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Supernova: progenitor compactness and future tests

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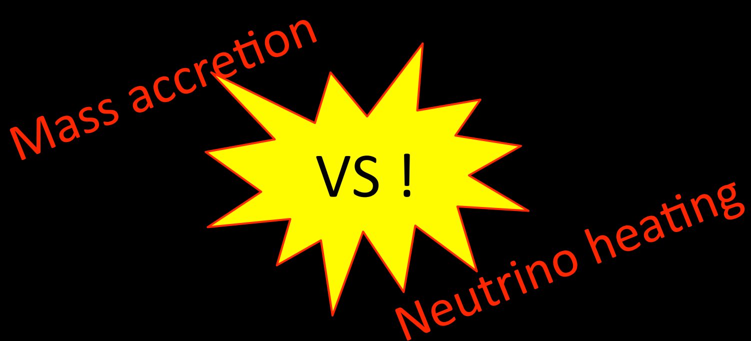
The explosion mechanism

Stalled shock:
The bounce shock stalls, pressure inside balanced by ram pressure outside:

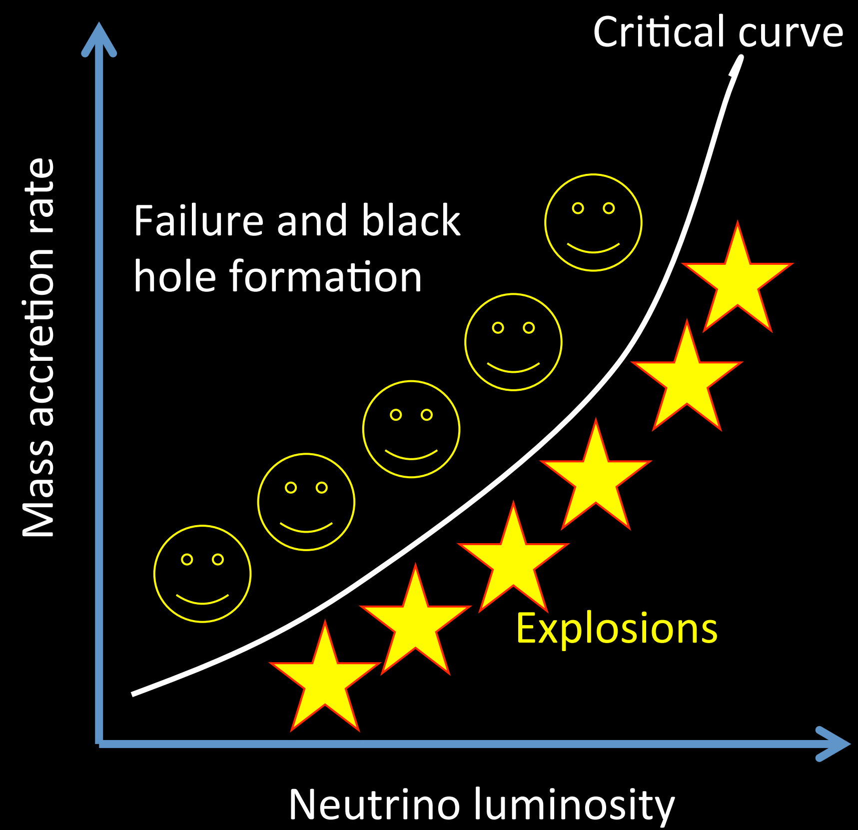
$$p = \rho \Delta v^2$$

The neutrino mechanism:
Deposit a fraction of the energy in neutrinos via capture on free neutrons & protons

Bethe & Wilson (1985), Colgate et al (1966), …



➔ Critical curve



To be tested with simulation & observations

Systematic core-collapse simulations

Sophisticated simulations [no systematic studies yet]

- 3D with neutrino transport
- Few progenitor models
- Address: explosibility, neutrino and gravitational wave signals

First systematic studies in spherically symmetry

- Spherically symmetric with parameterized neutrino heating
- $O(100\sim1000)$ progenitor models
- Address: progenitor dependence, black hole formation

Ugliano et al (2012), O'Connor & Ott (2011, 2013), Pejcha & Thompson (2014)
Ertl et al (2015), Sukhbold et al (2016)

Systematic study in axis-symmetry

- Axis-symmetric with simplified neutrino transport (IDSA)
- $\sim$400 progenitor models
- Newtonian gravity
- Address: progenitor dependence, SASI, other observables (M_{Ni}, etc)

Nakamura et al (2015), Summa et al (2016)

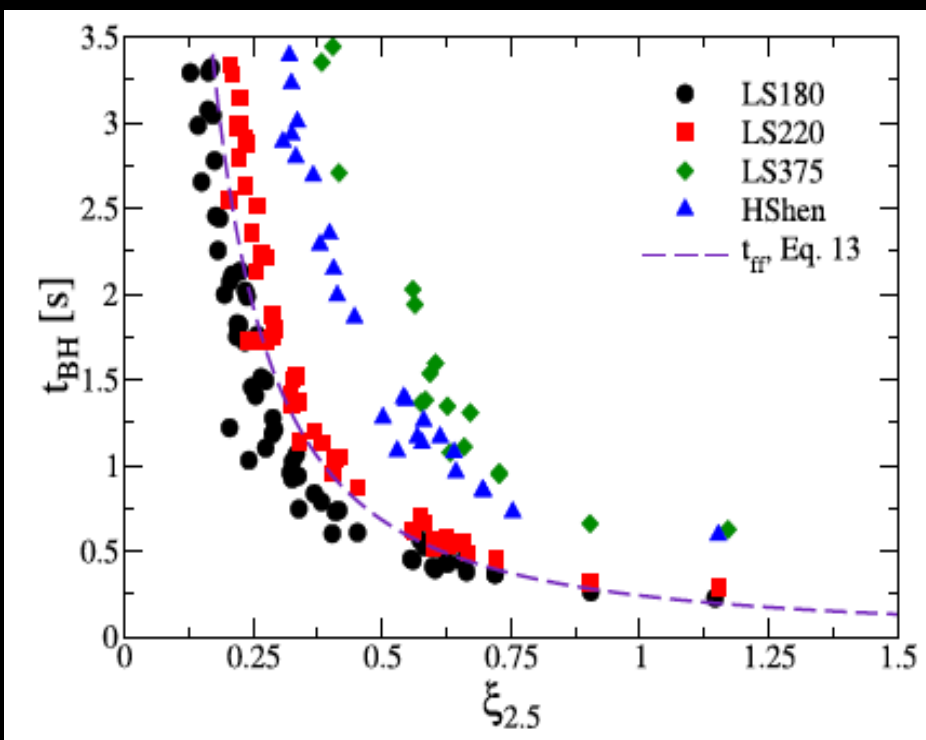
Explodability and compactness

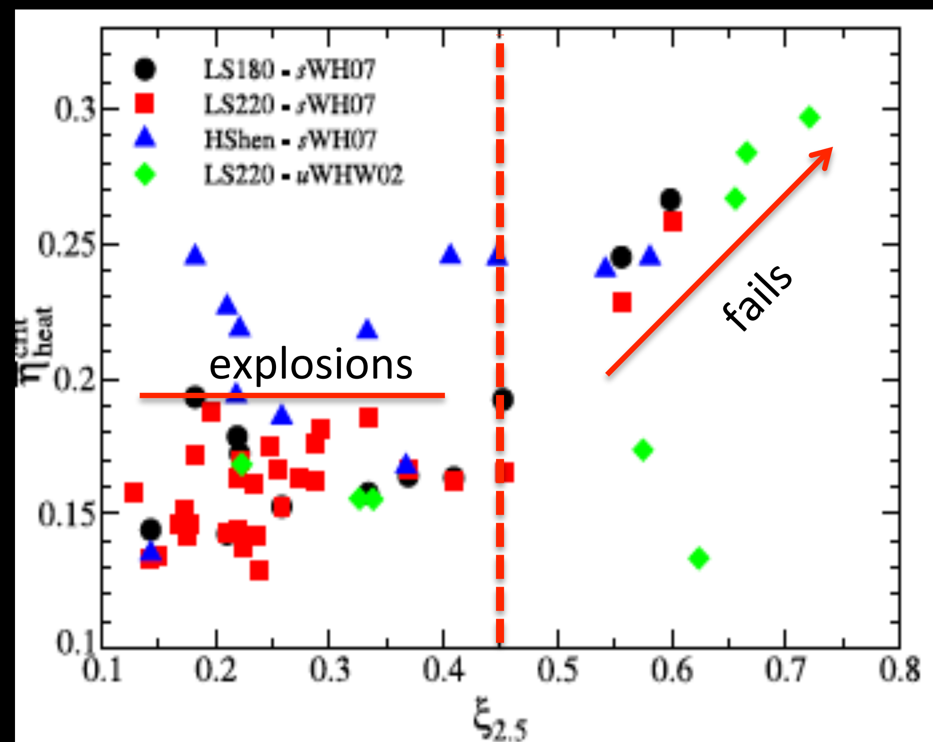
Compactness: is a useful indicator to discuss the eventual outcome of core collapse

$$\xi = \frac{M/M_{\odot}}{R(M_{\rm bary} = M)/1000\,{\rm km}}\bigg|_{t}$$

Black hole formation occurs more readily for larger compactness.

Successful / failed explosion threshold occurs approximately $\xi_{2.5} \sim 0.45$





O'Connor & Ott (2011)

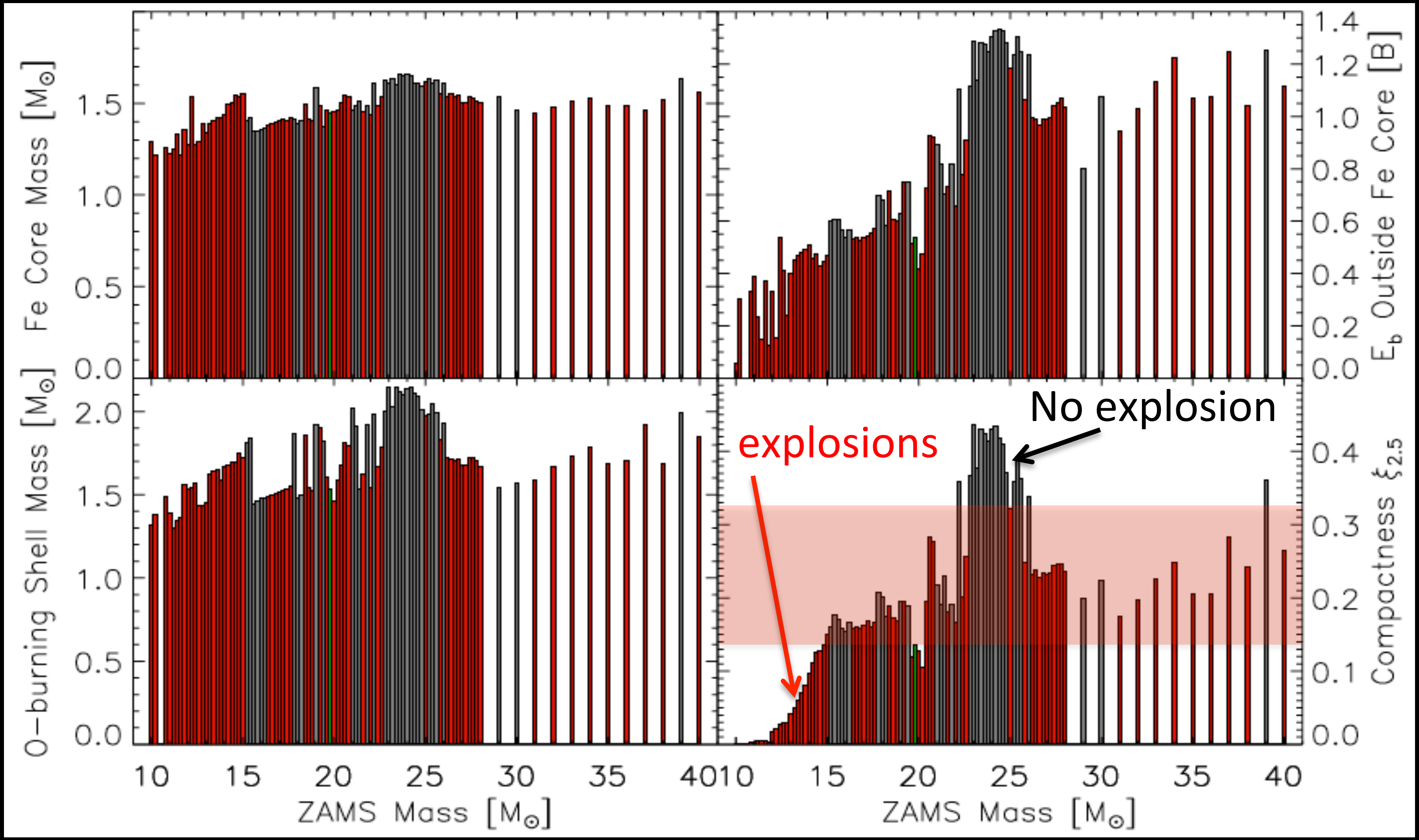
Explodability and compactness

Compactness is useful but not the whole picture.

