第2回超新星ニュートリノ研究会, Jan 6-7th 2016

マルチメッセンジャー観測による重力崩壊の探求

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Image credit: NASA/ESA

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Understanding core collapse: “compactness”

- Systematic simulations
- Hints from progenitor studies
- Predictions and constraints

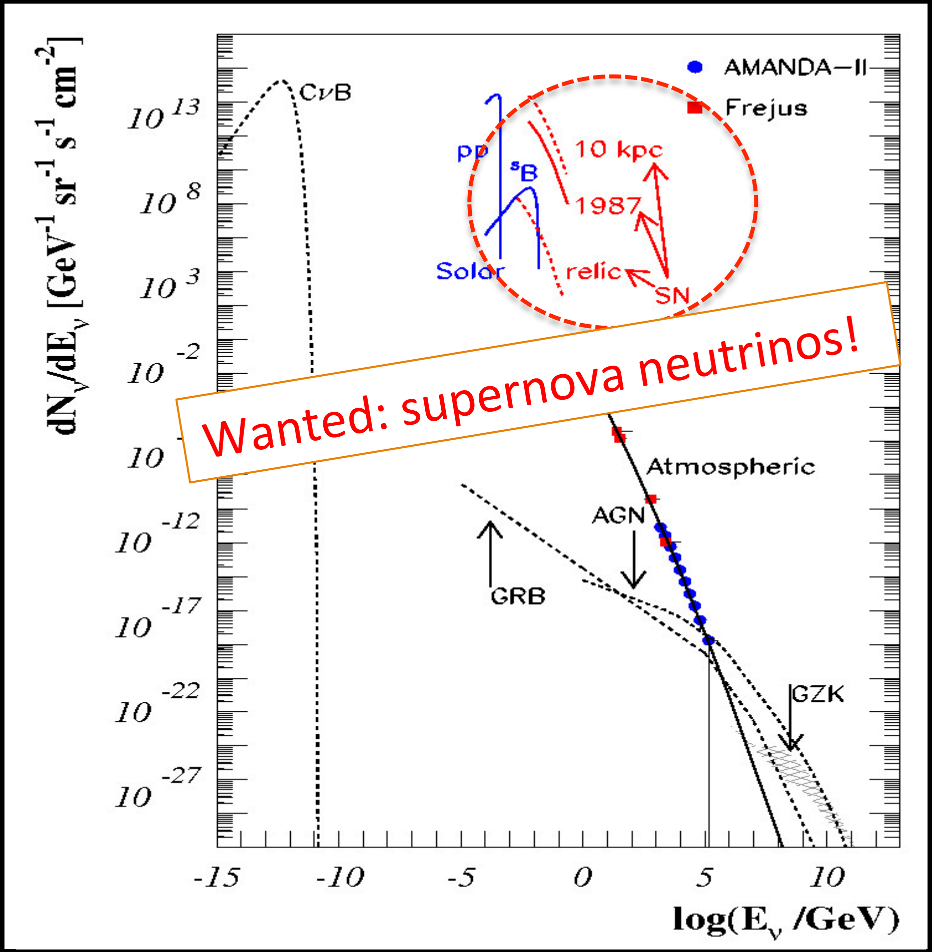
Future neutrino test

- Galactic supernova
- Diffuse supernova neutrinos

Let’s go supernova!

- Multi-messenger connections
- Observations strategies

Conclusions



Wanted: supernova neutrinos!

UNDERSTANDING CORE COLLAPSE: COMPACTNESS

Core-collapse supernova & compactness

The problem:

How is the stalled shock energetically revived? → “supernova mechanism”

The neutrino mechanism:

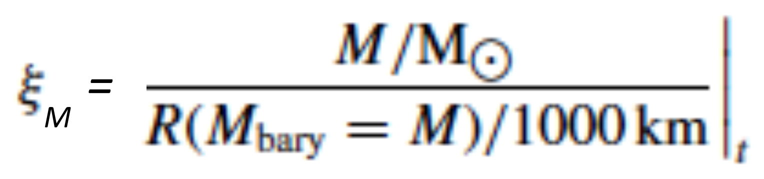
Deposit some of the energy in neutrinos behind the shock.

Mass accretion

VS !

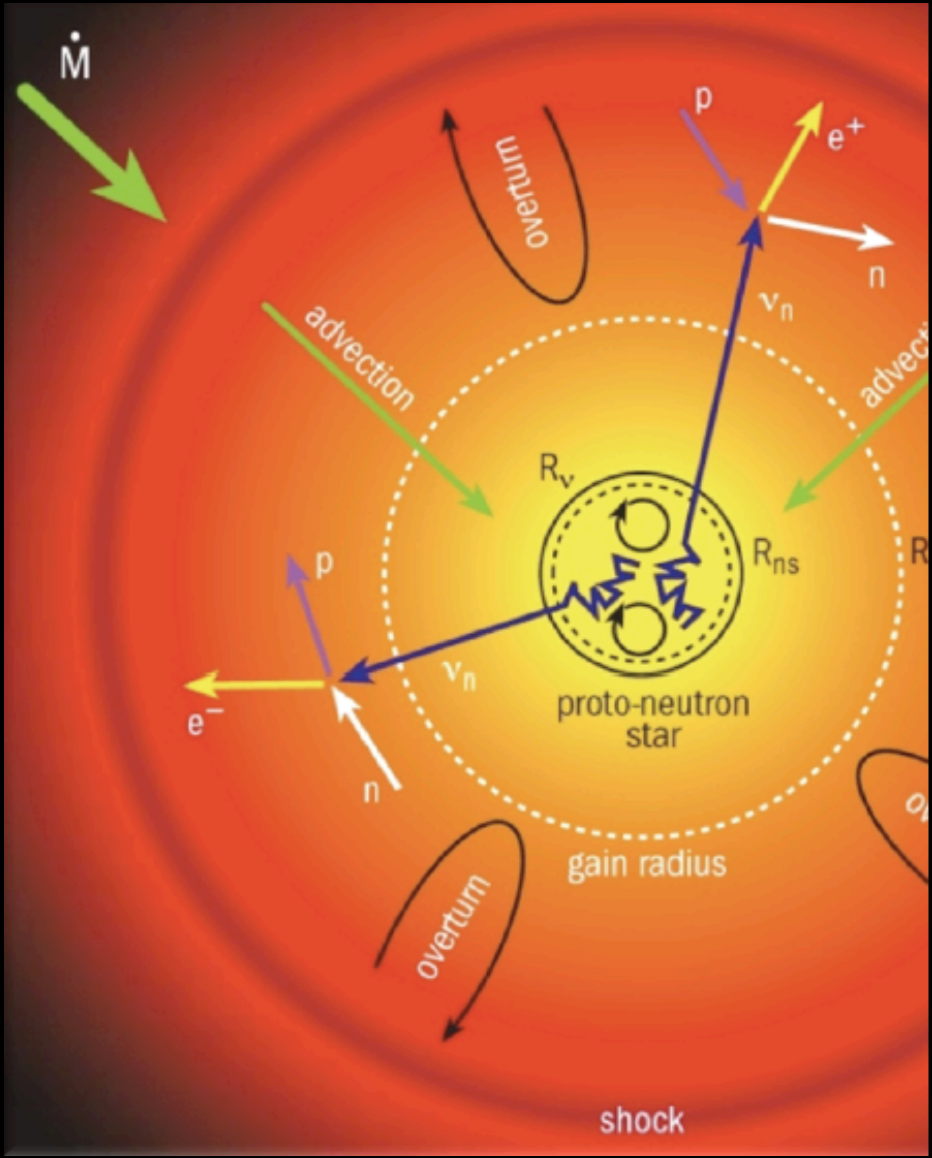
Neutrino heating

Compactness:



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

→ Takiwaki-san’s talk



Systematic core-collapse simulations

Sophisticated simulations [no systematic studies yet]

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

Mueller et al (2012, 2013, 2014), Hanke et al (2013), Takiwaki et al (2012, 2014), Bruenn et al (2013, 2014), …

Two-dimensional systematic study

- 2D with simplified neutrino transport (IDSA)
- ~400 progenitor models
- Address: systematic study of progenitor dependence, SASI, other observables (M_{Ni}, etc)

Nakamura et al (2014)

One-dimensional systematic study

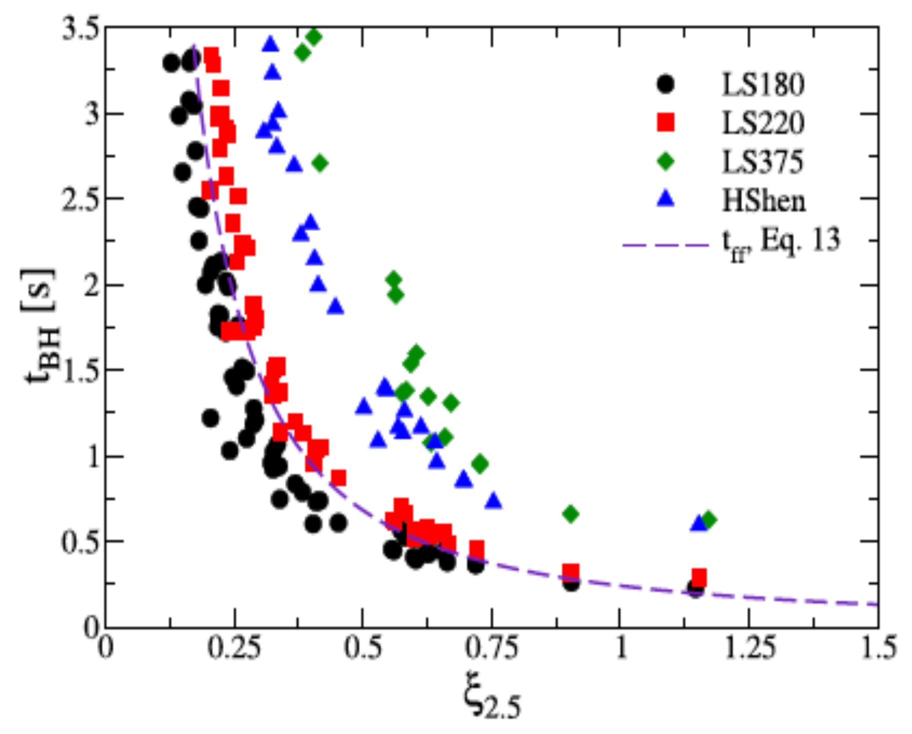
- 1D with parameterized neutrino heating
- ~700 progenitor models
- Address: progenitor dependence, black hole formation

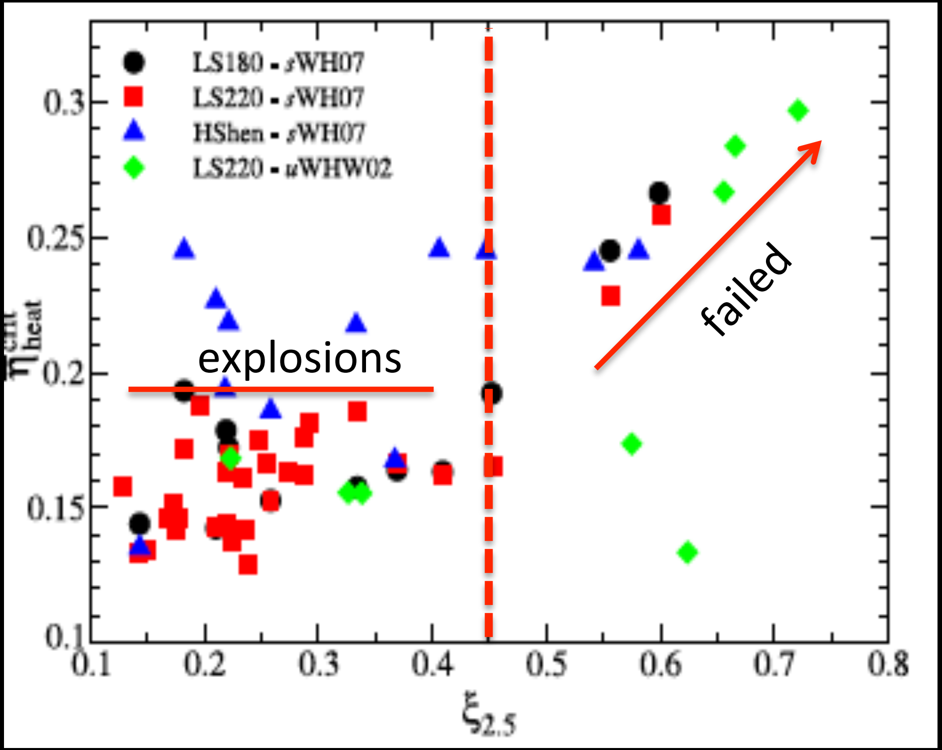
Ugliano et al (2012), O'Connor & Ott (2011, 2013)

Results in 1D

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)

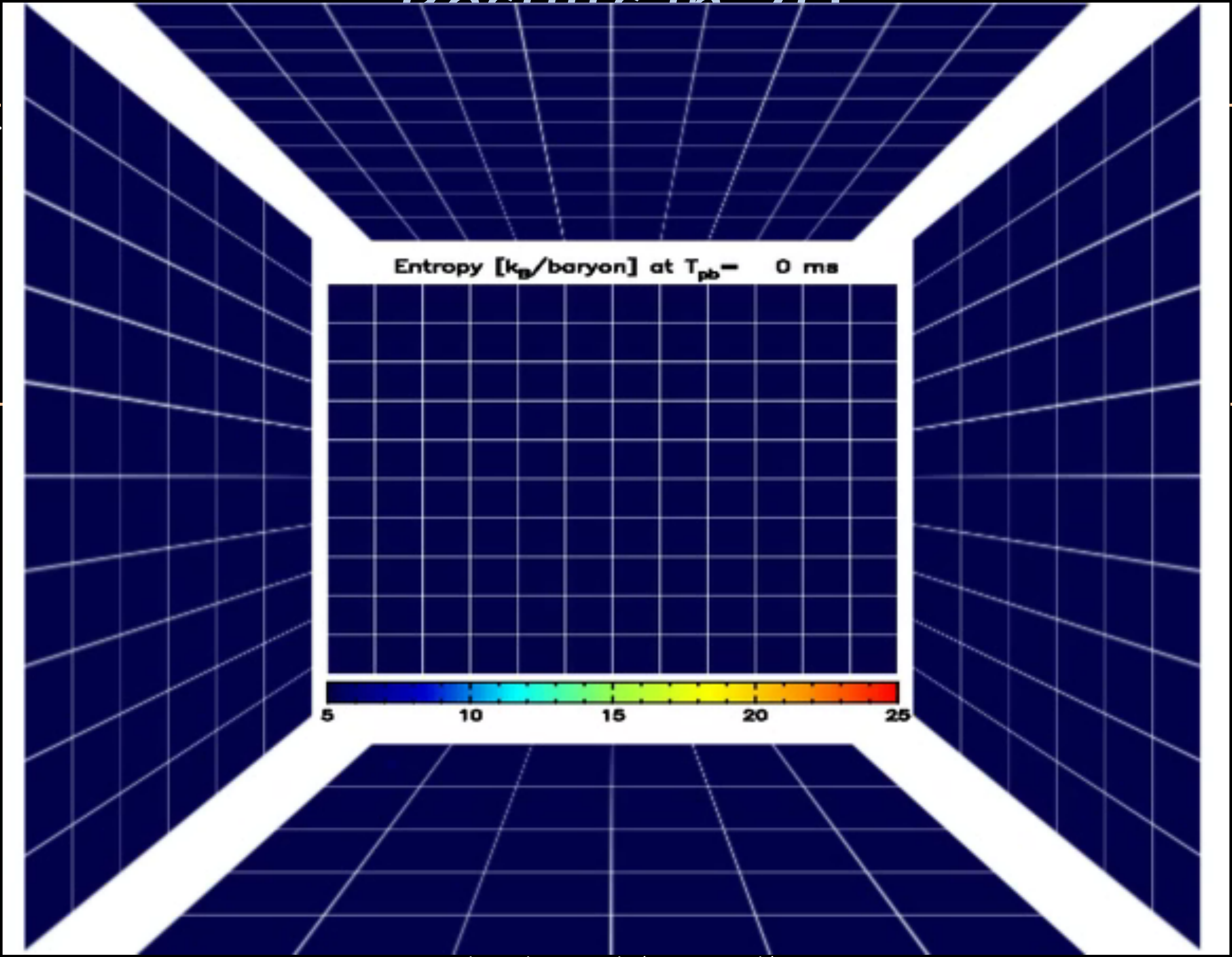
1D simulations, study of failed core-collapse supernova

Other estimates close: explosions for $\xi_{2.5} < 0.15$, BH formation for $\xi_{2.5} > 0.35$

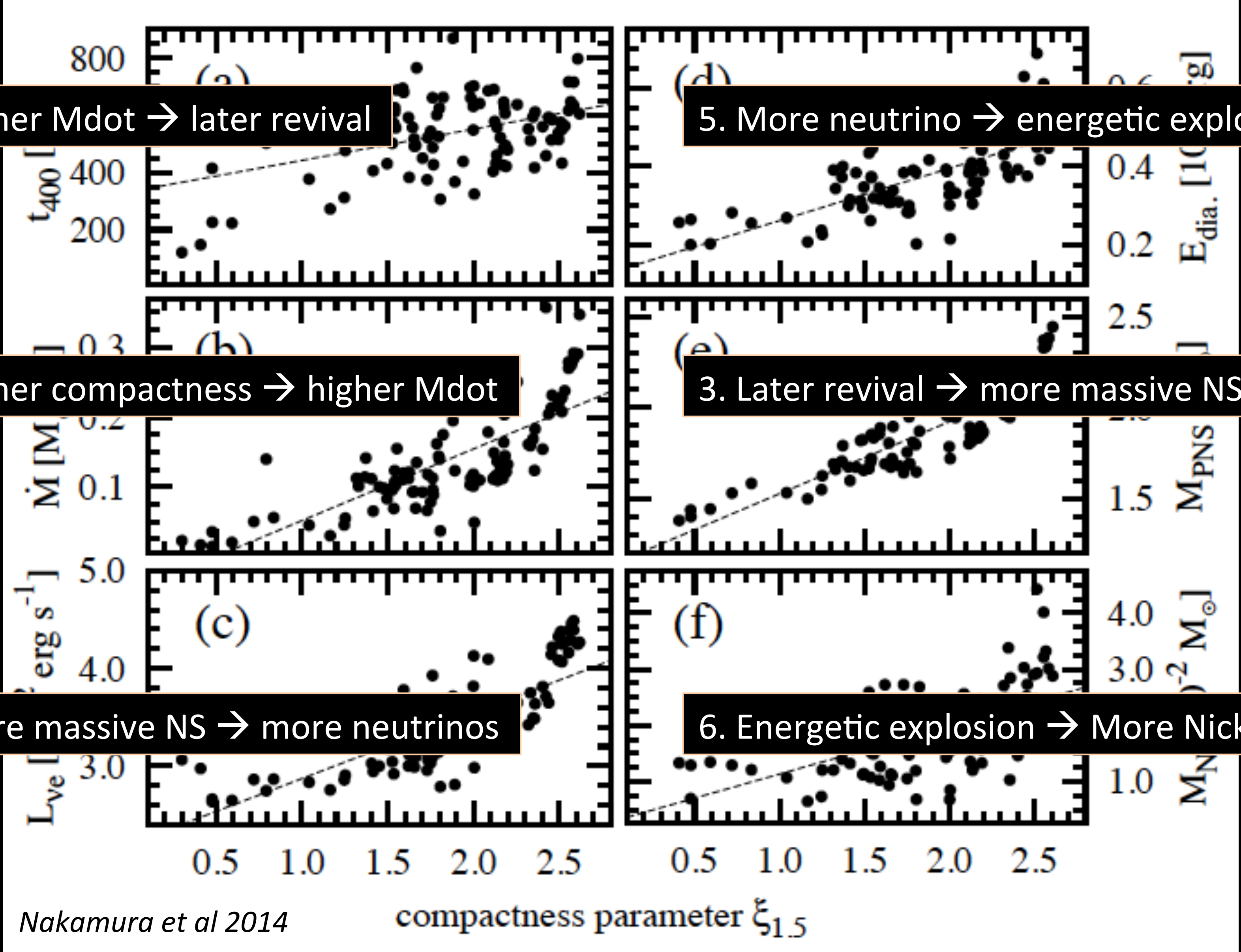
Ugliano et al (2012)

Results in 2D

T



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 2014

Critical compactness in 2D

Failed explosions:

- 2D setup is conducive to explosions

  e.g., Hanke et al (2012)

- Still, some low metal progenitors do not explode
- Remnants above 2.4 Msun not realistic and may not explode in reality.

