Abundance Constraints
on Sources of Nucleosynthesis, and on the Chemical Evolution of the Universe and its Components

- Characteristic Cosmic Gamma-Rays -

NIC School 2008

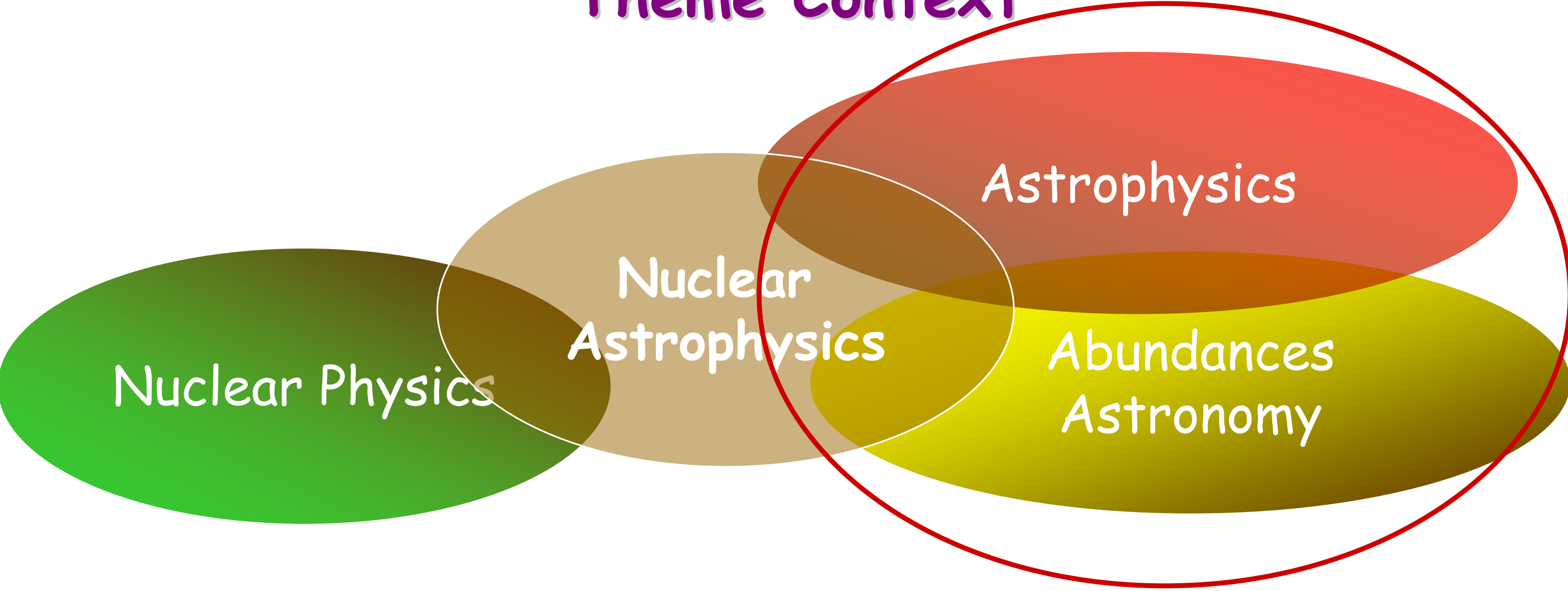
24 Jul 2008

by Roland Diehl

Outline

- ☆ Themes of my lectures, the context, the role of abundances
- ☆ How cosmic gamma-rays set "abundance constraints"
- ☆ What we learned from gamma-ray constraints
- ☆ How else do we obtain "abundance constraints"
- ☆ What we learned from "abundance constraints"

Theme Context



Observing Nuclear Reactions in Cosmic Environments

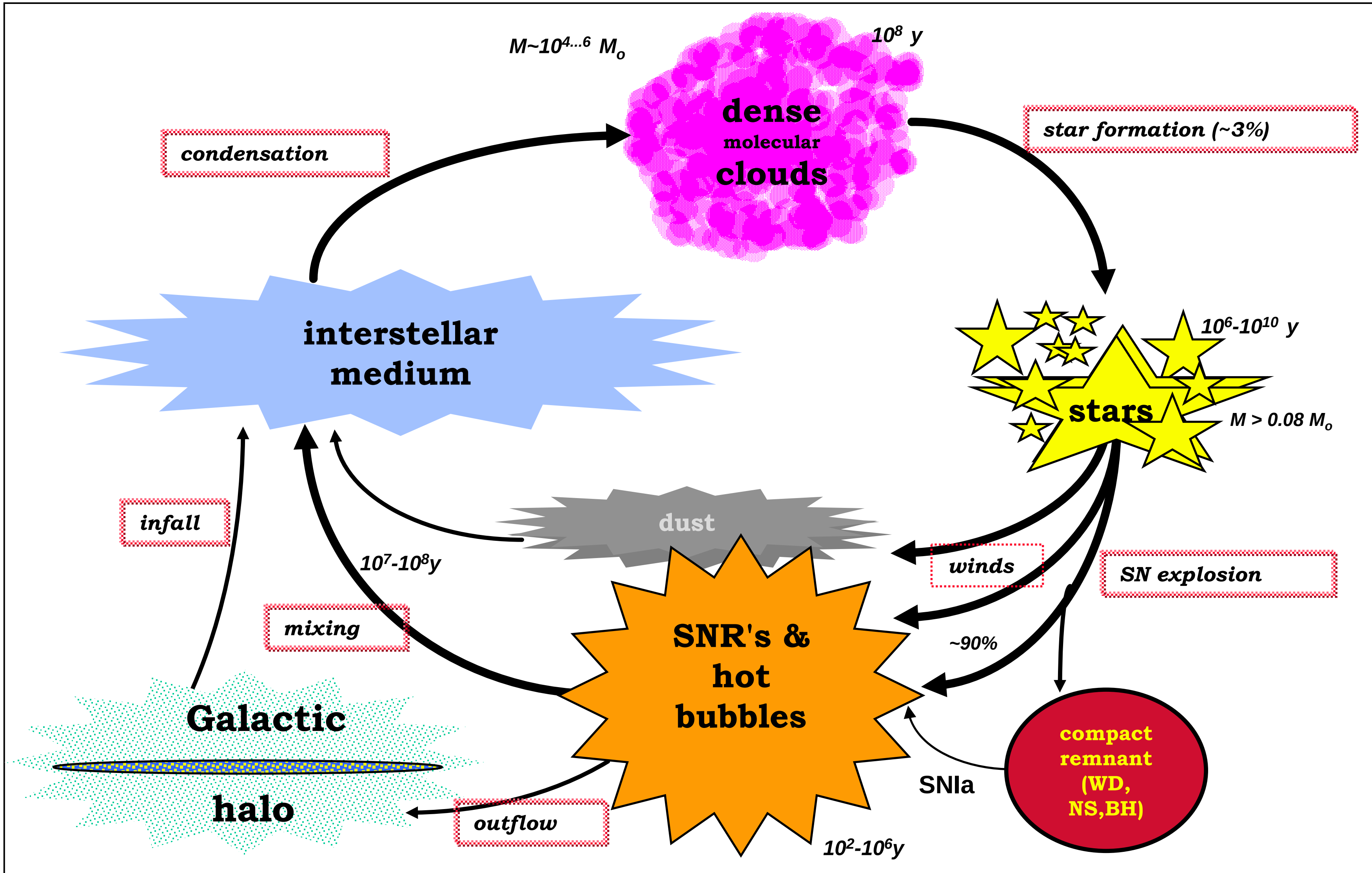
Observations of Nuclear Ashes: Radioactive Isotopes, Absorption Lines, Presolar Grains, ...: Abundances, Kinematics,...

- H-Burning
- He-Burning
- C/O-Burning
- Si-Burning
- NSE, QSE
- α-Process
- r-Process
- s-Process
- p/γ-Process

- Stellar Interiors (Core, Shells)
- WD/NS Accretion
- Novae
- Supernovae (thermonuclear, core collapse)
- ISM / Cosmic Rays

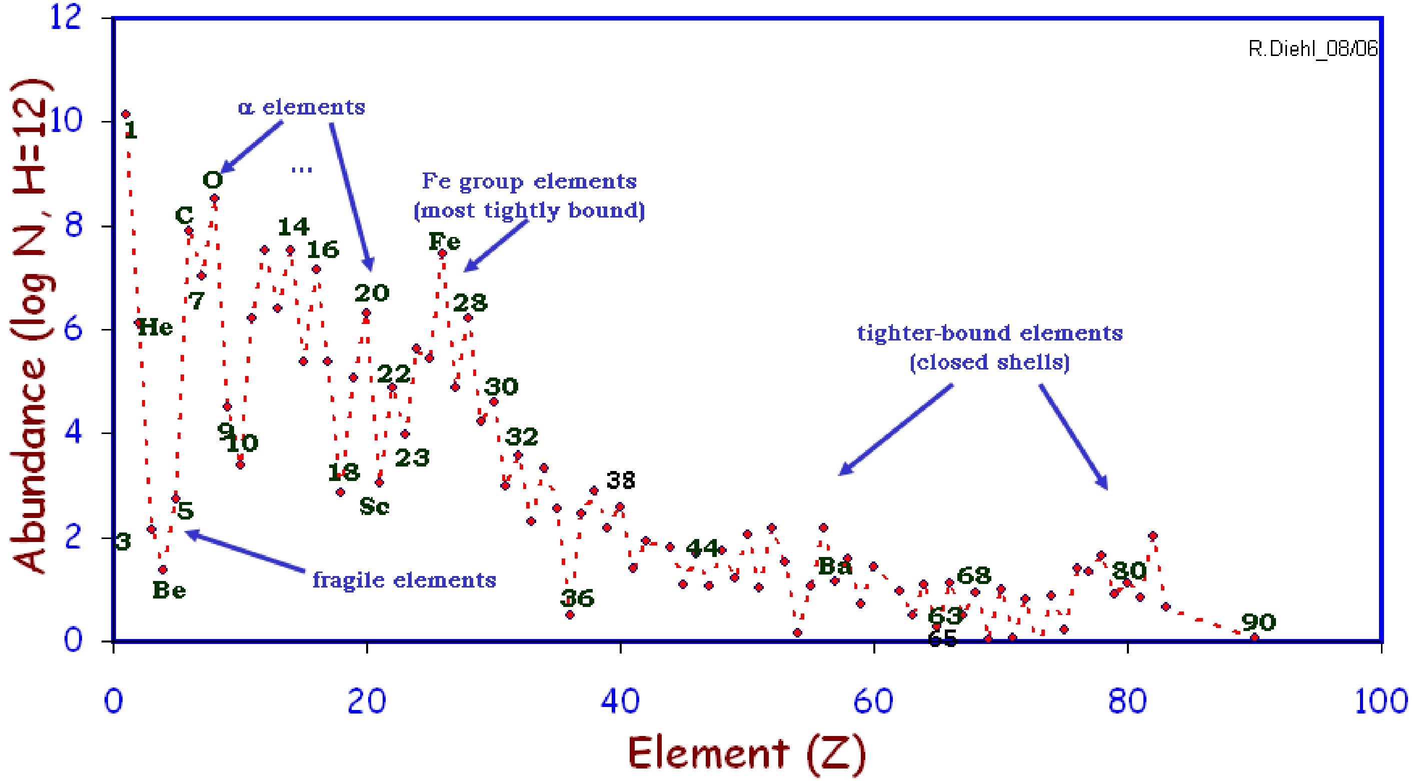
The General Context:

How Do Nucleosynthetis Sources Enrich the Universe with Heavy Elements?



- ☆ Nuclear Reactions in Stars and Supernovae Rearrange Baryons -> New Atoms
- ☆ New Atoms are Mixed into ISM which Forms New Stars & Planets

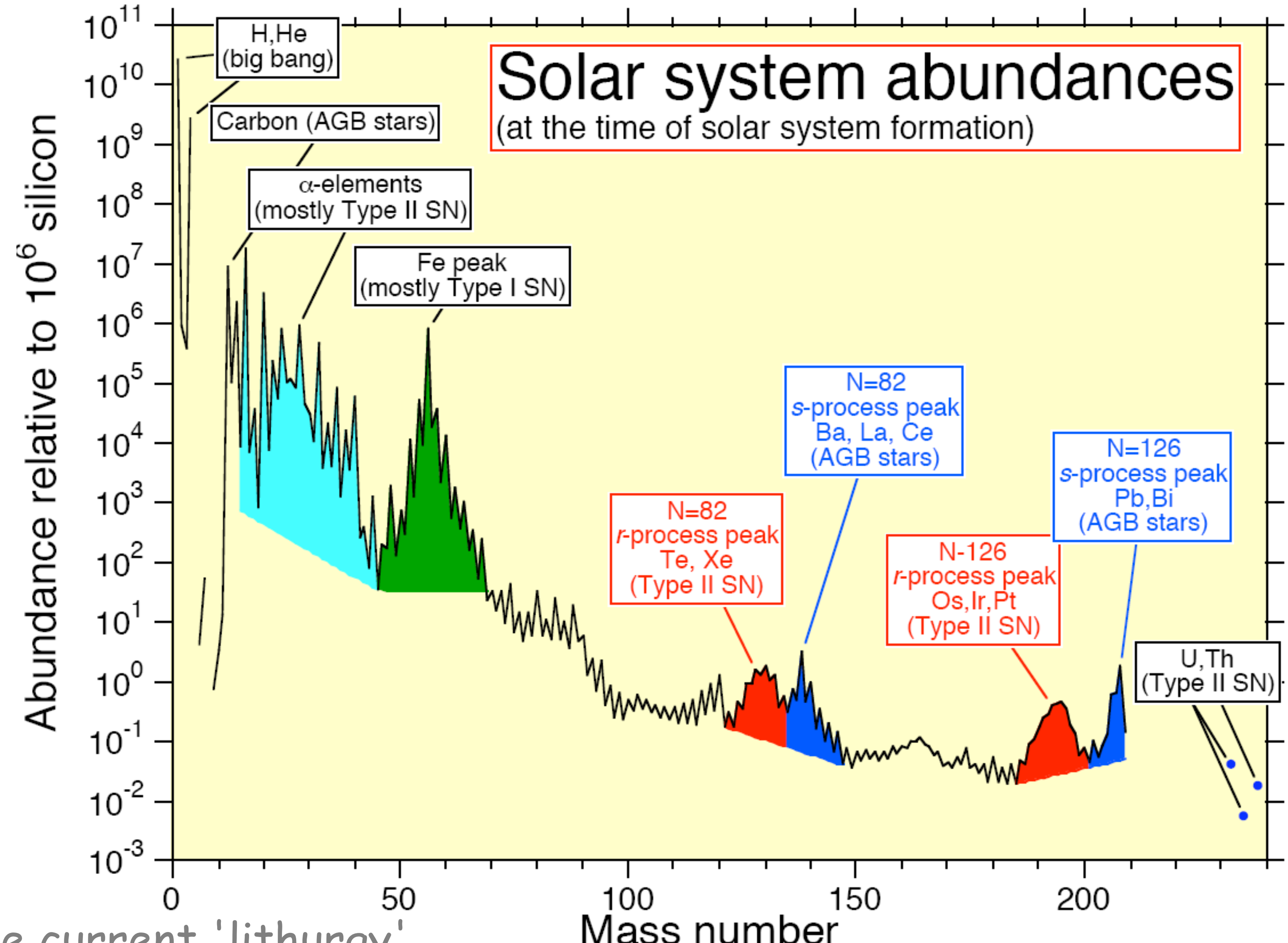
Abundances: An Astronomical Measurement



☆ 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

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

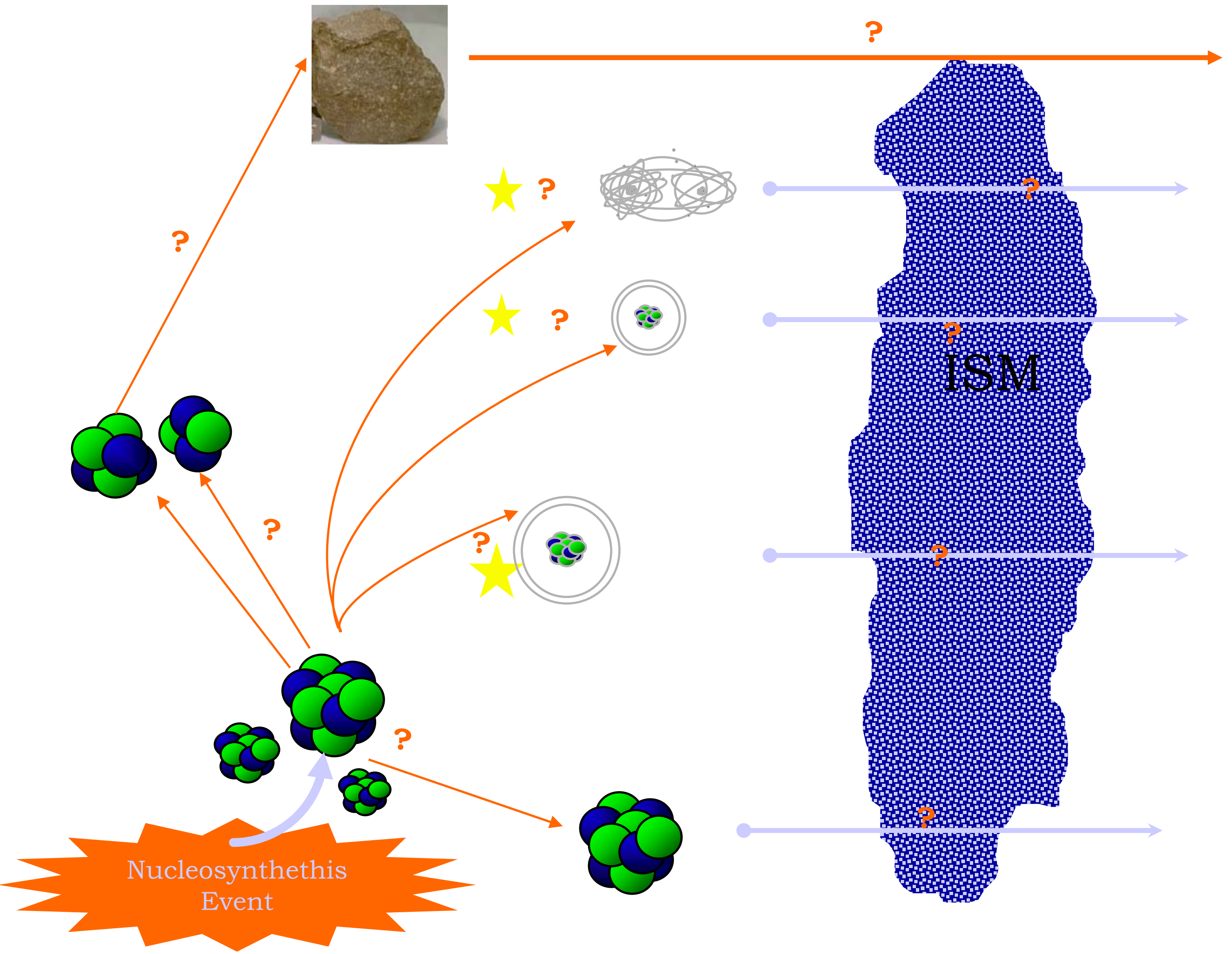


☆ ... the current 'lithurgy'

-> how much do we understand?

Courtesy: Andy Davis

Diversity of Complementing Observing Methods

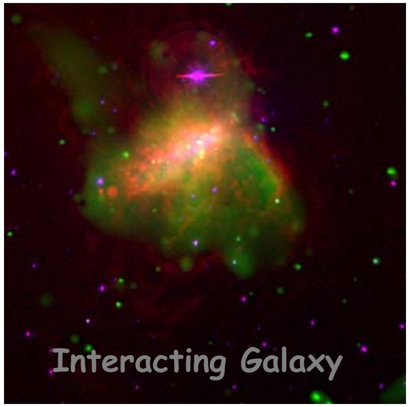


☞ ...more next Lecture....