- BH formation for $\xi_{2.5} > 0.35$
- Explosions for $\xi_{2.5} < 0.15$
- Mixture in between

Predicts outcome of at most ~88% of cases

Pejcha & Thompson (2015)



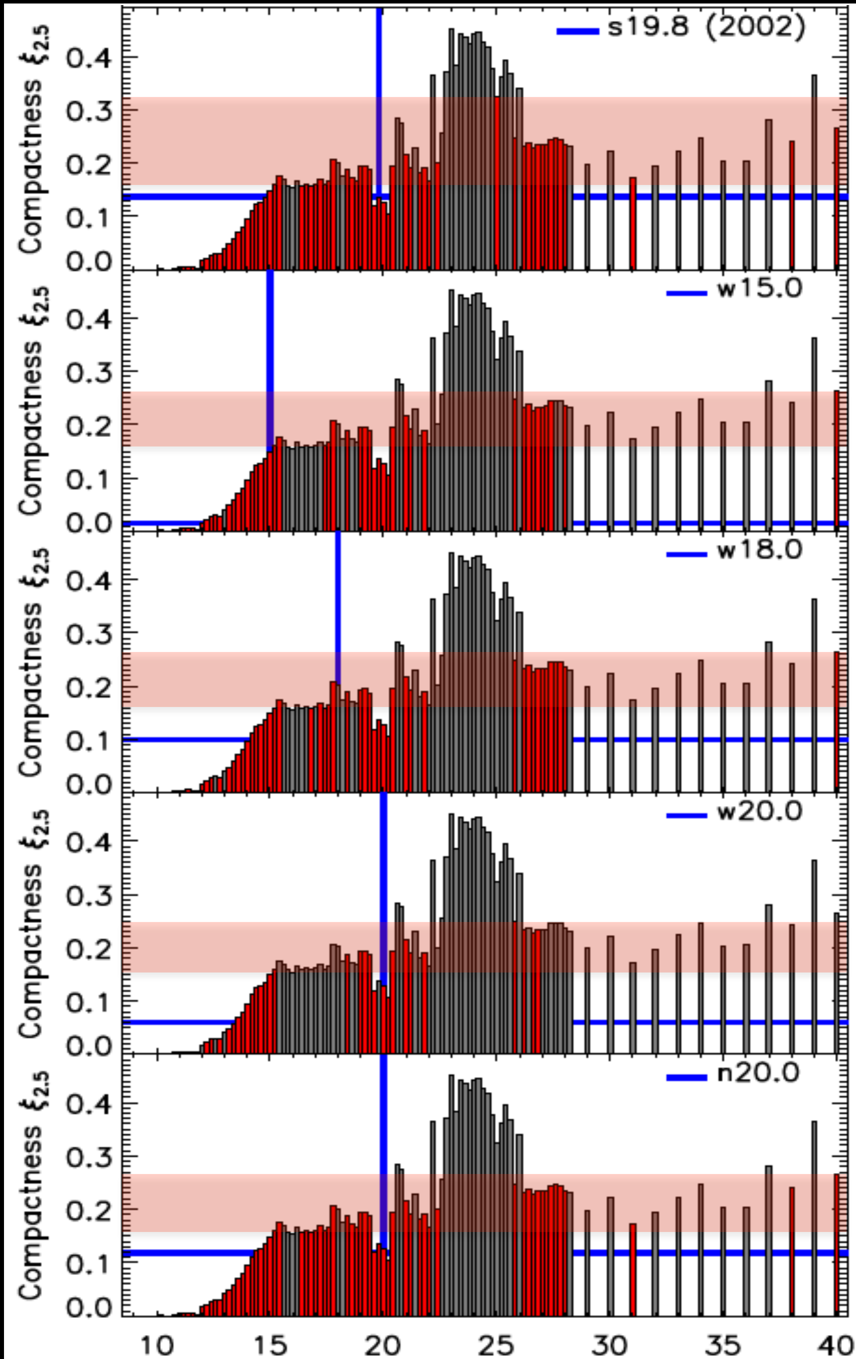
Ugliano et al (2012)

and compactness

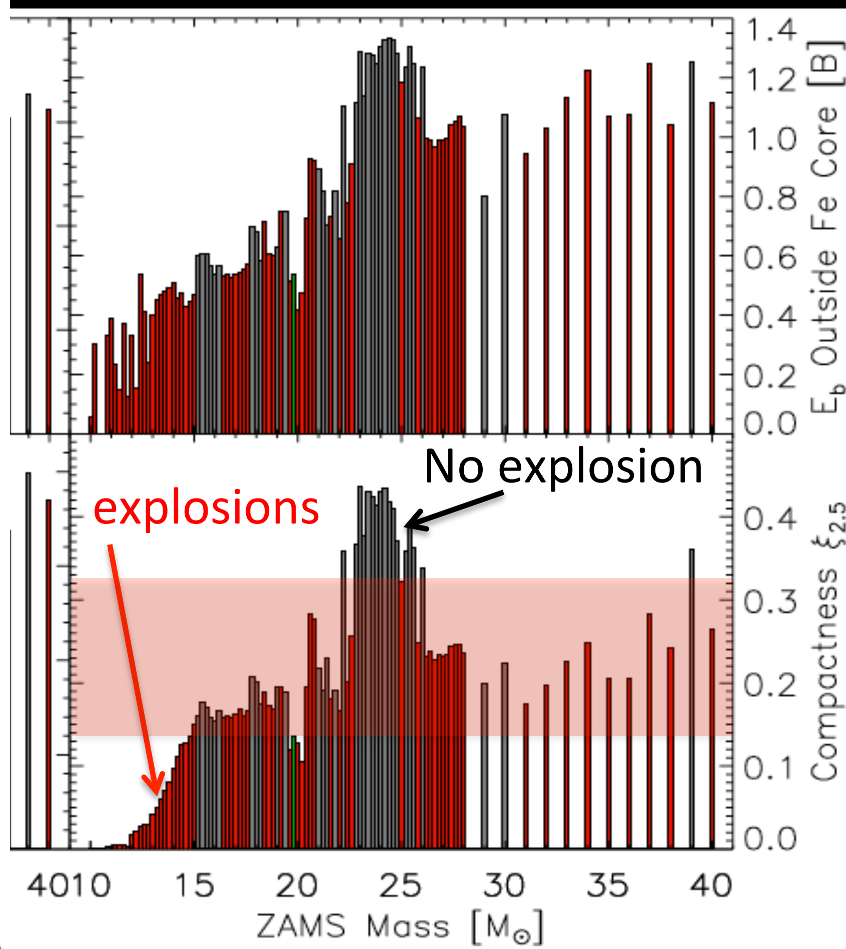
- on for $\xi_{2.5} > 0.35$
- for $\xi_{2.5} < 0.15$
- between

Predicts outcome of at most ~88% of cases

Pejcha & Thompson (2015)



Ertl et al (2015)



Ugliano et al (2012)

Two parameters

Towards better predictability:
Compactness captures well mass accretion but neutrino luminosity depends also on M_{pns}.

$$L_\nu^{\rm acc} \propto G \frac{M_{\rm pns} \dot{M}}{R_{\rm pns}}$$

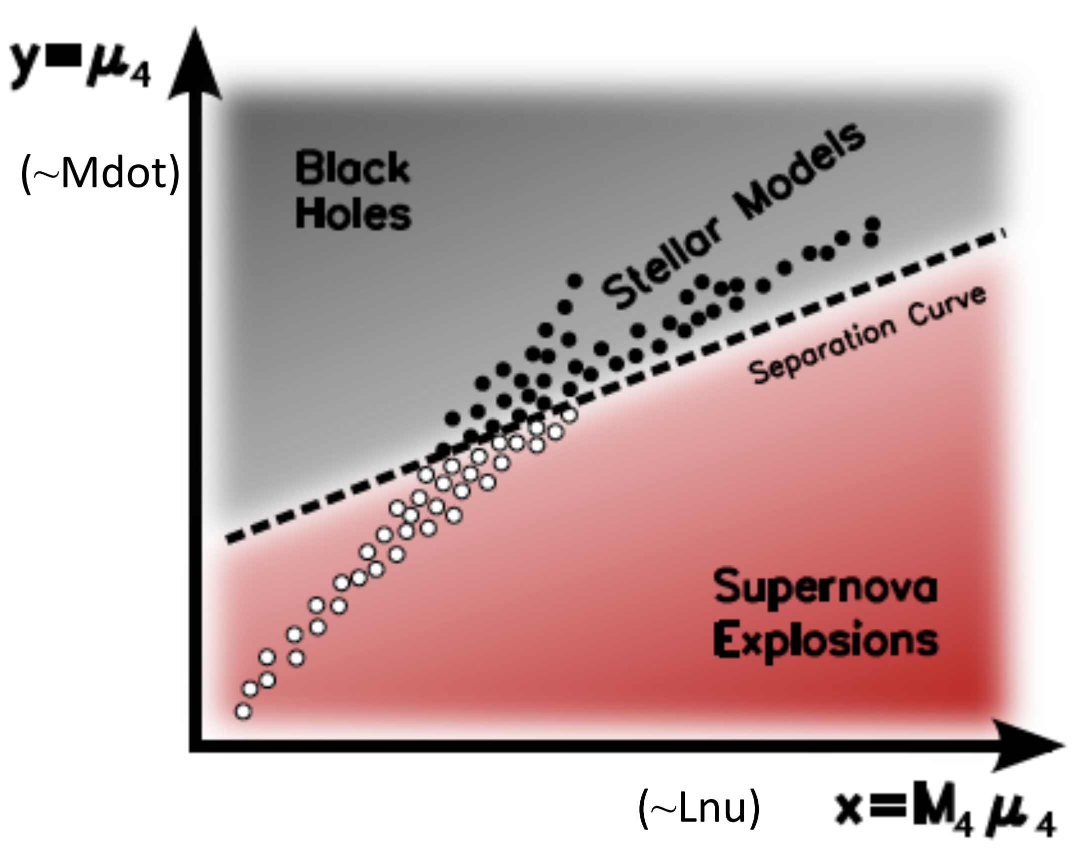
So, critical $\xi_{2.5}$ increases with M_{pns}.

→ Use two parameters that captures Mdot and Lnu.

$$M_4 \equiv m(s=4)/M_\odot$$

$$\mu_4 \equiv \left. \frac{\mathrm{d}m/M_\odot}{\mathrm{d}r/1000\,\mathrm{km}} \right|_{s=4}$$

Yields much better predictability (~97% of cases).



