INT 15-2a: Neutrino Astrophysics and Fundamental Properties

Multi-messenger investigation of core-collapse supernovae

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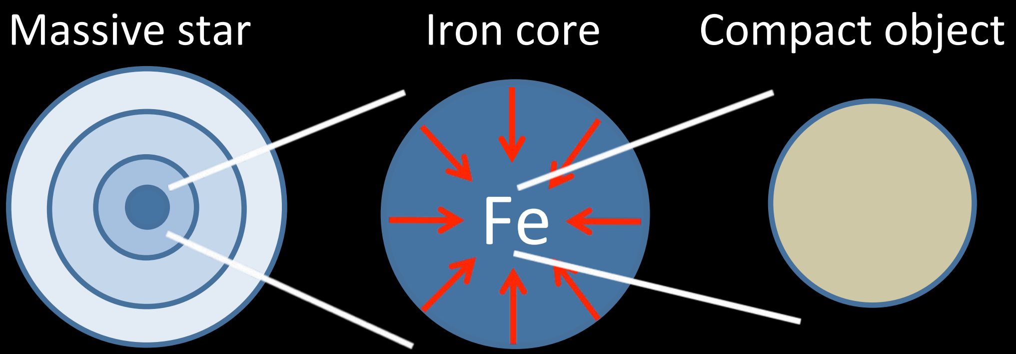
Image credit: NASA/ESA

Core-collapse supernova



Energy budget $\sim 3 \times 10^{53}$ erg

SN shock stalls →
- Shock revives → supernova
  - Negligible fall back mass → NS
  - Significant fall back mass → BH
- Shock does not revive → no supernova
  - BH remnant
  - Possible weak transient

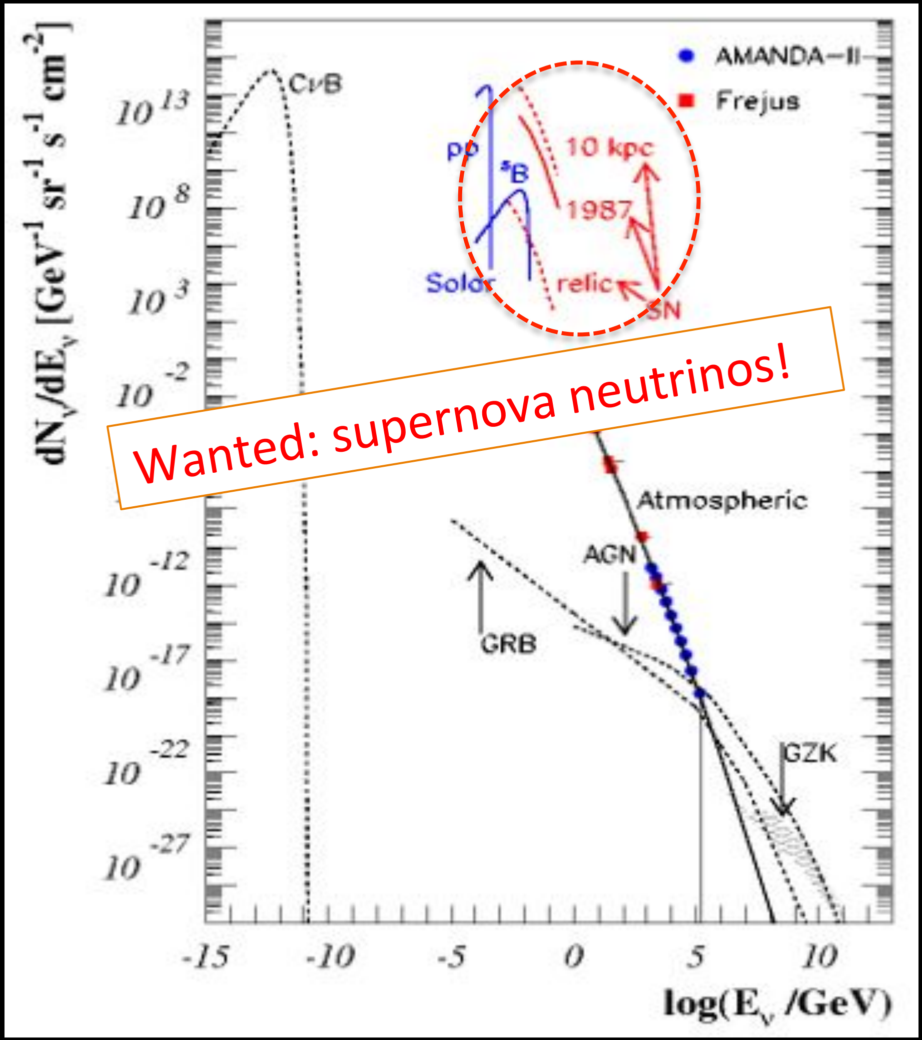
99%	into neutrinos
1%	into shock KE
0.01%	into photons

Nadezin (1980), Lovegrove & Woosley (2013), Piro (2013)

Strategy: approach this divide with a multi-messenger eye, connecting core-collapse studies to existing survey data

Contents

- Summary of systematic supernova simulations
- Observation: red supergiant problem
- Connection with supernova simulations
- Predictions & neutrino tests
- Conclusions



Wanted: supernova neutrinos!

Supernova simulations

Sophisticated simulations

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

Bruenn, Blondin, Burrows, Mueller, Hanke, Janka, Kotake, Liebendorfer, Messer, Mezzacappa, Suwa, Takiwaki, …

Two-dimensional systematic study

- 2D with approximate neutrino transport, Newtonian gravity
- $\sim$400 progenitor models
- Address: systematic study of progenitor dependence, SASI, other observables (M_{Ni}, etc)

Nakamura et al (2015)

One-dimensional systematic study

- 1D with parameterized neutrino heating, GR, many EOS
- $\sim$700 progenitor models
- Address: progenitor dependence, failed supernova collapse

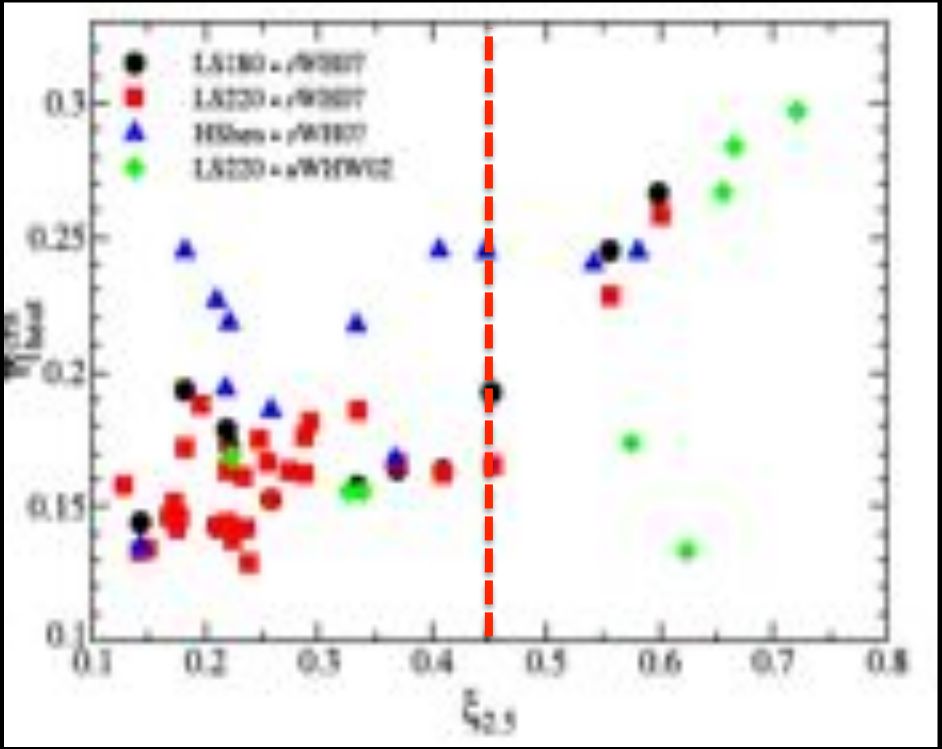
O'Connor & Ott (2011, 2013), also Ugliano et al (2012)

Explodability and compactness

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

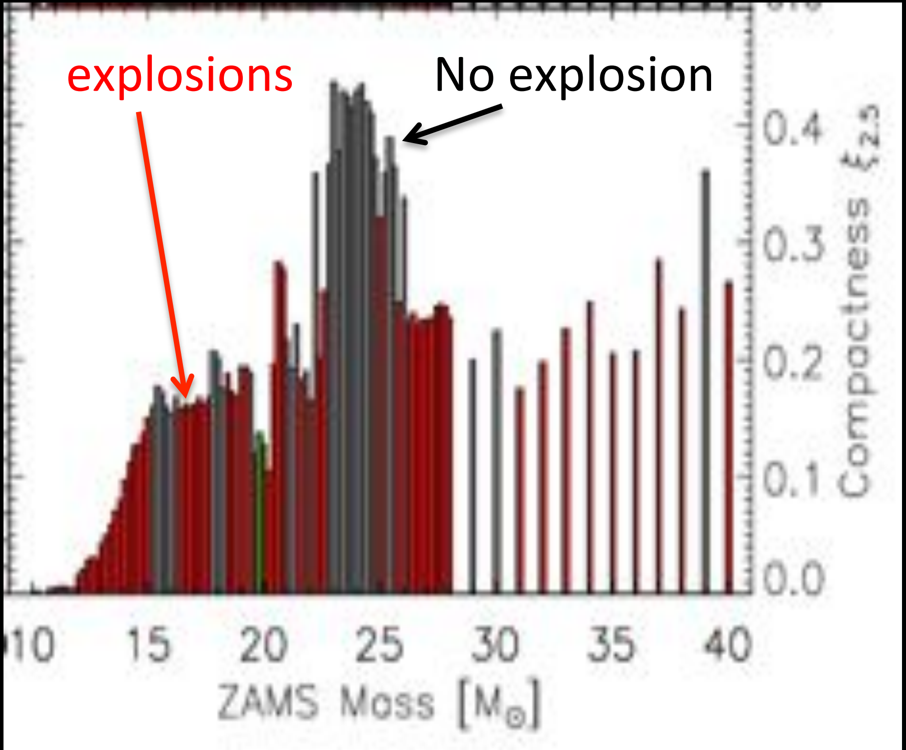
$$\xi = \left.\frac{M/\mathrm{M}_\odot}{R(M_{\mathrm{bary}} = M)/1000\,\mathrm{km}}\right|_t$$

Prompt BH formation (no explosion) requires $\xi_{2.5} > 0.45$



O'Connor & Ott (2011)

Explosions for $\xi_{2.5} < 0.15$, BH formation requires $\xi_{2.5} > 0.35$



Ugliano et al (2012)

See also Pejcha & Thompson (2015), Ertl et al (2015)

