16th Recontres du Vietnam: TMEX 2020 – Jan 6-11th 2020

Multi-messenger opportunities from core-collapse supernovae

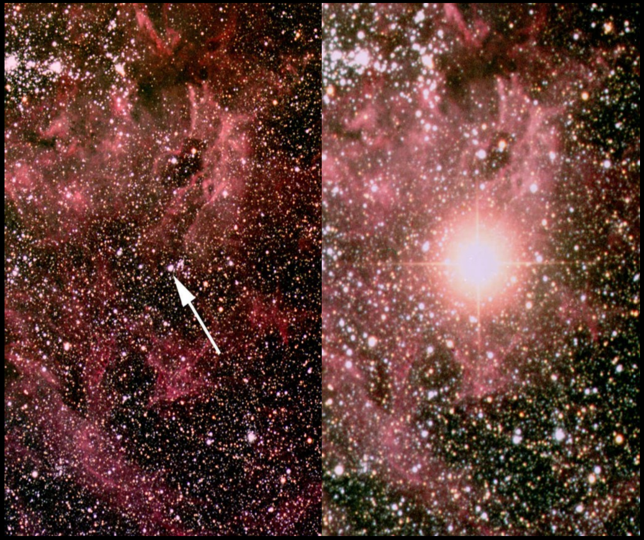
Shunsaku Horiuchi

Virginia Tech

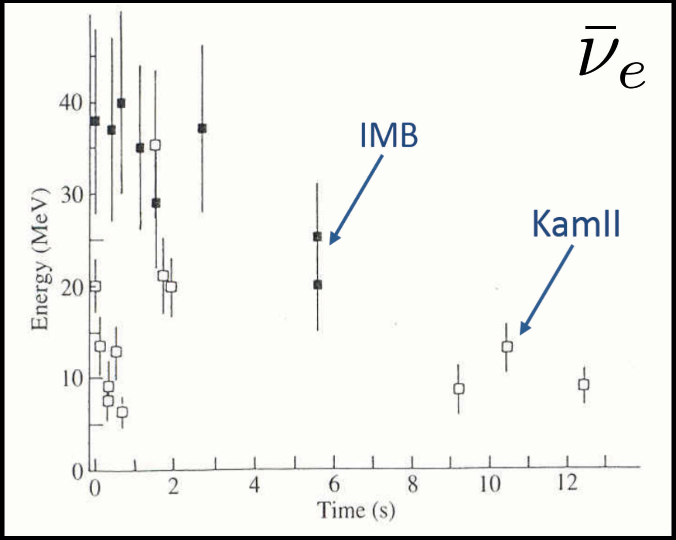
Image credit: NASA/ESA

SN1987A

Observation: Type II supernova progenitors are massive stars



Observation: 10 – 40 MeV neutrino signal lasting ~10 s



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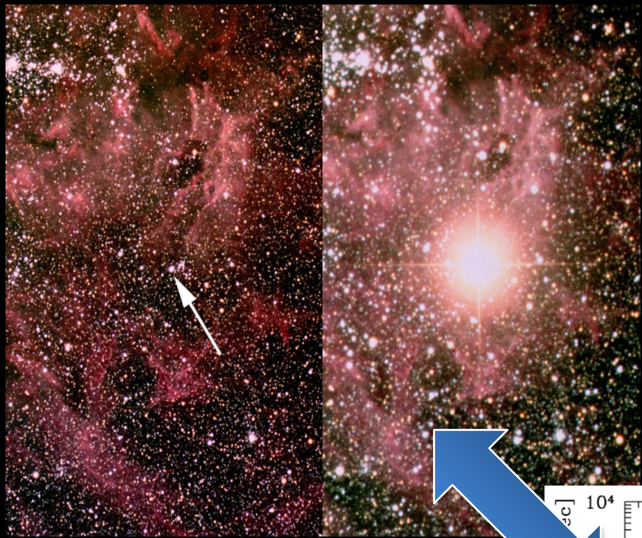
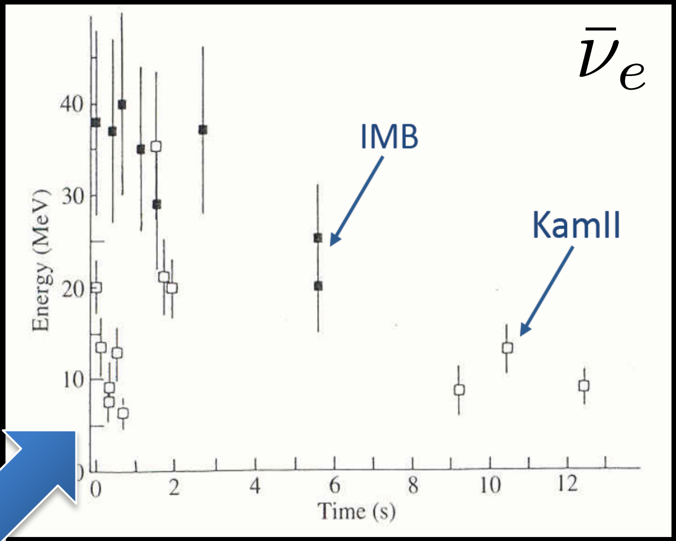
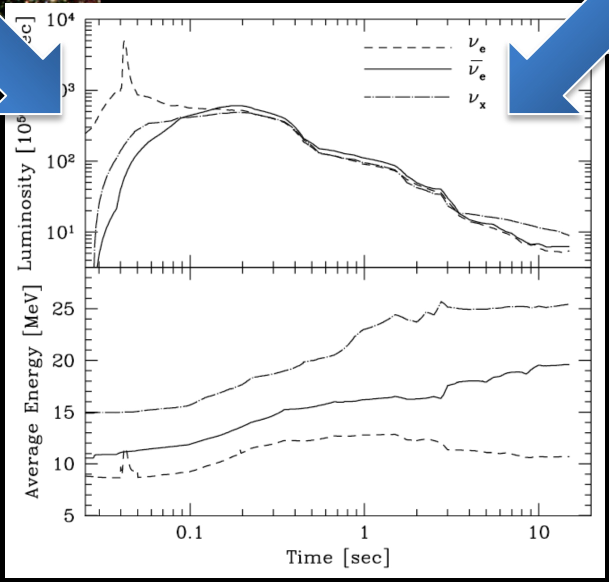


Theory: massive star undergoes collapse, emits neutrinos, launches shock, causes supernova

Observation: 10 – 40 MeV neutrino signal lasting ~10 s





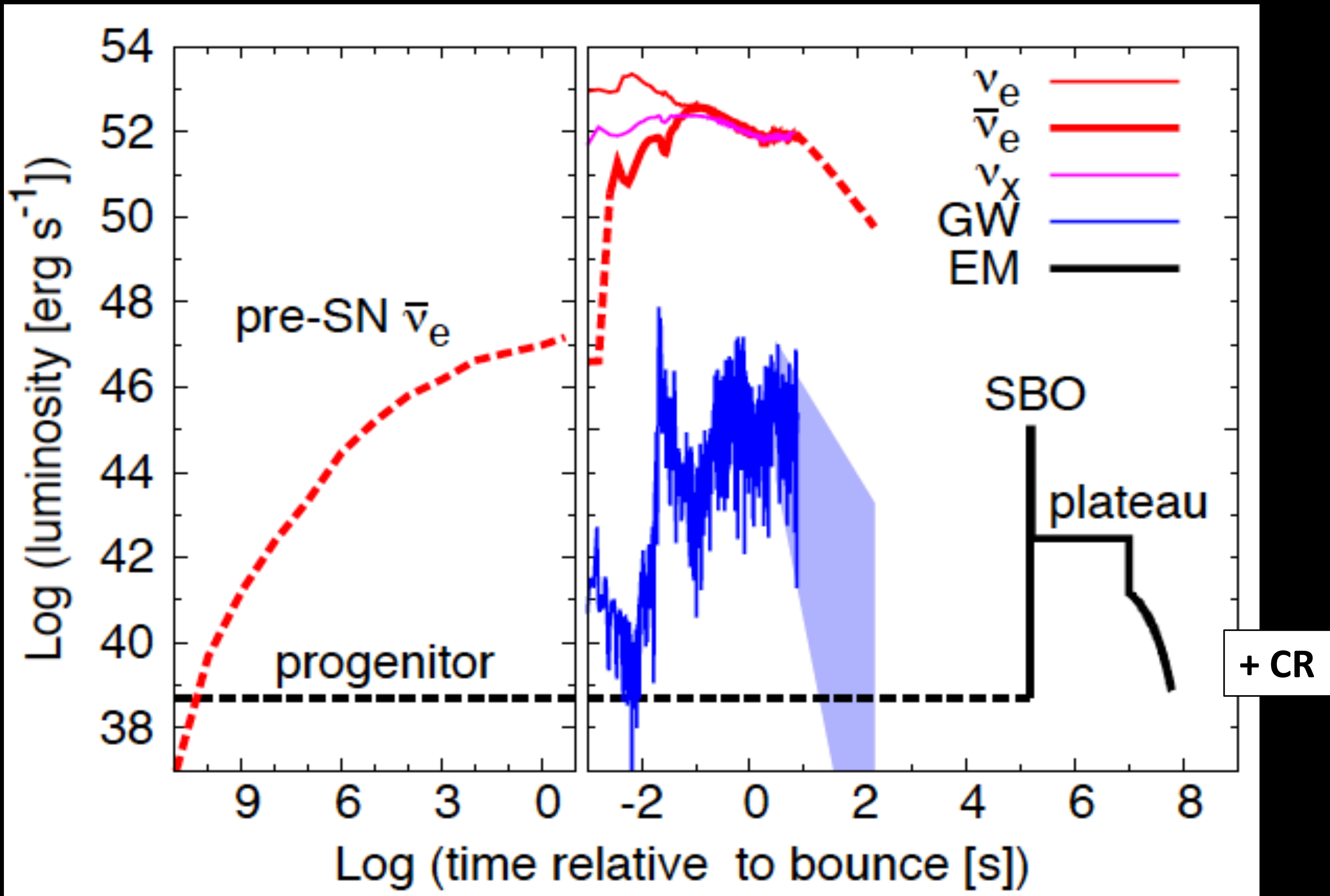
Great confirmations!

- Progenitor of supernovae
- Dominance of neutrinos
- ν thermalization
- Limits on new particles
- And many more

But also much left unknown:

- Explosion mechanism
- GW counterpart
- NS and BH remnants
- Neutrino mixing effects
- Equation of state
- And many more

The next Galactic supernova (20XX)



Nakamura, Horiuchi et al (2016)

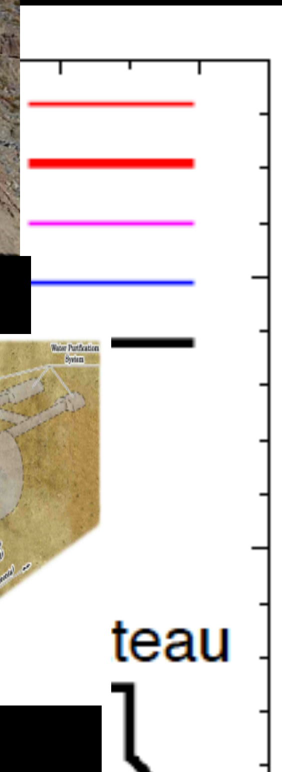
(20XX)

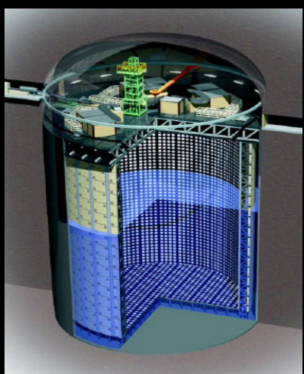
ASAS-SN

Palomar

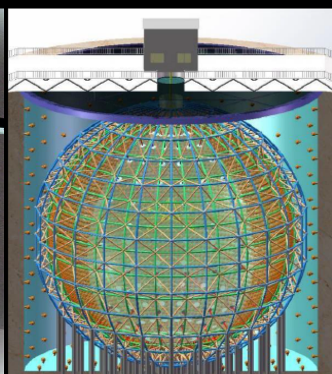
Subaru

Vera Rubin Obs

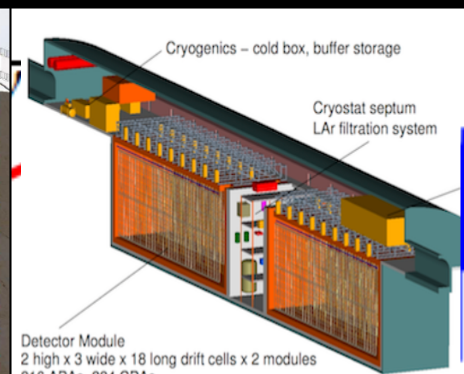




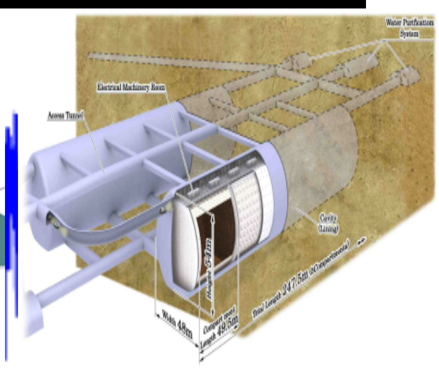
Super-K



JUNO



DUNE



Hyper-K

+ CR

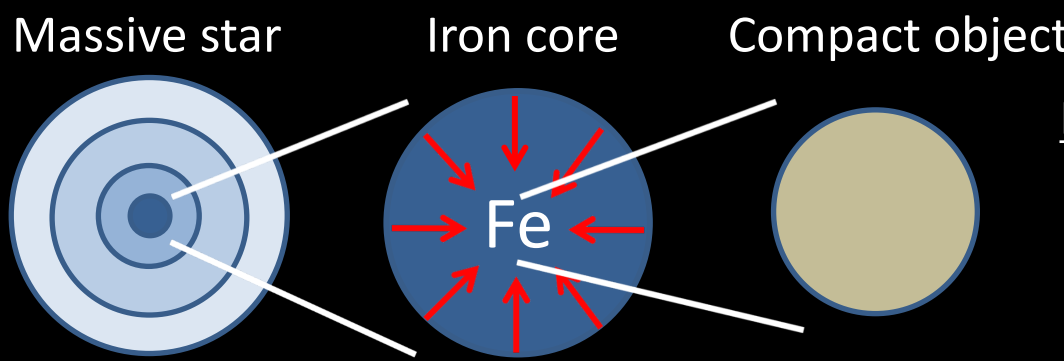
LIGO

VIRGO

KAGRA

Sh 6)

Core collapse to explosion



Energy budget ~ 10^{53} erg

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

Explosion mechanism

- Needs energy reservoir and transfer.
- Prevalent mechanism is the turbulence-enhanced neutrino energy deposition
- Complex numerical problem