Ertl et al (2015)

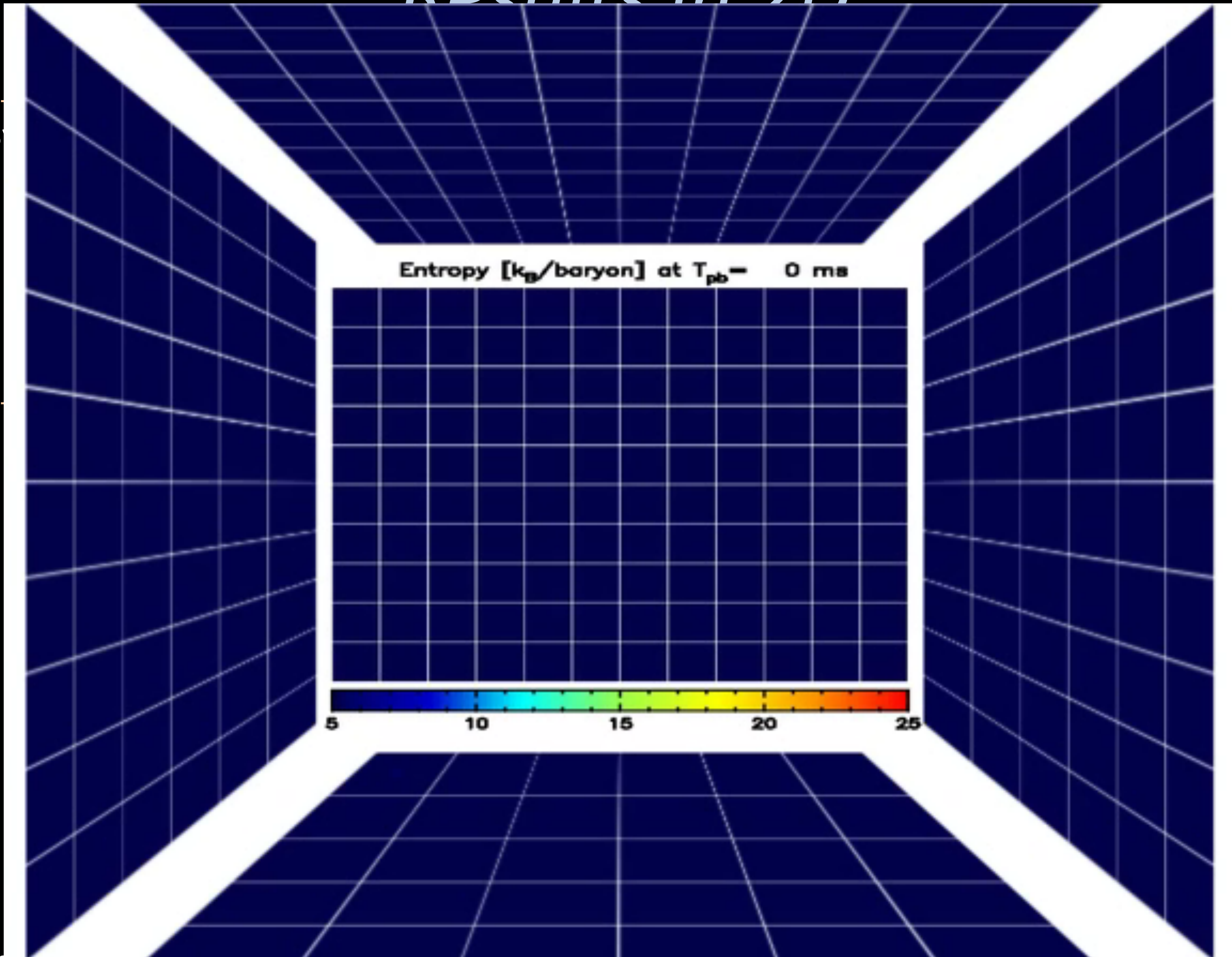
Results in 2D

Systematic study in axis-symmetry

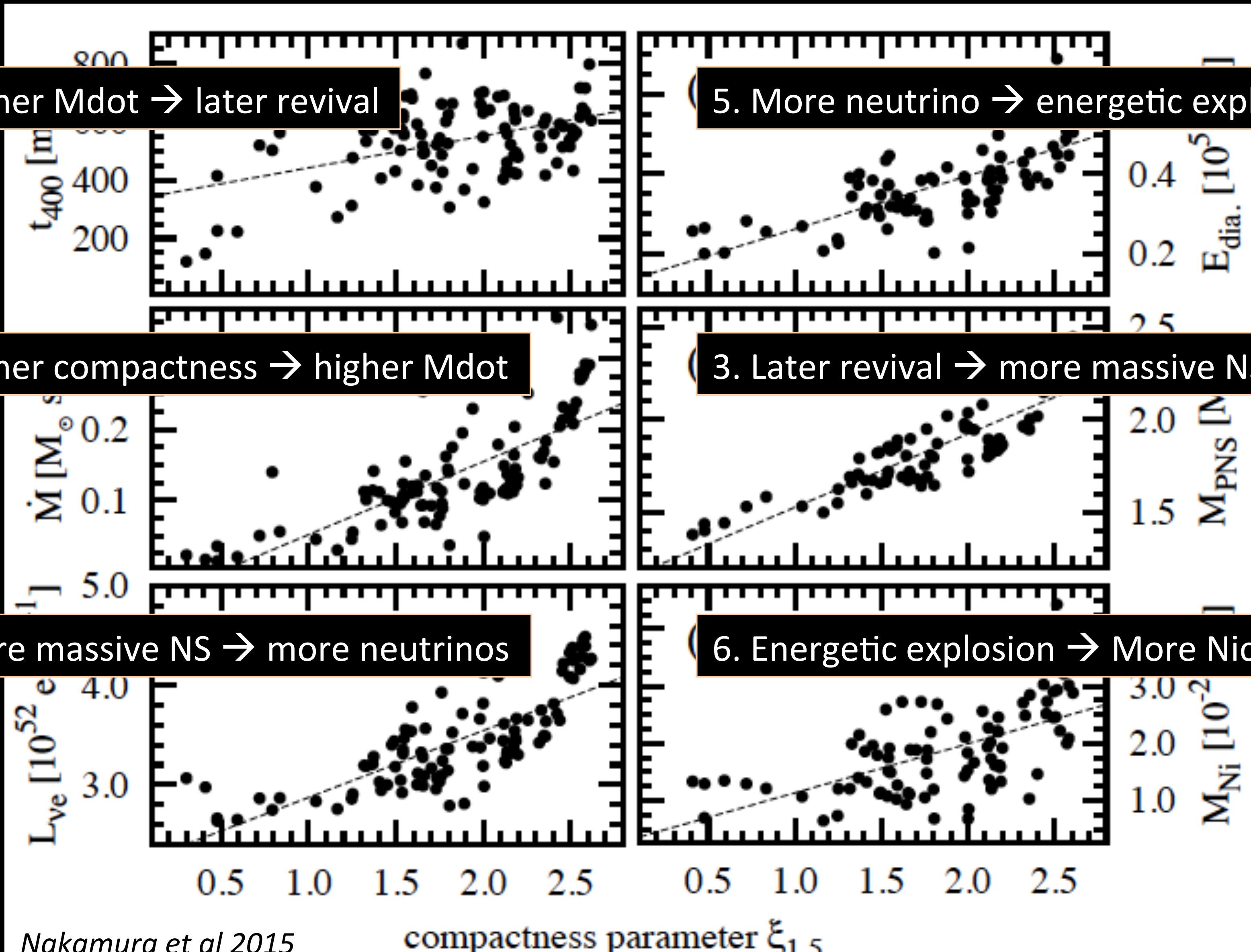
- Axis-symmetric with simplified neutrino transport (IDSA)
- 378 progenitor models (101 solar, 247 $Z = 10^{-4}$, 30 zero metal; WHW02)
- Newtonian gravity
- LS(K=220) EOS

Nakamura et al (2015)

Results in 2D



Results in 2D



Nakamura et al 2015

Critical compactness in 2D

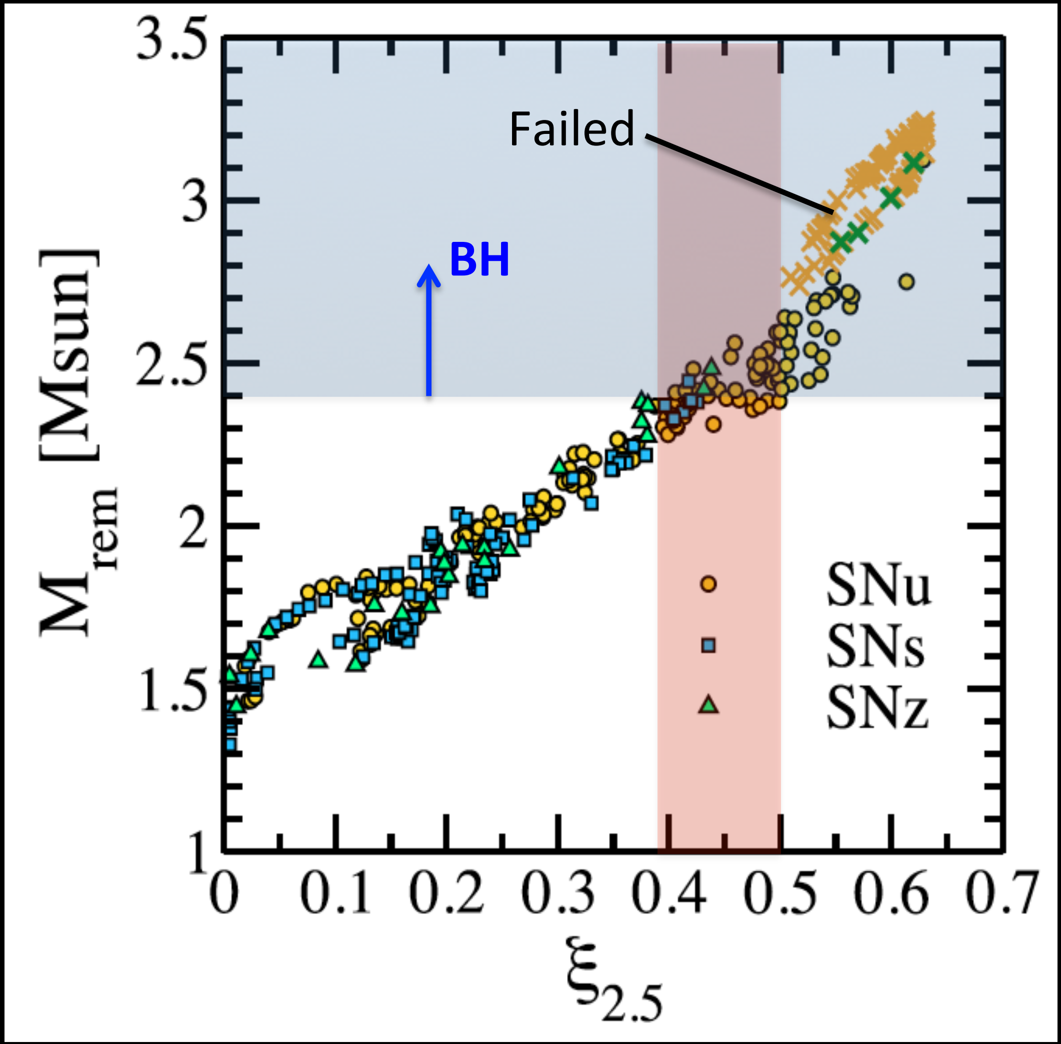
Limitation:

- All solar metal stars explode
- But 2D setup is conducive to explosions

  e.g., Hanke et al (2012)
- Remnants above 2.4 Msun baryonic mass not realistic and may not explode in reality.

→ Critical $\xi_{2.5}$ < ~0.4 – 0.5

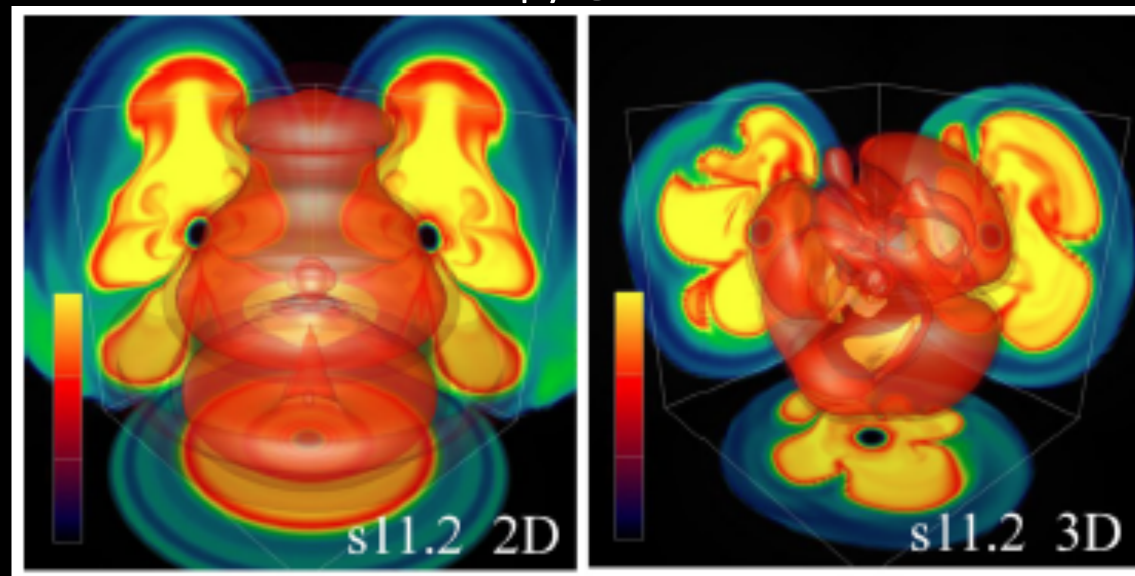
Critical compactness $\xi_{2.5}$
1D: 0.15 – 0.35
2D: < 0.4 – 0.5