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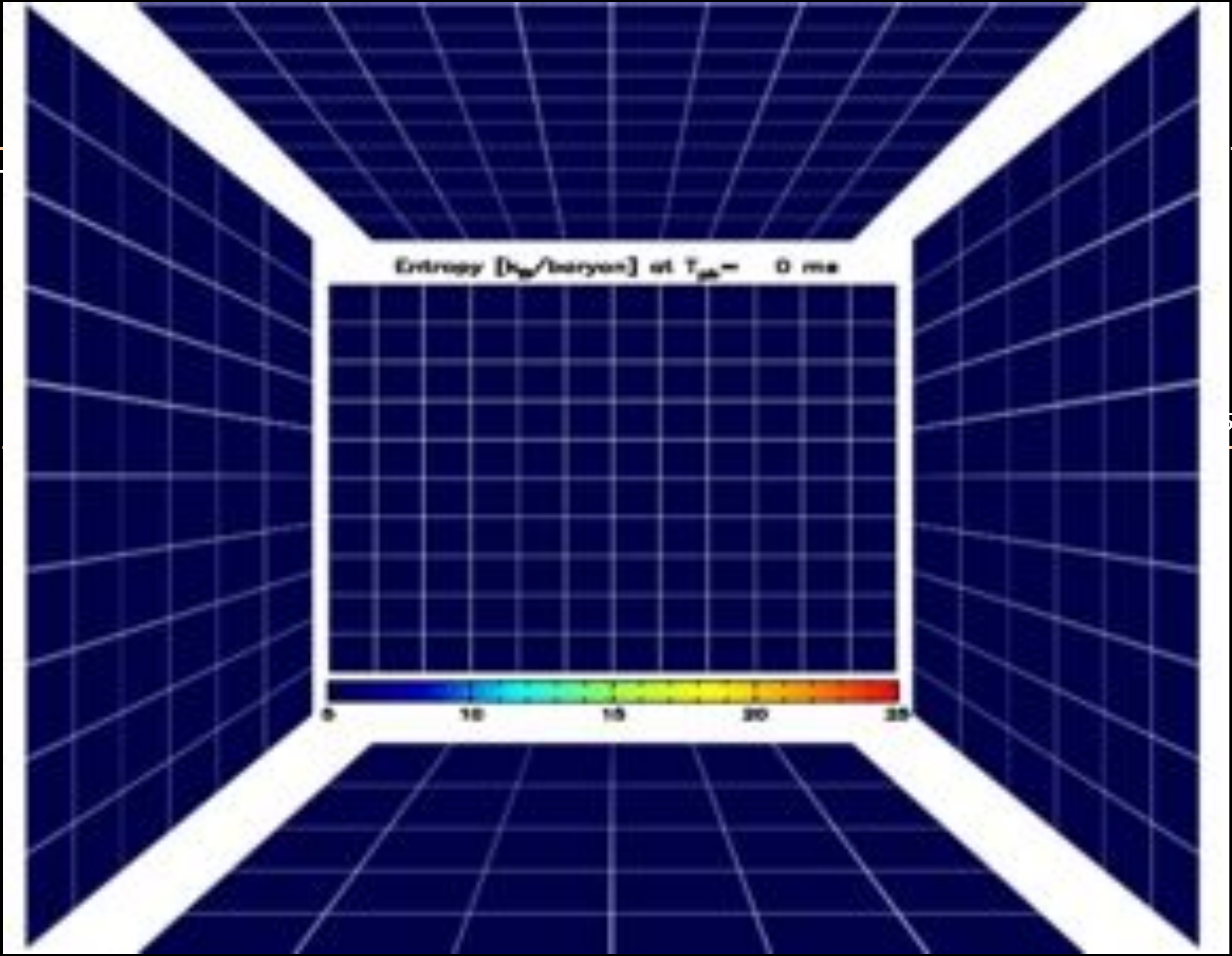
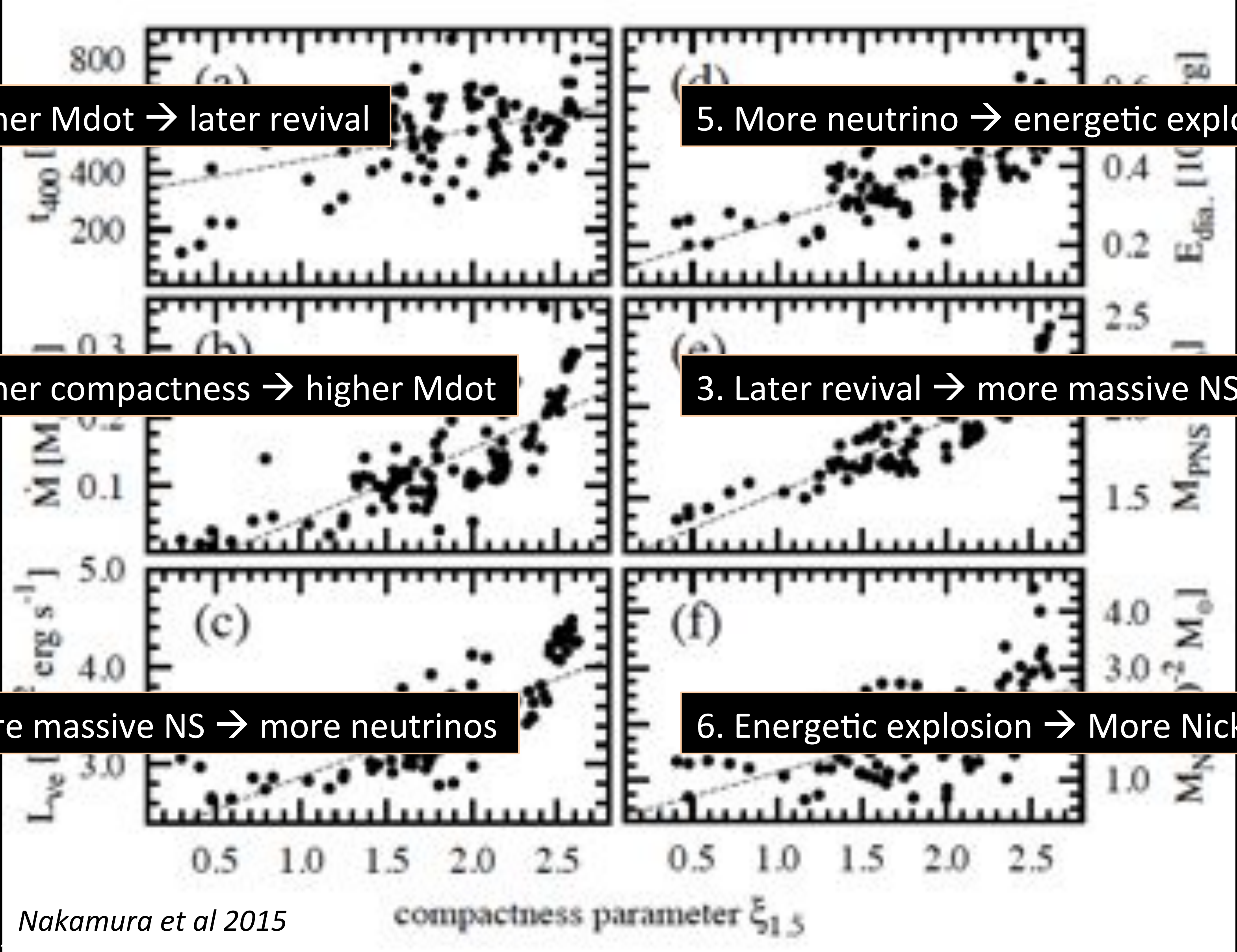


5)

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

1D and 2D

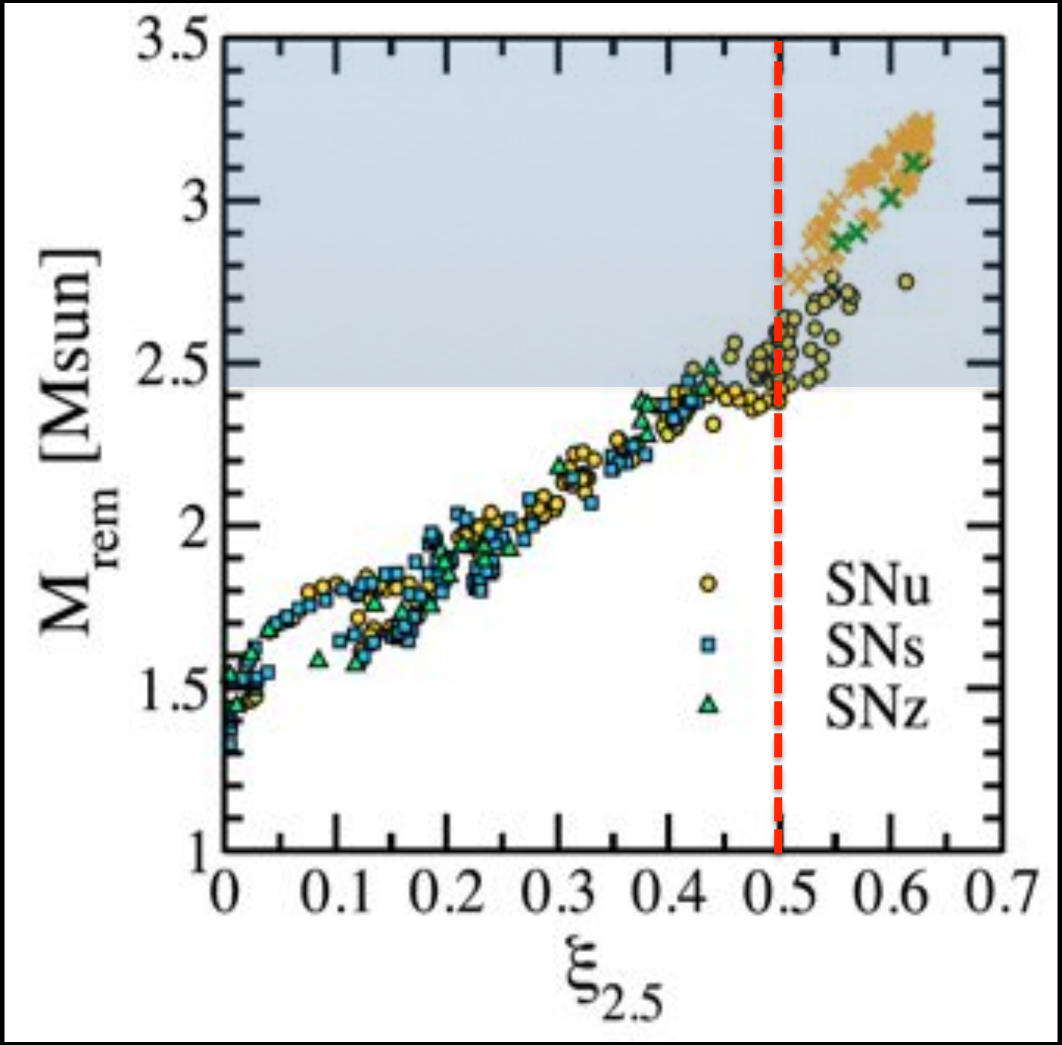
Failed explosions:
All solar metalicity progenitors explode, but some low metal progenitors with large compactness, $\xi_{2.5} > 0.5$

However, the setup is conducive to explosions

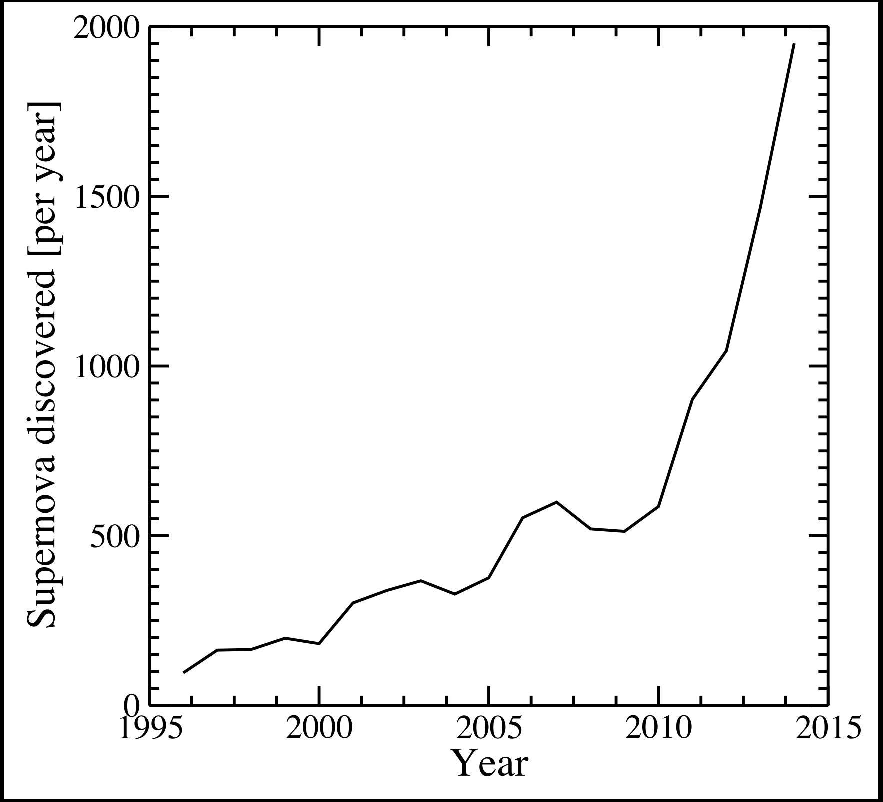
e.g., Hanke et al (2012)

Also, many nearby progenitors will make BHs, and supernova may be weak

→ In reality, the critical compactness should be smaller than $\xi_{2.5} \sim 0.5$



Horiuchi et al (2014)

