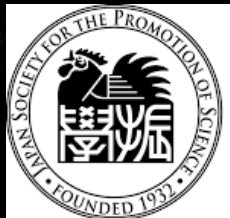


OLivES 2026, August 28th 2026

Diffuse supernova neutrino background

Shunsaku Horiuchi

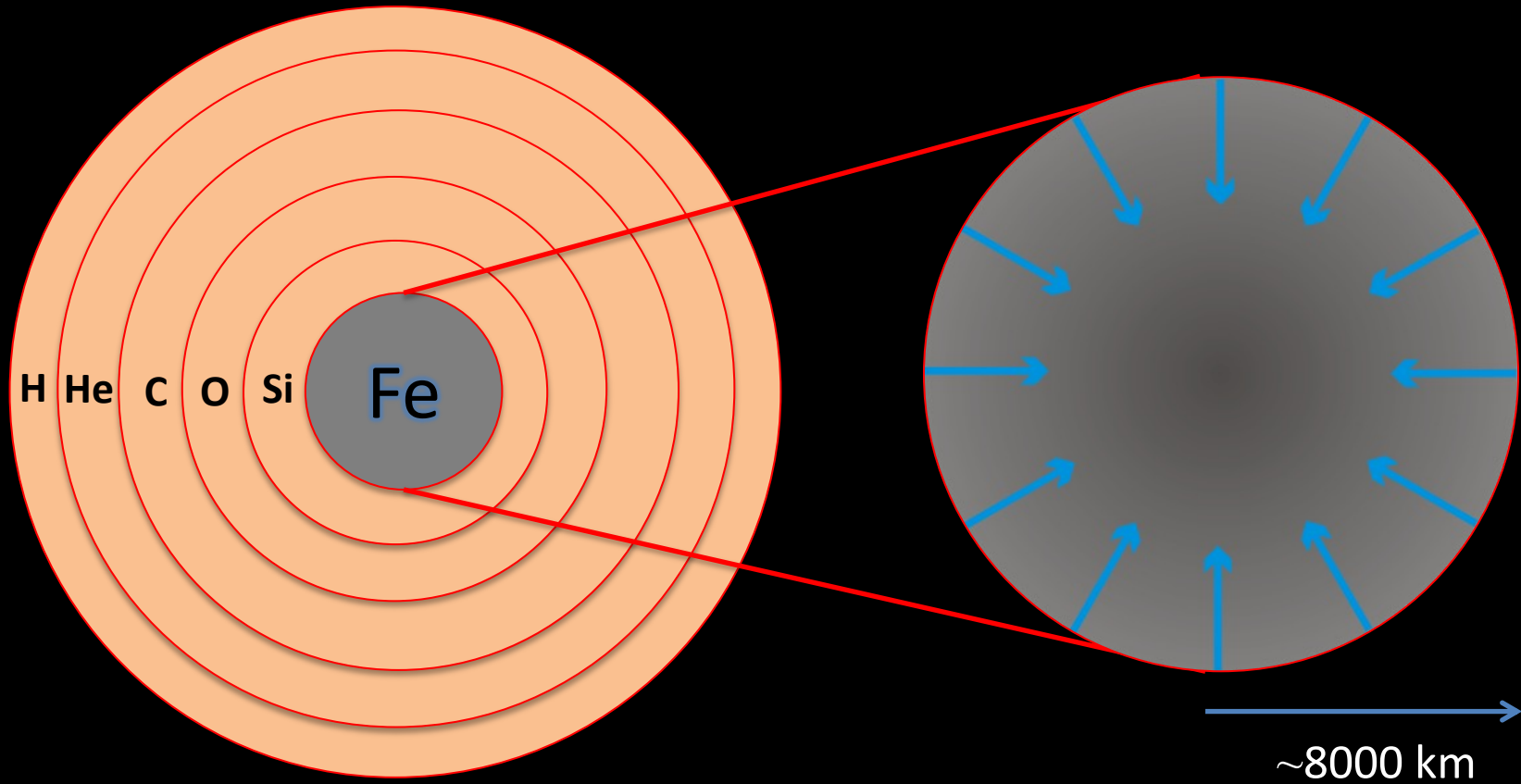
Institute of Science Tokyo
Virginia Tech
Kavli IPMU



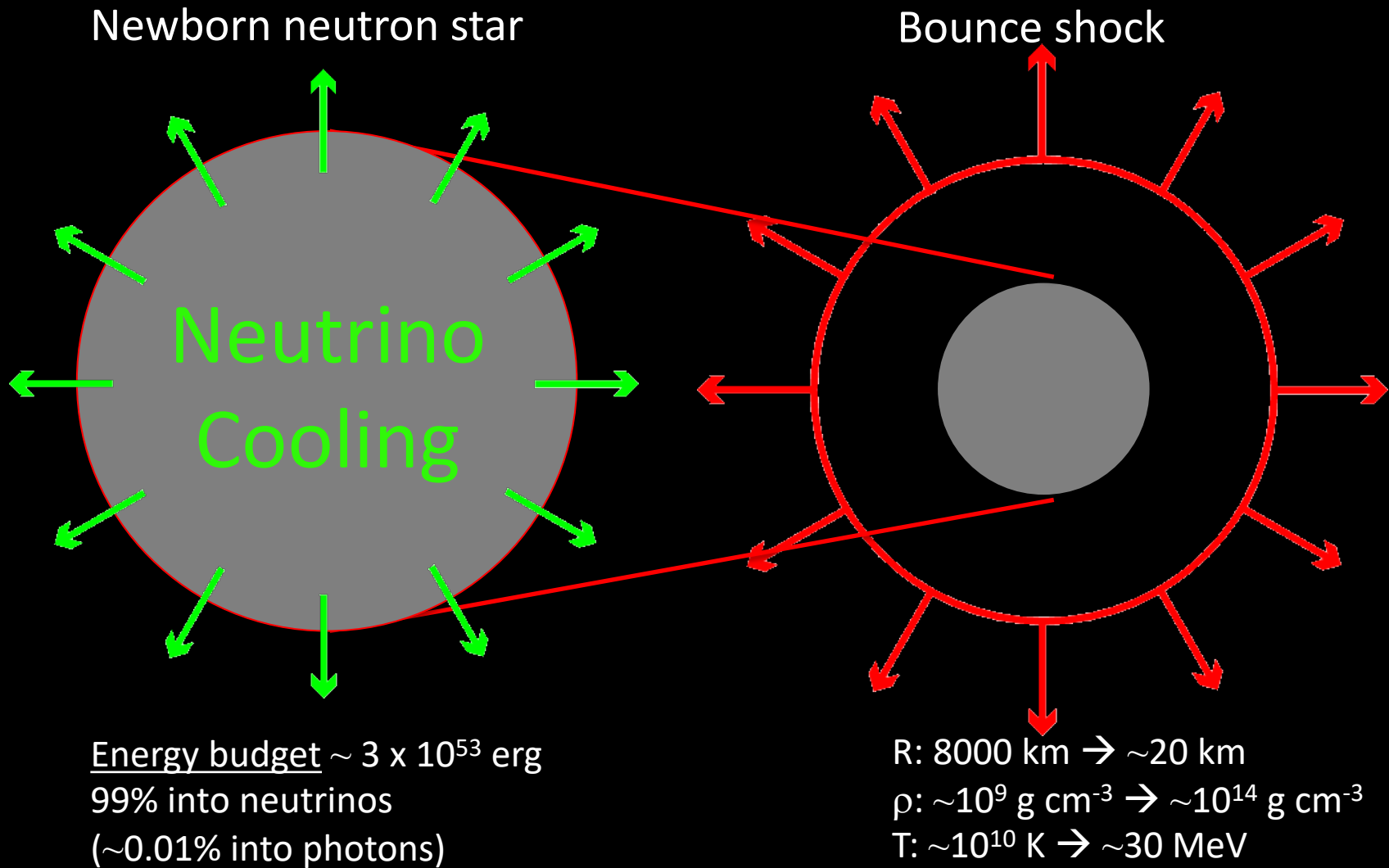
Under the hood

Massive ($>8M_{\text{sun}}$) star structure

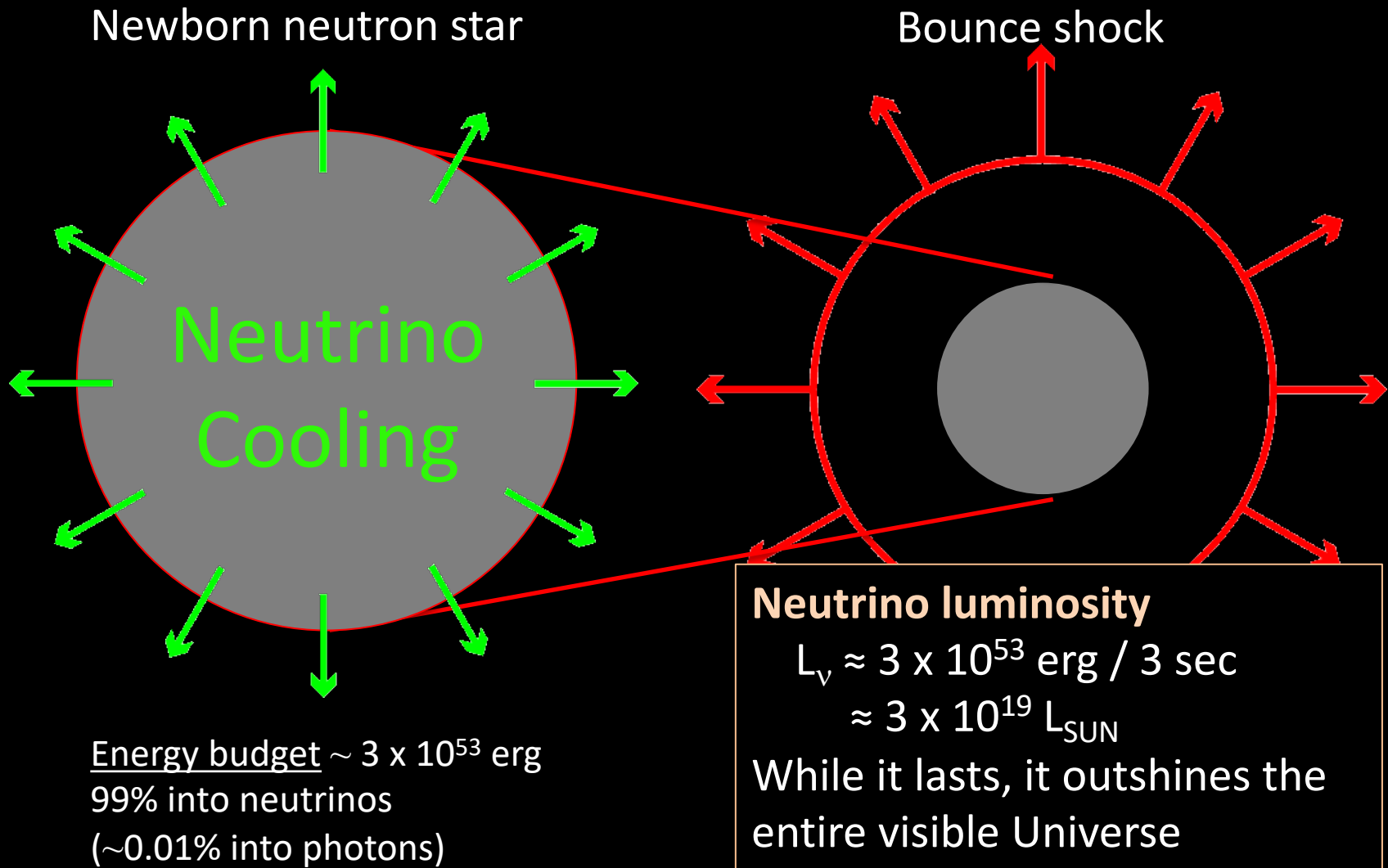
Core collapse (implosion)



Under the hood

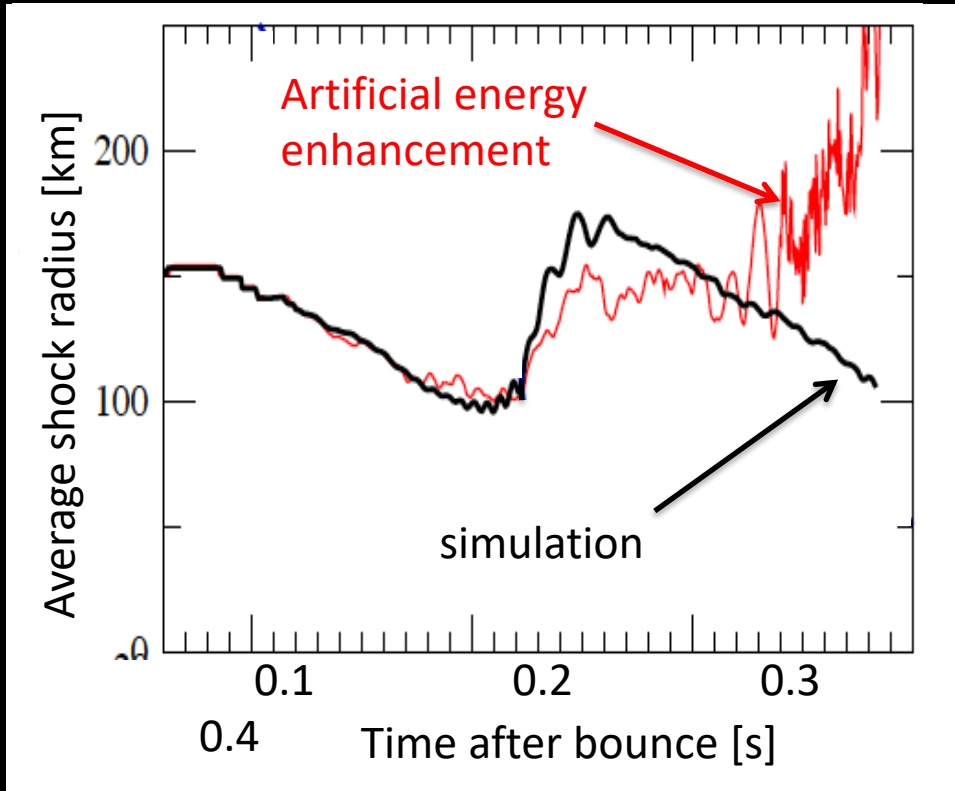


Under the hood

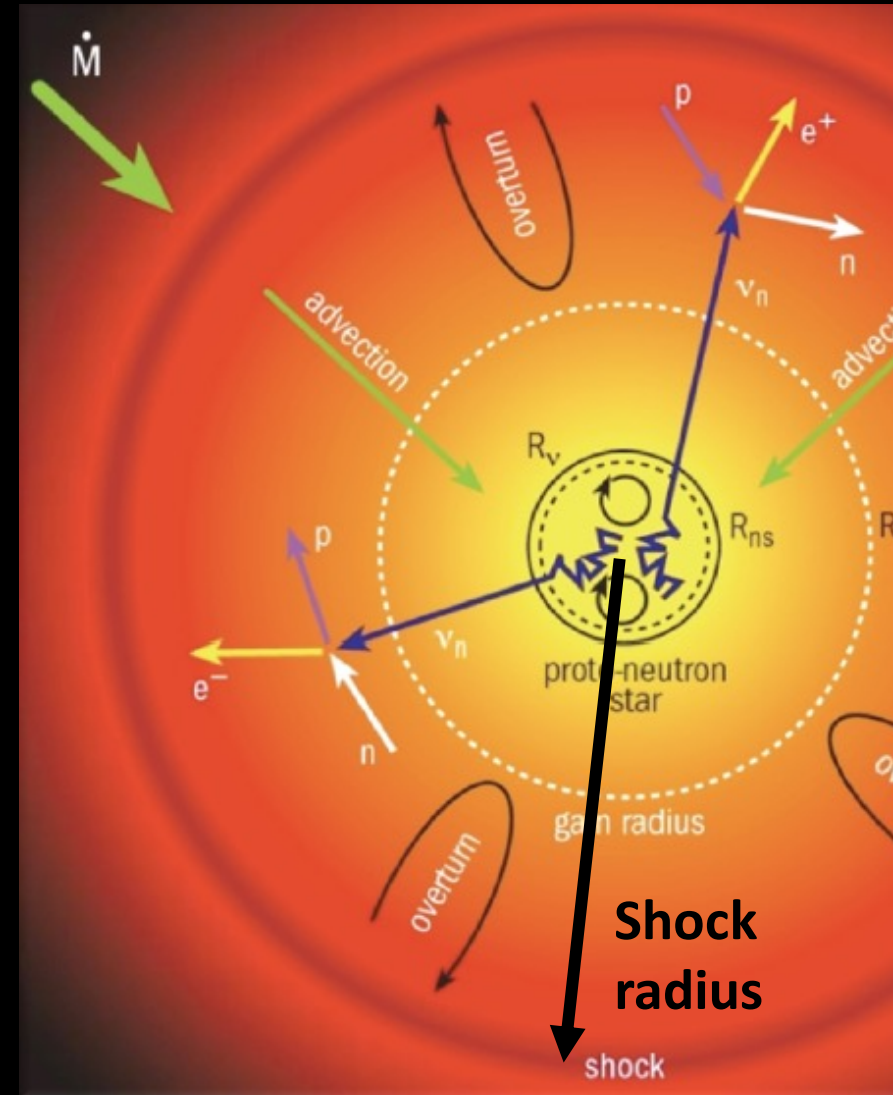


The bounce shock stalls

The bounce shock loses energy and stalls at ~ 150 km, eventually gets overwhelmed by infalling mass and collapses



Hanke et al (2014)



(Image from B. Messner)

The explosion mechanism

The bounce shock loses energy and stalls at ~ 150 km, eventually gets overwhelmed by infalling mass and collapses

How can we revive it? This is the explosion mechanism.

