Constraints on the Progenitor of Cassiopeia A

KITP Supernova/GRB Connection

February 10, 2006

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LA-UR-05-4652

Cassiopeia A

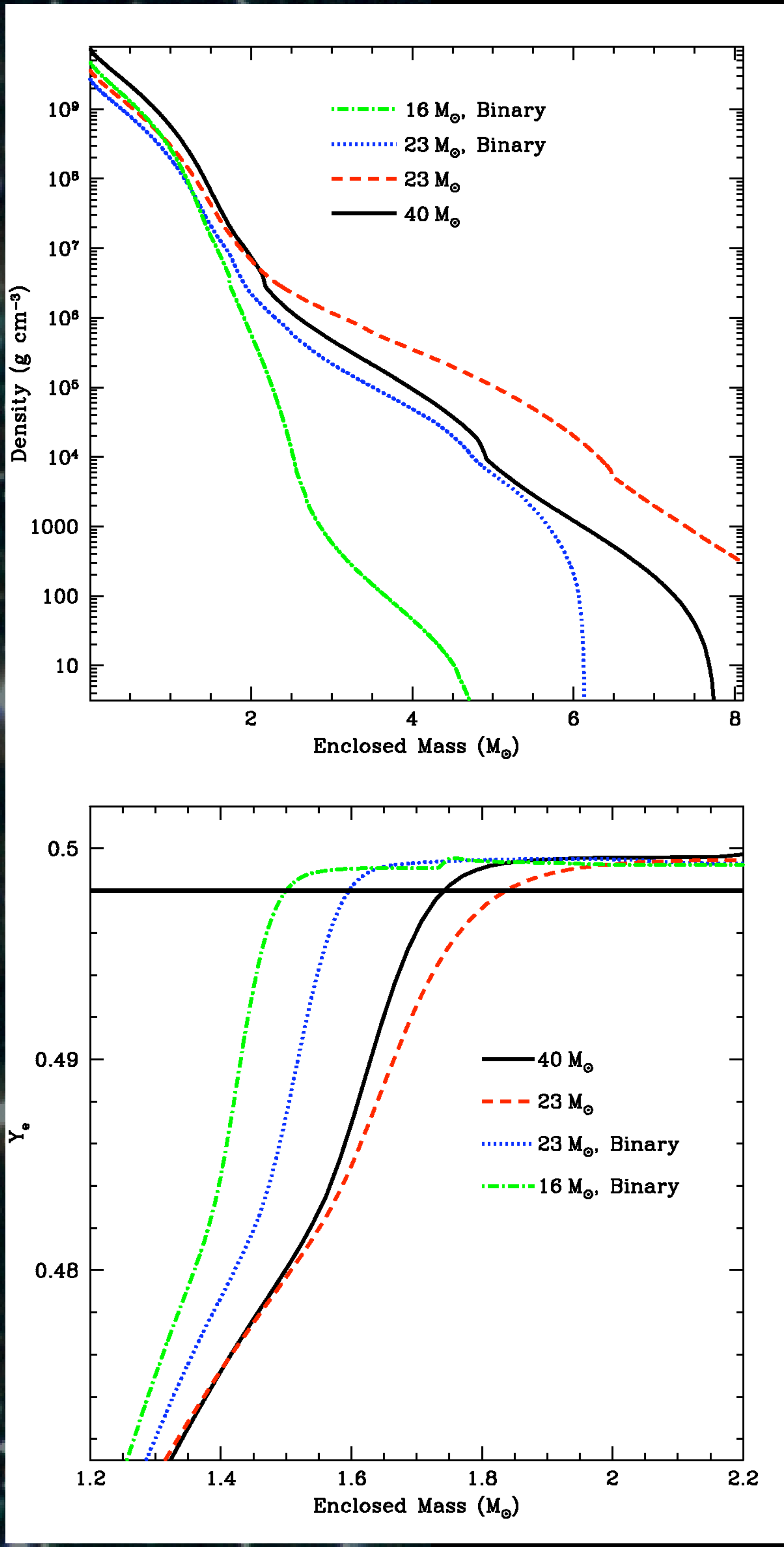
- •Young (325yr), nearby (3.4 kpc)
- •High spatial resolution data from radio - γ-ray, including abundances and secular evolution
- •Estimates range from 16 to 60 $M_{\odot}$ single stars and binary scenarios
- •Several independent observational constraints
- •1D/3D neutrino-driven collapse/explosion calculations + advanced progenitor models
- •What parameter space for the progenitor is allowed by each constraint?

Step 0: What do we mean by “progenitor”?

- Define Progenitor Mass to be mass of the star at H ignition or the Zero Age Main Sequernce (ZAMS)
- Mass at explosion is generally very different for massive stars
- 16 to 60 $M_{\odot}$ refers to progenitor mass
- Estimates of mass at explosion also vary greatly
    - 12 $M_{\odot}$ (from nucleosynthesis, Willingale et al. 2002)
    - 3.7 $M_{\odot}$ (from x-ray spectral fits, Willingale et al. 2003)

Progenitor models

- Progenitors produced with TYCHO including convective boundary hydrodynamics and wave-driven mixing
- Evolved in 1D until collapse velocities > 500 km s^{-1}
- 40 $M_\odot$ with LBV and Wolf-Rayet mass loss
    - final 7.75 $M_\odot$ WC/O
- 23 $M_\odot$ with normal red supergiant mass loss
    - final 14.4 $M_\odot$ RSG
- 23 $M_\odot$ “binary” - H envelope ejected on 1st ascent RGB
    - final 6.2 $M_\odot$ WN
- 16 $M_\odot$ “binary”
    - final 5.0 $M_\odot$ WN



Explosion Calculations

•Collapse & launch of explosion in 1D (Fryer '99)

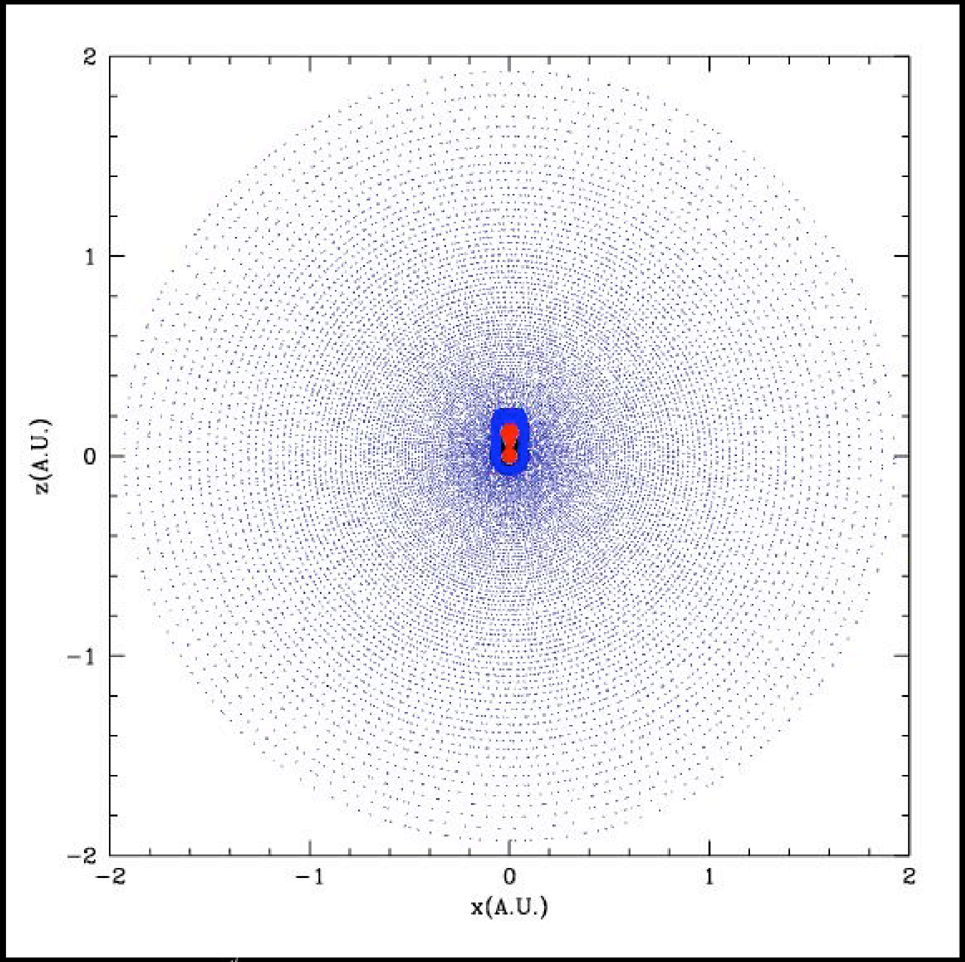
•Propagation of shock through star in 3D (SNSPH, Fryer et al. '05)

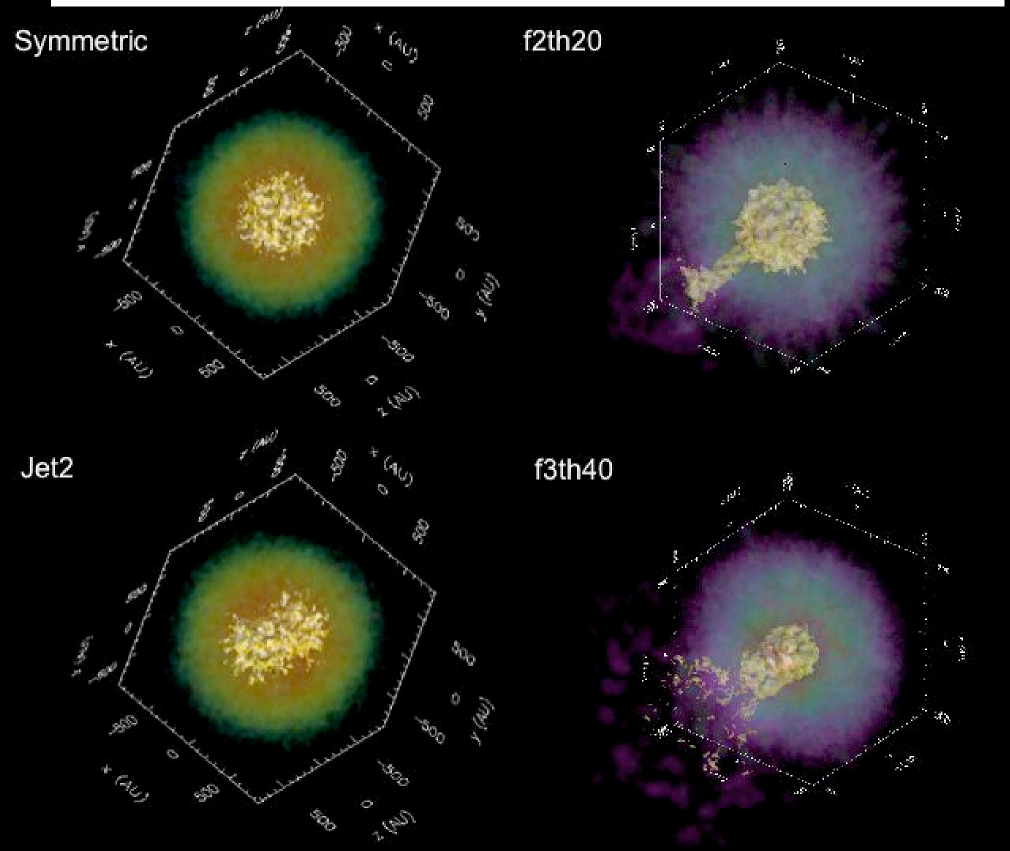
•14 element inline nuclear network with 500 element network post-processing

•Varied explosion energies (final kinetic energy of ejecta)

