Multi-messenger physics opportunities from core-collapse supernovae

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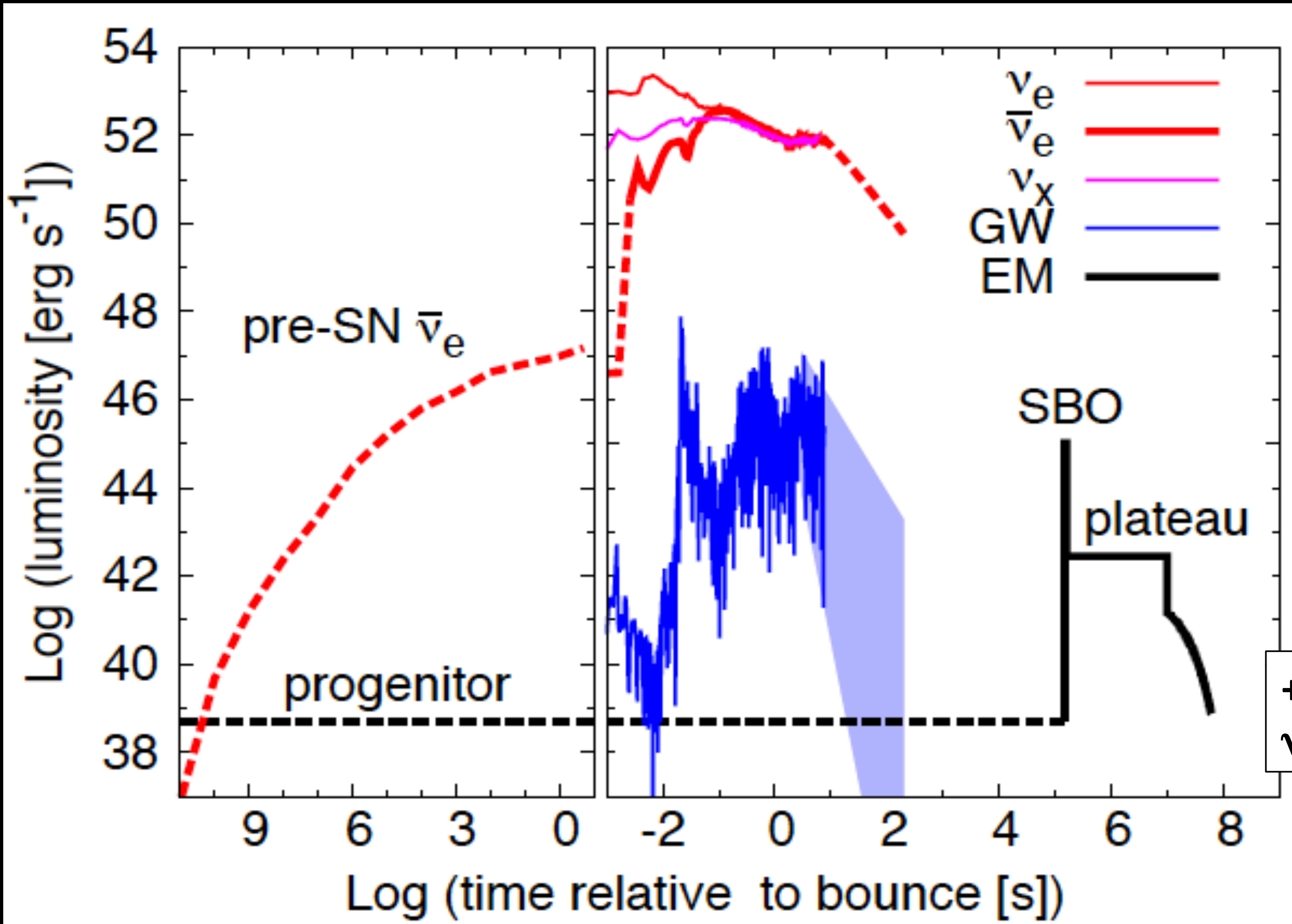
VIRGINIA TECH

The Center for Neutrino Physics

Image credit: NASA/ESA

Inherently a multi-messenger source



+ CR, ν, γ

Nakamura, Horiuchi et al (2016)

Outline

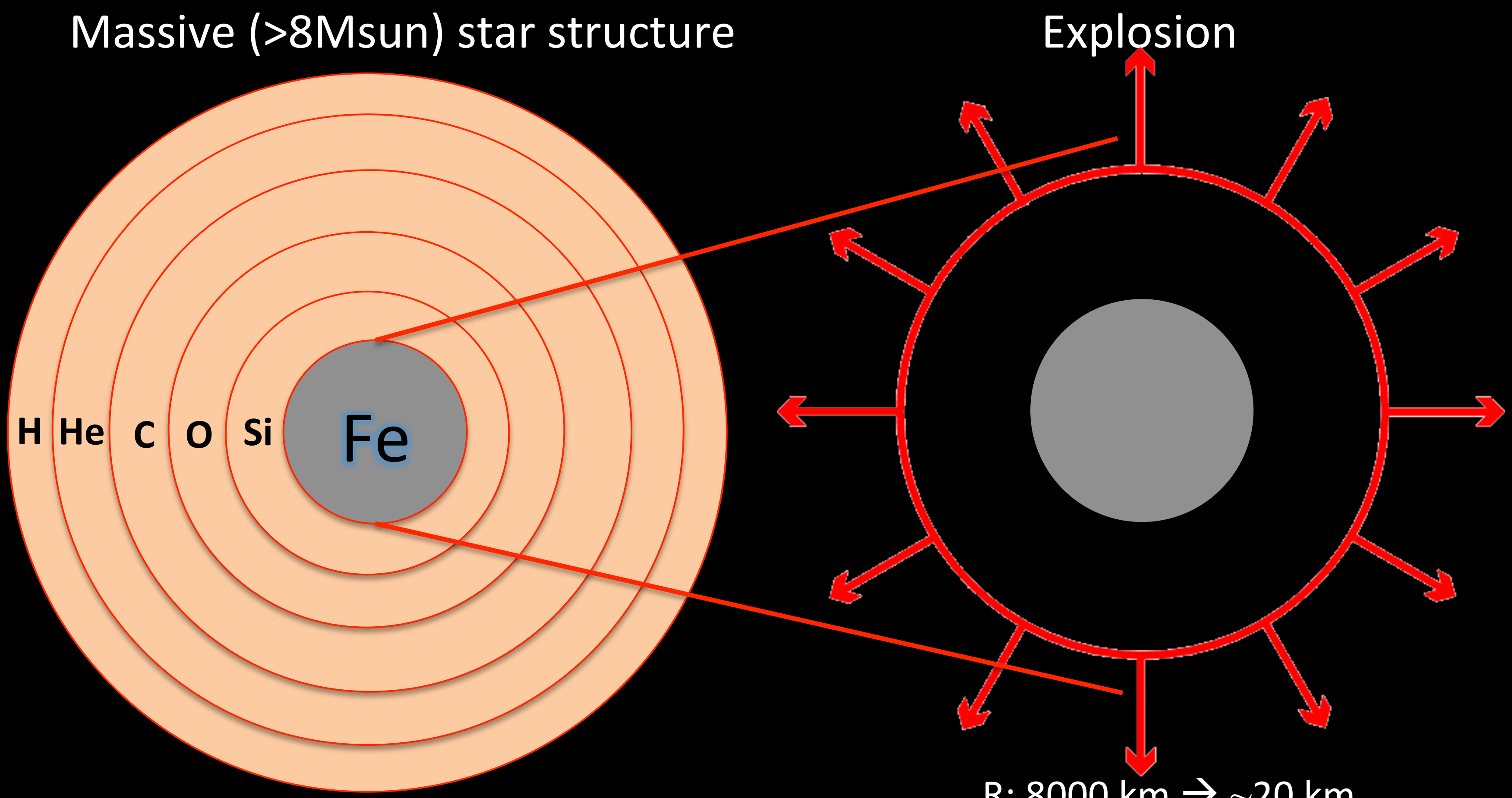
Review of core-collapse supernovae

Multi-messenger opportunities with Galactic supernovae

Beyond the Milky Way

Concluding remarks

Collapse of massive stars



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

Explosion mechanism

Stalled shock

The bounce shock stalls (photodissociation & neutrino emission). Pressure inside balanced by external ram pressure

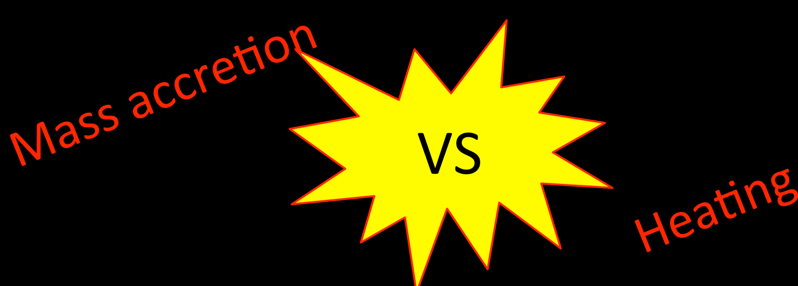
$$p = \rho \Delta v^2$$

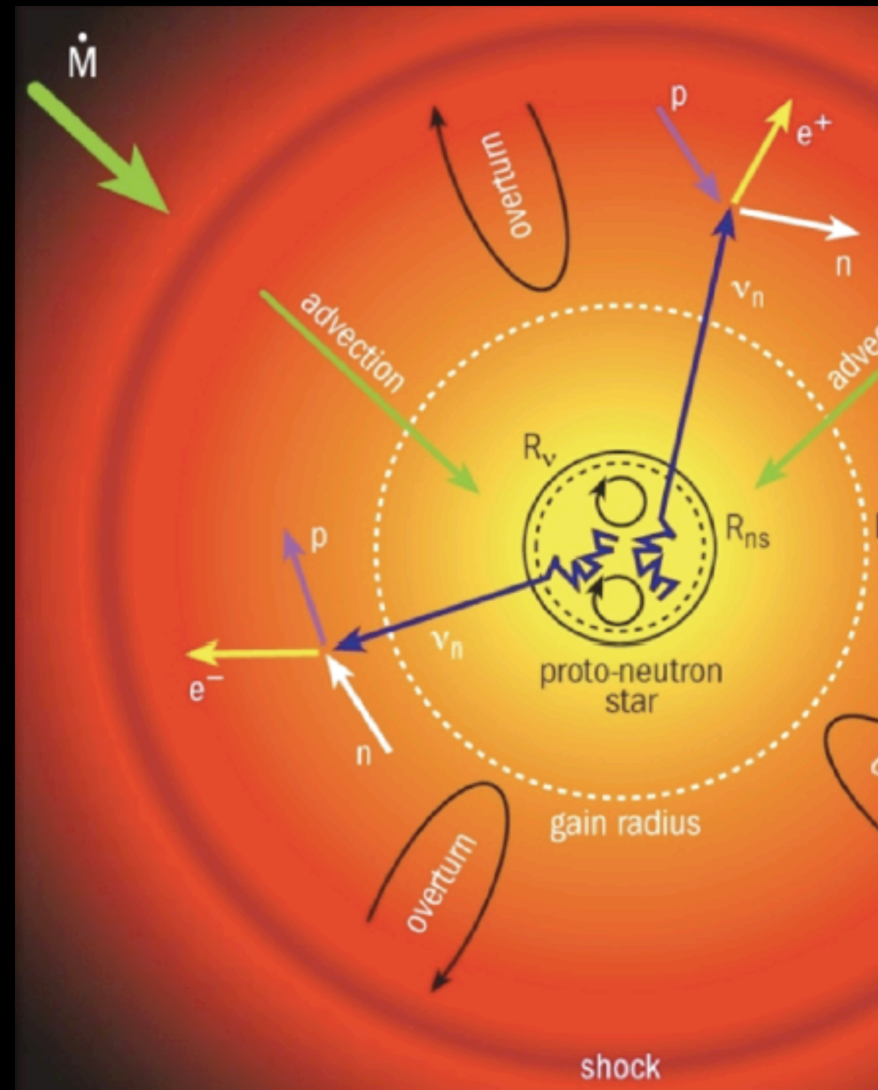
Explosion mechanism

e.g., deposit a fraction of the energy in neutrinos to behind the shock

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

And/or, rotation, magnetic, phase transition, exotic, …



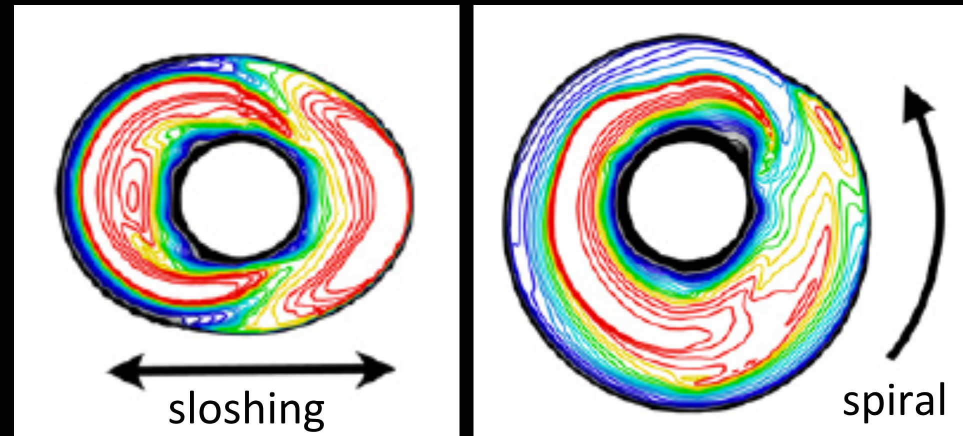


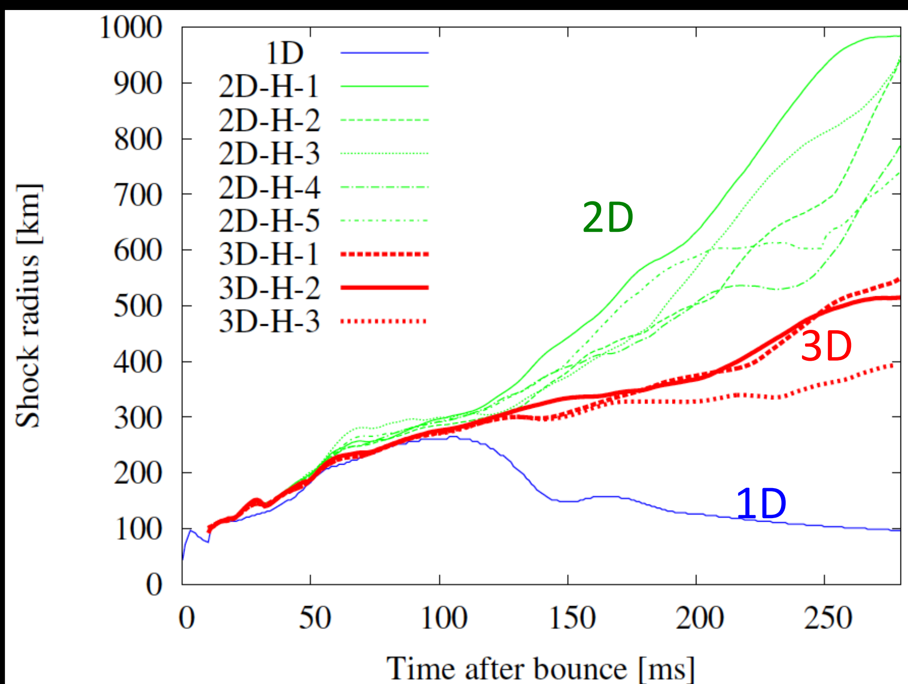
Importance of asphericity

Consensus in the 2000s that 1D doesn't work. *e.g., Liebendoerfer et al (2001, 2004)*

