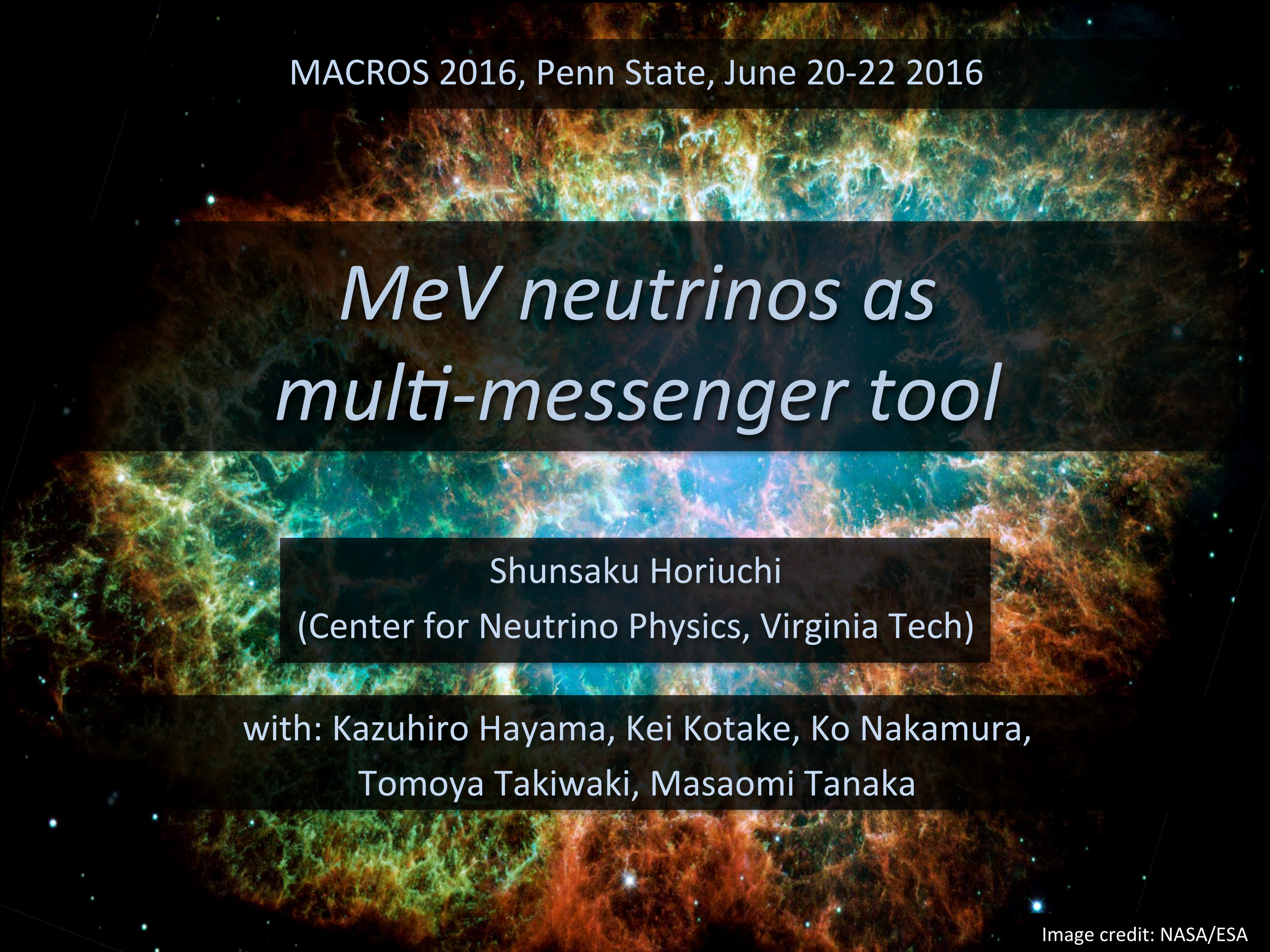


MACROS 2016, Penn State, June 20-22 2016

MeV neutrinos as multi-messenger tool

Shunsaku Horiuchi
(Center for Neutrino Physics, Virginia Tech)

with: Kazuhiro Hayama, Kei Kotake, Ko Nakamura,
Tomoya Takiwaki, Masaomi Tanaka

Image credit: NASA/ESA

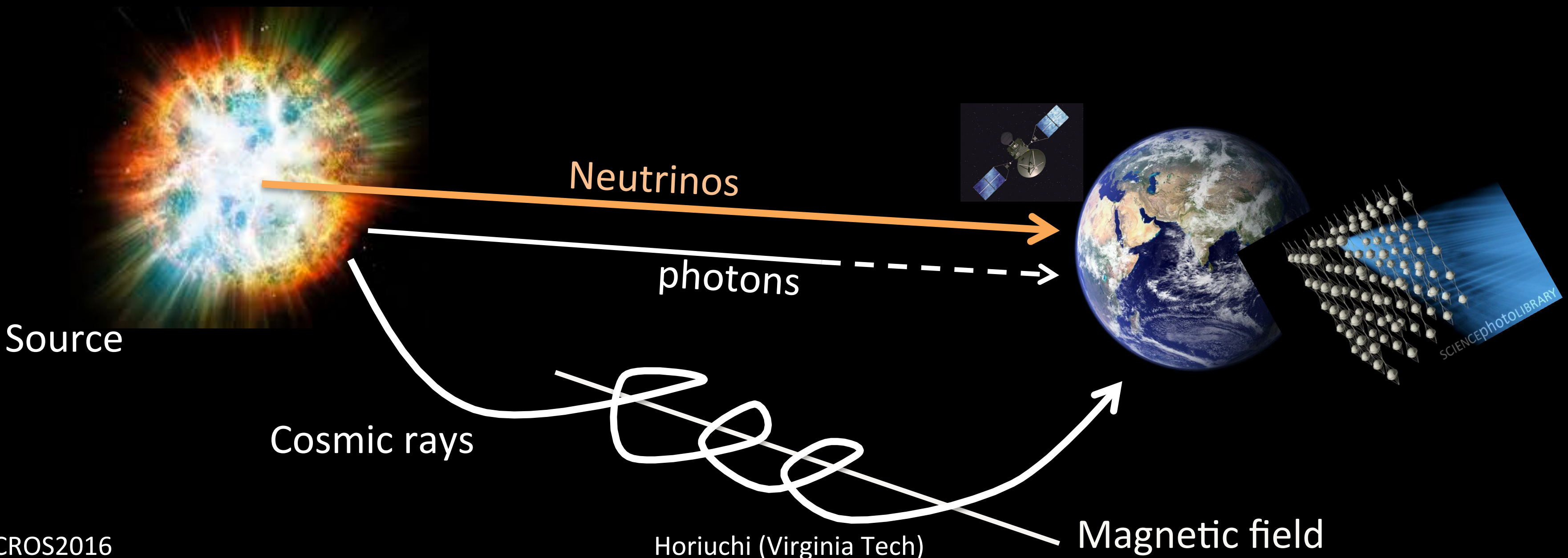
Neutrinos as messenger particles

> *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:

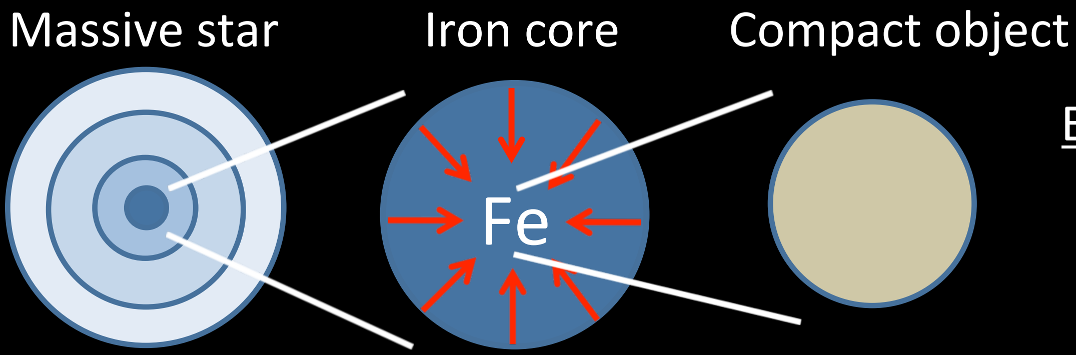
- allow us to see optically thick (to photons) regions
- experience little attenuation through cosmic space
- travel in straight lines

This makes detection difficult; but this has been addressed by modern neutrino detectors, e.g., IceCube, Super-Kamiokande, and others



Supernovae: sources of MeV neutrinos

Stellar core collapse energetics is dominated by neutrinos



Energy budget ~ 10^{53} erg

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

Neutrinos hold the key to probing many questions in core-collapse supernovae:

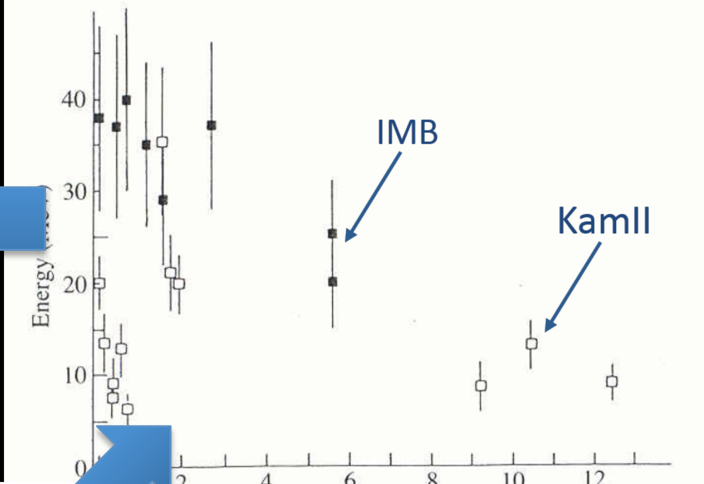
- *The supernova explosion mechanism*
- *The physics of high temperature and density matter*
- *The formation of compact objects*
- *The formation of jets*
- *Properties of neutrinos*
- *Test existence of beyond the standard model physics*
- *etc…*

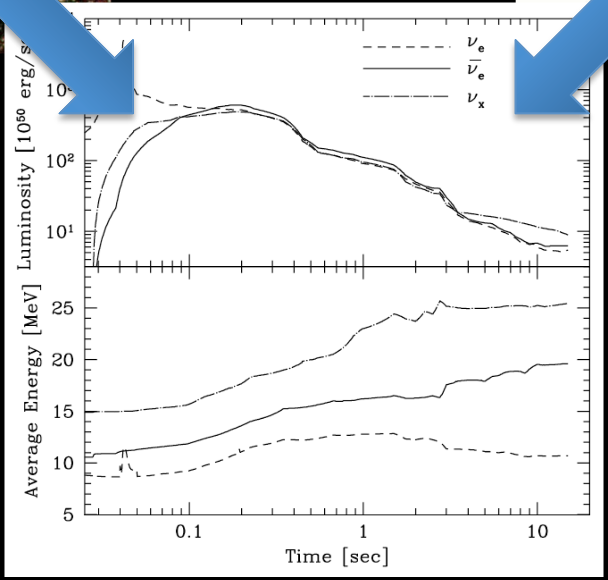
SN1987A as an example

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

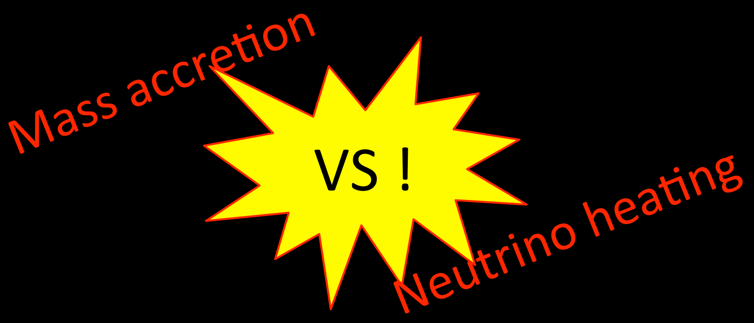
The explosion mechanism

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

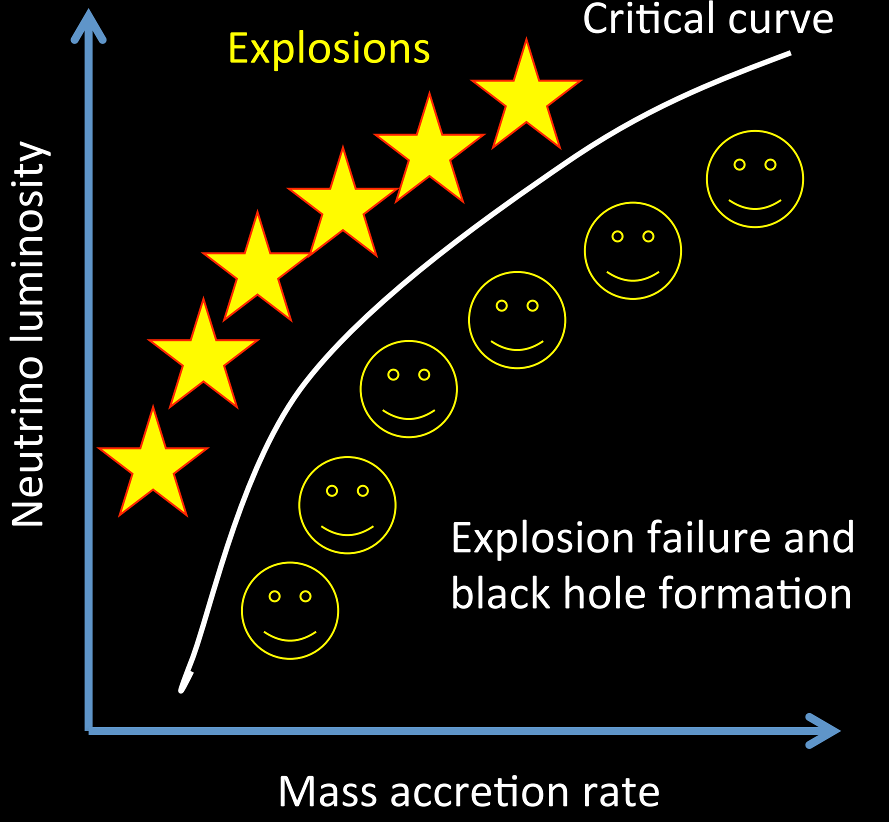
$$p = \rho \Delta v^2$$

The neutrino mechanism: deposit a fraction (~10%) of the energy in neutrinos via capture on free neutrons & protons

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



➔ Critical curve

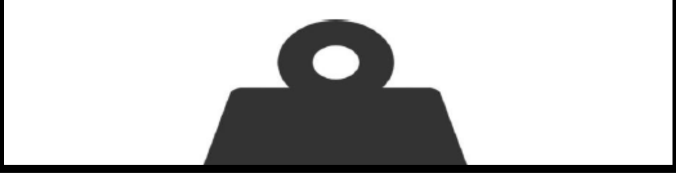


To be tested with simulation & observations!

