8th Symposium on Large TPCs, Dec 5-7th, 2016

Status & neutrino probes of failed explosions

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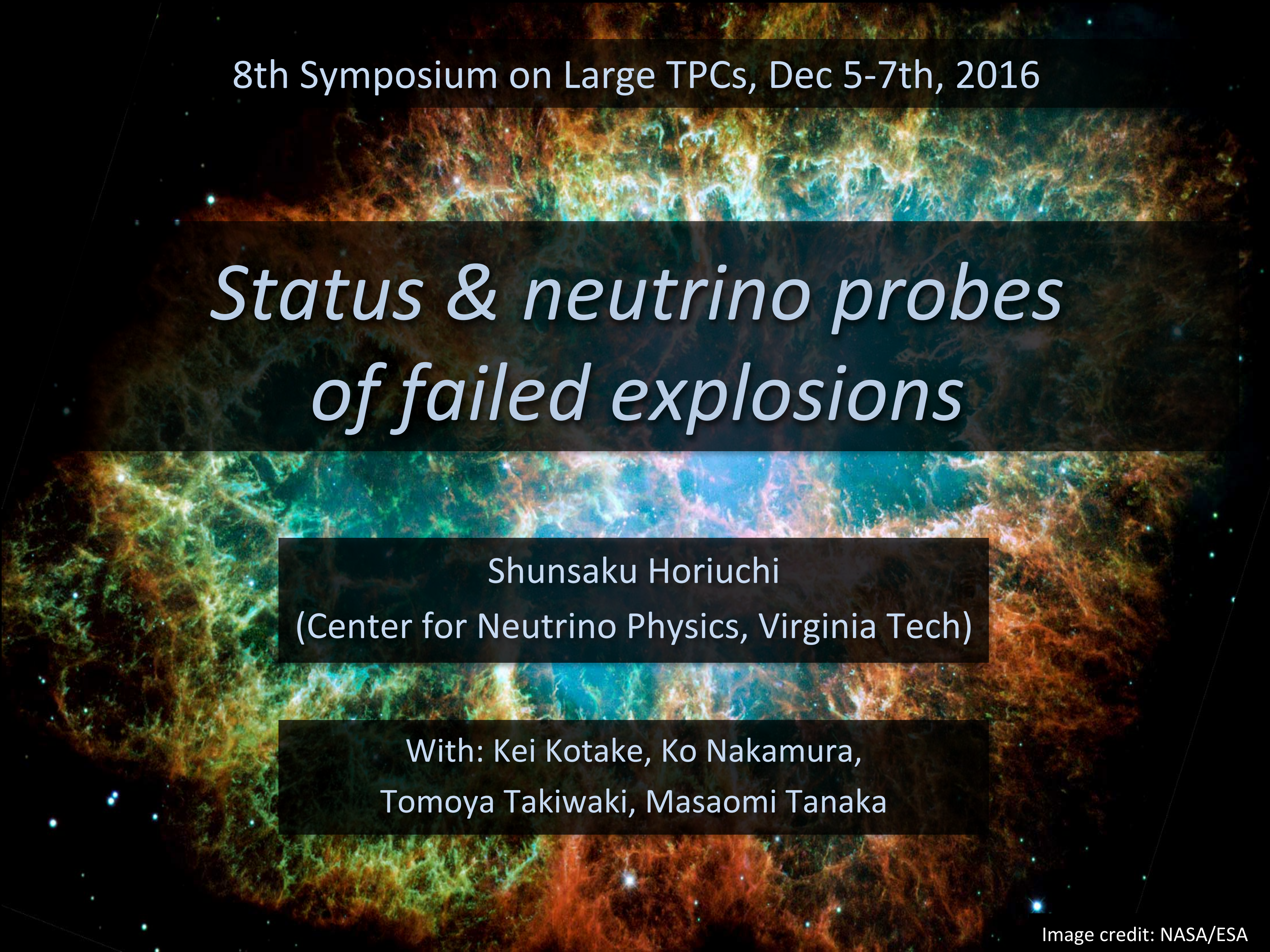


Image credit: NASA/ESA

The explosion mechanism

Stalled shock:

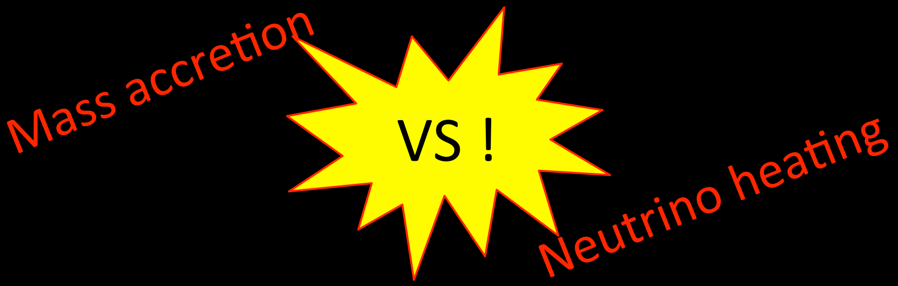
The bounce shock stalls, pressure inside balanced by ram pressure outside:

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

The neutrino mechanism:

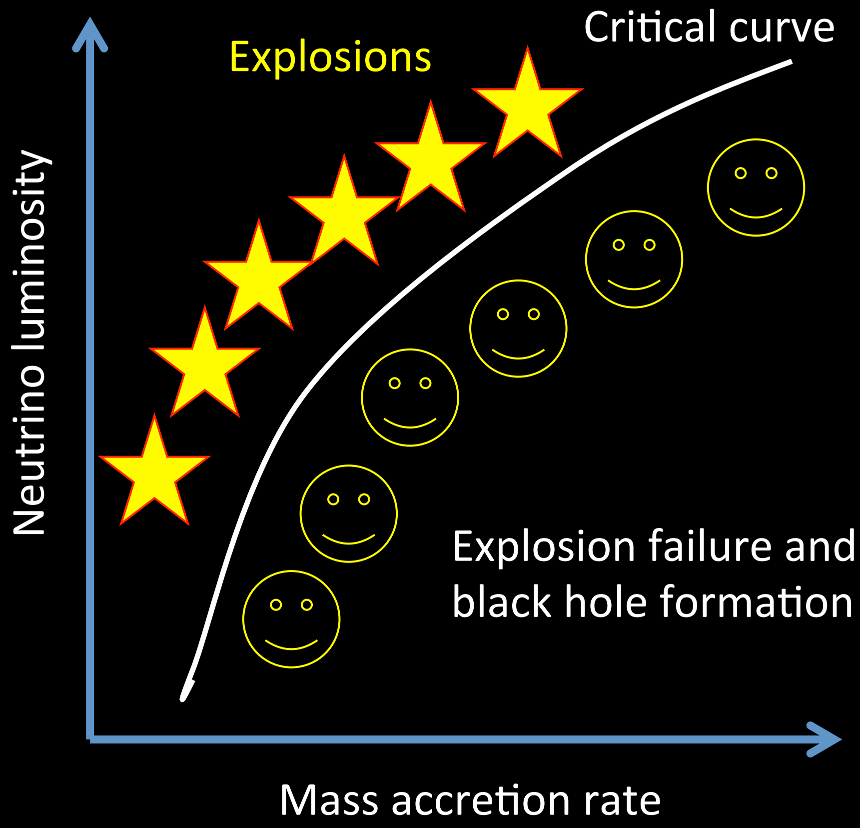
Deposit a fraction of the energy in neutrinos to behind the shock

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



Importance of multi-dimensional effects, General Relativistic treatment, turbulence vs convection vs SASI

➔ 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 GW signals, others

First systematic studies in spherically symmetry

- With parameterized neutrino heating
- *O*(100~1000) progenitor models
- Address: progenitor dependence, black hole formation, others

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

Systematic studies in axis-symmetry

- With simplified neutrino transport
- *O*(10-100) progenitor models
- Address: progenitor dependence, SASI, others

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

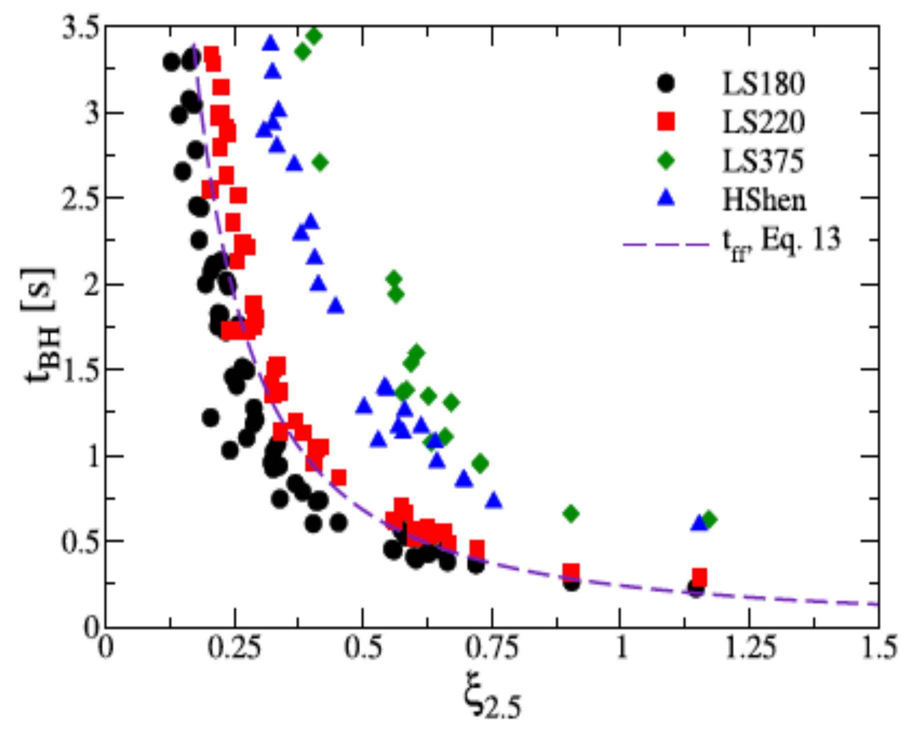
Explodability and compactness

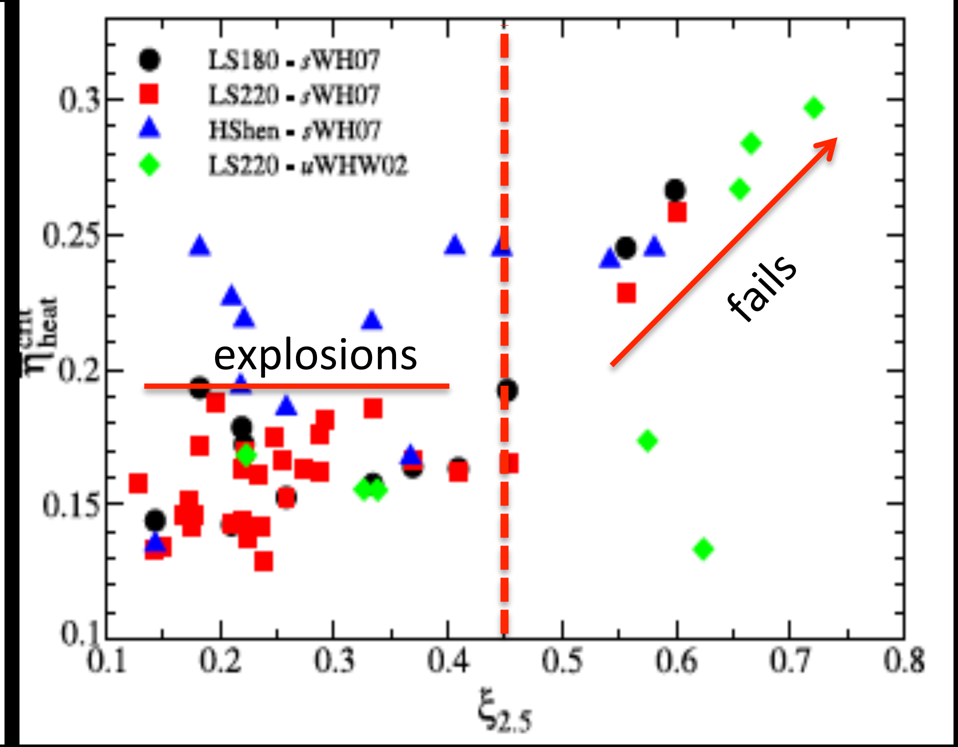
Compactness: is a useful indicator to discuss the eventual outcome of core collapse

$$\xi_M = \left.\frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}}\right|_t$$

Black hole formation occurs more readily for larger compactness.