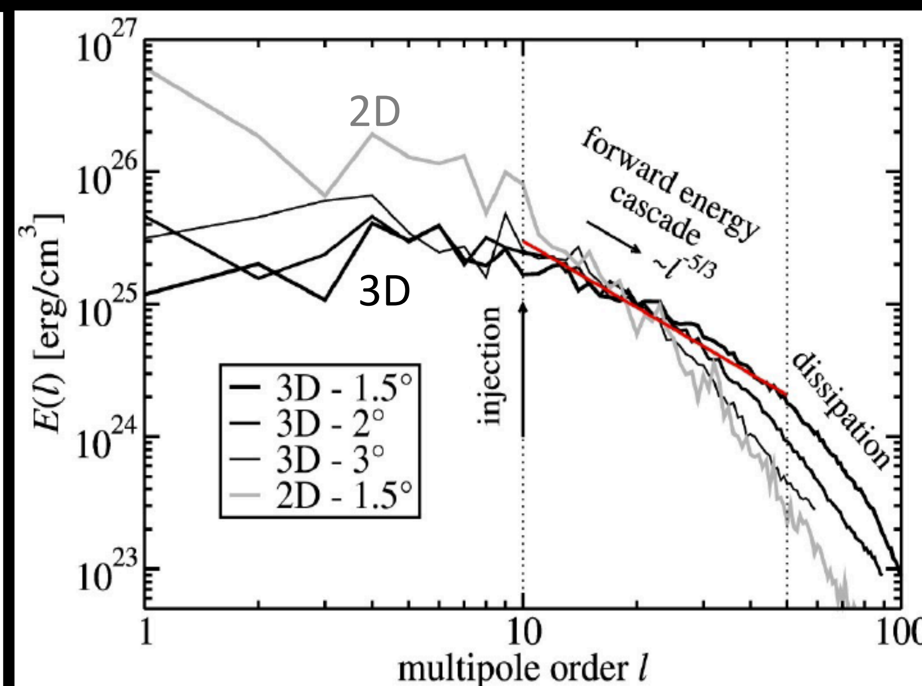
Hydrodynamical instabilities aid explosions, e.g., standing accretion shock instability (SASI), convection

e.g. US, German, Japan, Australian groups





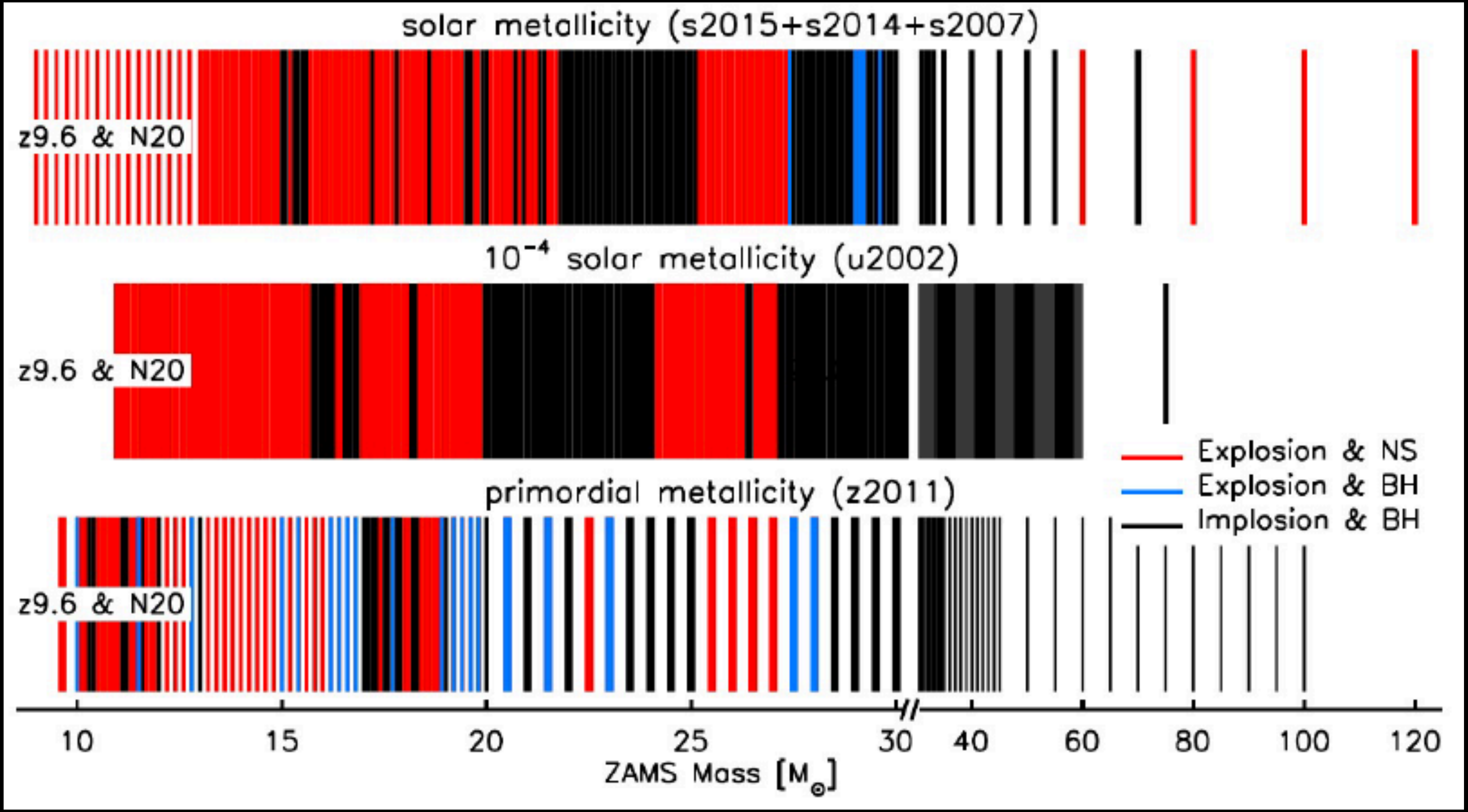
Takiwaki et al (2014)



Janka et al (2016)

Supernova diversity

Systematic studies: thinking in mass looks incomplete



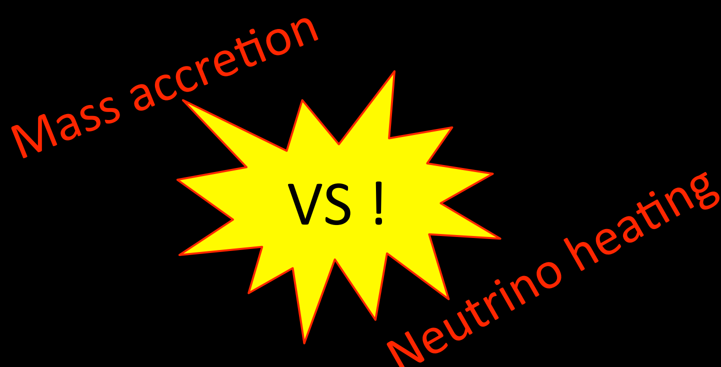
Janka 2017; see also O'Connot & Ott (2011), Pejcha & Thompson (2015), Sukhbold et al (2016), Mueller et al (2016)

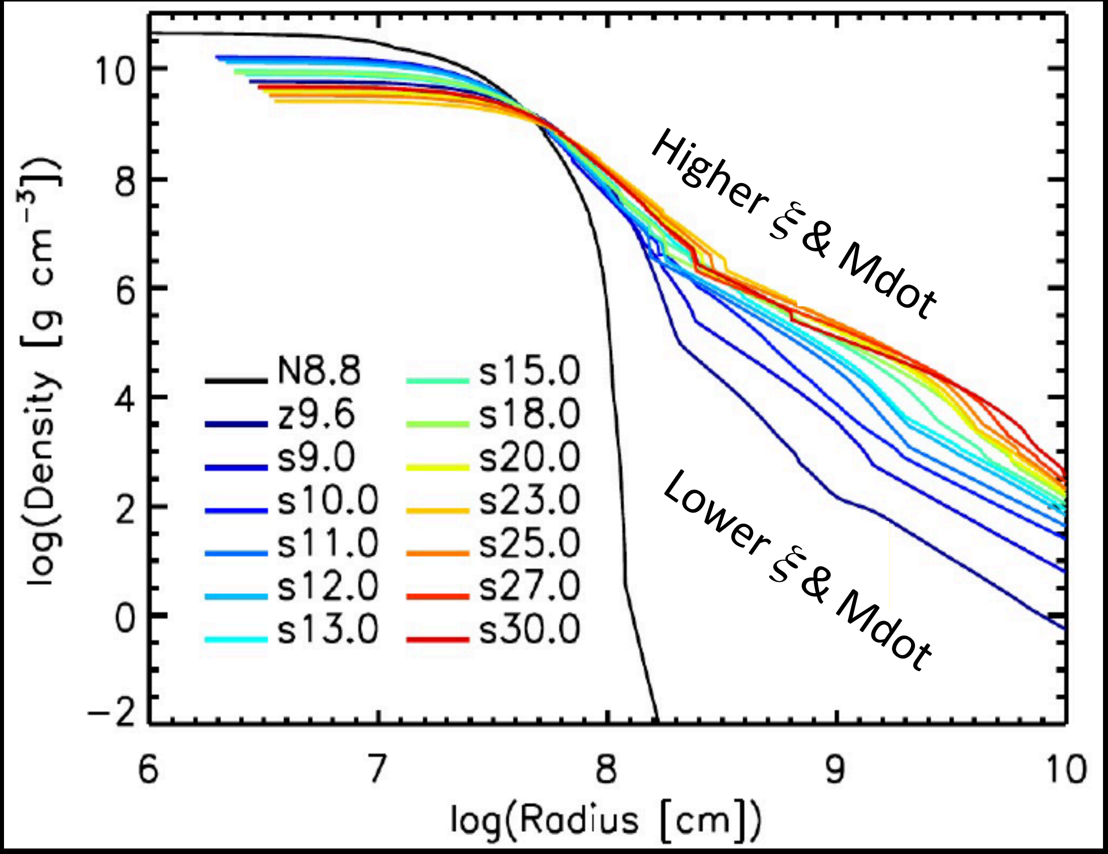
Compactness: a useful indicator

Compactness:
Captures the density structure of the progenitor, which drives mass accretion evolution

O'Connor & Ott (2011)

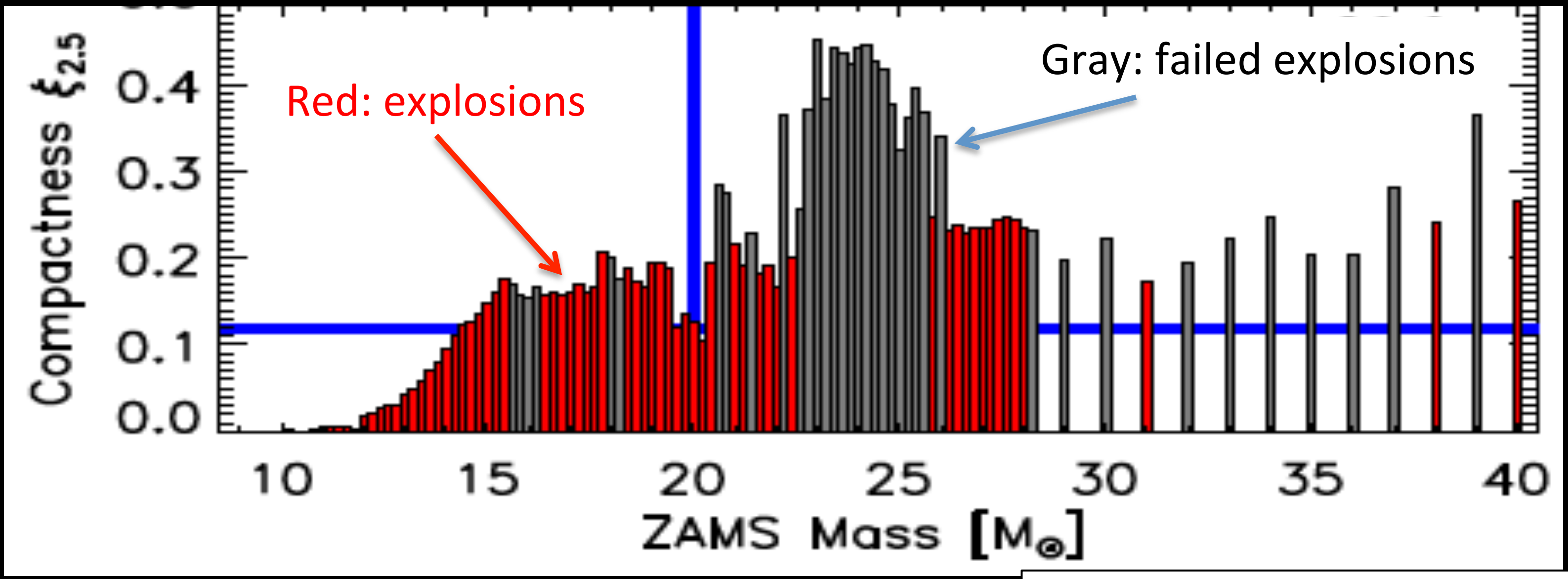
$$\xi_M = \left. \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}} \right|_t$$





Islands of un-explodability

Failed explosions appear in islands, and correspond to stars with large compactness



Ertl et al (2015) ; see also Ugliano et al (2012

- BH formation for $\xi_{2.5} > 0.3$
- Explosions for $\xi_{2.5} < 0.15$
- Mixture in between

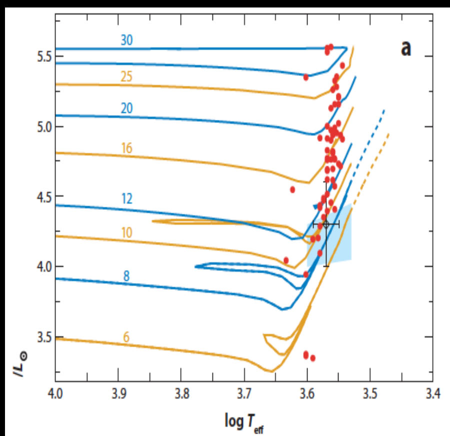
- 1 compactness predicts outcome in at most ~88% of cases
- 2 parameters successfully predicts in ~97% of cases

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

Failed fraction could be large

Many circumstantial evidence for a large fraction of failed explosions.

