SUPERNOVA NEUTRINOS: BEYOND THE BASICS

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Contents

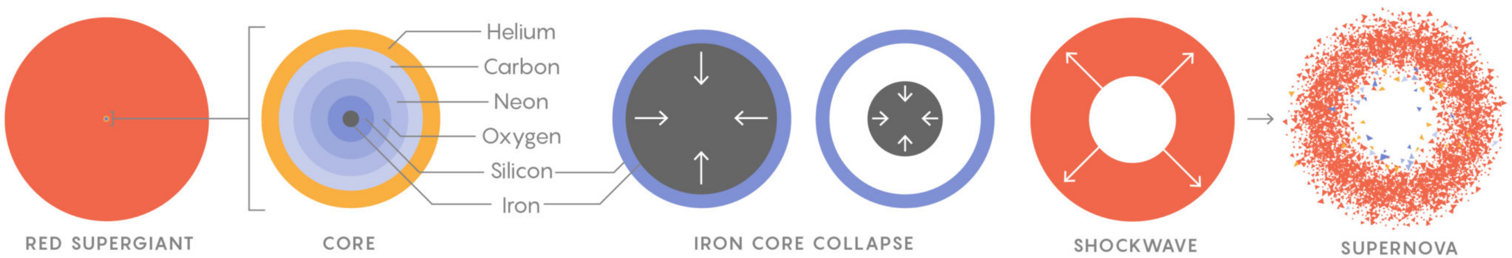
Beyond the basics:
neutrinos reflect the complexity of core collapse supernovae

- Mini-review: scenarios for the next 10-20 years
- Highlights of my recent work

INTRODUCTION: THE BASICS

Stellar death: a core collapse supernova

Credit: Lucy Reading-Ikkanda/Quanta Magazine



time

Advanced stellar evolution

Loss of pressure; free fall; core formation

Falling matter bounces; shockwave; ***Cooling via neutrinos***

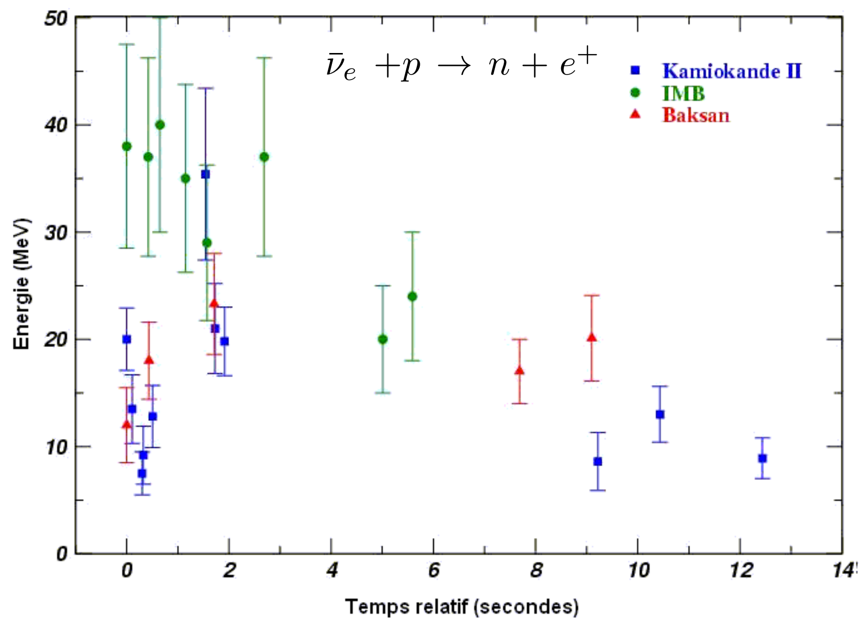
Star explodes

Neutrino burst, ~ 10 s

The only detection: SN1987A

- in the Large Magellanic Cloud, D=51.4 kpc
- Detected at O(1) Kt water/scintillator detectors

Bionta et al., PRL 58,1987, Hirata et al., PRL 58,1987, Alekseev et al. JETP Lett. 45 (1987)



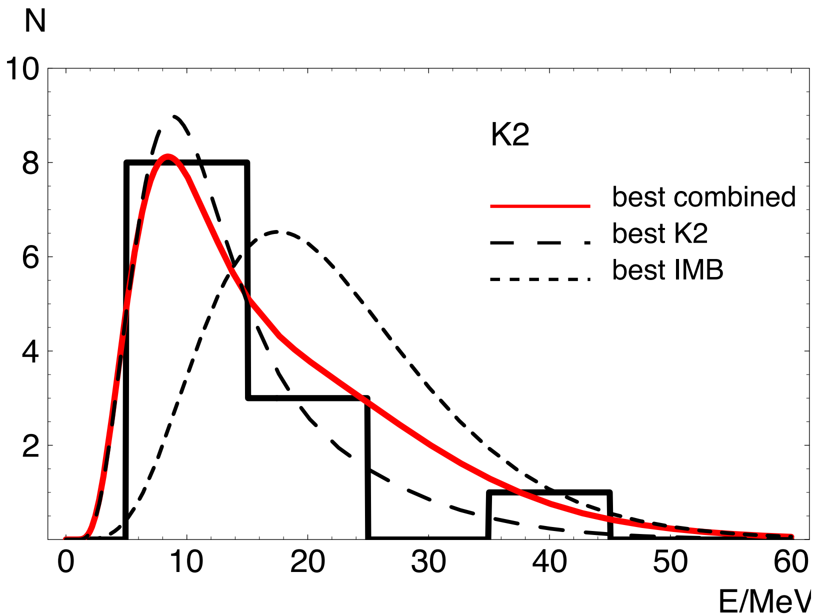


Figure: CL, Astropart.Phys. 26 (2006) 190-201

The *neutrinosphere*

- Neutrinos *thermalized* in ultra-dense matter
  - Surface emission
  - Fermi-Dirac spectrum, E ~ 10-15 MeV
- Neutrino cooling of proto-neutron star is most efficient
  - *gravitational* binding energy:
    $L_\nu \sim G\,M^2{}_f/R_f - G\,M^2{}_i/R_i \sim 3\;10^{53}$ ergs ($R_f \sim 10$ Km)
- Cooling timescale ~ neutrino diffusion time
  - Time ~ (size^2)/(mean free path) ~ 10 s

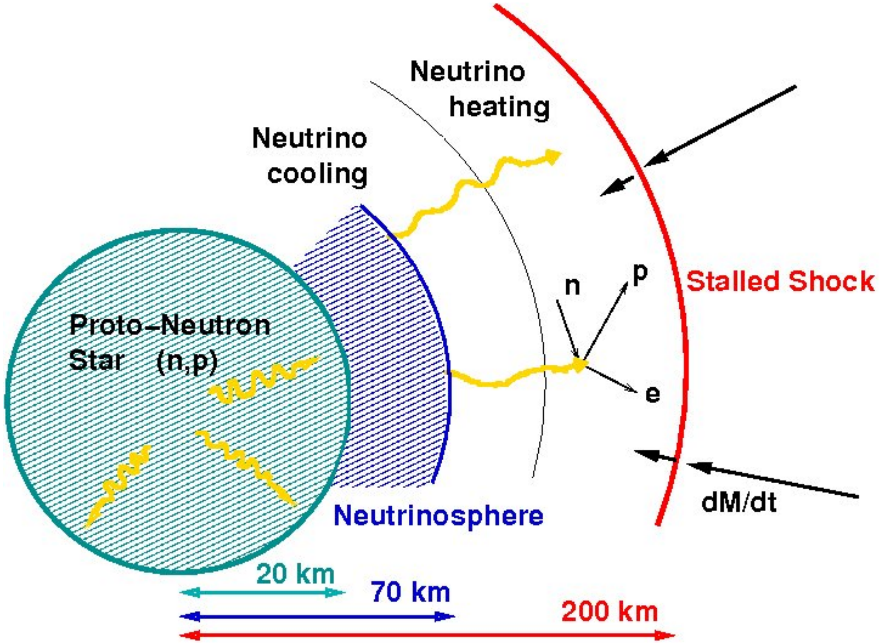


Figure: Amol Dighe, talk at WHEPP XV, 2017

The future: learning more in-depth

Theory has reached a new level of detail

We need new data to test the theory… ***When? What?***

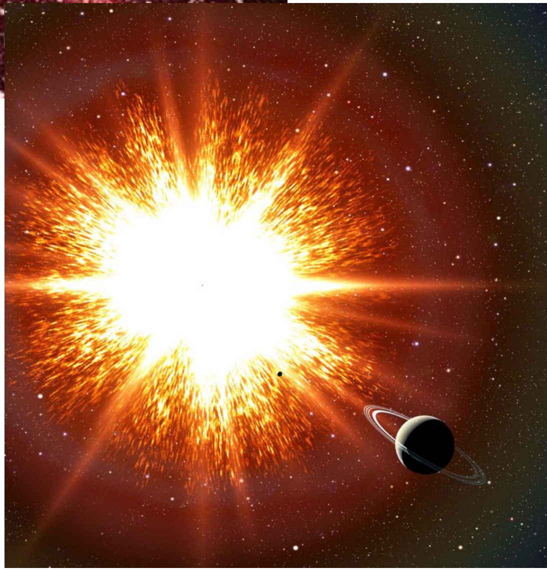
Within our lifetime....

Credit: ESA/Hubble, NASA

Guaranteed:
multiple SNe, (quasi-)diffuse flux

Credit: Anglo-Australian observatory

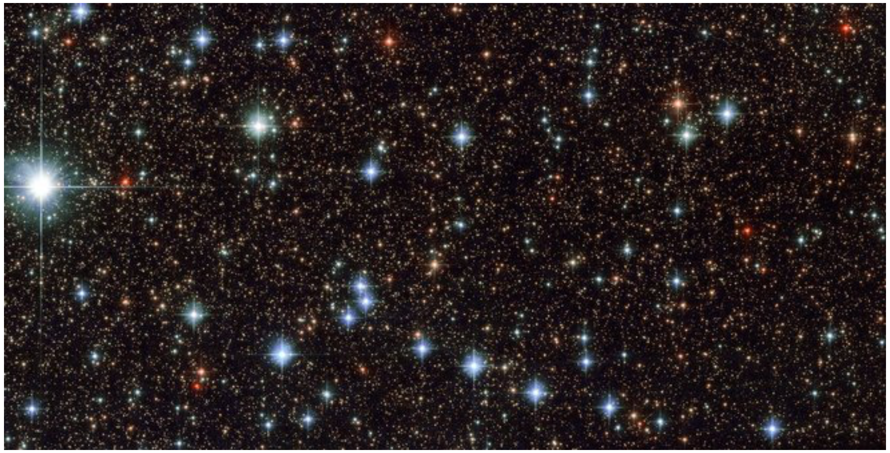
Possible:
single, galactic SN burst



Exceptional:
single, near-Earth
SN burst

SmithsonianScience.org

GUARANTEED: (QUASI-)DIFFUSE FLUX

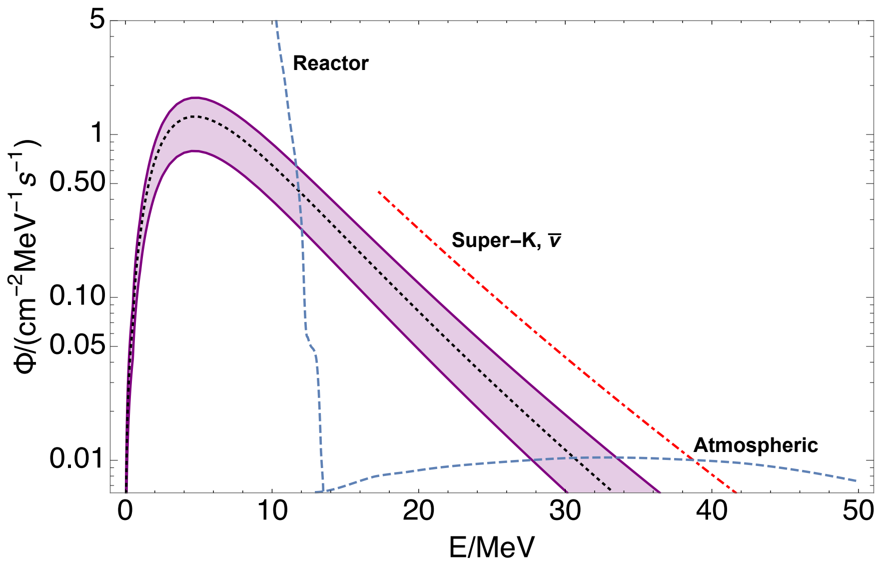


Diffuse Supernova Neutrino Background (DSNB)