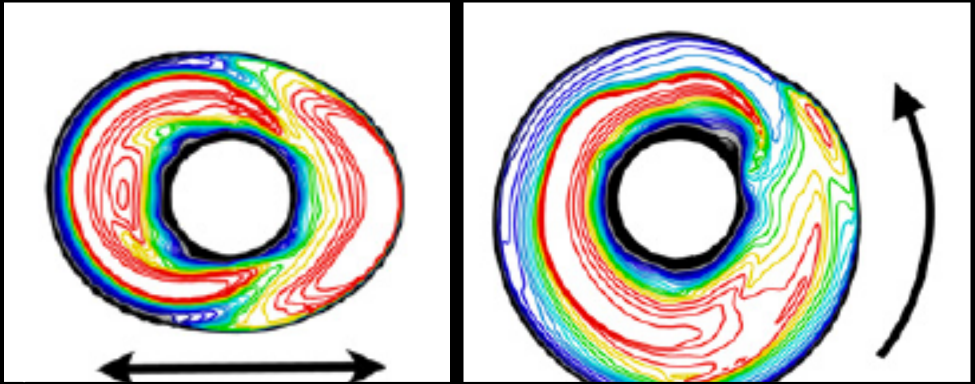
Importance of asphericity

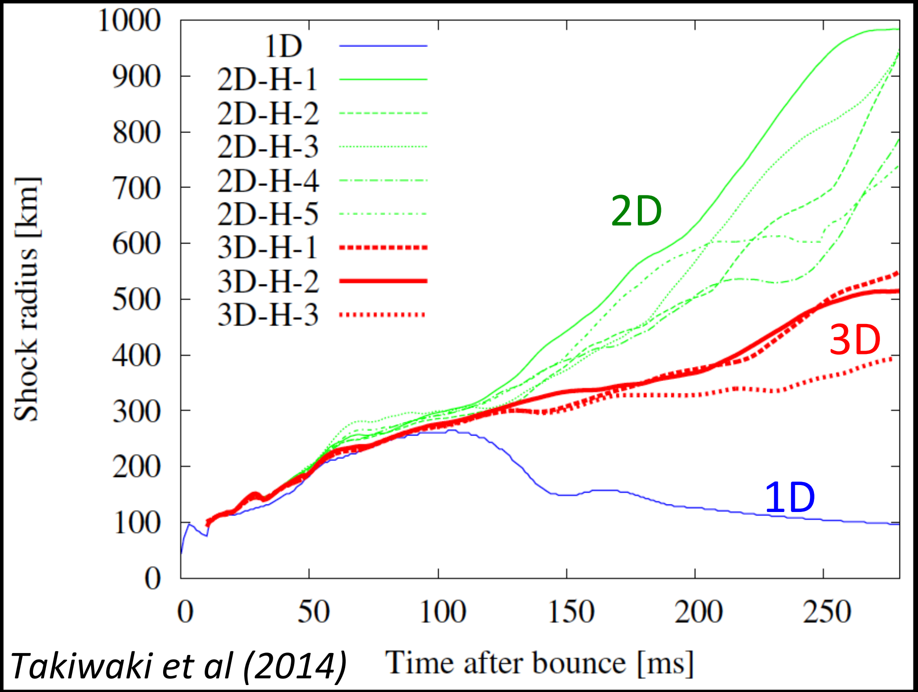
Failure in spherical symmetry: long problem since the 1980, confirmed in 2000s

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

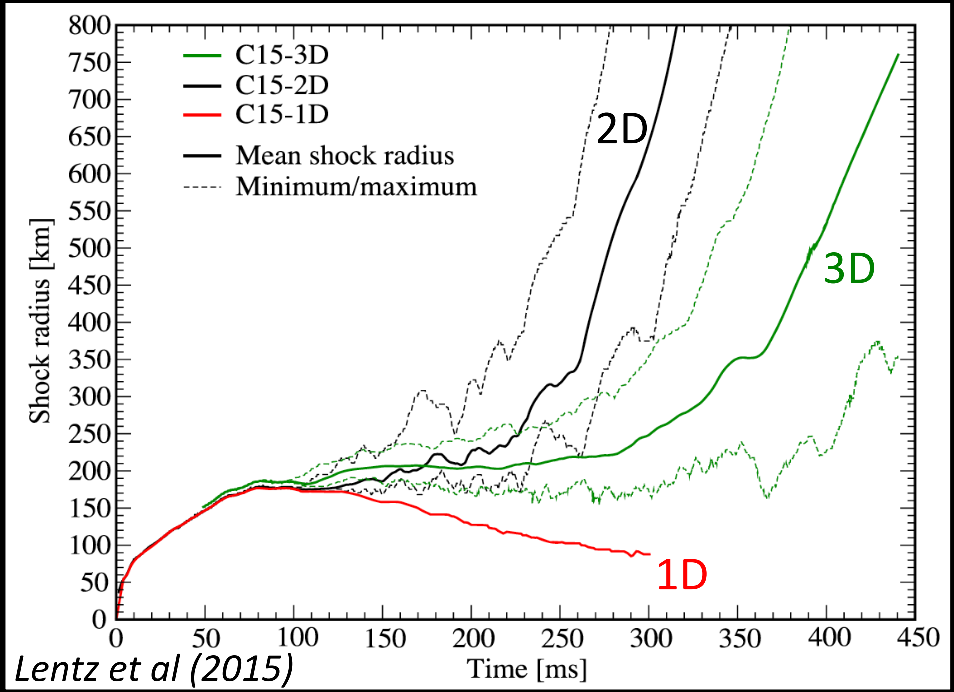


SASI:





Takiwaki et al (2014)



Lentz et al (2015)

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)]

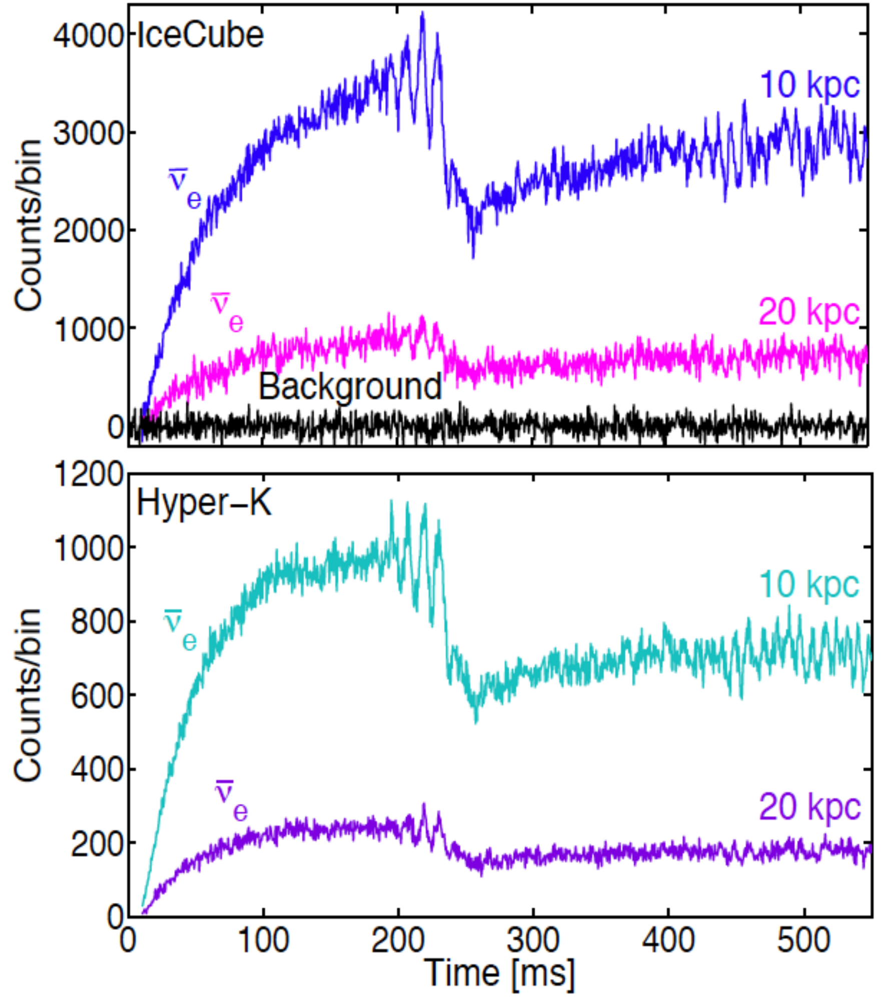
Super-Kamiokande (32 kton H_2O)
EGADS (200 ton H_2O + Gd)
KamLAND (1 kton LqSc)
[Hyper-Kamiokande (~0.6 Mton H_2O)]

LVD (1 kton LqSc)
Borexino (300 ton LqSc)
Icarus (600 ton LAr)
[LENA (50 kton LqSc)]]

IceCube (Gton Ice)

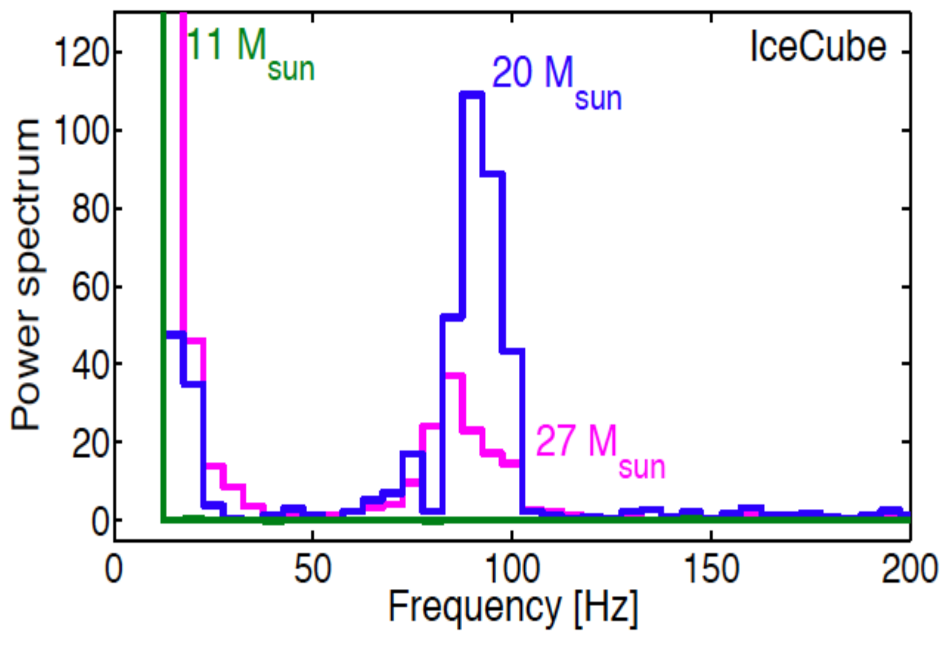
Daya Bay (300 ton LqSc)
[JUNO (~20 kton LqSc)]