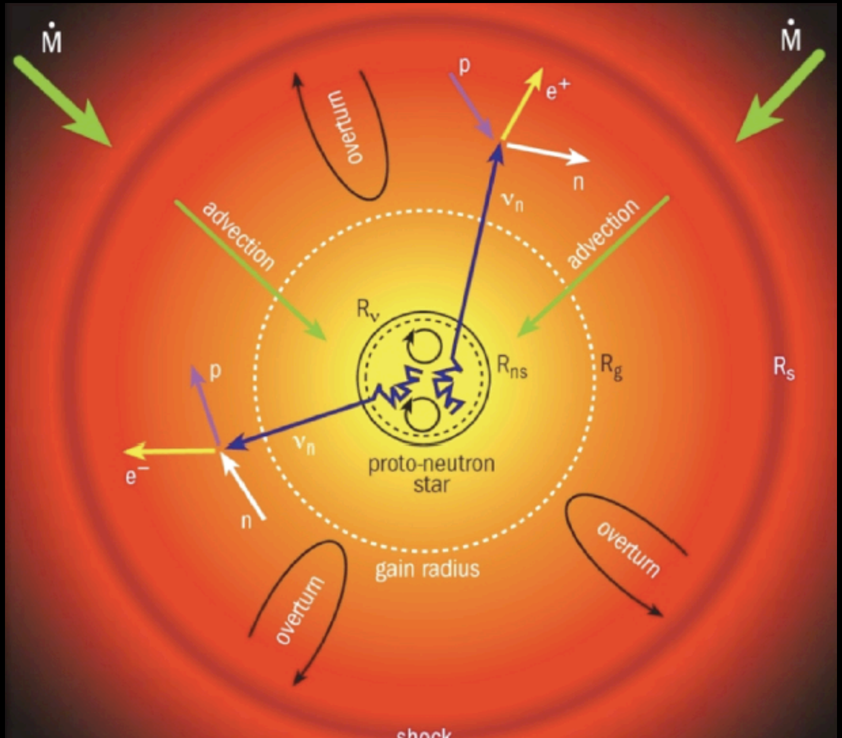
3D (magneto-) hydrodynamics

Nuclear EOS

General relativity

Neutrino transport

Nuclear reactions



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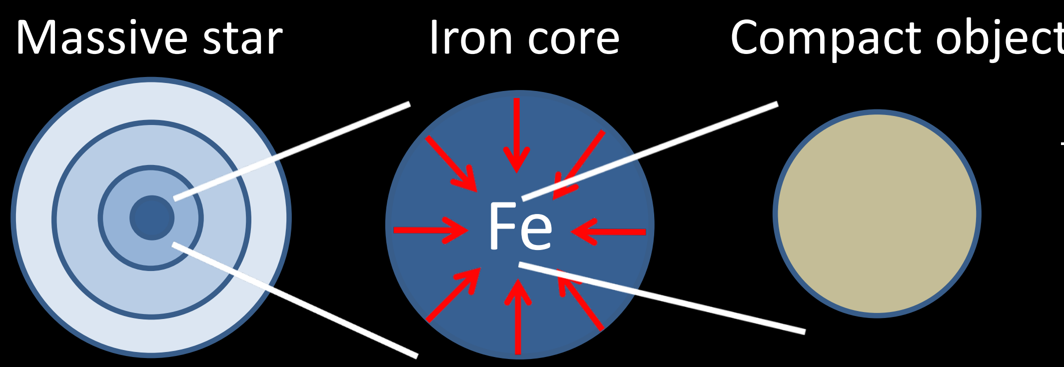

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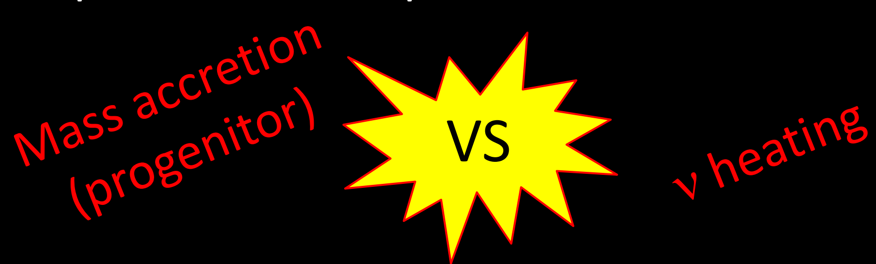
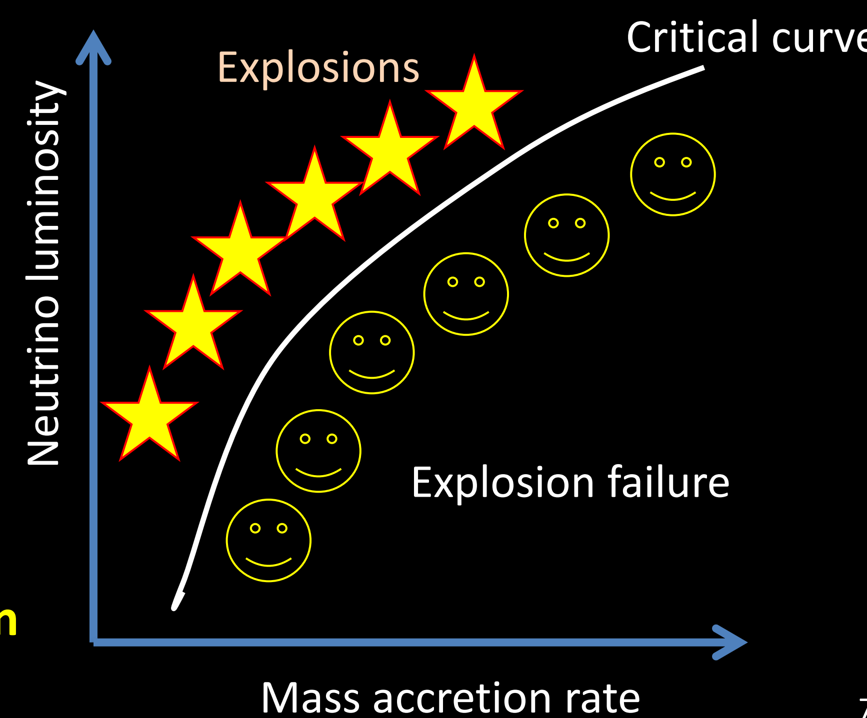




➔ **Need neutrino <u>and</u> progenitor information**

Neutrino confidence

Reveal IF to look: number statistics expected from a Galactic event

Running

Detector	Type	Mass (kt)	Location	Events	Flavors
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	$\bar{\nu}_e$
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)	$\bar{\nu}_e$

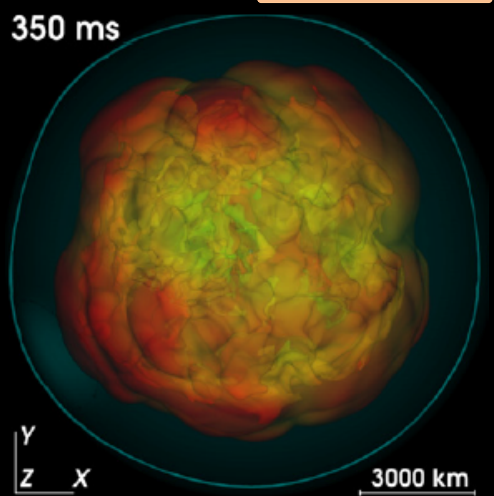
Not shown: direct dark matter detectors

Mirizzi et al (2015); Scholberg (2012)

Neutrino heating mechanisms

Neutrino heating needs turbulence-enhanced neutrino energy deposition

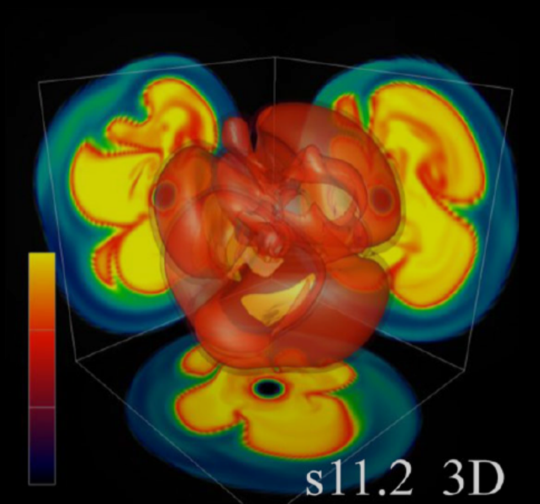
For mass < 10 Msun



9.6 Msun, Melson et al 2015, Kitaura et al 2006

Readily explodes by neutrino heating, even in spherical symmetry.

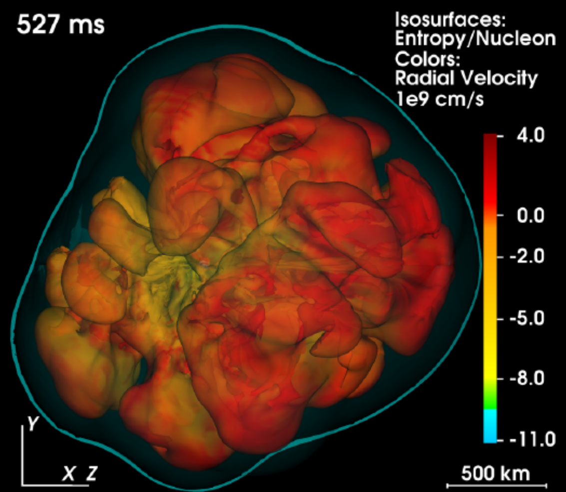
For mass < 15 Msun



11.2 Msun, Takiwaki et al 2014

Explodes in axisymmetric and full 3D via convection

For mass < 40 Msun

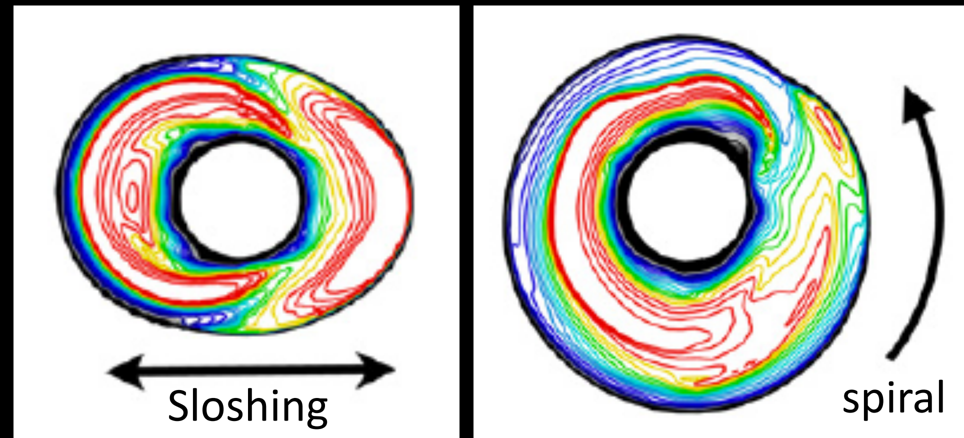


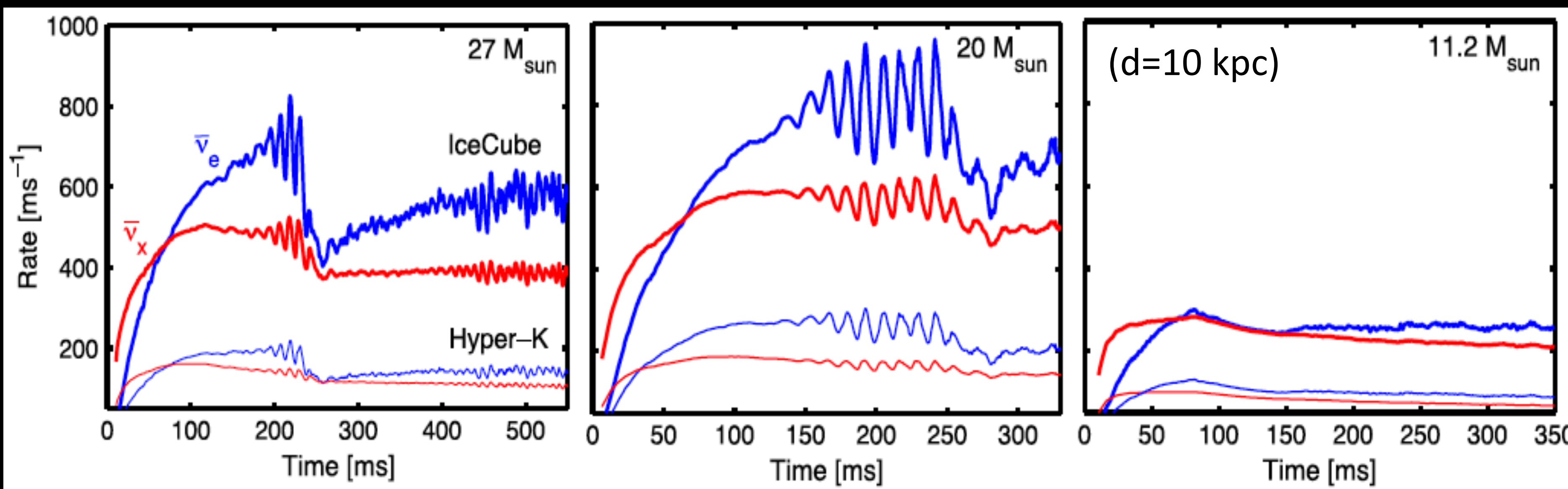
20 Msun, Melson et al 2015

Explodes in axisymmetric and full 3D with SASI

Imprints of hydrodynamical instabilities

Signatures:
- SASI's time variations (~10-20 ms) get imprinted on the neutrino luminosity and energy.
- Can be measured with large volume detectors





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)