- Whole sky flux; constant in time

$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int_{M_0}^{M_{\max}} \underbrace{dM}_{\text{Progenitor mass}} \int_0^{z_{\max}} dz\, \frac{\overbrace{\dot{\rho}_{SN}(z,M)}^{\text{SN rate}}\,\overbrace{F_{\nu_\beta}(E',M)}^{\textit{Propagated}\text{ neutrino flux}}}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$

$$M_0 \simeq 8M_{sun}$$
$$M_{max} \simeq 125M_{sun}$$



Bisnovatyi-Kogan & Seidov, Sov. Ast. 26 1982,
Krauss, Glashow and Schramm, Nature 310 (1984)

For **quasi-diffuse**, see Kistler et al., PRD **83**, 2008;
CL & Yang, PRD84 (2011)

Detectable within the next decade

- Main channel: $\bar{\nu}_e + p \to n + e^+$
  - Sensitivity is *background-limited*

- Under construction:
  - **SuperK-Gd** (50 kt), specific design for DSNB
    - Water + Gadolinium, for n-tagging
  - **JUNO** (Jiangmen Underground Neutrino Observatory) (17 kt)
    - Liquid scintillator

- detection will change from exceptional to *routine!*

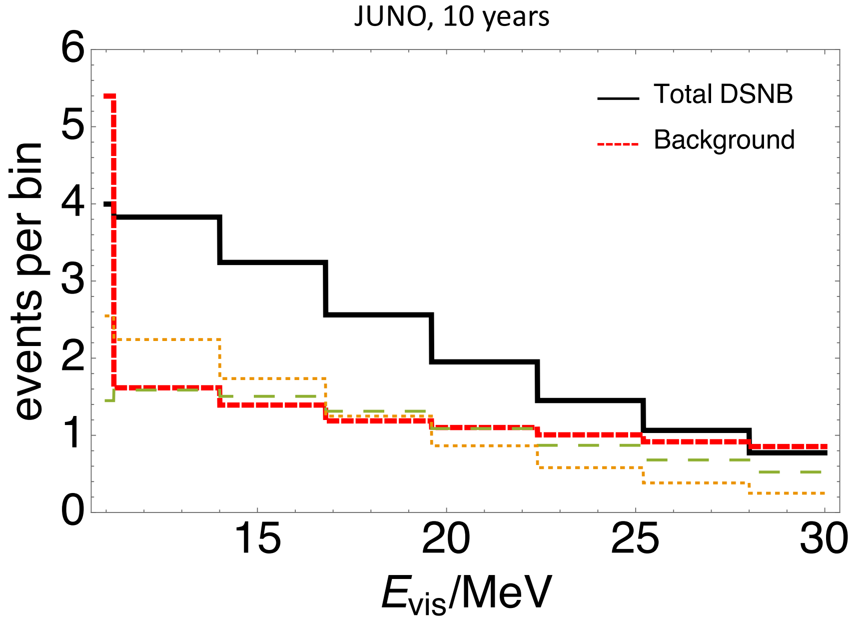


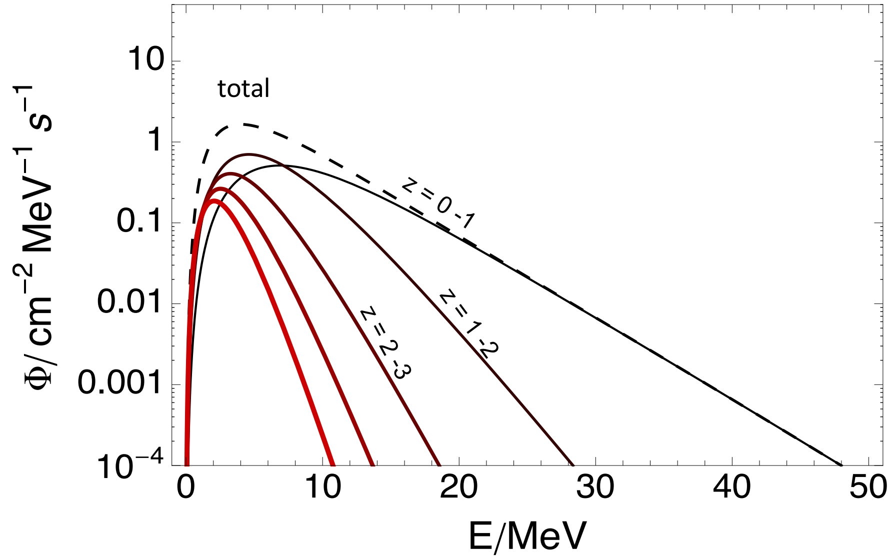
Figure: A. Priya and CL, JCAP 1711 (2017) no.11, 031

Beacom and Vagins, PRL93, 2004
Xu et al., J. Phys: Conf. Ser. 718 (2016)
An et al., J. Phys. G: Nucl.Part. Phys. 43 (2016) 030401.

Unique potential

- Strong *cosmological* component
  - Core collapse at high redshift?
  - evolution of SN rate (z-dependence)

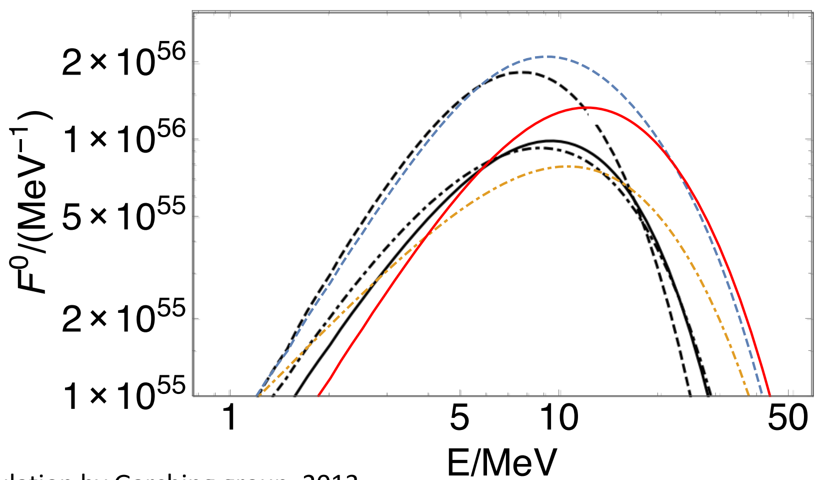
- Gives image of the *whole* SN population
  - Was SN1987A typical or exceptional?
  - Diversity of core collapses (ONeMg cores, black hole formation, …)



Ando & Sato, New J.Phys. 6 (2004) 170

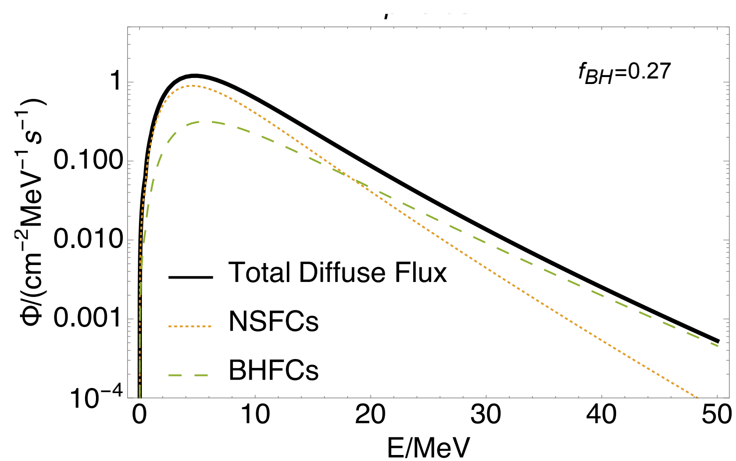
Neutrinos from a failed supernova

- Failed supernovae are *brighter* in neutrinos
  - Direct collapse into black hole, no explosion
  - Higher luminosity, hotter spectrum
  - Can *dominate the DSNB* flux if more than ~30% of all collapses



Simulation by Garching group, 2013.

Black: exploding SN, 11.2 Msun prog.;
Color: failed SN, 40 Msun prog.
dashed, solid, dot-dashed: ν_e, $\bar{\nu}_e$ and ν_x



Figures from A. Priya and CL, JCAP 1711 (2017) no.11, 031

See also: CL, PRL 102 (2009);
Lien et al., PRD81 (2010);
Keehn & CL, PRD85 (2012);
Mathews et al., arXiv:1405.0458
Horiuchi et al., *MNRSAS* 475 (2018) 1, 1363-1374
Moller, Suliga, Tamborra and Denton, *JCAP* 05 (2018) 066

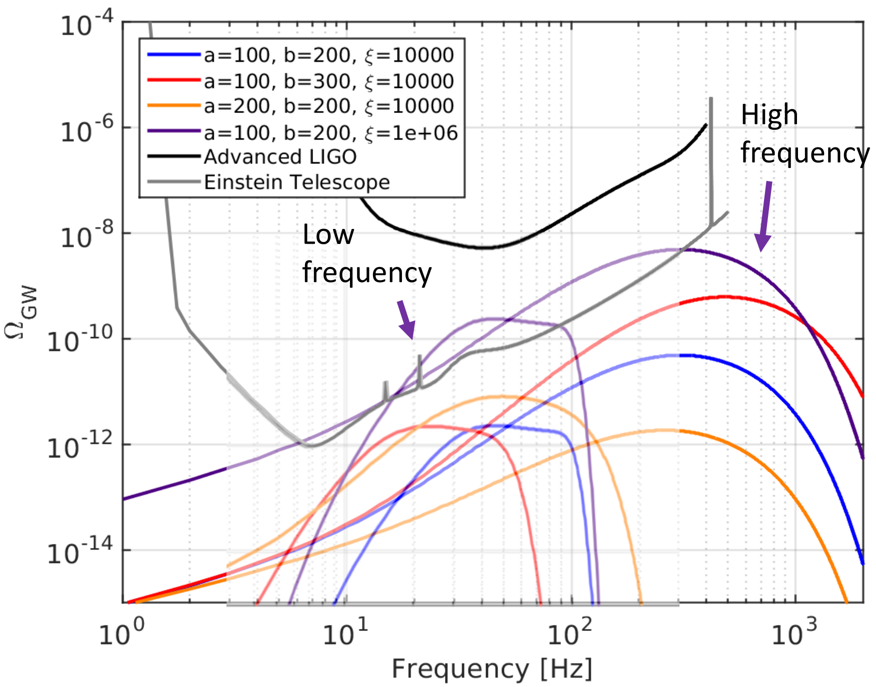
Multi-messenger: stochastic GW background

- Orders of magnitude uncertainty
  - Possible low frequency component (SASI?)
  - Failed SNe : black hole ringdown
  - Sensitivity to extensions of general relativity

    Buonanno et al., PRD72 (2005) 084001,
    K. Crocker et al., PRD92 (2015) no.6, 063005,
    K. Crocker et al., PRD95 (2017) no.6, 063015
    Du, PRD 99, 044057 (2019)