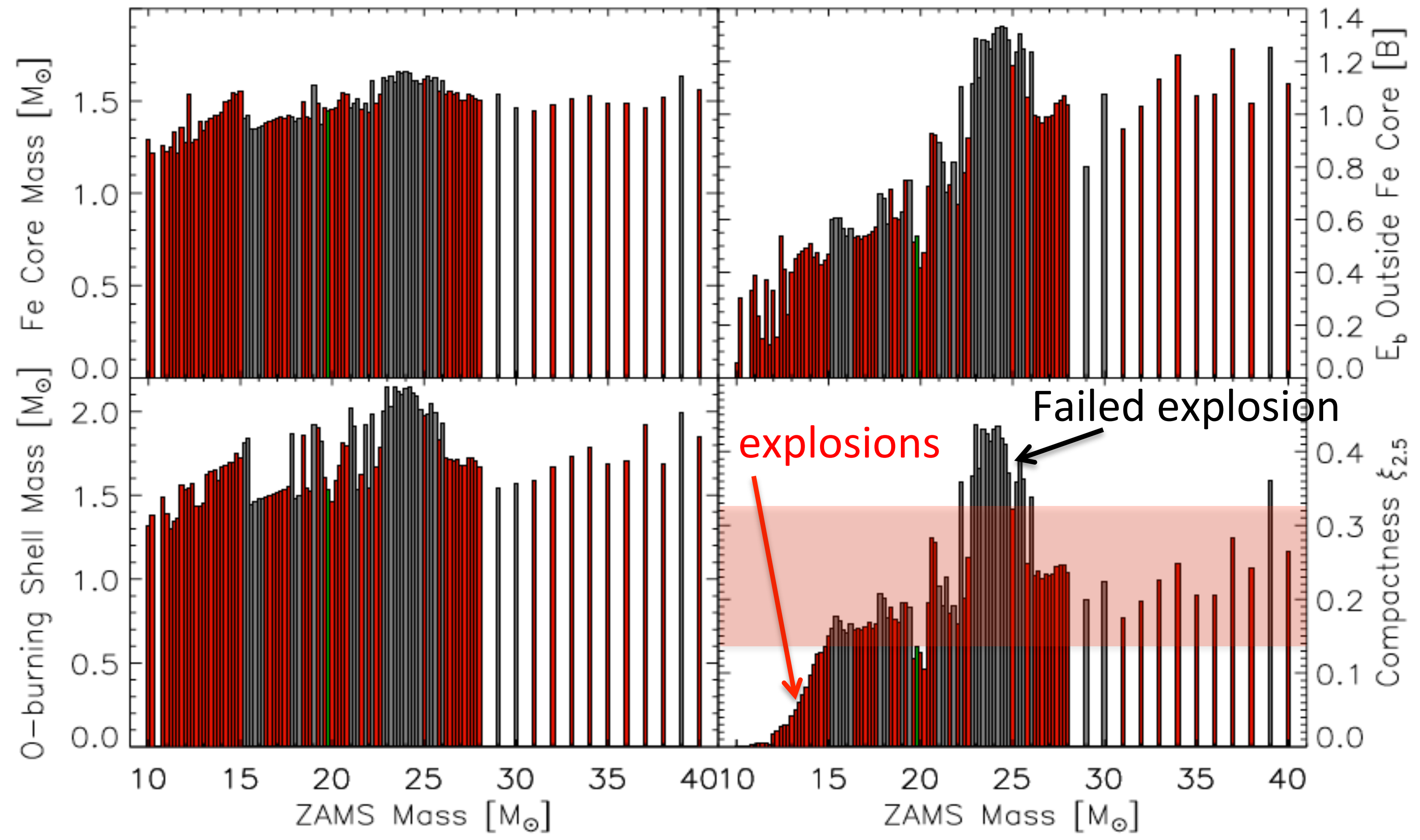
Successful / failed explosion threshold occurs approximately $\xi_{2.5} \sim 0.45$





O'Connor & Ott (2011)

Explodability and compactness

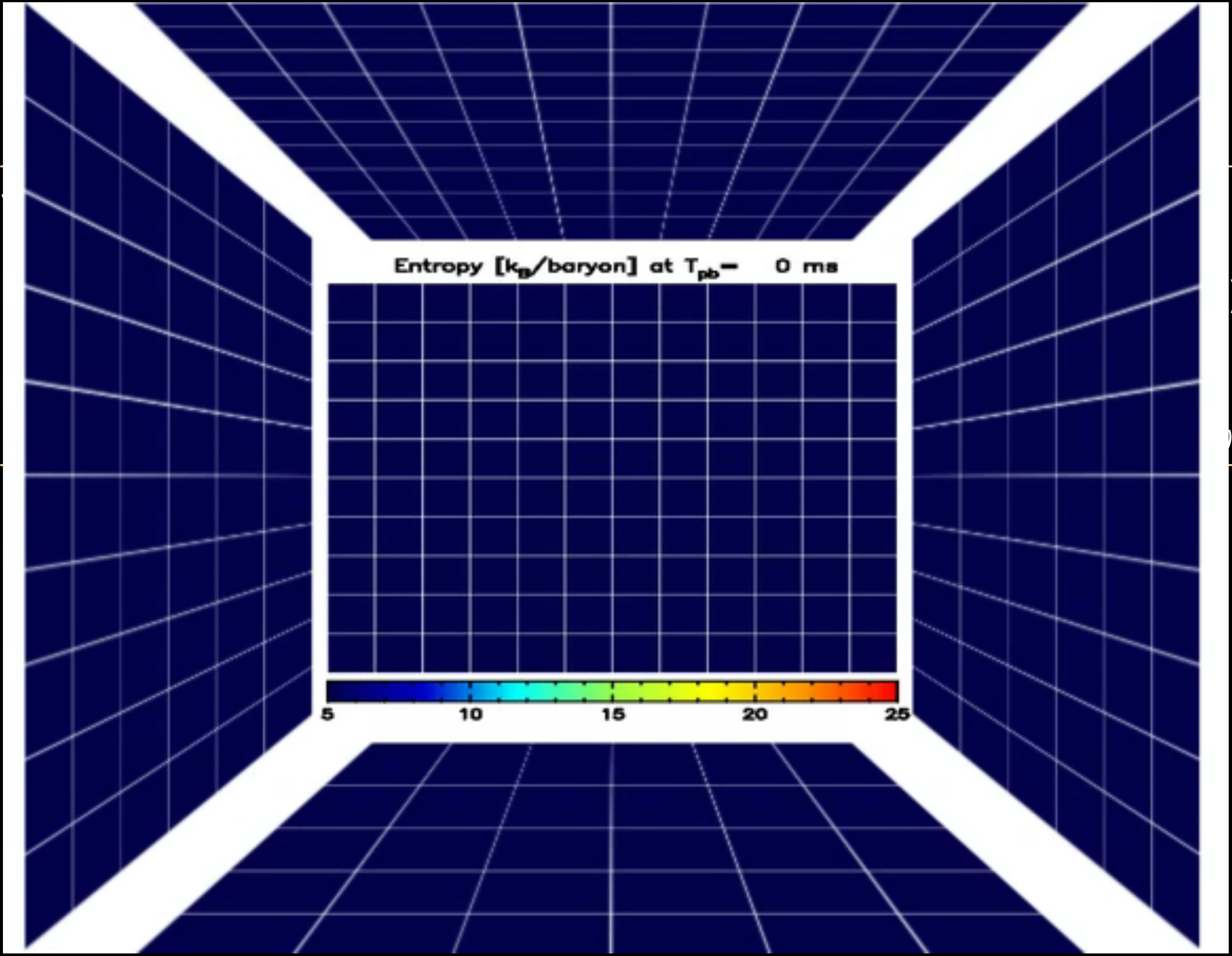


Ugliano et al (2012)

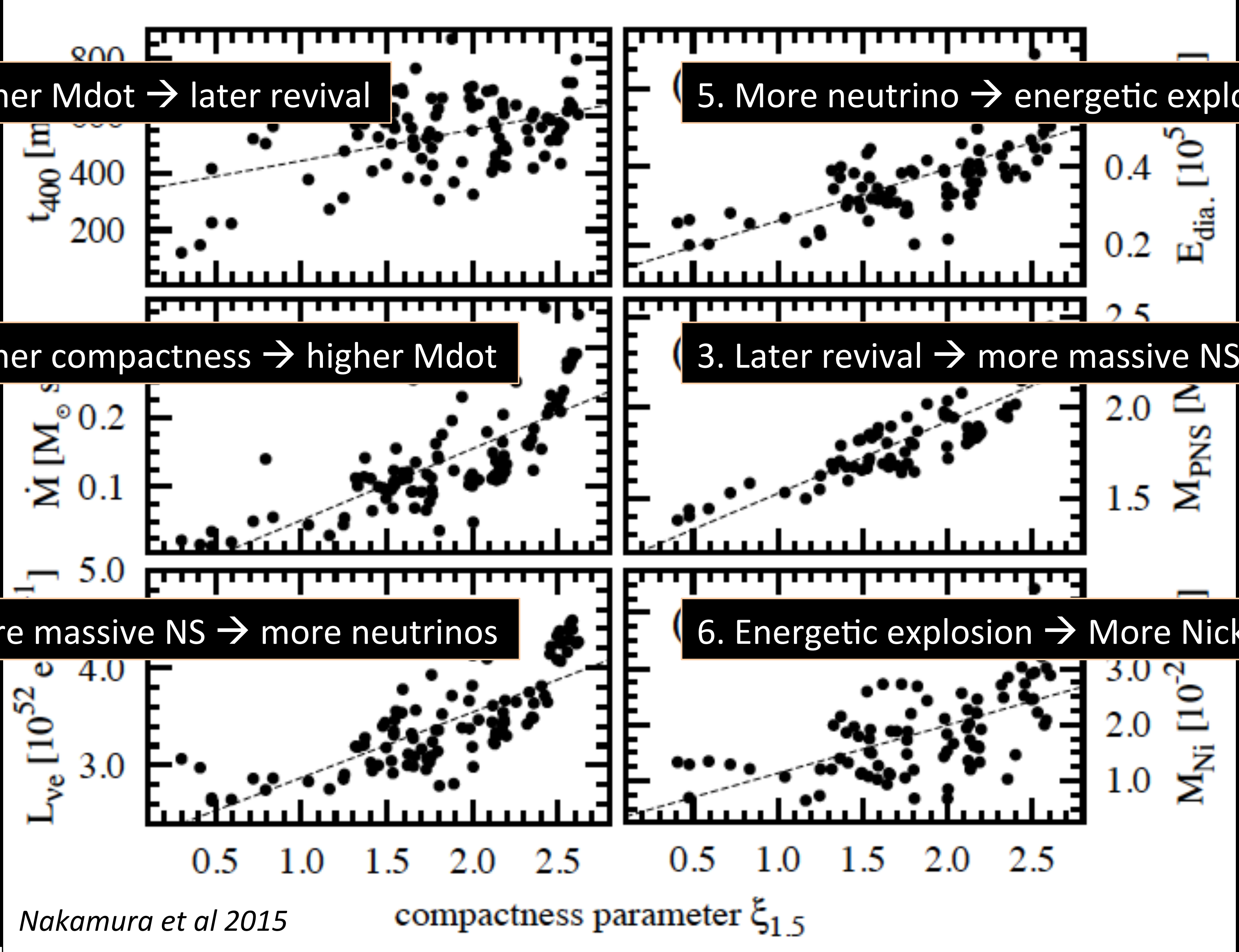
- BH formation for $\xi_{2.5} > 0.35$
- Explosions for $\xi_{2.5} < 0.15$
- Mixture in between

Predicts outcome of at most ~88% of cases

Pejcha & Thompson (2015)