Alerting the community

Neutrinos: 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

Rapid ALERTs

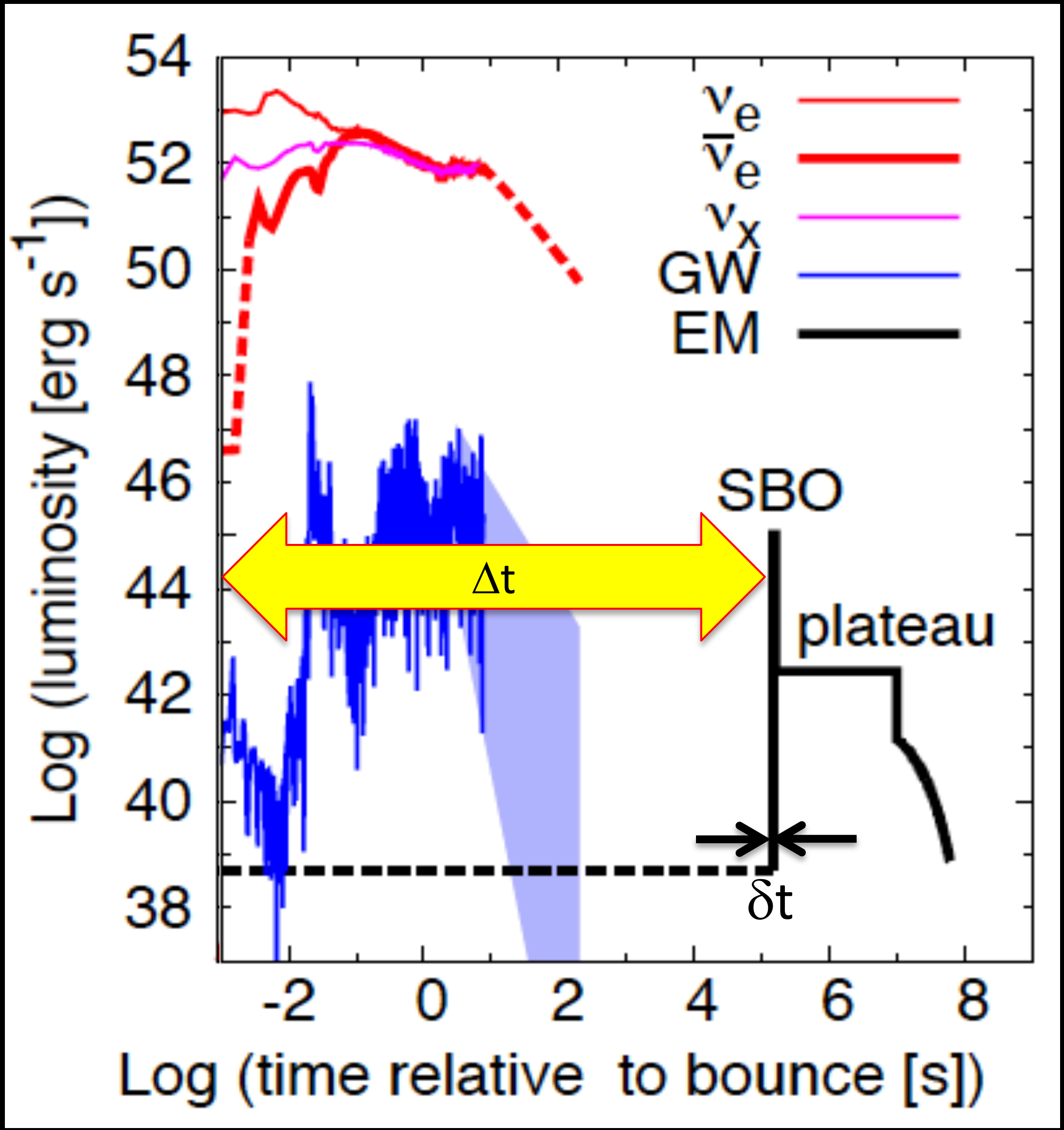
Email, IAU, Atel, GCN

✓ Individual detectors

- EGADS: automated alert within ~ 1 s
- Super-K: alert within ~ 0.5-1 hour of neutrino burst (info: time, duration, total events, pointing)

e.g., Adams et al (2013)

Multi-messenger: electromagnetic



Shock breakout (SBO):

- First radiation to leak out when supernova shock reaches photosphere
- Helps reveal stellar radius, circumstellar environment, recent mass-loss, envelop mass, and so on…

Timescales

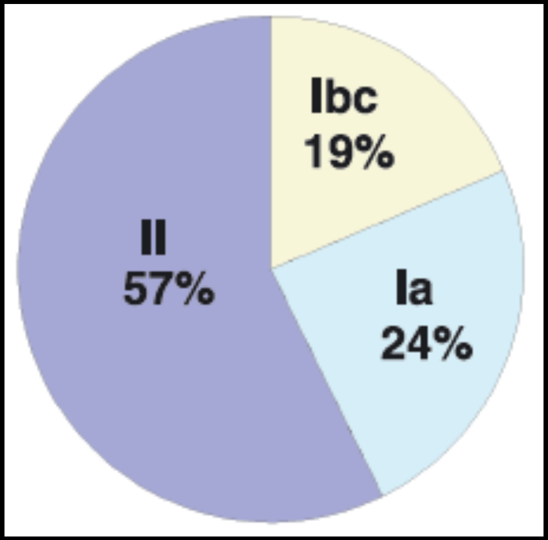
- For RSG (=type IIP): 1000 Rsun, 10 Msun
  → duration $\delta t \sim$ ***hours***
  → delay $\Delta t \sim$ ***days***

Nakamura, Horiuchi et al (2016)

Multi-messenger: electromagnetic

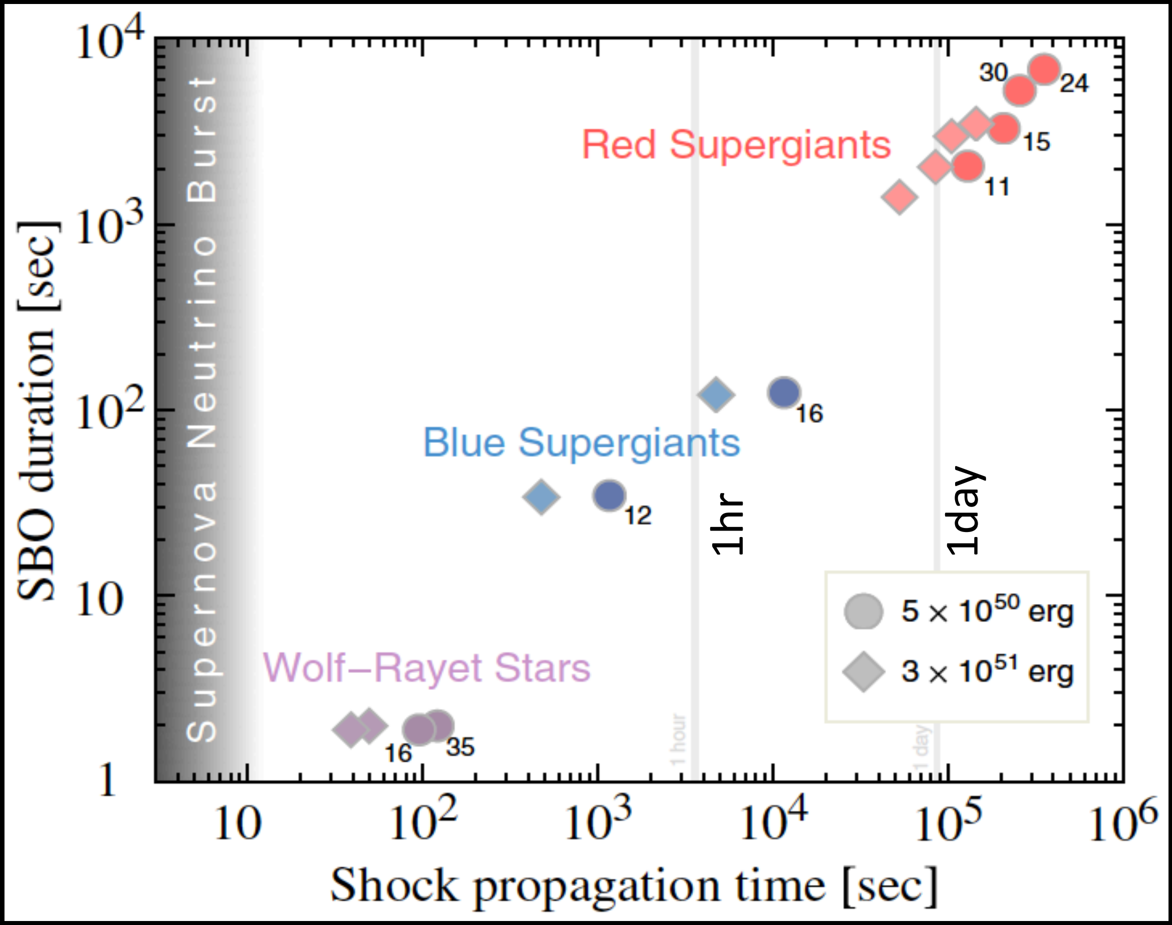
Shock breakout (SBO) timescales:

- For WR (=type Ibc): 1 Rsun, 1-10 Msun → delay *minutes*, duration *seconds*
- Approx 25% of cases in nearby volume-limited sample



Li et al (2010)

→ Rapid alert helps chase the shock breakout signal



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

Pointing

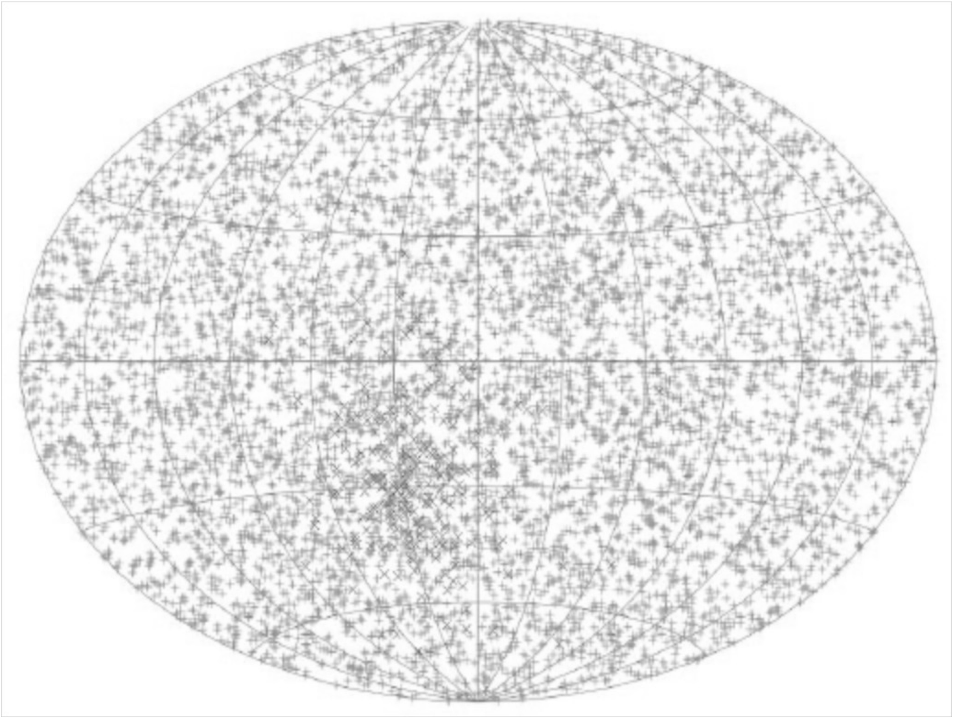
Reveals WHERE to look

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

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

Background mostly due to IBD

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



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

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

Pointing with Gadolinium

Reveals WHERE to look

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

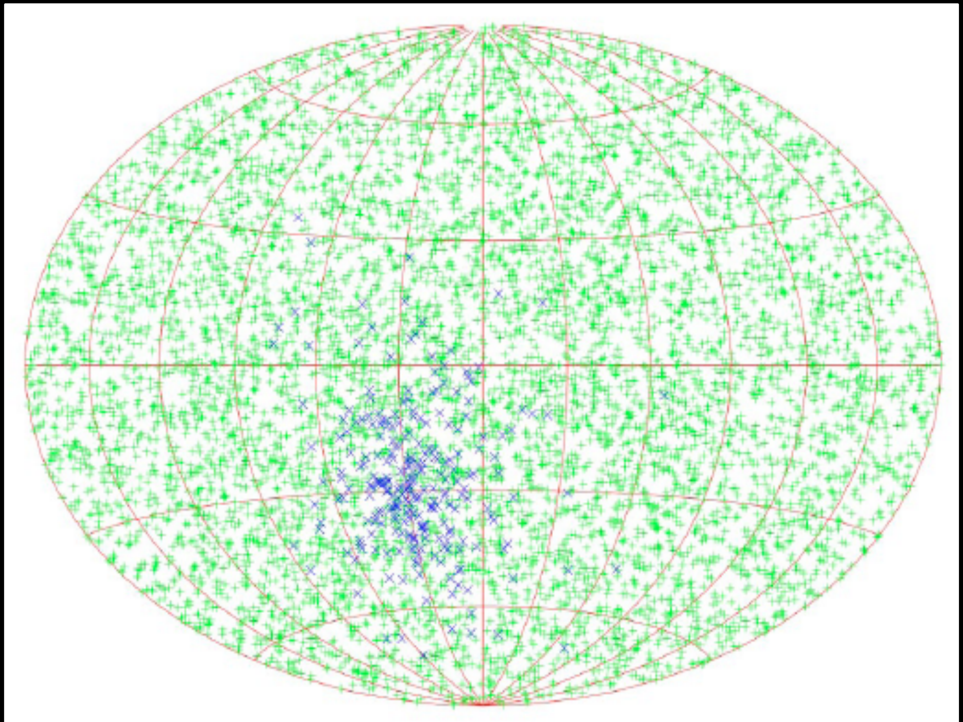
$$\nu + e^- \rightarrow \nu + e^-$$

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)

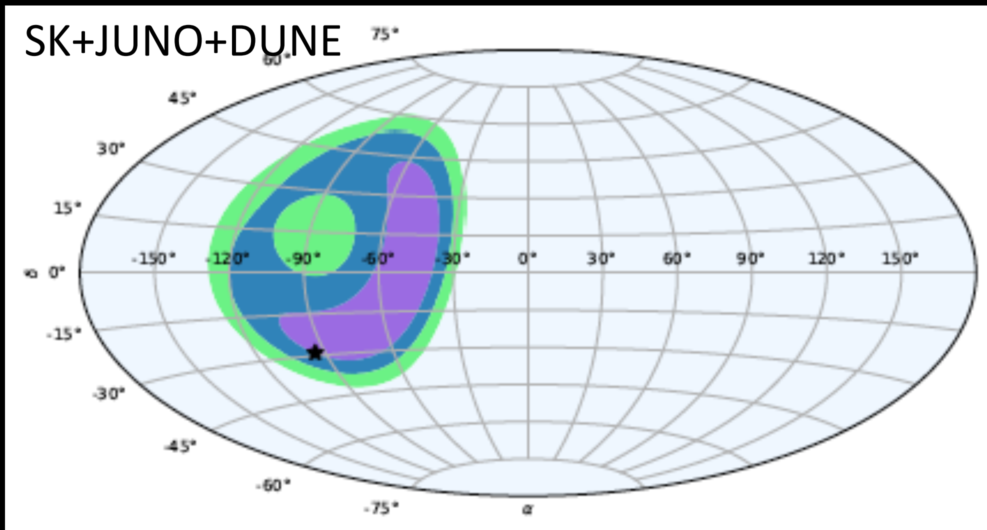
→ Pointing accuracy of several degrees ✓

