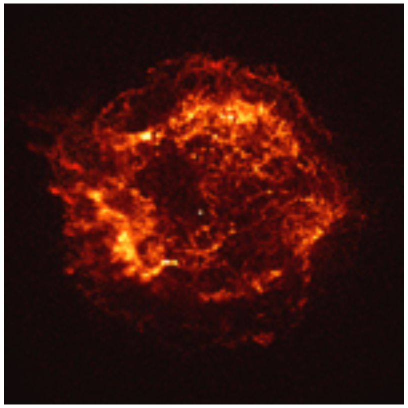
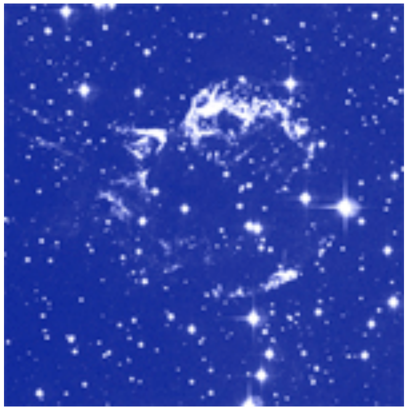
A Detailed Look at Cas A:

Progenitor, Explosion & Nucleosynthesis

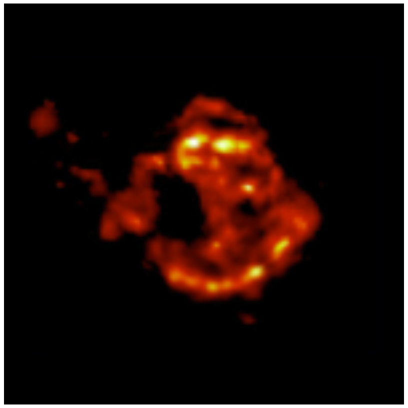
X-ray



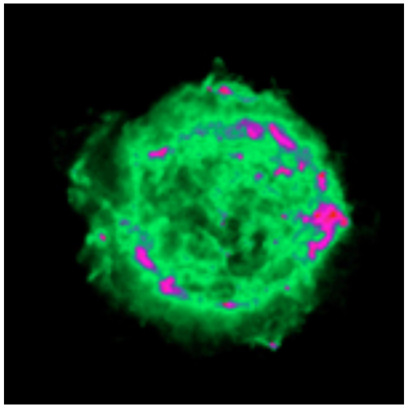
Optical



Infrared

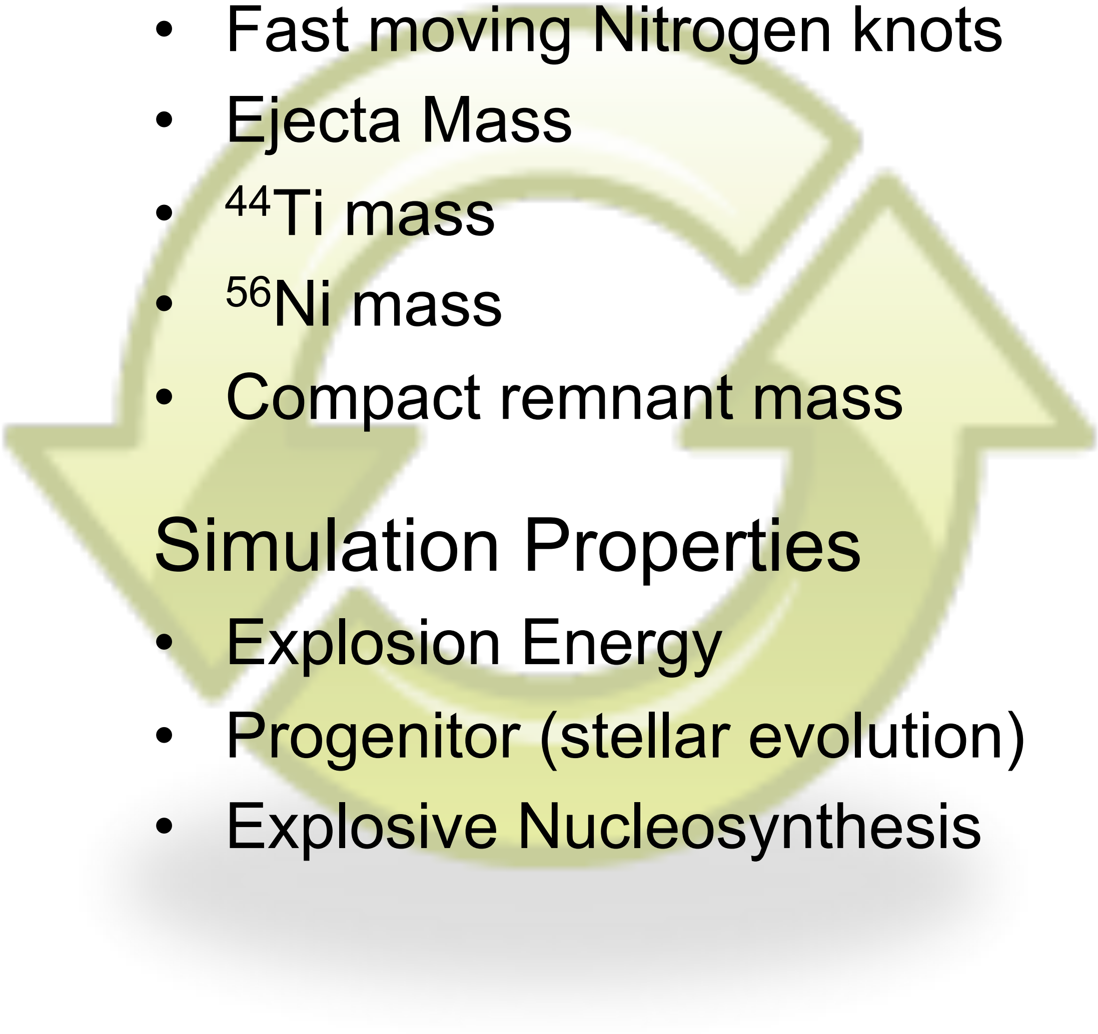


Radio



Aimee Hungerford
INT - July 28, 2011

Circle of Scientific Life



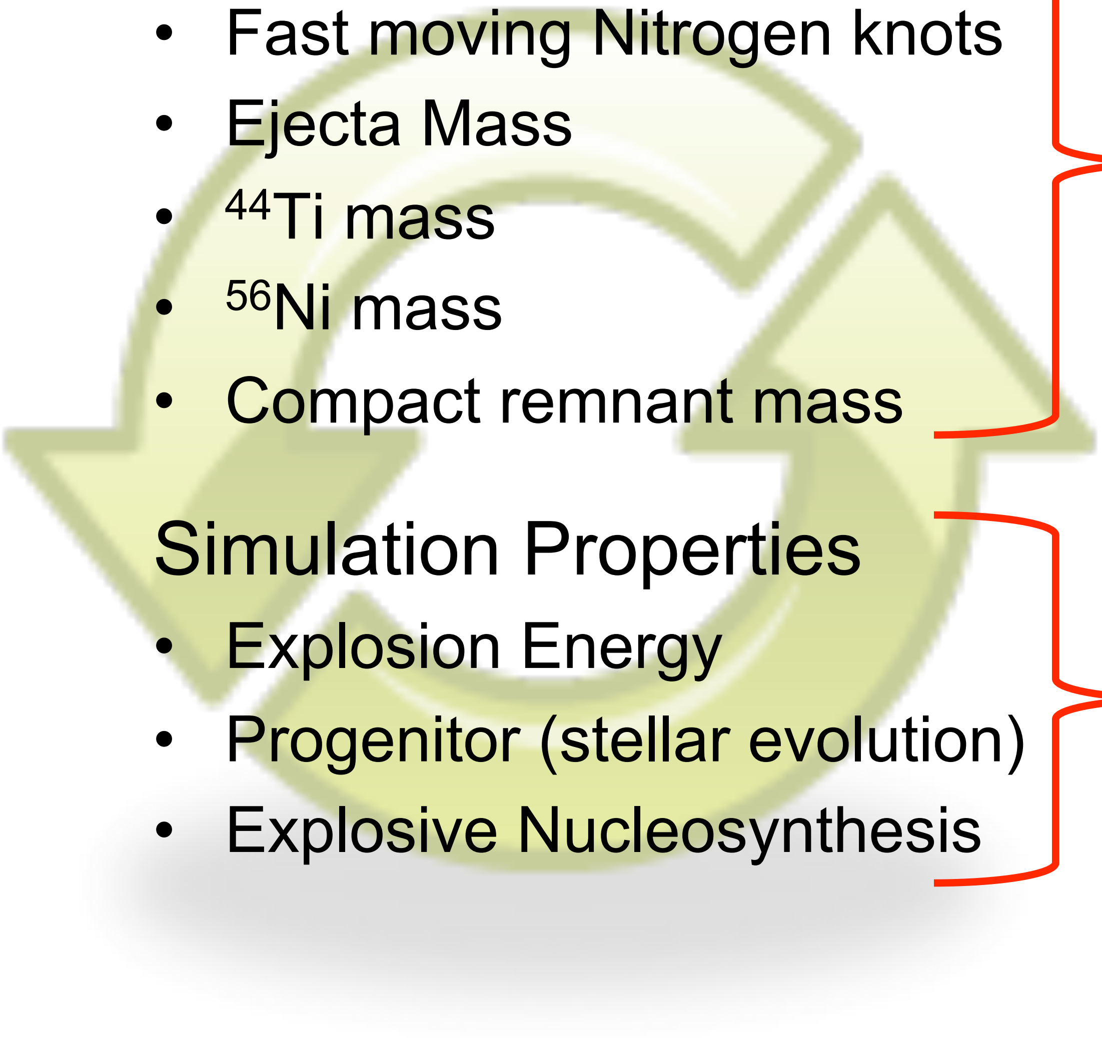
Cas A Properties

- Fast moving Nitrogen knots
- Ejecta Mass
- ^{44}Ti mass
- ^{56}Ni mass
- Compact remnant mass

Simulation Properties

- Explosion Energy
- Progenitor (stellar evolution)
- Explosive Nucleosynthesis

Circle of Scientific Life



Cas A Properties

- Fast moving Nitrogen knots
- Ejecta Mass