Many proposed solutions:

- ## 1. Neutrino mechanism $E(neutrino)$

Wilson (1985), ...

- ## 2. Phase transition $E(\text{gravity})$

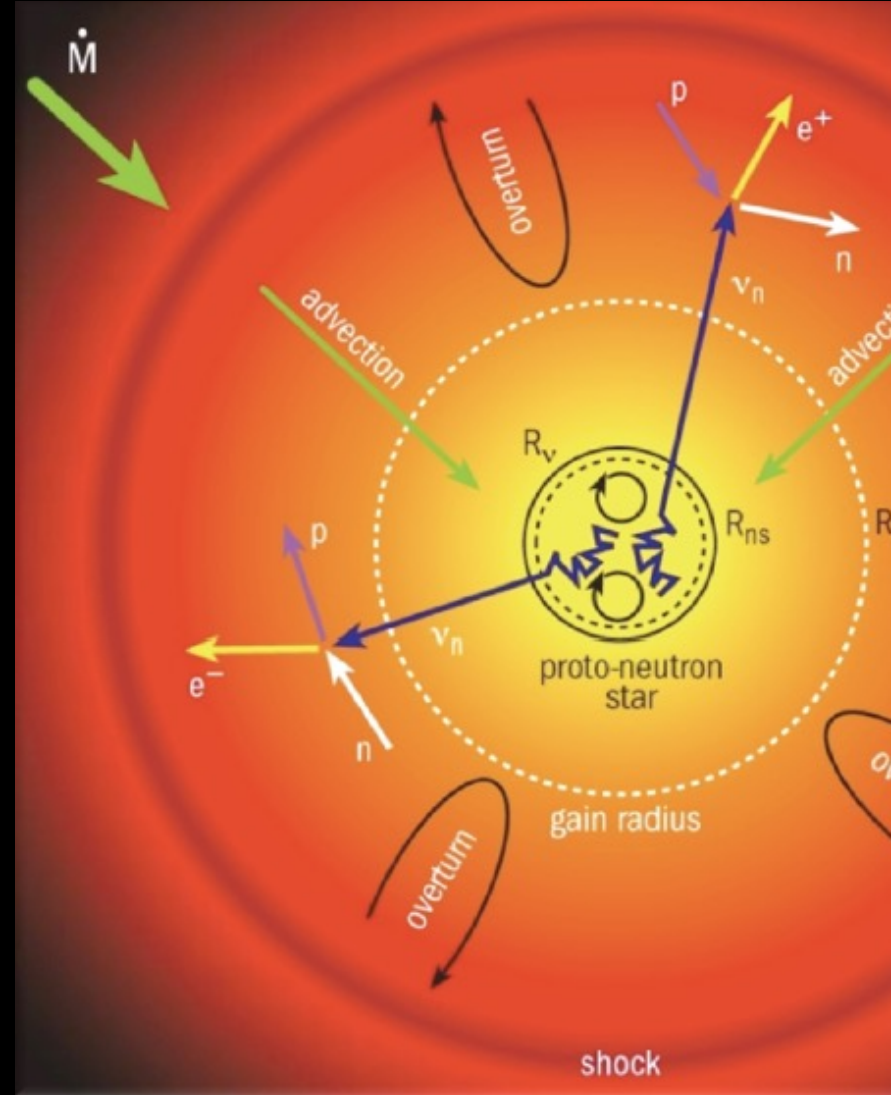
Migdal et al (1971), ...

- ### 3. Magneto-rotational $E(rotation)$

Bisnovatyi-Kogan (1976), ...

- #### 4. Others, e.g., exotic neutrinos

Kainulainen et al (1991), ...



(Image from B. Messner)

Why are neutrinos so crucial?

Energy source:

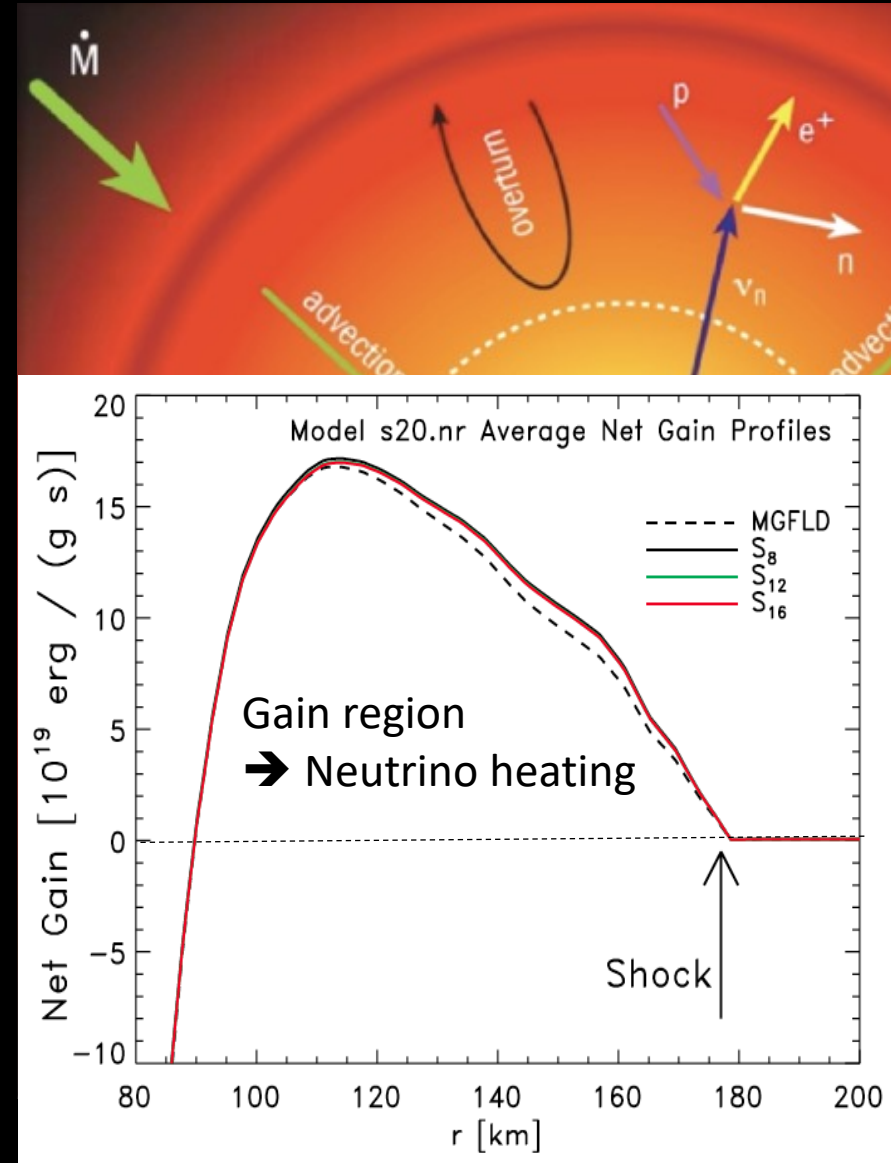
- ✓ Very luminous source of neutrinos at the center

Energy transport

- ✓ Neutrinos can travel with minimal hinderance

Energy deposition

- ✓ Gain region where net energy deposition occurs



Why are neutrinos so crucial?

Energy source:

- ✓ Very luminous source of neutrinos at the center



Energy transport

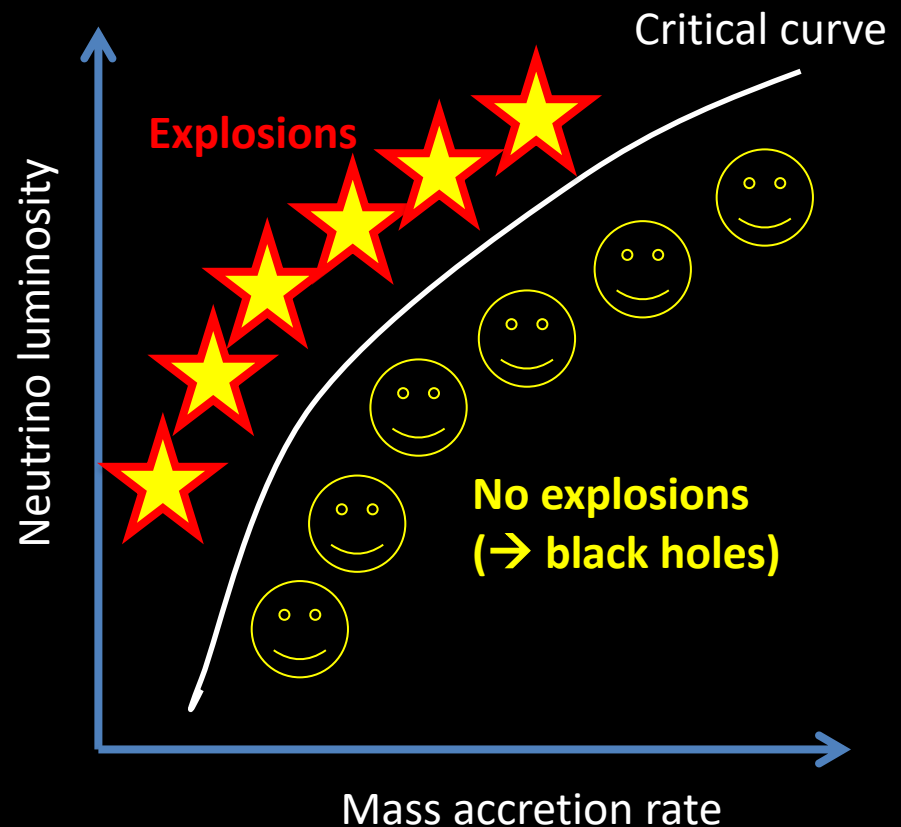
- ✓ Neutrinos can travel with minimal hinderance

Energy deposition

- ✓ Gain region where net energy deposition occurs

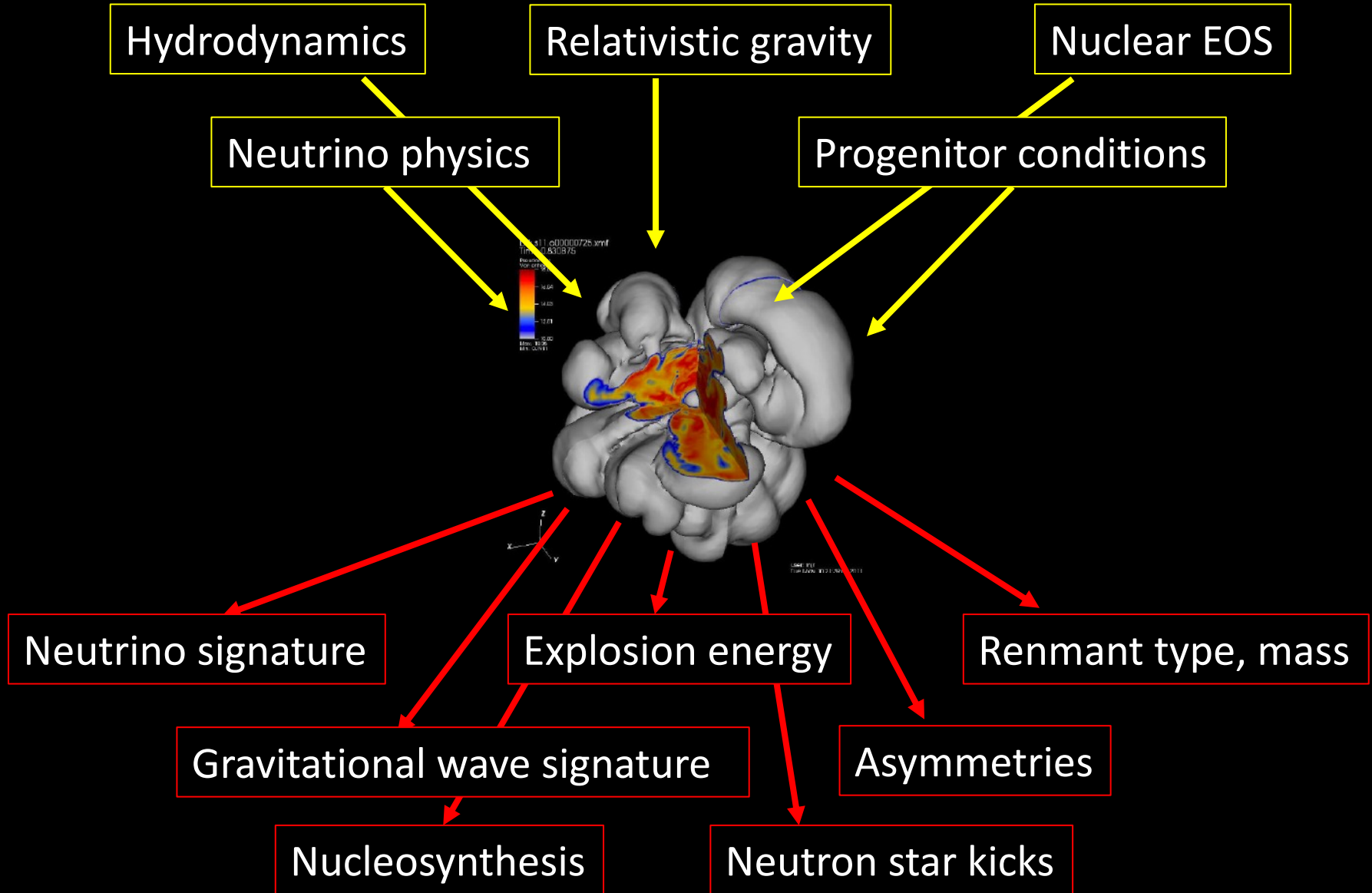
→ Neutrino-powered explosions

When neutrino heating is efficient enough to trigger an explosion



Burrow & Goshy (1993)

Numerical simulations



Neutrino signature

Cooling

- NS cooling on diffusion time scale
- Good probe of equation of state, newly-born neutron star, mass, etc

Accretion

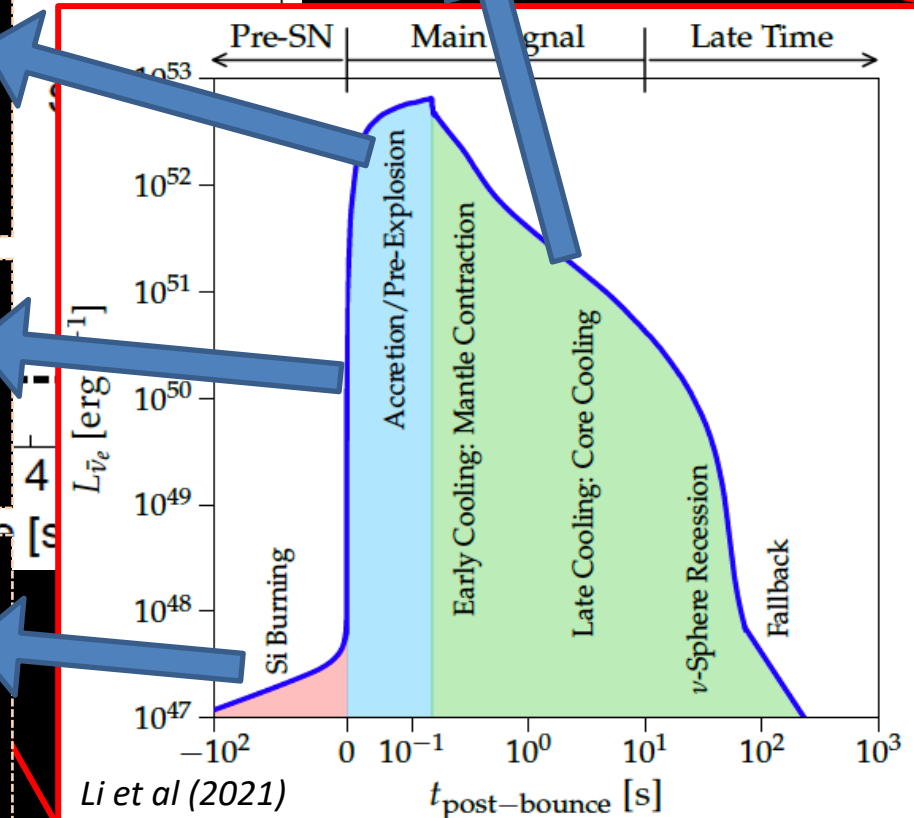
- Powered by matter accretion
- Good probe of models: explosion mechanism, instabilities