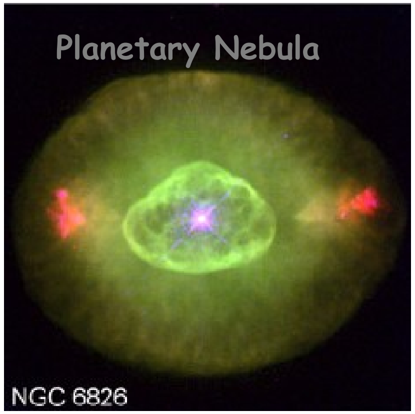
- Meteoritic Studies
- Molecular Absorption-lines (Radio,IR)
- Atomic Absorption-lines (opt,UV)
- Atomic Emissionlines (opt,UV,X)
- Gamma-Ray Lines from Radioactive Isotopes

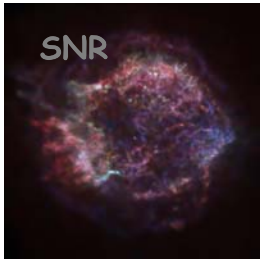
Nucleosynthesis Products: Where We See It

- ☆ We Would Like to Know Compositions in… (for the study of…)
  - ☞ Intergalactic Medium, Galaxies — cosmic evolution
  - ☞ Interstellar Medium — galaxy evolution, mixing
  - ☞ Supernovae, Novae, and their Remnants — specific sources
  - ☞ Planetary Nebulae — specific sources



- ☆ We Can Measure Compositions in
  - ☞ Material Samples
    - » Meteorites, Planets, Comets…
    - » Cosmic Rays ('CRs'), Solar Energetic Particles ('SEPs')
    - » Meteoretic Inclusions: Presolar Grains
  - ☞ Stellar Photospheres
    - » Stars with Original/Natal Composition in Photosphere
    - » Stars with Internal Mixing
  - ☞ Gas Clouds
    - » Absorbing ISM in front of Stars
    - » Absorbing IGM in front of Quasars & Galaxies





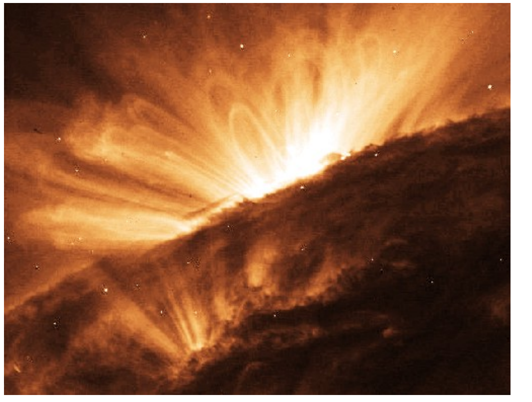
Abundance Observation Sites (1 of 4)

- Earth Crust
  - ☆ Planet Formation from Condensed Matter
    - ☞ Corrections for
      - » Planet Formation Physics
      - » Gravitational Differentiation
      - » Chemical Differentiation
      - » Radioactive Decays

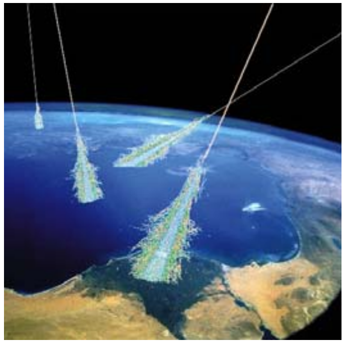
- Meteorites
  - ☆ Rocks
    - ☞ Diversity
      - » Meteorites with/without Glass-Like Inclusions (Chondrites/Achondrites)
      - » Stony Iron Meteorites
      - » Iron-Like Meteorites
    - ☞ Corrections for
      - » Rock Formation
      - » Radioactive Decays
      - » Cosmic-Ray Bombardement
      - » Outgassing
      - » Chemical Differentiation
      - » Presolar Inclusions

Abundance Observation Sites (2 of 4)

- Solar Energetic Particles
  - ☆ Particles Accelerated from Solar Activity
    - ☞ Corrections for
      - » Acceleration Process (First-Ionization Potential Selection)
      - » Acceleration Region Sampling Bias



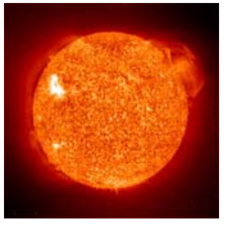
- Cosmic Rays
  - ☆ Particles Accelerated from ??? (ISM Shock Regions?)
    - ☞ Corrections for
      - » Acceleration Process (First-Ionization Potential Selection)
      - » Acceleration Region Sampling Bias
      - » Propagation Effects (Spallation Secondaries & Losses)

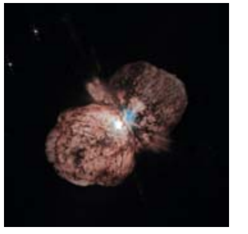


- Interstellar Medium
  - ☆ Particles Mixed from Turbulence, with Source Injections
    - ☞ Corrections for
      - » Propagation Effects (Gravitational Selections, Magnetic-Field Selections)
      - » Condensations on Dust Grains

Abundance Observation Sites (3 of 4)

- Stellar Photospheres (general)
  - ☆ Gas Globe, Stabilized from Gravity & Nuclear Burning in Interior
    - ☞ Diversity
      - » Evolved Stars (Giant Phases, i.e. after "Dredge-Ups"; C-Stars; WR Stars)
      - » Variability (AGB Stars, RCrB Stars)
      - » Binaries (BaII Stars, Be Stars)
    - ☞ Corrections for
      - » Atmospheric Structure Details
      - » Radioactive Decays
      - » Chemical History of Birth Place in Galaxy
      - » Extrastellar Contributions (anomalous Cosmic Rays, Dust)

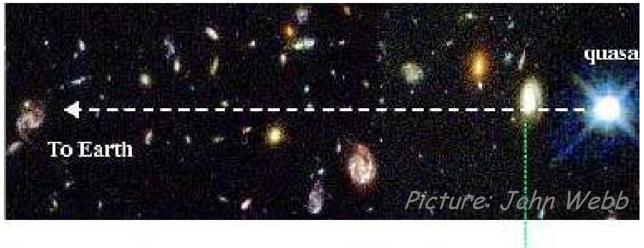




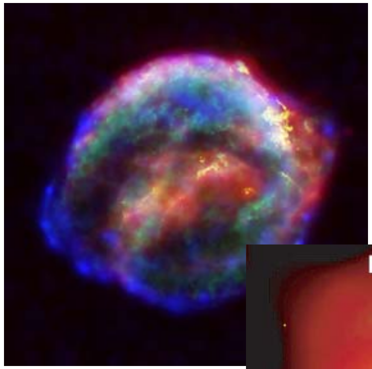
- Solar Photosphere
  - ☆ Solar System Formation 4.6 Gy ago
    - ☞ Corrections for
      - » Solar-System Birth Place in Galaxy
      - » Extrasolar Contributions (anomalous Cosmic Rays, Dust)

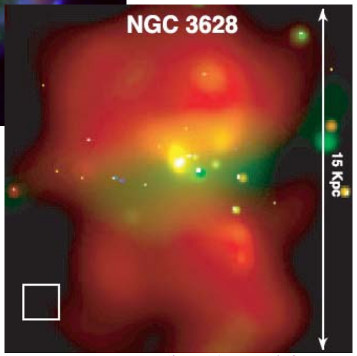
Abundance Observation Sites (4 of 4)

- Gas as Radiation Absorber
  - ☆ Gas Assembly, Illuminated from Back Side



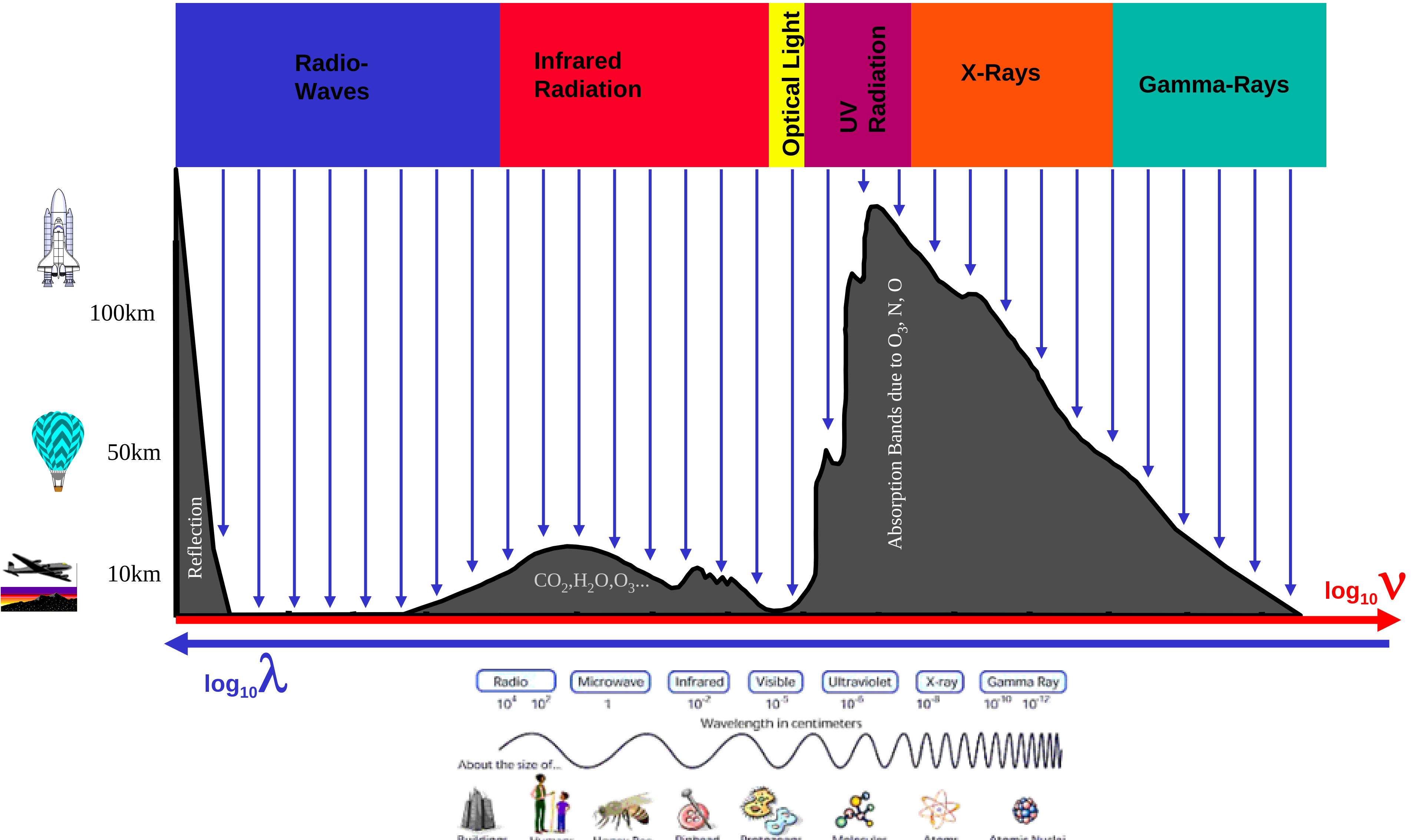
    - ☞ Diversity
      - » Interstellar Gas Against Background Stars
      - » Interstellar and Intergalactic Gas Across Range of Redshifts
      - » Circumstellar Gas Around a Source
    - ☞ Corrections for
      - » Background-Source Spectral Energy Distribution
      - » Foreground or Background Absorbers
      - » Selection Effects due to Background Source Type
- Hot, Recombining Gas
  - ☆ Hot States of Interstellar/Intergalactic Gas





    - ☞ Diversity
      - » Interstellar Gas around an Energetic Source (HII Regions, PWNe, SNR)
      - » Interstellar and Intergalactic Gas Heated by Diversity of Sources (SB's, Starburst Gal., ICM)
    - ☞ Corrections for
      - » Central-Energy Source Properties (time variations, energy flow variations)
      - » Non-Equilibrium States of Recombining Gas

Astronomical Observations throughout the e.m. Spectrum



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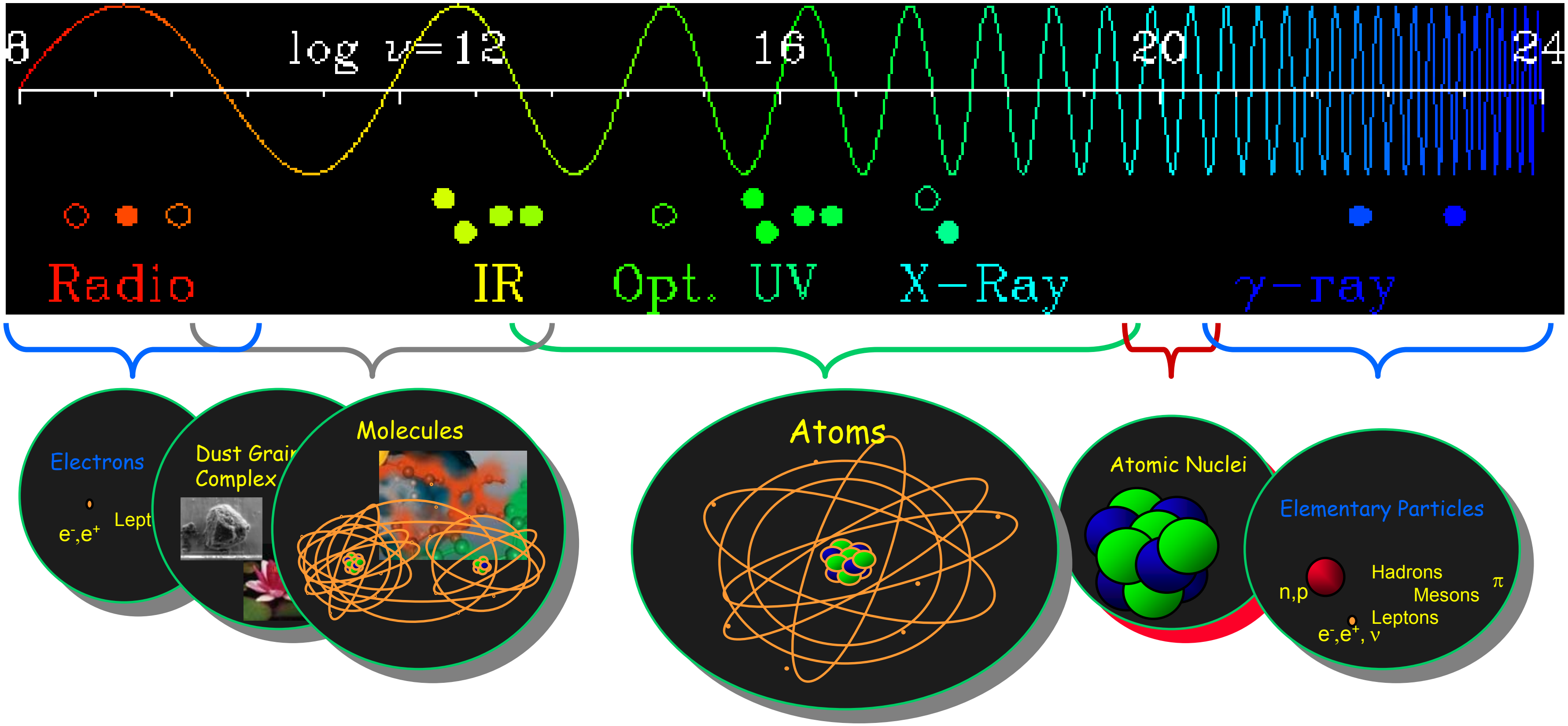
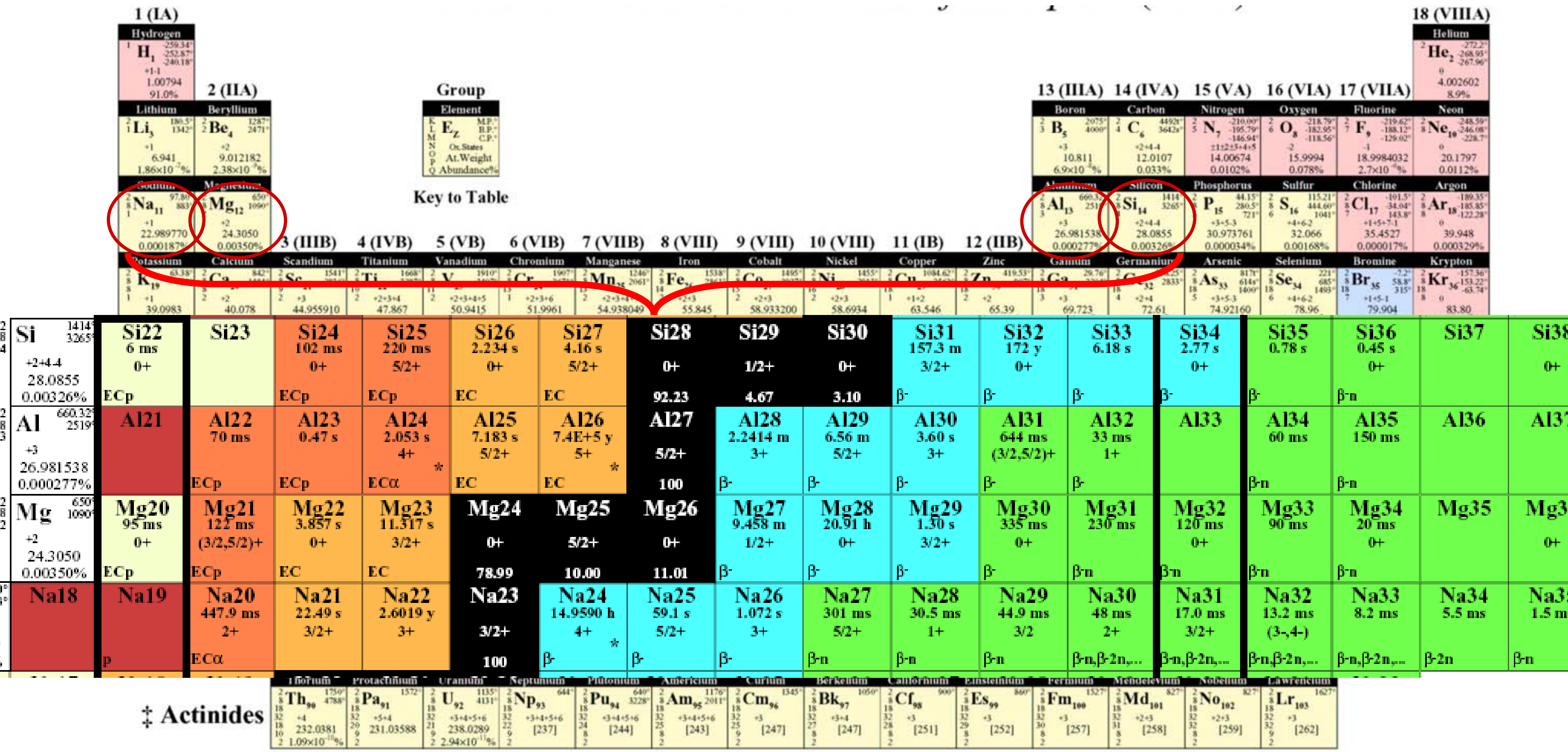
Spectroscopic Studies of Cosmic Elements



- Mostly: Atomic-Shell Absorption-Line Spectra
  - -> Galactic Archeology; Metallicity Gradients; Cosmic Chemical Evolution
- Specific Enhancements:
  - Atomic Emission & Recombination-Line Spectroscopy -> Gas in Special Sites
  - Molecular Lines -> Cold Gas/Clouds
  - and: Nuclear Lines, Annihilation Lines, Cyclotron Lines,... -> ...

From Atomic to Nuclear Physics

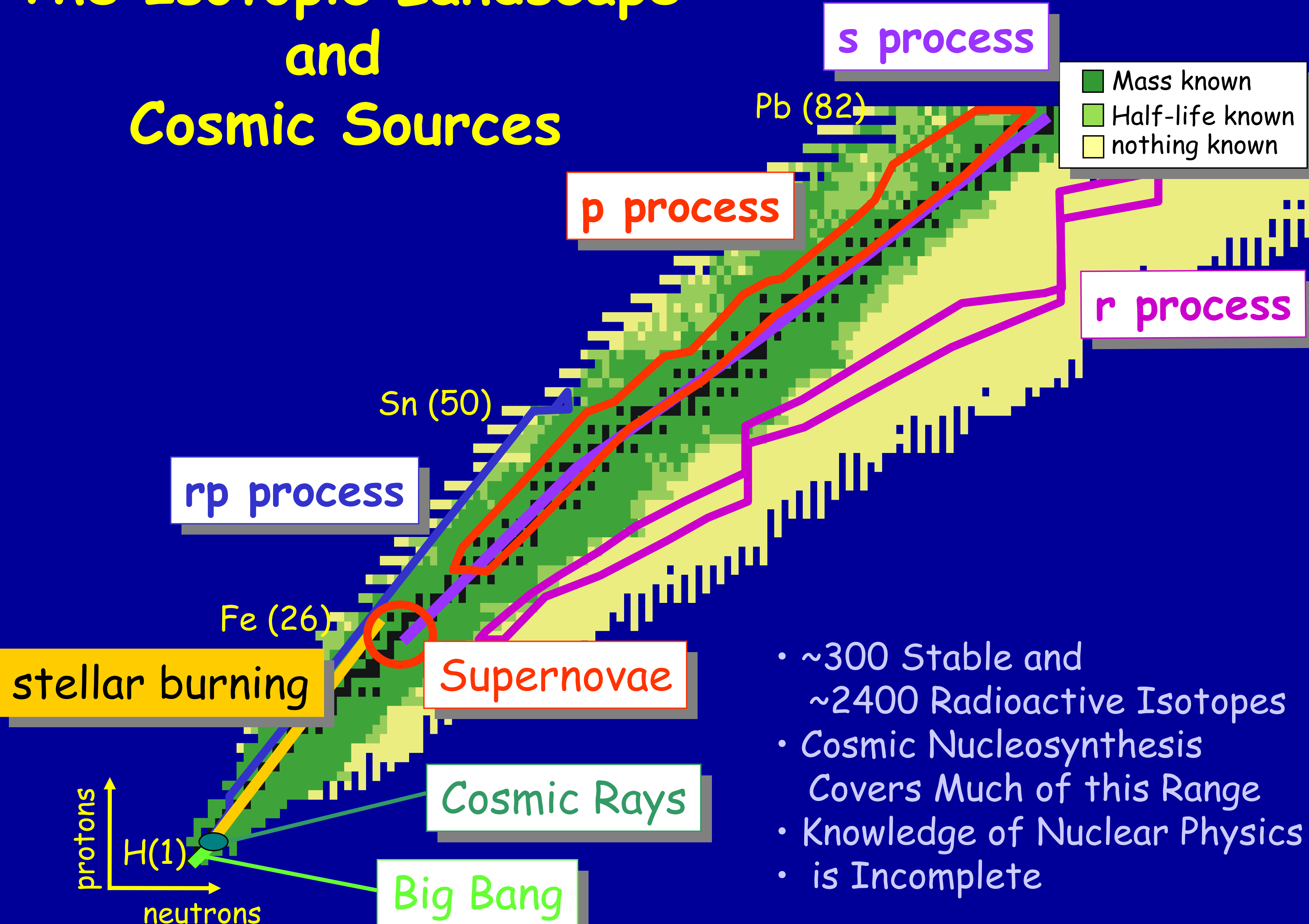


☆ Cosmic Nucleosynthesis Produces New **Isotopes**

☞ Diagnostics of Nuclear Fusion Reactions

→ Thermodynamic Variables in Hot (GK) Sites

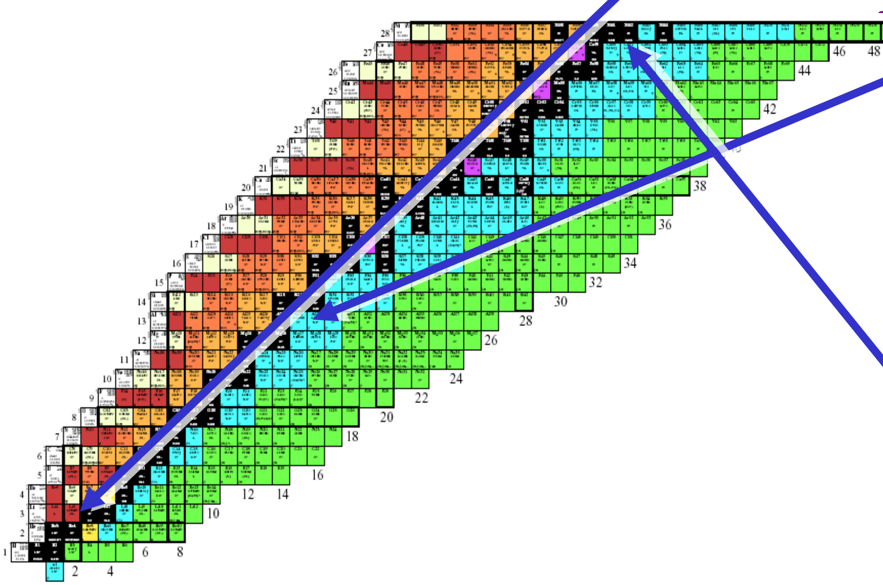
The Isotopic Landscape and Cosmic Sources