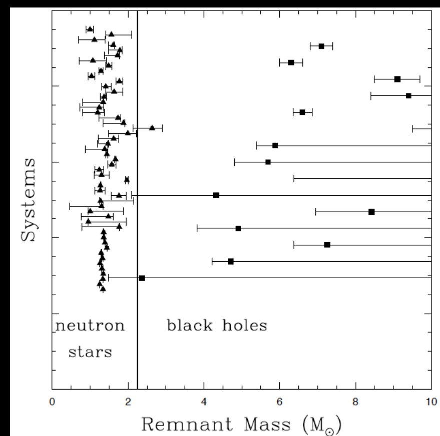
Red supergiant problem



f_{BH}**~20-30%**

Smartt et al (2009)

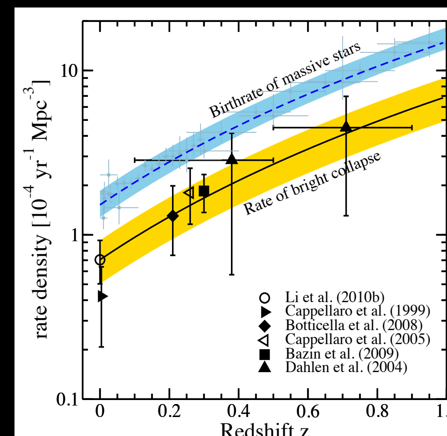
Black hole mass function



f_{BH}**~10-40%**

Kochanek et al (2014, 2015)

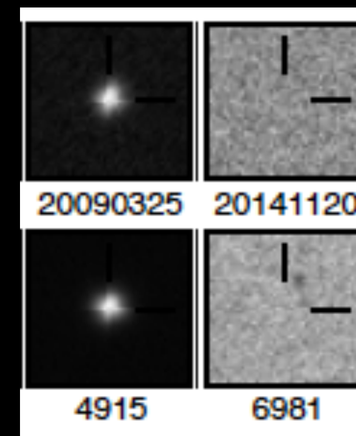
Supernova rate



f_{BH}**~10-30%**

Horiuchi et al (2010)

Survey about nothing



f_{BH}**~4-43%**

Gerke et al (2015)

Insights for compactness:

These can be explained by a critical compactness $\xi_{2.5} \sim 0.2$
(i.e., explosions $\xi_{2.5} < 0.2$ and fails for $\xi_{2.5} > 0.2$)

e.g., Kochanek (2014), Horiuchi et al (2014)

MULTI-MESSENGER OPPORTUNITIES WITH GALACTIC SUPERNOVAE

Galactic supernova neutrinos: multi-messenger astronomy

Goals:

The next Galactic supernova neutrino signal will

1. Reveal IF one should look – ‘significance’
2. Reveal WHEN one should look – ‘timing resolution’
3. Provide TIMELY alert – ‘TOO’
4. Reveal WHERE one should look – ‘astronomy’

(see Adams et al 2013)

1. Reveals IF to look

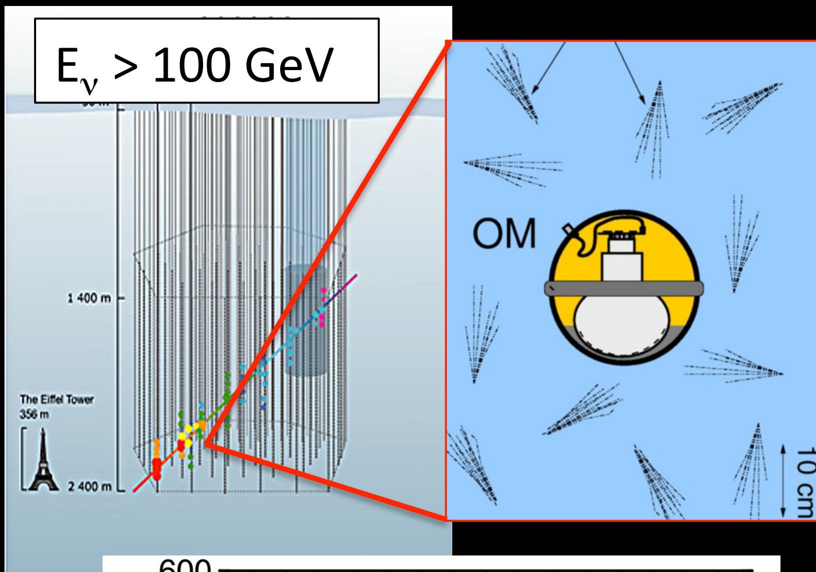
Reveal IF: High number statistics expected from a Galactic core collapse ✓

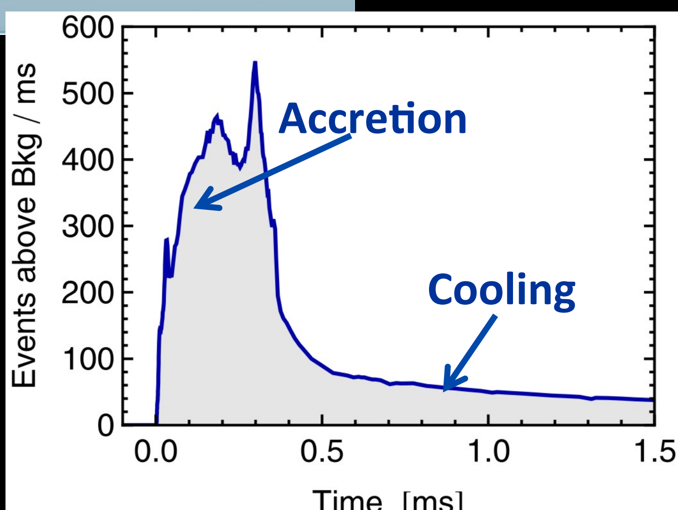
	Detector	Type	Mass (kt)	Location	Events	Flavors
Running	Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$
	LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$
	KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$
	Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$
	IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$
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

Mirizzi et al (2015)

2. Reveals WHEN to look

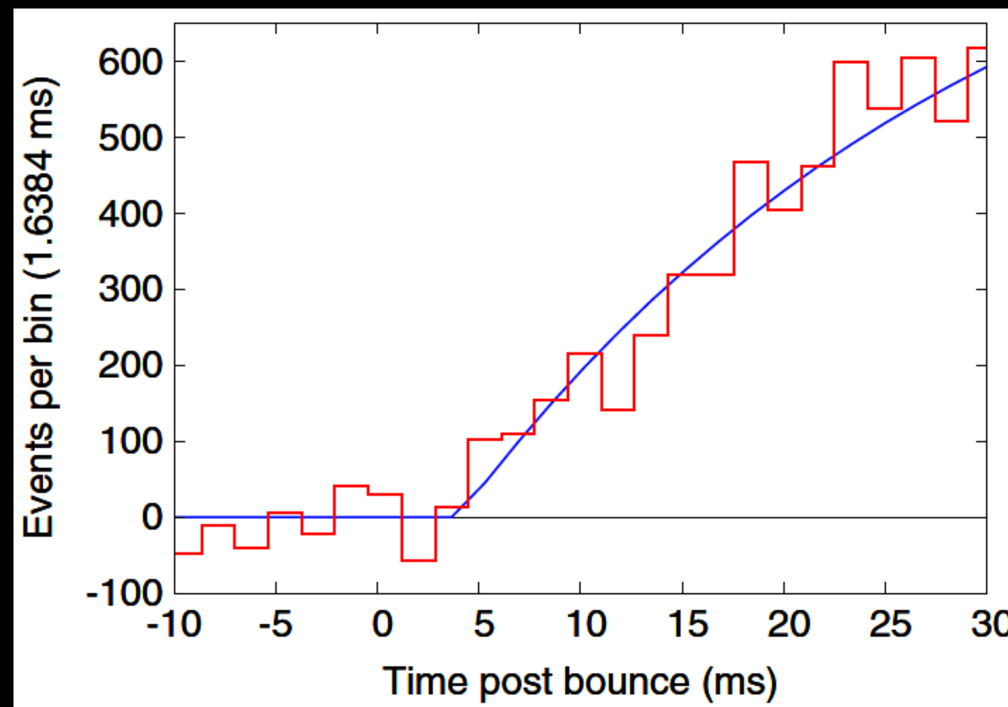
WHEN one should look: from reconstruction of the core bounce time





Abbasi et al. (2011)

e.g., with IceCube: bounce time can be estimated to within ±3.5 ms at 95 % C.L.



Halzen & Raffelt (2009)

→ Neutrinos can determine the bounce time to *O*(10) ms

Multi-messenger: gravitational wave

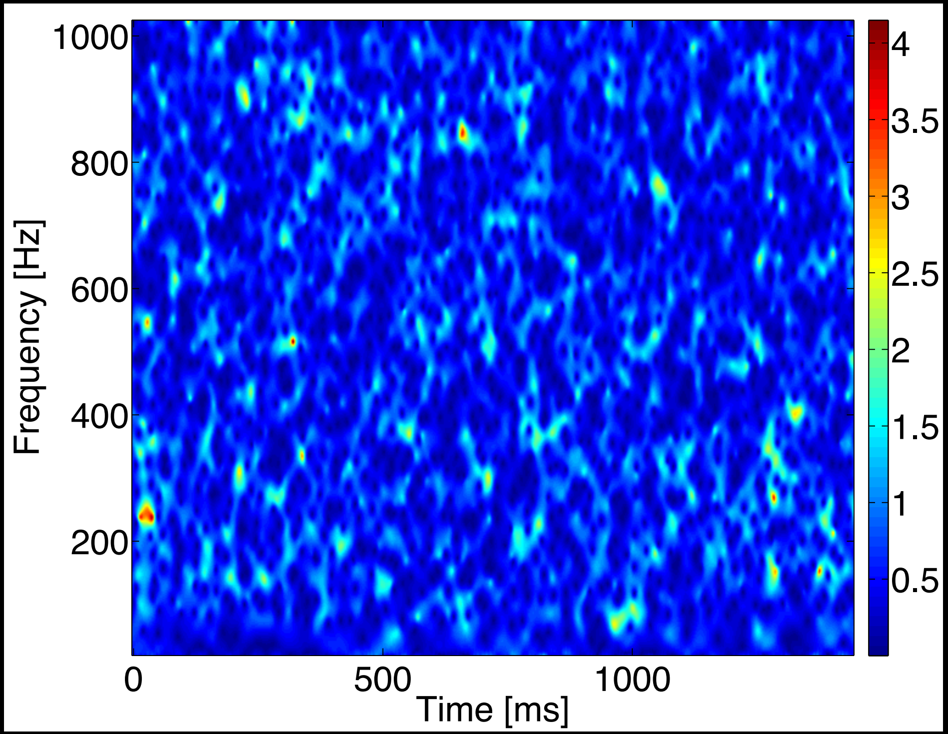
Without neutrino timing

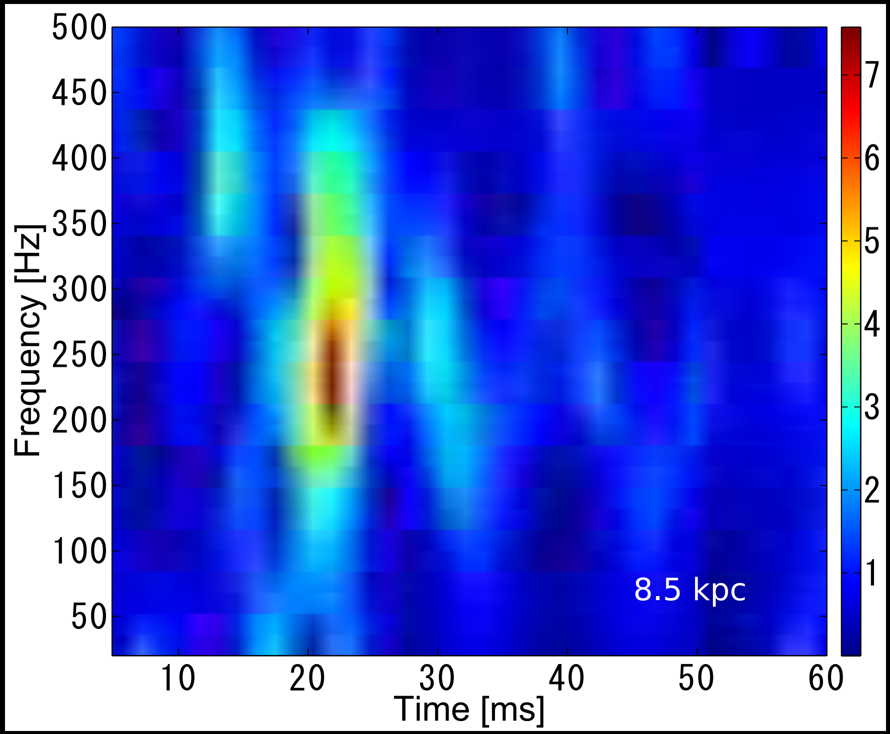
Maximum signal-to-noise ratio is ~3.5 occurring at ~200Hz: but no strong detection (using H-L-V-K network)

With neutrino timing

Narrowing window to 60 ms and freq [50, 500] Hz: SNR ~7 → `correlated' detection

→ Pagliaroli talk





(for non-rotating progenitor)

Nakamura, Horiuchi et al (2016); see also Pagliaroli et al (2009)

→ Timing of core bounce helps GW detection

3. TIMELY alerts

TIMELY alert: rapid sharing of core collapse occurrence

✓ SNEWS:

- Borexino
- DayaBay
- HALO
- IceCube
- KamLAND
- LVD
- Super-K

Coincidence server (@BNL)

http://snews.bnl.gov
astro-ph/0406214

E-mail ALERT ✓

Rapid alerts!

