Connecting How Stars Die with How They Lived

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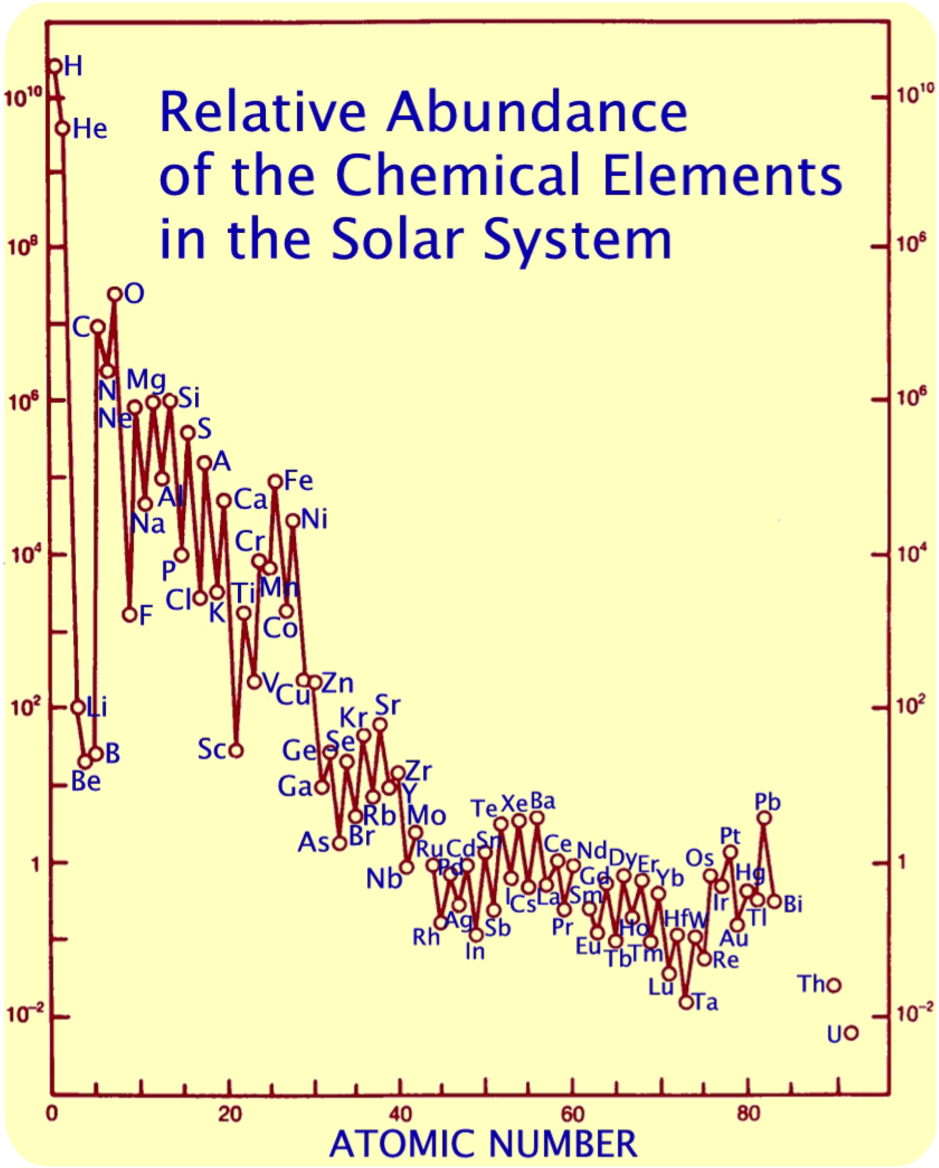
Galactic Archaeology and Precision Stellar Astrophysics, January 22, 2015


Supernovae are super…

- **Crucial for the origin of the elements**
- Shape galaxy evolution
- Study of astrophysical explosions



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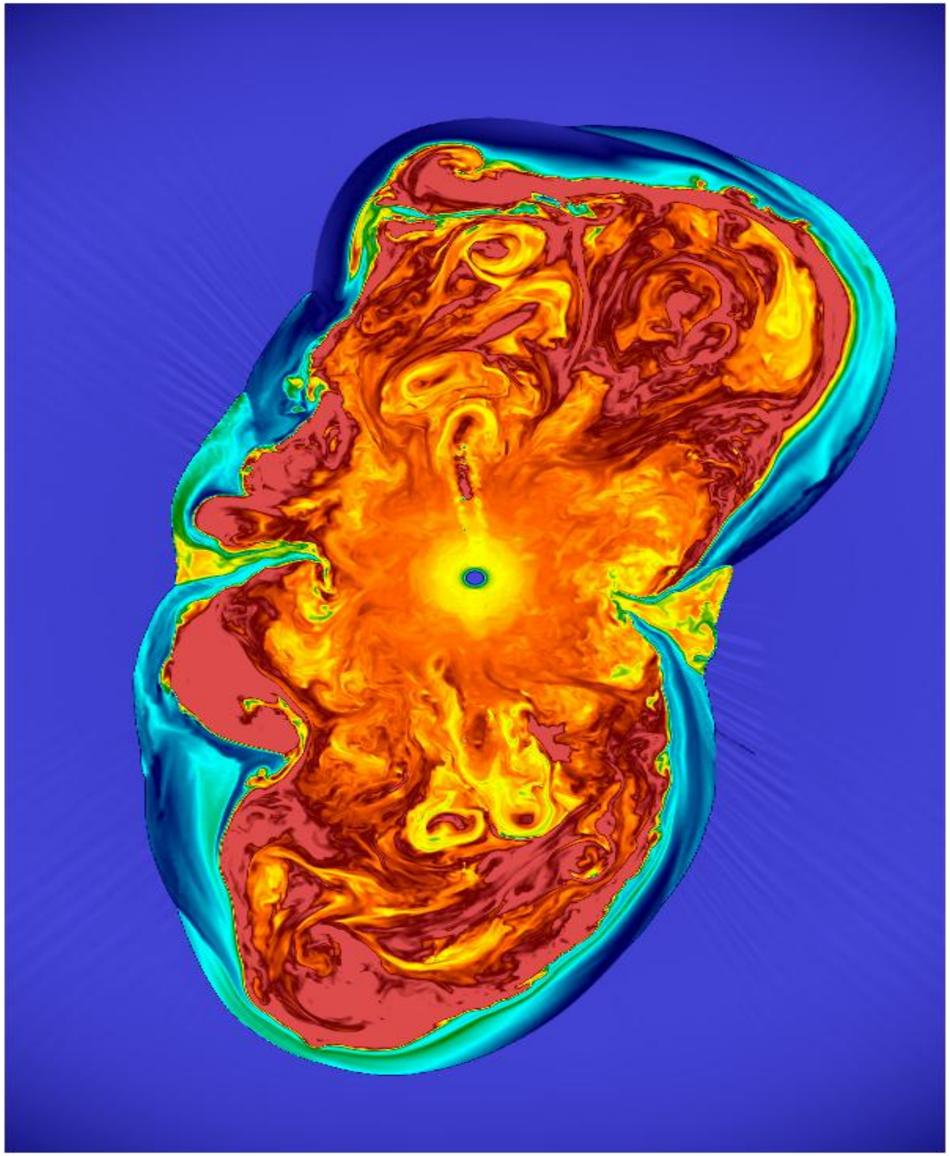
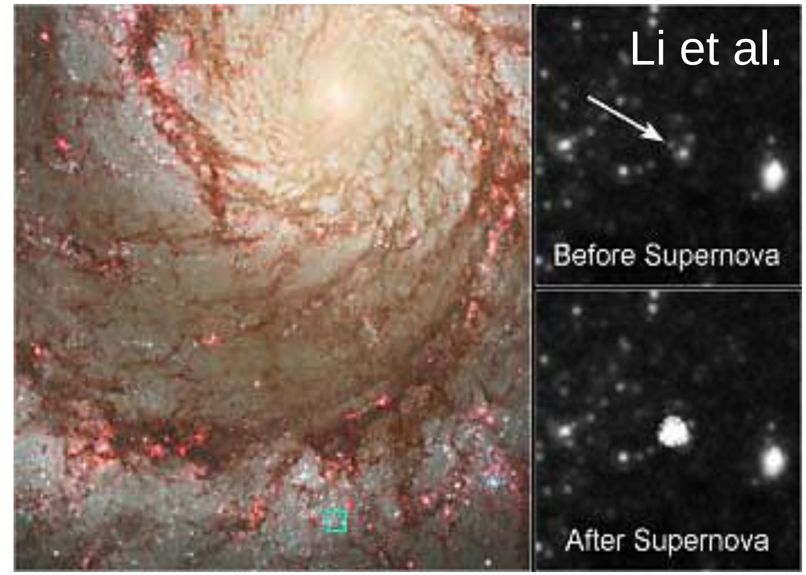


Moestra,… Piro, et al. (2014)

…but which stars make SNe?

