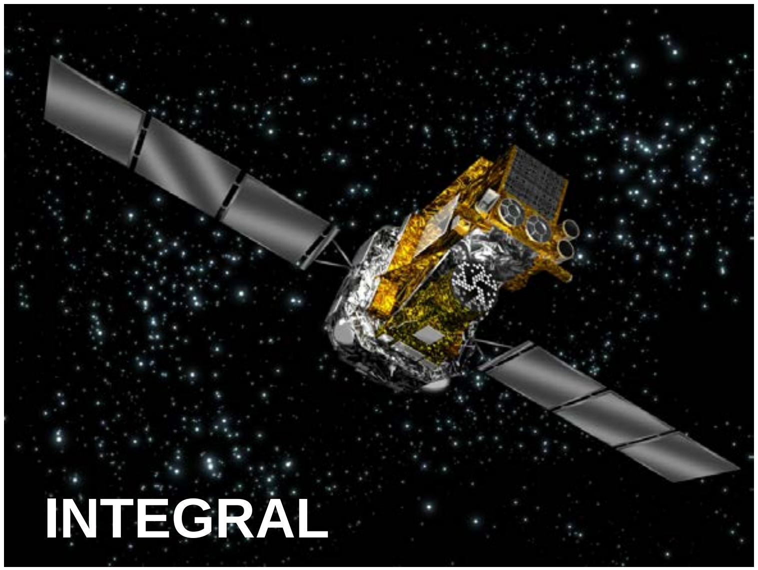
Probing Explosion Asymmetries with NuSTAR

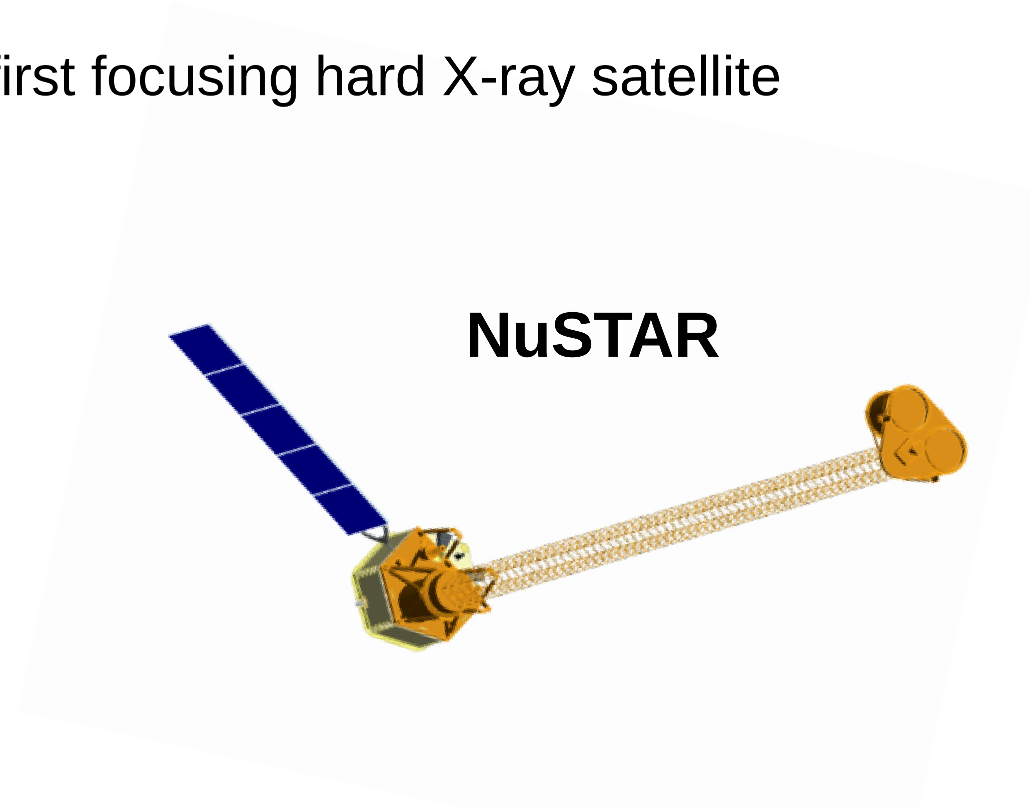
Chris Fryer, Carola Ellinger, Aimee Hungerford, Patrick Young and the NuSTAR team

- Basic Core-Collapse Mechanism (Theory and Observational Support)
- Observational Evidence for Asymmetries
- Possible Mechanisms Driving Asymmetries
- Observational Tests of those Mechanisms

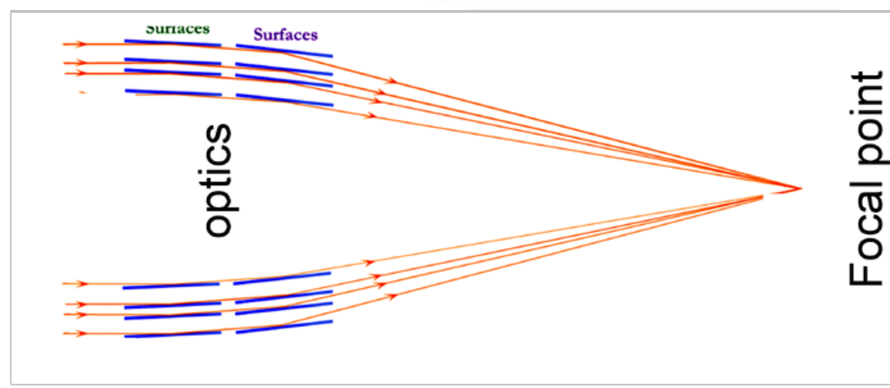
TALK by Daniel Stern

NuSTAR will be the first focusing hard X-ray satellite





Coded Aperture Optics:
high background, large detector



Focusing Optics:
low background, compact detector

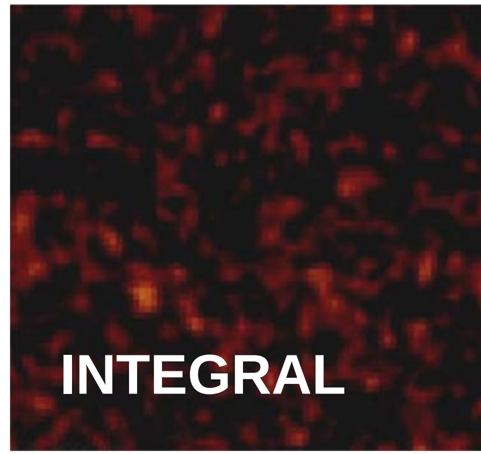
TALK by Daniel Stern

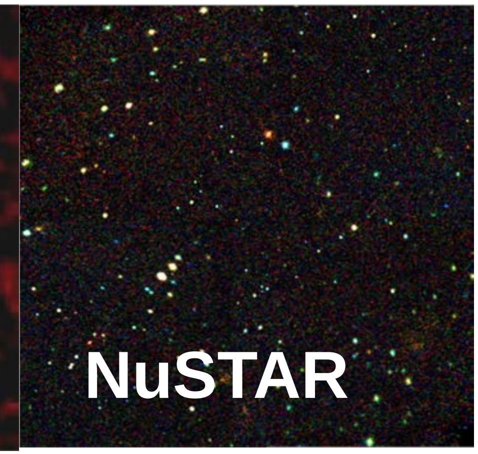
Energy Range:	6-80 keV
Angular Resolution:	45 arcsec (HPD)
Field of View (50% response):	10 arcmin (10 keV) 8 arcmin (40 keV) 6 arcmin (68 keV)
Strong Source Positioning (>10Ã):	1.5 arcsec (1Ã radius)
Spectral Resolution:	1.2 keV at 68 keV (FWHM)
Sensitivity (3Ã, 1 Ms):	2×10^{-15} erg/cm^2/s (6-10 keV) 1×10^{-14} erg/cm^2/s (10-30 keV)
Timing Resolution:	1 msec
ToO Response:	<24 hr
Launch Date:	August 2011
Orbit:	6 degrees 550 km x 600 km
Mission Lifetime: **Orbit Lifetime:**	2 years baseline >7 years orbit lifetime
Saturating Count Rate:	250 cts/sec in HPD

current best estimates (CBEs), as of September 2009

Summary

NuSTAR will bring the high energy universe into focus

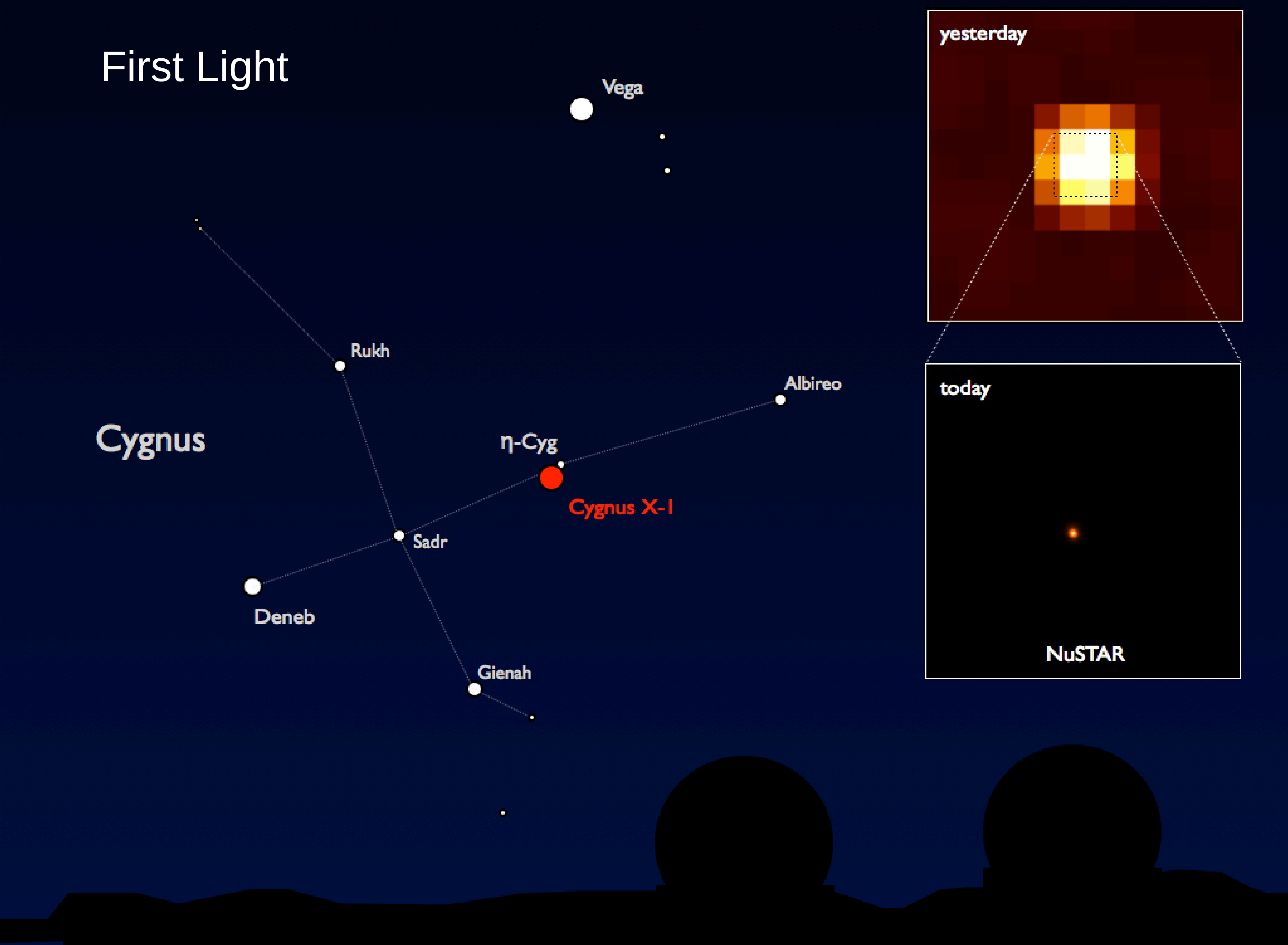




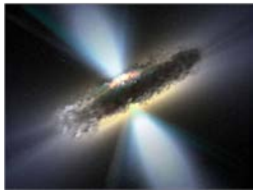
two orders of magnitude improvement in sensitivity over any previous hard X-ray mission

http://www.nustar.caltech.edu/

First Light

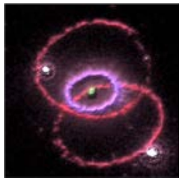

Vega
Rukh
Albireo
Cygnus
η-Cyg
Cygnus X-1
Sadr
Deneb
Gienah
yesterday
today
NuSTAR

NuSTAR Baseline Science Plan (2 yr)

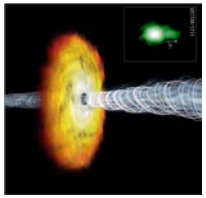


Objective #1: How are black holes distributed through the cosmos, and how do they affect the formation of galaxies?