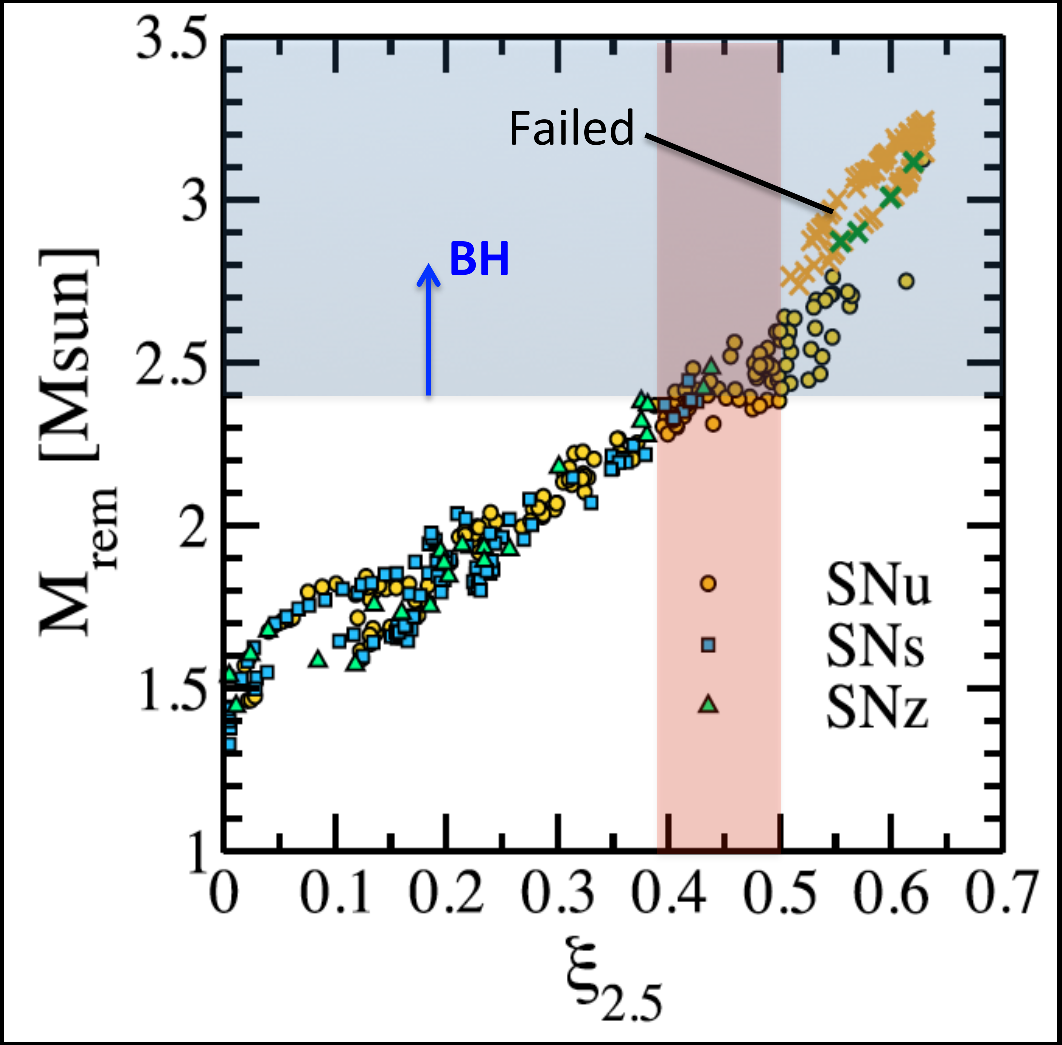
→ Critical $\xi_{2.5} < \sim 0.4 - 0.5$

Critical compactness $\xi_{2.5}$

In 1D: 0.35 – 0.45

In 2D: < 0.4 – 0.5

In 3D: ?

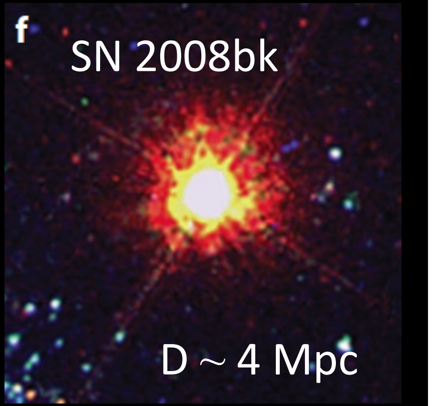


Horiuchi et al (2014)

Hints from progenitors of supernovae?

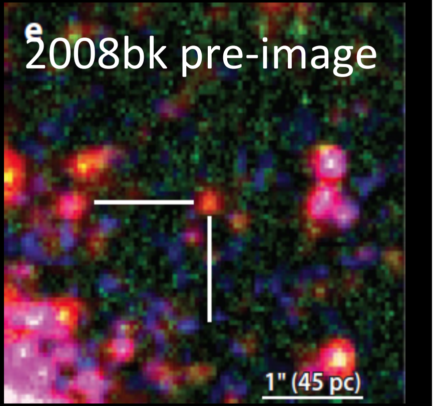
Pre-imaging:

Very successful for Type IIP Sne (now 12 + ~32 limits)



SN 2008bk

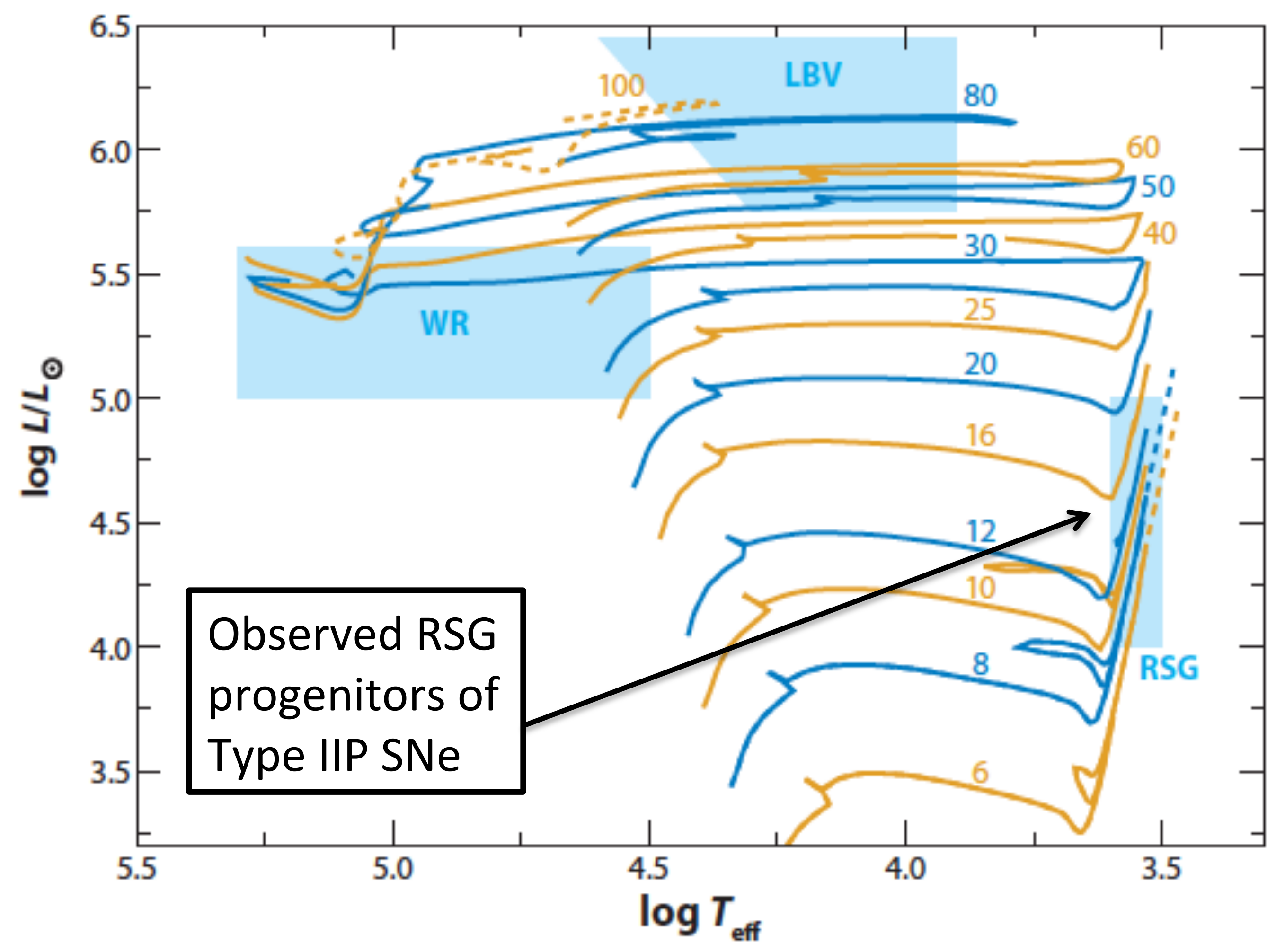
D ~ 4 Mpc



2008bk pre-image

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

→ Umeda-san's talk, Maeda-san's talk



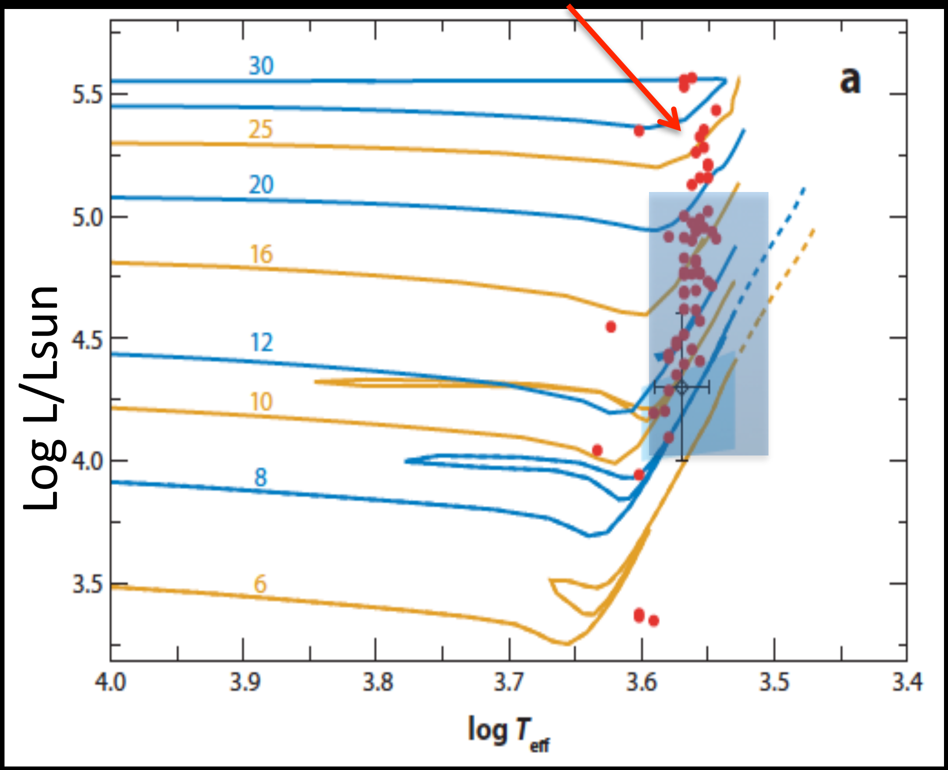
Observed RSG progenitors of Type IIP SNe

Smartt (2009), Smartt (2015)

The red-supergiant problem

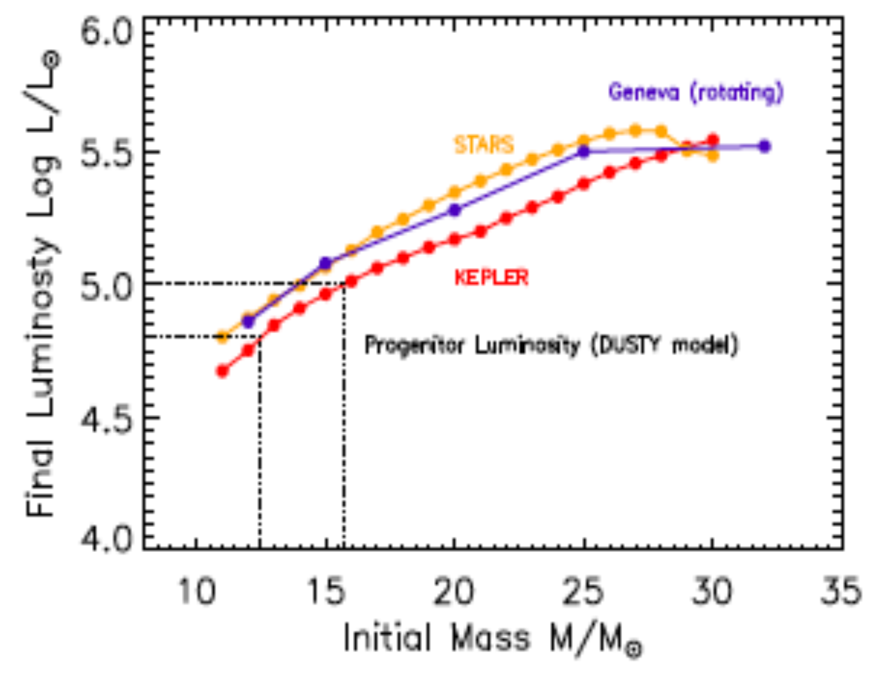
Known RSG (@MW, LMC):

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



Mass estimation:

Observed luminosity to initial stellar mass



$$\rightarrow \begin{cases} M_{min} \approx 9.5^{+0.5}_{-2.0} \text{ Msun} \\ M_{max} \approx 16.5 \pm 1.5 \text{ Msun} \end{cases}$$

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

   → but require unreasonably steep IMF *e.g., Smartt et al (2009)*

2. Change stellar evolution so that the missing red supergiants explode as other types of supernovae (e.g., strip stars → Ibc?)

   → but maybe too many Ibc with mass < 25 Msun *e.g., Groh et al (2013)*

   (16.5 – 30 Msun is ~22% of core collapse)

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

   → but dust models are still unrealistic; radio and x-ray limits

   e.g., Walmswell & Eldridge (2012), Kochanek (2013), Dwarkadas (2014)

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

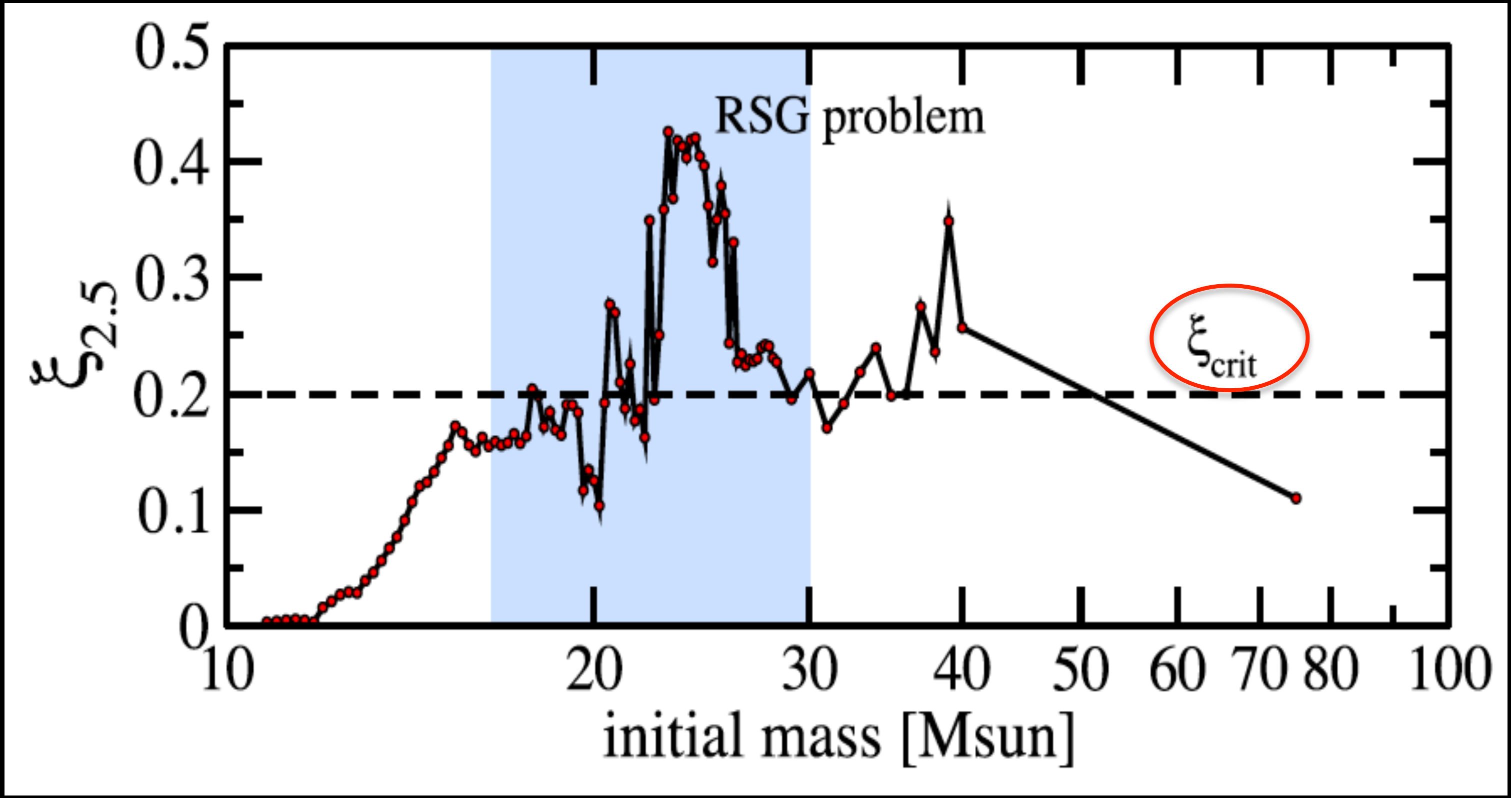
   e.g., Smartt et al (2009)

   → but why must they collapse to black holes?

Connection to compactness

- Possible connection to compactness

Peak in the distribution of compactness matches the RSG problem mass range



Horiuchi et al (2014)

➔ Critical compactness: $\xi_{2.5} \sim 0.2$

In 3D?

Critical compactness

In 1D: 0.35 – 0.45

In 2D: < 0.4 – 0.5

Progenitor study: ~ 0.2

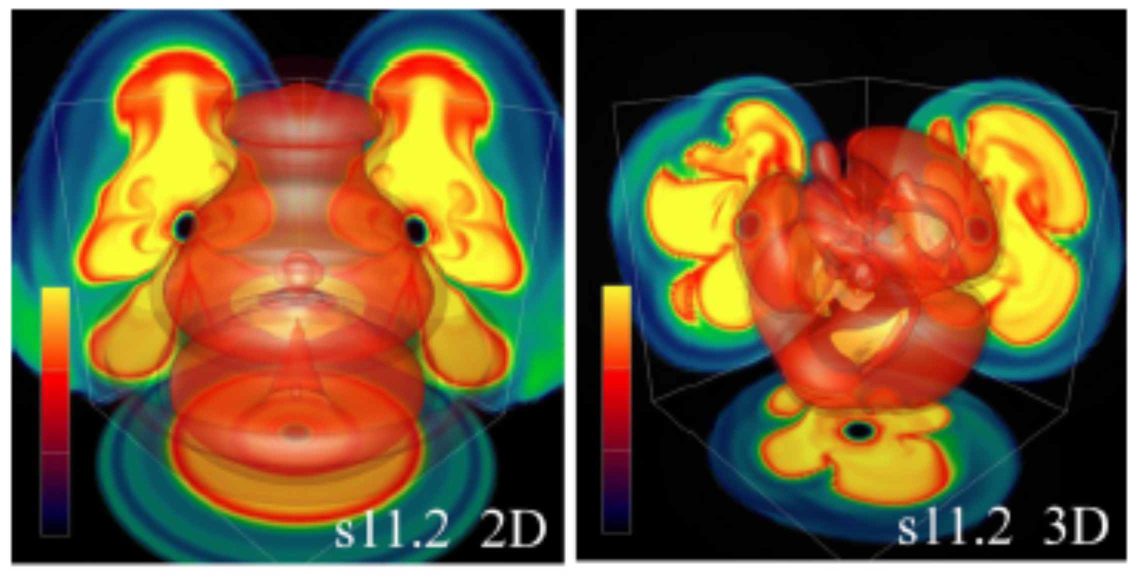
In 3D: ?

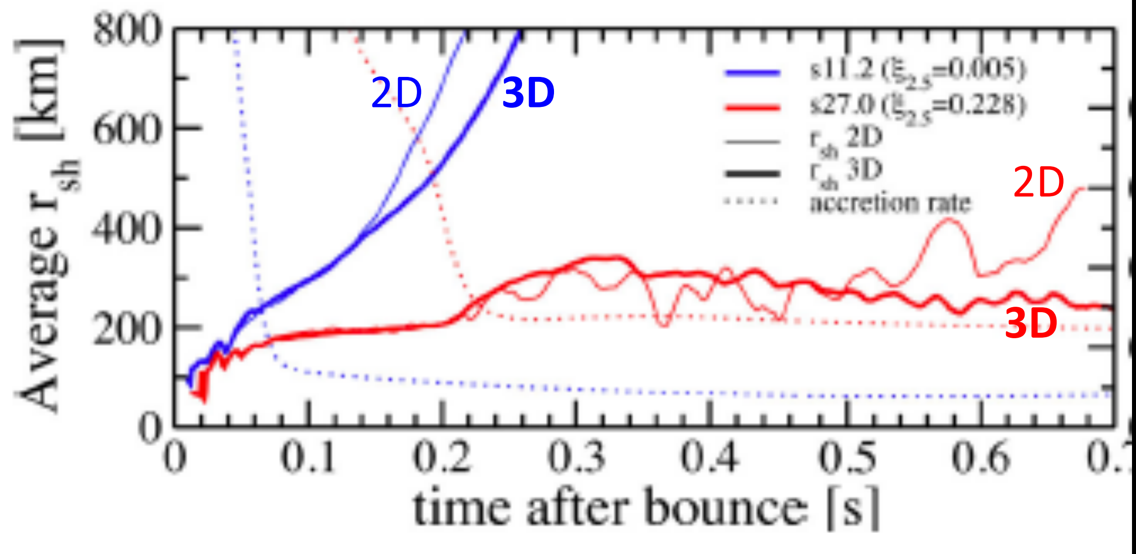
No systematic study with 3D sims yet.