- Might be detectable at next generation GW observatories

- *Interplay with neutrinos?*



Adapted from K. Crocker et al., PRD95 (2017) no.6, 063015

POSSIBLE: GALACTIC SUPERNOVA

Proto-neutron star (PNS) evolution

- Direct narrative of events at R < 200 Km

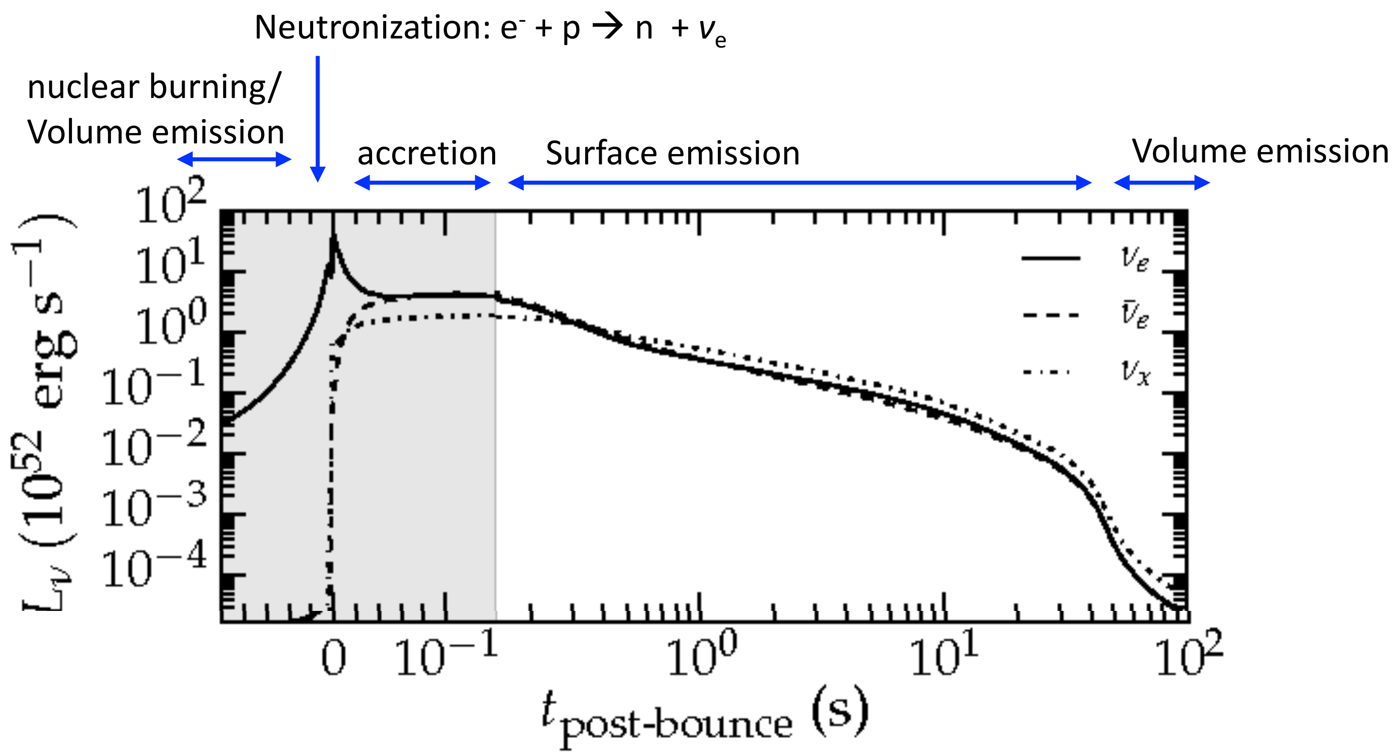


Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

Accretion: Standing Accretion Shock Instability (SASI)

- Stalled shock wave
- Deformation, sloshing of shock front
    - Fluctuating ν emission rate

  Blondin, Mezzacappa, DeMarino, ApJ. 584 (2003); Scheck et al., A&A. 477 (2008)

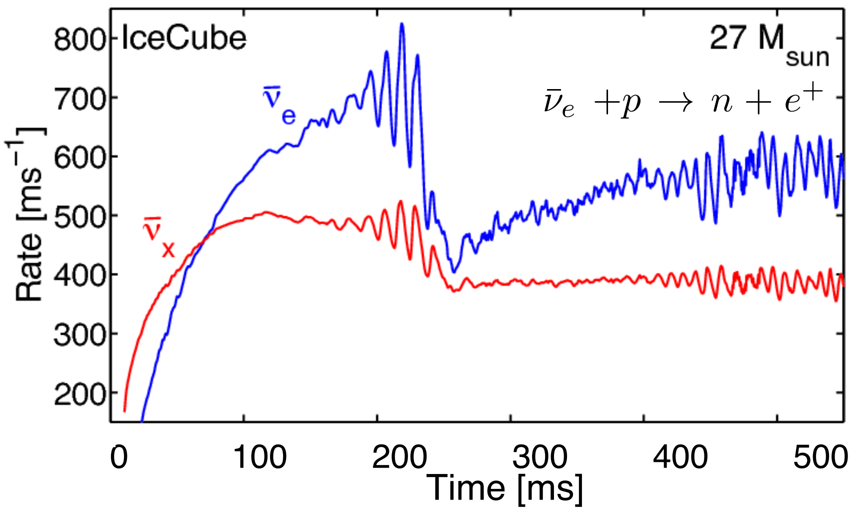


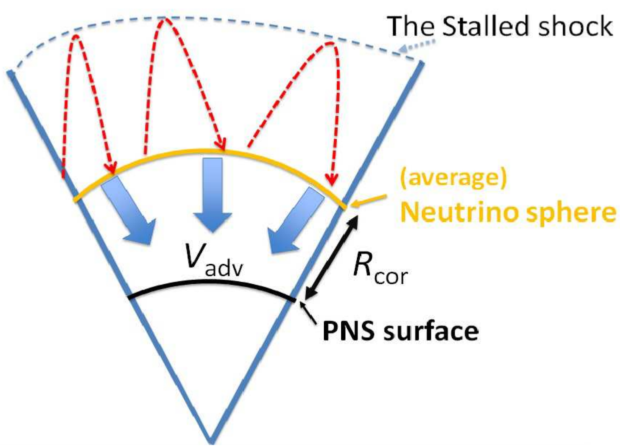
Figure from Tamborra et al., arXiv:1307.7936

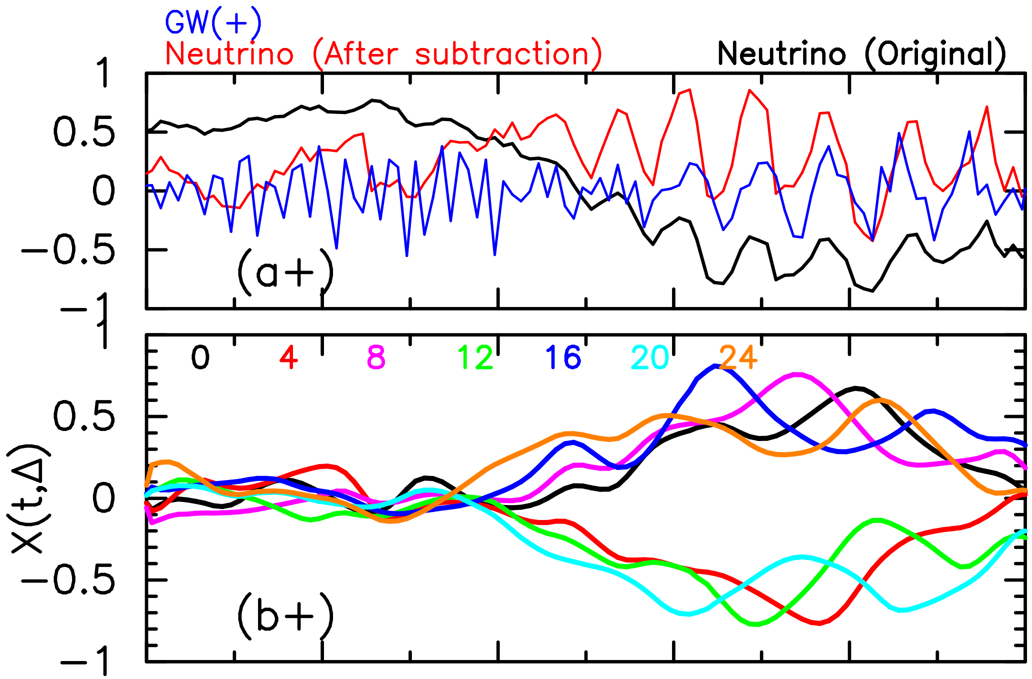
- Strong in 3D with detailed neutrino transport

Tamborra et al., arXiv:1307.7936
See also Lund et al., PRD 82, (2010), PRD 86, (2012)
Kuroda, Kotake, Hayama and Takami, ApJ, 851:62, 2017
Walk, Tamborra, Janka and Summa, *PRD* 98 (2018) 12, 123001, PRD 100, 063018 (2019)

multi-messenger: neutrinos and GW

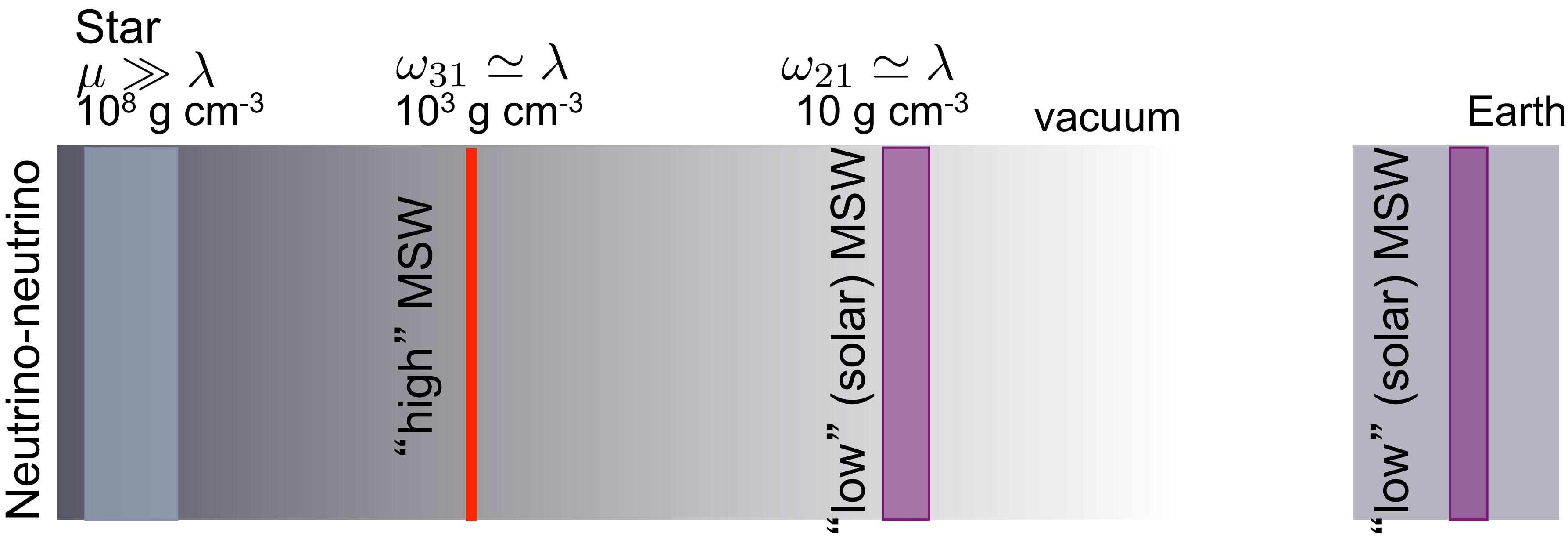
- SASI signature in gravitational waves, potentially observable
  - Multi-messenger analysis can enhance sensitivity
  - Phase shift due to distance between nu-sphere and PNS surface





Kuroda, Kotake, Hayama and Takami, ApJ, 851:62, 2017

Oscillations: *unique* interplay of frequencies



- Kinetic
- *ν*-e potential
- *ν*-*ν* potential

$$\omega_{ij} = \Delta m^2_{ij}/2E$$

$$\lambda = \sqrt{2} G_F n_e \propto R^{-3}$$

$$\mu \simeq \sqrt{2} G_F n_\nu^{\mathrm{eff}} \propto R^{-4}$$

Wolfenstein, PRD 17 1978, Mikheyev & Smirnov, Yad. Fiz. 42, 1985
See also: Dighe & Smirnov, Phys.Rev. D62 (2000)