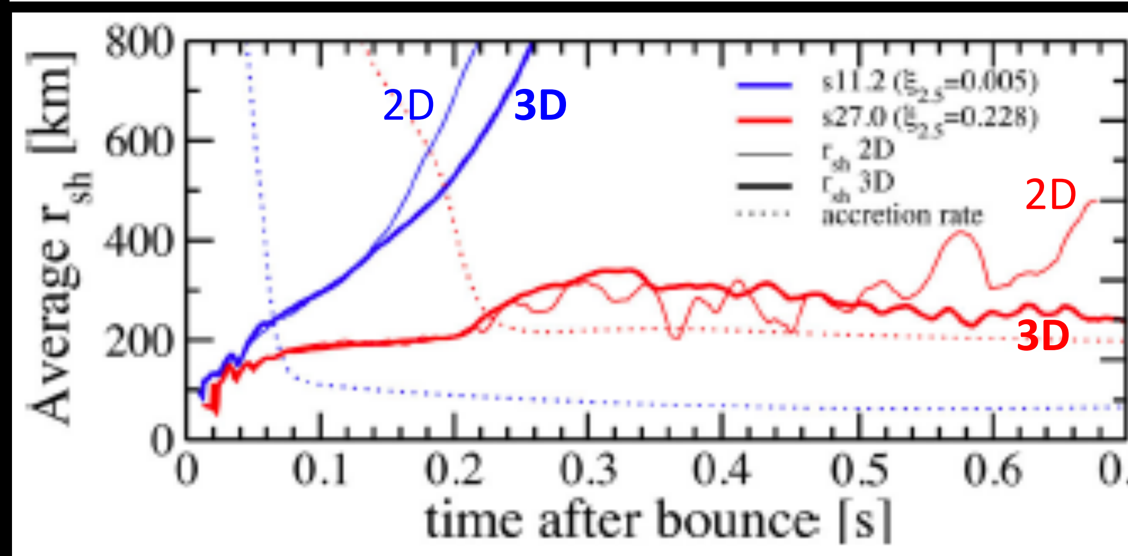


Horiuchi et al (2014)

In 3D?

entropy @200ms





Speculating about 3D

No systematic study with 3D simulations yet.

But qualitatively:

- 3D explosions are more spherical
- 3D explosions have later shock revival times

For a progenitor with $\xi_{2.5} = 0.228$, exploded in 2D (late), no sign of explosion in 3D.

Critical compactness

1D: 0.15 – 0.35

2D: < 0.4 – 0.5

3D: ~ 0.2 ? Needs investigations.

Horiuchi et al (2014)

OBSERVATIONAL HINTS

Impacts of threshold compactness

Simulation insights:

Critical compactness for failed explosions is uncertain but in the range $\xi_{2.5}$ = 0.2 – 0.4

Critical compactness affects NS vs BH formation

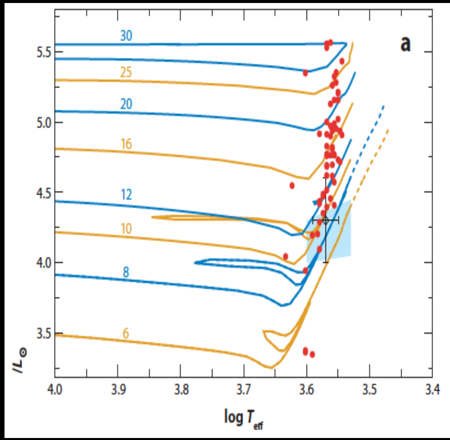
→ Fraction of stars that explode vs fail

→ Mass function and mean mass of NS and BH

Observation insights:

Recent observational hints that the failure rate may be moderately high:

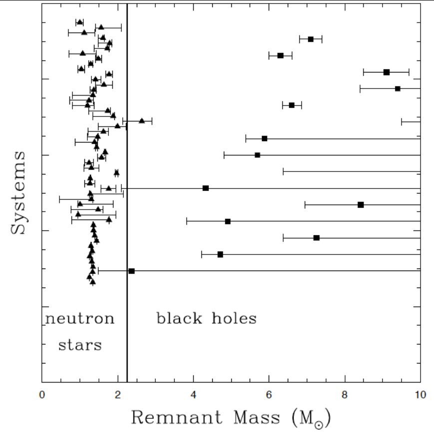
Red supergiant problem



~20-30%

Smartt et al (2009)

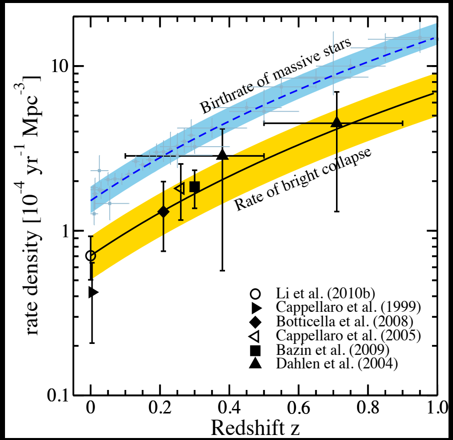
Black hole mass function



~20-30%

Kochanek et al (2014)

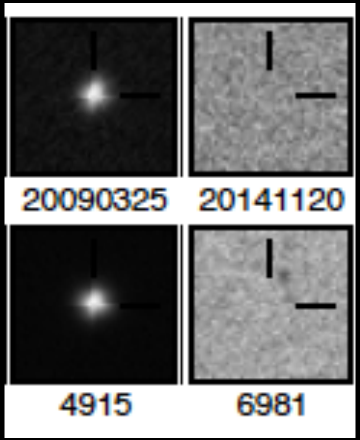
Supernova rate



~10-30%

Horiuchi et al (2010)

Survey about nothing



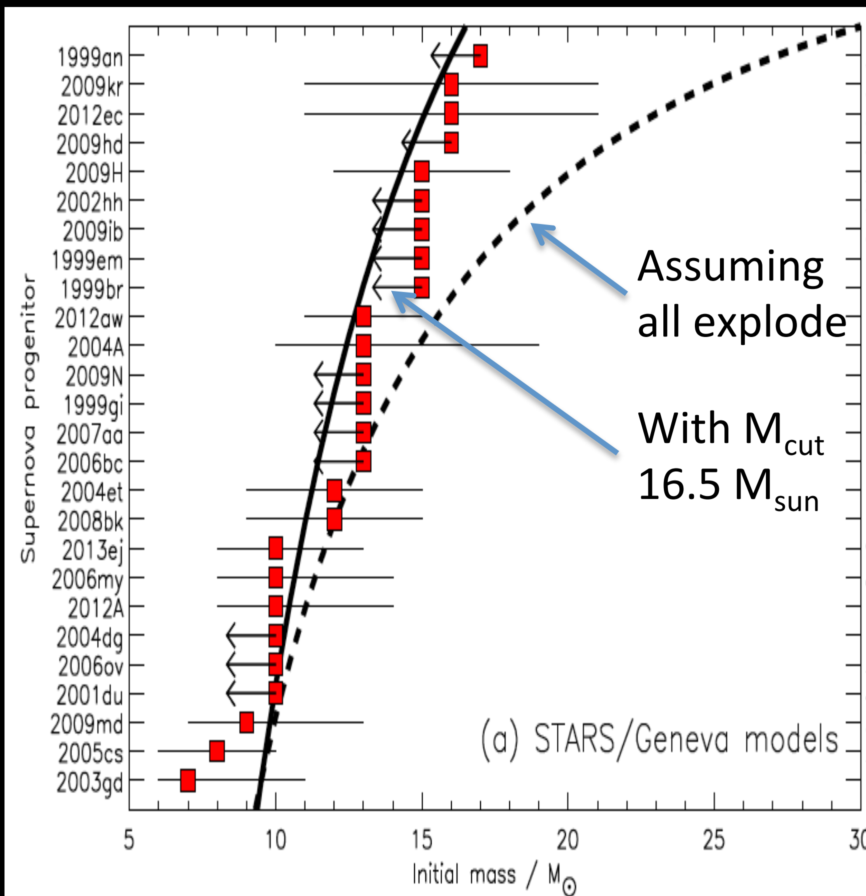
~10-40%

Gerke et al (2014)

1. Red supergiant problem

Some stars don't explode?

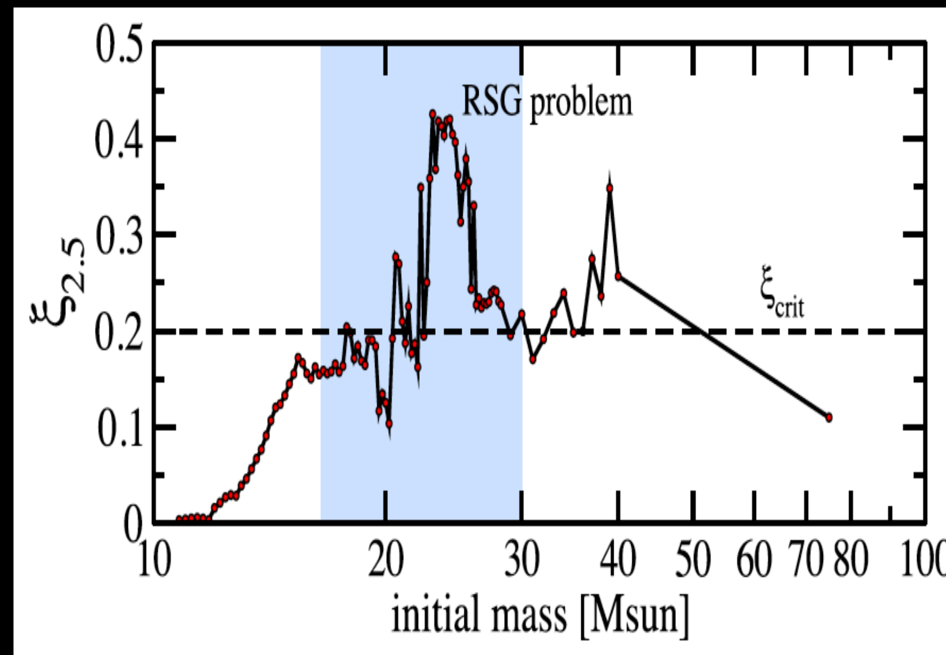
Observationally, the red supergiants with mass 16 – 25 Msun are not exploding (as IIP)



Smartt (2015)

They may be high compactness stars

The mass range in question is an island of high compactness → theoretically more likely to form black holes.