But qualitatively:

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

entropy @200ms





Horiuchi et al (2014)

In 3D?

Critical compactness

In 1D: 0.35 – 0.45

In 2D: < 0.4 – 0.5

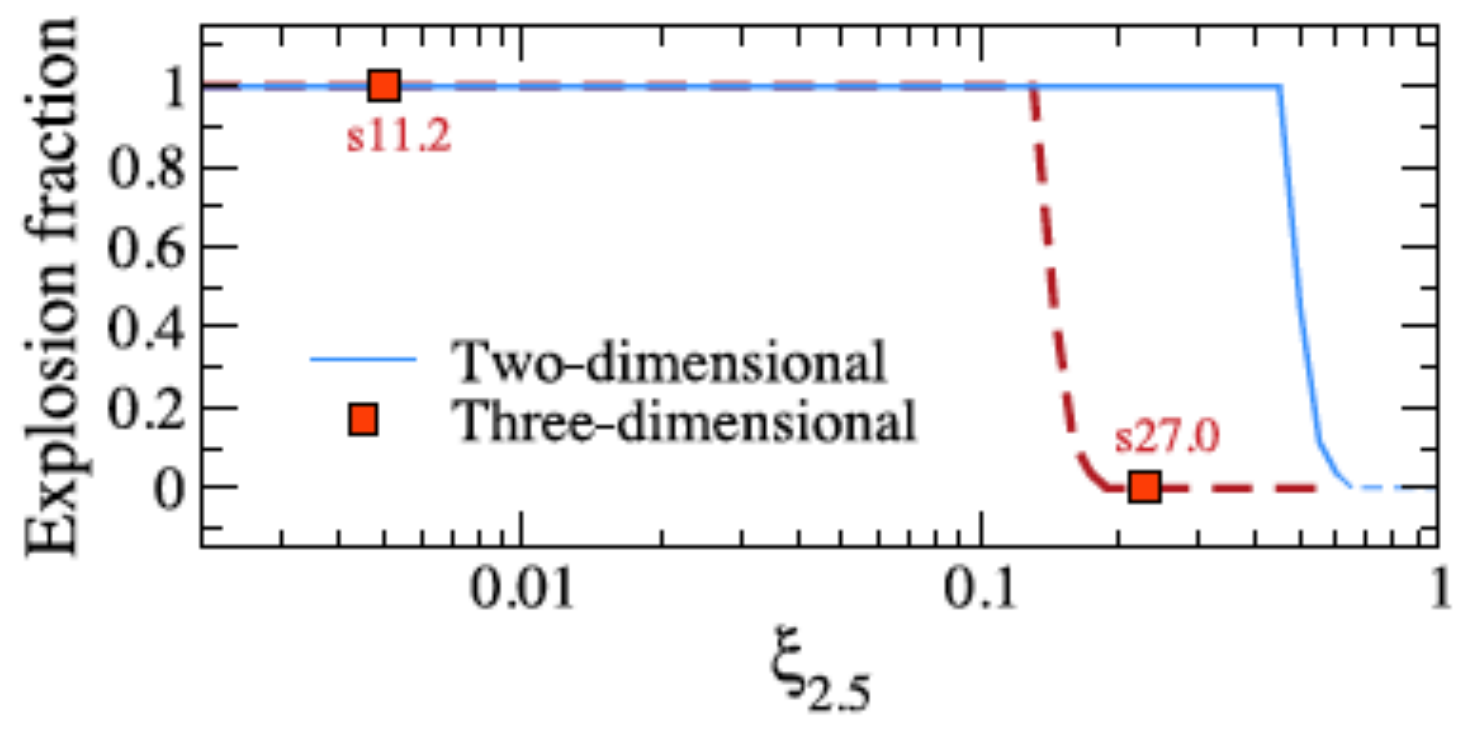
Progenitor study: ~ 0.2

In 3D: < ~ 0.2

➜ The explosion fraction

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

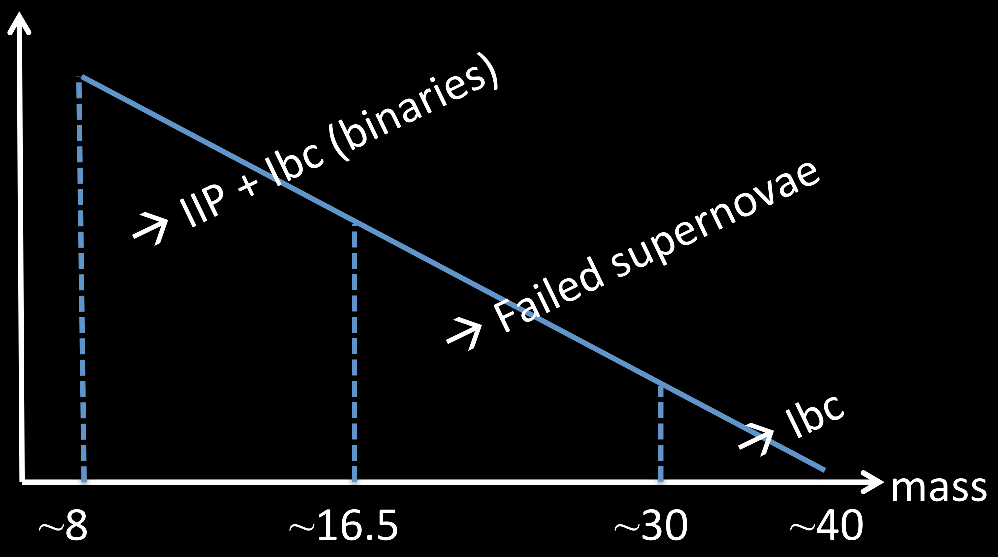
Perhaps more noisy in reality. Awaits more 3D simulations to confirm.



Horiuchi et al (2014)

IMPLICATIONS OF CRITICAL COMPACTNESS$_{2.5} \sim 0.2$

Prediction 1: SN type ratio

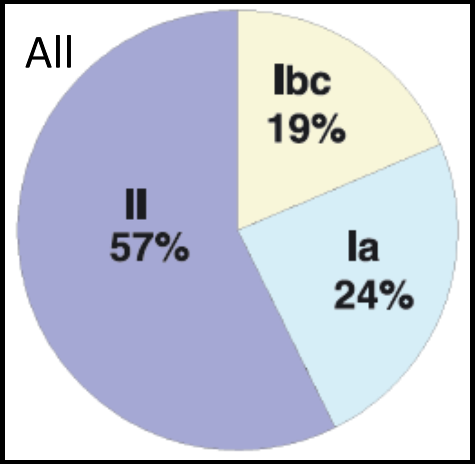


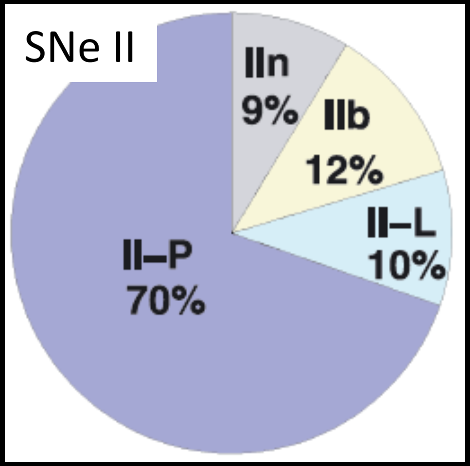
To match observed IIP / Ibc ratio:

➔ Binary fraction 30% (of 8–16.5 Msun) needed

➔ 3/4 of Ibc arise from binary stripped stars of ZAMS mass < 16.5 Msun

According to volume-limited sample (LICK):



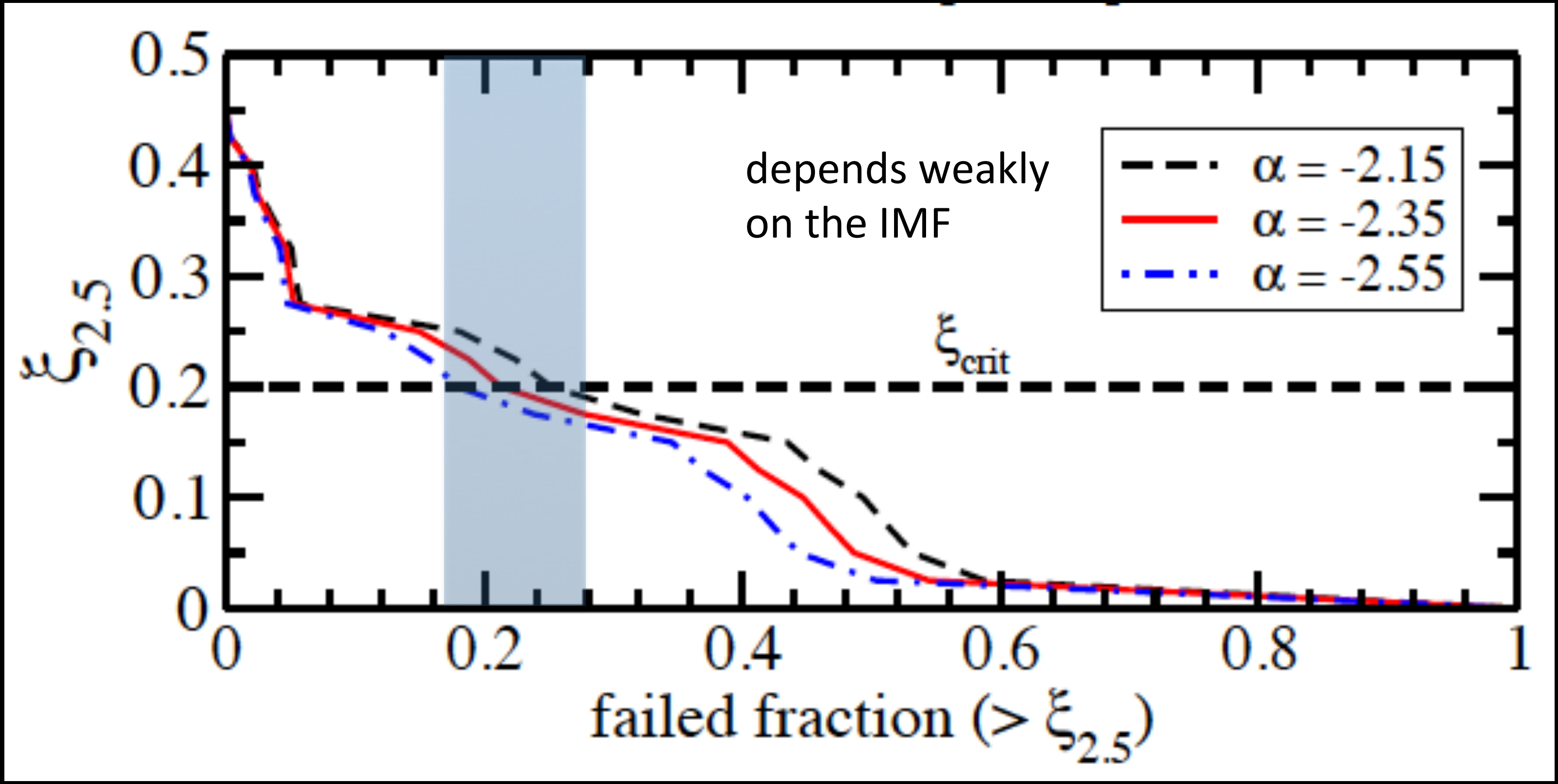


IIP / Ibc ~ 0.57*0.7 / 0.19 ~ 2.1

Prediction 2: fraction of failed supernovae

Failed fraction

The fraction of failed supernovae (stars with compactness $\xi_{2.5} > 0.2$) is 20-30% of all core collapse



depends weakly on the IMF

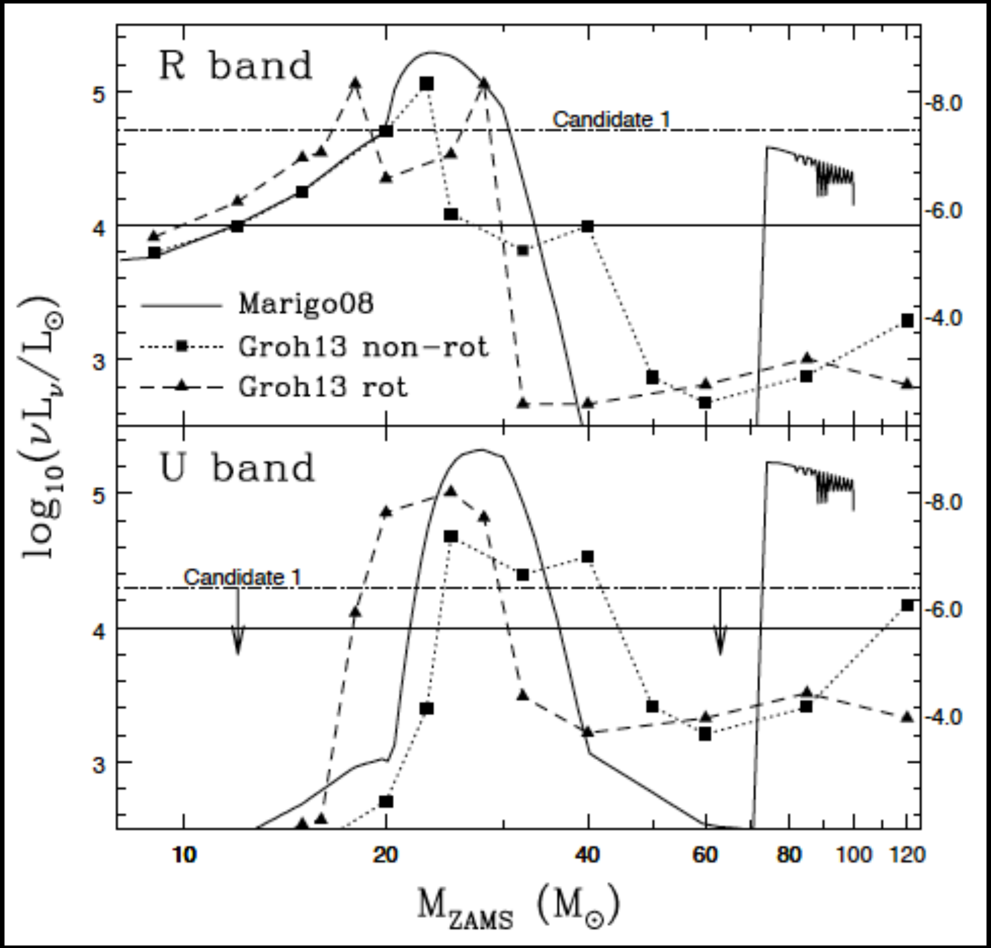
Horiuchi et al. (2014)

Searching for failed explosions: Survey about nothing

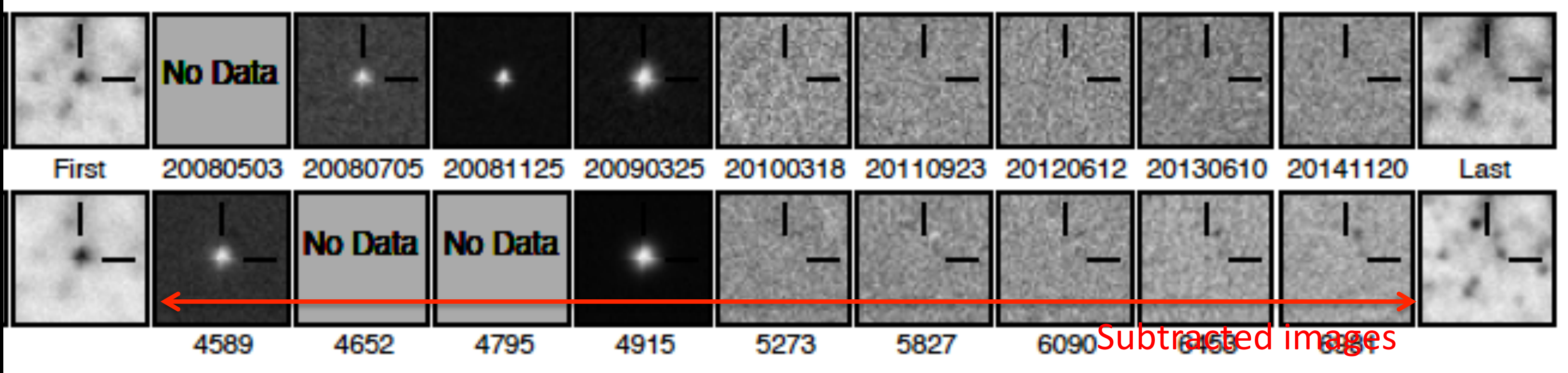
Survey About Nothing

- 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 $\sim$1 core collapse /yr
  - → In 10 years, sensitive to 20 – 30% failed fraction at 90%CL

Kochanek et al. (2008)



Gerke et al. (2015)



Results so far:

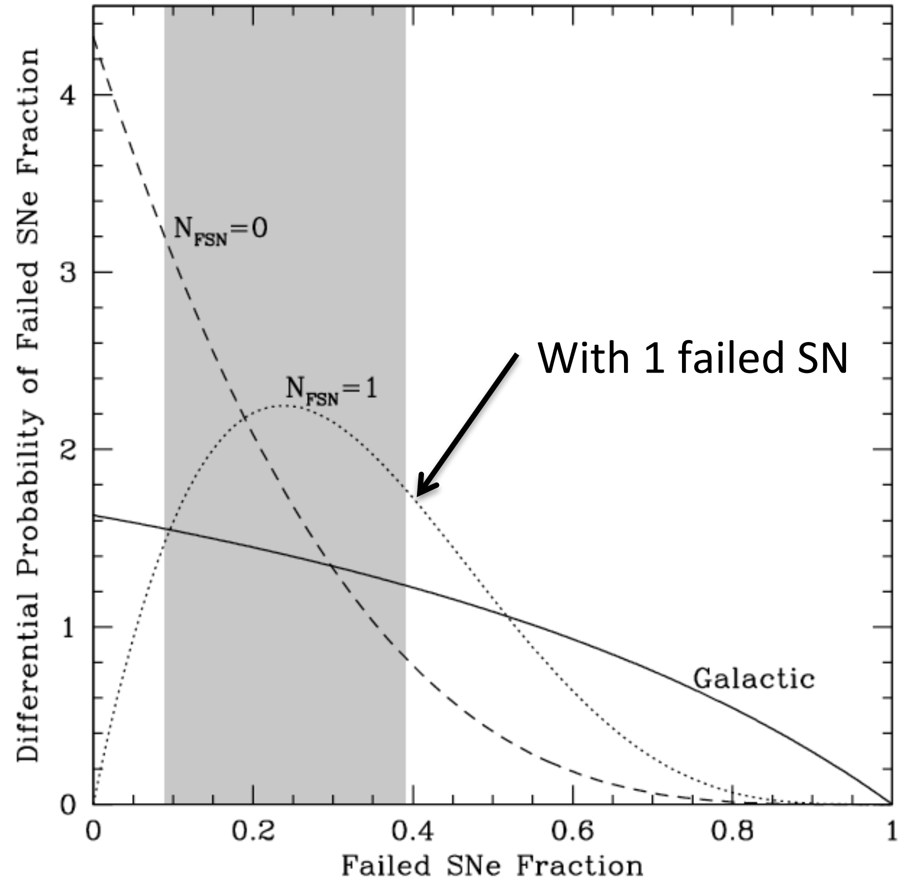
In 4 years running,

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

→ Consistent with 20 – 30% fail rate.