- ^{44}Ti mass
- ^{56}Ni mass
- Compact remnant mass

Observational Uncertainty

Simulation Properties

- Explosion Energy
- Progenitor (stellar evolution)
- Explosive Nucleosynthesis

Uncertainties in physics prescriptions

- Electron Fraction
- Nuclear networks
- Mass Loss
- Stellar mixing

Circle of Scientific Life

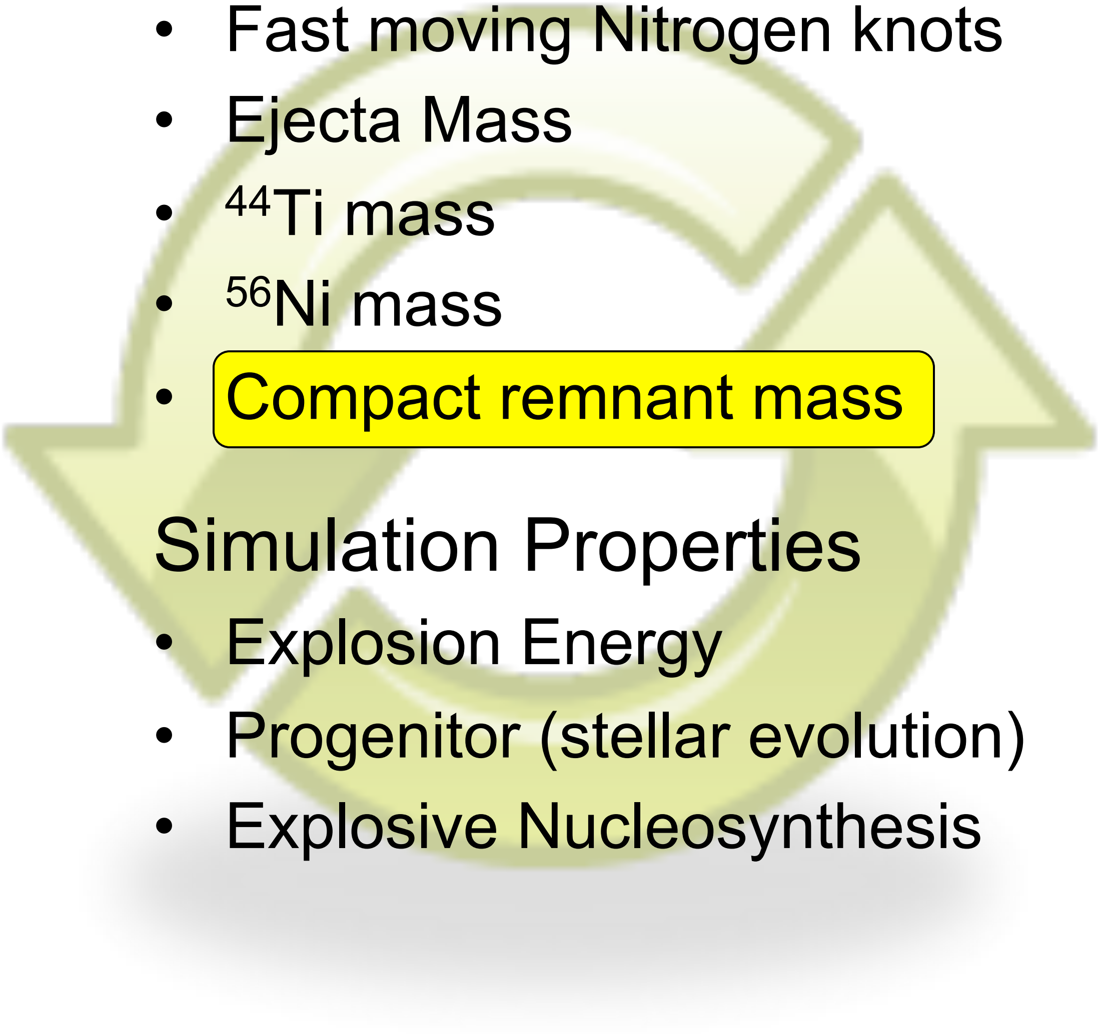
Cas A Properties

- Fast moving Nitrogen knots
- Ejecta Mass
- ^{44}Ti mass
- ^{56}Ni mass
- Compact remnant mass

Simulation Properties

- Explosion Energy
- Progenitor (stellar evolution)
- Explosive Nucleosynthesis

Circle of Scientific Life



Cas A Properties

- Fast moving Nitrogen knots
- Ejecta Mass
- ^{44}Ti mass
- ^{56}Ni mass
- Compact remnant mass