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

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

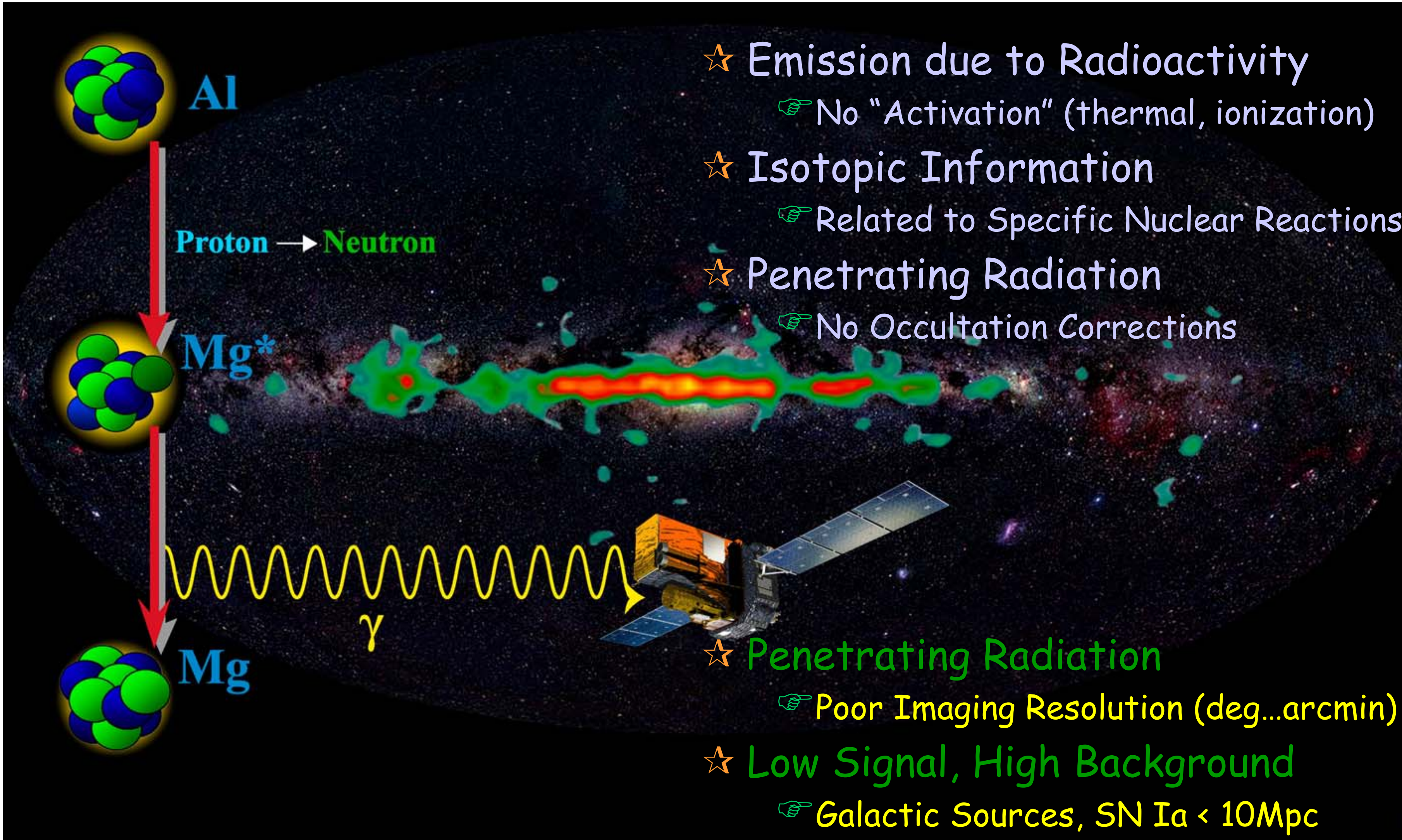
Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	^{7}Be → ^{7}Li*	478
^{56}Ni	111 d	^{56}Ni → ^{56}Co* → ^{56}Fe*+e^{+}	158, 812; 847, 1238
^{57}Ni	390 d	^{57}Co → ^{57}Fe*	122
^{22}Na	3.8 y	^{22}Na → ^{22}Ne* + e^{+}	1275
^{44}Ti	89 y	^{44}Ti → ^{44}Sc* → ^{44}Ca*+e^{+}	78, 68; 1157
^{26}Al	1.04 10^{6}y	^{26}Al → ^{26}Mg* + e^{+}	1809
^{60}Fe	2.0 10^{6}y	^{60}Fe → ^{60}Co* → ^{60}Ni*	59, 1173, 1332
e^{+}	.... 10^{5}y	e^{+}+e^{-} → Ps → γγ..	511, <511



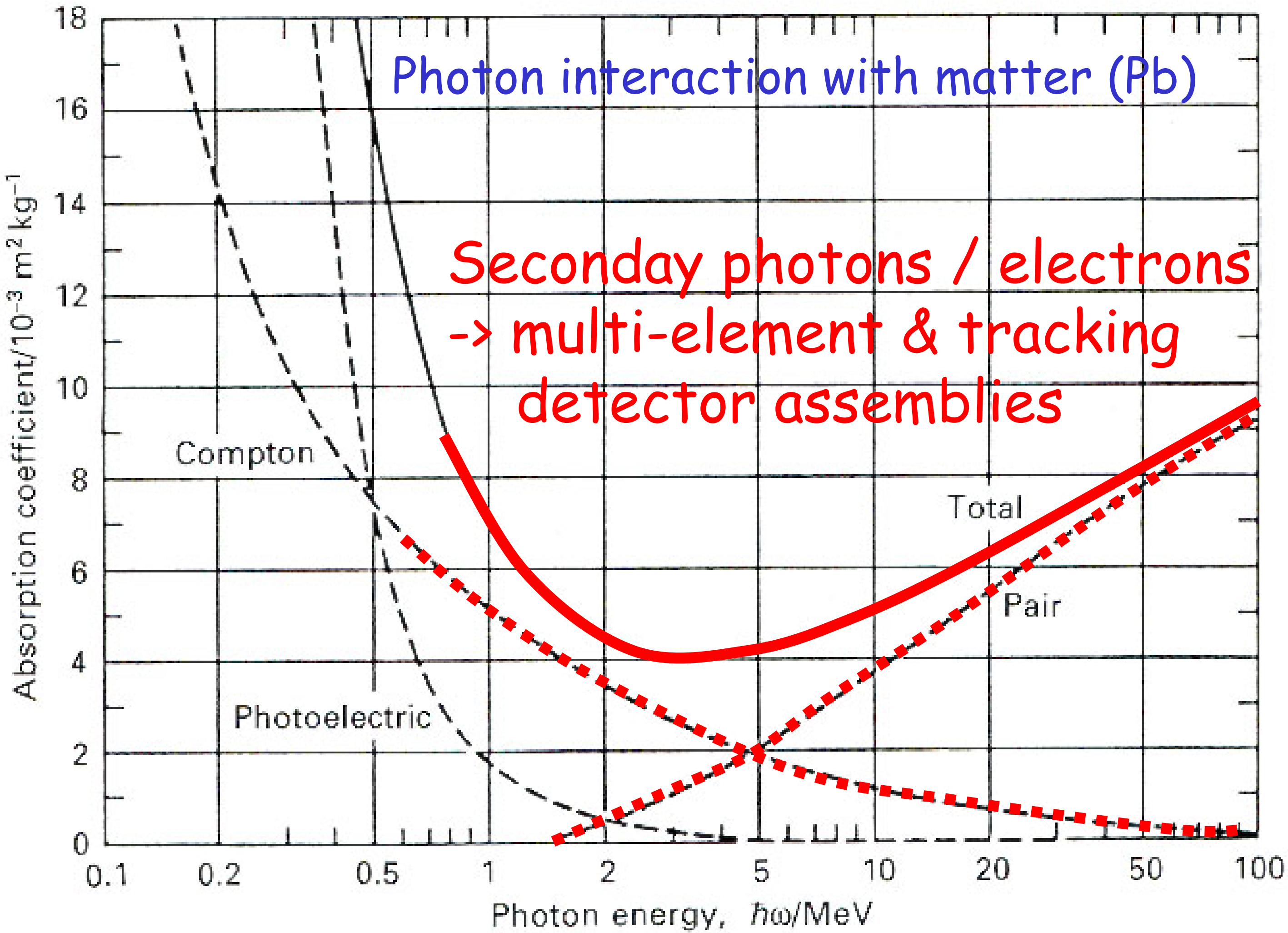
- 511 keV, ^{7}Be -> Novae
  -> p-Captures, β^{+} Decays
  -> ^{19}F Production...
- ^{26}Al -> Reaction Path Details in Stars/SNe, ν-Process
  -> Metal/Fe Ratio, Si/Fe
- ^{44}Ti, ^{56}Ni -> Most Stable Isotopes
  ^{56}Ni/^{4}He, Freeze-Out of NSE
  -> Metal/Fe Ratio, Heavies/Fe

Gamma-Rays for Cosmic-Isotope Measurements

Special Characteristics:

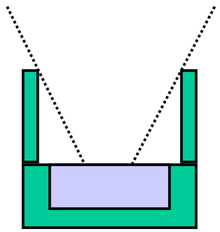


Interaction of HE photons with matter

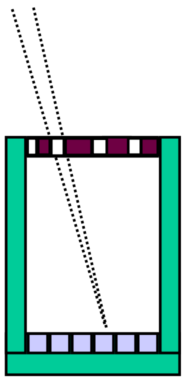


-> Secondary Particles … -> e.m. cascade

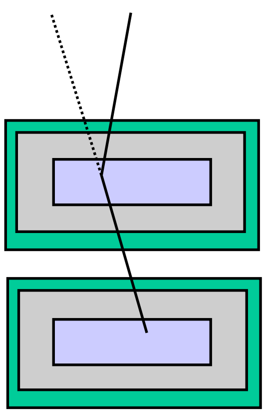
MeV Range Gamma-Ray Telescope Principles



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



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



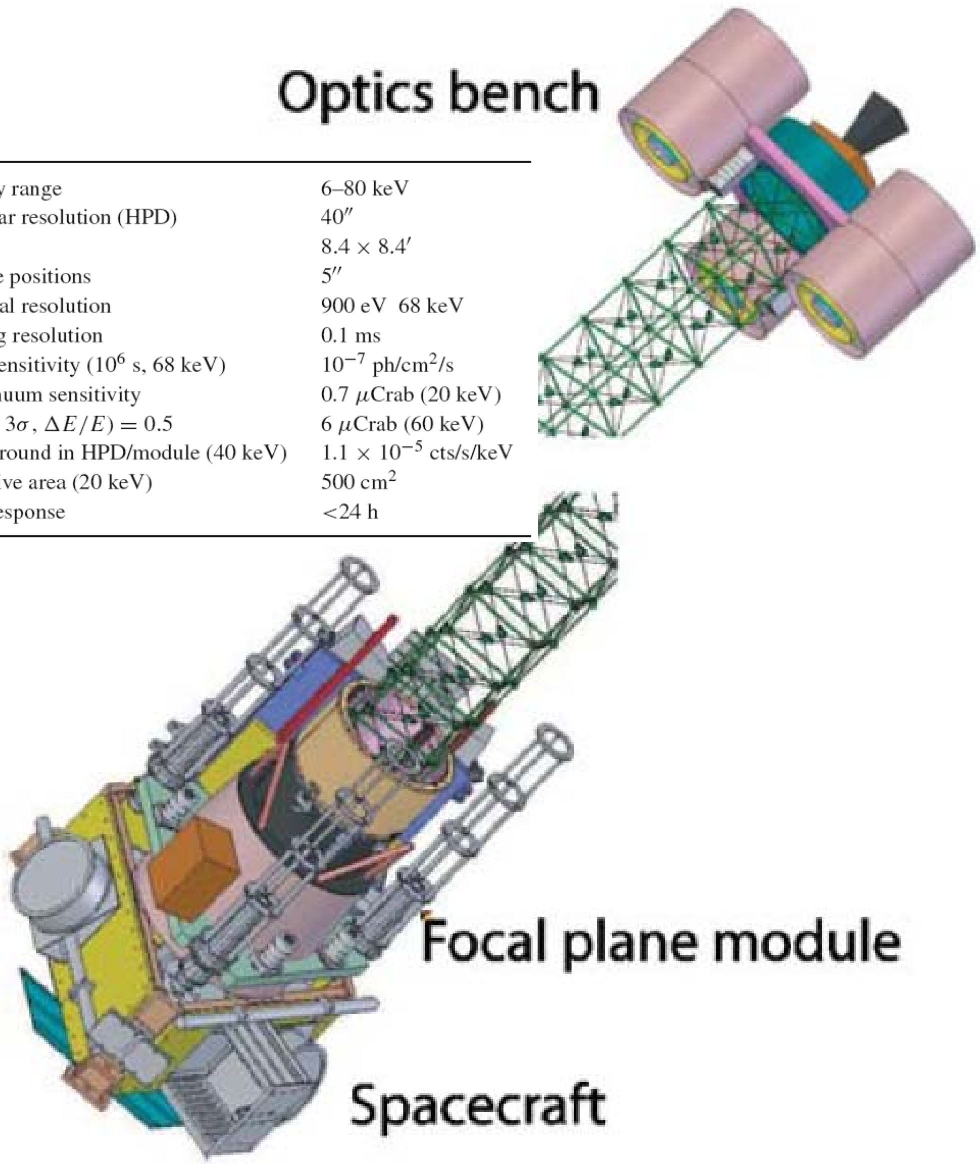
- **Compton Telescopes**
  (Coincidence-Setup of Position-Sensitive Detectors)
  (e.g. CGO-COMPTEL, MEGA, ACT,...)
  Spatial Resolution Defined by Detectors' Spatial Resolution

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

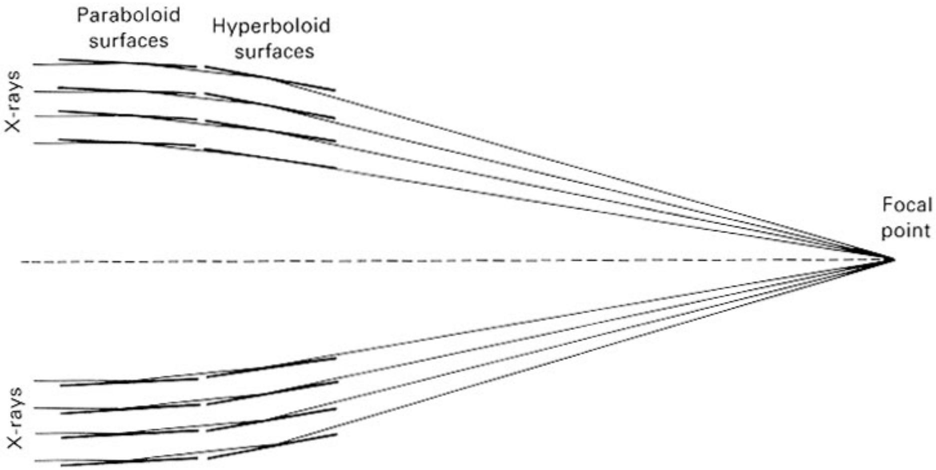
"Supermirrors": Extending X-Ray Optics to γ-Rays

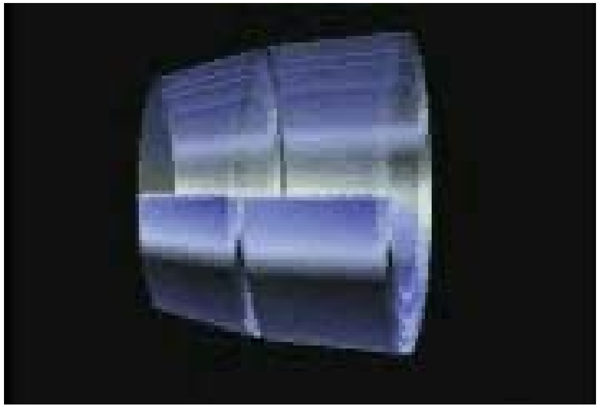
- ☆ "NUSTAR" Mission Concept
  - ☞ Two-Spacecraft Formation
  - ☞ Optics with
    - 130 Nested Shells of Grazing-Incidence Mirrors: W/SiC and Pt/SiC
    - Surface Reflectivity up to W K-Edge @69 keV + Grazing Incidence -> Use Up To 80 KeV
  - ☞ 10 m Focal Length
  - ☞ 40 arcsec Spatial Resol.
  - ☞ PI: F. Harrison / CalTech
- ☆ Status:
  - ☞ Phase A Study 2003-05, Selection 2005 for Launch in 2009
  - ☞ On Hold Since 2006

Energy range	6–80 keV
Angular resolution (HPD)	40″
FOV	8.4 × 8.4′
Source positions	5″
Spectral resolution	900 eV 68 keV
Timing resolution	0.1 ms
Line sensitivity (10^6 s, 68 keV)	10^{-7} ph/cm^2/s
Continuum sensitivity	0.7 μCrab (20 keV)
(10^6 s, 3σ, $\Delta E/E) = 0.5$	6 μCrab (60 keV)
Background in HPD/module (40 keV)	1.1 × 10^{-5} cts/s/keV
Effective area (20 keV)	500 cm^2
ToO response	<24 h



X-Ray Telescopes: Concentrating Radiation



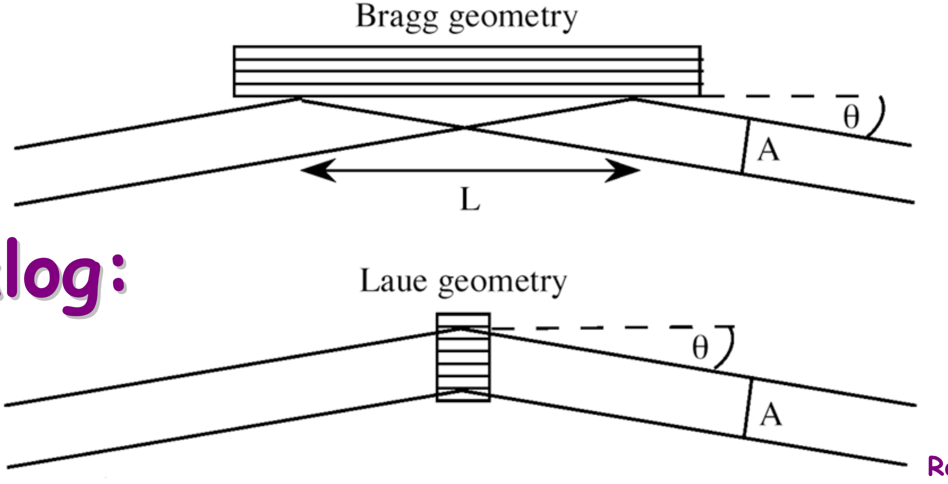


☆ Concentration of Cosmic Radiation

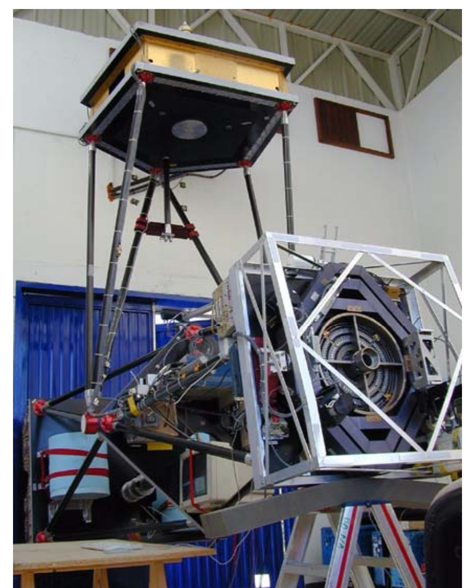
- Signal ~ Telescope Area
- Background ~ Detector Volume

☞ Signal/Background Ratio Improves with Radiation Concentration

Gamma-Ray Analog:



Balloon Experiment with Laue Lens: "Claire" (Gap->Bordeaux, June 2001)



courtesy P.von Ballmoos

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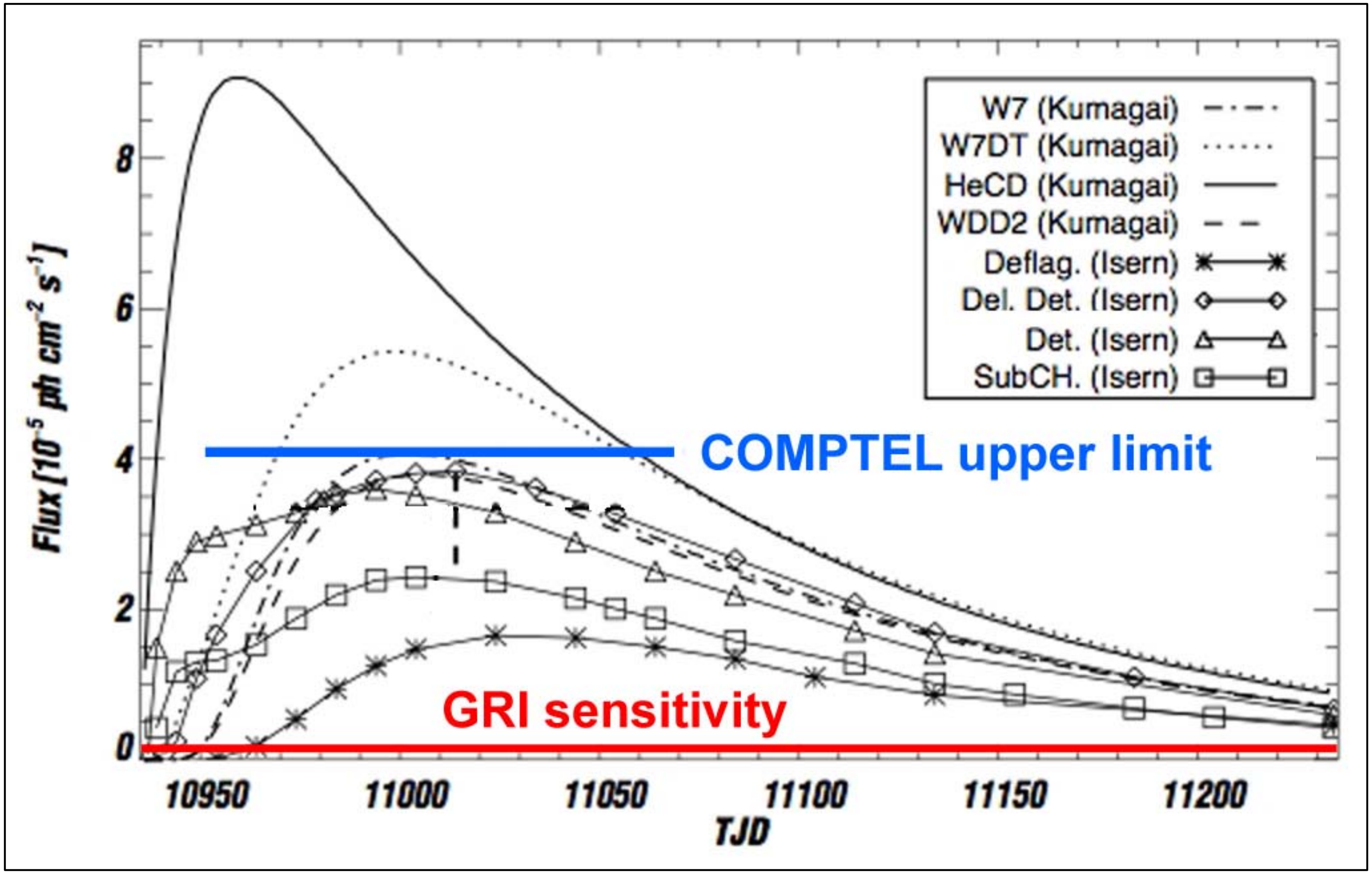
Example: SNIa with COMPTEL vs. GRI

☆ A Narrow-Field Gamma-Ray Lens Could Substantially Advance Sensitivity!