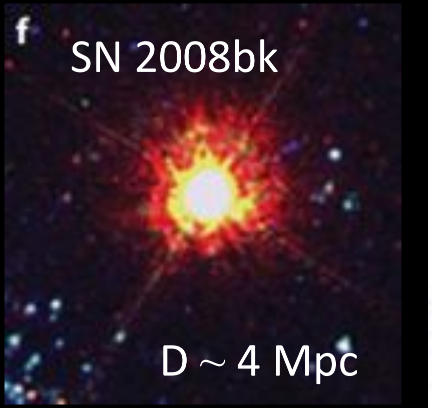


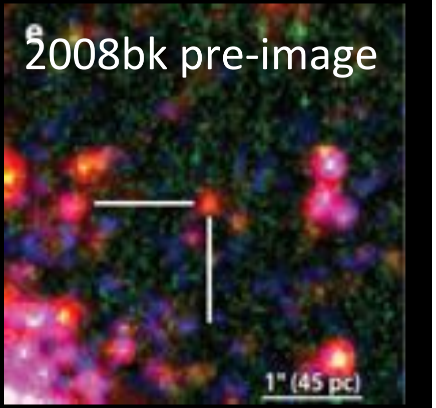
OBSERVATIONS

Progenitors of supernovae

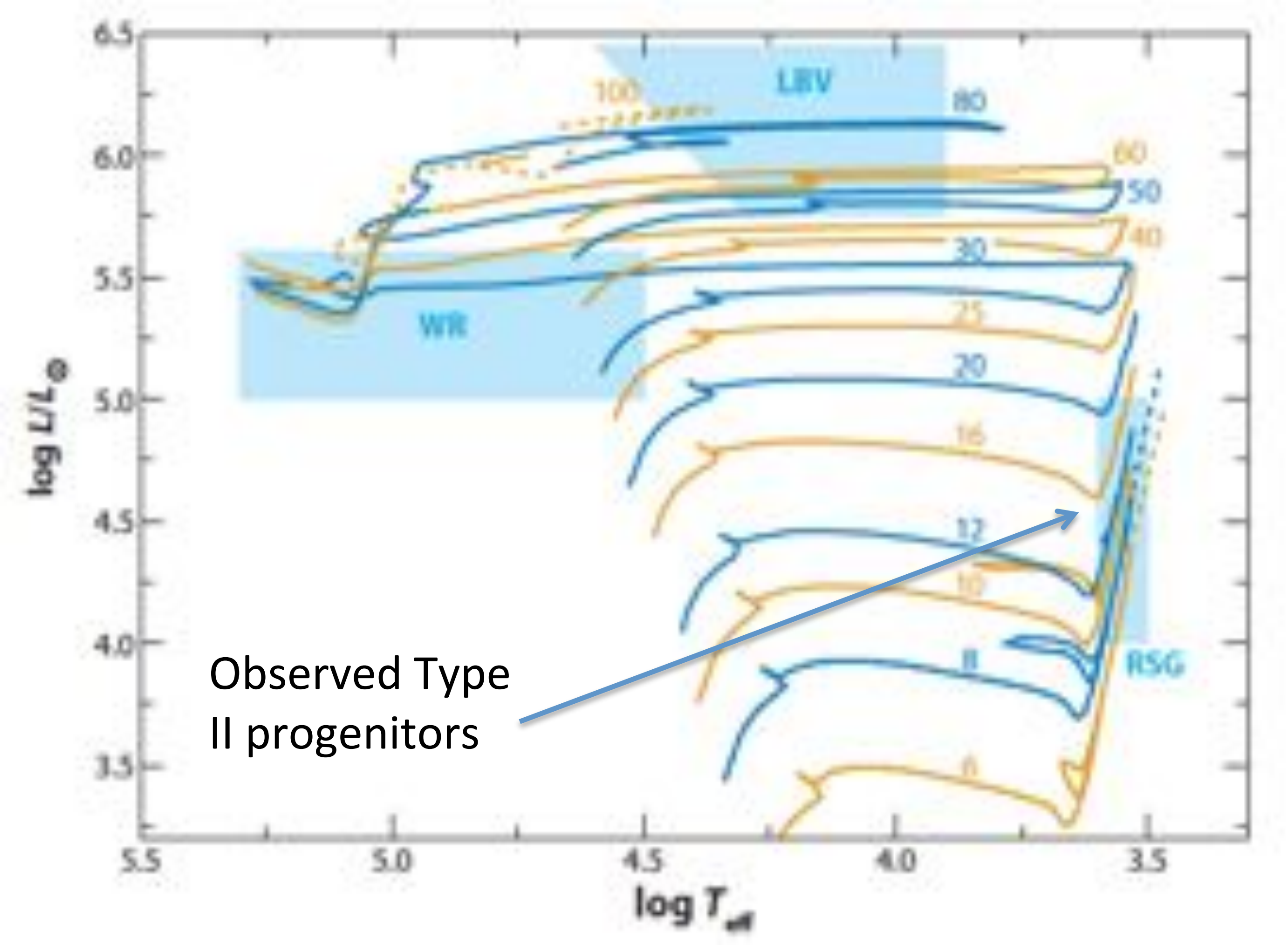
Pre-imaging:

Very successful for Type IIP





Smart et al (2001),
Van Dyk et al (1999),



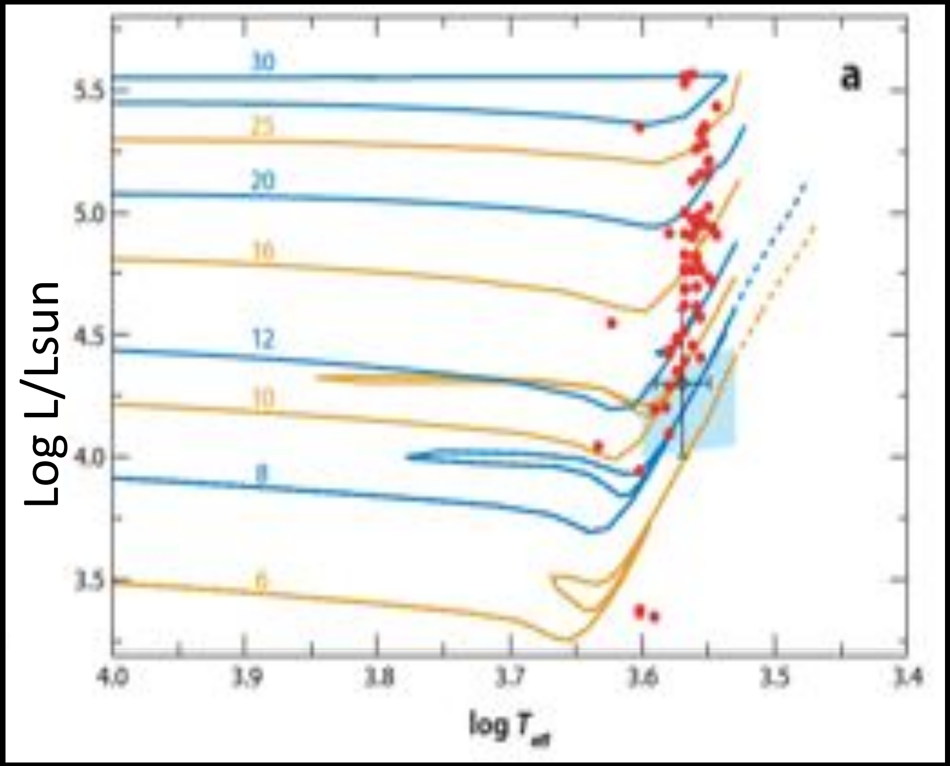
Observed Type II progenitors

Smartt (2009), Smartt (2015)

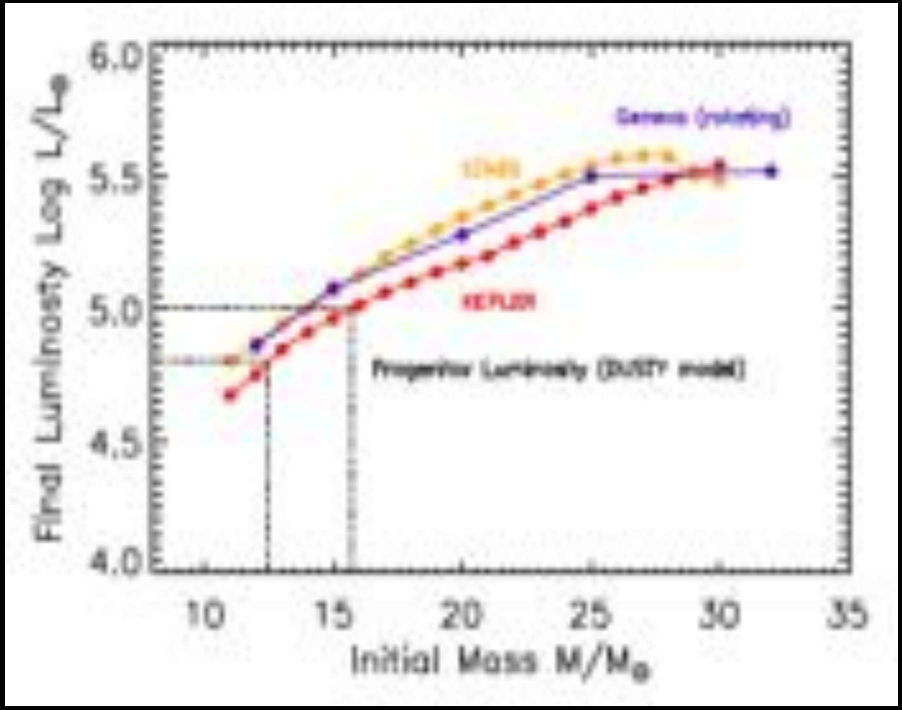
The red-supergiant problem

Red supergiants:

Reach higher luminosity, ~$10^{5.5}$ Lsun



Mass conversion:



$M_{min} \approx 9.5^{+0.5}_{-2.0}$ Msun

$M_{max} \approx 16.5 \pm 1.5$ Msun

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.

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

Some possible solutions

1. Change the number of expected missing red supergiants by postulating a steeper IMF

Smartt et al (2009)

2. Change stellar evolution so that the missing red supergiants explode as other types of supernovae (e.g., stripped Wolf-Rayet stars into Ibc)

Groh et al (2013)

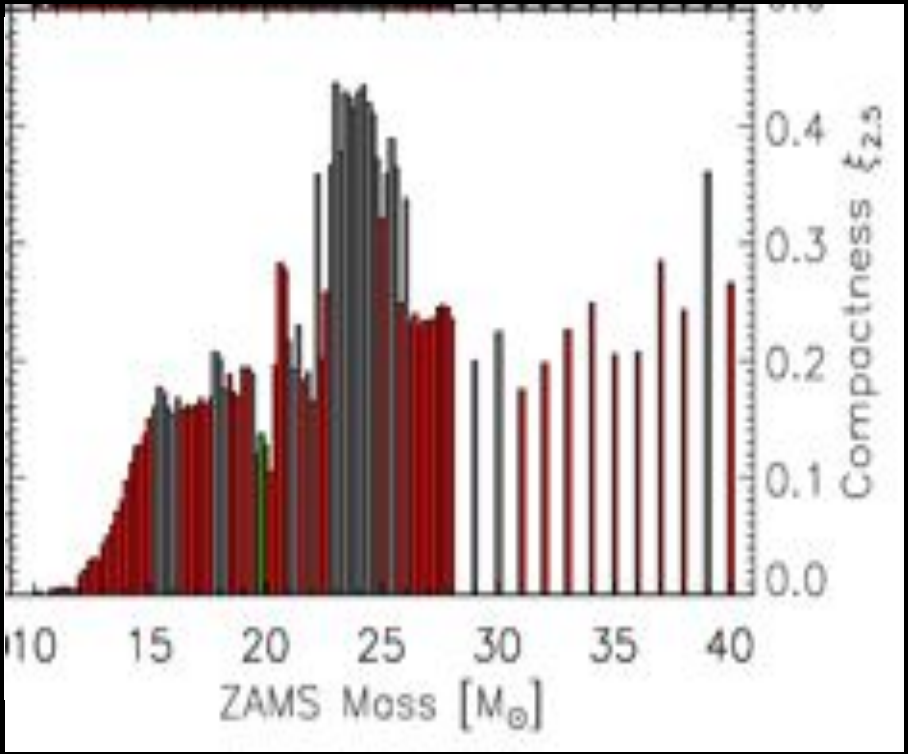
3. Change mass loss or dust to make mass estimates systematically low