•Symmetric & asymmetric explosions

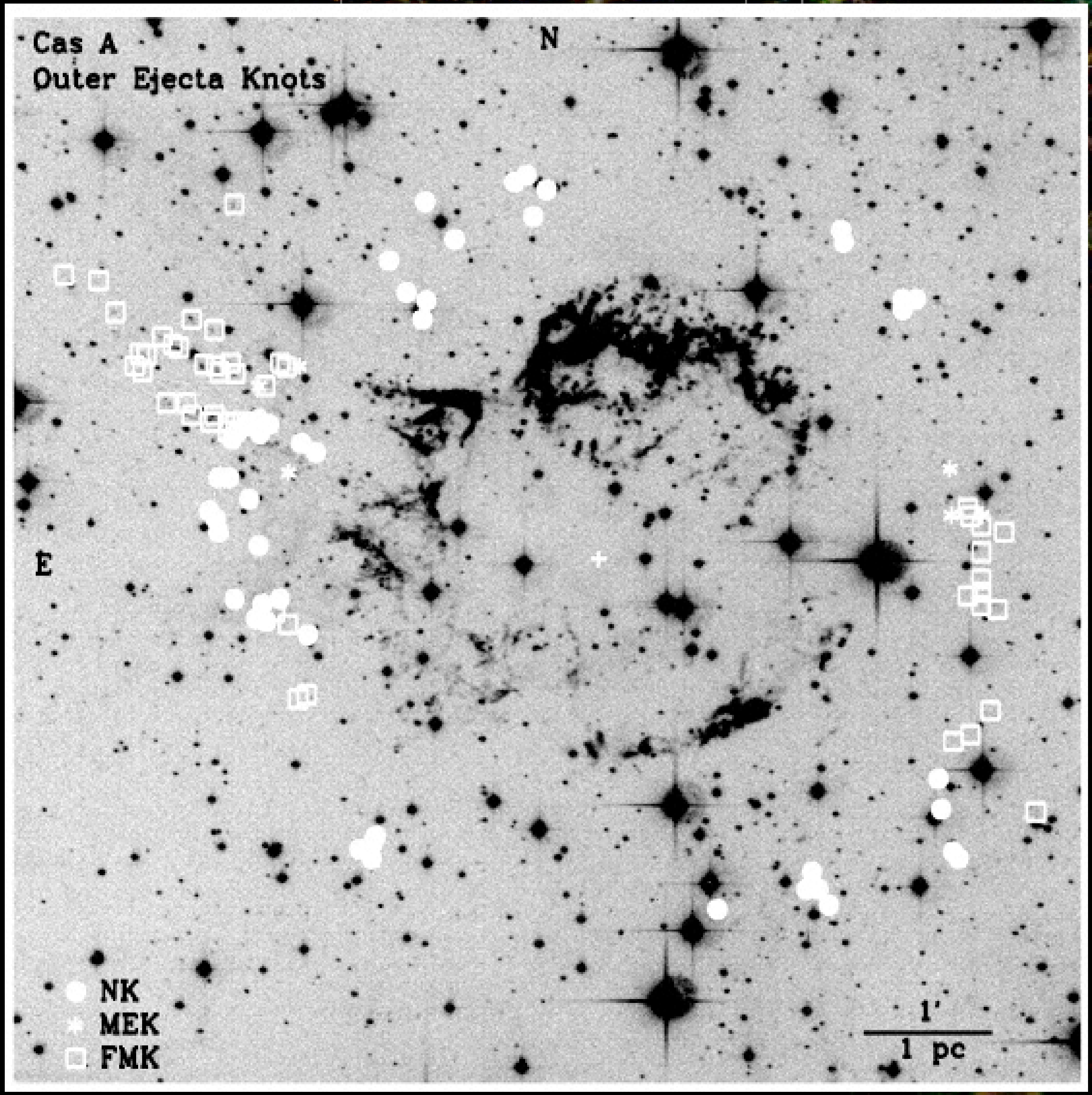
  •factor of 2 variation in *v* from pole to equator imposed on 3D mapping