Objective #2: How are stellar remnants distributed within the Galaxy and near the Galactic center?



Objective #3: How do stars explode and forge the elements that compose the Earth?

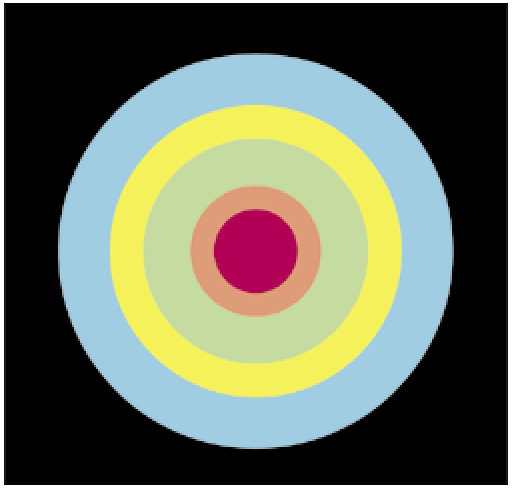


Objective #4: What powers the most extreme active galactic nuclei?

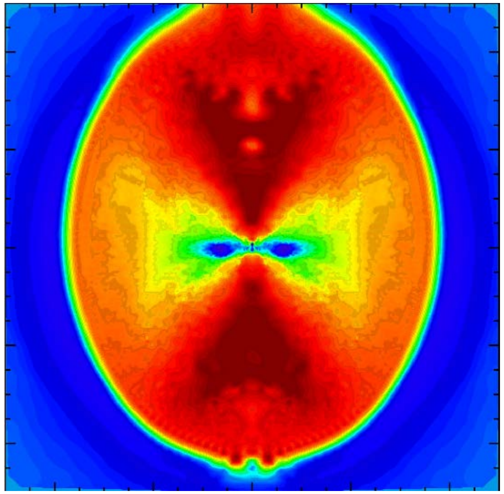
~6 months of unallocated science observing time in first 2 years: for ToO's, additional programs, and/or to respond to primary program

Are explosions symmetric? Models actually suggest a variety of asymmetries.

Spherically Symmetric



Fryer & Heger 2000



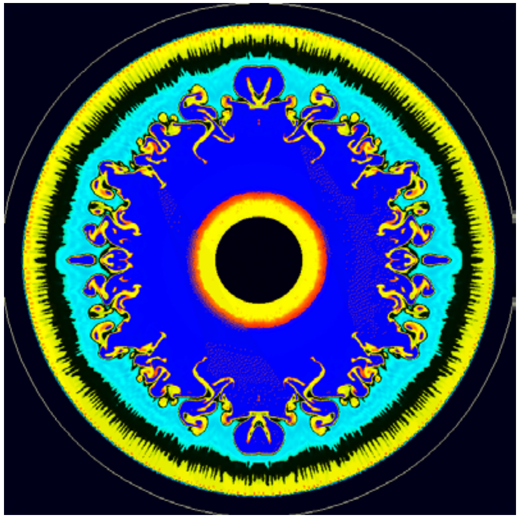
Globally Asymmetric

(bipolar)

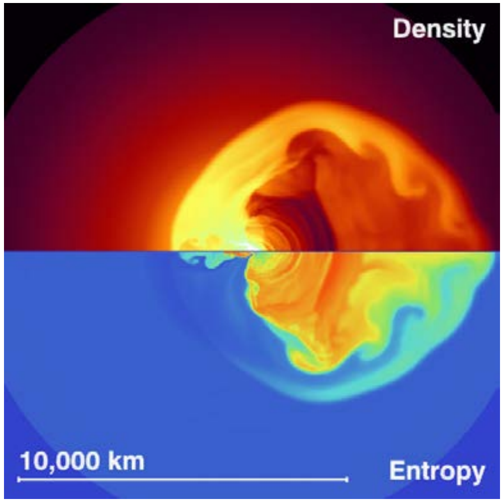
Symmetric

or

Globally Symmetric



Burrows et al. 1995



Scheck et al. 2004

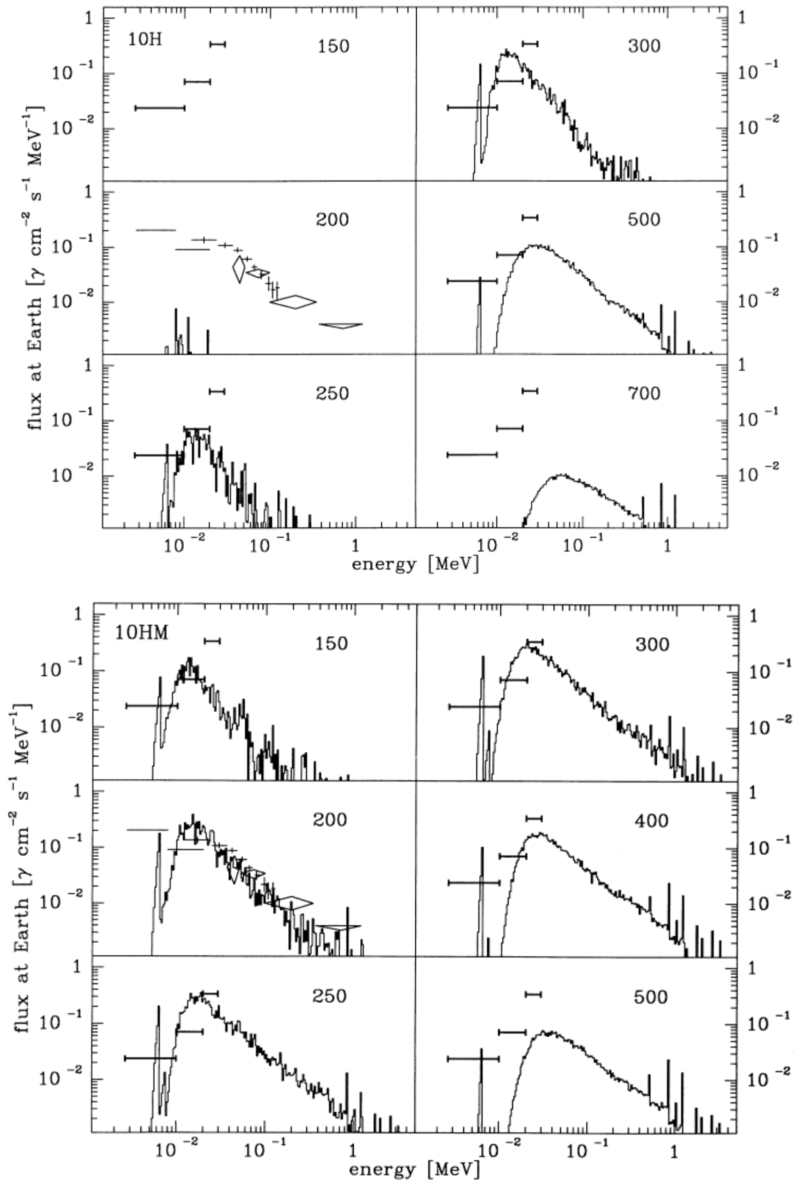
Globally Asymmetric

(single lobe)

Observational Evidence

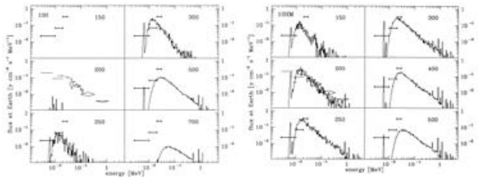
Global Asymmetry	Break in Spherical Symmetry

Theoretical fits to hard X-ray Spectra from SN 1987A

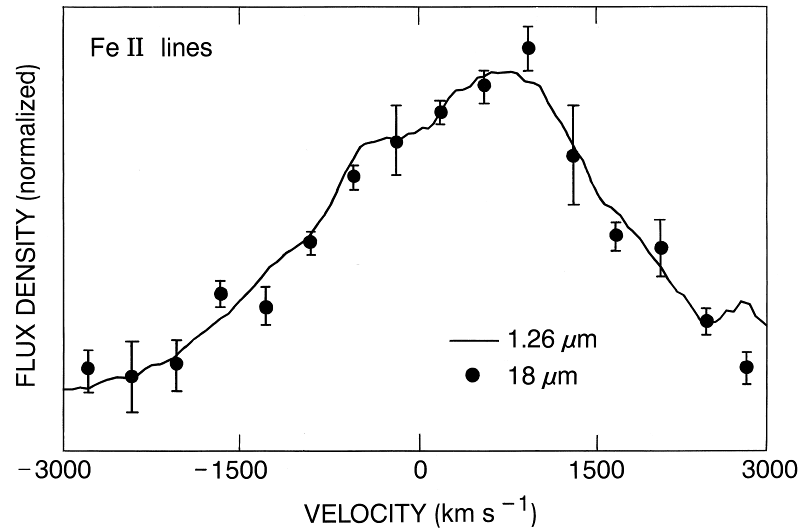


Observational Evidence

Global Asymmetry	Break in Spherical Symmetry

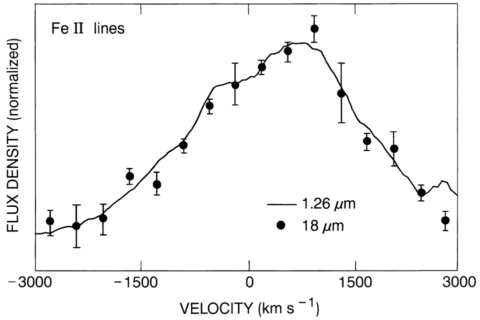


Broad lines of [Fe II] and [Ni II]
Implied presence of Fe and Ni
Into the hydrogen “layer” of SN87A



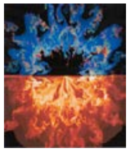
Hydrodynamic modelling of this
Mixing in symmetric models cannot
Achieve such broad lines, BUT
Global asymmetry might fix this!