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

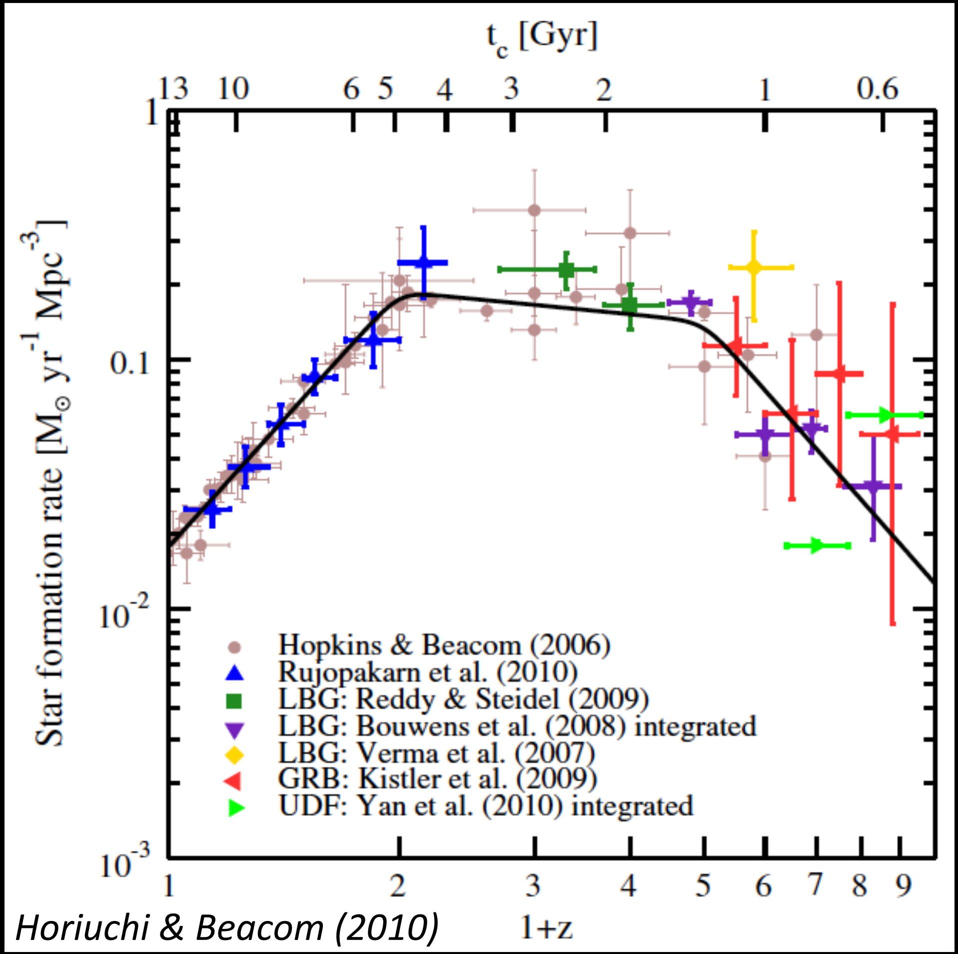
Gerke et al. (2015)



The beginning: star formation

Core collapse rate = Birth rate of massive stars

*because lifetime of massive stars are cosmologically short



Horiuchi & Beacom (2010)

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 et al (2013)
Mathews et al (2014)

Cosmic supernova rate

Two different methods:

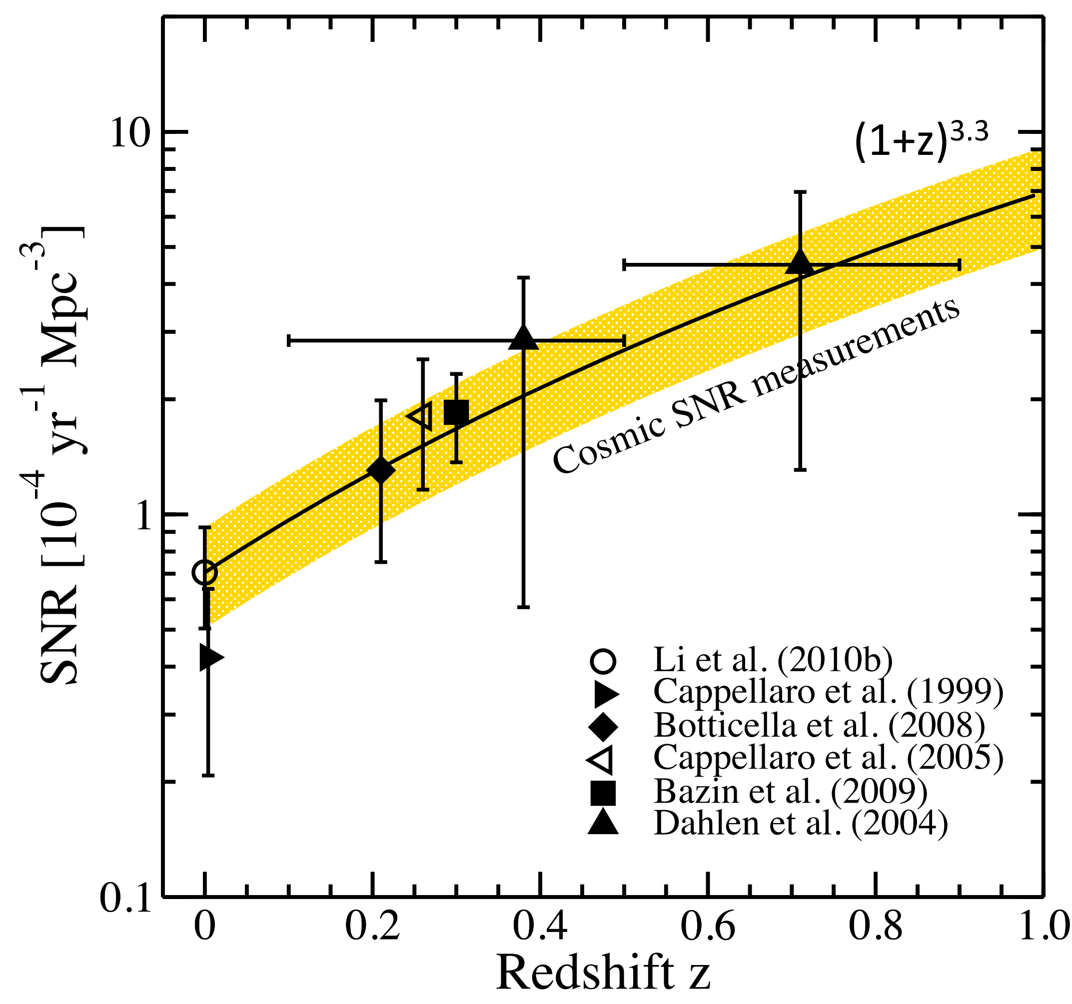
- Target pre-selected galaxies, e.g., LOSS, STRESS
- Target pre-selected fields, e.g., SNLS, HST-ACS, SDSS, DES

Different systematics:

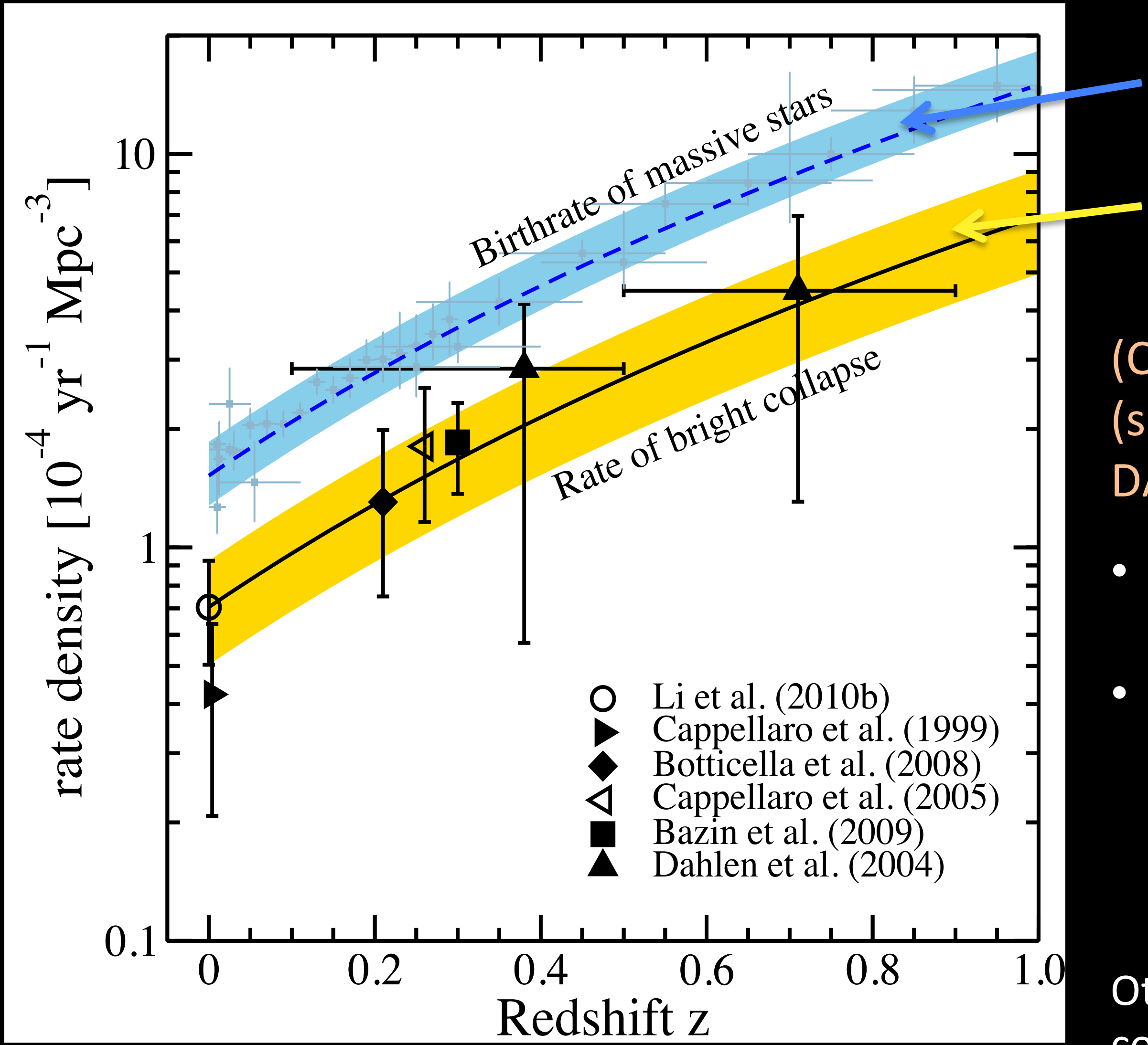
Dust corrections, sample sizes, supernova-ID, supernova luminosity function, etc…

Nevertheless measurements converging.

And improving quickly



Searching for failed explosions: rates



Horiuchi et al (2010)

Birth rate of massive stars

Supernova rate derived from *luminous* supernovae

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

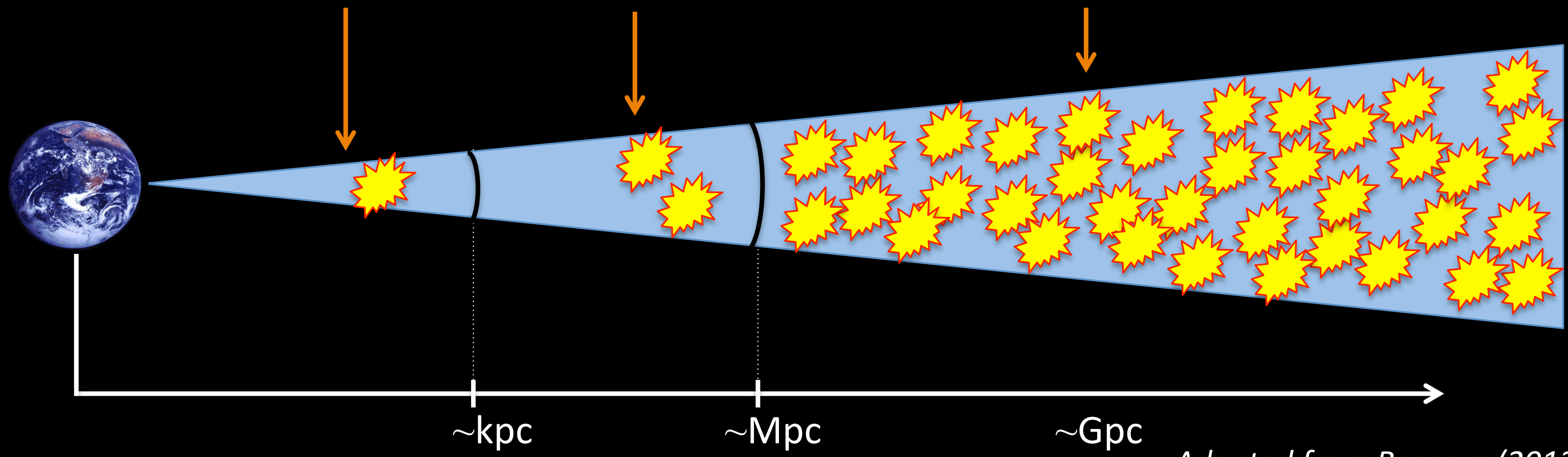
- Consistent with 30% failed supernova fraction
- Other possibilities include ONeMg collapse, dust (especially from mass loss), fall back intense collapse, …

Others probes: abundances, compact object mass function

Brown & Woosley (2013)
Kochanek (2013)

FUTURE NEUTRINO TESTS

Distance scales and physics outcomes



$N_\nu \gg 1$: BURST

SN rate ~ 0.01 /yr

$N_\nu \sim 1$: MINI-BURST

SN rate ~ 0.5 /yr

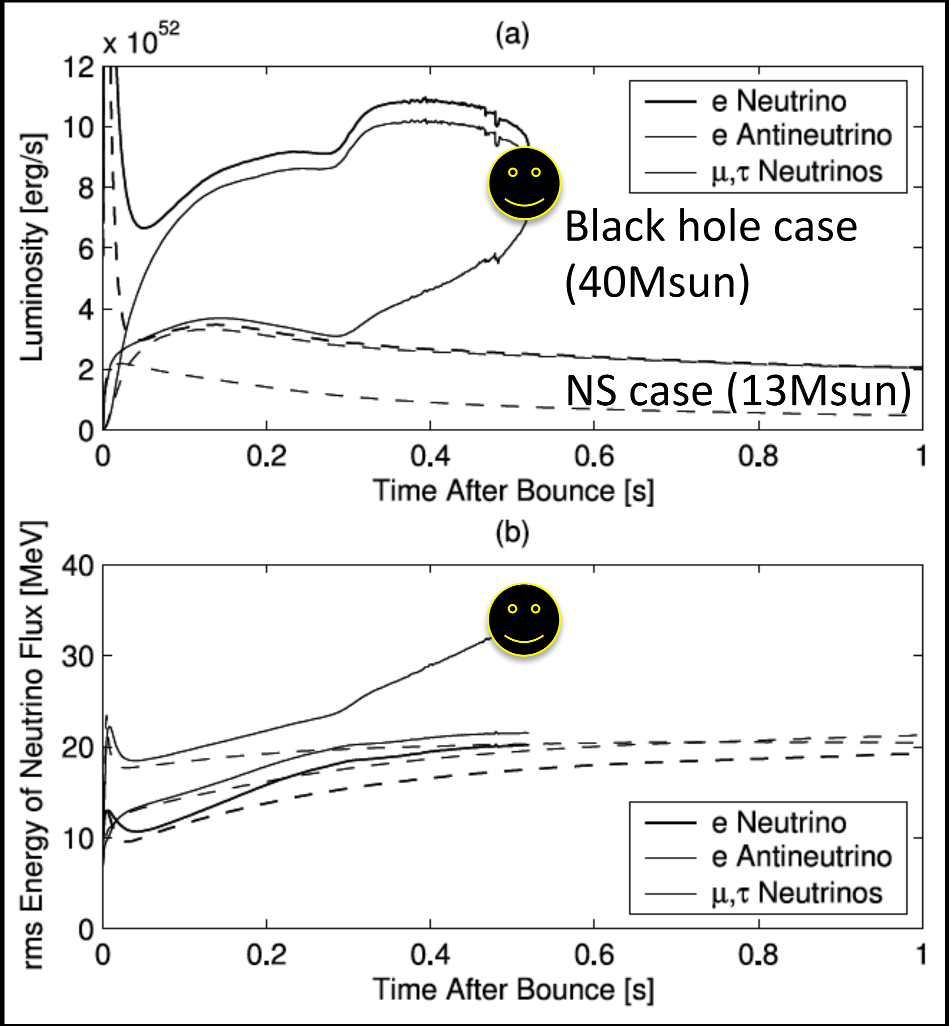
$N_\nu \ll 1$: DIFFUSE

SN rate ~ 10^8 /yr

Adapted from Beacom (2012)

	Galactic burst	**Mini-bursts**	**Diffuse signal**
Physics reach	Explosion mechanism, astronomy	supernova variety with individual ID	Average emission, multi-populations
Required detector	Basics are covered	Next generation	Upcoming upgrades

Neutrino emission in black hole formation



Black hole case (40Msun)

NS case (13Msun)

Liebendoerfer et al (2004)

Neutrino emission:

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

Mass profile <--> neutrino luminosity

1. Mass profile → mass accretion rate

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

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:

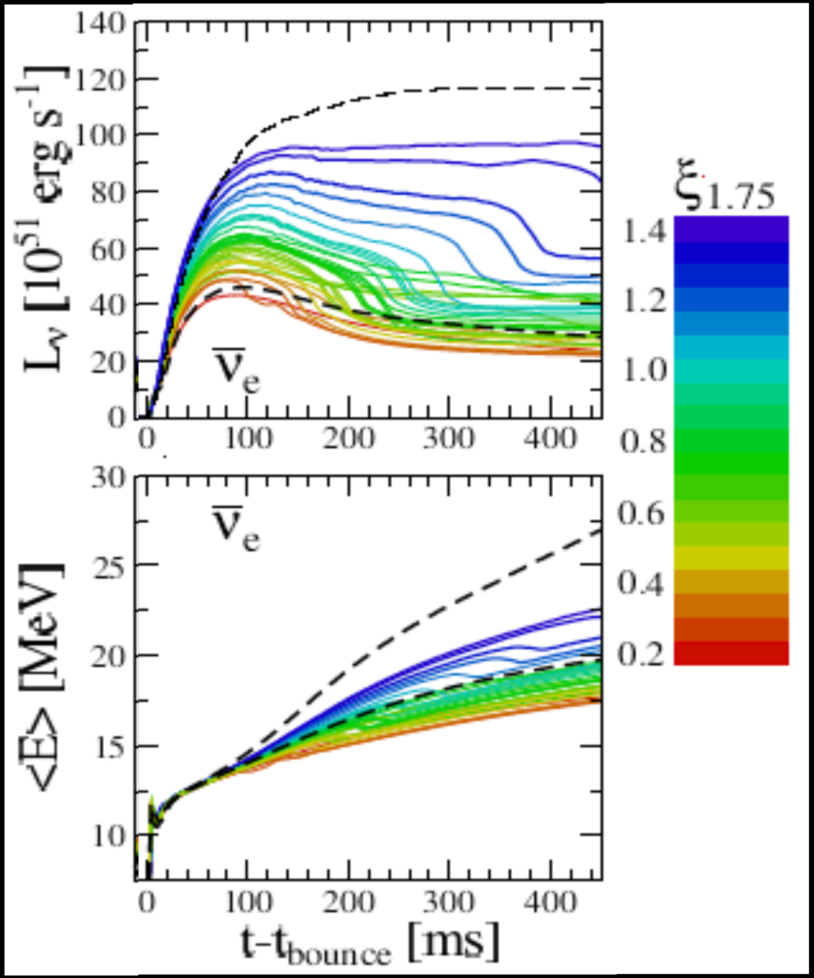
$$\boxed{L_\nu} = \frac{L_{diff}}{1 + t/t_{diff}} = \frac{E_{int}}{t_{ff} + t_{diff}}$$

$t_{ff} \sim O(100)$ ms $t_{diff} \sim O(400)$ ms

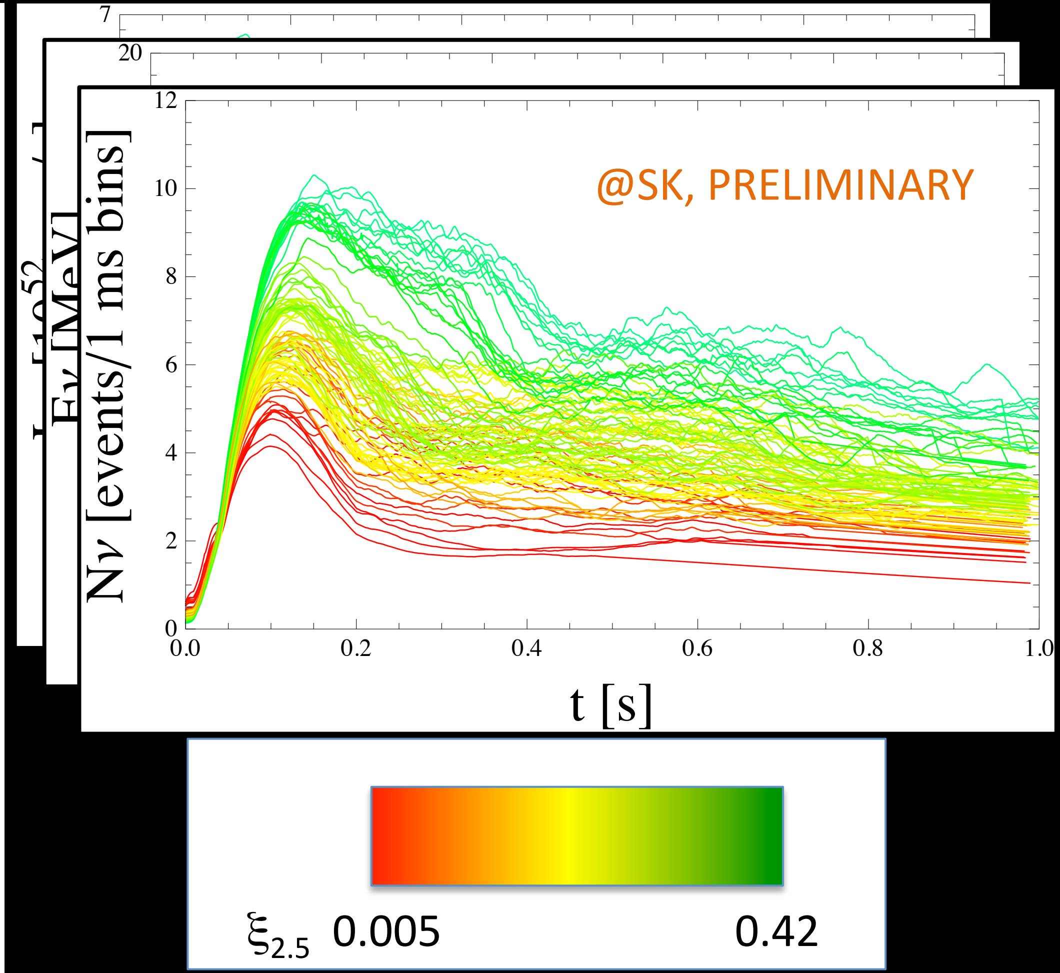
Fischer et al (2009)
Suwa et al (2014)