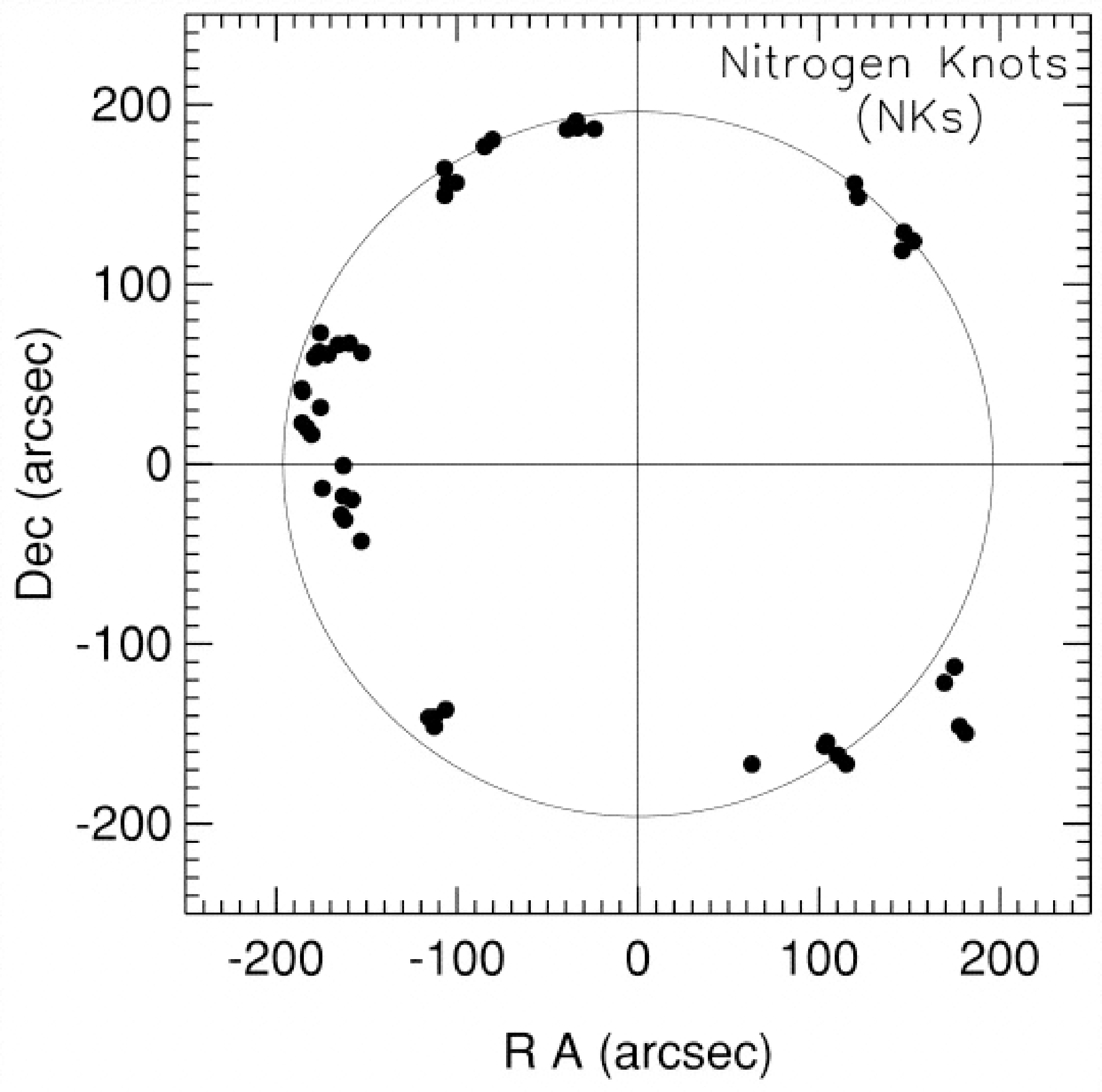




Observational Constraints

- Nitrogen knots (NKs) - Nitrogen rich, hydrogen poor, v ~ 8000 km s^{-1}



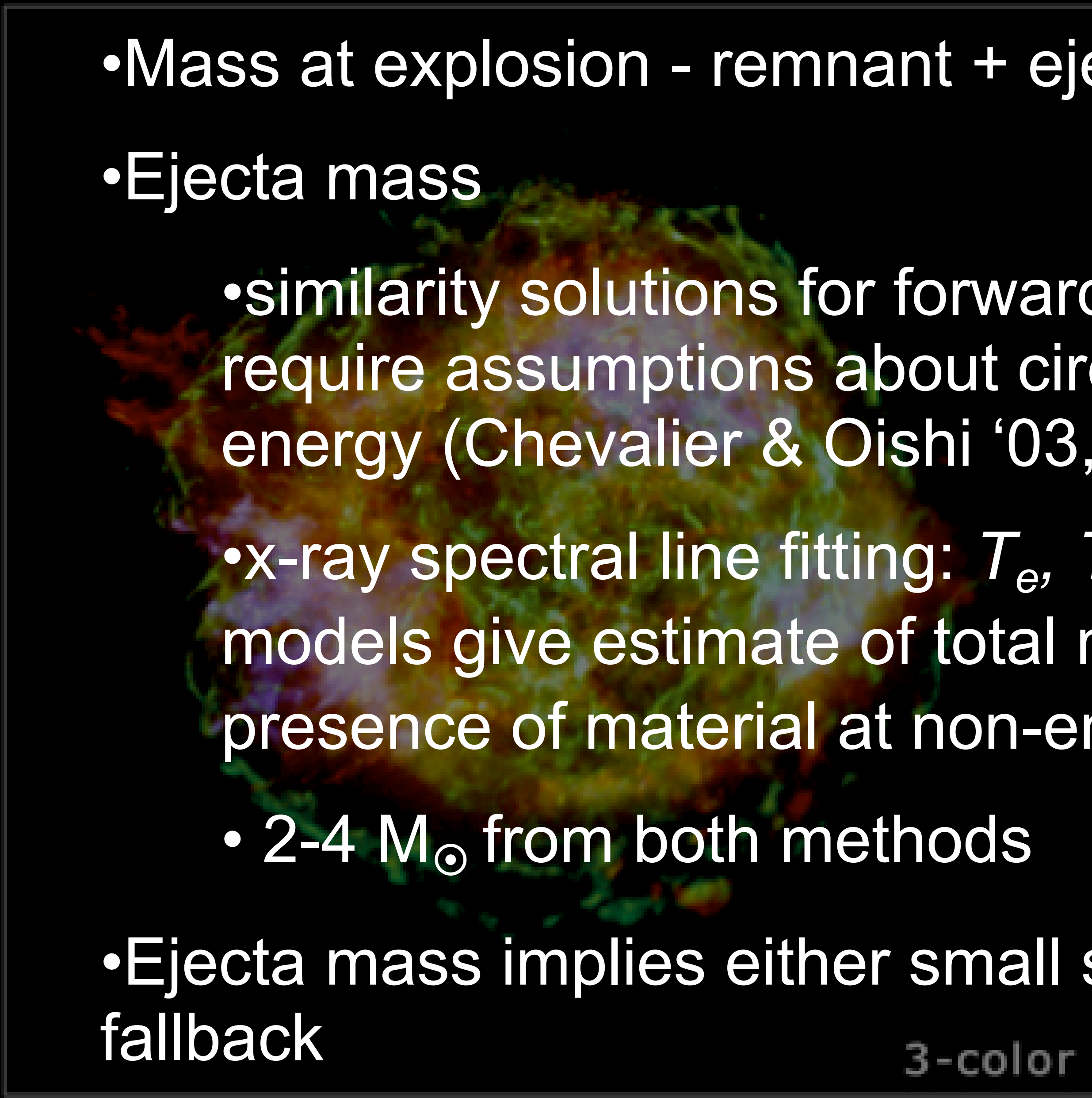


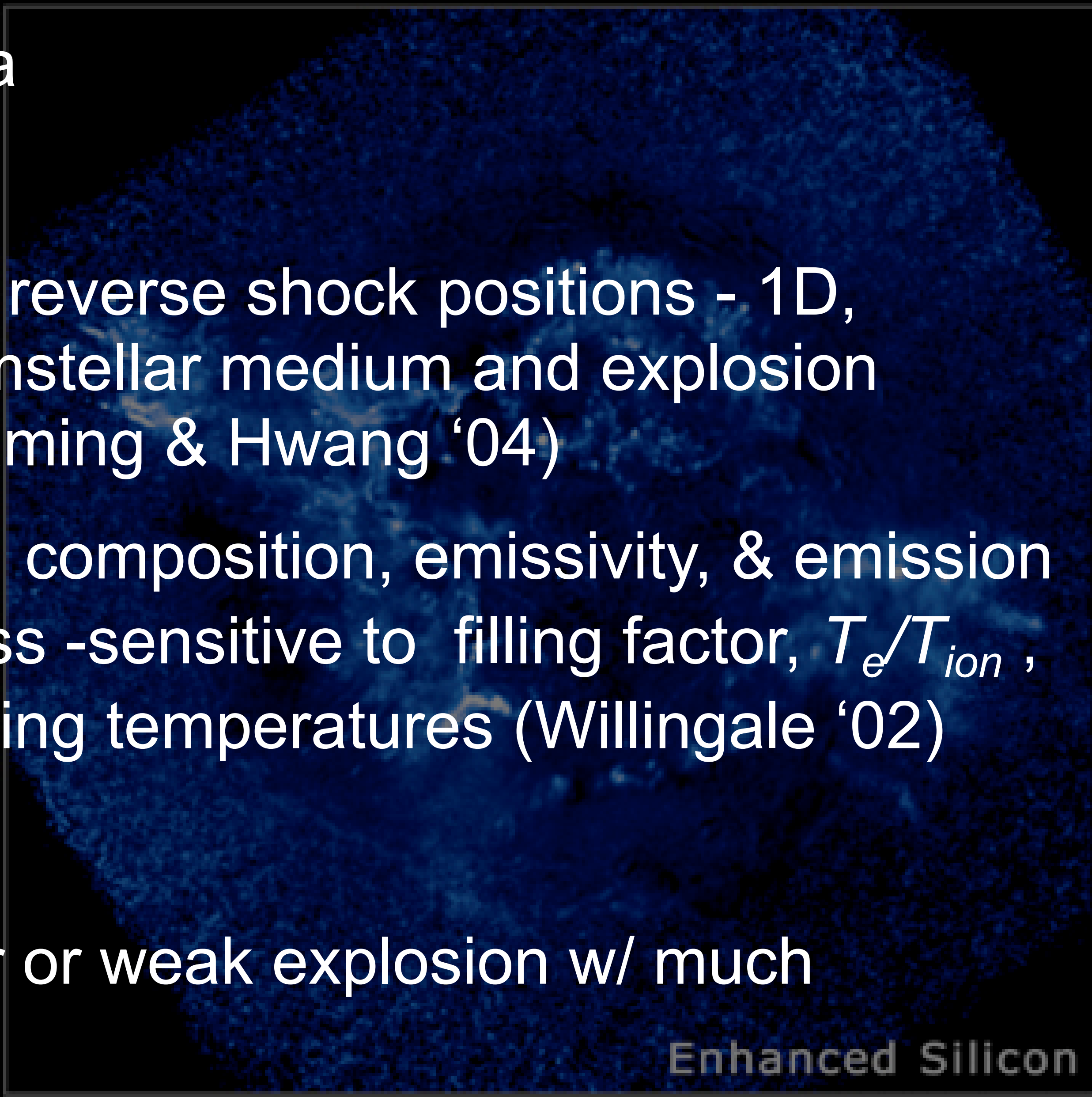
Fesen 2001

Observational Constraints

- Nitrogen knots (NKs) - Nitrogen rich, hydrogen poor, v ~ 8000 km s^{-1}
    - Star must have had primarily CNO ash at surface at explosion (N/H ~ 30x solar implies >90% of H exhausted)
    - Massive Wolf-Rayet models lose CNO ash as wind, have He burning products at surface
    - Very low mass WRs (~25 $M_{\odot}$ if such things exist) lose H envelope as red supergiant - CNO ash mixed with H envelope by dredge-up
    - Low mass single stars don't lose H envelope
- Two possibilities available:
    - Low mass WR (~28-30 $M_{\odot}$?)
    - Low mass (<25 $M_{\odot}$) loses envelope in binary

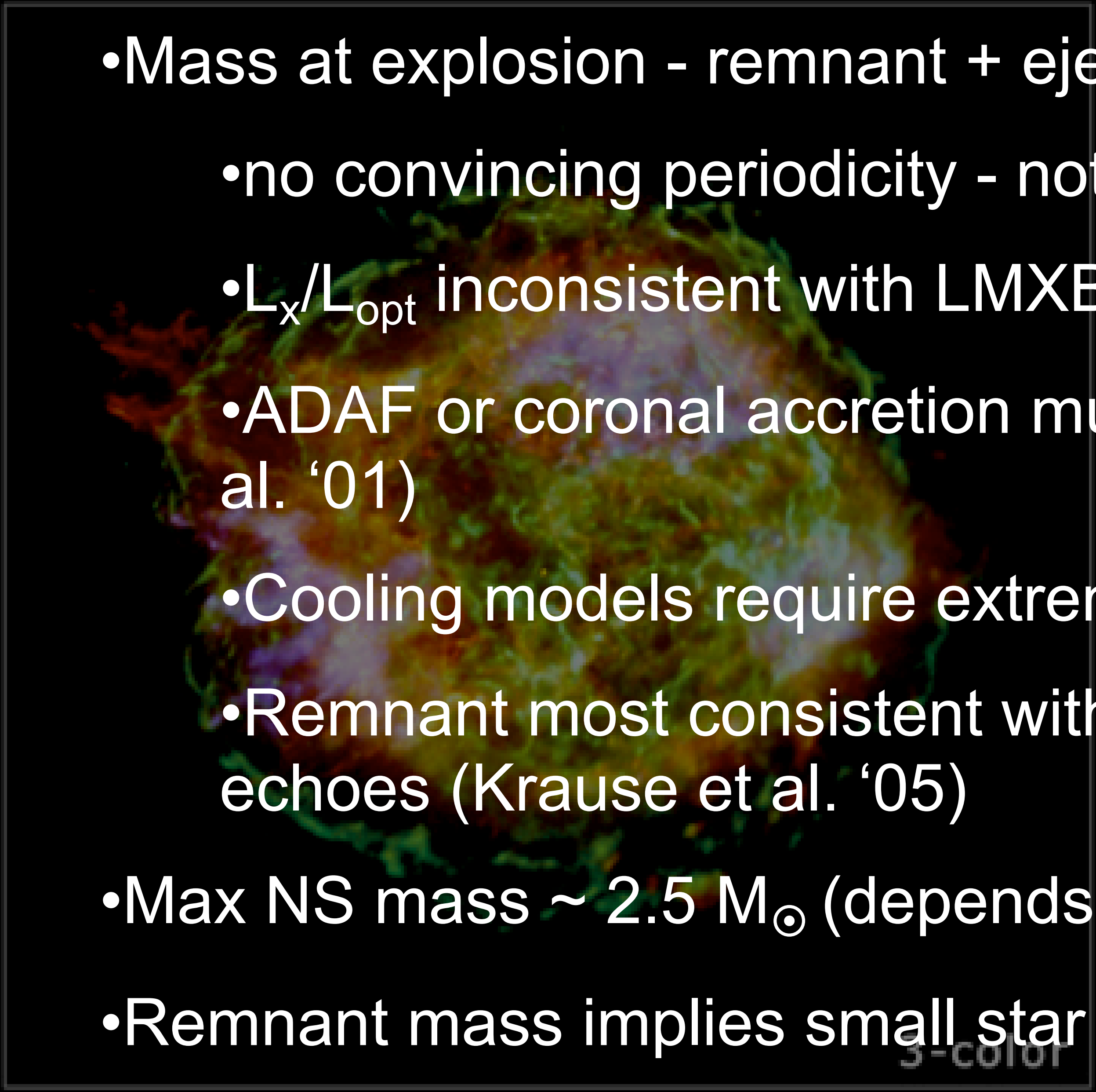
Observational Constraints

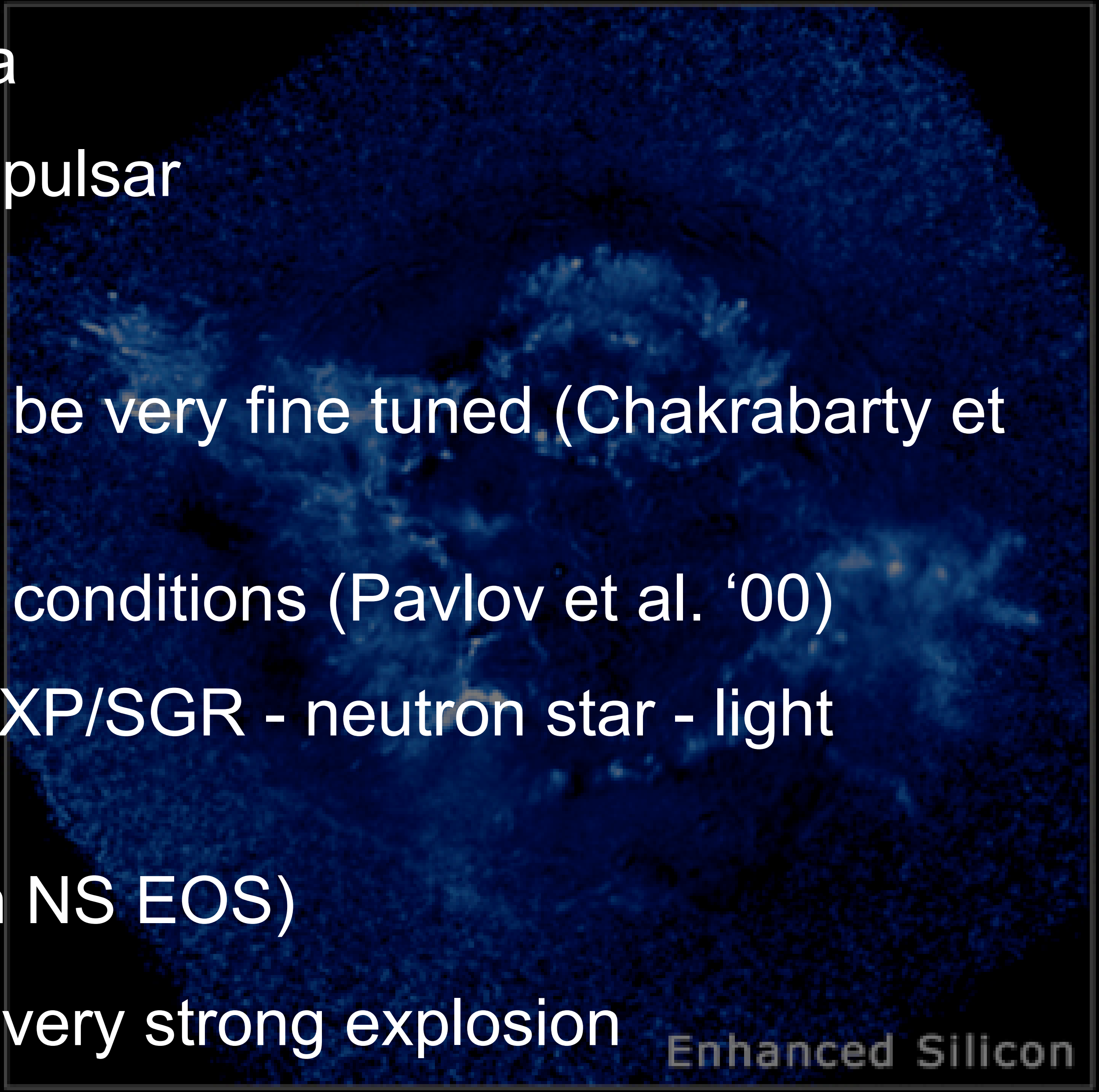




- Mass at explosion - remnant + ejecta
- Ejecta mass
  - similarity solutions for forward & reverse shock positions - 1D, require assumptions about circumstellar medium and explosion energy (Chevalier & Oishi ‘03, Laming & Hwang ‘04)
  - x-ray spectral line fitting: T_e, T_{ion}, composition, emissivity, & emission models give estimate of total mass -sensitive to filling factor, T_e/T_{ion} , presence of material at non-emitting temperatures (Willingale ‘02)
  - 2-4 $M_\odot$ from both methods
- Ejecta mass implies either small star or weak explosion w/ much fallback
- An asymmetric explosion will result in more fallback for a given energy