Walmswell & Eldridge (2012)

4. Collapse goes to a black hole, with no or dim supernova

Connecting to core-collapse simulation

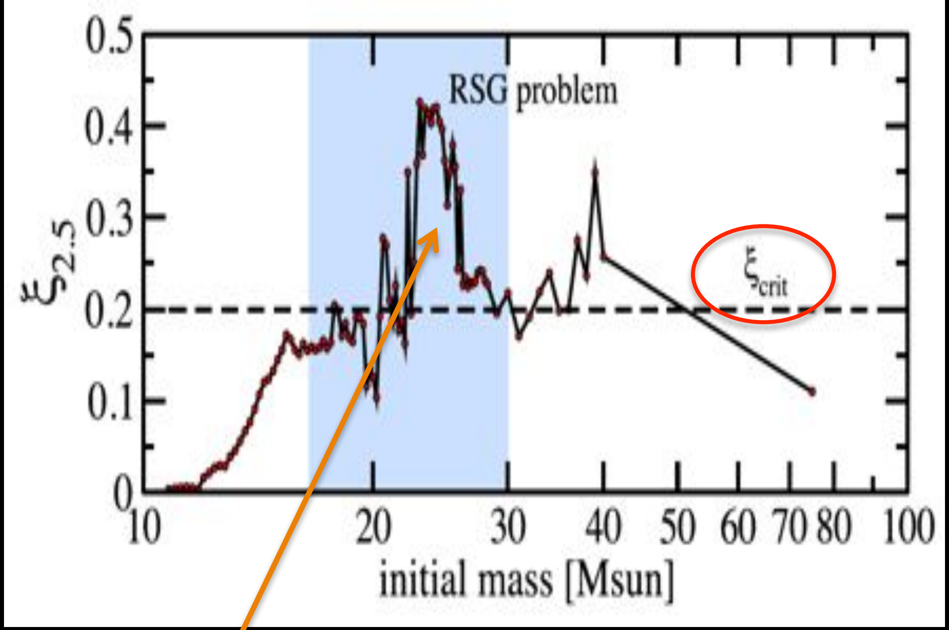
Compactness distribution:
The compactness does not increase monotonically with ZAMS mass



Ugliano et al (2012),
See also O'Connor & Ott (2011), Sukhbold & Woosley (2014)

NB: stellar evolution uncertainties

Possible connection to RSG problem:
There is a peak in the distribution of compactness in the red-supergiant problem mass range



Failed IIP supernovae?

Horiuchi et al (2014)

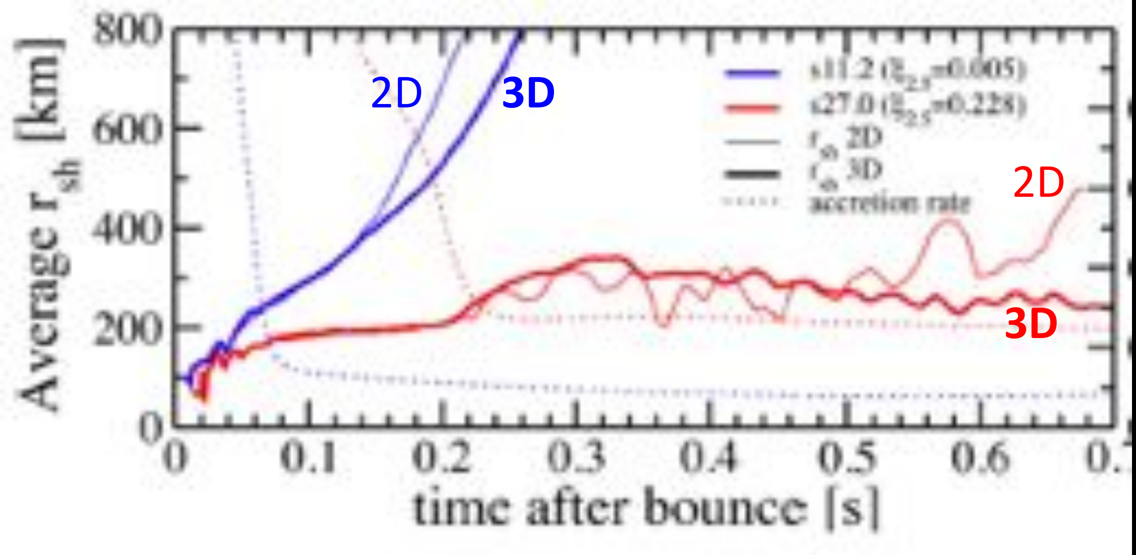
3D neutrino-driven simulations

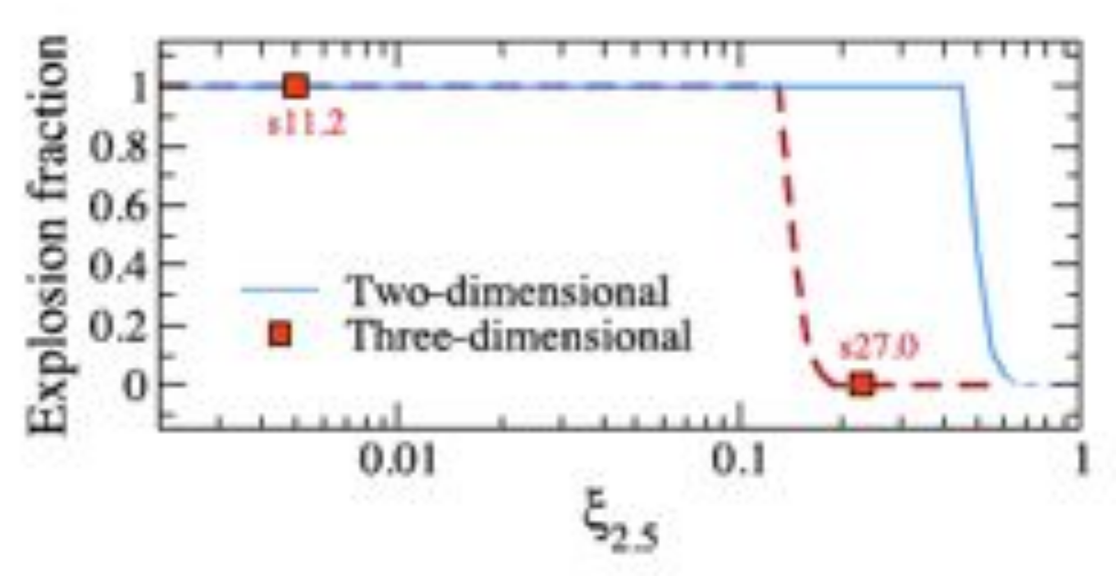
Critical compactness
In 1D: 0.35 – 0.45
In 2D: < 0.5
In 3D: ?

3D shows later shock revival, more spherical explosions.

A critical compactness for explosion of $\xi_{2.5} \sim 0.2$ is consistent with state-of-the-art 3D simulations

➔ The explosion fraction
The fraction of progenitors that successfully explode, binned in compactness.





Horiuchi et al (2014)

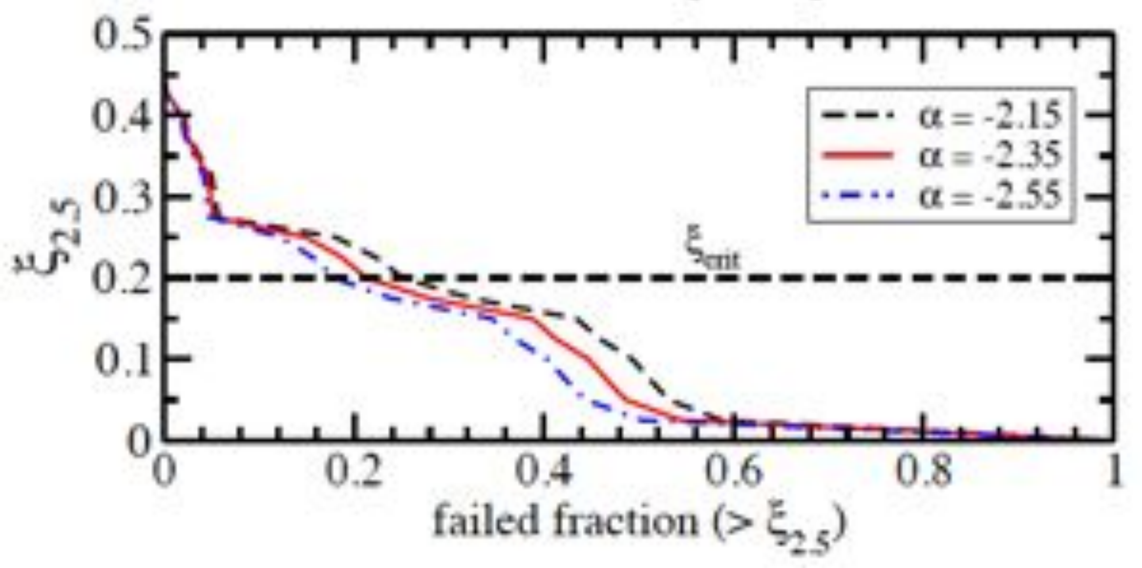
PREDICTION & TESTS

1. Fraction of failed explosions

→ Failed fraction

The fraction of massive stars with compactness $\xi_{2.5} > 0.2$ is around 20-30% (depends weakly on the IMF)

Is this too high?



Horiuchi et al. (2014)

1. Constraints from nucleosynthesis are weak *Brown & Woosley (2013), Clausen et al (2015)*

2. Survey About Nothing *Kochanek et al. (2008), Gerke et al (2015)*
   - Look for the disappearance of red-supergiants in nearby galaxies
   - Monitor $\sim 10^6$ red-supergiants (→ $\sim$1 core collapse per year)
   - So far, in 4 years running, 1 candidate observed (and 2 luminous supernovae)

→ $f_{fail} < 30\%$ (7–62% at 90%CL) or $f_{fail} < 0.40$ (90%)

Hints from rates

Two different methods:

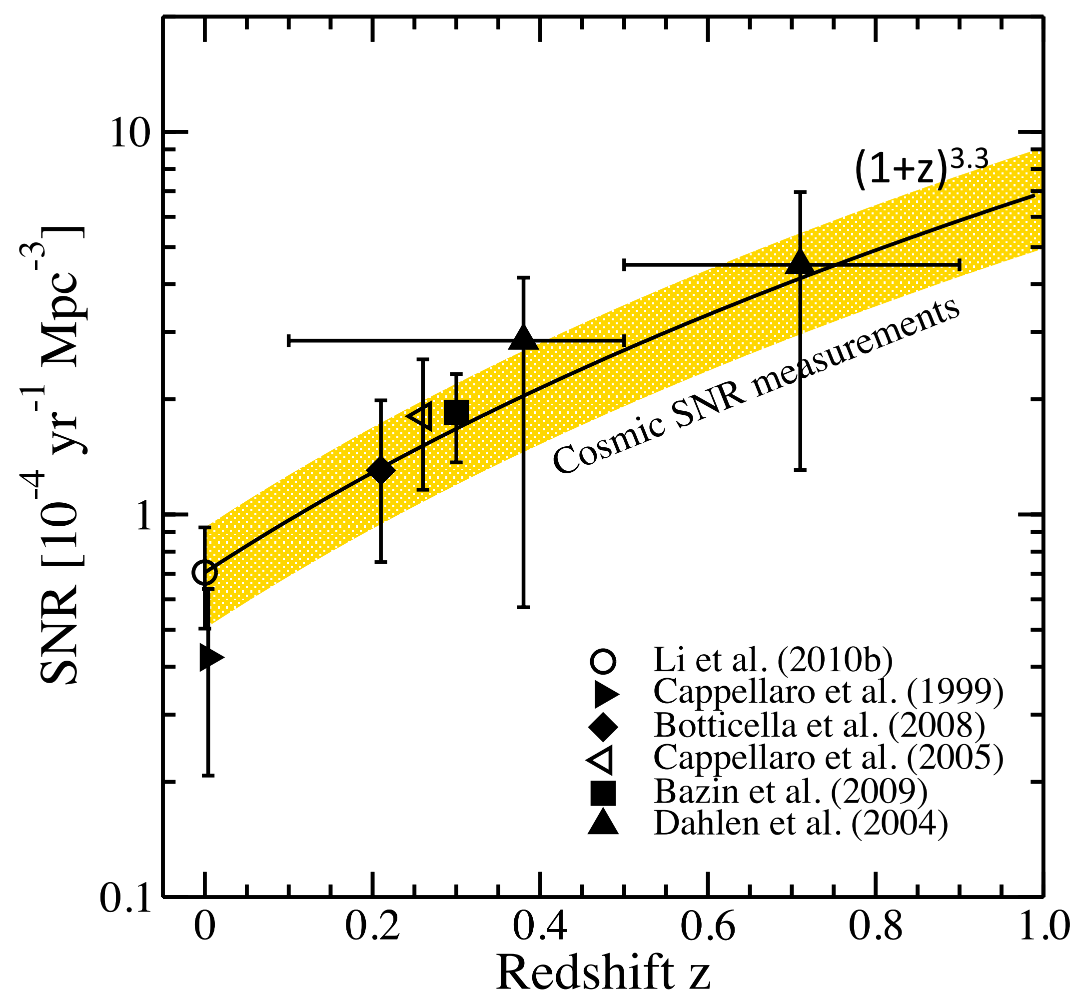
- Target pre-selected galaxies, e.g., LOSS, STRESS
- Target pre-selected fields, e.g., SNLS, HST-ACS

Different systematics:

Dust corrections, sample sizes, supernova-ID, supernova luminosity function, etc…

Nevertheless measurements converging.