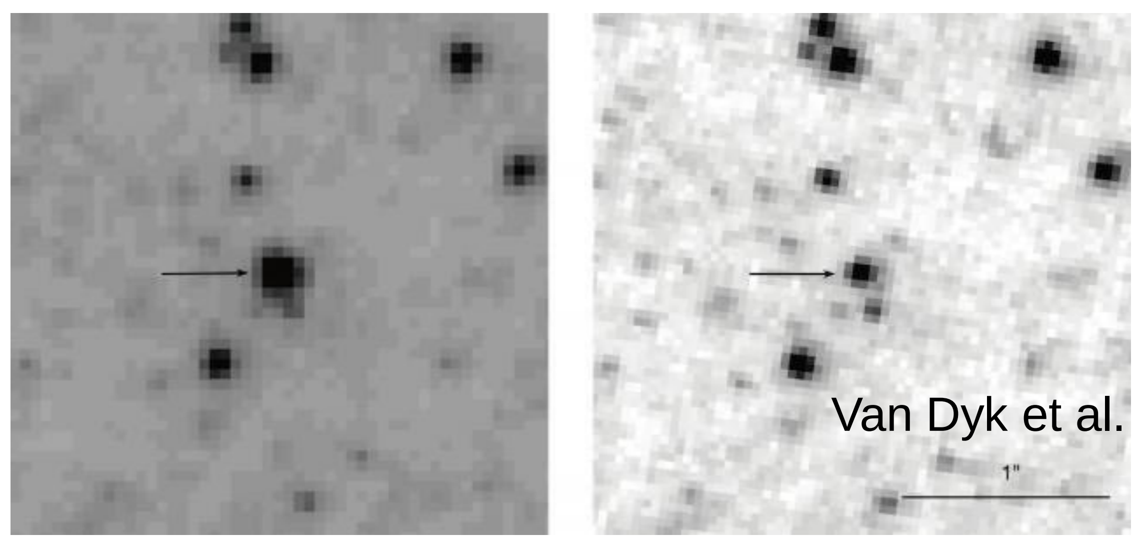
Sometimes pre-explosion imaging:

- 1987A => Blue supergiant
- Type IIP => Red supergiant
- Type IIb => Yellow supergiant



But this leaves **many** supernovae without clear progenitors!

Also, which stars instead make **black holes?**



Outline of Talk

Can we make **general statements** about which stars produce which supernovae?

1. Radius: what is the size of the exploding star?

2. Mass: how much mass was in the explosion?

3. Black Holes: which events make BHs?

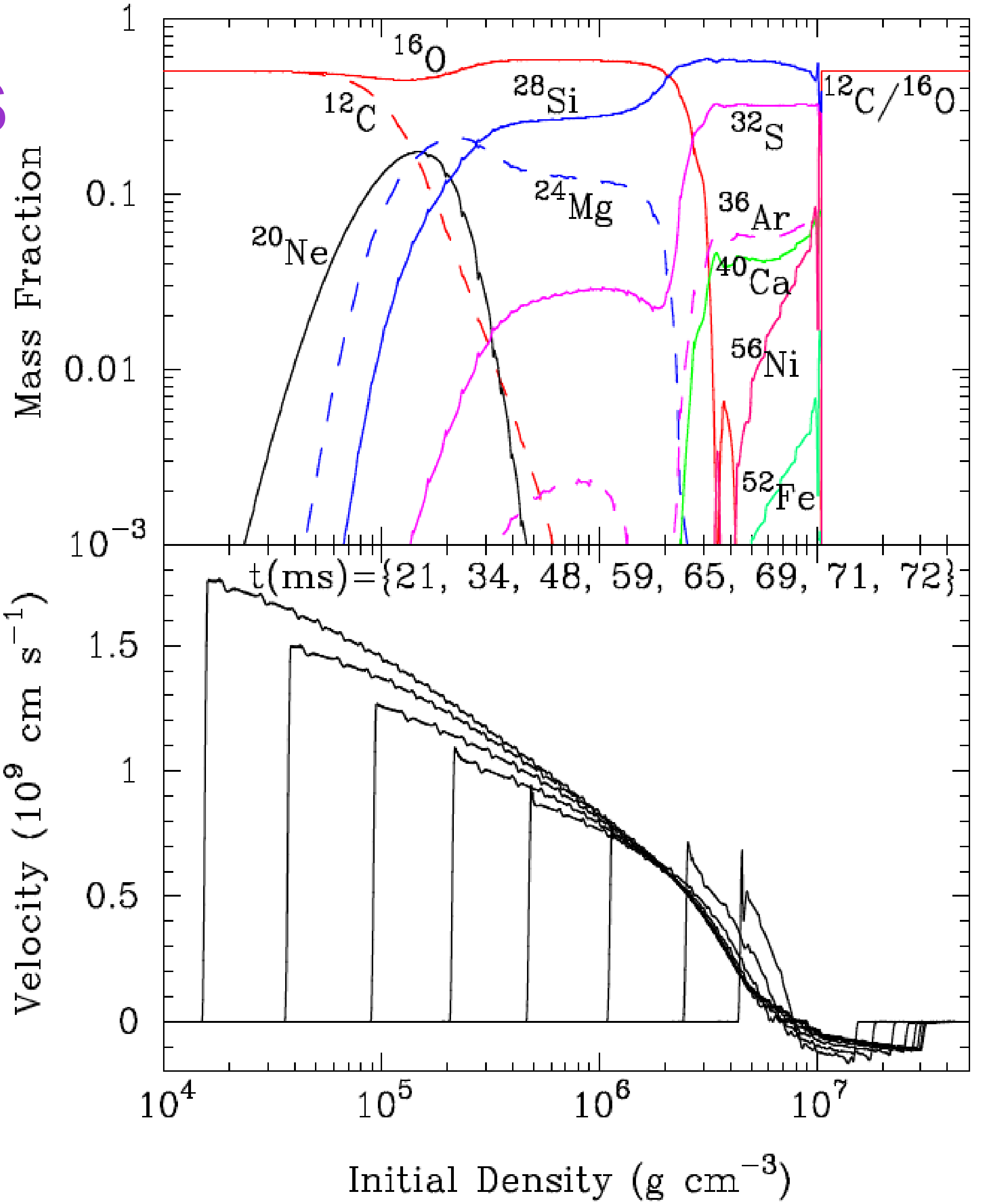
Shock-Heated Surface Layers

The first optical emission from SNe is shock cooling

Luminosity proportional to initial radius

$$L \sim \frac{R_0 c}{\kappa} \frac{E}{M}$$

Piro et al. (2010)

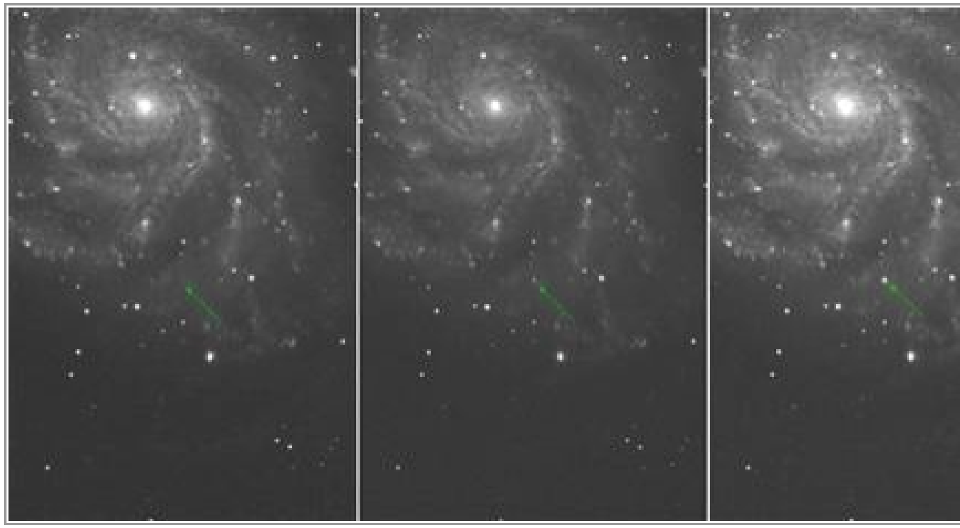


Closest supernova in 25 years a 'cosmic classic'

Astronomers expect 'wild ride' as the drama unfolds — and you can see it, too

SPACE.com

updated 8/26/2011 1:51:33 PM ET Print | Font: A A + −



Peter Nugent and the Palomar Transie

The arrow marks PTF 11kly in images taken on the Palomar 48-inch telescope over nights of, from left to right, Aug. 22, 23 and 24. The supernova wasn't there Aug. 2 discovered Aug. 23 and brightened considerably by Aug. 24.

Astronomers have spotted the closest supernova in a generation — and in a week or so, stargazers with a good pair of binoculars might be able to see it, too.

The supernova, or exploded star, flared up Tuesday night in the Pinwheel Galaxy, just 21 million light-years from Earth. It's the closest star explosion of its type observed since 1986, and astronomers around the world are already scrambling to train their instruments on it.