Observational Constraints



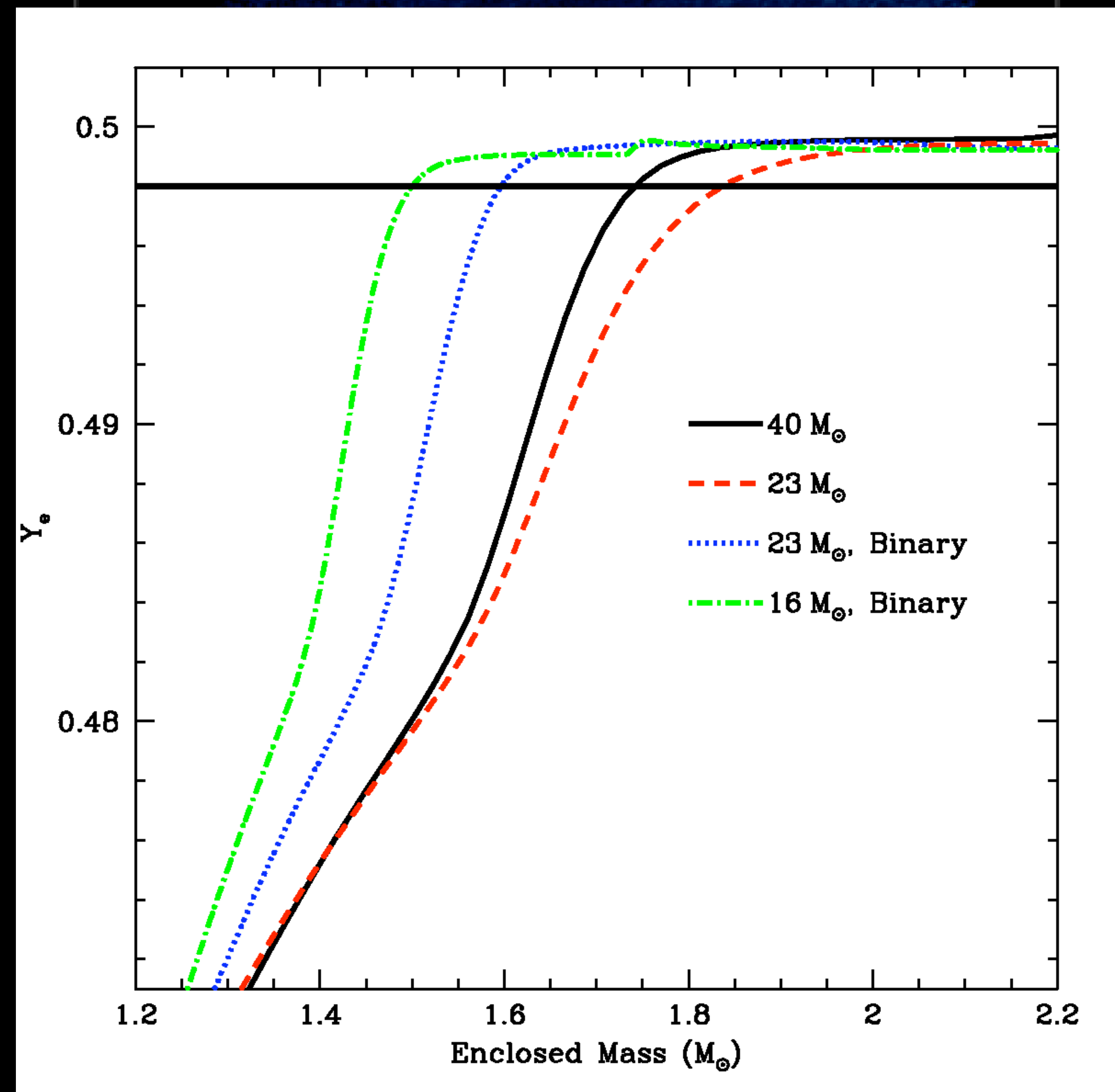


- Mass at explosion - remnant + ejecta
    - no convincing periodicity - not a pulsar
    - L_x/L_{opt} inconsistent with LMXB
    - ADAF or coronal accretion must be very fine tuned (Chakrabarty et al. ‘01)
    - Cooling models require extreme conditions (Pavlov et al. ‘00)
    - Remnant most consistent with AXP/SGR - neutron star - light echoes (Krause et al. ‘05)
- Max NS mass ~ 2.5 $M_\odot$ (depends on NS EOS)
- Remnant mass implies small star or very strong explosion

Observational Constraints

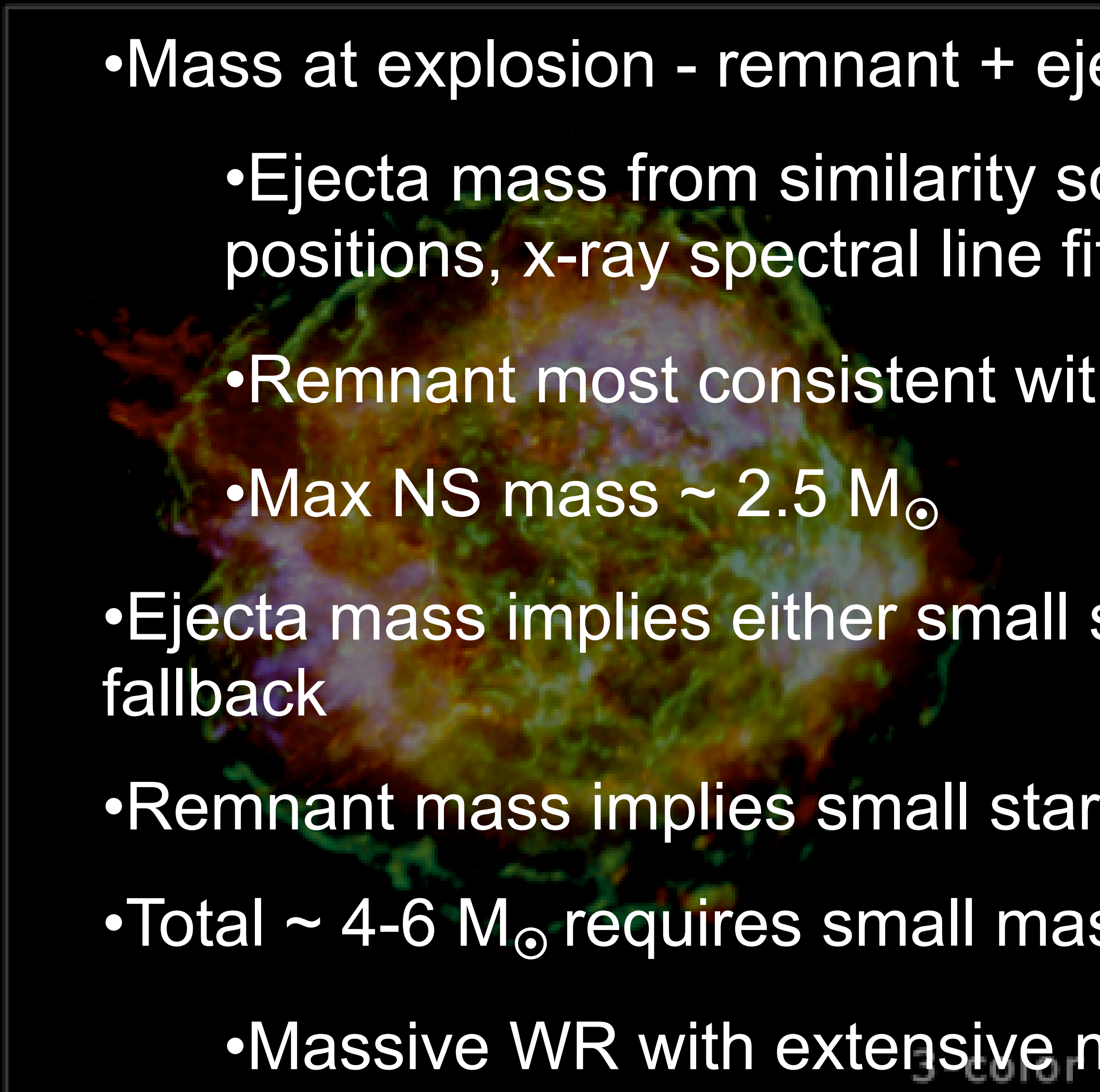
- Mass at explosion - remnant + ejecta
- Min NS mass *IF* we assume ejecta can't be more neutron rich than solar
- Y_e of material reset by neutrinos only very close to the neutron star - subject to fallback
- 1.5-1.75 $M_\odot$, depending on progenitor

