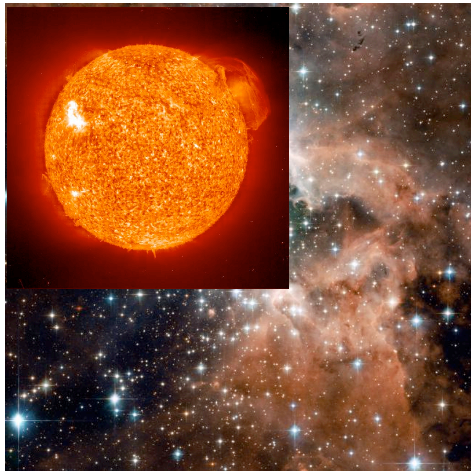


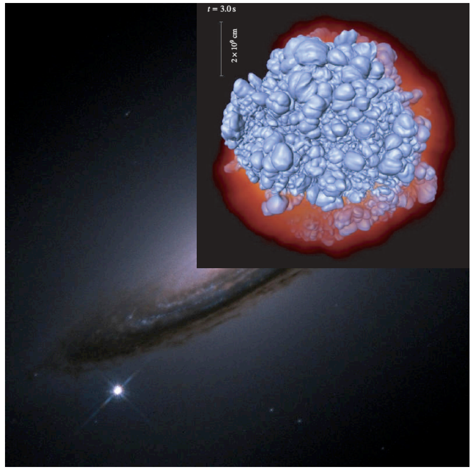
©SPI Team 2009

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

Astrophysics and Nuclear Physics

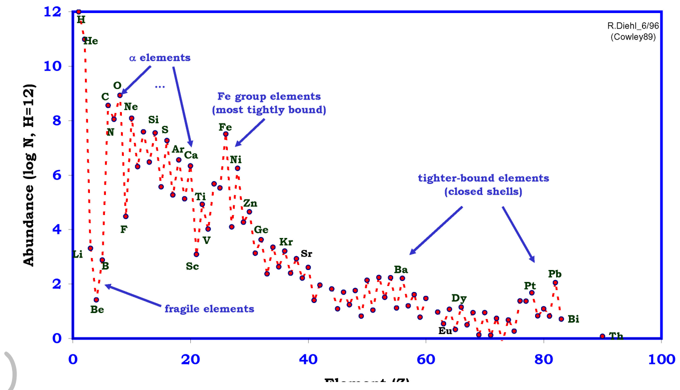
- Nuclear Physics in Cosmic Environments – where is it relevant?



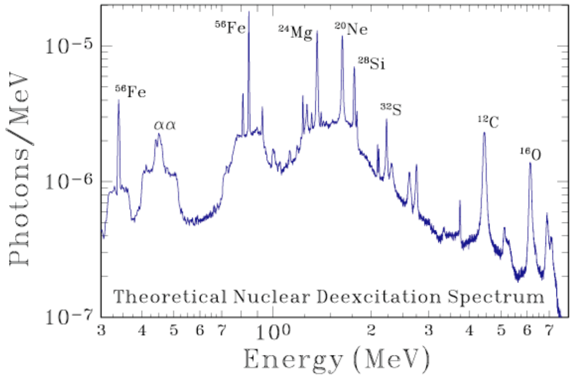


☆ Nuclear Energy Release
  - Structure of Stars
  - Dynamics of Explosions

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



☆ Characteristic Nuclear Radiation
  - Nuclear Excitation (Emission/Absorption Lines)
  - Radioactive Decay



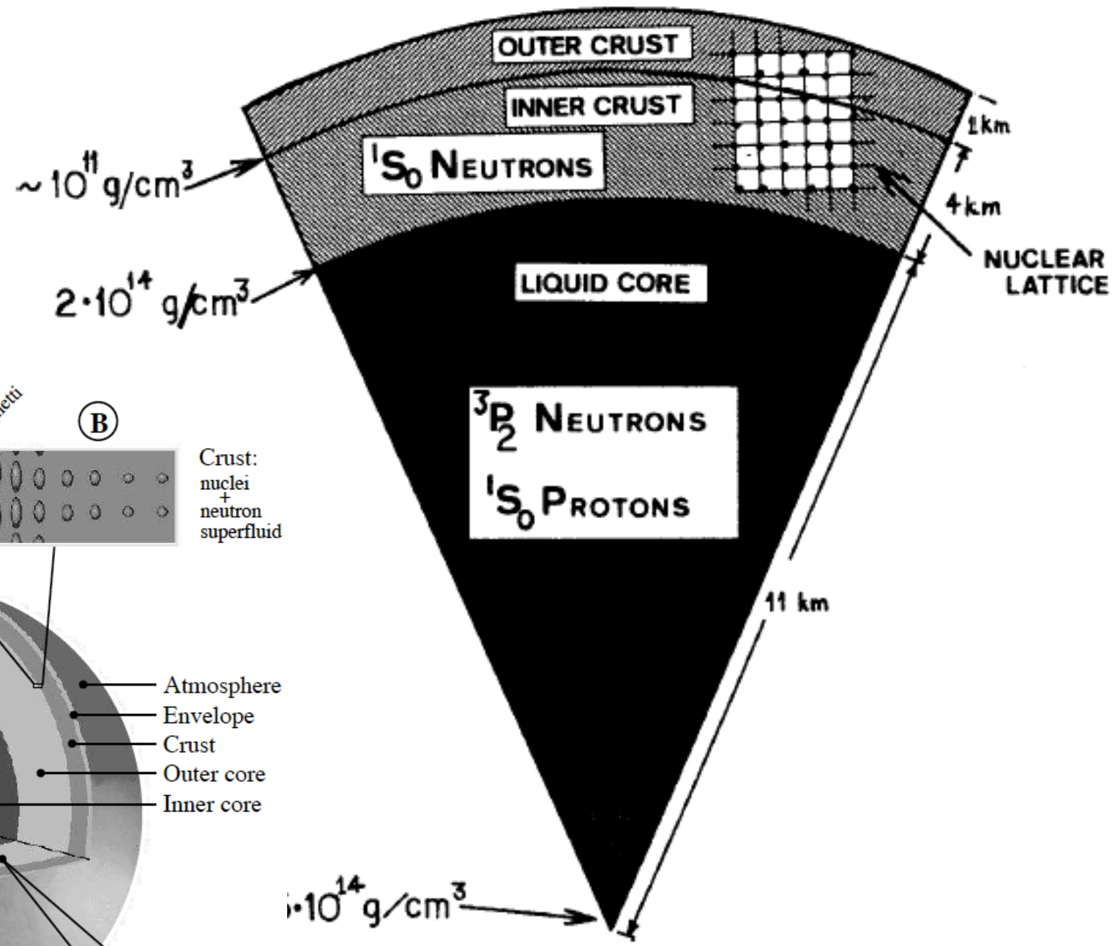
=>

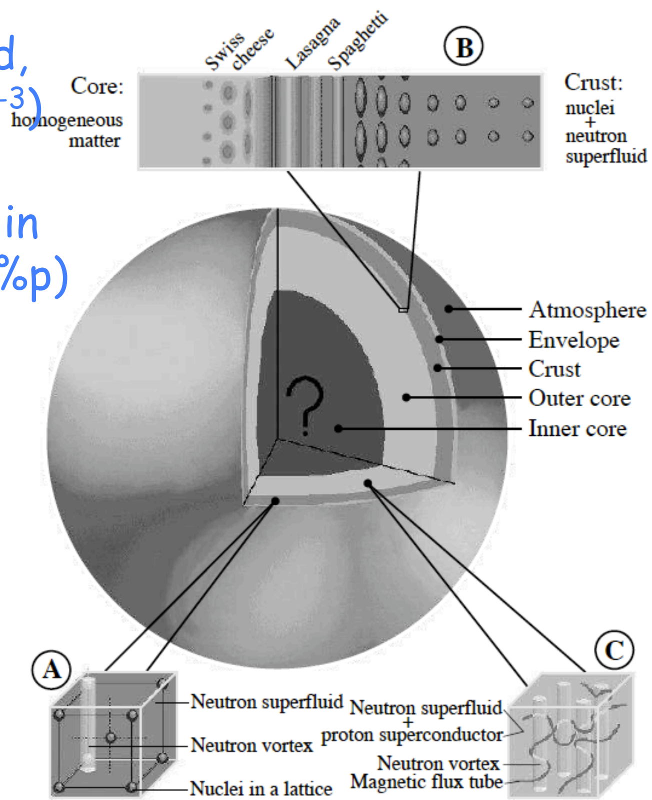
☞ **Nature of Cosmic Sources, Cosmic Processes**

☞ **Search for New Phenomena**

Neutron Stars

- ☆ Birth at T~10 MeV, Rapid Cooling to < MeV -> “cold” nucleons
- ☆ Structural Layers:
  - ☞ Atmosphere (ions, $\rho<10^4$ g cm^{-3})
  - ☞ Outer Crust (Neutronized Nuclei, $\rho<4.3\ 10^{11}$ g cm^{-3})
  - ☞ Inner Crust (Nuclei & n Fluid, $\rho<2.5\ 10^{14}$ g cm^{-3})
  - ☞ Core (nucleonic fluid in β equilibrium, 5%p)





Neutron Stars and Properties of Nuclear Matter

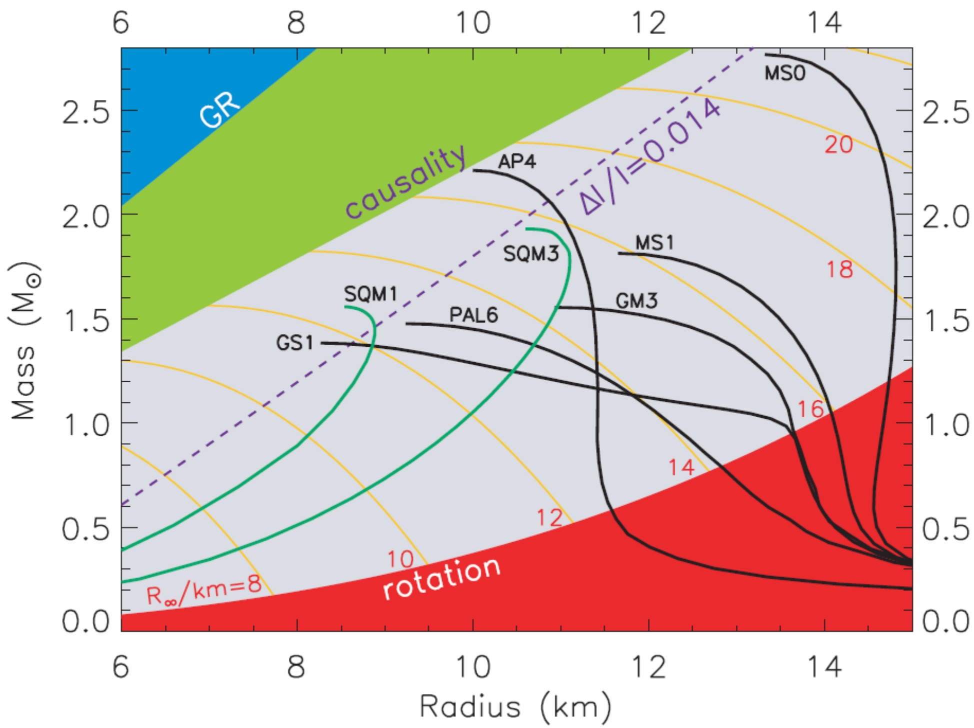
- Key Issue:

  How Densely-Packed are Nucleons inside Neutron Stars?

  ☞ Sizes of NS (M-R)

  ☞ Thermal Properties (Cooling)

  ☞ Moments of Inertia (Spin, Glitches, Braking, QPOs)



 Roland Diehl

Neutron Star Observables

- Magnetospheric Emission
  - ☆ Non-thermal; magnetosphere as particle accelerator
- Thermal Emission
  - ☆ Radiative Cooling, T~X-rays
  - ☆ Heating from Internal Energy
  - ☆ Heating from Matter Accretion
  - ☆ Heating from Nuclear Burning
- Temporal Modulations
  - ☆ NS Spin
  - ☆ Accretion Flow Irregularities
  - ☆ Nuclear Ignition
  - ☆ Structural Rearrangements
  - ☆ Relativistic Distortions

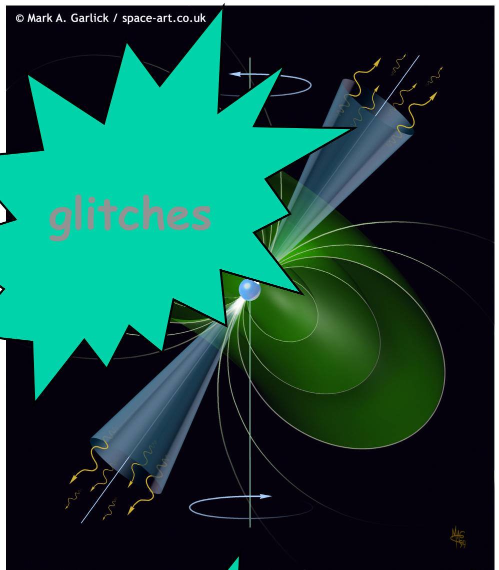
NS Interior / EoS

NS Crust

Faces of Observable Neutron Stars

see Lecture by Jörn Wilms

- Radio/HE Pulsars

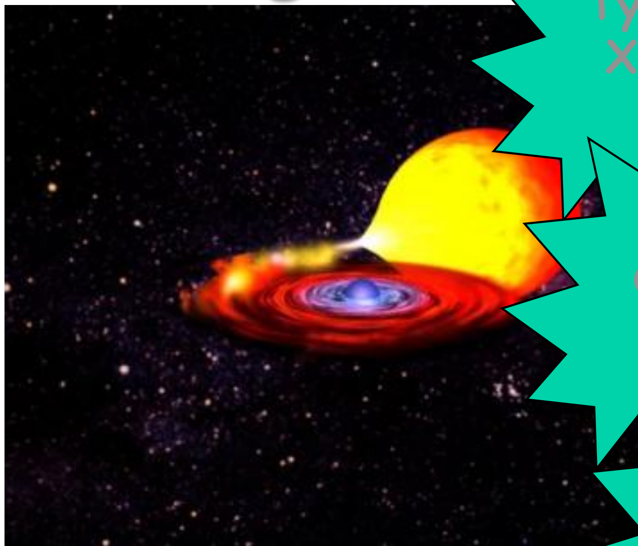


glitches

AXPs

SGRs

- Accreting NS



Type I XRBs

States, Jets, B(e) Systems...