Neutronization

- Burst of ν_e from $p + e^- \rightarrow \nu_e + n$
- Quasi-standard candle

Si burning

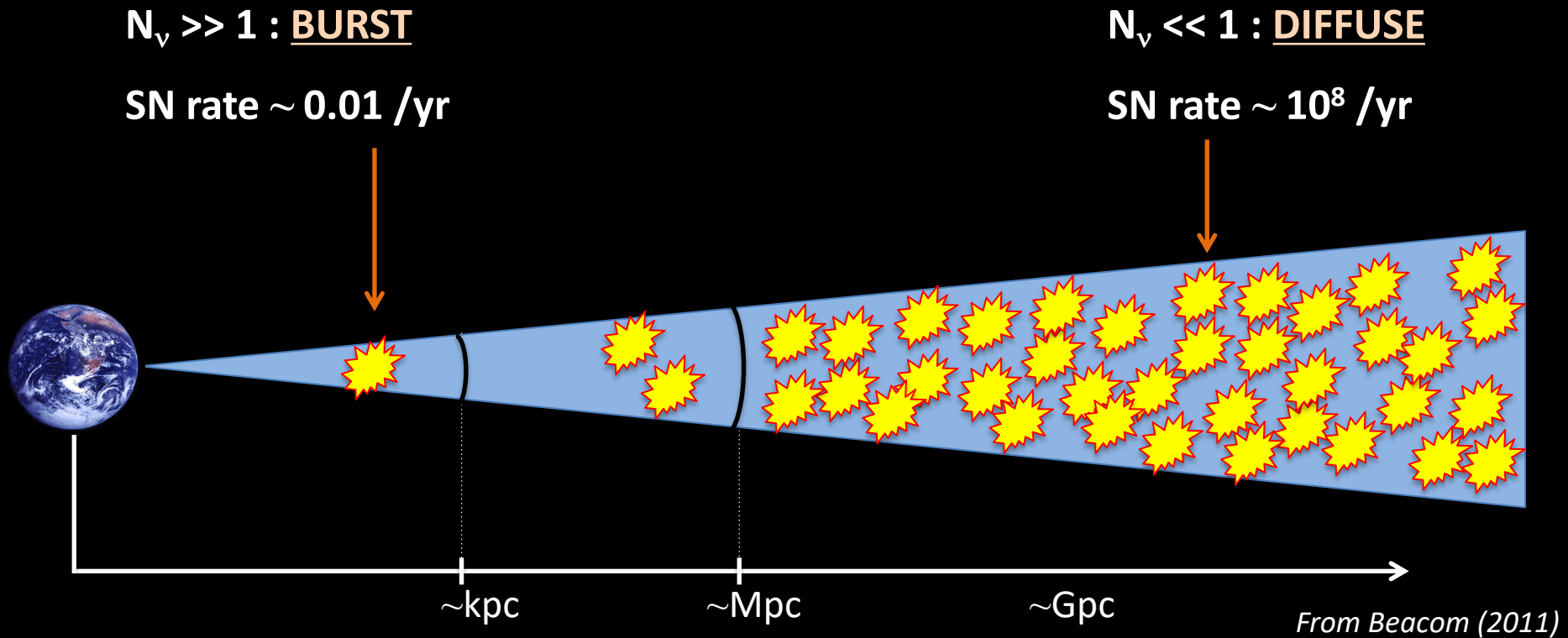
- Stellar evolution
- Important initial condition for core collapse



Li et al (2021)

$t_{\text{post-bounce}}$ [s]

Future Supernova Neutrinos



Features:

- Rich multi-messenger data
- Precision on 1 system
- Surprises?

Features:

- Guaranteed signal (no waiting)
- Many progenitors, population studies
- Surprises?

Diffuse supernova neutrinos

$$R = N_t \int dE \sigma_{\text{IBD}} \int dz c \frac{dN}{dE'} (1+z) R_{\text{CC}}(z) \left| \frac{dt}{dz} \right|$$

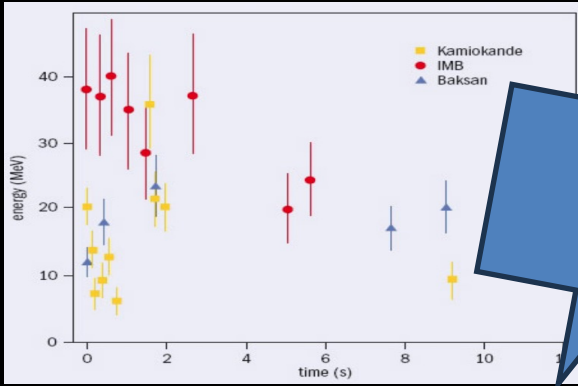
Neutrino detector capabilities

Time-integrated neutrino emission

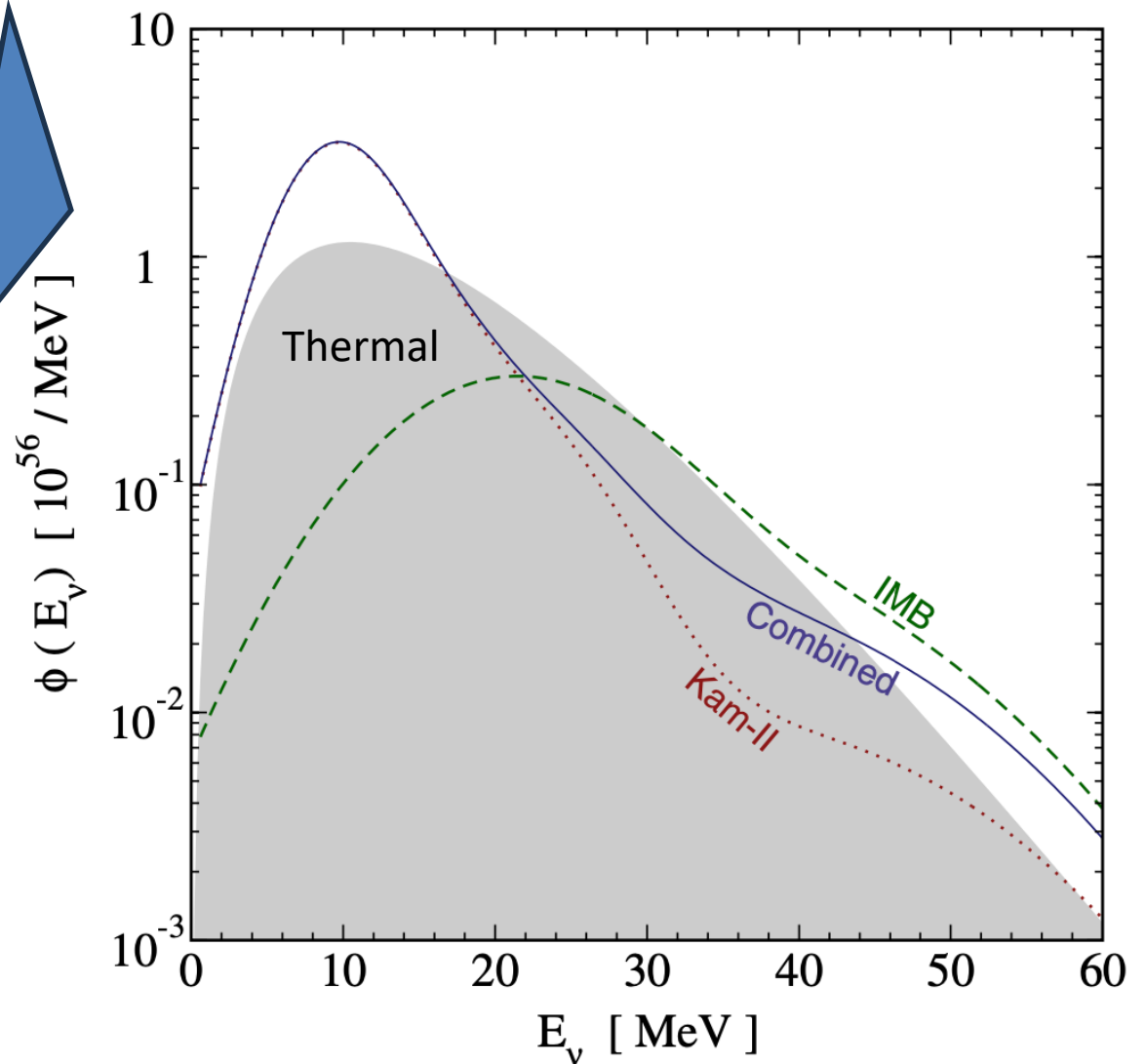
Rate of massive star core collapse

Guidance from data

Look to SN1987A for guidance



Yuksel & Beacom (2007)
See also Krauss (1987),
Bahcall (1987), Vissani (2015)

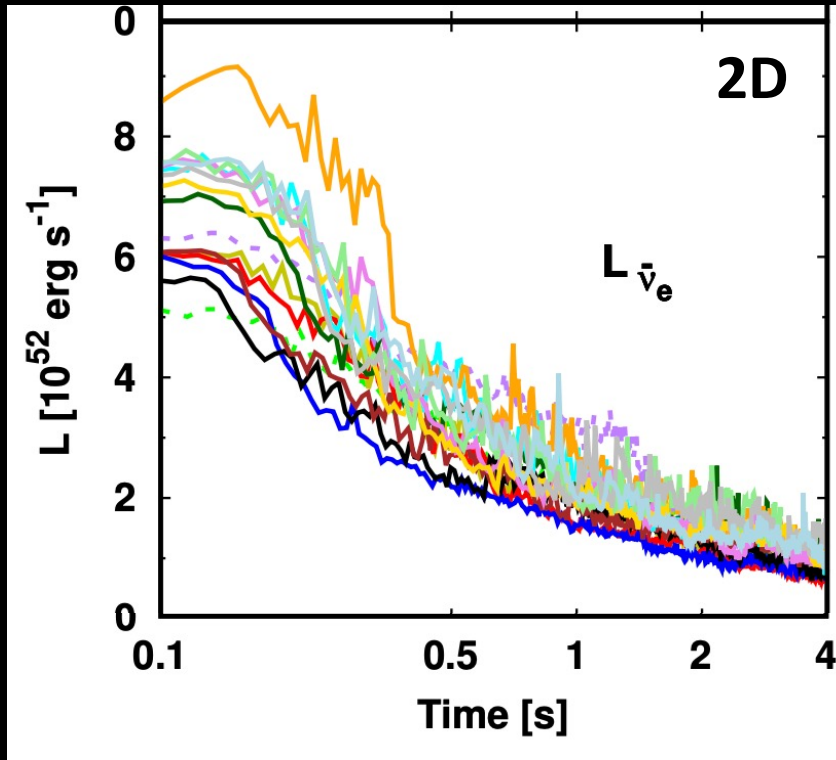


Simulation guidance

Look to simulations for guidance:

- Rapid sophistication
- Simulations routinely explode stars
- Code comparisons starting

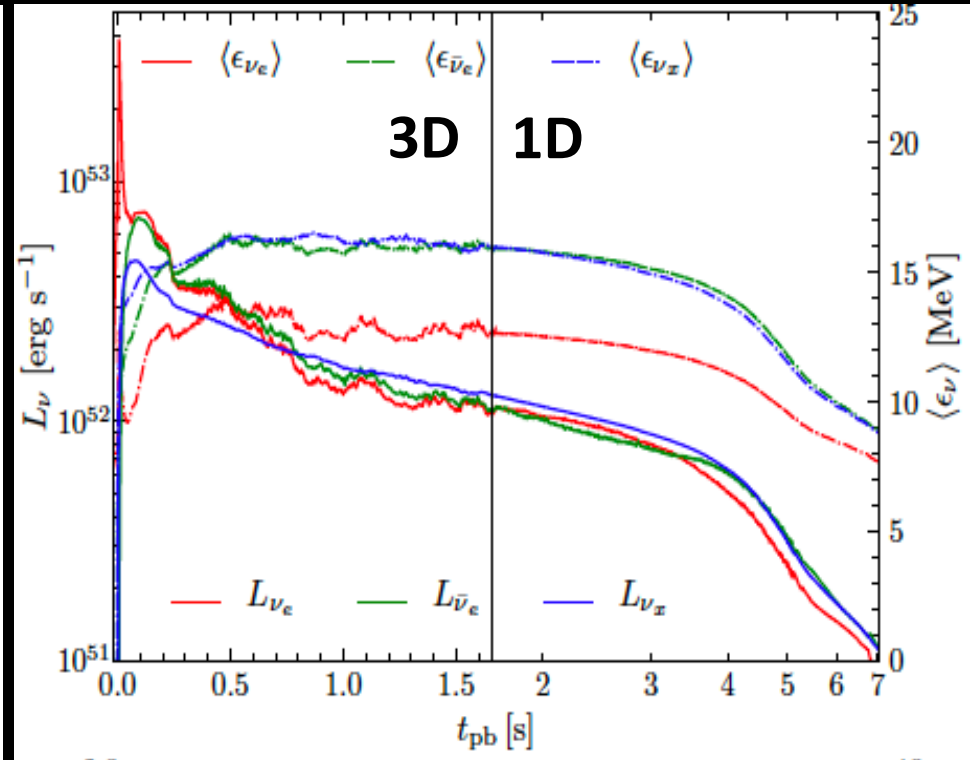
O'Connor et al (2018)



Nagakura et al (2021)

However:

- Mostly still $< 1 \text{ sec}$
- Sparsely sampled progenitors

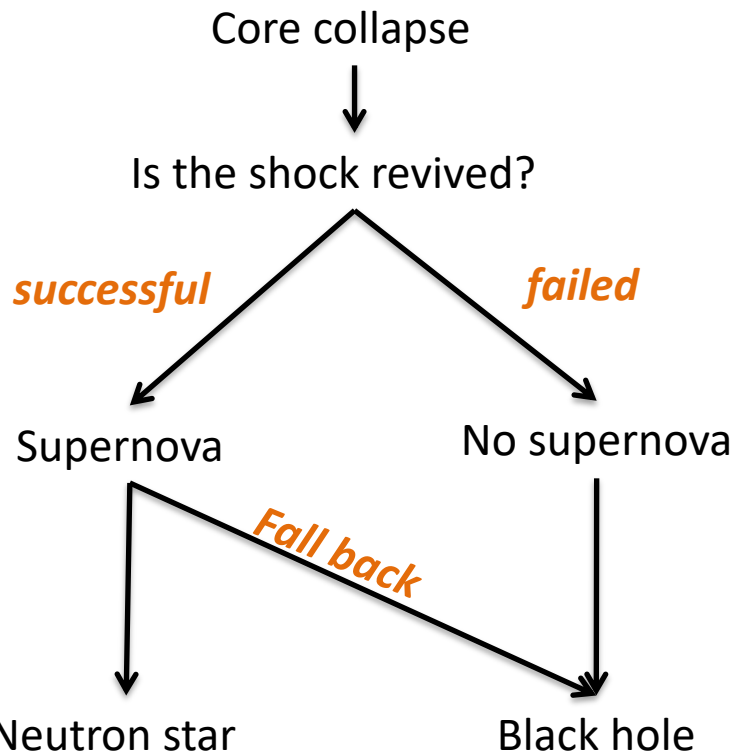


Bollig et al (2021)