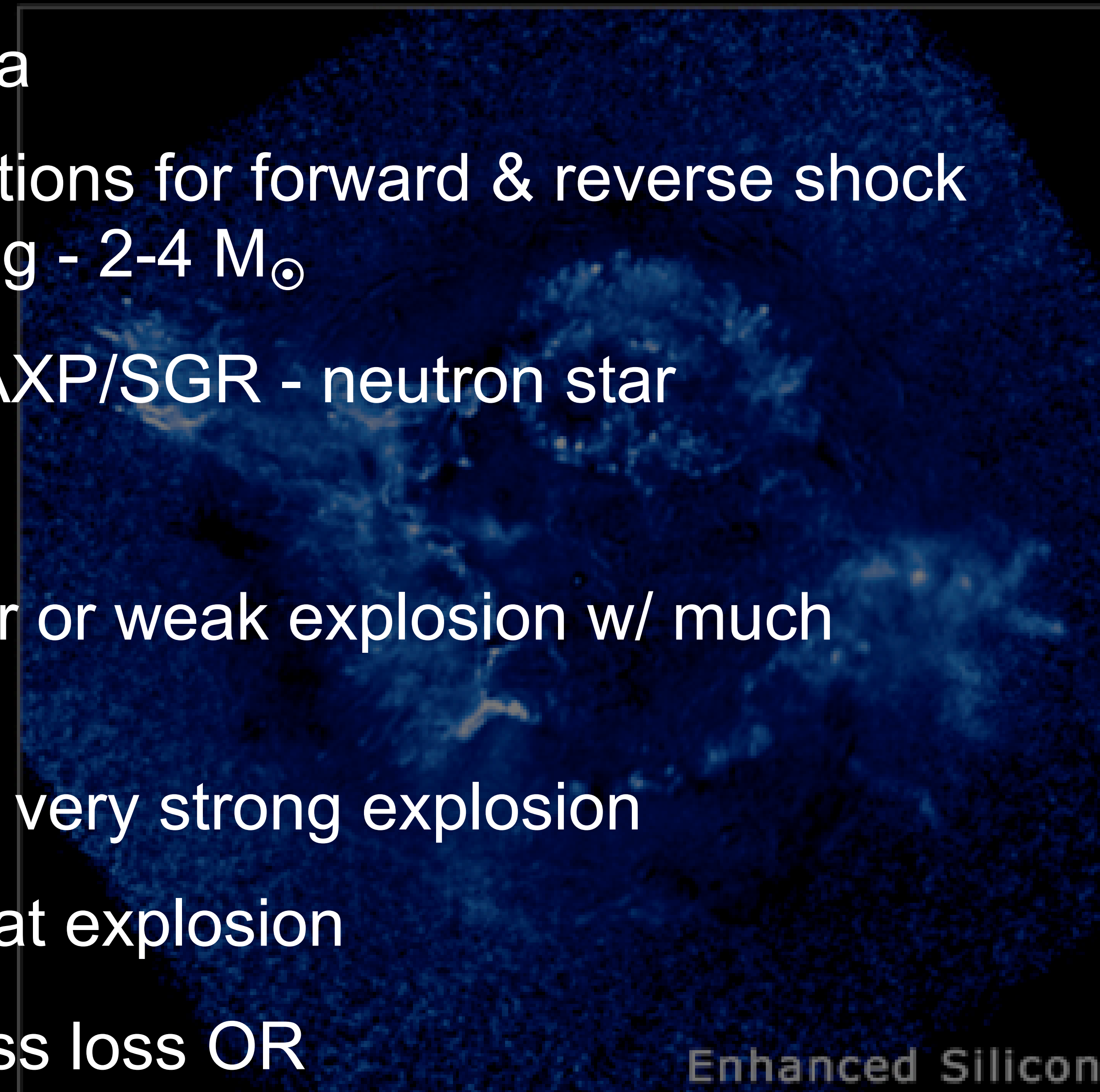
3-color



Observational Constraints

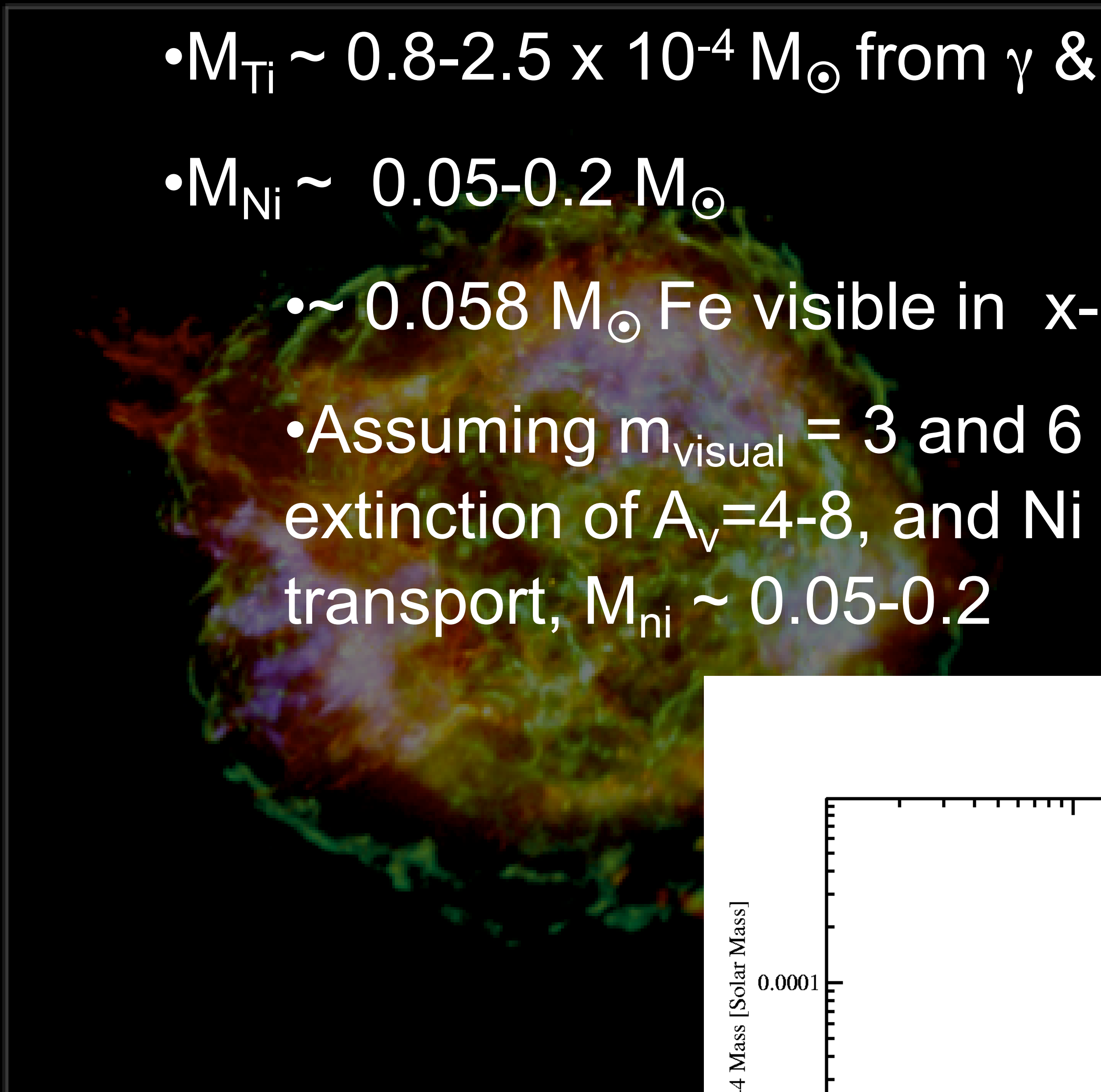
- Mass at explosion - remnant + ejecta
  - Ejecta mass from similarity solutions for forward & reverse shock positions, x-ray spectral line fitting - 2-4 $M_\odot$
  - Remnant most consistent with AXP/SGR - neutron star
  - Max NS mass ~ 2.5 $M_\odot$
- Ejecta mass implies either small star or weak explosion w/ much fallback
- Remnant mass implies small star or very strong explosion
- Total ~ 4-6 $M_\odot$ requires small mass at explosion
  - Massive WR with extensive mass loss OR
  - Low mass star with binary envelope ejection

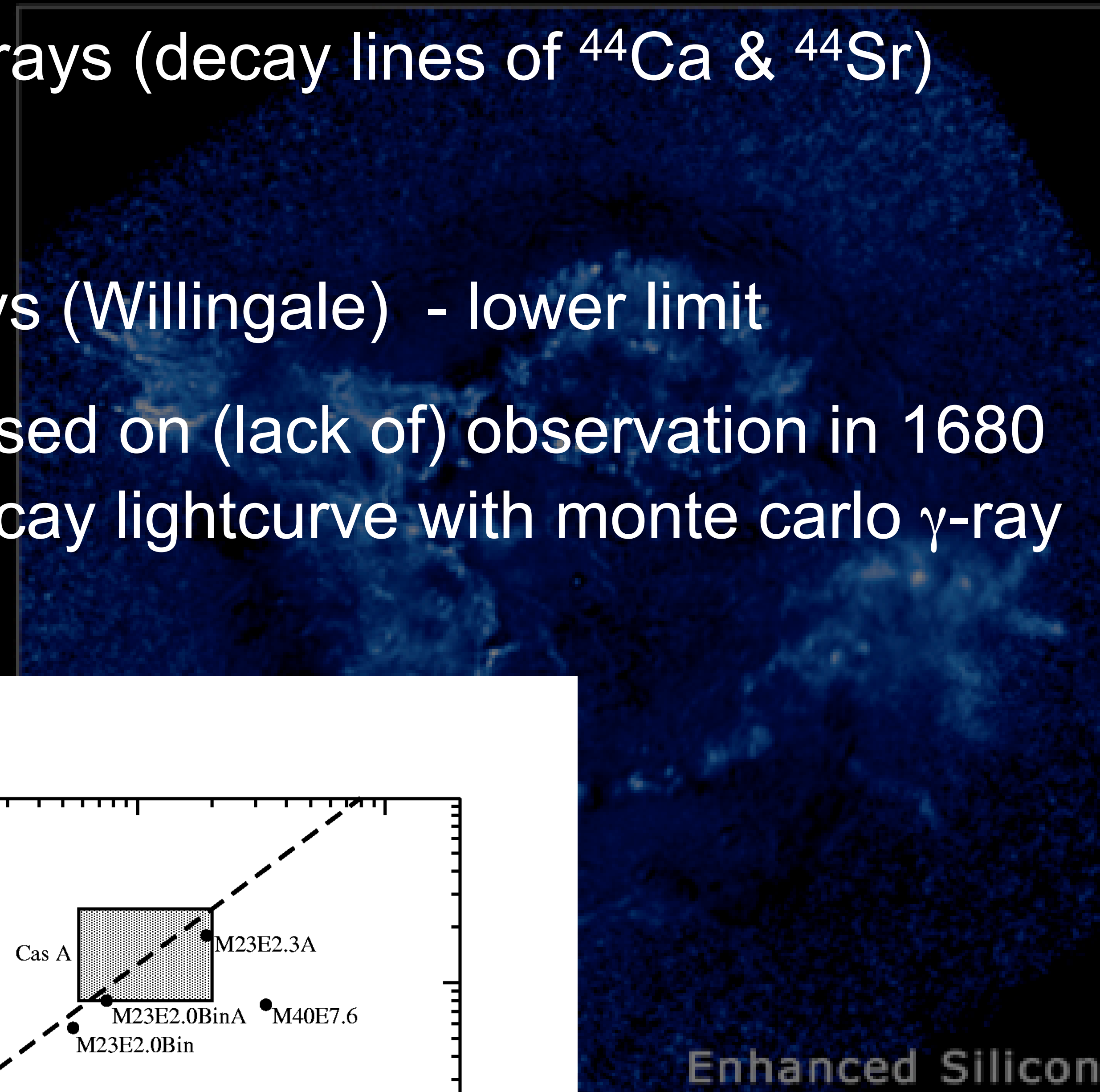


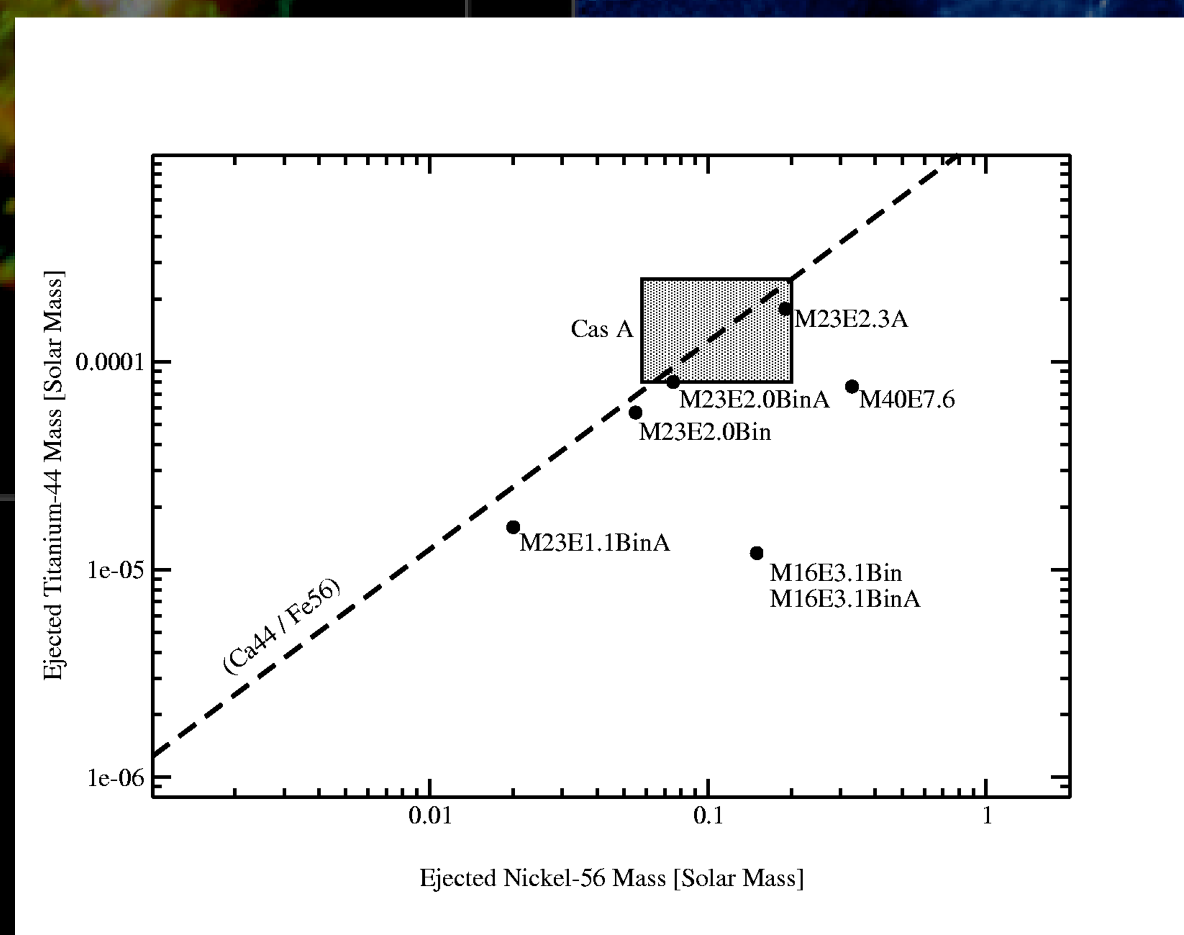


Observational Constraints

- ^{44}Ti and ^{56}Ni
  - M_{Ti} ~ 0.8-2.5 x 10^{-4} $M_{\odot}$ from γ & x-rays (decay lines of ^{44}Ca & ^{44}Sr)
  - M_{Ni} ~ 0.05-0.2 $M_{\odot}$
    - ~ 0.058 $M_{\odot}$ Fe visible in x-rays (Willingale) - lower limit
    - Assuming m_{visual} = 3 and 6 based on (lack of) observation in 1680 extinction of A_v=4-8, and Ni decay lightcurve with monte carlo γ-ray transport, M_{ni} ~ 0.05-0.2