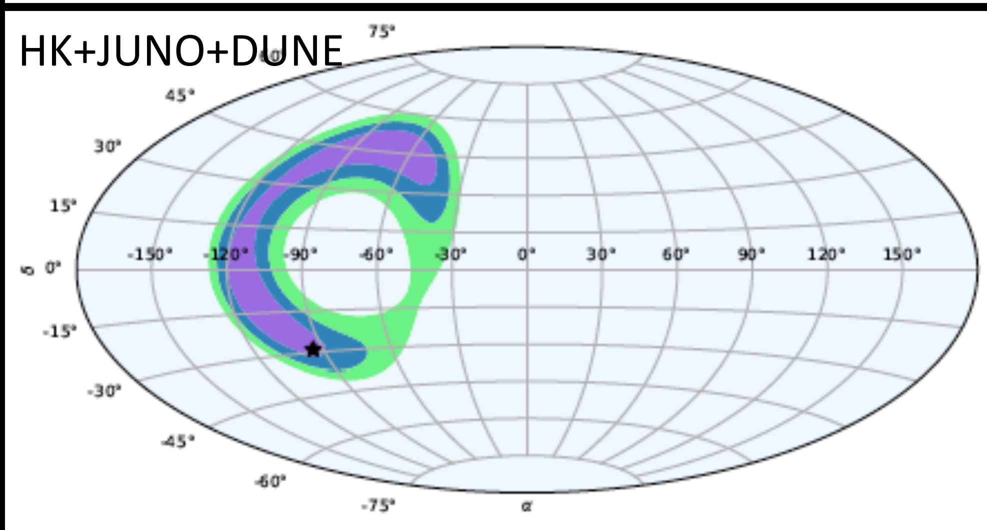


	Super-K	Hyper-K
Water only	~6 deg	~1.4 deg
Water + Gd (90% tag)	~3 deg	~0.6 deg

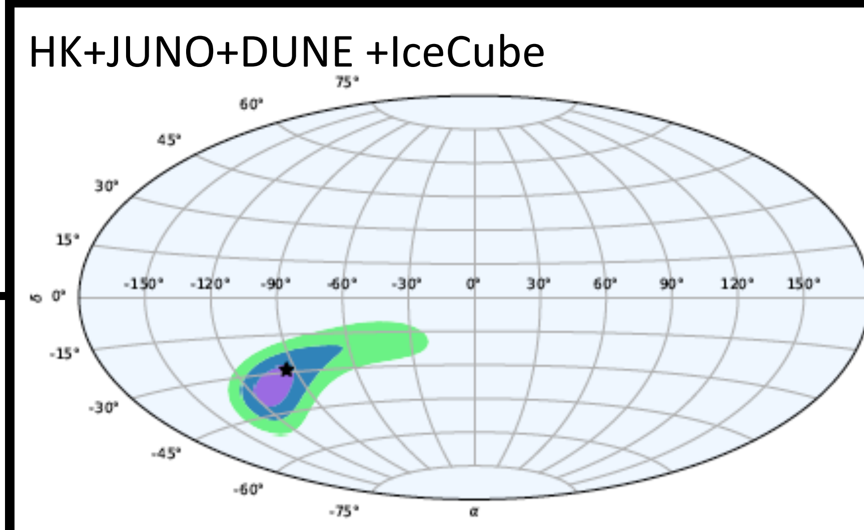
Beacom & Vogel (1999), Tomas et al (2003)

SNEWS2.0: Triangulation





Coordinated pointing:
Automate triangulation into upgraded SNEWS2.0 alerts

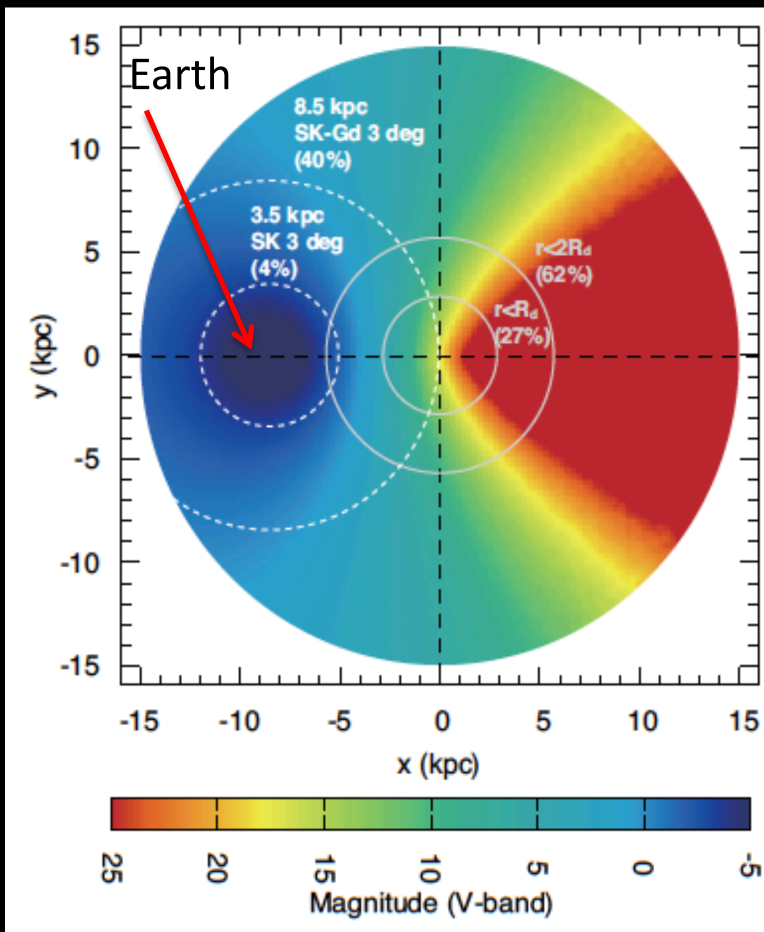


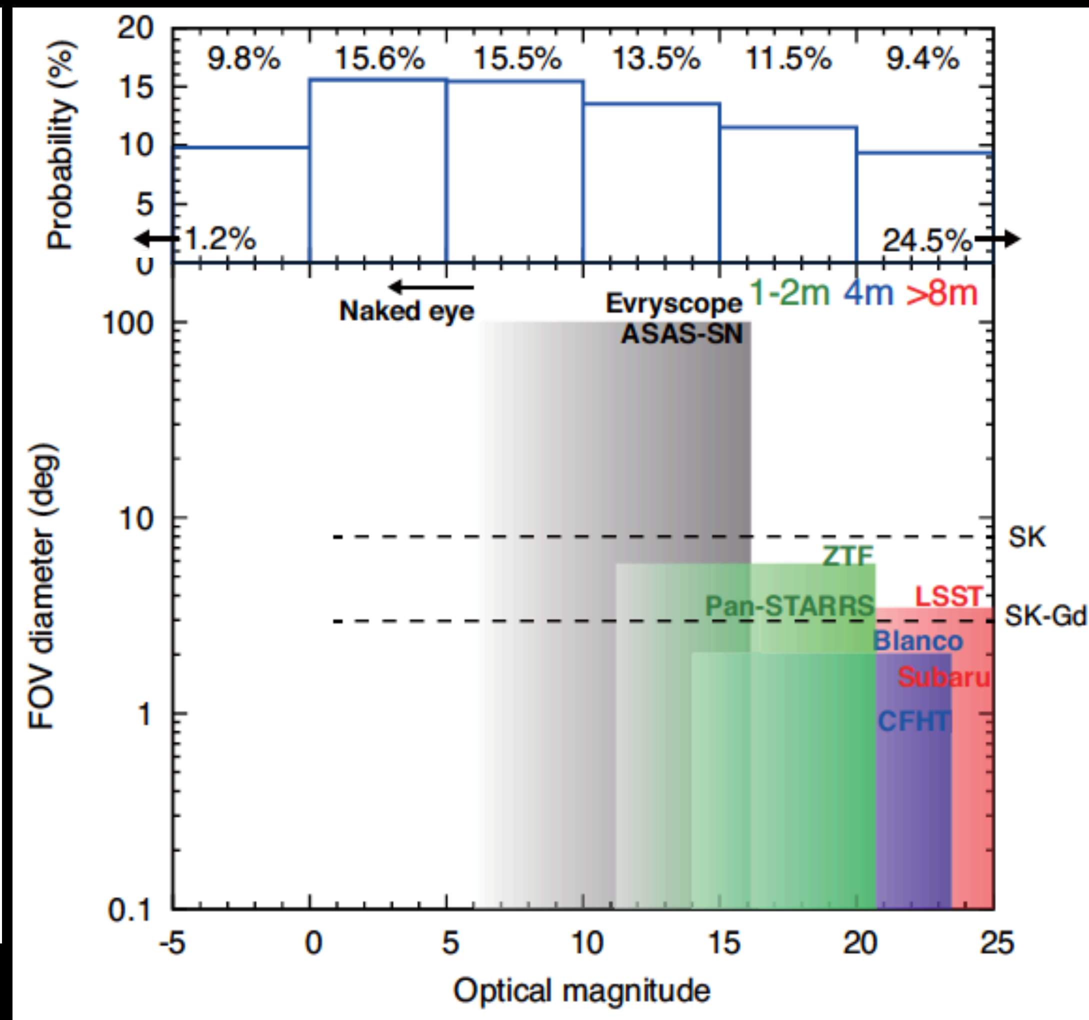
Linzer & Scholberg (2019);
See also, Brdar et al (2018),
Beacom & Vogel (1999),
Mhlbeier et al (2013),

Multi-messenger: electromagnetic

Important WHERE supernova occurs:

The Milky Way puts severe attenuation in the optical regime (not so much in IR)





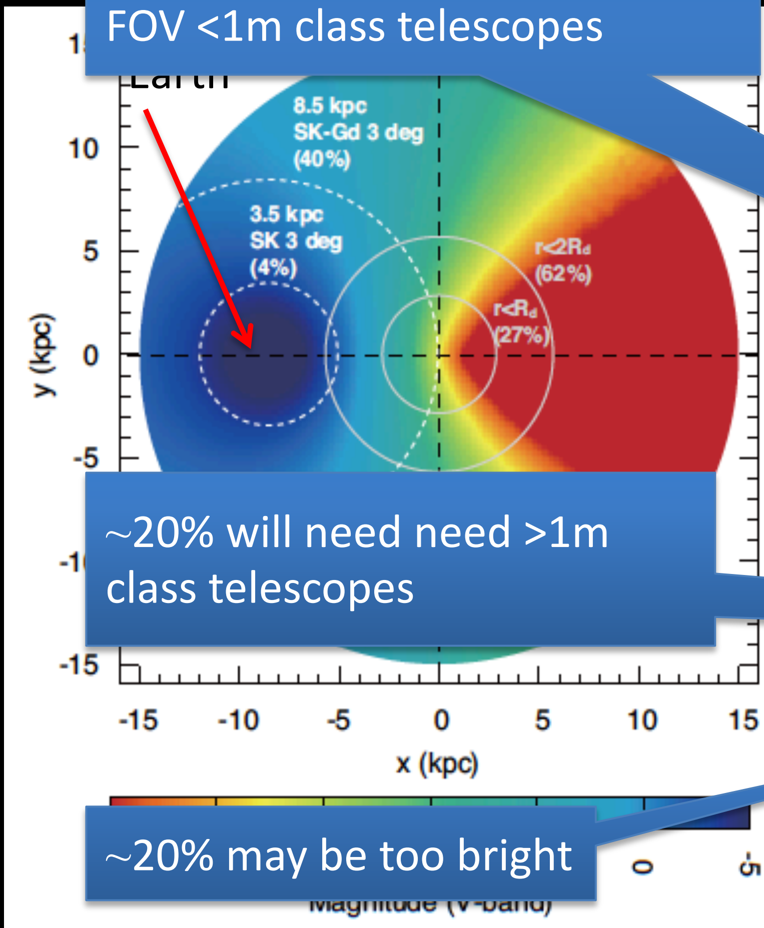
Nakamura et al (2016)

Multi-messenger: electromagnetic

~25% of CCSNe are hard to reach optically

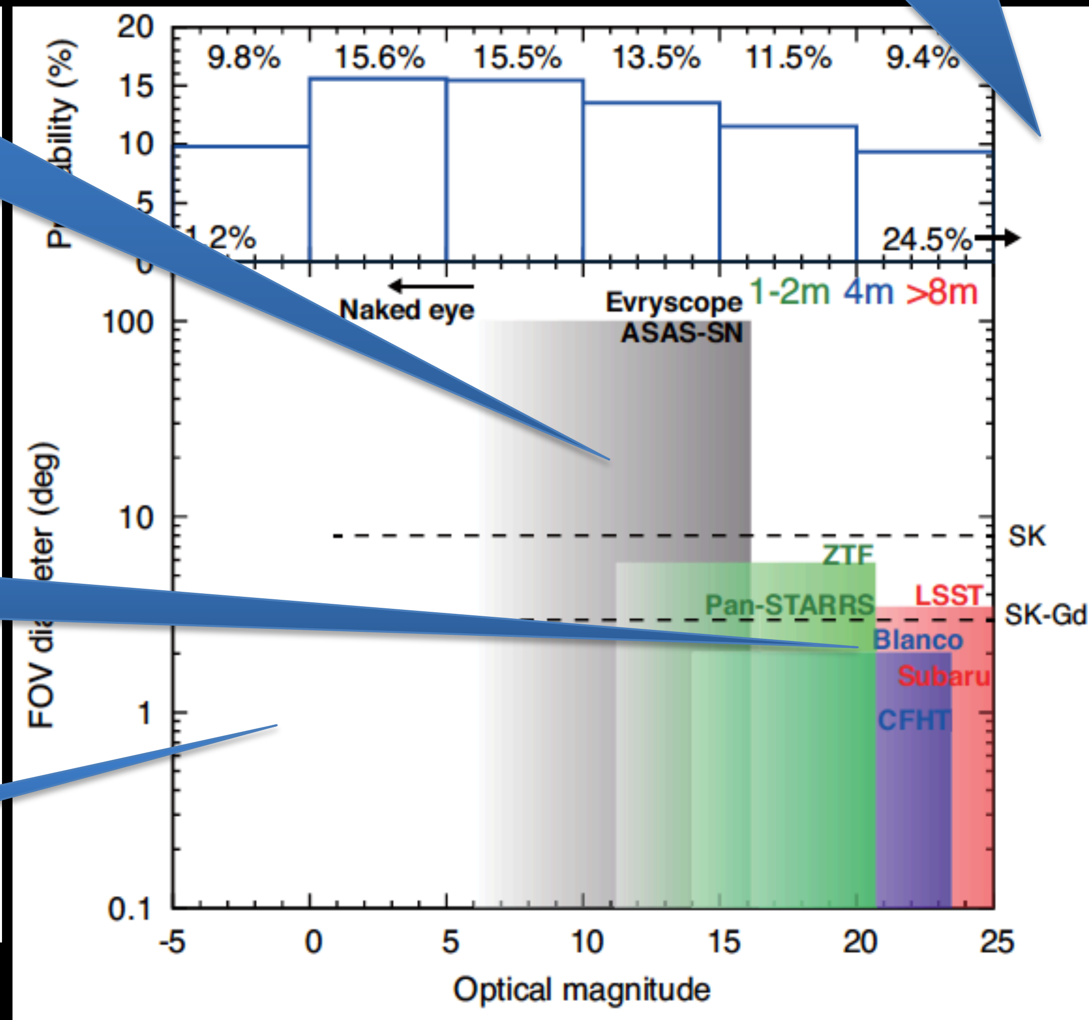
Important WHERE supernova occurs:

The ~35% are within reach of large FOV <1m class telescopes ation in the optical regime (not so much i



~20% will need need >1m class telescopes

~20% may be too bright

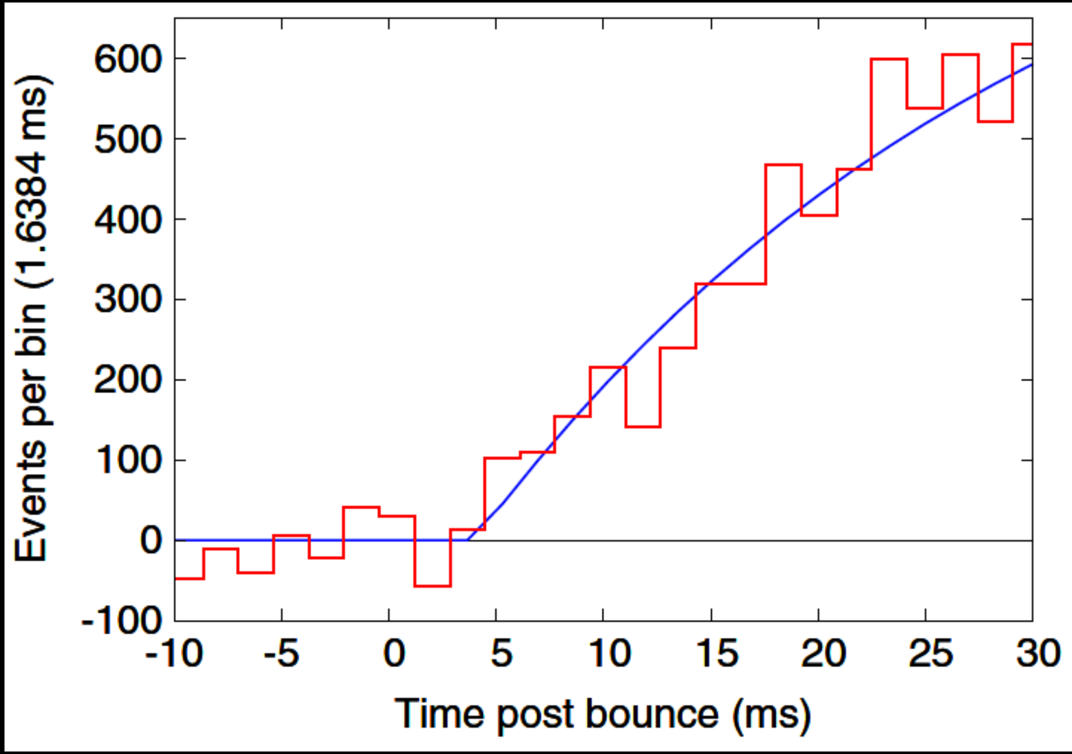


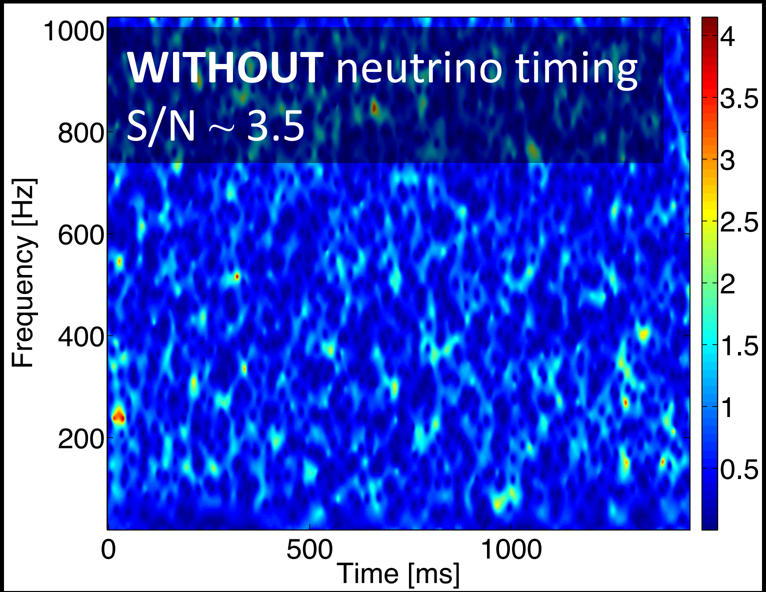
Nakamura et al (2016)

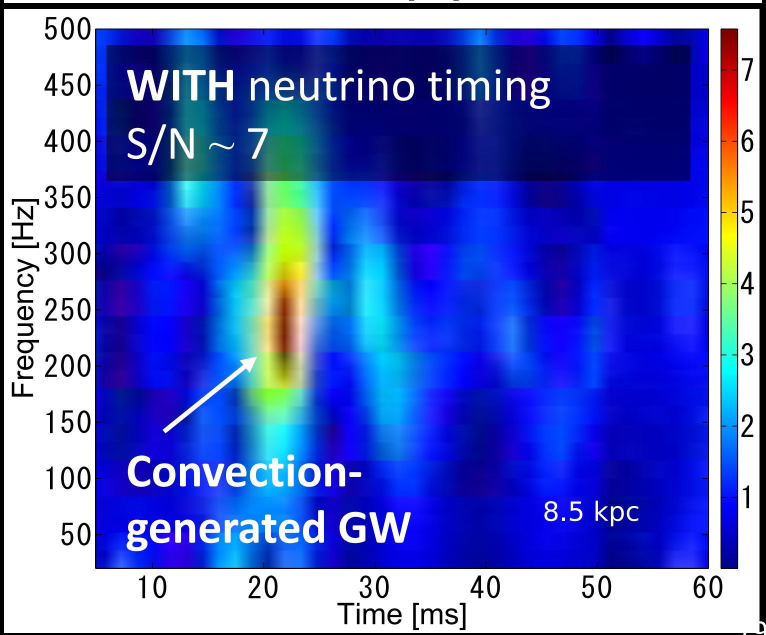
Multi-messenger: gravitational waves

- Gravitational waves can be challenging to detect for non-rotating progenitors;
- Bounce time estimates will help, e.g., to within ±3.5 ms at IceCube

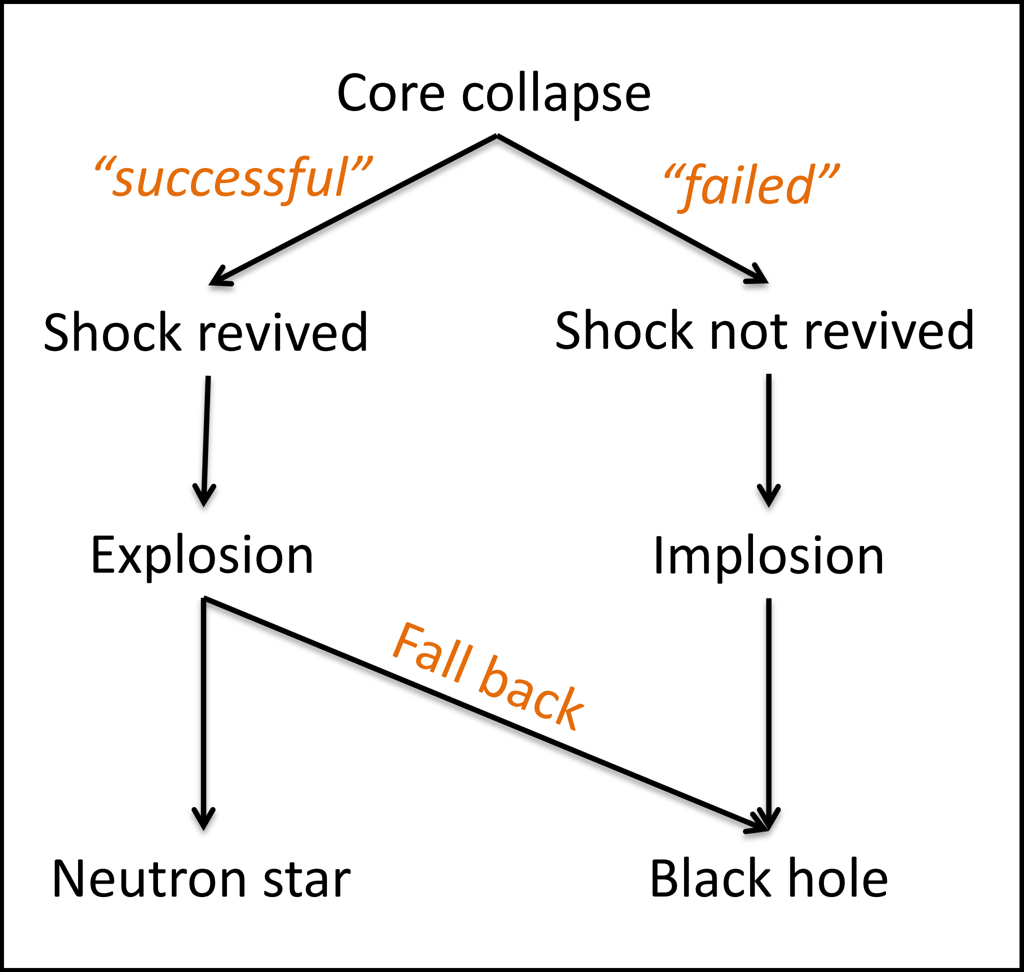
Halzen & Raffelt (2009)
Nakamura, Horiuchi et al (2016), Hansel et al (2019)







Core collapse: possible channels

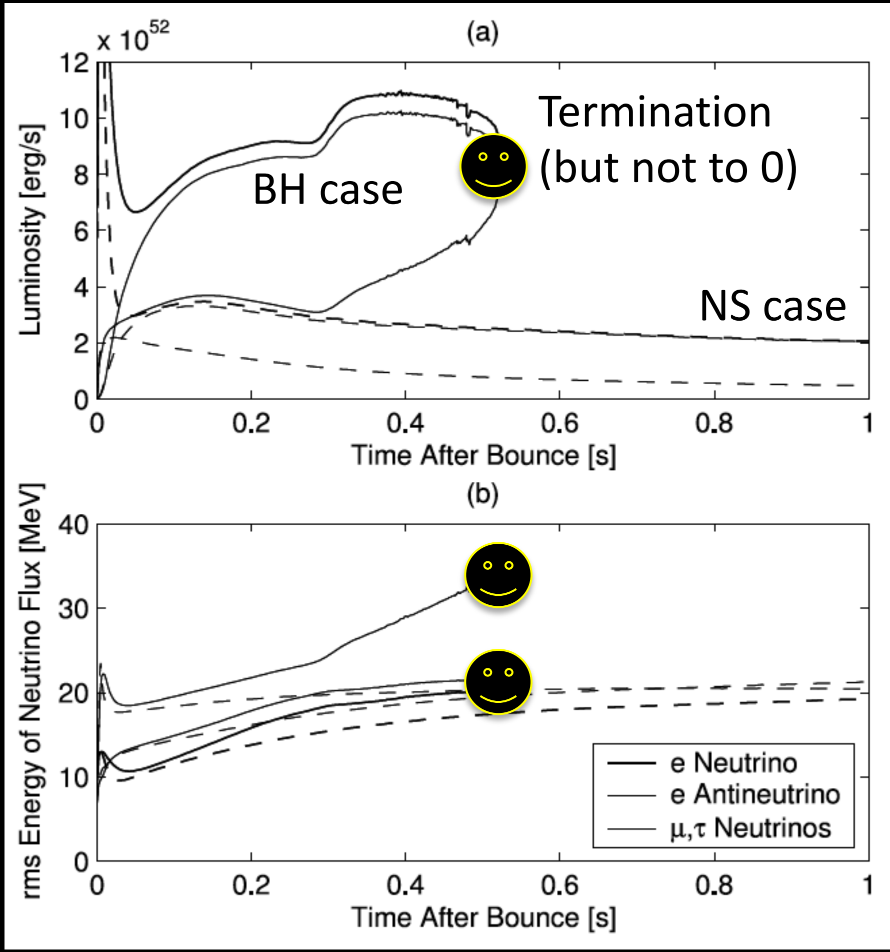


Both should occur

Imprints of black hole formation

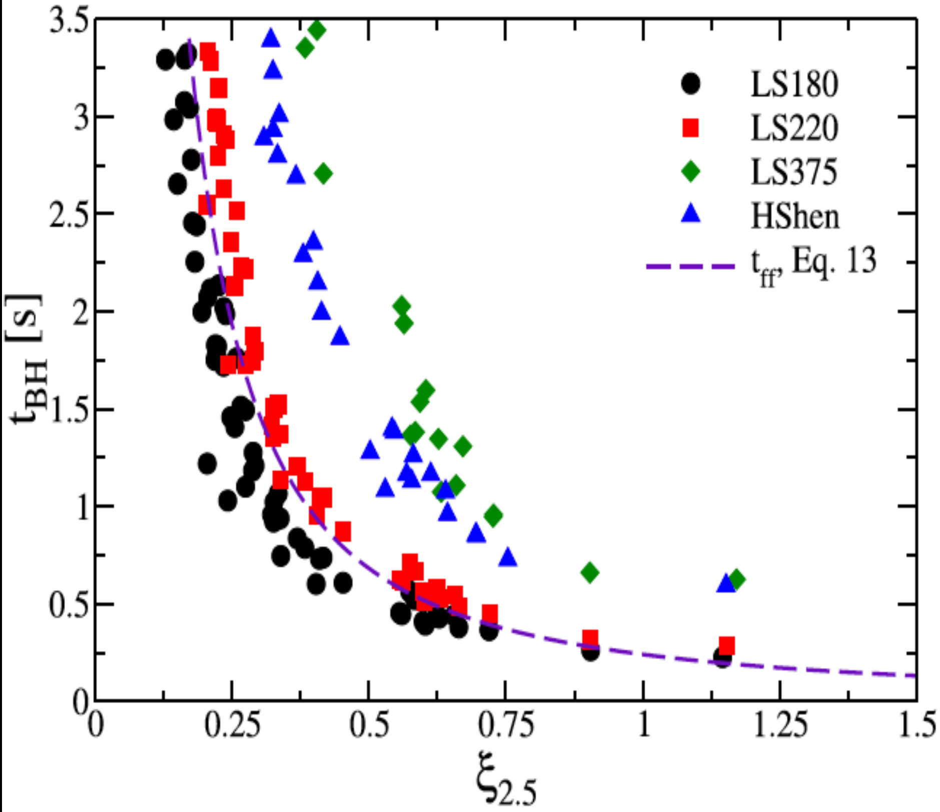
Moment of black hole formation

Neutrinos light curve can reveal the moment of black hole formation



Liebendoerfer et al (2004)