+



Observational Evidence

Global Asymmetry	Break in Spherical Symmetry



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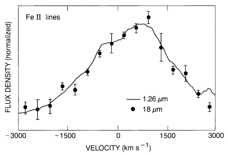
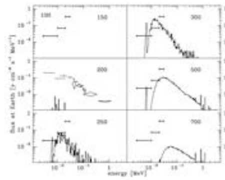
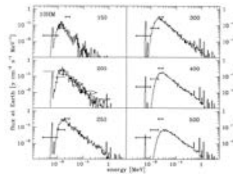
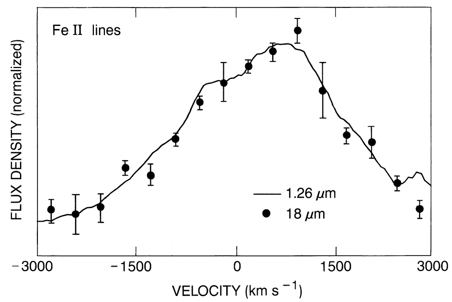


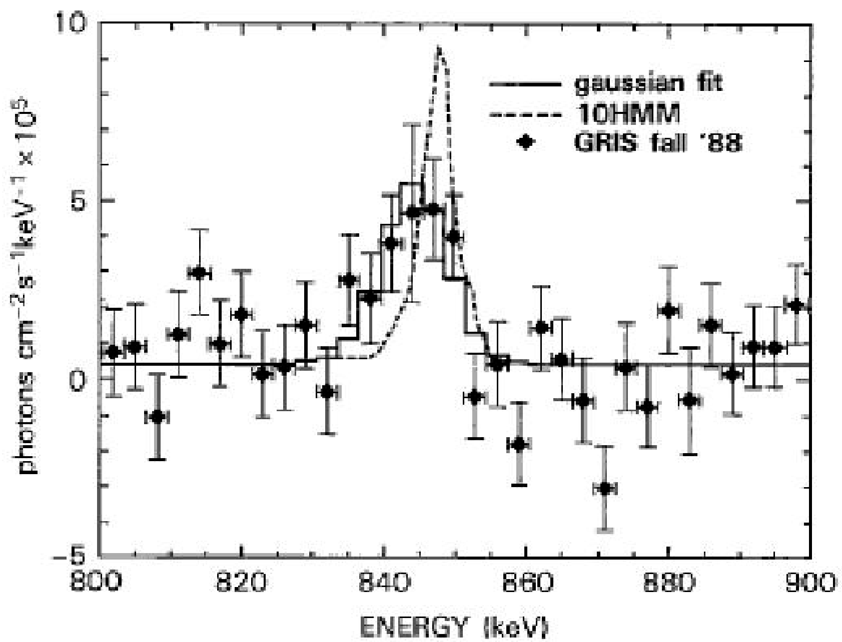






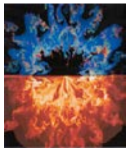
Redshifted gamma-ray lines!

And also broad gamma-ray lines…



Observational Evidence

Global Asymmetry	Break in Spherical Symmetry



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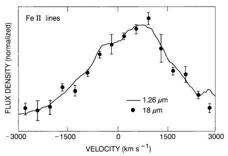
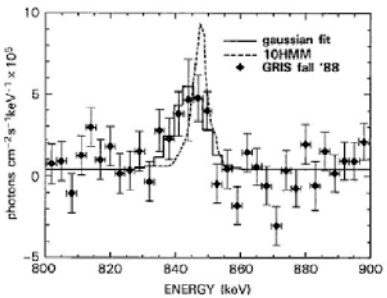
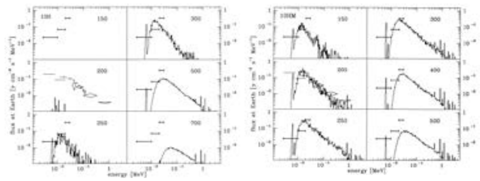
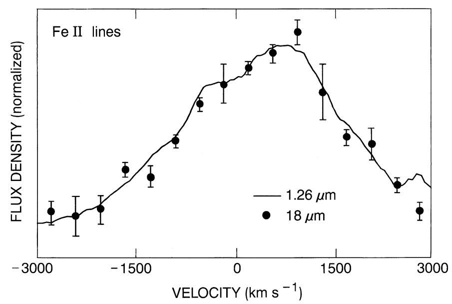


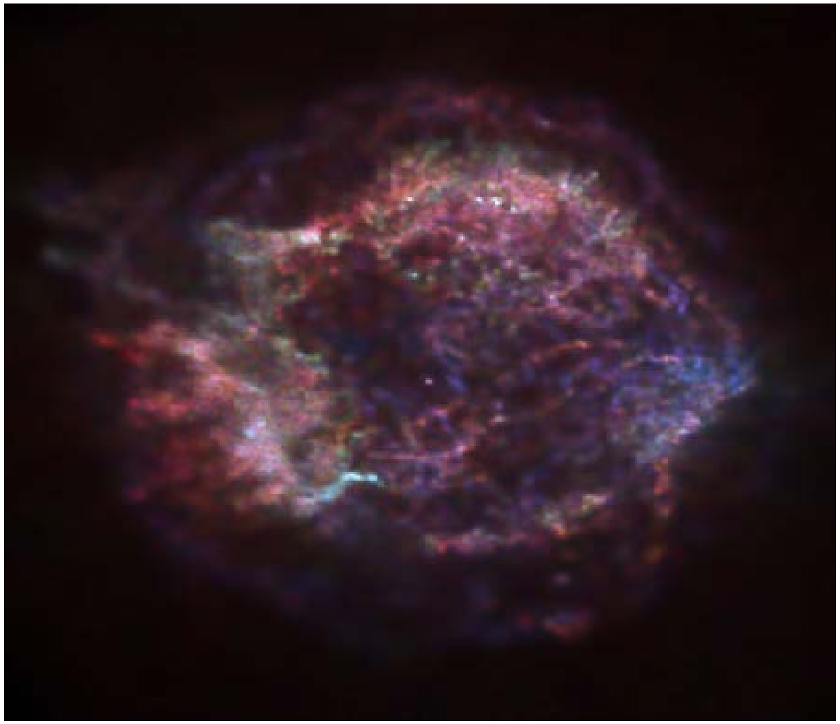






Red = Fe-rich material
White = Si-rich material

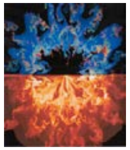
Why is Fe outside of Si?



Jet-like structure to the North East …
But iron is just outside jet

Observational Evidence

Global Asymmetry	Break in Spherical Symmetry



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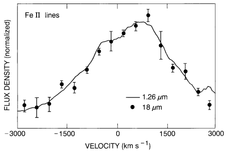
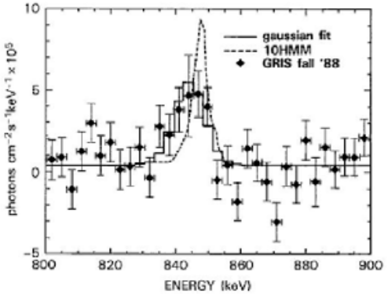
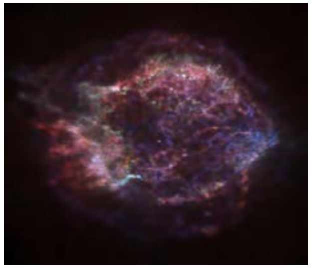
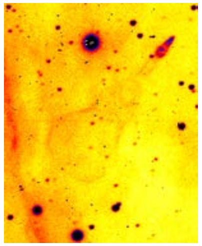
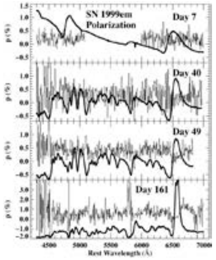
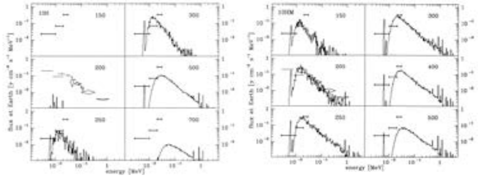


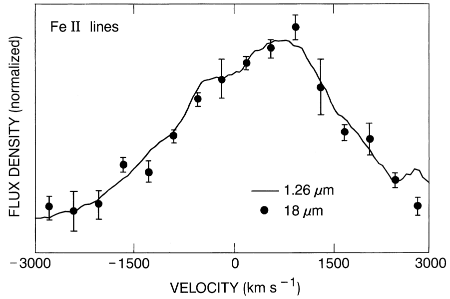


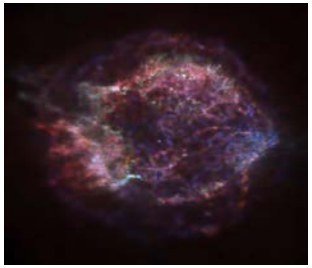












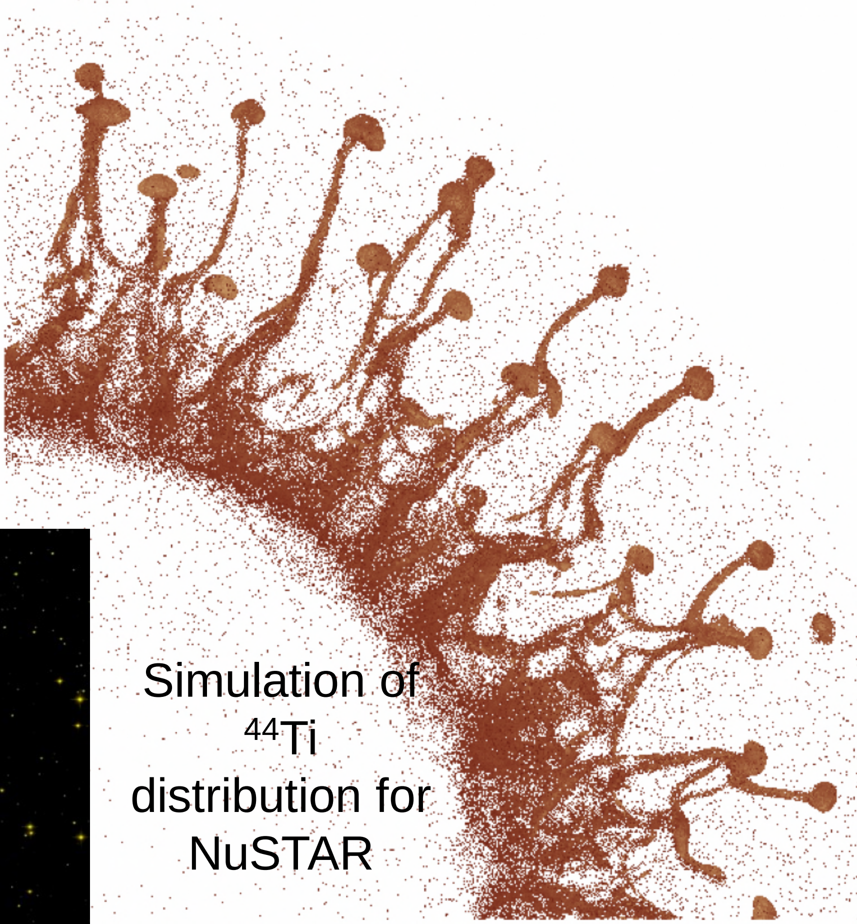
Added to neutron star kicks and polarization measurements, the case for asymmetries is becoming indisputable.