Measuring the compactness

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



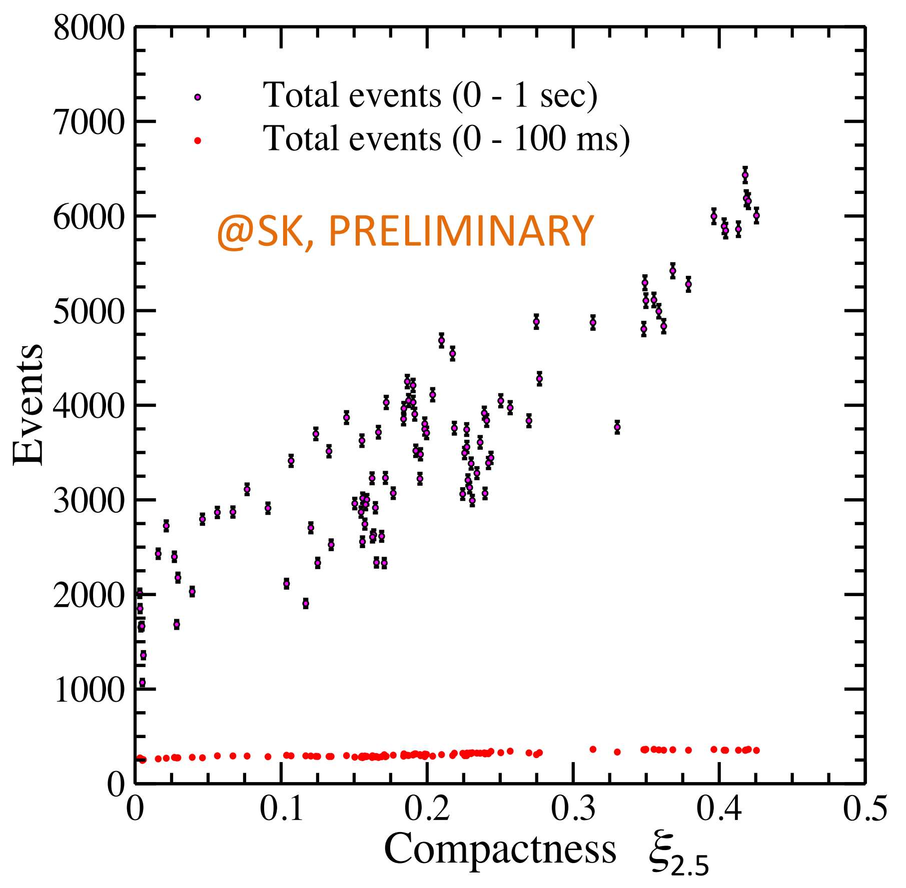
O'Connor & Ott (2013)

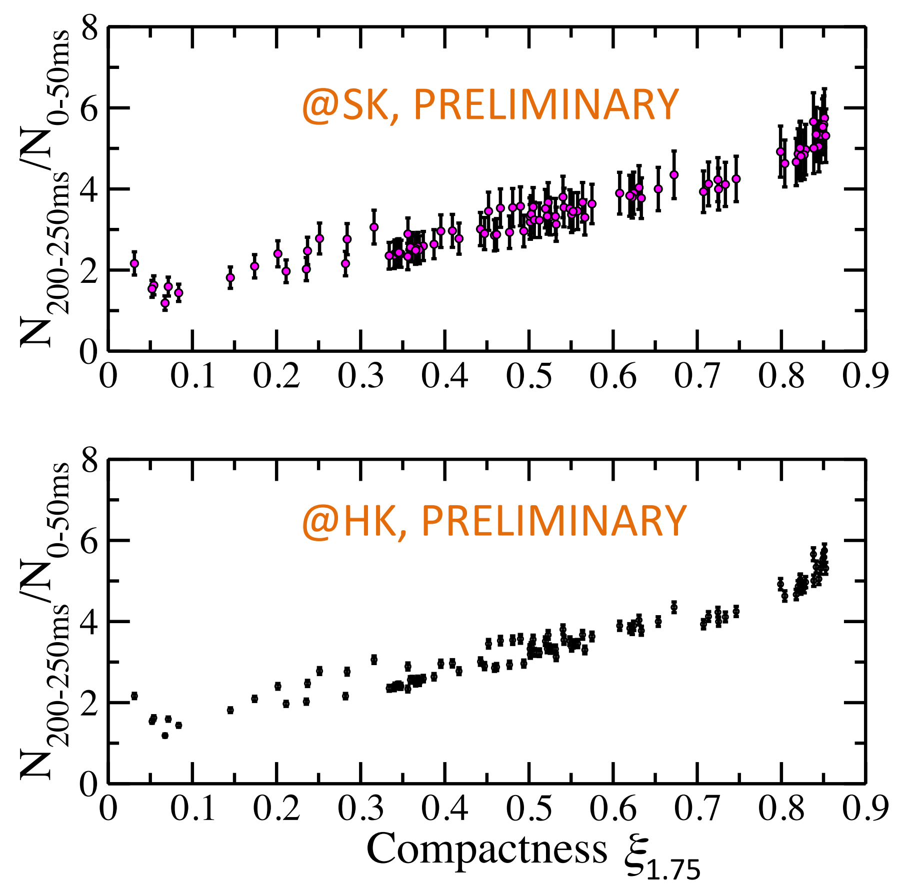


Measuring the compactness

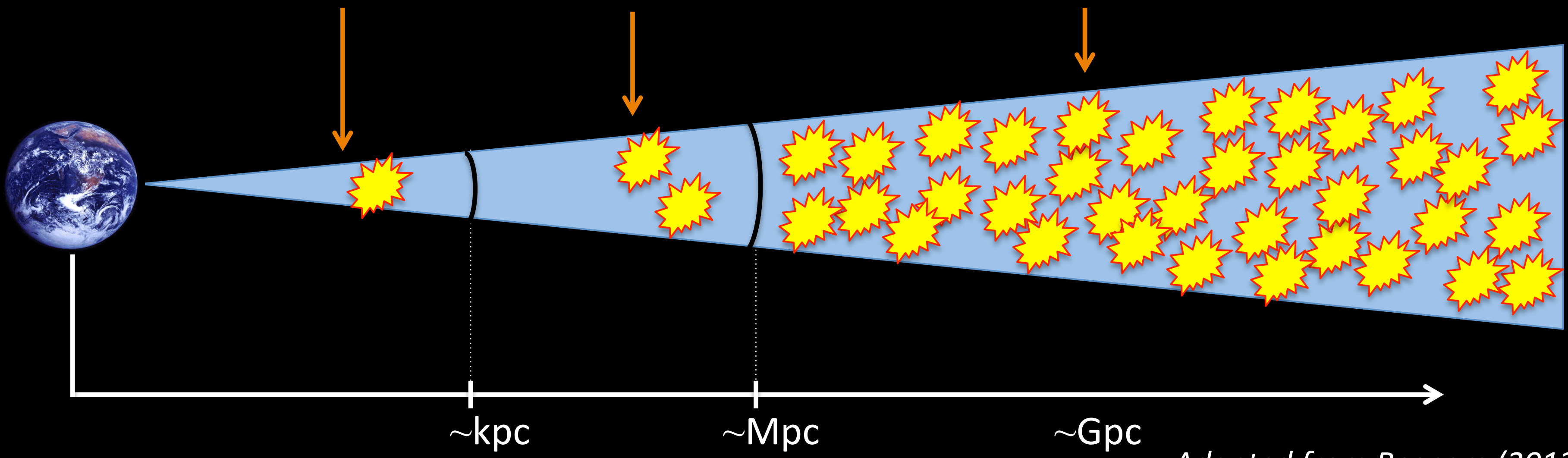
Events scale with compactness, but this is degenerate with many other effects (distance, rotation, EOS, flavor mixing)

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





Distance scales and physics outcomes



$N_\nu >> 1$: BURST

SN rate ~ 0.01 /yr

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SN rate ~ 0.5 /yr

$N_\nu << 1$: DIFFUSE

SN rate ~ 10^8 /yr

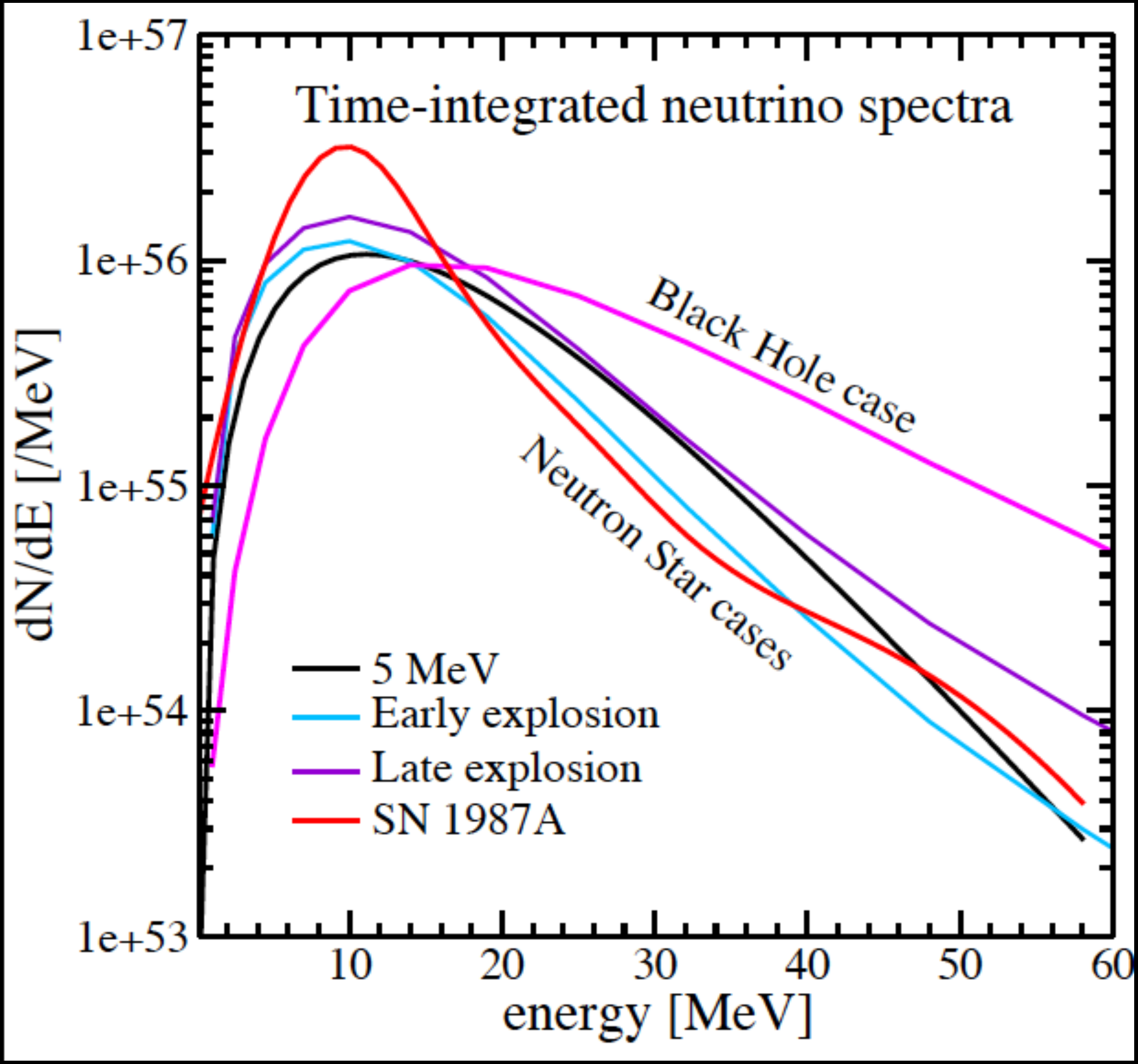
Adapted from Beacom (2012)

	Galactic burst	**Mini-bursts**	**Diffuse signal**
Physics reach	Explosion mechanism, astronomy	supernova variety with individual ID	Average emission, multi-populations
Required detector	Basics are covered	Next generation	Upcoming upgrades

Time-integrated neutrino signal

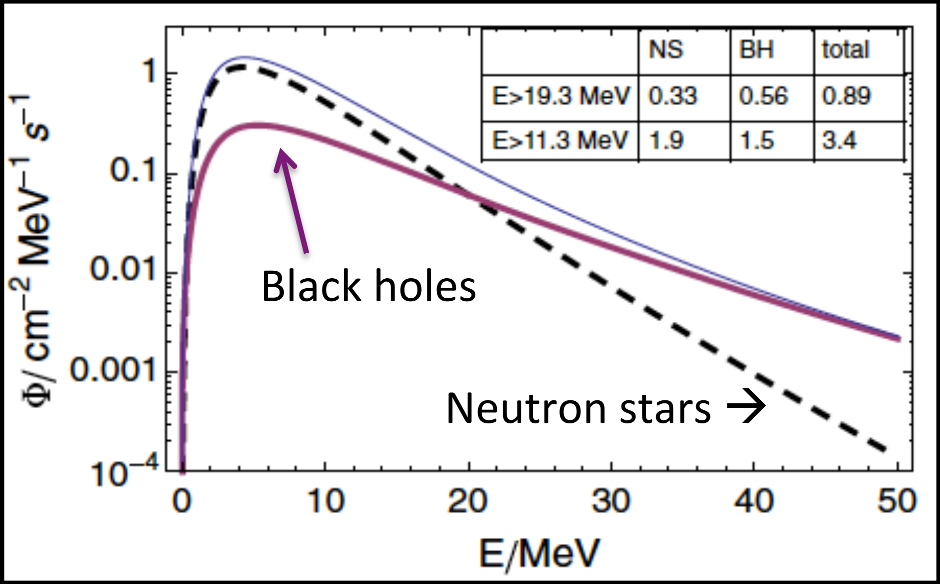
Neutrino emission:
Compared to collapse to neutrino stars, the duration of neutrino emission is shorter for collapse to black holes.

However, the time-integrated neutrino emission is still different



Event rates

Diffuse neutrino fluxes:

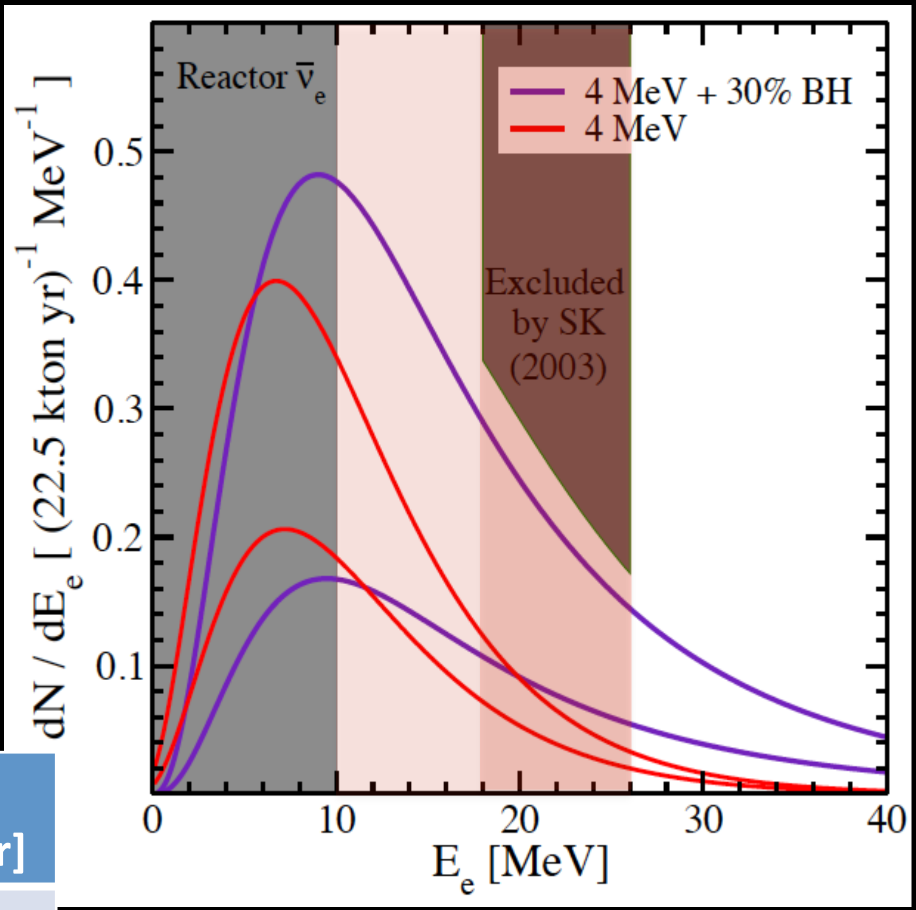


	NS	BH	total
E>19.3 MeV	0.33	0.56	0.89
E>11.3 MeV	1.9	1.5	3.4

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

Event spectra with uncertainties:

Adapted from Horiuchi et al (2009)



Searches: *Malek et al (2003)*
Bays et al (2012)

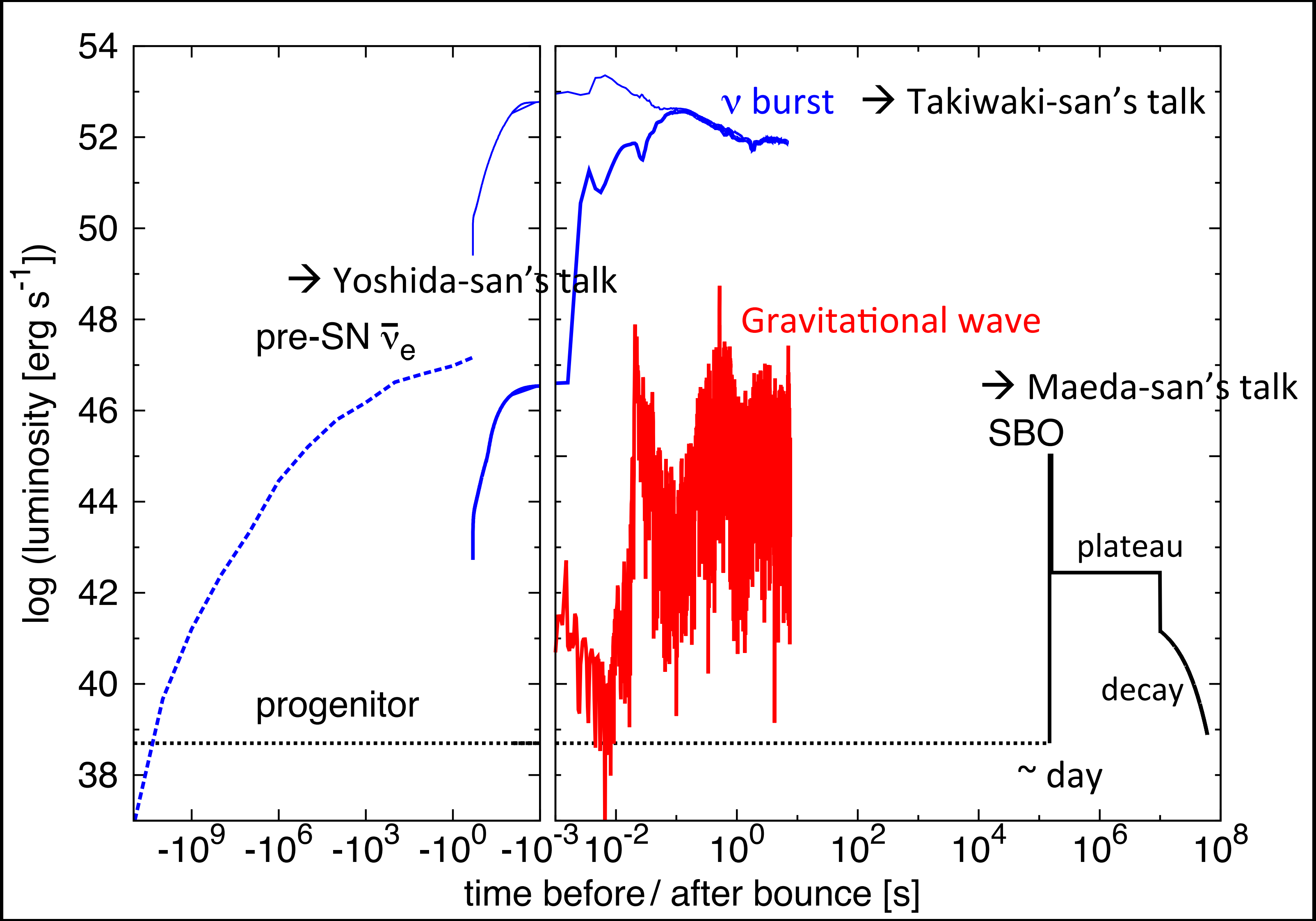
Event rate at 0.5 Mton FV:

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

LET'S GO SUPERNOVA!