Simulation Properties

- Explosion Energy
- Progenitor (stellar evolution)
- Explosive Nucleosynthesis

Nitrogen Knots

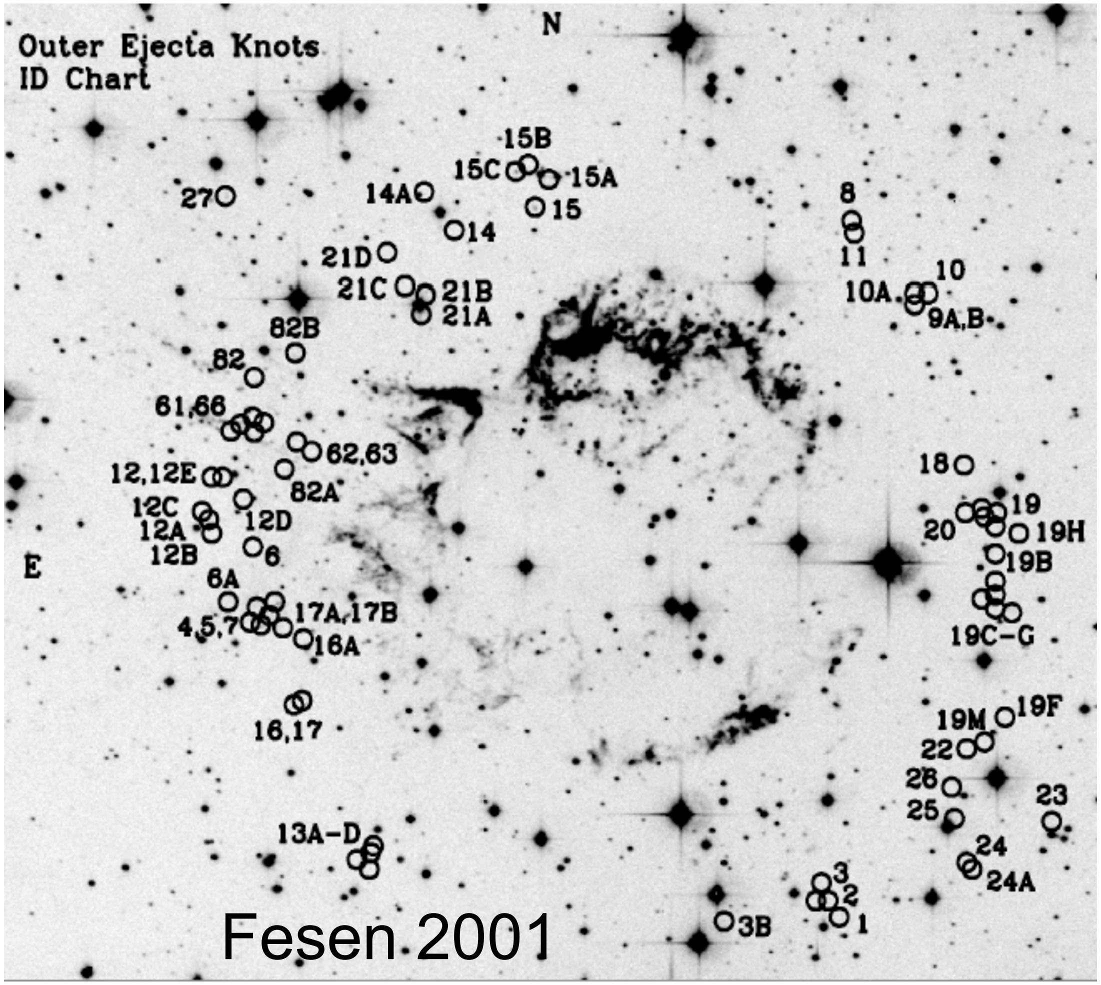
Roughly fifty Nitrogen-rich knots moving at ~9000km/s

Most are Hydrogen-poor as well

Such fast velocities indicate that this material was near the outside of the star when it exploded.

Composition is consistent with pure CNO ashes.

Existence of these knots suggests the need for a layer of CNO ashes on outer layer of the star.



Fesen 2001

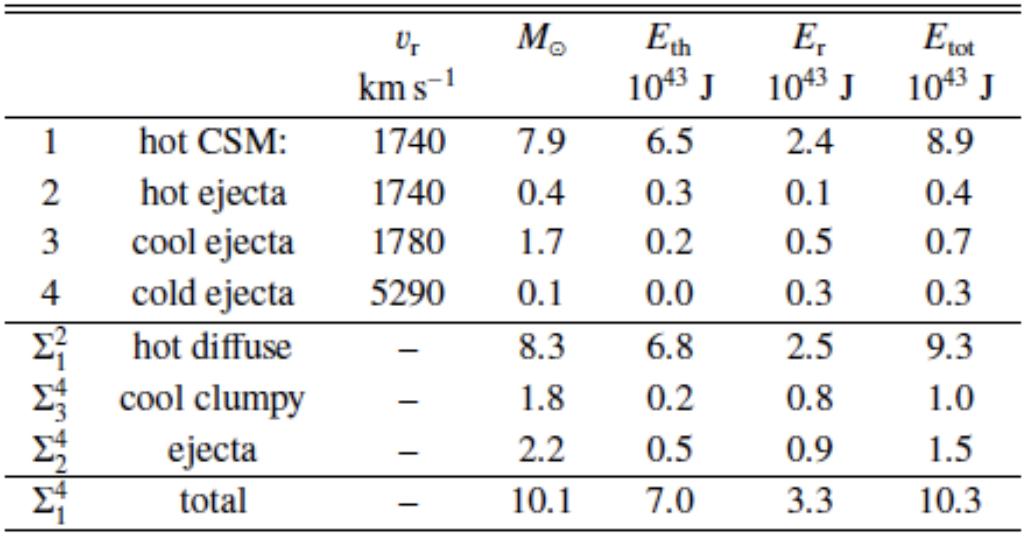
Ejecta Mass

X-ray spectral line-fitting of XMM data are fit to infer the mass of emitting material in the supernova remnant.

Infer a mass of the ejecta to be roughly 2.5 solar masses

Chevalier & Oishi 2003 take the position of the forward and reverse shock and expansion rate to derive a mass of the supernova ejecta (using self-similarity arguments.)

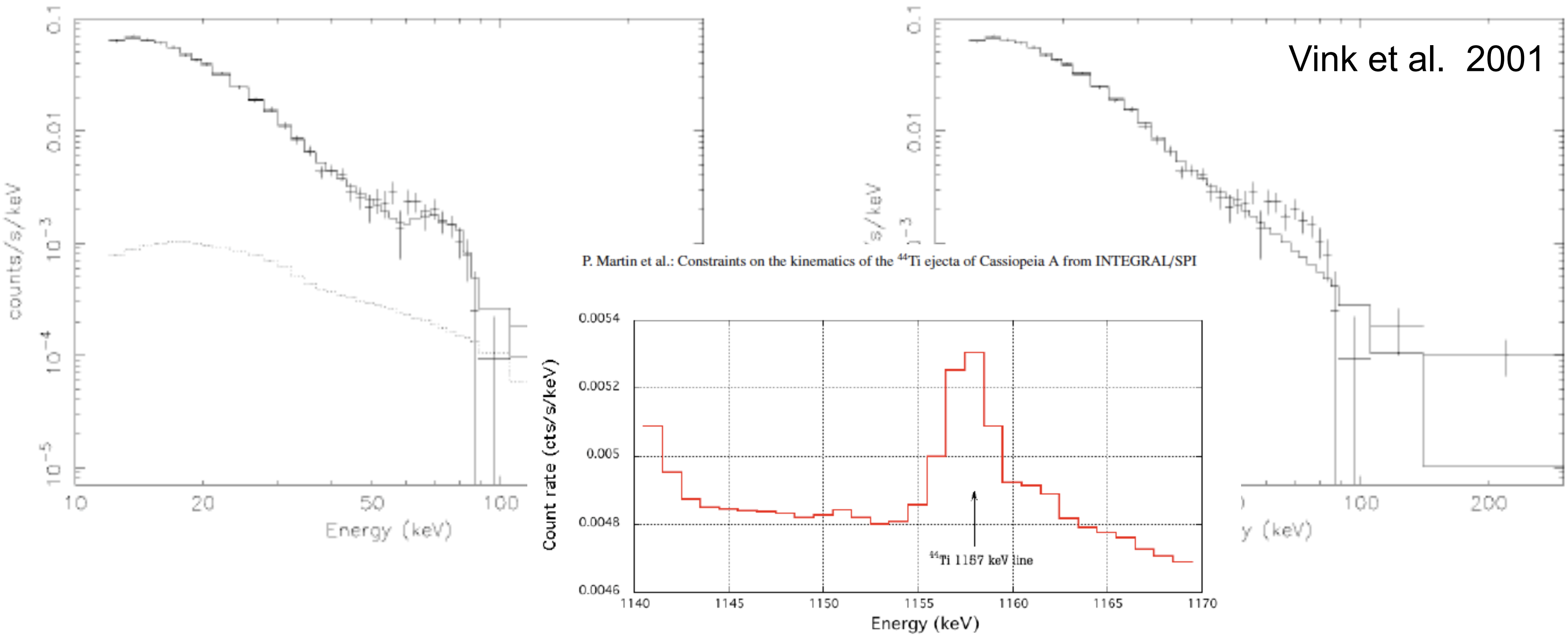
Ejecta mass is determined to be ~3.5 solar masses



