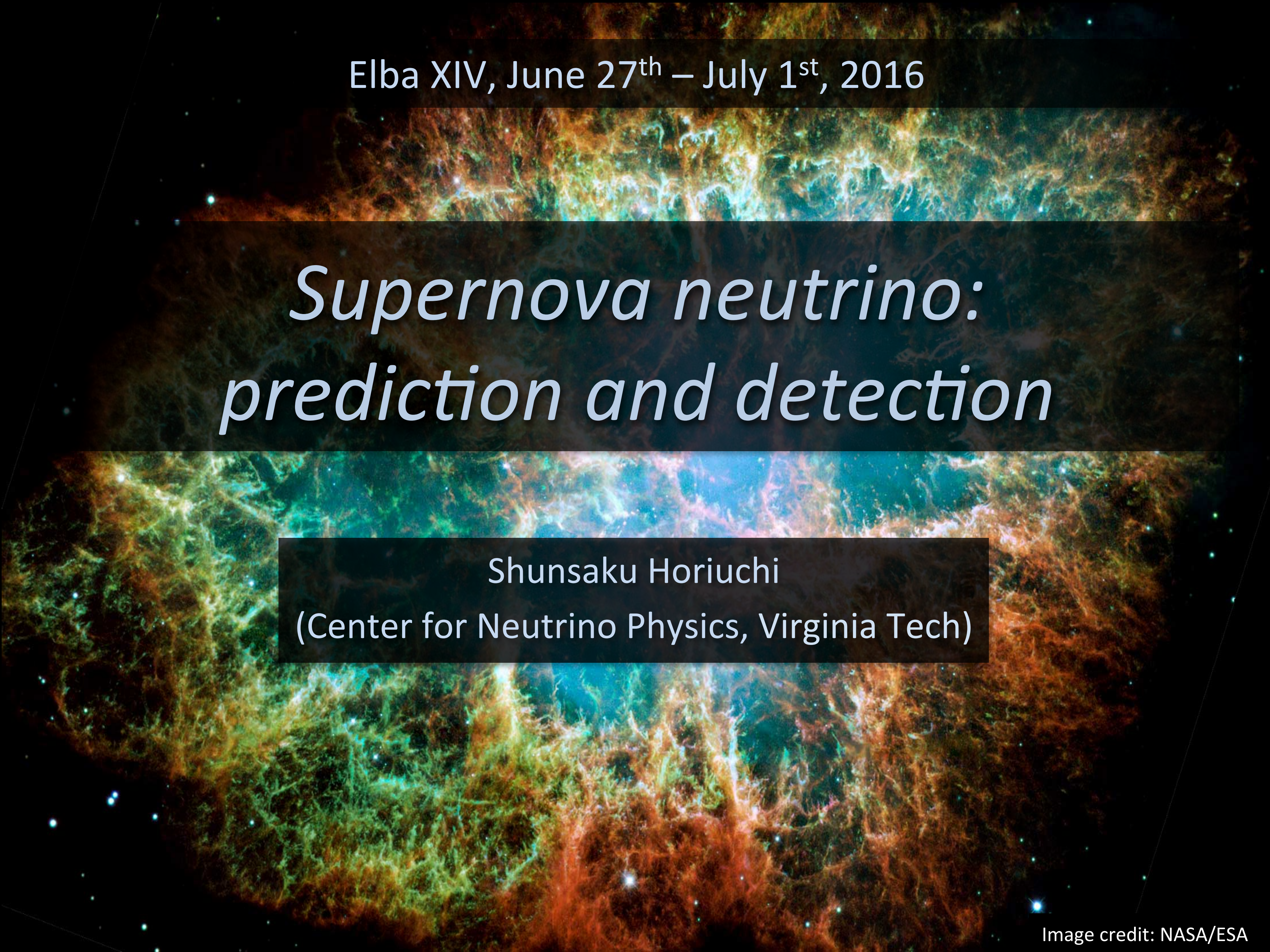


Elba XIV, June 27th – July 1st, 2016

Supernova neutrino: prediction and detection

Shunsaku Horiuchi
(Center for Neutrino Physics, Virginia Tech)

Image credit: NASA/ESA

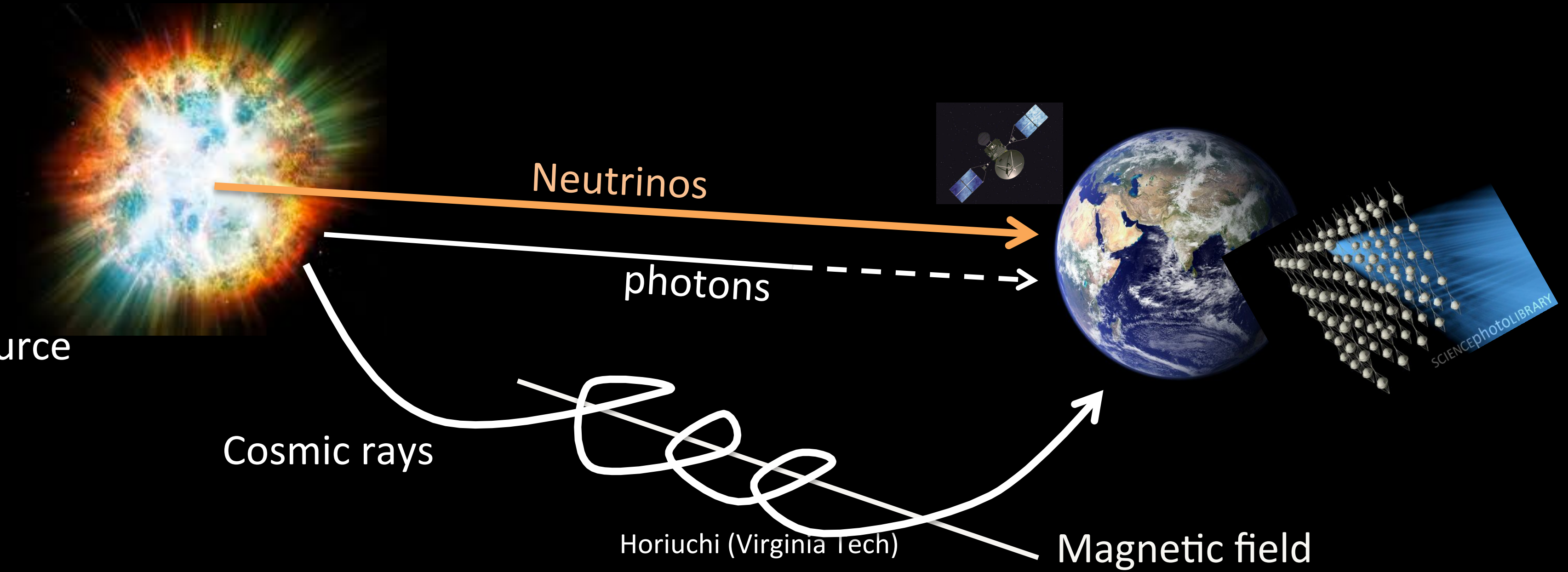
Neutrinos as cosmic messengers

> *Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star...*
>
> John N. Bahcall, *Phys. Rev. Lett.* 12, 303 (1964)

Neutrinos:

- allow us to see optically thick (to photons) regions
- experience little attenuation through cosmic space
- probes unrivaled extreme environments
- direct hadronic indicator

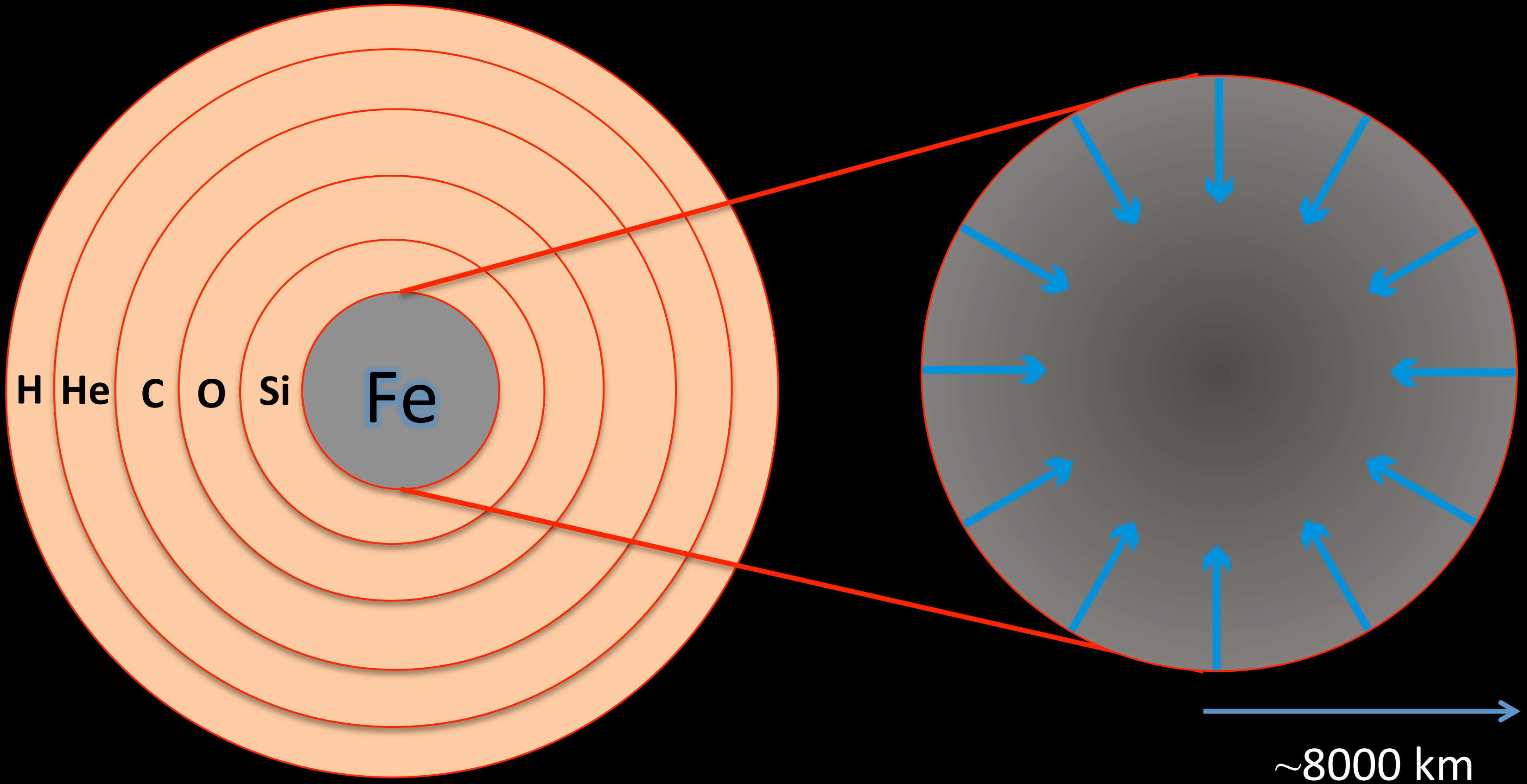
Neutrino detection is difficult; has been addressed by detectors, e.g., IceCube, Super-Kamiokande, and many others



Massive stars core collapse

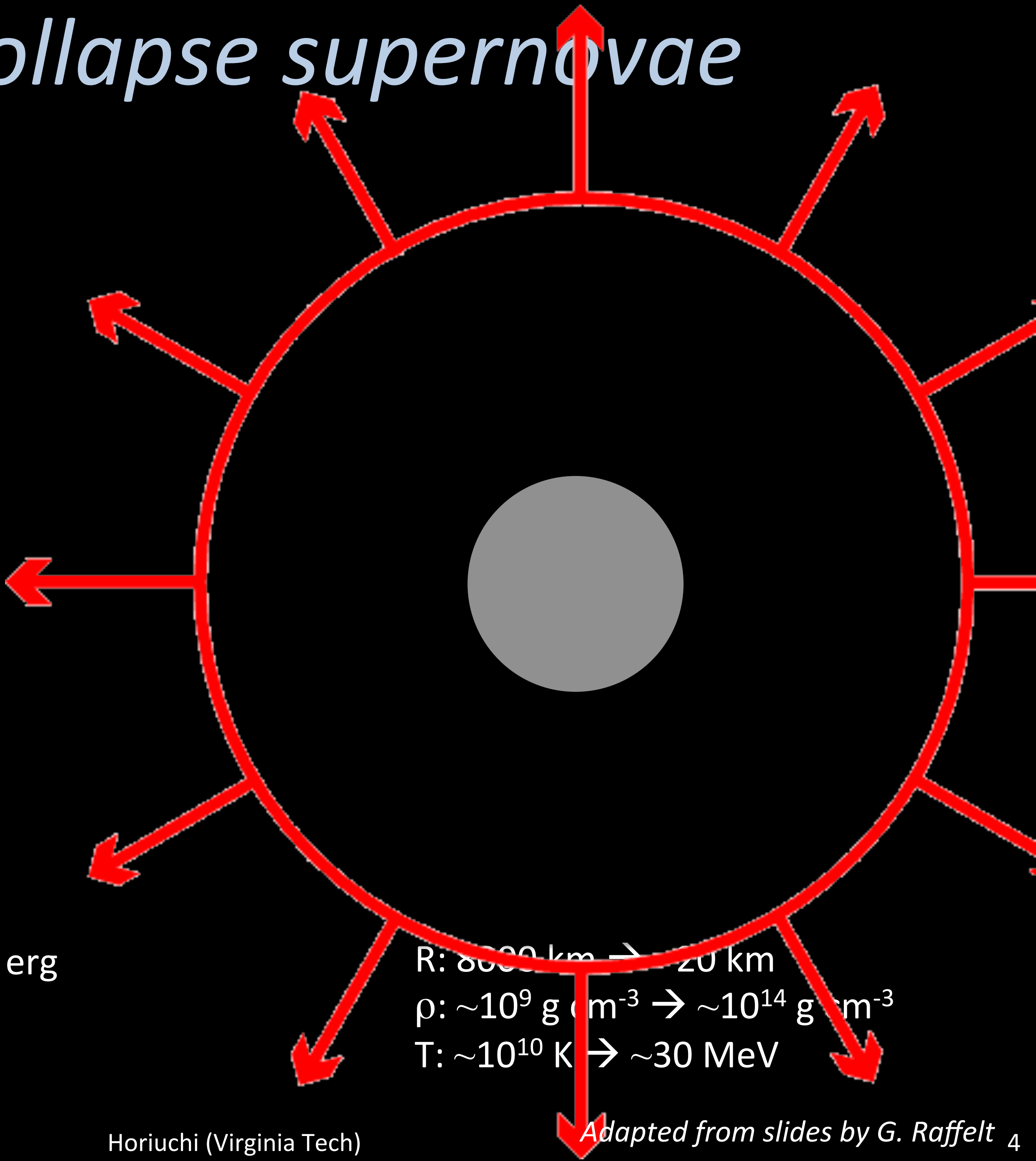
Massive (>8Msun) star structure

Core collapse (implosion)



Adapted from slides by G. Raffelt

Core-collapse supernovae



Energy budget ~ 3 x 10^{53} erg
99% into neutrinos
(0.01% into photons)