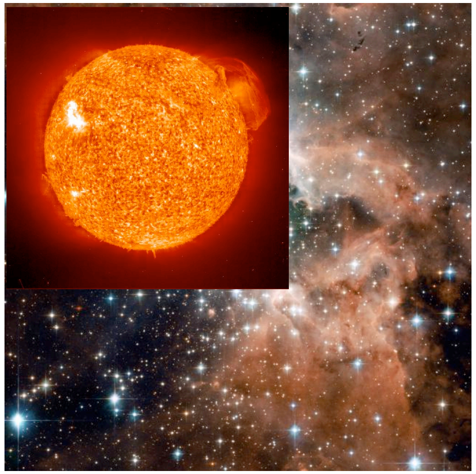
QPOs

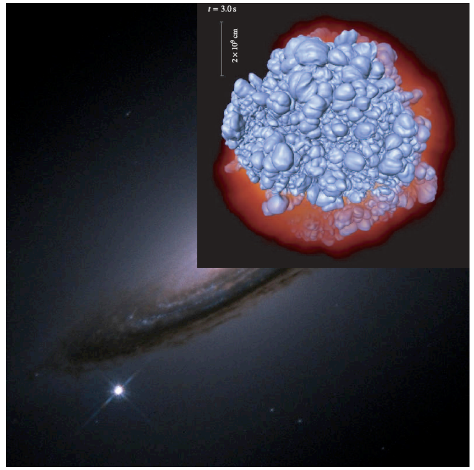
ms Pulsars

- Cooling NS

Astrophysics and Nuclear Physics

- Nuclear Physics in Cosmic Environments – where is it relevant?





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  - Structure of Stars
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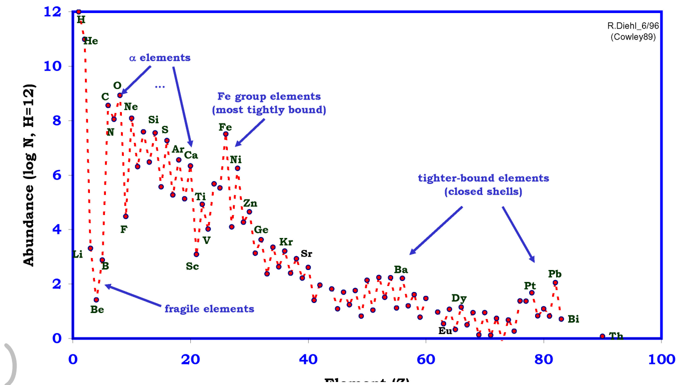

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=>

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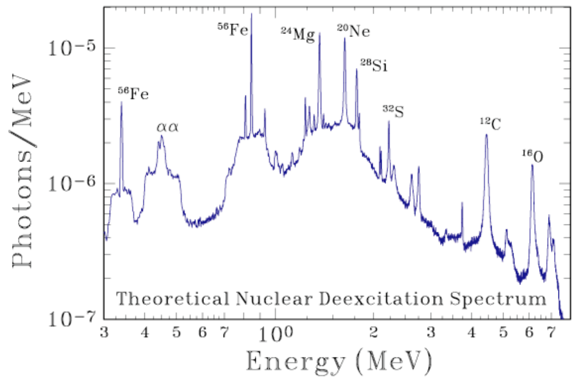
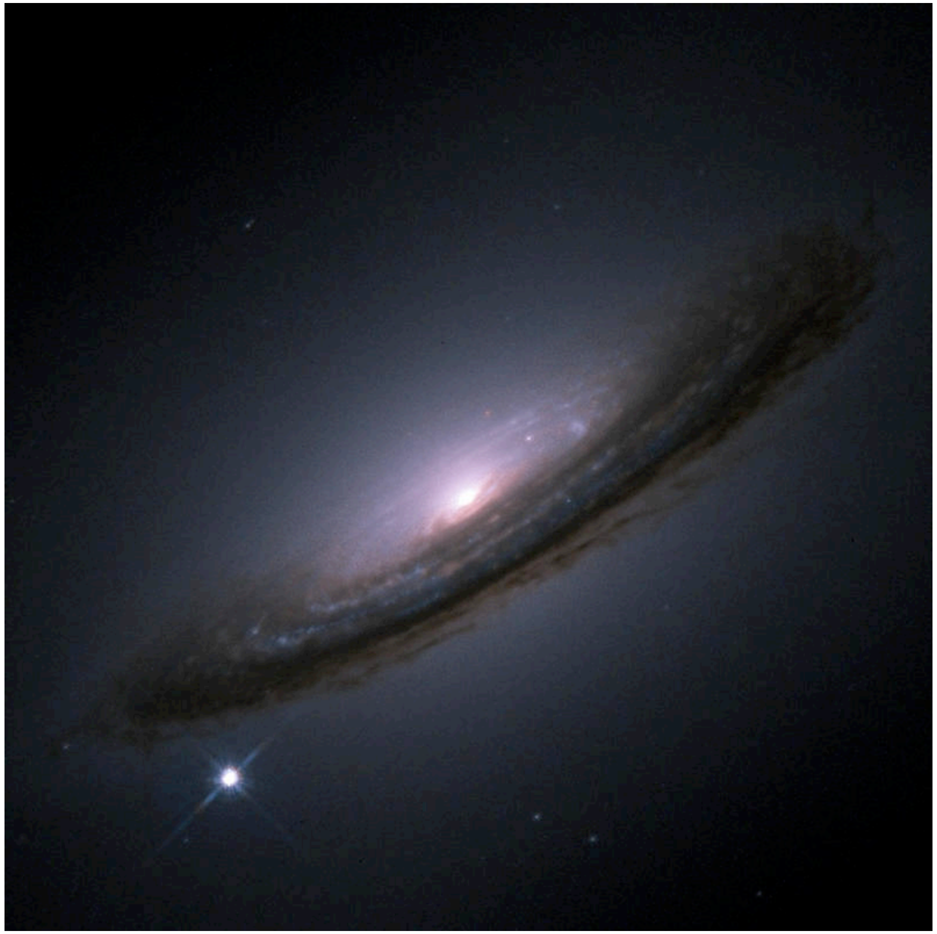
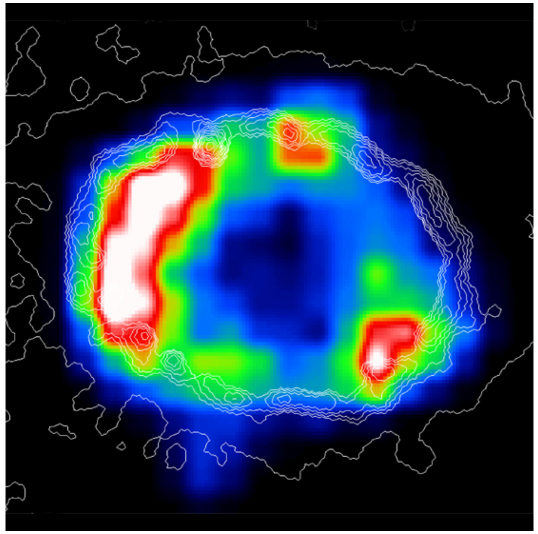
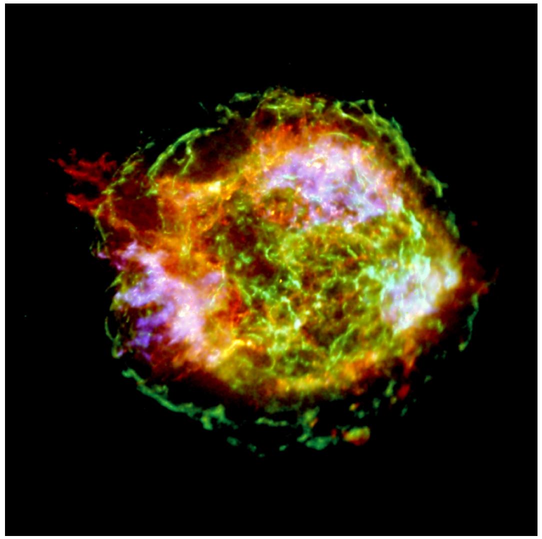


Roland Diehl

Latest Stage of Stellar Evolution: Supernovae

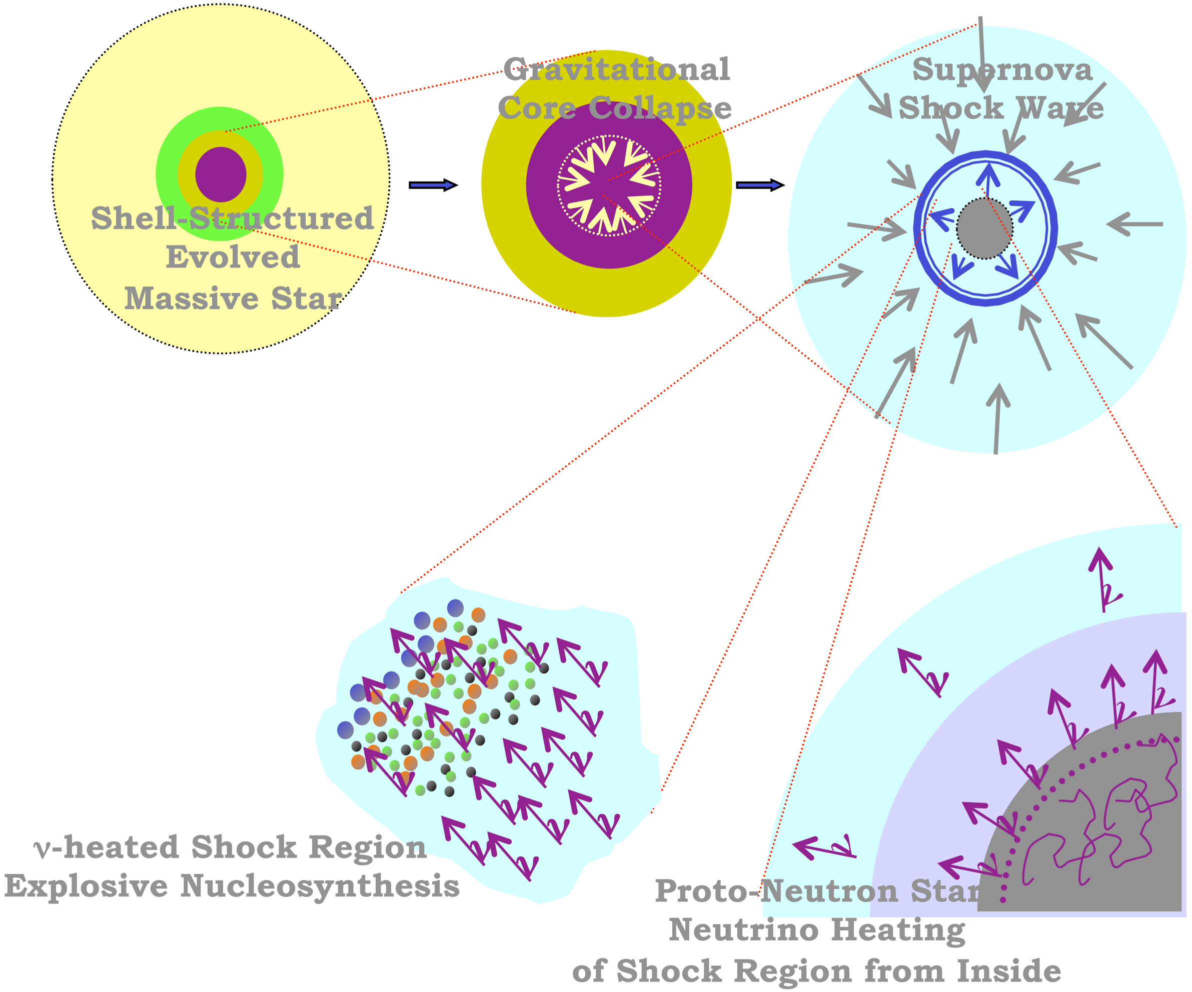






- ☆ Nuclear Fuel Exhausted
- ☆ Gravitation Leads to 'Extreme' Stars
- ☆ The "Remains" are Spread

Core Collapse-Supernovae: The Model

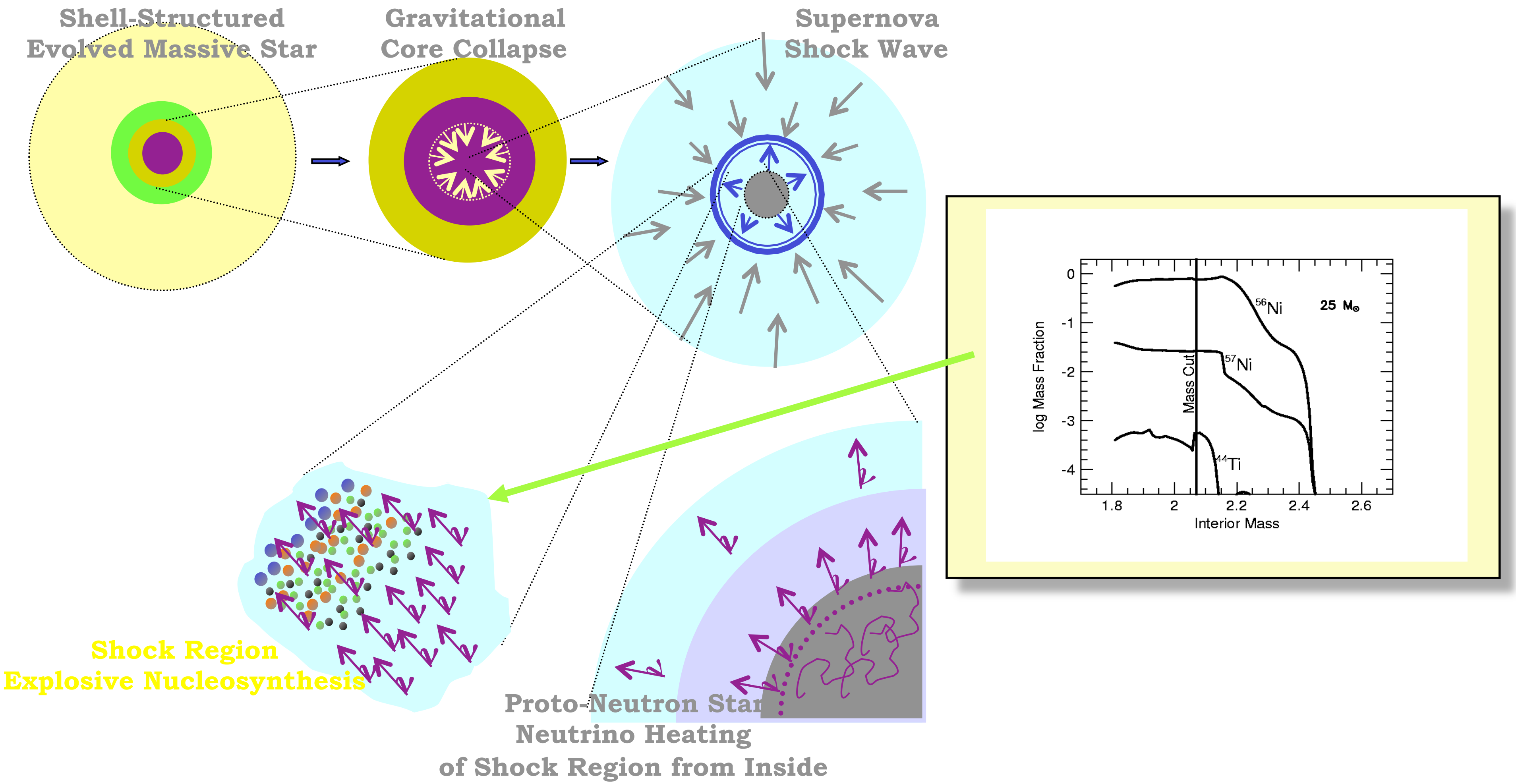


Empirical / Parametrized Models for Explosion (Explosion Energy, Mass Cut)