Guidance from simulations: wish list

1. Coverage over many progenitors
2. Coverage over long durations
3. Account for black hole channel

Challenging, but making progress



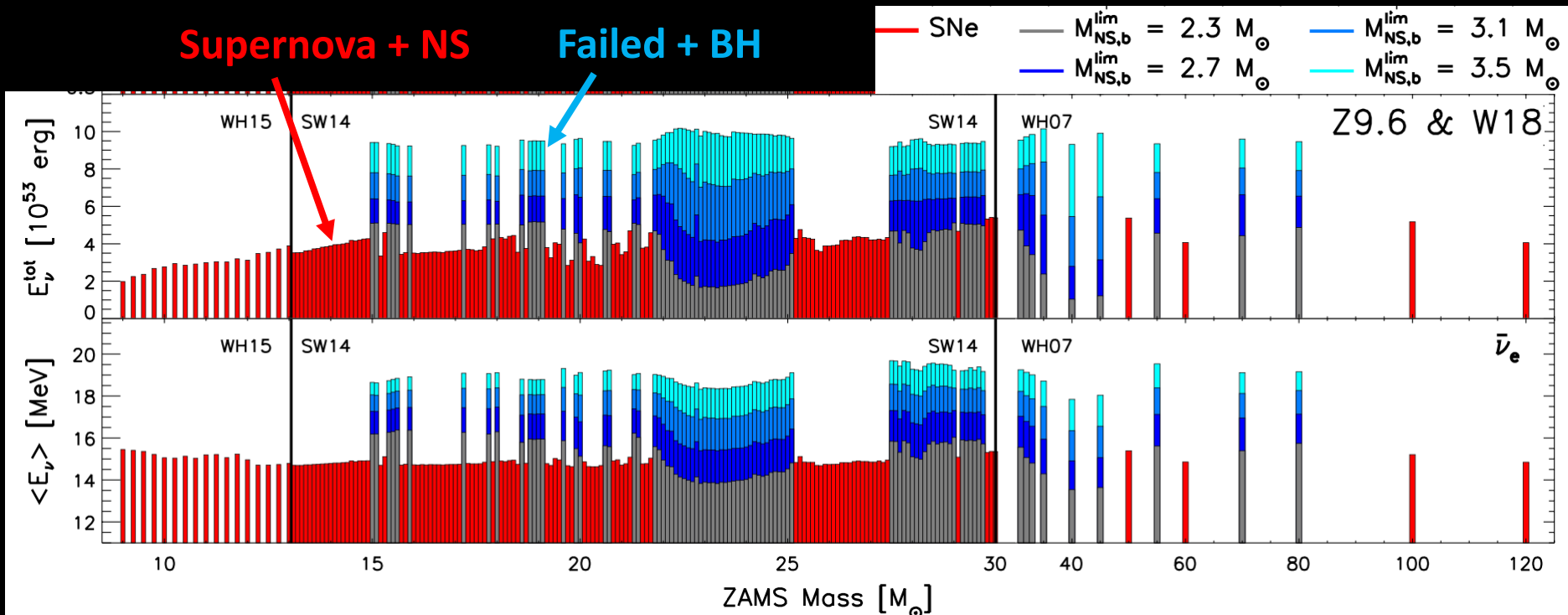
Author	Time ^a	$T_{\nu_e}^i$ ^b	$T_{\bar{\nu}_e}^i$ ^b	$T_{\nu_x}^i$ ^b	Ref.
Myra and Burrows (1990)	0.2	3.3	4.0	8.0	[119]
Totani <i>et al.</i> (1998)	0.5	3.9	4.9	6.3	[120]
	10	3.5	6.3	7.9	
Rampp and Janka (2000)	0.5	2.3	3.4		[121]
Liebendoerfer <i>et al.</i> (2001)	0.5	4.2	4.6	5.3	[122]
Mezzacappa <i>et al.</i> (2001)	0.5	3.6	4.2	5.2	[123]
Keil <i>et al.</i> (2003)		3.7	4.0	5.2	[124]
Thompson <i>et al.</i> (2003)	0.2	2.9	3.5	4.5	[125]
Liebendoerfer <i>et al.</i> (2004)	0.5	3.7	4.2	4.5	[126]
	0.5 ^c	4.5	4.8	7.5	
Sumiyoshi <i>et al.</i> (2007)	1.4 ^c	6.6	7.0	10	[127]

Note: Horiuchi *et al.* (2009) simply assumes Fermi-Dirac and equipartition into neutrino flavors

Spherical models

Long-term (~ 10 sec) predictions for multiple progenitors

1. Spherical, calibrated central neutrino engines



Kresse et al (2021)

+ 4 other engine models (calibrated to Crab and SN1987A)

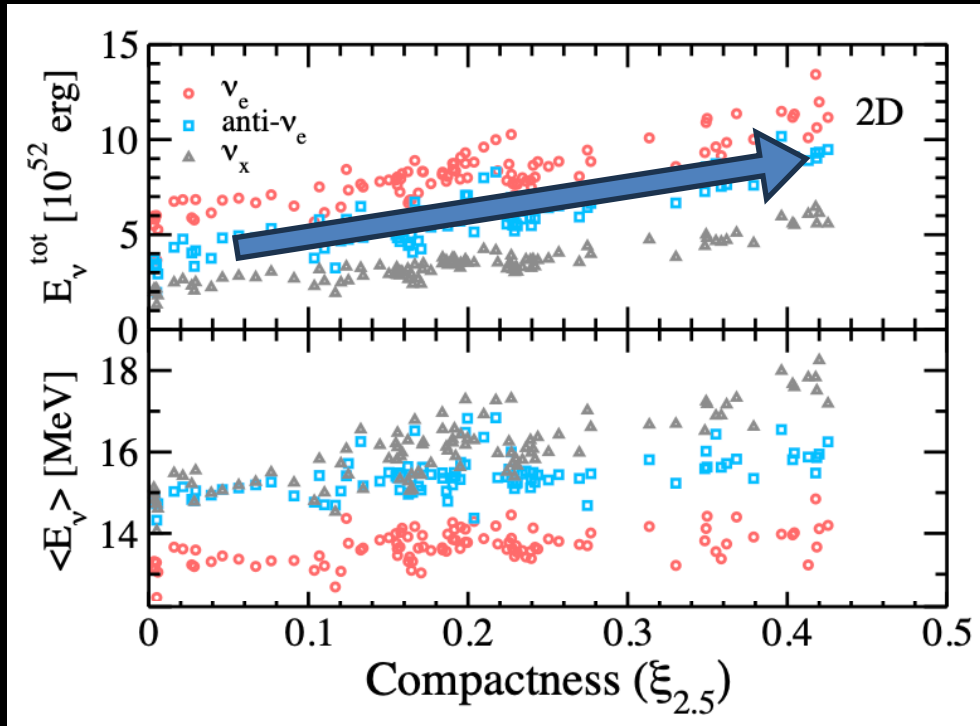
See also, Ugliano et al (2012), Sukhbold et al (2016)

Beyond spherical models

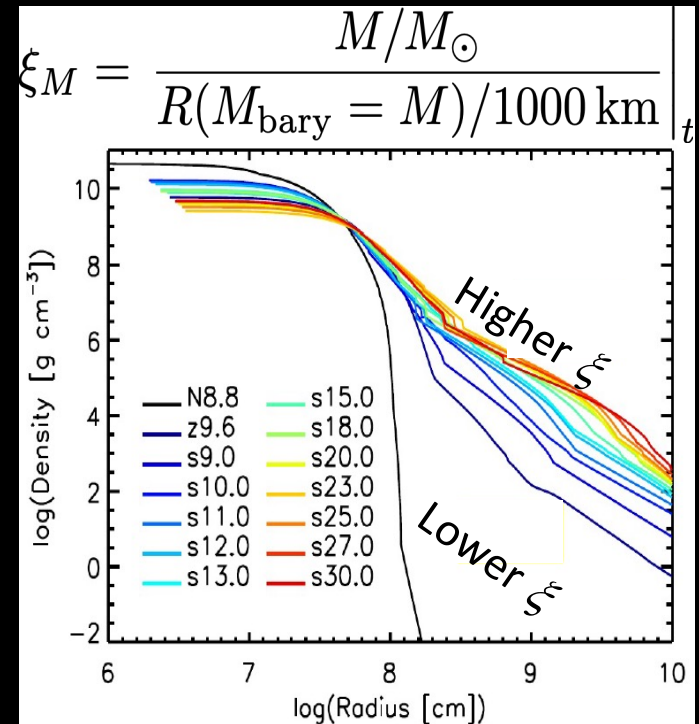
Long-term (~ 10 sec) predictions for multiple progenitors

1. Spherical, calibrated central neutrino engines
2. Axis-symmetric + simple cooling

Simulations until ~ 1 sec, after that account only for radius contraction



Horiuchi et al (2018), based on Nakamura et al (2015);
see Ekanger et al (2022) for updates



O'Connor & Ott (2013)

Compactness: a progenitor indicator

Compactness:

Captures the density structure of the progenitor, which impacts mass accretion evolution

O'Connor & Ott (2011)

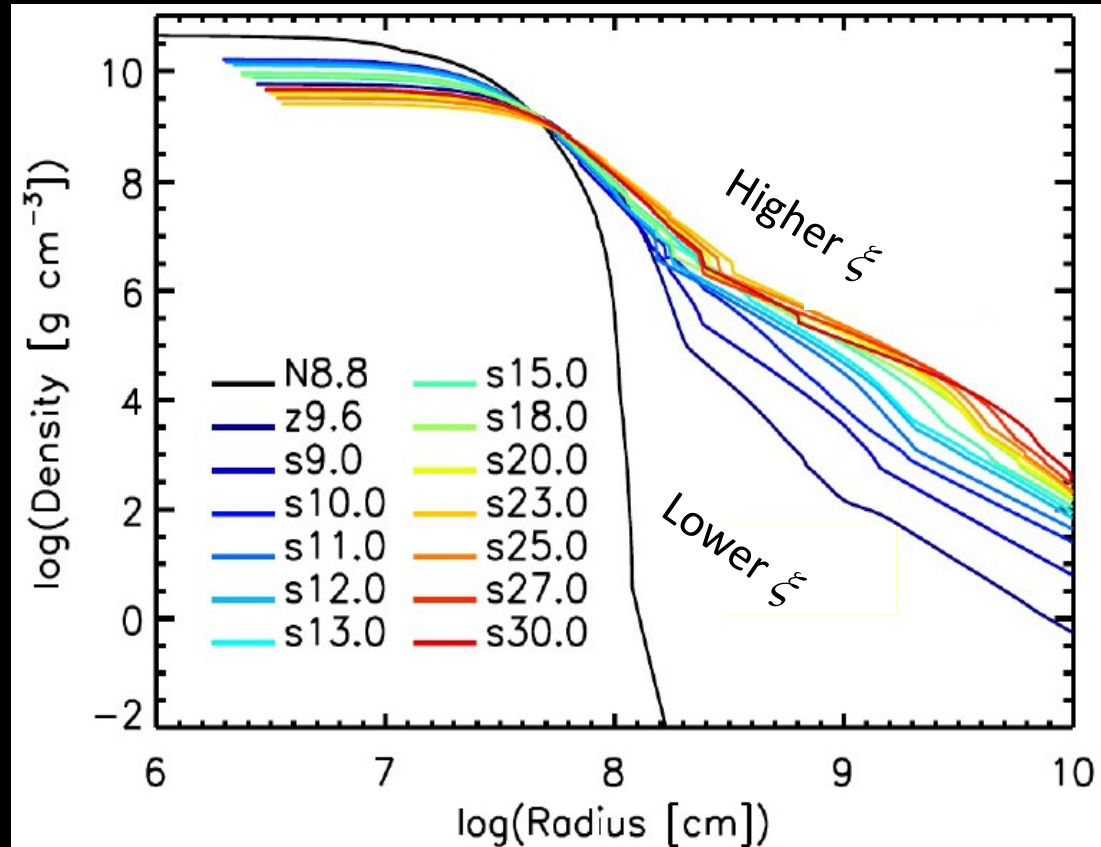
Mass accretion

VS !

Neutrino heating

- Higher $\xi \rightarrow$ higher $\dot{M}_{\text{dot}}$
- Lower $\xi \rightarrow$ lower $\dot{M}_{\text{dot}}$

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



Neutrino emission synthesis

Long-term (~10 sec) predictions for multiple progenitors

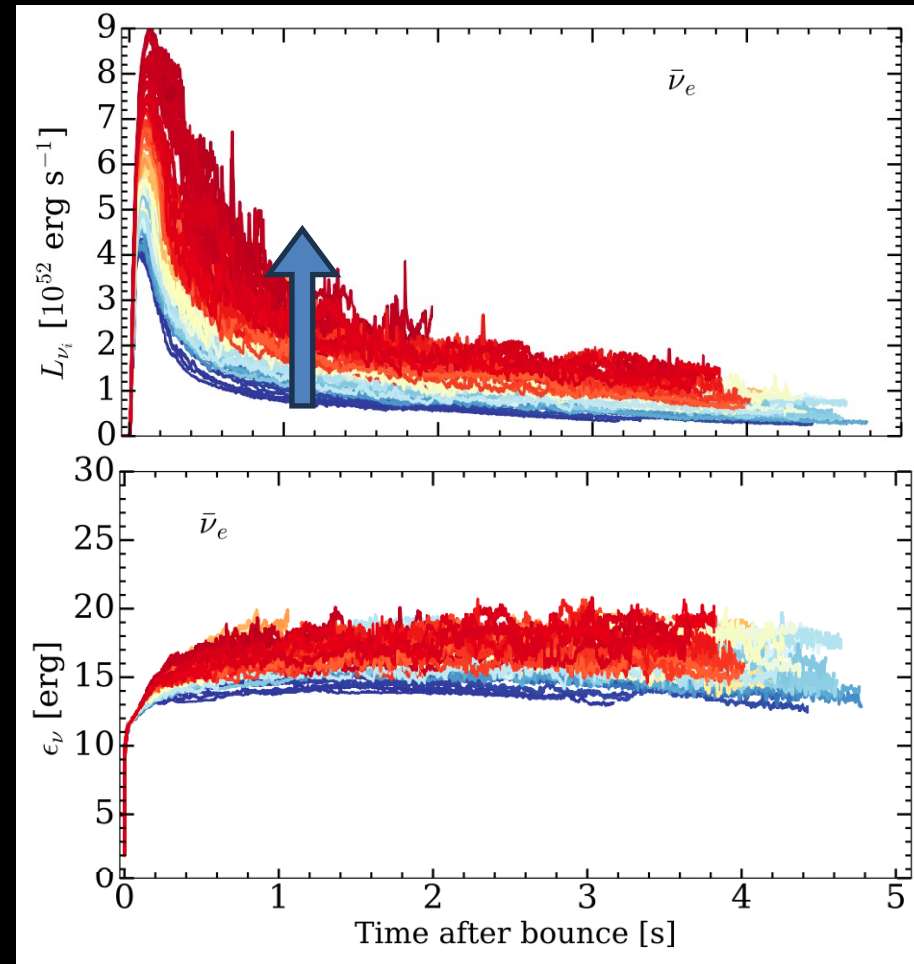
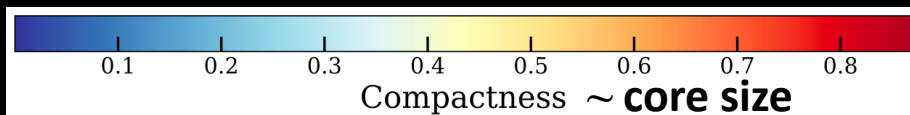
1. Spherical, calibrated central neutrino engines
2. Axis-symmetric + simple cooling
3. Large sets of numerical models

*e.g., Nagakura et al (2021),
Vartanyan & Burrows (2023)*

Supports importance of
progenitor (eg compactness).