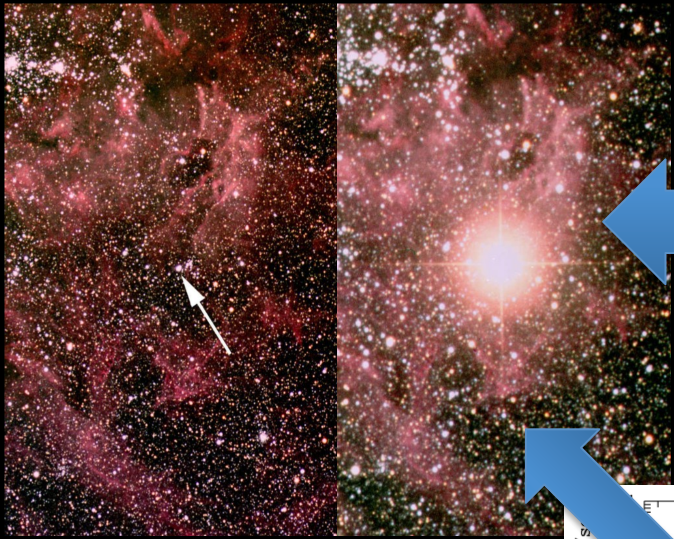
R: 8000 km → ~20 km
ρ: ~10^{9} g cm^{-3} → ~10^{14} g cm^{-3}
T: ~10^{10} K → ~30 MeV

Adapted from slides by G. Raffelt

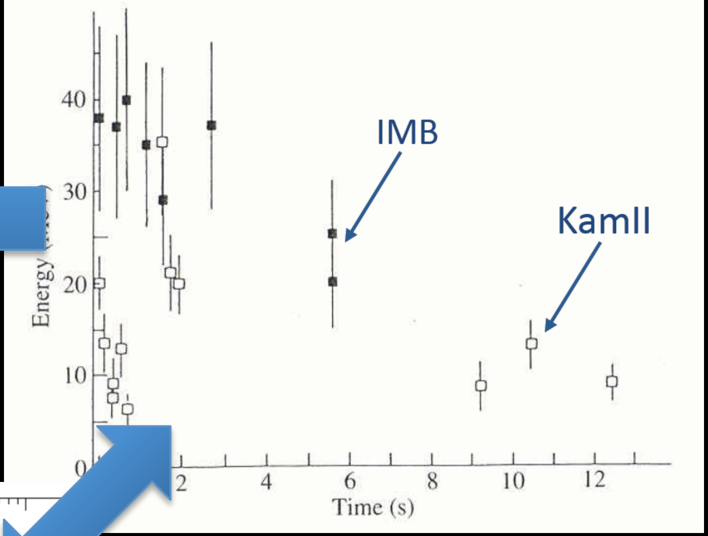
SN1987A as an example

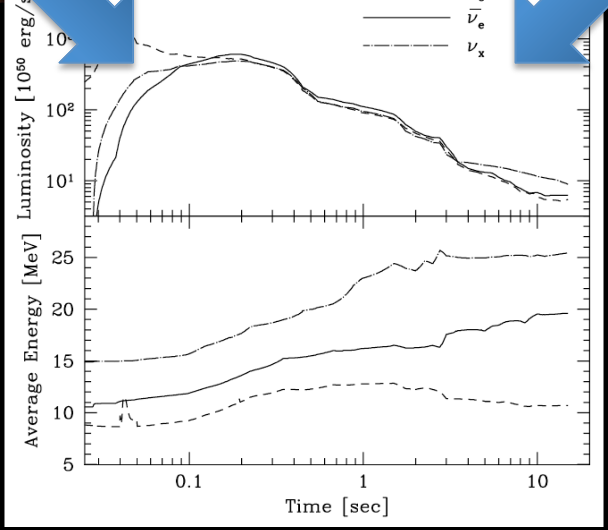
Observation: massive star progenitor, Type II supernova, nuclear decay lines, etc

Observation: MeV neutrino burst lasting ~10s



A few hours





Theory: core collapse emits neutrinos and launches supernova shock, causes explosive nucleosynthesis

Great insights!

- Importance of weak interactions
- Total binding energy
- Direct evidence of Ni synthesis
- Limits on axions and similar new particles
- Many others

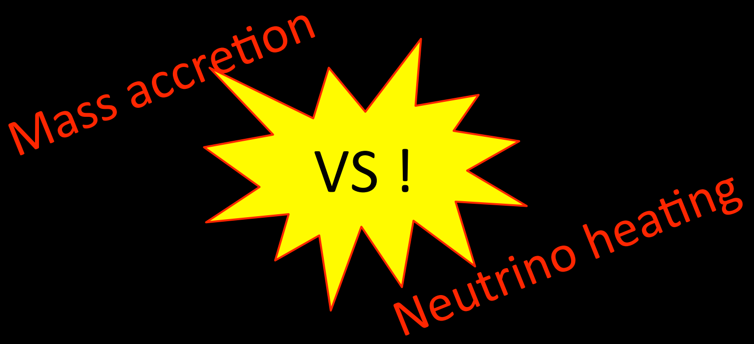
The explosion mechanism

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

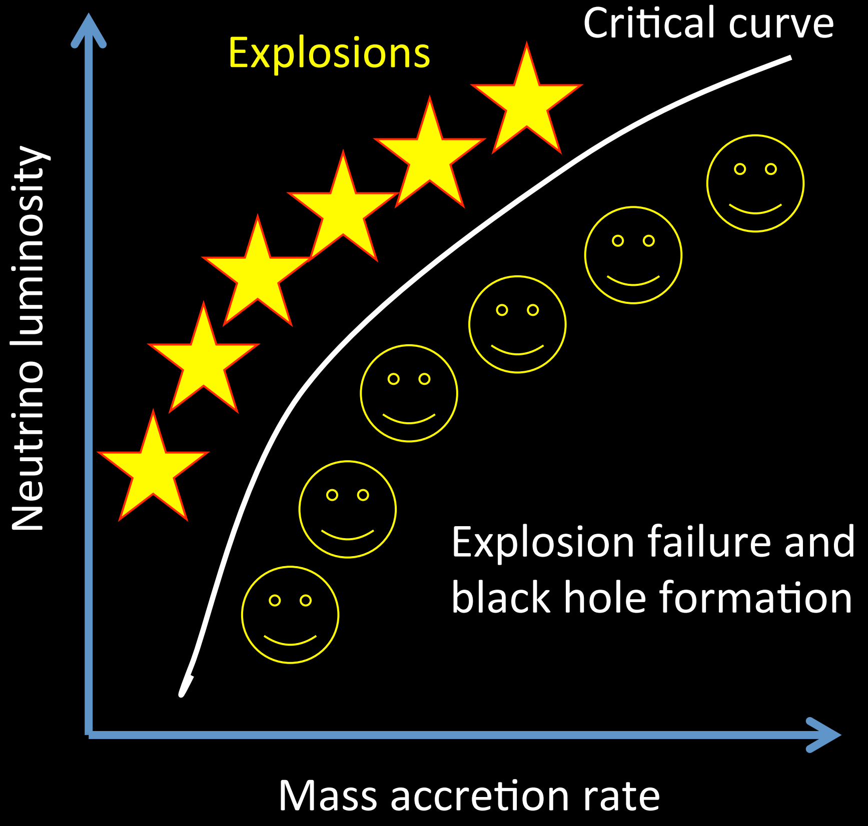
$$p = \rho \Delta v^2$$

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

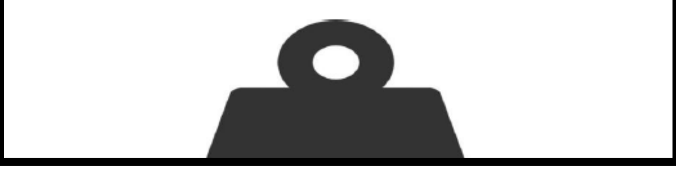


To be tested with simulation & observations!

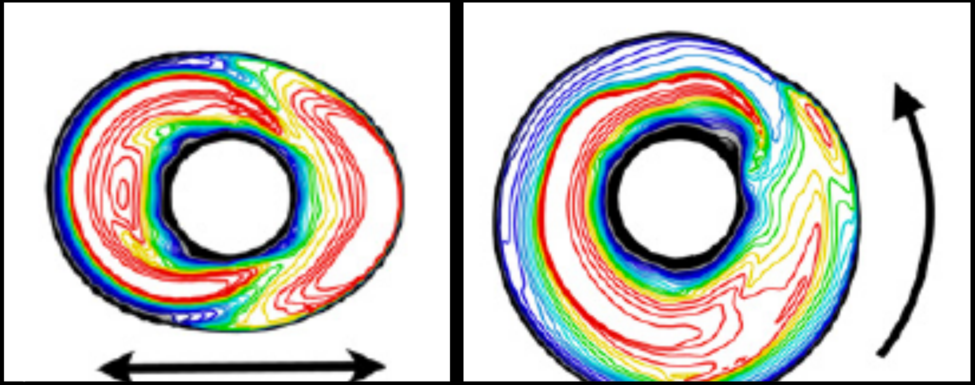
Importance of asphericity

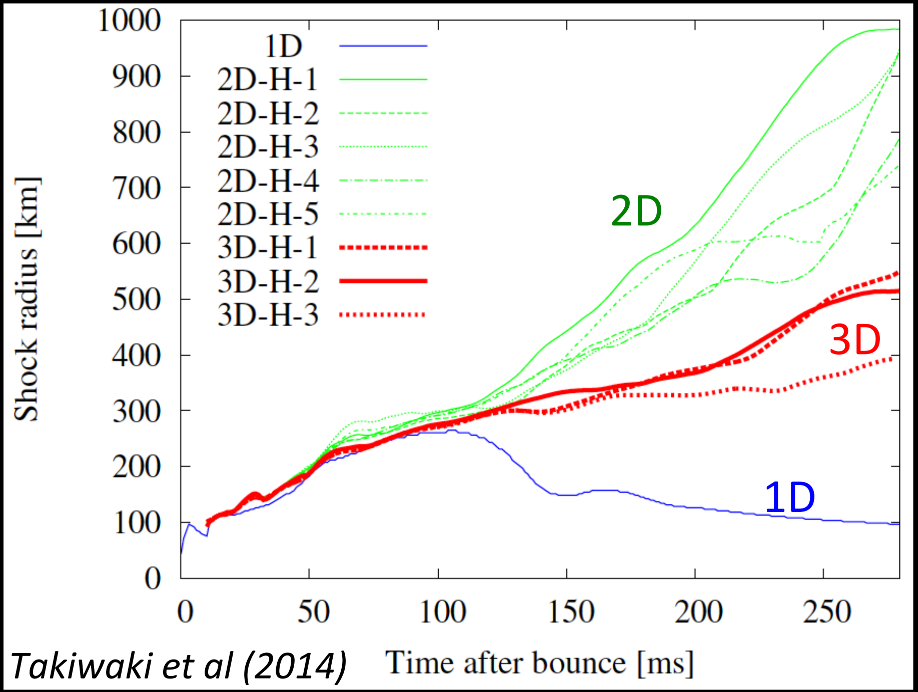
Failure in spherical symmetry:
long problem since the 1980,
confirmed in 2000s

e.g., Liebendoerfer et al (2001, 2004)

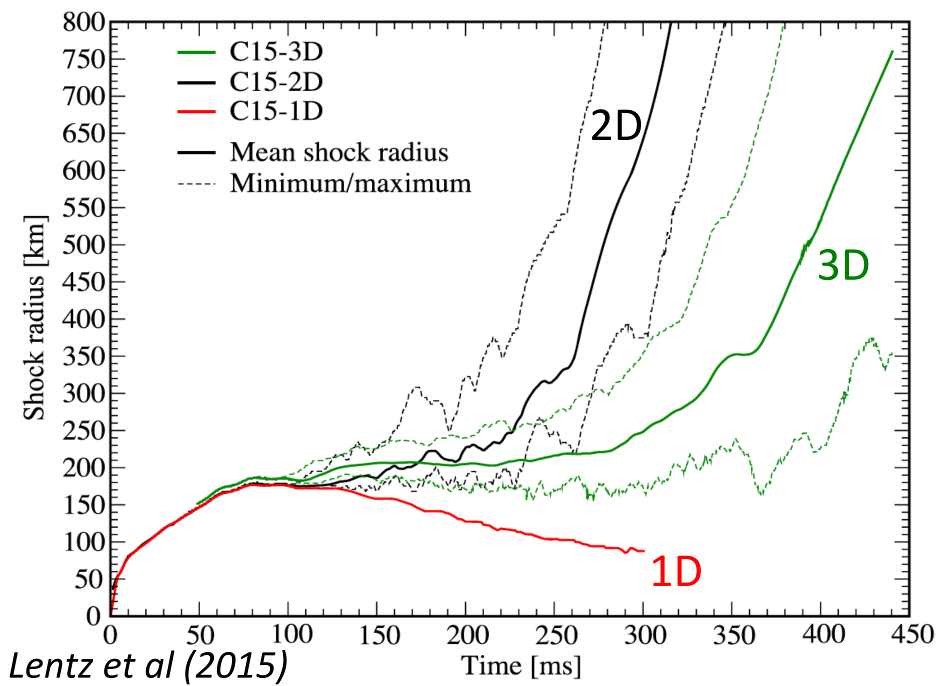


SASI:





Takiwaki et al (2014)



Lentz et al (2015)

Systematic core-collapse simulations

Sophisticated simulations [no systematic studies yet]

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

Hanke et al (2013, 2014), Melson et al (2015), Lentz et al (2015), Takiwaki et al (2016) …

First systematic studies in spherically symmetry

- Spherically symmetric with parameterized neutrino heating
- $\sim$700 progenitor models
- GR gravity
- Address: progenitor dependence, black hole formation

Ugliano et al (2012), O'Connor & Ott (2011, 2013), Ertl et al (2015)

Recent 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)

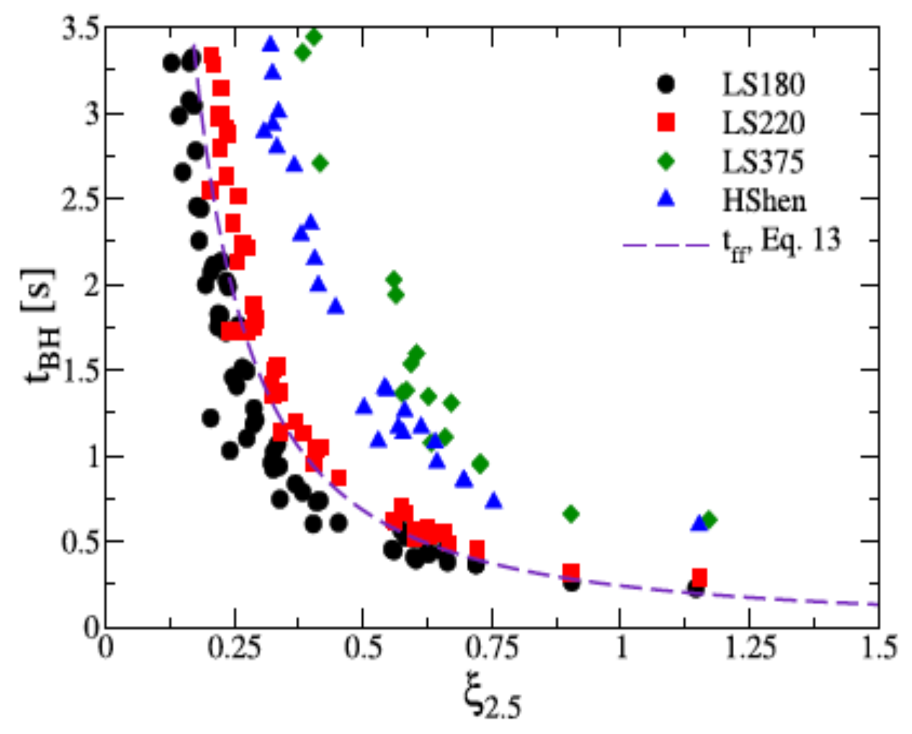
Nakamura et al (2014)