Mechanisms for Asymmetries

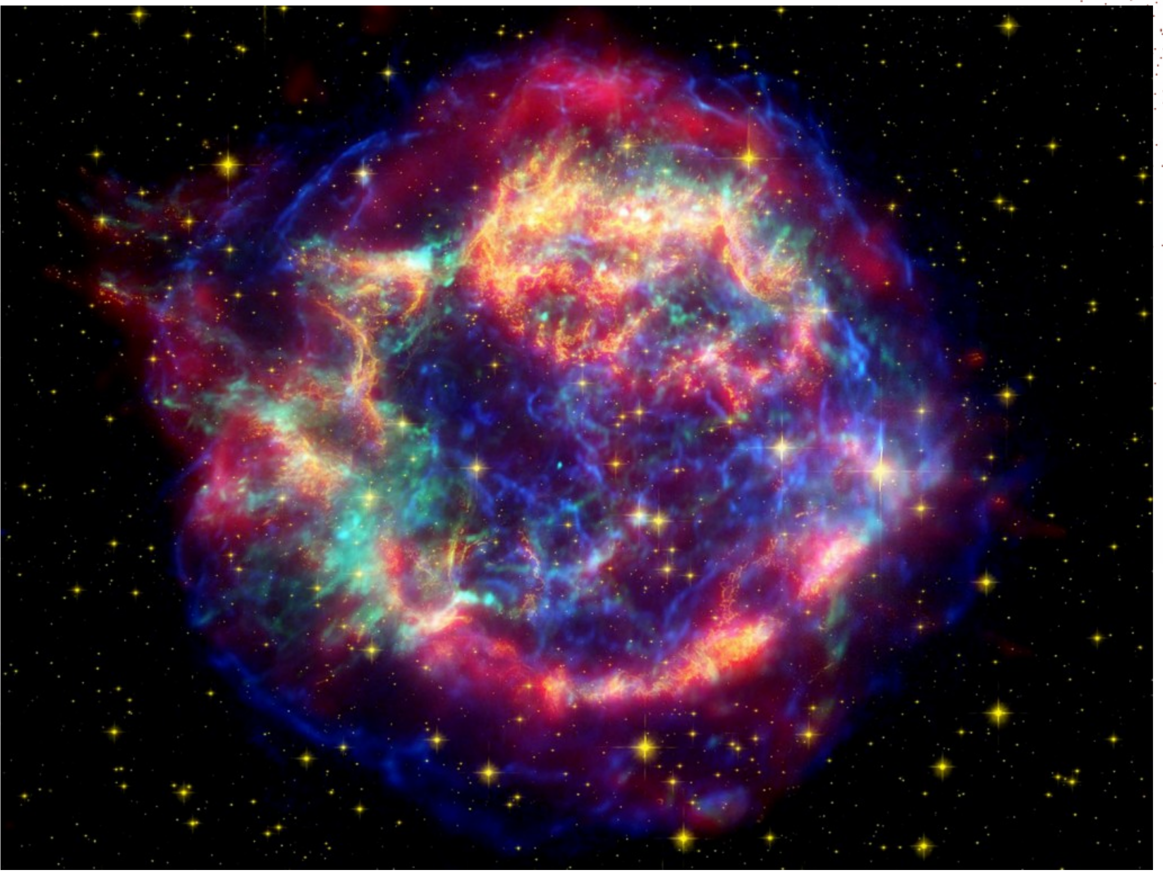
- Asymmetries in Collapse
- Matter Asymmetries in the Turbulent (SASI, RT, …) Engine
- Asymmetries in the Neutrino Emission

Supernova Remnants

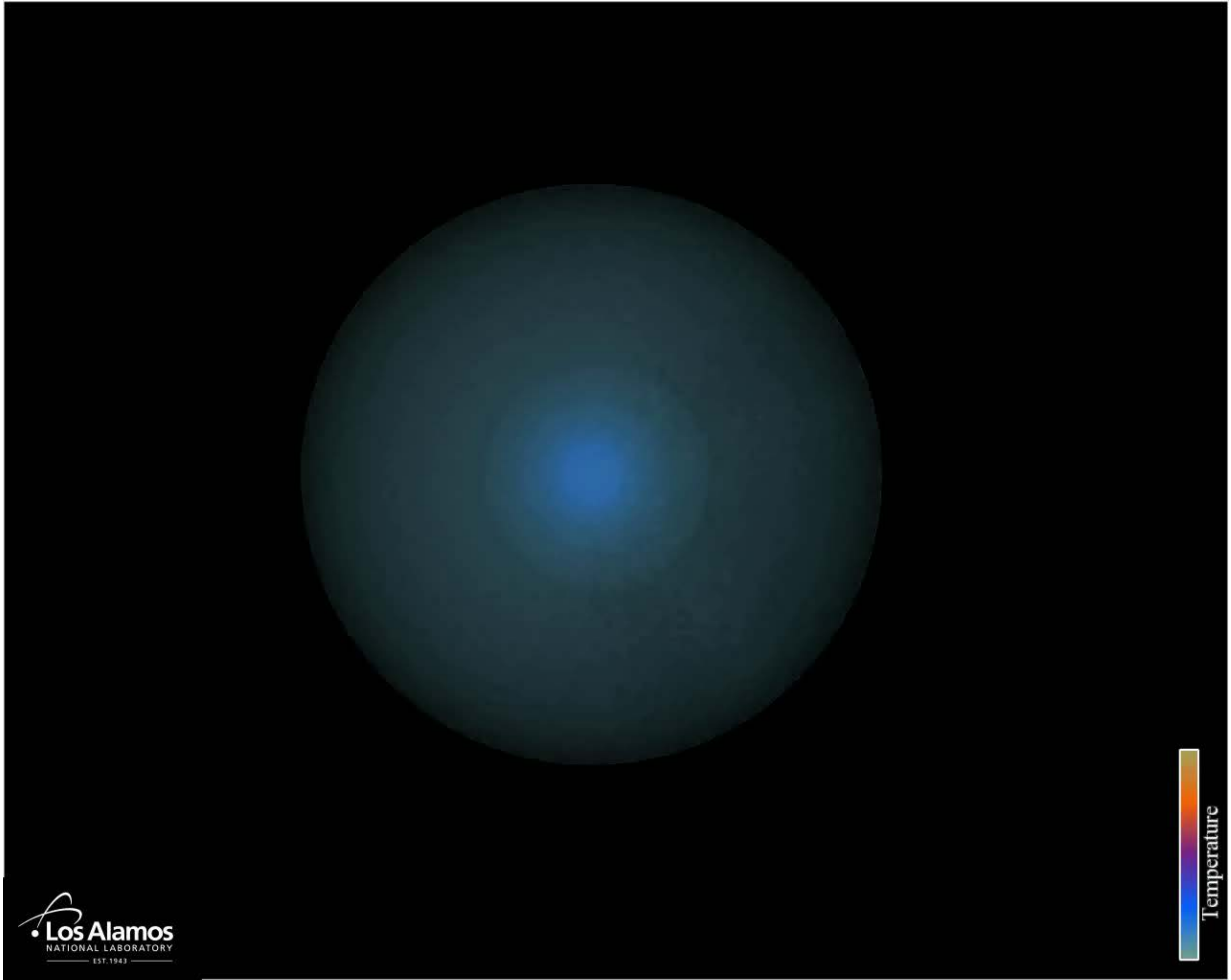
NuSTAR will map out ^{44}Ti abundances in supernova remnants - ^{44}Ti is an ideal tracer of supernova asymmetries



Simulation of ^{44}Ti distribution for NuSTAR



- ^{44}Ti yield is sensitive to explosion details
- But we must understand all the uncertainties to probe these details.


Temperature
Los Alamos
NATIONAL LABORATORY
EST. 1943

Uncertainties in ^{44}Ti Calculations

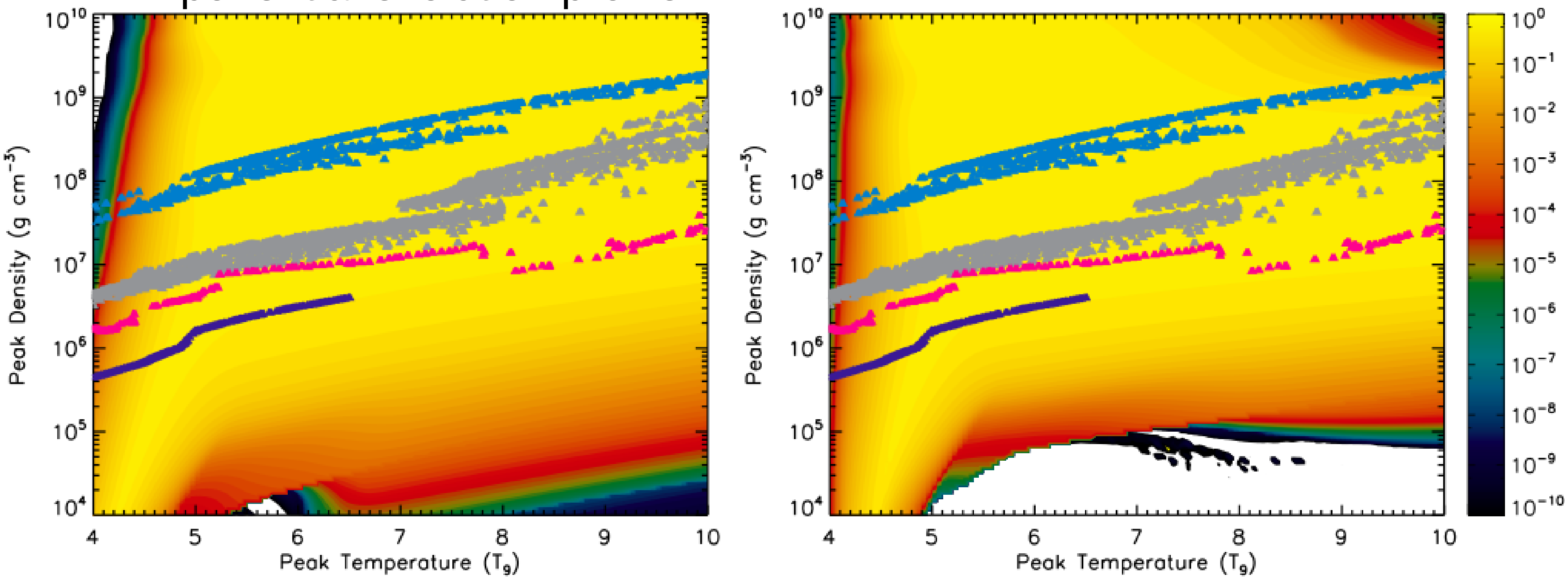
- Stellar Structure – we focus on Cas A and SN 1987A (progenitors are relatively well constrained).
- Explosion: Asymmetry, electron fraction – What we'd like to measure
- Hydrodynamics: Modeling Turbulent Mixing
- Dependence on rates

The explosion determines the peak temperature/densities as well as the density/temperature evolution of the ejecta.