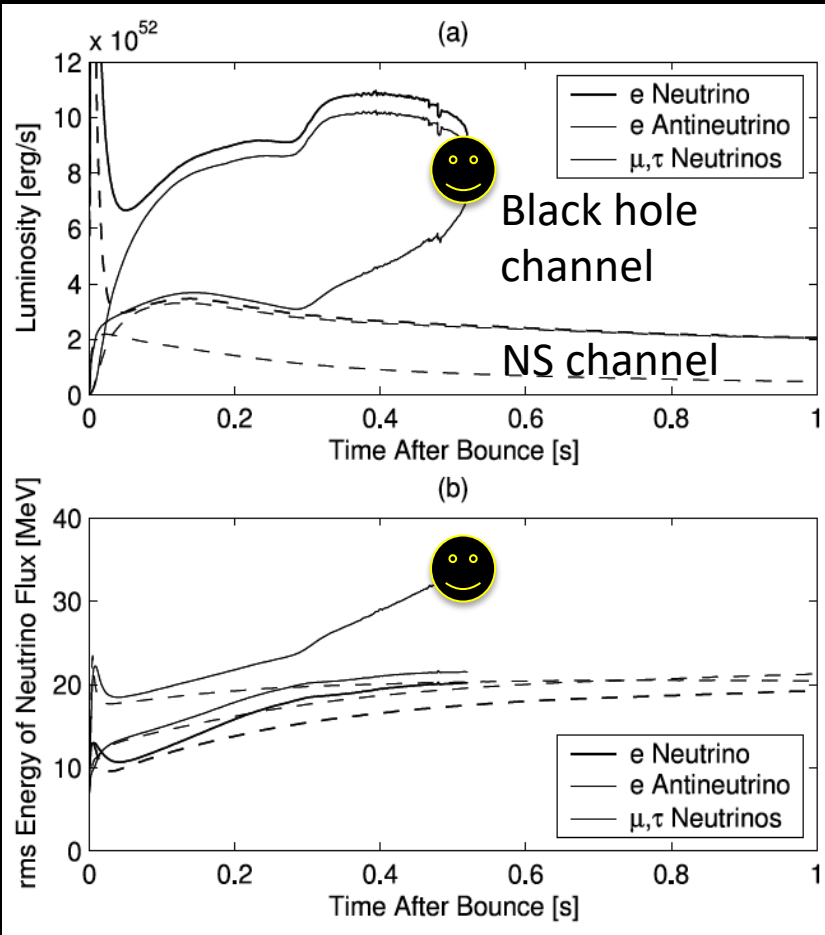
*see also, O'Connor & Ott (2011),
Nakamura et al (2015), Horiuchi et al (2016)*

Vartanyan & Burrows (2023)



Black hole channel

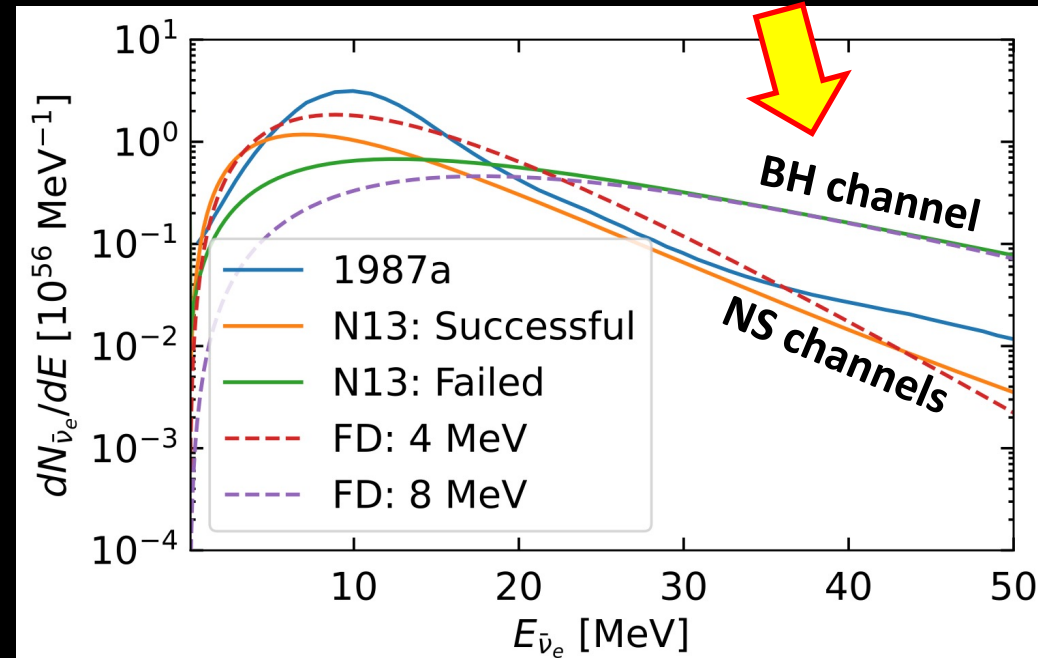
Look to simulations for guidance: collapse to black hole are different



Liebendoerfer et al (2004)

- Neutrino luminosities are higher ☺
- But don't last as long ☹

➔ **Time-integrated, shows a systematically higher-energy spectrum**



Ando, Ekanger, Horiuchi, Koshio (2023)

Compactness: BH formation

Compactness:

Captures the density structure of the progenitor, which impacts mass accretion evolution

O'Connor & Ott (2011)

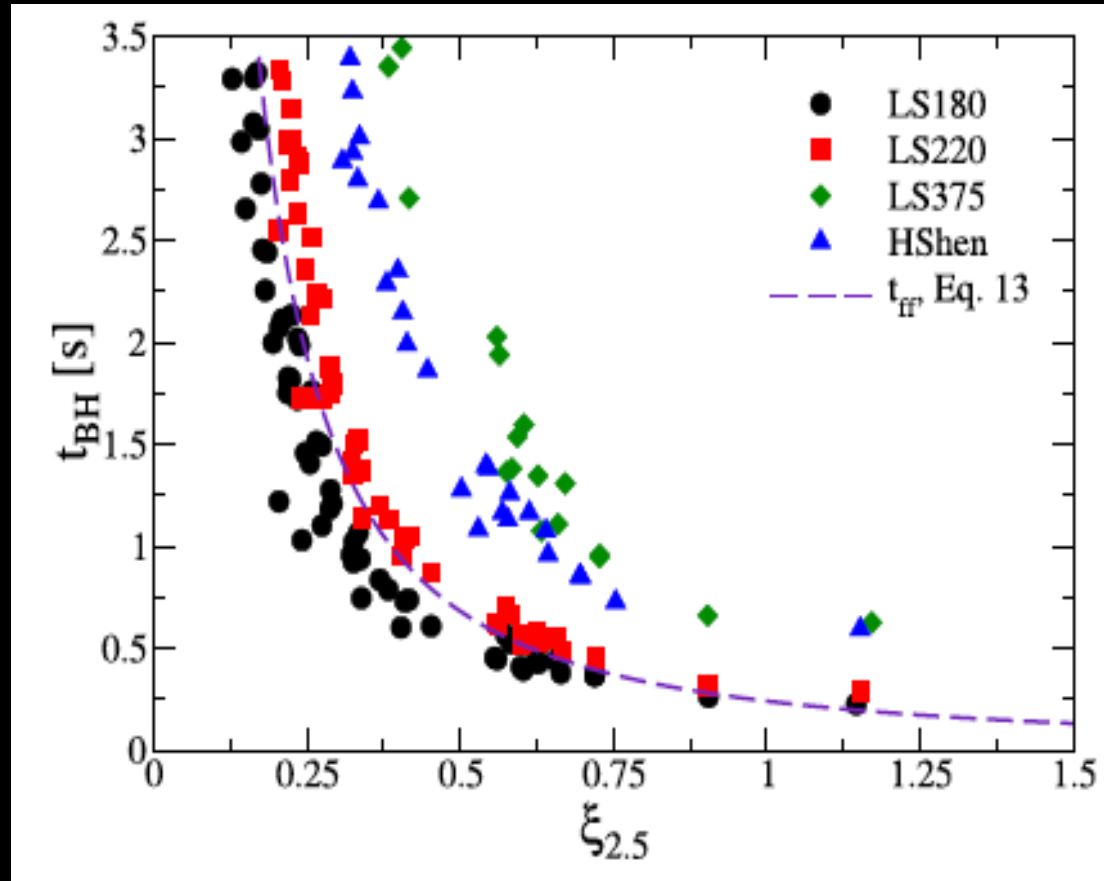
Mass accretion

VS !

Neutrino heating

- Higher $\xi \rightarrow$ higher $\dot{M}$ $\rightarrow$ BH forms earlier
- Lower $\xi \rightarrow$ lower $\dot{M}$ $\rightarrow$ BH formation takes longer

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



O'Connor & Ott (2011)

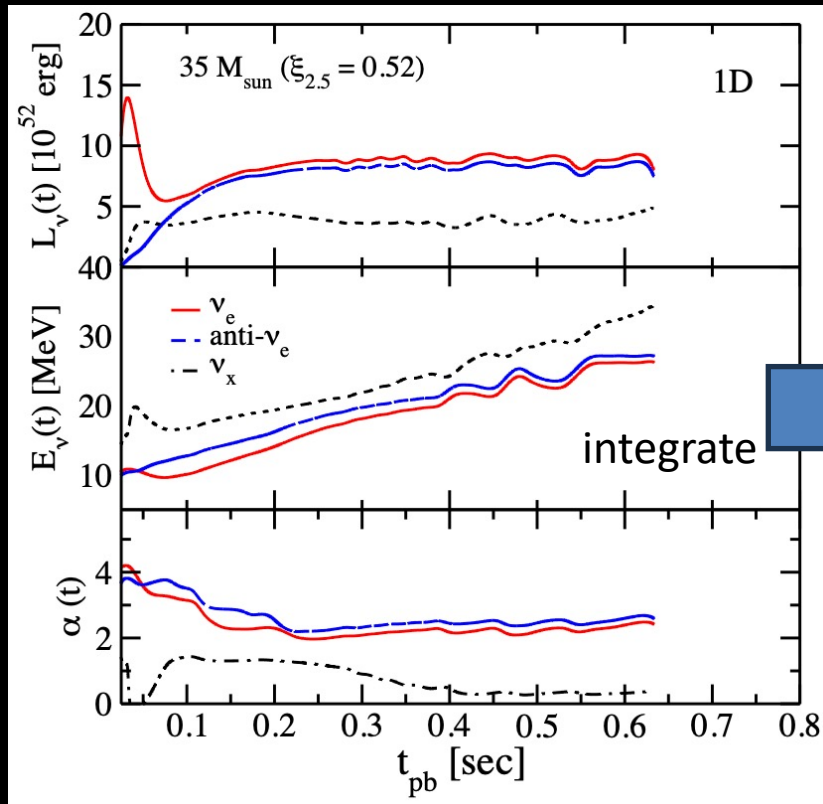
Black hole channel

Duration

Larger cores (=compactness)

→ higher mass accretion

→ earlier black hole formation

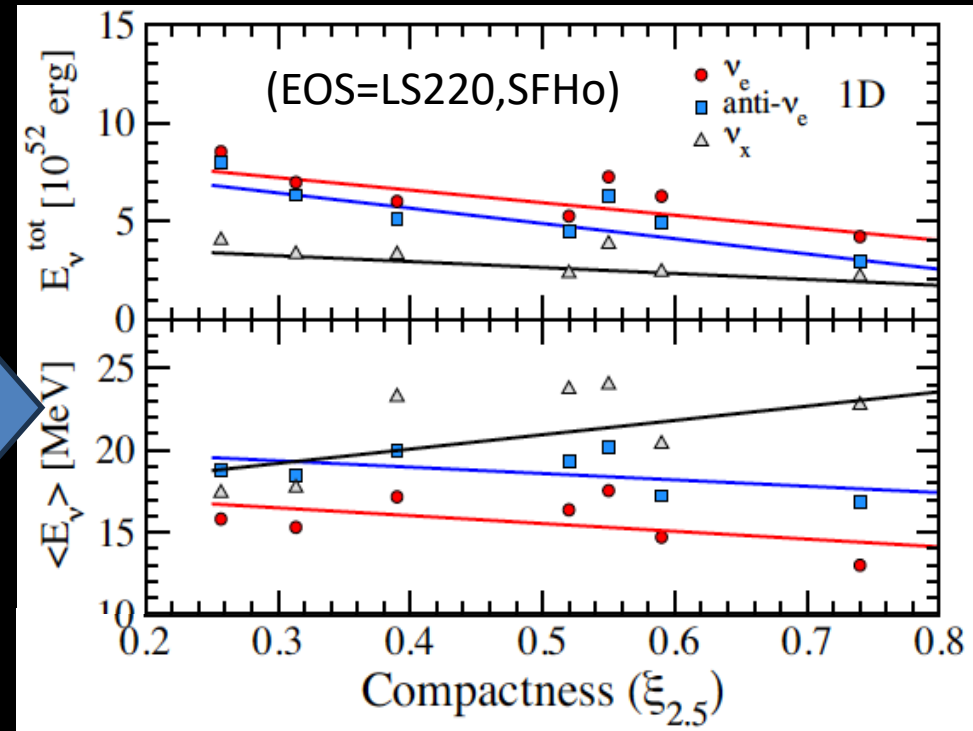


Time-integrated

Larger cores (=compactness)

→ higher L_{ν} but shorter duration

→ net decline (maybe except ν_x)



Horiuchi et al (2018)

Diffuse supernova neutrinos

$$R = N_t \int dE \sigma_{\text{IBD}} \int dz c \frac{dN}{dE'} (1+z) R_{\text{CC}}(z) \left| \frac{dt}{dz} \right|$$

Neutrino detector capabilities

Time-integrated
neutrino emission

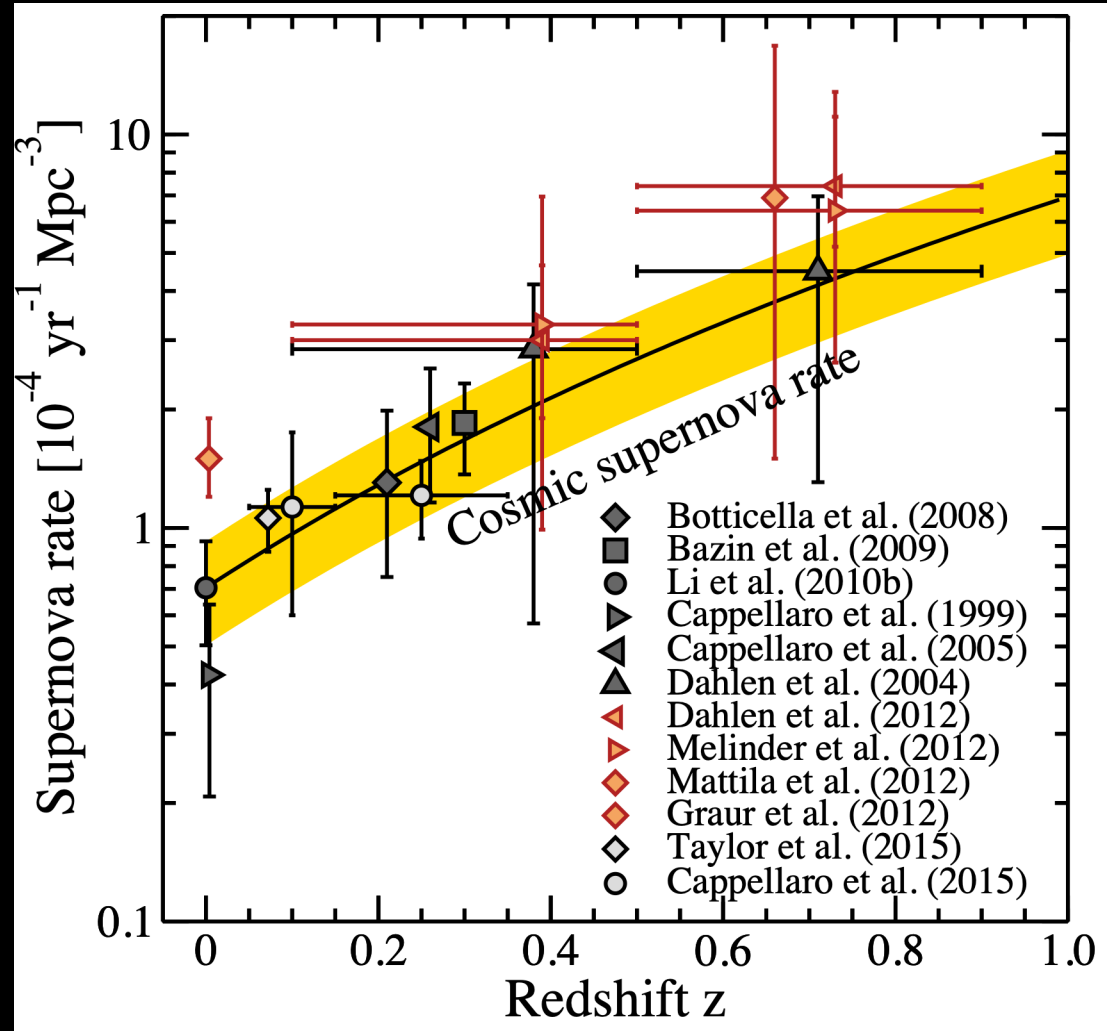
Rate of massive
star core collapse

Core-collapse supernova rate

Direct measurements

- Important redshift range ($z < 1$) observed by surveys
- Uncertainty: factor ~ 3
 - Different survey strategy, sample size, dust correction, supernova luminosity function

But: supernova rate only gives the exploding core collapse rate



Updated from Horiuchi et al (2011)

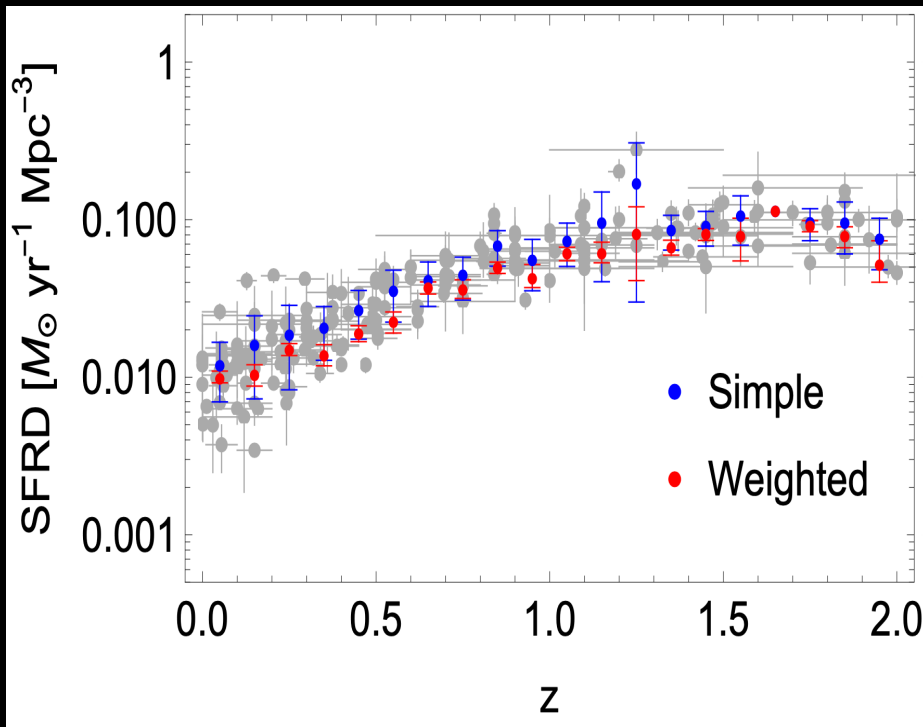
Rate of cosmic core collapse

Since core-collapse progenitors have short lifetimes:

$$\left(\frac{dN}{dt}\right)_{\text{stellar birth}} = \left(\frac{dN}{dt}\right)_{\text{bright collapse}} + \left(\frac{dN}{dt}\right)_{\text{dark collapse}}$$