		v_r km s^{-1}	$M_\odot$	E_{th} 10^{43} J	E_r 10^{43} J	E_{tot} 10^{43} J
1	hot CSM:	1740	7.9	6.5	2.4	8.9
2	hot ejecta	1740	0.4	0.3	0.1	0.4
3	cool ejecta	1780	1.7	0.2	0.5	0.7
4	cold ejecta	5290	0.1	0.0	0.3	0.3
Σ_1^2	hot diffuse	–	8.3	6.8	2.5	9.3
Σ_3^4	cool clumpy	–	1.8	0.2	0.8	1.0
Σ_2^4	ejecta	–	2.2	0.5	0.9	1.5
Σ_1^4	total	–	10.1	7.0	3.3	10.3

Willingale et al. 2002, 2003

^{44}Ti Mass



Vink et al. 2001

P. Martin et al.: Constraints on the kinematics of the ^{44}Ti ejecta of Cassiopeia A from INTEGRAL/SPI

X-ray lines from the ^{44}Ti->^{44}Sc->^{44}Ca decay chain have been observed with CGRO, BeppoSAX, INTEGRAL…

Consistent suggestion for a ^{44}Ti mass of ~10^{-4} solar masses

^{56}Ni Mass

More slippery to constrain, since we didn't actually see the supernova…

Or did we?

Flamsteed – August of 1680
- Recorded a transient 6th magnitude object at the position of Cas A roughly 330 years ago.
- If this was the outburst, then this places constraints on how much ^{56}Ni could have been ejected in the supernova.

$$L_{\rm peak} = M_{\rm Ni}\Theta(t_{\rm peak})\Lambda(t_{\rm peak}),$$

$$\Theta(t) = \frac{N_{\rm Av}}{56}\left[\frac{E_{\rm Ni}}{\tau_{\rm Ni}}e^{-t/\tau_{\rm Ni}} + \frac{E_{\rm Co}}{\tau_{\rm Co}-\tau_{\rm Ni}}\left(e^{-t/\tau_{\rm Co}} - e^{-t/\tau_{\rm Ni}}\right)\right],$$

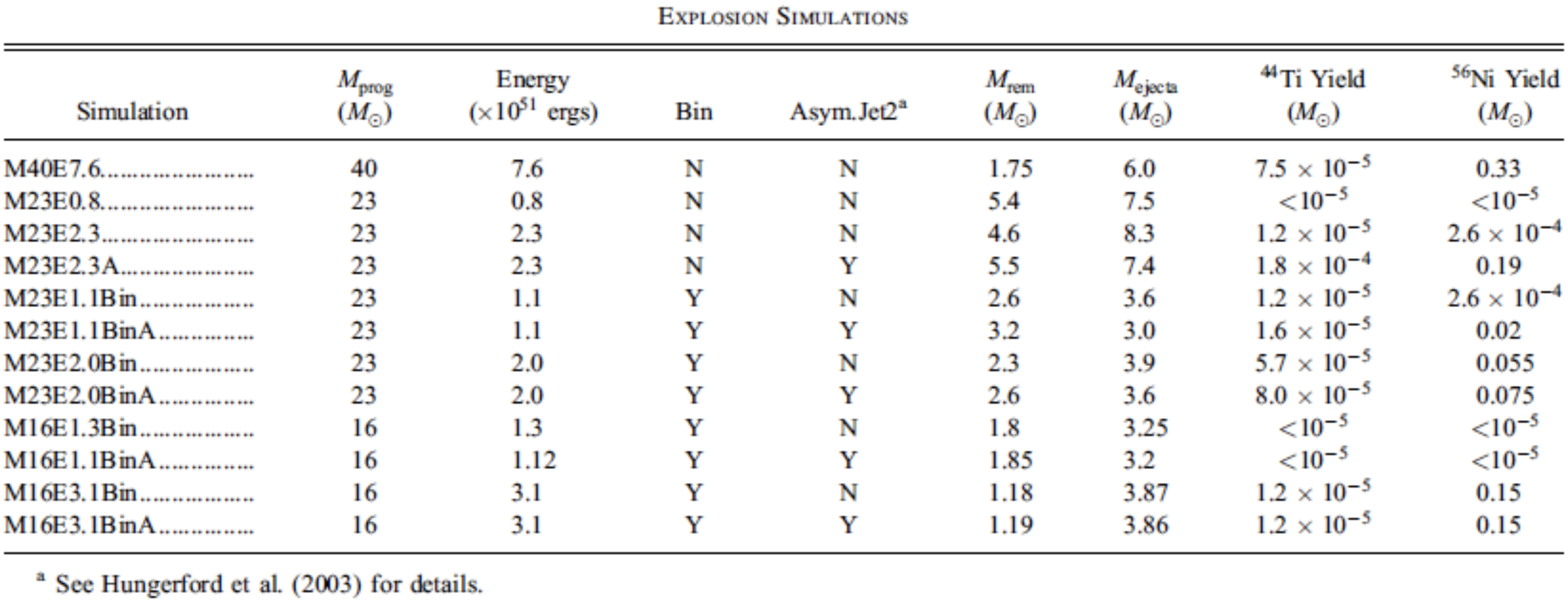
Arnett 1982

Infer an upper limit to the 56Ni produced of ~0.2 Msun
- Can also get a lower limit ~0.05 Msun from inventory of iron using X-ray lines

Constraining the Models

40 Msun Single	23 Msun Binary
23 Msun Single	16 Msun Binary

Asymmetry, Explosion Energy



EXPLOSION SIMULATIONS

Simulation	M_{prog} ($M_\odot$)	Energy ($\times 10^{51}$ ergs)	Bin	Asym.Jet2[a]	M_{rem} ($M_\odot$)	M_{ejecta} ($M_\odot$)	^{44}Ti Yield ($M_\odot$)	^{56}Ni Yield ($M_\odot$)
M40E7.6	40	7.6	N	N	1.75	6.0	7.5×10^{-5}	0.33
M23E0.8	23	0.8	N	N	5.4	7.5	$<10^{-5}$	$<10^{-5}$
M23E2.3	23	2.3	N	N	4.6	8.3	1.2×10^{-5}	2.6×10^{-4}
M23E2.3A	23	2.3	N	Y	5.5	7.4	1.8×10^{-4}	0.19
M23E1.1Bin	23	1.1	Y	N	2.6	3.6	1.2×10^{-5}	2.6×10^{-4}
M23E1.1BinA	23	1.1	Y	Y	3.2	3.0	1.6×10^{-5}	0.02
M23E2.0Bin	23	2.0	Y	N	2.3	3.9	5.7×10^{-5}	0.055
M23E2.0BinA	23	2.0	Y	Y	2.6	3.6	8.0×10^{-5}	0.075
M16E1.3Bin	16	1.3	Y	N	1.8	3.25	$<10^{-5}$	$<10^{-5}$
M16E1.1BinA	16	1.12	Y	Y	1.85	3.2	$<10^{-5}$	$<10^{-5}$
M16E3.1Bin	16	3.1	Y	N	1.18	3.87	1.2×10^{-5}	0.15
M16E3.1BinA	16	3.1	Y	Y	1.19	3.86	1.2×10^{-5}	0.15

[a] See Hungerford et al. (2003) for details.