The ^{56}Ni yield is rather insensitive to both

Exponential evolution profile

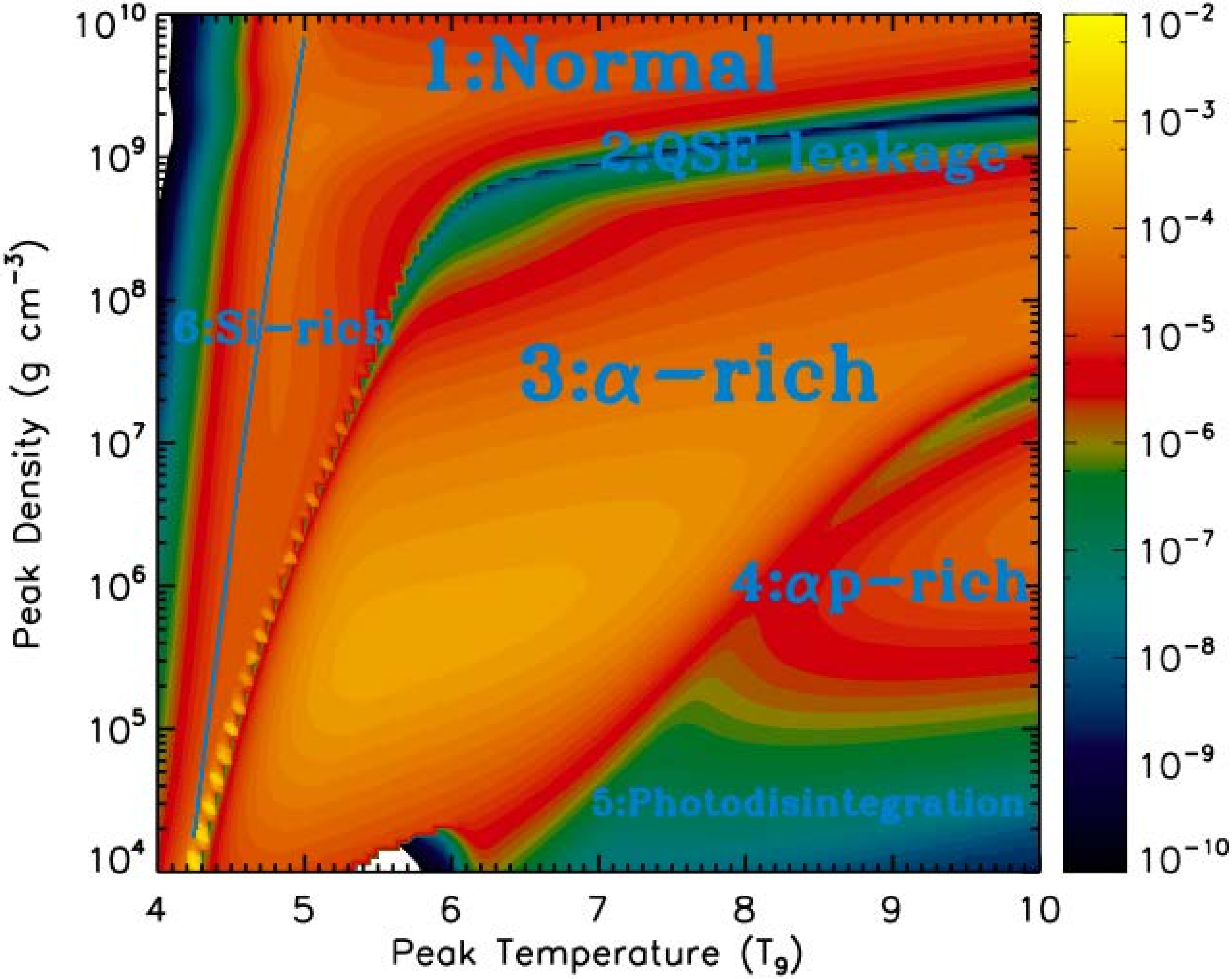
Power-law evolution profile



Blue: 1D Cas A model (Young et al. 2006), Gray: 2D rotating E15B explosion (Fryer & Heger 2000), Pink: hypernova model (Fryer et al. 2006), cyan: 2D magnetohydrodynamic collapsar

Magkotsios et al. 2010

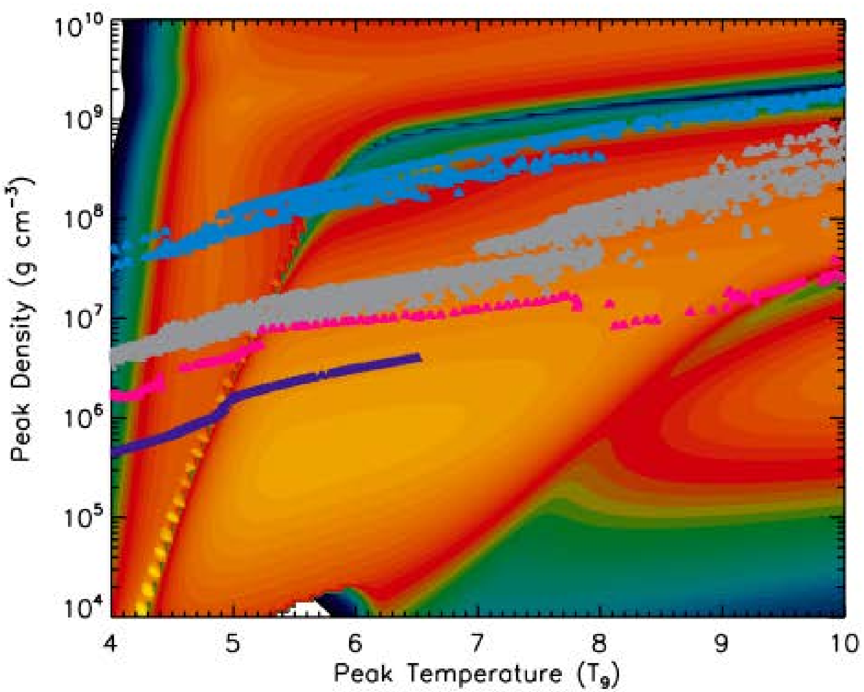
The critical rates for ^{44}Ti production depend upon the peak temperature and density



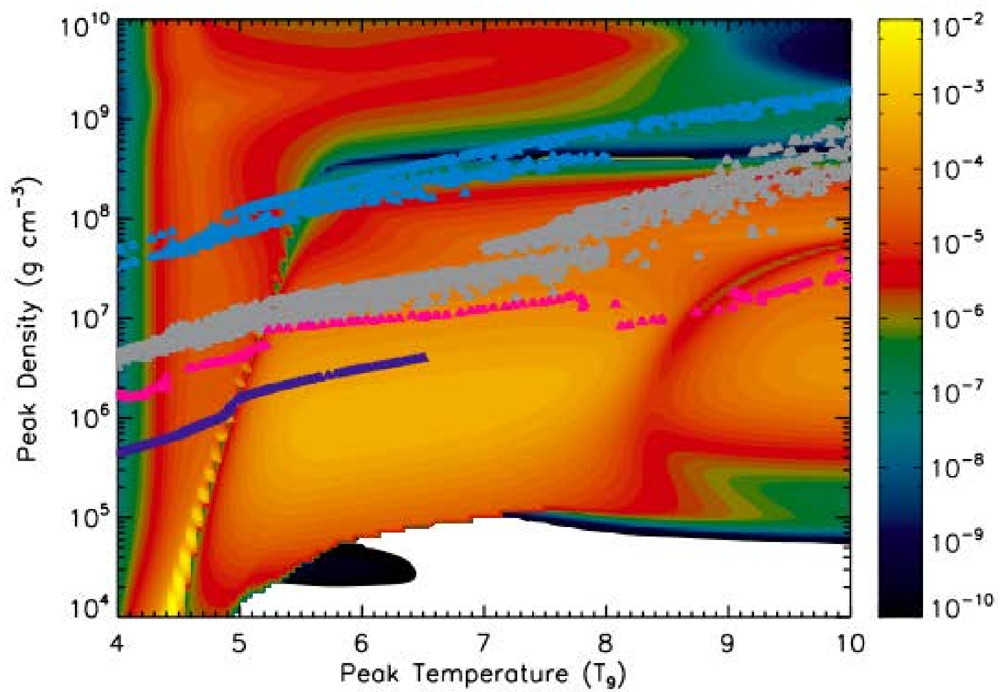
Magkotsios et al. 2010

But for ^{44}Ti, the yield can change dramatically based on both the explosion energy and the evolution of the ejecta.

Exponential evolution profile



Power-law evolution profile



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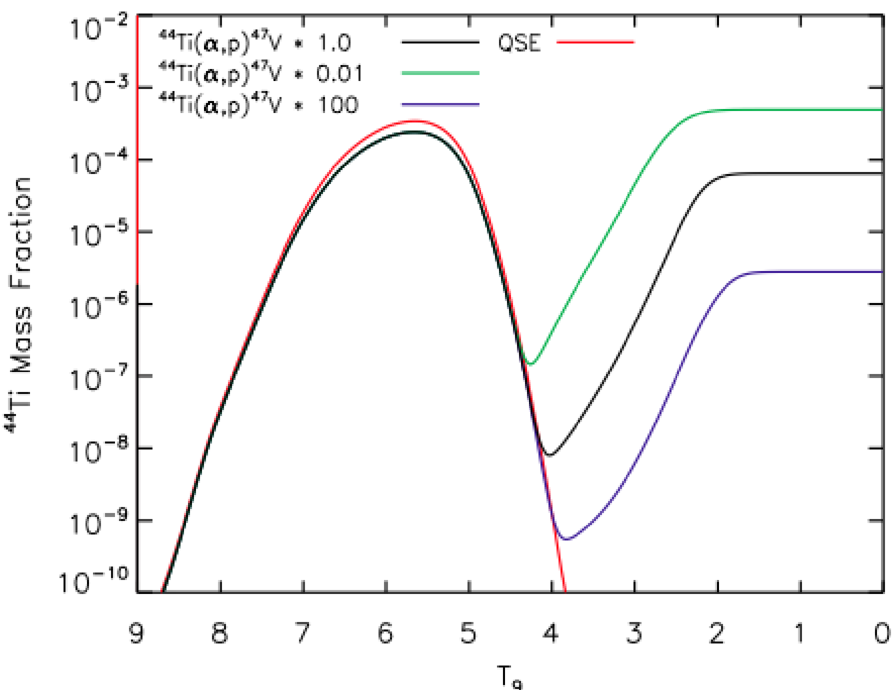
Magkotsios et al. 2010

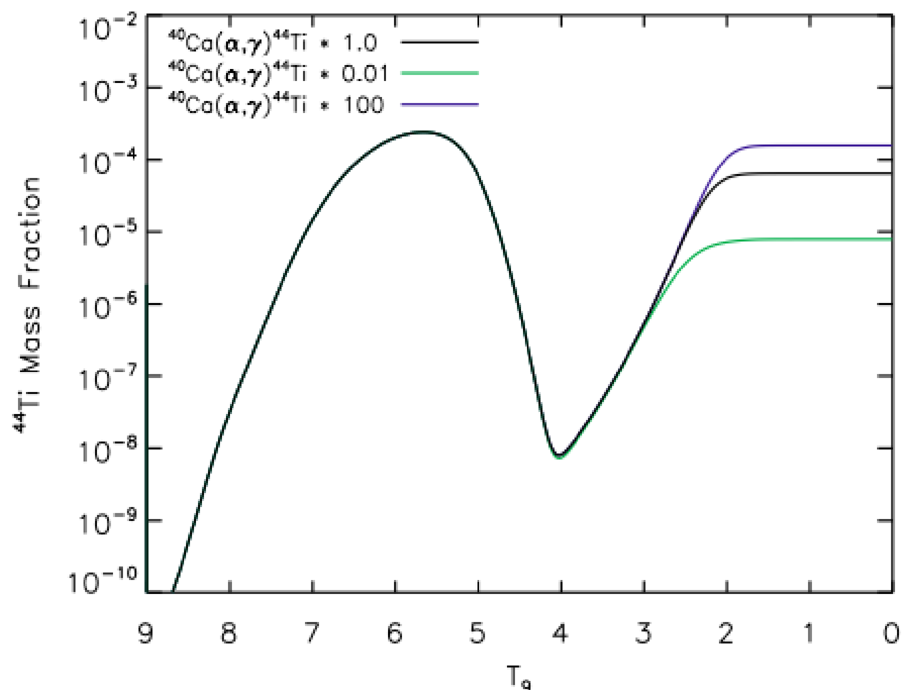
^{44}Ti is sensitive to peak temperature, density because different rates dominate the production/destruction in different regimes. This means, ^{44}Ti production is sensitive to a number of rates. There is not a single golden rate to measure.

What astrophysics can do is try to place firm constraints on the explosion details.