Well-measured

Improving



Star formation rate:

- ✓ Measured by many groups, many wavebands, many data sets
- ✓ Uncertainty is < 2 (in $z < 1$)
 - Main causes: dust correction, sample selection, initial mass function...
- Many cross checks exist

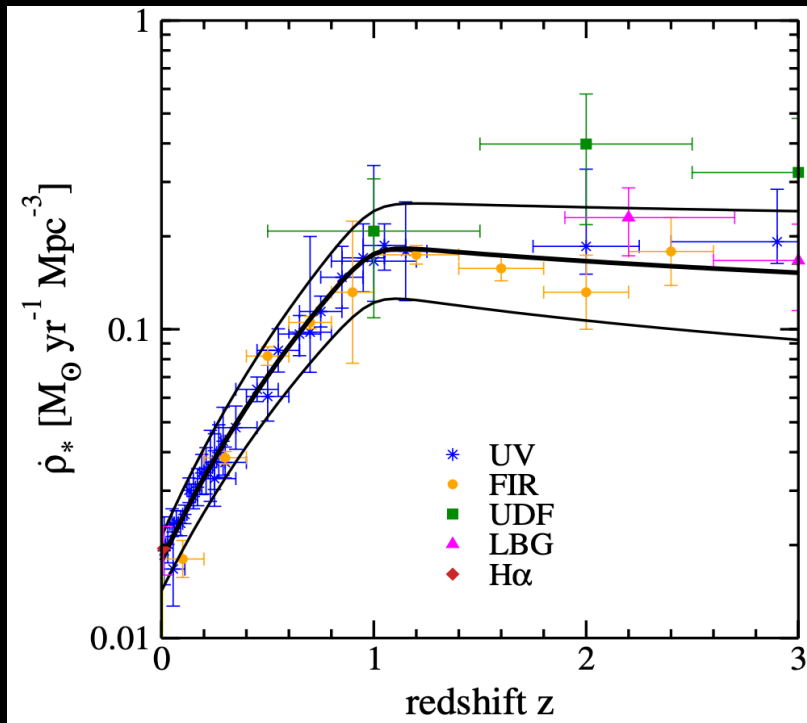
Ekanger et al (2024), see also

Madau & Dickinson (2014), Hopkins & Beacom (2006)

Fits versus data

Fits are handy

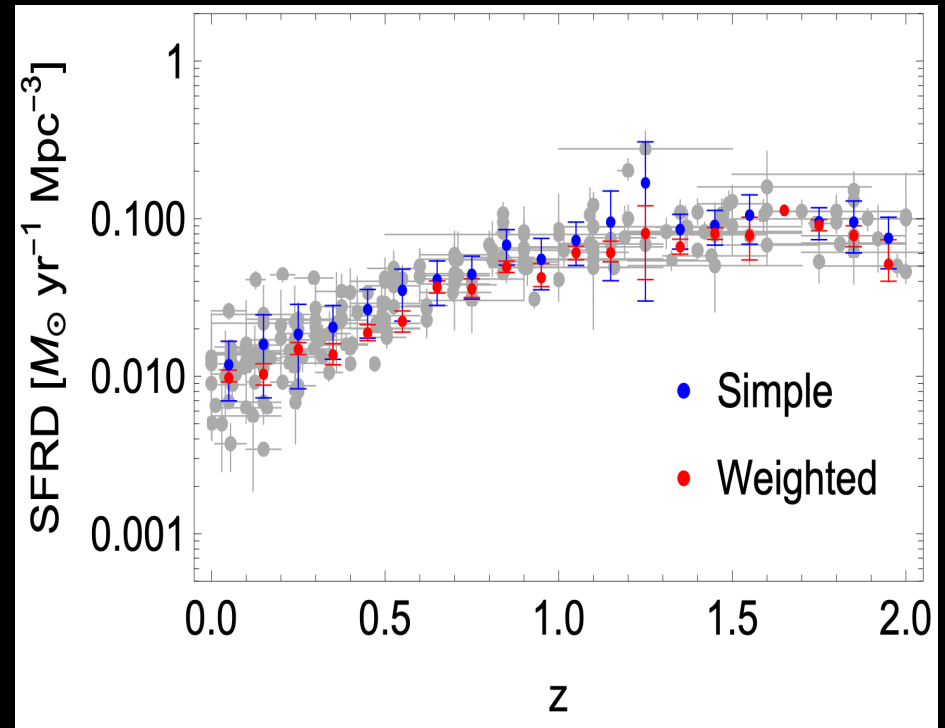
Standard practice has been to use functional fits to data with parameter estimation & errors



Horiuchi et al (2009), following Hopkins & Beacom (2006) and Yuksel et al (2008)

Data driven

Large dataset allows more direct estimates of rates & errors in redshift space



Ekanger et al (2024)

Rate of cosmic core collapse

Since core-collapse progenitors have short lifetimes:

$$\left(\frac{dN}{dt}\right)_{\text{stellar birth}} = \left(\frac{dN}{dt}\right)_{\text{bright collapse}} + \left(\frac{dN}{dt}\right)_{\text{dark collapse}}$$

Well-measured Improving Frontier

Collapse to black holes

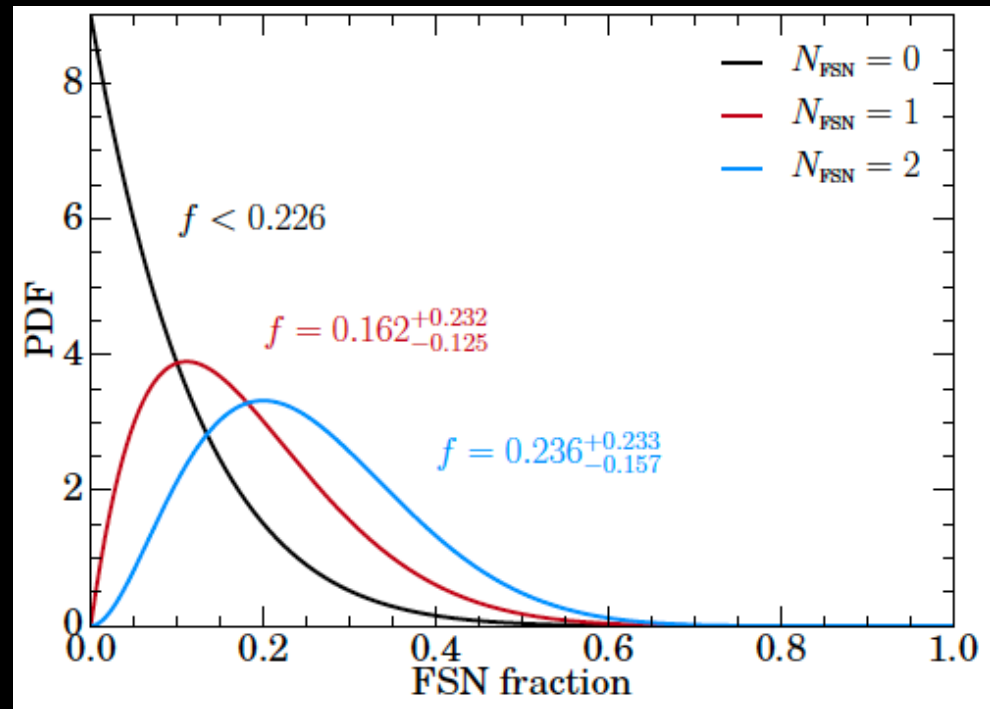
1. Inferred by mismatch of stellar birth rate and supernova rate

Eg Strigari et al (2008), Horiuchi et al (2011), Mathews et al (2014), Yuksel & Kistler (2014), Gaur et al (2015), Ekanger et al (2024), ...

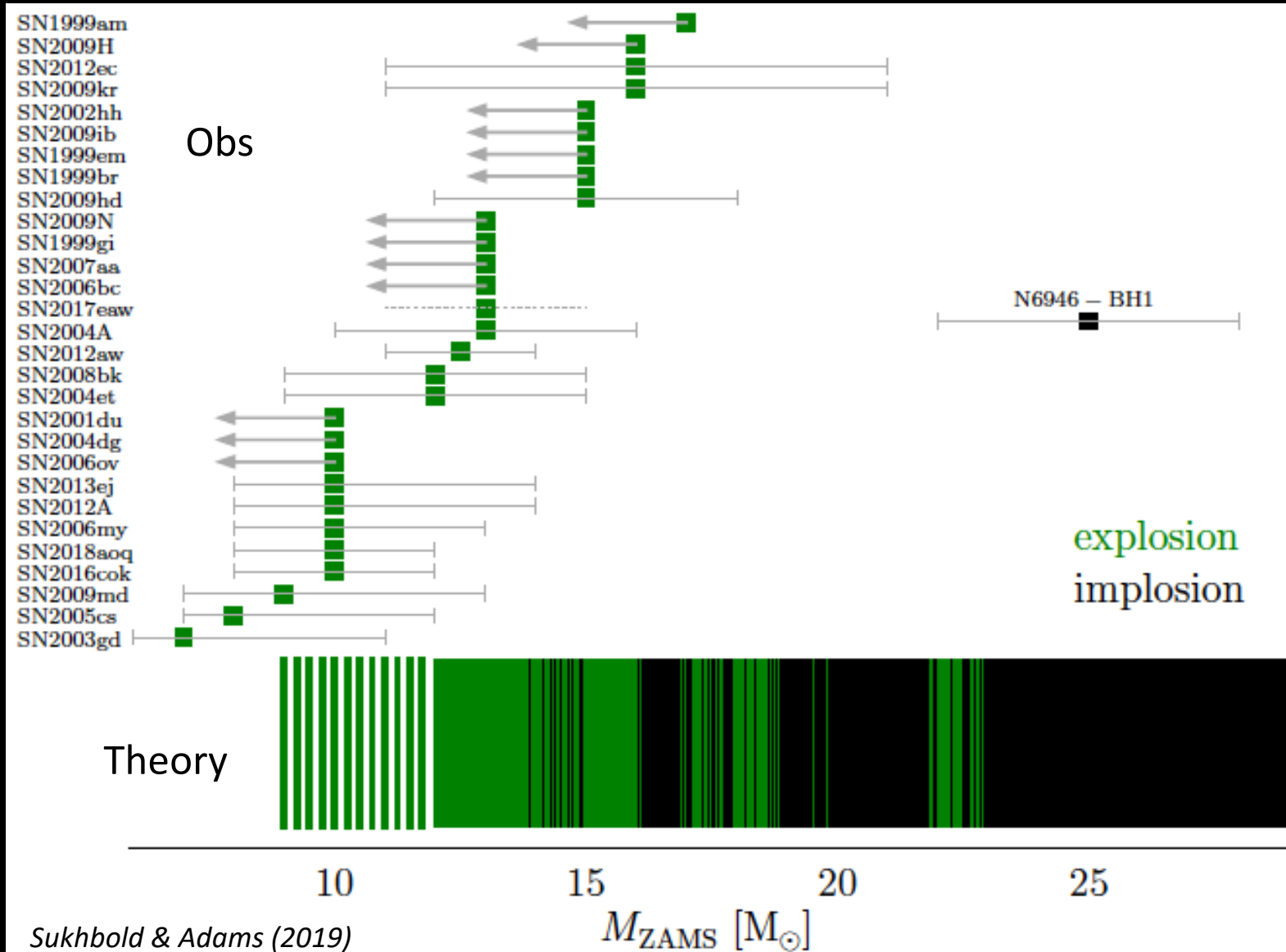
2. Candidates of disappearing stars

Kochanek et al (2018), Gerke et al (2015), Adams et al (2017), Reynolds et al (2016), Neustadt et al (2021)

Neustadt et al (2021)

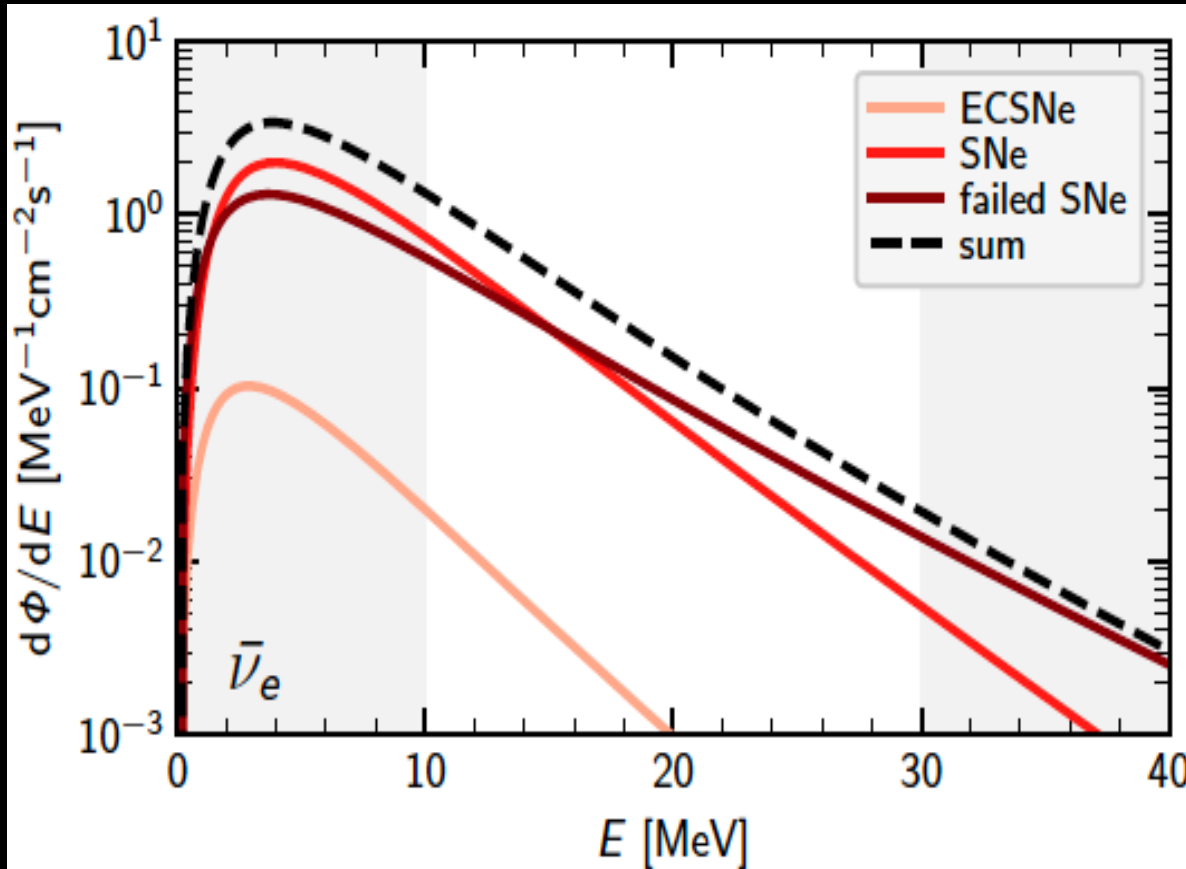


Potential emerging picture



DSNB predictions

Common to separate 3 populations. (uncertainties not shown)



Review & public code to estimate the neutrino flux (*pyDSNB*)