IAU, ATel alerts ✓

✓ Individual detectors

- Super-K will release alert within ~ 1 hour of neutrino burst (info: time, duration, total events, pointing)
- EGADS to automate and release alert within ~ 1 sec

Adams et al (2013)

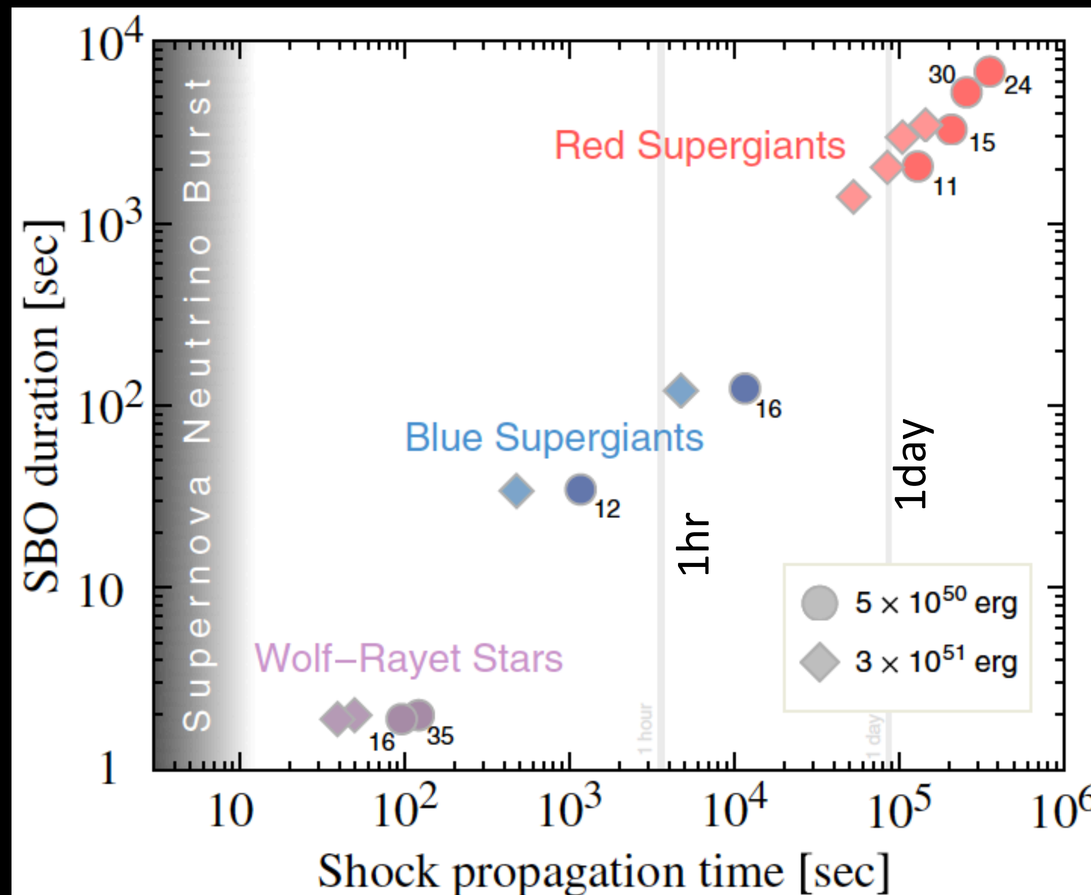
Multi-messenger: electromagnetic

Shock breakout

- Among the first EM signatures of a supernova
- Helpful for early light curve modeling, revealing progenitor radius and envelope properties (R, M_{ej}), as well as explosion energetics (E_{exp}).

- For RSG (type IIP): 1000 Rsun, 10 Msun → *hours* duration arriving *days* delay
- For WR (type Ibc): 1 Rsun, 1-10 Msun → *seconds* duration arriving with *minutes* delay

→ Rapid alert will help chase the shock breakout signal



Kistler et al (2013)
based on Matzner & McKee (1999)

4. Reveals WHERE to look

WHERE one should look

Use e⁻ scattering in the forward cone: ~300 events at SK

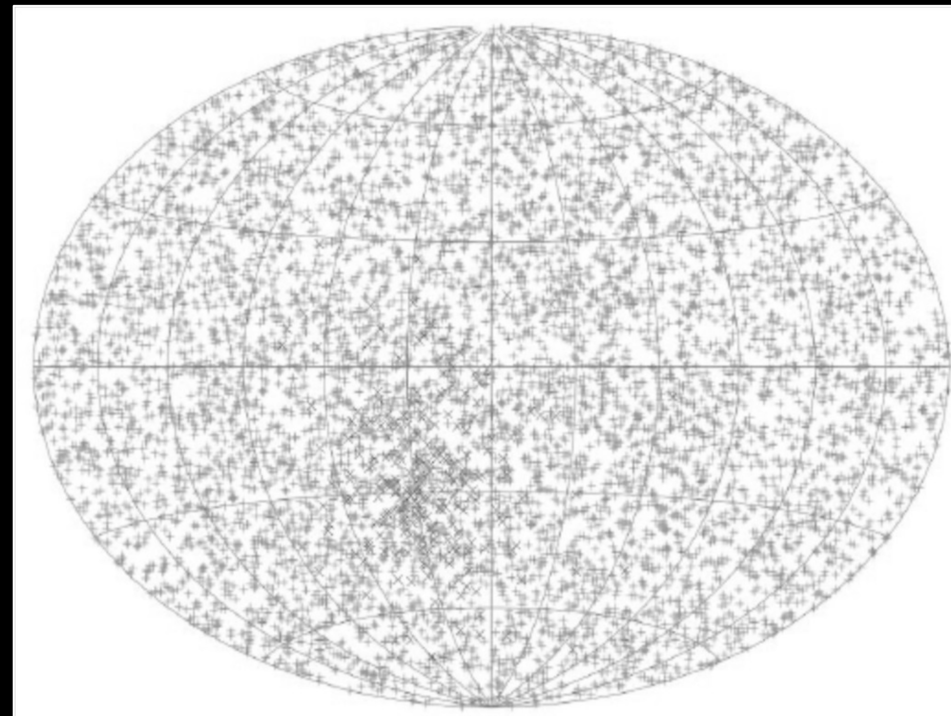
$$\nu + e^- \rightarrow \nu + e^-$$

Background to be reduced by neutron tagging with Gd (~90% efficiency):

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

Remaining background is the ~10% of IBD and νe absorption on ^{16}O (~20-80 events)

→ Pointing accuracy of several degrees



	Super-K	Hyper-K
Water only	~6 deg	~1.4 deg

Beacom & Vogel (1999), Tomas et al (2003)
For triangulation: Beacom & Vogel (1999), Mhlbeier et al (2013), Brdar et al (2018)

Input 3: Super-K with Gadolinium

Background rejection:
In water Cherenkov the signal produces a neutron, while backgrounds typically do not

Beacom & Vagins (2004)

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

w/out Gd → Capture on protons, signal mostly lost (~18% tagging)

with Gd → Capture on Gadolinium, yields a coincidence signal (~90% tagging)

After many R&D tests and studies, approved in 2015 and begun in June 2018!

EGADS: Evaluating Gadolinium's Action on Detector Systems

4. Reveals WHERE to look

WHERE one should look

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Background to be reduced by neutron tagging with Gd (~90% efficiency):

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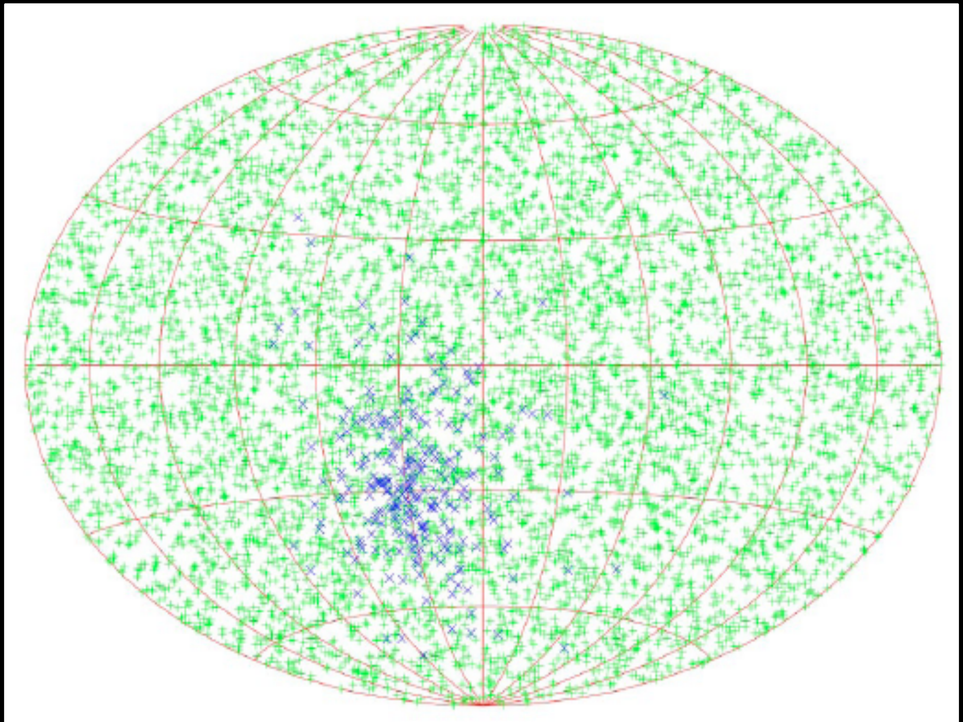
→ Pointing accuracy of a few degrees ✓



	Super-K	Hyper-K
Water only	~6 deg	~1.4 deg
Water + Gd (90% tag)	~3 deg	~0.6 deg

Beacom & Vogel (1999), Tomas et al (2003)
For triangulation: Beacom & Vogel (1999), Mhlbeier et al (2013), Brdar et al (2018)