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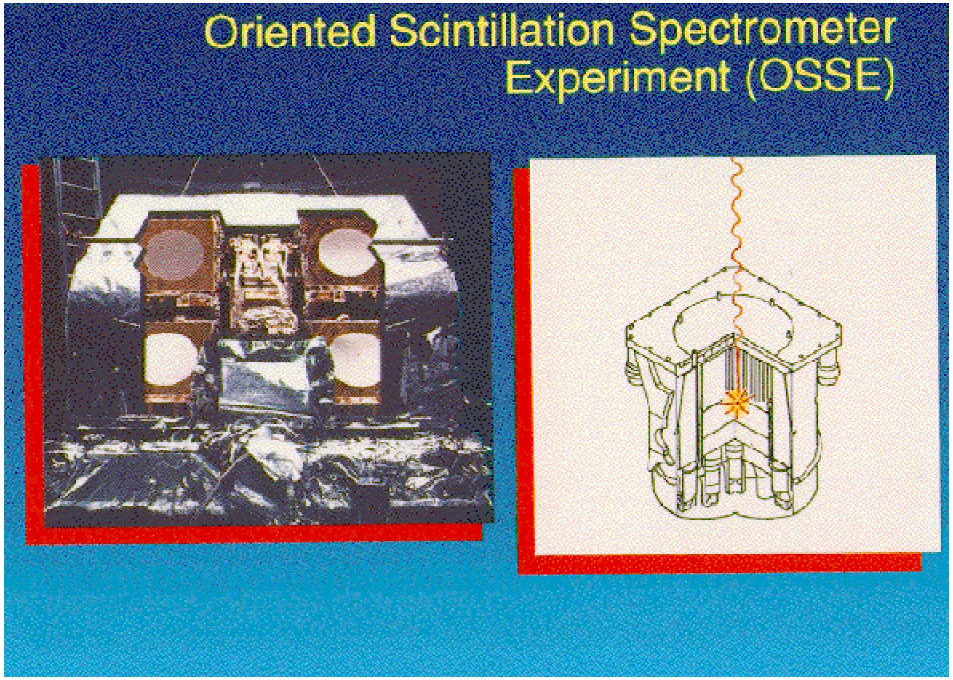
Collimated Gamma-Rays: OSSE on CGRO



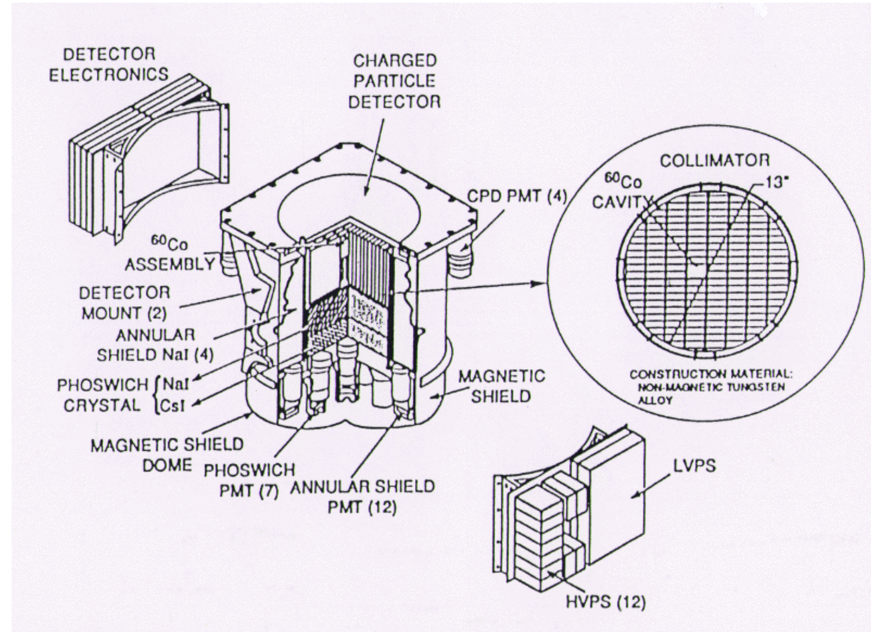
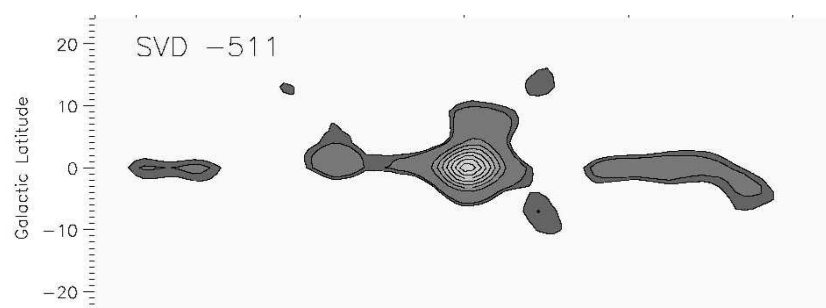


Figure II-2. OSSE Detector Assembly

- ☆ Tungsten Collimators
  - ☞ Field of View 3.8° x 11.4°
  - ☞ Scanning Observations, Deconvolution Imaging Analysis



The Japanese 'NEXT' Mission

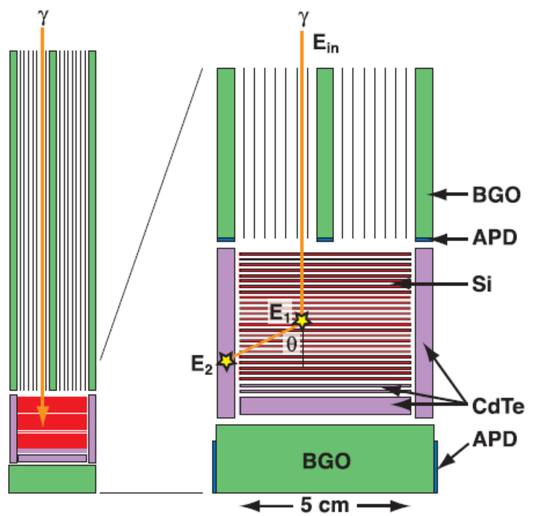
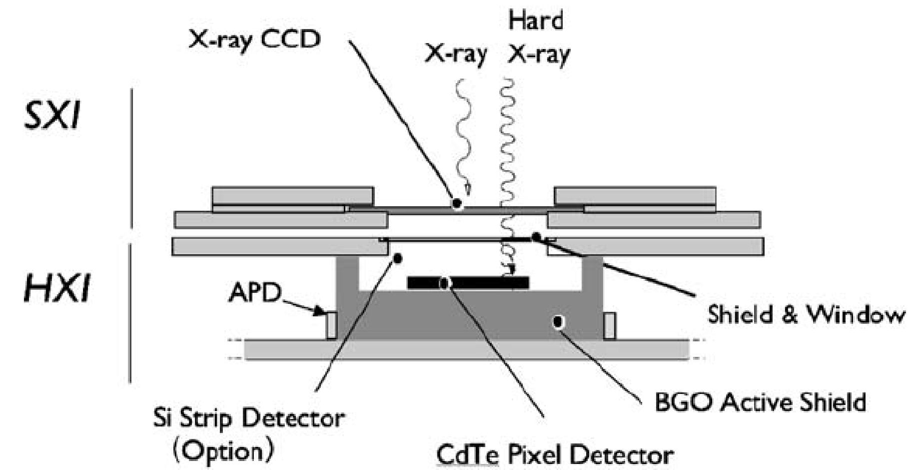
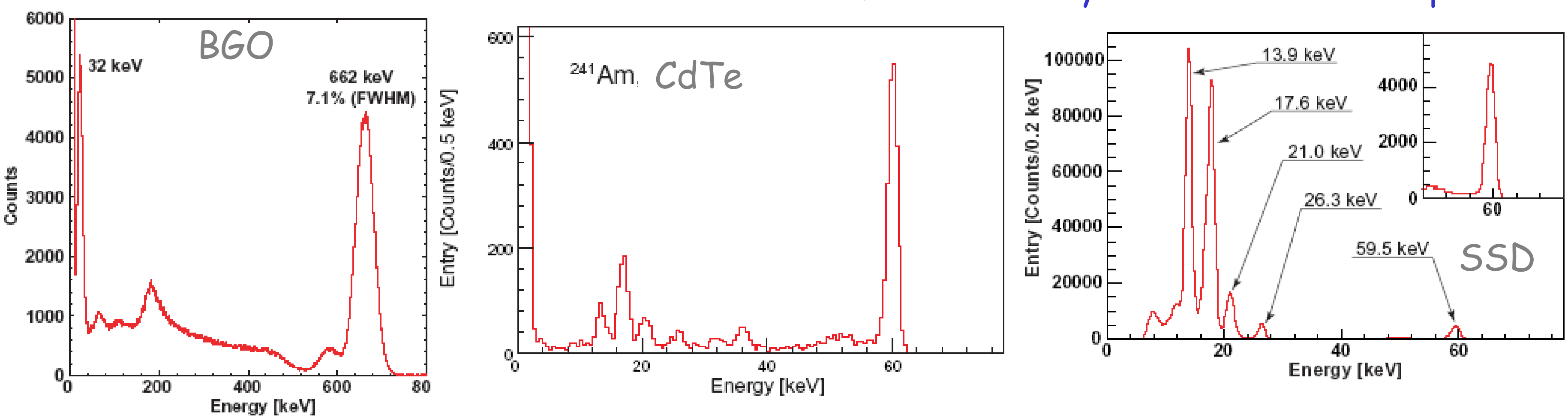


Fig. 1
CONCEPTUAL DRAWING OF A SGD DETECTOR UNIT.



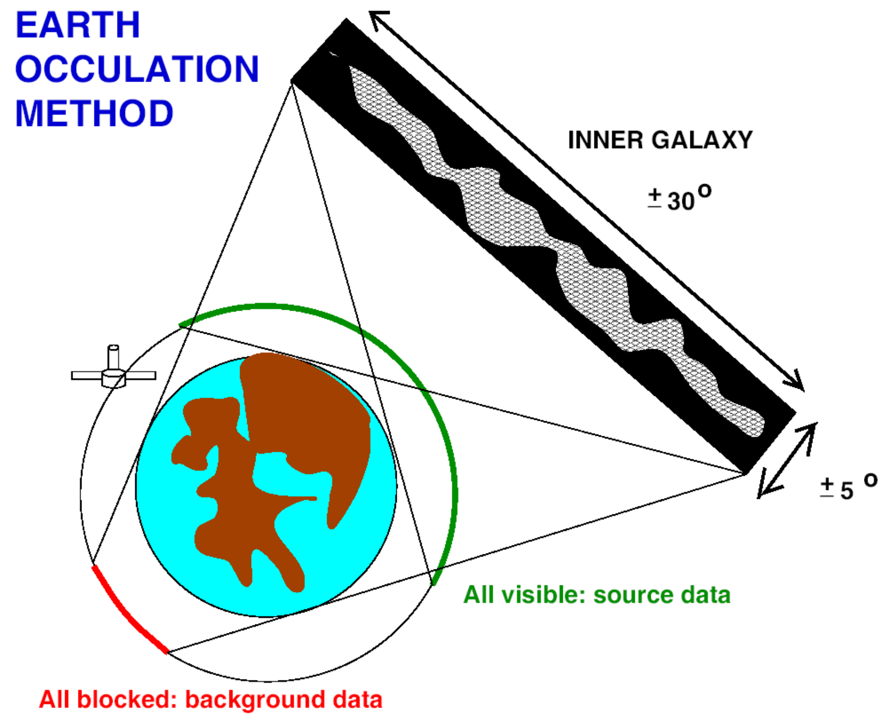
☆ Combination of
- ☞ Hard-X-Ray Supermirror Telescope
- ☞ Soft Gamma-Ray Collimated Telescope



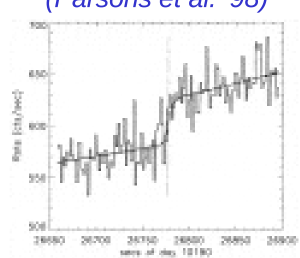
"Imaging" using Earth Occultation

- Data Selection
  - ☆ "Source" = Region of Interest Exposed
  - ☆ "Background" = Region of Interest Behind Earth

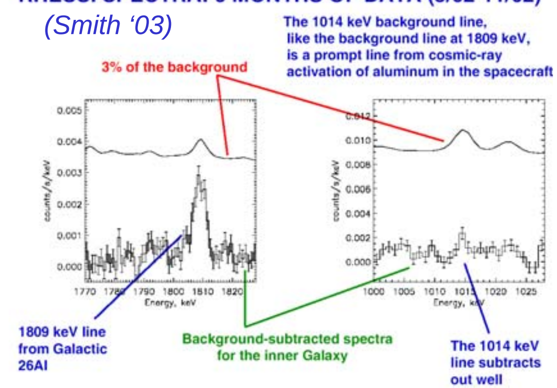
- Applications
  - ☆ BATSE on CGRO
    - ☞ Monitoring of Point Sources; *Harmon et al. 1991; …*
  - ☆ RHESSI
    - ☞ Imaging Diffuse Galactic Emission; *Smith 2003*



BATSE NGC 4151
(Parsons et al. '98)



RHESSI SPECTRA: 9 MONTHS OF DATA (3/02-11/02)
(Smith '03)



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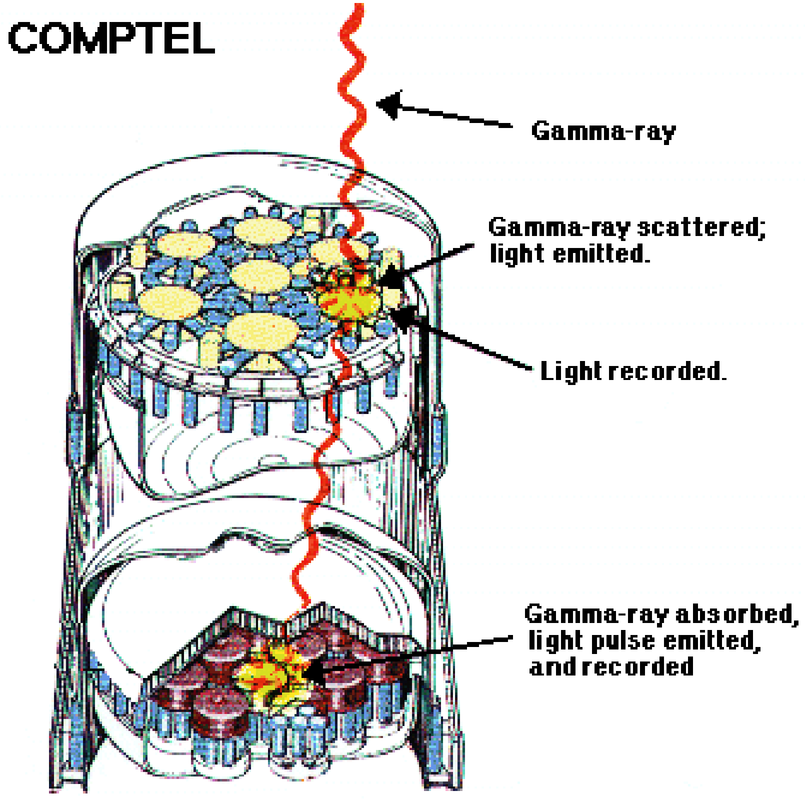
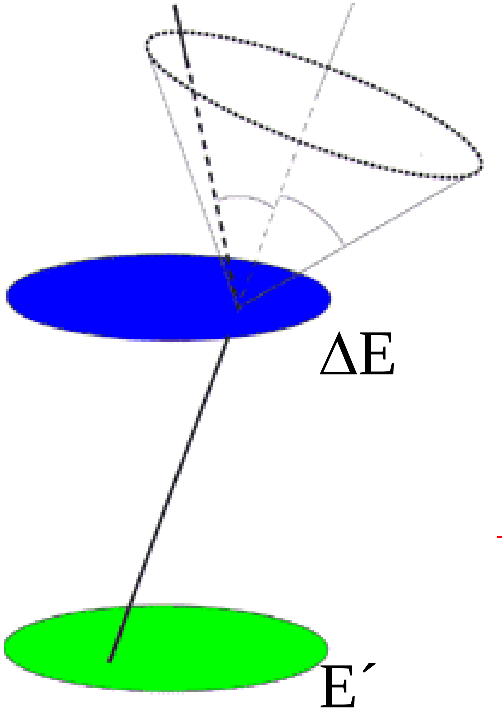
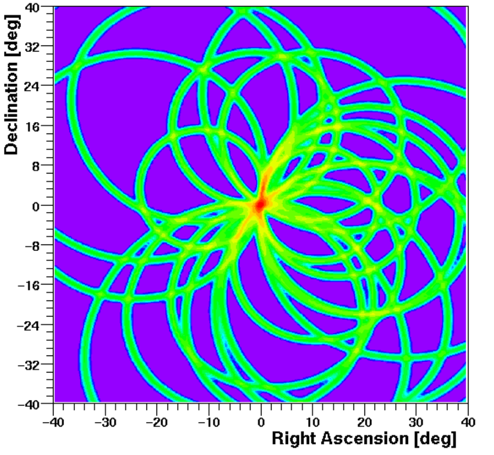
The Imaging Compton Telescope

Compton Scattering: A Coincidence Technique



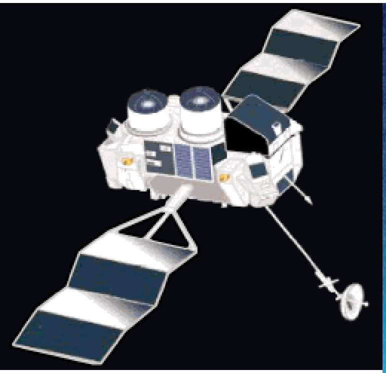


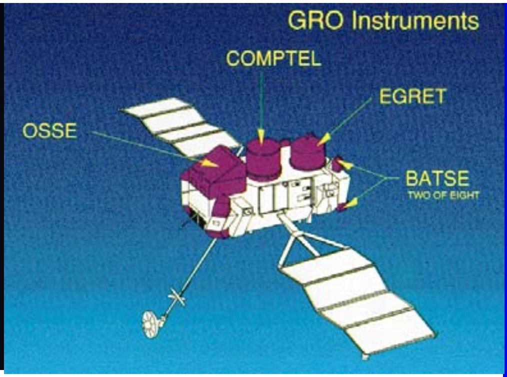


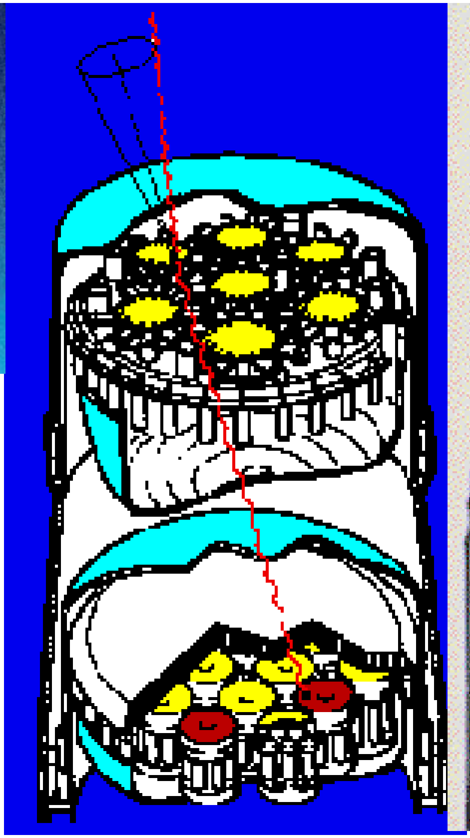
$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