Entropy [k_B/baryon] at T_{pb}= 0 ms
5
10
15
20
25

Results in 2D



2. Higher Mdot → later revival

5. More neutrino → energetic explosion

1. Higher compactness → higher Mdot

3. Later revival → more massive NS

4. More massive NS → more neutrinos

6. Energetic explosion → More Nickel

Nakamura et al 2015

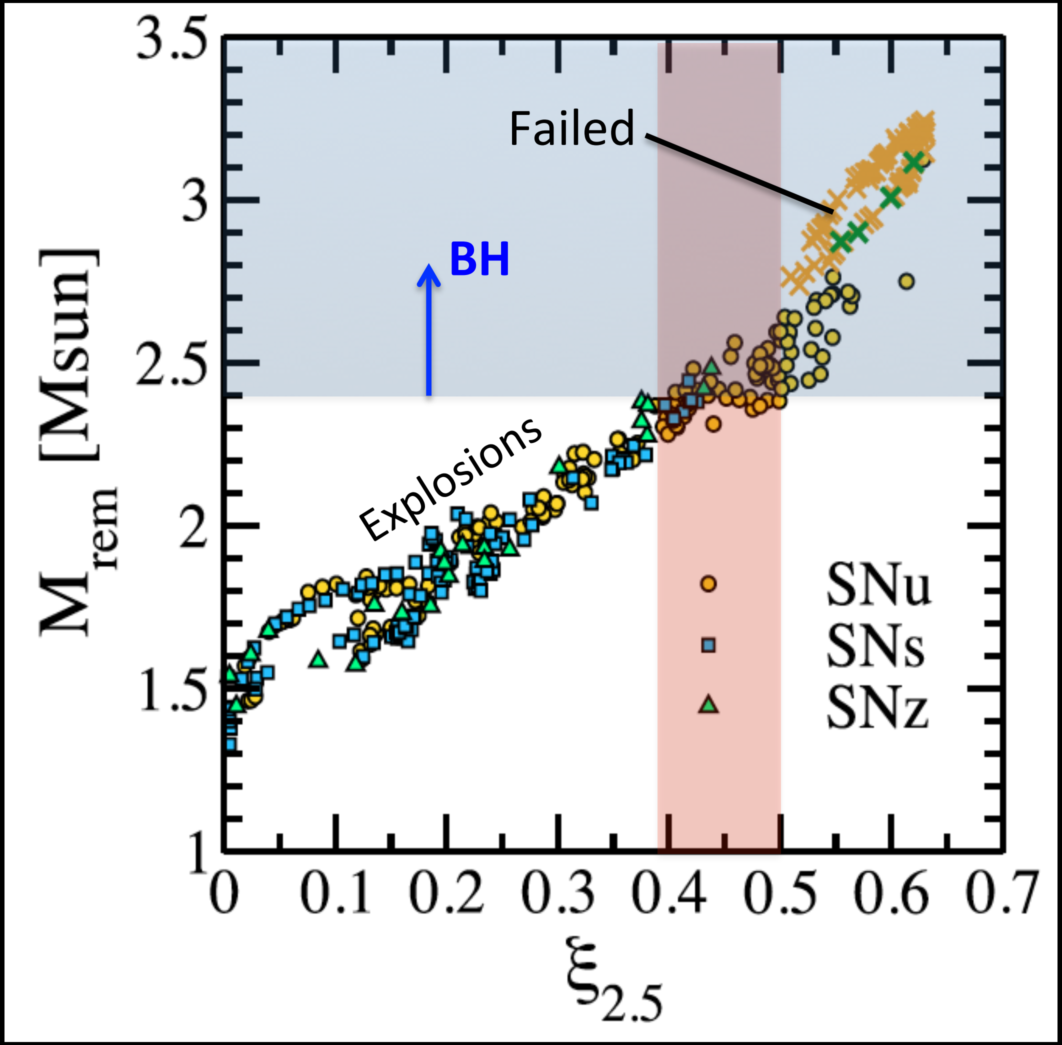
Critical compactness in 2D

Caveats:

- 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 $\xi_{2.5} < \sim 0.4 – 0.5$

Critical compactness $\xi_{2.5}$
1D: 0.15 – 0.45
2D: < 0.4 – 0.5



Horiuchi et al (2014)

In 3D?

Speculate about 3D

No systematic study with 3D simulations yet.

But qualitatively, 3D explosions are more spherical and have later shock revival times

- 11Msun progenitor with $\xi_{2.5}$ = 0.005 explode in both 2D and 3D
- 27Msun progenitor with $\xi_{2.5}$ = 0.228 explode (late) in 2D, but no signs in 3D.

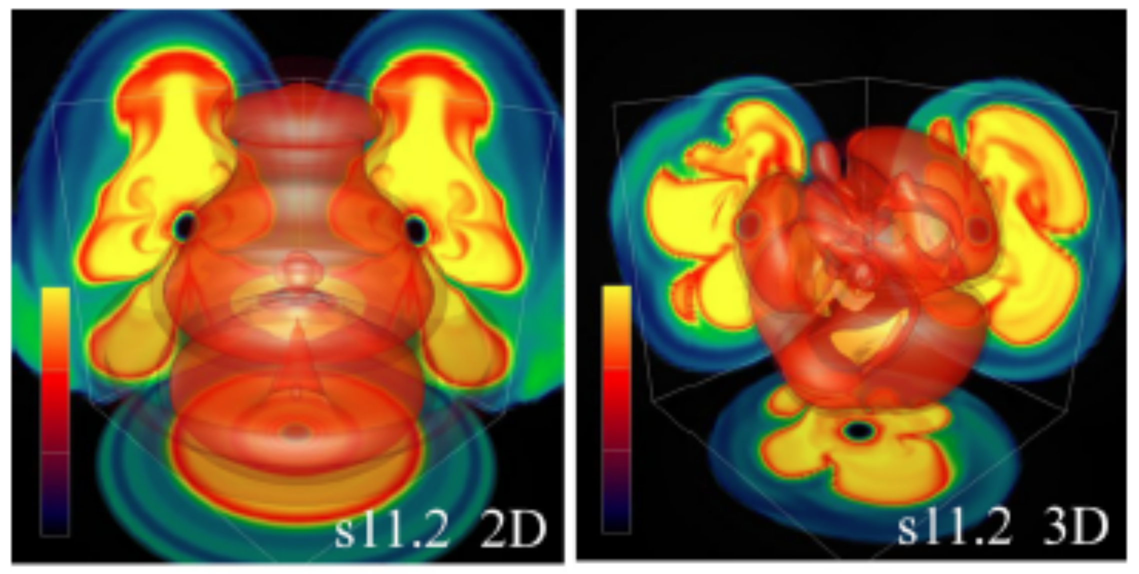
Critical compactness

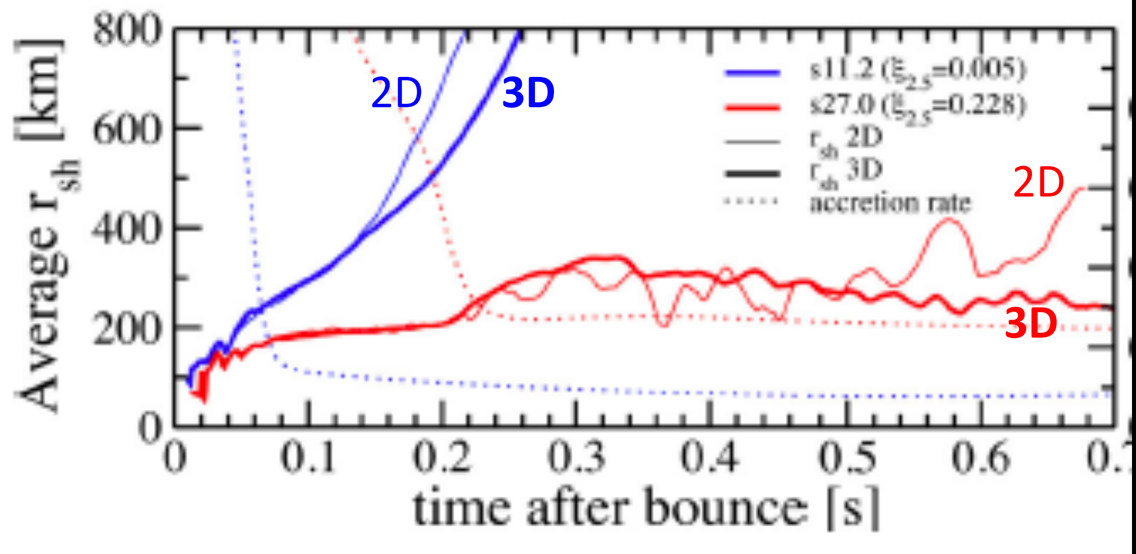
1D: 0.15 – 0.45

2D: < 0.4 – 0.5

3D: < 0.2 ? Needs investigations.

entropy @200ms





Horiuchi et al (2014)

Simulation insights:

- whether a star explodes or fails can be ~predicted by the compactness of the star.
- The critical compactness is in the range $\xi_{2.5} = 0.2 – 0.4$