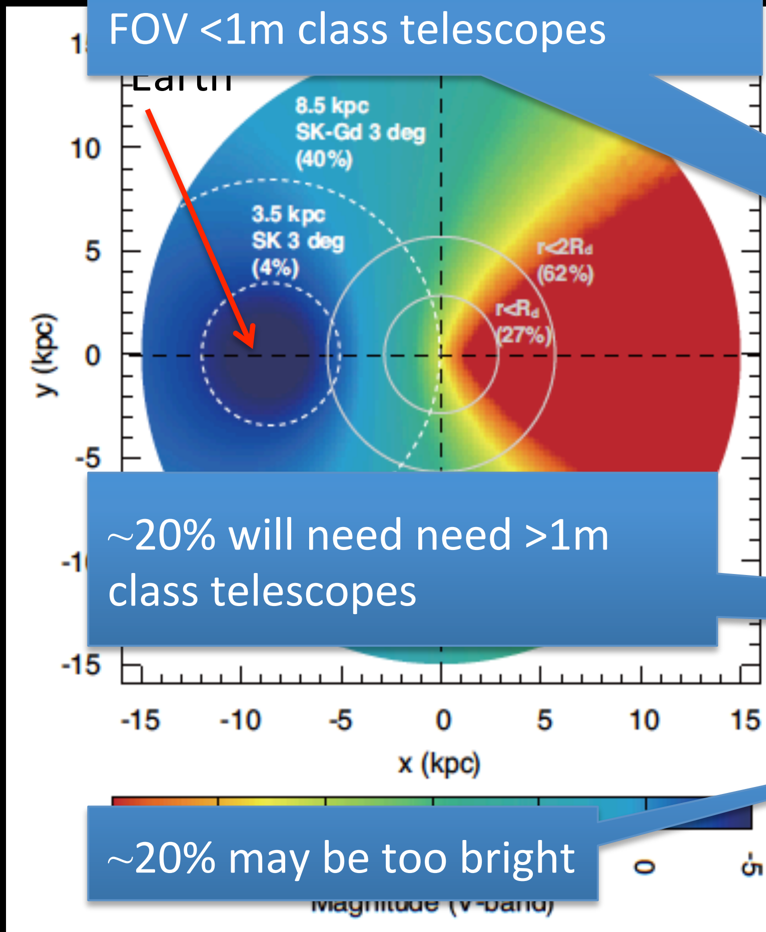
Multi-messenger: electr

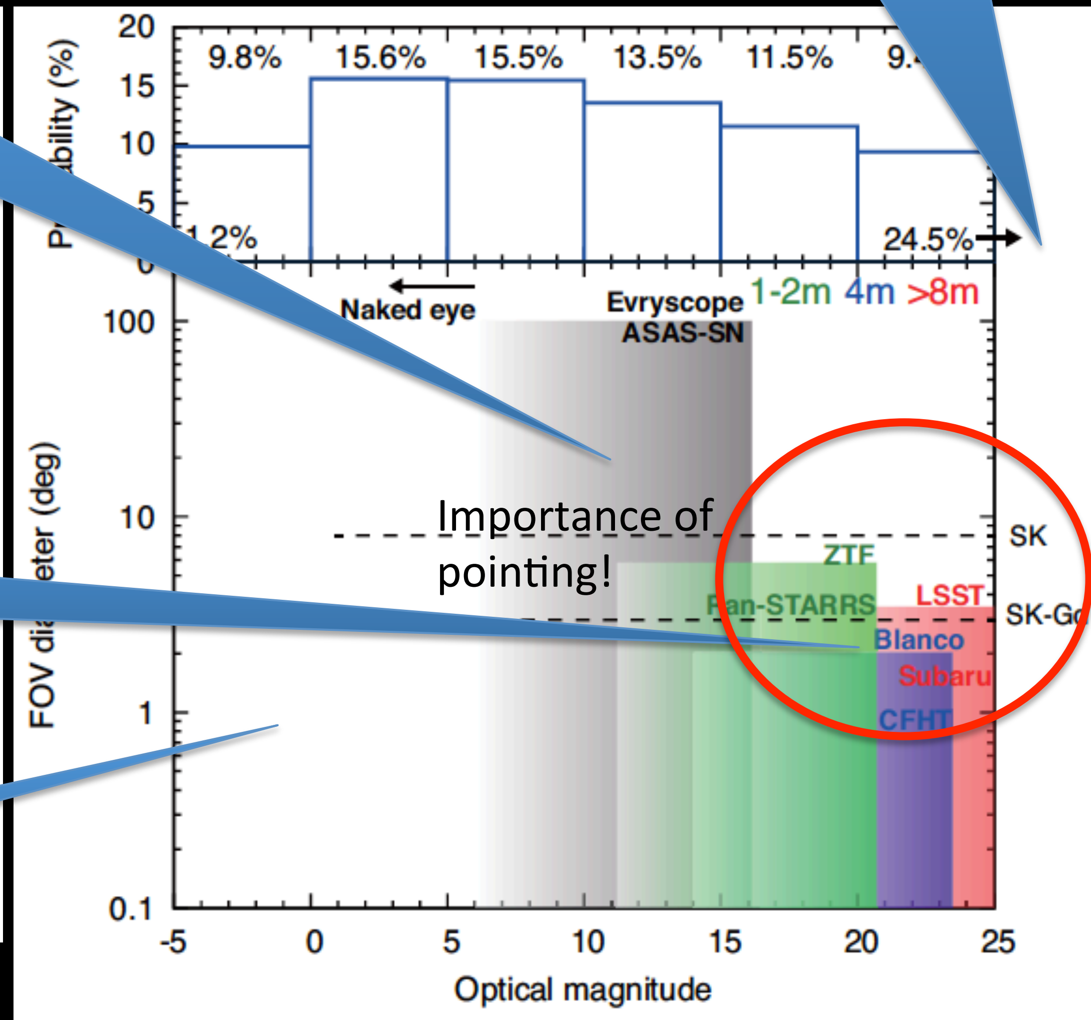
~25% of CCSNe are hard to reach even with modern 8m telescopes

Magnitude of optical signal:

Imp rs:

~35% are within reach of large FOV <1m class telescopes





Importance of pointing!

~20% will need need >1m class telescopes

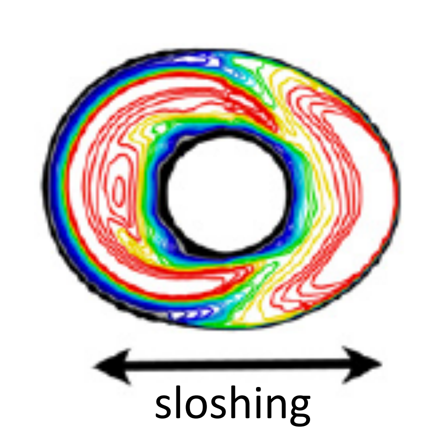
~20% may be too bright

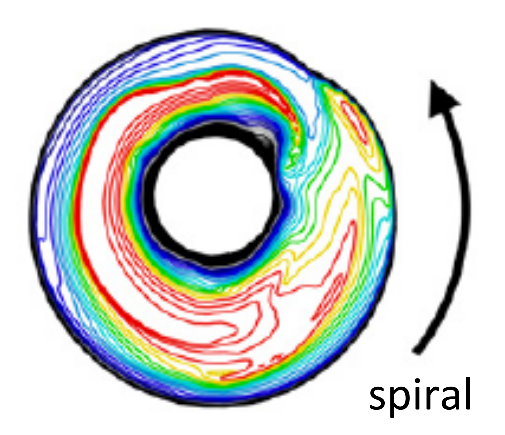
Nakamura et al (2016)

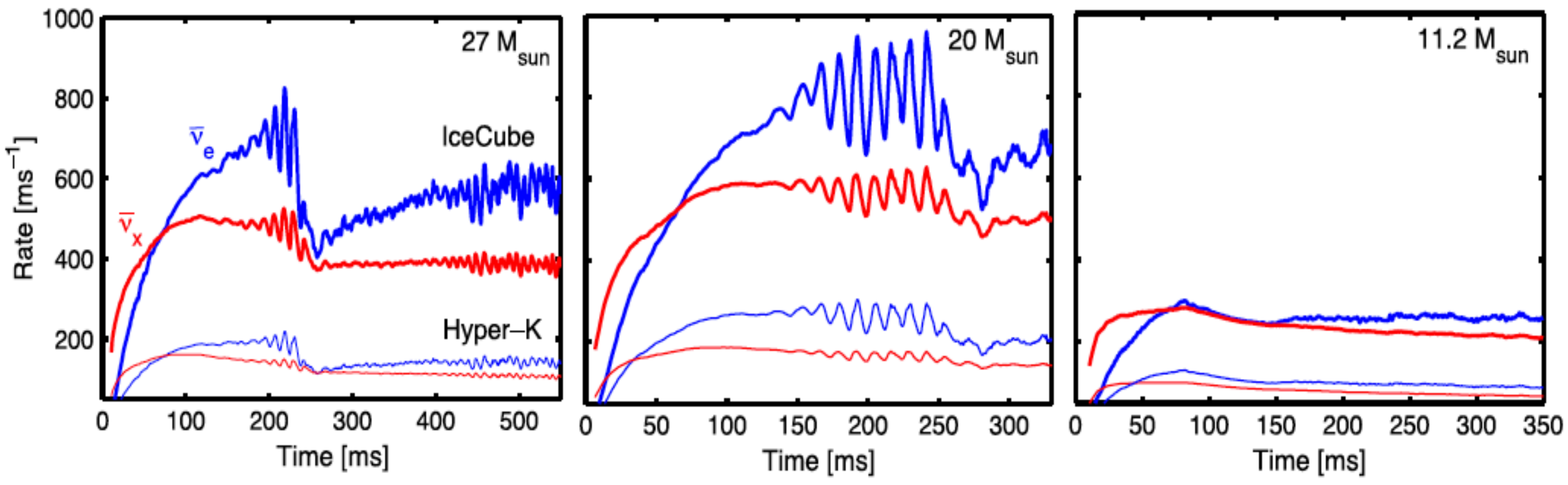
Q: was the explosion SASI-driven?

Signatures:

SASI's time variations (~10-20 ms) in the neutrino luminosity and energy can be measured with the excellent neutrino event statistics expected.







Multiple SASI episodes + convection

Single SASI episode + convection

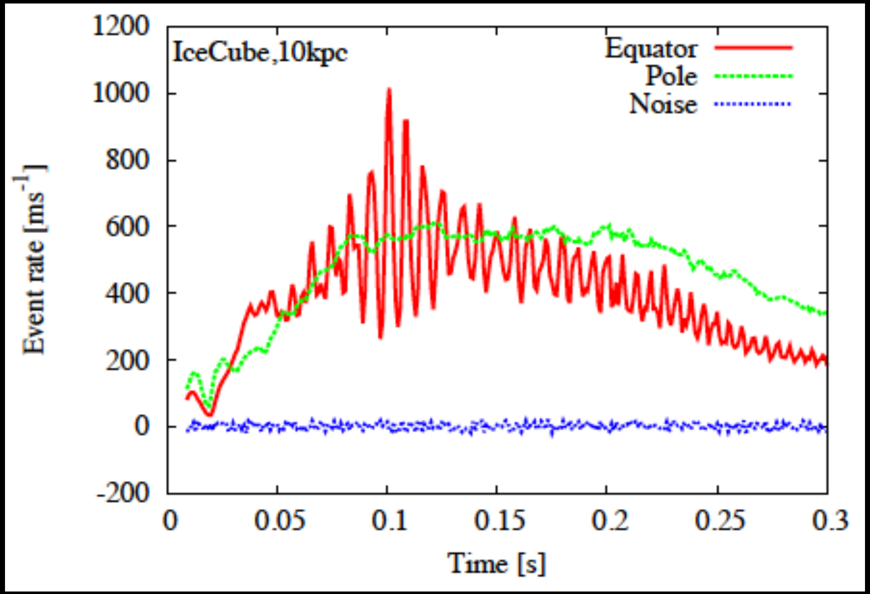
No SASI episode, only convection

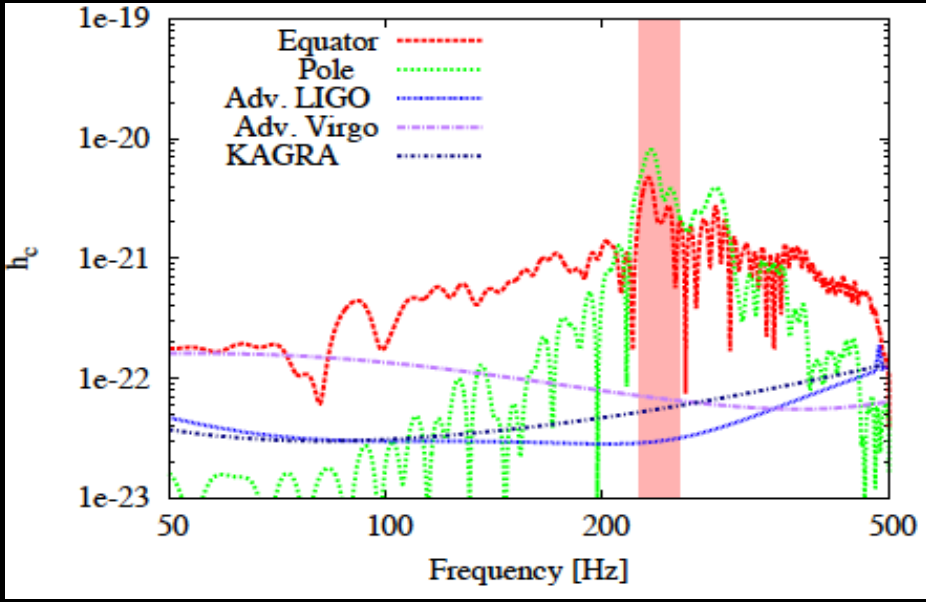
Tamborra et al (2013, 2014), based on Hanke et al (2013)
see also Lund et al (2010, 2012)

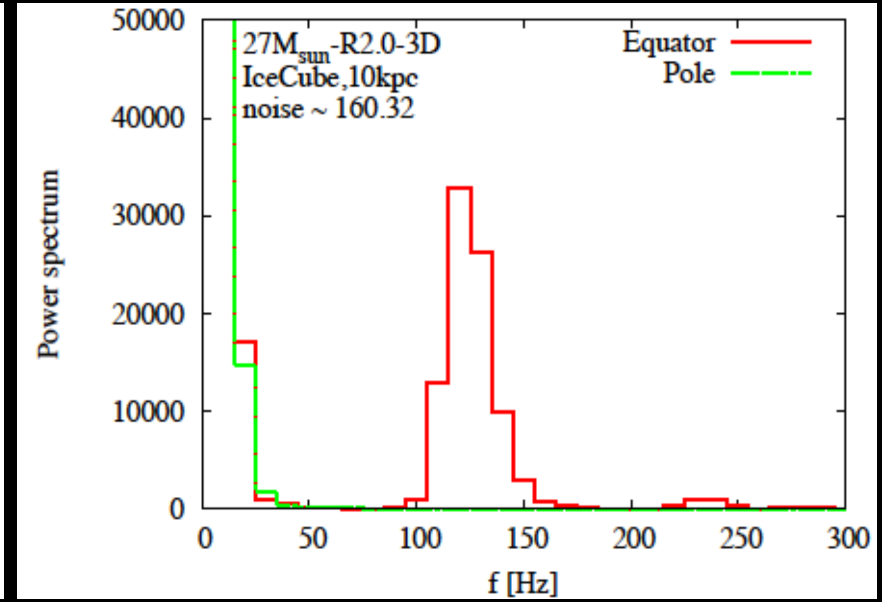
Q: was the progenitor rotating?

Signatures

- Rotation leaves signatures in neutrinos and gravitational waves
  - Lighthouse effect of spiral flows
  - Complementary viewing angle by gravitational wave
- Frequency matching can help confirm peak





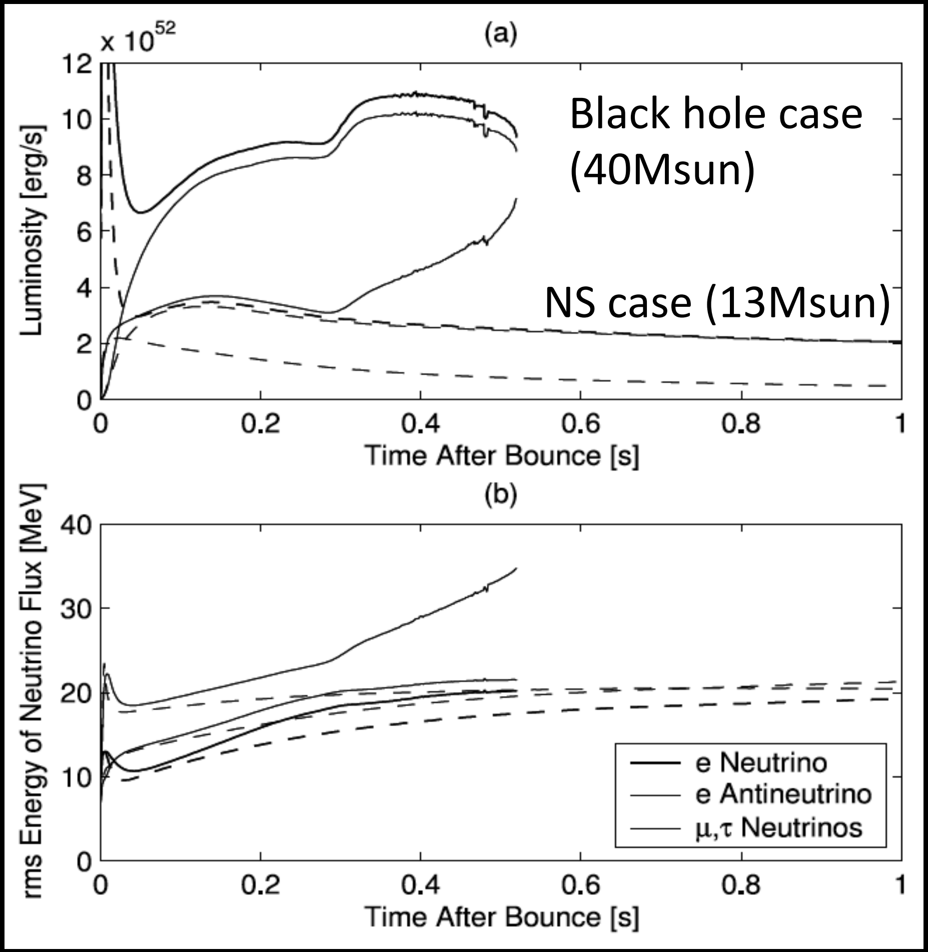


Takiwaki & Kotake (2018); Ott et al (2005)

Q: what was the progenitor?