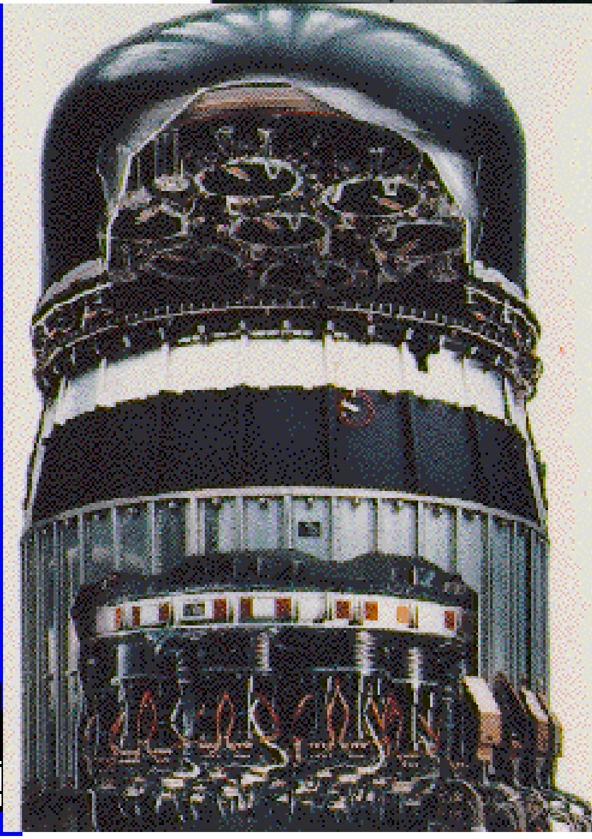
$$\varphi_{geometric} = \arccos\left\{1 + m_e c^2\left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma - \Delta E}\right)\right\}$$

Pioneering Space Compton Telescope: COMPTEL on CGRO (1991-2000)

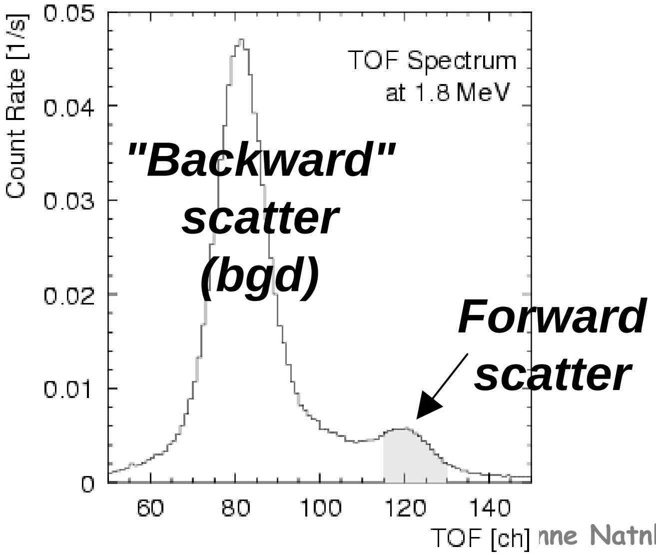






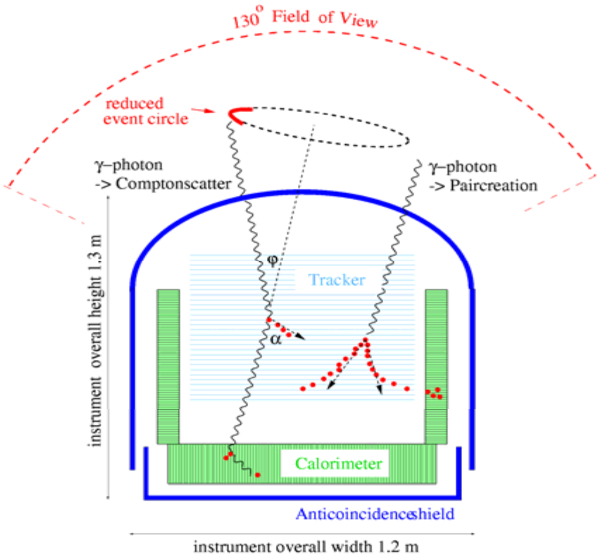


Interaction sequence obtained by time-of-flight (TOF) measurement.

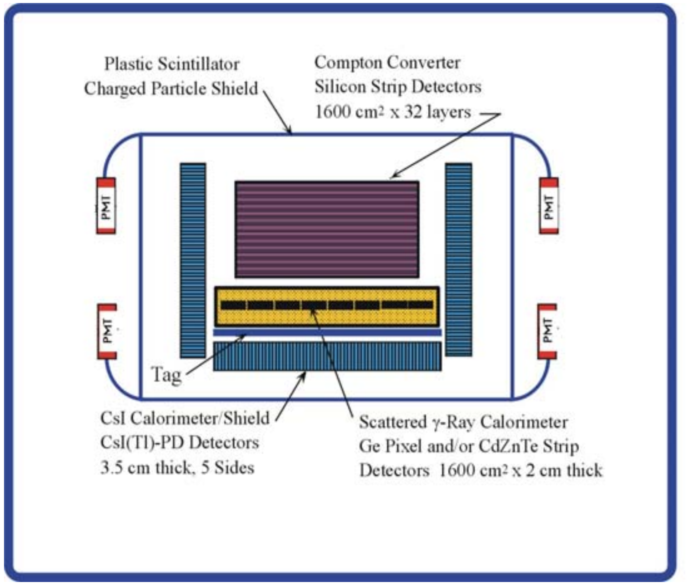


Advantage: clear separation of forward and backward events.
Disadvantage: low efficiency due to solid angle effect.

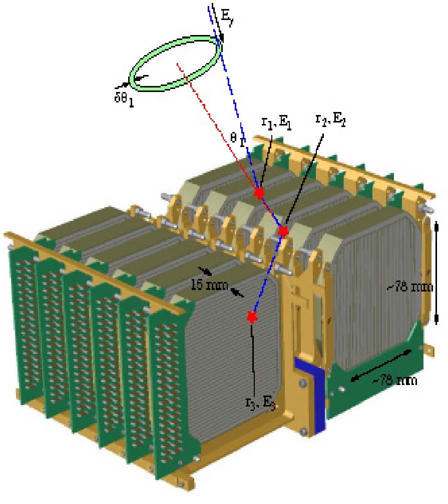
Compton Telescopes



GRIPS



TIGRE



Nuclear Compton Telescope (NCT)

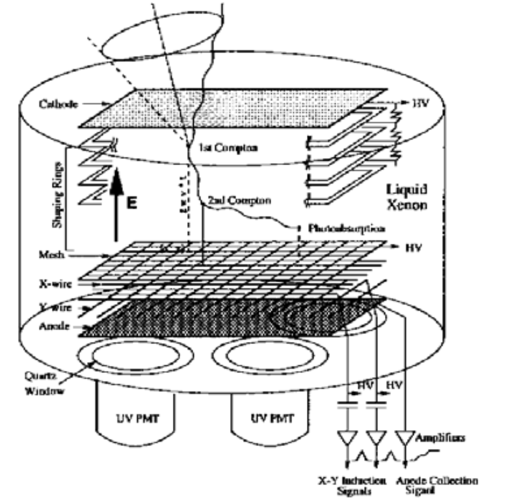
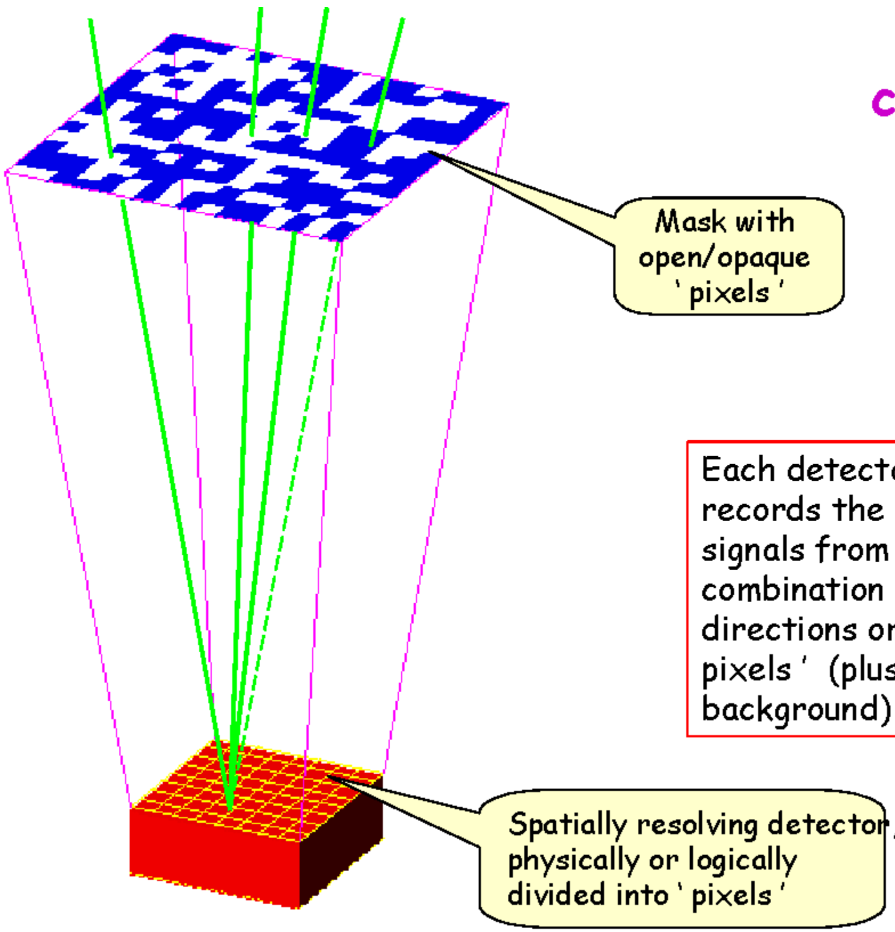


FIGURE 1. Schematic of the liquid xenon time projection chamber

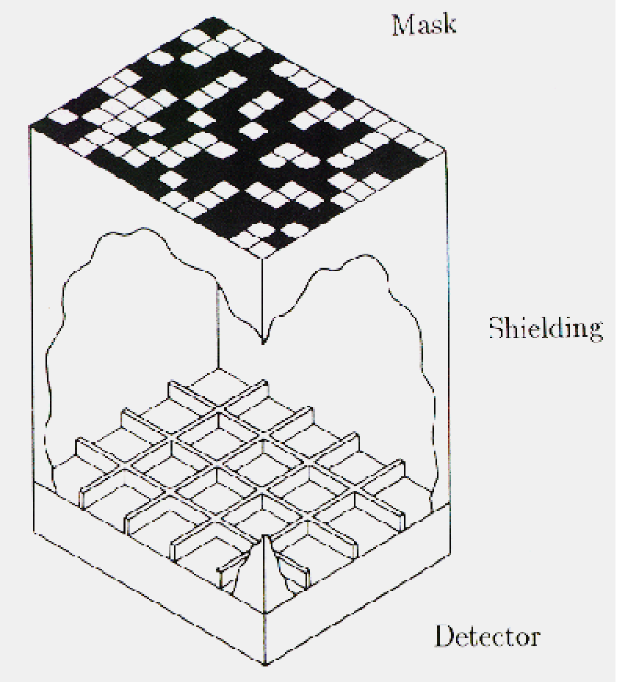
LXeGRIT

Coded Mask Imaging

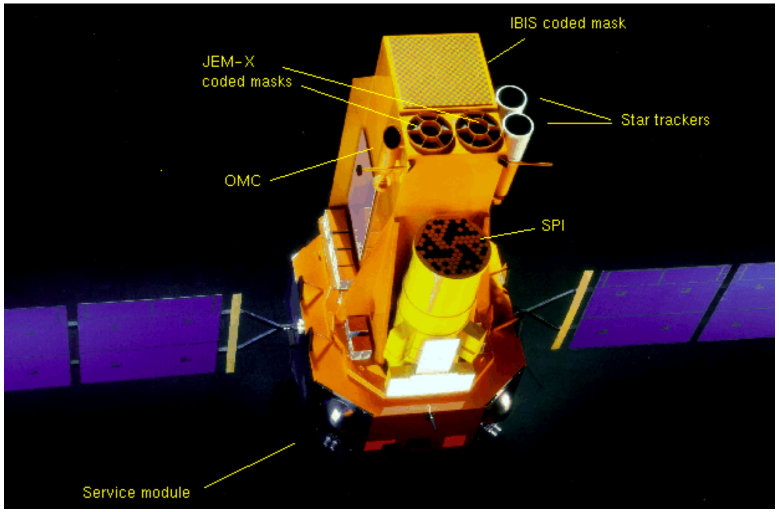
A generic coded mask telescope



Each detector pixel records the sum of the signals from a different combination of incident directions or 'sky pixels' (plus background)



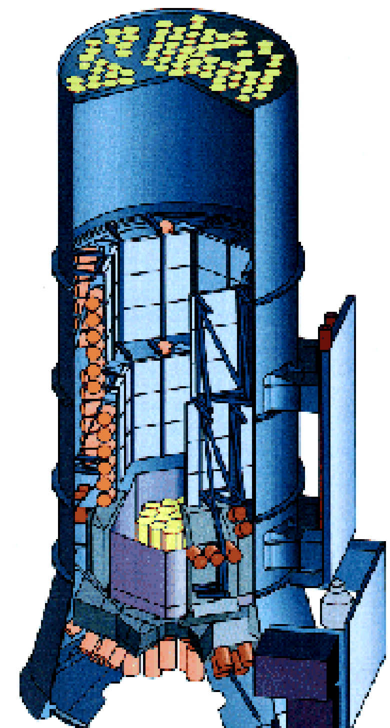
INTEGRAL: Ge γ-Spectrometry in Space!

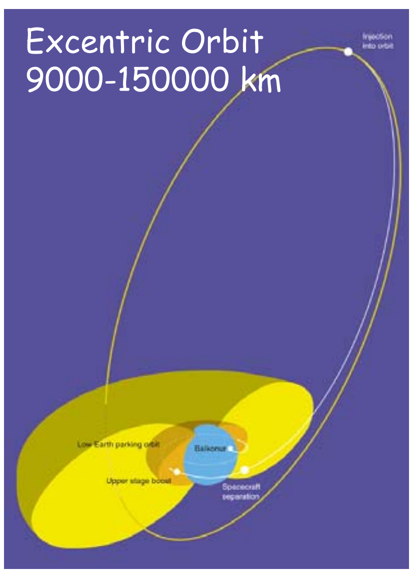


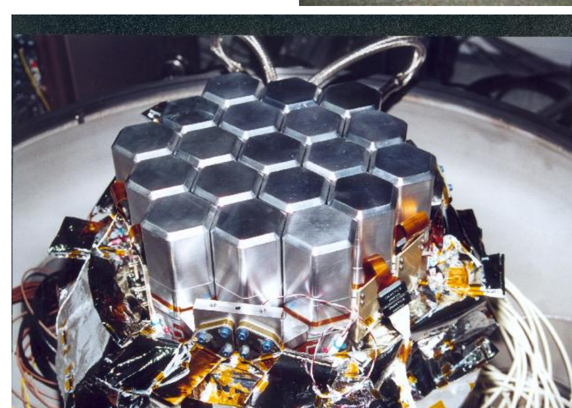
17 October 2002:
06:41 Launch from Baikonur / Kasachstan

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°

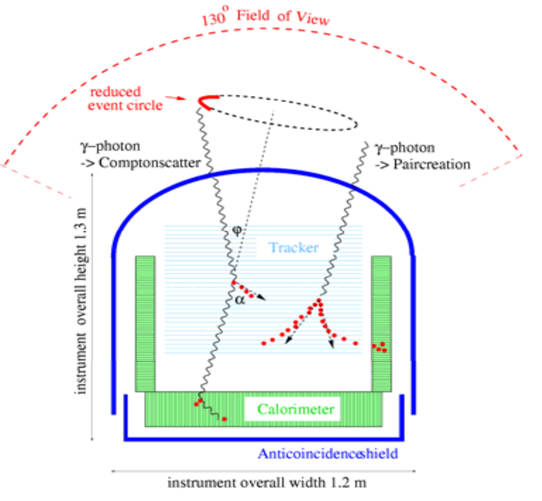




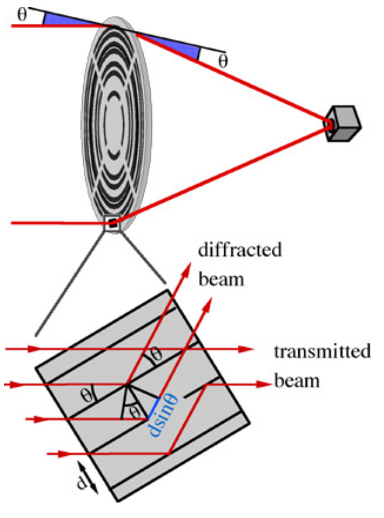


Future Mission Options: 0.1…100 MeV

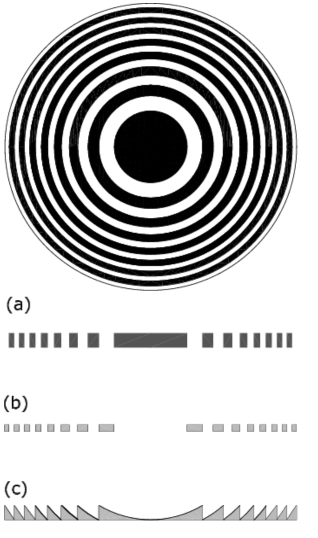
Large Area Coded Aperture--(EXIST…)



Advanced Compton Telescopes (MEGA, ACT)



Laue Gamma-Ray Collector (Max)



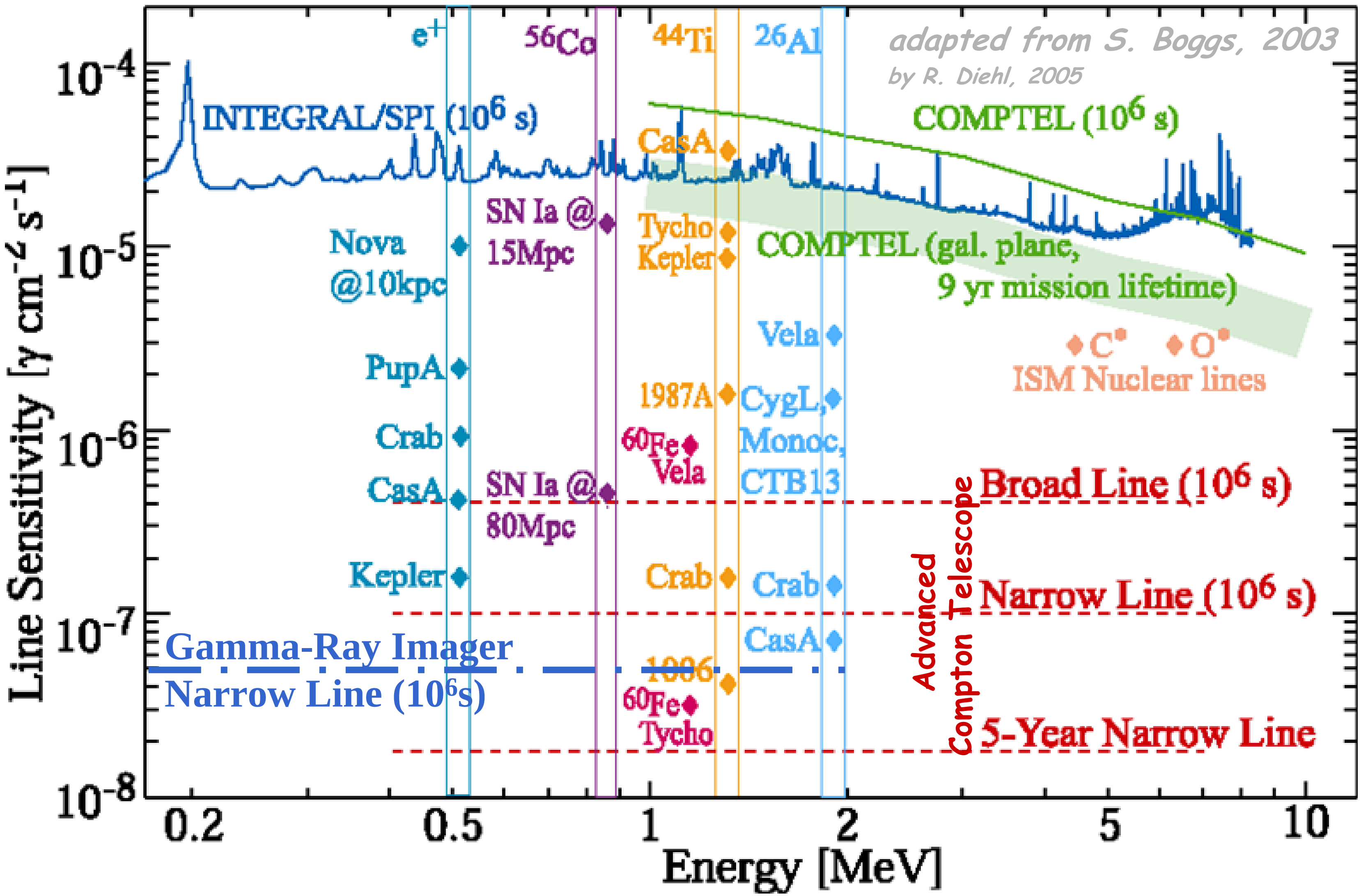
Gamma Ray Fresnel Lens (Multiple Spacecraft)