Observing the SASI mechanism



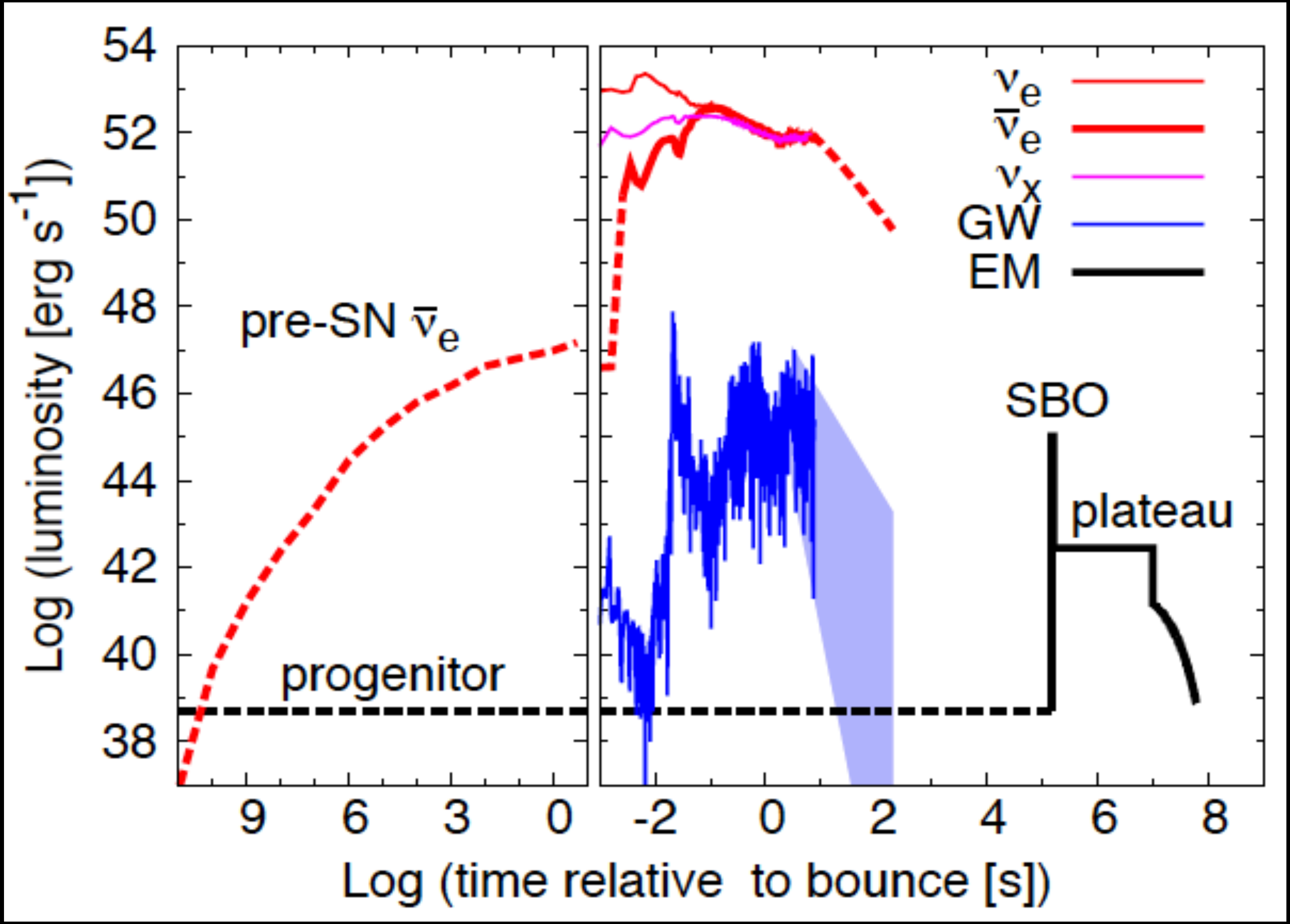
SASI signatures:

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)

Multi-messenger astronomy



Nakamura et al (2016)

Supernova neutrino and multi-messenger astronomy

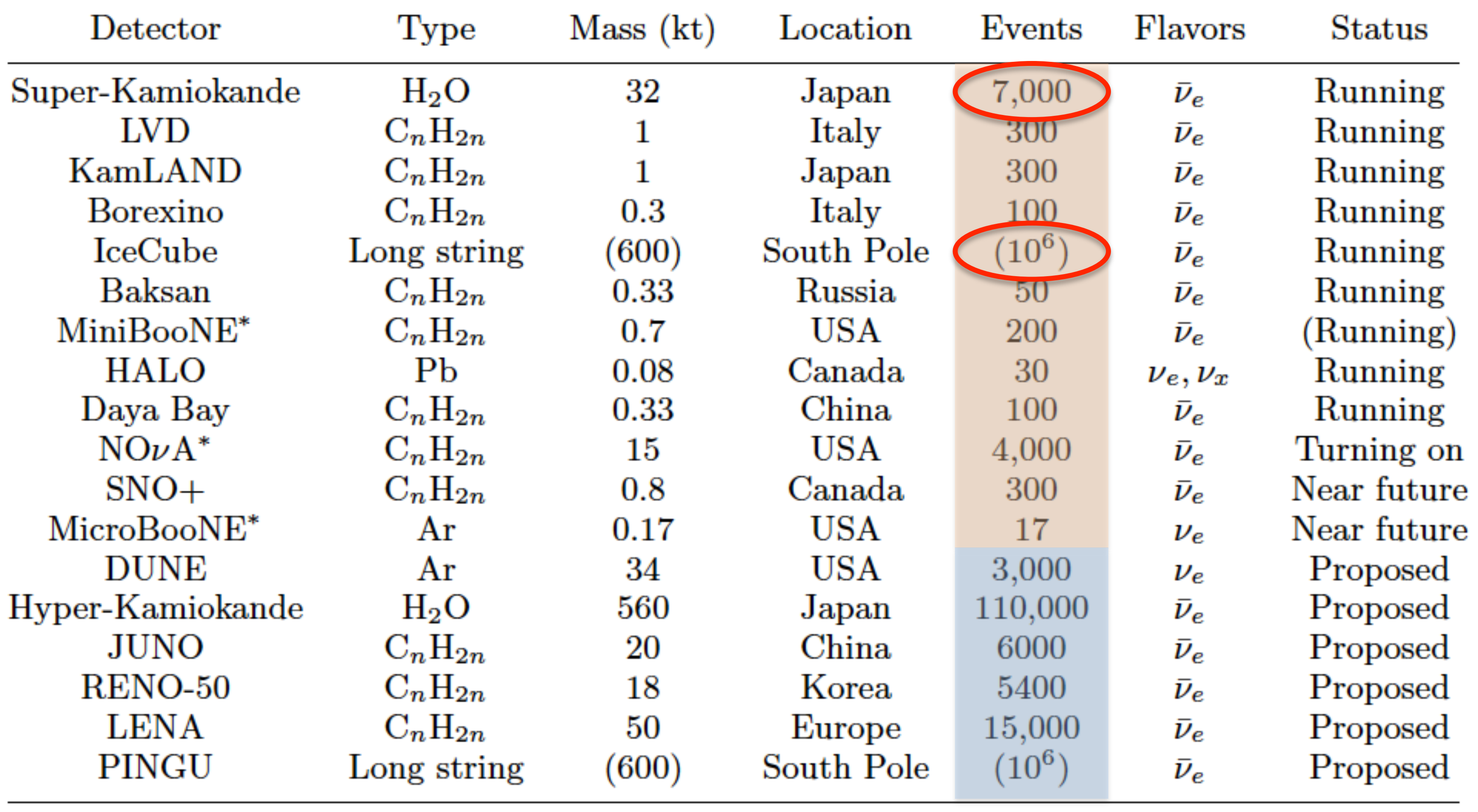
Supernova MeV neutrinos as a tool for multi-messenger astronomy: thoughts

Goals / requirements:

1. Reveal <u>IF</u> one should look – ‘significance’
2. <u>TIMELY</u> alert – ‘speed’
3. Reveal <u>WHEN</u> one should look – ‘timing’
4. Reveal <u>WHERE</u> one should look – ‘astronomy’

MeV transient detection

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



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)

MeV neutrino ‘astronomy’ : IF to look

2) TIMELY alert: The SBO arrives minutes to hours after the neutrino signal

$$v \sim (E/M)^{1/2} \;\; ; \;\; \Delta t \sim R / v \sim 100 \text{ sec } (R/R_{sun})(E/10^{51} \text{ erg})^{-1/2}(M/M_{sun})^{1/2}$$

- For RSG (type IIP): 1000 Rsun, 10 Msun → a few days
- For WR (type Ibc): 1 Rsun, 1-10 Msun → several minutes

✓ SNEWS:

Borexino
DayaBay
HALO
IceCube
KamLAND
LVD
Super-K

Coincidence server (@BNL)

E-mail ALERT ✓

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

- Rapid alert

✓ Individual detectors, e.g, Super-K, IceCube

IAU, ATel alerts ✓

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

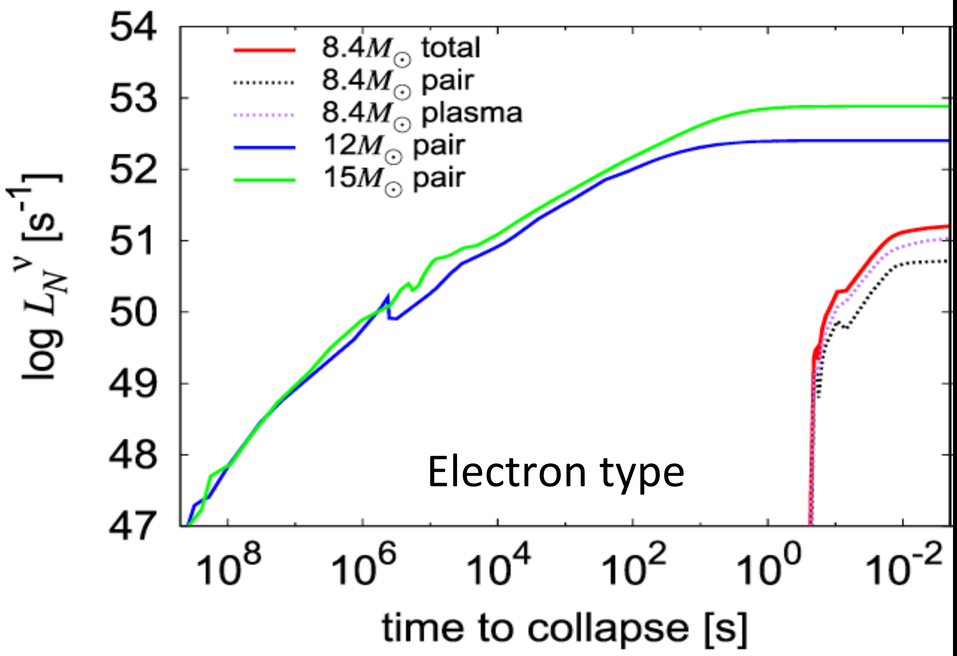
Adams et al 2014

Early early warning

Pre-supernova neutrinos:

ν emission rapidly rises during the last stages of stellar nucleosynthesis

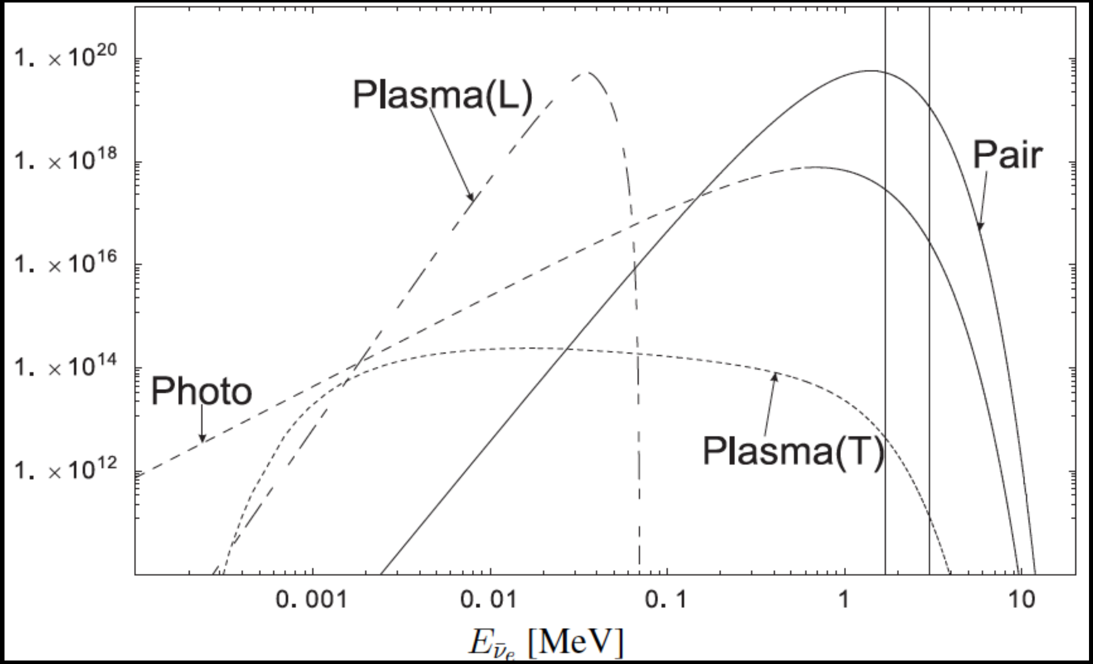
→ **Provides an early-early warning for a core collapse if it can be detected**



Low detection threshold and low backgrounds are keys for detection

	Range [kpc]
Super-K	~0.3
KamLAND	~1
JUNO	~few
Hyper-K	~few?