Did a black hole form?

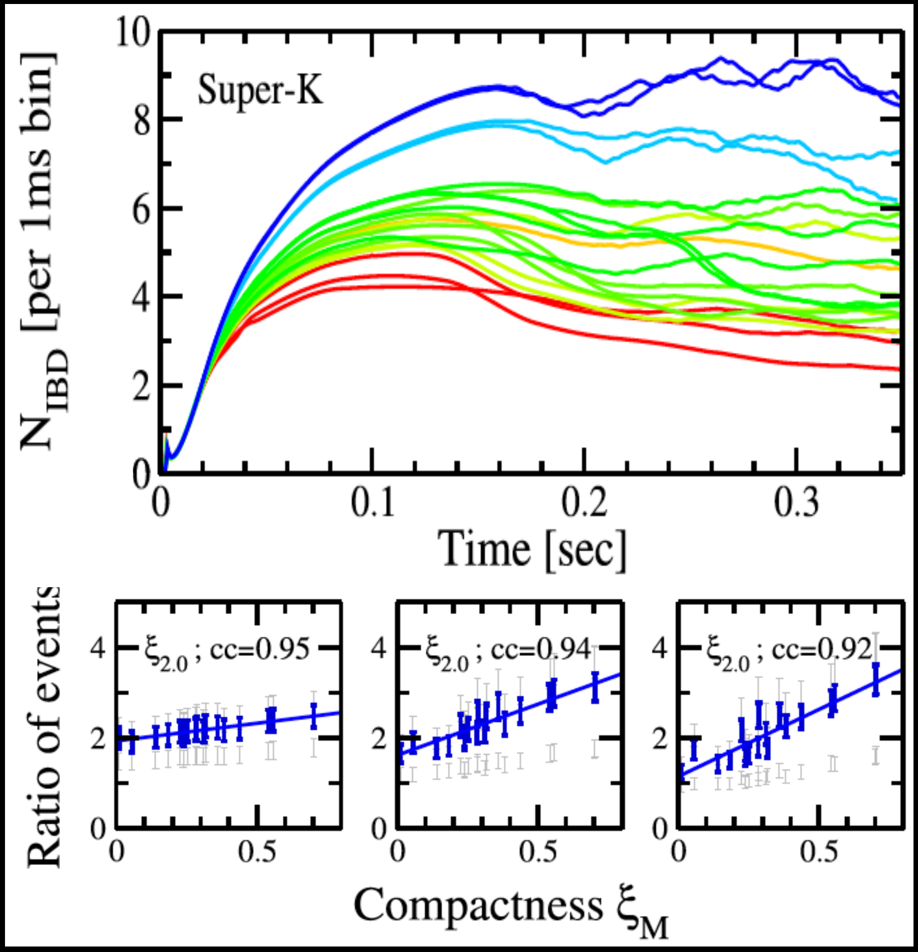
Neutrinos directly reveal the moment of black hole formation *Beacom et al (2001)*



Liebendoerfer et al (2004)

Progenitor compactness

The neutrino emission reflects the progenitor compactness



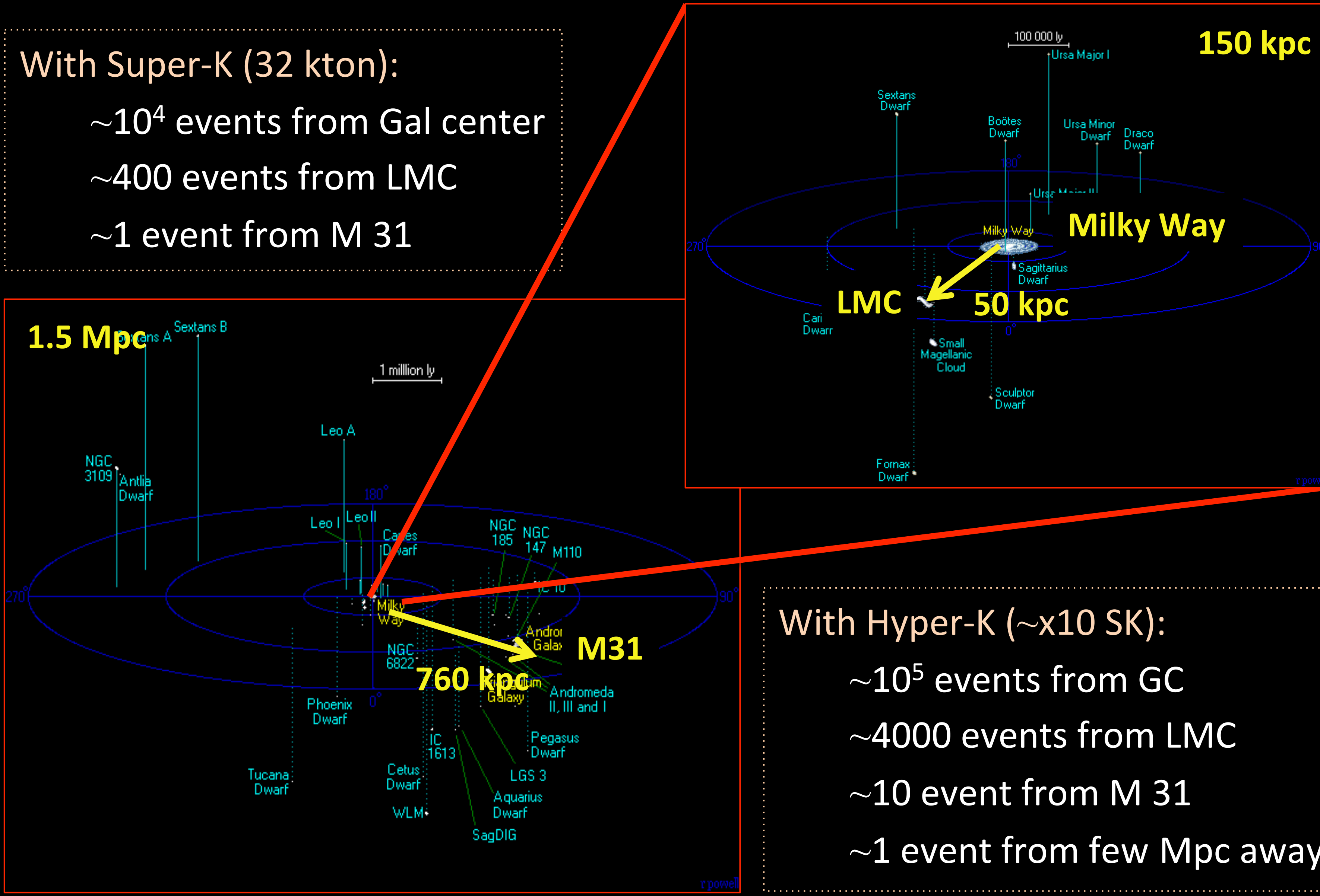
Horiuchi et al (2017); see also O'Connor & Ott (2013)

BEYOND THE MILKY WAY

Reach to our neighbors

With Super-K (32 kton):

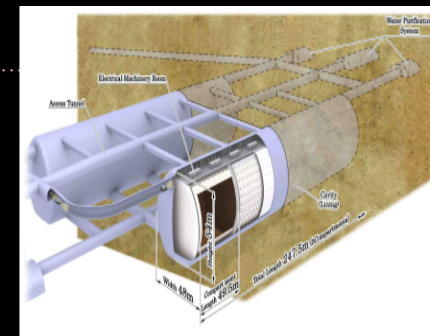
- ~10^4 events from Gal center
- ~400 events from LMC
- ~1 event from M 31



With Hyper-K (~x10 SK):

- ~10^5 events from GC
- ~4000 events from LMC
- ~10 event from M 31
- ~1 event from few Mpc away

The challenge: beating background



Two approaches :

1. Neutrino trigger: look for doublets or higher multiplets, depending on bkg rate:
   - Atmospheric neutrinos
   - Invisible muon decays
   - Spallation daughter decays

e.g., doublets in 10 sec occurs once per ~10 years (scaling SK-II to 0.56 Mton)

2. EM trigger: use SBO or early SN light curve to model constrain the bounce time

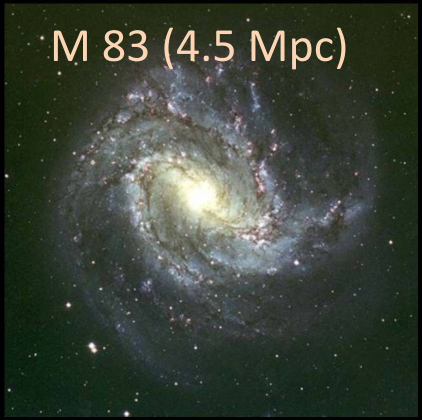
e.g., Cowen et al (2009)

e.g., background rate in signal region is ~0.8 /day/0.56Mton (scaling from SK-II)
→ maybe even can use neutrino singlets

	H_2O only	H_2O + Gd
Search energy window [MeV]	18-30	12-38
Signal ν (in 10 sec, d = 1 Mpc, 0.56Mton)	~5	~10
Background ν (over 1 day, 0.56Mton)	~0.8	~1.1

Ando et al (2005)