Astronomy in the Range of Nuclear Lines

- Sources of Cosmic Gamma Ray Line Radiation:
  - ☆ Typical Intensities ~10^{-3}... 10^{-6} ph cm^{-2} s^{-1}
  - ☆ Embedded / Occulted Sources
  - ☆ Examples:
    - ☞ Interstellar-Medium Interactions
    - ☞ Cosmic Radioactivities

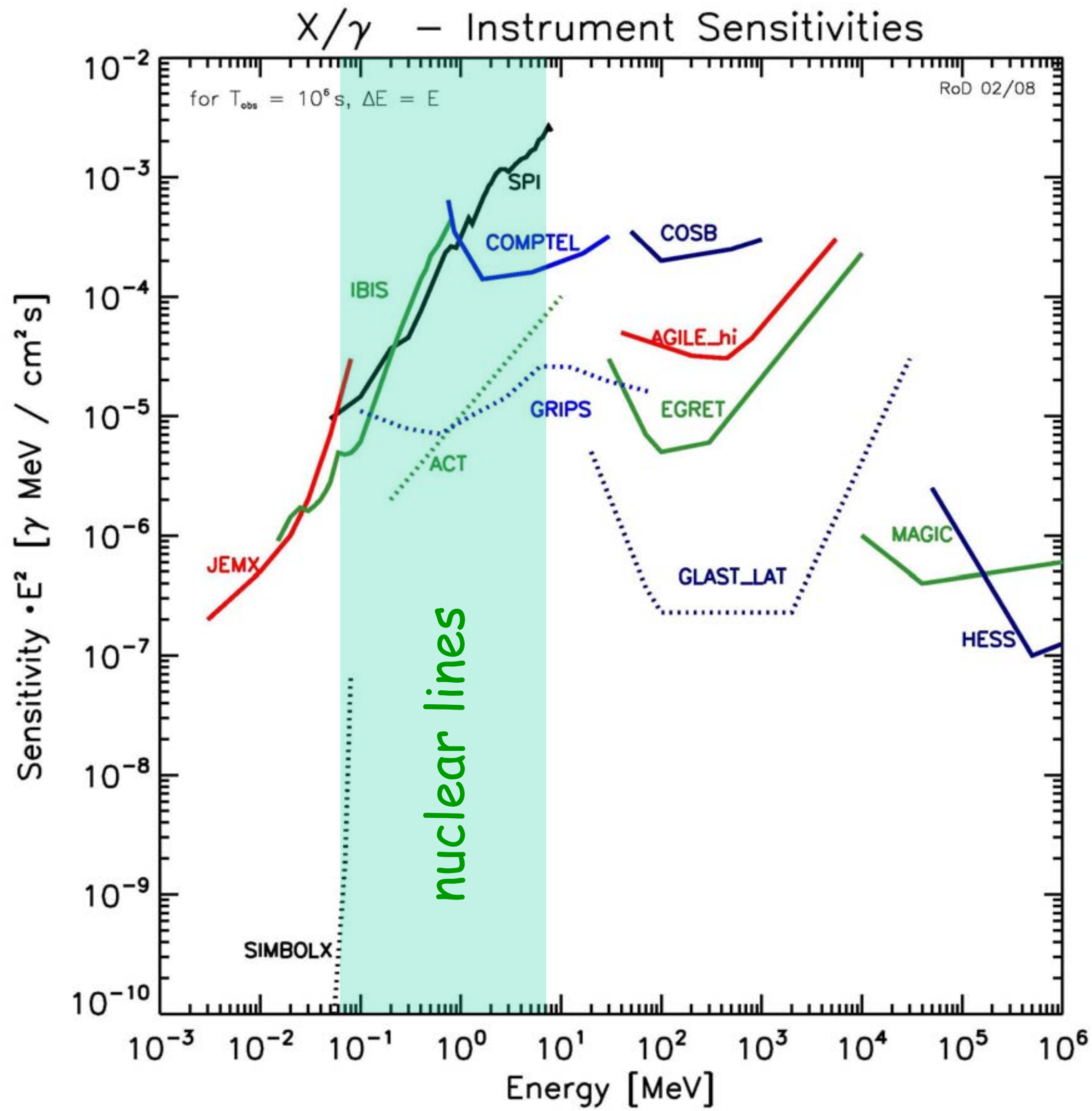
- Instrumental Constraints:
  - ☆ Low Interaction Cross Sections
  - ☆ No/Problematic Reflecting Surfaces
  - ☆ Instrumental Background from Cosmic-Ray Activation

Future Goals for γ-Ray Line Astronomy



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

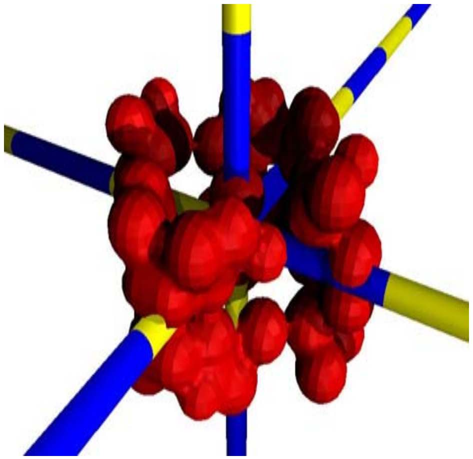


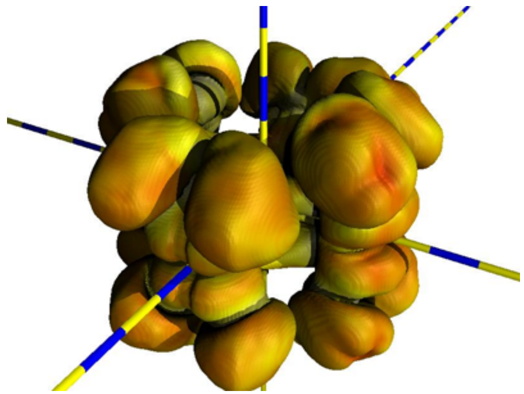
What Did We Achieve?

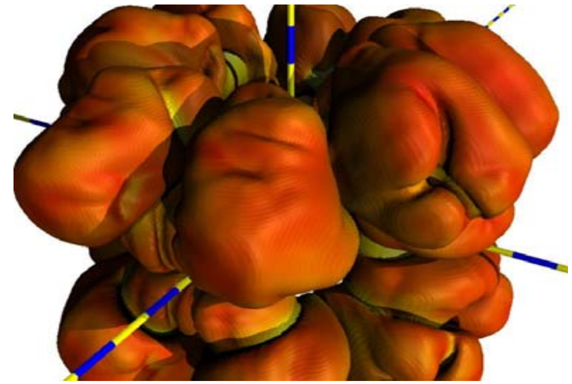
☆ Comments on Science Results, and How They Have Been Obtained

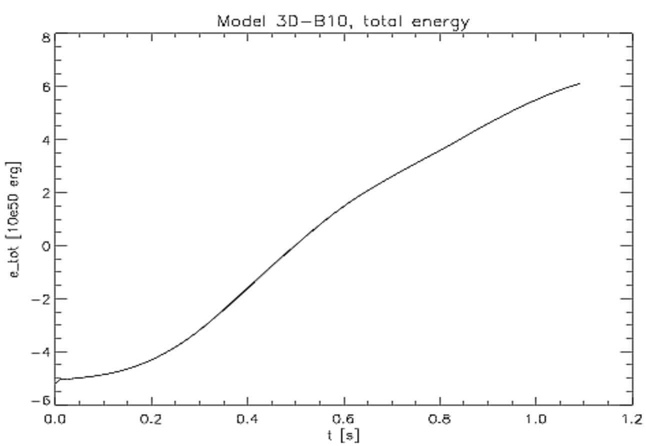
A Supernova

How Does a SNIa Explode?







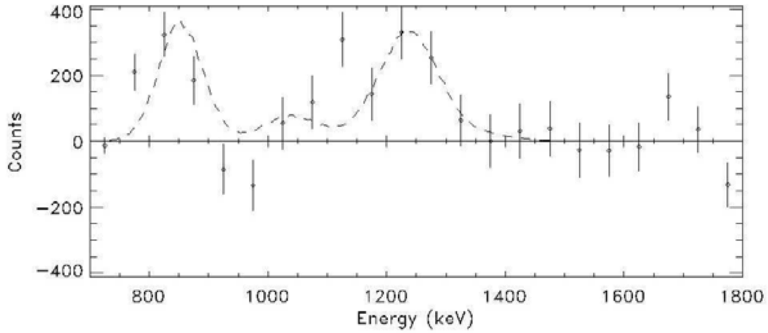


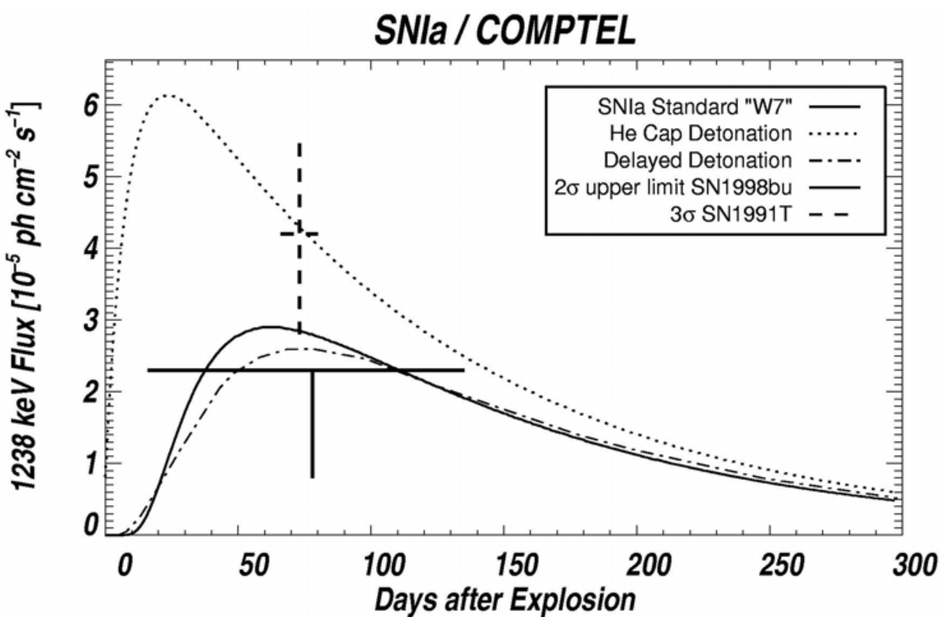
- C Ignition at M_{Ch} Limit (possibly many ignition points)
- Turbulent Flame Propagation
- WD Expansion -> Flame Extinction

- Issues: Rapid Time Scales!
  - Nuclear Burning C+O->^{56}Ni...
  - Expansion
  - Mixing

☞ Measure Amount and Velocity Distribution of ^{56}Ni Directly in γ-Rays!

Gamma-Rays from Supernovae Ia





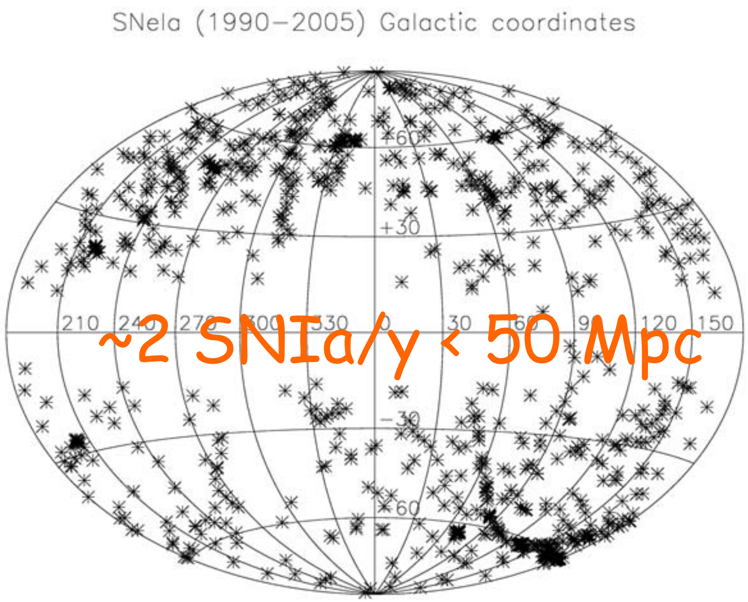
- Rarely SNIa ^{56}Ni Decay Gamma-Rays are Above Instrumental Limits ($\sim 10^{-5}$ ph cm^{-2} s^{-1})
  - ~2 Events / 9 Years CGRO
  - ~2 Events / 2 Years INTEGRAL Mission
- COMPTEL
  - ☞ Signal from SN1991T (3σ) (13 Mpc) -> 1.65 $M_\odot$ of ^{56}Ni!
  - ☞ Upper Limit for SN1998bu (11 Mpc)

☆ The ^{56}Ni Power Source: 0.5 M_o of ^{56}Ni??

☆ Which Model Flavor?

- ☞ W7 / HeD / DDT / DD /...

Still No Luck with SNIa Events



~2 SNIa/y < 50 Mpc

- ☆ Spectroscopy Can Discriminate Between Models only for Nearby (hence rare) SNe (<5 Mpc)

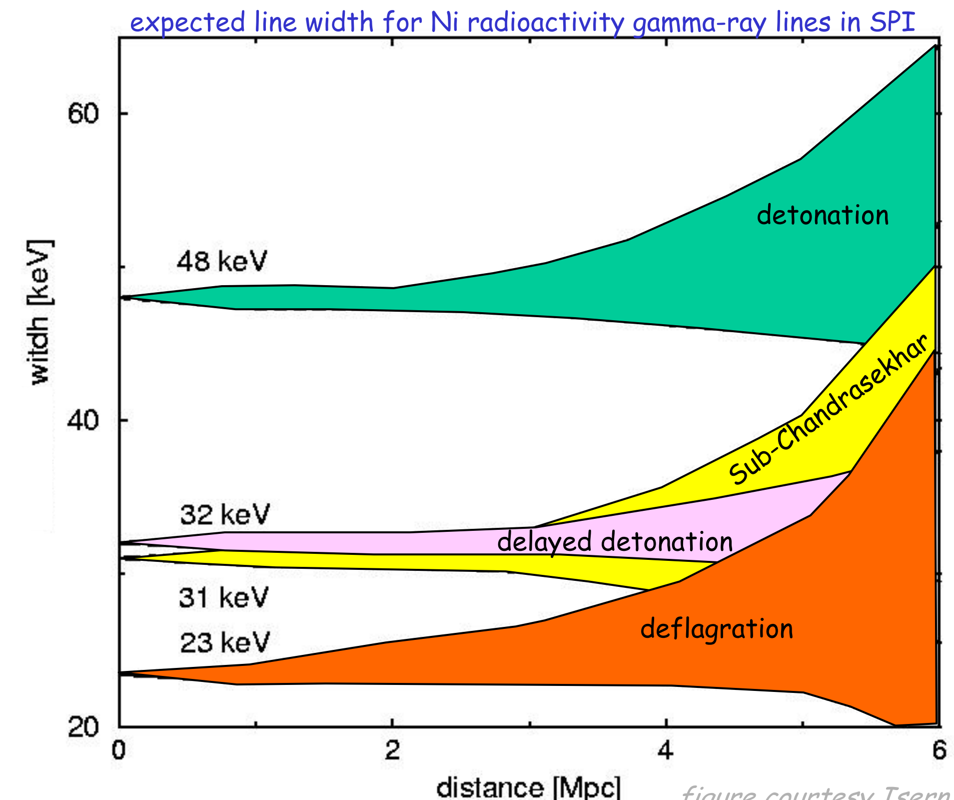
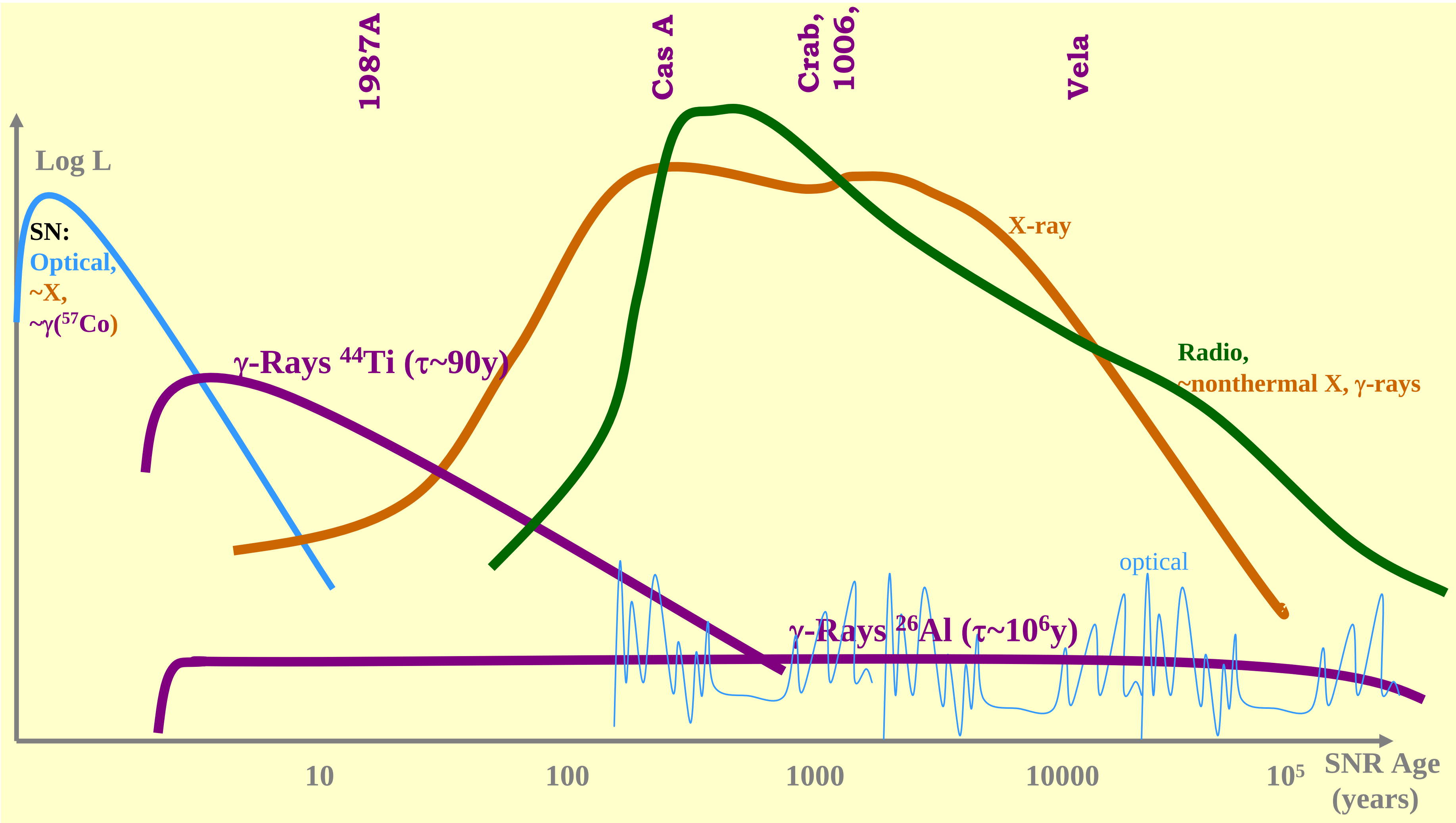


figure courtesy Isern

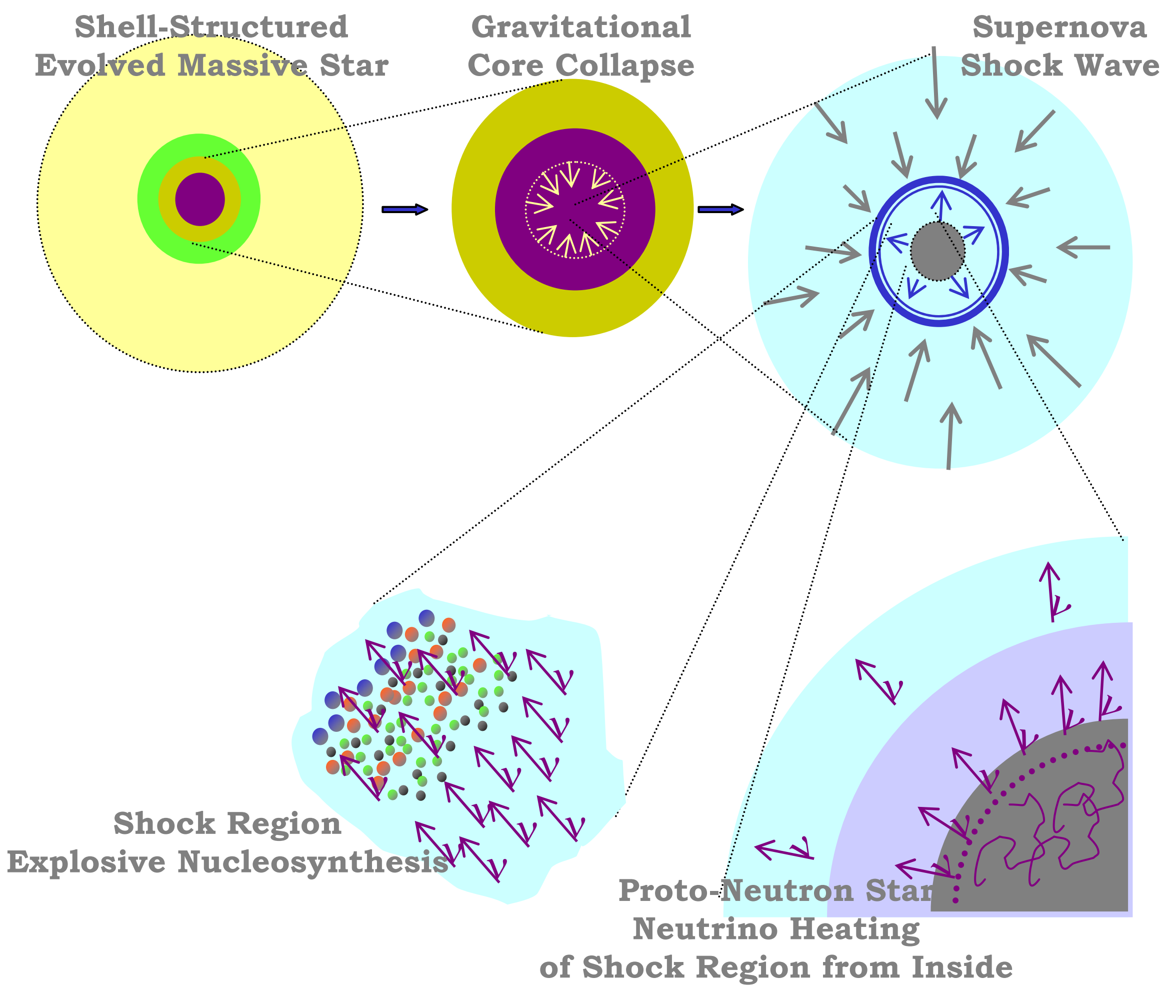
Supernova Remnants: Evolutionary States

Gamma-Rays Can Extend Presently-Favourable X/R/O Regime:

- ☆ Search for New SNR
- ☆ Diagnostics from Line Shape & Light Curve



Core Collapse-Supernovae: Model



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

Nuclear-Physics Issues in CC-Supernova Models

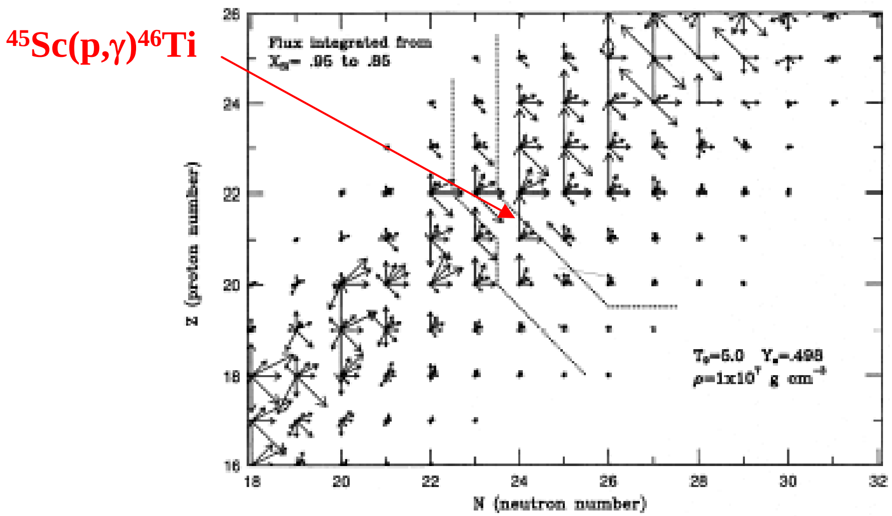
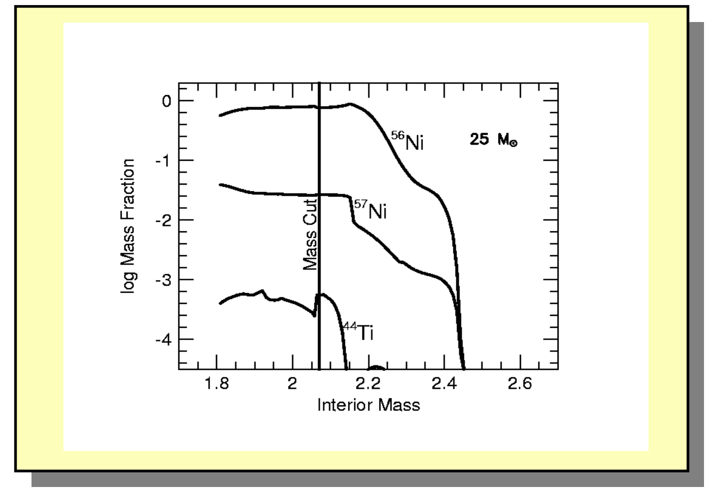


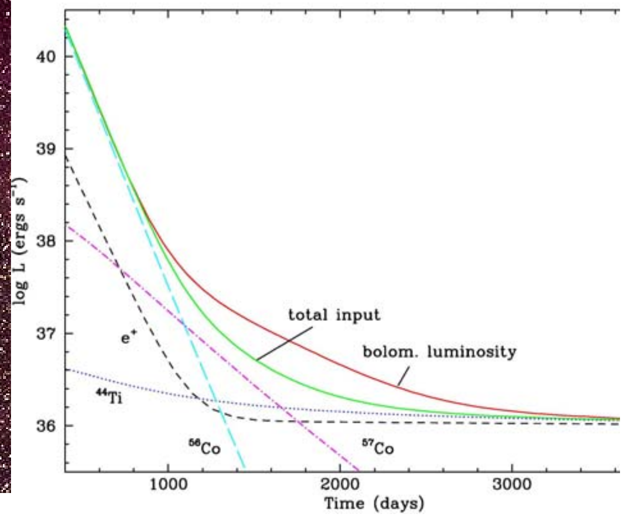
FIG. 6a



- 3D-Effects Important for Energy Budget AND Nucleosynthesis
- Location of Ejecta/Remnant Separation?

- ^{44}Ti Produced at r < 10^3 km from QSE/Si-Burning & α-rich Freeze-Out,
  => ^{44}Ti Gamma-Rays are Unique Probe (+Ni Isotopes)

SN1987A



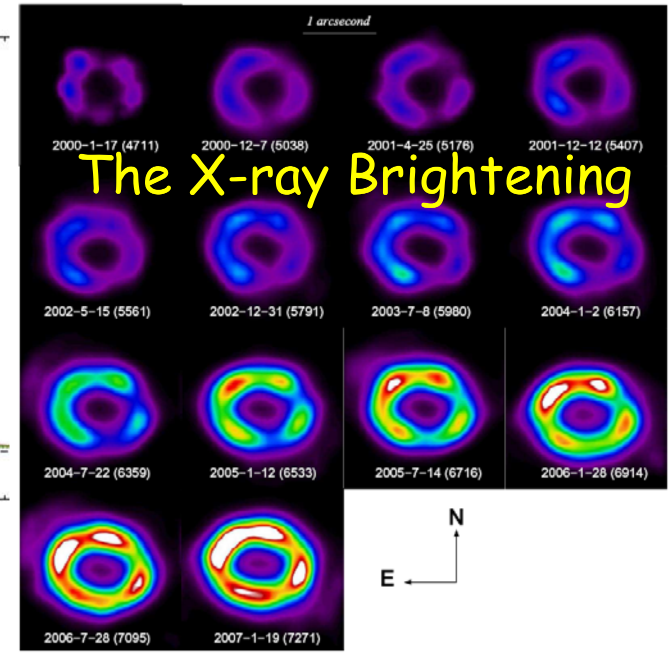


FIGURE 1. *Chandra* ACIS (in the 0.3–8 keV band) false-color images of SNR 1987A. In each panel, the observation date and age (days since the SN, in parentheses) are presented.

- ☆ The late SN light originates in enegy input from ^{44}Ti decay
  - ☞ Estimate from light-curve modelling *(Fransson & Kozma 1993; 2002)*
    - – $(1.5 \pm 1.0)\ 10^{-4}\ M_\odot$ of ^{44}Ti
  - ☞ Estimate from late optical emission *(d2875) (Chugai et al. 1997)*
    - – $(1\text{-}2)\ 10^{-4}\ M_\odot$ of ^{44}Ti
  - ☞ Upper limit from FeII lines in IR (= main emission in late phase) *(25.99 μm, d3999, d3425, Lundquist et al. 1999, 2001)*
    - – $<1.1\ 10^{-4}\ M_\odot$ of ^{44}Ti

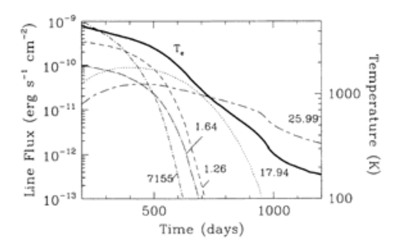


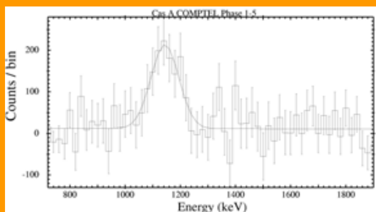
Fig. 1. Evolution of temperature for the iron-rich region in SN 1987A, together with the fluxes of the strongest Fe II lines. The IR-catastrophe is seen to set in at ~ 600 days.

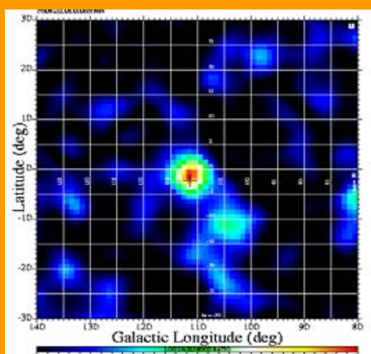
  - ☞ Direct ^{44}Ti Gamma-Ray Measurements not Feasible with Current Instruments

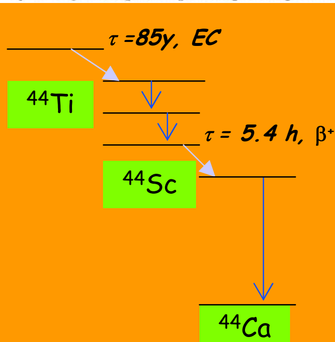
^{44}Ti γ-rays from Cas A

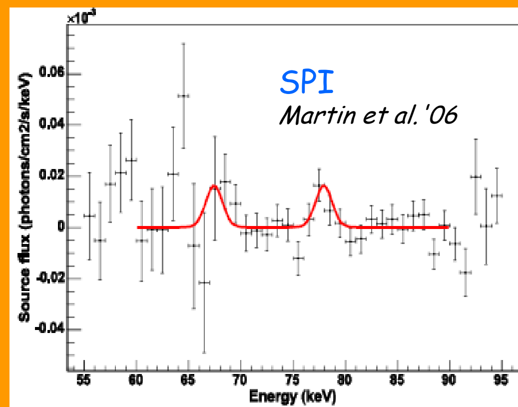
τ=85y (Ahmad et al. 2006)

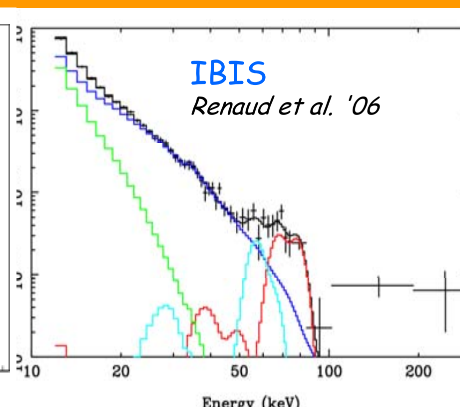
89 y	$^{44}Ti \rightarrow ^{44}Sc^* \rightarrow ^{44}Ca^* + e^+$	78, 68; 1157

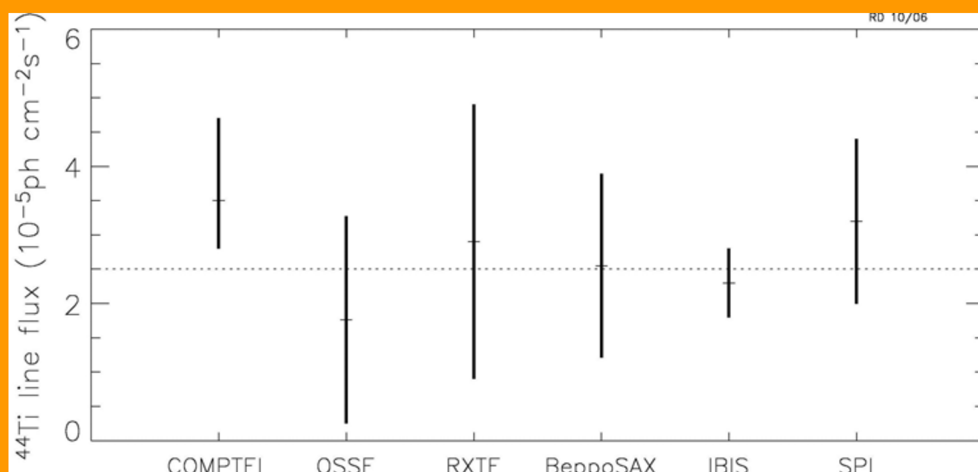


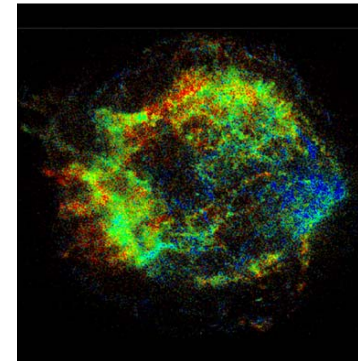


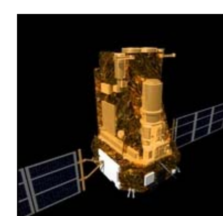






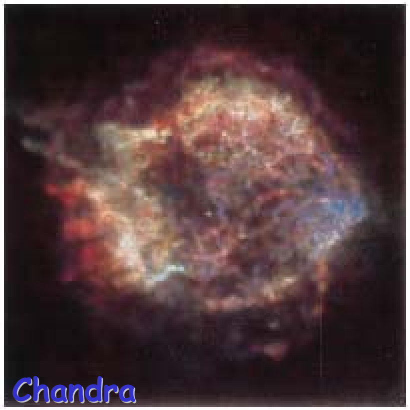






↳ ^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} M_{o}

Cas A: A Well-Studied Young Nearby SNR



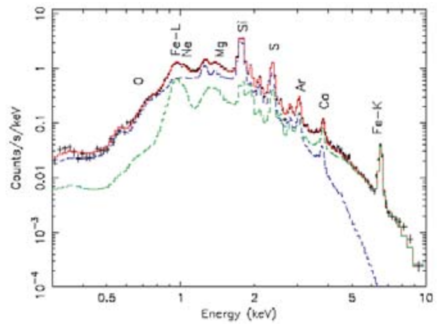
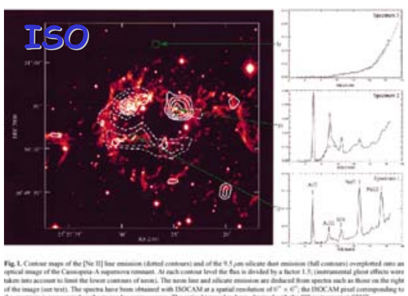
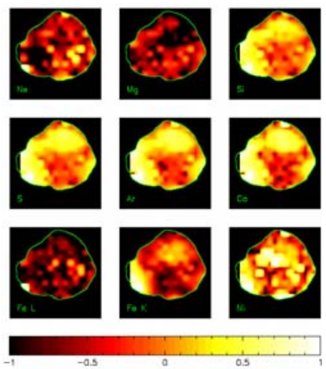
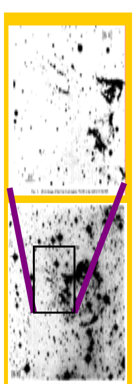


Fig. 2. An example of a spectral fit within a single 20″ × 20″ pixel – cool component in blue, hot component in green and full model in red.

XMM-Newton





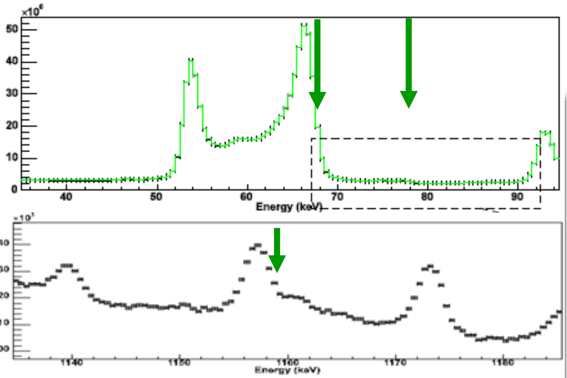


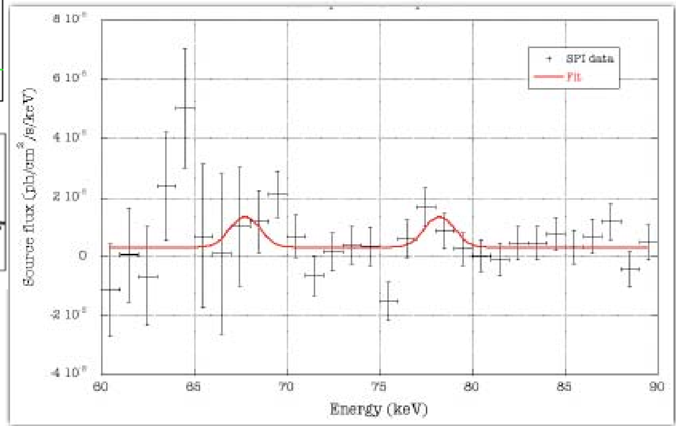
- ~330 year-old SNR at ~3.4 kpc
- Massive Progenitor (10-25 M_o)
- Filaments, Fast Ejecta (knots), Fe-rich Clumps, No Onion-Shell-Like Elemental Morphology, Jet: Asymmetric Explosion
- ^{44}Ti (and ^{56}Ni) Ejection
- Unseen SN -> CSM Dust
- Central Object (NS/BH?)

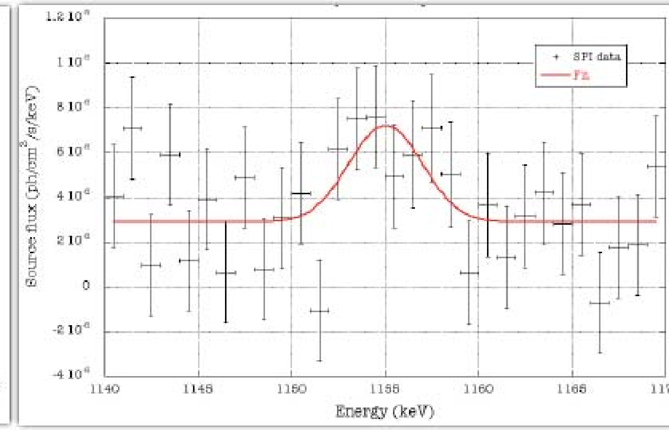
=> (?)

- Core Collapse SN with Unusual Asymmetries?
- ^{44}Ti Emission Affected by Ionization?

SPI and ^{44}Ti from Cas A







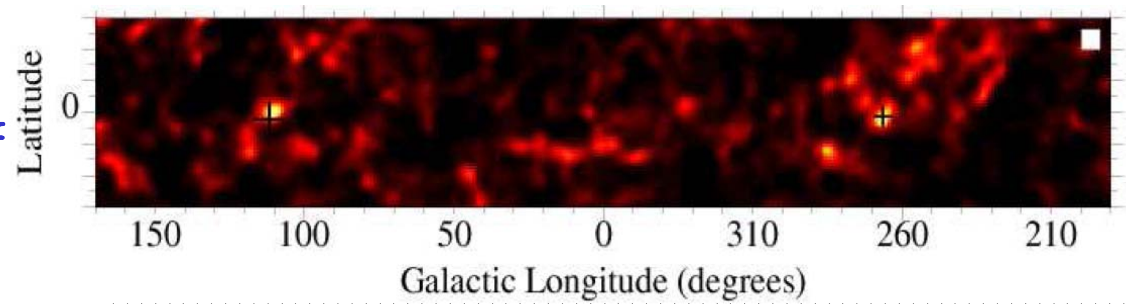
- Joint analysis of all lines with SPI (INTEGRAL's spectrometer)
- Total significance ~3 sigma
- Flux consistent with IBIS $(2.1\pm0.7)\times10^{-5}$ ph cm^{-2}s^{-1}
- Additional line broadening: 430±240 km/s
- Bulk velocity: 500±200 km/s (redshifted, like Fe-K?)
- I.e. ^{44}Ti is within reverse shock (i.e. cold/freely expanding)

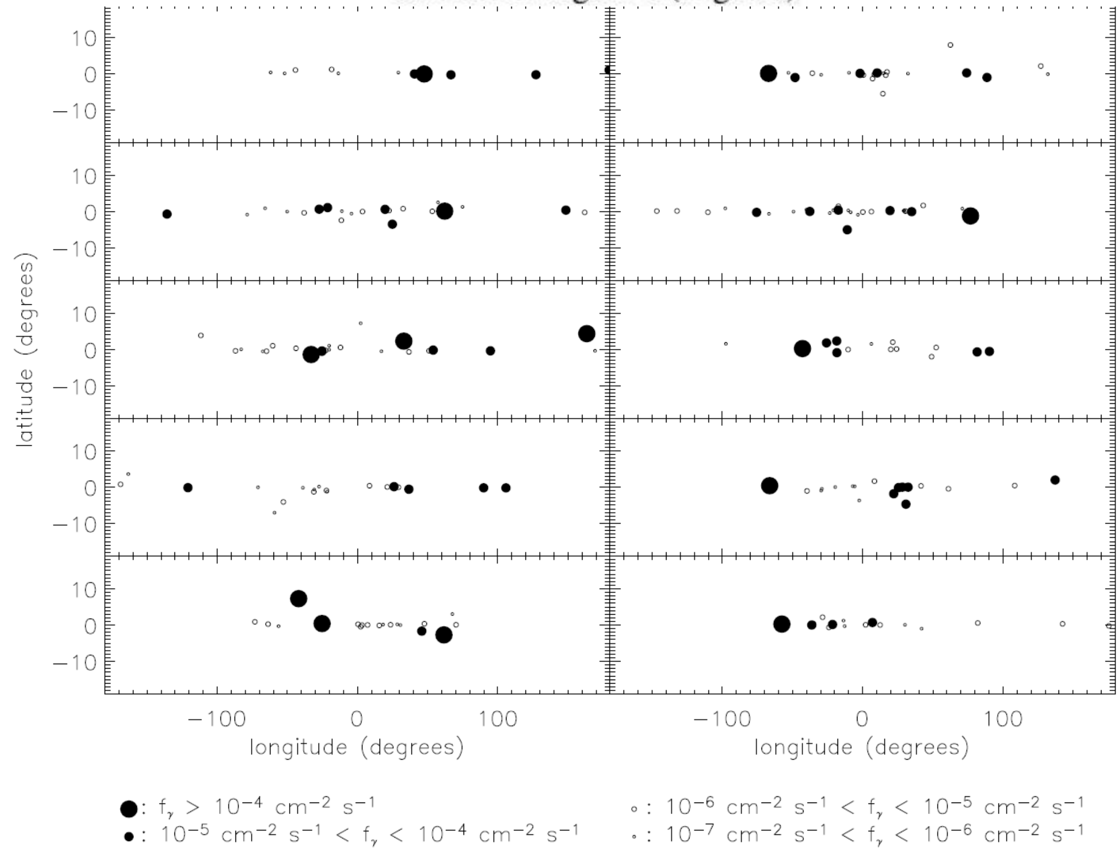
Jacco Vink Integral observations of Cas A: ^{44}Ti properties & hard X-ray continuum 14
Schloß Ringberg, January 8, 2008