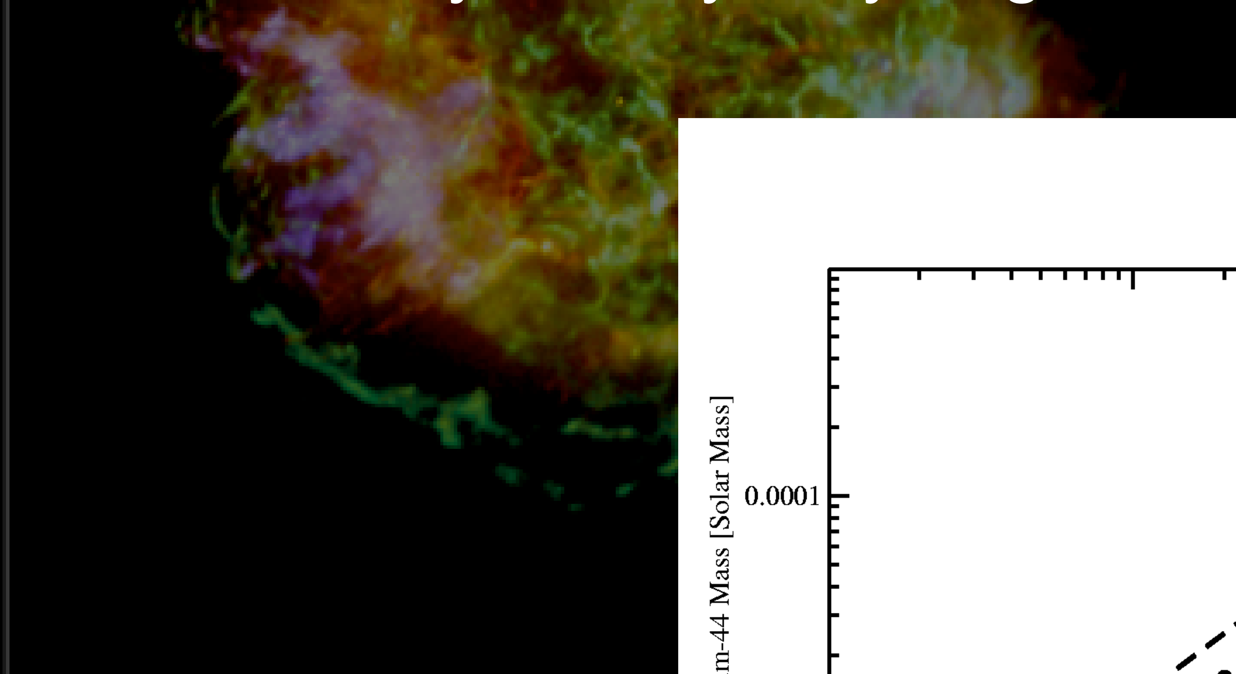


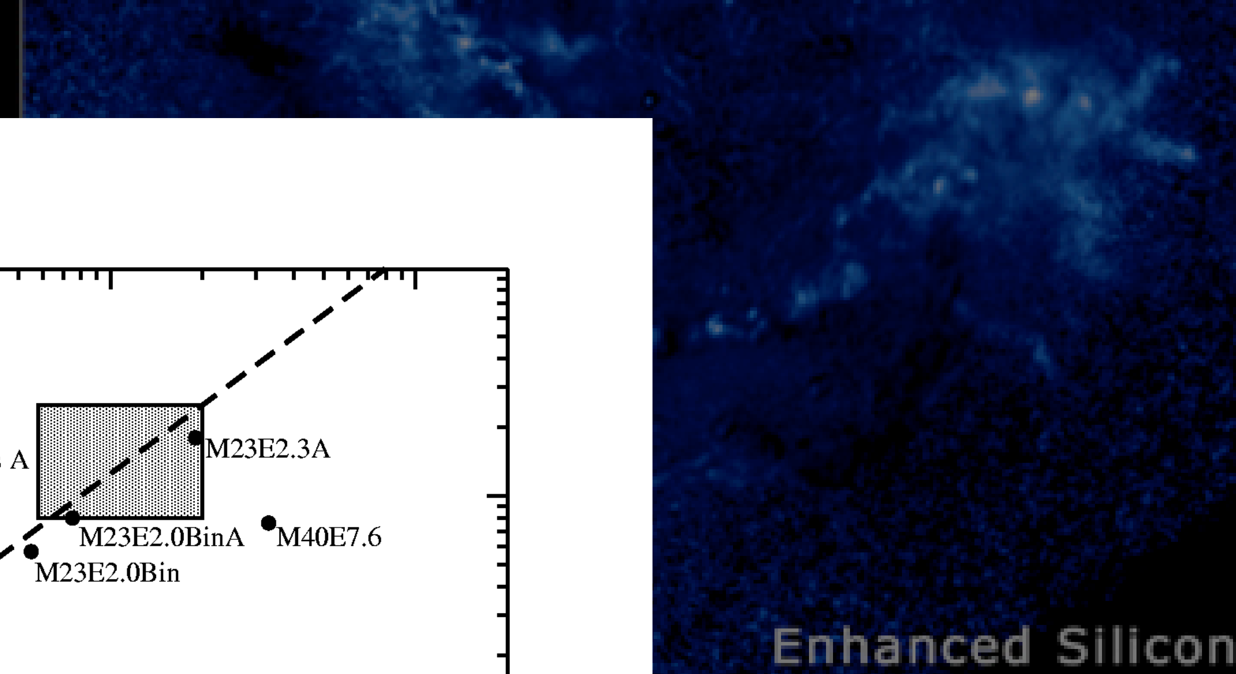


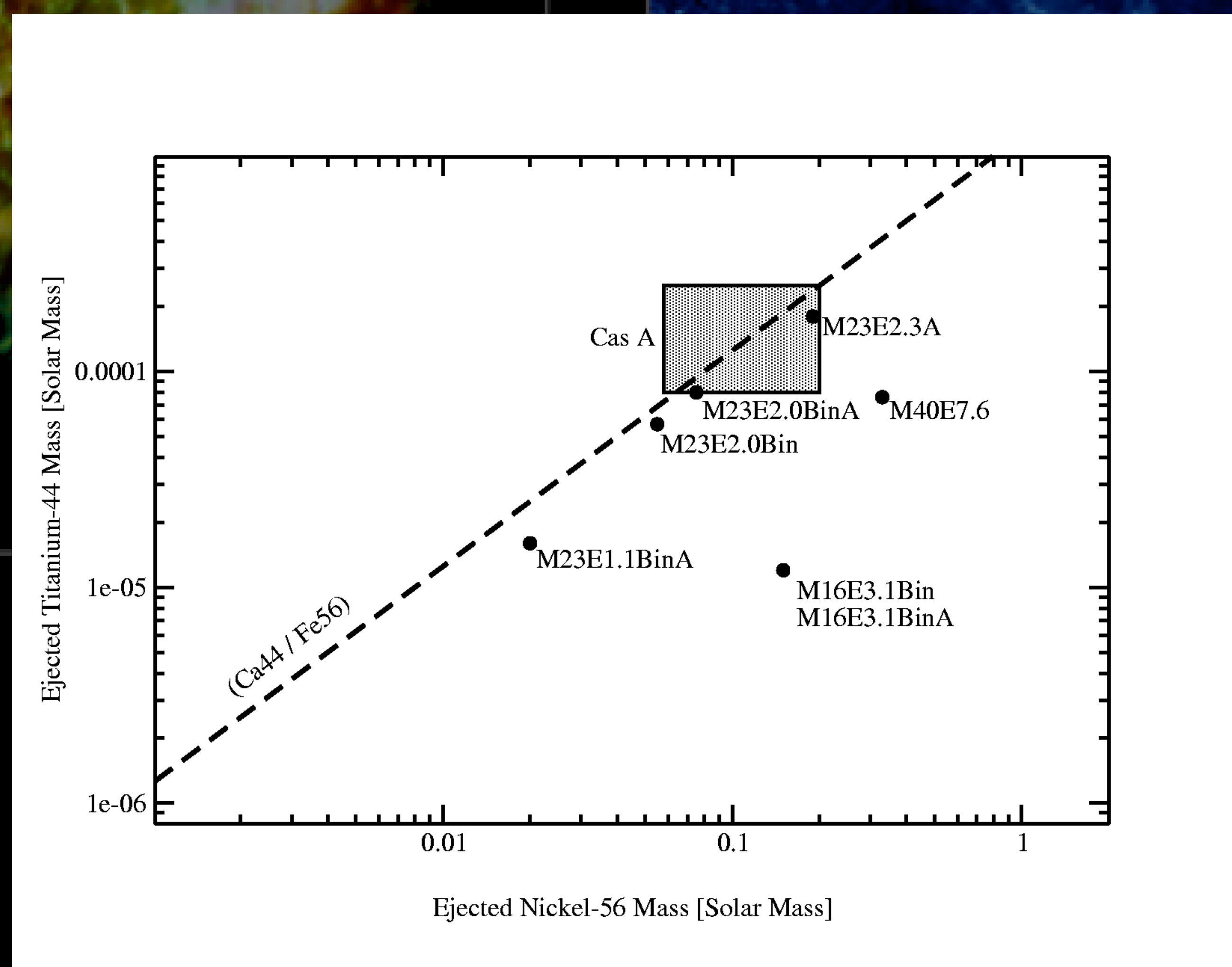


Observational Constraints

- ^{44}Ti and ^{56}Ni
  - $M_{Ti} \sim 0.8\text{-}2.5 \times 10^{-4}\ M_{\odot}$ from γ & x-rays (decay lines of ^{44}Ca & ^{44}Sr)
  - $M_{Ni} \sim 0.05\text{-}0.2\ M_{\odot}$ from brightness of SN
- BUT yields are uncertain - multi-D effects; explosion energy; neutron excess, entropy, temperature, & density evolution can change Fe peak / freezeout yields by very large amounts