Constraining the Models

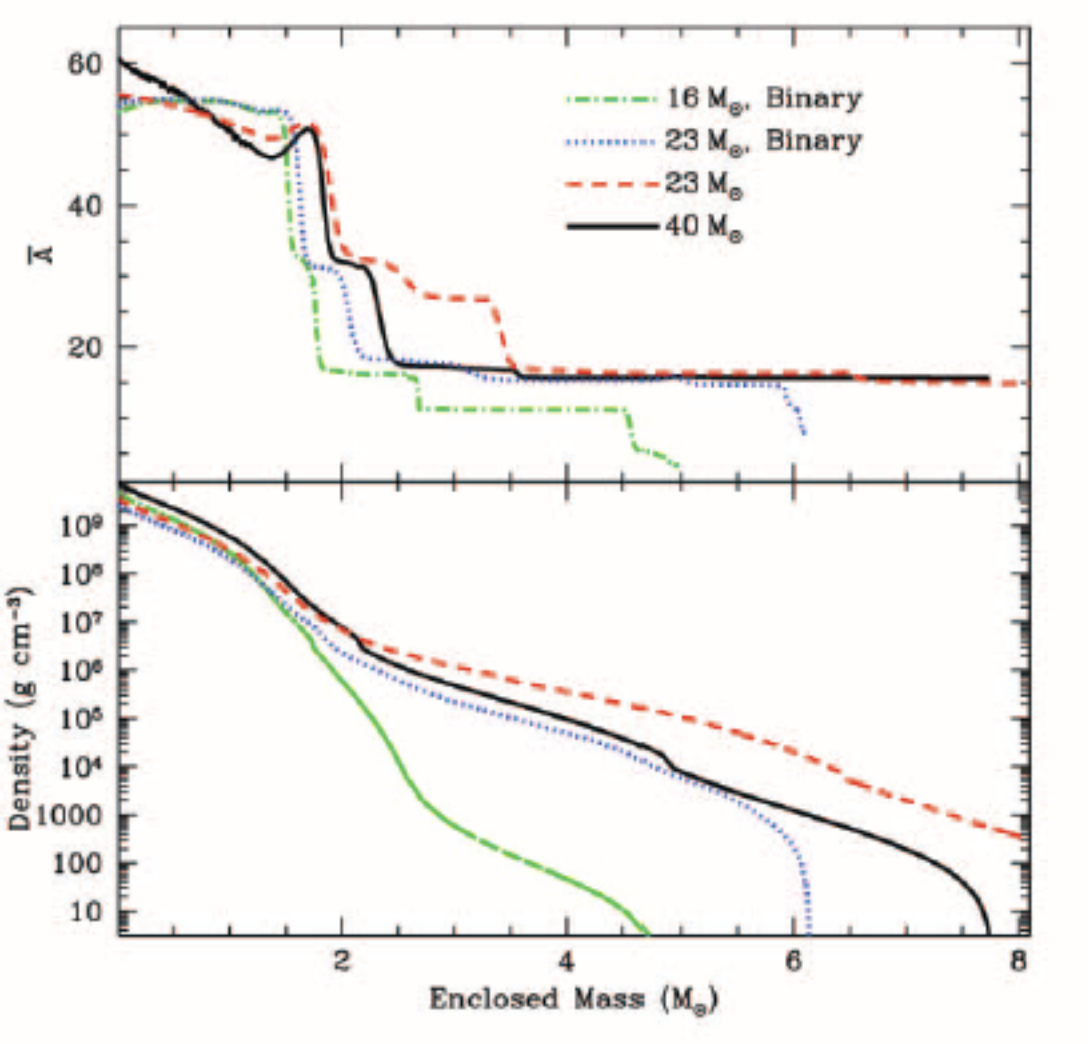
Assumptions:

- we want their to be a little H-burning ash on the star surface at explosion (a la the N knots)

- we want this to happen at an enclosed mass of 4-7 Msun (a la the ejecta mass)

➢ The single star models do not satisfy these constraints

  They still have Abar indicating the Carbon/Oxygen layer out to an enclosed mass of >8 Msun.

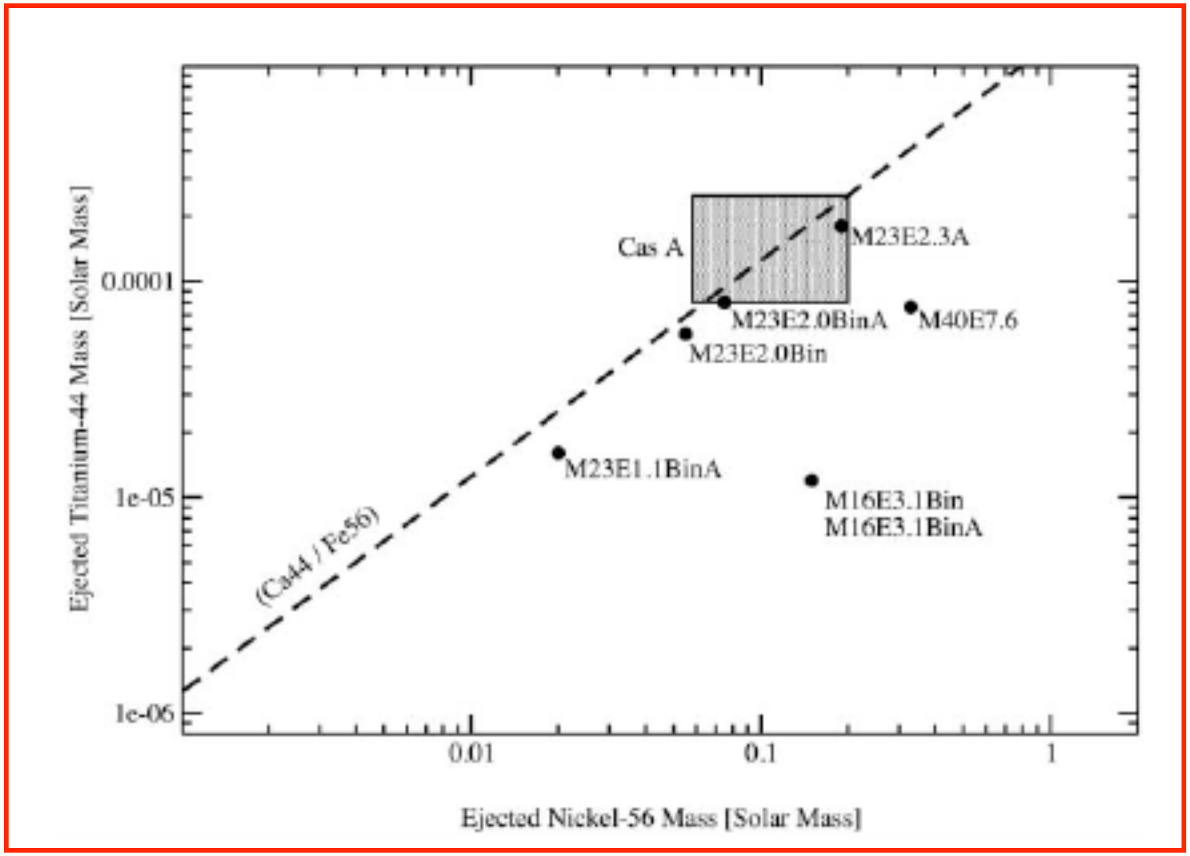


^{44}Ti / ^{56}Ni

The ratio places an even stronger constraint because Nickel and Titanium are largely speaking synthesized in the same place in the explosion.