Explodability and compactness

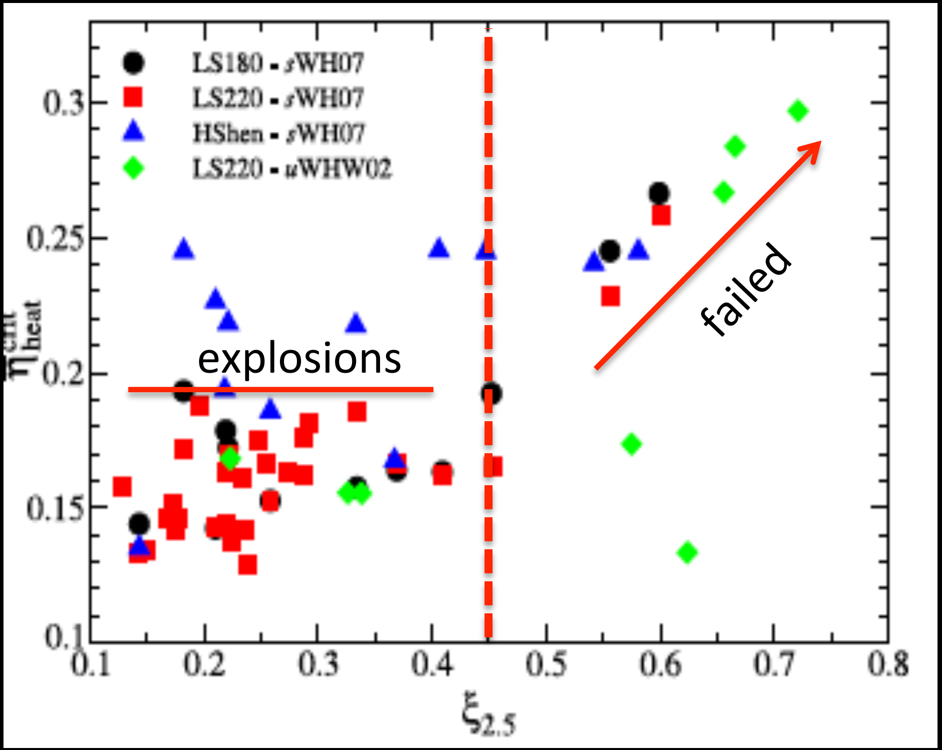
Compactness: is a useful indicator to discuss the eventual outcome of core collapse

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

Black hole formation occurs more readily for larger compactness.



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

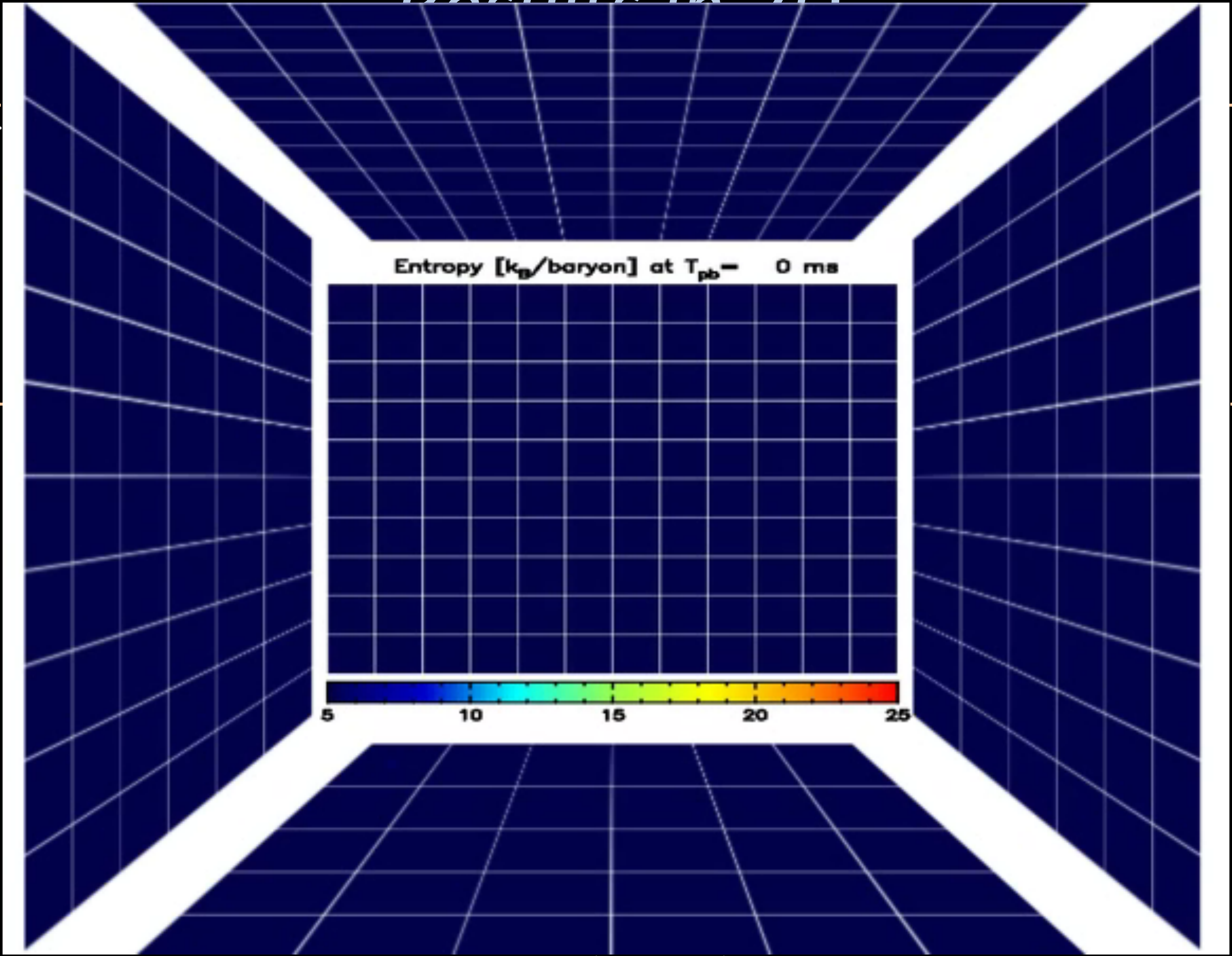


O'Connor & Ott (2011), Ugliano et al (2012); see also Pejcha & Thompson (2015), Ertl et al (2015)

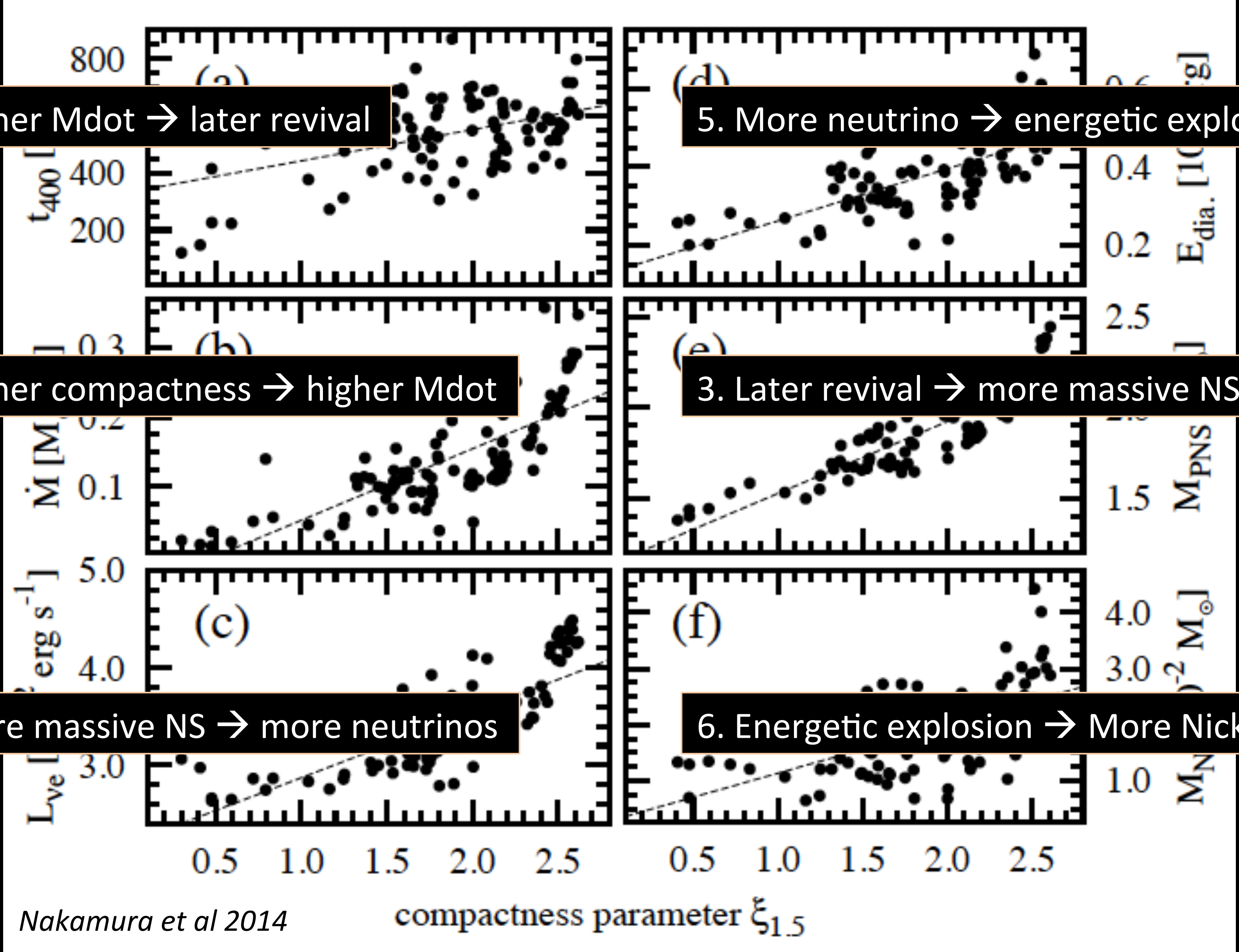
Other are close: BH formation for $\xi_{2.5} > 0.35$ (and explosions for $\xi_{2.5} < 0.15$)

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

Limitation:

- 2D setup is conducive to explosions

  e.g., Hanke et al (2012)

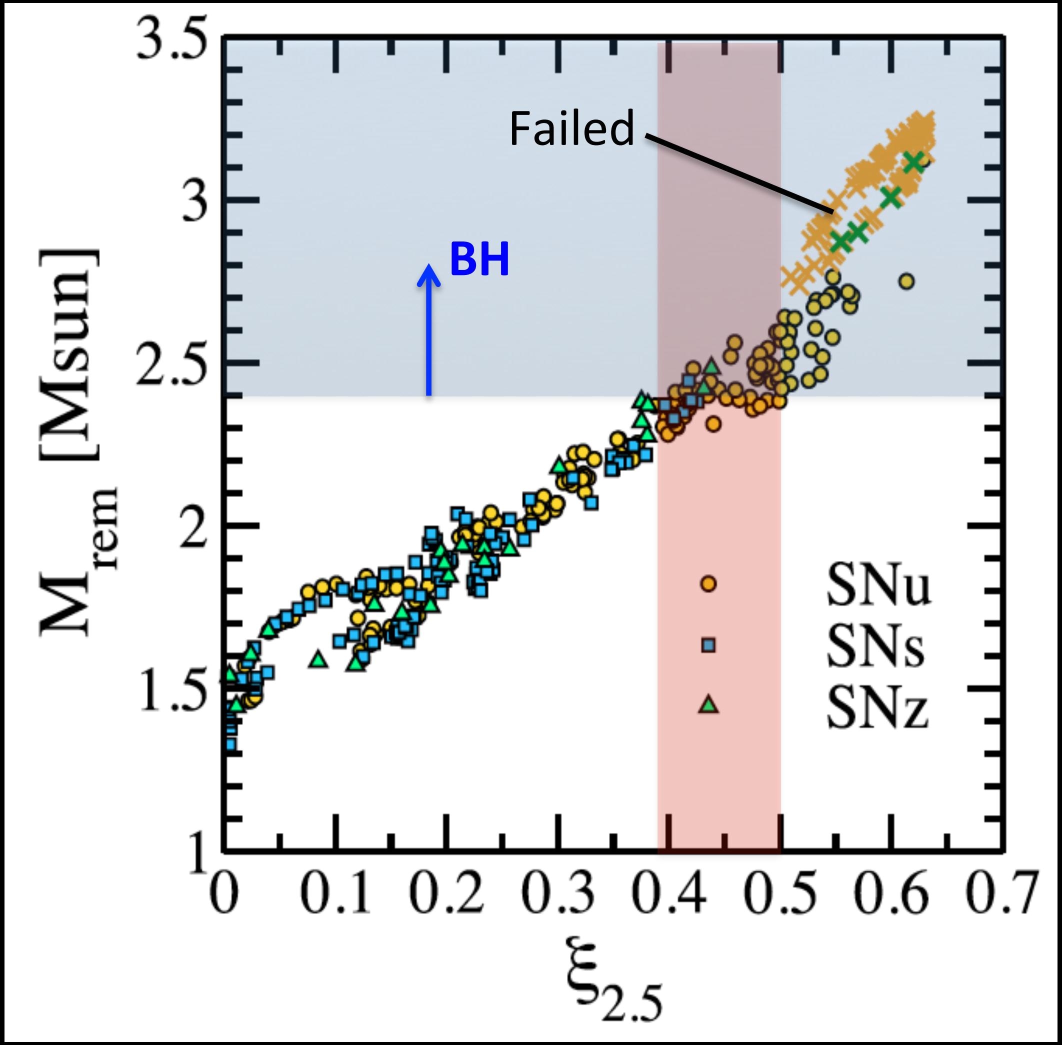
- Remnants above 2.4 Msun baryonic mass not realistic and may not explode in reality.