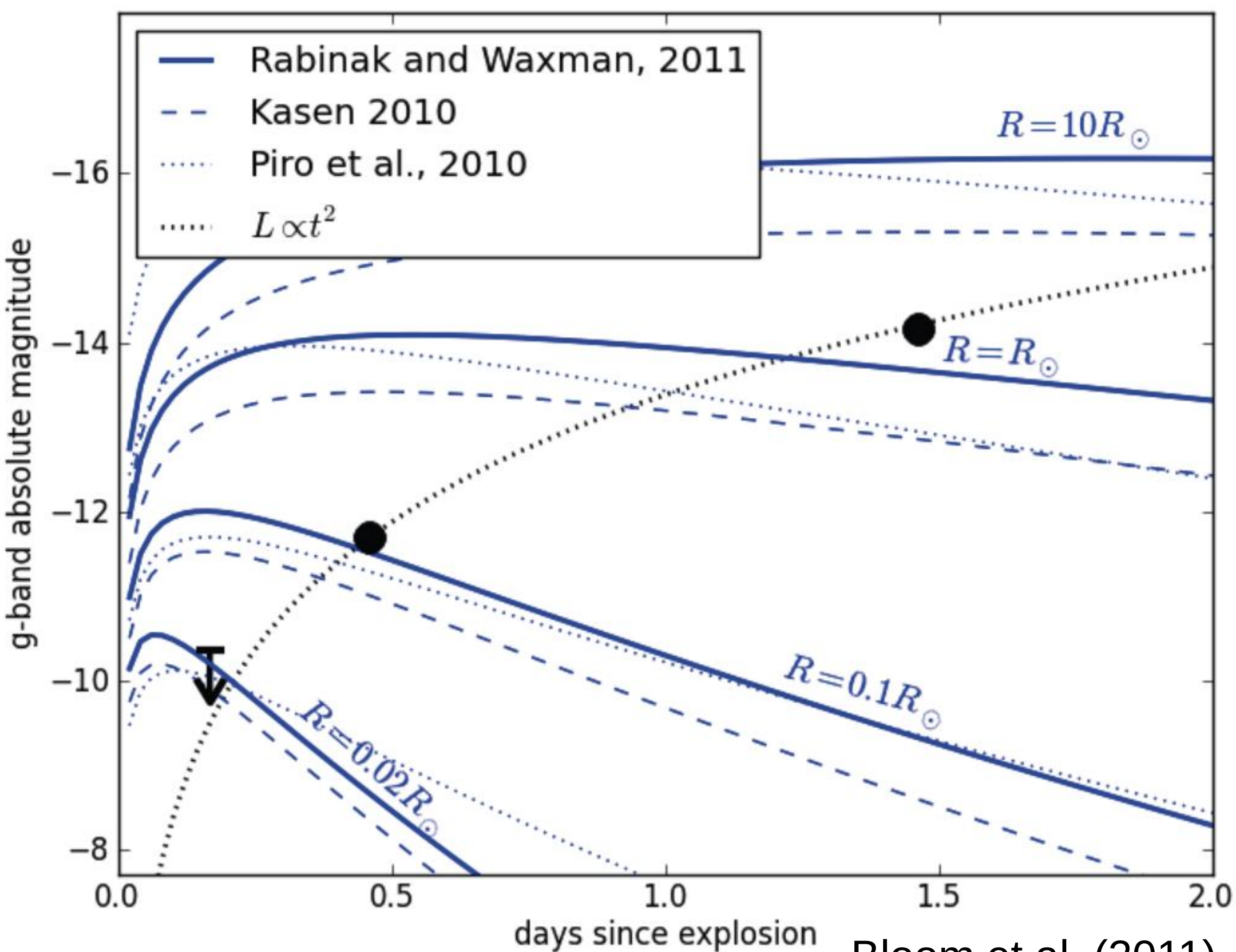
Researchers said they think they caught the supernova, named PTF 11kly, within hours of its explosion.

"PTF 11kly is getting brighter by the minute. It's already 20 times brighter than it was yesterday," Peter Nugent, of the Lawrence Berkeley National Laboratory and the University of California, Berkeley, said in a statement Thursday.


SN 2011fe

Rising Light Curve of SN 2011fe

- No evidence of cooling from shock heating
- Upper limits require that progenitor radius is <0.02 R_{sun}
- **1^{st} direct evidence that Type Ia SNe come from white dwarfs!**

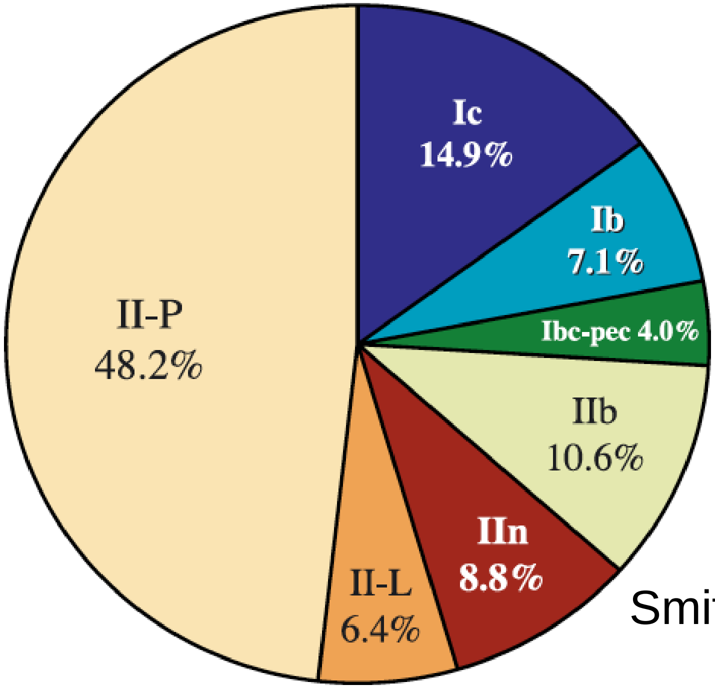


Bloom et al. (2011)

Origin of stripped-envelope SNe?

Appears to be a sequence in mass stripping

Type IIP (H-rich) → **Type IIb** (He-rich with some H) → **Type Ib** (He-rich no H) → **Type Ic** (no He no H)



Smith et al. ‘11

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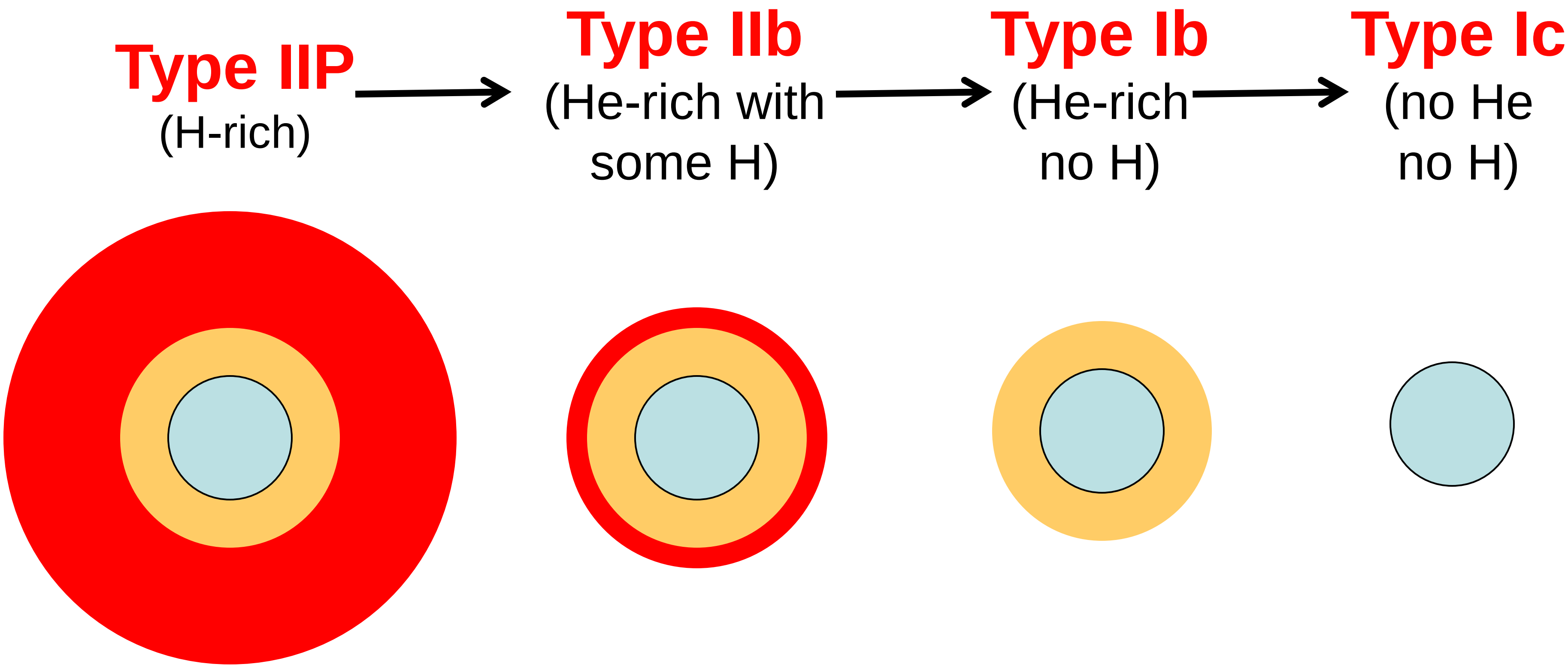


Is this a sequence of increasing mass?