Multi-messenger light curve

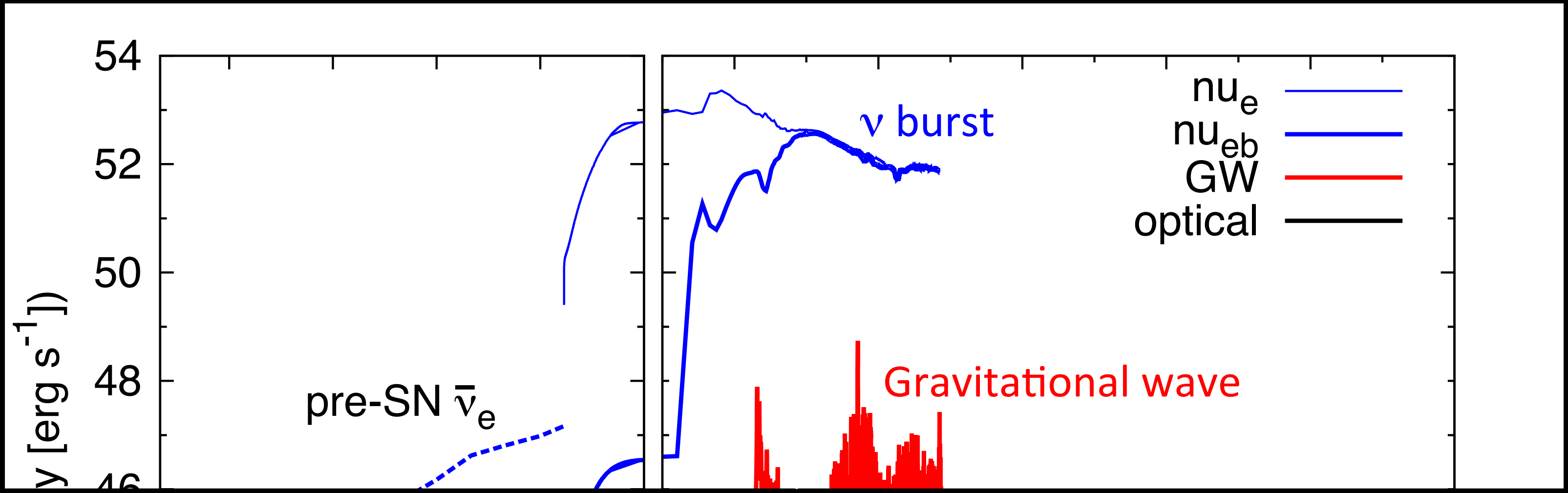
Based on long-term (~7s) axisymmetric core-collapse simulation of 17Msun RSG progenitor

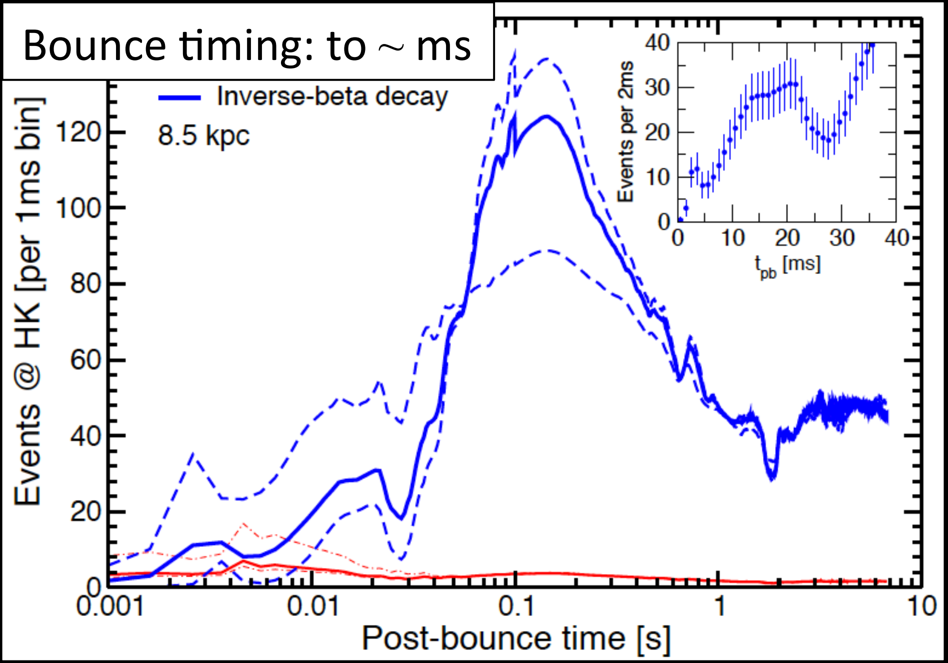


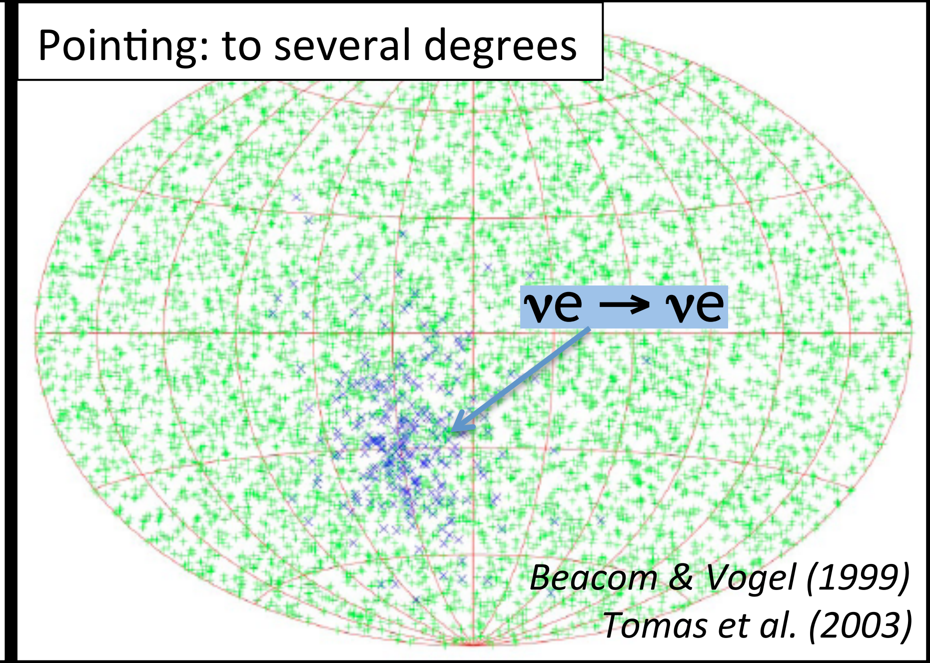
Nakamura, Horiuchi, et al (in prep)

Neutrino signals

Inverse-beta decay, electron scattering



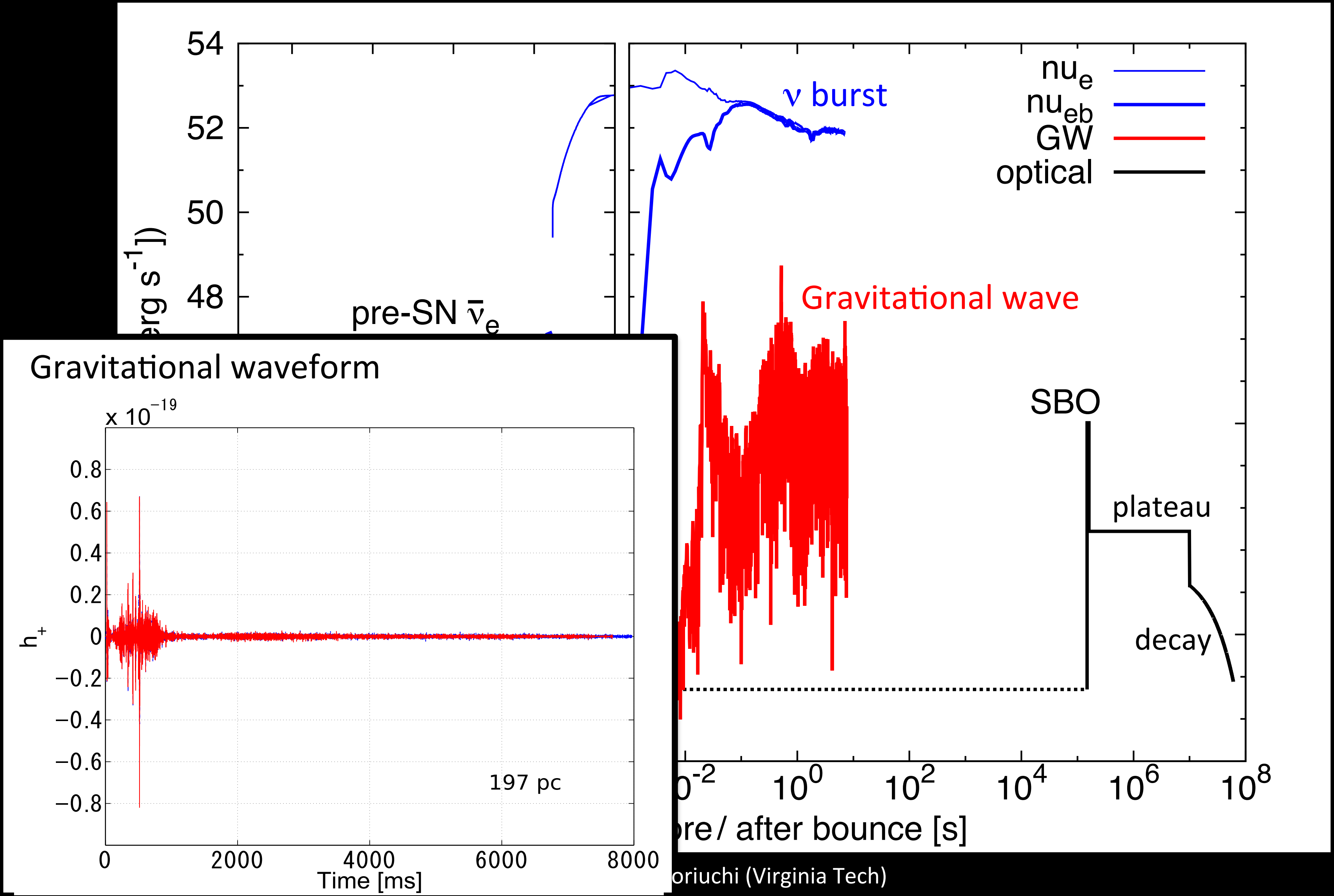

Bounce timing: to ~ ms


Pointing: to several degrees

Beacom & Vogel (1999)
Tomas et al. (2003)

Gravitational wave signal

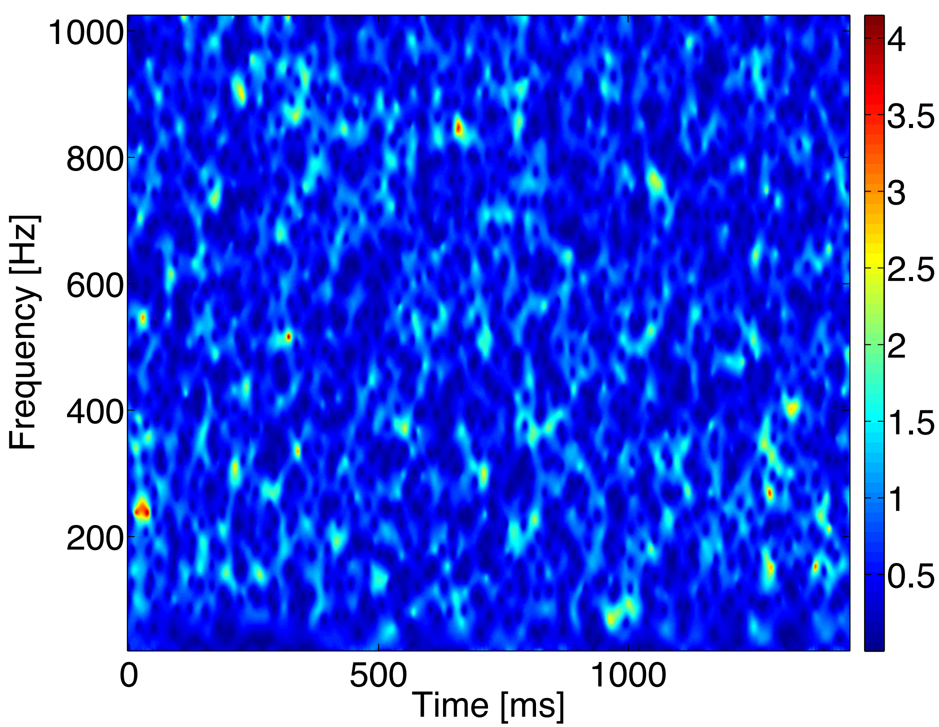
Using quadruple formula



Timing improves GW detectability

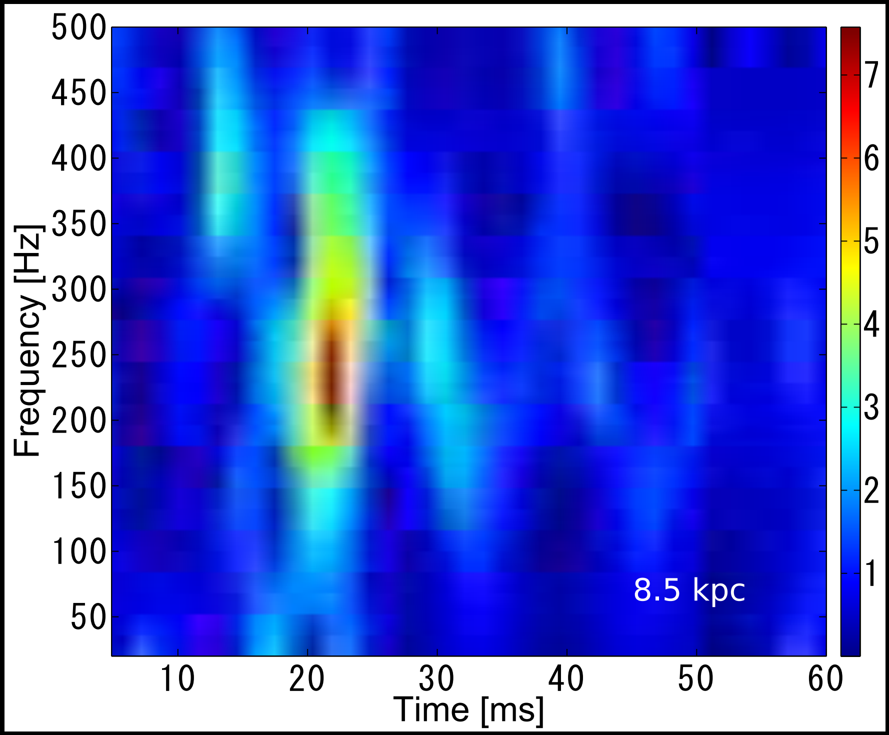
Without neutrino timing

Signal-to-Noise over first 1.5 sec of GW signal reaches some ~3.5 @200Hz corresponding to prompt convection GW: no strong detection



With neutrino timing

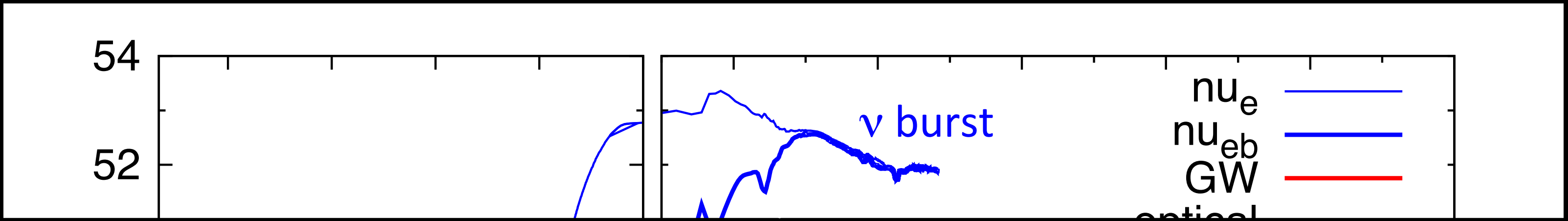
Narrow time window to 60 ms and expected frequency [50, 500] Hz: signal to noise reaches ~7, can claim `correlated' detection



➔ Timing of core bounce helps GW detection

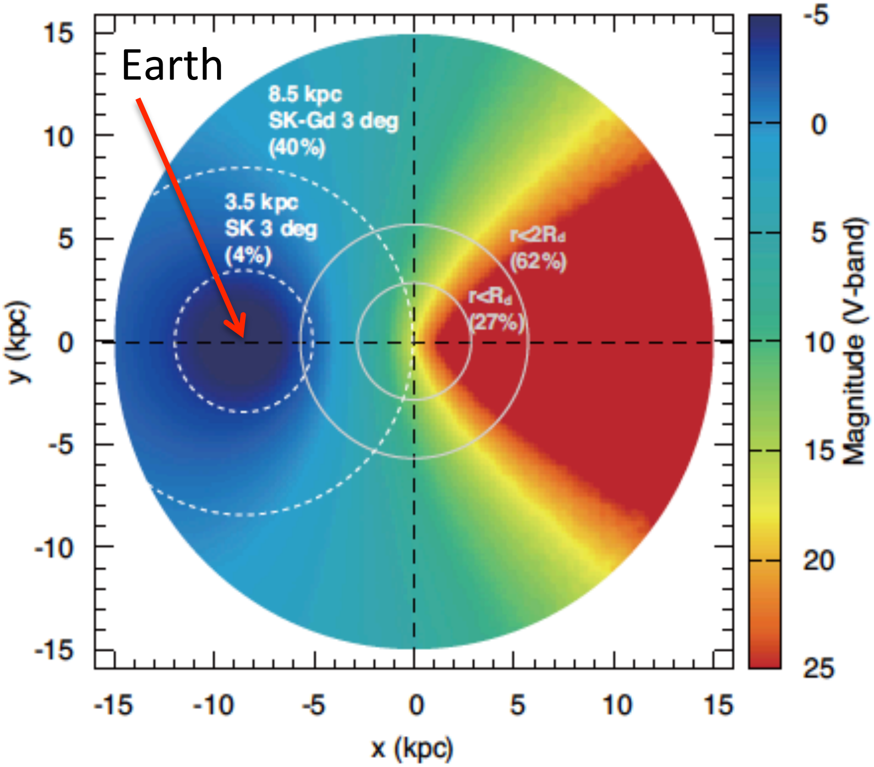
Electromagnetic signal: plateau

Using Popov et al (1993) → Maeda-san’s talk



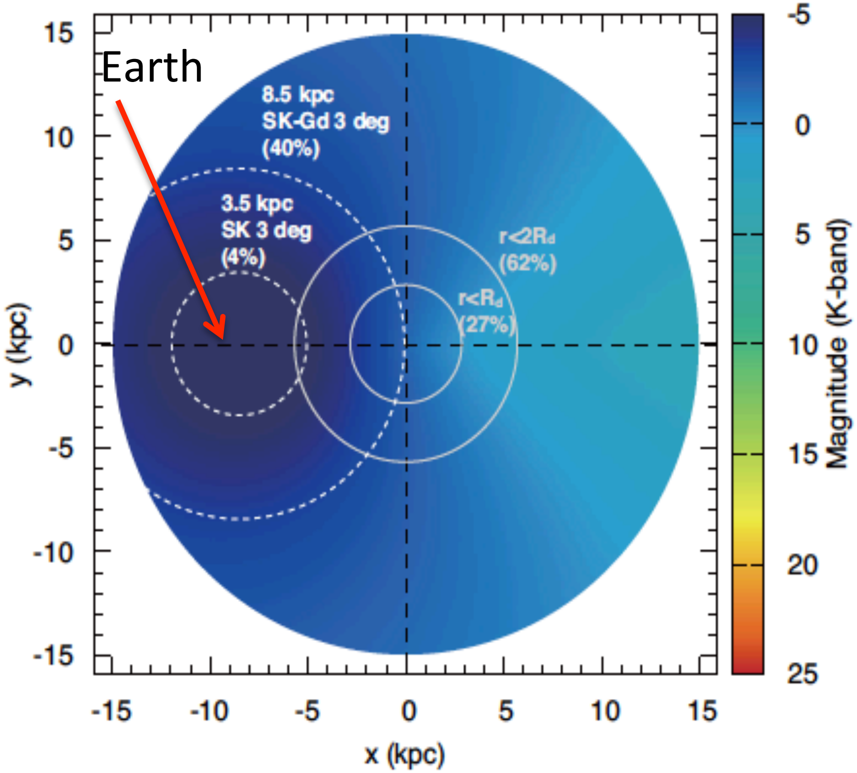
Magnitude of optical signal:

Important WHERE the CCSN occurs:



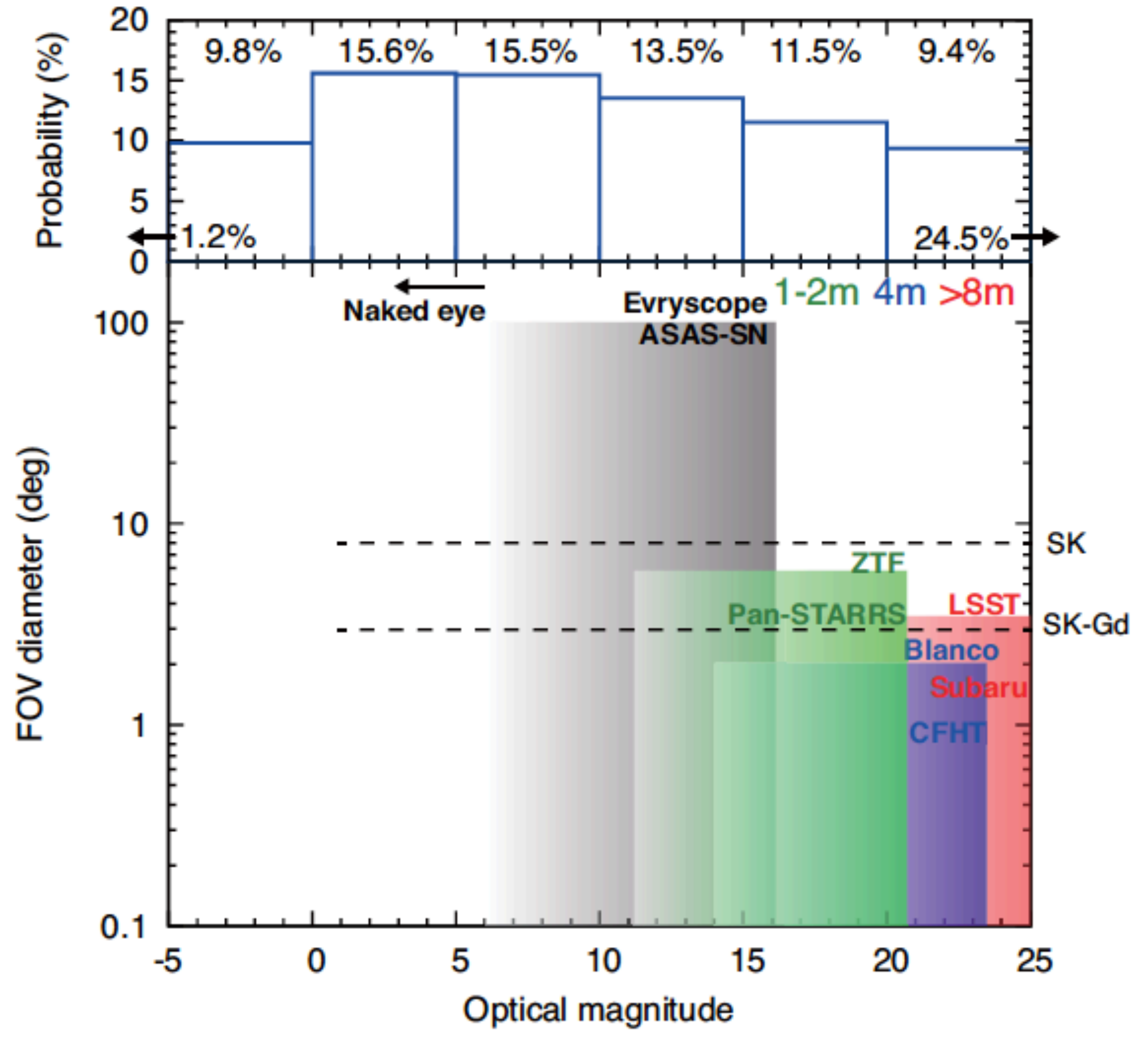
Magnitude of infra-red signal:

Luminous anywhere in the Galaxy:



Pointing improves optical detectability

Expected optical flux & detector capabilities:



Key points:

1. ~60% of CCSNe are within reach of modern optical telescopes
   - ~40% of CCSNe can be followed by large FoV < 1 m telescopes
   - ~20% of CCSNe need rapid pointing information and modern > 1m telescopes

   → Need SK + Gd accuracy!

2. ~25% of CCSNe are hard to reach even with modern 8m telescopes

3. ~15% may to too bright

Nearby target database

NOT complete lists, but useful when pointing is difficult *Nakamura, Horiuchi, et al (in prep)*

1. Extremely nearby events *O*(100) pc:

For pre-SN neutrino & EM follow-up

- Wolf-Rayet star lists exist

  e.g., van der Hutch (2001), Rosslowe & Crowther (2015)
- Red supergiant list: (~212 in < 3 kpc)

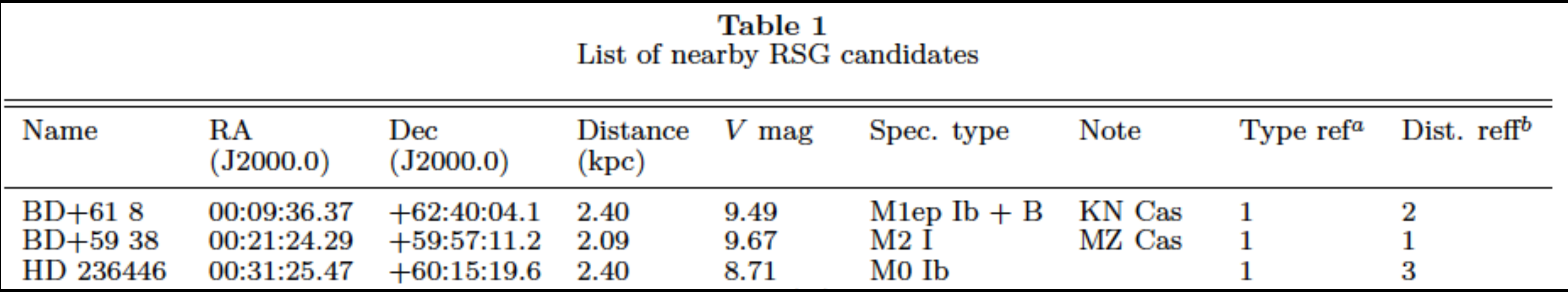


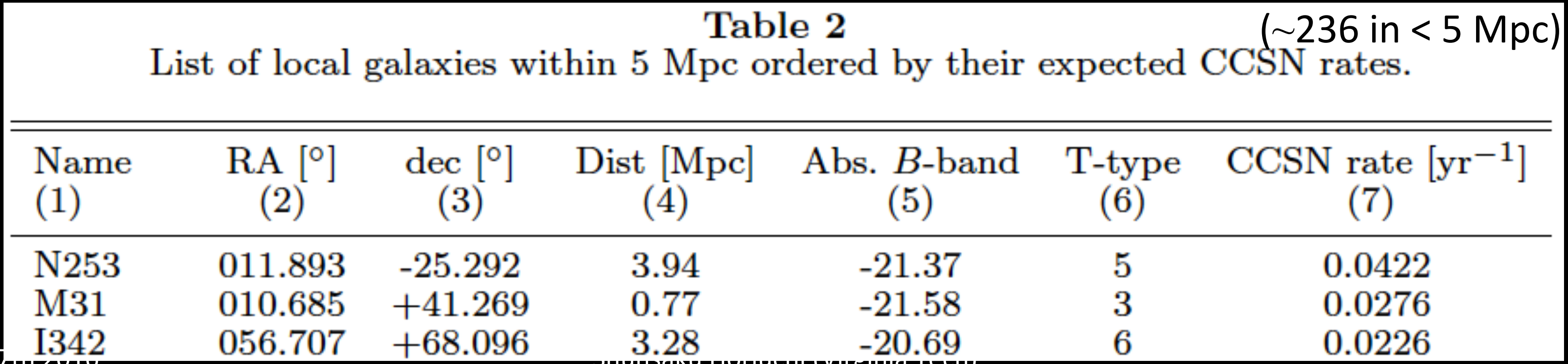
Table 1
List of nearby RSG candidates

Name	RA (J2000.0)	Dec (J2000.0)	Distance (kpc)	V mag	Spec. type	Note	Type ref[a]	Dist. ref[b]
BD+61 8	00:09:36.37	+62:40:04.1	2.40	9.49	M1ep Ib + B	KN Cas	1	2
BD+59 38	00:21:24.29	+59:57:11.2	2.09	9.67	M2 I	MZ Cas	1	1
HD 236446	00:31:25.47	+60:15:19.6	2.40	8.71	M0 Ib		1	3

2. Nearby extragalactic events *O*(1) Mpc:

For SN burst neutrino & EM follow-up

- Nearby galaxy list *Karachentsev et al (2013)*
- With estimated CCSN rate *Horiuchi et al (2013)*



(~236 in < 5 Mpc)

Table 2
List of local galaxies within 5 Mpc ordered by their expected CCSN rates.

Name (1)	RA [°] (2)	dec [°] (3)	Dist [Mpc] (4)	Abs. B-band (5)	T-type (6)	CCSN rate [yr^{-1}] (7)
N253	011.893	-25.292	3.94	-21.37	5	0.0422
M31	010.685	+41.269	0.77	-21.58	3	0.0276
I342	056.707	+68.096	3.28	-20.69	6	0.0226

Summary & Discussions

Compactness is a useful quantity to discuss core-collapse outcome: supernova or failed supernova

- Critical compactness may be $\xi_{2.5} \sim 0.2$
- To be investigated by future 3D simulations and various observations

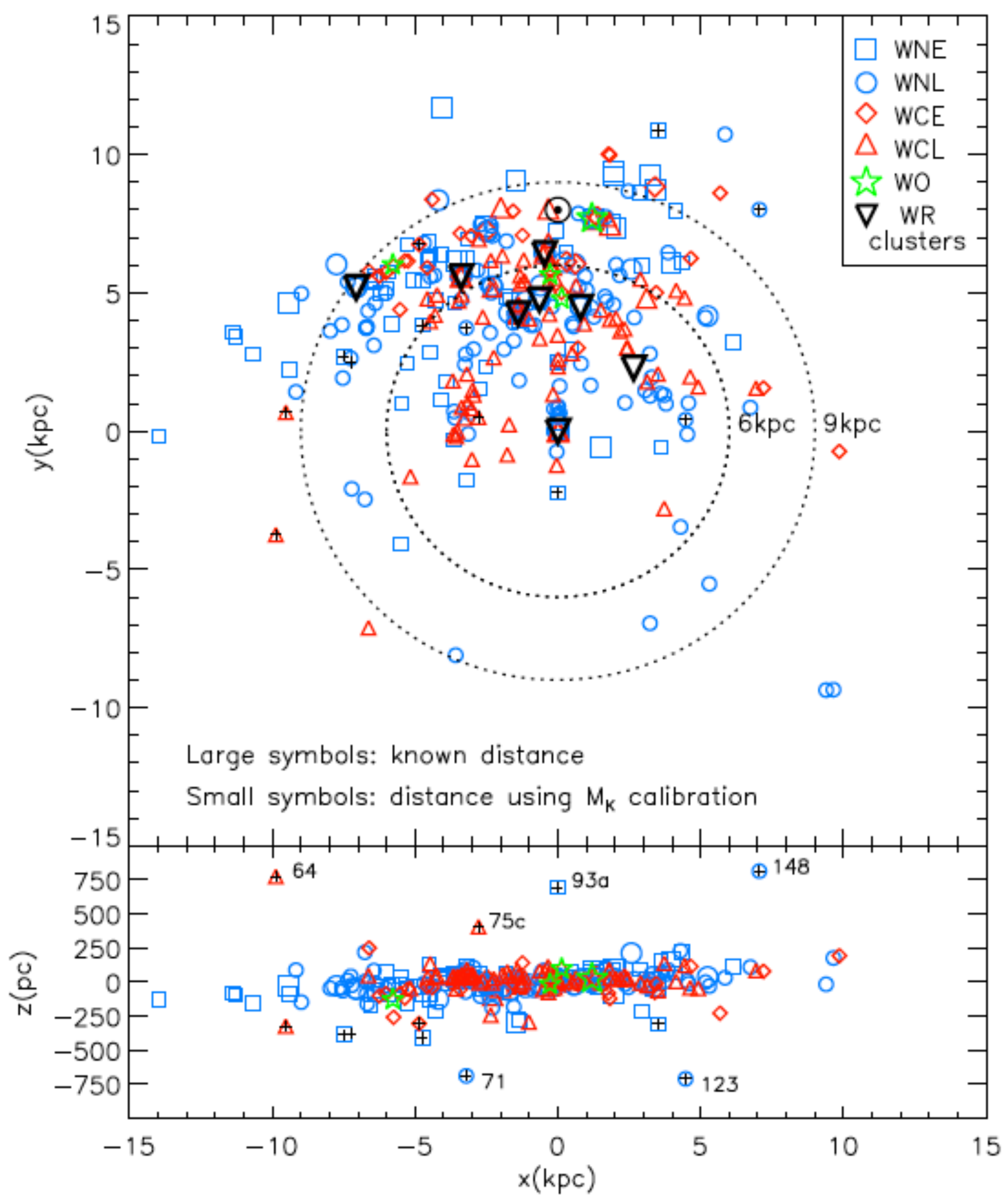
Can be probed by future neutrinos

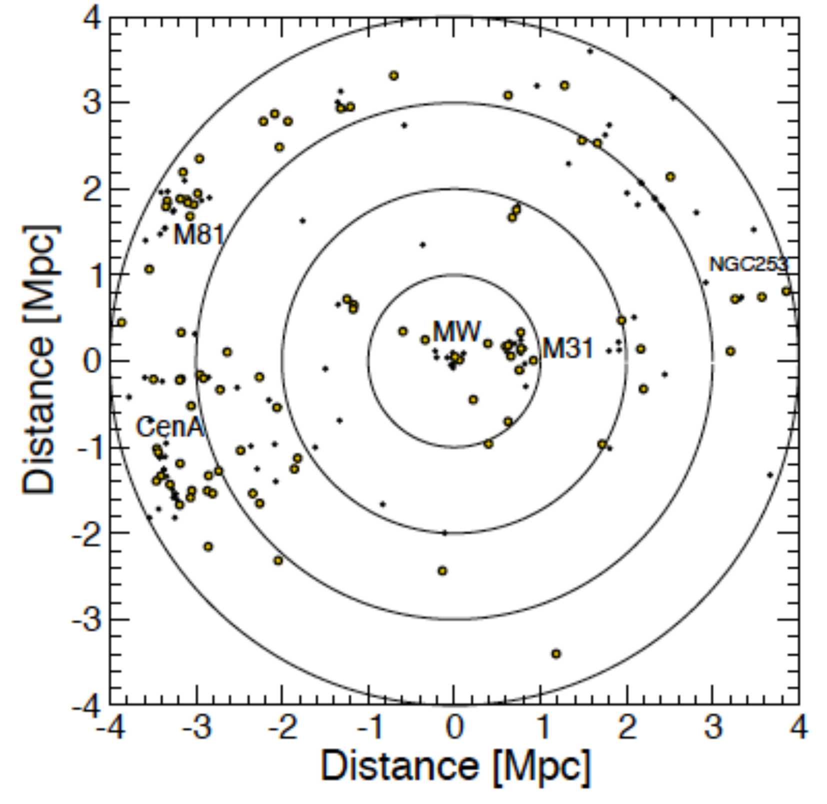
- Galactic supernova neutrinos
  → measure BH formation and/or compactness
- Diffuse supernova neutrinos
  → test BH contribution

Let's go supernova!

- Neutrino timing helps gravitational wave detection
- Neutrino pointing helps electromagnetic follow-up

Back-up slides





Top 10 galaxies contain 60% of the CCSN rate within 5 Mpc

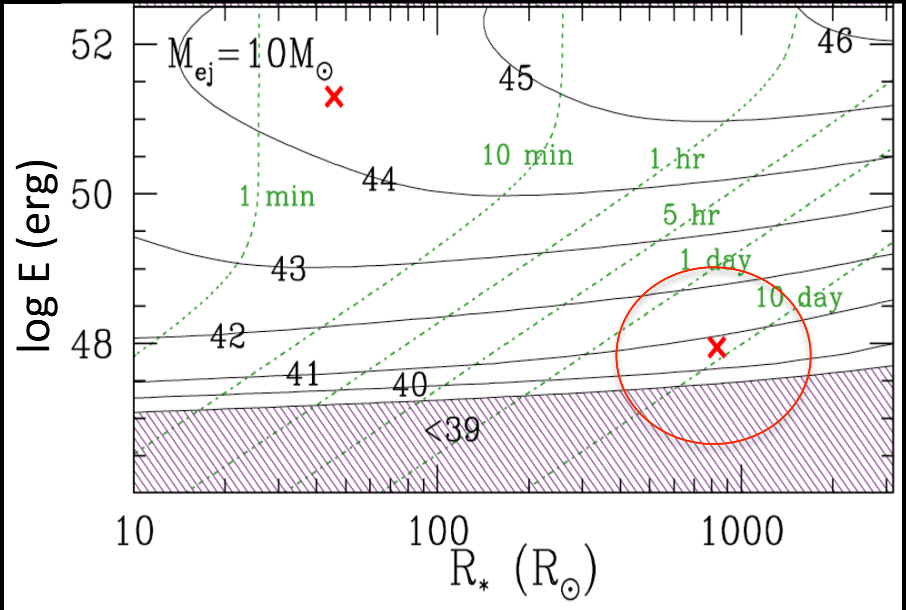
Optical signatures of direct collapse to BH

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

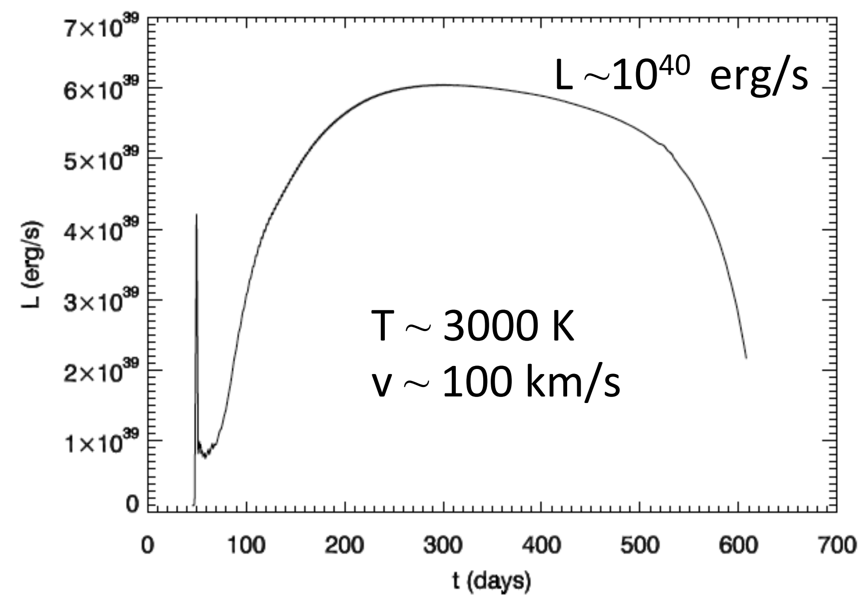
→ shock breakout emission → H-recombination emission

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)

The future is coming…ASAS-SN

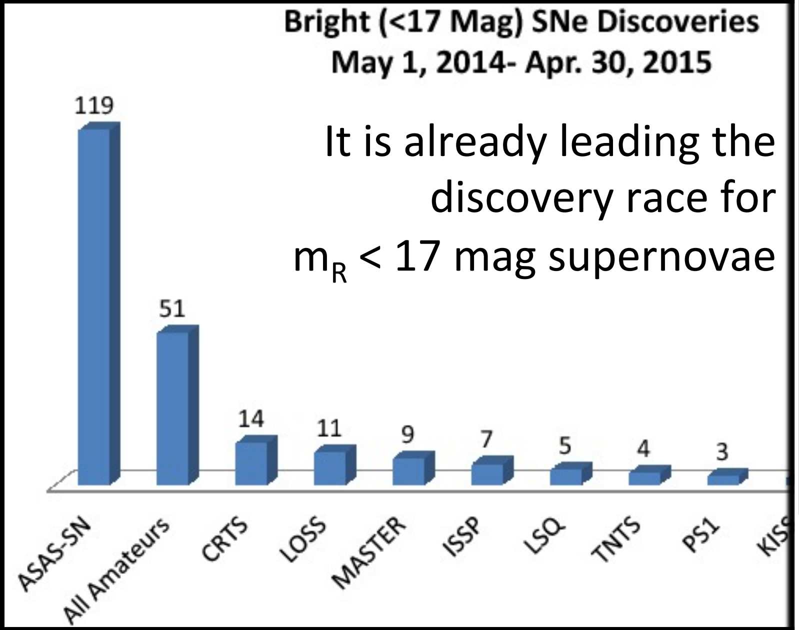
GOAL: observe the entire sky every night (4 sites 16 cameras) !