Vacuum + matter + self-interaction

$$\mathsf{H}_E = \mathsf{H}_E^{\mathrm{vac}} + \mathsf{H}_E^{\mathrm{m}} + \mathsf{H}_E^{\nu\nu}$$

$$\mathsf{H}_E^{\mathrm{vac}} = \mathsf{U}\,\mathrm{diag}\left(-\frac{\omega_{21}}{2}, +\frac{\omega_{21}}{2}, \omega_{31}\right)\mathsf{U}^{\dagger}\ ,$$

$$\mathsf{H}^{\mathrm{m}} = \sqrt{2}G_{\mathrm{F}}\ \mathrm{diag}(N_e, 0, 0)$$

$$\mathsf{H}_E^{\nu\nu} = \sqrt{2}G_F \int dE'(\rho_{E'} - \bar{\rho}_{E'})(1 - \cos\theta)$$

θ angle between incident momenta

$$\Delta m^2_{31} > 0 \quad \mathrm{normal\ hierarchy, NH}$$
$$\Delta m^2_{31} < 0 \quad \mathrm{inverted\ hierarchy, IH}$$

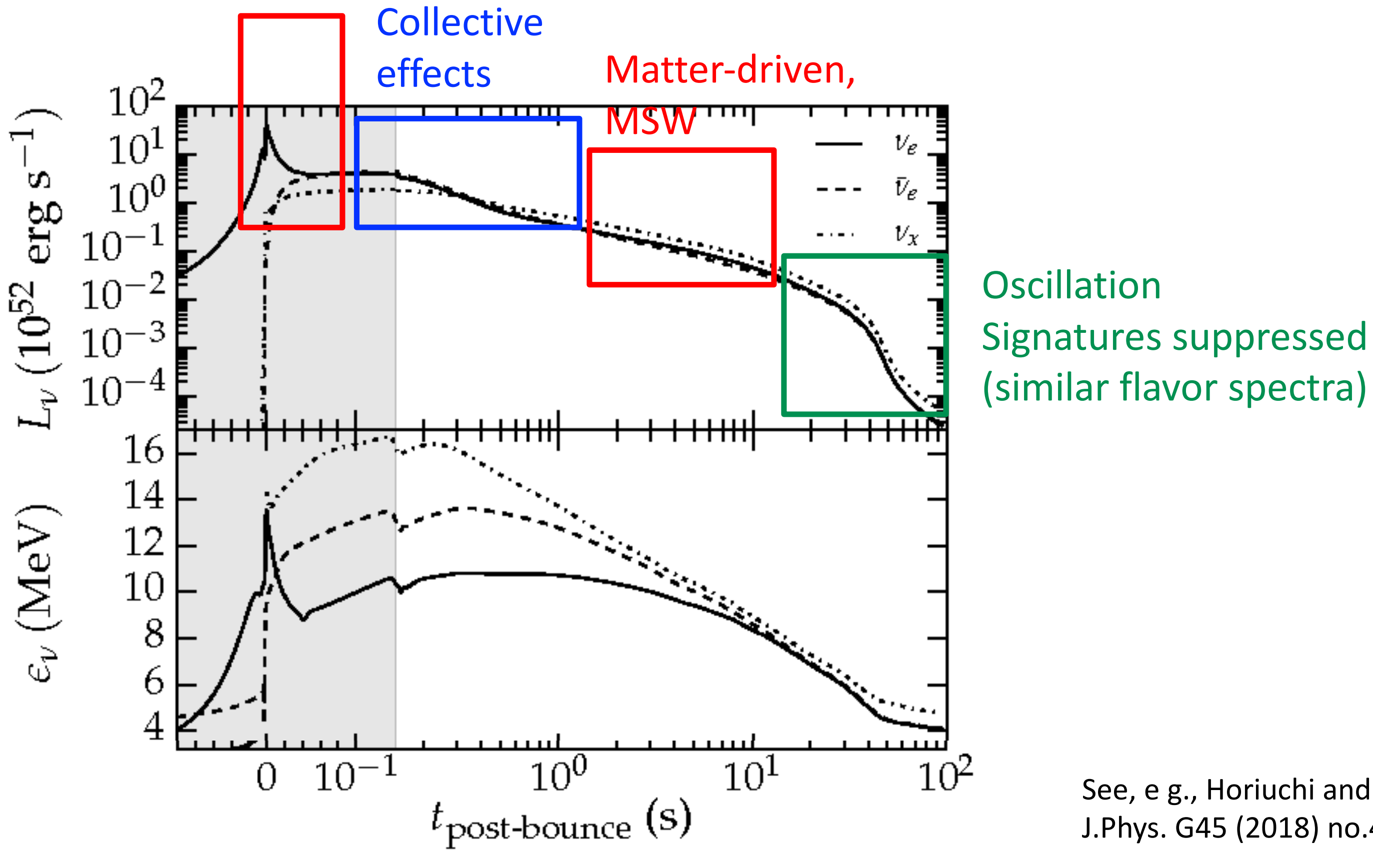
- Nu-nu interaction : non-linear, collective effects
  - Spectral splits/swaps, no general solution

See talk by A. Mirizzi at Neutrino2020

Seminal works: Duan, Fuller & Qian, PRD74 (2006), Duan et al., PRD74 (2006)

Time-dependent pattern

- Potential to disentangle different oscillation mechanisms



See, e g., Horiuchi and Kneller, J.Phys. G45 (2018) no.4, 043002

Robust oscillation signatures

- Distinguishable from stellar physics effects

Suppression of ν_e neutronization peak
due to θ_{13}-driven MSW resonance,
For Normal mass hierarchy

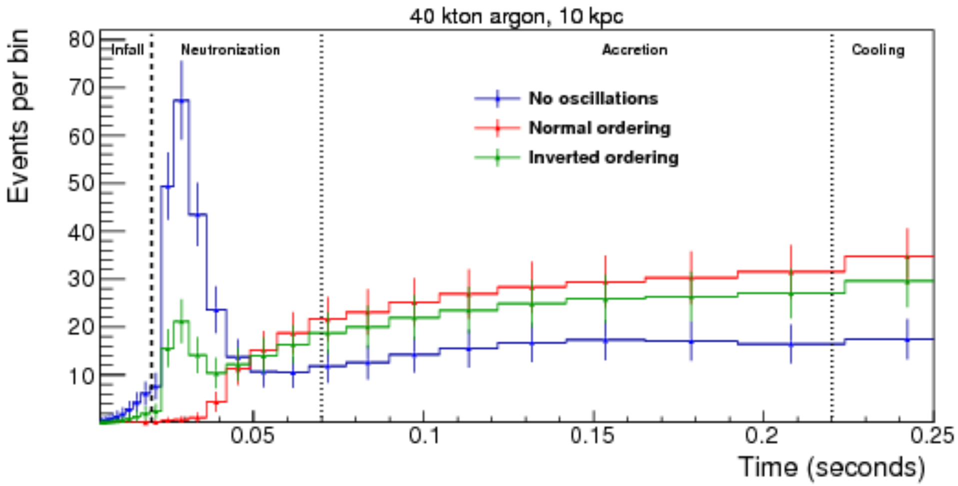
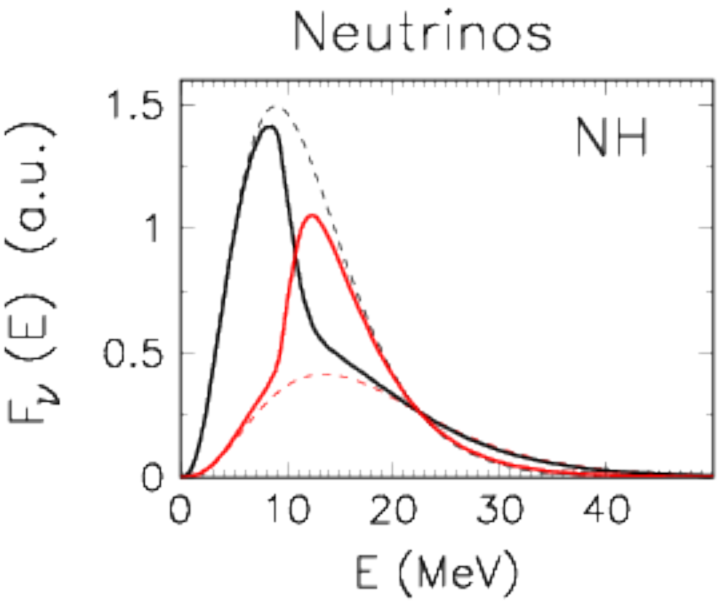


Figure from K. Scholberg, J.Phys. G45 (2018) no.1

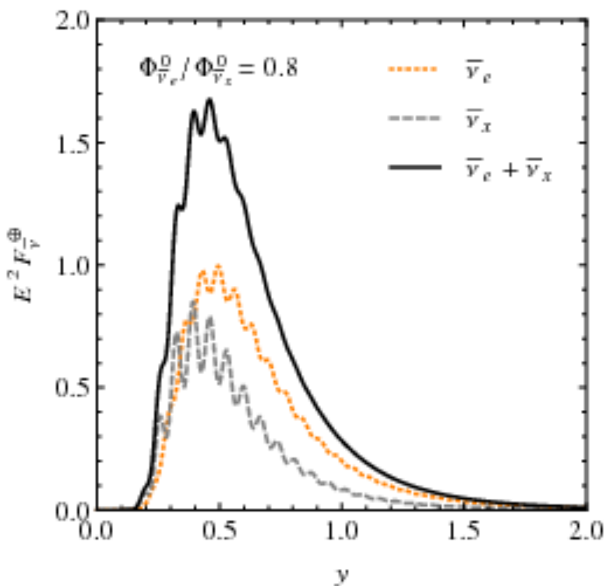
Spectral splits due to collective effects

Figure from Chakraborty and Mirizzi,
PRD90 (2014) no.3, 033004

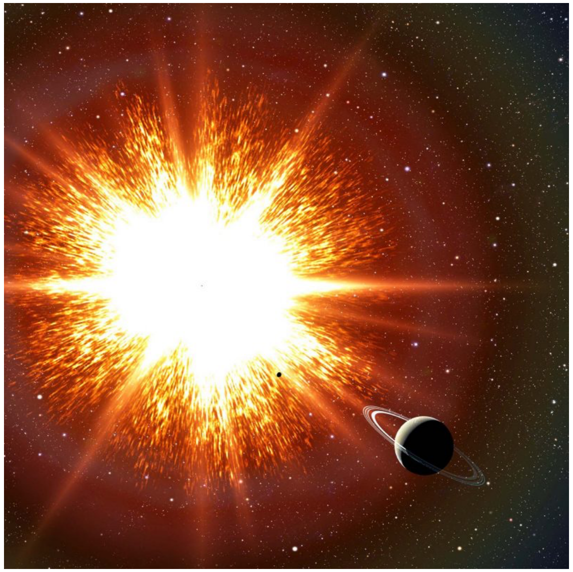


Electron flavor re-generation inside the Earth; sensitive to spectral difference of states in the θ_{12}-driven MSW resonance

Figure from Borriello et al., PRD86 (2012) 083004



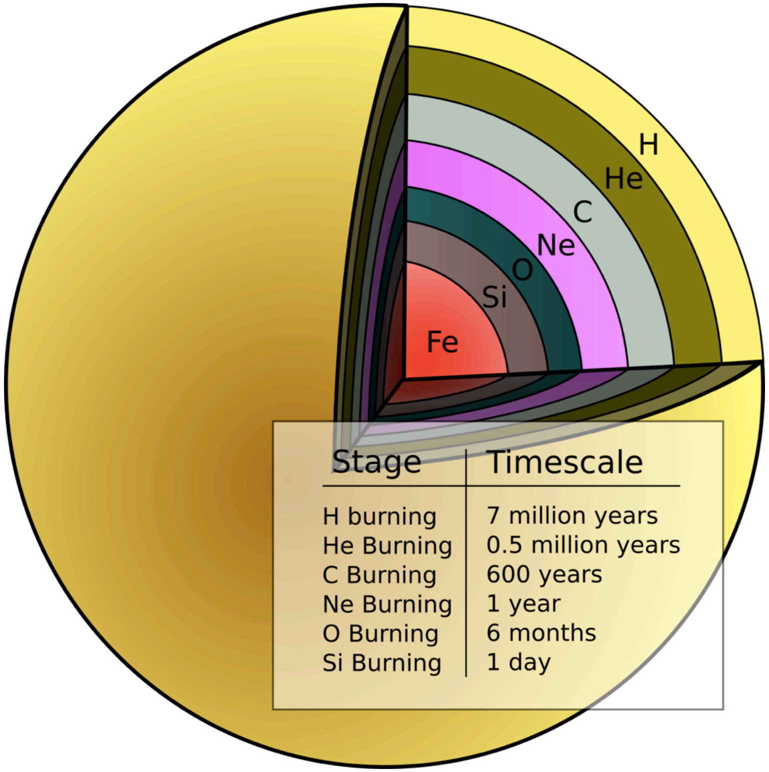
EXCEPTIONAL: NEAR-EARTH SUPERNOVA



Pre-supernova neutrinos

- Last stages of fusion chain
  - rapid evolution of isotopic composition
  - increase of core density, temperature
  - *increase of neutrino emission*
    - *detectable!*