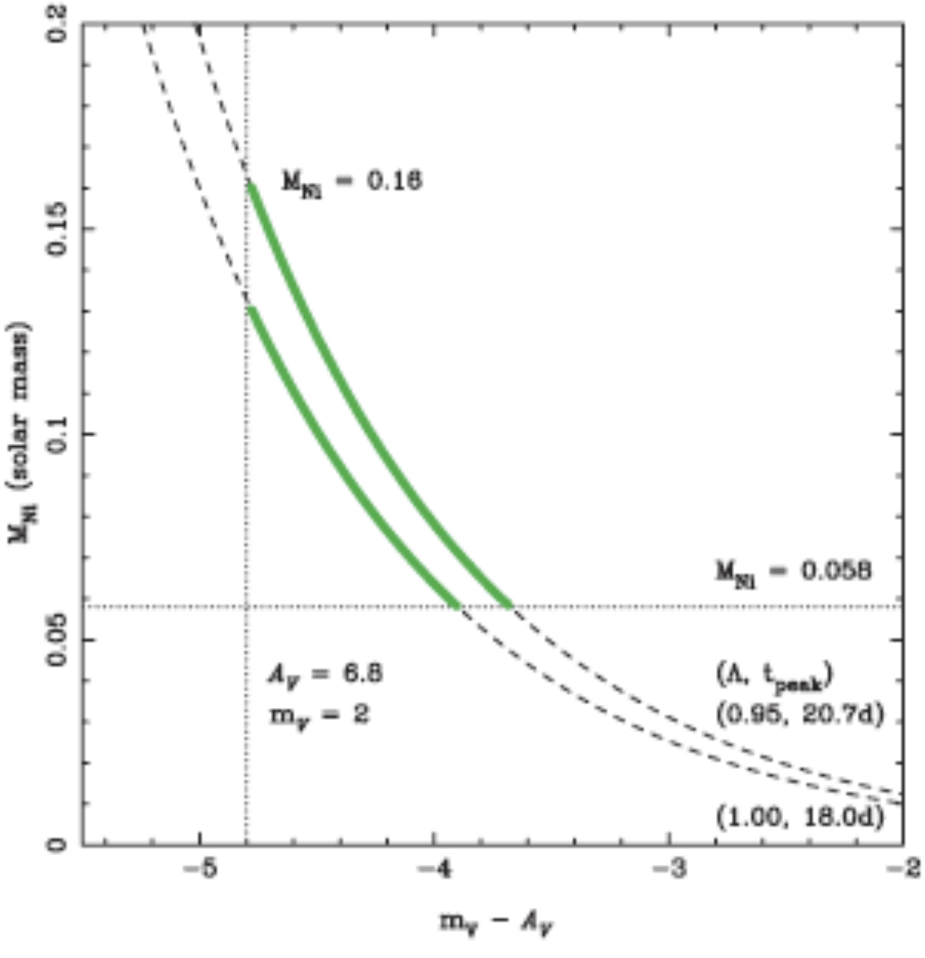
- So if the titanium was ejected for all the world to see, so was the nickel!
- Uncertainty box for ^{44}Ti / ^{56}Ni is consistent with solar abundance of ^{44}Ca/^{56}Fe

While very uncertain, this is still a nice constraint for the models as it probes the “mass cut”



^{56}Ni

Recent work going beyond the simple arguments for ^{56}Ni mass estimates has been done by Eriksen et al. 2009



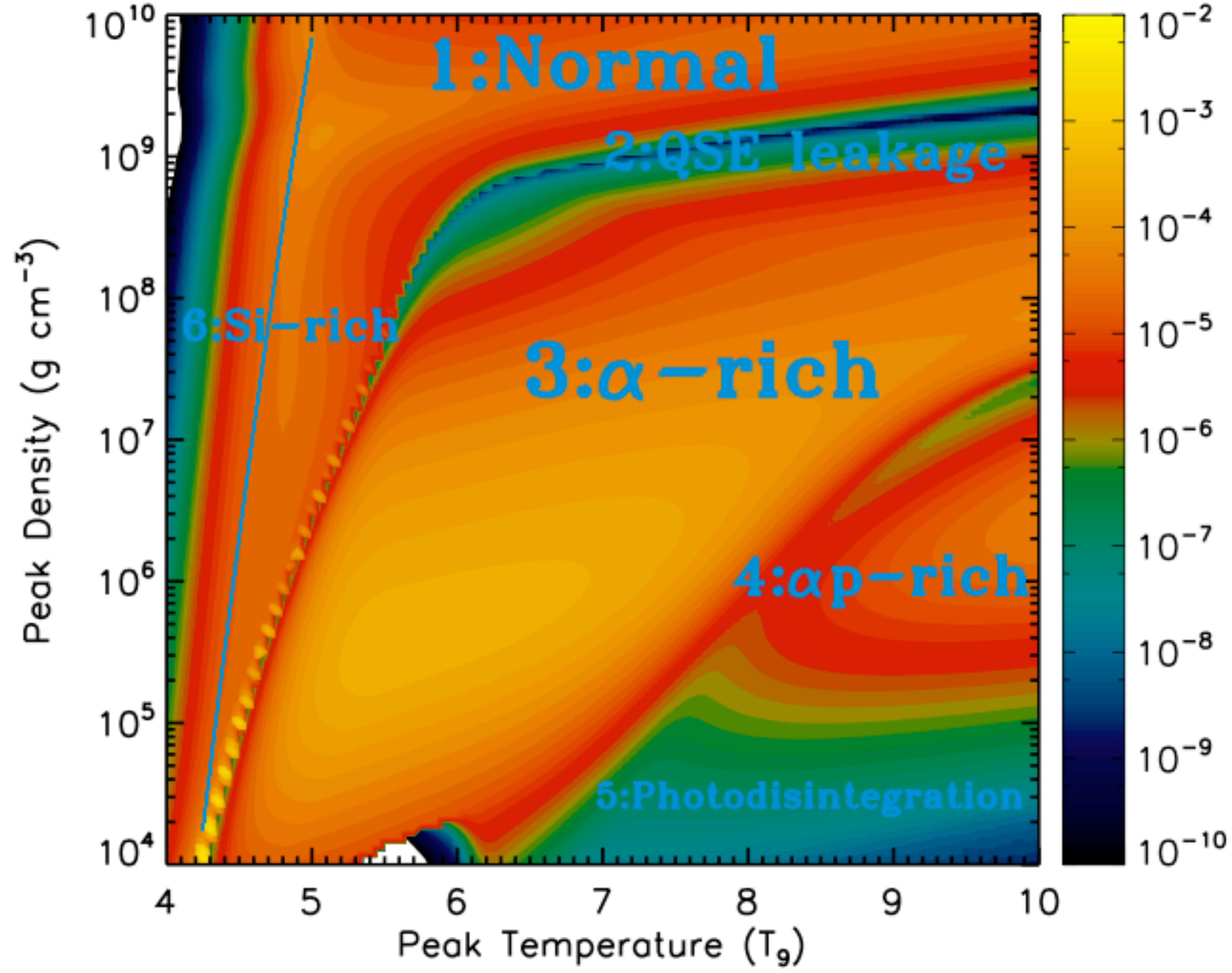
Nucleosynthesis

Heavy element synthesis in stellar collapse occurs either:

- near the surface of the compact star (neutrino driven winds)
- In the outward-moving shock, a.k.a. explosive nucleosynthesis.