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

Critical compactness $\xi_{2.5}$

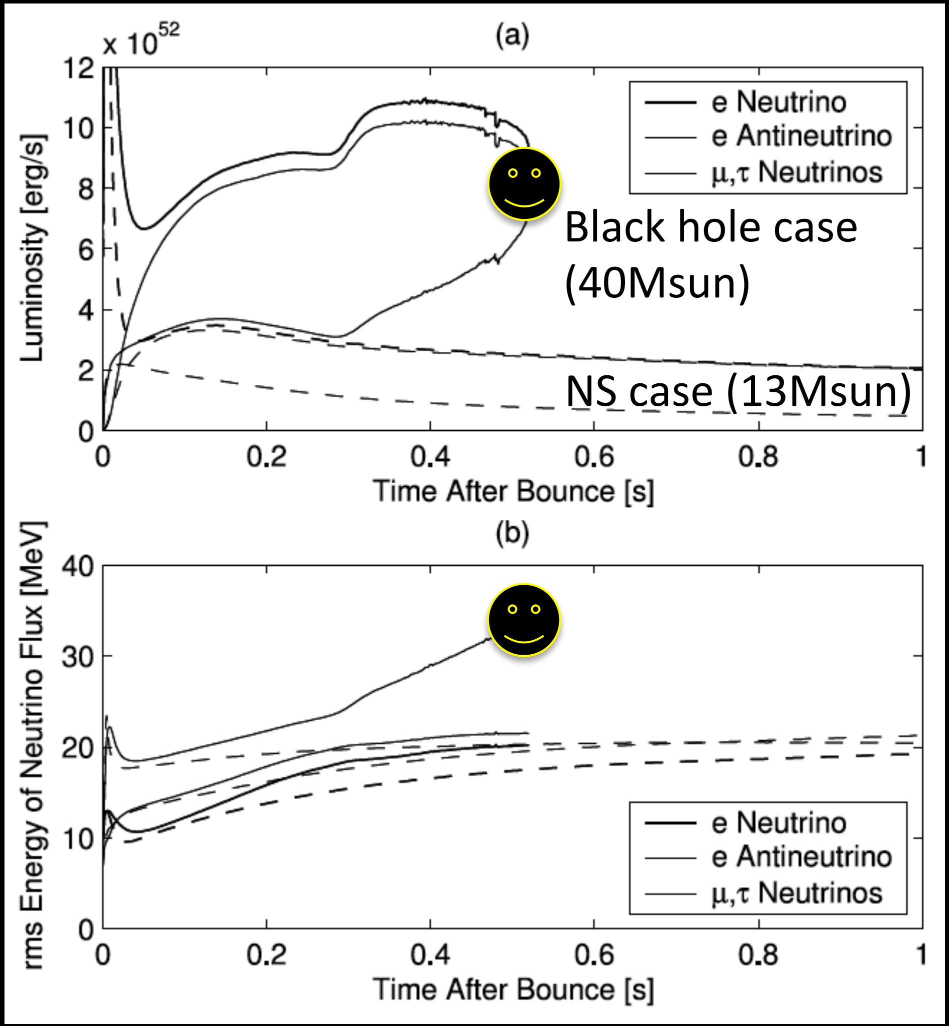
In 1D: 0.35 – 0.45

In 2D: < 0.4 – 0.5



Horiuchi et al (2014)

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

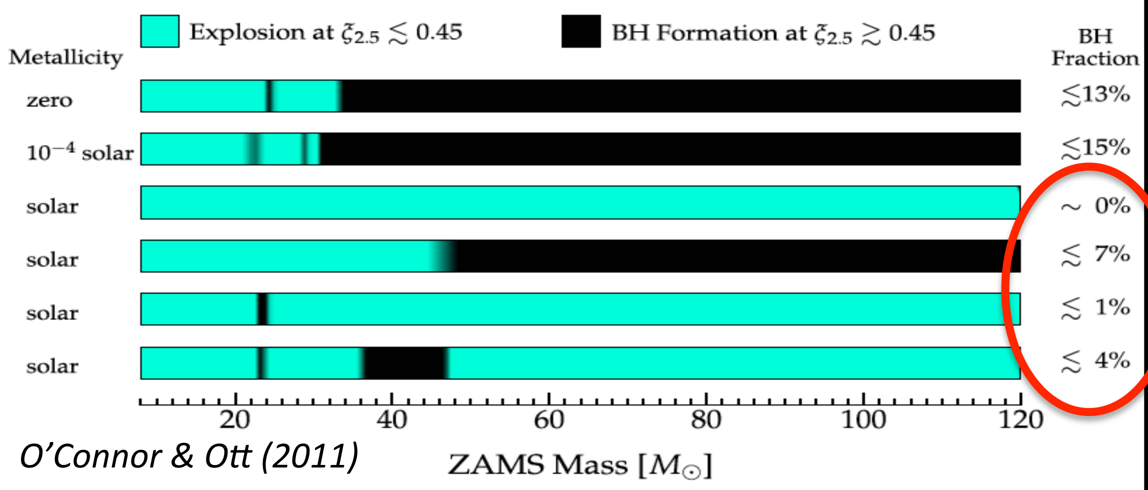
Neutrino termination:

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

Beacom et al (2001)

What is the failed collapse rate?

O'Connor & Ott (2011)

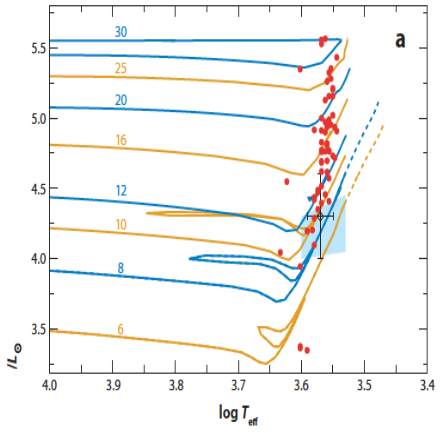


O'Connor & Ott (2011)

Expected to be low (<7%) among solar metallicity stars.

But it may be higher: many recent hints suggest the rate could be higher

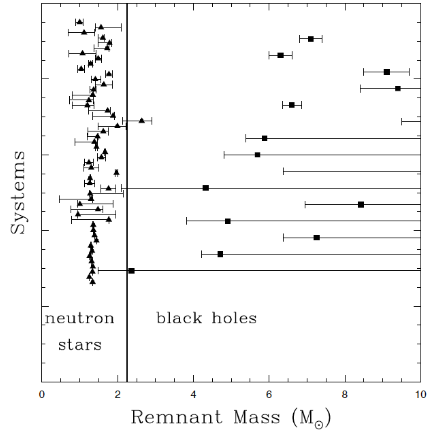
Red supergiant problem



~20-30%

Smartt et al (2009)

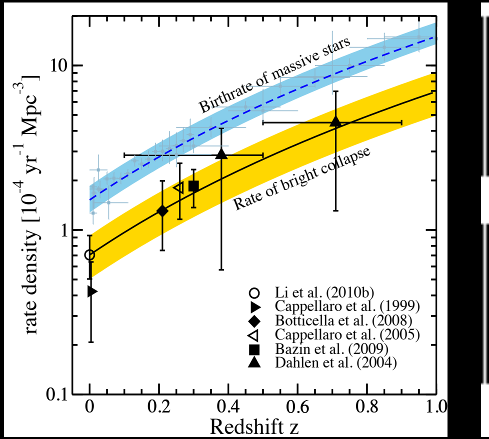
Black hole mass function



~20-30%

Kochanek et al (2014)

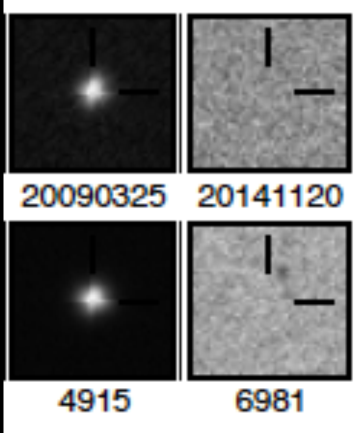
Supernova rate



~10-30%

Horiuchi et al (2010)

Survey about nothing



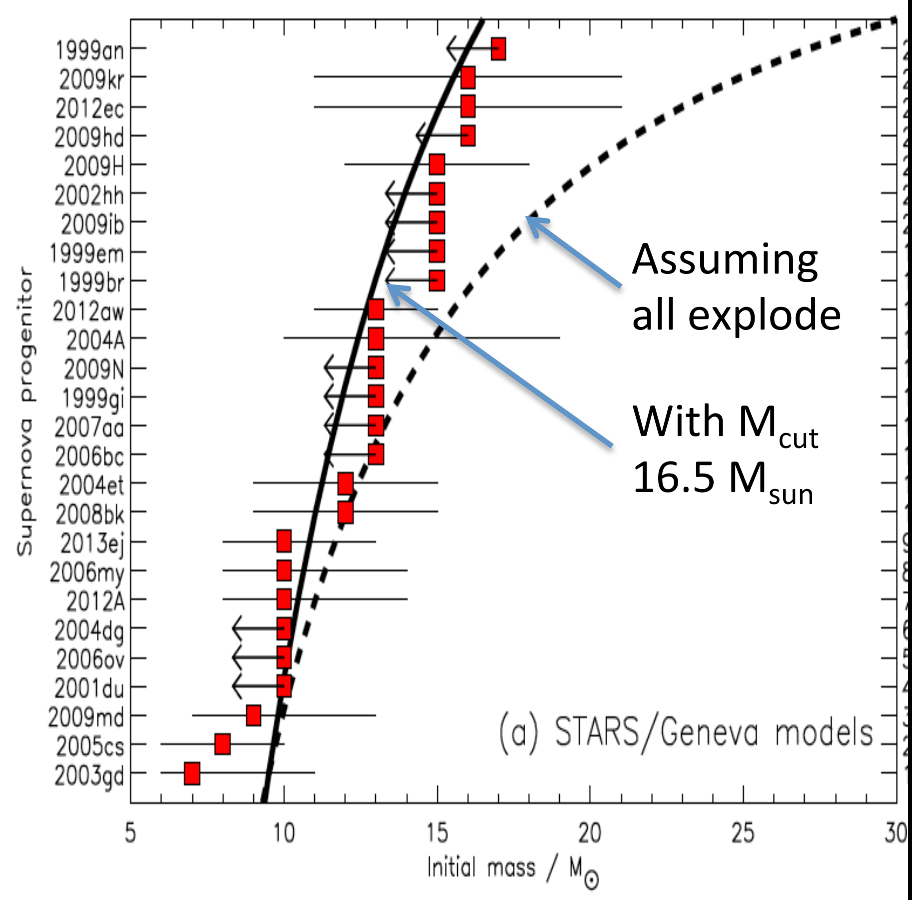
~10-40%

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



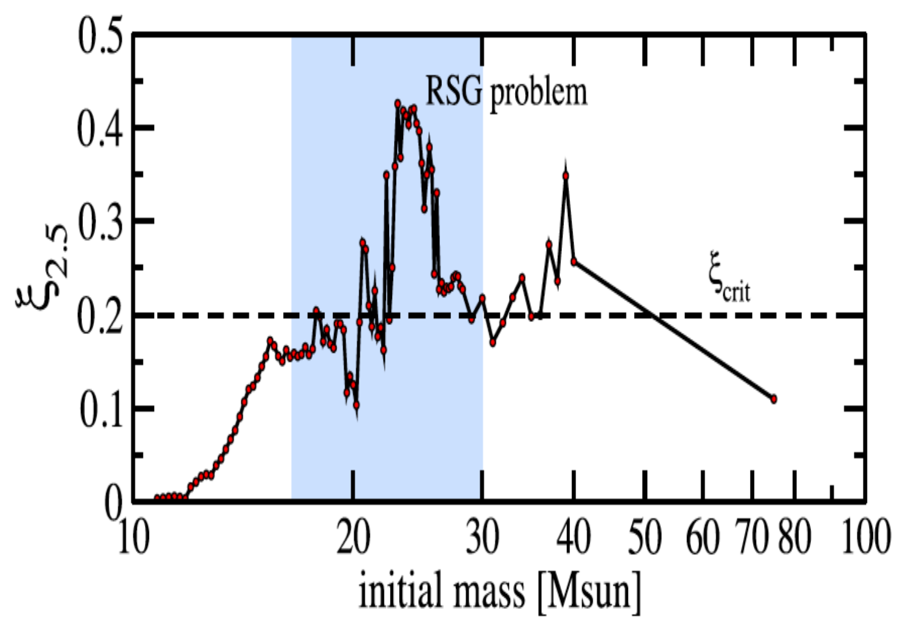
Assuming all explode

With M_{cut} 16.5 M_{sun}

Smartt (2015)

This is ~20% of massive stars.

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



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

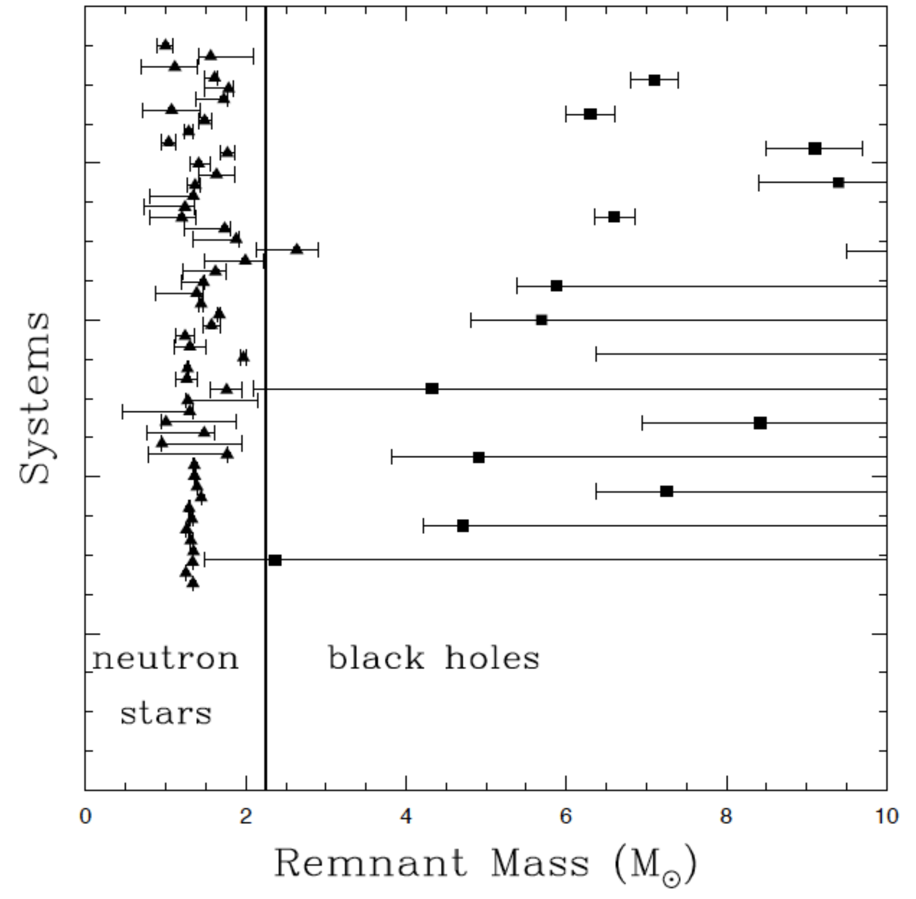
Requires low critical $\xi_{2.5}$ ~ 0.2

→ Needs testing by 3D simulations

2. Black hole mass function

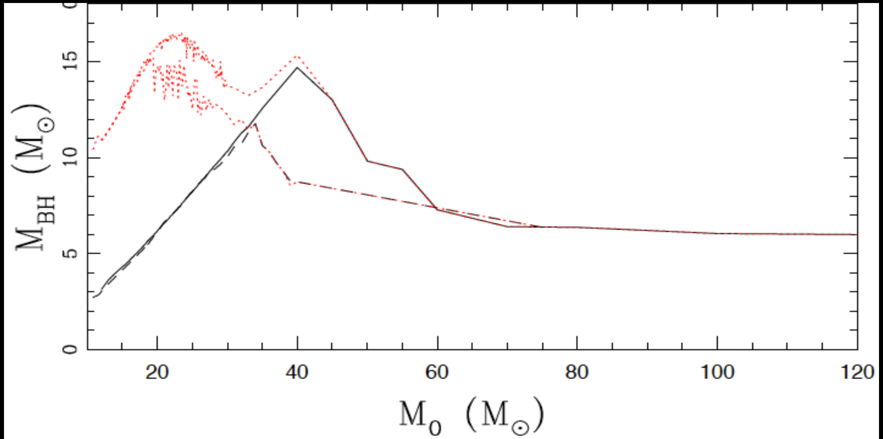
Compact object mass function:

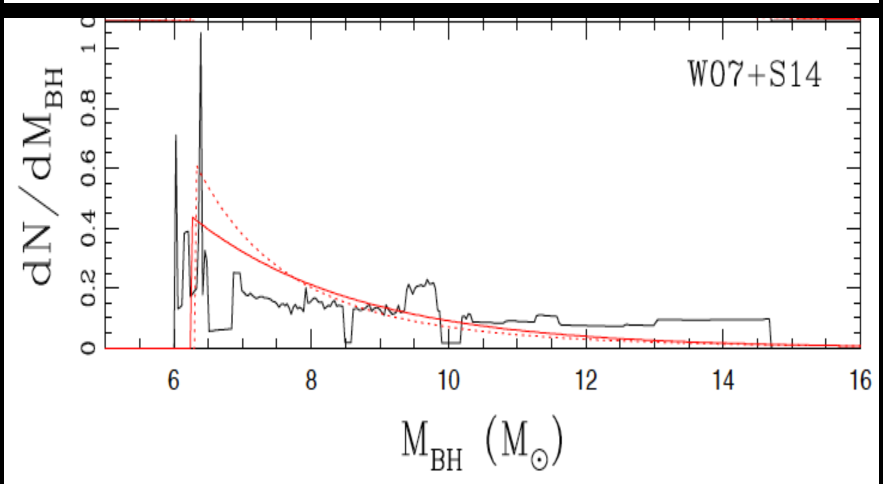
There are hints of a dearth of compact black holes just above the NS mass range



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

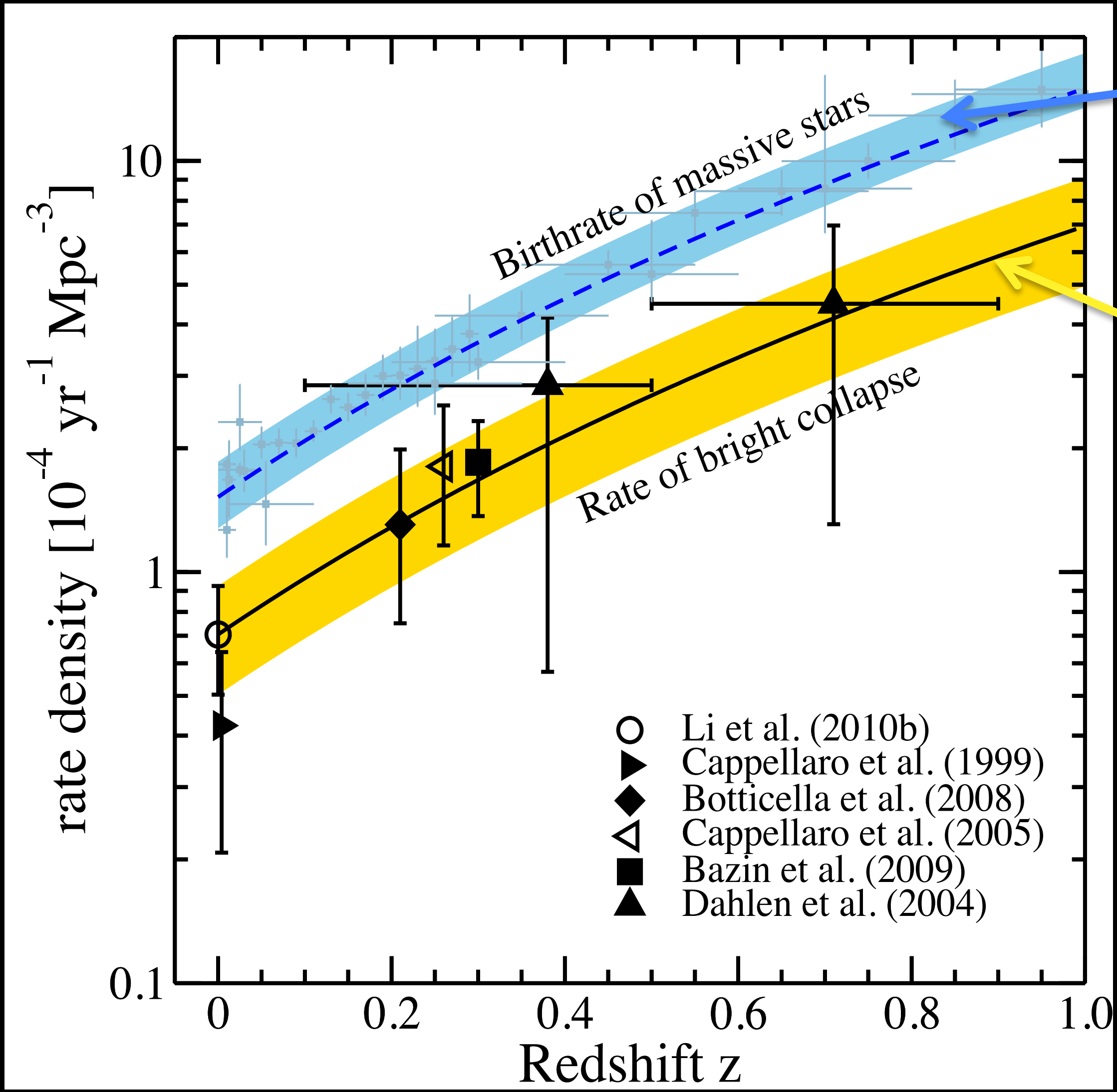
A critical compactness $\xi_{2.5}$~0.2 predicts a black hole mass function with a cutoff





Lovegrove & Woosley 2013, Kochanek (2014)

3. Cosmic core-collapse 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

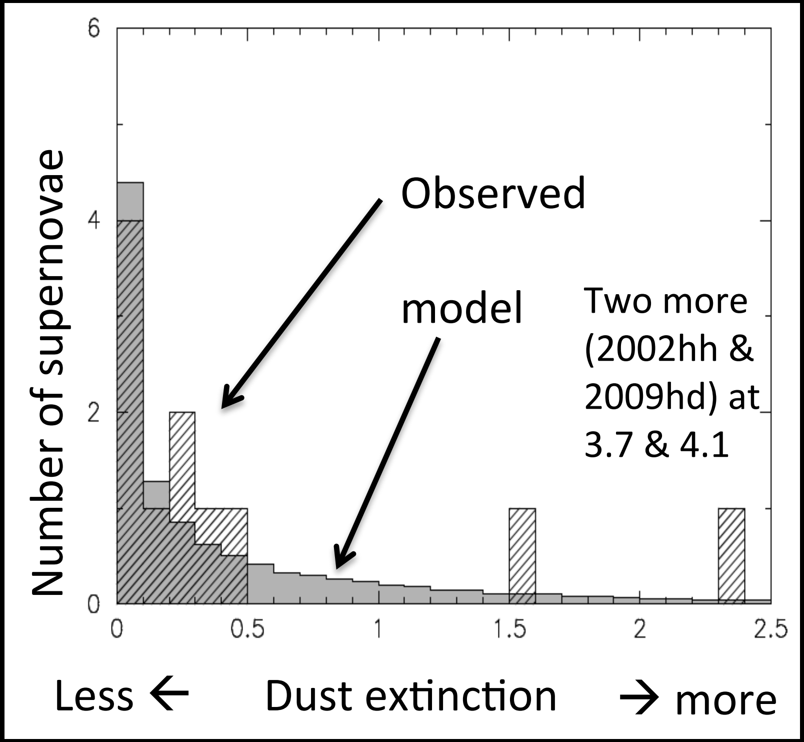
Approximately 30 – 50 %

- 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

Correction due to dim supernovae

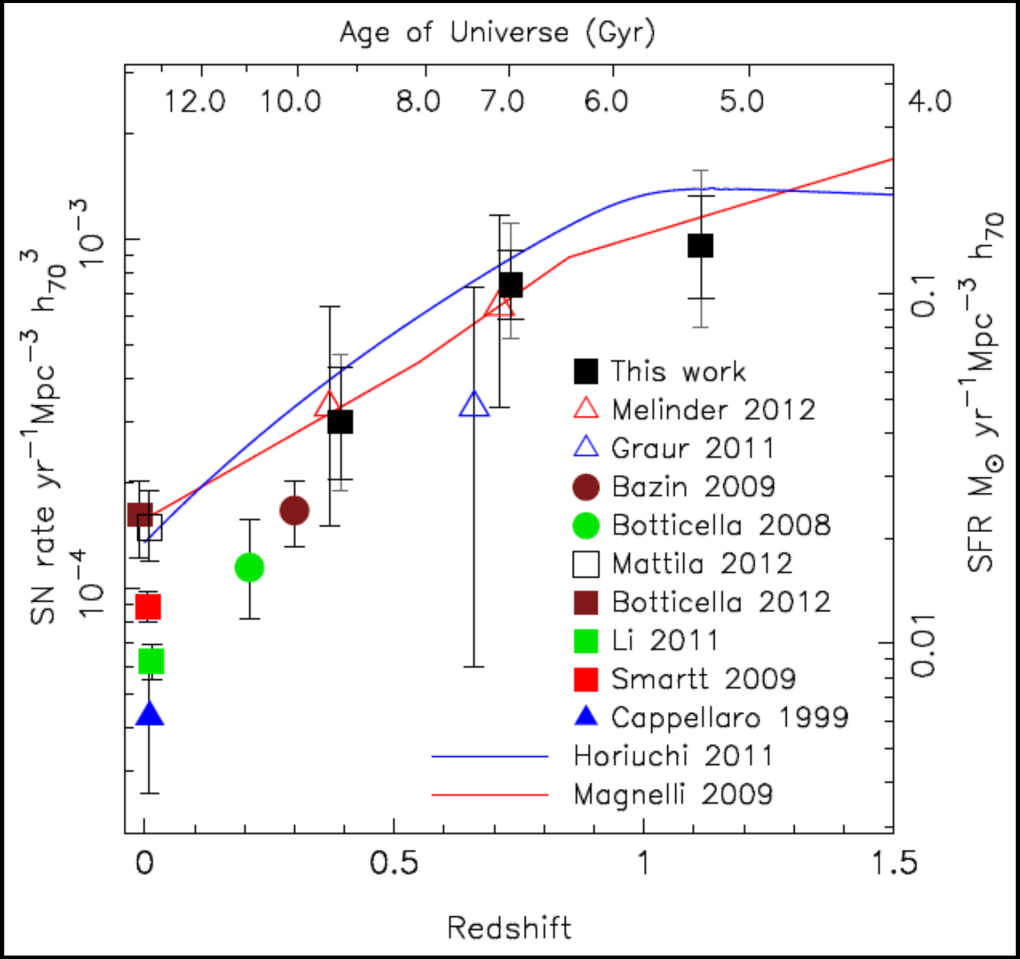
Dust extinction distribution

Large uncertainty from dust attenuation → better model raises CCSN rate 30-50%



Mattila et al (2012)

→ Failed collapse fraction reduced to 10-30%



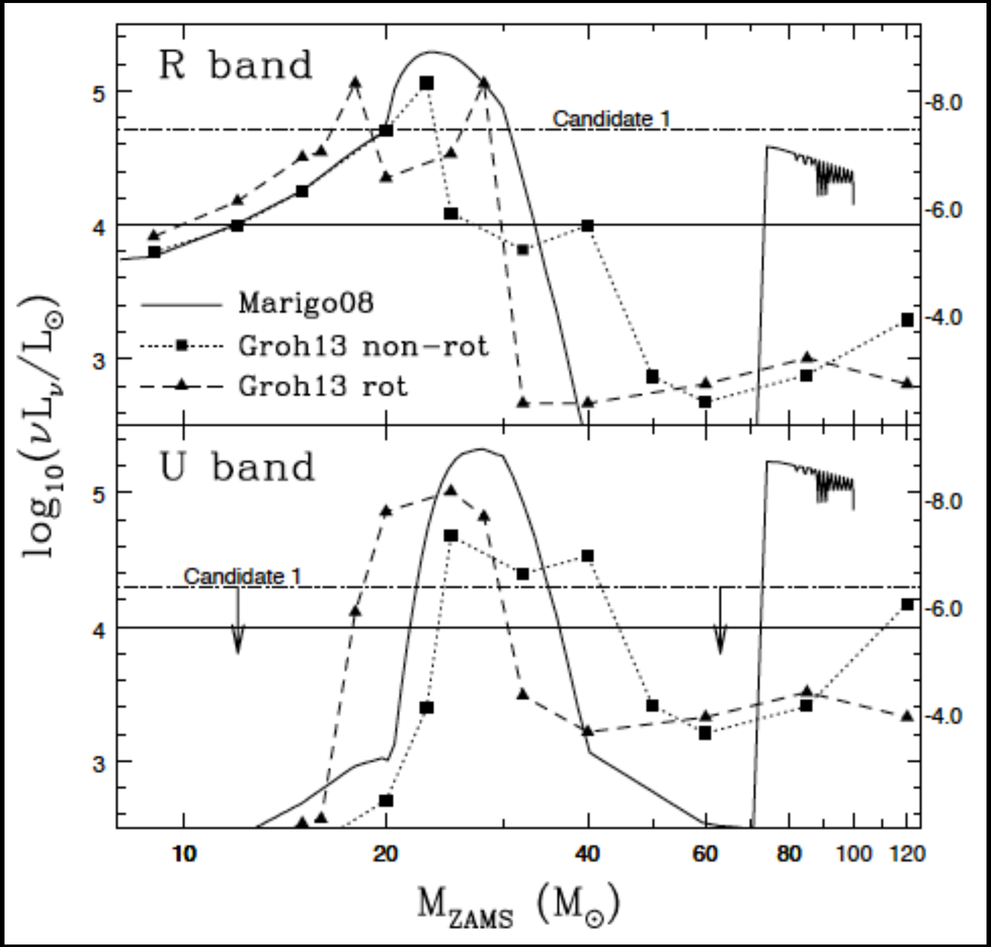
Dahlen et al, ApJ (2012)

4. Searching for failed explosions: Survey about nothing

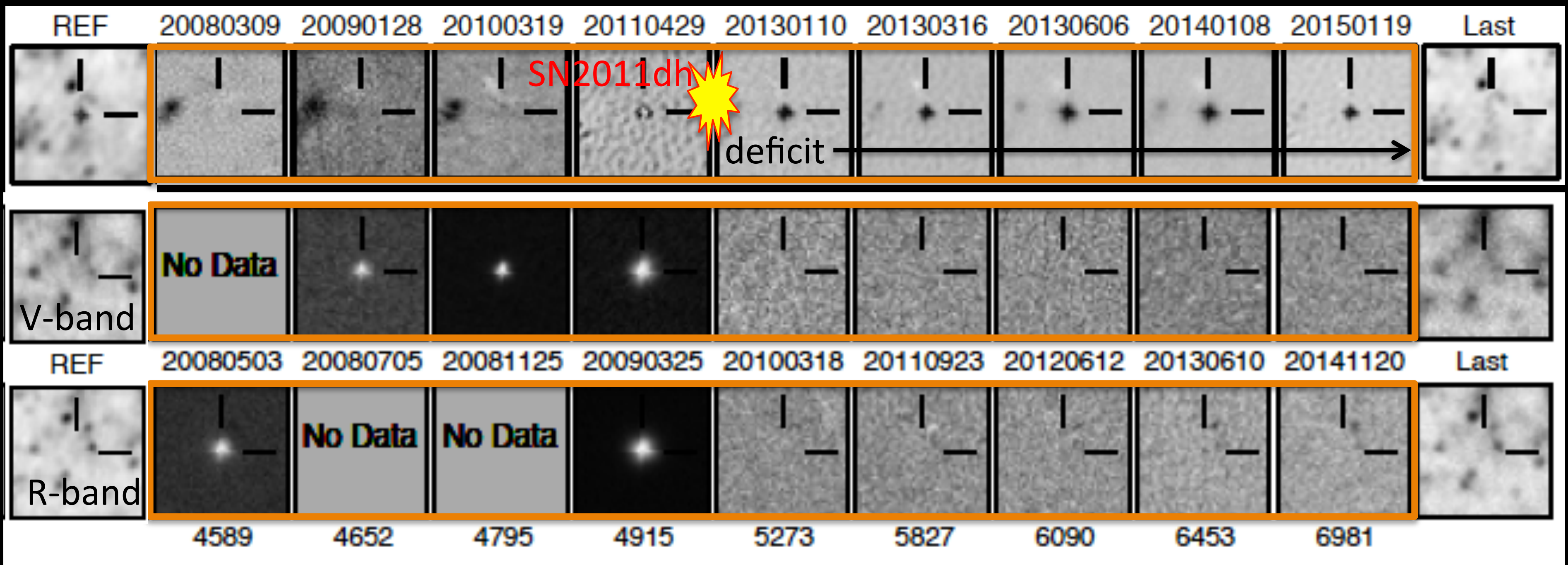
Survey About Nothing

- 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:

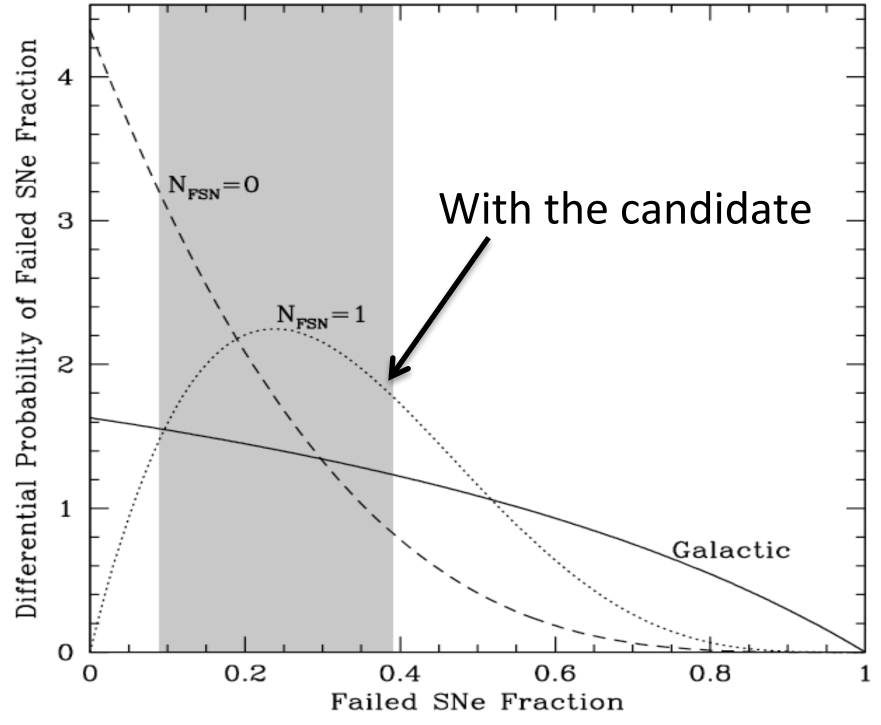
In 4 years running,

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

→ Peak failed collapse rate 10 – 40%

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

Gerke et al. (2015)



NEUTRINO PROBES

Modern neutrino detectors

MiniBooNE (800 ton LqSc)
Nova (15 kton LqSc)
SNO+ (800 ton LqSc)
HALO (76 ton Pb)
[DUNE (~34 kton LAr)]

[RENO (~18 kton LqSc)]

Super-Kamiokande (32 kton H_2O)
EGADS (200 ton H_2O + Gd)
KamLAND (1 kton LqSc)
[Hyper-Kamiokande (~0.6 Mton H_2O)]

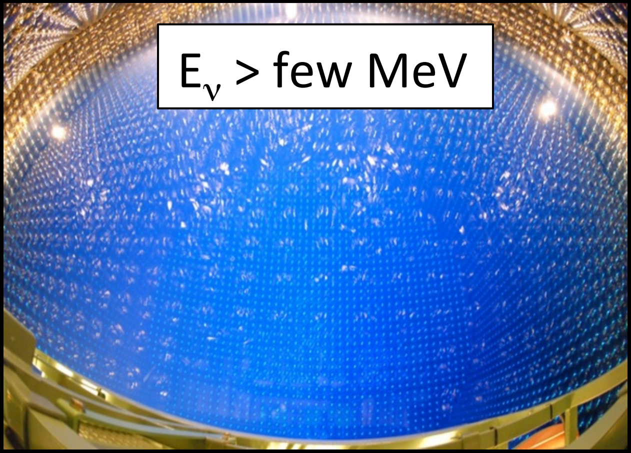
LVD (1 kton LqSc)
Borexino (300 ton LqSc)
[km3Net (Gton water)]
[LENA (50 kton LqSc)]

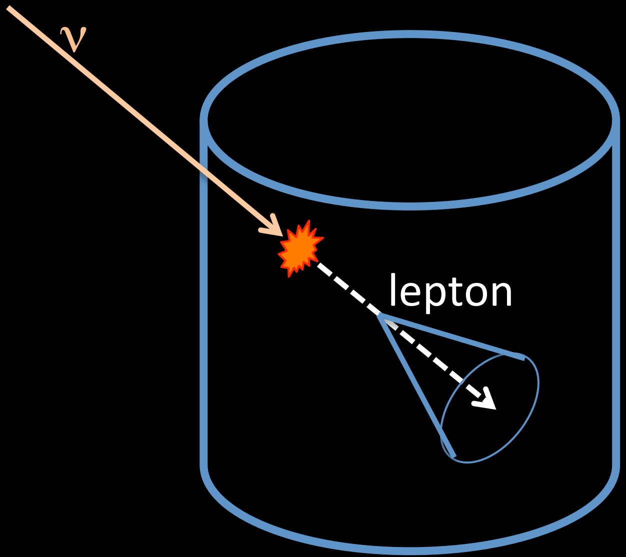
IceCube (Gton Ice)

Daya Bay (300 ton LqSc)
[JUNO (~20 kton LqSc)]

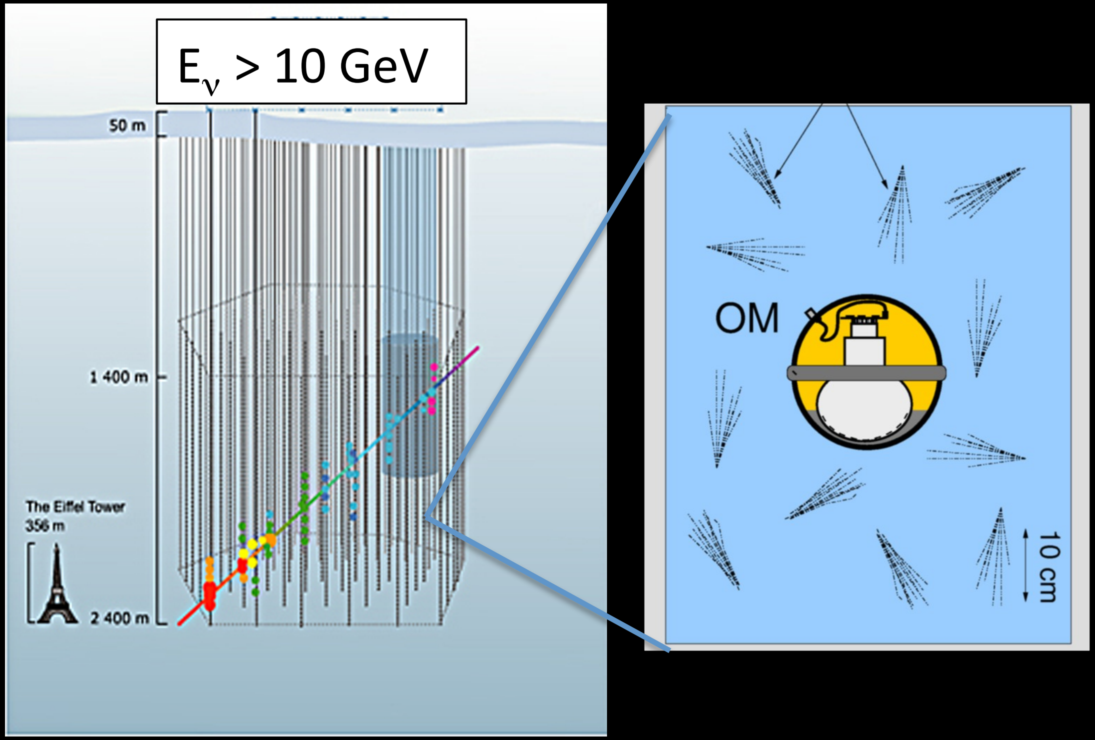
Neutrino detection: Cherenkov

Super-Kamiokande





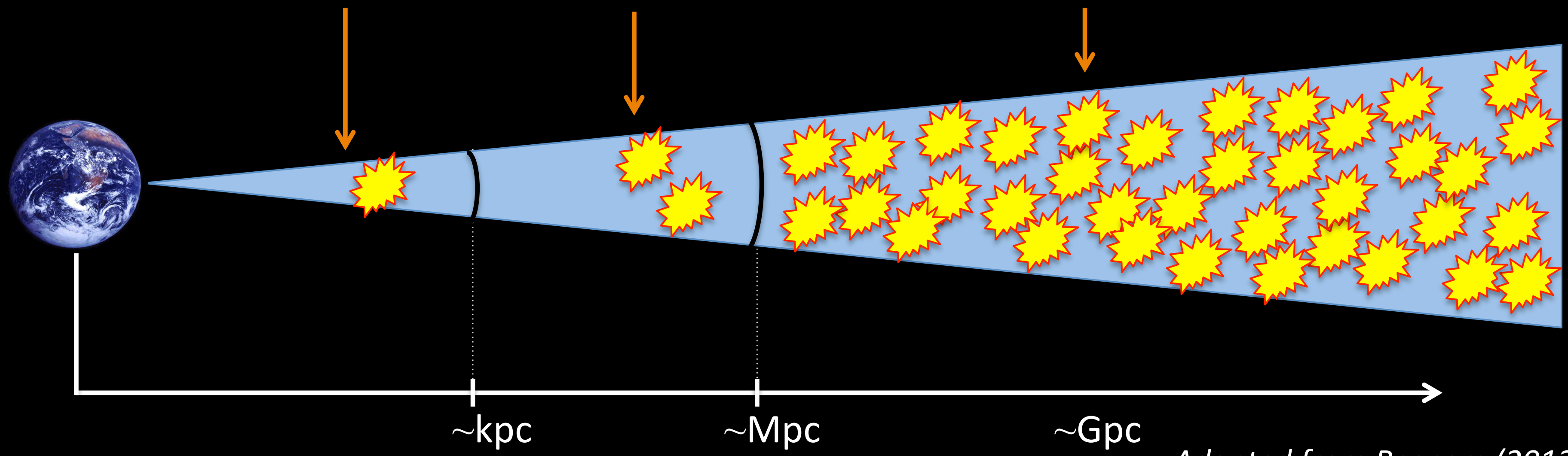
IceCube



- Each OM has intrinsic noise of ~300 Hz
- Supernova at 10 kpc yields ~200 (L/10^{52} erg/s) Hz hits per OM
- Supernova appears as correlated noise in 5000 OMs

e.g., Halzen et al (1995)