Odrzywolek, Misiaszek, and Kutschera, Astropart. Phys. 21, 303 (2004)

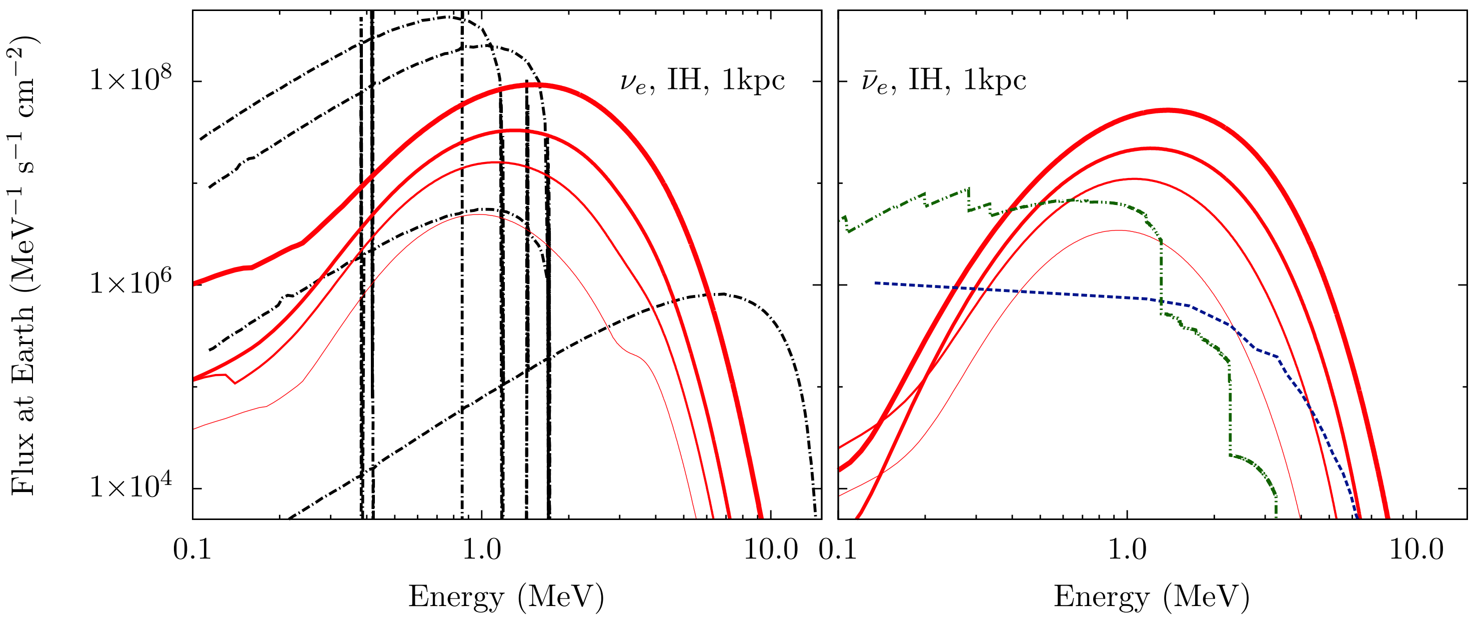


A. C. Phillips, *The Physics of Stars, 2nd Edition* (Wiley, 1999)

Itoh, Hayashi, Nishikawa and Kohyama, 1996, ApJS, 102, 411
Kato, Azari, Yamada, et al. 2015, ApJ, 808, 168
Kato, Yamada, Nagakura, et al. 2017, arXiv:1704.05480
Simpson et al., Astrophys.J. 885 (2019) 133
Guo et al., *PLB* 796 (2019)
Kato, Hirai and Nagakura, arxiv:2005.03124
Li et al. JCAP 05 (2020) 049
Mukhopadhyay, CL, Timmes and Zuber, 2004.02045

Detectability

D=1 kpc ; dashed/dotted: solar, reactor, atmospheric



t4	0 hrs
t3	-1 hr
t2	-2 hrs
t1	-12 hrs

K .M. Patton. CL, R. Farmer and F. X. Timmes, ApJ 851 (2017) no.1, 6

spectacular signal for Betelgeuse (D=200 pc), in ~6 hrs:

- ~ 50 events at DUNE
- ~ 800 events at HyperK (E>4.5 MeV)
- *> 2000 events at JUNO*

HIGHLIGHT

Neutrino signatures of Standing Accretion Shock Instability (SASI)

Zidu Lin, CL, M. Zanolin, K. Kotake and C. Richardson, PRD 101, 123028 (2020)

SASI or no-SASI?

- SASI or statistical fluctuations? $s^2(t_j) = N(t_j)$

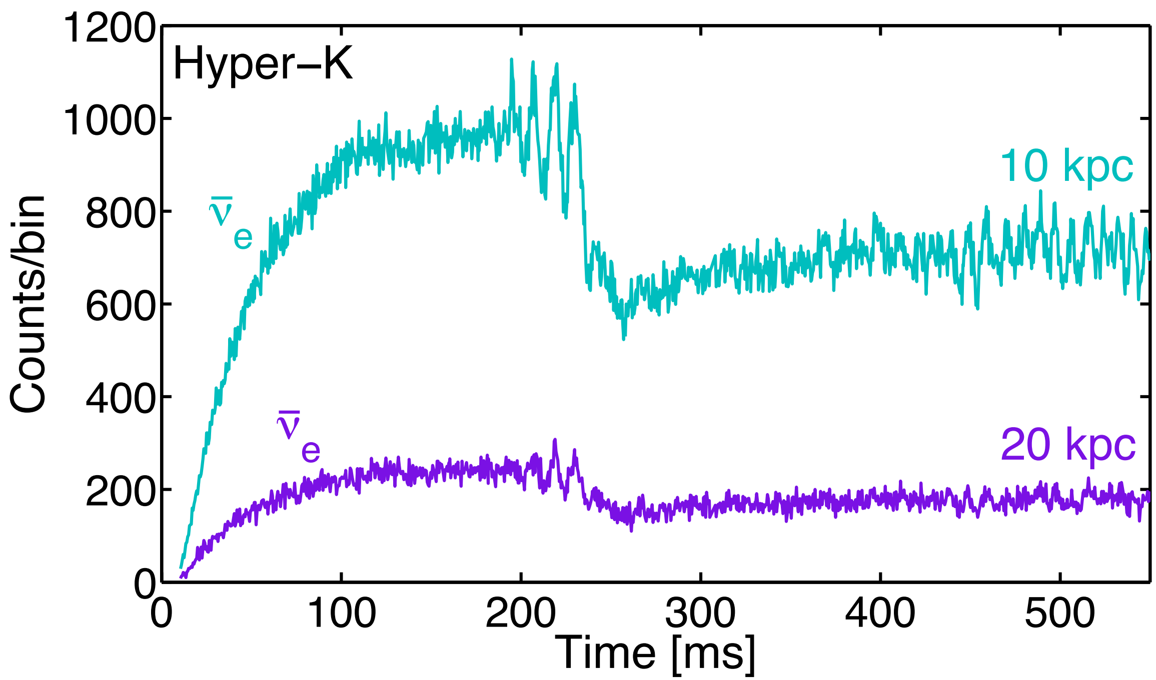
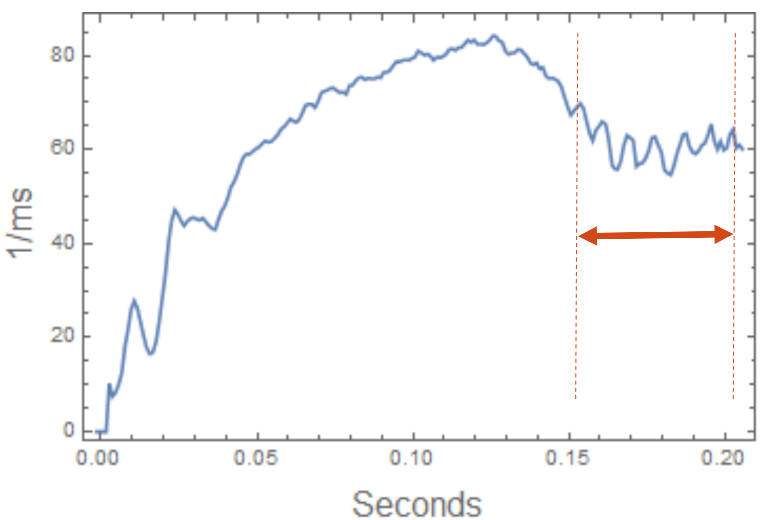


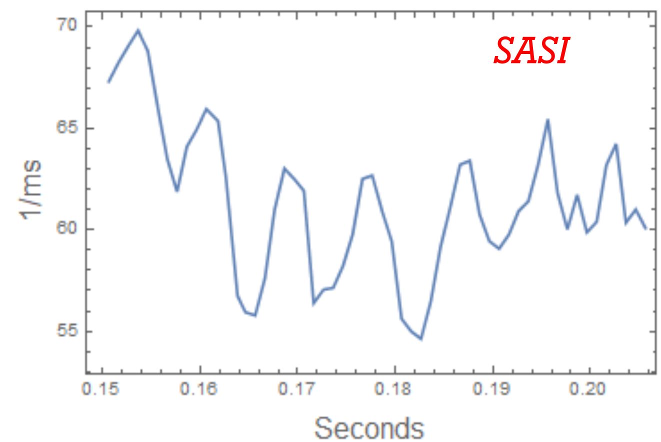
Figure from Tamborra et al., arXiv:1307.7936

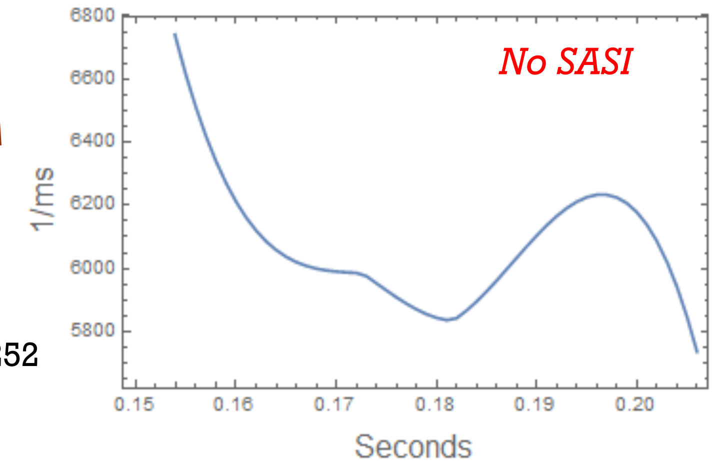
Constructing a SASI-meter: possibilities…

Zidu Lin, CL, M. Zanolin, K. Kotake and C. Richardson, PRD 101, 123028 (2020)