- ➢ Detailed studies of a handful of trajectories insufficient.
- ➢ The simple picture from 1-dimensional models is too simple!
- ➢ We need to broaden our studies, studying a larger variety of trajectories.

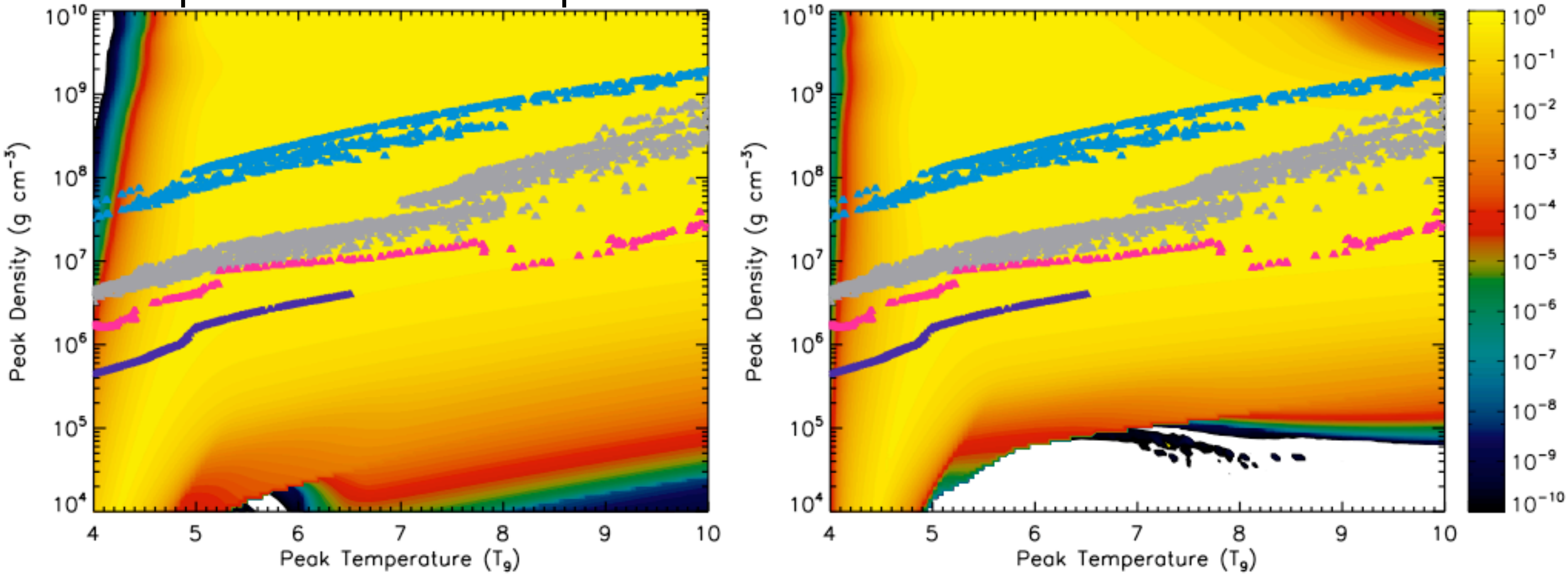
The critical rates for ^{44}Ti production depend upon the peak temperature and density