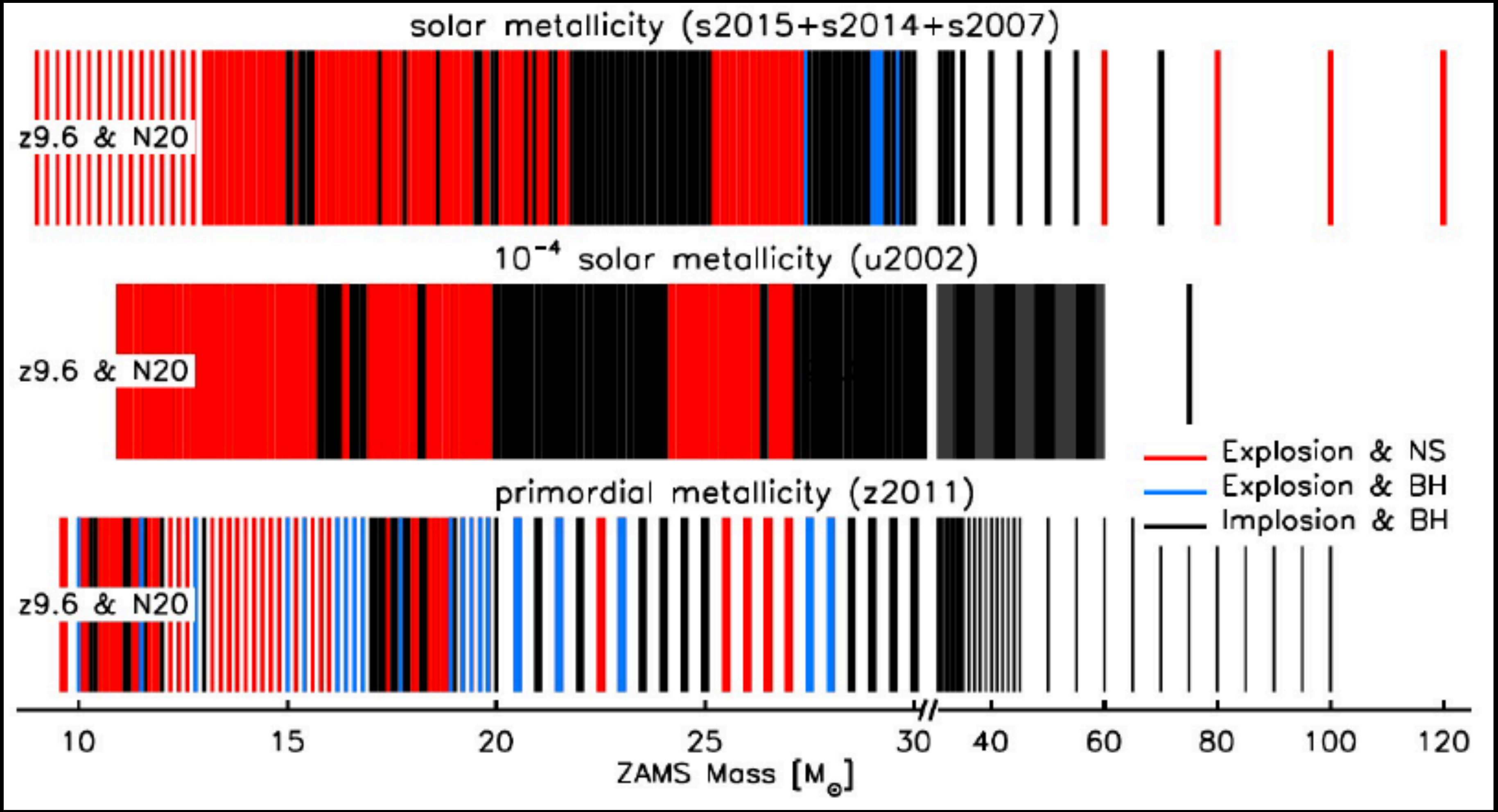
Time of black hole formation depends on mechanism & progenitor & EOS



O'Connor & Ott (2011)

Failed explosion may not be so rare

Supernova diversity: explosion / implosions in the neutrino mechanism



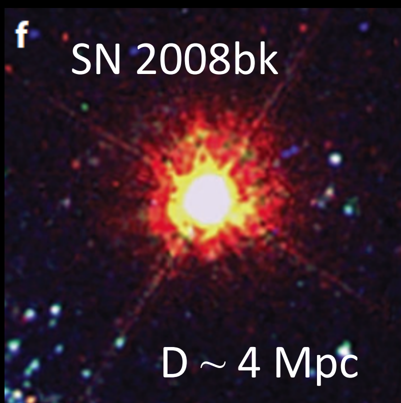
1D: O'Connor & Ott (2011), Erlt et al (2015), Pejcha & Thompson (2015), Sukhbold et al (2016)

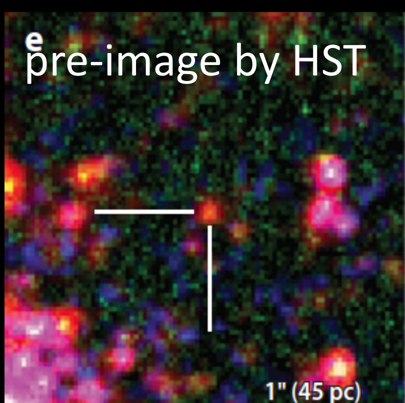
1D continued: Mueller et al (2016), Warren et al (2019)

2D: Horiuchi et al (2014), Summa et al (2016)

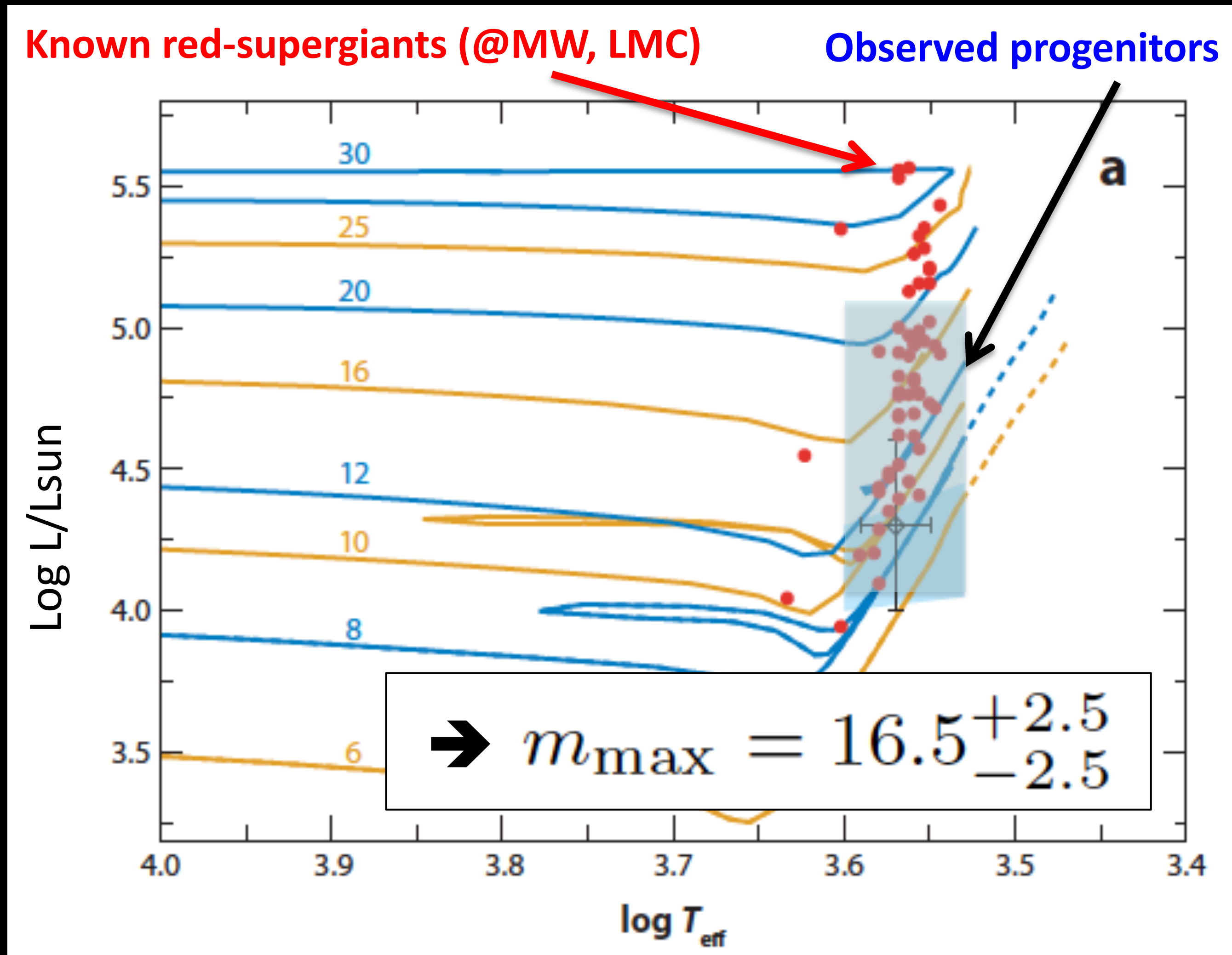
Supernova progenitors

Pre-imaging:
Limited to nearby SNe, but very successful for Type II





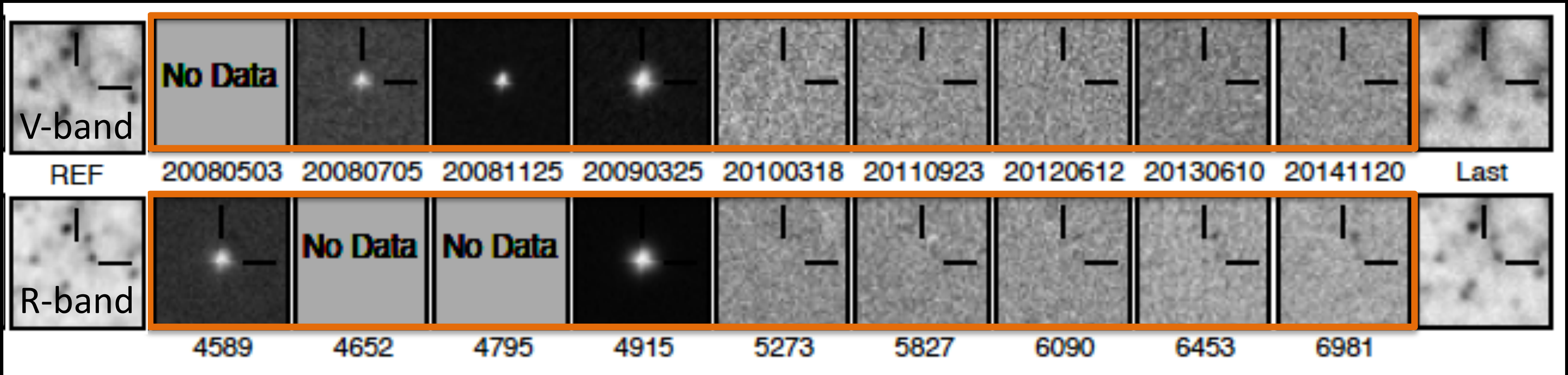
Why: most luminosity missing from progenitor sample?



$$\rightarrow m_{\max} = 16.5^{+2.5}_{-2.5}$$

Smartt (2009), Smartt (2015)

Searching for disappearing stars

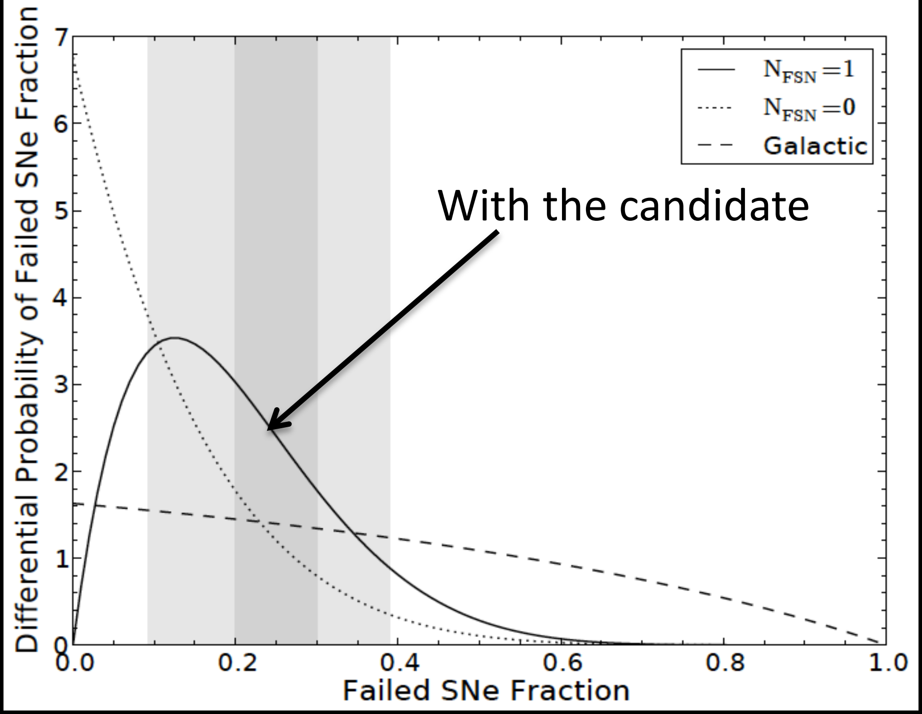


"Survey of nothing"