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

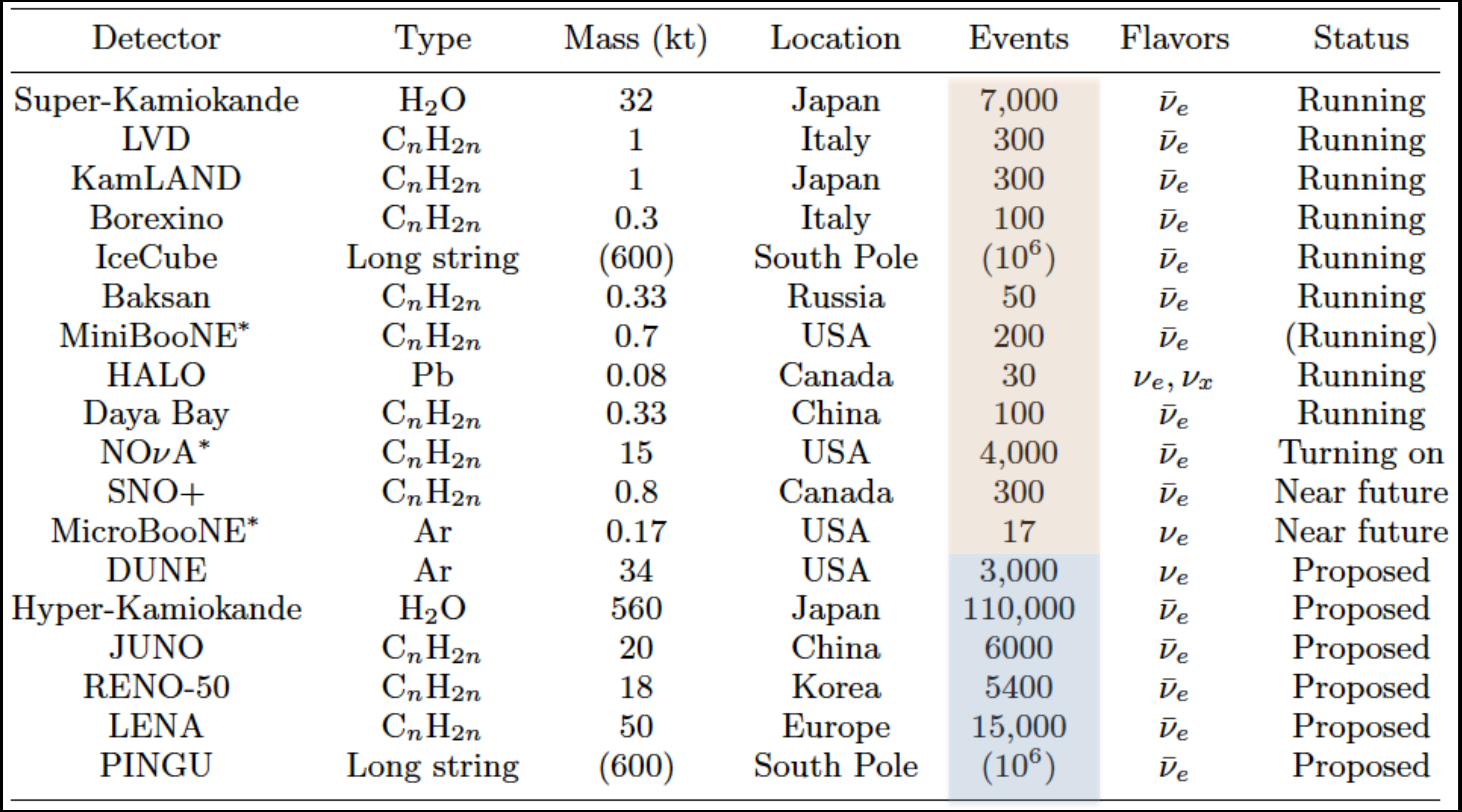
SN rate ~ 10^8 /yr

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

Supernova neutrino detection

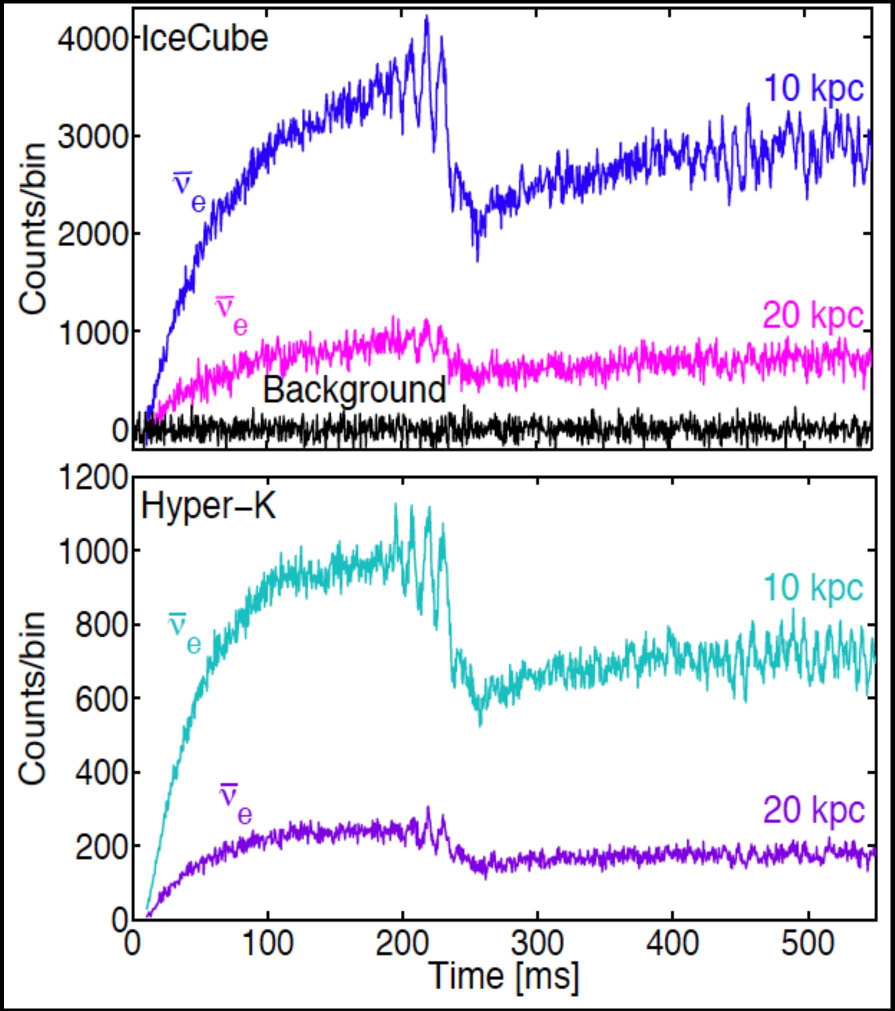
High number statistics expected from a Galactic core collapse (at 10 kpc distance)



Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

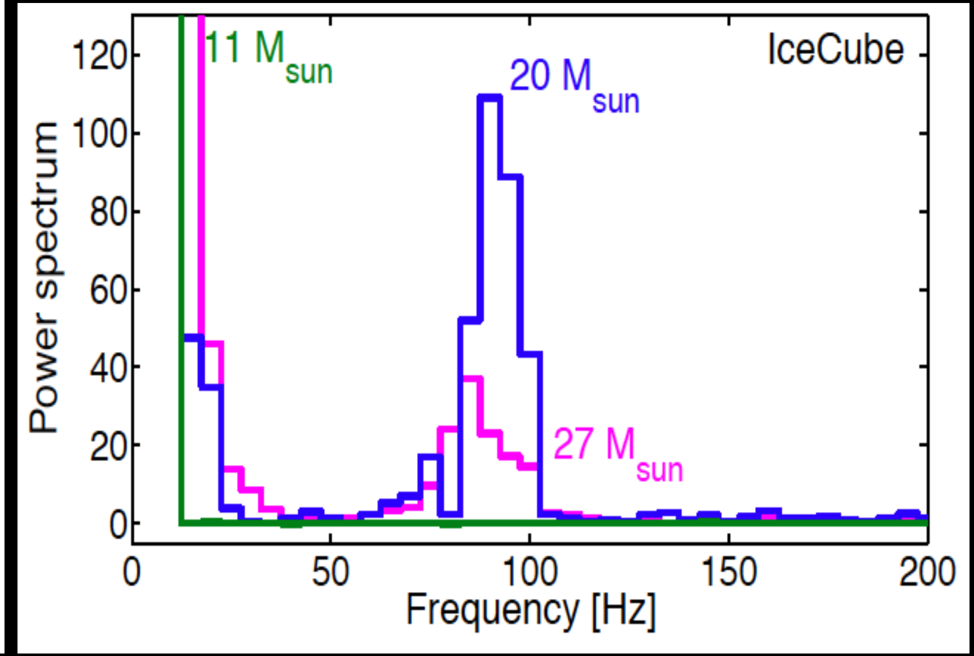
Mirizzi et al (2015)

Observing the SASI mechanism



SASI signatures:

SASI's time variations (~10-20 ms) in the neutrino luminosity and energy can be measured, if we have excellent statistics.



Tamborra et al (2013), see also Lund et al (2010, 2012), based on Hanke et al (2013)

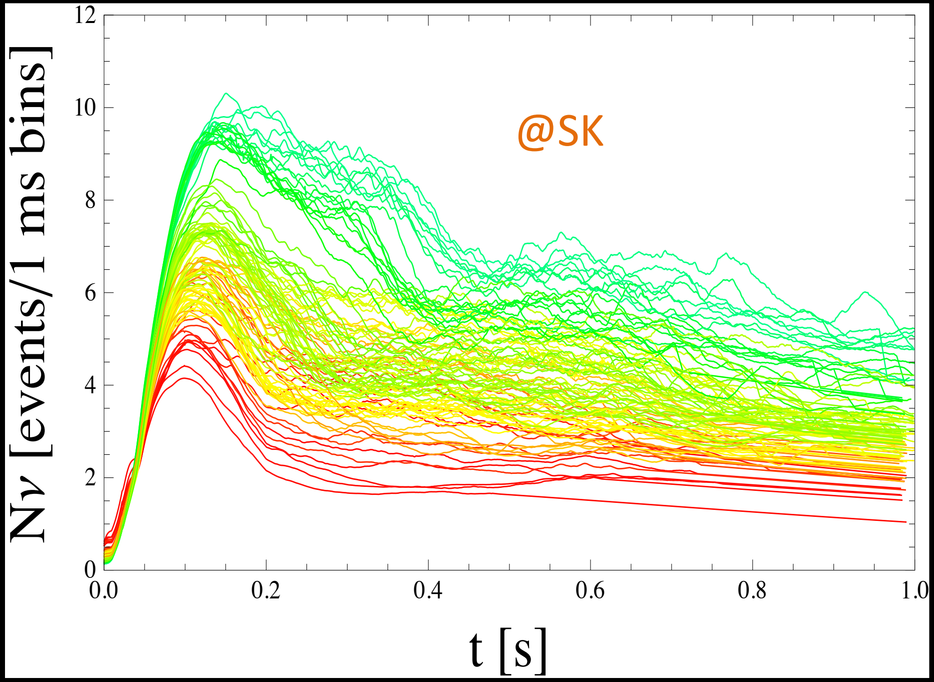
Measuring the compactness

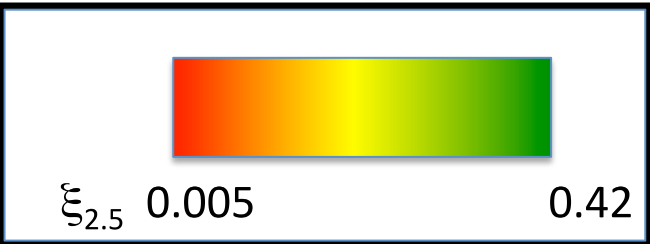
Events light curve at SK:

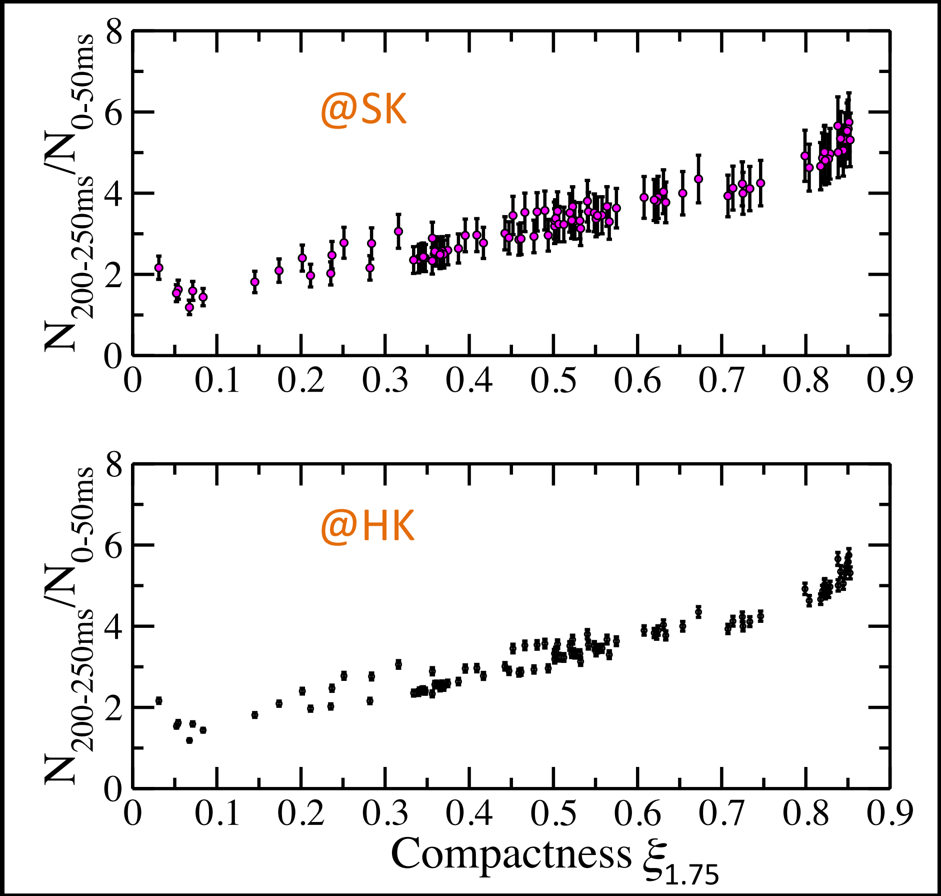
See a clear dependence on the ξ, which drives the accretion history

The ratio of events:

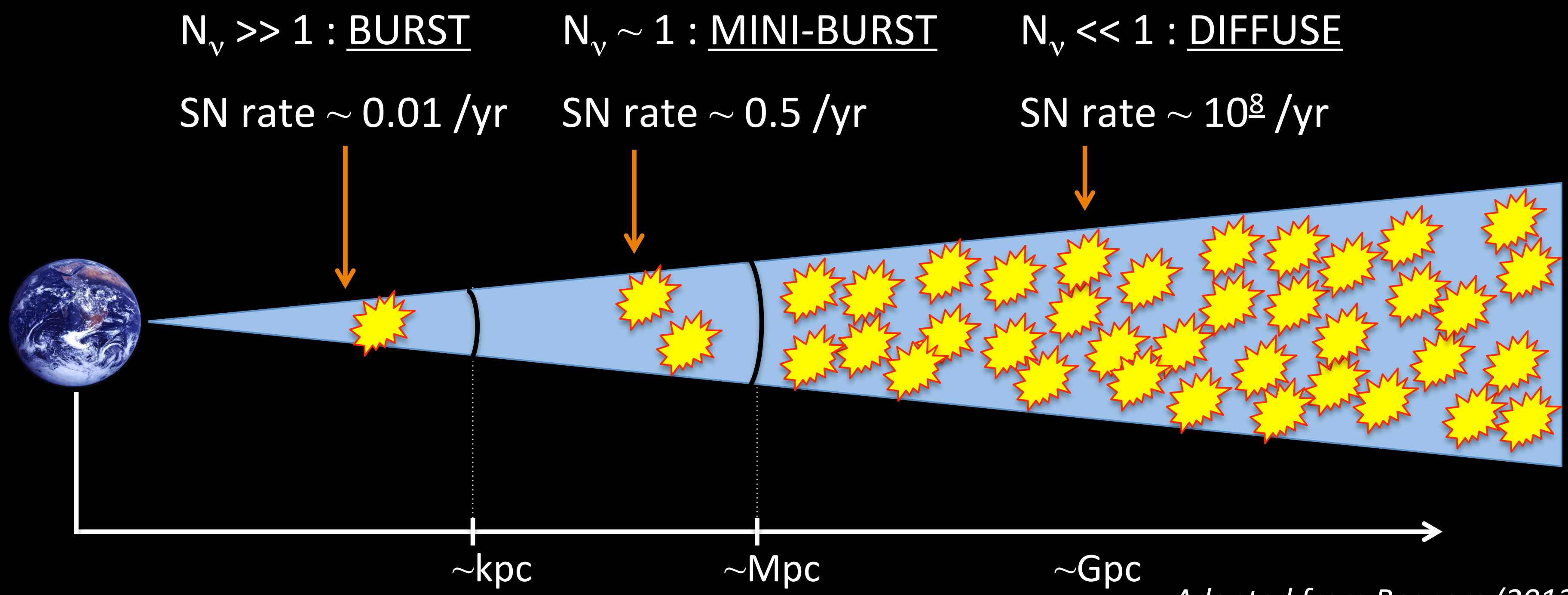
is useful in light of systematic uncertainties. Many choices of time bins for specific ξ







Distance scales and physics outcomes



$N_\nu >> 1$: <u>BURST</u>

SN rate ~ 0.01 /yr

$N_\nu \sim 1$: <u>MINI-BURST</u>

SN rate ~ 0.5 /yr

$N_\nu << 1$: <u>DIFFUSE</u>

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

Diffuse Supernova Neutrino Background

Observed positron spectrum

Input 1: supernova neutrino spectrum (intensely studied, quantity *__of interest__*)