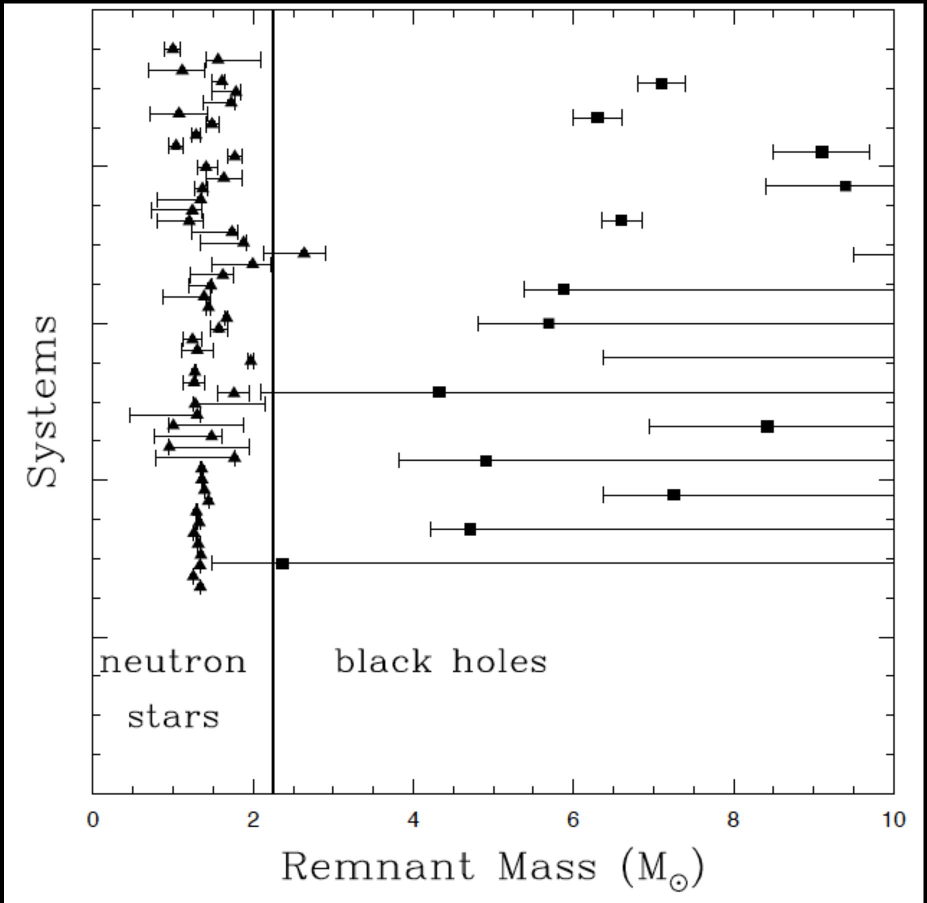


Horiuchi et al (2014); also Kochanek (2014)

→ Requires critical $\xi_{2.5} \sim 0.2$

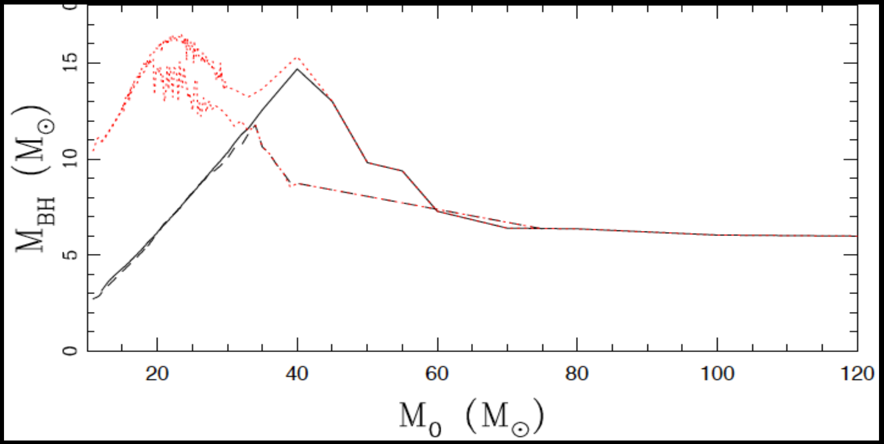
2. Black hole mass function

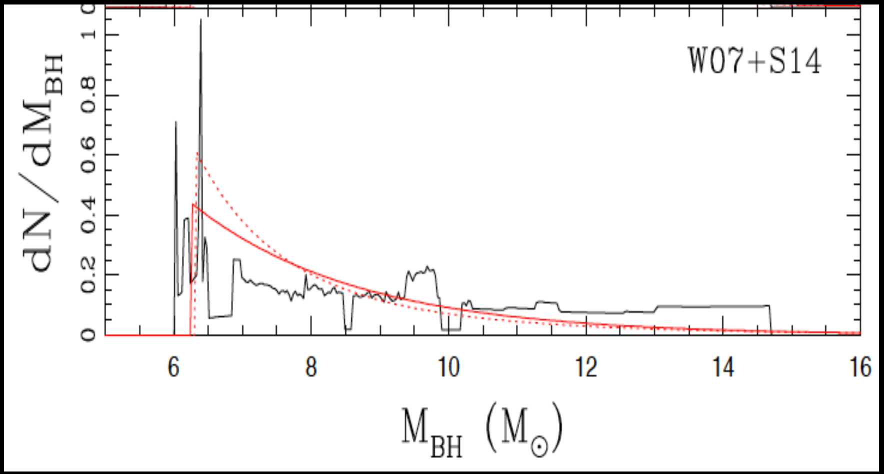
Compact object mass function:
There are hints of a dearth of stellar black holes just above the NS mass range



e.g., Kreidberg et al. (2012), Kizeltan et al. (2013)

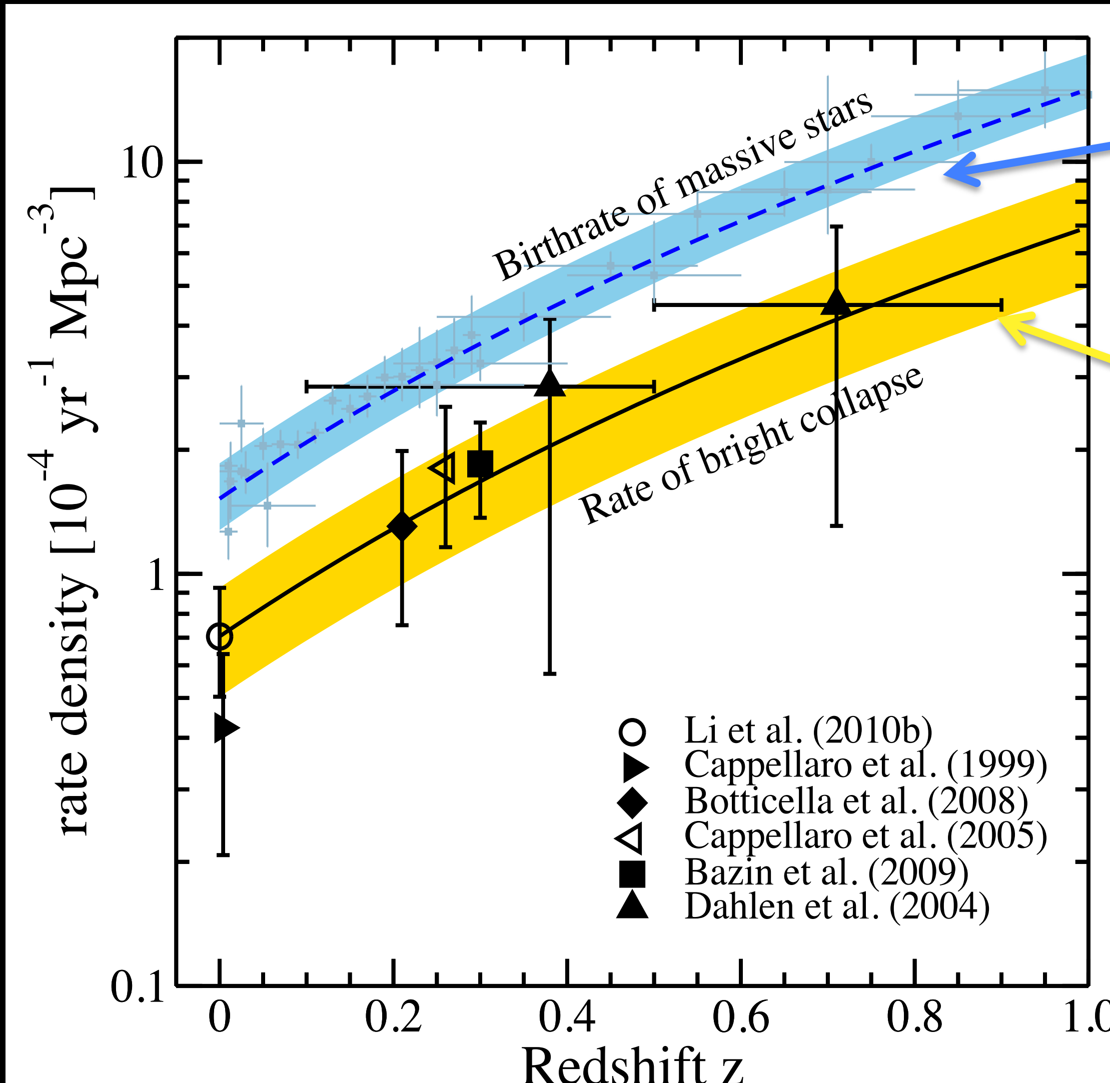
A **critical compactness $\xi_{2.5}$~0.2** predicts a black hole mass function with a cutoff





Kochanek (2014); also Ugliano et al (2012)

3. Supernova rate



Horiuchi et al (2011)

Birth rate of massive stars
From many observations (hundreds)

Observed supernova rate
Derived from observations of *luminous* supernovae (many recent updates)

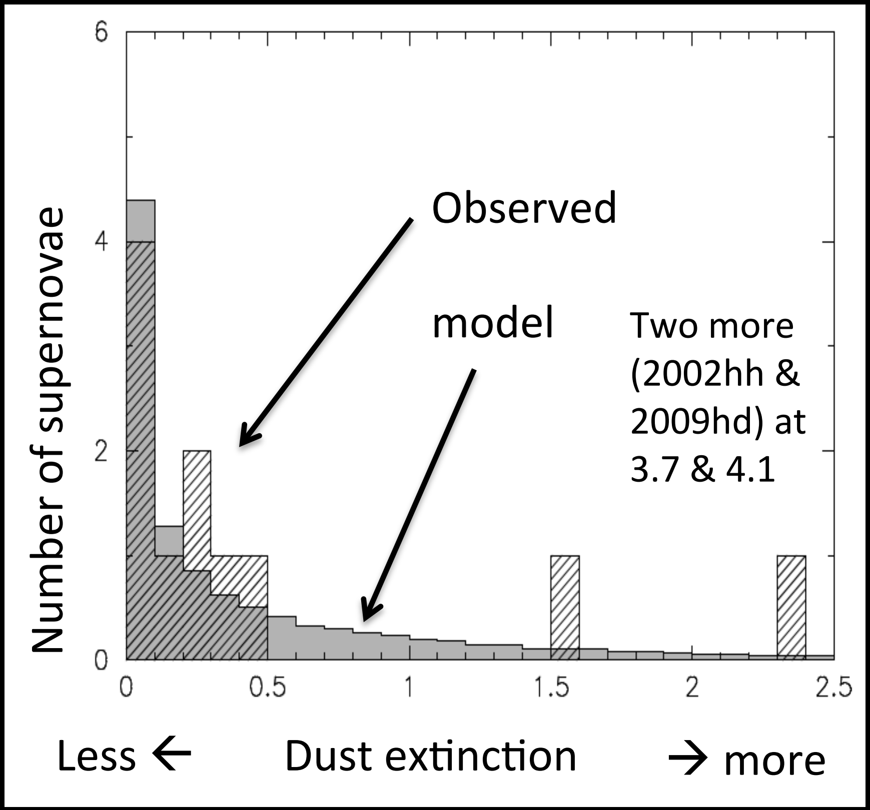
(Core-collapse rate) – (supernova rate) = DIM or DARK collapse rate

- Some of this can be due to collapse to black holes.
- Other possibilities include ONeMg collapse, dust (especially from mass loss), fall back intense collapse

3. Supernova rate

Dust extinction distribution

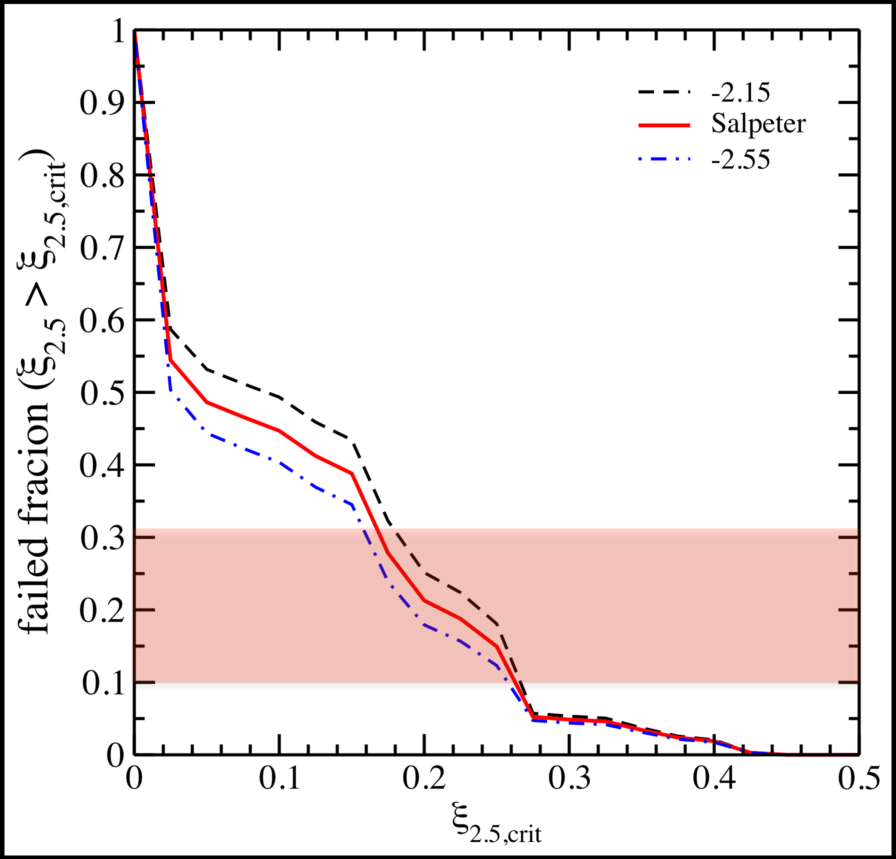
Improve uncertainty from dust attenuation
→ better model raises CCSN rate



Mattila et al (2012); Dahlen et al (2012)

Implication

Failed collapse fraction is reduced to 10–30%.
Convolving with IMF yields link to critical ξ.