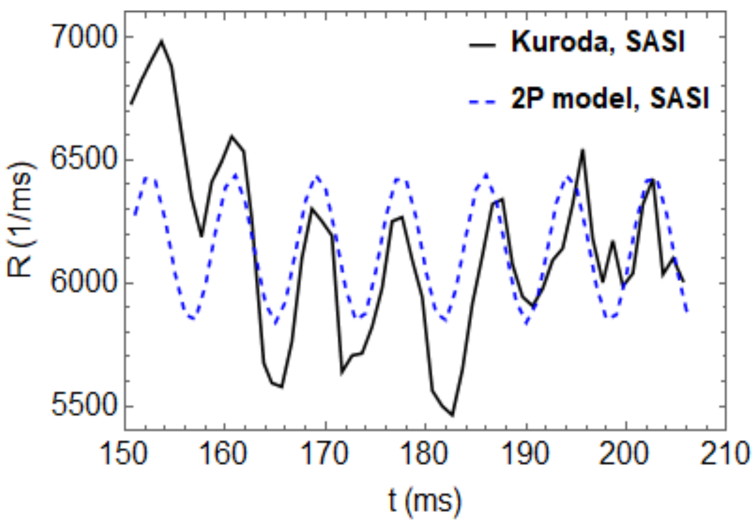
T. Kuroda, K. Kotake, K. Hayama, T. Takiwaki, arXiv:1708.05252

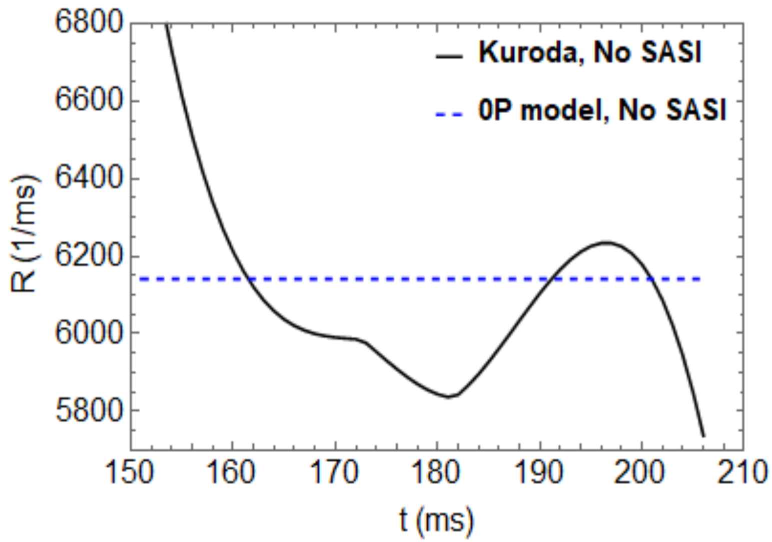




Templates, time domain

- Simplified model which shows fundamental characteristics extracted from groups of models with SASI/without SASI

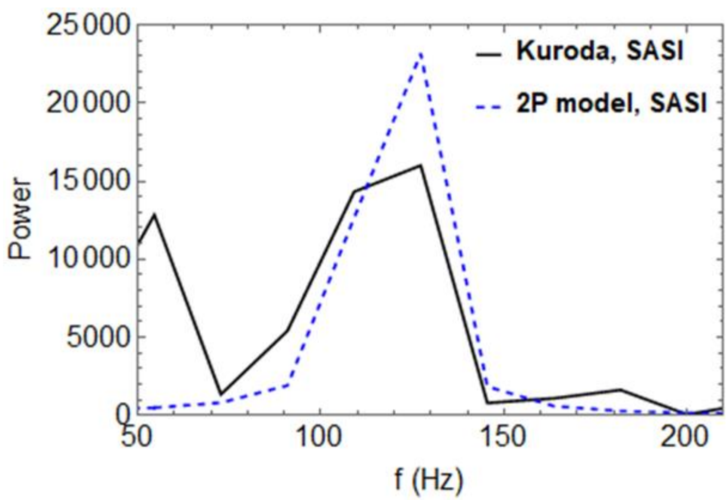


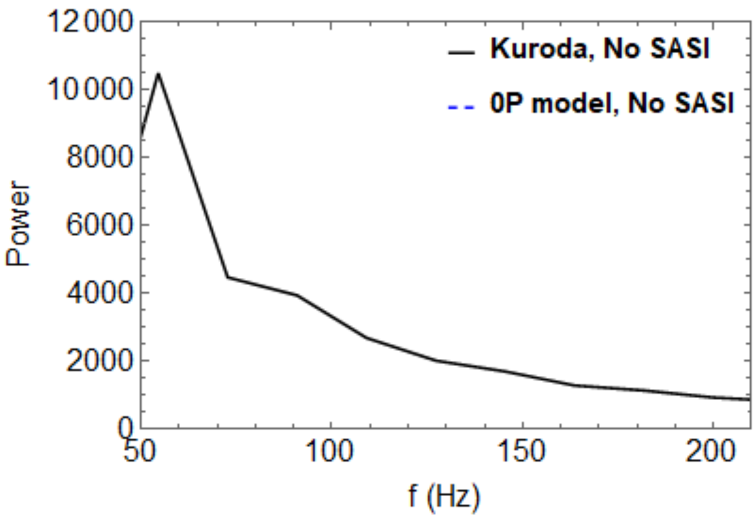


R(t) = (A−n)(1 +a*Sin(2π*f*t)) +n

R(t) = A

- In frequency domain (discrete Fourier transform):





The SASI-meter

- Test-statistics: likelihood ratio *in frequency space*
  - Commonly used in GW community

$$L(\tilde{\mathcal{P}}, \Omega) = \prod_{k=3}^{12} Prob(\tilde{\mathcal{P}}_k, P_k(\Omega))$$

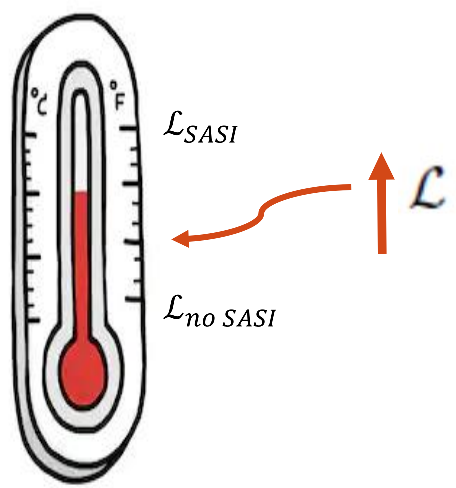
(frequency cut: 54 Hz < f < 216 Hz)

$$\mathcal{L}(\tilde{\mathcal{P}}) = \frac{Max_{\Omega}[L(\tilde{\mathcal{P}}, \Omega)]}{Max_{\Omega_0}[L(\tilde{\mathcal{P}}, \Omega_0)]}$$

Fit using R(t) = (A–n)(1 +a*Sin(2π*f*t)) +n

Fit using R(t) = A

This is our
“SASImeter” !!

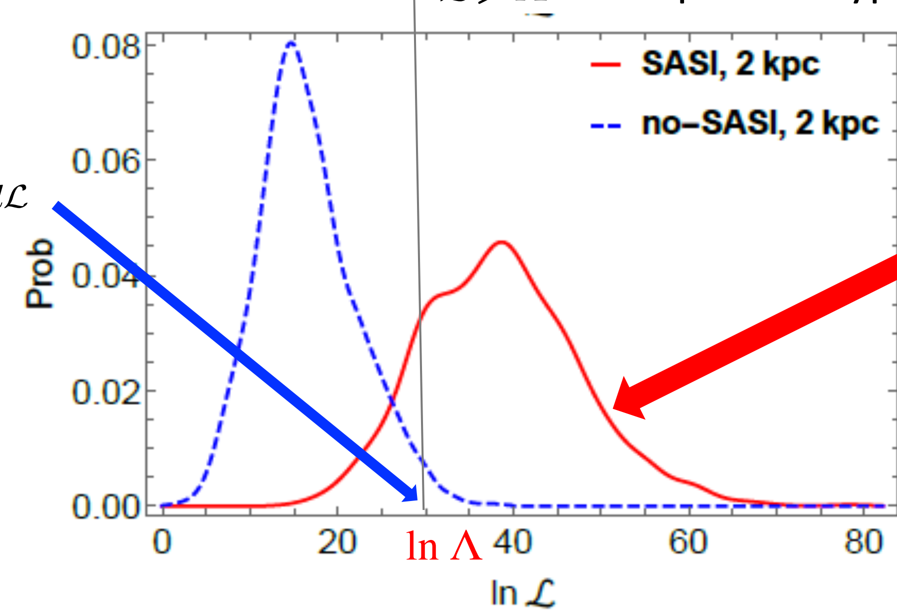


- The SASI-meter is “calibrated” using a numerical model:
  - Statistical distribution of $\mathcal{L}$ due to statistical fluctuations in numbers of events in each bin

$\mathcal{L} > \Lambda$: accept SASI hypothesis

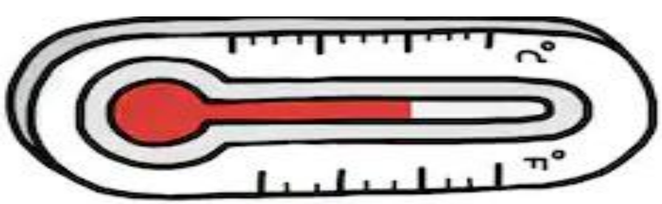
Probability of **false identification**:

$$P_{FI} = \int_{\mathcal{L}>\Lambda} Prob(\mathcal{L}|nS)d\mathcal{L}$$



Probability of **detection**:

$$P_D = \int_{\mathcal{L}>\Lambda} Prob(\mathcal{L}|S)d\mathcal{L}$$

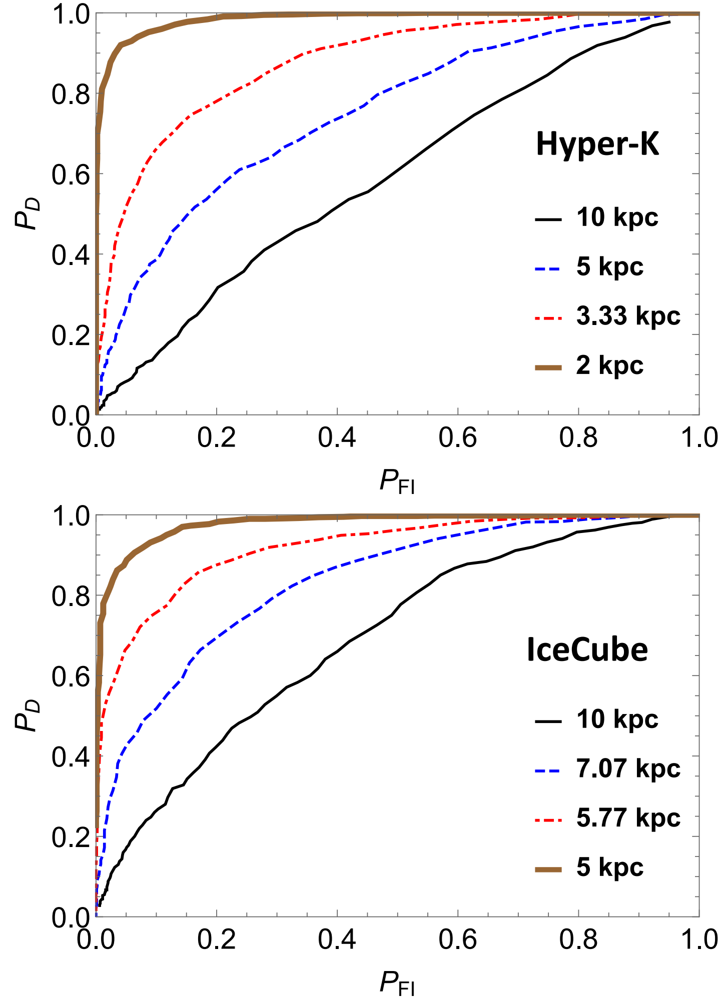


How effective is the SASI-meter?