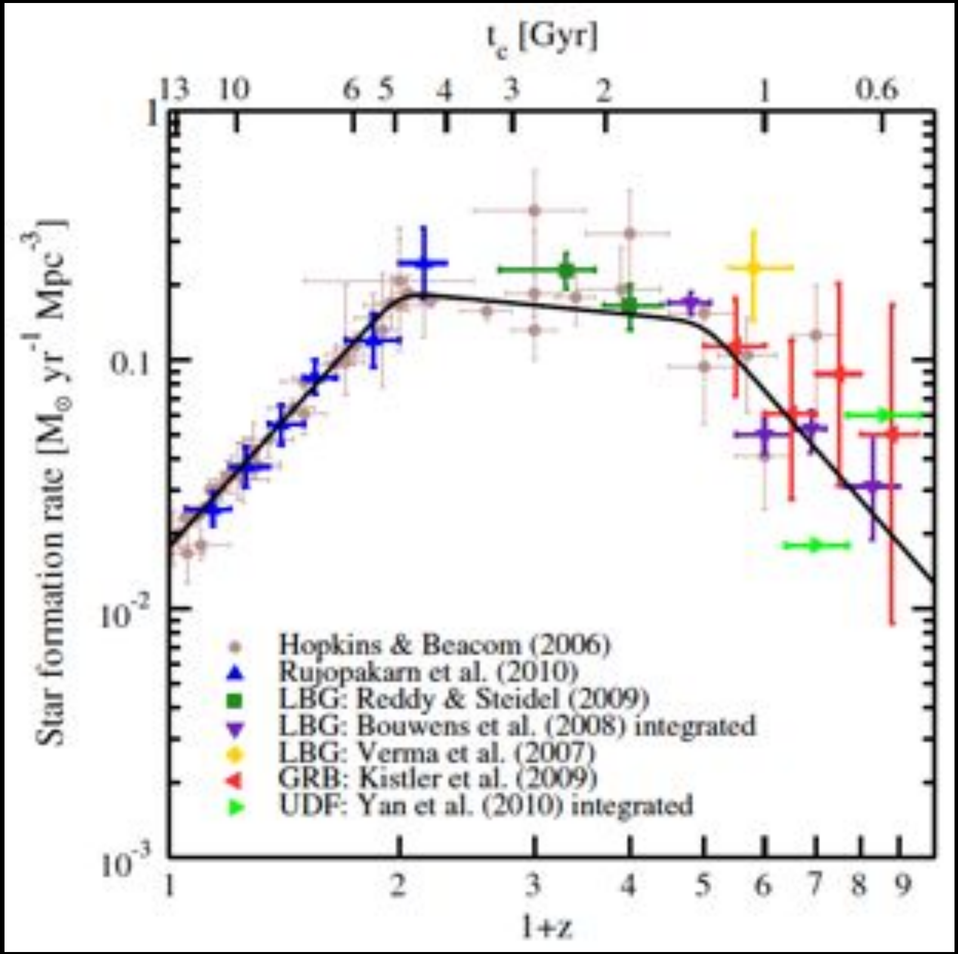
And improving quickly



Hints from rates

Core collapse rate = Birth rate of massive stars

*because lifetime of massive stars are cosmologically short



The star formation rate:

Has been measured by many groups, using many wavebands (radio, FIR, MIR, NIR, Hα, UV, X rays) and many data sets

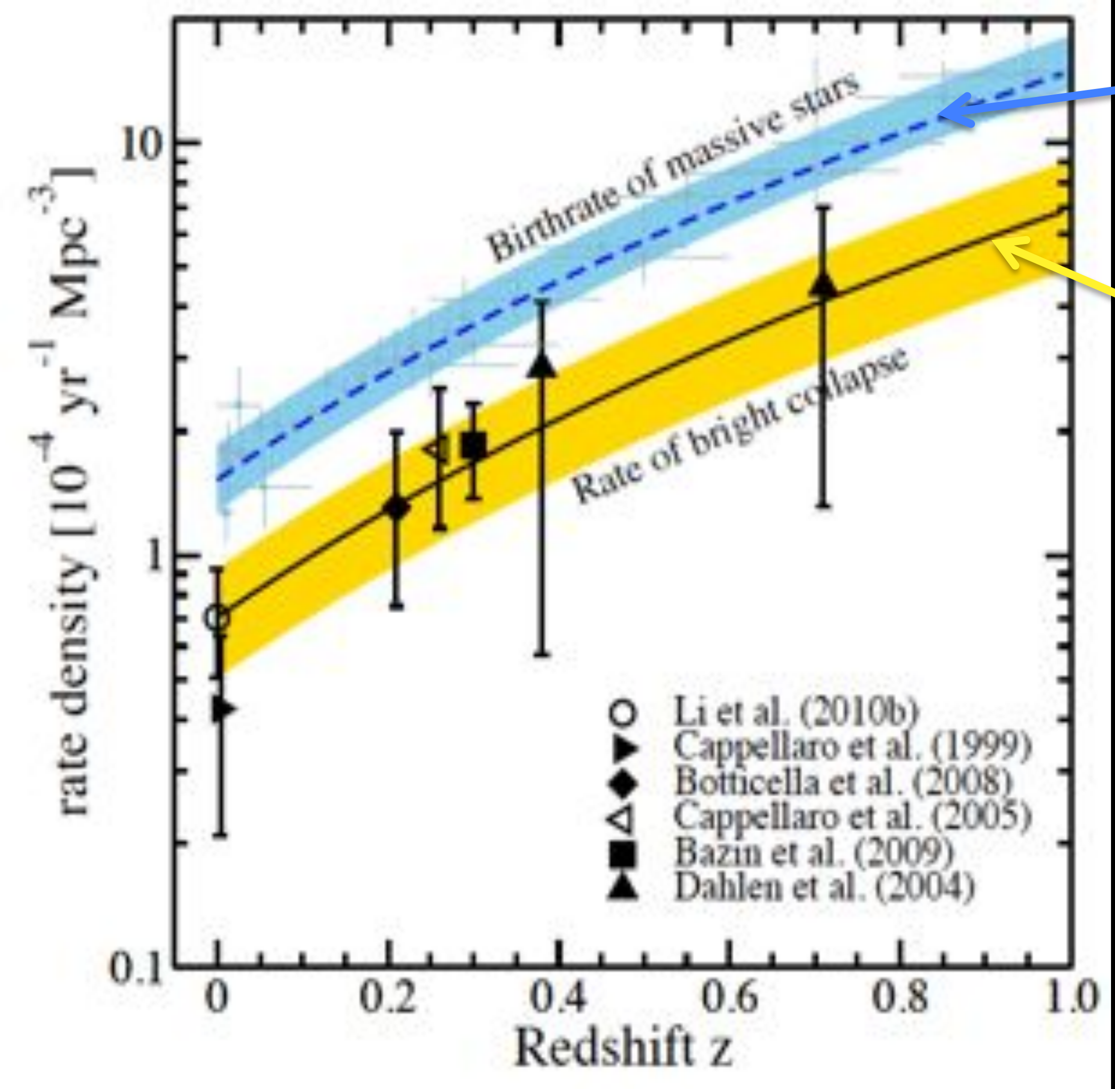
Uncertainties are mostly systematic

SFR data have rapidly increased and the uncertainty is now mainly:

- dust correction
- SFR calibration factors
- (Initial mass function is not)

Hopkins & Beacom (2006)
Horiuchi & Beacom (2010)
Horiuchi et al (2013)
Mathews et al (2014)

Hints from rates



Horiuchi et al (2010)

Core-collapse rate
Derived from the birth rate of massive stars

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

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

Approximately 30 – 50 %

- 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, etc

Hints from rates

The inferred BH fraction:

- Taking the measurements at face value, ~45%
- Including the dust attenuated supernova correction, ~30% *Mattila et al (2012)*

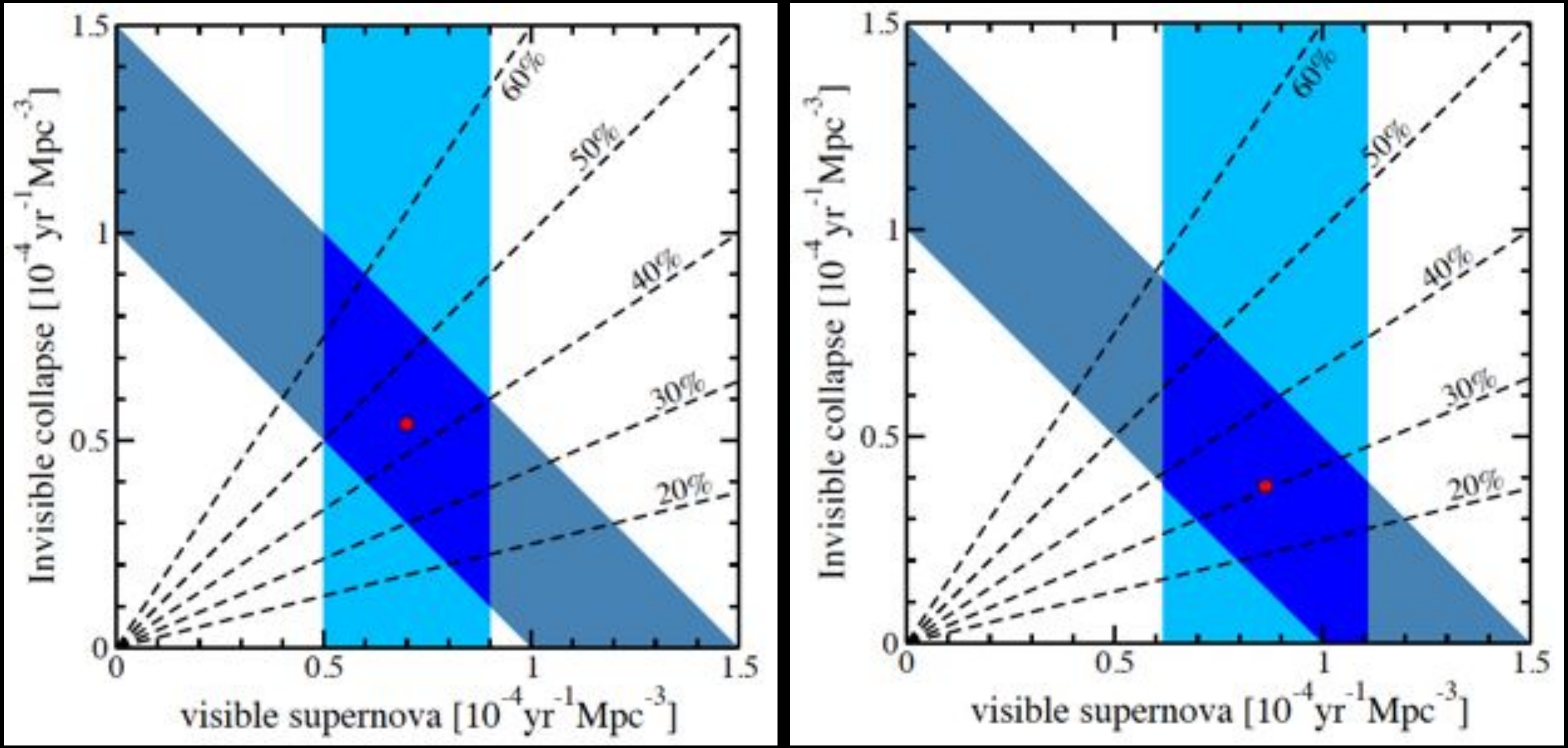


Figure adapted from Lien et al (2010)