Nuclear Physics:
- ν Luminosities
  - PNS EoS, Pasta Phases
- Nucleosynthesis
  - Shock Region
  - Explosive

- Explosion Mechanism = Competition Between Infall and Neutrino Heating
- 3D-Effects Important for Energy Budget AND Nucleosynthesis

Nucleosynthesis in CC-Supernova Models

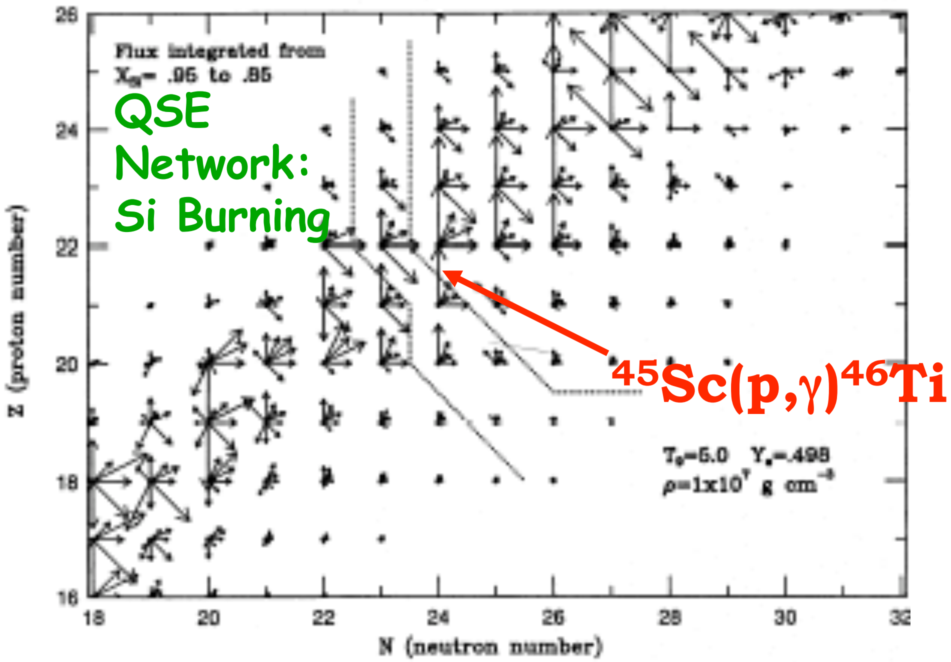


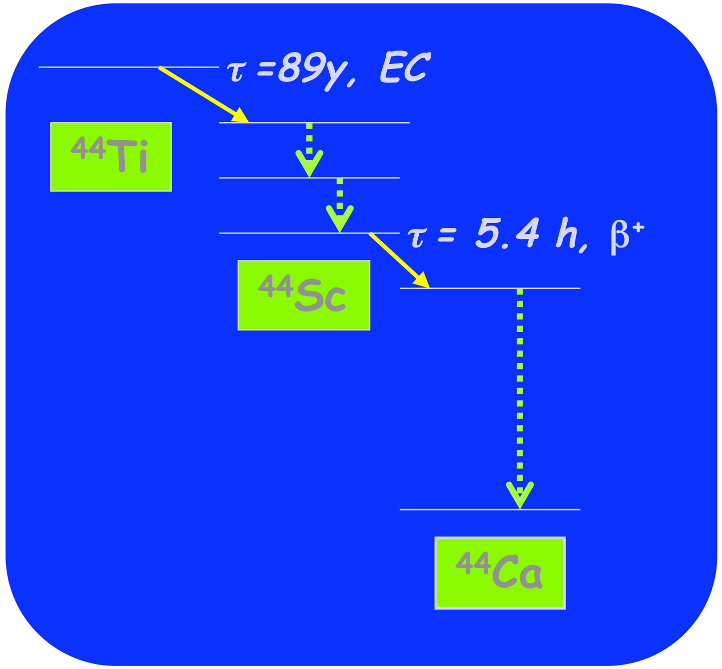
- 3D-Effects Important for Energy Budget AND Nucleosynthesis
- Location of Ejecta/Remnant Separation
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out, => Unique Probe (+Ni Isotopes)

Roland Diehl

Core-Collapse SN Nuclear Reactions -> ^{44}Ti

- Why are ^{44}Ti Gamma-Rays Interesting?



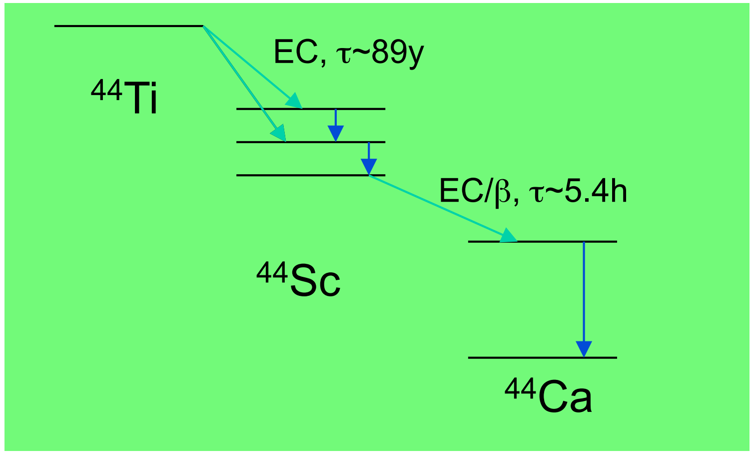


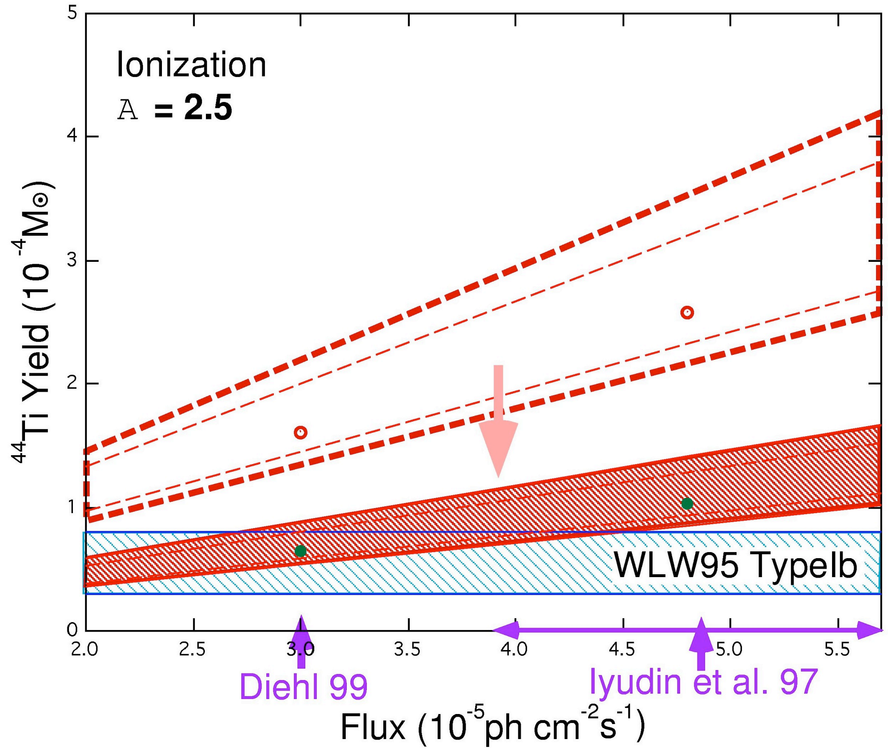
☆Complex Nuclear-Reaction Dynamics

☞ A Specific Isotopic Abundance as "Calibration Point"

^{44}Ti Decay in a Young SNR

- ☆ ^{44}Ti Decay: e Capture -> Ionization!?!
  - $E_{ion,K}$=6.6 keV, $E_{ion,L}$=1.6 keV
- ☆ SN Composition Profile: Fe & Ti Similar
- ☆ Fe/Ti Clump Ionization by Reverse Shock
- ☆ ^{44}Ti Decay Rate Modifications:
  - ☞Inhibit Early, -> Enhance Later (wrt ^{44}Ti Mass / Exponential Decay)
    - ~0.5 @ Days 50...200
    - ~1.5-2.5 @ Days 250...400
- ☆ Cas A ^{44}Ti Mass ~ as Predicted by Theory?

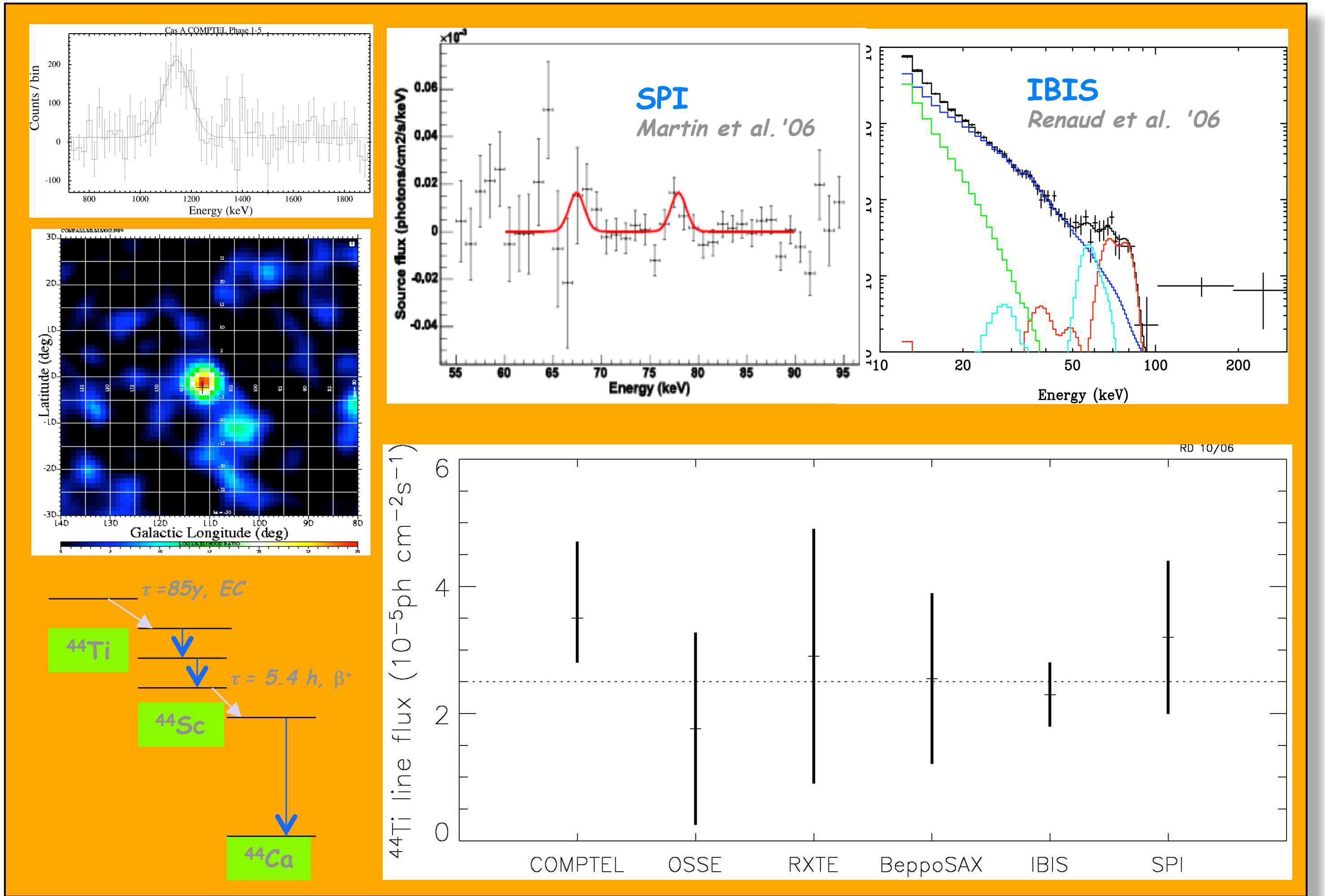


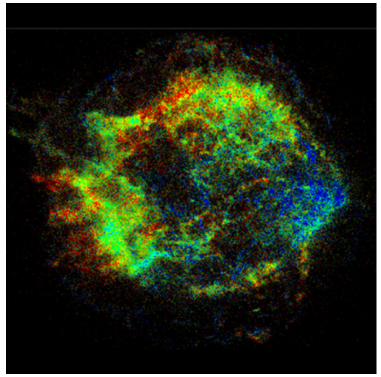


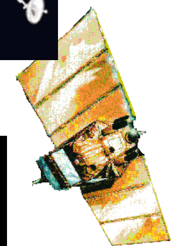
^{44}Ti γ-rays from Cas A

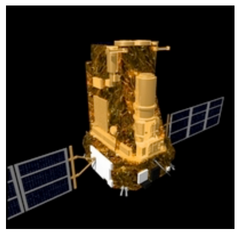
τ=85y (Ahmad et al. 2006)