Odrzywolek et al (2004)
Kato et al (2015)
Patton & Lunardini (2016)



Odrzywolek et al (2004)

MeV neutrino 'astronomy' : when to look

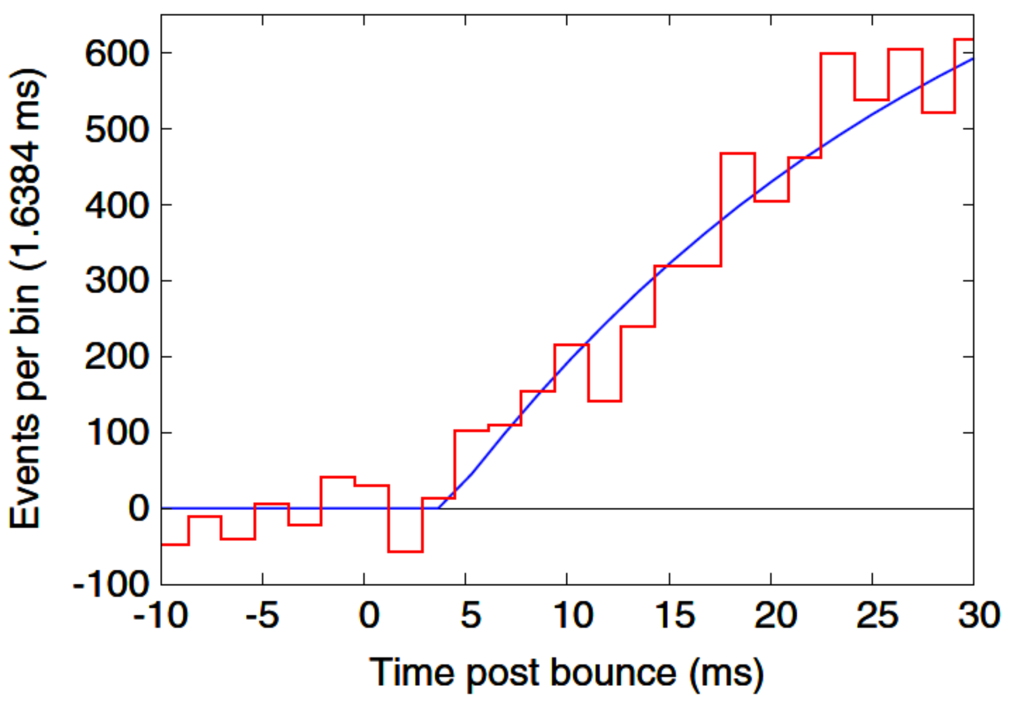
3) WHEN one should look: Reconstruction of the core bounce time

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

Halzen & Raffelt (2009)

e.g., with Super-K, similar error of ~10 ms

Pagliaroli et al (2009)

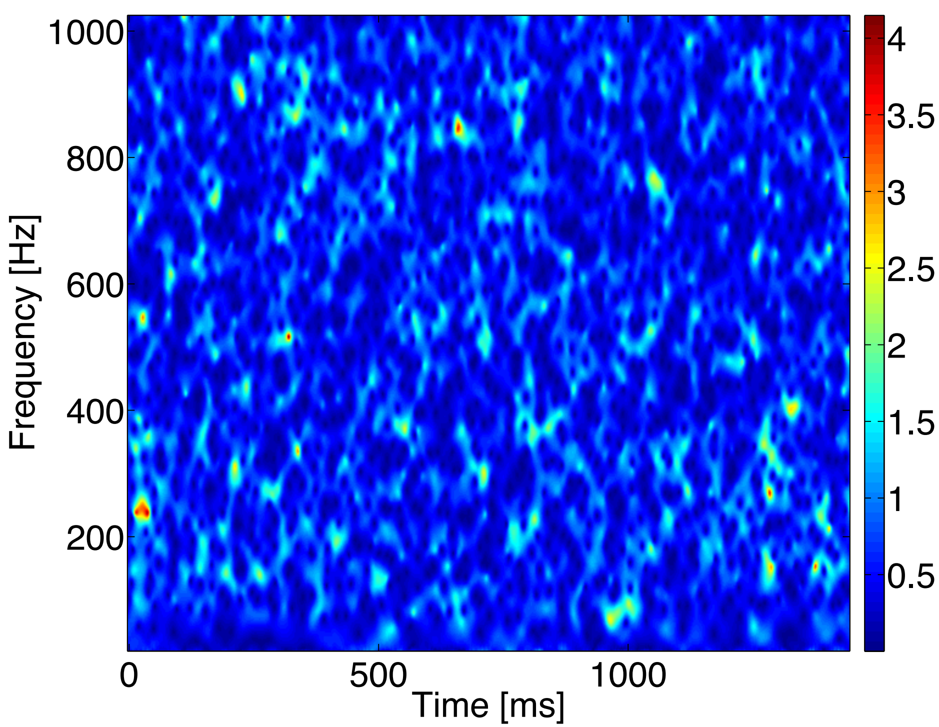


→ Neutrinos can determine the bounce time to several ms ✓

Multi-messenger: gravitational wave

Without neutrino timing

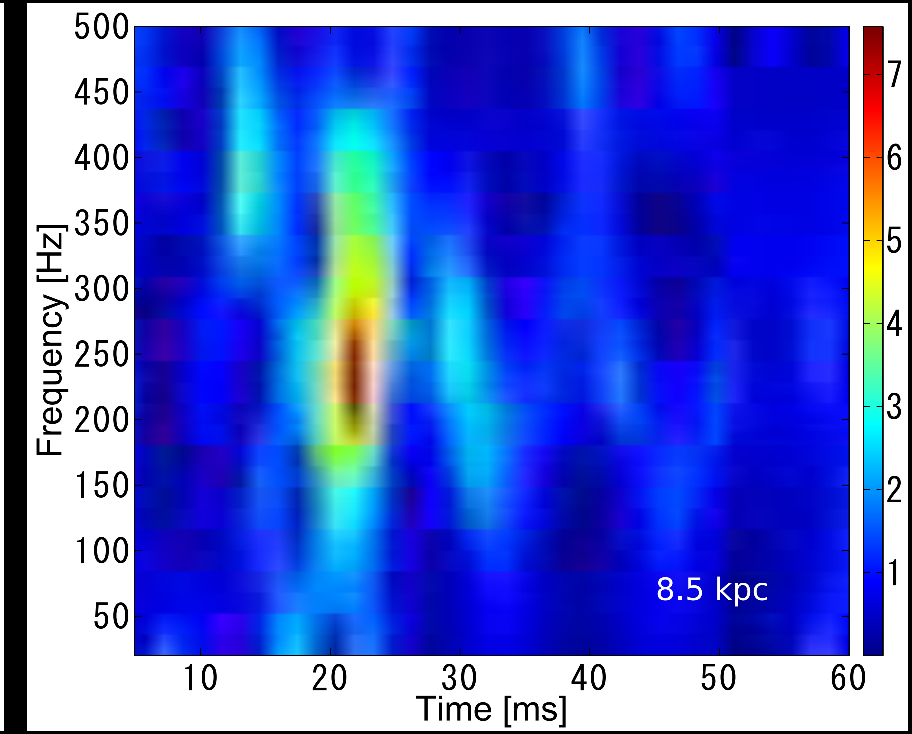
Signal-to-Noise over first 1.5 sec of GW signal reaches some ~3.5 @200Hz corresponding to prompt convection GW: no strong detection



e.g., for non-rotating progenitor

With neutrino timing

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



→ Timing of core bounce helps GW detection

MeV neutrino Astronomy

4) WHERE one should look

Use e^- scattering forward cone

$\nu e \rightarrow \nu e$

Will be enhanced by neutron tagging with dissolved Gd (~90% efficiency):

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

current

with Gd

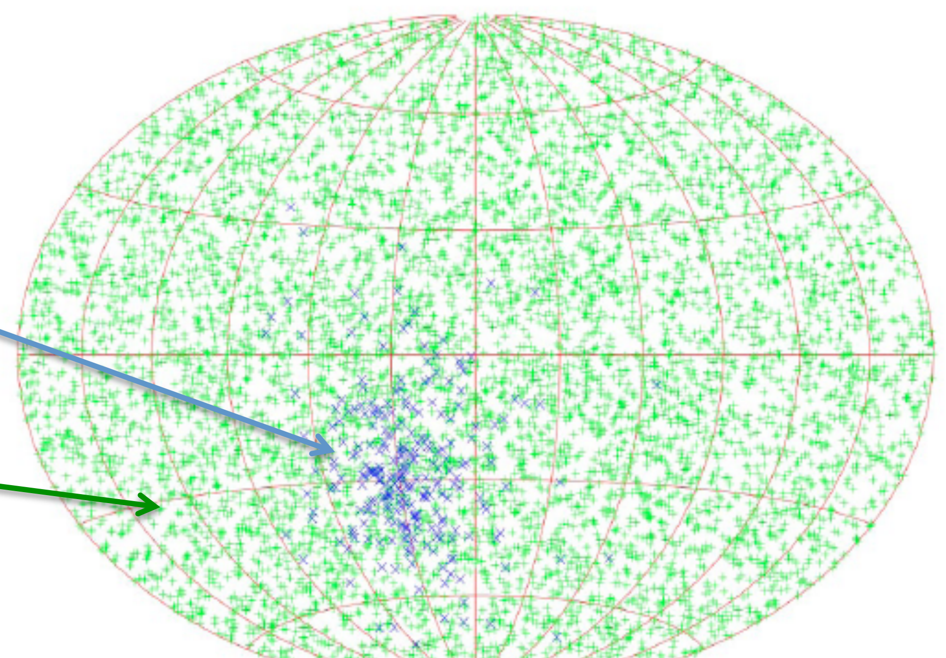
Capture on protons, signal lost

Capture on Gd, provides a coincidence signal

Beacom & Vagins (2004)

Background then remaining IBD and νe absorption on ^{16}O

$$\nu_e + {}^{16}\mathrm{O} \rightarrow X + e-$$



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

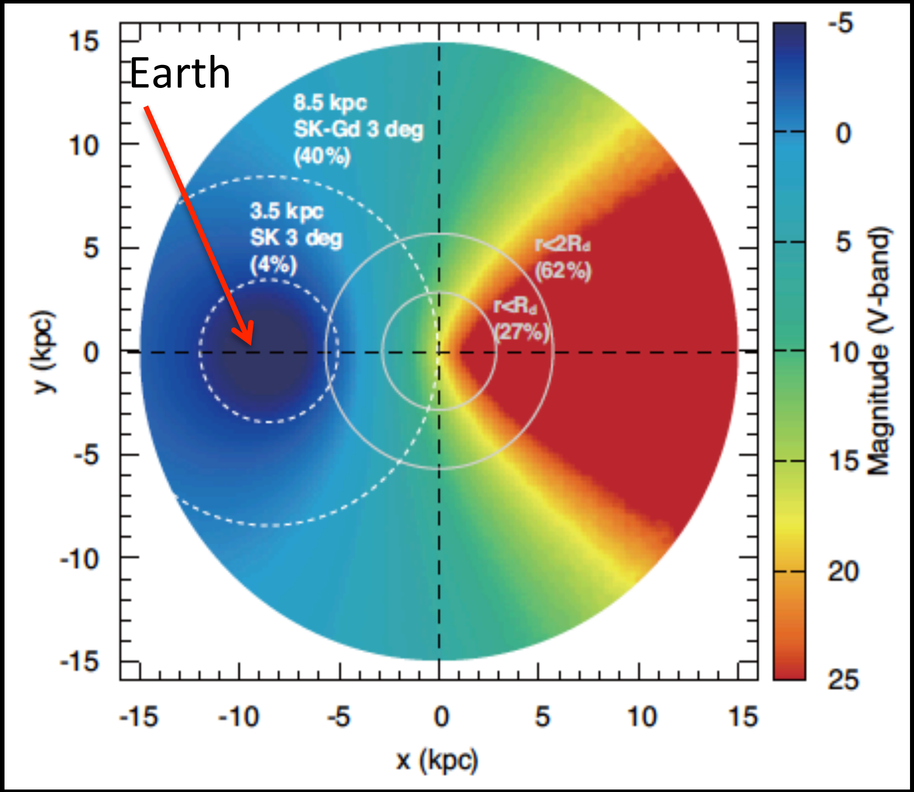
	Super-K	Hyper-K
Water only	6 deg	1.4 deg
Water + Gd (90% tag)	3 deg	0.6 deg

→ **Pointing accuracy of several degrees** ✓

Multi-messenger: electromagnetic

Magnitude of optical signal:

Important WHERE supernova occurs:

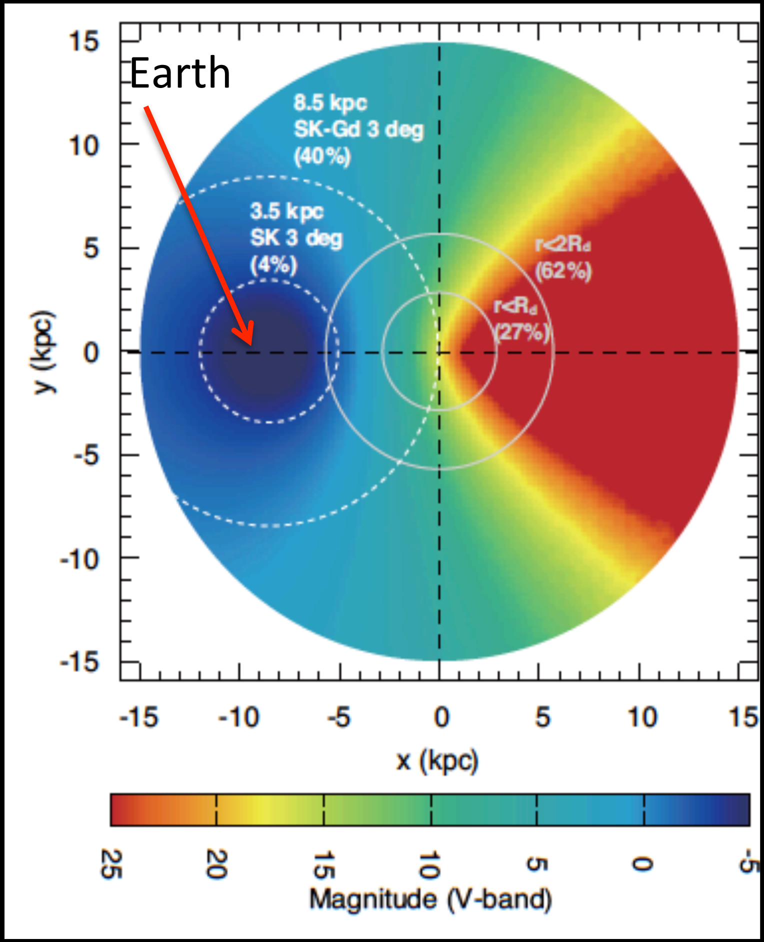


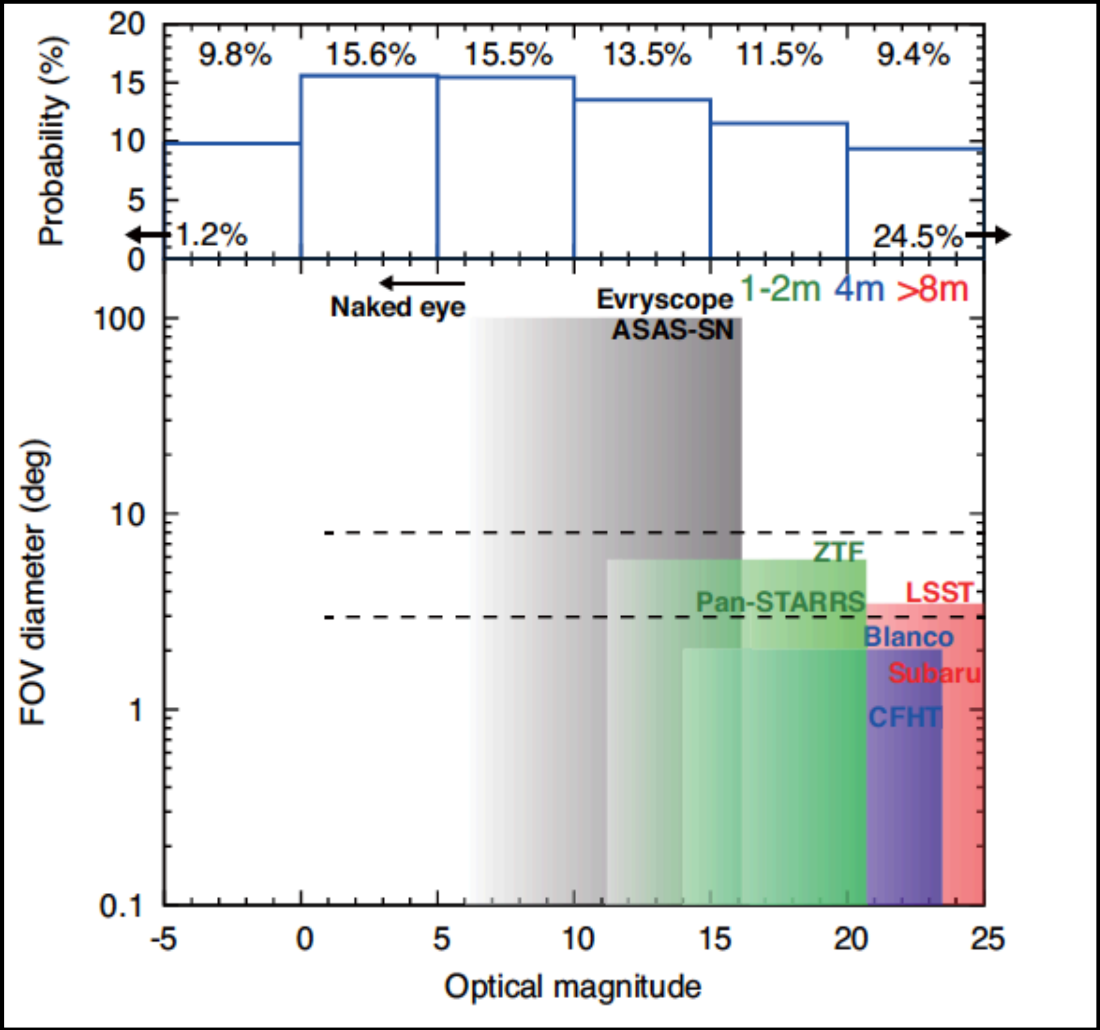
Nakamura et al (2016)

Multi-messenger: electromagnetic

Magnitude of optical signal:

Important WHERE supernova occurs:





Nakamura et al (2016)

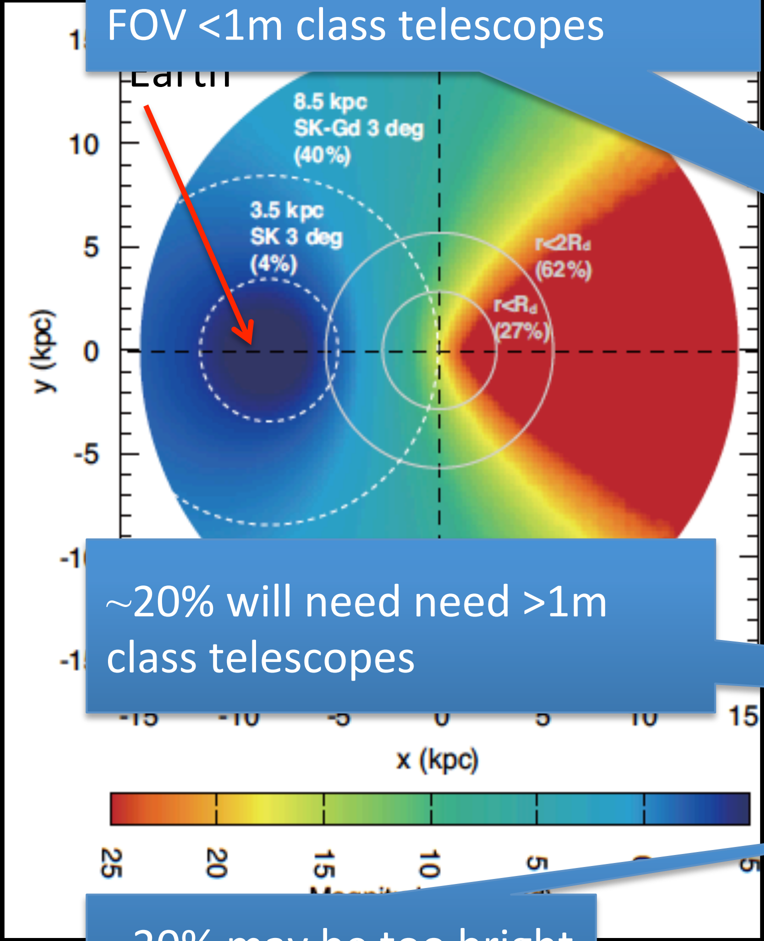
Multi-messenger: electr

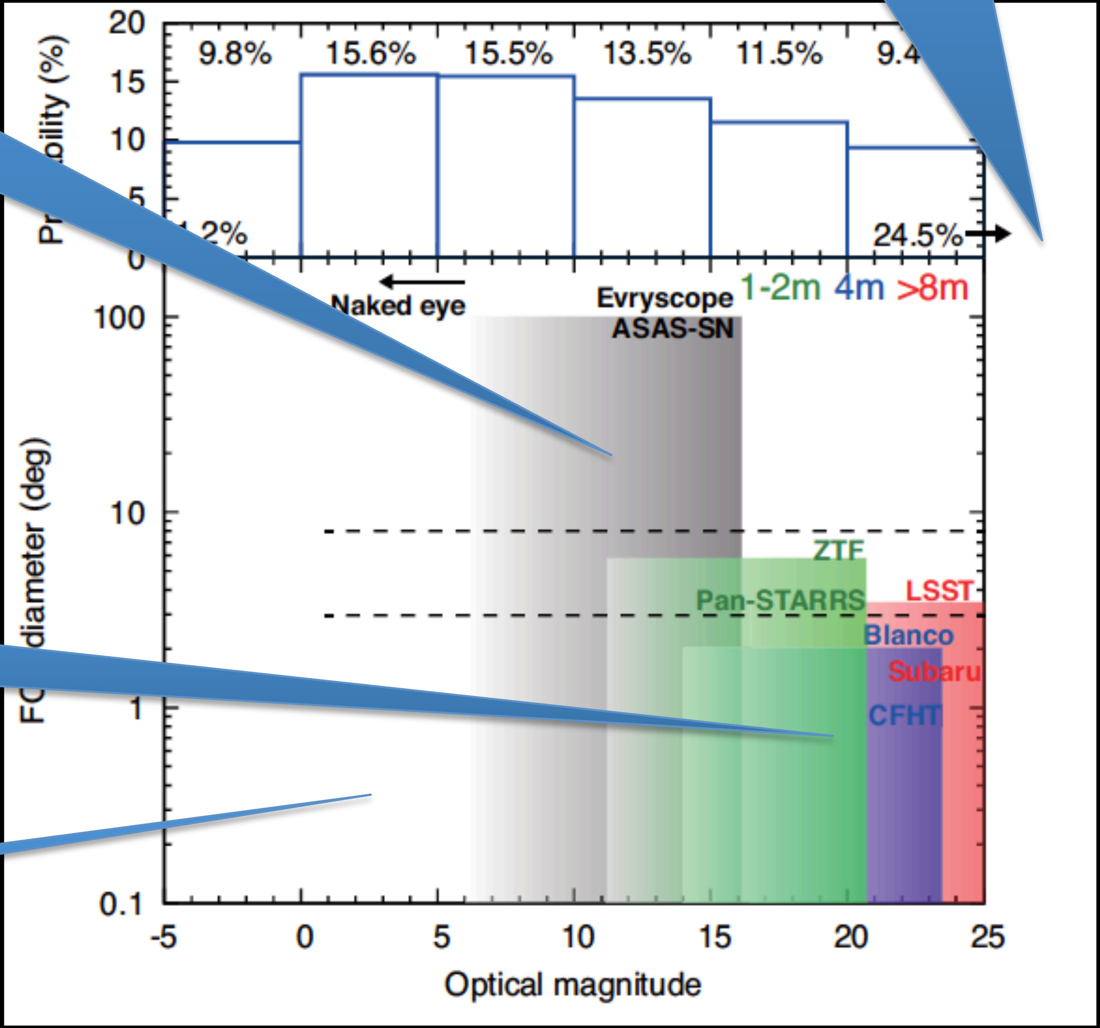
~25% of CCSNe are hard to reach even with modern 8m telescopes

Magnitude of optical signal:

Imp   rs:

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





~20% will need need >1m class telescopes

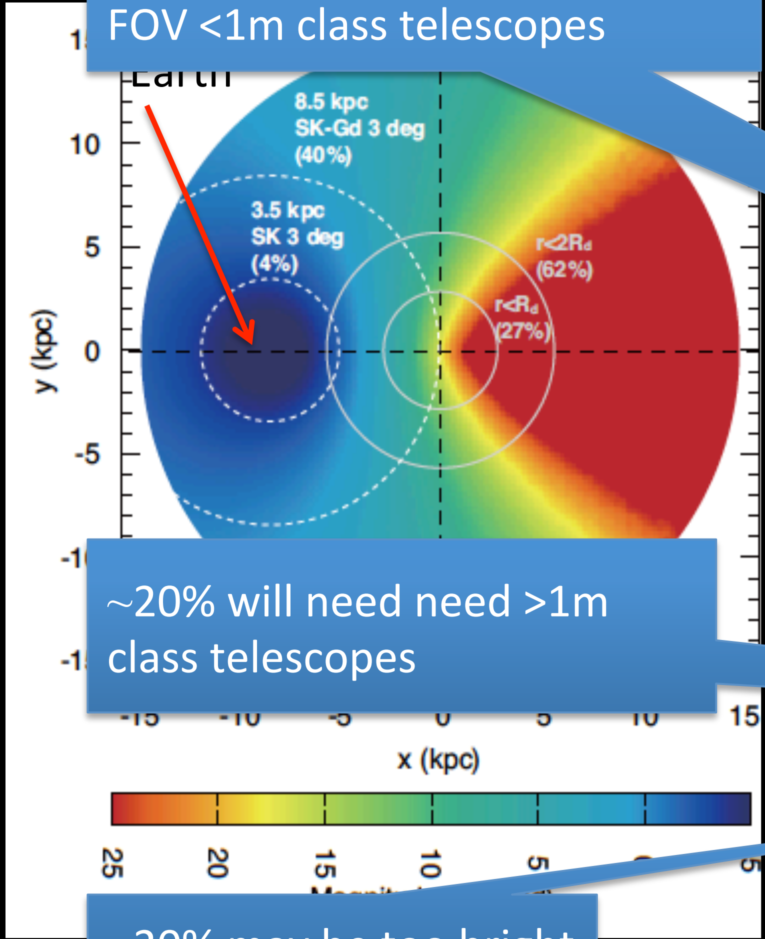
~20% may be too bright

Nak

Multi-messenger: electr

Magnitude of optical signal:

Imp rs:

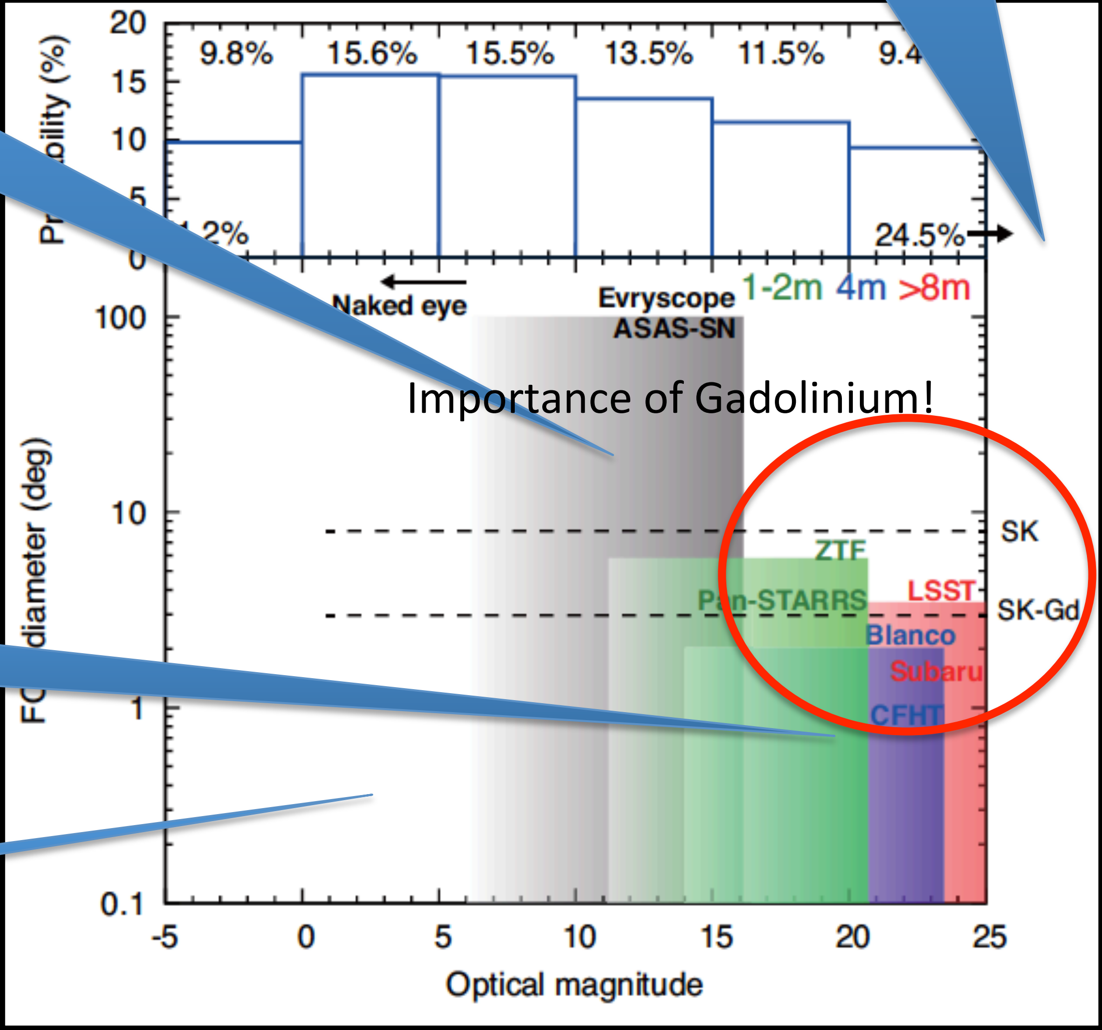


~35% are within reach of large FOV <1m class telescopes

~20% will need need >1m class telescopes

~20% may be too bright

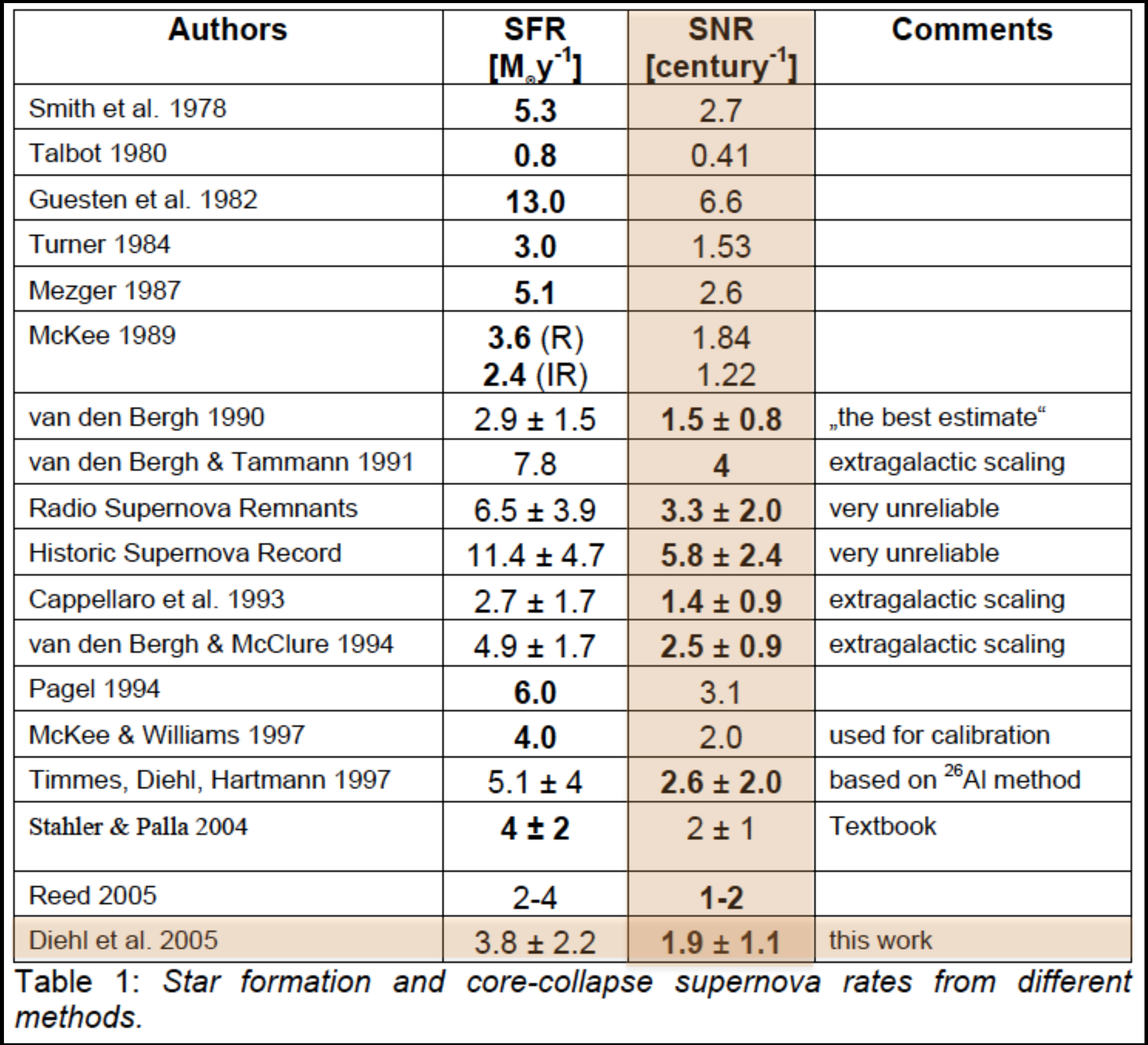
Nak et al. (2016)



Importance of Gadolinium!

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

Galactic supernova rate



Authors	SFR [$M_\odot y^{-1}$]	SNR [century^{-1}]	Comments
Smith et al. 1978	**5.3**	2.7	
Talbot 1980	**0.8**	0.41	
Guesten et al. 1982	**13.0**	6.6	
Turner 1984	**3.0**	1.53	
Mezger 1987	**5.1**	2.6	
McKee 1989	**3.6** (R) **2.4** (IR)	1.84 1.22	
van den Bergh 1990	2.9 ± 1.5	**1.5 ± 0.8**	„the best estimate“
van den Bergh & Tammann 1991	7.8	**4**	extragalactic scaling
Radio Supernova Remnants	6.5 ± 3.9	**3.3 ± 2.0**	very unreliable
Historic Supernova Record	11.4 ± 4.7	**5.8 ± 2.4**	very unreliable
Cappellaro et al. 1993	2.7 ± 1.7	**1.4 ± 0.9**	extragalactic scaling
van den Bergh & McClure 1994	4.9 ± 1.7	**2.5 ± 0.9**	extragalactic scaling
Pagel 1994	**6.0**	3.1	
McKee & Williams 1997	**4.0**	2.0	used for calibration
Timmes, Diehl, Hartmann 1997	5.1 ± 4	**2.6 ± 2.0**	based on ^{26}Al method
Stahler & Palla 2004	**4 ± 2**	2 ± 1	Textbook
Reed 2005	2-4	**1-2**	
Diehl et al. 2005	3.8 ± 2.2	**1.9 ± 1.1**	this work

Table 1: *Star formation and core-collapse supernova rates from different methods.*

Generally a few per century

Historical Galactic SNe yields:
~4.6 per century
Adams et al 2013

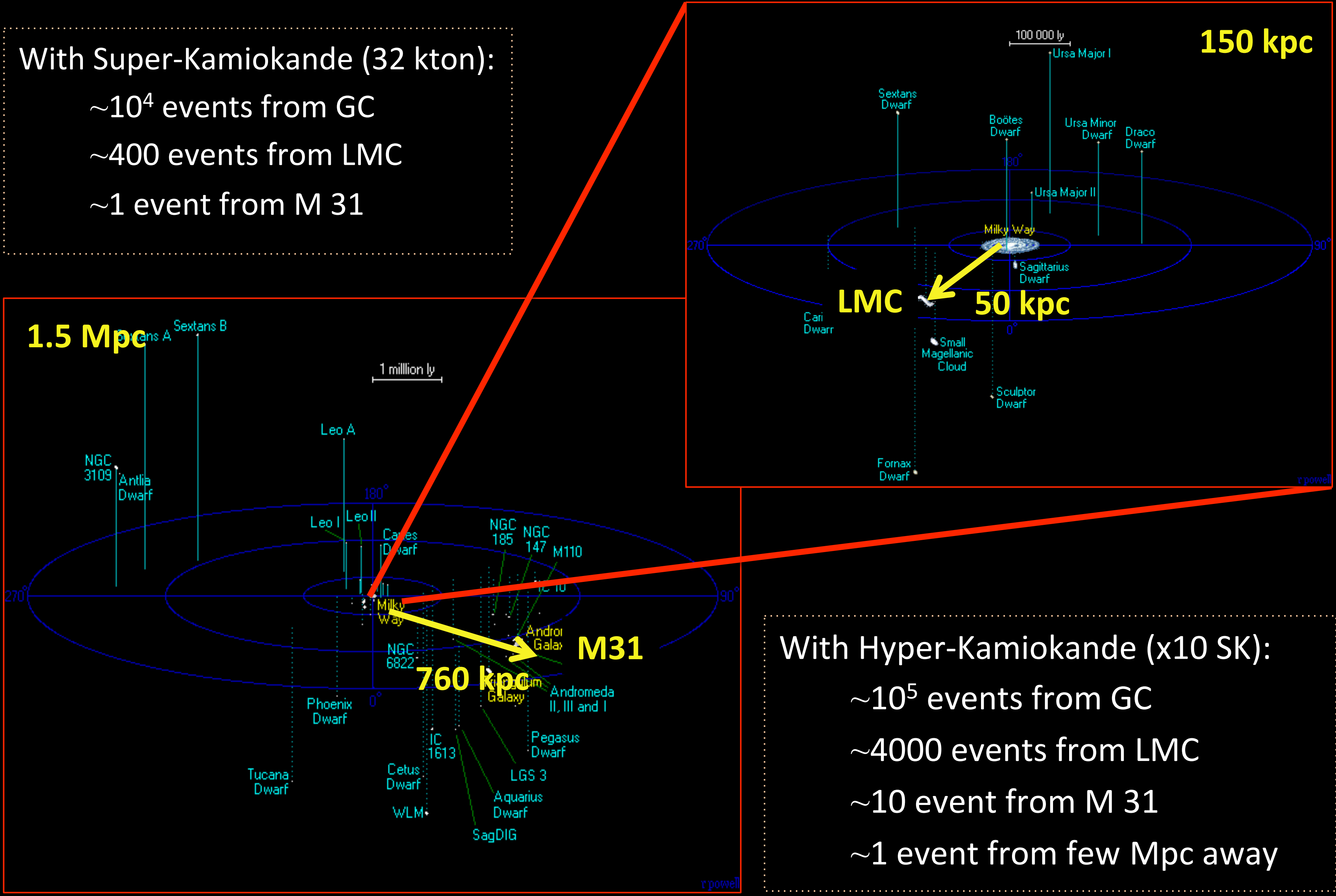
Null observation of neutrino bursts yields a consistent rate:
< 9 SN (90% CL)

Diehl et al 2006

Reach to our neighbors

With Super-Kamiokande (32 kton):

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



With Hyper-Kamiokande (x10 SK):

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

The nearby supernova rate

M 83 (4.5 Mpc)