The nearby supernova rate

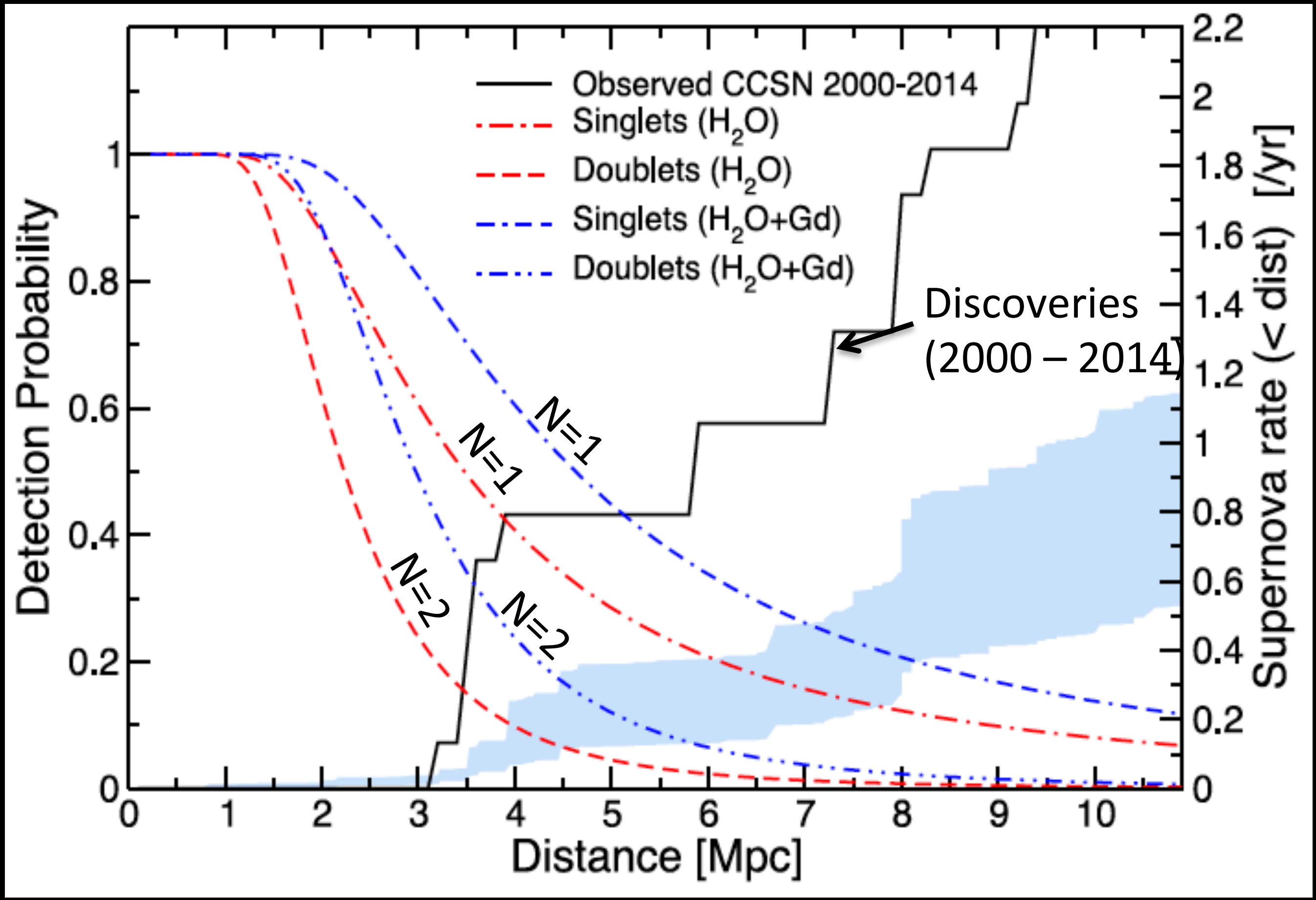


1923A, 1945B, 1950B, 1957D, 1968L, 1983N

1917A, 1939C, 1948D, 1968D, 1969P, 1980K, 2002hh, 2004et, 2008S

Over-dense region of the Universe
→ high rates: one every few years

Detection probability for P(N=1), P(N≥2), w/ and w/out Gd

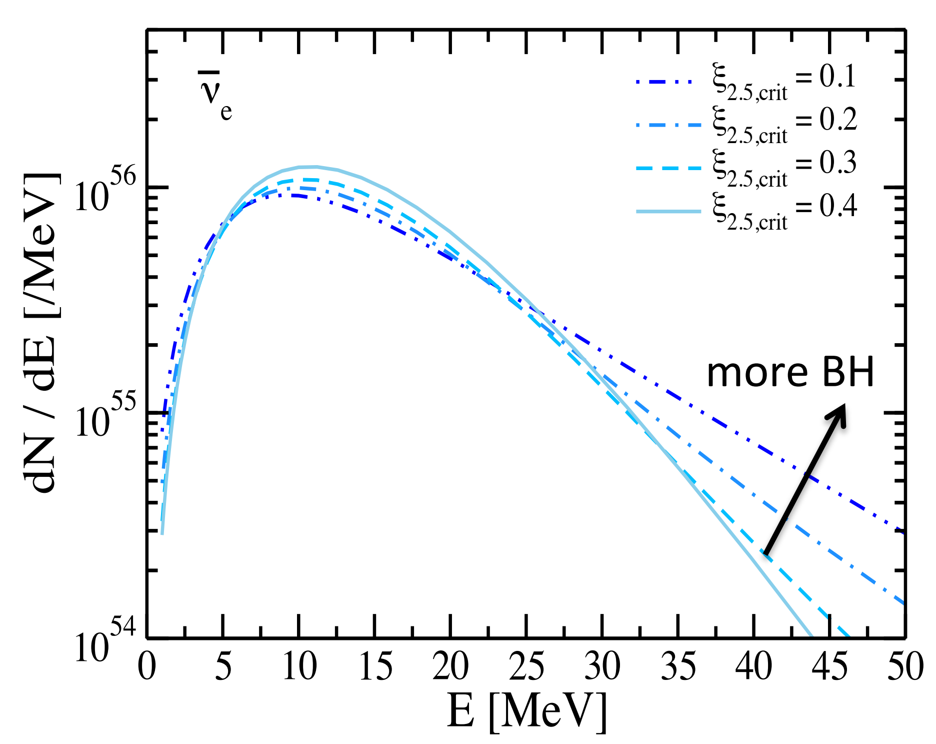


Nakamura et al (2016); see also Ando et al (2005)

Diffuse supernova neutrino background

Average neutrino emission

- Use >100 simulations to characterize progenitor dependence of neutrinos
- Include collapse to black holes, characterized by critical compactness

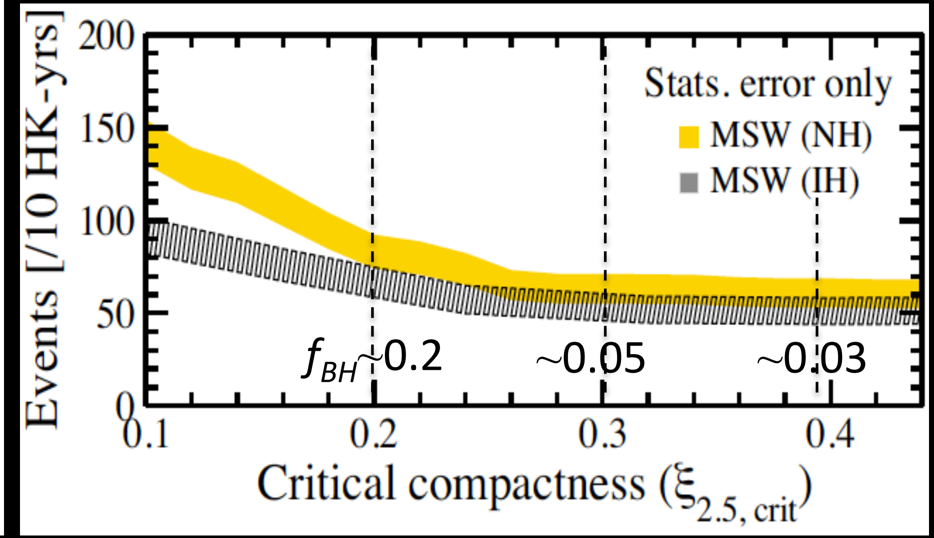


reviews by Beacom (2010), Lunardini (2010)

Event rate predictions

Hyper-K sensitive to small compactness ($\xi_{2.5}$ < 0.2, or f_{BH} > 0.2)

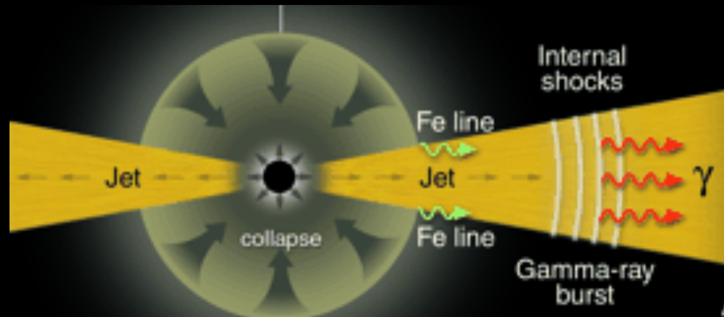
Spectrum	SK + Gd (>10MeV) [/yr]
4 MeV	1.8 +/- 0.5
4 MeV+BH	< 2.5
SN1987A	1.7 +/- 0.5



Horiuchi et al (2018); see also Lunardini (2009), Lien et al (2010), Moller et al (2018)

High-energy phenomena

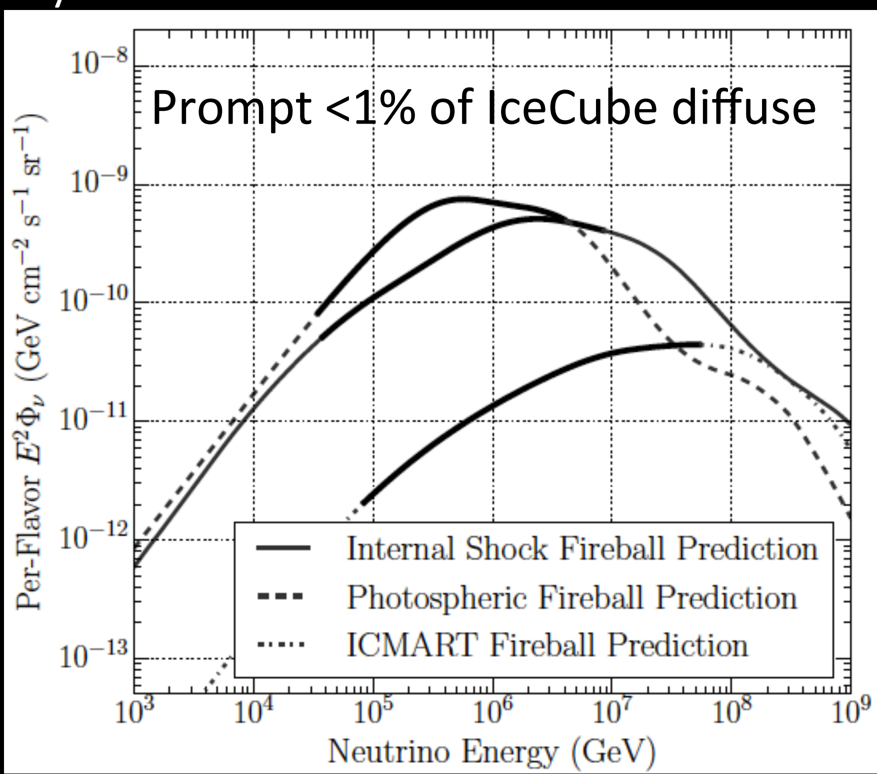
GRB connection:



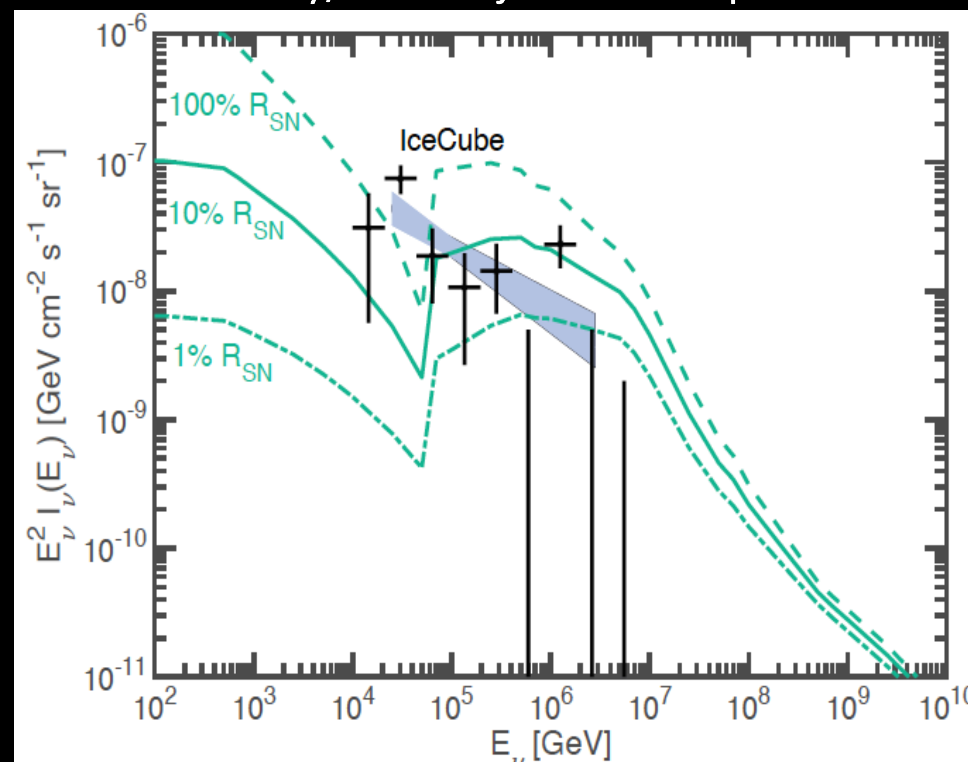
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_e + \nu_{\mu}$$

High-luminosity GRB jets are constrained by null results from stacked searches



Low-luminosity/choked jets remain possible



IceCube (2016) *Tamborra & Ando (2016)*

Ultra-high energy phenomena

Ultra-high energy cosmic rays

High-luminosity and low-luminosity jets capable of accelerating CRs to ultra-high energies (~10^{20} eV).

Waxman (1995), Vietri (1995)
Murase et al (2008), Wang et al (2008)

Afternoon talks

Composition

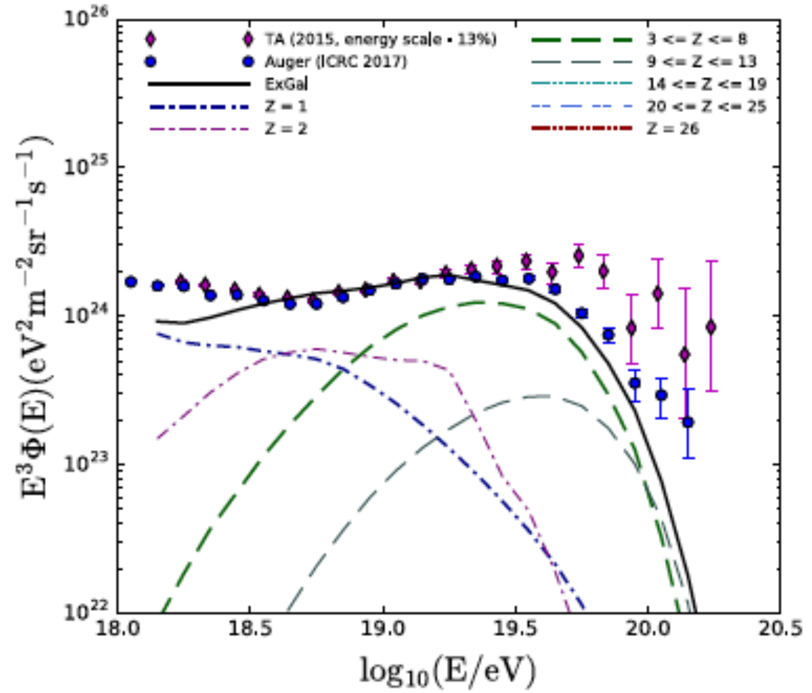
Possible sites for sourcing nuclei UHECR

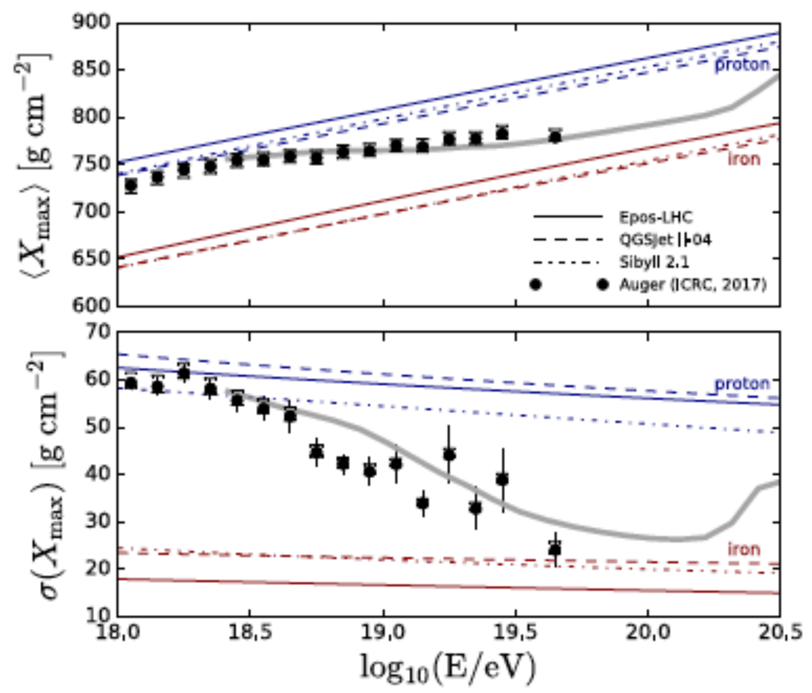
- Initial loading
- Entrainment
- In-situ nucleosynthesis