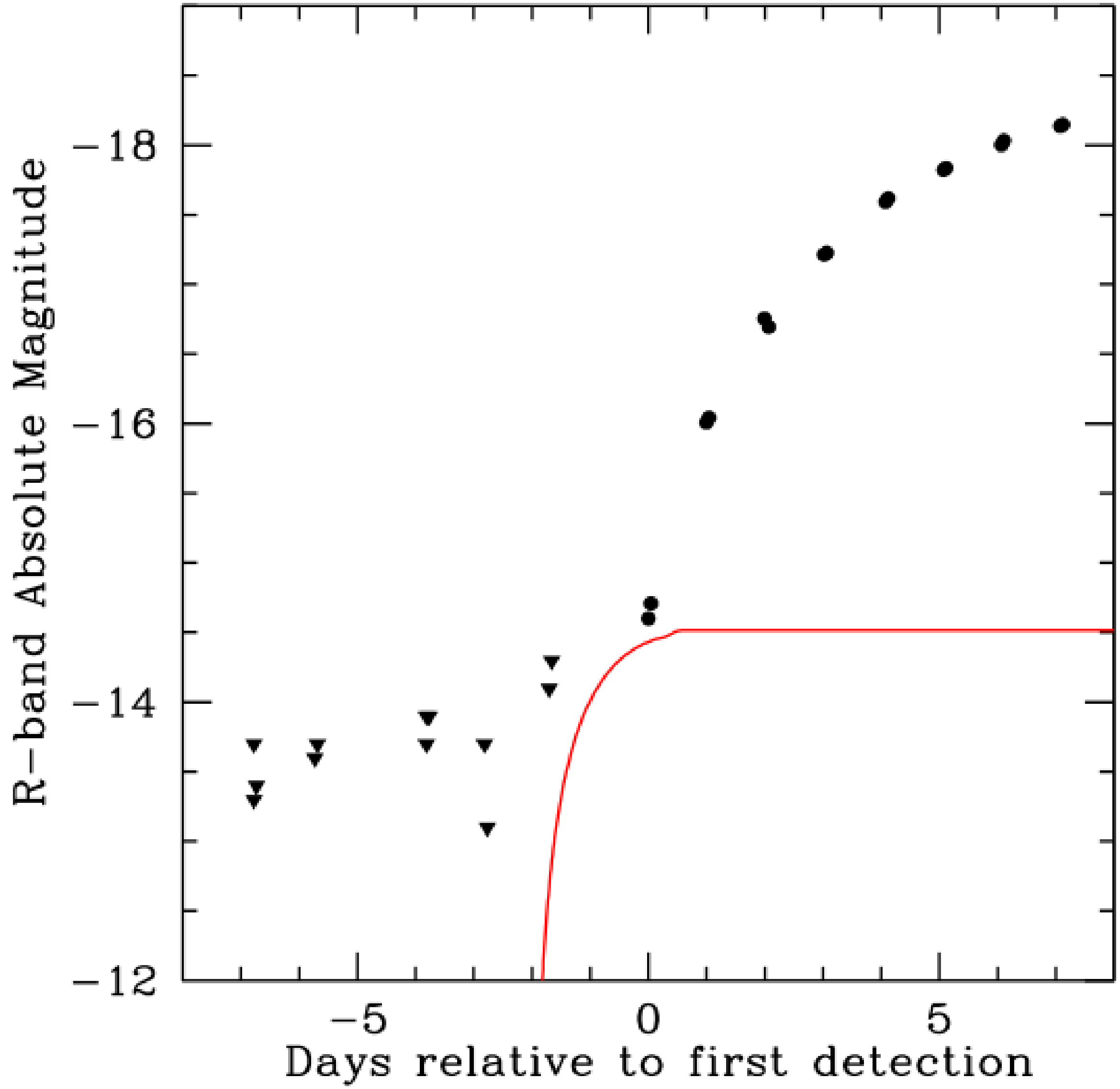
PTF 10vgv

Piro & Nakar (2013)

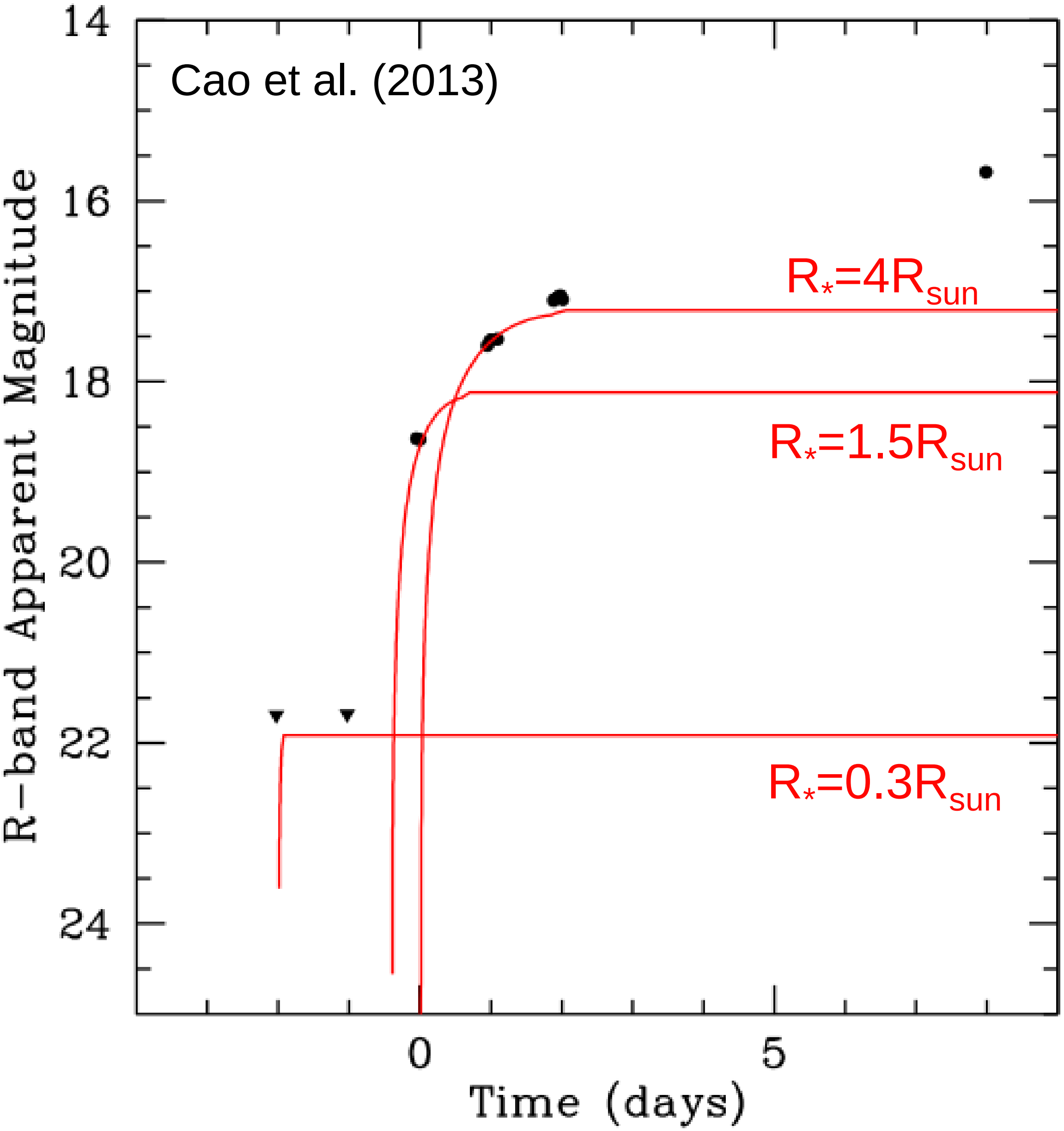
Type Ic with no detection of shock cooling

Can still place interesting limits

$R_* < 3R_{sun}$



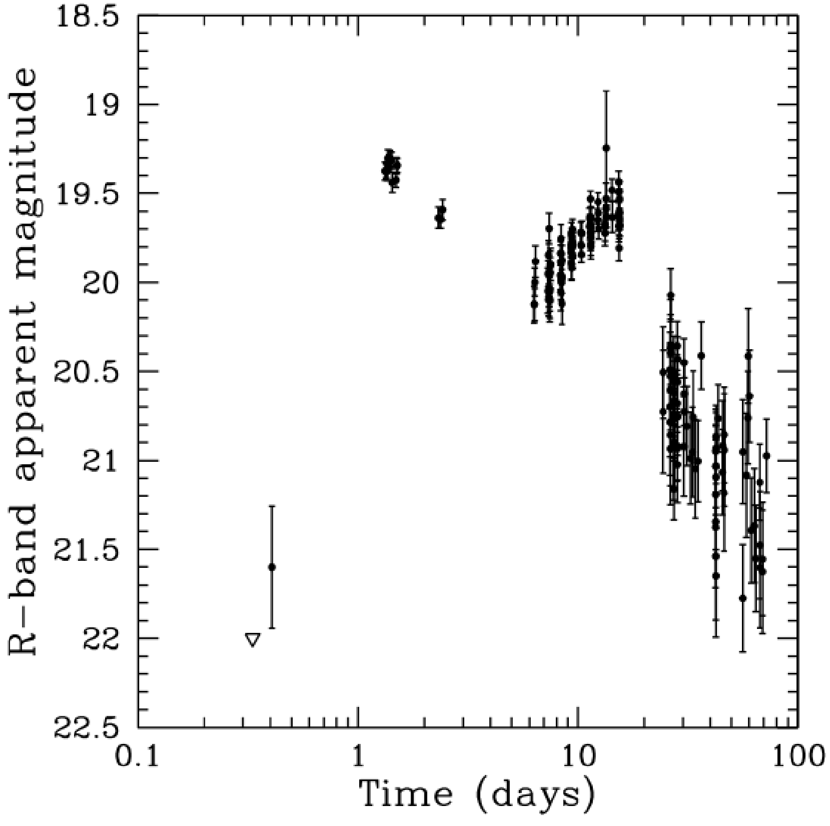
PTF 13bvn

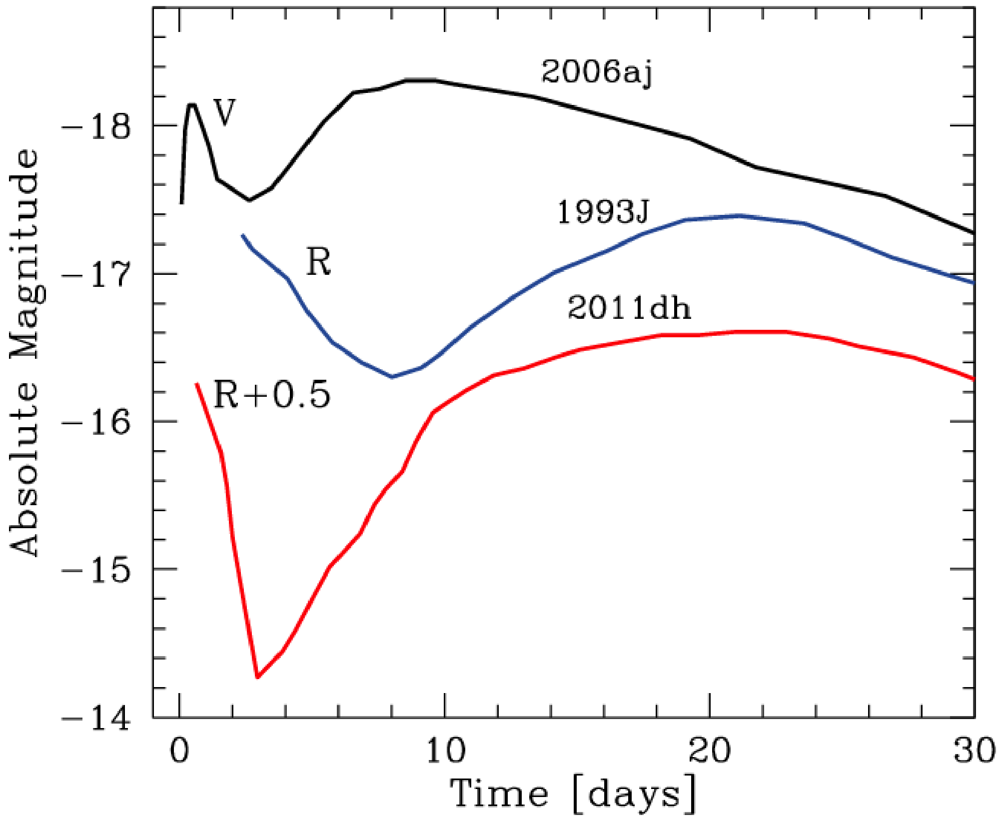


- Type Ib
- $R_* \sim$ few R_{sun}

Double-peaked supernovae

~ ten of these seen, including Types IIb, Ibn, and Ic





What structure must these stars have?