^{44}Ti(α,p)^{47}V

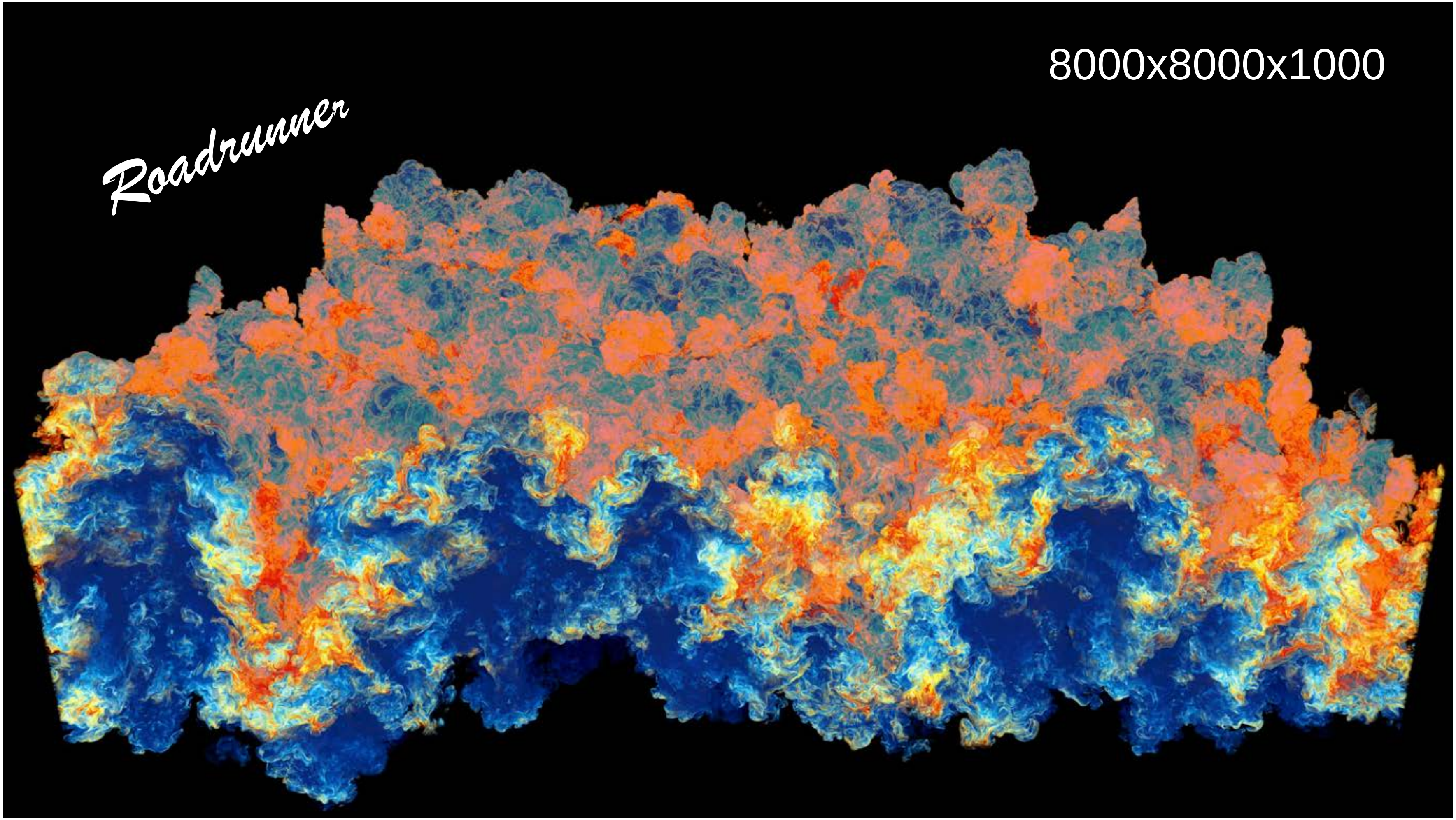
Magkotsios et al. 2010



^{40}Ca(α,p)^{44}Ti

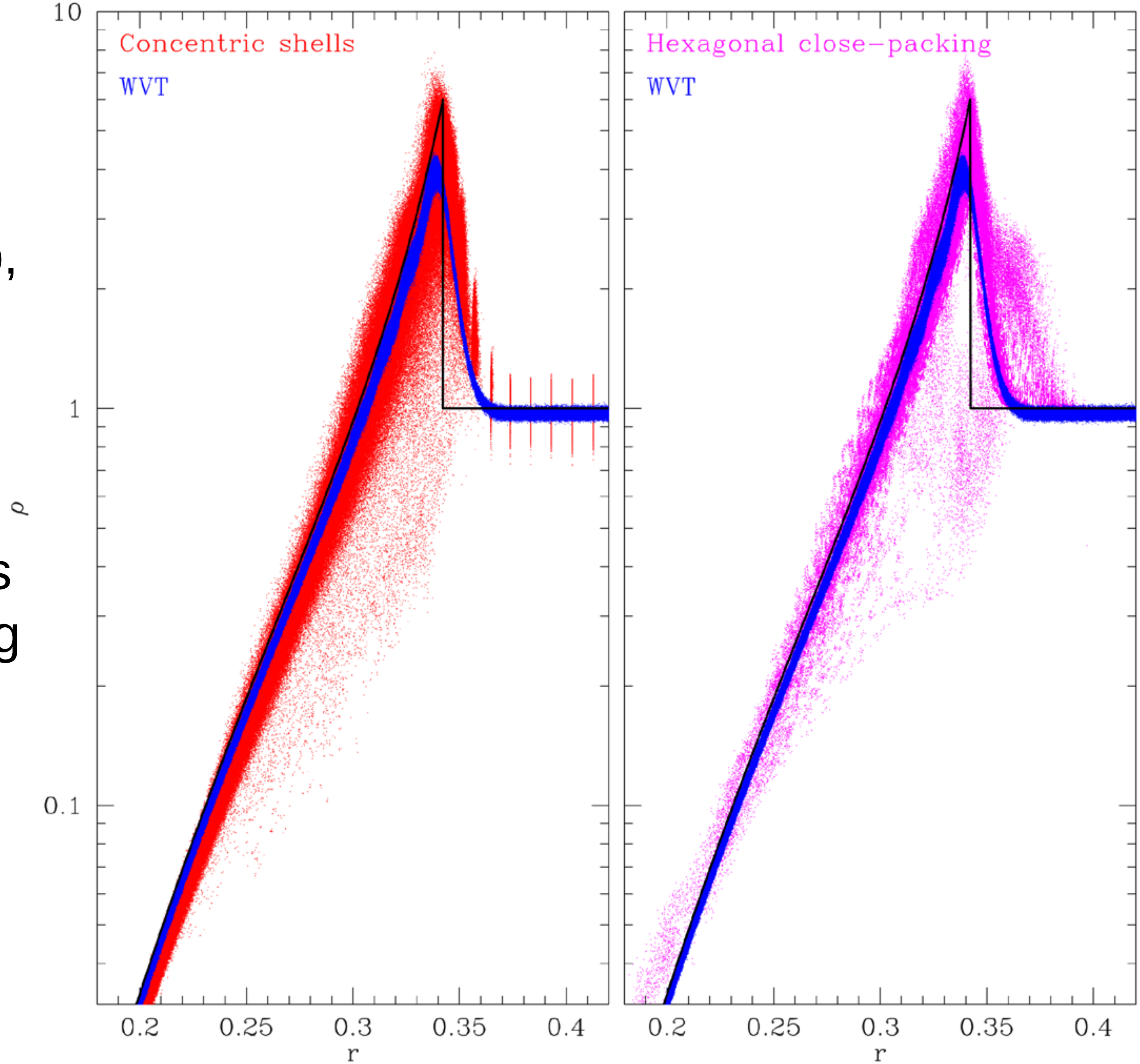
Turbulence and Numerical Hydrodynamics

We use highly-resolved turbulence calculations to test our code's capabilities.

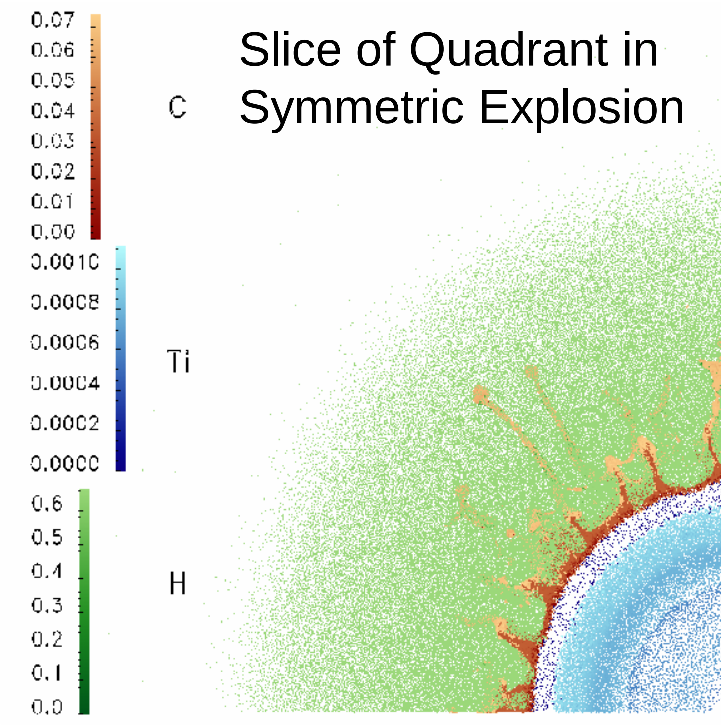


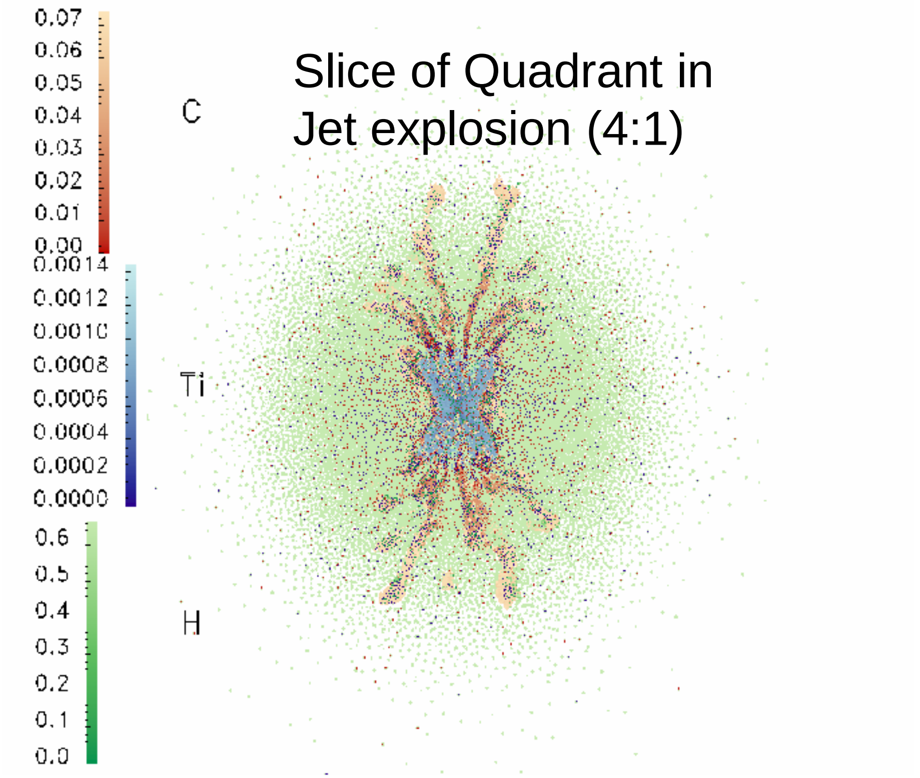
Dimonte et al.

By improving the initial SPH setup, we have greatly improved our capabilities in modeling shocks.