<https://github.com/shinichiroando/PyDSNB>

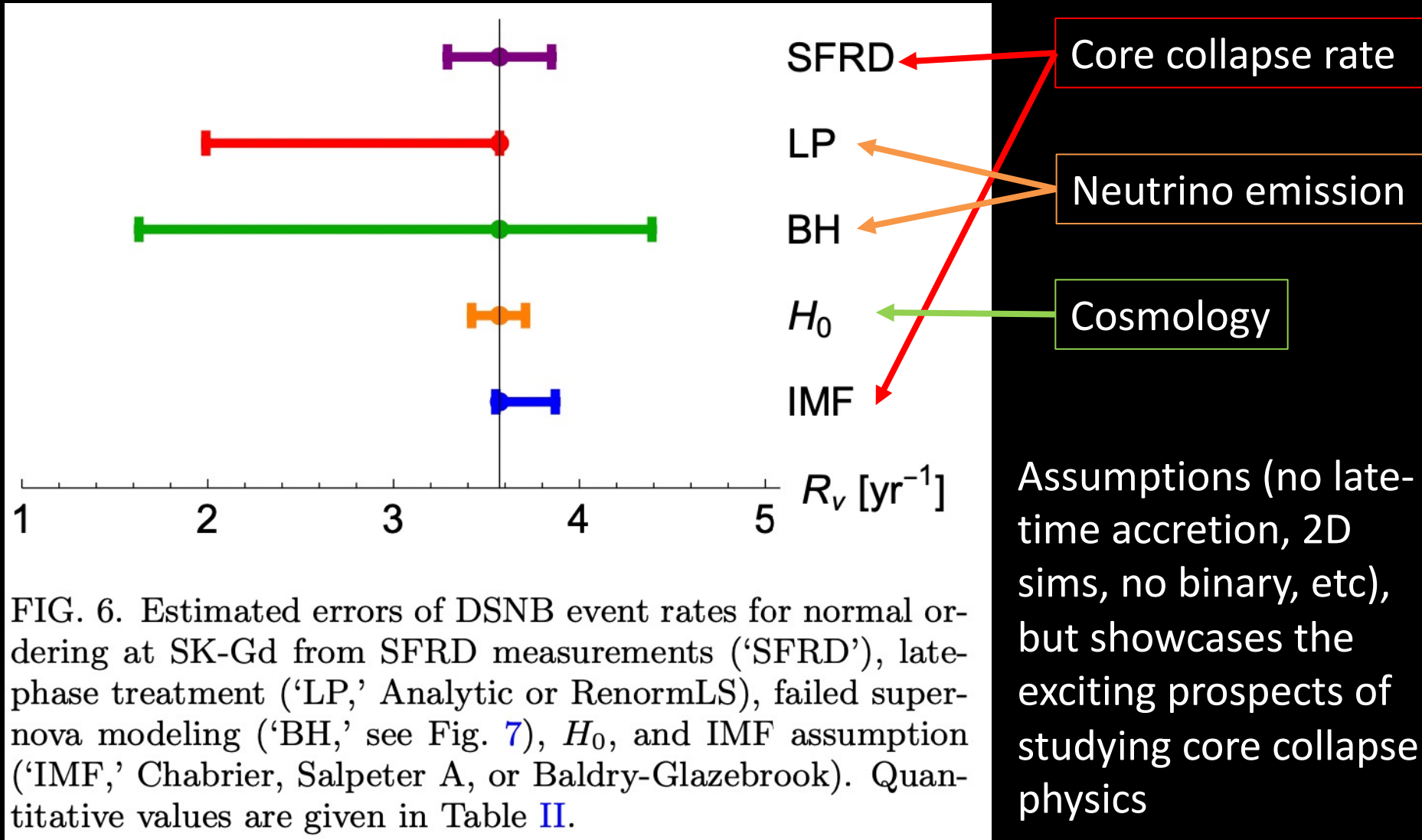


Ando, Ekanger, Horiuchi, Koshio (2023)

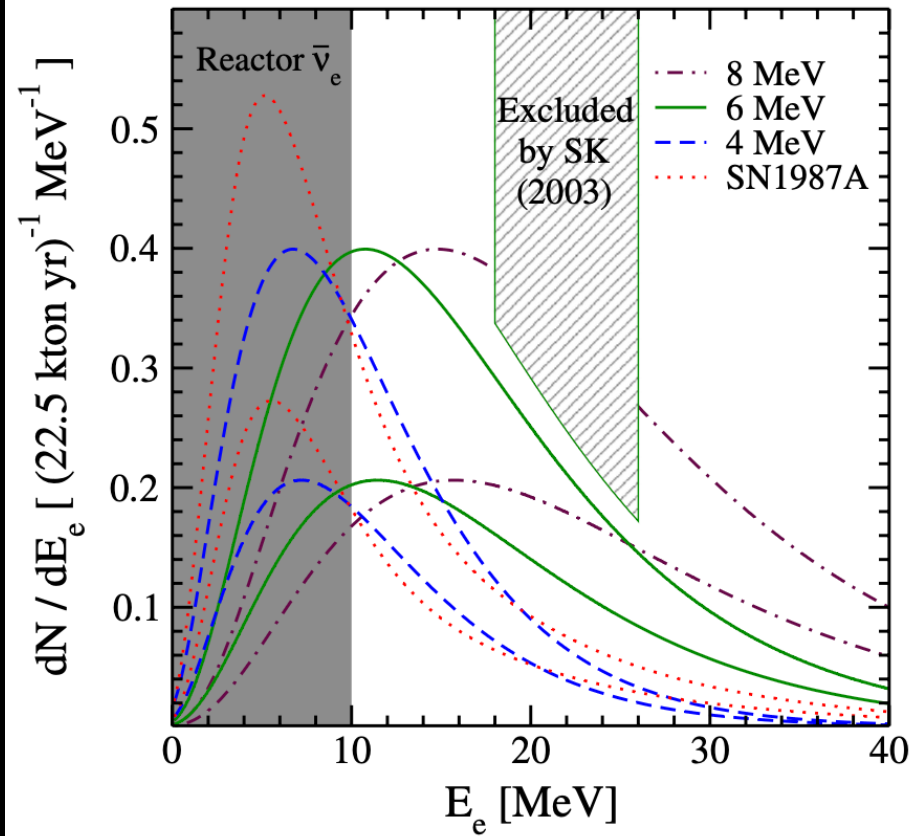
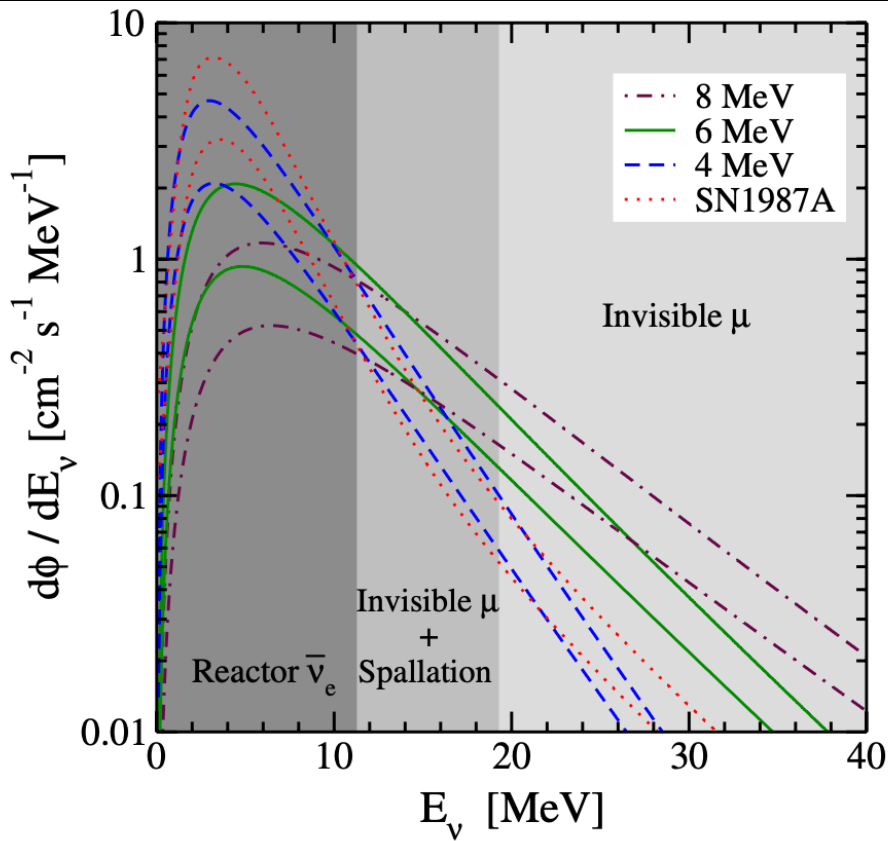
See also: Lunardini (2009), Lien et al (2010), Yang & Lunardini (2011), Keehn & Lunardini (2012), Nakazato (2013), Mathews et al (2014), Yuksel & Kistler (2015), Nakazato et al (2015), Hidaka et al (2016), Priya & Lunardini (2017), Moller et al (2018), Horiuchi et al (2018), Sing & Rentala (2021), Kresse et al (2021), Horiuchi et al (2021), Ashida & Nakazato (2022), Ekanger et al (2022), Ziegler et al (2023)

Uncertainties (for 'standard' model)

An attempt at the error budget:



Simple model

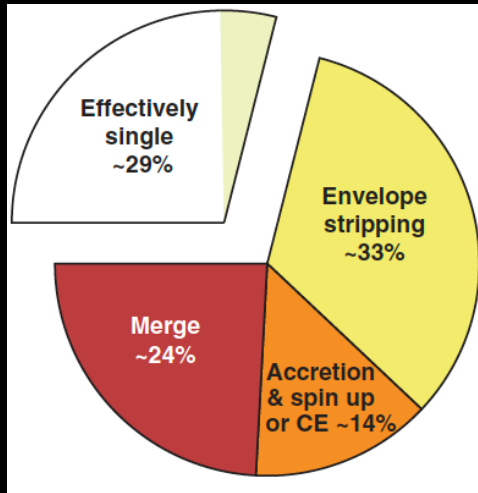


Horiuchi et al (2009)

- No black holes
- Supernova rate from fitting function
- Fermi-Diract neutrino spectrum
- Equipartition of energy

Various effects

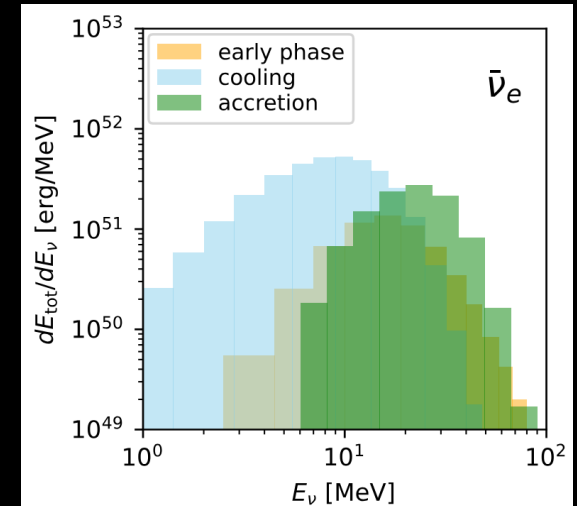
Stellar binaries: are common and can affect progenitors



Horiuchi et al (2021)
Lunardini et al (2025)

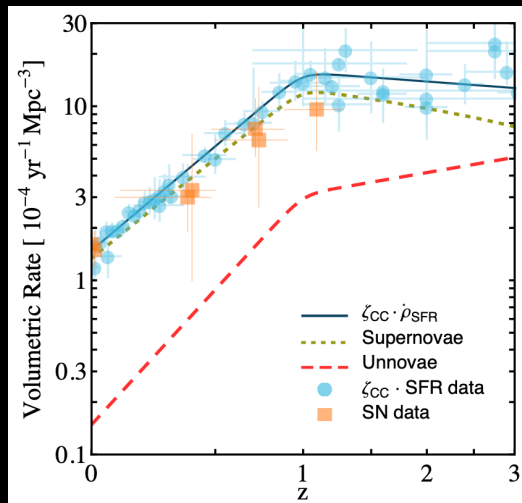
Fall back channel: can be large contribution if black hole takes time to form

Nakazato et al (2024)



Black holes: may be more commonly formed at high redshifts. EOS dependence

Yuksel & Kistler (2014)
Nakazato et al (2020)
Ashida et al (2023)



Neutrino decay: competitive probes of decay times $\sim 10^{10} \text{ s/eV}$

de Gouvea et al (2020)

Non-Universal IMF: hints of environmental dependence

Zieger et al (2022), Ashida et al (2023)

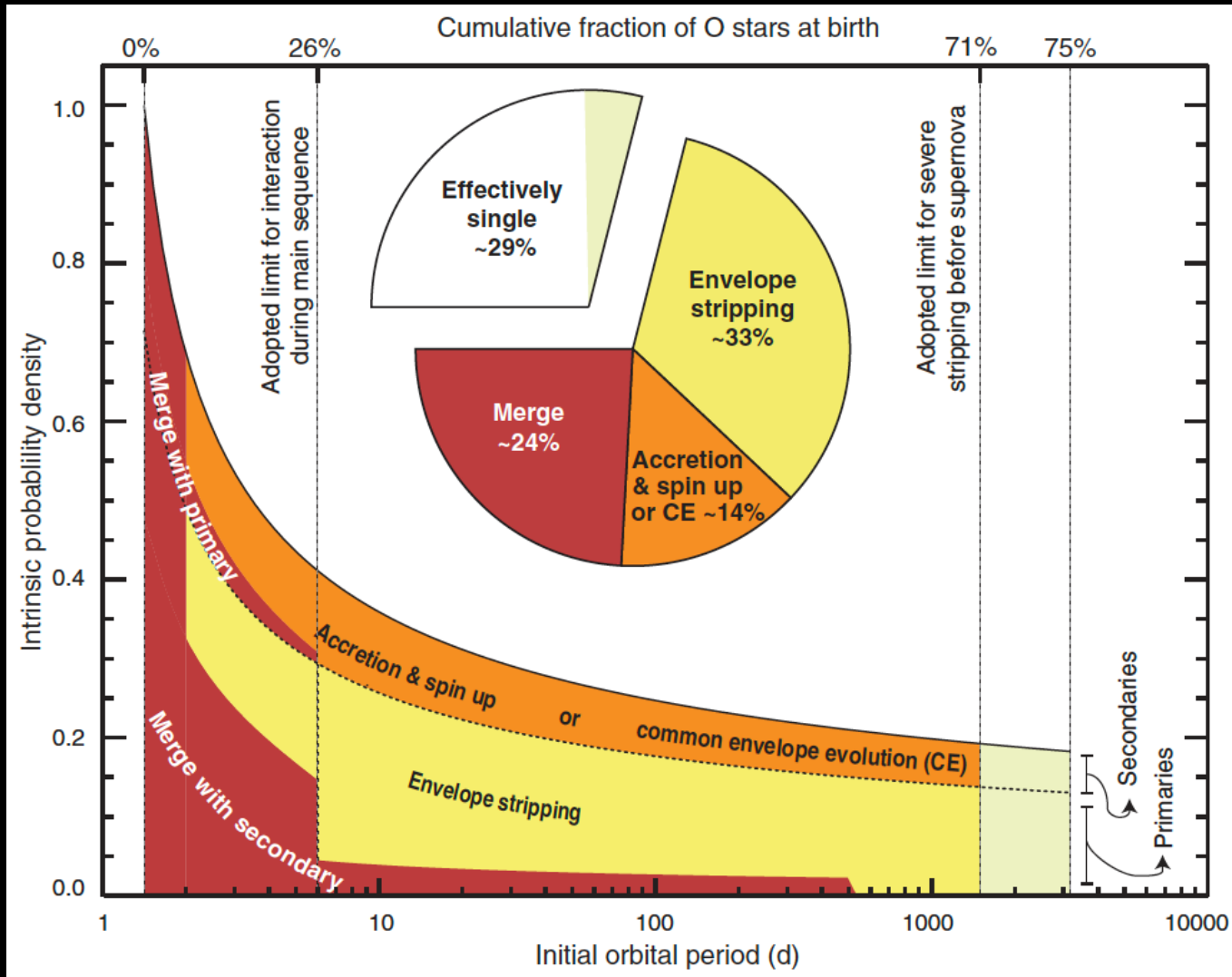
DM- ν interactions

Eg, Farzan & Palomares-Ruiz (2014), Das et al (2024)