Magkotsios et al. 2010

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



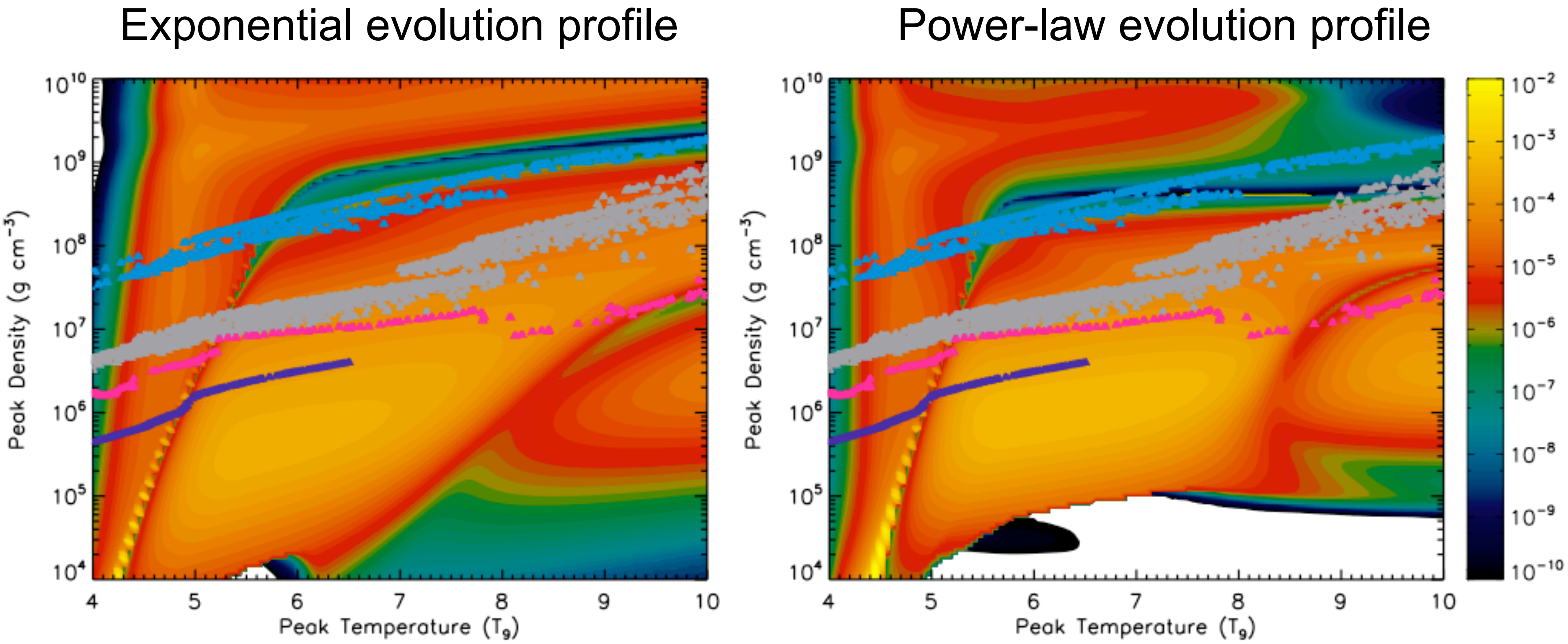
Exponential evolution profile

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

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



Exponential evolution profile

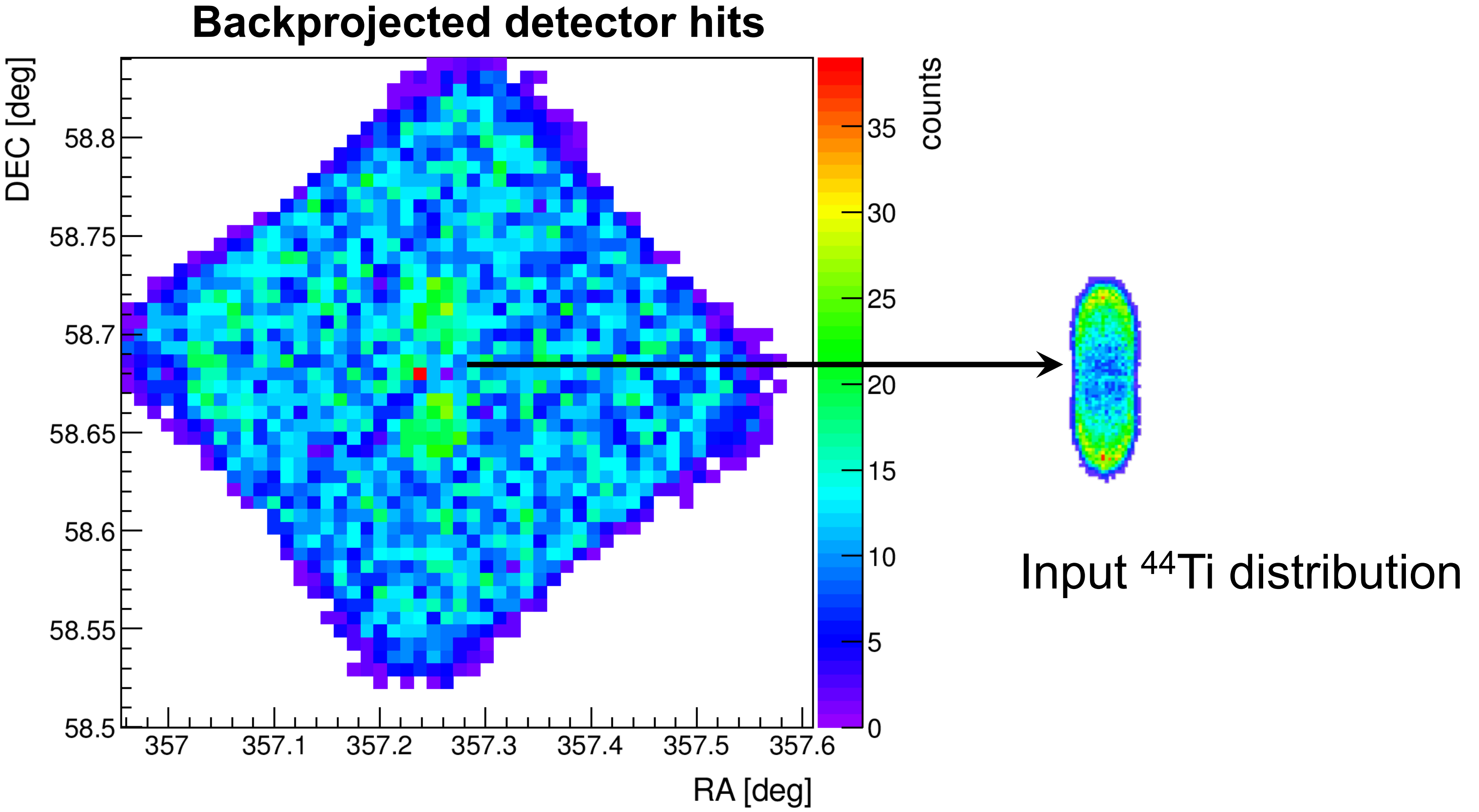
Power-law evolution profile

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

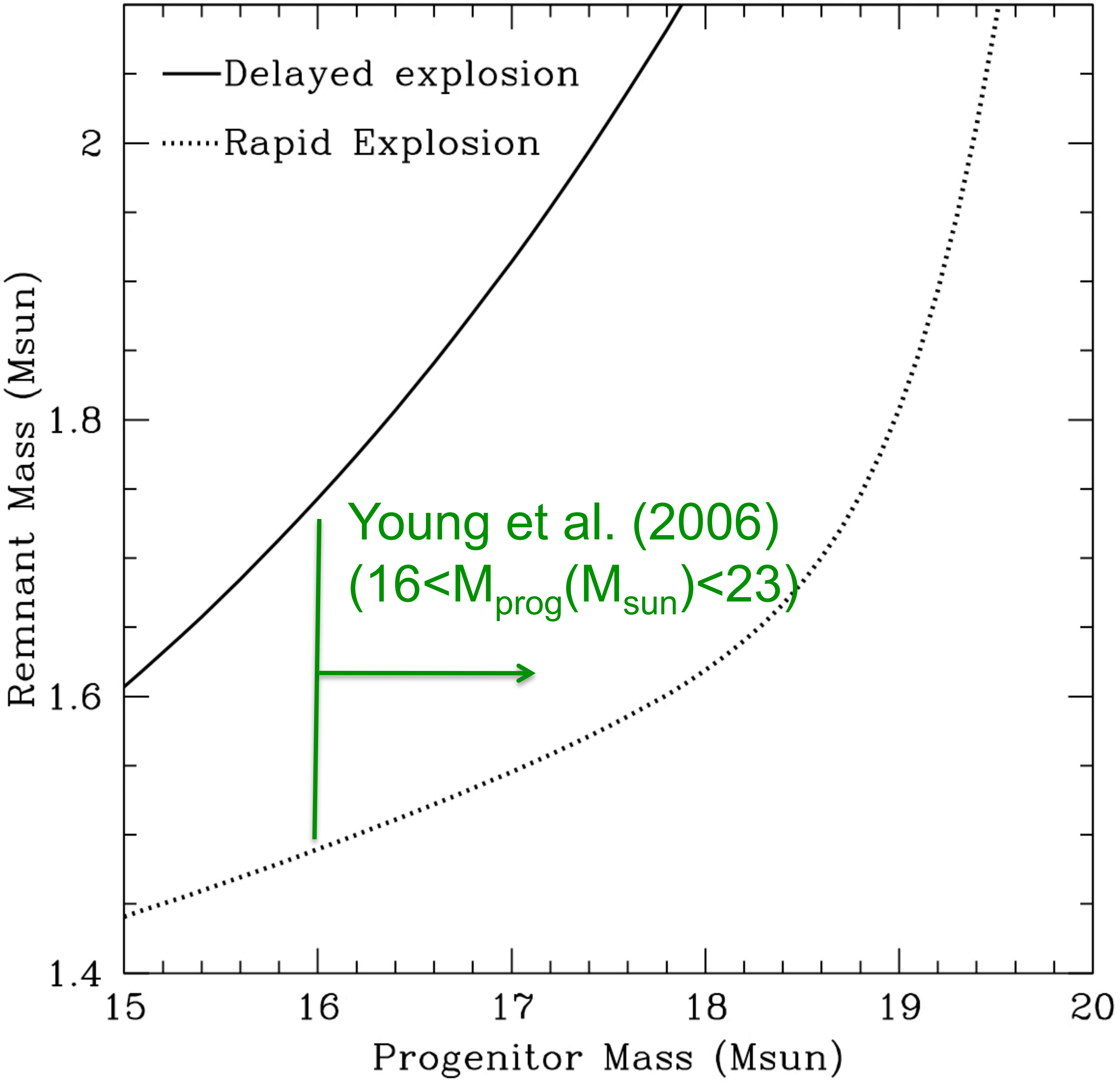
Magkotsios et al. 2010

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



Input ^{44}Ti distribution



Remnant Mass Estimates Using single star models from Fryer et al. 2011. The binary 23Msun model from Young et al. 2006 is closer to a 16 Msun model.