- Receiver Operating Characteristic curve (ROC):

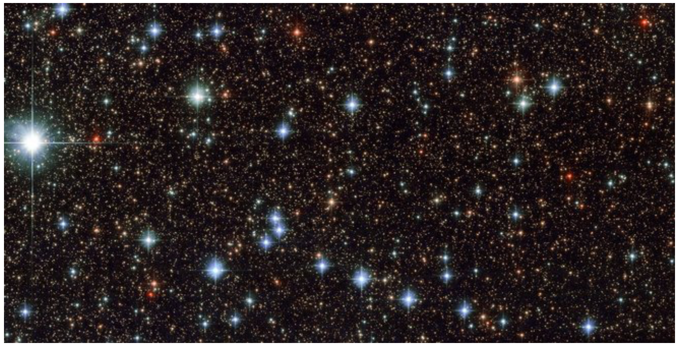
$$P_D = \int_{\mathcal{L}>\Lambda} Prob(\mathcal{L}|S)d\mathcal{L} \ ,$$
$$P_{FI} = \int_{\mathcal{L}>\Lambda} Prob(\mathcal{L}|nS)d\mathcal{L}$$

- Detectability distance: somewhere for which P_D is large and P_{FI} is small
  - E.g., D<3 kpc for Hyper-K, D<6 kpc for IceCube



CONCLUSIONS AND OPEN QUESTIONS

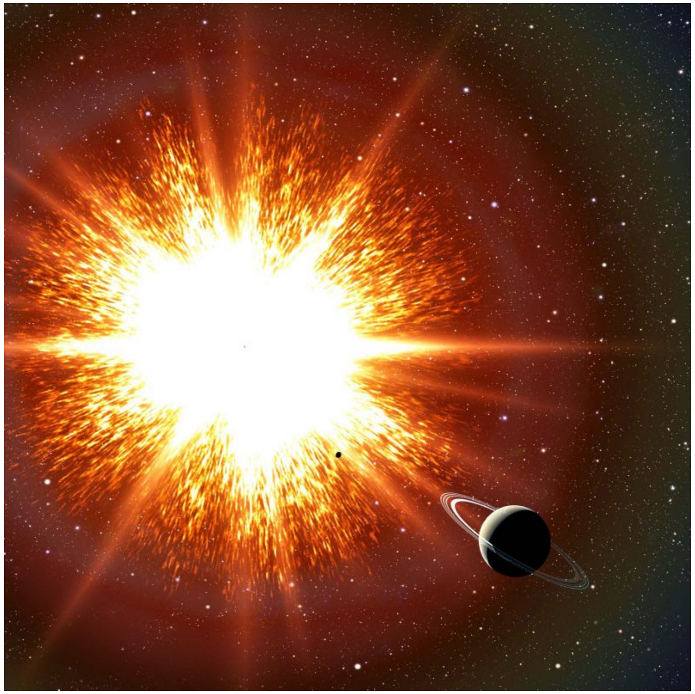
The future is bright for SN neutrinos

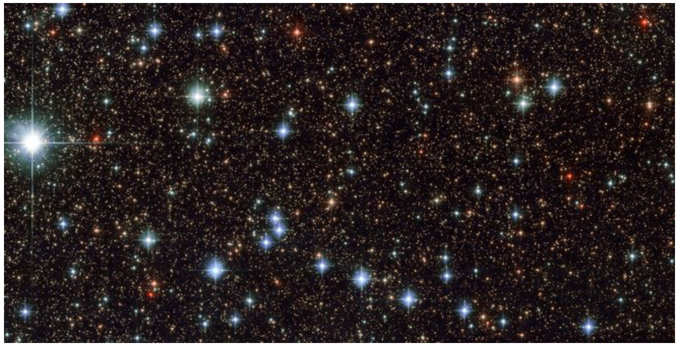


- *The wait for new data is almost over*
  - Guaranteed: diffuse flux detection
  - Transition from rare event to constant data-taking
  - Will reveal diverse picture

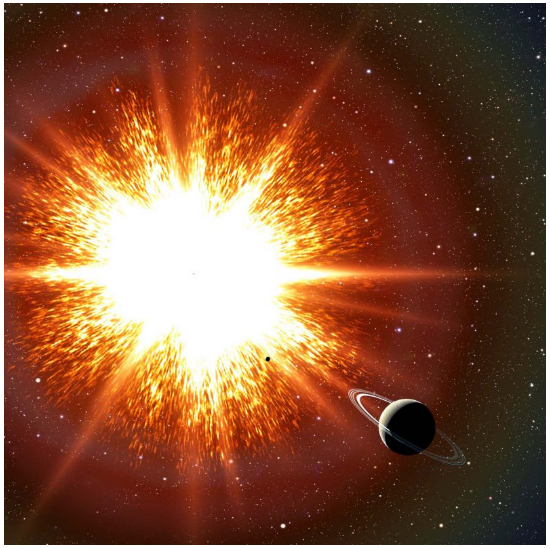
- There will be a galactic supernova detection
  - Possible, same probability every day
  - First time detailed narrative of collapse, shock propagation, PNS cooling

- Betelgeuse could collapse at any time
  - You will have a few hours to prepare for the show
  - Watch terminal stellar evolution in real time





Thank you!



BACKUP

Diversity: *failed* supernovae

- collapse *directly* into a black hole, *no explosion!*
  - ~10 - 40% of collapses

- Supported by:
  - numerical simulations
  - Problem of missing red supergiants
  - Evidence of a disappearing star (a “survey about nothing”)

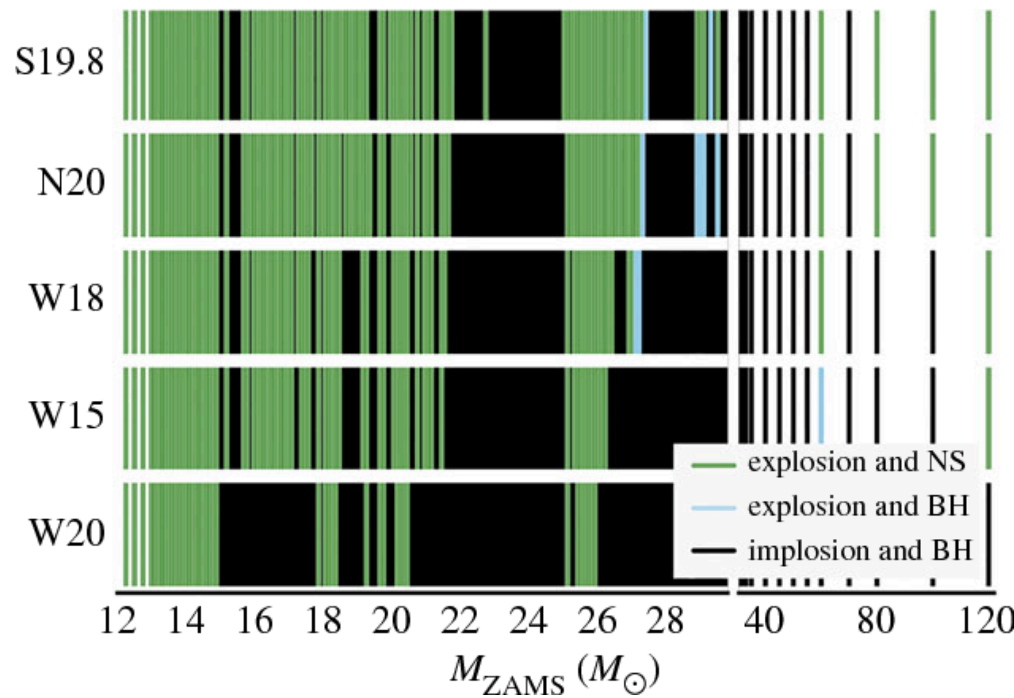


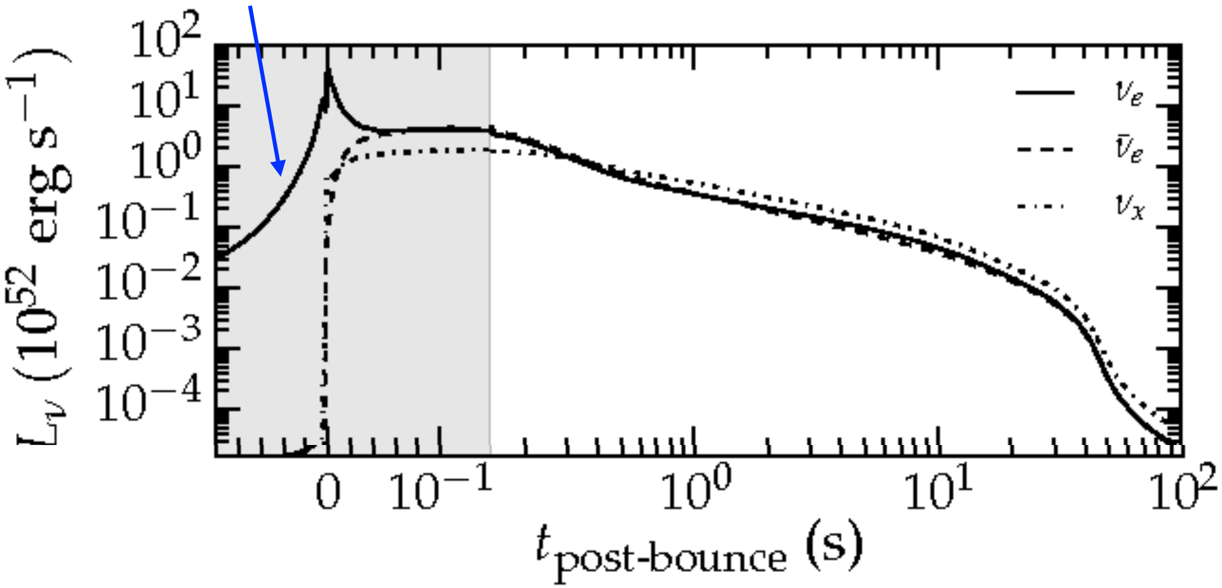
Figure from Sukhbold et al., Astrophys.J. 821 (2016) no.1, 38

See also works by:
E. O’Connor and C. D. Ott,
Pejcha and Thompson,
Ertl, Janka, Woosley, Sukhbold and Ugliano,
Hudephol and Janka
Kuroda, Takami, Kotake, Theielemann

Horiuchi et al., MNRAS Lett. 445 (2014) L99
Kochanek, ApJ 785 (2014) 28
Kochanek et al. ApJ 684 (2008) 1336
Adams et al., MNRAS, 468, 4, p. 4968-4981

Pre-supernova neutrinos!

nuclear burning/
Volume emission



Accretion: Standing Accretion Shock Instability (SASI)

- Stalled shock wave
- Deformation, sloshing of shock front
  - Fluctuating ν emission rate

    Blondin, Mezzacappa, DeMarino, ApJ. 584 (2003); Scheck et al., A&A. 477 (2008)