Murase et al (2008)
Metzger et al (2011)
Horiuchi et al (2012)

Simple loading model + propagation (CRPropa3) can describe the spectrum & composition measurements by Auger

Zhang et al (2018)





Concluding remarks

Supernova is a multi-messenger phenomenon

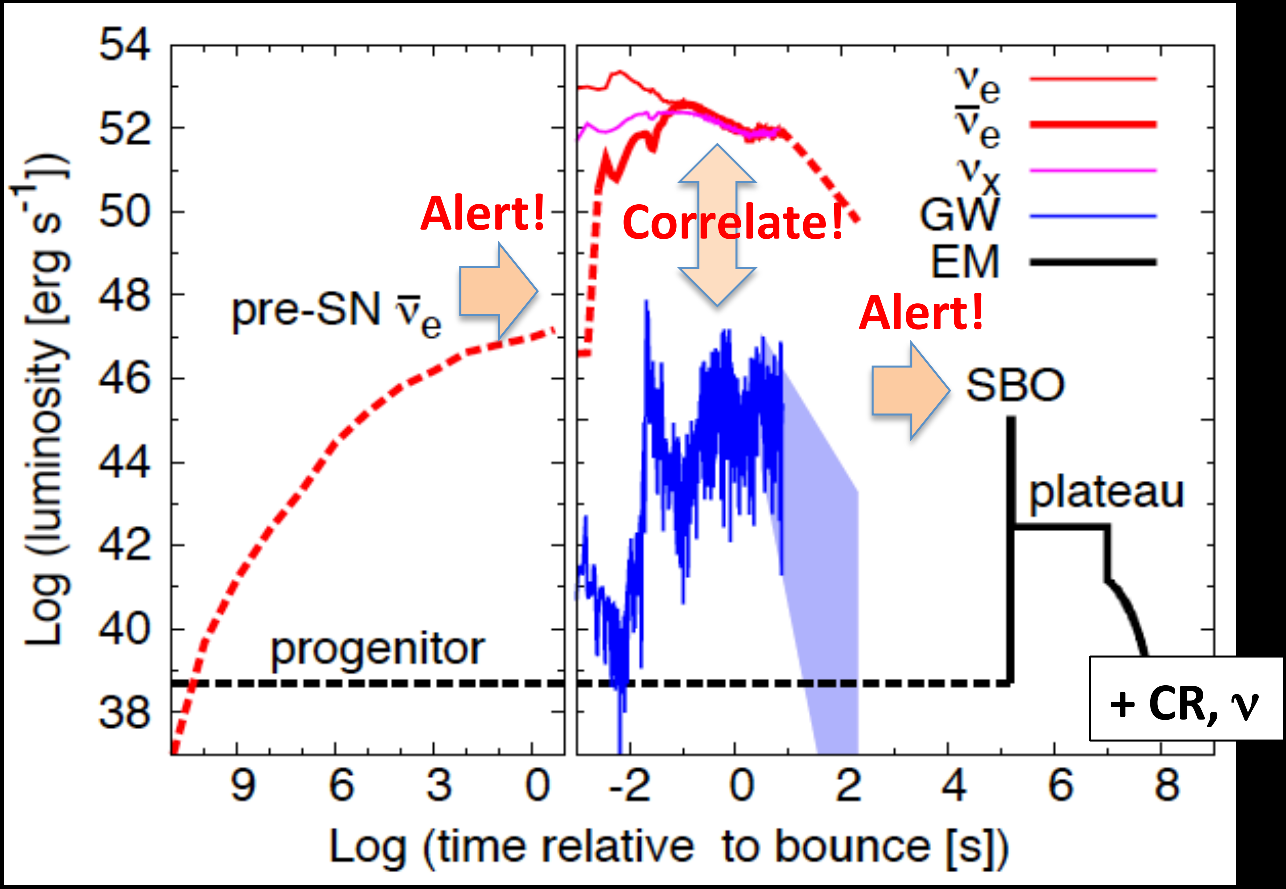
- The whole range: photons, neutrinos, gravitational waves, cosmic rays

Galactic multi-messenger opportunities

- Neutrinos will reveal IF, WHEN, and WHERE to look – in RAPID alert
- Neutrinos will help detect GW and photon counterparts

Beyond Milky Way

- Photon-neutrino synergy nearby
- Source candidates of HE neutrino & UHE cosmic rays



BACKUP

#4: Searches of failed explosions: Survey about nothing

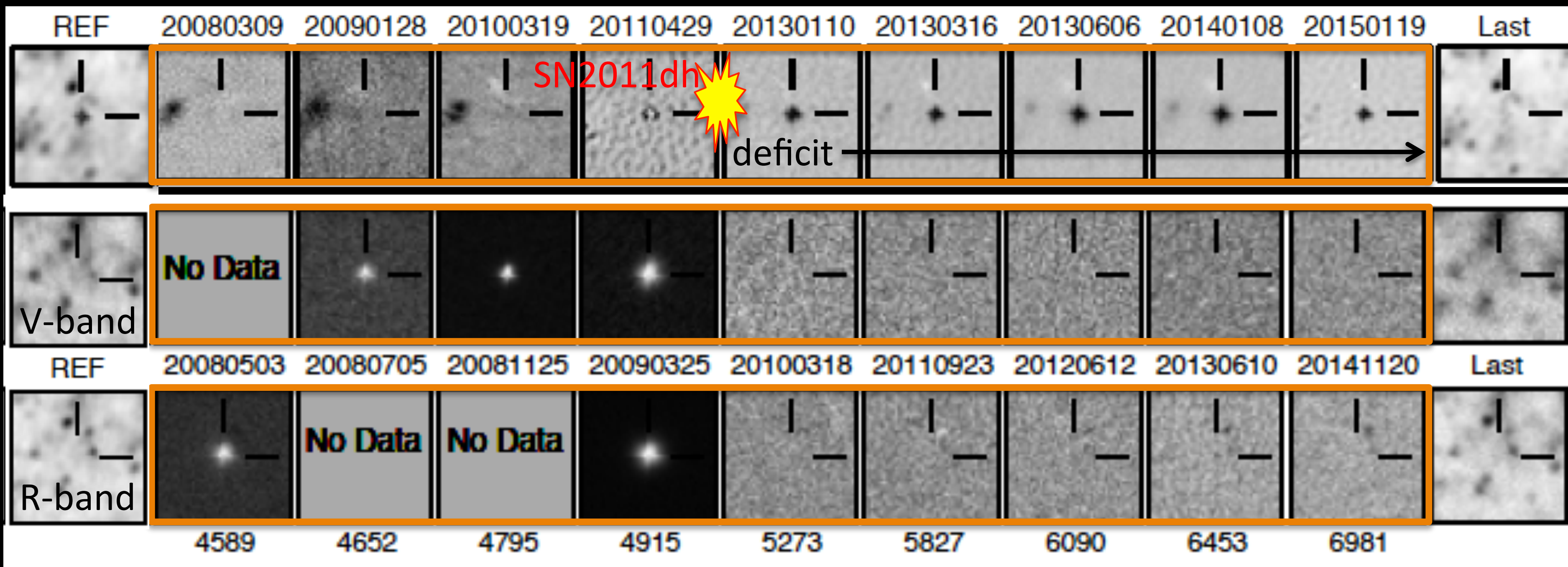
Survey About Nothing

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 $\sim 10^6$ red supergiants with luminosity sensitivity > 10^4 Lsun
- → expect ~ 1 core collapse /yr
- → In 10 years, sensitive to 20 – 30% failed fraction at 90% CL

Kochanek et al. (2008)



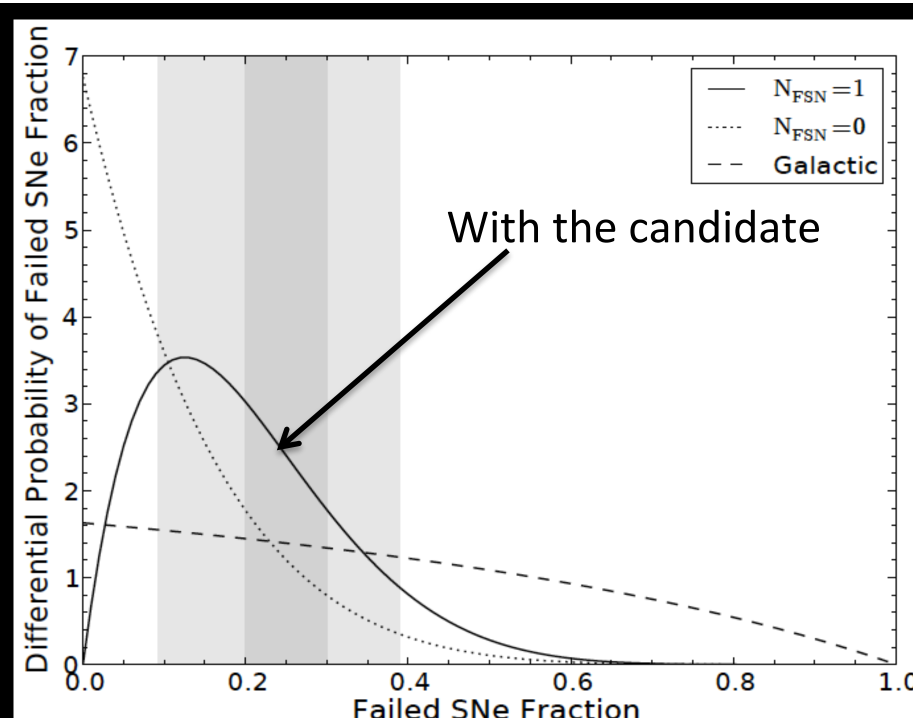
Gerke et al. (2015)

Results so far:

In 7 years running,

- 6 luminous CC supernovae (SN2009dh, SN2011dh, SN2012fh, SN2013ej, SN203em, SN2014bc)
- 1 candidate failed supernova: NGC6946-BH1 (@~6Mpc); SED well fit by 25Msun RSG

→ Failed fraction 4 – 43% (90%CL)

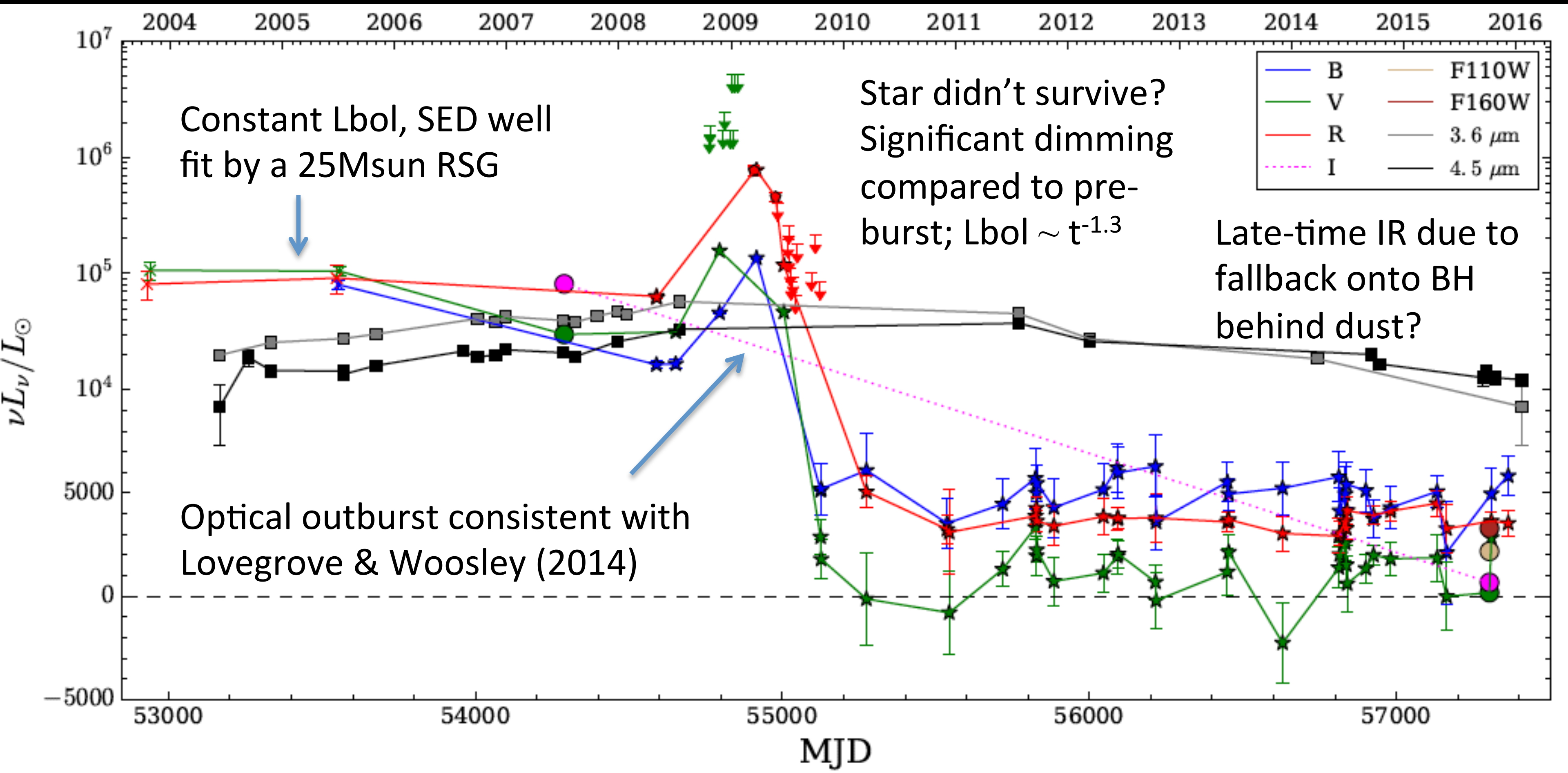


Adams et al (2016)

The NGC6946-BH1 candidate

False positive?

New search will have new false positive → multi- wavelength follow-up is needed to vet failed SN candidates and determine whether the star survived or disappeared



Adams et al (2016)