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





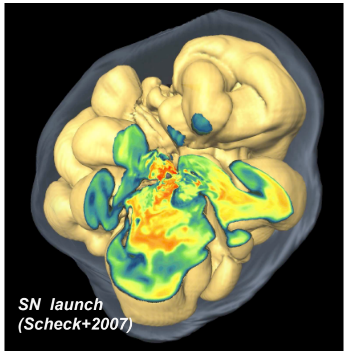


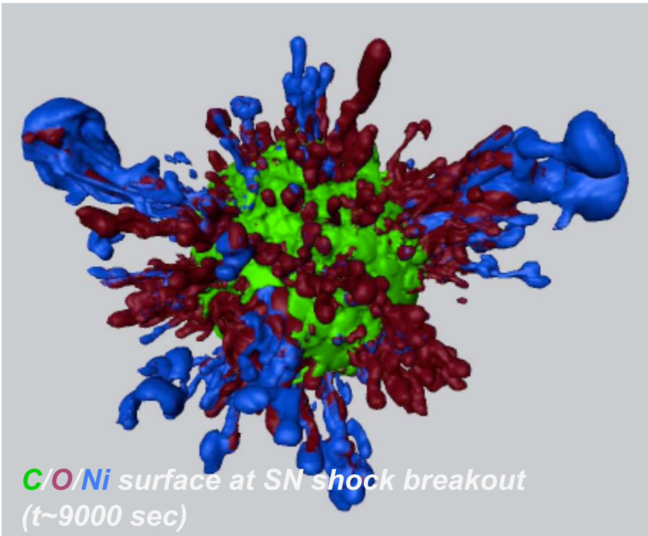


^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} $M_{\odot}$

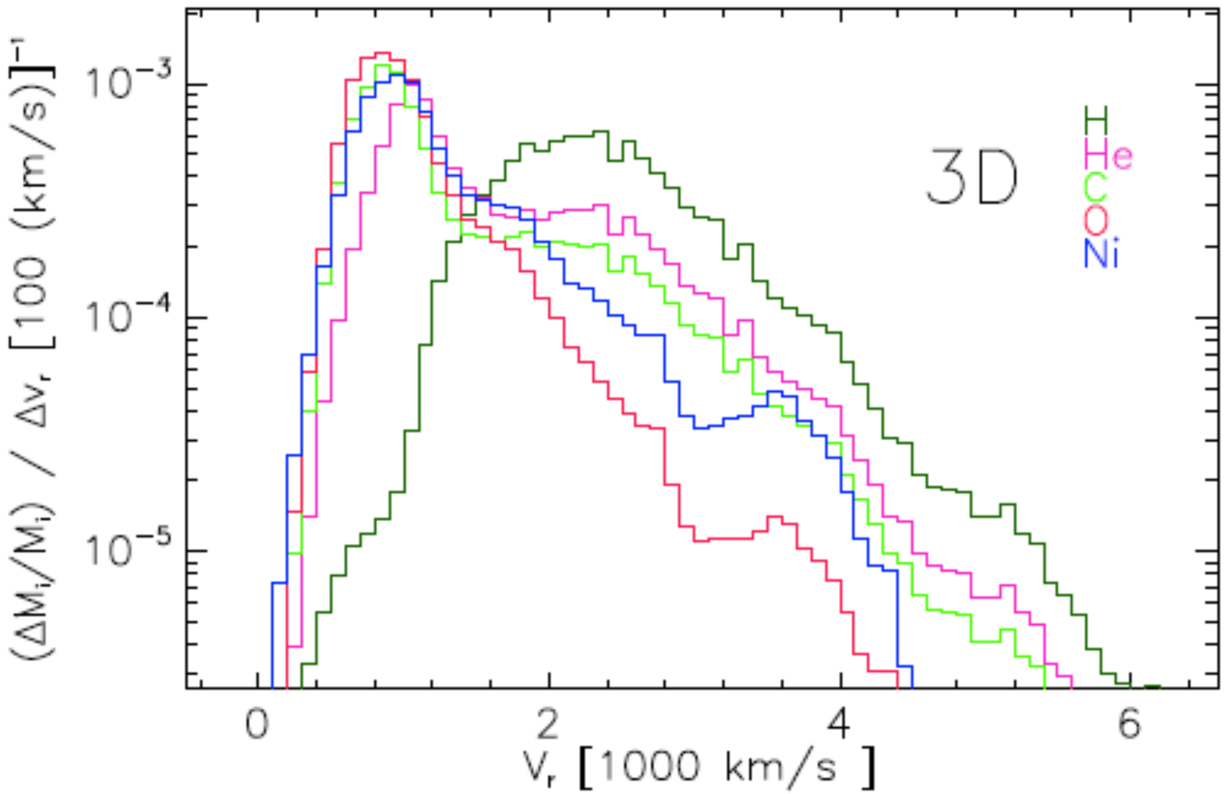
Velocity Distributions of Inner cc-SN Ejecta

- ✩ Inner Explosions' Convection Seeds Rayleigh-Taylor Instabilities at Interfaces to O and He Shells
  - ☞ Macrosopic Matter Clumps in Ejecta at a Range of Velocities
  - ☞ Steep He/H Shell Transition Homogenizes this in case of SNII





Hammer, Janka, & Müller (2010)



^{44}Ti Ejecta Velocities

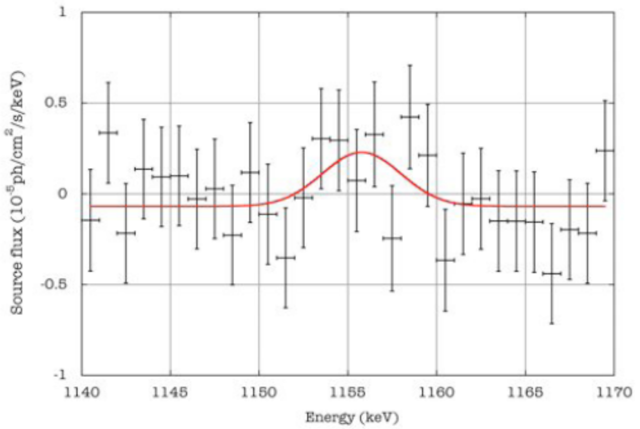


Fig. 4. Cassiopeia A spectrum at 1157.0 keV combining SE and ME2; red solid curve is the fit of a Gaussian shape.

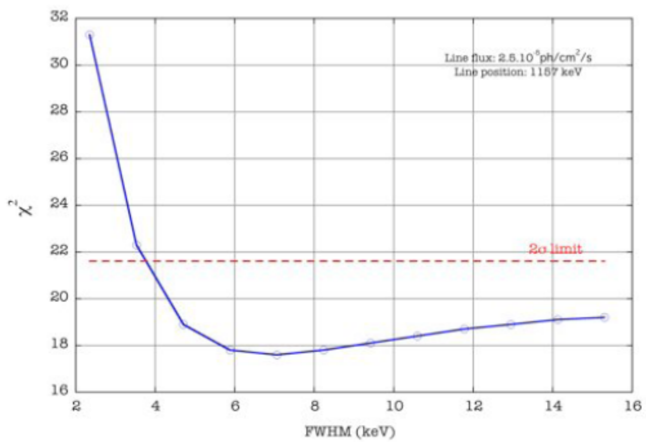
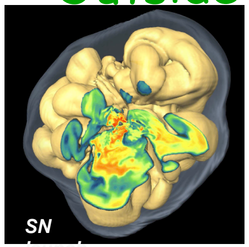
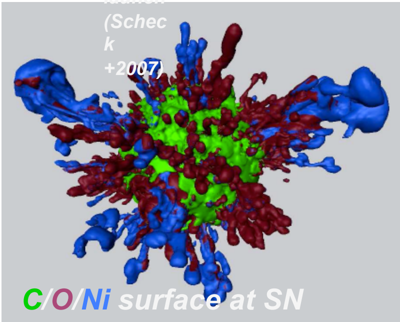
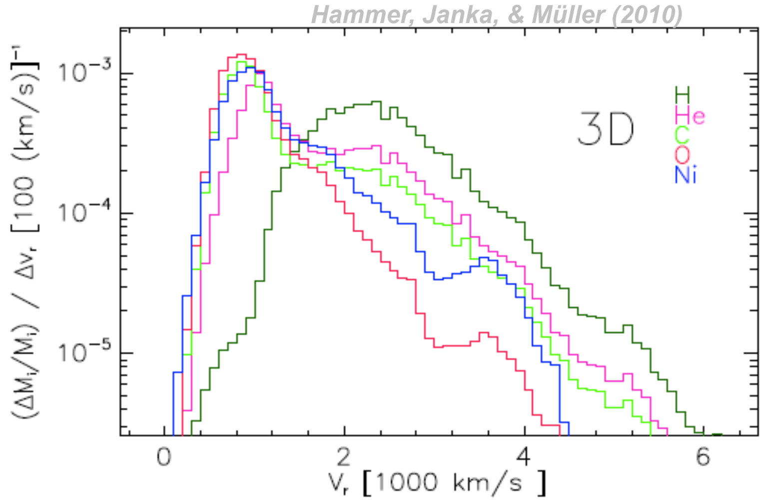


Fig. 5. χ^2-curve for the total line width (including intrinsic and instrumental broadening), assuming a line flux of 2.5×10^{-5} ph cm^{-2} s^{-1} and no position shift.

- ☆ High-Energy Line Not Seen with SPI
  - ☞ Broadened, so 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



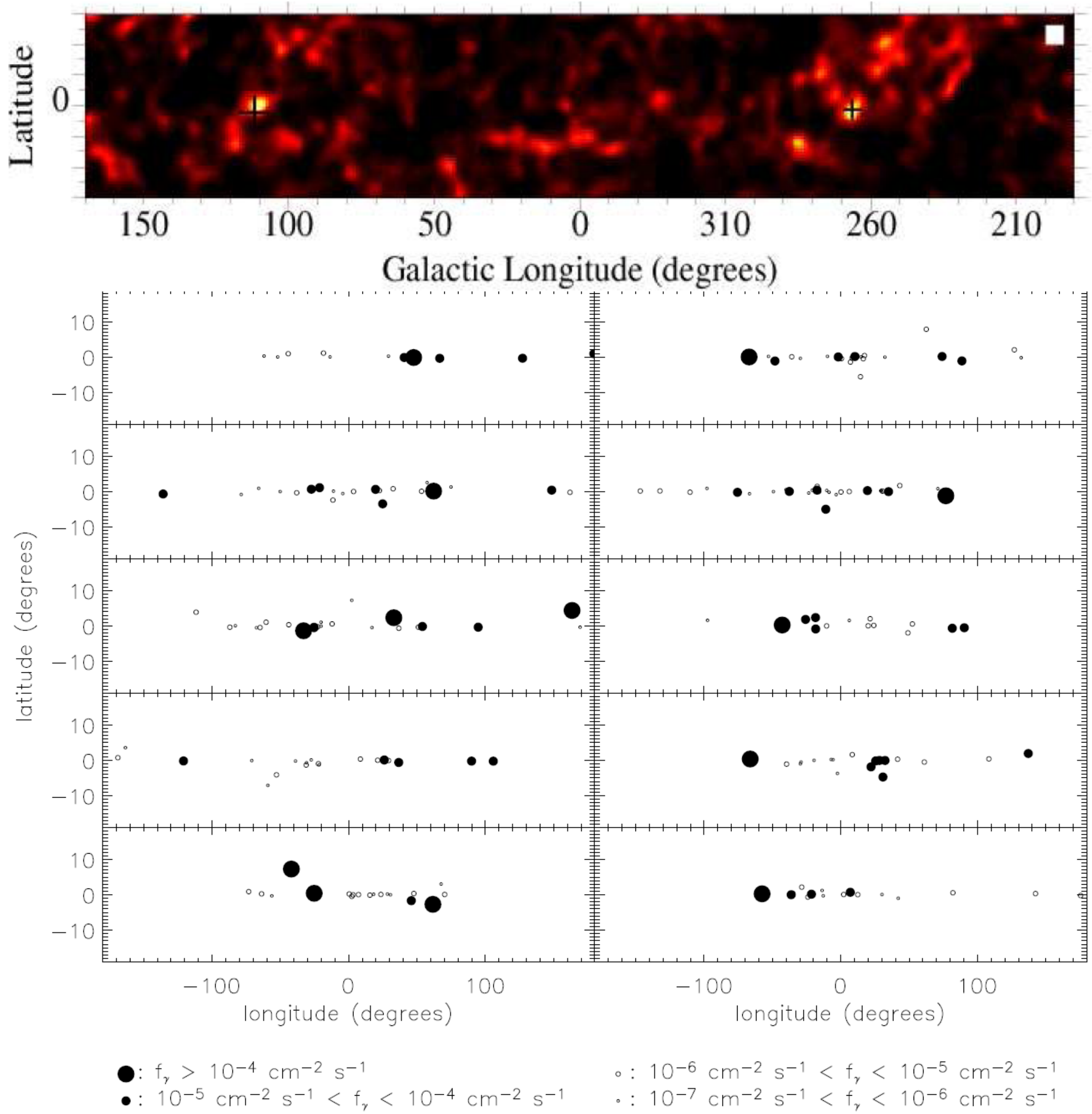




- ☆ NuStar Mission 2011+: X-ray Imaging

The Sky in ^{44}Ti Gamma-Rays

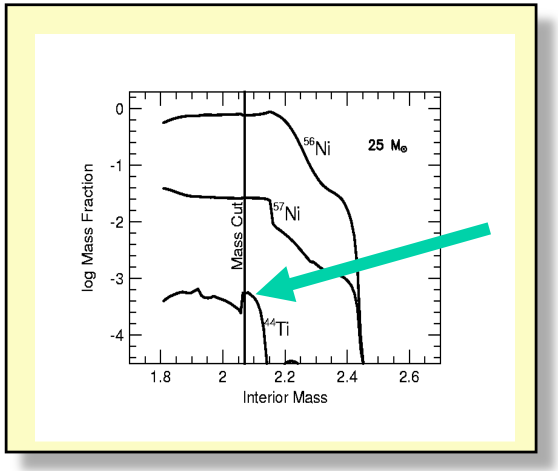
The et al. 2006

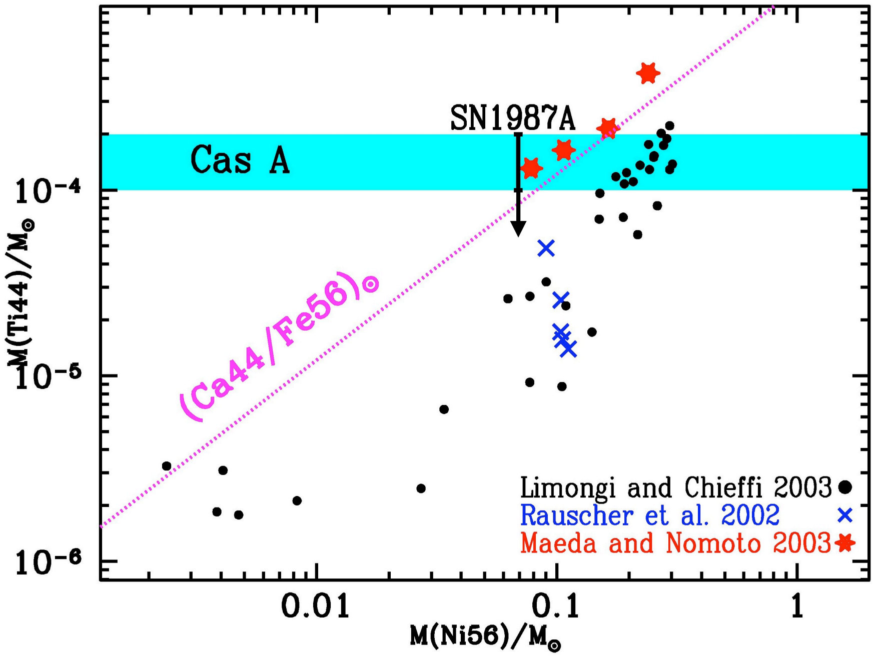


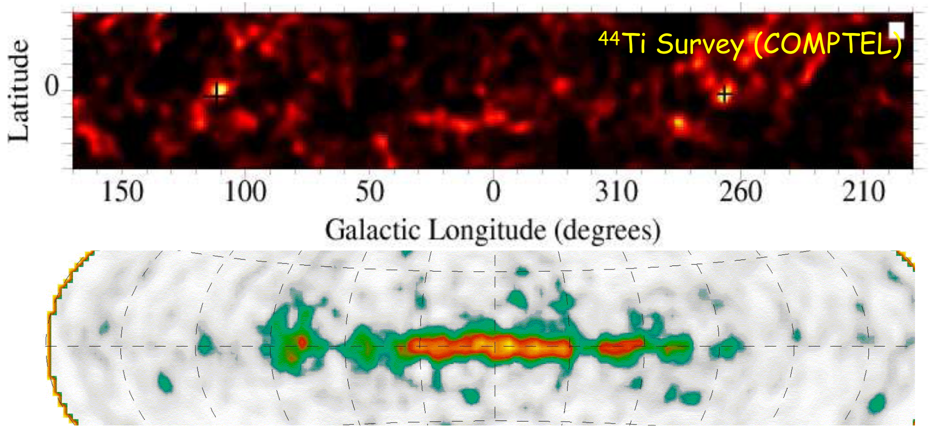
- We do NOT see the Number of Expected Young SNRs
  - ☆ Assumptions
    - ☞ Galactic SNR Spatial Distribution from Massive Stars
    - ☞ cc-SN Frequency 1/30y
    - ☞ SN Yields in ^{44}Ti Must Explain Standard Abundance of ^{44}Ca (= 3* Model Yields)
  - ☆ Expectations
    - ☞ More than a few Sources
    - ☞ P(0)=0.0017, P(1)=0.012
- ^{44}Ti is NOT from Common cc-SNe
    - ☞ 3D Effects?
    - ☞ Exceptional SNIa?