ASAS-SN is a synoptic survey searching for local transients. Improvements:

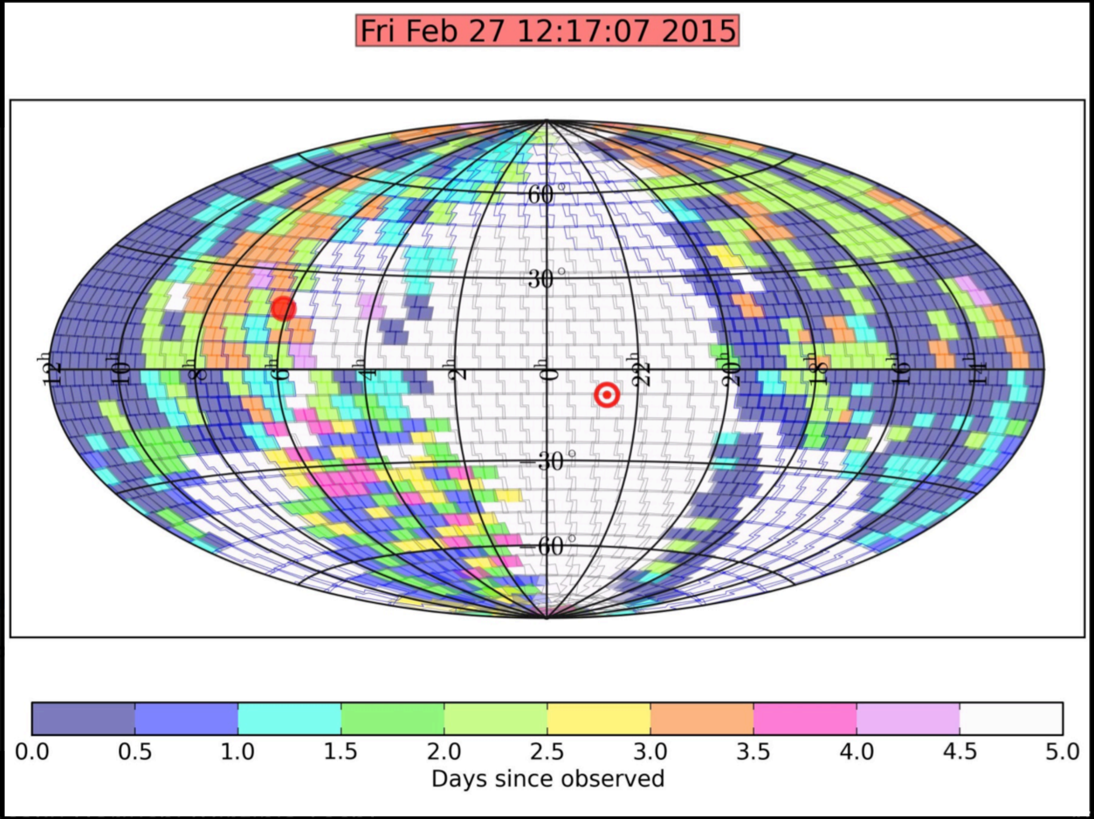
- Northern sky dominated → all sky
- Observe lists of galaxies → sky patches
- Variable cadence (days to months) → days

→ More complete and narrower time window for ν search!

(also would be useful for follow up survey in Galactic supernova)



It is already leading the discovery race for $m_R < 17$ mag supernovae

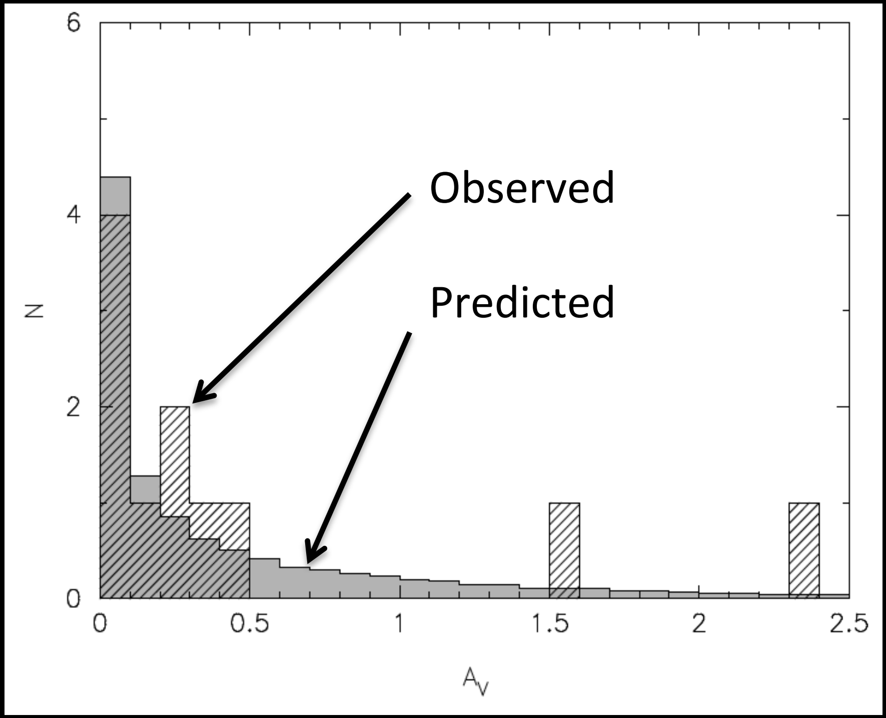


(Figures from Stanek 2015)

What is the nature of dim supernovae?

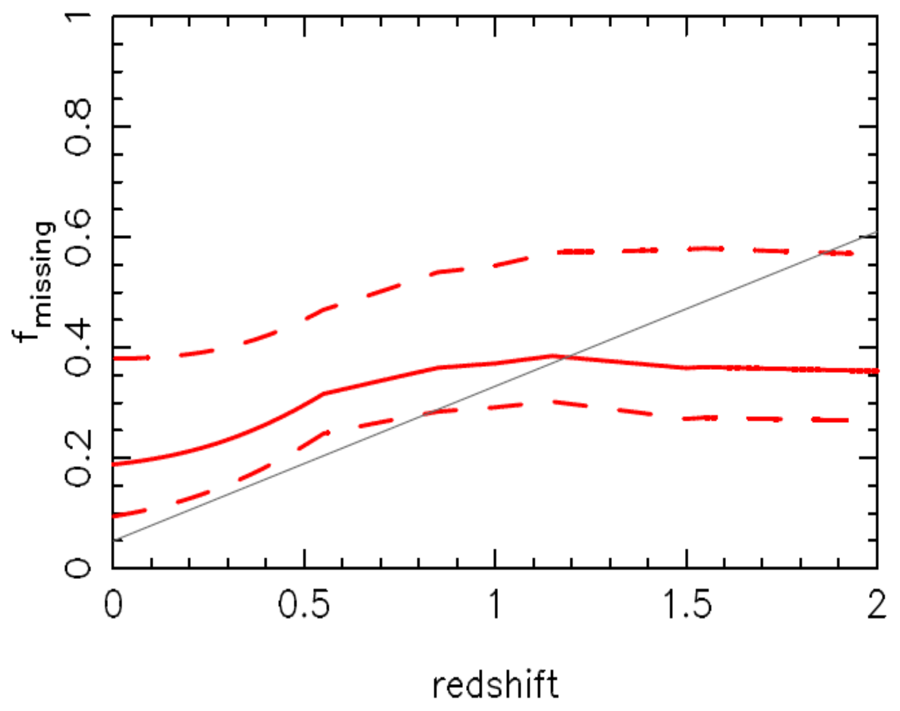
About half of the offset is due to stronger than expected dust extinction

Actual dust extinction distribution



(Plus, outliers 2002hh & 2009hd at A_V = 3.7 & 4.1)

Resulting missing fraction



Mattila et al (2012)

de-bias factor: $\dfrac{1}{1 - f_{\mathrm{miss}}} \sim 1.3 \sim 1.5$

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)*

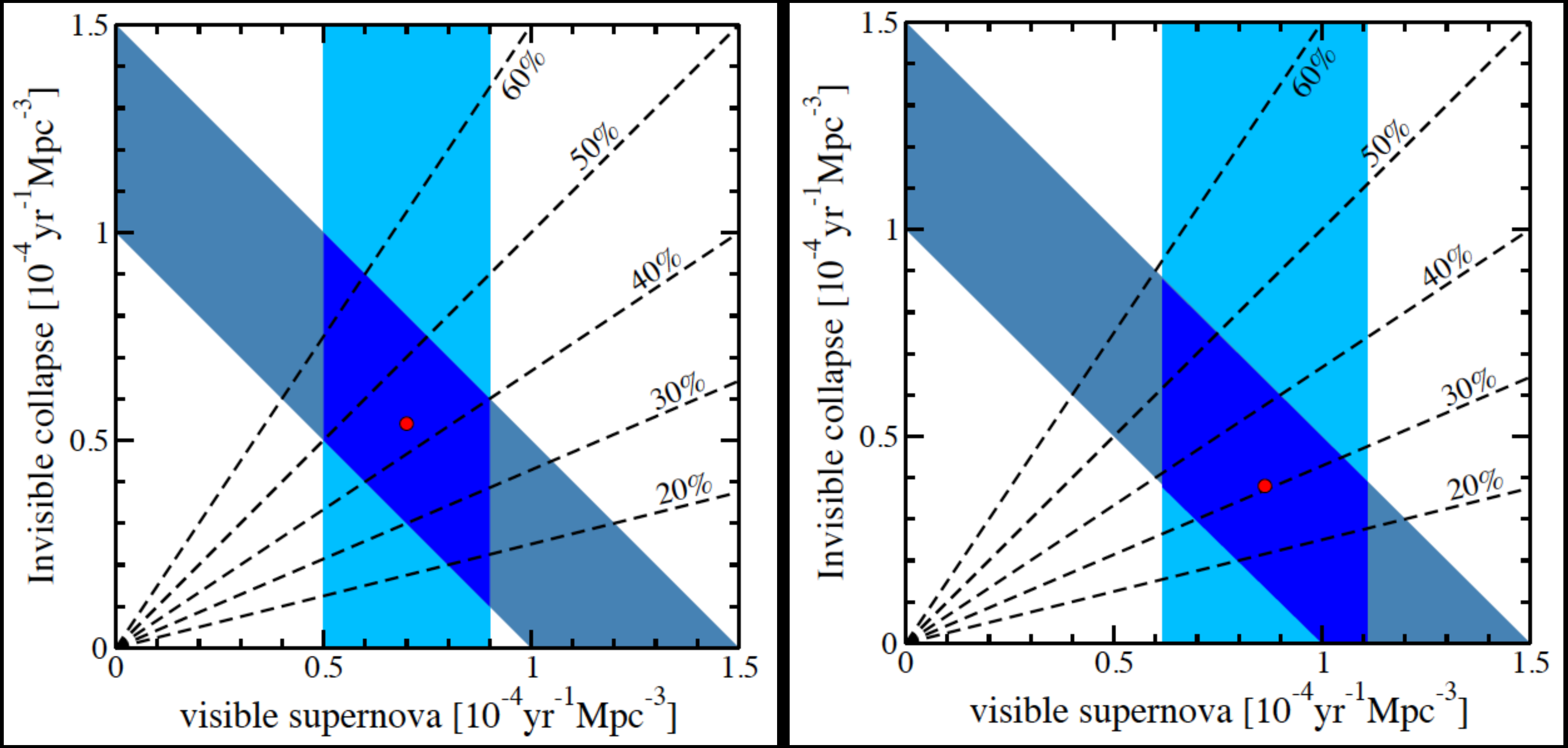
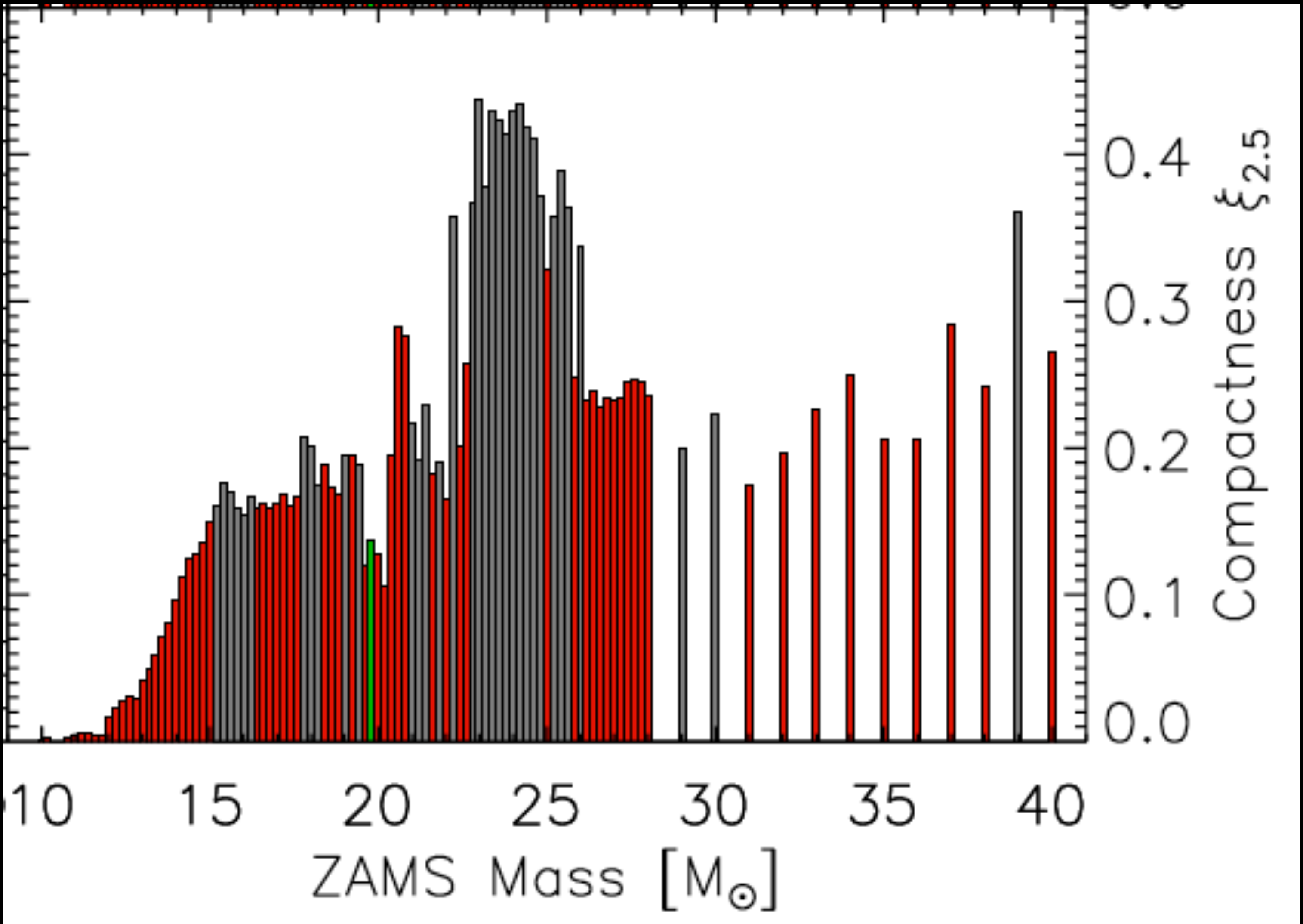


Figure adapted from Lien et al (2010)

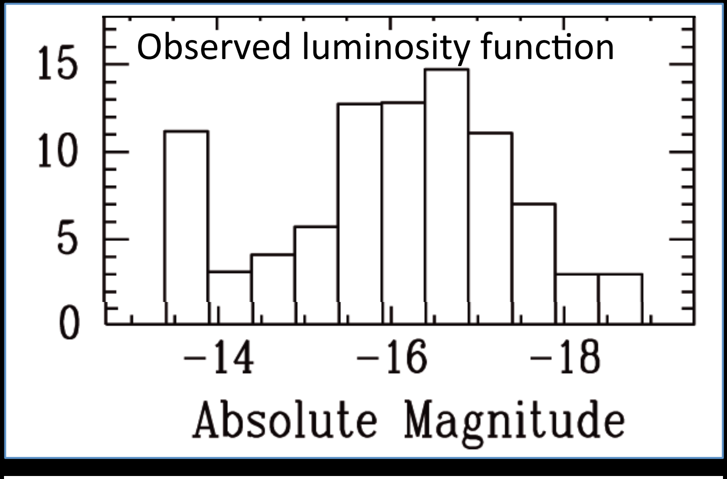

0.0
0.1
0.2
0.3
0.4
Compactness $\xi_{2.5}$
10
15
20
25
30
35
40
ZAMS Mass [$M_\odot$]

Dim supernovae may be quite common

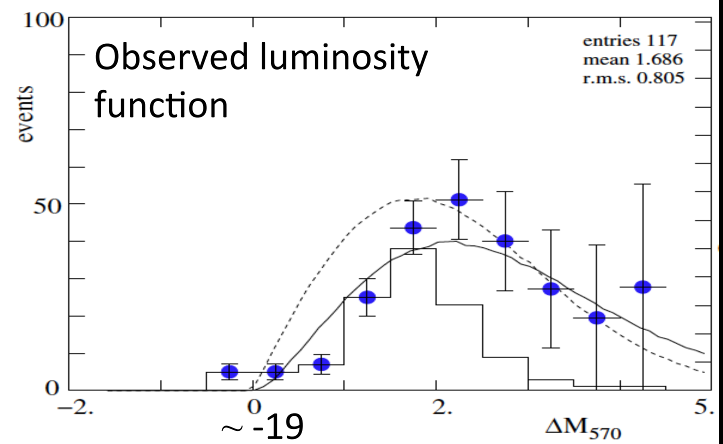
There is a clear Malmquist bias:

$f_{dim} = N_{dim} / N_{tot}$ the fraction of dim supernovae, is much higher locally:

Cosmic (> 100 Mpc) distances

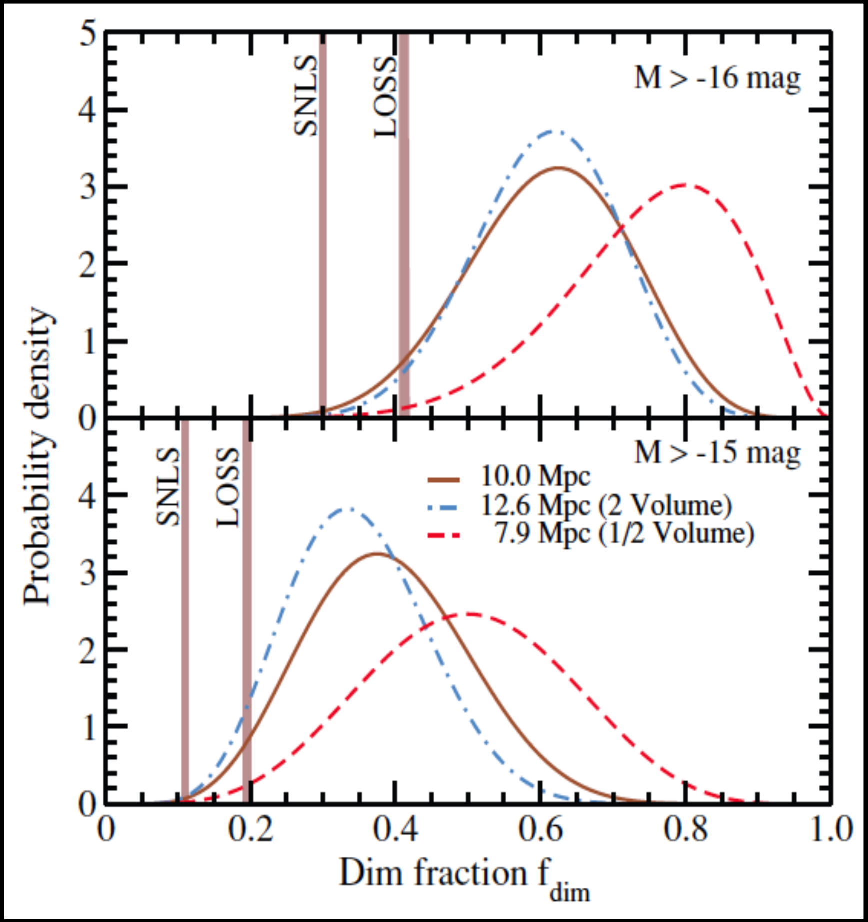


LOSS (Li et al 2011)



SNLS (Bazin et al 2009)

Local (< 13 Mpc) distances



Horiuchi et al (2010)