2. Tests with neutrinos

1. Mass falls on free-fall time scale

$$\dot{M} = \boxed{\frac{dM}{dr}} \frac{dr}{dt_{ff}}$$

$t_{\mathrm{ff}} \sim O(100)$ ms

2. Mass accretion → internal energy budget

$$E_{int} = \frac{3}{5}\frac{GM^2}{R_\nu} \qquad M = \int \dot{M} dt$$

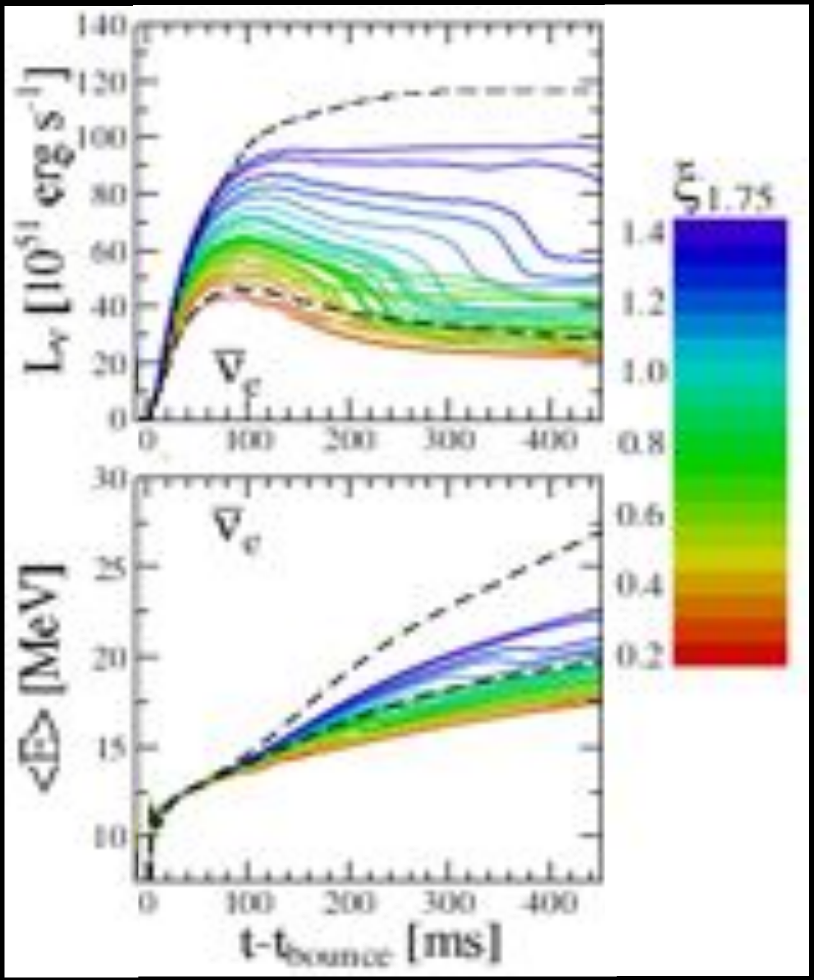
3. Energy is released as neutrinos over the diffusion time scale:

$$\boxed{L_\nu} = \frac{L_{diff}}{1 + t/t_{diff}} = \frac{E_{int}}{t_{ff} + t_{diff}}$$

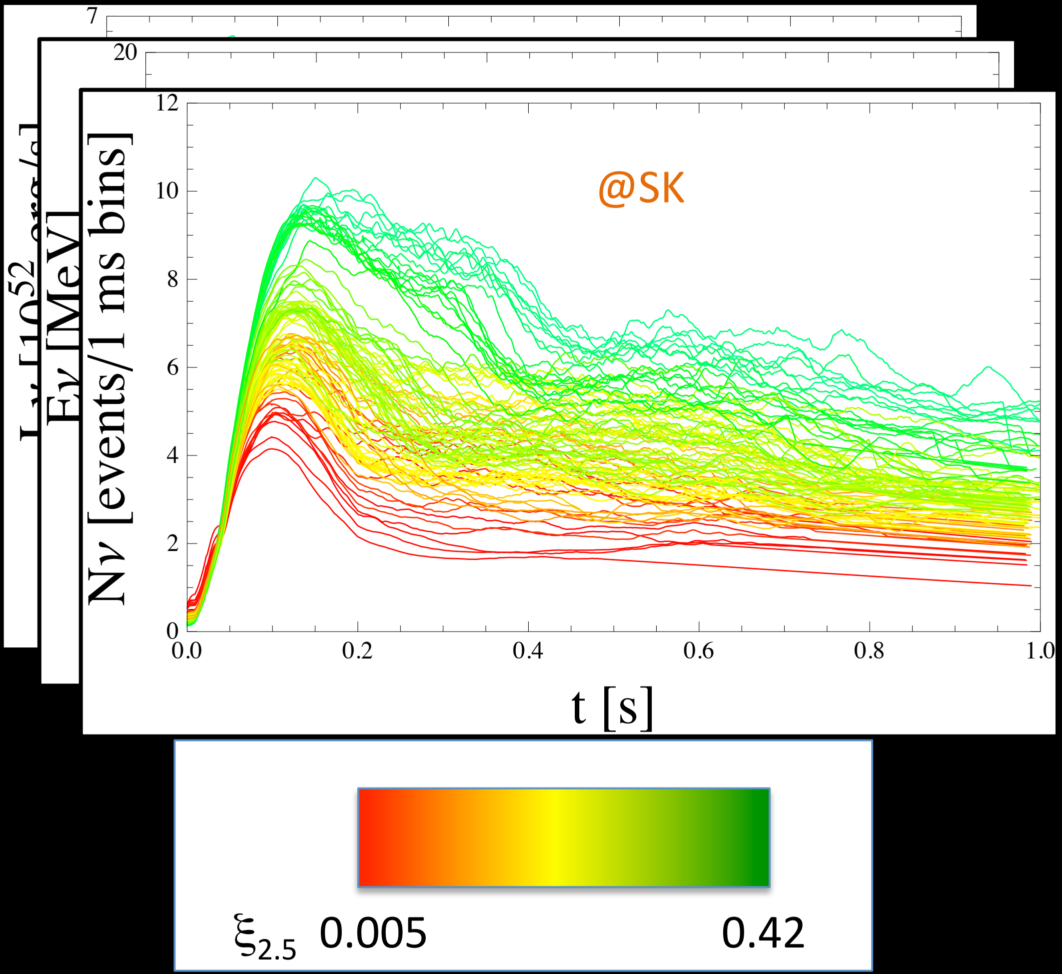
$t_{\mathrm{diff}} \sim O(400)$ ms

Measuring the compactness

1D studies ➔ ➔ ➔ ➔ ➔ Current 2D studies

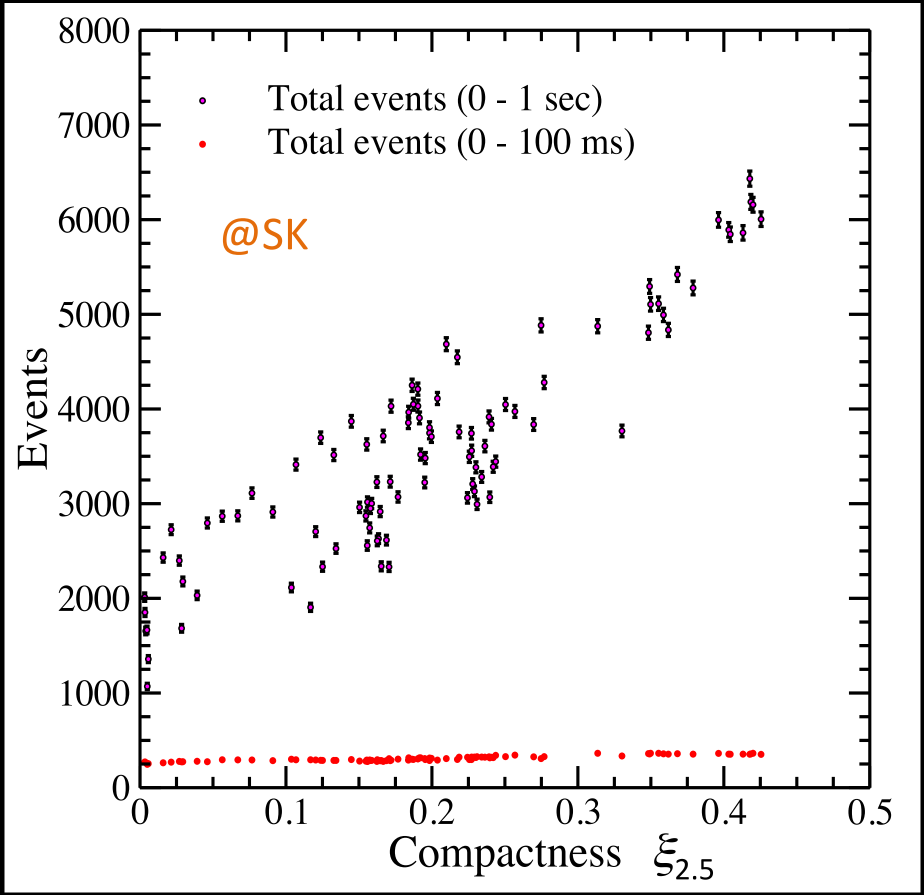


O'Connor & Ott (2013)

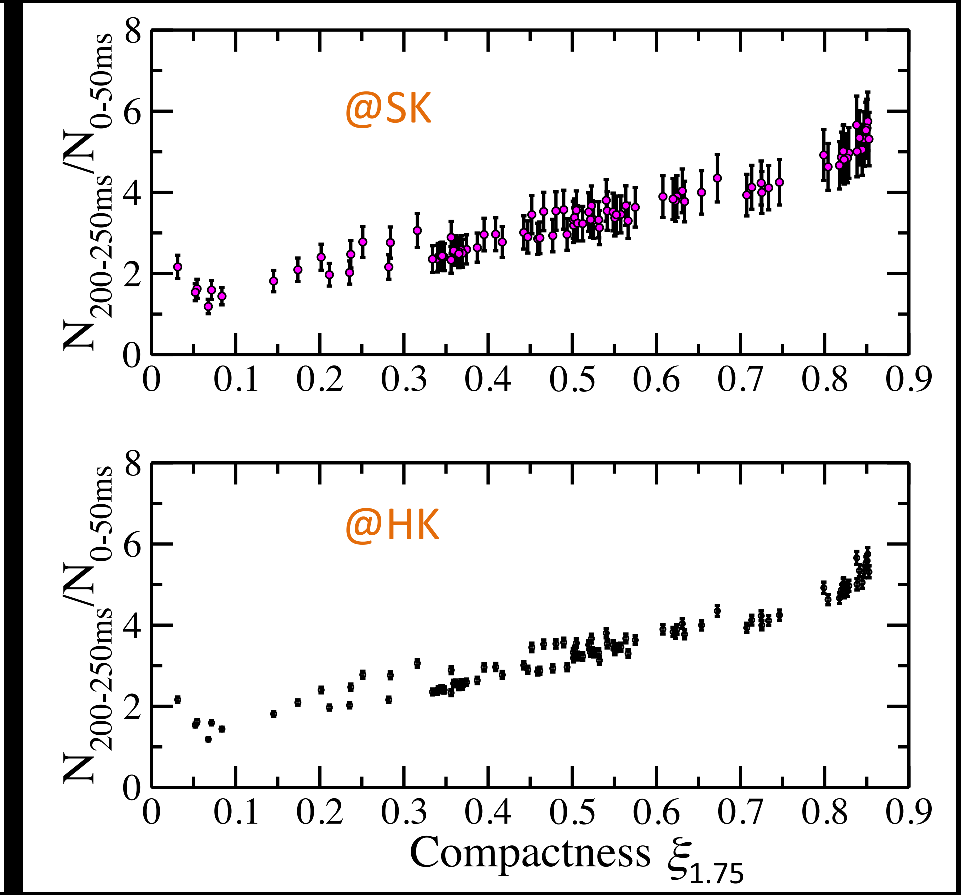


Measuring the compactness

Events scale with compactness, but this is degenerate with many other effects (e.g., distance, rotation, etc)