→ Critical $\xi_{2.5} \sim$ 0.15–0.25

4. Searching for failed explosions:

Survey About Nothing

- Look for the disappearance of red-supergiants in nearby galaxies
- Monitor 27 galaxies with the Large Binocular Telescope
  - → $\sim 10^6$ red supergiants with luminosity > 10^4 Lsun
  - → expect ~1 core collapse /yr
  - → In 10 years, sensitive to 20 – 30% failed fraction at 90%CL

Kochanek et al. (2008)

Results so far:

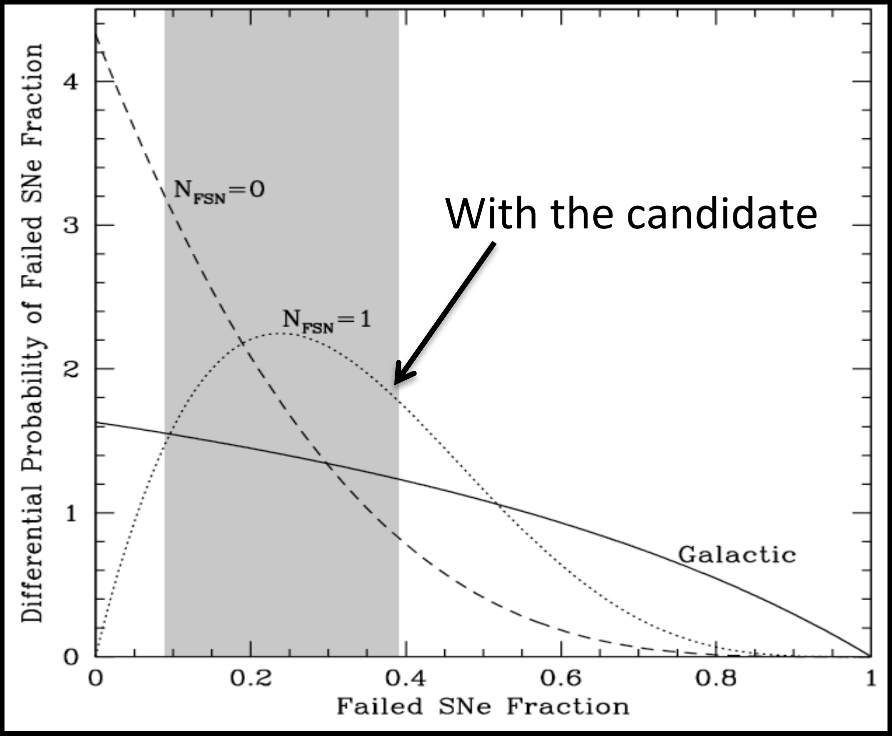
In 4 years running,

- 3 luminous CC supernovae: SN2009dh, SN2011dh, SN2012fh
- 1 Type Ia (SN2011fe)
- 1 candidate failed supernova: NGC6946-BH1 (@~6Mpc)

→ Peak failed collapse rate 10 – 40%

Note: the candidate's mass estimate is 18–25 Msun (!)

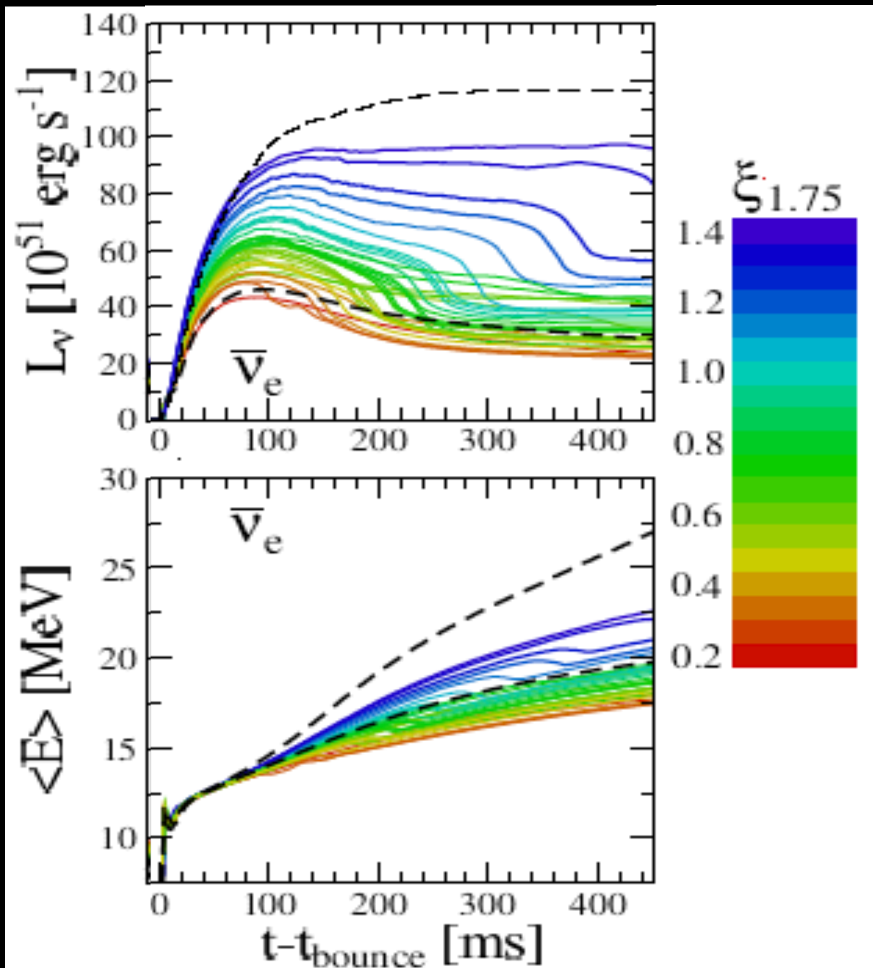
Gerke et al. (2015)

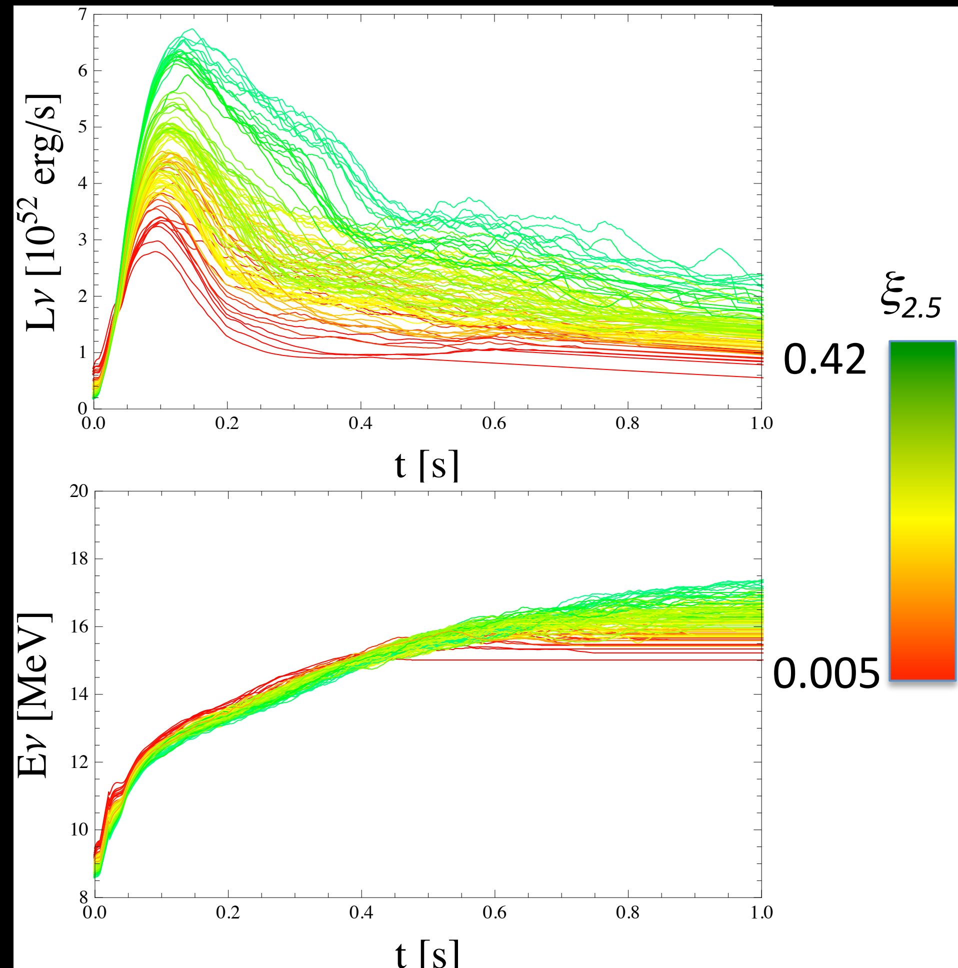


NEXT GALACTIC CORE COLLAPSE

Compactness and neutrino emission

1D ➔ ➔ ➔ ➔ 2D





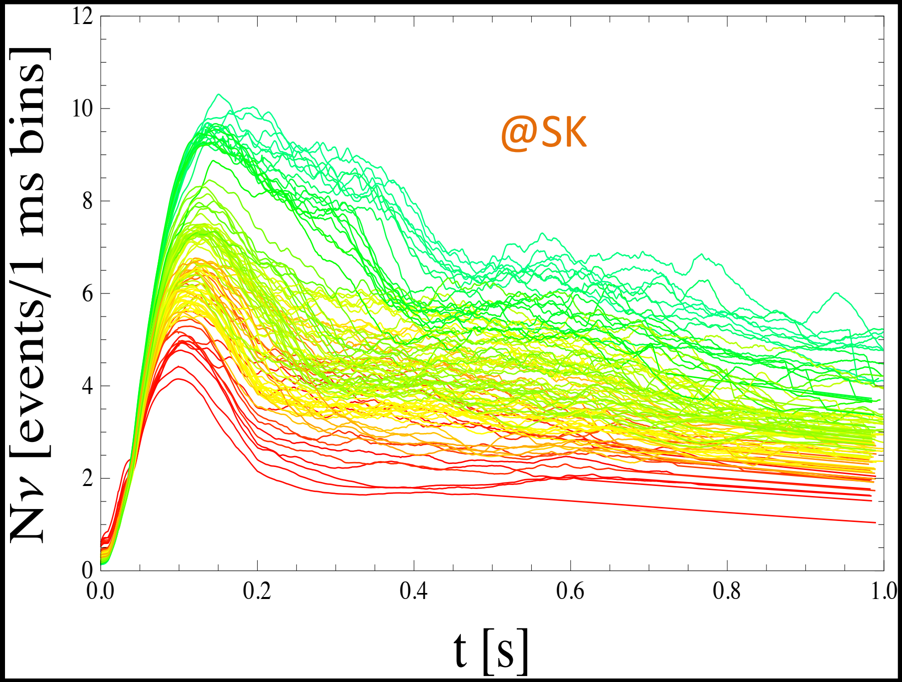
O'Connor & Ott (2013)

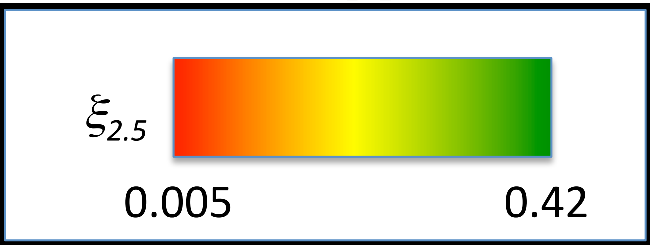
Based on Nakamura et al (2015)