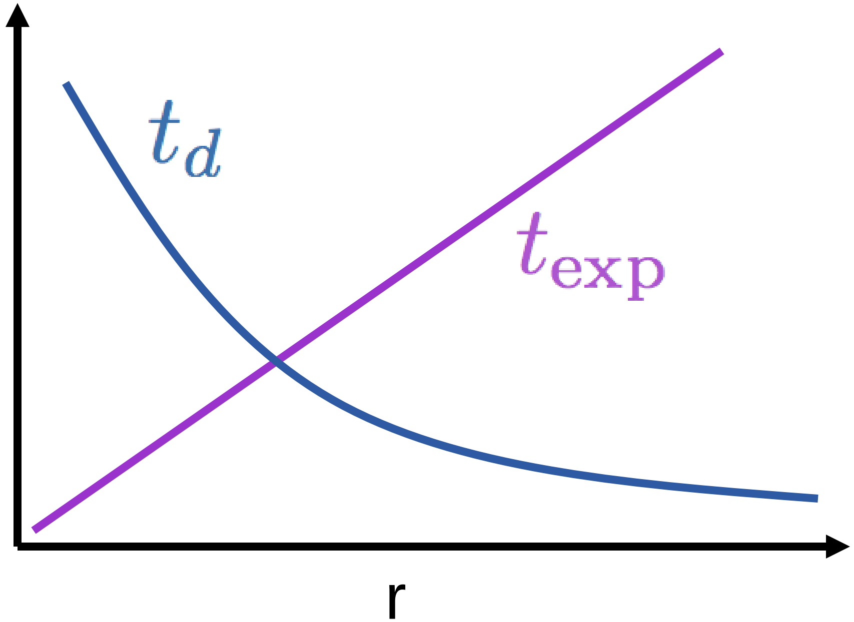
Why do light curves peak? (Arnett's law)

Photons reach the surface on a "thermal diffusion time"

$$t_d \sim \frac{M\kappa}{rc}$$

Photons adiabatically cool on an "expansion time"

$$t_{\exp} \sim r/v$$



Light curve peaks when

$$t_d \sim t_{\exp}$$

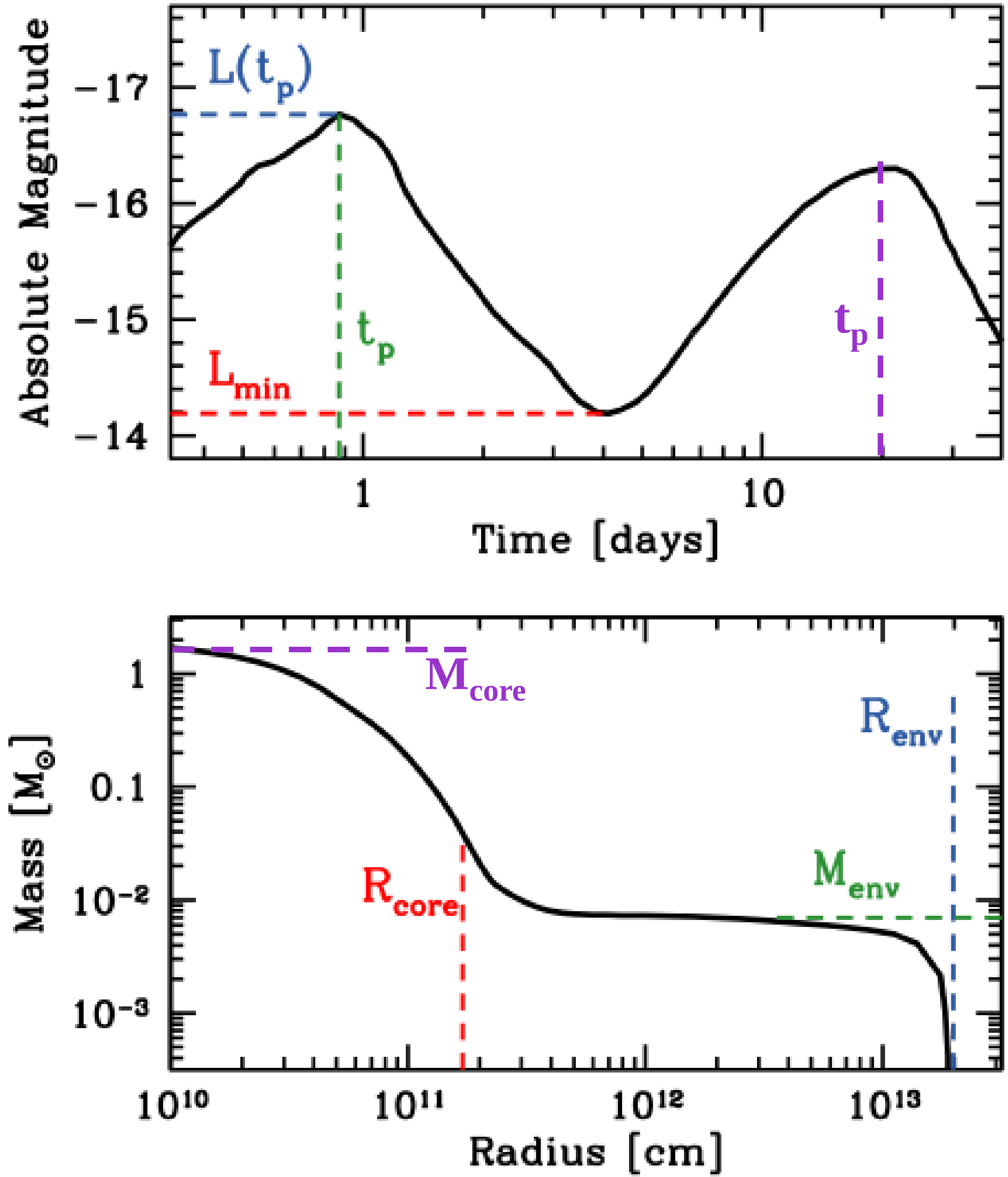
$$t_p \sim \left(\frac{M\kappa}{vc}\right)^{1/2}$$

Probing the star's structure

- Peak luminosity measures radius of extended material
- Time of 1st peak measures mass of extended material
- Minimum luminosity provides upper limit to the core radius
- Time of 2nd peak measure core mass

See Nakar & Piro (2014) for analytic expressions

Nakar & Piro (2014)



Summary for stripped-envelope SNe

- Type Ib and Ic < few R_{sun} (compact!)
- Type IIb ~300 R_{sun} envelope with ~few R_{sun} core
- Extended material in Type IIb is ~0.01 M_{sun}
- Ejecta masses ~1-4 M_{sun} (relatively low)