Observational impacts

Critical compactness affects NS vs BH formation

→ Fraction of stars that explode vs fail

→ Mass function and mean mass of NS and BH

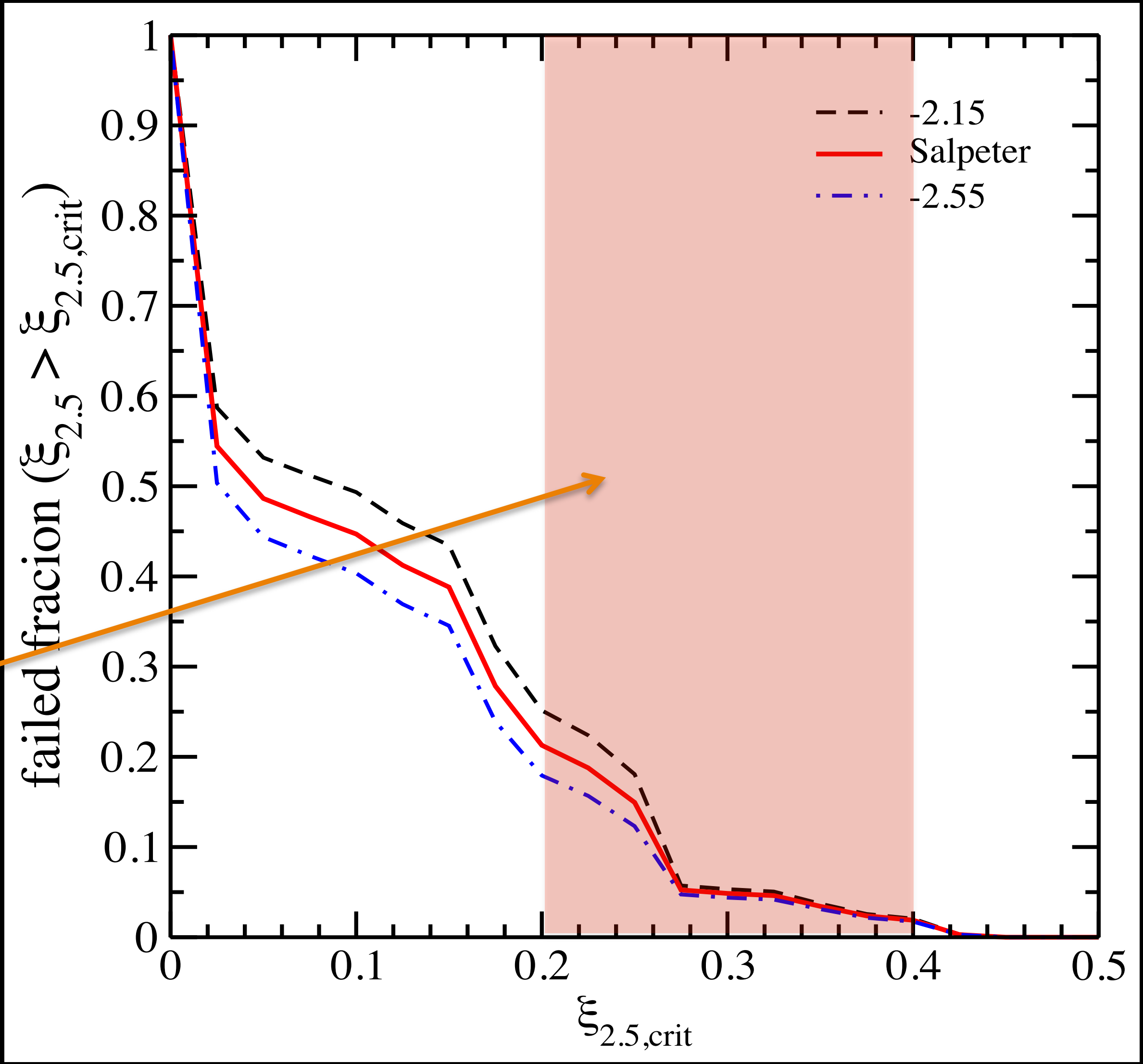
STATUS OF OBSERVATIONAL CONNECTIONS

Prediction 1: fraction of failed supernovae

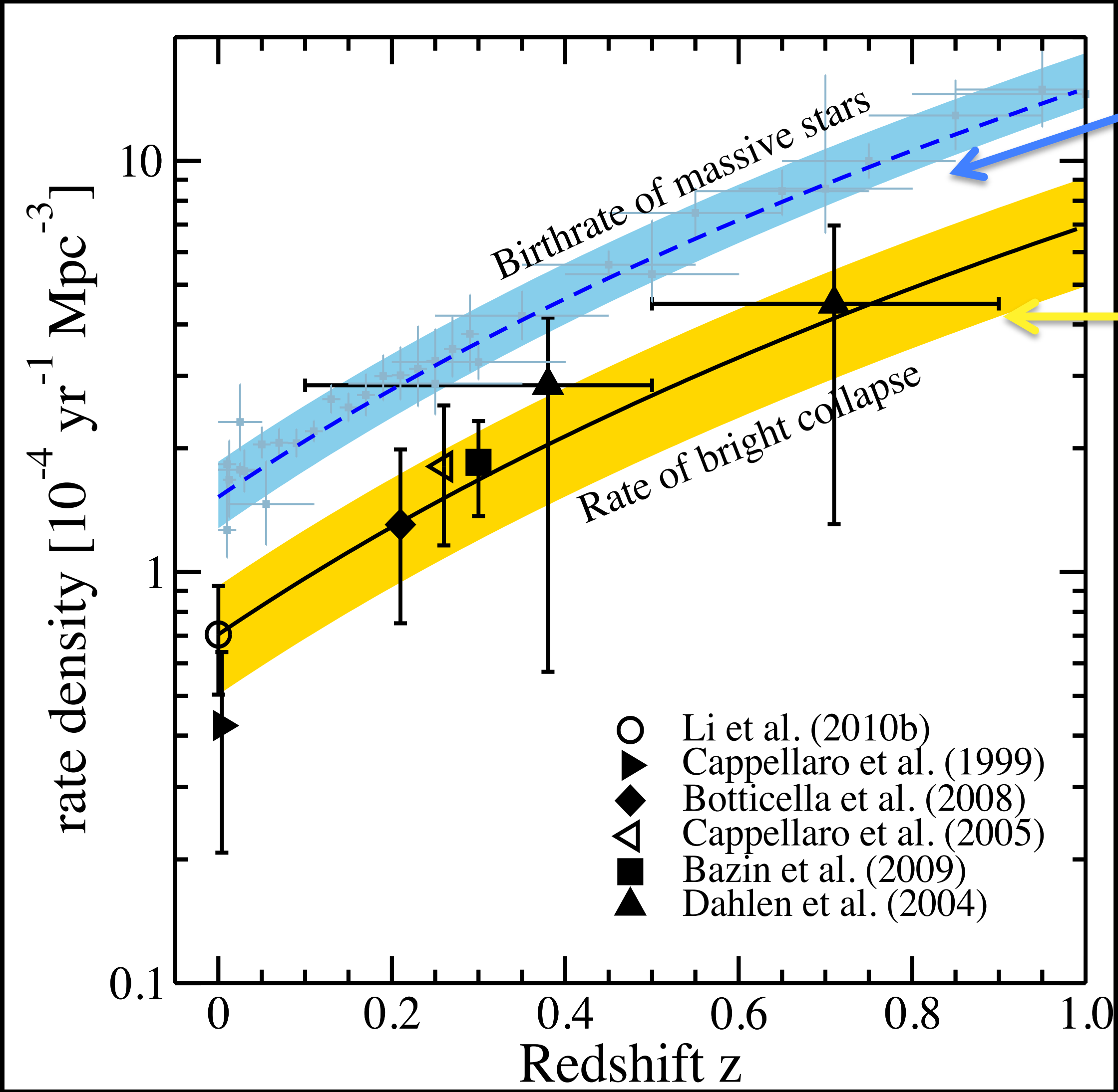
Failed fraction

Predicts that the fraction of massive stars that fail to explode is up to ~20%
(stars with compactness $\xi_{2.5} > 0.2$ is ~20%)

Critical compactness is in the range $\xi_{2.5} = 0.2 - 0.4$



Hints from supernova rate



Horiuchi et al (2011); updates by e.g., Dahlen et al (2012), Cappellaro et al (2015)

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

- Updates to dust corrections suggest up to 30% of massive stars are missing (either failed or dim explosions)

e.g., Mattila et al (2012)
But see, e.g., Mathews et al (2014)

Hints from searches of failed explosions: Survey about nothing

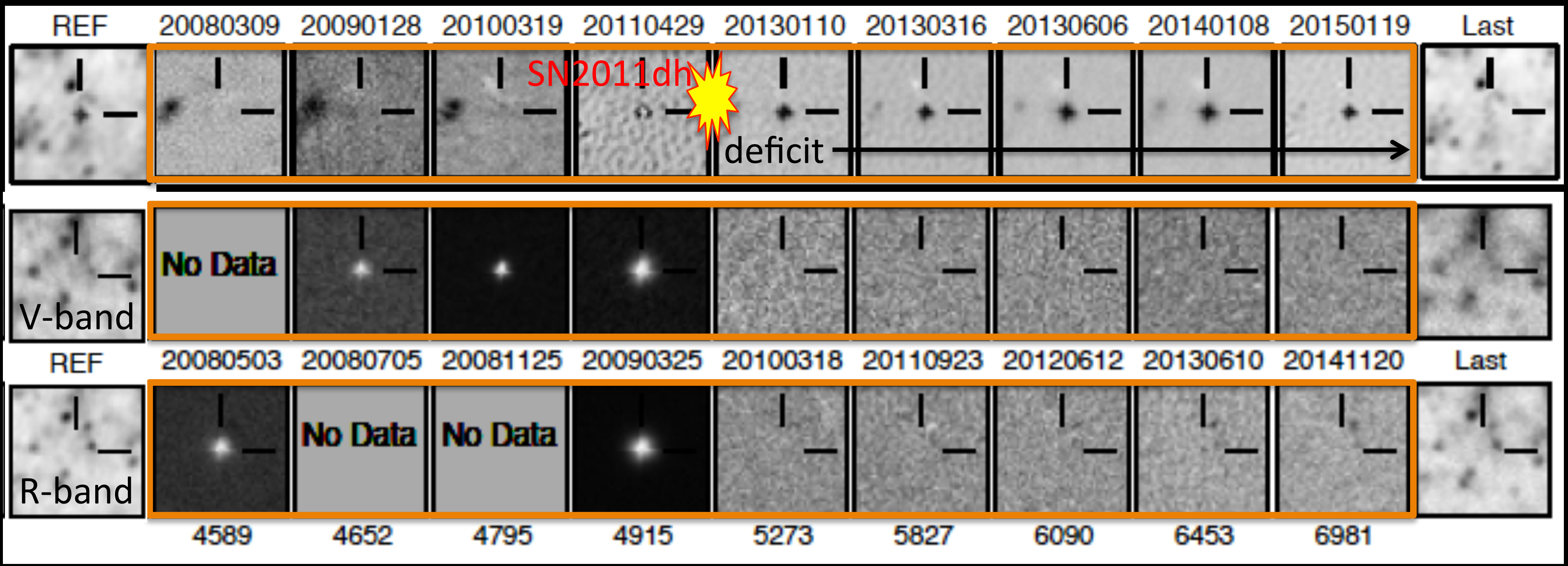
Survey About Nothing

Look for the disappearance of red-supergiants in nearby galaxies caused by core collapse to black holes

Monitor 27 galaxies with the Large Binocular Telescope

- → Survey ~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)



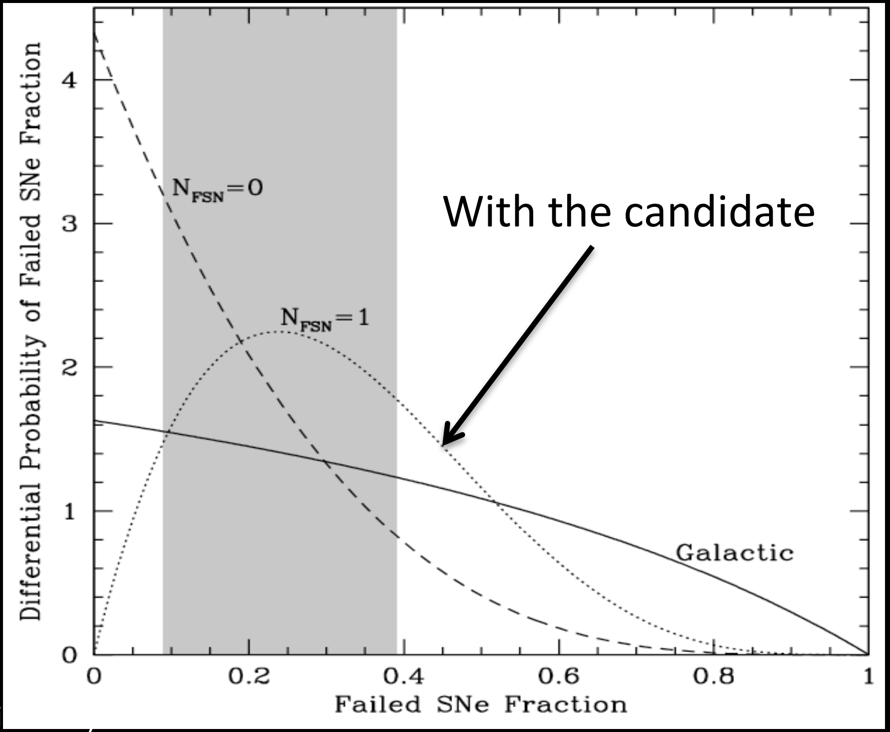
Results so far:

In 4 years running,

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

→ Failed fraction 10 – 40%

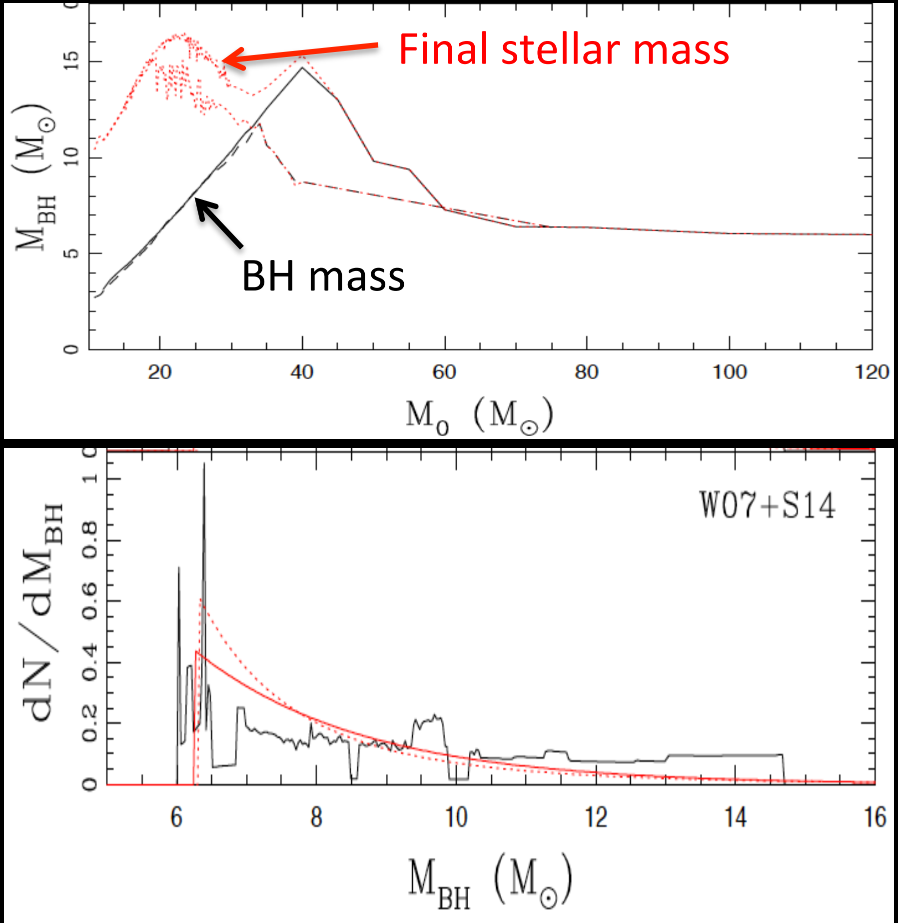
Gerke et al. (2015)