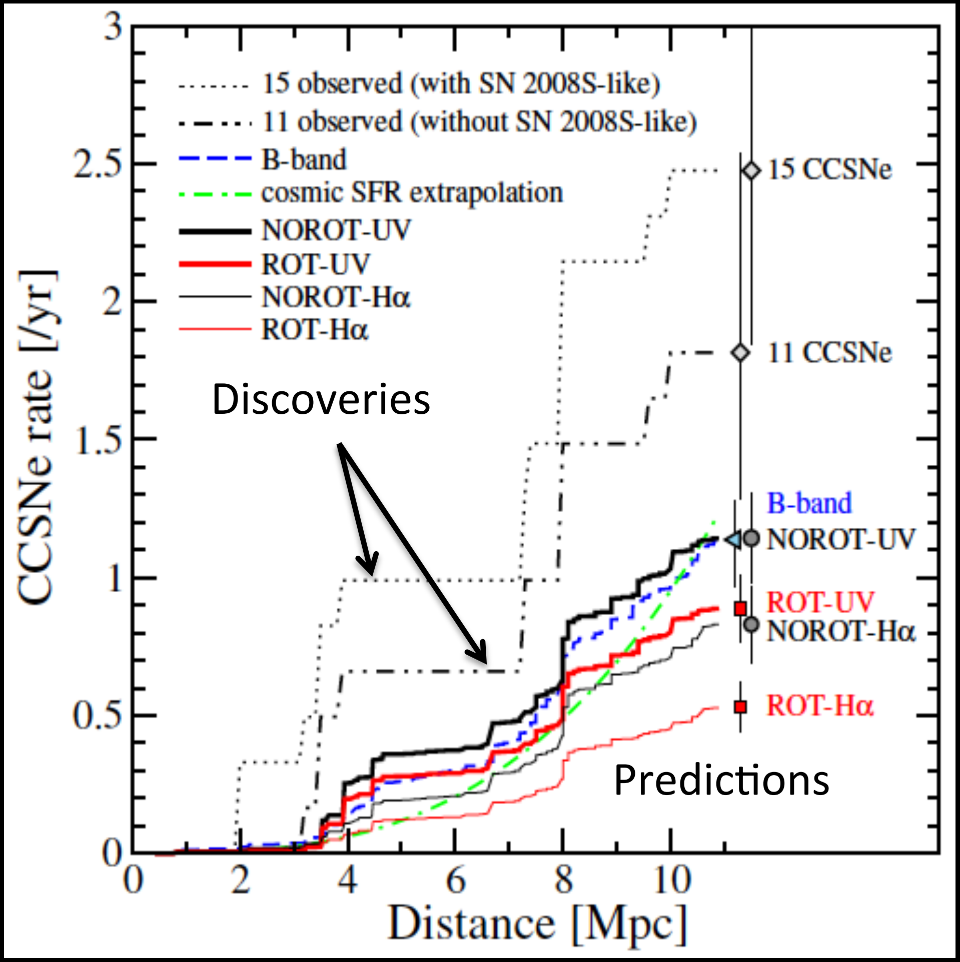
1923A, 1945B, 1950B,
1957D, 1968L, 1983N

NGC 6946 (5.9 Mpc)

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

Lower-limit:

Current rates are <u>not</u> full-sky surveys, so many supernovae, and also galaxies, are likely missing



Horiuchi et al (2013)
Ando et al (2005)

The challenge: beating background

Neutrino trigger:

Look for doublets and larger multiplets depending on background rate:

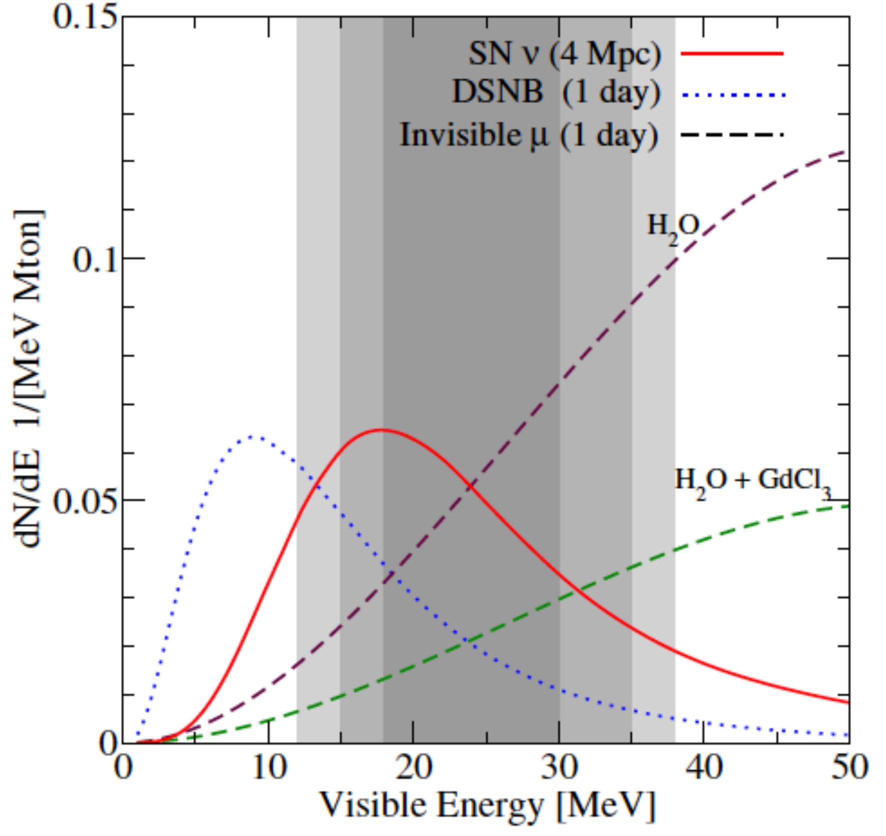
- Atmospheric neutrinos
- Invisible muon decays

Gadolinium helps reduce backgrounds

EM trigger:

Use SBO and/or early SN light curve to model constrain the bounce time

→ can use neutrino singlets if window can be reduced vs background rate



Ando et al (2005)

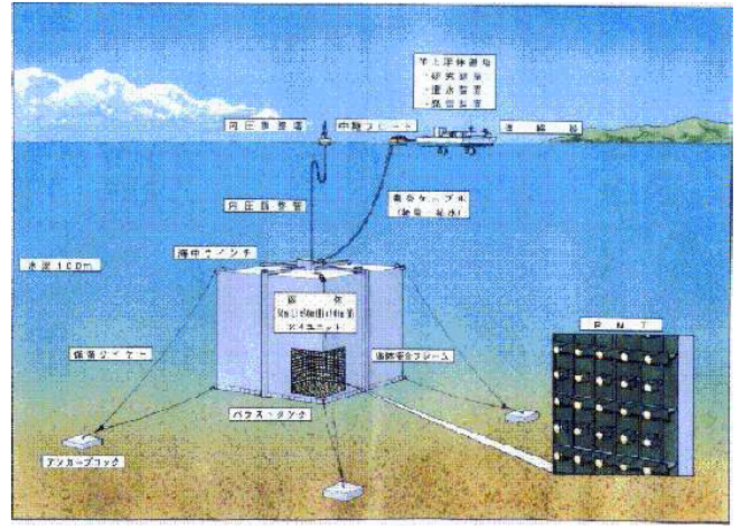
	H_2O only	H_2O + Gd
Energy range [MeV]	18-30	12-38
Signal ν (in ~10 sec, d = 1 Mpc, HK)	5	10
Background ν (over 1 day, HK)	0.5	0.6

→ Maybe to a few Mpc

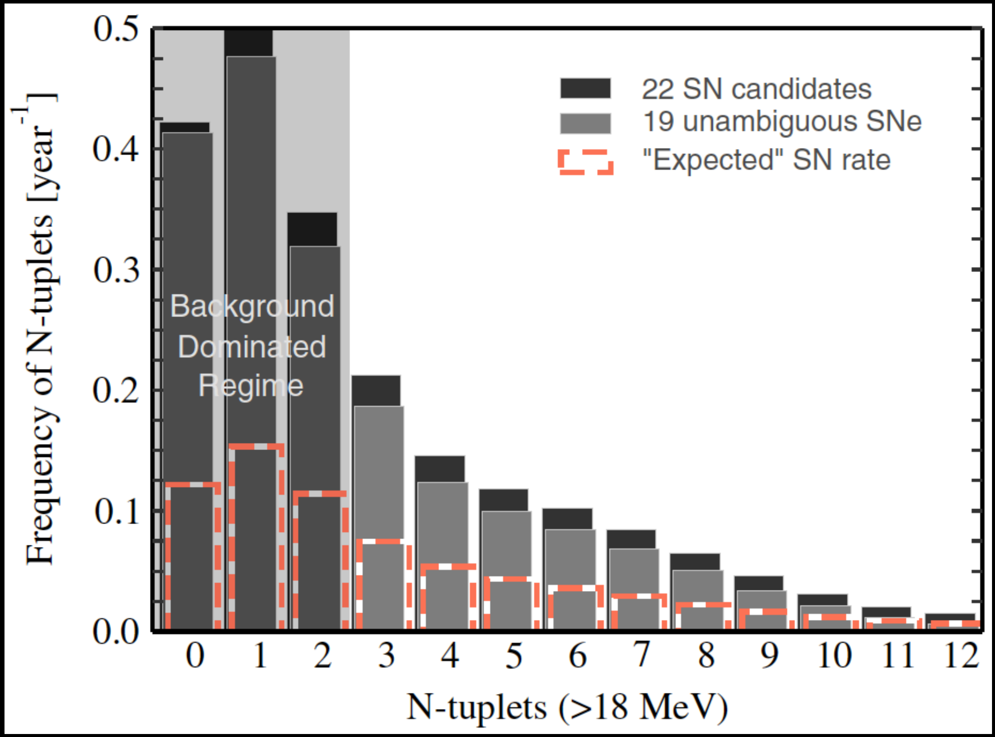
Looking further to a ∼5 Mton detector

$N_\nu > 3$ \`mini-bursts’ from nearby supernovae possible with Deep-TITAND

Higher backgrounds (less shielding and no tagging), but $N_\nu = 3$ is expected to occur once every ∼5 years



Suzuki (2001)



Kistler et al (2011)

- Will give close to annual core collapse early alert

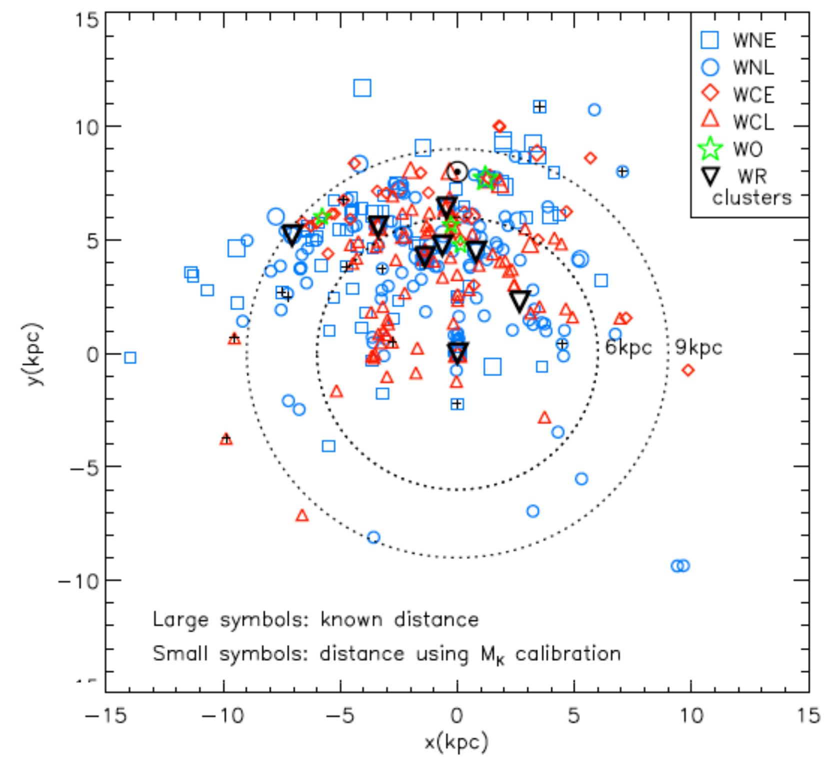
  However, an efficient SBO trigger may be more cost effective *Adams et al (2014)*
- Will yield an expected collective total ν rate of ∼50 events per year