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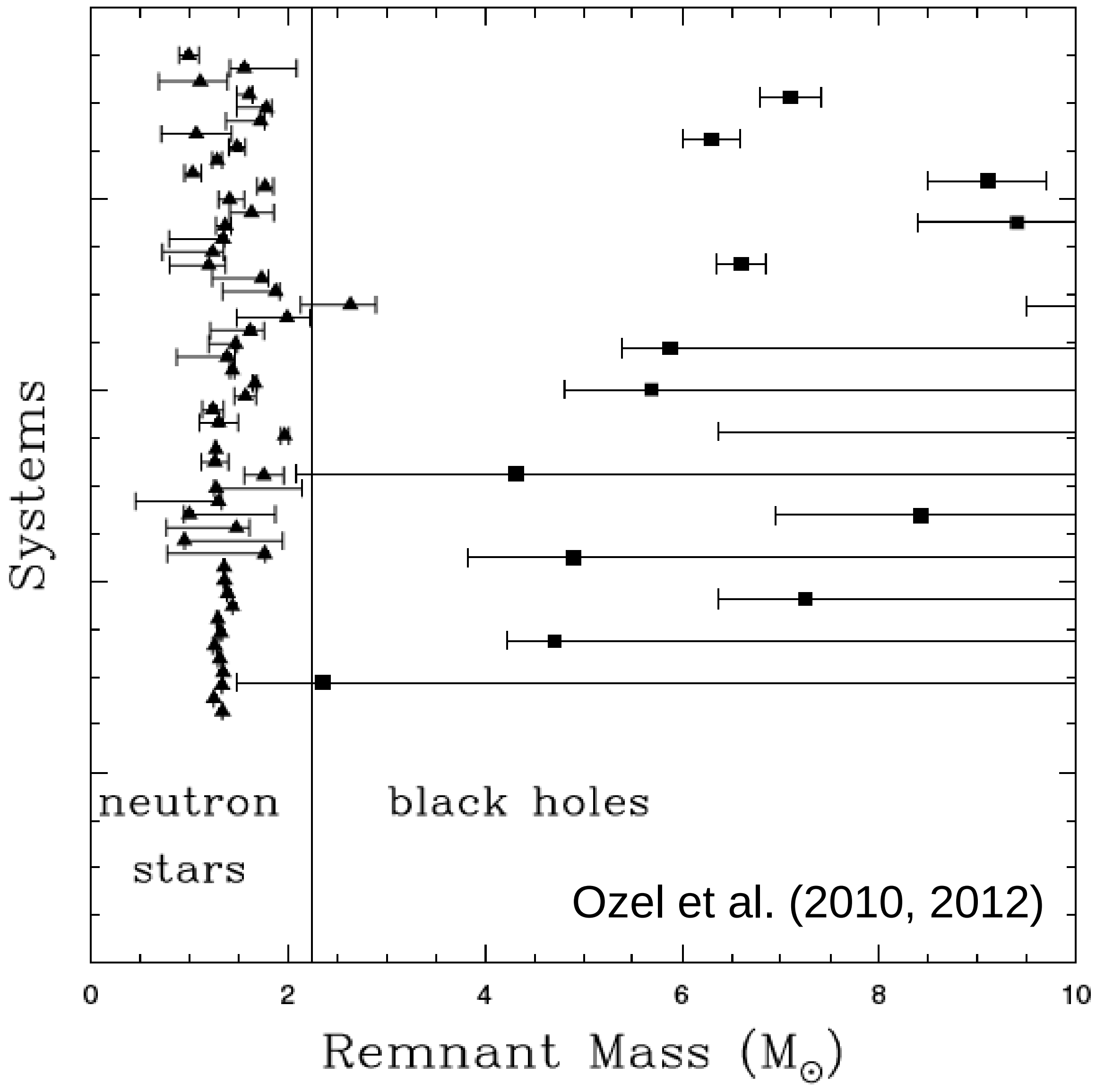
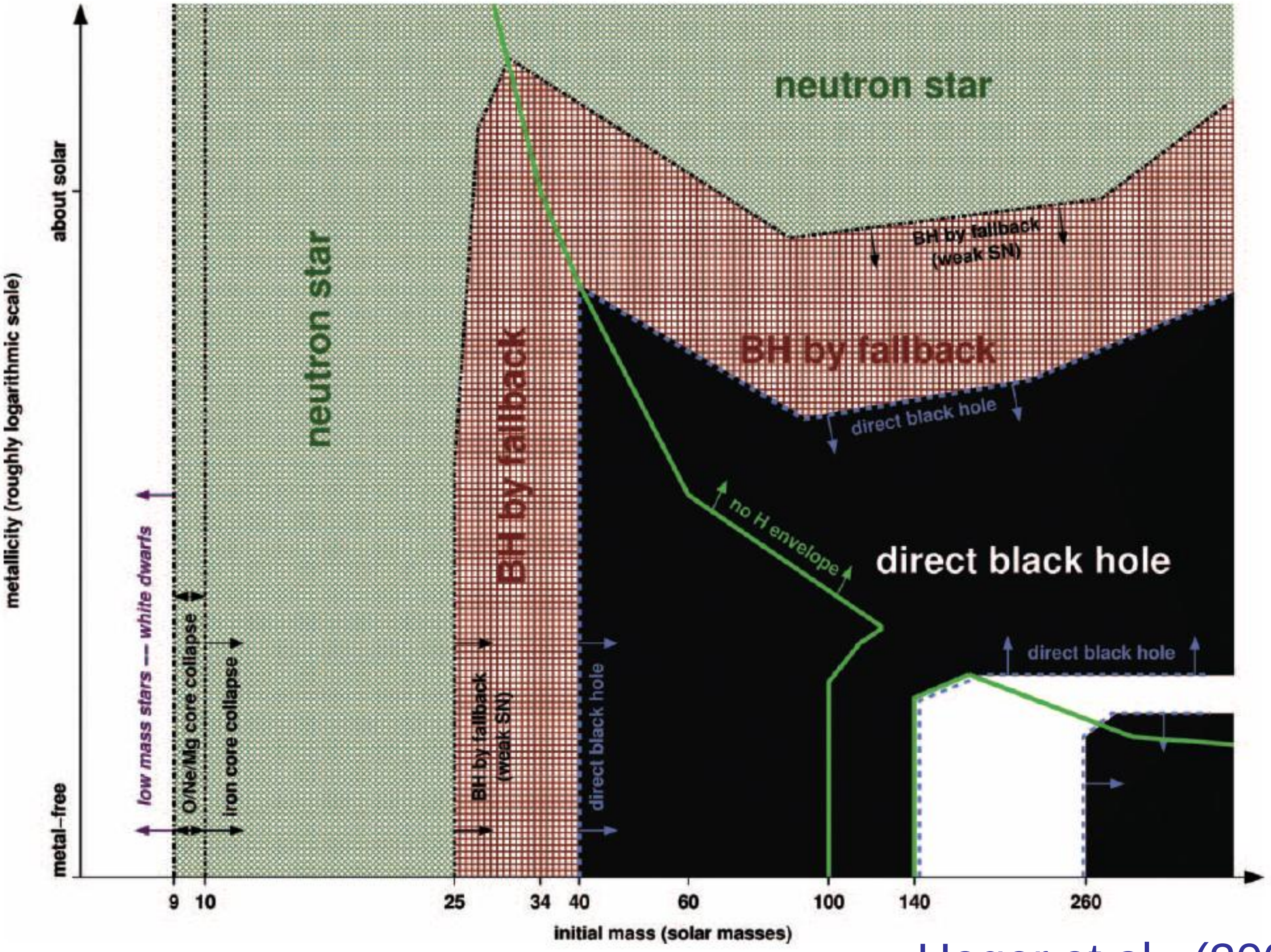
Most stripped-envelope SNe are from ~8-20 M_{sun} stars in binaries (NOT 30-40 M_{sun}!)

Questions about black holes?

- **Where do the black holes in our galaxy come from?**
- Supernovae? "Unnova"?
- There is apparent "compact object desert" between ~2 and ~4 M_{sun}. Important clue?



Which stars produce black holes?

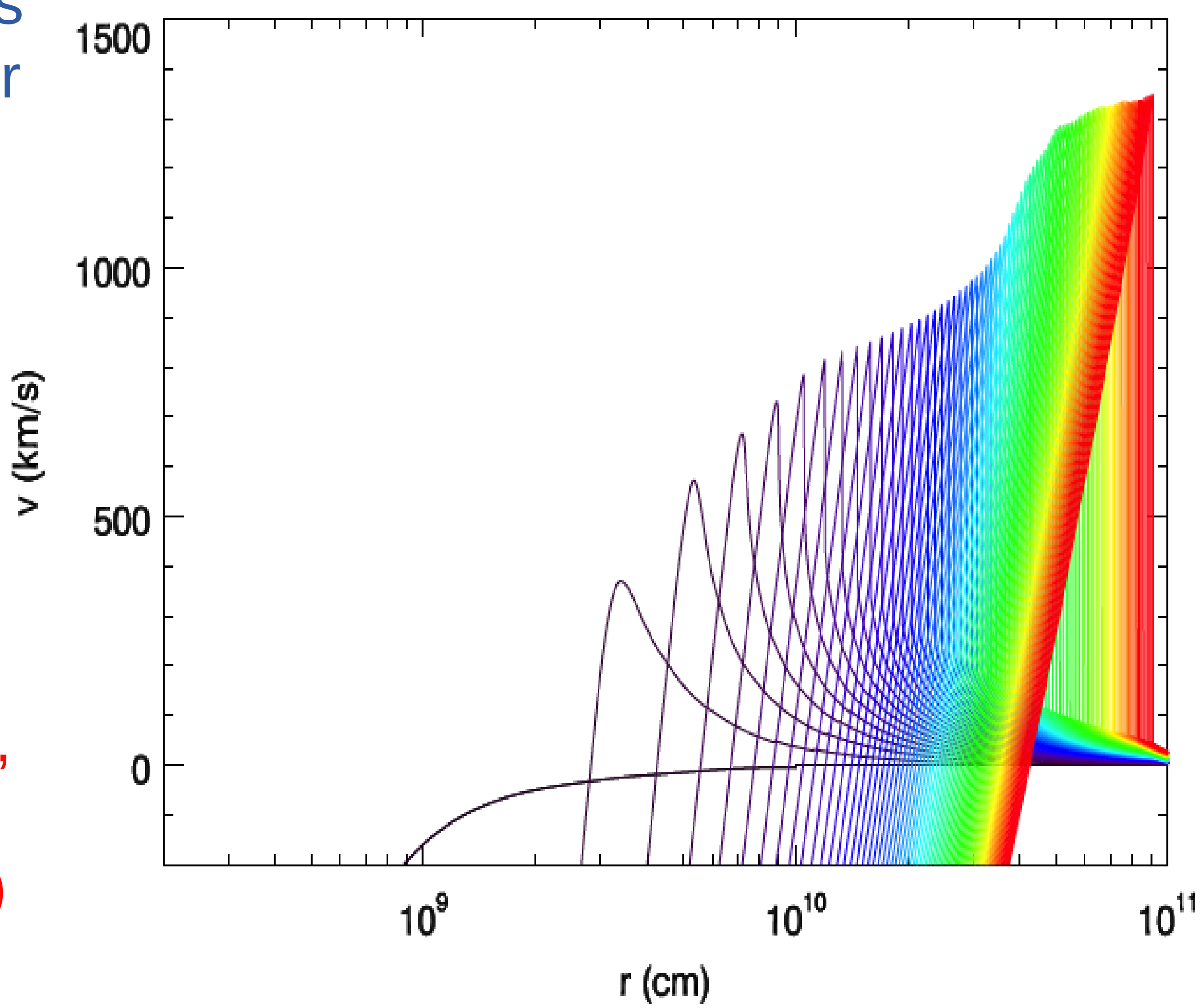


Heger et al. (2003)