With the candidate

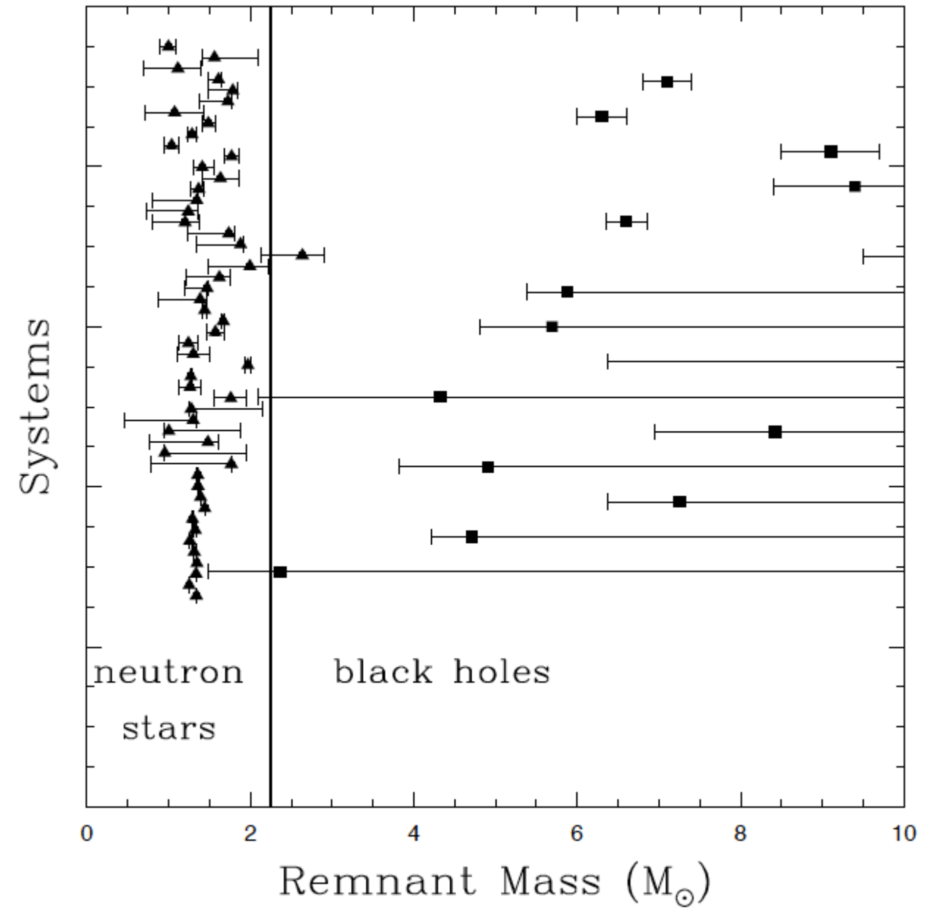
Prediction 2. Compact object mass function

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



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

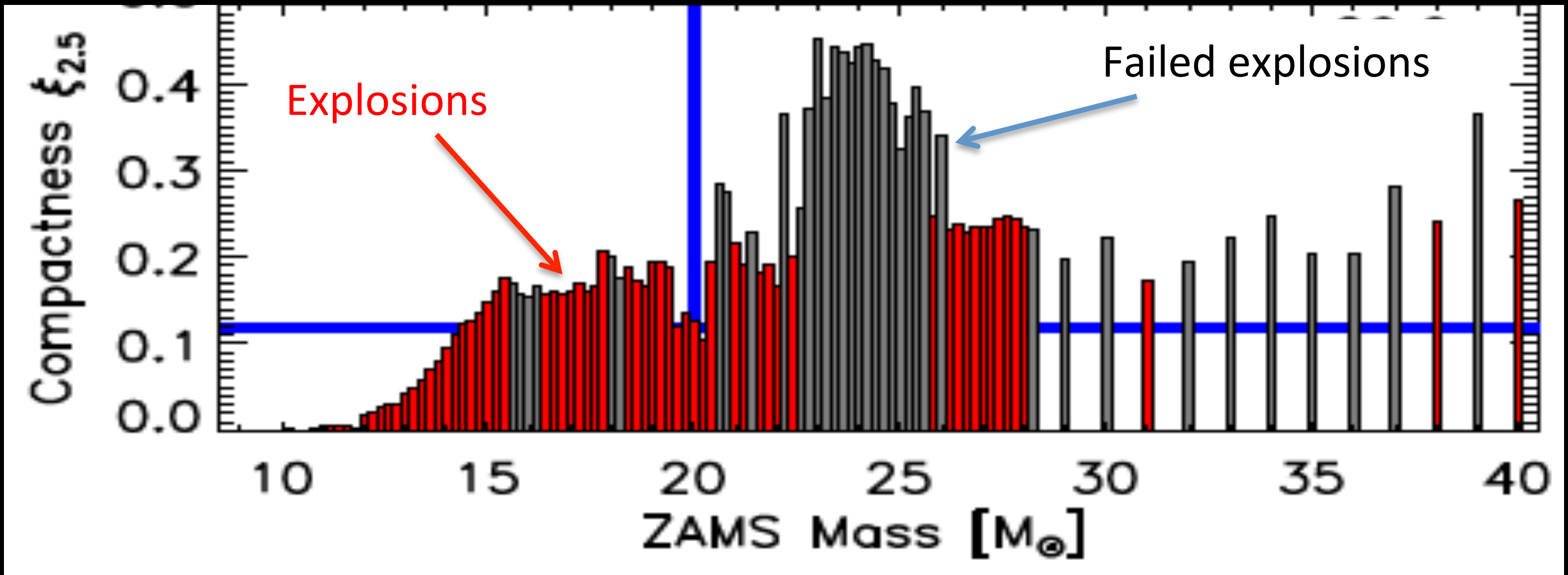
There are hints of a dearth of stellar black holes just above the NS mass range



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

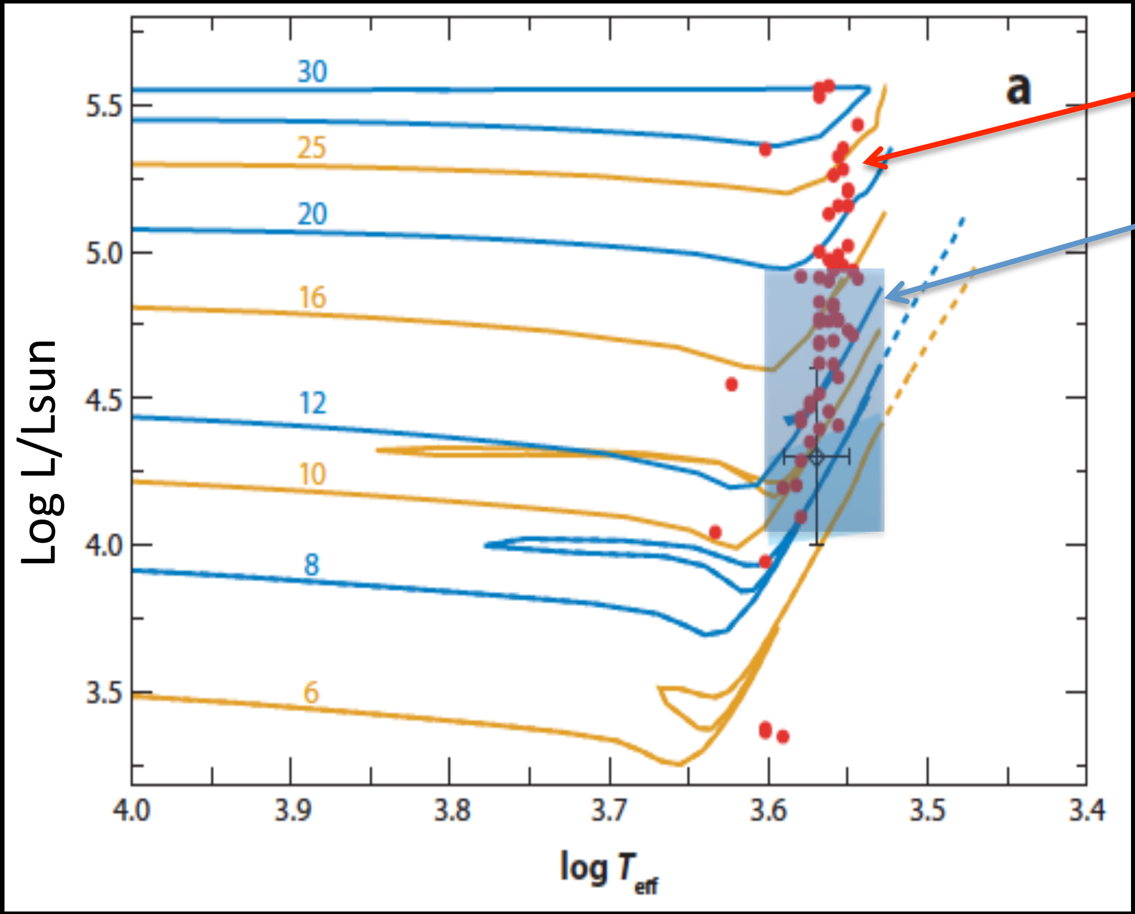
Prediction 3: islands of failed explosions

- Compactness is not monotonic in stellar mass, but rather come in islands (but uncertainties remain) *e.g., Sukdhbold & Woosley (2014)*
  → Explosions / failed explosion populations also come in islands



Ertl et al (2015)

Hints from the red supergiant problem



Smartt et al. (2009), Smartt (2015)

Known red-supergiants

Red-supergiant stars that explode as Type IIP supernovae

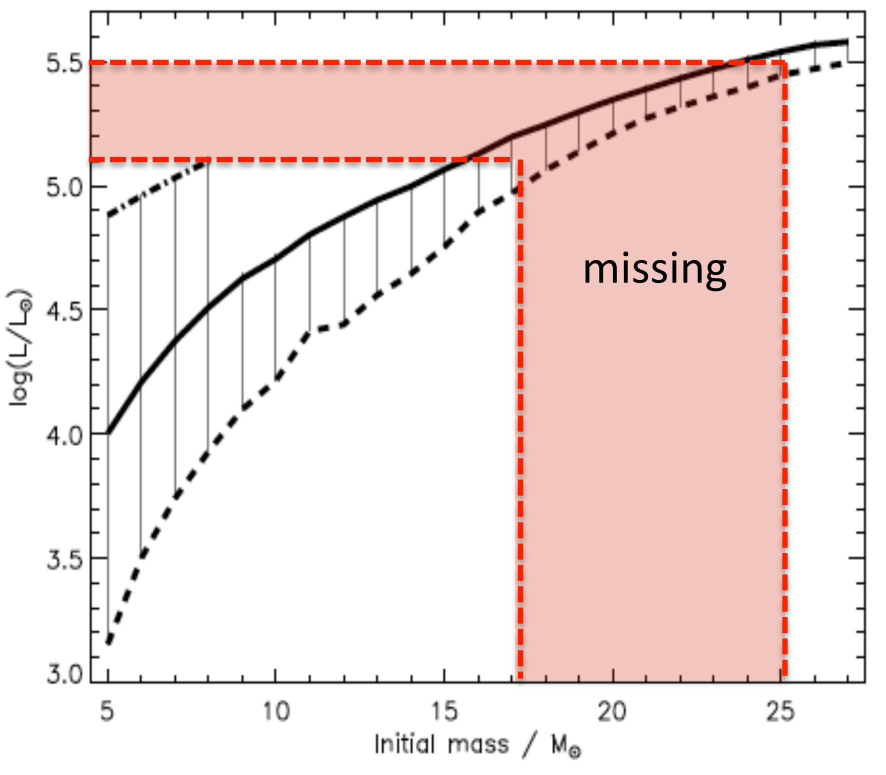
Why do we not see Type IIP progenitors with luminosity between $10^{5.1}$ – $10^{5.5}$ Lsun?