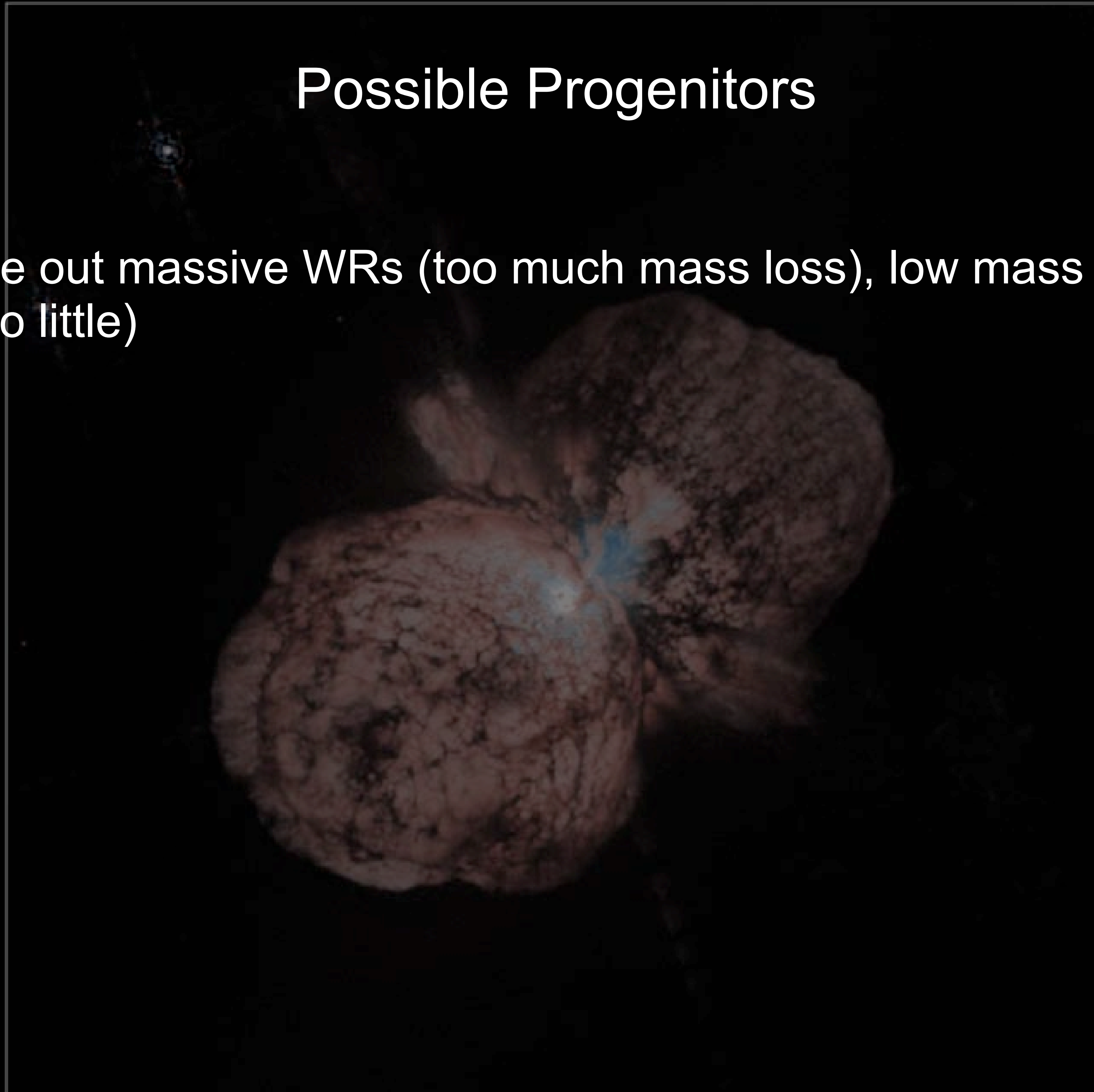
Simulations vs. Constraints

White satisfies constraints, red inconsistent with constraints, yellow marginal

Simulation	Explosion Energy (foe)	Nitrogen Knots	Ejecta Mass	Remnant Mass	^{44}Ti Yield	^{56}Ni Yield
40 $M_\odot$	7.6	N	6.0	1.75	7.5x10^{-5}	0.33
23 $M_\odot$	0.8	N	7.5	5.4	<10^{-5}	<10^{-5}
23 $M_\odot$	2.3	N	8.3	4.6	1.2x10^{-5}	2.6x10^{-4}
23 $M_\odot$ asymmetric	2.3	N	7.4	5.5	1.8x10^{-4}	0.019
23 $M_\odot$ binary	1.1	Y	3.6	2.6	1.2x10^{-5}	2.6x10^{-4}
23 $M_\odot$ bin, asymm	1.1	Y	3.0	3.2	1.6x10^{-5}	0.02
23 $M_\odot$ binary	2.0	Y	3.9	2.3	5.7x10^{-5}	0.055
23 $M_\odot$ bin, asymm	2.0	Y	3.6	2.6	8.5x10^{-5}	0.075
16 $M_\odot$	1.3	Y	3.2	1.8	<10^{-5}	<10^{-5}
16 $M_\odot$ asymmetric	1.12	Y	3.2	1.8	<10^{-5}	<10^{-5}
16 $M_\odot$	3.1	Y	3.8	1.2	1.2x10^{-5}	0.15
16 $M_\odot$ asymmetric	3.1	Y	3.8	1.2	1.2x10^{-5}	0.15

Possible Progenitors

•NKs rule out massive WRs (too much mass loss), low mass single stars (too little)



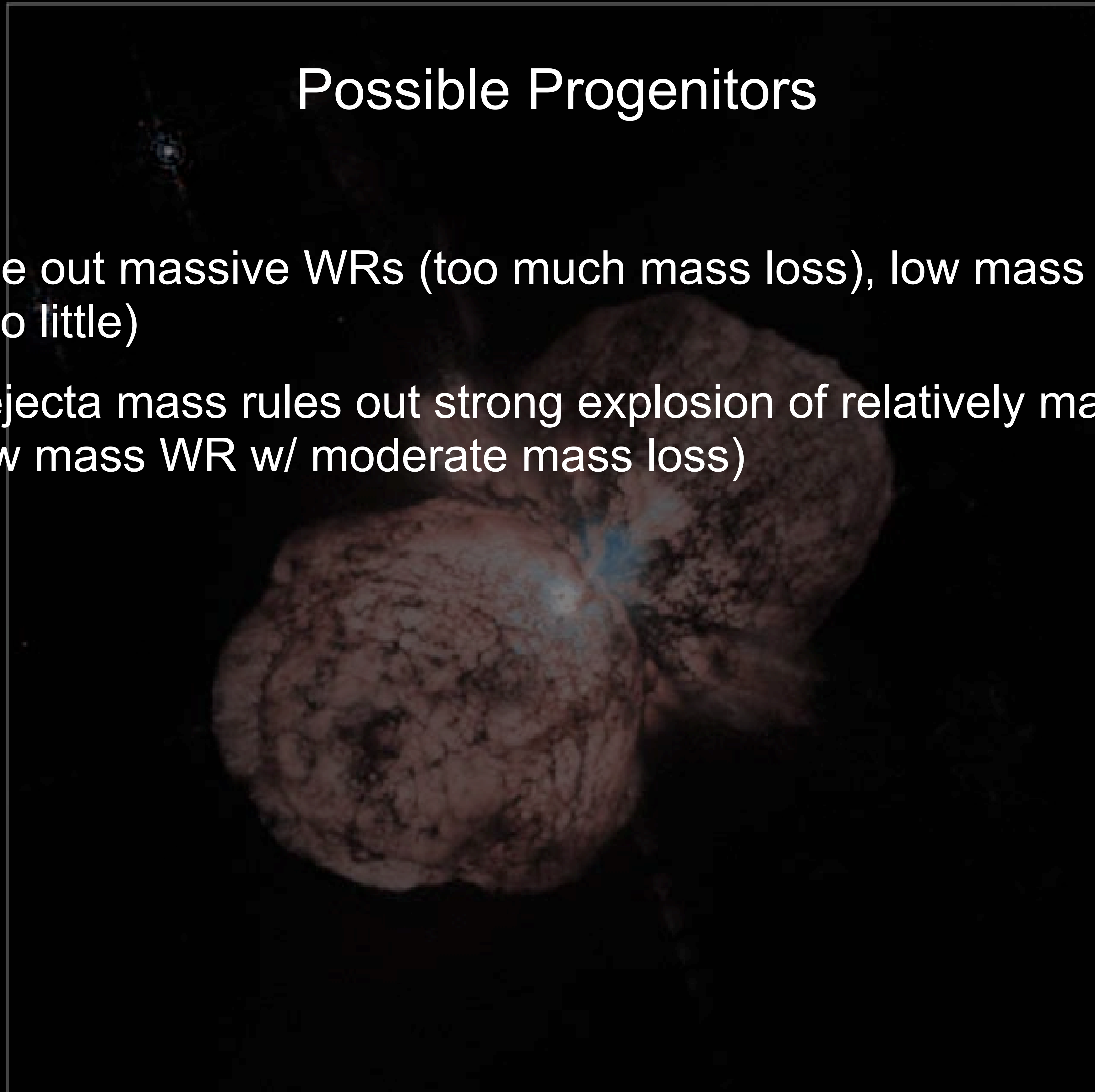
Eta Carinae HST • WFPC2

PRC96-23a • ST ScI OPO • June 10, 1996

J. Morse (U. CO), K. Davidson, (U. MN), NASA

Possible Progenitors

- NKs rule out massive WRs (too much mass loss), low mass single stars (too little)
- Small ejecta mass rules out strong explosion of relatively massive core (low mass WR w/ moderate mass loss)



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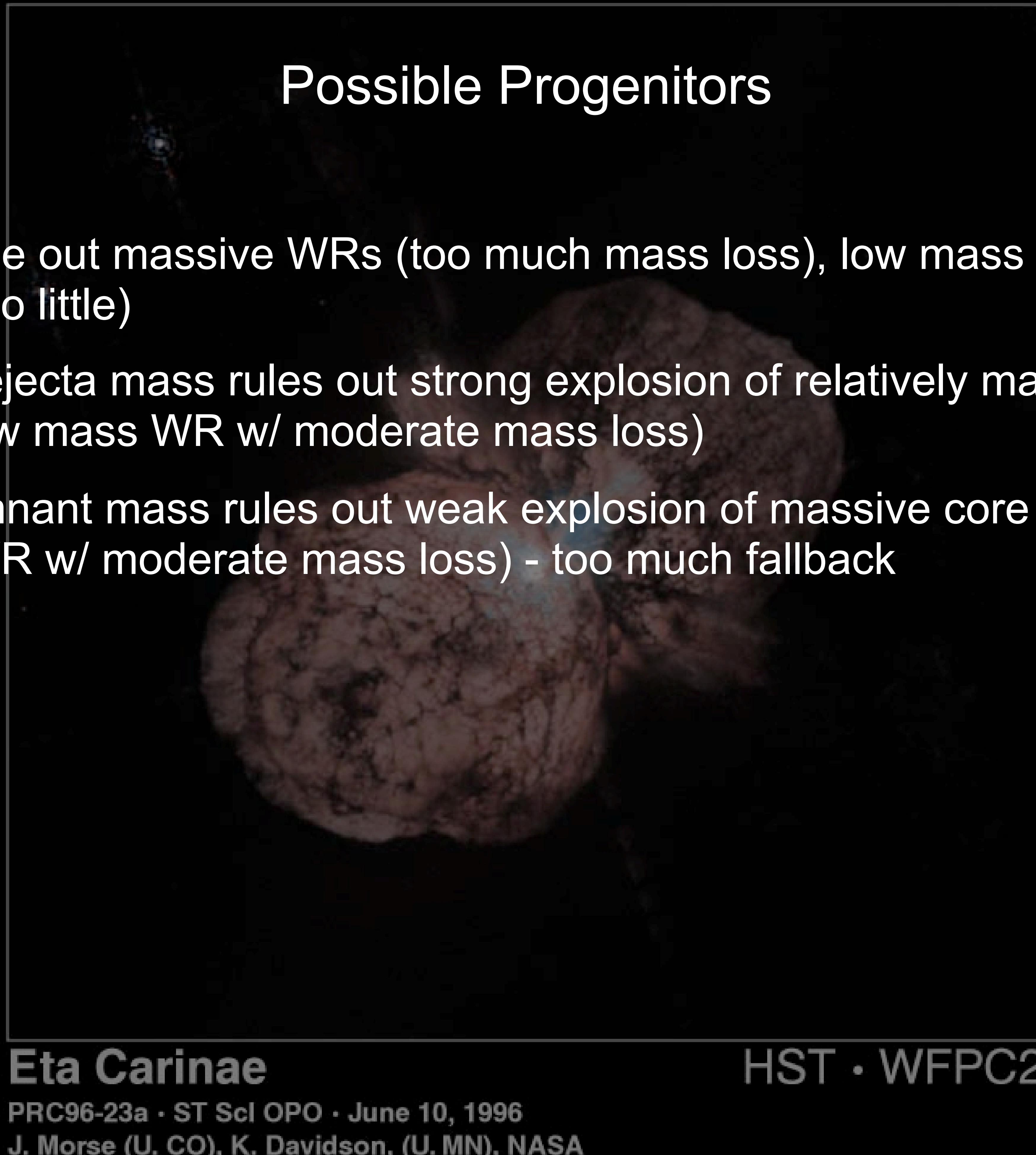
- Small ejecta mass rules out strong explosion of relatively massive core (low mass WR w/ moderate mass loss)
- NS remnant mass rules out weak explosion of massive core (low mass WR w/ moderate mass loss) - too much fallback