In 7 years running

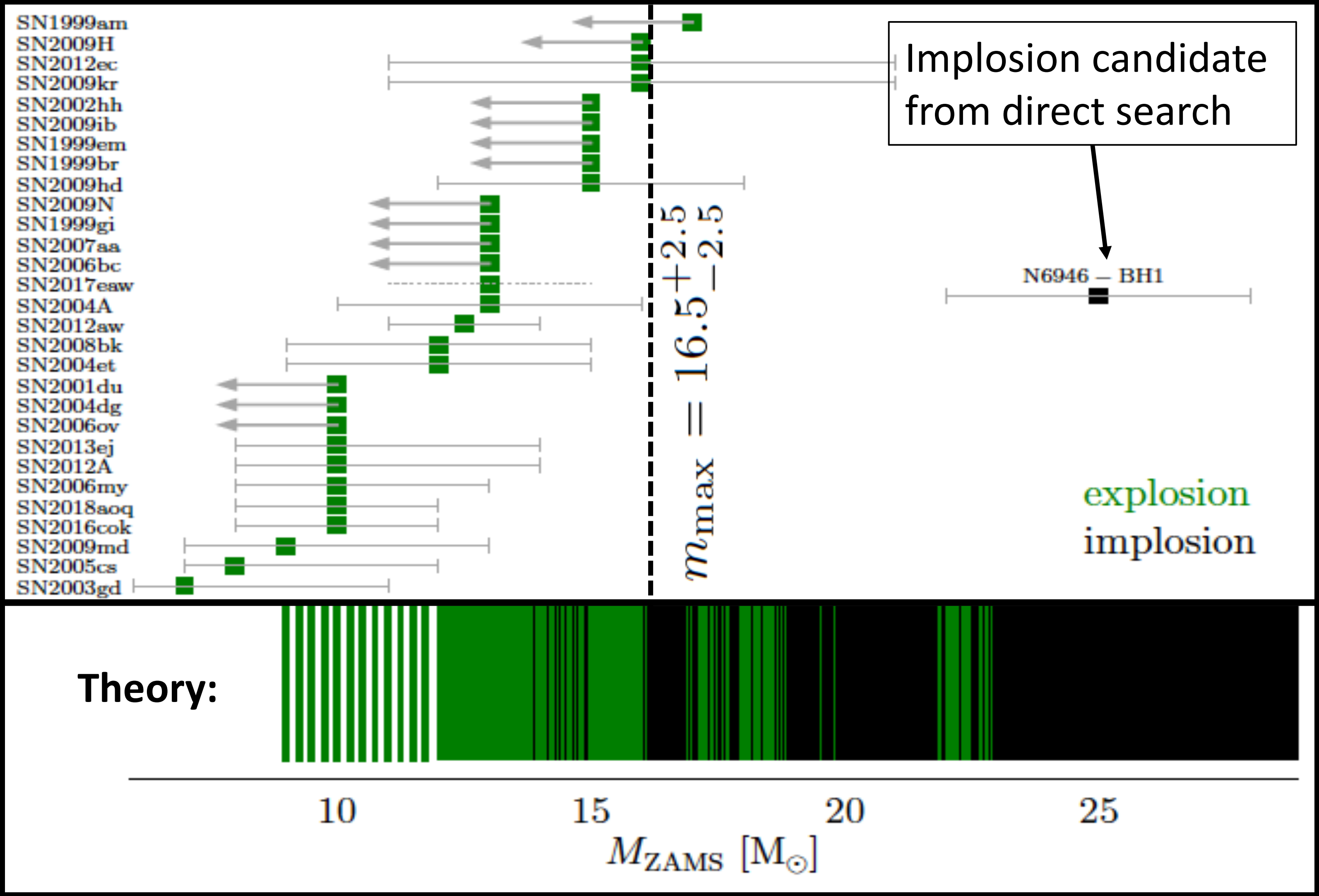
- 6 luminous supernovae (09dh, 11dh, 12fh, 13ej, 03em, 14bc)
- 1 candidate failed supernova: NGC6946-BH1 (@~6Mpc); SED well fit by 25Msun RSG

➔ **Failed fraction** $f = 0.14^{+0.33}_{-0.10}$ **(90%CL)**



Kochanek et al (2008), Gerke et al (2015), Adams et al (2016)

Explosions & implosions

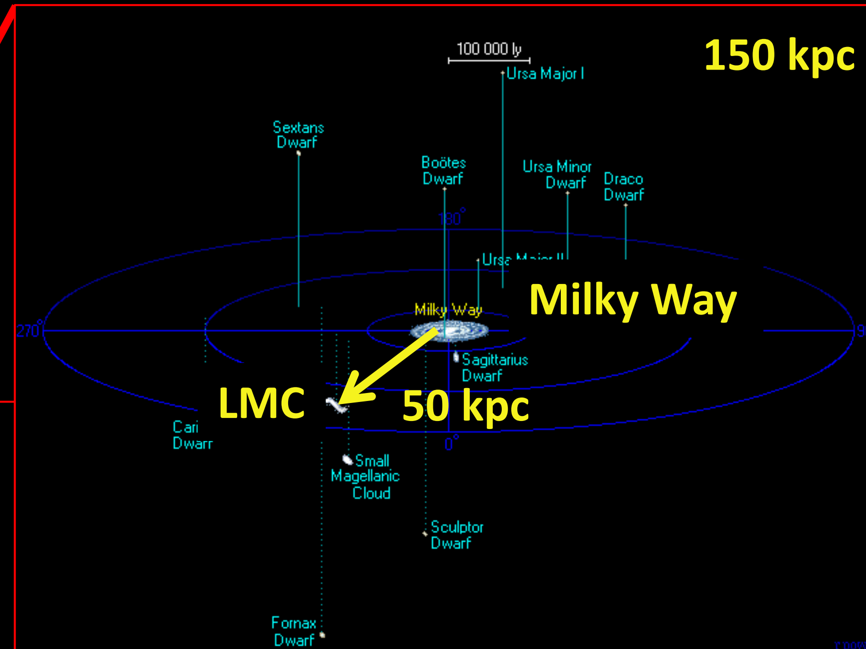


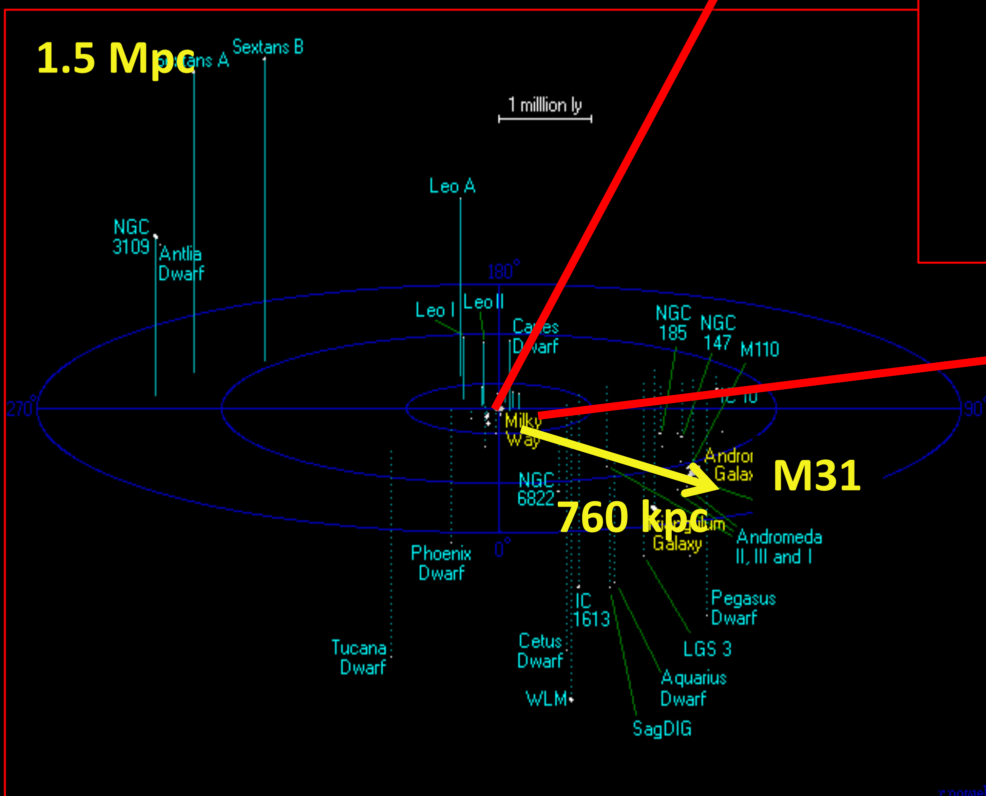
➔ **Failed explosion may not be rare. Fraction can be 10–40% of all core collapse**

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

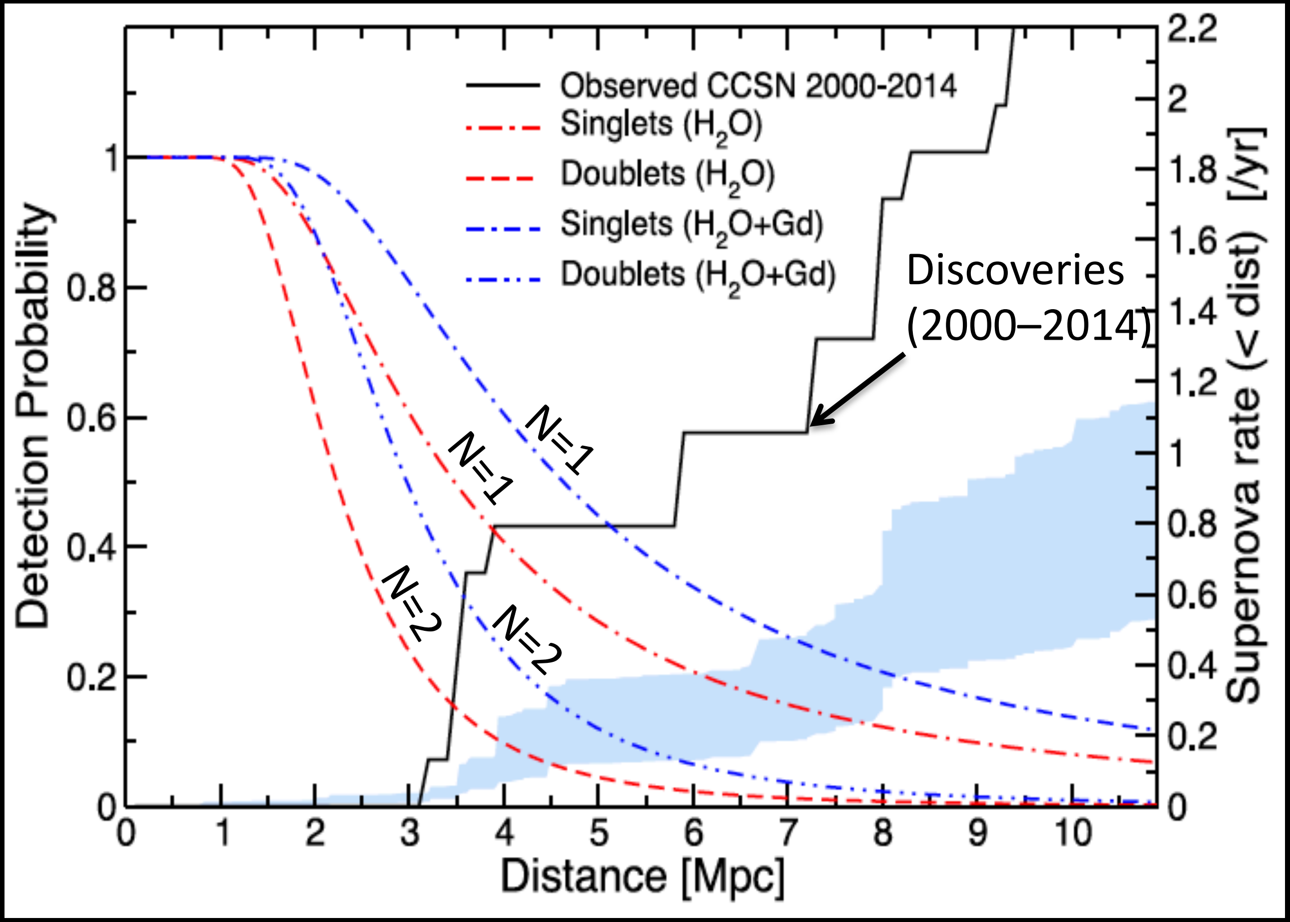
Detecting nearby neutrinos

Two approaches :

1. Neutrino trigger: look for doublets or higher multiplets (e.g., doublets in 10 sec occurs once per ~10 years scaling from SK-II)

2. EM trigger: use SBO or early SN light curve to model the bounce time (e.g., background rate in signal region is ~0.8 /day/0.56Mton scaling from SK-II) → maybe even singles

- Rate: one every several years due to over density
- Detection: probabilities possibly out to a few Mpc

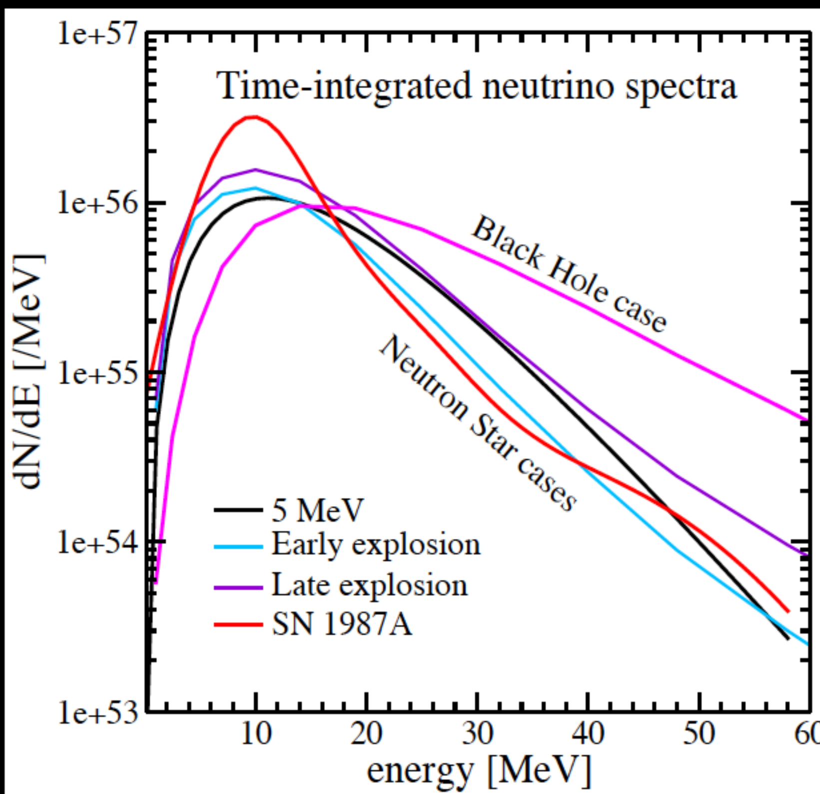


Nakamura, Horiuchi, et al (2016); based on Ando et al (2005)