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

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

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

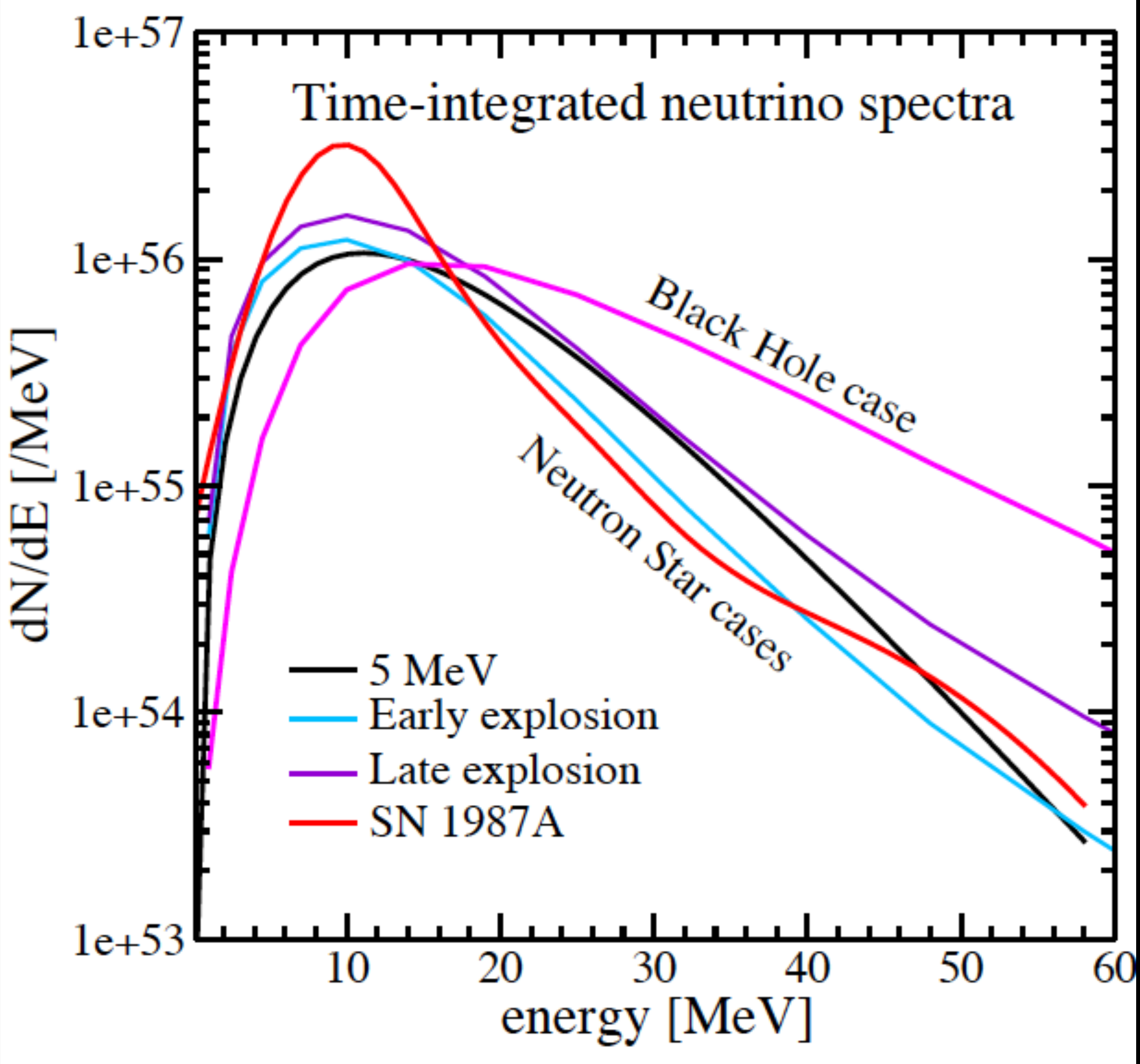
Input 3: neutrino detector capabilities (well understood for H_2O)

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

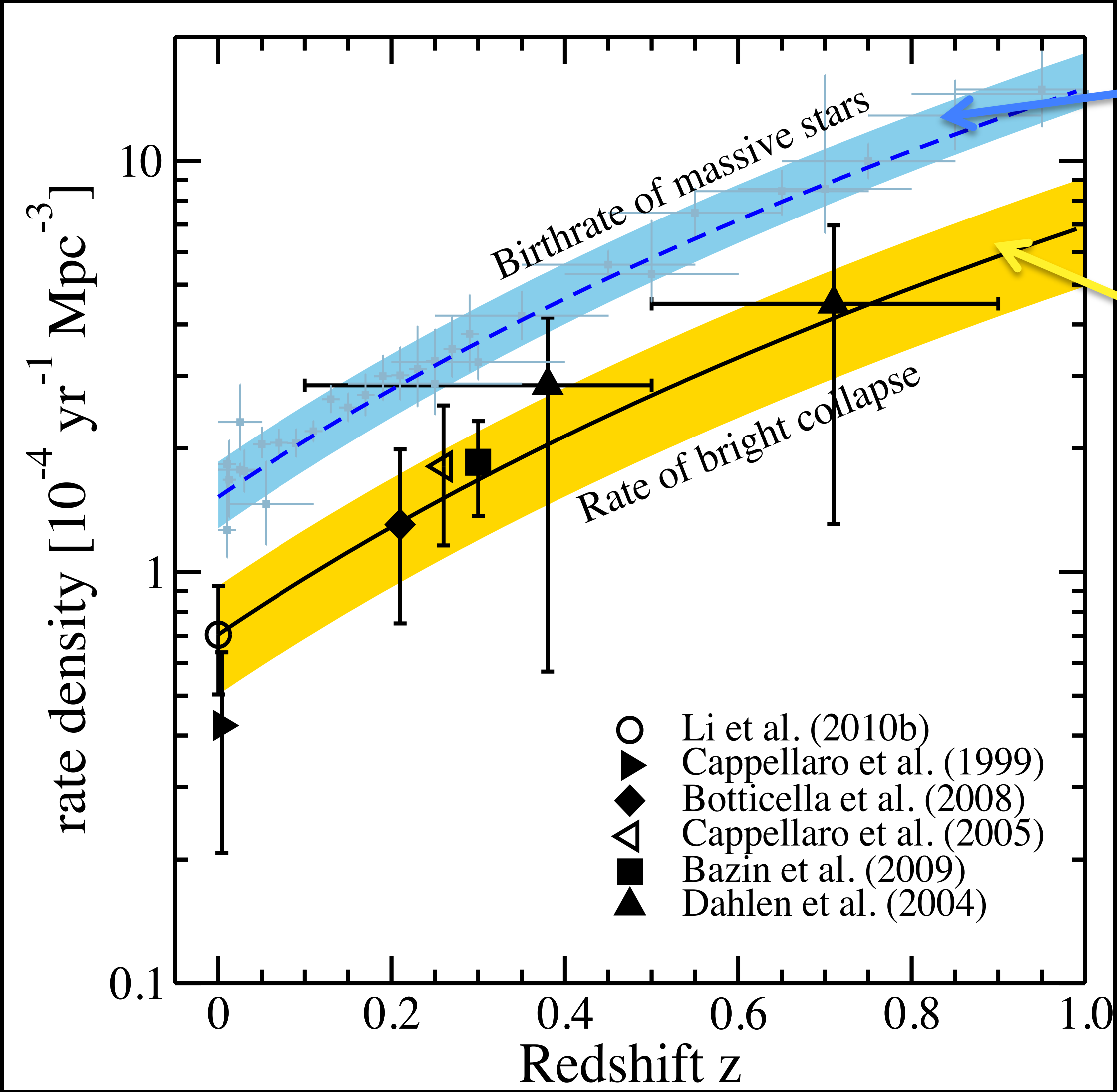
Input 1: Time-integrated neutrino signal

Neutrino emission:
Black hole cuts off the neutrino emission, but it necessarily goes through rapid mass accretion → ν emission is more luminous and hotter (EOS dependent)

Liebendoerfer et al 2004,
Fischer et al 2009,
Sumiyoshi et al 06, 07, 08, 09,
Nakazato et al 2008, 2010,
O'Connor & Ott 2011, …



Input 2: cosmic core-collapse rate



Horiuchi et al (2011)

Core-collapse rate

From the birth rate of massive stars

Observed supernova rate

Derived from observations of <u>*luminous*</u> supernovae (many recent updates)

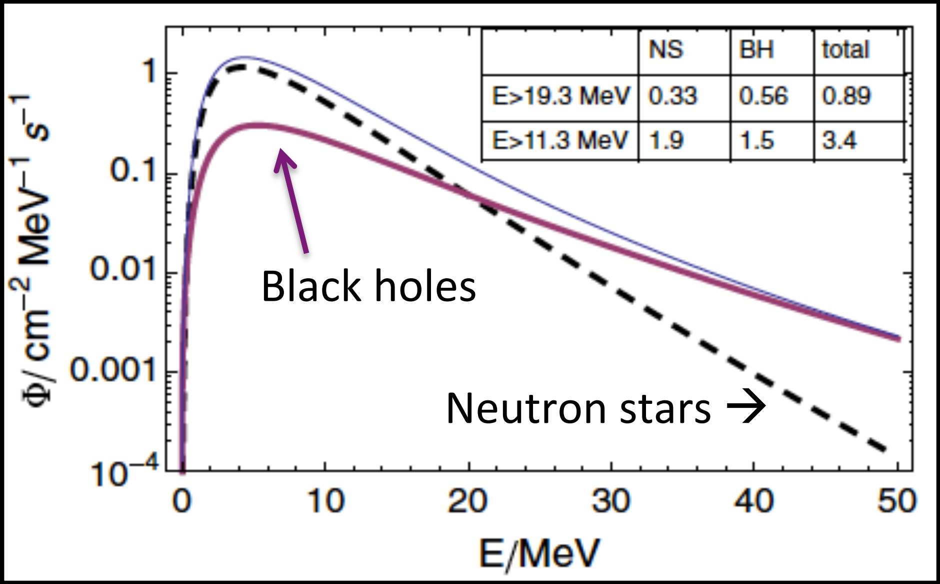
(Core-collapse rate) – (supernova rate) = DIM or DARK collapse rate

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

Predictions

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

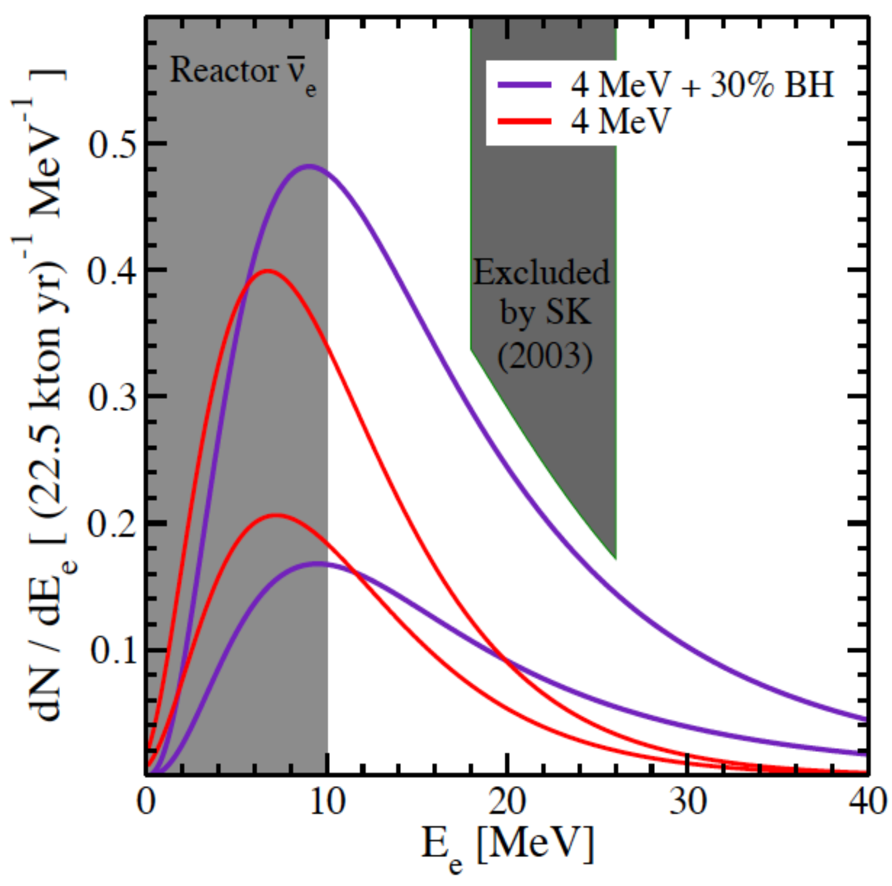
Lunardini (2009); Lien et al (2010),Keehn & Lunardini (2010), Nakazato (2013), Yuksel & Kistler (2014)

Event rate at SK (22.5 kton FV):

Spectrum	18 MeV threshold [/yr]
4 MeV	0.4 +/- 0.1
4 MeV+BH	< 1.8
SN1987A	0.5 +/- 0.1

Event spectra with uncertainties:

Assuming 30% collapse to black holes

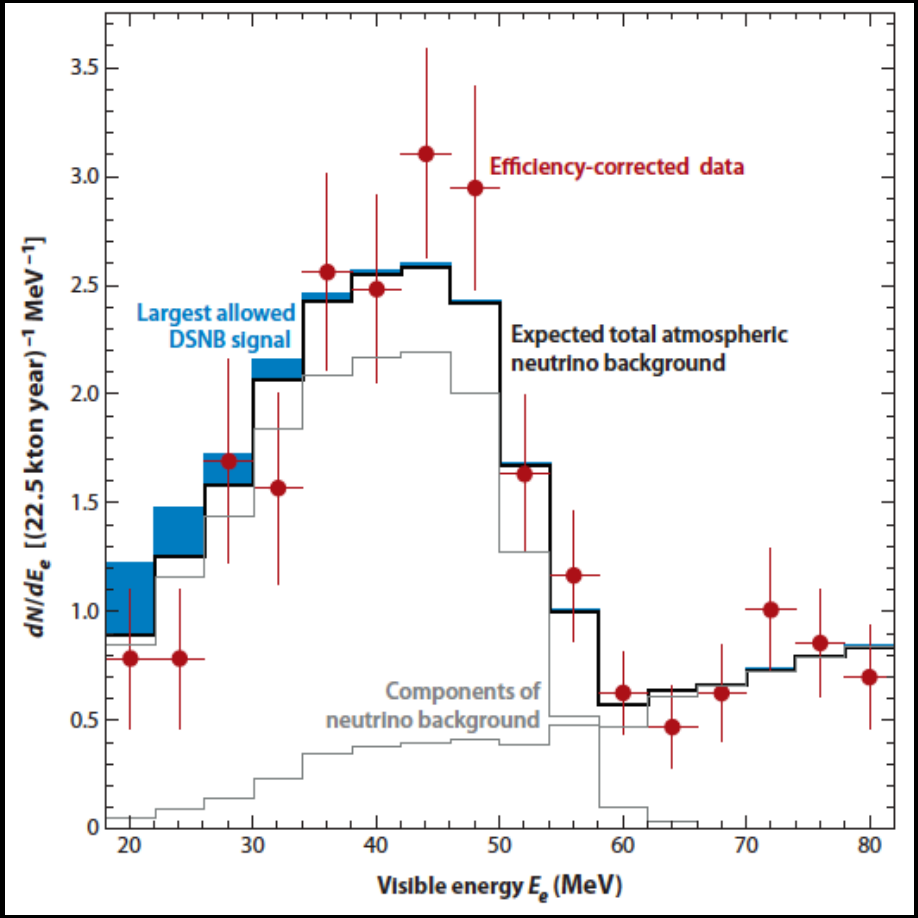


Adapted from Horiuchi et al (2009)

Searches and forecast

Background-limited:

Significant backgrounds at present:



Beacom 2010, from SK limits (Malek et al 2003, for update see Bays et al 2012)

R&D towards a signal-limited regime

Use dissolved Gadolinium (Gd) for effective neutron-tagging

Beacom & Vagins (2004)

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

current

Capture on protons, signal lost

with Gd

Capture on Gd, provides a coincidence signal

→ Opens an event limited search

→ Increases energy window

Spectrum	18 MeV threshold [/yr]	10 MeV threshold [/yr]
4 MeV	0.4 +/- 0.1	1.8+/- 0.5
4 MeV+BH	< 1.8	< 4.5
SN1987A	0.5 +/- 0.1	1.5 +/- 0.5

Summary

Take away messages:

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

2. Observationally, the fraction of collapse to black holes may be as high as ~ 30% of core collapse. This would explain:
    - The red supergiant problem
    - The black hole mass function
    - The supernova rate discrepancy
    - Recent results from Survey about Nothing

3. Neutrinos provide a valuable test, both via the next Galactic supernova, and via the diffuse supernova neutrino background. (Survey About Nothing will provide important information also)

Thank you!