→ red-supergiant problem

What happens to them?

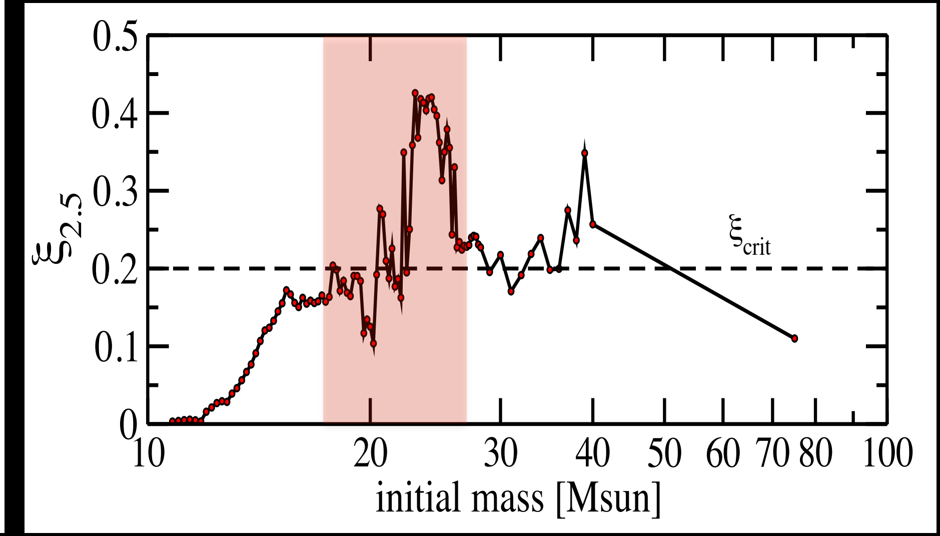
Hints from the red supergiant problem

"Missing" red-supergiants due to core collapse to black holes?



Smartt et al (2009)

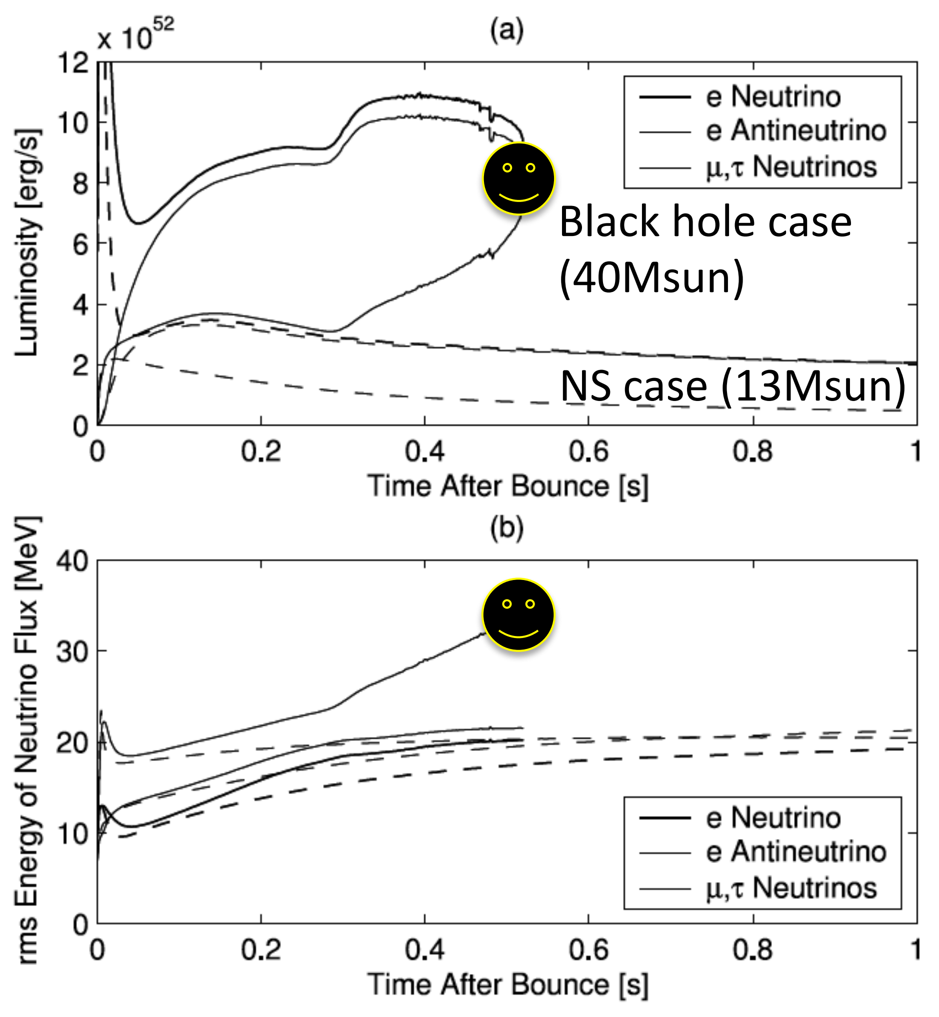
The mass range is around an island of high compactness → theoretically more likely to form black holes.



Horiuchi et al (2014), see also Kochanek (2014)

NEUTRINO PROBES

Neutrino emission



Black hole case (40Msun)

NS case (13Msun)

Liebendoerfer et al (2004)

Neutrino emission:

Black hole necessarily goes through rapid mass accretion & contraction → More accretion luminous and higher energies (EOS dependent)

Sumiyoshi et al 2006, 2007, 2008, 2009
Fischer et al 2009
Nakazato et al 2008, 2010, 2012
Sekiguchi & Shibata 2011
O'Connor & Ott 2011
Plus various others

Neutrino termination:

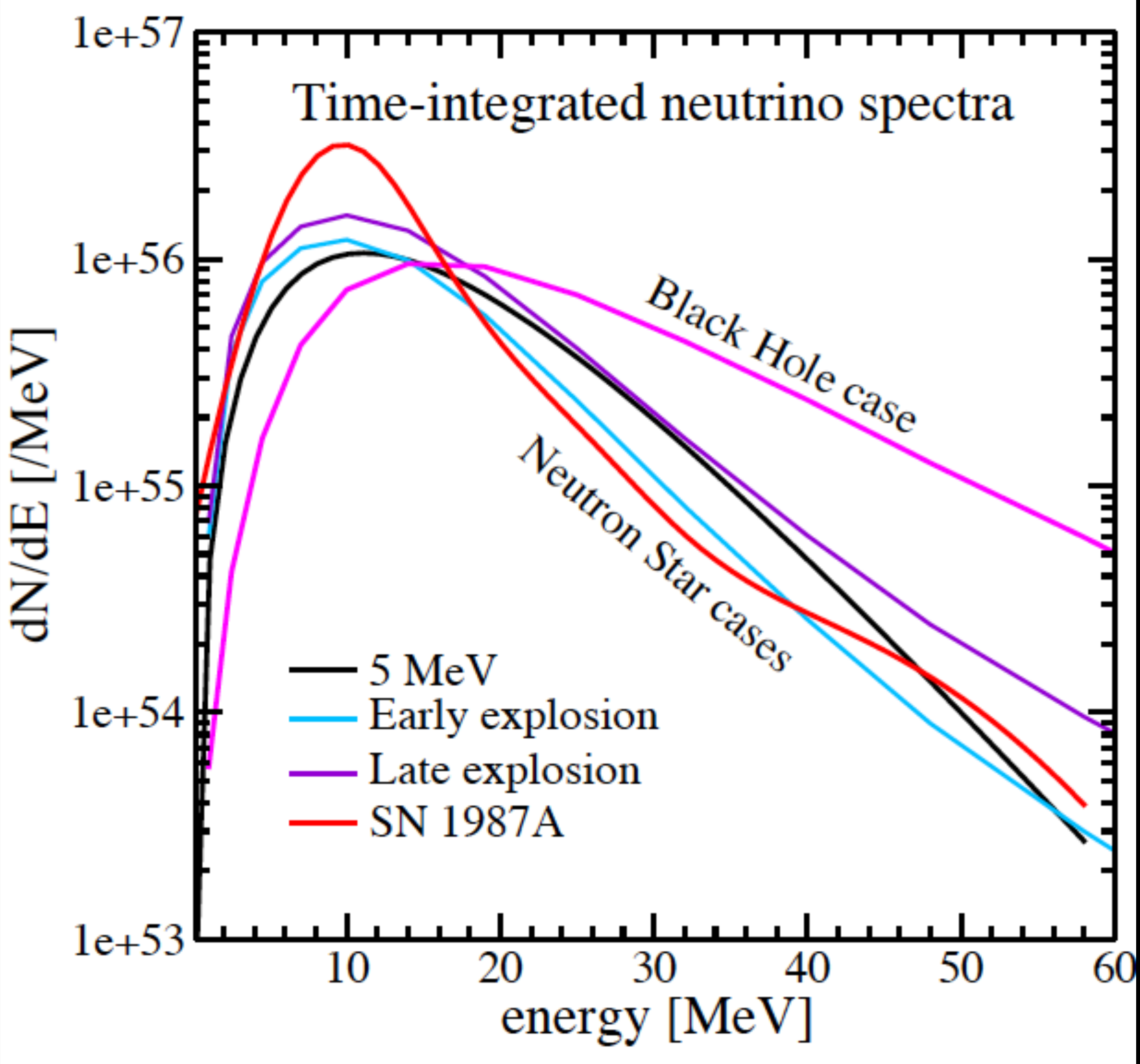
Neutrino detectors can directly detect the moment of black hole formation (if it occurs during the first *O*(10) seconds)

Beacom et al (2001)

Time-integrated neutrino signal

Neutrino emission:
Compared to collapse to neutrino stars, the duration of neutrino emission is shorter for collapse to black holes.

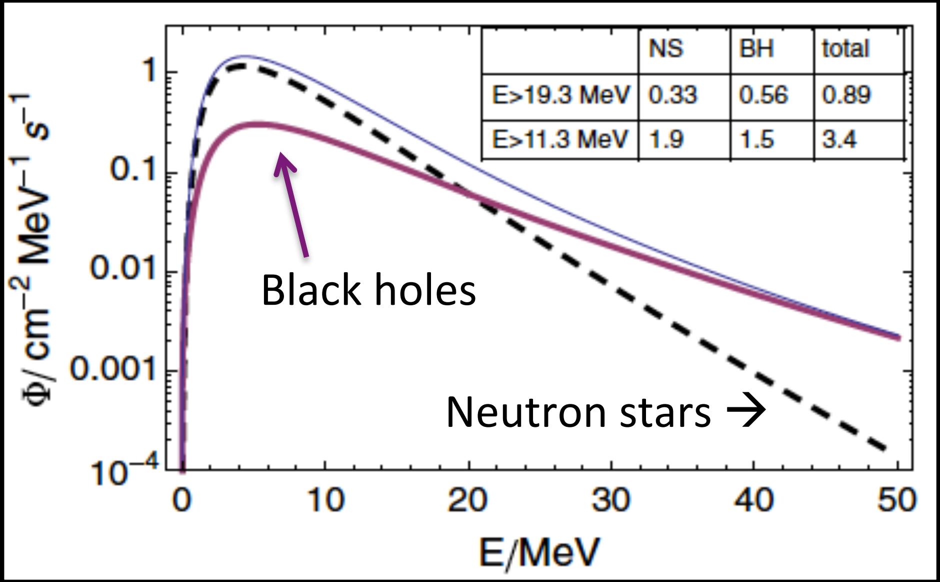
The time-integrated neutrino emission is noticeably different.