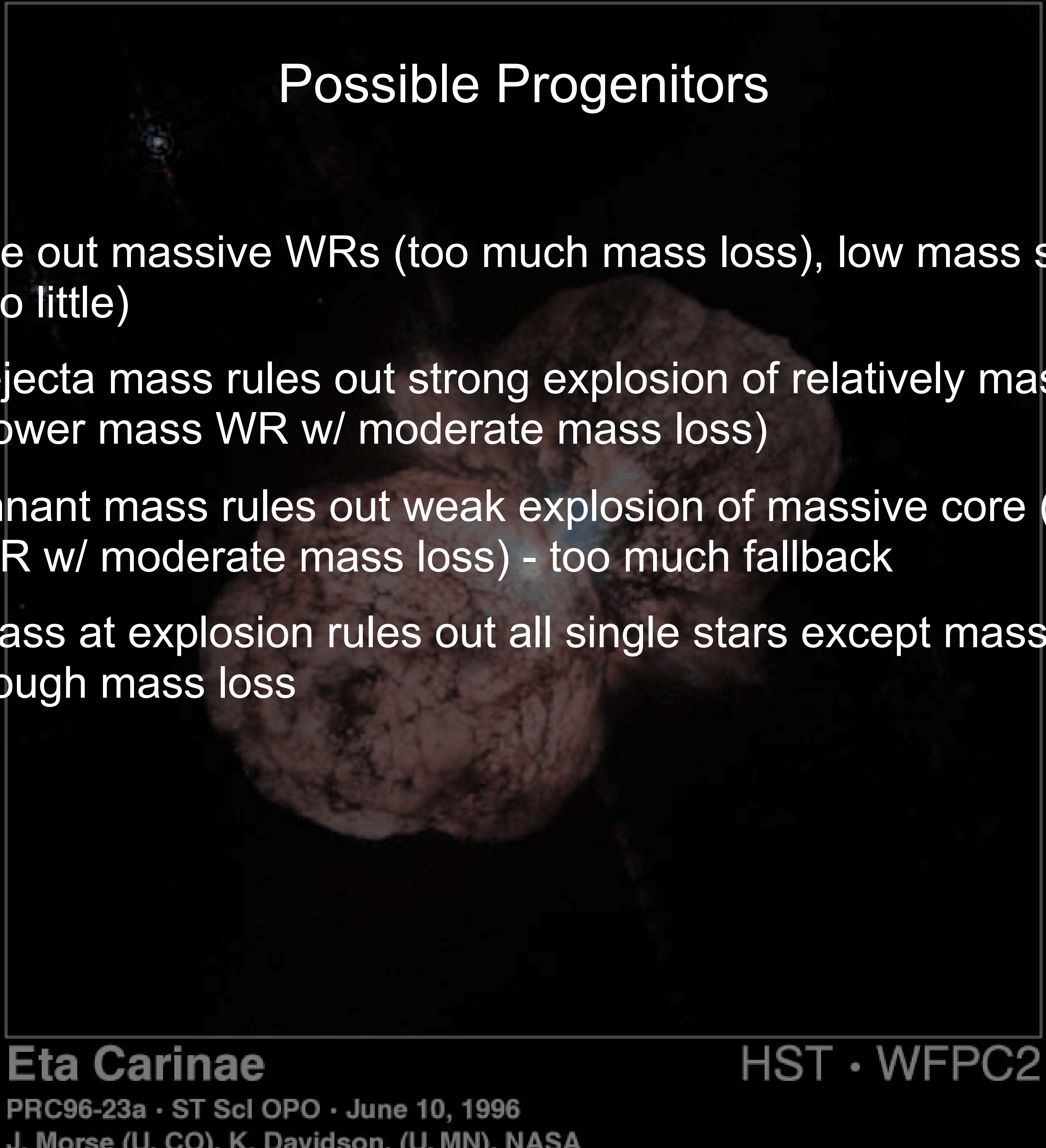
Possible Progenitors

•NKs rule out massive WRs (too much mass loss), low mass single stars (too little)

•Small ejecta mass rules out strong explosion of relatively massive core - (lower mass WR w/ moderate mass loss)

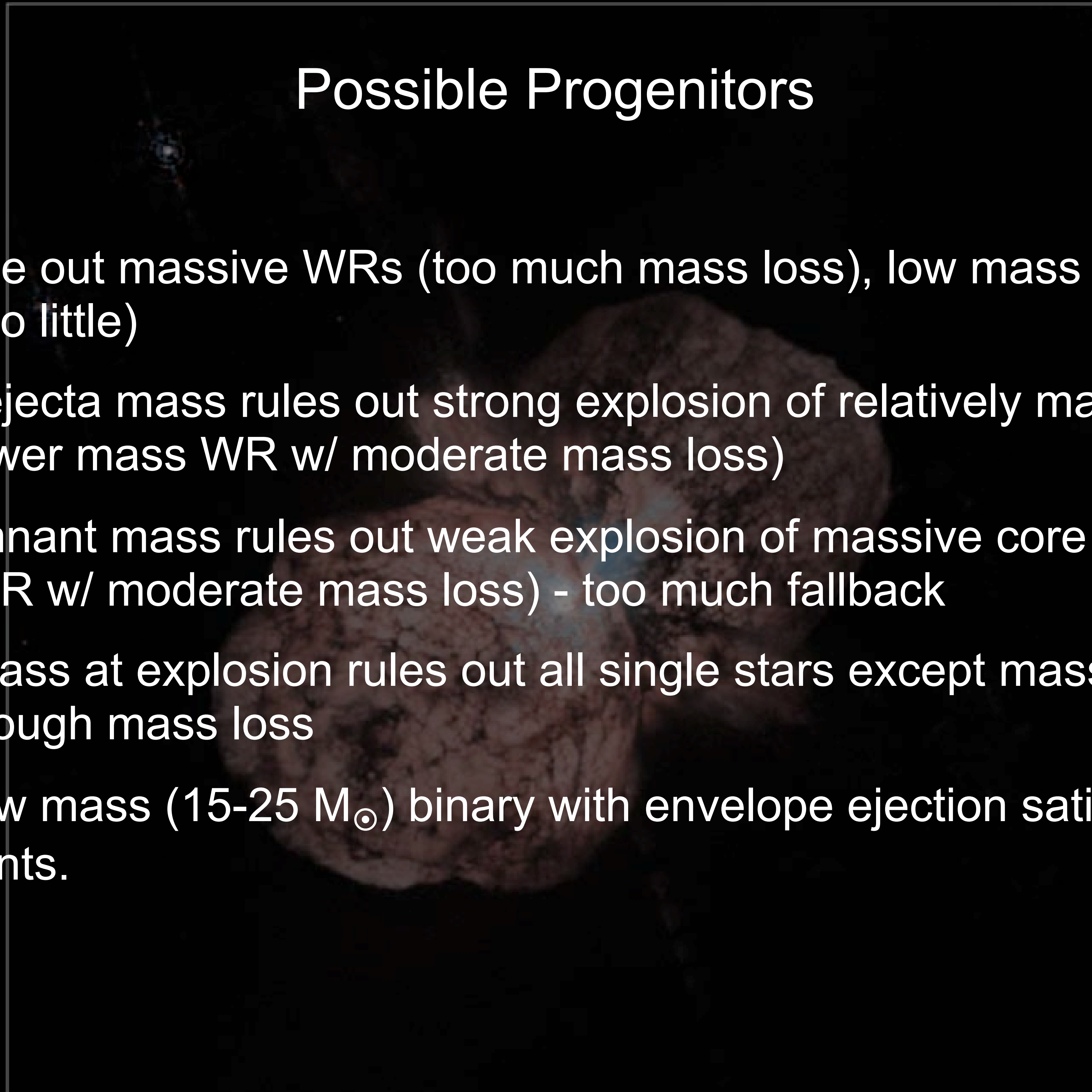
•NS remnant mass rules out weak explosion of massive core (low mass WR w/ moderate mass loss) - too much fallback

•Total mass at explosion rules out all single stars except massive WRs - not enough mass loss



Possible Progenitors

- NKs rule out massive WRs (too much mass loss), low mass single stars (too little)
- Small ejecta mass rules out strong explosion of relatively massive core (lower mass WR w/ moderate mass loss)
- NS remnant mass rules out weak explosion of massive core (low mass WR w/ moderate mass loss) - too much fallback
- Total mass at explosion rules out all single stars except massive WRs - not enough mass loss
- Only low mass (15-25 $M_{\odot}$) binary with envelope ejection satisfies all constraints.



Eta Carinae HST · WFPC2
PRC96-23a · ST ScI OPO · June 10, 1996
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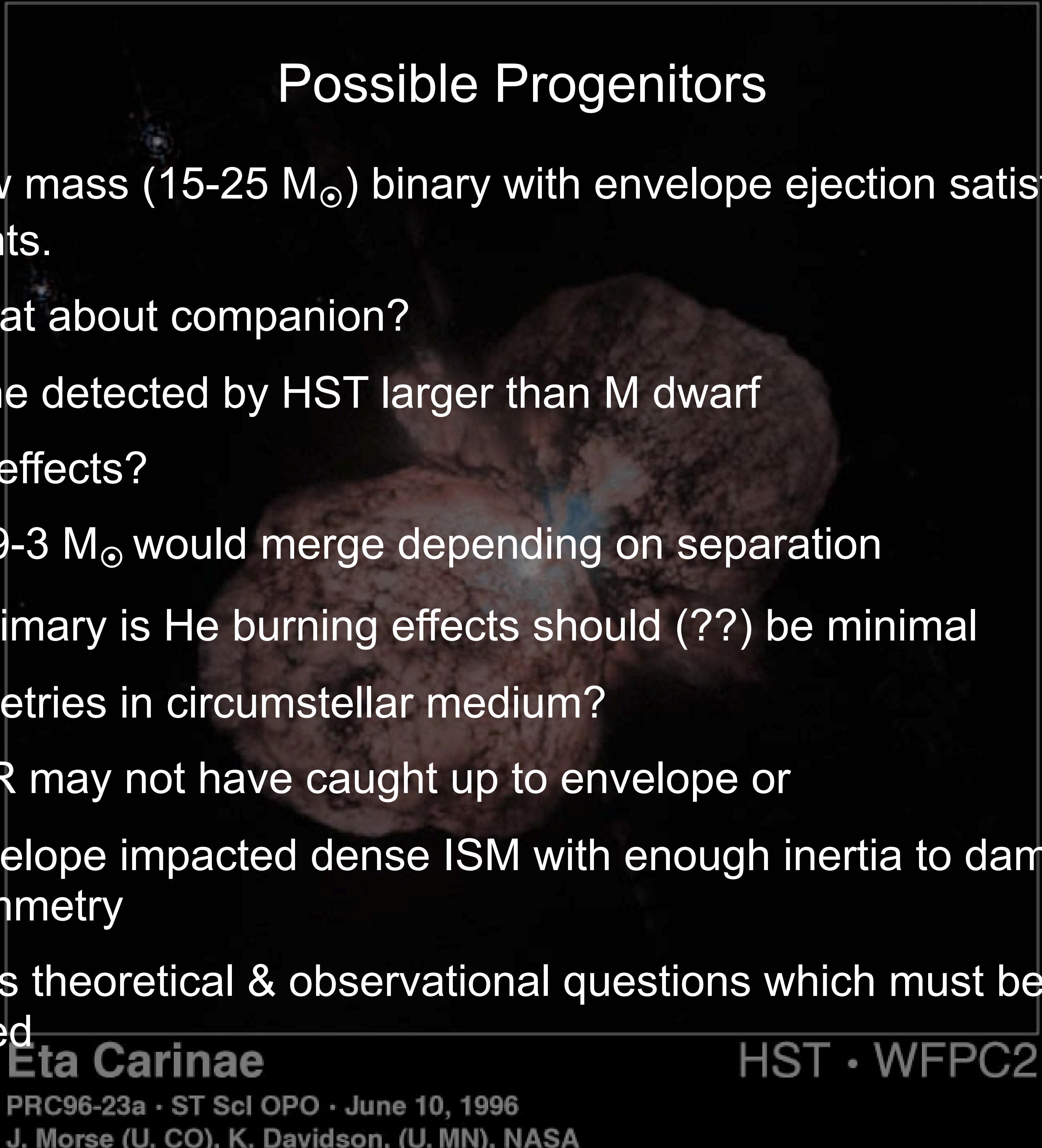
Possible Progenitors

- Only low mass (15-25 $M_{\odot}$) binary with envelope ejection satisfies all constraints.
- BUT what about companion?
  - None detected by HST larger than M dwarf
- Merger effects?
  - ~0.9-3 $M_{\odot}$ would merge depending on separation
  - If primary is He burning effects should (??) be minimal
- Asymmetries in circumstellar medium?
  - SNR may not have caught up to envelope or
  - Envelope impacted dense ISM with enough inertia to damp asymmetry
- Identifies theoretical & observational questions which must be addressed



Conclusions

- Progenitor models with advanced stellar physics
- 3D explosion calculations w/ detailed nucleosynthesis post-processing
- Main observational constraints
    - Fast moving N-rich, H-poor knots - CNO ash surface composition
    - Ejecta mass ~ 2 -4 $M_{\odot}$
    - Remnant mass < 2.2 $M_{\odot}$ (AXP most likely compact remnant)
    - ^{44}Ti and ^{56}Ni mass
- Accepting all constraints requires 15-25 $M_{\odot}$ binary progenitor
- Nucleosynthesis is *not* a good constraint - several factors cause Ni/Ti yields to vary by large amounts
- Observational focuses: refined mass estimates, total and spatially resolved yields, isotopic yields, evidence for/against binary interaction
- Theoretical focuses: mechanism, 3D effects, binary evolution & effect on CSM, pre-SN mass loss