"Normal" Core Collapse Supernovae (?)

- Consistency Check: Cas A vs. what we know about ^{44}Ti...
  - ^{44}Ti from SAD/Models/SN1987A/γ-Rays, vs. ^{56}Ni
  - Only Non-Spherical Models Reproduce Observed Ratios
  - Sky Regions with Most Massive Stars are ^{44}Ti Source-Free (COMPTEL, INTEGRAL)





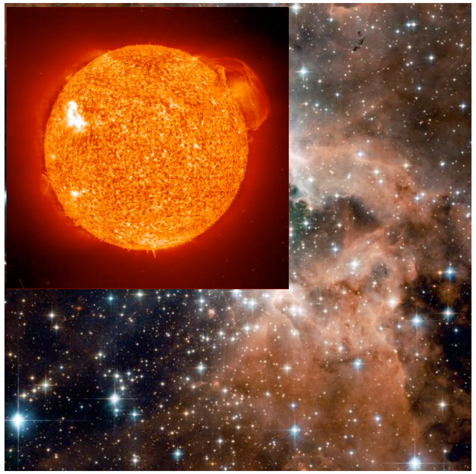


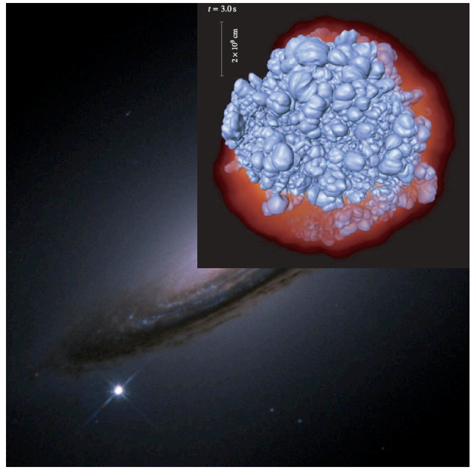
Non-spherical explosions?? (->GRB)

Need Event Statistics, ^{44}Ti Spectra

Astrophysics and Nuclear Physics

- Nuclear Physics in Cosmic Environments – where is it relevant?





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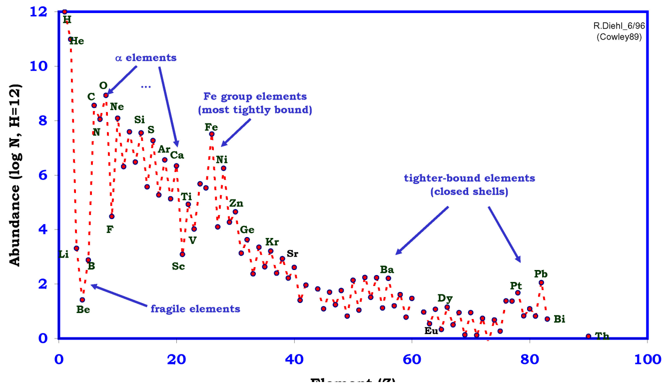

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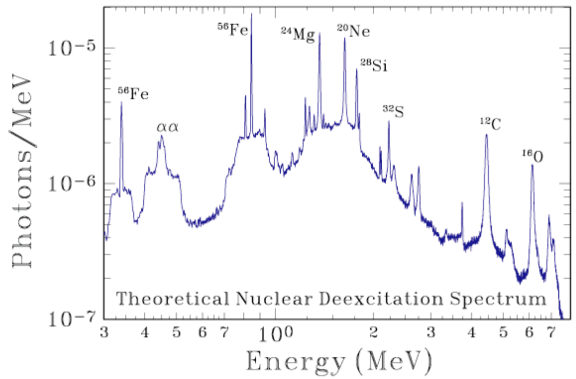
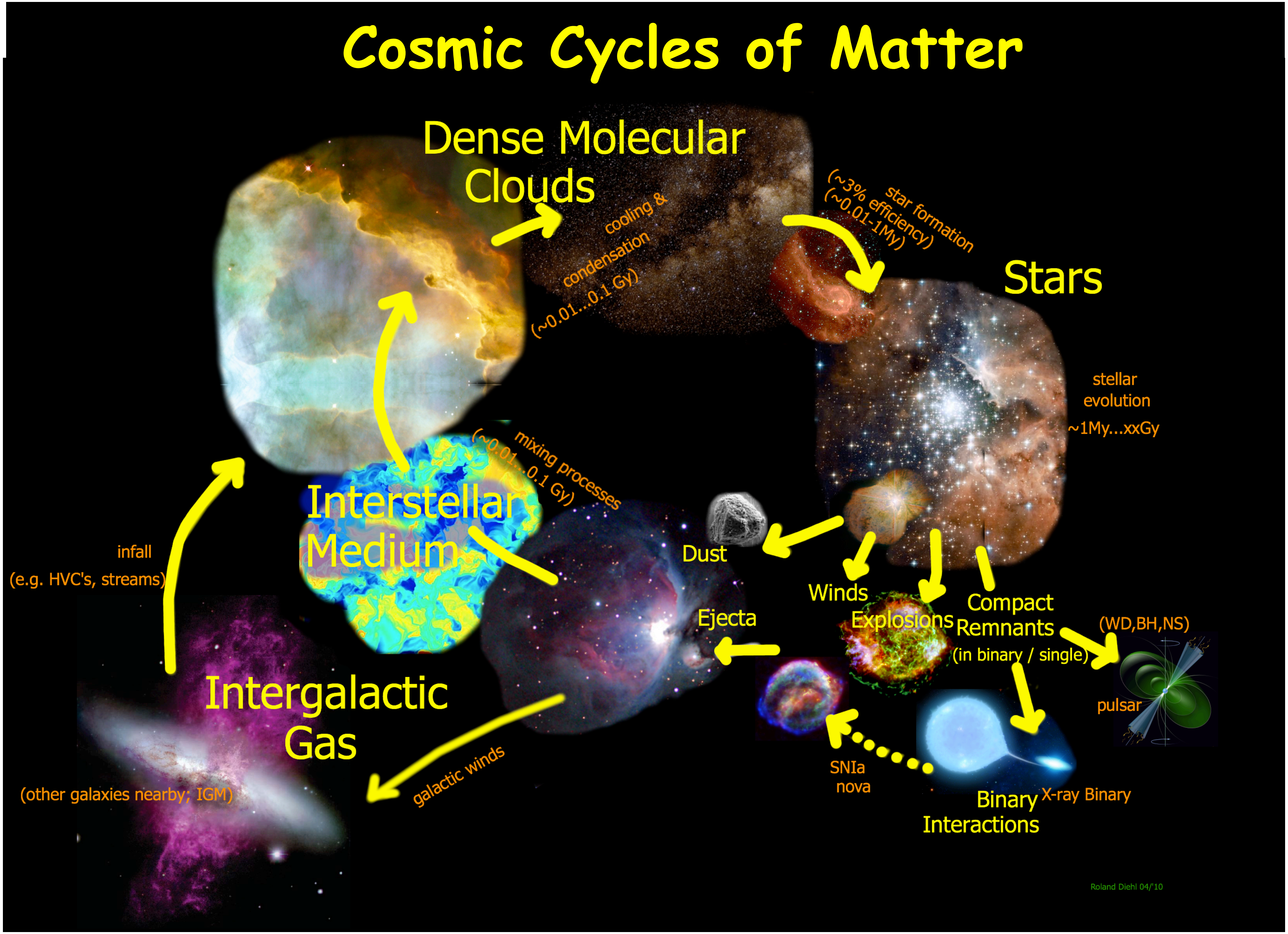
☞Nature of Cosmic Sources, Cosmic Processes

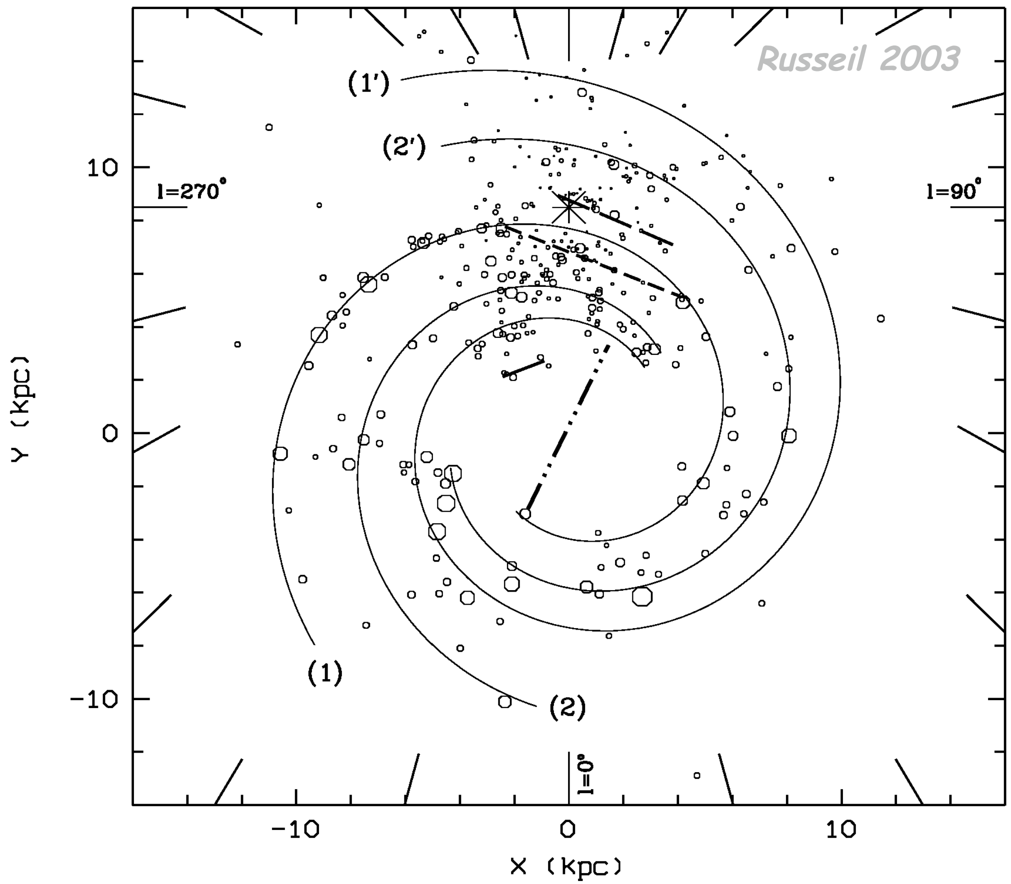
☞Search for New Phenomena

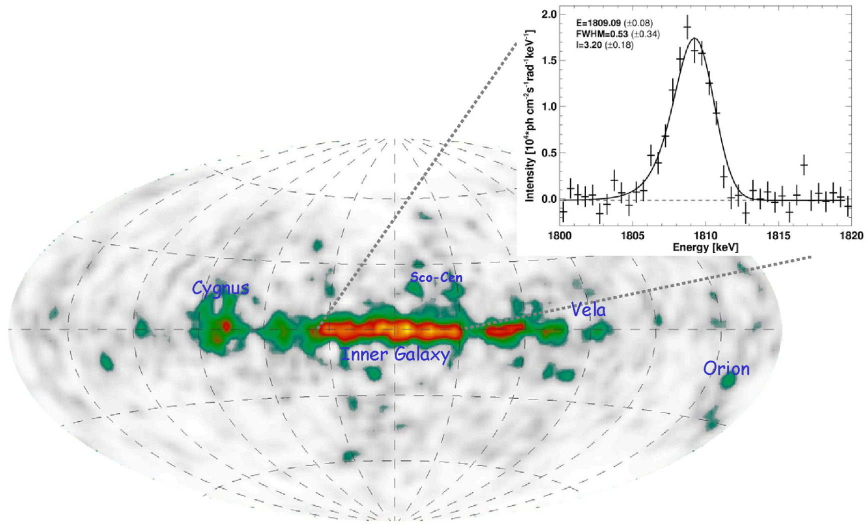


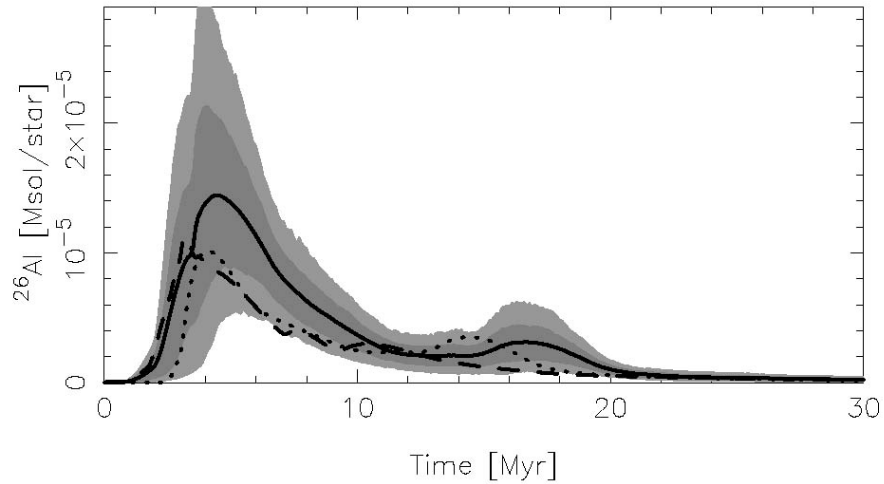

Cosmic Cycles of Matter
Dense Molecular Clouds
cooling & condensation (~0.01...0.1 Gy)
(~3% efficiency) star formation (~0.01-1My)
Stars
stellar evolution ~1My...xxGy
Interstellar Medium
mixing processes (~0.01...0.1 Gy)
Dust
Winds
Ejecta
Explosions
Compact Remnants (in binary / single)
(WD,BH,NS)
pulsar
SNIa nova
Binary Interactions
X-ray Binary
infall (e.g. HVC's, streams)
Intergalactic Gas
(other galaxies nearby; IGM)
galactic winds
Roland Diehl 04/'10

Current Galactic Nucleosynthesis

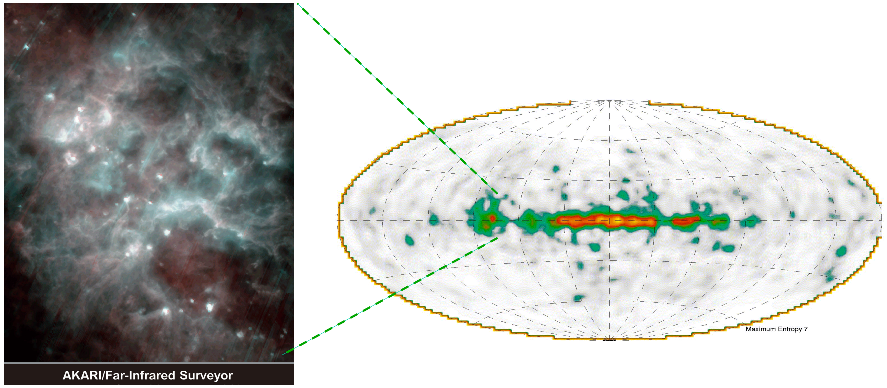
- ^{26}Al gamma-rays probe the entire Galaxy
  - Is a steady-state view appropriate?