Diffuse supernova neutrino background

Diffuse neutrino fluxes:

Sensitive to contribution of black holes

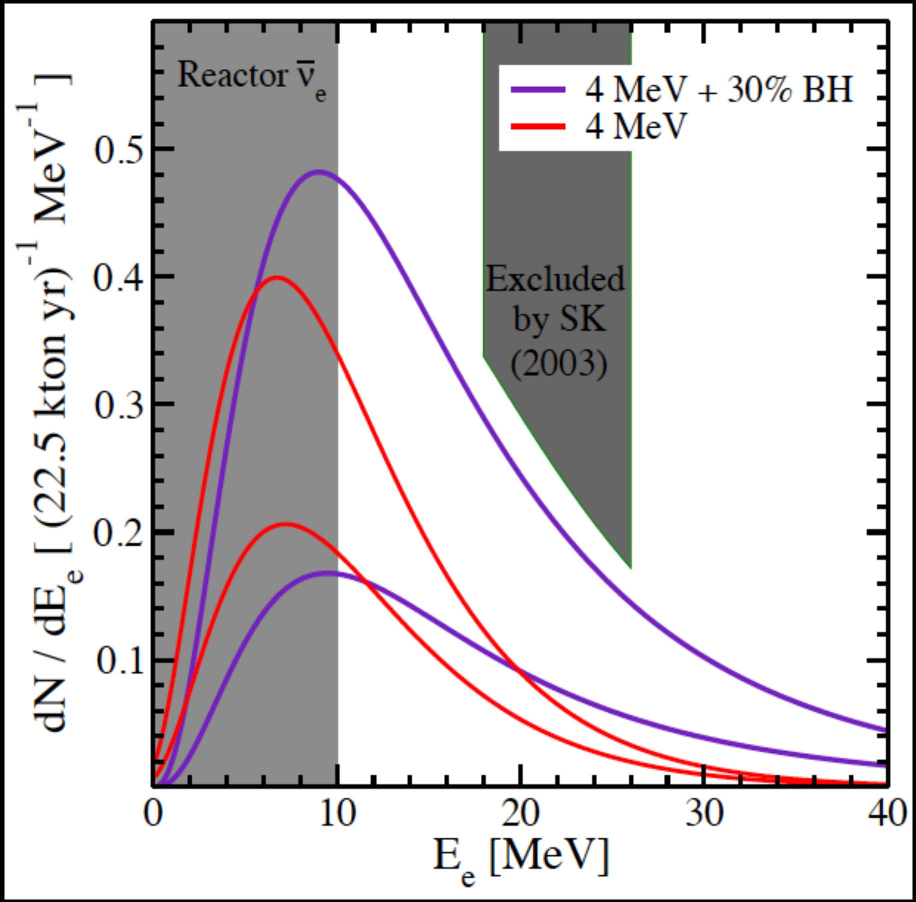


	NS	BH	total
E>19.3 MeV	0.33	0.56	0.89
E>11.3 MeV	1.9	1.5	3.4

Lunardini (2009); see also Lien et al (2010), Keehn & Lunardini (2010), Nakazato (2013), Yuksel & Kistler (2014)

Event spectra with uncertainties:

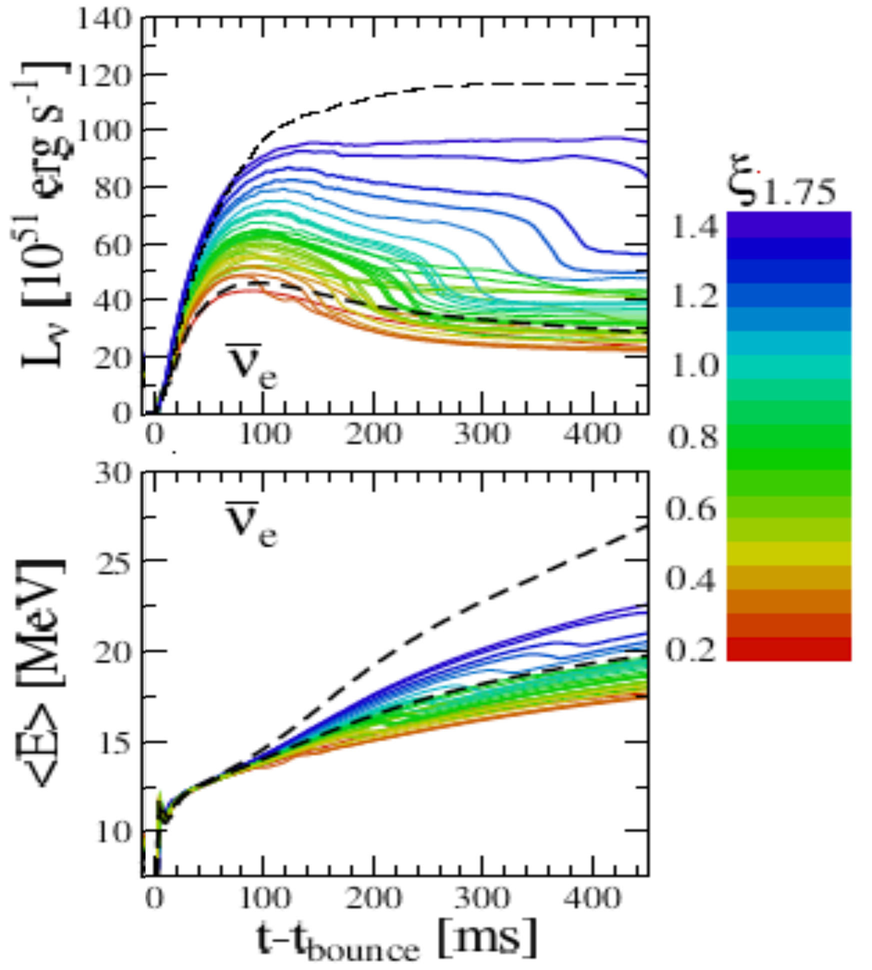
For example, at Super-Kamiokande

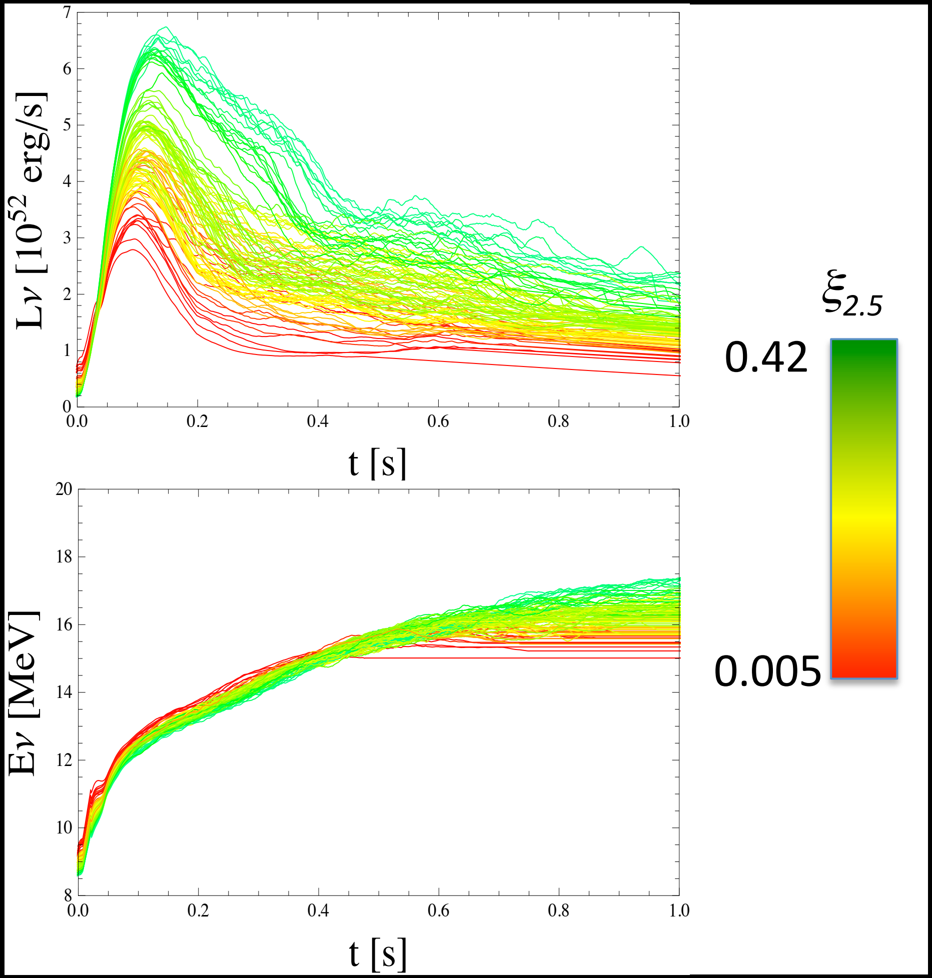


Adapted from Horiuchi et al (2009)

Compactness probes

1D → → → → 2D





O'Connor & Ott (2013)

Based on Nakamura et al (2015)

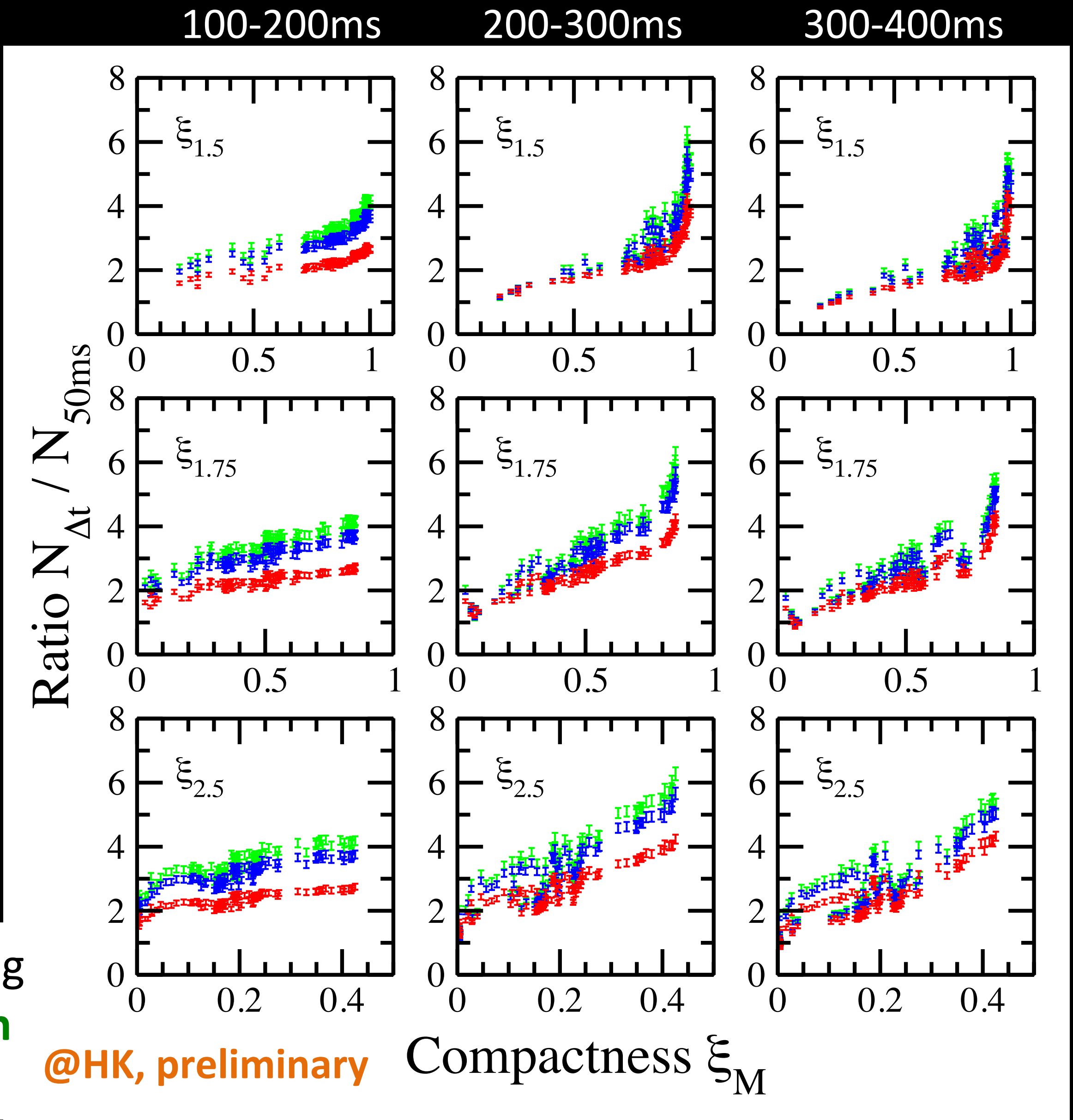
Measuring the compactness

Uncertainty

Absolute rate is degenerate with other systematics, e.g., distance uncertainty. Taking the ratio removes many of these.