Late-time ν mass generation

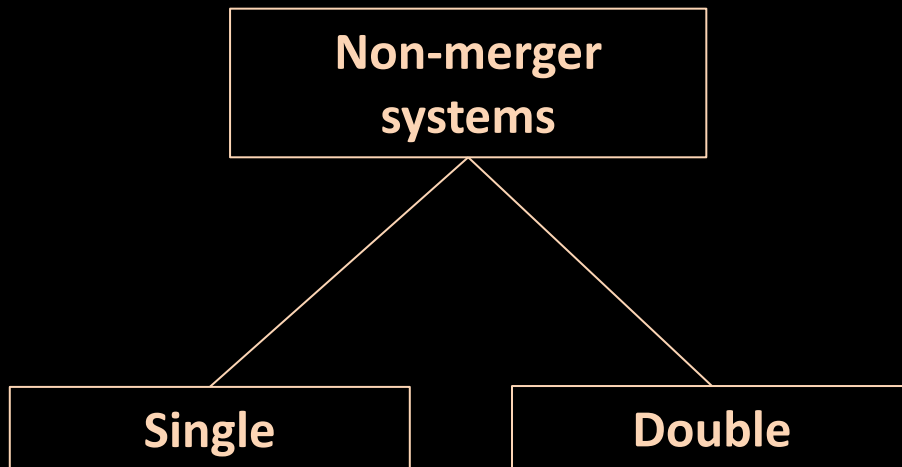
*de Gouvea et al (2022)*₃₂

Even more detailed: binaries

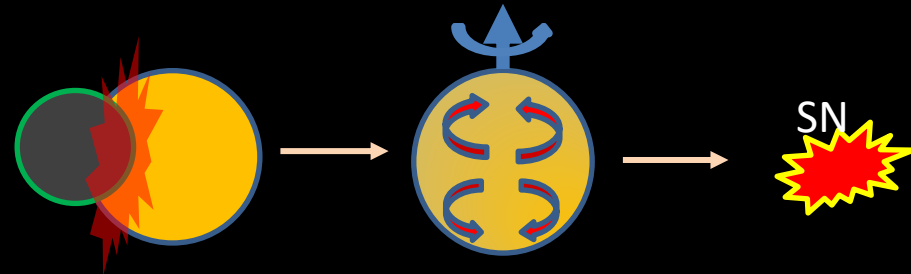
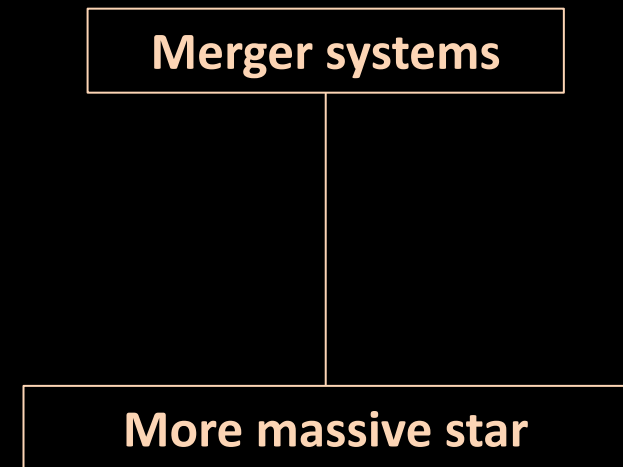


Sana et al (2012)

Binary outcomes



→ Masses of stars changed

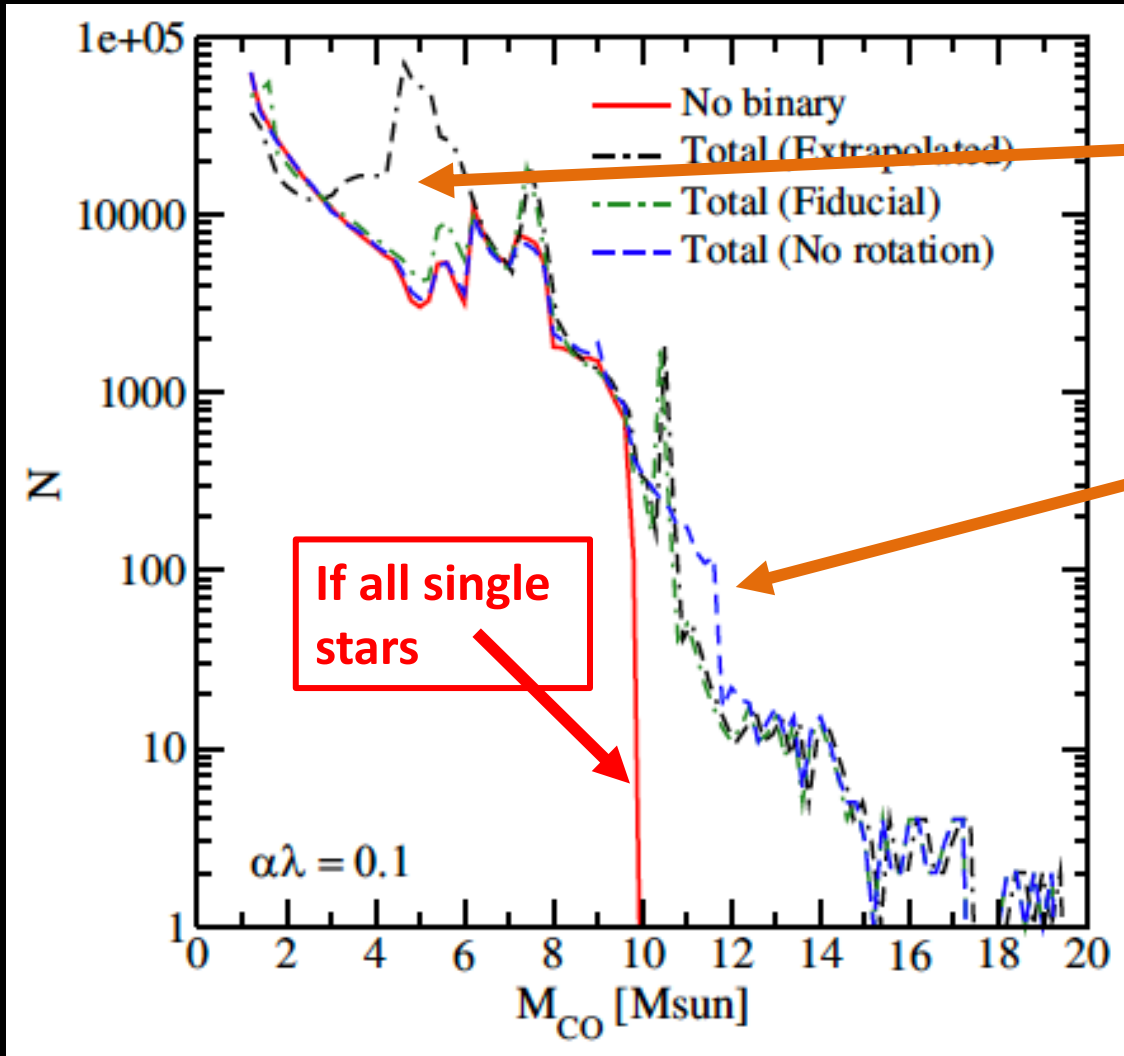


→ Masses of stars changed
→ Number of stars changed

Visuals: thanks to Kinugawa-san

Potential binary effects

Binary effect creates more and higher mass cores for collapse



Boost to number of progenitors due to mergers: $\sim 25\%$ more progenitors

Boost to masses of progenitors due to mergers and mass transfers (at the expense of donor's mass)

Effect on DSNB is $\sim 10\text{-}20\%$, and max $\sim 70\%$

See also, Kresse et al (2021), Kinugawa et al (2024), Lunardini et al (2025)

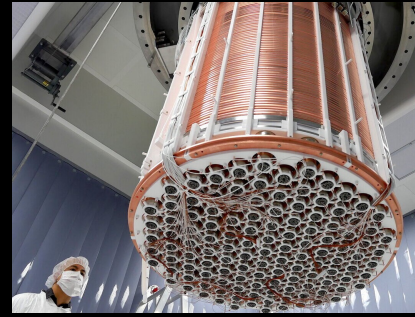
Horiuchi et al (2021)

Beyond nuebar flavor



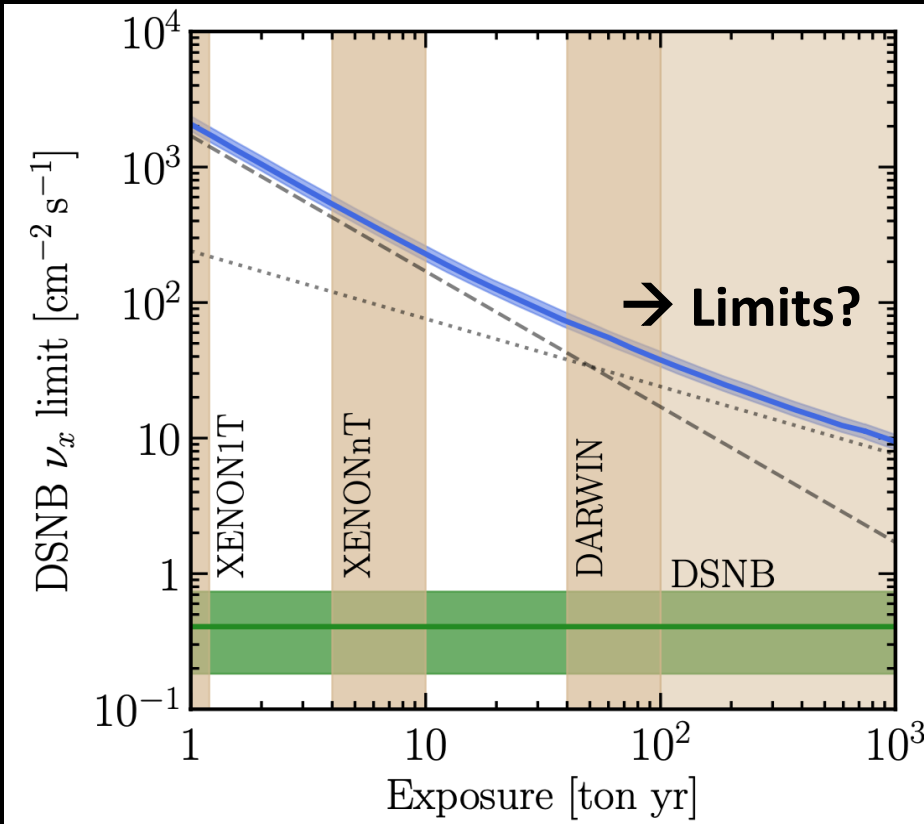
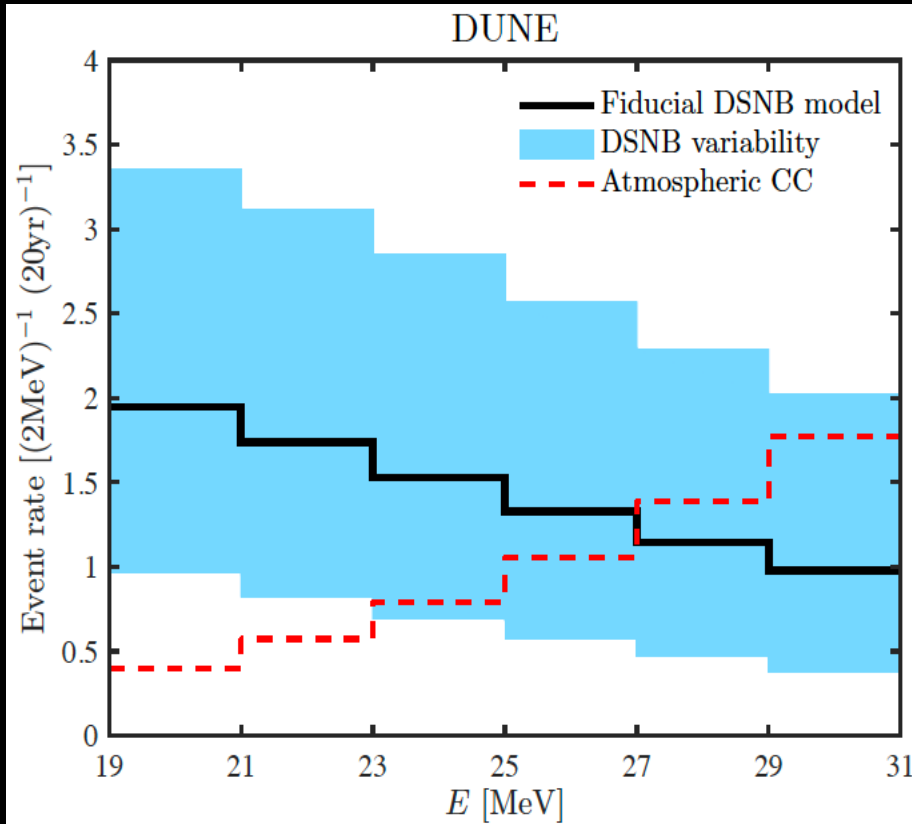
DUNE

- 40k ton lq Ar
- Signal & bkg studies ongoing
- CC int. for nue



Direct DM detector

- Xe or Ar targets
- Solar & atm. bkg
- CEvNS for all flavor



Detection with geological minerals?

Use old rocks?

- Natural solid-state track detectors
- R&D of fast nm resolution mapping of macroscopic samples



Competitive exposure

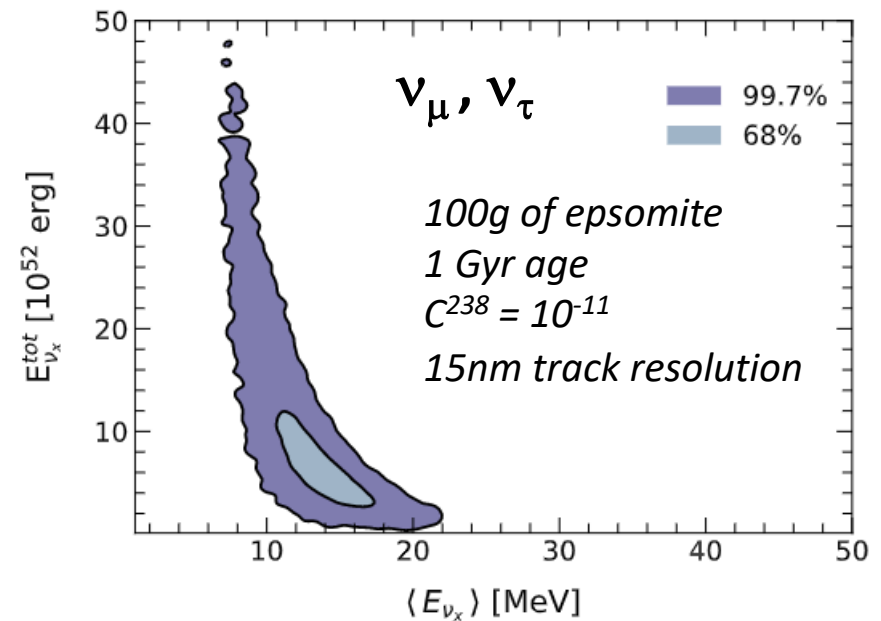
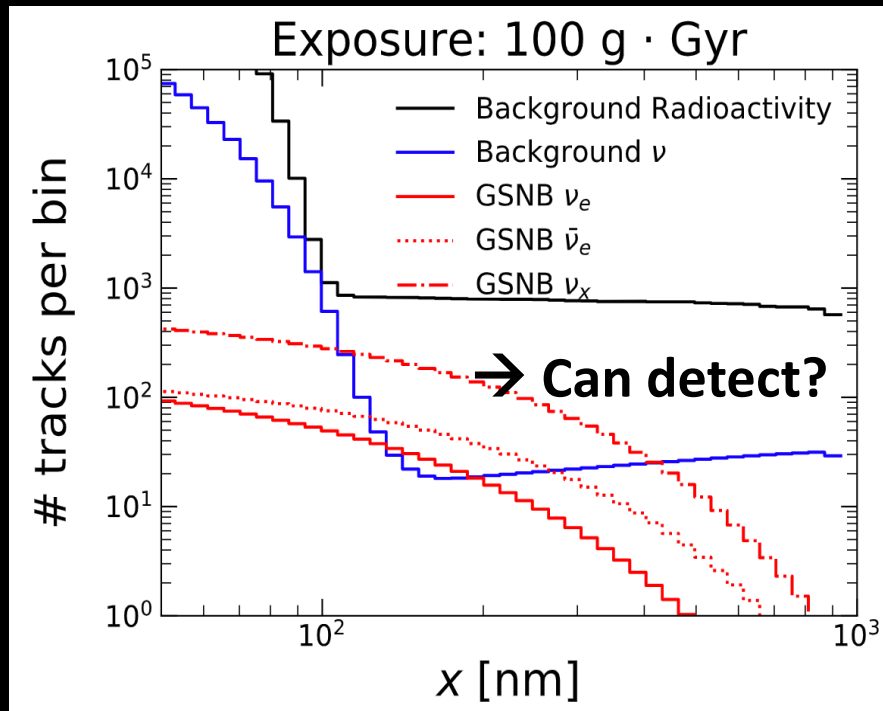
100 grams over 10^9 yr = 10^5 t yr

All flavors

CEvNS relevant for MeV neutrinos

Records thousands of core collapse

Duration $\gg$ inverse of Galactic supernova rate



Final remarks

- ✓ **Key open questions in supernova physics can only be solved with neutrinos**

Direct observation of collapsing core

Study the explosion models, black hole formation, and more

- ✓ **We have unique opportunities with future discovery**

DSNB is a search of the average neutrino emission per core collapse. It can test models of explosion models, black hole contributions, and neutrino properties.

- ✓ **Future observations may yield confirmation and/or surprises**

DSNB will be the first confirmed extraterrestrial neutrinos since solar and SN1987A neutrinos, this time over cosmological distances.

Please find them -- thank you!