Signal prediction

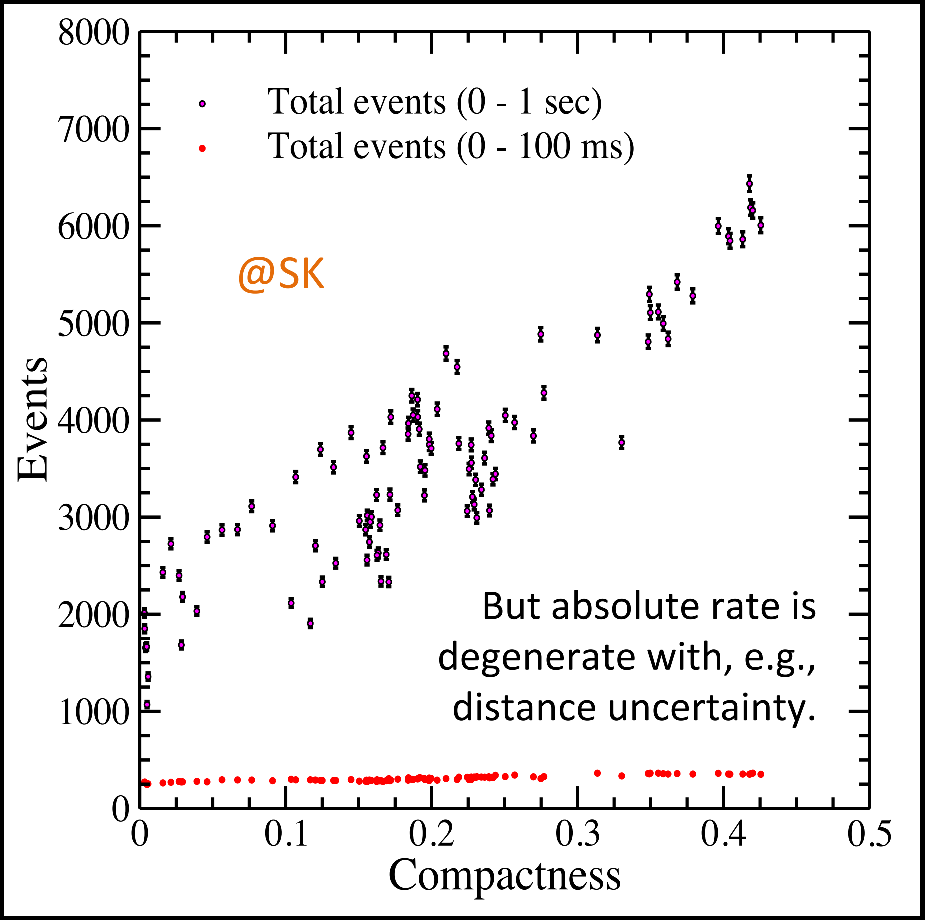
Events light curve at SK:
Clear dependence on ξ.

Using only MSW mixing.





Epochs and compactness:
Early epoch traces ~similar core structure, while later epochs trace stronger progenitor-dependent accretion *cf., Kachelrieß et al 2005*

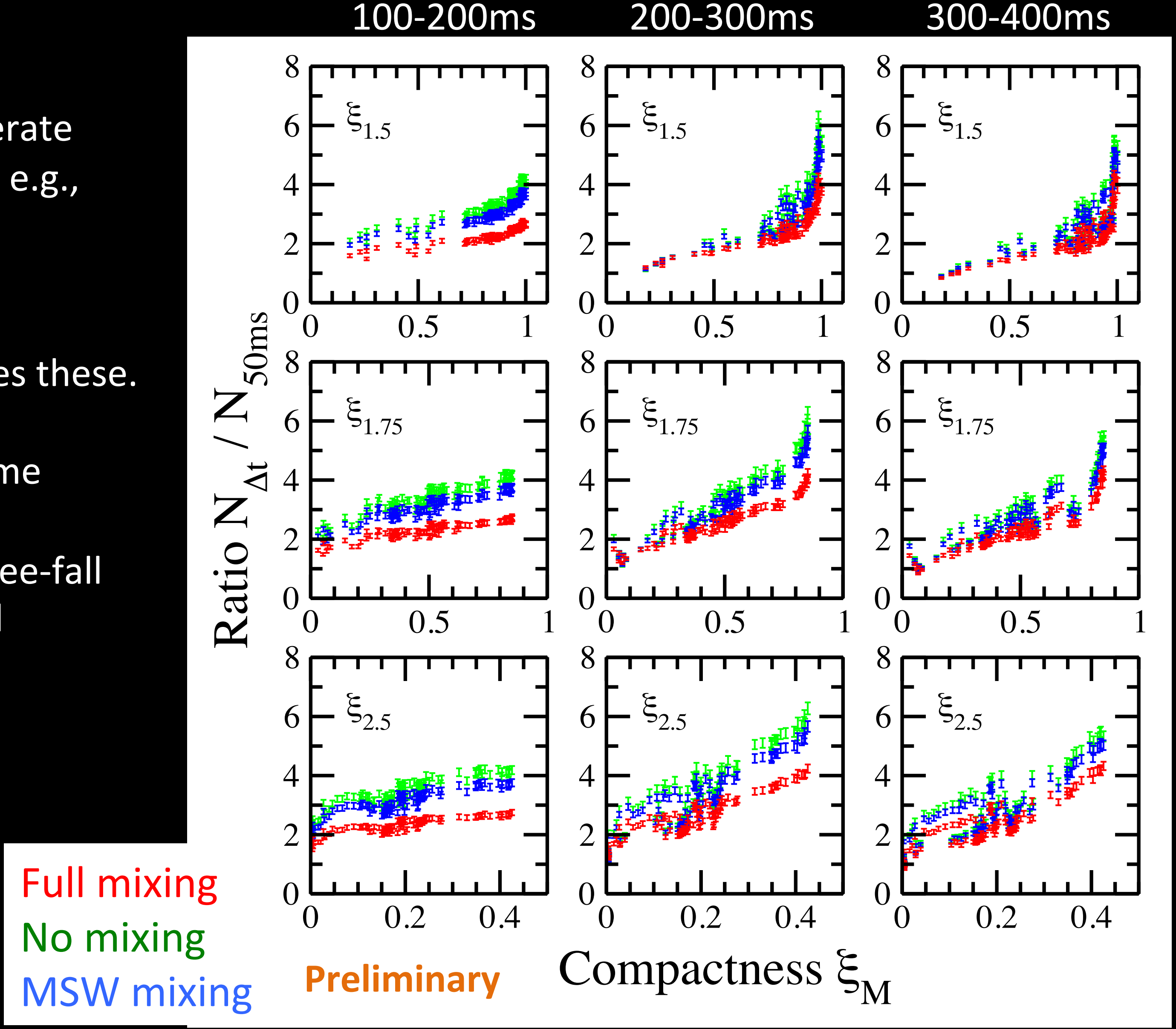


Measuring the compactness

Uncertainty
Absolute rate is degenerate with other systematics, e.g., distance uncertainty.

Ratio:
Taking the ratio removes these.

There is an optimum time window for a given ξ_M corresponding to the free-fall time for that mass shell

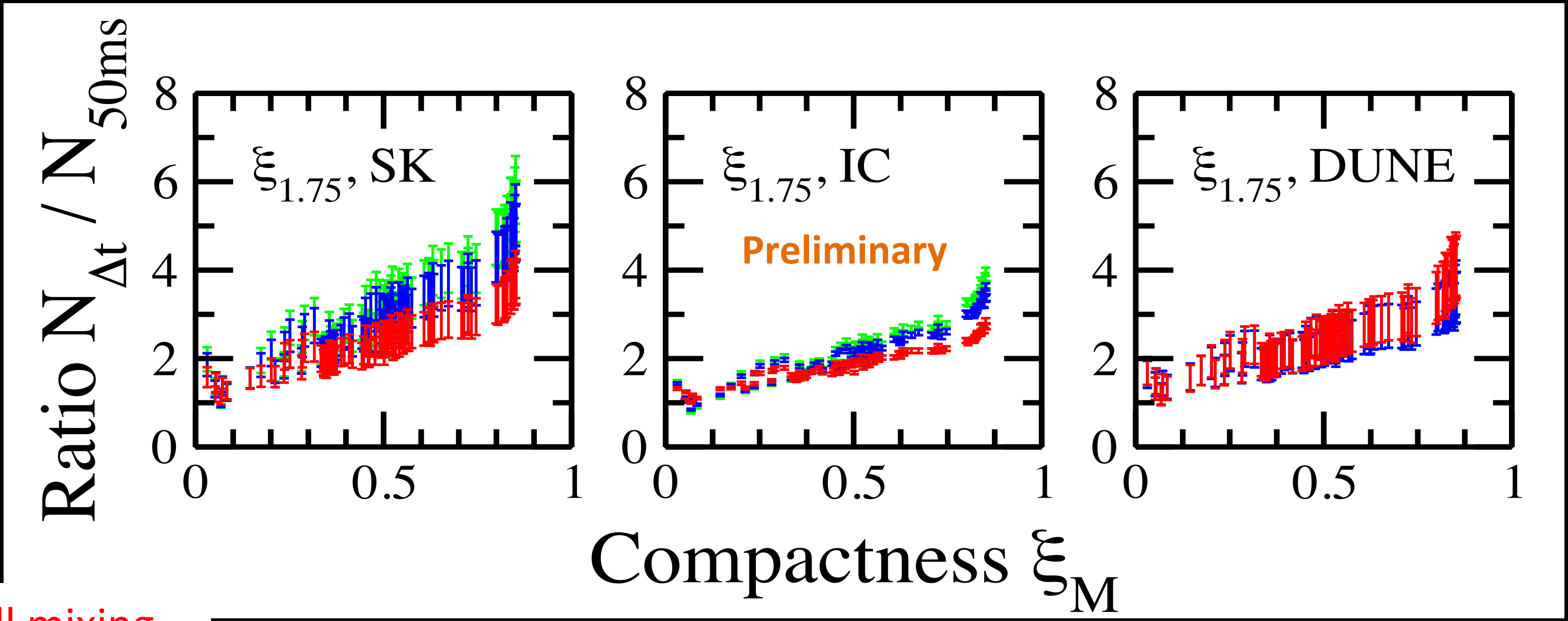


Measuring the compactness

Super-K
The errors would still be sizable, different mixing scenarios look ~similar

IceCube
Would be powerful for this (as it is based on the LC)

DUNE
The neutronization burst is useful, statistics limited



Full mixing
No mixing
MSW mixing

32.5 kton water
3 MeV threshold

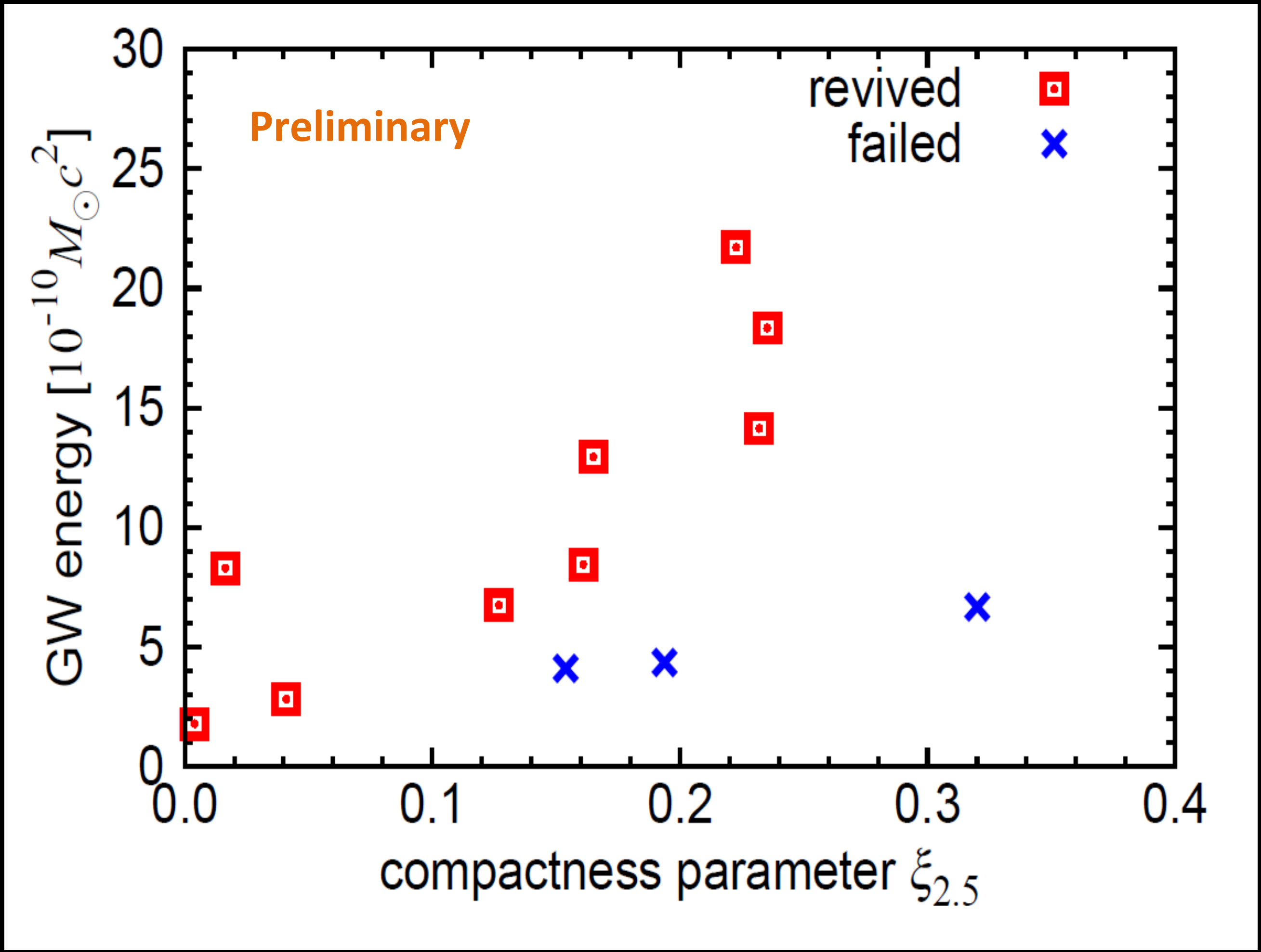
Correlated noise
in 5160 OMs.