Black holes don't die quietly…

- Prior to BH formation a NS emits copious neutrinos for ~few seconds
- Adjustment of the envelope steepens into a shock and ejects H envelope (Nadezhin '80)
- Shock breakout leads to ~week long, subluminous transient (Piro 2013)

Lovegrove & Woosley (2013)



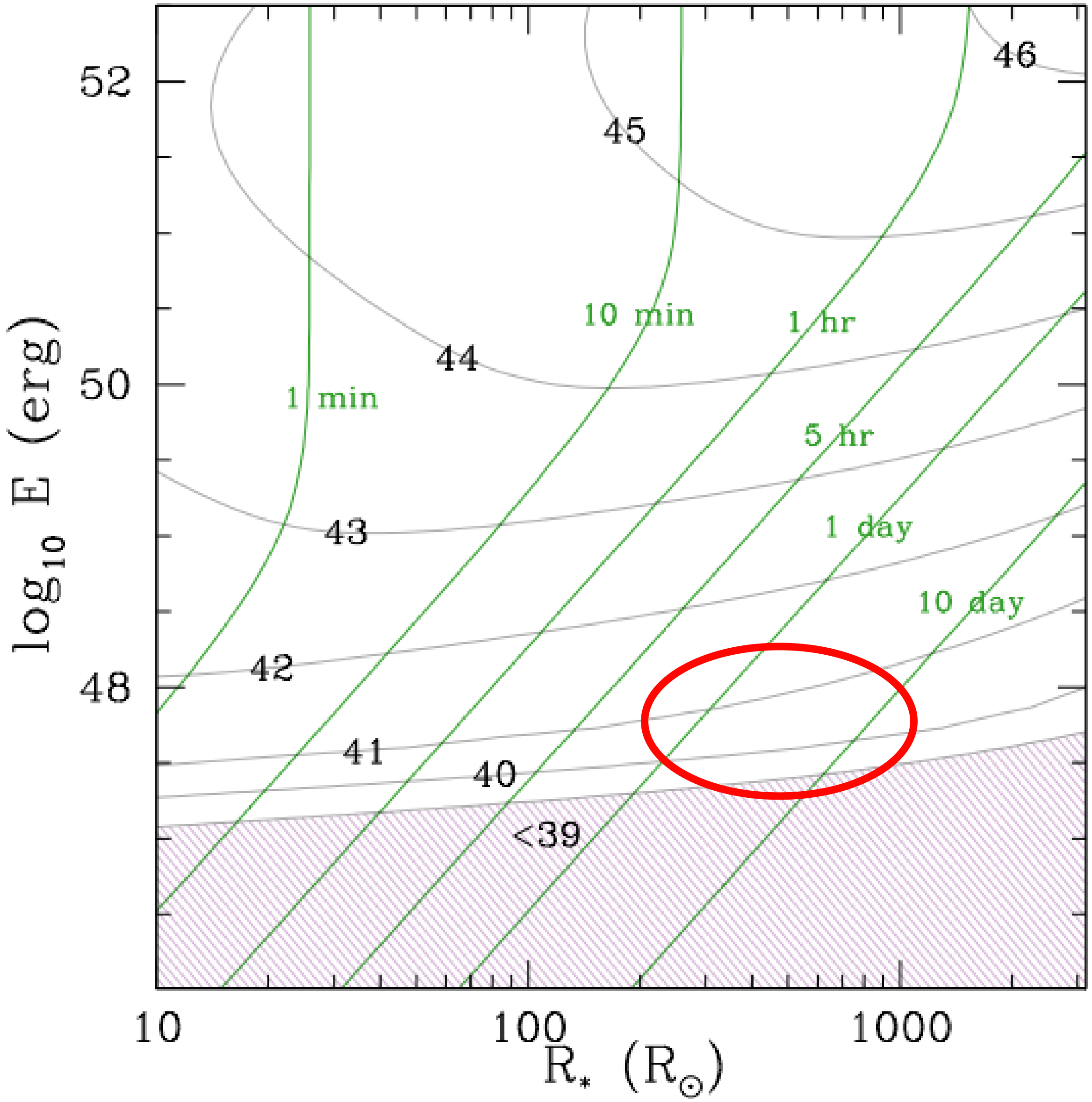
Shock Breakout Following BH Formation

Piro (2013) ApJL 768 14

Key properties:

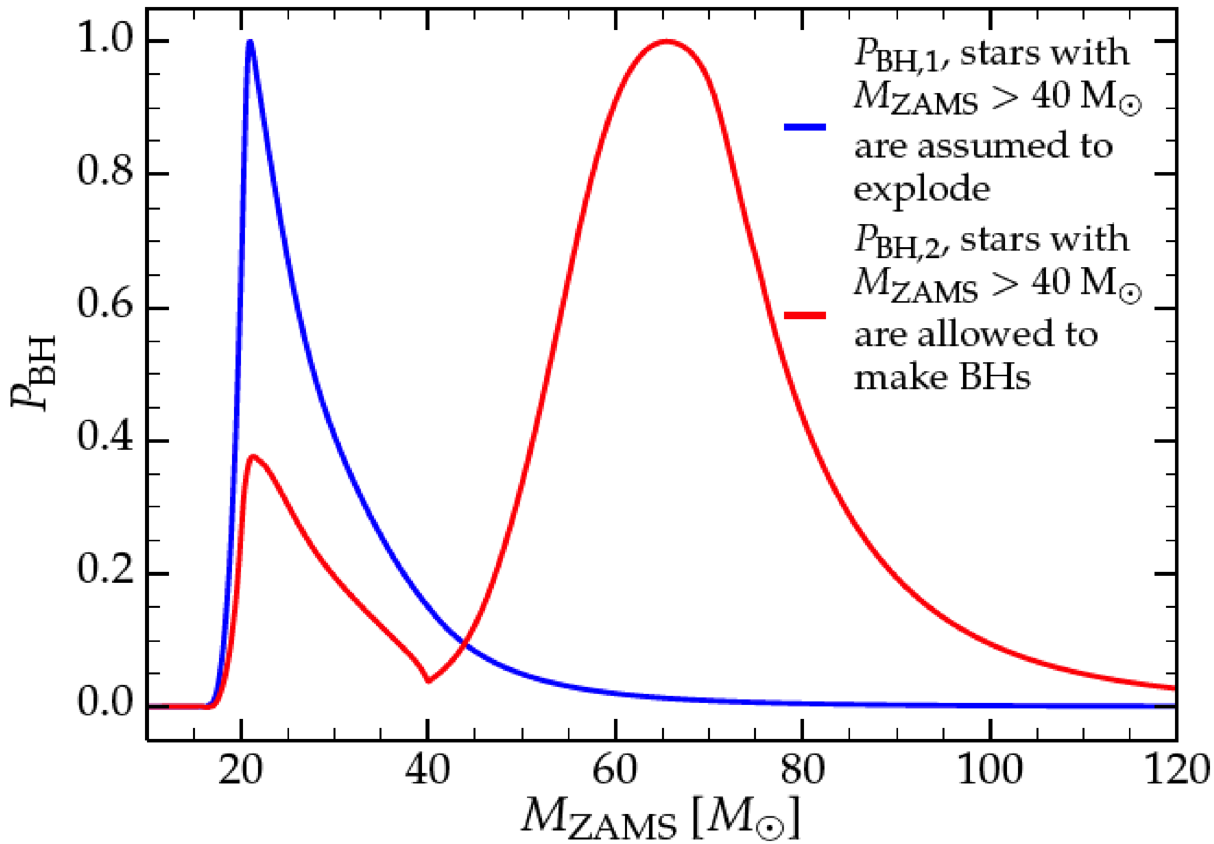
- Low velocities (~200-1000 km/s)
- T ~ 10^4 K
- Hydrogen-rich composition, devoid of burning products

<u>Key point</u>: shock ejects hydrogen envelope so helium core becomes the BH! (Kochanek '14)



Black Hole Formation Probability

Clausen, Piro, and Ott (2014)