Comparing Symmetric and Asymmetric Explosions

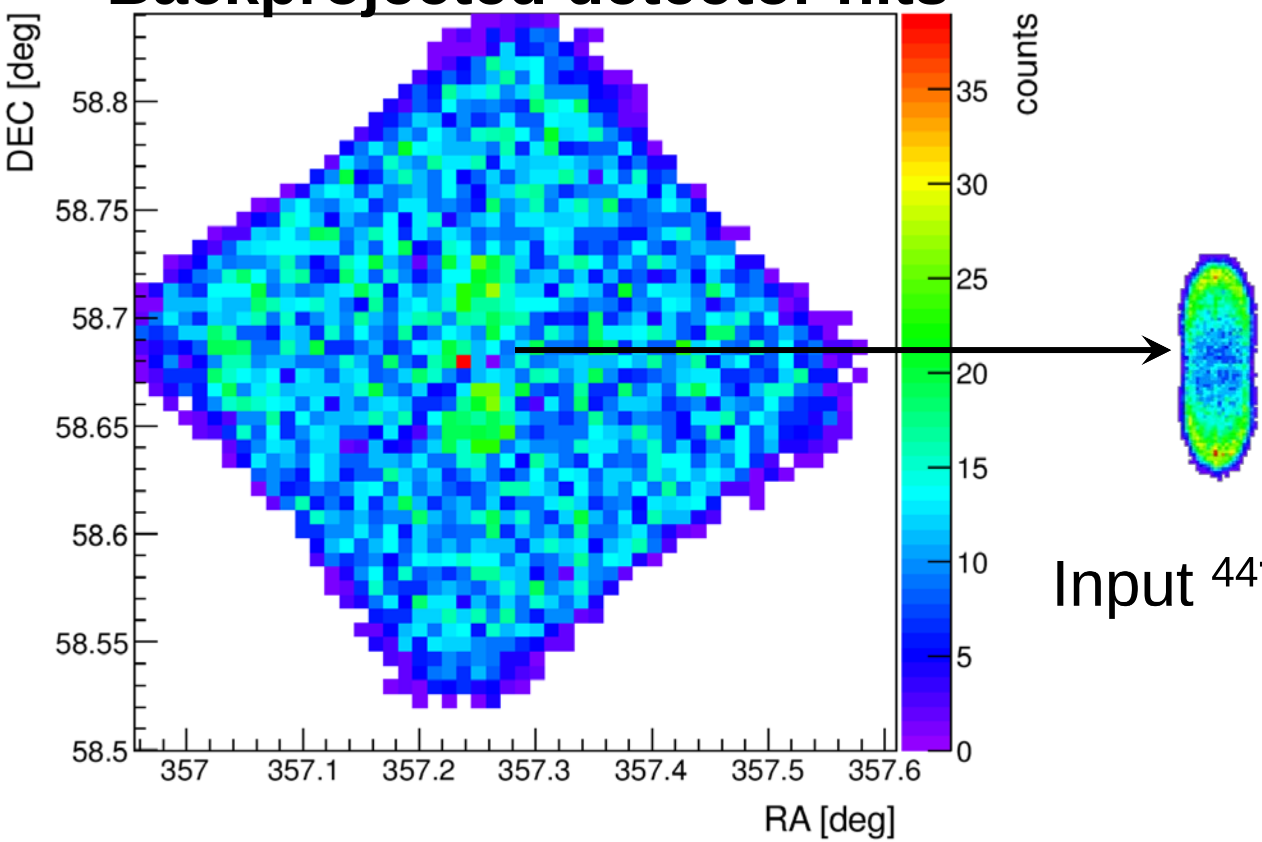




Cas A ^{44}Ti simulation

Input flux: 2.5 10^{-5} ph/cm^2/s @ 68 keV line
Simulation: Background & ^{44}Ti line only!
Observation time: 1 Ms

Backprojected detector hits



Input ^{44}Ti distribution

NuSTAR Remnants

- Cas A observations by NuSTAR will be able to detect asymmetries in the 44Ti distribution.
- If present, this will be very strong evidence for explosion asymmetries in Cas A.
- The next step will be to try to characterize the asymmetry.

Observing Supernova Outbursts

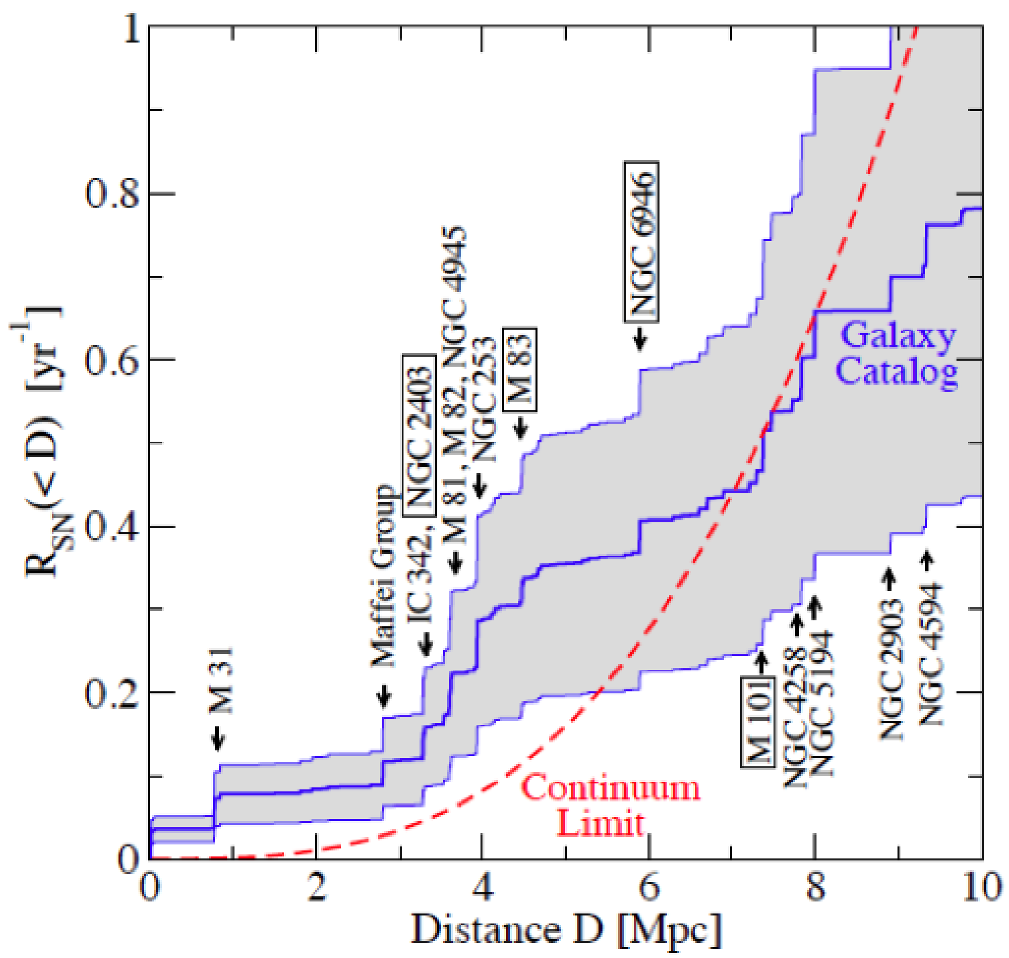
- NuSTAR will also observe nearby supernova (both core-collapse and thermonuclear) outbursts (<5-10Mpc)
- The NuSTAR signal will be sensitive to shock break-out (+shell interaction) and downgraded ^{56}Ni decay gamma-rays.

For TOO, what do we gain with NuSTAR?

- Light-curves typically can be used to infer stellar radii, surrounding environment, explosion energy and ^{56}Ni yield (with late-time results).
- Shock breakout and Shell interactions peak in UV/X-ray. Observations probe stellar radii and immediate surroundings.
- NuSTAR can also probe the outward mixing of ^{56}Ni.

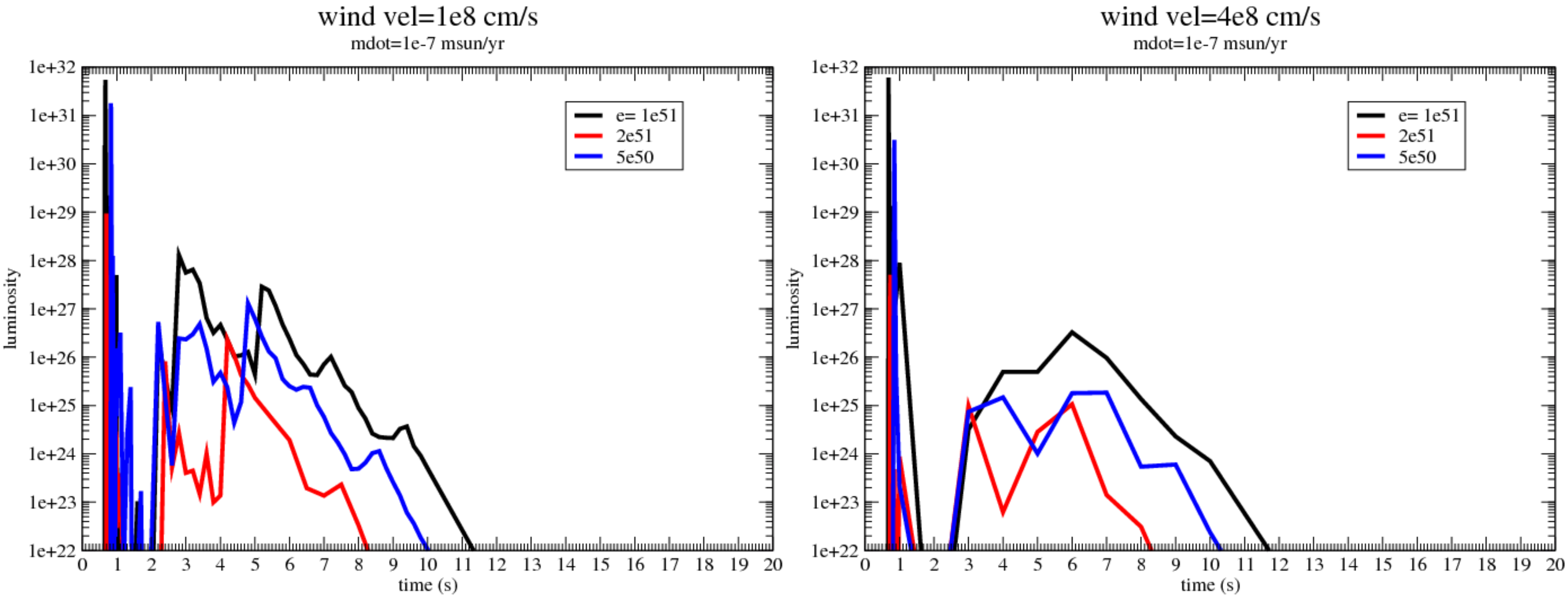
Rates

- Rates nearby do not follow r^3 (volume) extrapolations.
- Out to 10Mpc, the rate is roughly 1/year.