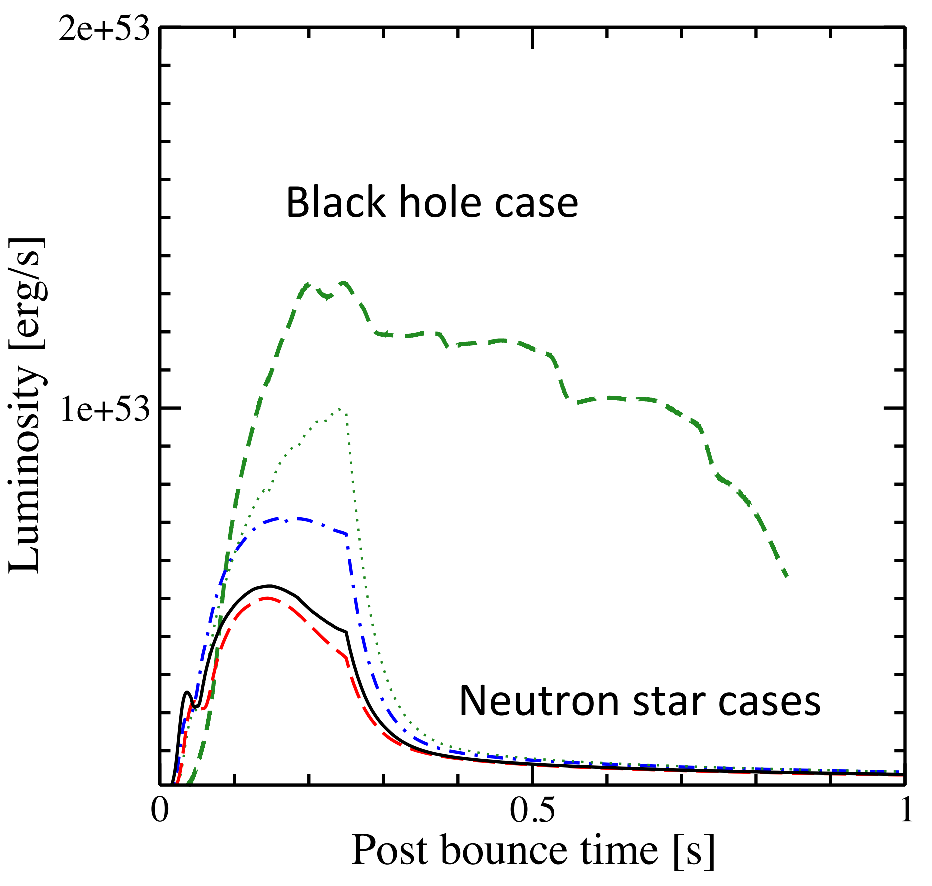


The ratio of events is more robust to such uncertainties. Many choices of time bins; here, 200-250ms is chosen:



(Collective oscillations not included)

Neutrino emission in black hole formation



Constructed from Nakazato et al (2012)

Neutrino emission:

Black hole necessarily goes through rapid mass accretion → ν emission is more luminous and hotter

Sumiyoshi, Fischer, Nakazato, Sekiguchi, Shibata, O'Connor, Ott, others

Neutrino probe:

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

Beacom et al (2001)

But statistically speaking, we may get a collapse to a neutron star…then what?

Diffuse Supernova Neutrino Background

Observed positron spectrum

Input 1: supernova neutrino spectrum (intensely studied, this program, quantity *of interest*)

$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu)\int R_{\mathrm{CCSN}}(z)\left|\frac{c\,dt}{dz}\right|(1+z)\frac{dN_\nu}{dE_\nu}\left[E_\nu(1+z)\right]dz$$

See, e.g., reviews by Beacom (2010), Lunardini (2010)

Input 2: core-collapse rate (intensely studied by astronomers using photons, *rapidly improving*)

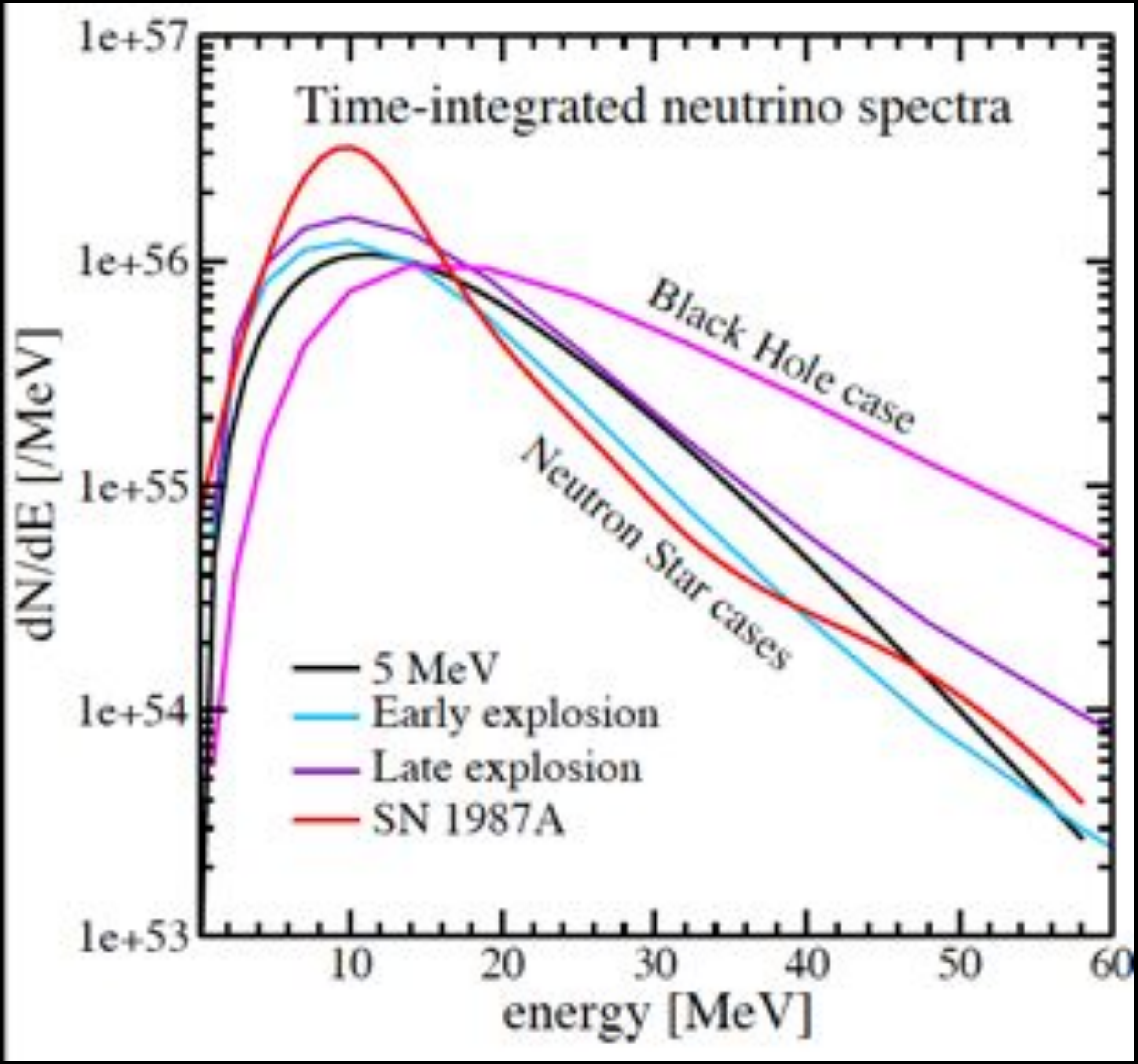
Input 3: neutrino detector capabilities (mostly well understood for H_2O)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Input 1: time-integrated neutrino signal

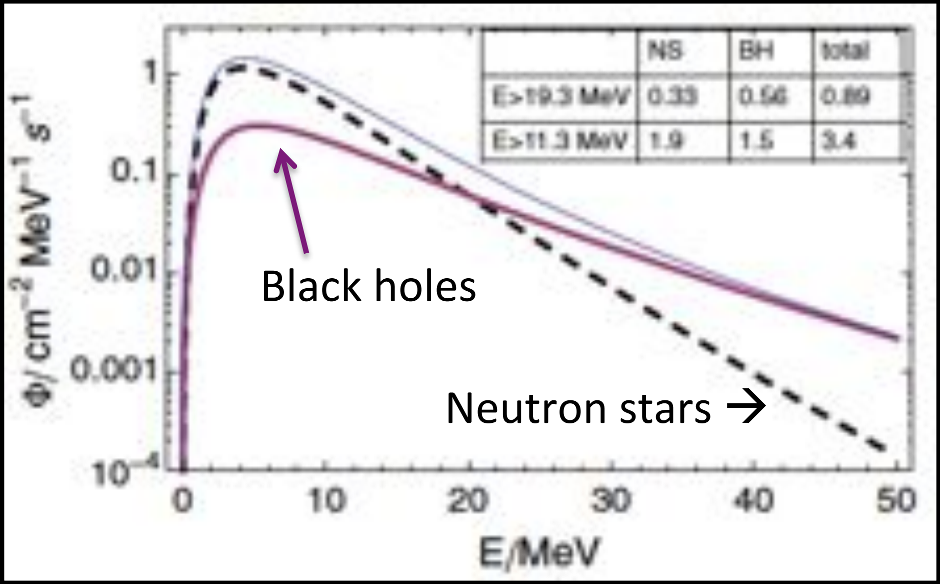
Neutrino emission:
Compared to collapse to neutrino stars, the duration of neutrino emission is shorter for collapse to black holes.

However, the time-integrated neutrino emission is still different



Event rates

Diffuse neutrino fluxes:



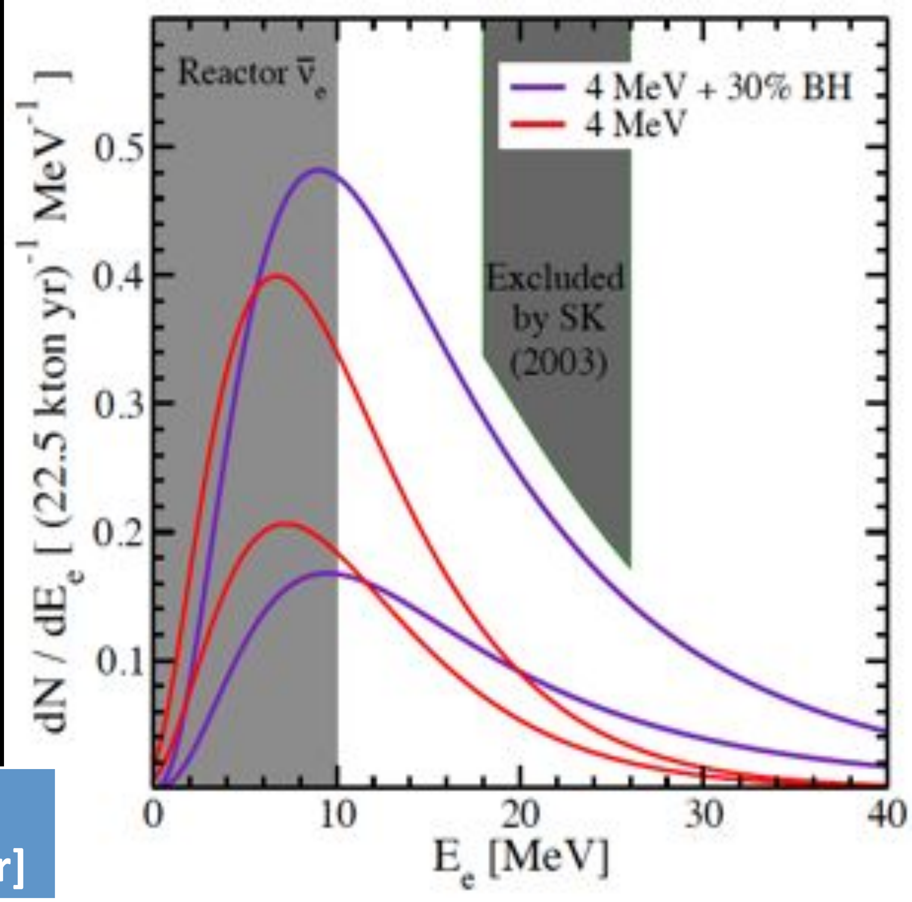
	NS	BH	total
E>19.3 MeV	0.33	0.56	0.89
E>11.3 MeV	1.9	1.5	3.4

Black holes

Neutron stars →

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

Event spectra with uncertainties:



Adapted from Horiuchi et al (2009)

Event rate at 0.5 kton H_2O detector:

Spectrum	18 MeV threshold [/yr]	10 MeV threshold [/yr]
4 MeV	9.2 +/- 2.5	39.0 +/- 11.7
4 MeV+BH	< 39.9	< 99
SN1987A	10.3 +/- 3.1	36.5 +/- 11.3

Conclusions

Take away messages:

1. Compactness is a useful parameter to characterize the diversity of core-collapse simulations
2. Observationally, massive stars between 18 – 25 Msun are not showing up as supernova progenitors (red supergiant problem)
3. These stars could be collapsing to black holes with weak optical display. Current constraints are consistent with this scenario
4. Neutrinos provide a valuable test, both via the next Galactic supernova, and via the diffuse supernova neutrino background. Survey About Nothing will provide important constraints also.