40 kton Ar
5 MeV threshold
With ID for ν_e CC

Another possibility: gravitational waves

Predictions: based on 2D neutrino-driven models (includes prompt-convection, SASI/convection phase, and explosion phases)

Nakamura et al (in prep)



For explosions:
Higher compactness
→ Higher Mdot
→ violent SASI/convection
→ Efficient GW emission

Correlation
→ Another ~direct impact of compactness
→ Other dependencies

Summary

Take away messages:

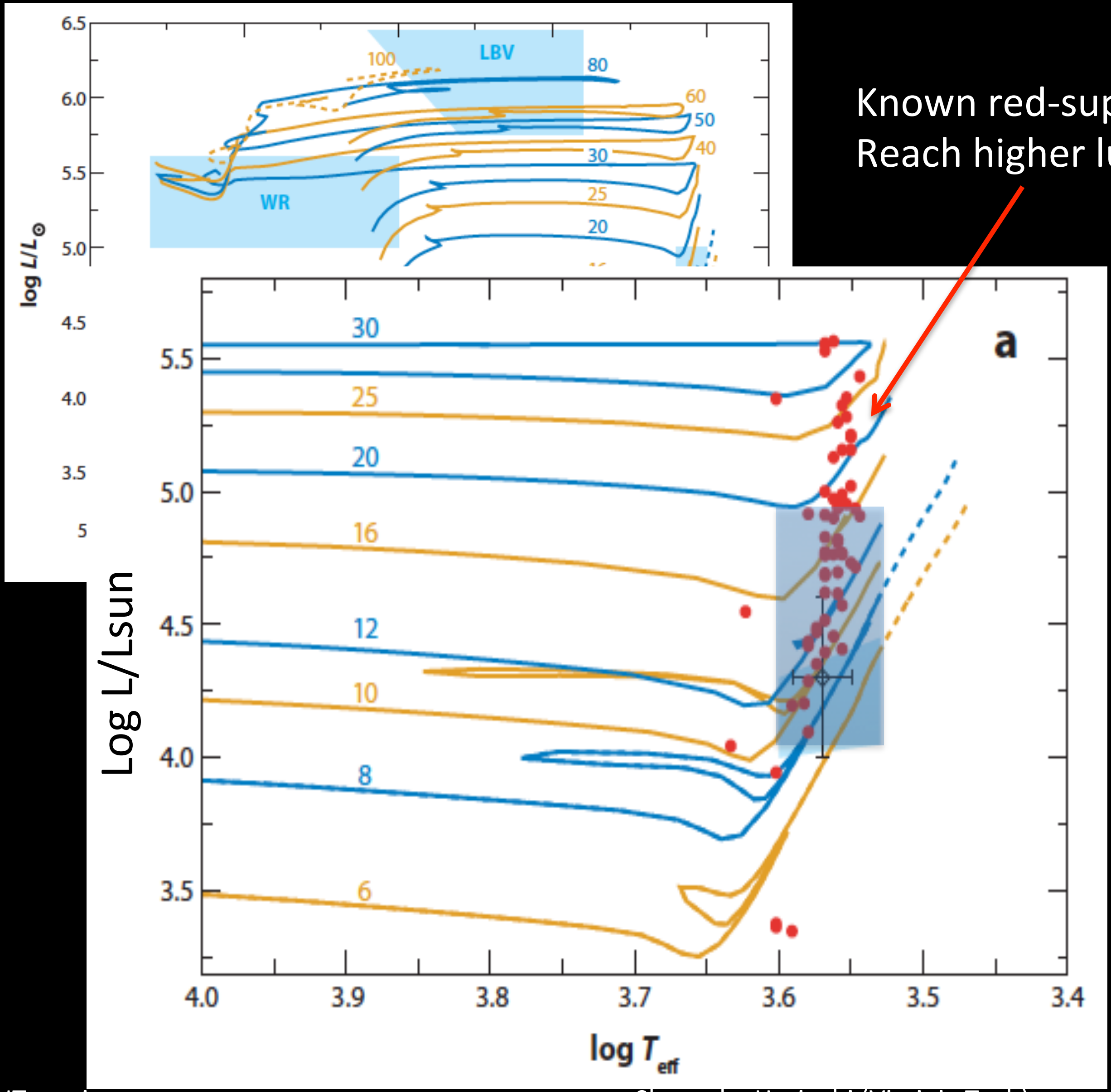
1. Systematic simulations are revealing that compactness is a useful parameter to characterize the diversity of core-collapse simulations.
    - Two parameters better capture the physics

2. It is still early days, but observationally a low critical compactness $\xi_{2.5} \sim 0.2$ is hinted from:
    - The red supergiant problem
    - The black hole mass function
    - The supernova rate discrepancy
    - Results from Survey about Nothing

3. Neutrinos are one of the most direct probes of compactness, and the next Galactic supernova will yield good event statistics to study the connection between compactness and other observables.

Thank you!

But all is not rosy: red-supergiant problem



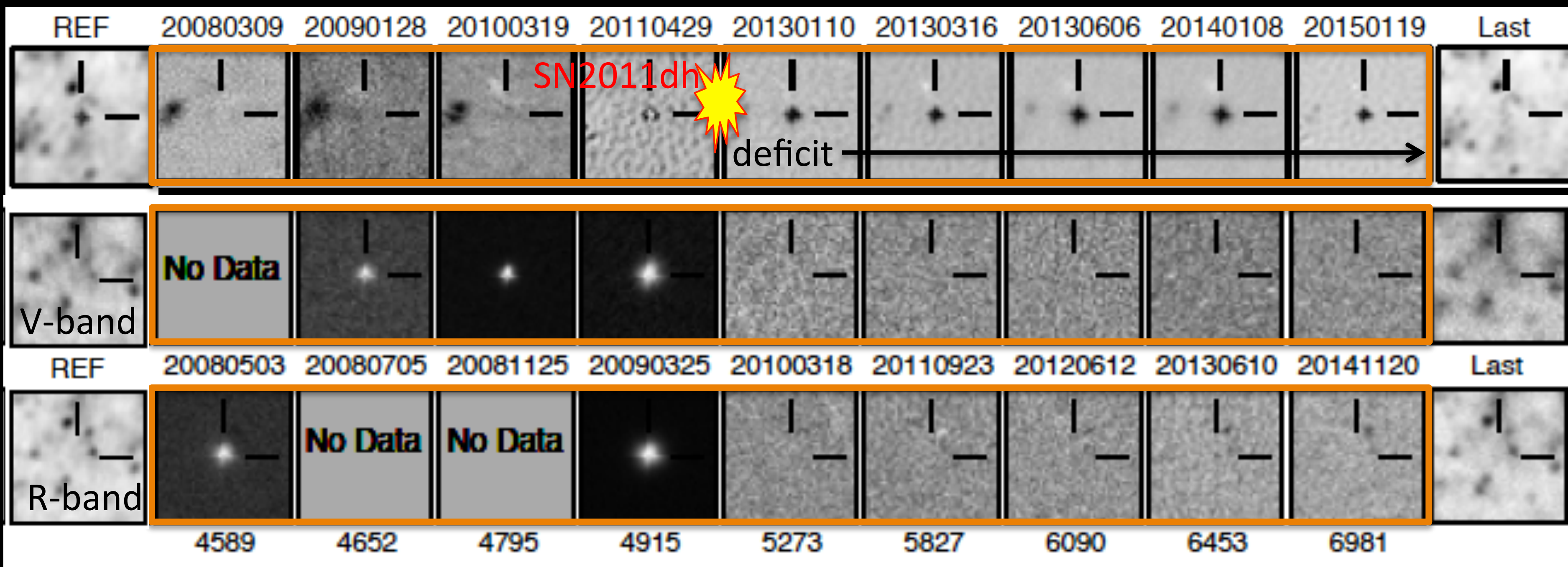
Known red-supergiants (@MW, LMC):
Reach higher luminosity, ~$10^{5.5}$ Lsun

The red-supergiant problem:
Why do we not see Type IIP progenitors with L above ~$10^{5.1}$ Lsun (or mass above ~16.5 Msun)?

Based on the Salpeter IMF, we should have seen ~13 by now.

What happens to these RSGs?

Smartt et al. (2009)
Smartt (2015)



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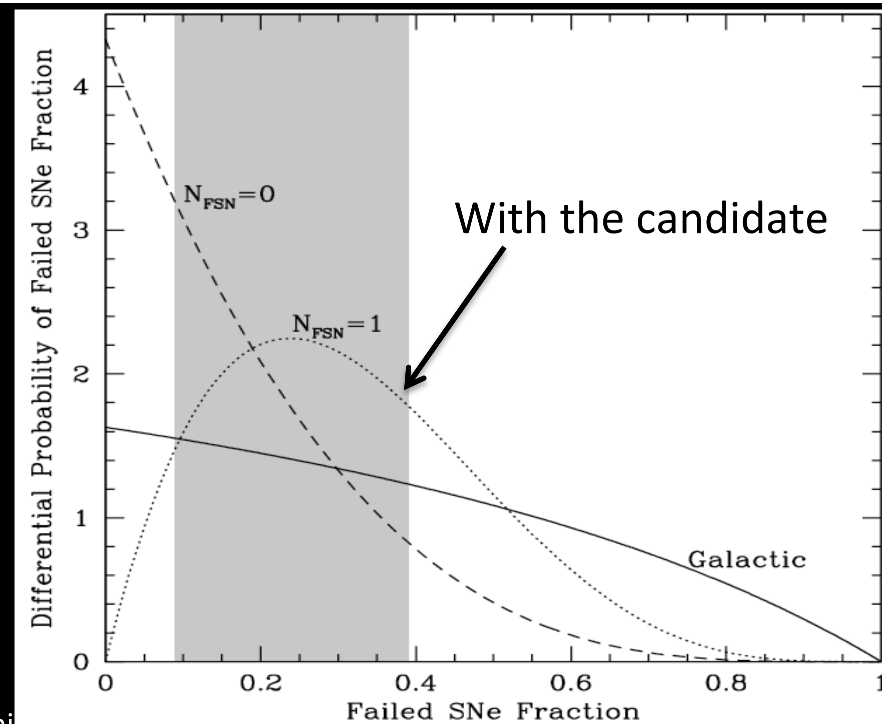
Note: the candidate's mass estimate is 18–25 Msun (!)

Gerke et al. (2015)



Abundance Tests

Removing supernovae removes chemical enrichment

Considering common contribution from winds, and truncating the supernova contribution, reasonable fit is still obtained even if all stars with mass > 20 Msun (i.e., 27% of all massive stars) fail to explode.

Brown & Woosley (2013)