Target database

NOT complete, but useful when pointing is hard

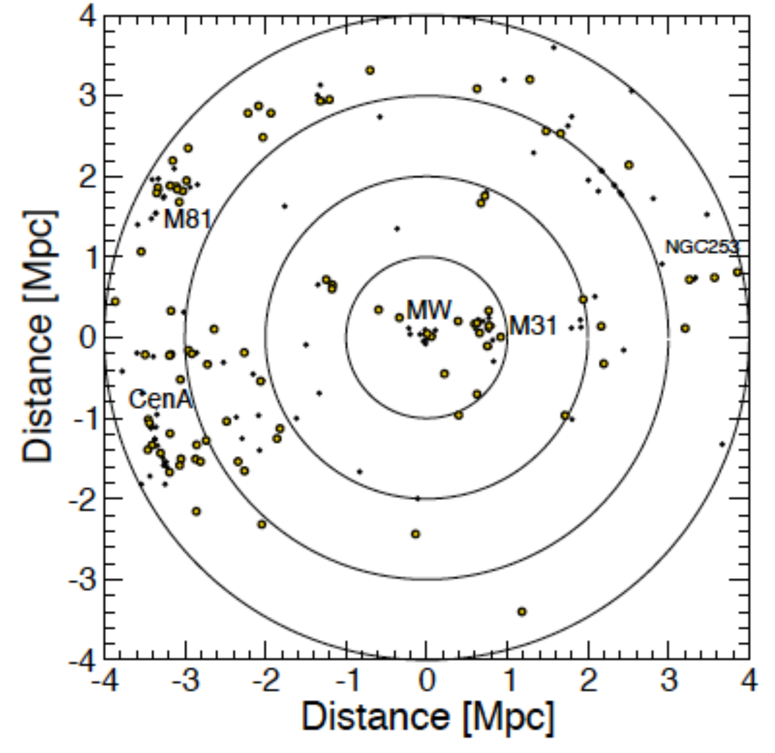
1. Extremely nearby events *O*(100) pc:
   - Wolf-Rayet star lists
     van der Hutch (2001), Rosslowe & Crowther (2015)
   - Red supergiant list: 212 in < 3 kpc
     Nakamura et al (2016)

2. Nearby extragalactic events *O*(1) Mpc:
   - Nearby galaxy list: 236 in < 5 Mpc
     Karachentsev et al (2013)
   - With estimated CCSN rate
     Horiuchi et al (2013)



Rosslowe & Crowther (2015)

→Within 5 Mpc, top 10 galaxies contain 60% of the CCSN rate



Nakamura et al (2016)

Conclusions

✓ Neutrino probes

Neutrinos allow us to study stellar interiors in real time and reveal new insights

✓ Success of SN 1987A [PAST]

Neutrino and electromagnetic signals confirmed many basic ingredients

✓ Multi-messenger astronomy [PRESENT & FUTURE]

MeV neutrinos as a major component of multi-messenger astronomy:

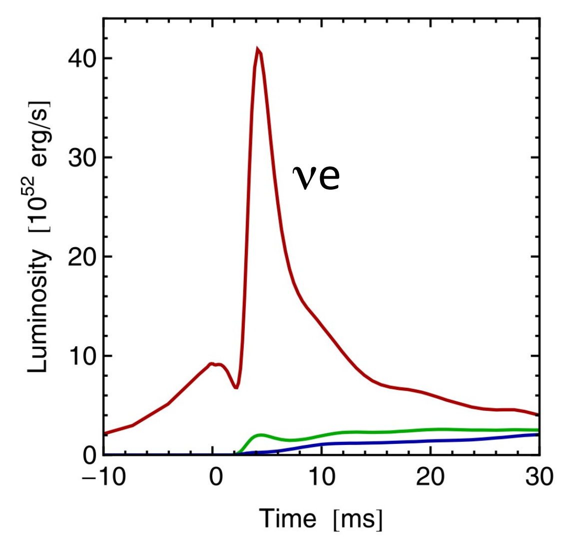
- Prime target: Galactic events
  1. Core collapse occurrence
  2. Core collapse timing
  3. Core collapse direction
- Future target: nearby galaxy events
  1. Interplay with EM (SBO) searches
  2. Near annual rate, probes variety of events

BACKUP

A typical neutrino spectrum

There are there distinct phases:

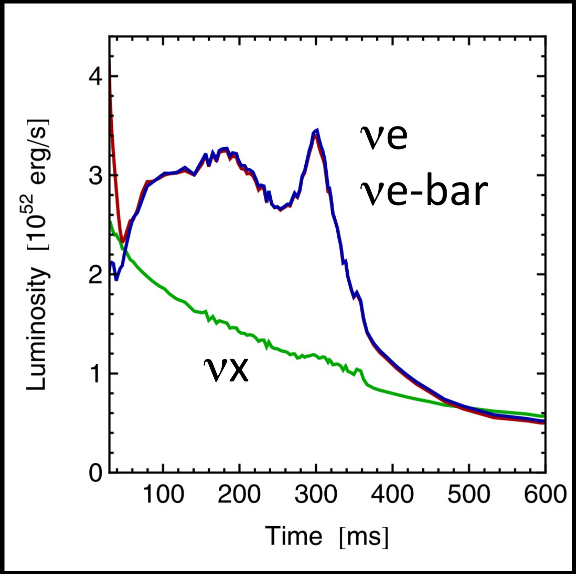
Prompt νe burst



- Shock breakout @neutrinosphere
- De-leptonization of outer core layers

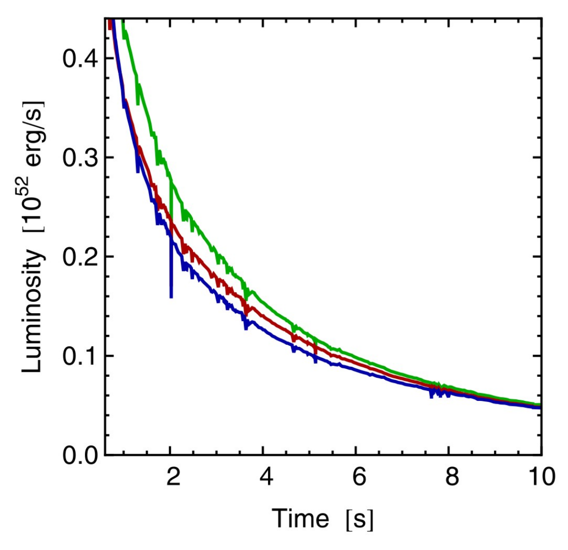
$$e^- p \rightarrow \nu_e n$$

Accretion



- Shock stalls at ~100 km
- Neutrinos powered by matter accretion

Cooling



- Proto-neutron star cooling on diffusion time scale

$$e^- p \rightarrow \nu_e n \quad e^+ e^- \rightarrow \nu_i \bar{\nu}_i \quad \gamma \rightarrow \nu_i \bar{\nu}_i$$

$$e^+ n \rightarrow \bar{\nu}_e p \quad NN \rightarrow \nu_i \bar{\nu}_i$$

The explosion mechanism

The problem: bounce shock loses its energy and stalls at ~150 km. Pressure inside is balanced by infalling ram pressure:

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

The neutrino mechanism: deposit a fraction (~10%) of the energy in neutrinos between the gain radius and the stalled shock, via capture on free neutrons & protons

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

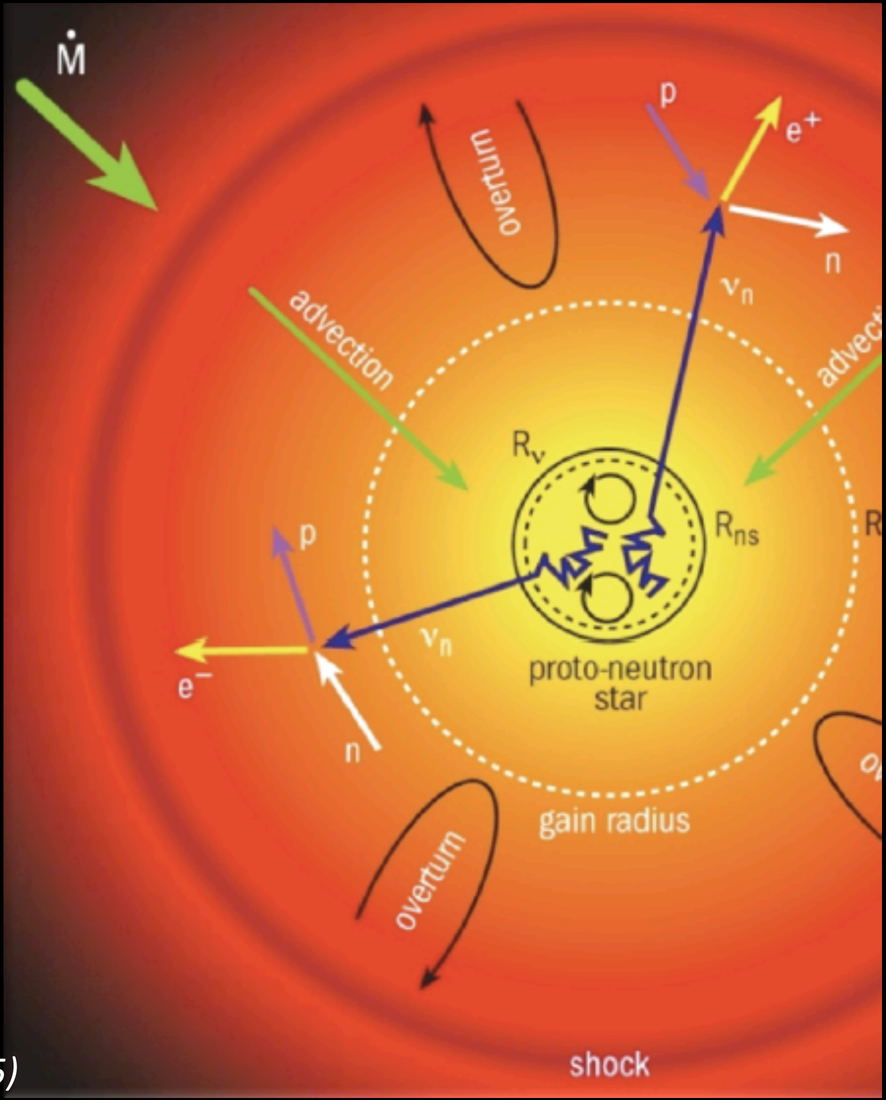
Mass accretion

VS !

Neutrino heating

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

e.g., Liebendoerfer et al (2001, 2004), Sumiyoshi et al (2005)



(Image from B. Messner)

Nearby target database

NOT complete lists, but useful when pointing is difficult

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

- Wolf-Rayet star lists exist — *van der Hutch (2001)*, *Rosslowe & Crowther (2015)*
- Red supergiant list: (~212 in < 3 kpc)

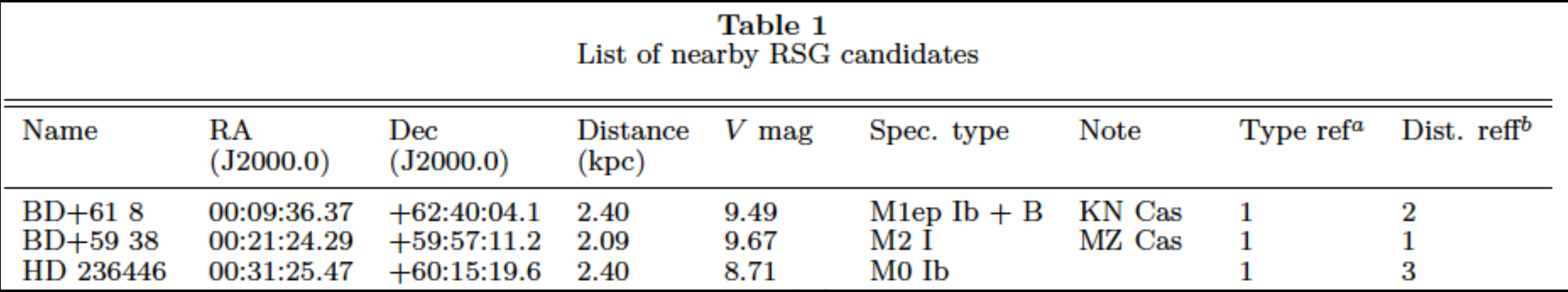


Table 1
List of nearby RSG candidates

Name	RA (J2000.0)	Dec (J2000.0)	Distance (kpc)	V mag	Spec. type	Note	Type ref^a	Dist. reff^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:

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

(~236 in < 5 Mpc)

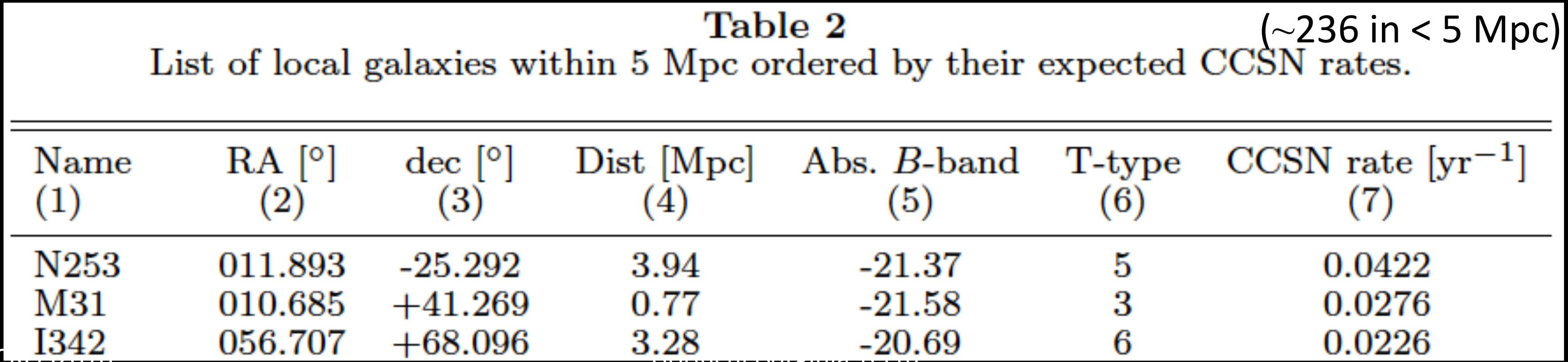


Table 2
List of local galaxies within 5 Mpc ordered by their expected CCSN rates.

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