Many compactness

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



MSW mixing
red & **green**
show range

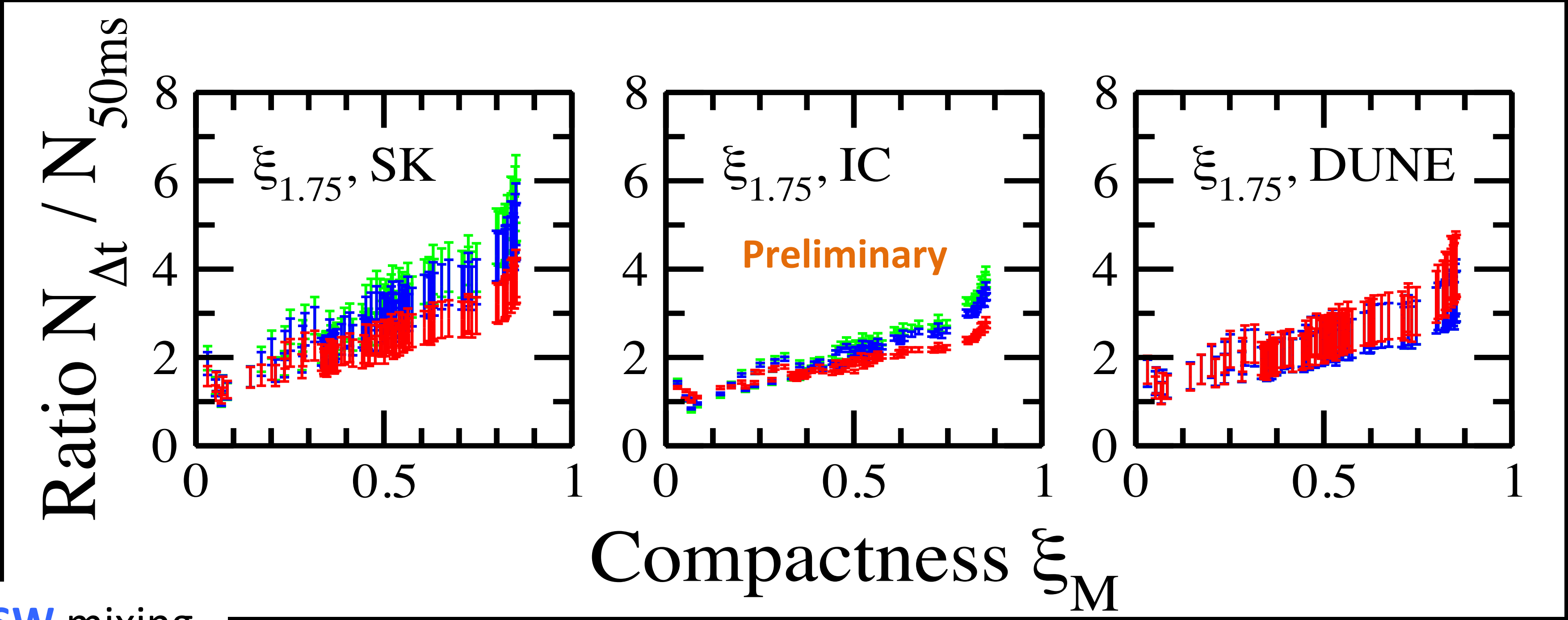
@HK, preliminary

Measuring the compactness

Super-K
The errors would still be sizable.

IceCube
Would be powerful (based on the LC)

DUNE
Less dependence on oscillation scenario due to neutronization burst



MSW mixing
red & **green** show range

32.5 kton water
3 MeV threshold

Correlated noise in 5160 OMs.

40 kton LqAr
5 MeV threshold, with ID for ν_e CC

Summary

Take away messages:

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

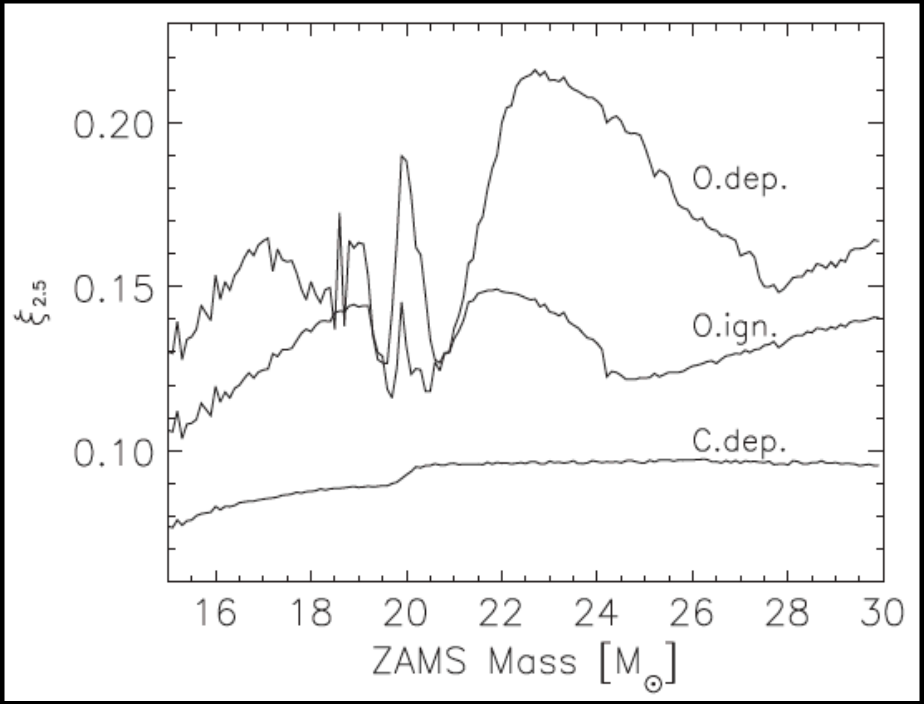
2. It is still early days, but observationally a low critical compactness $\xi_{2.5} \sim 0.2$ is consistent with or solves:
    - The supernova rate discrepancy
    - Results from Survey about Nothing
    - The black hole mass function
    - The red supergiant problem

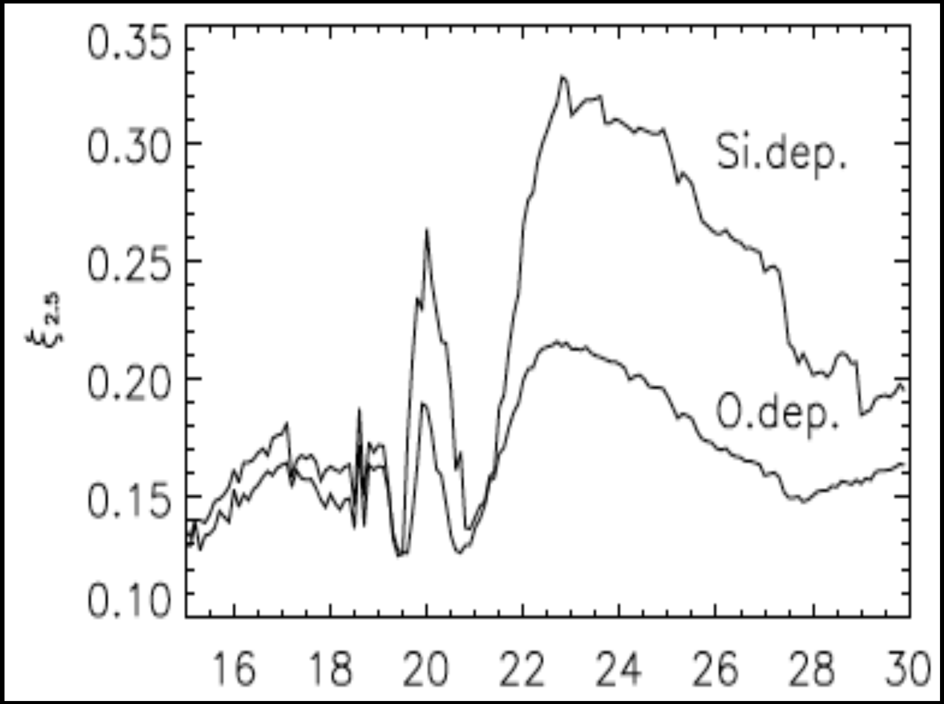
3. Neutrinos are one of the direct probes of compactness, by:
    - The next Galactic core collapse
    - Diffuse supernova neutrino background

Thank you!

Compactness

- Contraction drives compactness up.
- Convective C core burning (<20Msun) drives down compactness





- Convective carbon shell burning between central C depletion & O depletion drives features in compactness.

- Convective oxygen shell burning between central O depletion & Si depletion drives further compactness differences.

Two parameters

Towards better predictability:

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

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

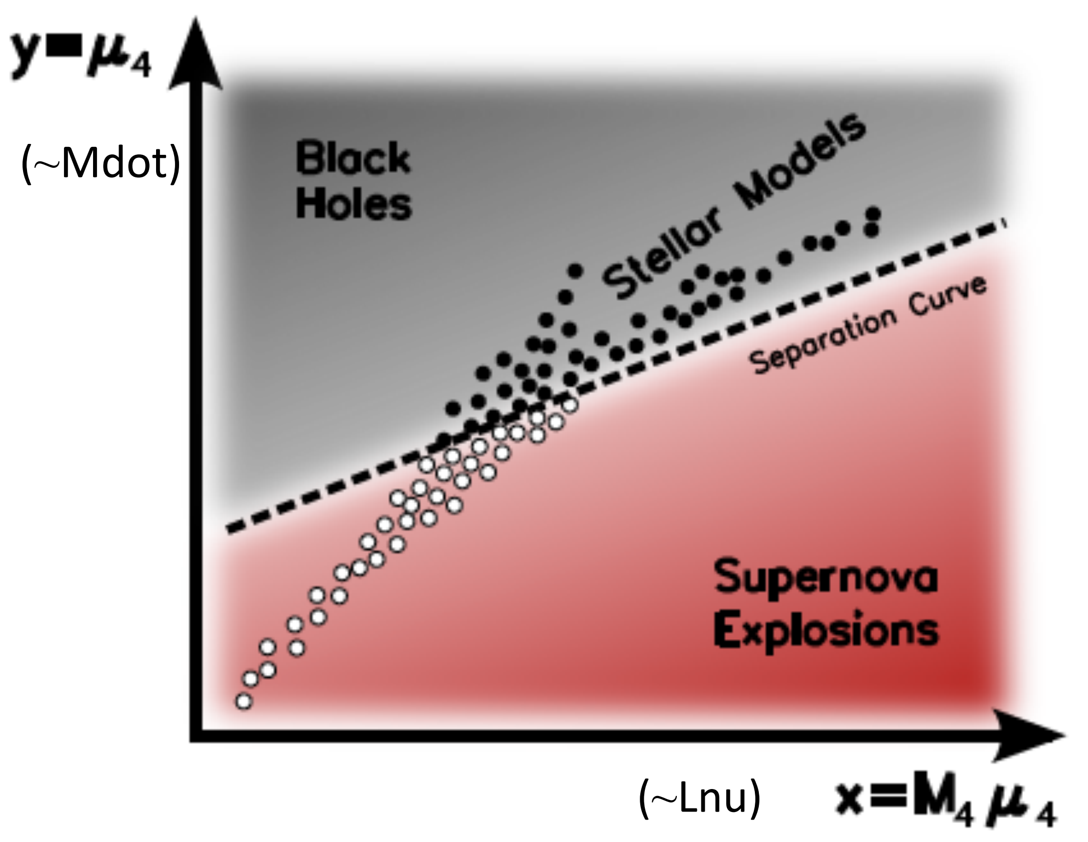
So, critical $\xi_{2.5}$ increases with M_{pns}.

→ 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)

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)