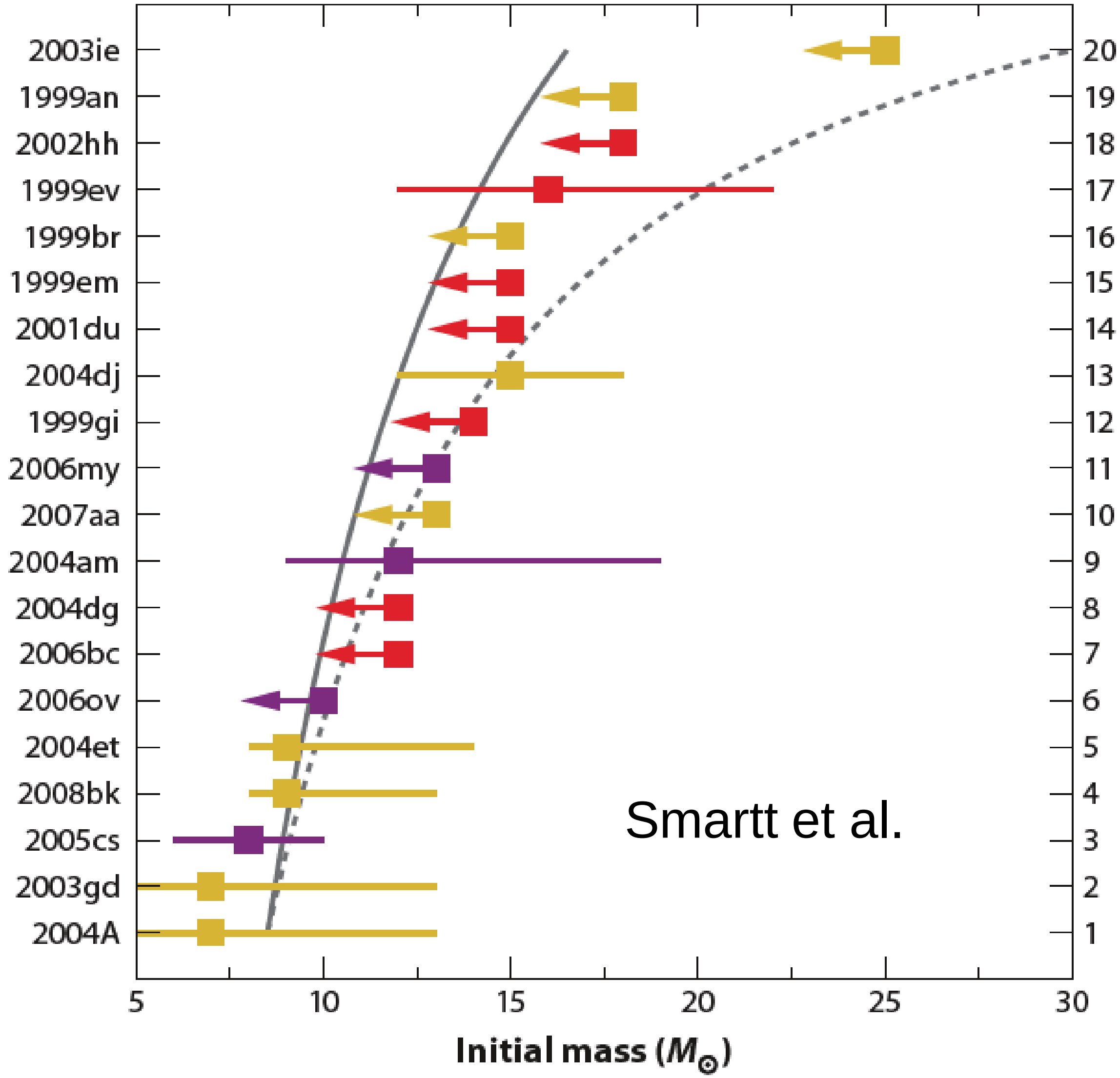
Bad news: Probability function not uniquely determined

Good news: No BHs below M_*~20 M_{sun} is robust

Connections to SN Progenitor Masses

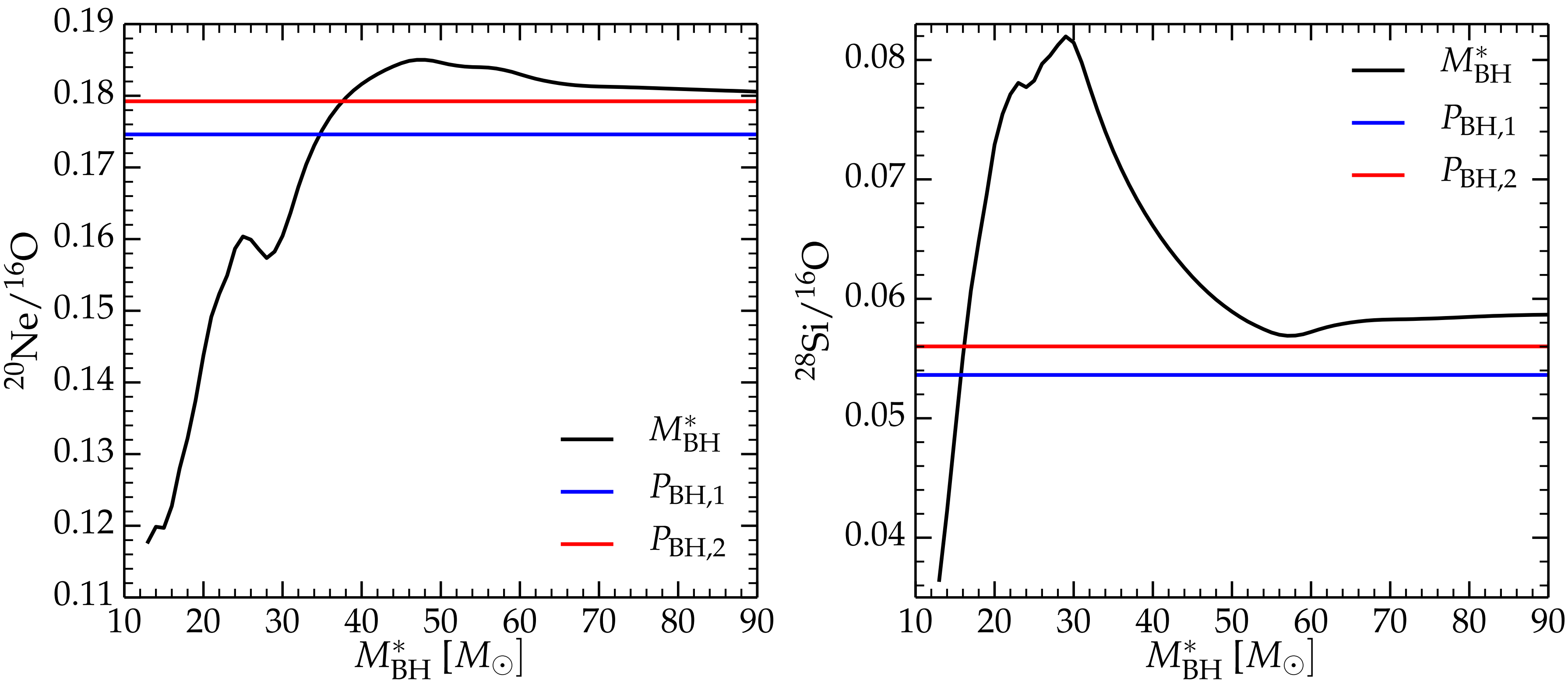
Clausen, Piro, and Ott (2014)

- Lower limit at ~20 M_{sun} roughly matches the maximum mass for observed Type II-P progenitors



Impact on Chemical Enrichment

Clausen, Piro, and Ott (2014)



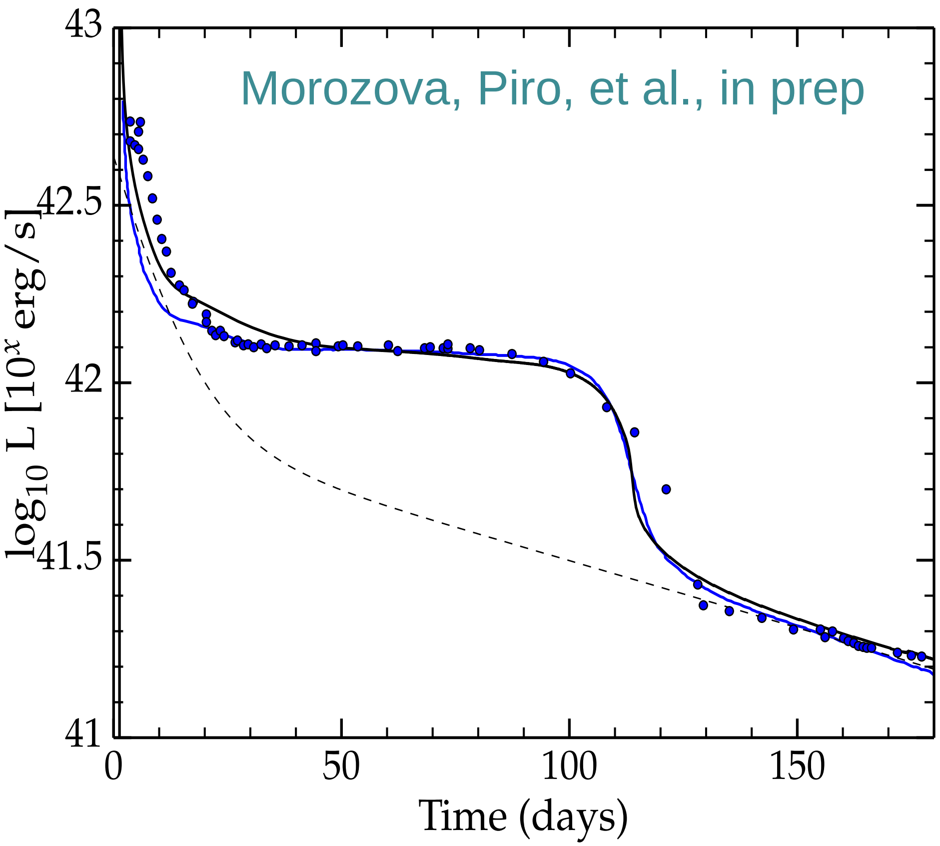
The composition of material ejected by massive stars during their life and death is impacted greatly by which stars make BHs versus NSs

Conclusions

We are regularly constraining *fundamental properties* of exploding stars

- Type Ia progentiors < few Earth radii
- Type Ib and Ic < few R_{sun}
- Type IIb ~300 R_{sun} envelope with ~few R_{sun} core
- Stripped-envelope SNe from ~10-20 M_{sun} stars
- Galactic black holes indicate ~20-40 M_{sun} stars make BHs instead of NSs (many implications!)

Future Work



Developing 1D Lagrangian hydrodynamic SuperNova Explosion Code (SNEC)

- More detailed comparisons with observations

- Complicated circumstellar structures

Explore broader implications of these constraints on progenitors

- Informing stellar models (how much mass loss? which stars make BHs vs NSs?)

- Chemical signatures and gravitational wave sources