Thank you!

BACK-UP SLIDES

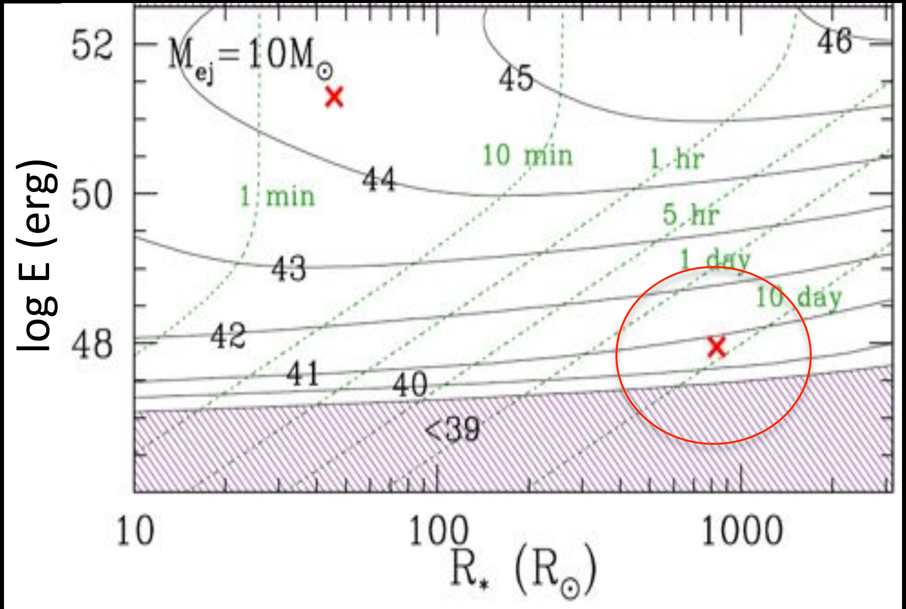
Optical signatures of direct collapse to BH

Even without a canonical supernova bounce shock, a shock can form as a result of hydrostatic response to neutrino emission

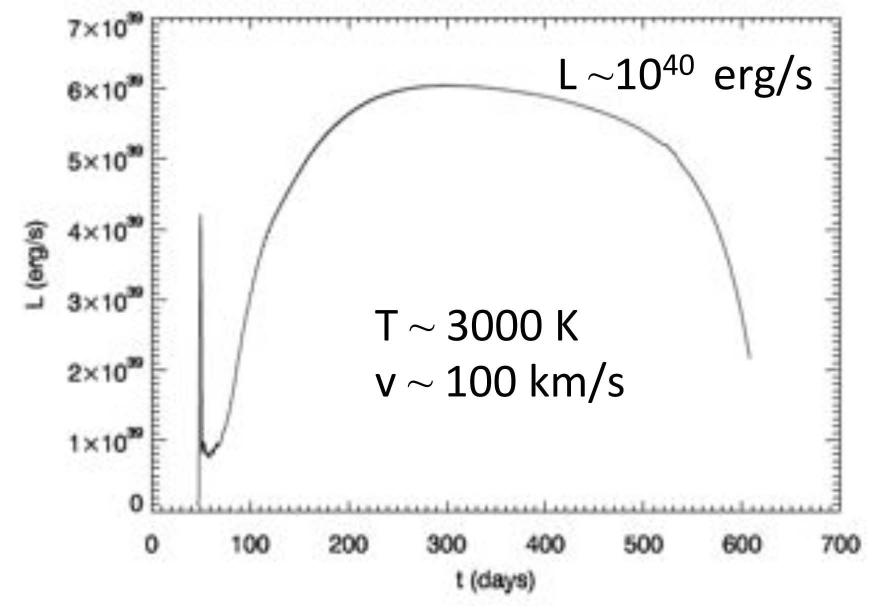
→ shock breakout emission → H-recombination emission

But generally it will not ID as a supernova: thus, one needs

1. dedicated survey trigger
2. neutrino probes (note larger horizon than NS case), or
3. "survey about nothing"



Piro (2013)



Lovegrove & Woosley (2013)

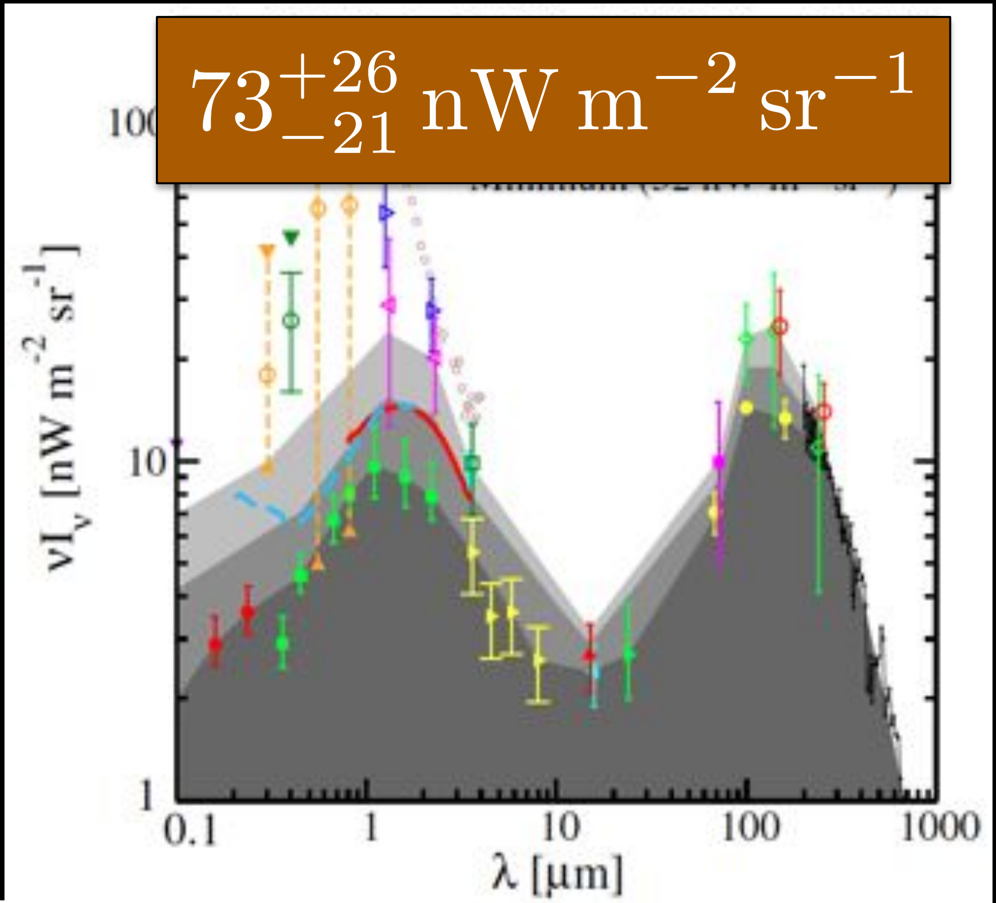
Extragalactic background light (EBL)

Stars leave imprints in other ways: they power the extragalactic background light

Hauser & Dwek (2001)

Observed EBL:
Various measurements and constraints. With recent results from distant blazar observations.

Calculated EBL from stars*
Depends on the IMF to some degree:



$$73^{+26}_{-21}\,\mathrm{nW\,m^{-2}\,sr^{-1}}$$

Horiuchi et al (2009), many updates, e.g., Gilmore et al (2012)

IMF	Total EBL intensity	Range
Salpeter (1955)	95 nW m^{-2} sr^{-1}	65–134
Kroupa (2001)	88 nW m^{-2} sr^{-1}	60–124
Baldy-Glazebrook (2003)	78 nW m^{-2} sr^{-1}	54–109

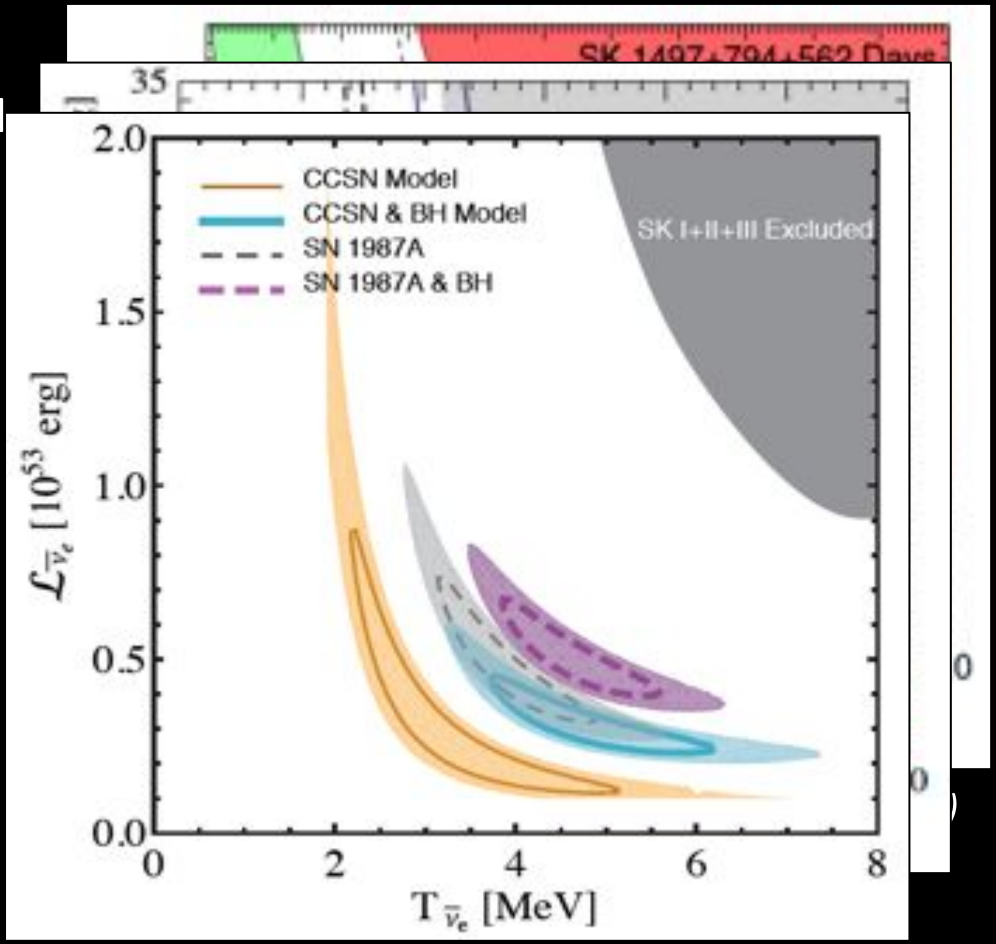
* Other contributions, e.g., AGN, contributes only a few % *e.g., Hopkins et al. (2006)*

Limits and future reach

Super-K limits:
state-of-the-art limits with SK-I, SK-II and SK-III data, employing improved background modeling power and statistics treatment.

Super-K with Gd:
Removes the largest background sources and enables a signal dominated search

Hyper-K with Gd:
The second component from black hole forming collapses can be studied



2σ and 5σ contours for 10 years running idealized 0.56 Mton with Gd (10 – 20 MeV) [Yuksel & Kistler 2013]