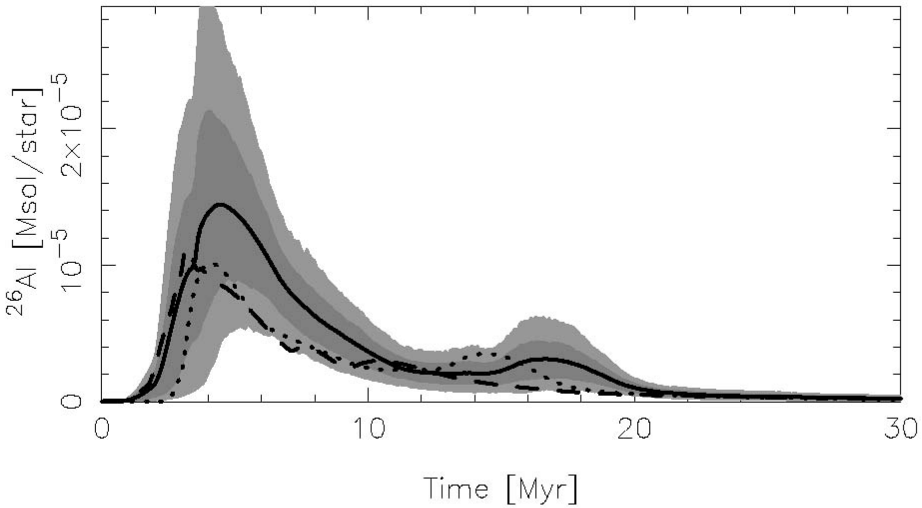


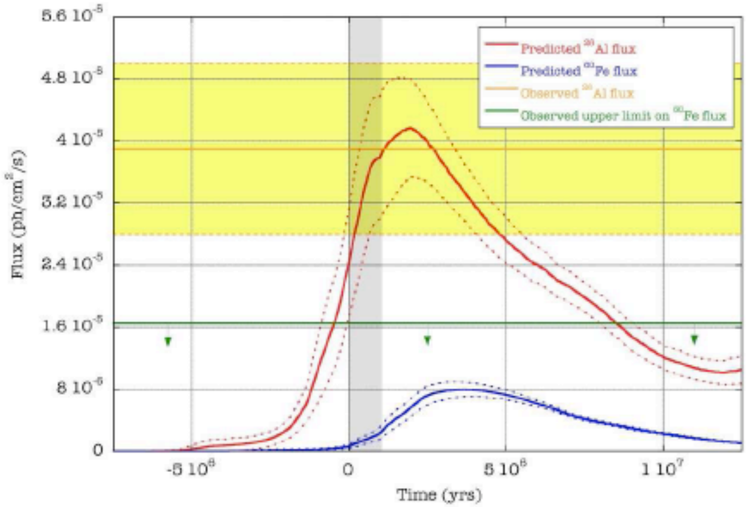
Evolving Abundances of Massive-Star Groups: Cygnus

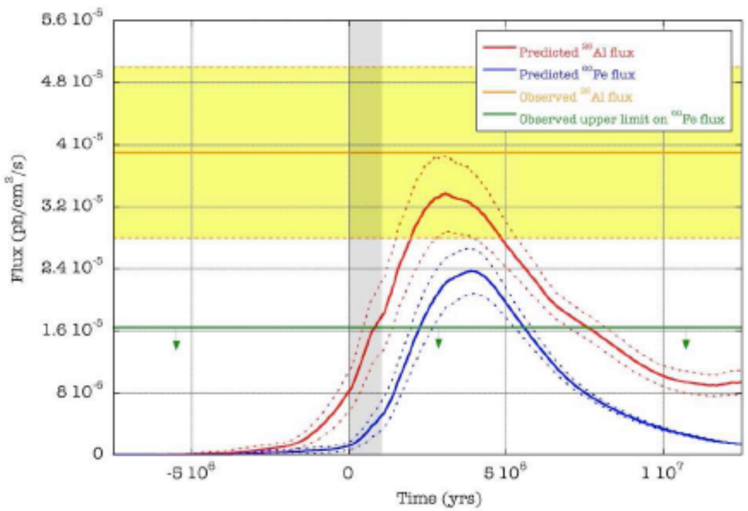


☆ Population Synthesis:
Application to Cygnus Region

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

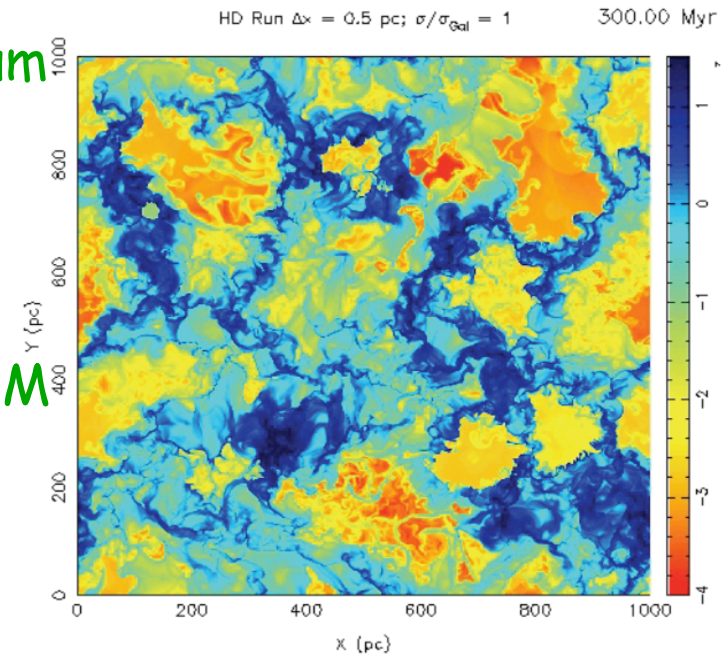


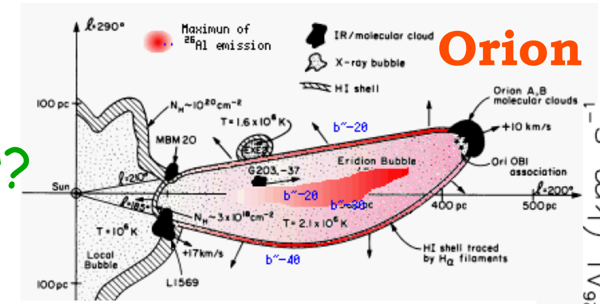


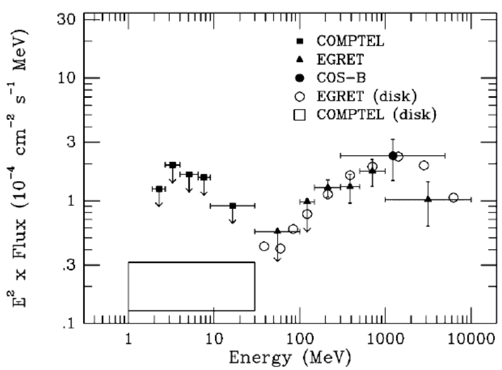


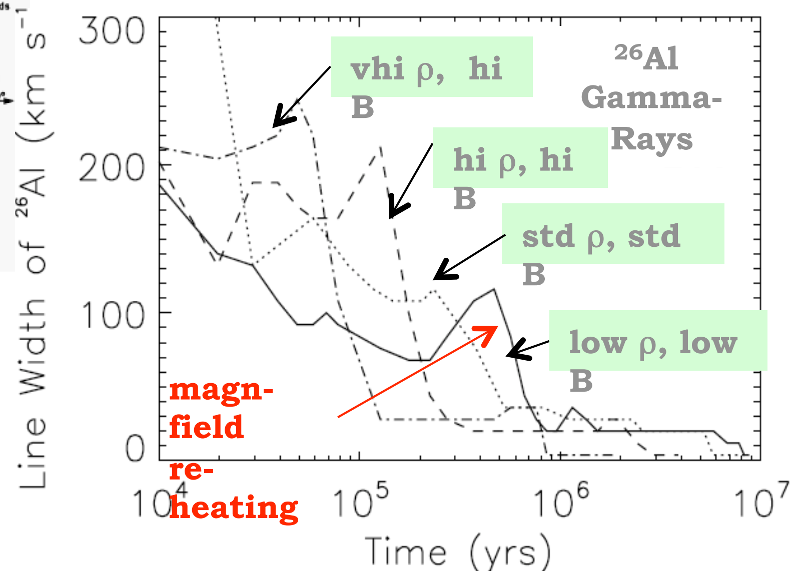
The Complex Interstellar Medium

- ☆ The ISM is a Highly-Dynamic Non-Equilibrium Medium
  - ☞ 2(3)-Phase Equilibrium Model is Obsolete (even NEI!)
  - ☞ Need Multi-Band & Messenger Observations (not only simulations!)
- ☆ How do Massive Stars and SNe feed the ISM with
  - ☞ Turbulent Energy?
  - ☞ Seed Matter for Subsequent Star Formation?
- ☆ What is the Role (and Morphology) of Magnetic Fields?
- ☆ Exploit γ-rays from
  - ☞ Long-lived ISM Radioactivities
  - ☞ Nuclear Excitation Lines
  - ☞ CR Interactions, e+



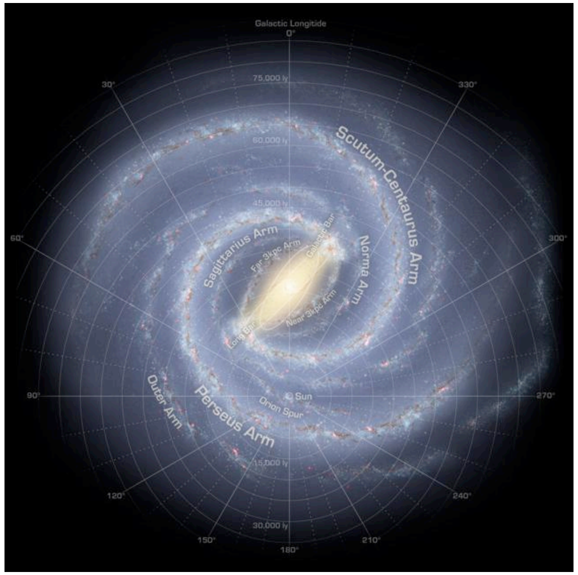


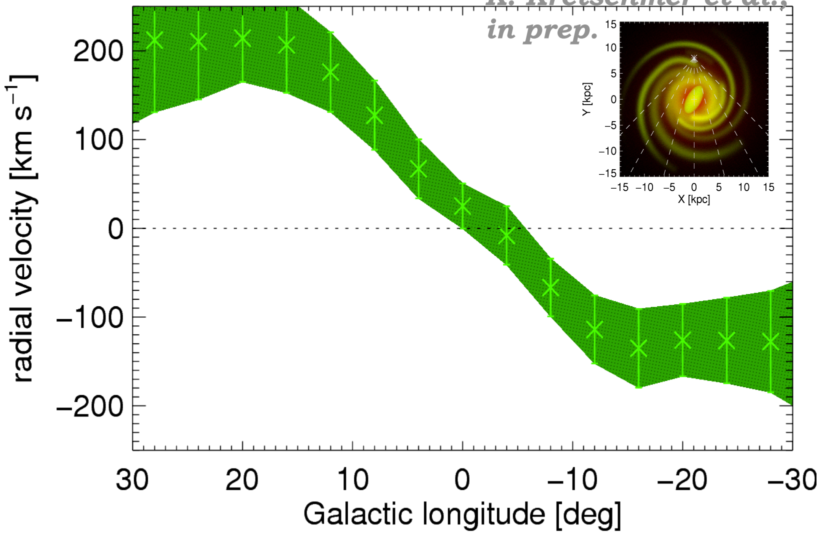




Roland Diehl

Astronomy with ^{26}Al: The Inner Galaxy

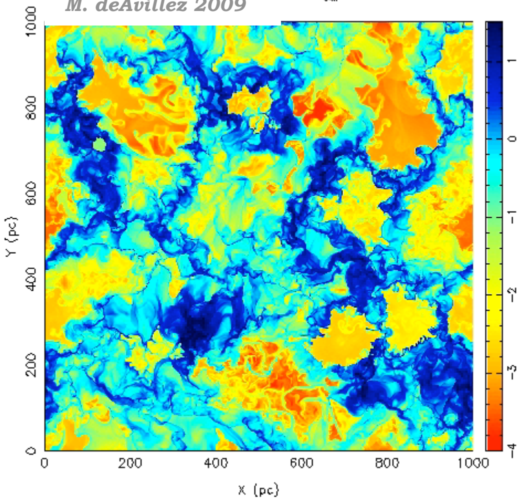




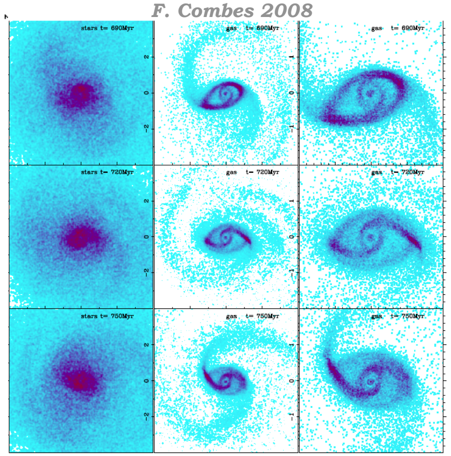
K. Kretschmer et al., in prep.