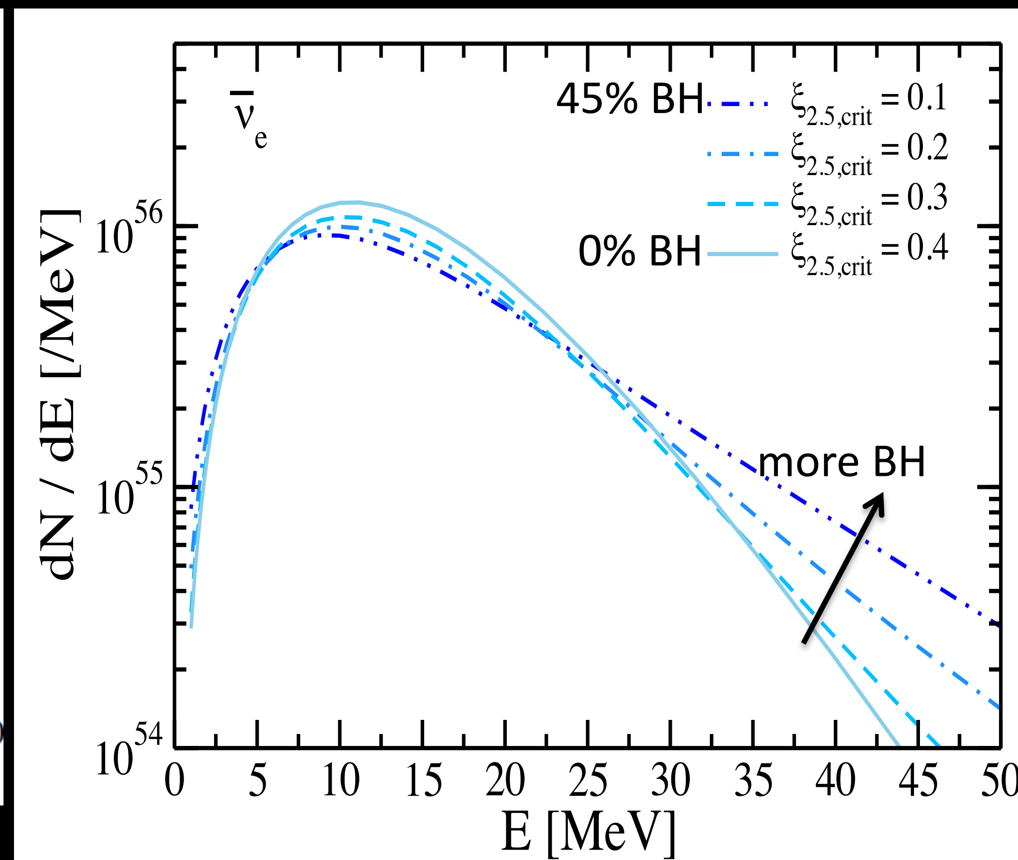
Average core-collapse neutrino flux

Average neutrino emission

- Use 100+ simulations to characterize neutrino's progenitor dependence
- Use initial mass function to distribute stars
- Include collapse to black holes (parameterized)



e.g., by Fischer et al, Sumiyoshi et al, Nakazato et al, O'Connor & Ott, …

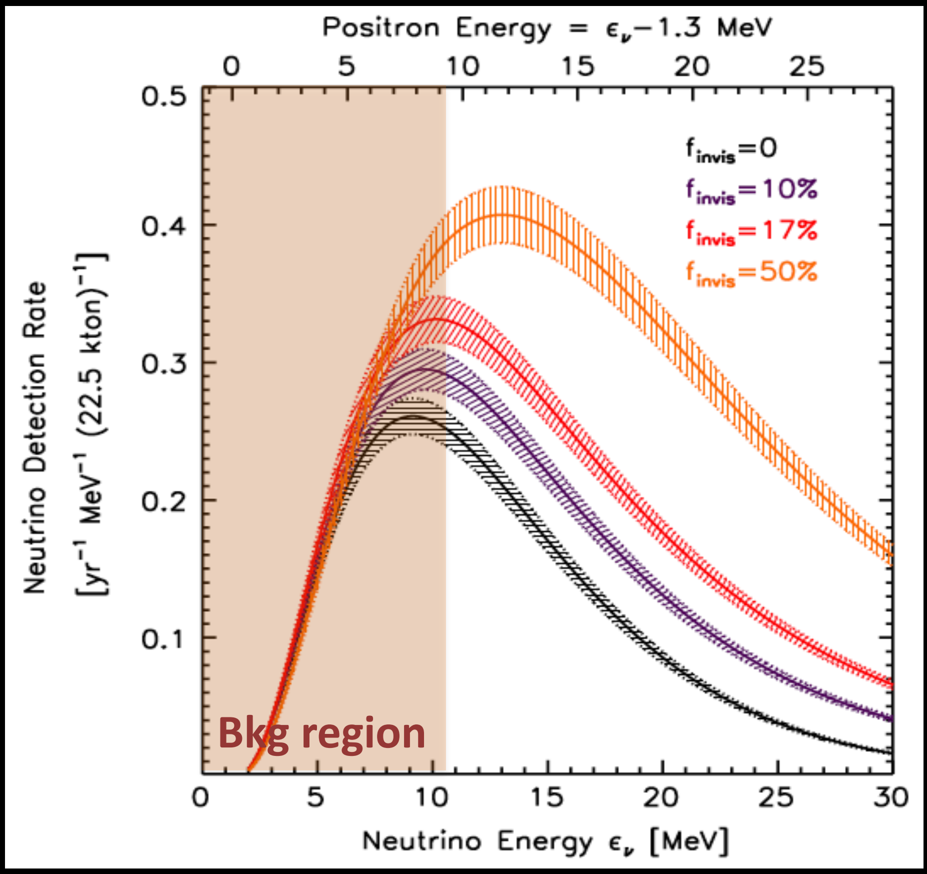


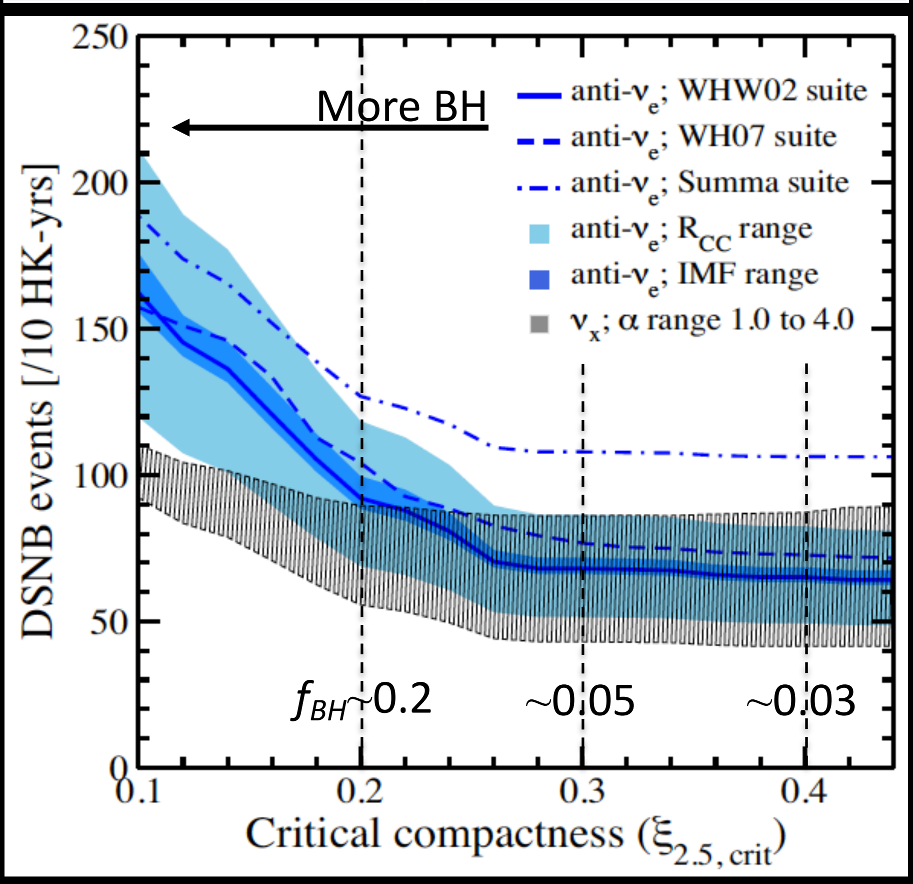
Horiuchi et al (2018)

Imprints of black hole formation

Diffuse supernova neutrino background:
- Sensitive to BHs
- Sensitive to core collapse history (→ tests of star formation history)

Spectrum	SK + Gd rate [/yr]
4 MeV	1.8 +/- 0.5
4 MeV+BH (30%)	~ 2.5
SN1987A	1.7 +/- 0.5



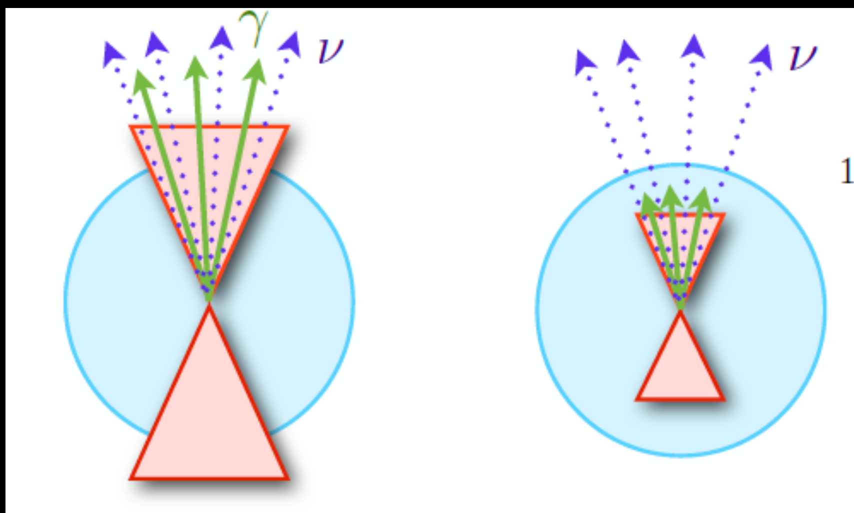


Lien et al (2010); also Lunardini (2009), Moller et al (2018), others   *Horiuchi et al (2018)*

High-energy phenomena

IceCube neutrinos

Strongly constrained by stacking studies of GRBs, but choked jets still possible



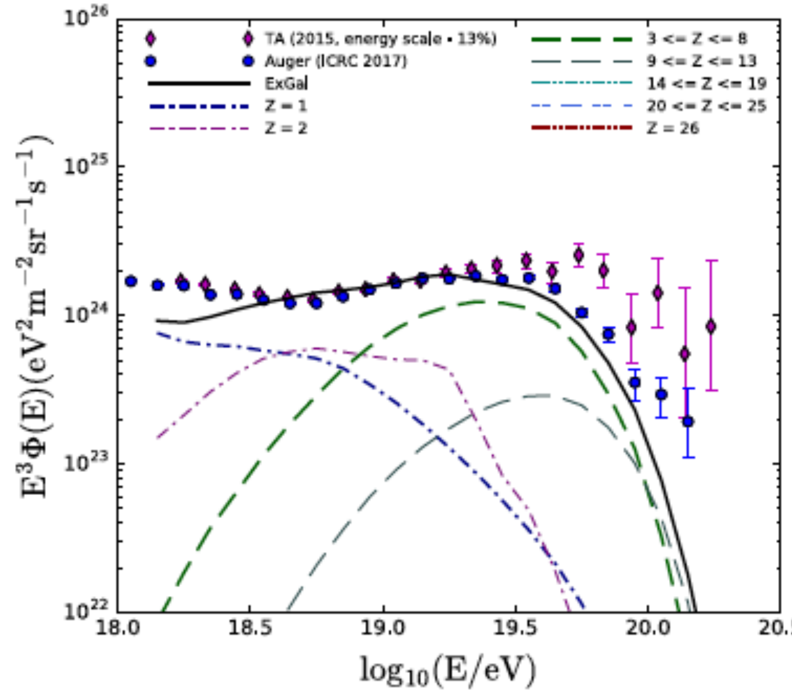
Tamborra & Ando (2016), Denton & Tamborra (2018), Esmaili & Murase (2018)

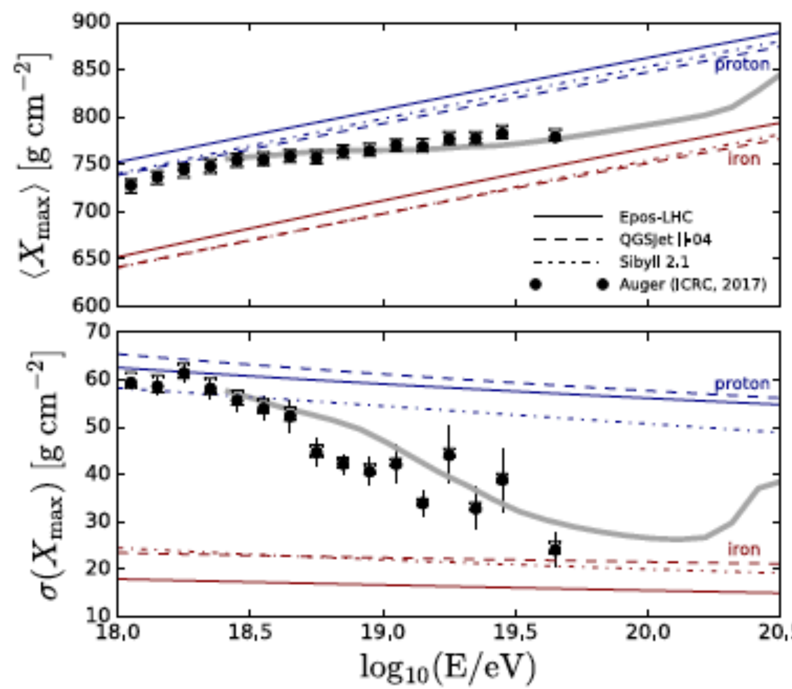
Ultra-high energy cosmic rays

Possible sites for sourcing nuclei UHECR.

Simple loading + propagation can describe the Auger spectrum & composition measurements

Murase et al (2008), Metzger et al (2011), Horiuchi et al (2012), Zhang et al (2018)





Shunsaku Horiuchi (Virginia Tech)

Concluding remarks

Supernova is an inherently multi-messenger phenomenon
Photons, neutrinos, gravitational waves, cosmic rays

Rich multi-messenger opportunities

- Neutrinos will reveal IF, WHEN, and WHERE to look – and RAPIDLY alert the community
- Multi-messengers will test explosion models, black hole formation, GRB connection, and many more…

Make sure we don't miss these opportunities!

Thanks!