- SNR Kinematics with γ-Ray Lines
  - ☞Internal Consistency Checks on Intensity, Systematics

The Sky in ^{44}Ti Gamma-Rays

The et al. 2006

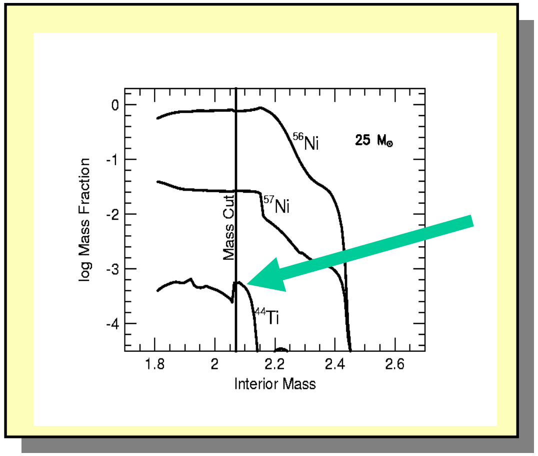


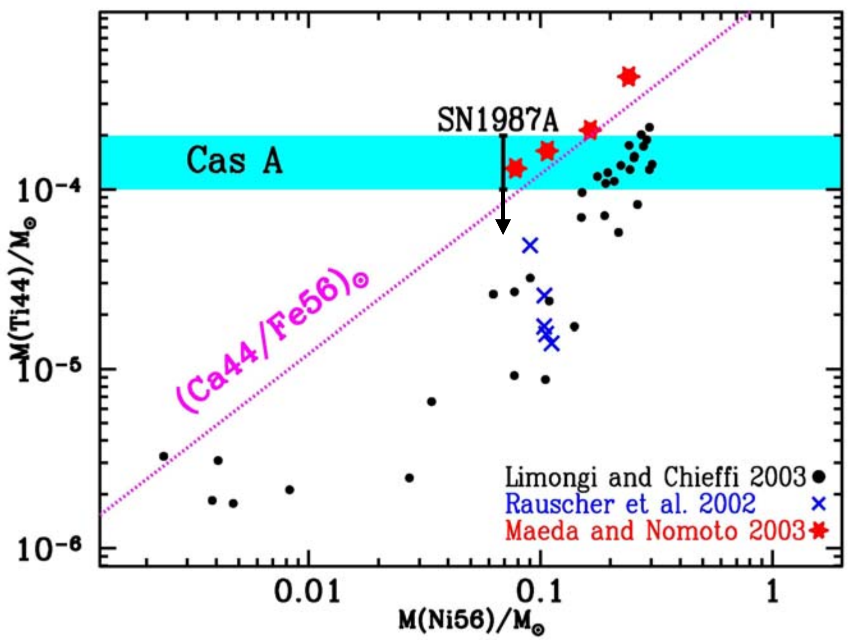


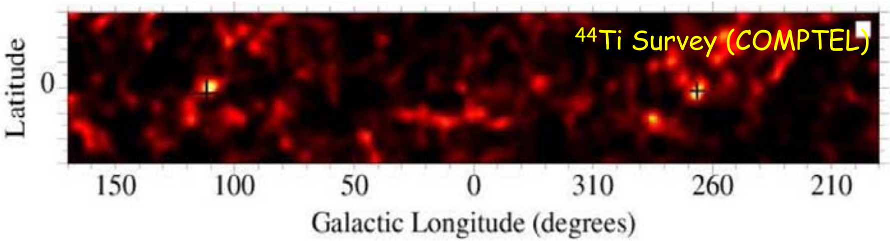
- We do NOT see the Number of Expected Young SNRs
  - ☆ Assumptions
    - ☞ Galactic SNR Spatial Distribution from Massive Stars
    - ☞ cc-SN Frequency 1/30y
    - ☞ SN Yields in ^{44}Ti Must Explain Standard Abundance of ^{44}Ca (= 3* Model Yields)
  - ☆ Expectations
    - ☞ More than a few Sources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

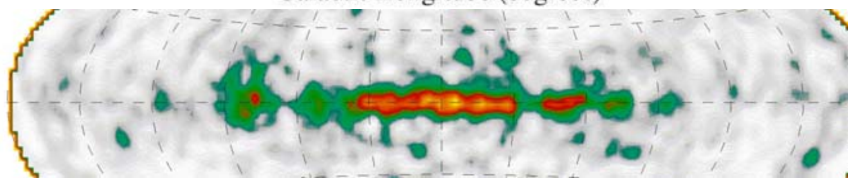
"Normal" Core Collapse Supernovae (?)

- 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)







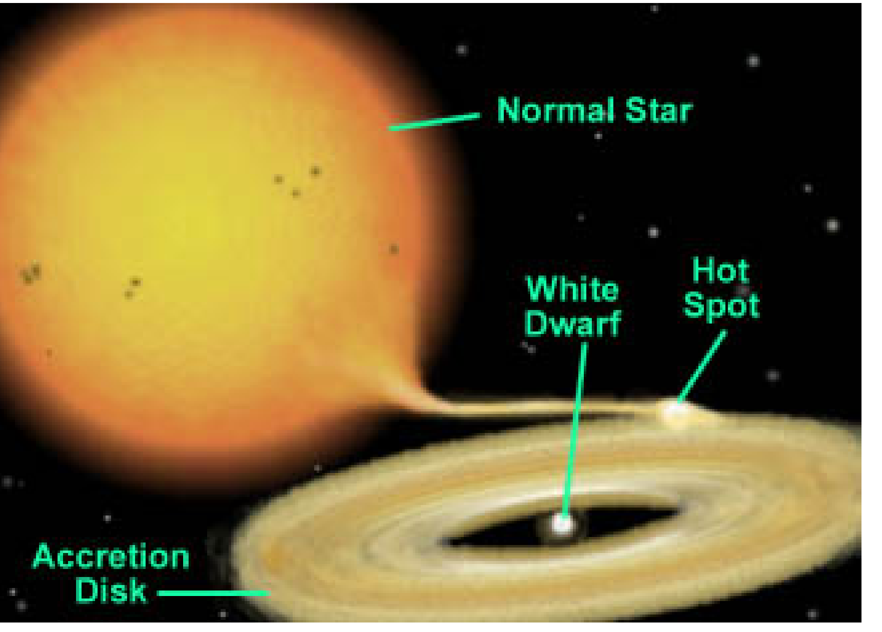


Non-spherical explosions?? (->GRB)

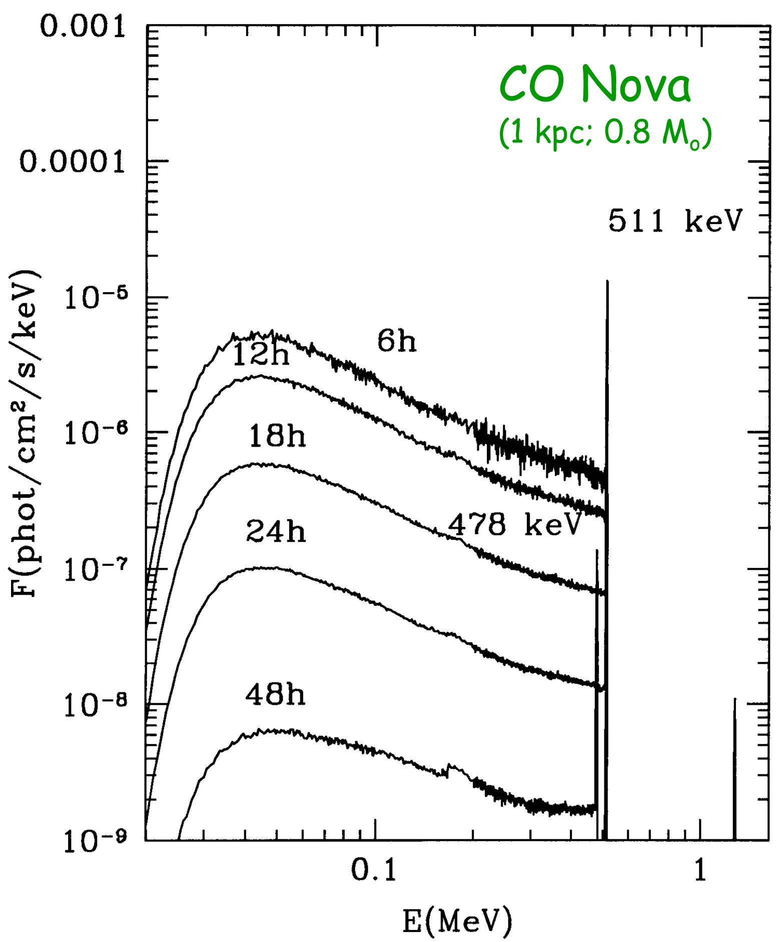
Need Event Statistics, ^{44}Ti Spectra

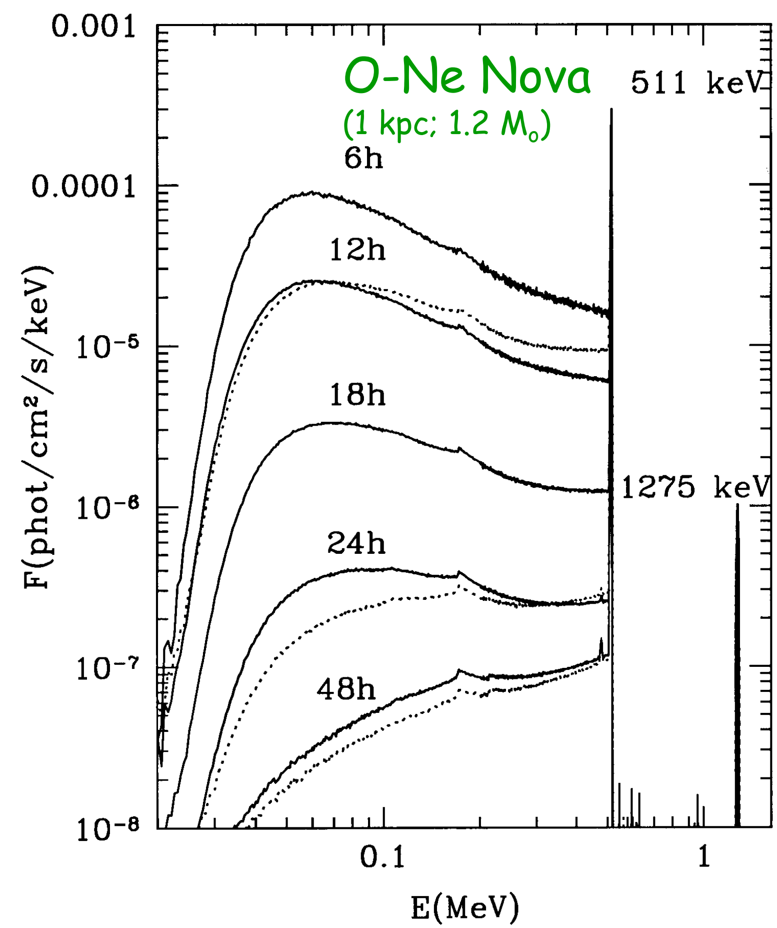
Novae

- Classical Novae:
  - ☆ Accreting WD in Binary System
  - ☆ Runaway H Burning with Nuclear Processing of Upper WD Layer (p process)
  - ☆ Ejection of ~10^{-4} M_o
- Issues:
  - ☞ Burning Time Profile
  - ☞ Fuel Composition and Mixing
  - ☞ Ejected Mass
  - ☞ Nuclear Reactions



Nova Diagnostics with Nuclear Lines



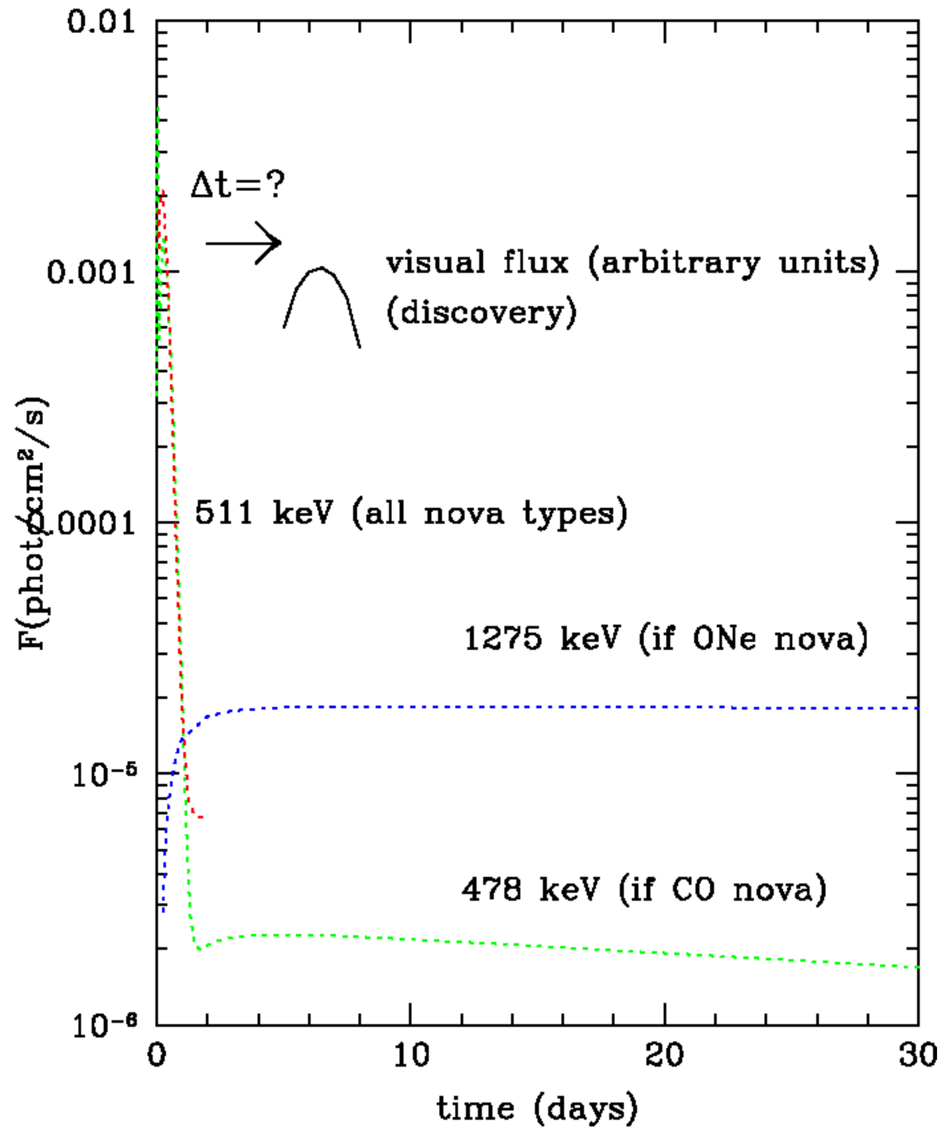


- ☆ Brief Annihilation Flash
- ☆ β Decay Continuum (before optical nova!)
- ☆ ^{22}Na Radioactivity (O-Ne Novae)

Nova Gamma-Ray Light Curves

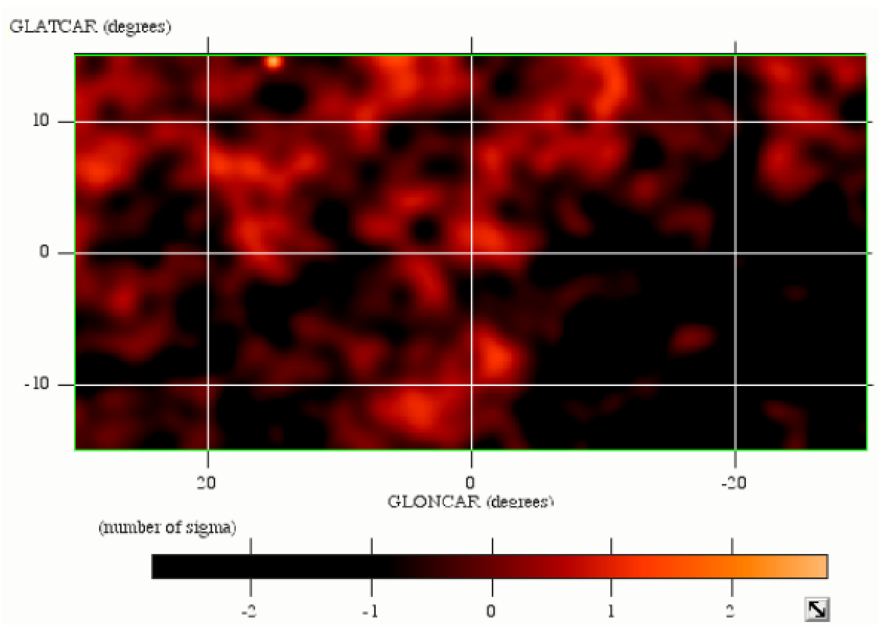
- ☆ Need Sky Survey
  - ☞ Optical Nova (=discovery) After Characteristic Gamma-Ray Signals

– *Hernanz et al., 1997-2003*

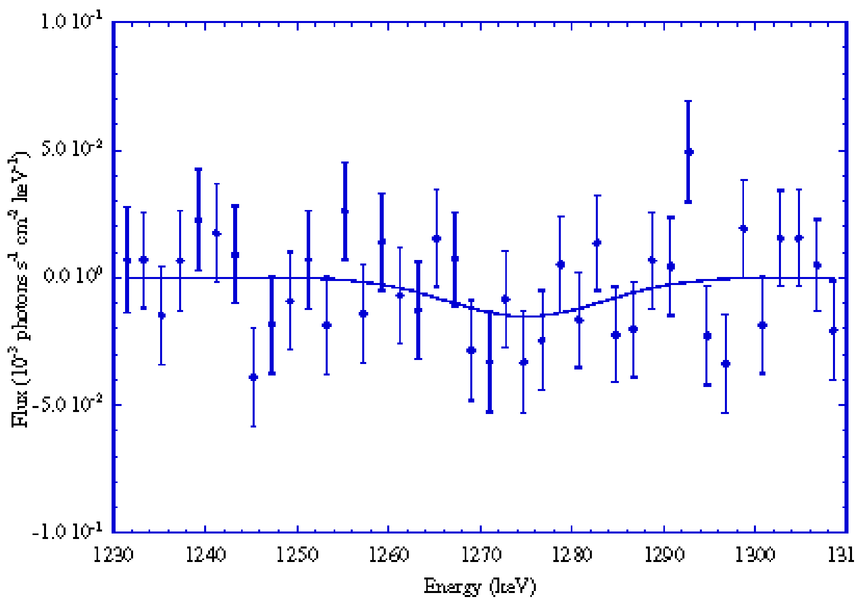


Still No Nova Lines Detected

- Expectations for I_{22Na} ~ Factor 10 Below Instrumental Sensitivities



^{22}Na Line:
SPI Galactic Bulge Skymap



Jean et al. 2005

Testing for a Nova Galaxy Model

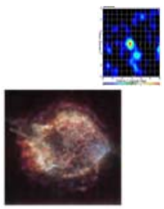
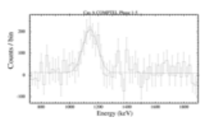
Partial Summary:
Methods of Cosmic Gamma-Ray Measurements

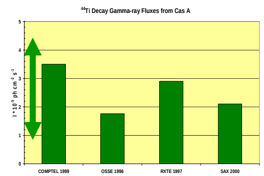
- Gamma-Ray Telescopes are Complex Instruments
  - ☆ Focusing Optics is Hardly Obtainable
  - ☆ Casting a Shadow is a Working Compromise
  - ☆ Multi-Detector Coincidence Instruments are Most Promising
  - ☆ Backgrounds from Internal Radioactivity are High
  - ☆ Analysis Techniques are Based on Constrained Deconvolutions
- Future Experiments/Mission Opportunities are Rare
  - ☆ ESA's Cosmic Vision Program for a 'Gamma-Ray Imager'?
  - ☆ National Programmes for Small Missions (Max, Simbol-X,...)?
  - ☆ A Future US Perspective for ACT?
- The Brightest Sources Have Been Seen
  - ☆ ^{26}Al Line Science is an "Astronomy"
  - ☆ ^{60}Fe and e+ Annihilation Adds Specific Aspects
  - ☆ ^{44}Ti is a Key Diagnostic for SN Interiors

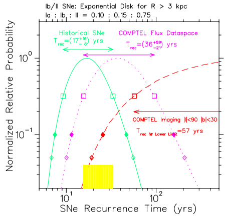
Gamma-Ray Lines Constraints on Cosmic Nuclei: Summary (I)

- Live Cosmic Nucleosynthesis Detected. More?
  - ISM: e^+ ^{26}Al ^{60}Fe; SNae: ^{56}Ni, ^{57}Ni, ^{44}Ti ^{22}Na?
- Cosmic Nucleosynthesis Environments Being Studied

☆ ^{44}Ti

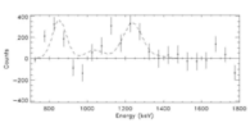
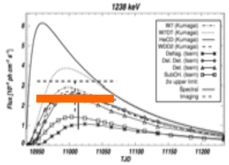







Thank you!

☆ ^{56}Ni

☆ ^{26}Al and e^+ Annihilation