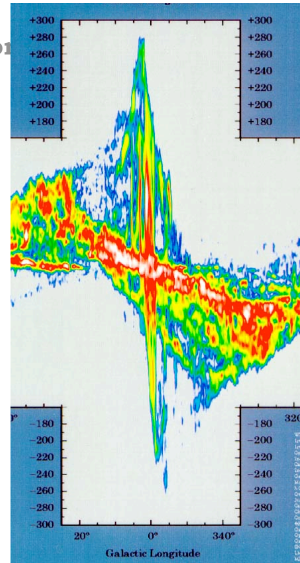
- ☆ **Issues**
  - ☞ Gas Motion versus Stellar Population?
  - ☞ Hot and Cold Gas Motions
  - ☞ Gas Flow (inward/ outward)

ISM Simulations
M. deAvillez 2009



Simulations of Inner-Galaxy Evolution
F. Combes 2008

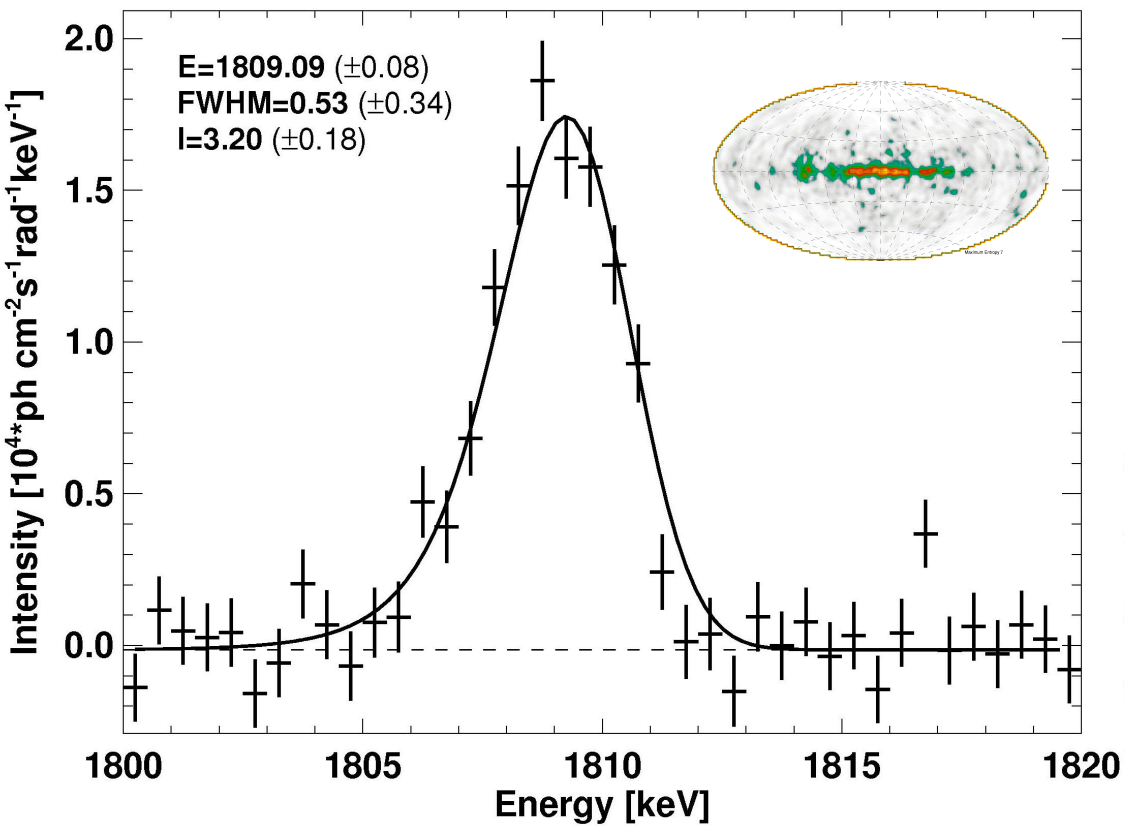




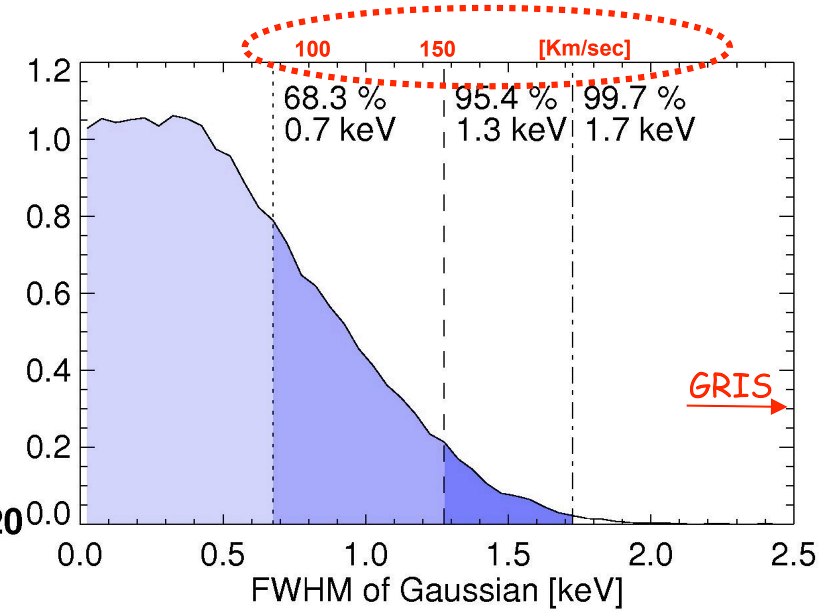
Molecular-Gas Kinematics (CO)
Dame et al. '89ff

How Wide is the Celestial ^{26}Al Line?

- ☆ SPI Response * Celestial Line -> Actually-Observed Line Feature
- ☆ Fit Expected Spectral Signature to the Sky&Bgd-Fitted Spectral Signal
- ☆ Perform Statistical Uncertainty Analysis (Monte Carlo Markov Chain)



Celestial Line Width Constraint



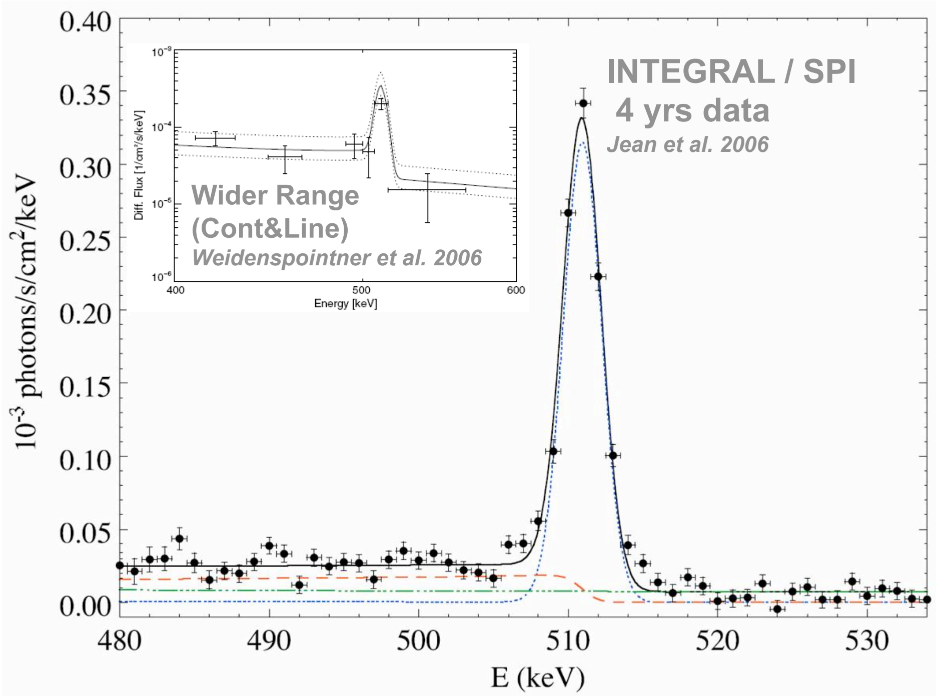
-> Data up to mid 2006; W.Wang et al., 2009
Line Width Probability Distribution by K.Kretschmer

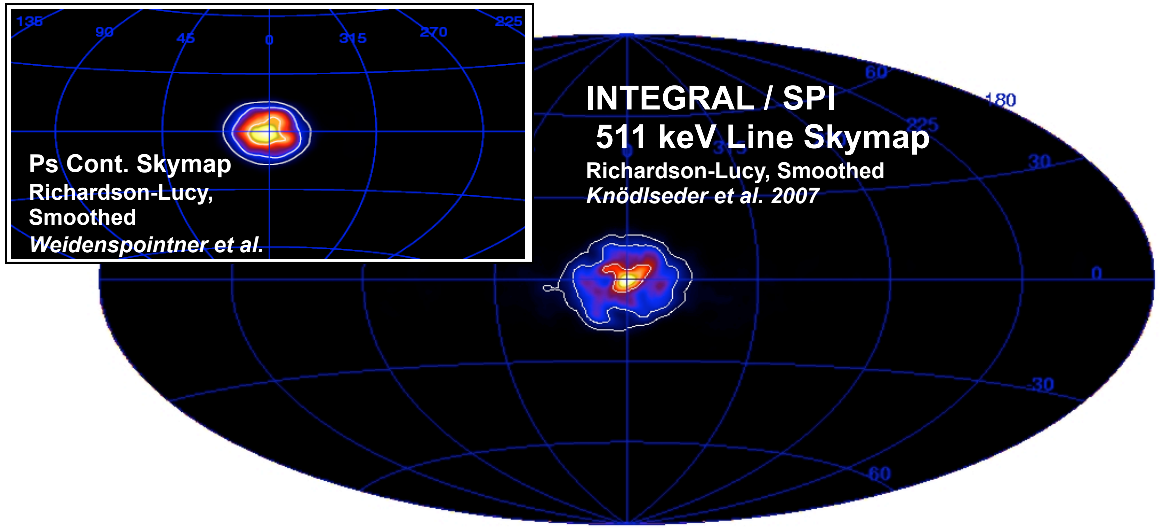
INTEGRAL/SPI & Annihilation of Positrons in the Galaxy

.... 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

INTEGRAL / SPI:

- Extended Emission (~8-10°) at 1.01 (±0.02) 10^{-3} ph cm^{-2} s^{-1}
- Ps Cont.: 4.3 (±0.3) 10^{-3} ph cm^{-2} s^{-1} f_{Ps} 0.967 ±0.022
- Corresponds to ~ 2 10^{43} e^+ s^{-1}
- Line Slightly Broadened

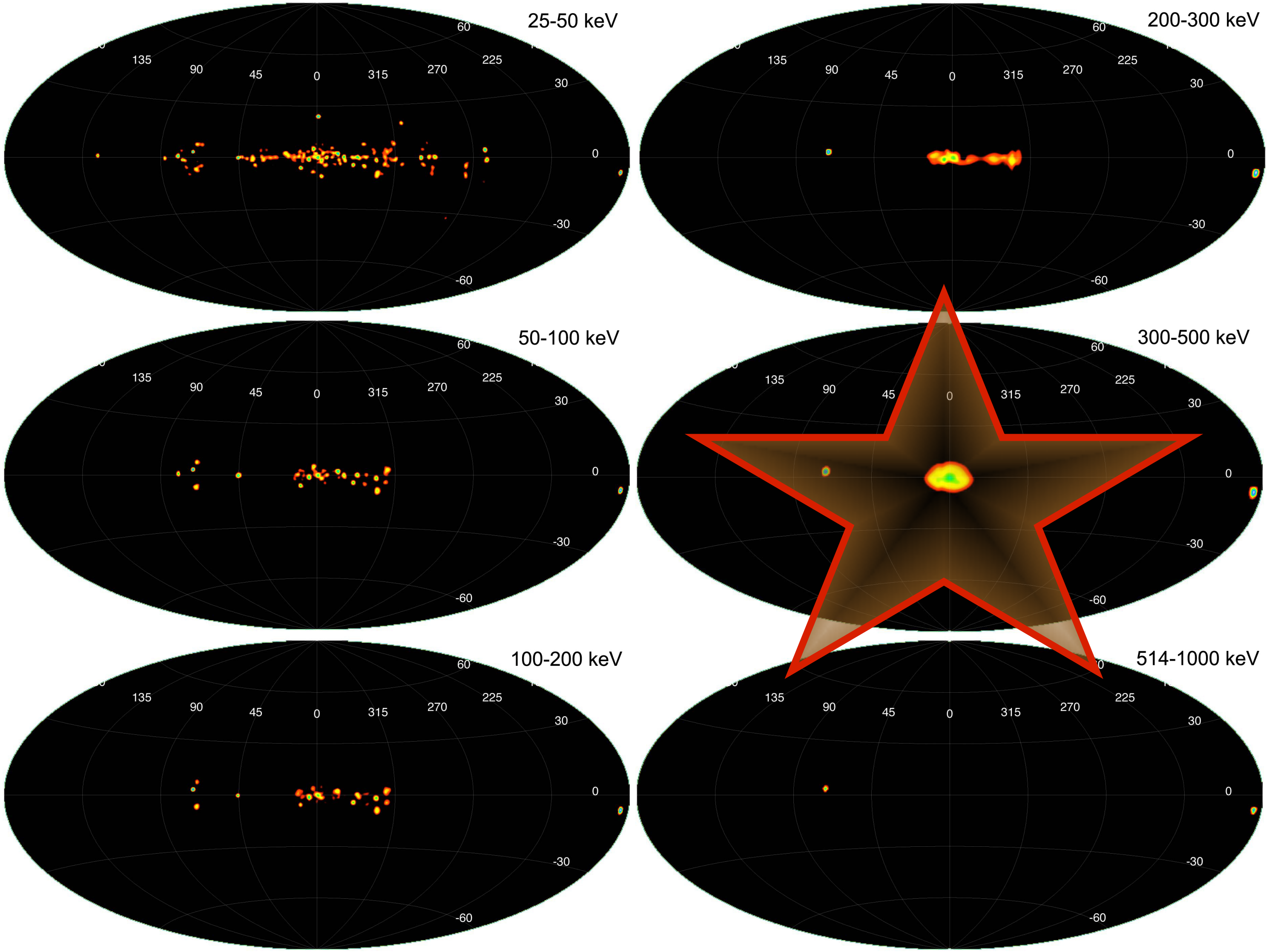


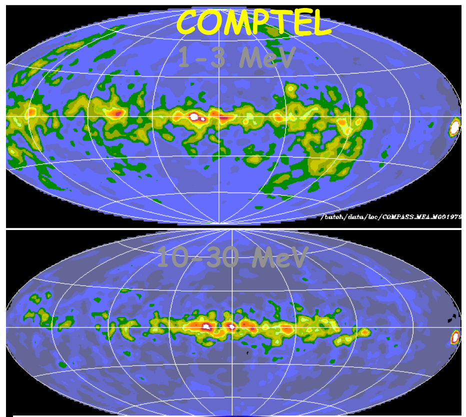


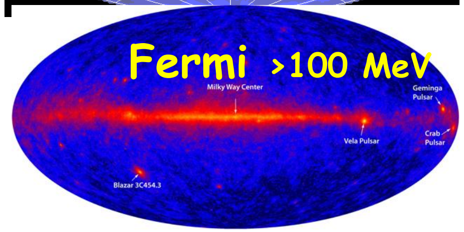
The High-Energy Sky (hard-X to HE γ-rays)

☆ Annihilation Emission is Different!