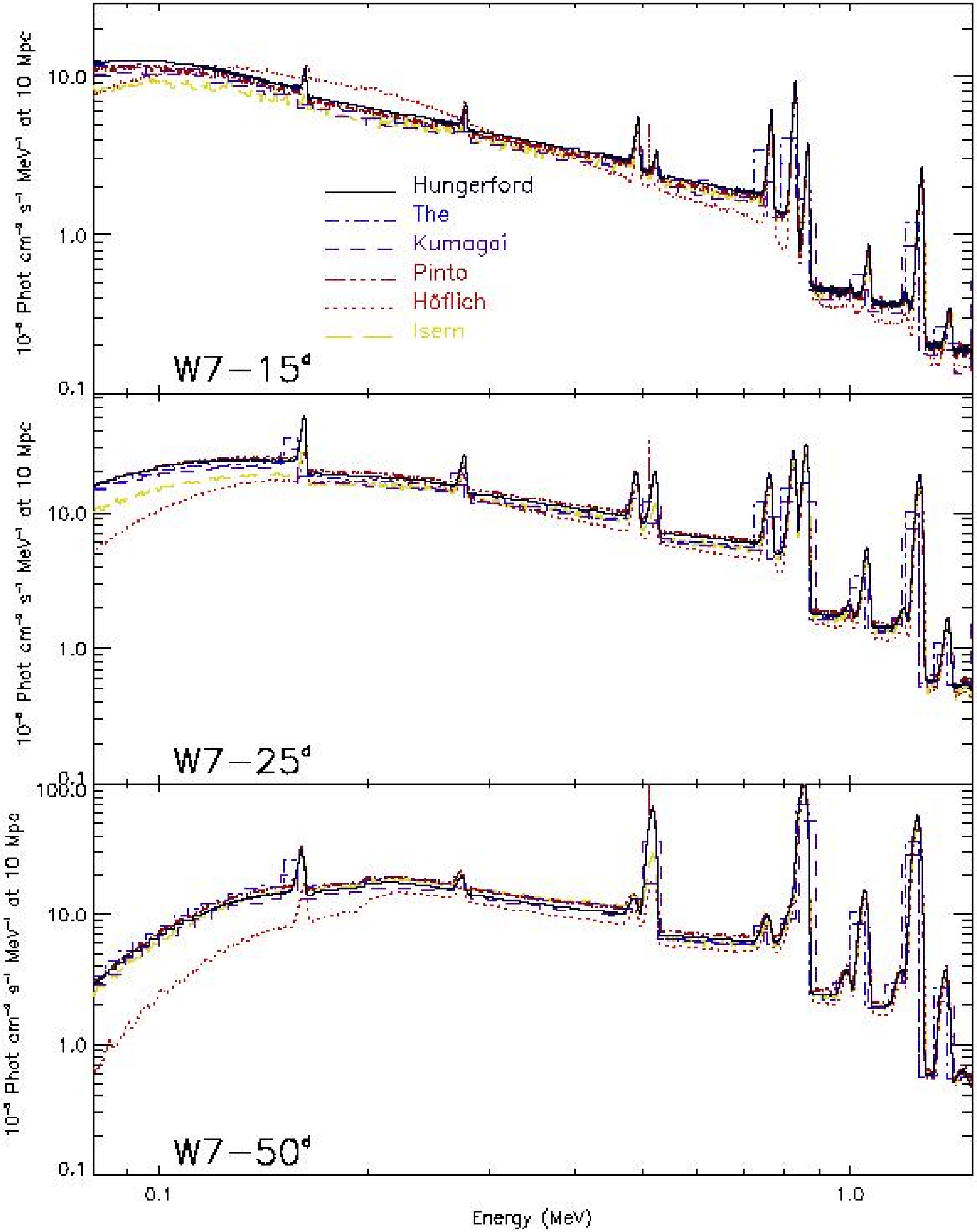


Ando, Beacom & Yuksel, PRL95, 2005

Shock Breakout and Shock/Shell interactions provide information about the explosion energy, outer layers of the star and its surroundings
NuSTAR contributes to the full spectrum.

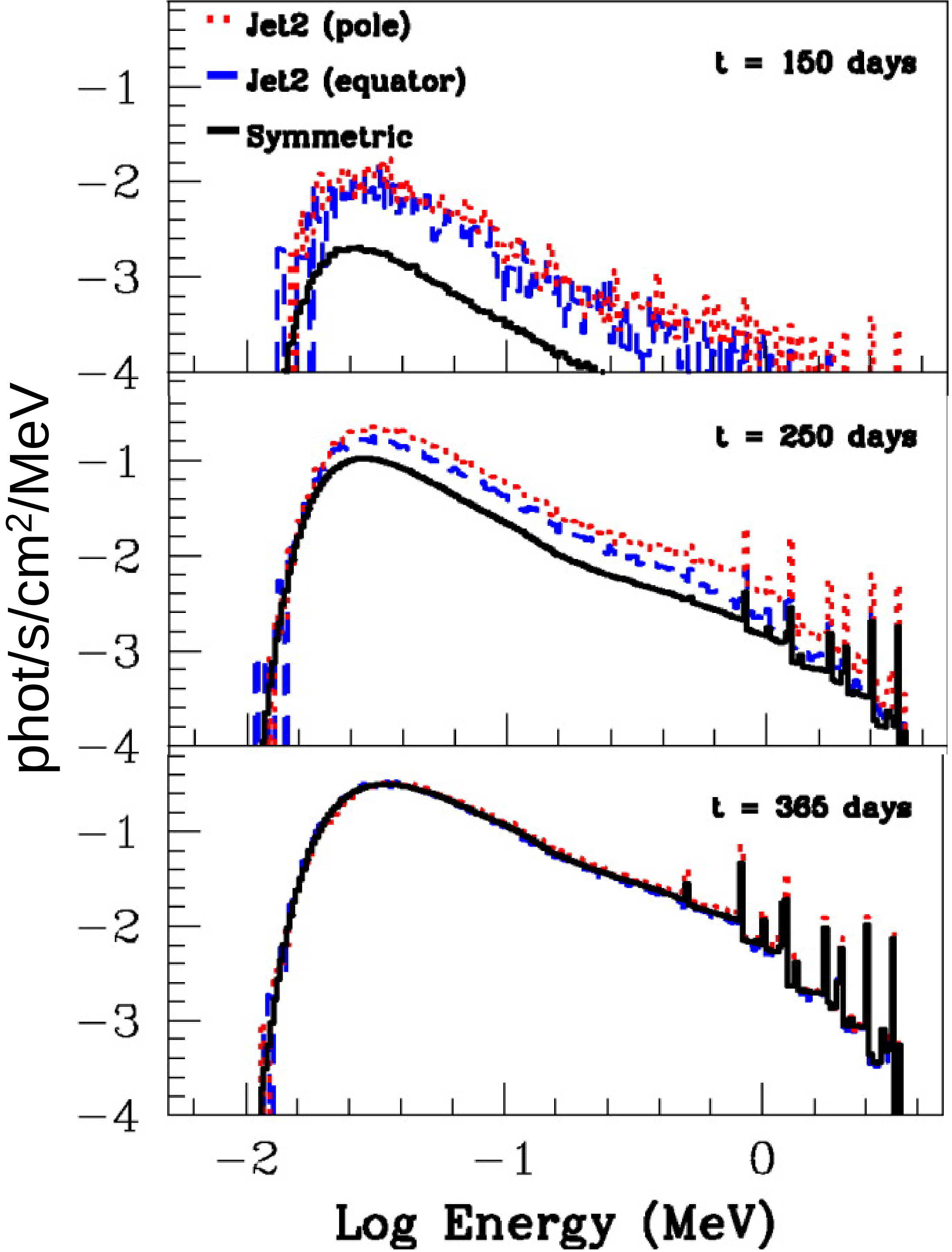


Radiation-Hydrodynamics Calculations of Shock Breakout: Frey et al. 2012



MAVERICK

- Linear Monte Carlo Technique
- Time Independent
- Numerical Recipes ran2 and SPRNG
- Radioactive decay photon source
- Special relativistic material motion corrections
- Compton scattering off cold electrons
- Photoelectric Absorption and Pair production

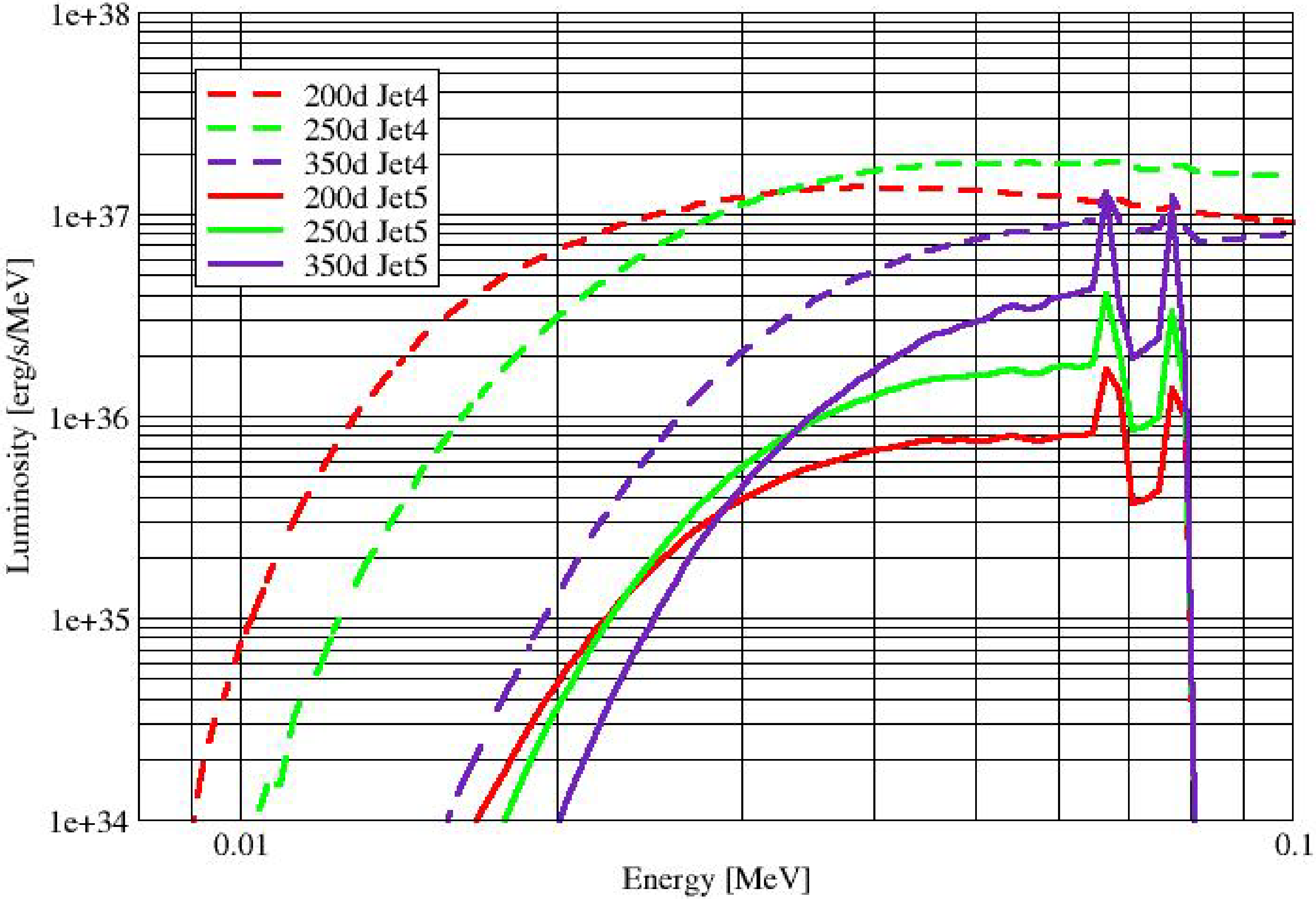


- Hard X-ray continuum is brighter at early times for the asymmetric explosion regardless of viewing angle

- Global asymmetry does result in earlier emergence of Hard X- & gamma-rays

- Level of hard X-ray continuum is roughly same for equator and pole views

- Hard X-ray continuum is brighter at early times for the asymmetric explosion regardless of viewing angle
- Level of hard X-ray continuum is roughly same for equator and pole views



What do we gain with NuSTAR

- In remnants:
- Exact 44Ti yield – good probe of stellar structure near core
- 44Ti distribution – good probe of explosion asymmetry
- In TOO:
- Additional data on shock break-out: better characterization of stellar radius and surroundings, better understanding of photoelectric absorption