INTEGRAL/SPI







Positron Production Processes

all over in the DISK of the Galaxy

✓ 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

$$p + p \to \pi^+ + X$$

$$\pi^+ \to \mu^+ + \nu_\mu \quad (\tau = 2{,}6\cdot 10^{-8}\ \mathrm{s})$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (\tau = 2{,}2\cdot 10^{-6}\ \mathrm{s})$$

✓ Hot-Plasma Pair Production

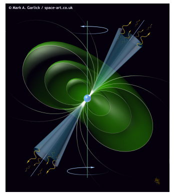
- ☆ 'kT>MeV'-Plasma
  - ☞ Accretion Columns & Disks
  - ☞ Jet Bases

$$\gamma+\gamma \to e^+ + e^-$$

✓ E.M.-Cascade Pair Production

- ☆ Strong Magnetic Fields
  - ☞ Pulsars
  - ☞ Jets

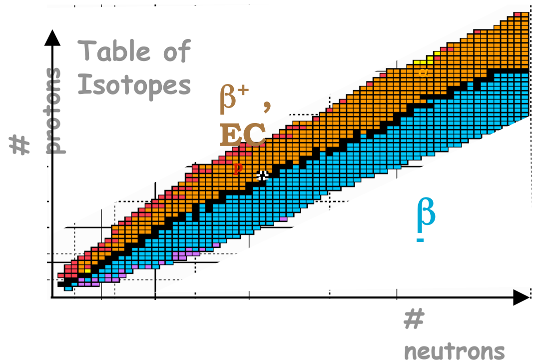
$$\gamma+B \to e^+ + e^-$$



✓ Nucleosynthesis

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

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



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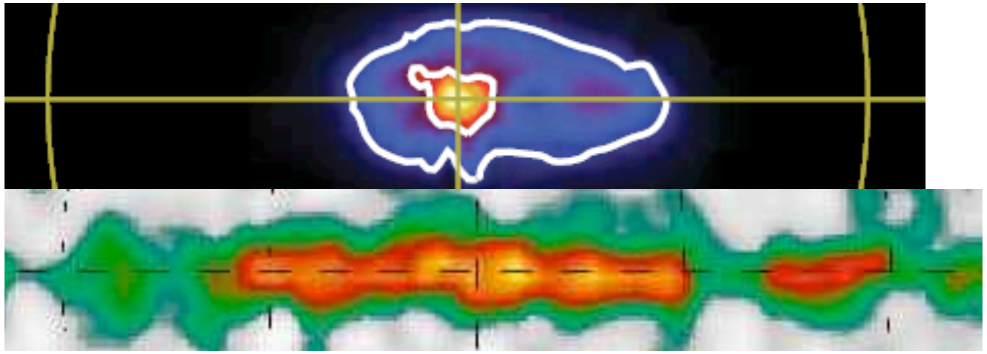
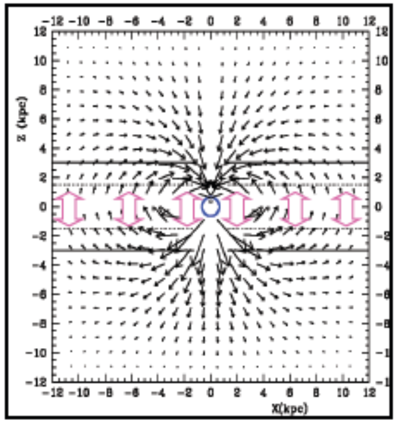
What are the Positron Sources??

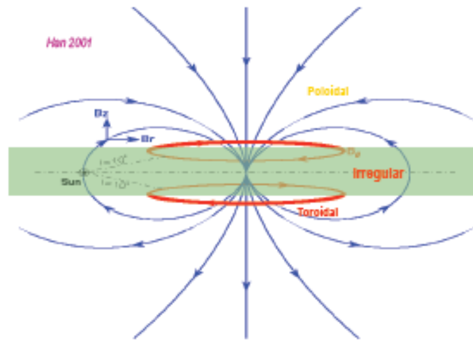
- ☆ **Identify Each of the KNOWN Types of Sources**
  - ☞ Individual Sources?
  - ☞ Morphology of Galactic-Disk Emission
  - ☞ Assemble a Sky Model for the Known Integrated Emission, e.g.:



- Positron Annihilation
- ^{26}Al Radioactivity

❍ Could e+ be transported from disk to central region of Galaxy?
- ☆ Escape from Source Regions in Champagne Flows / Fountains
- ☆ Large-scale transport in halo magnetic field
  - ☞ Large-Scale Study of Cosmic-Ray Transport E~MeV...GeV



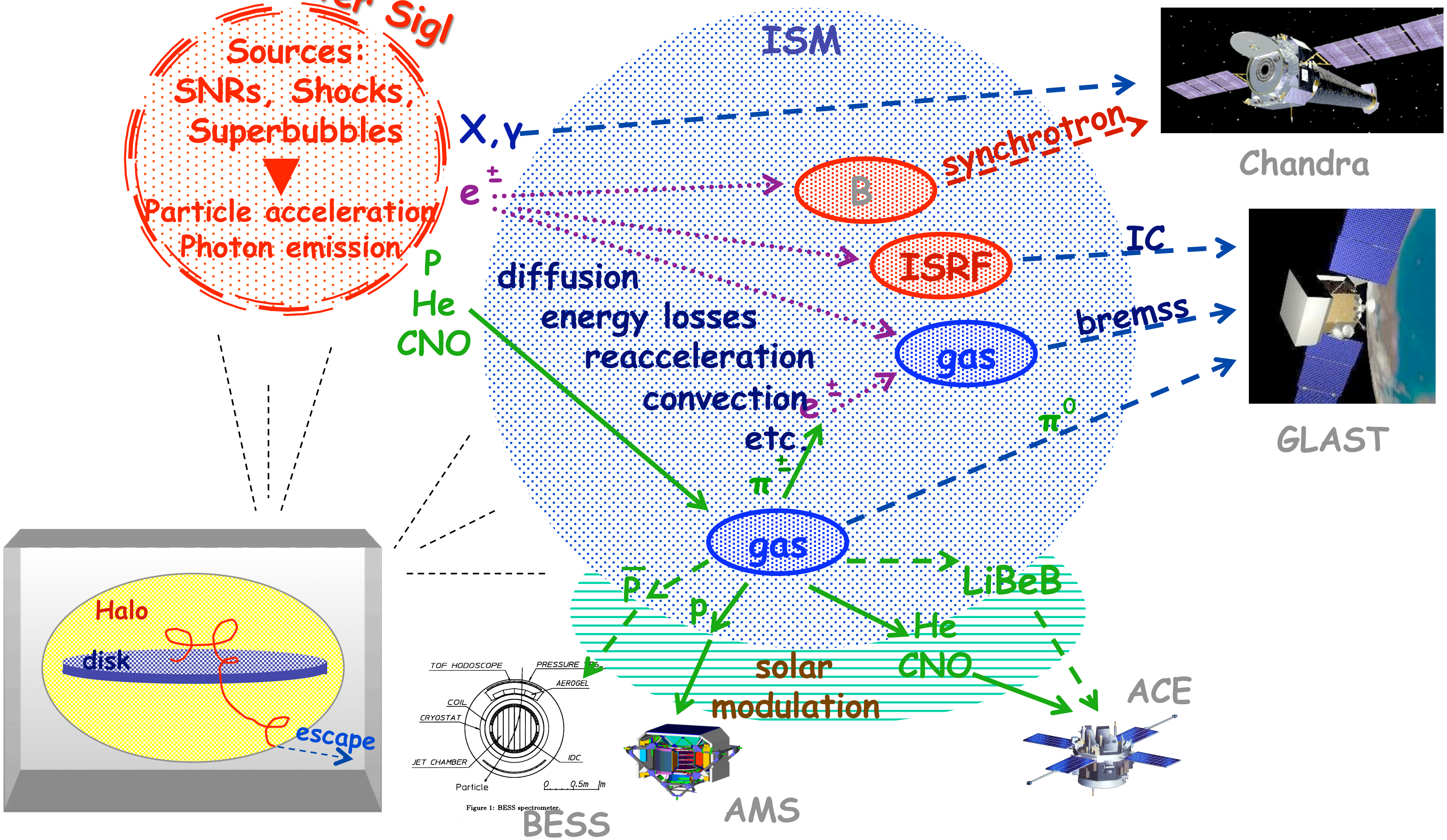


☞ Include Propagation Physics in Models and in Analysis

- ☆ **See if Significant Residual (bulge) Emission Remains**
- ☆ **An Unexpected / New Type of Sources? (e.g. DM?)**

Cosmic Rays: From Sources to Observation

See Lecture by Günter Sigl

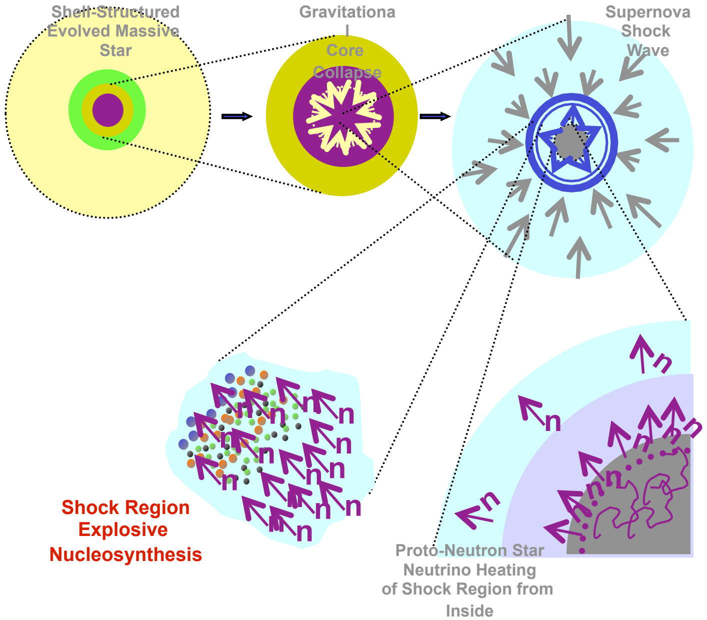


☞ *courtesy I. Moskalenko*

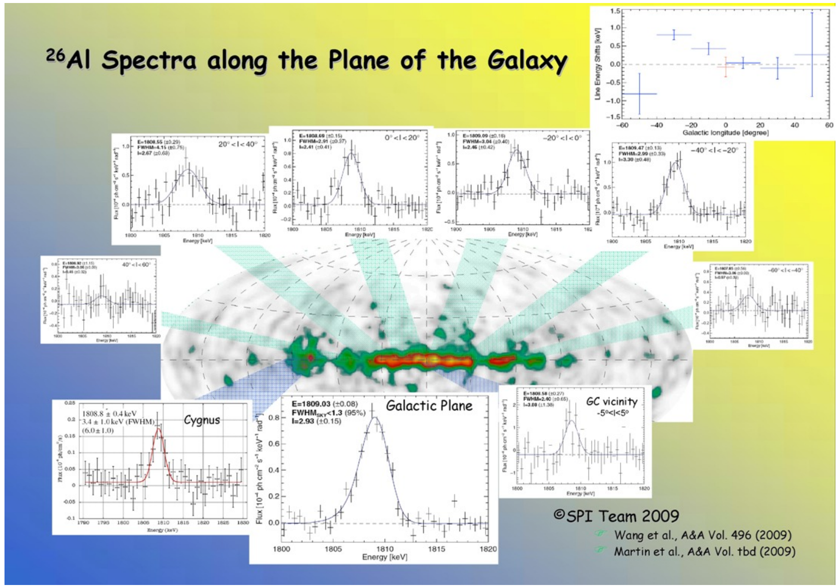
Summary: Gamma-Rays from Cosmic Radio-Isotopes

- ☆ Key Radio-Isotope Data from Novae & SNIa Need Luck
  - ☞ Novae <kpc, SNIa < 5 Mpc

- ☆ Inner Ejecta from a CC-SN (Cas A) -> Velocity Constraint
  - ☞ Cas A a Rare CC-SN?

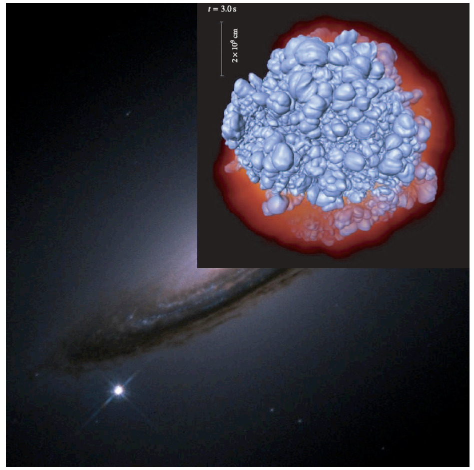


- ☆ The Present-Day Massive-Star Population of the Galaxy is Studied through ^{26}Al and ^{60}Fe
  - ☞ Isotopic Ratio as a Stellar-Structure Diagnostic
  - ☞ Gamma-Ray Spectroscopy -> Hot ISM around Massive-Star Groups
  - ☞ Galactic Structure & Nucleosynthesis Regions



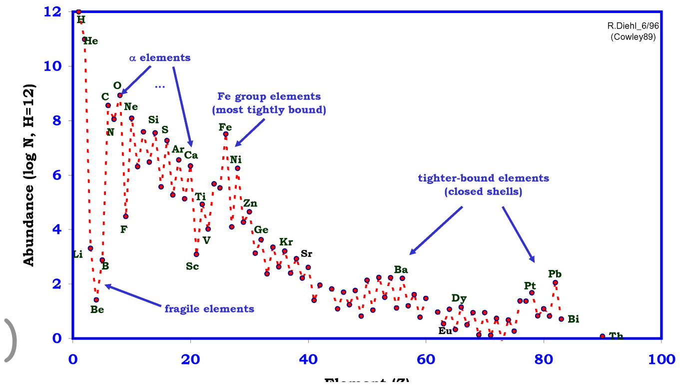
Astronomy, Astrophysics and Nuclear Physics

- Nuclear Physics Applications in Cosmic Environments:



☆ Nuclear Energy Release
  - Structure of Stars
  - Dynamics of Explosions

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



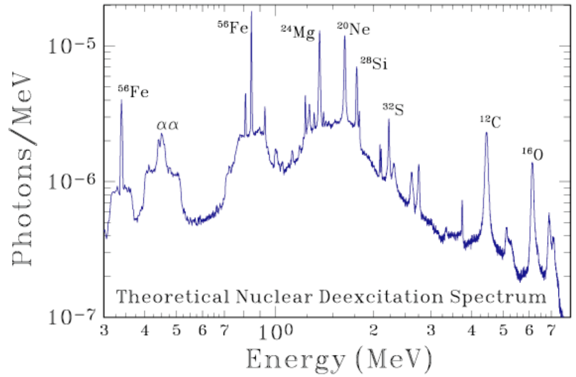
☆ Characteristic Nuclear Radiation
  - Nuclear Excitation (Emission/Absorption Lines)
  - Radioactive Decay

Thank You!

=>

☞ Nature of Cosmic Sources, Cosmic Processes

☞ Search for New Phenomena



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