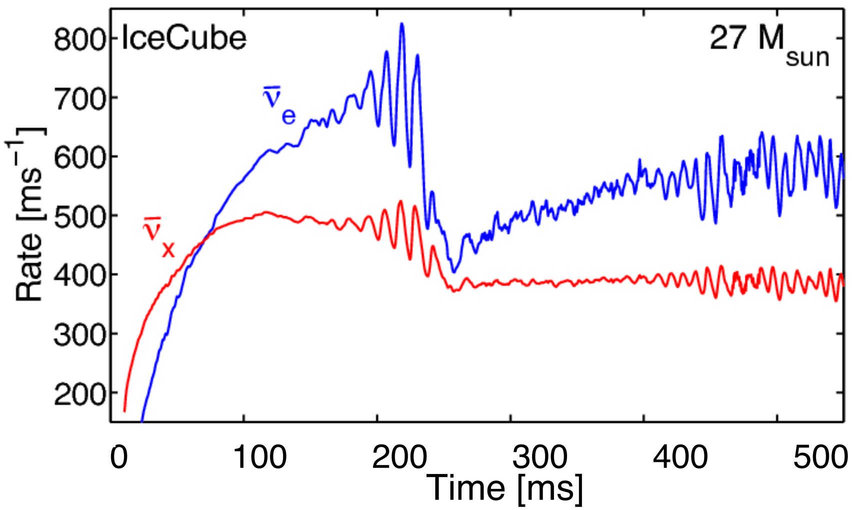
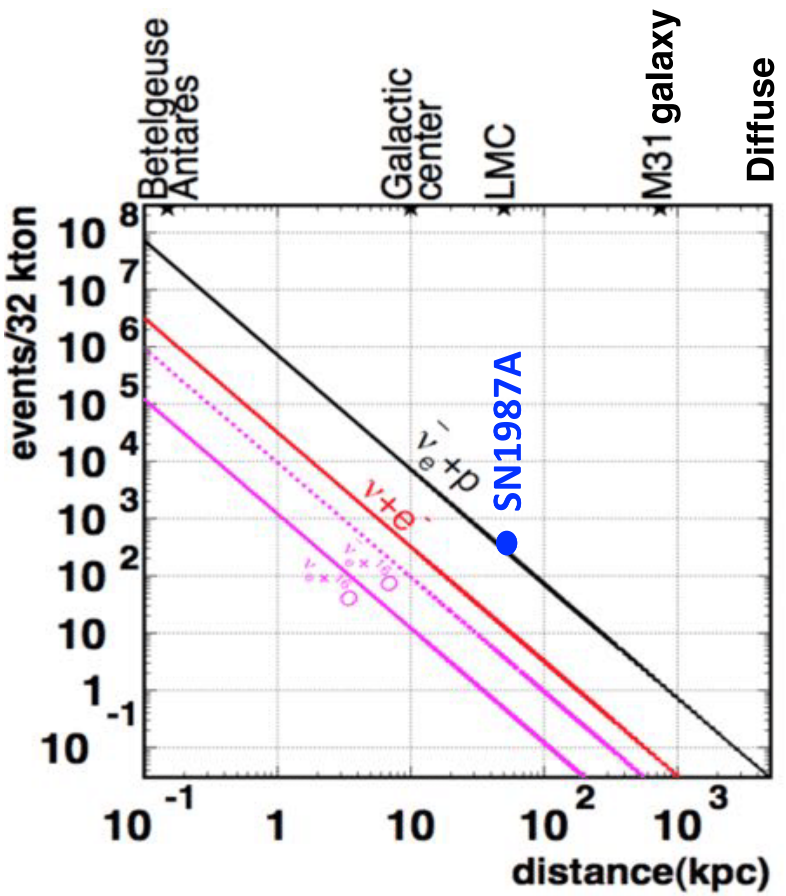


Figure from Tamborra et al., arXiv:1307.7936

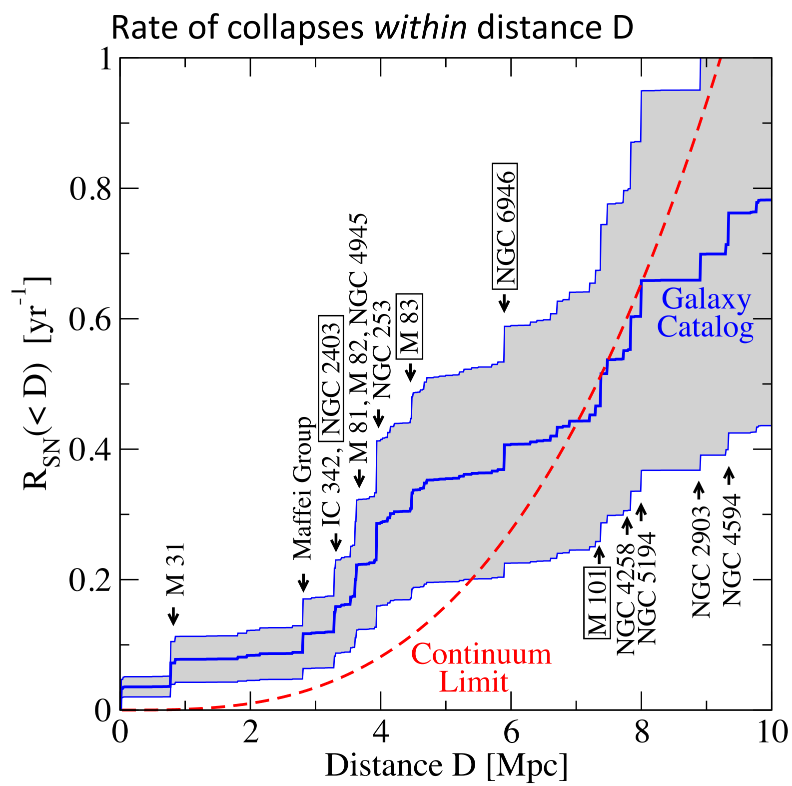
- Strong in 3D with detailed neutrino transport

Tamborra et al., arXiv:1307.7936
See also Lund et al., PRD 82, (2010), PRD 86, (2012)
Kuroda, Kotake, Hayama and Takami, ApJ, 851:62, 2017

High (low) statistics, low (high) probability



Pablo Fernandez, Super-Kamiokande coll., PhD thesis, 2017.

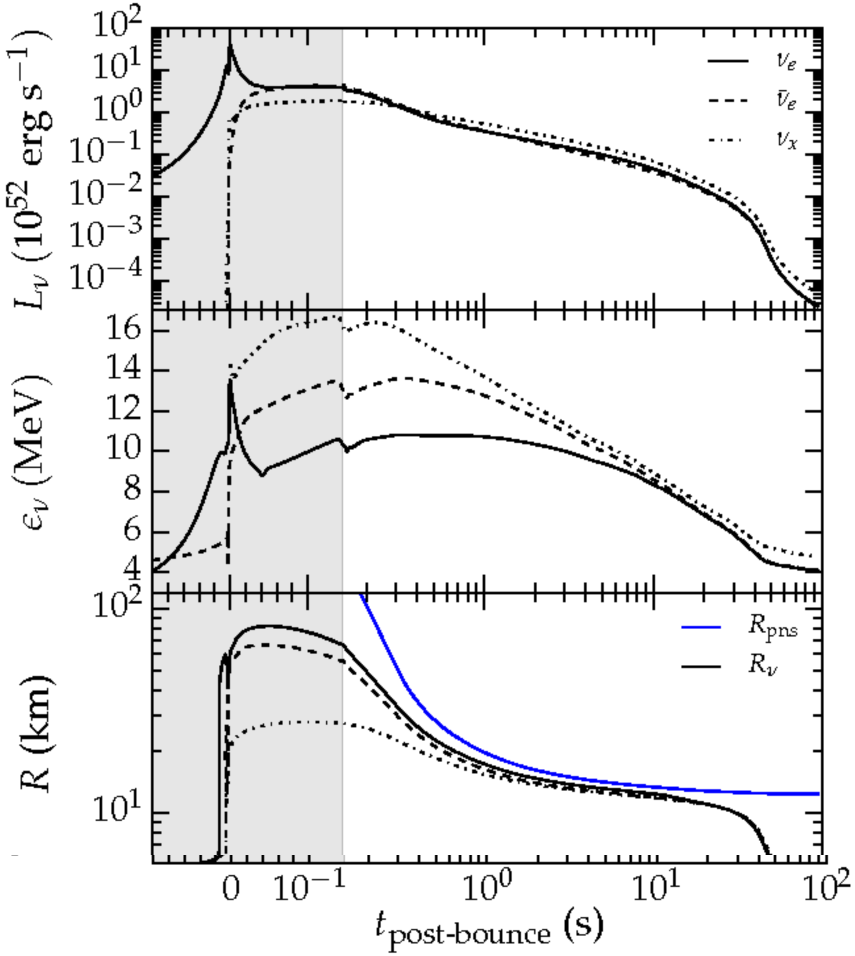


Ando, Beacom & Yuksel, PRL 95 (2005)

Late time: volume emission

- Nu-sphere recedes; disappears at t~40 s.
  - transition to transparency, *volume emission*
- *Direct* sensitivity to ν production processes
  - Properties of nuclear matter in PNS
- Potential to measure PNS radius

Gallo Rosso, Abbar, Vissani and Volpe, arxiv:1809.09074



Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017
See also Fischer et al., 1112.3842 ; Pons et al., Phys.Rev.Lett.86,2001

Early alert!

- Days/hours to:
  - Optimize neutrino detectors for upcoming burst
  - Point directional detectors (telescopes, axion detectors, etc.)
  - Shield sensitive equipment
  - Alert governments/public (?)

Direct probe of advanced stellar evolution

- Evolution of temperature, density
  - ν from thermal processes

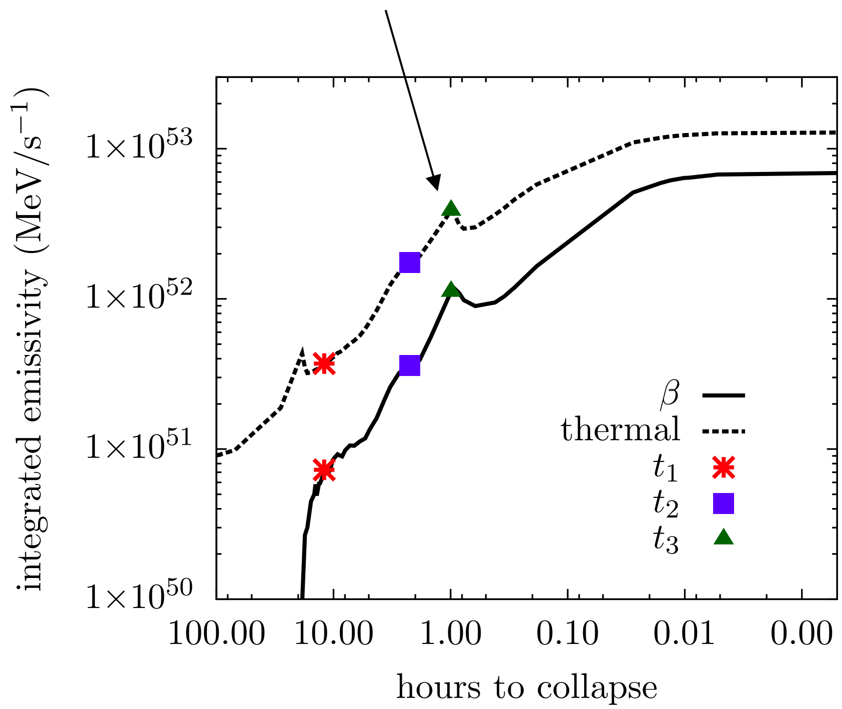
$$\gamma^* \to \nu_\alpha + \overline{\nu}_\alpha$$
$$e^\pm + \gamma \to e^\pm + \nu_\alpha + \overline{\nu}_\alpha$$
$$e^+ + e^- \to \nu_\alpha + \overline{\nu}_\alpha$$

- isotopic evolution
  - ν from beta processes

$$A(N,Z) \to A(N-1,Z+1) + e^- + \overline{\nu}_e$$
$$A(N,Z) \to A(N+1,Z-1) + e^+ + \nu_e$$

$$A(N,Z) + e^- \to A(N+1,Z-1) + \nu_e$$
$$A(N,Z) + e^+ \to A(N-1,Z+1) + \overline{\nu}_e$$

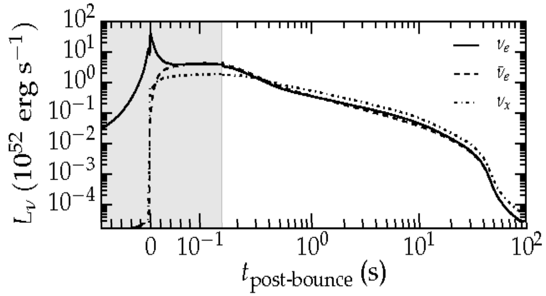
Si shell burning ignition



K .M. Patton. C. Lunardini, R. Farmer and F. X. Timmes, ApJ 851 (2017) no.1, 6 ; ApJ. 840 (2017) no.1, 2

Multi-messenger: gravitational "memory"

- Time-integrated, non-oscillatory effect, due to neutrino cooling
  - Requires *anisotropy* of emission



$$h^{TT}_{+,\mathrm{eq}}(t) = \frac{2G}{c^4 D} \int_{-\infty}^{t-D/c} \alpha(t') L_\nu(t') dt' \ ,$$

R. Epstein. Astrophys. J., 223, 1037, 1978
M. S. Turner. Nature, 274, 565, 1978.

See reviews: Ott , Class.Quant.Grav.26:063001,2009,
Kotake et al., Adv.Astron. 2012 (2012) 428757 ,

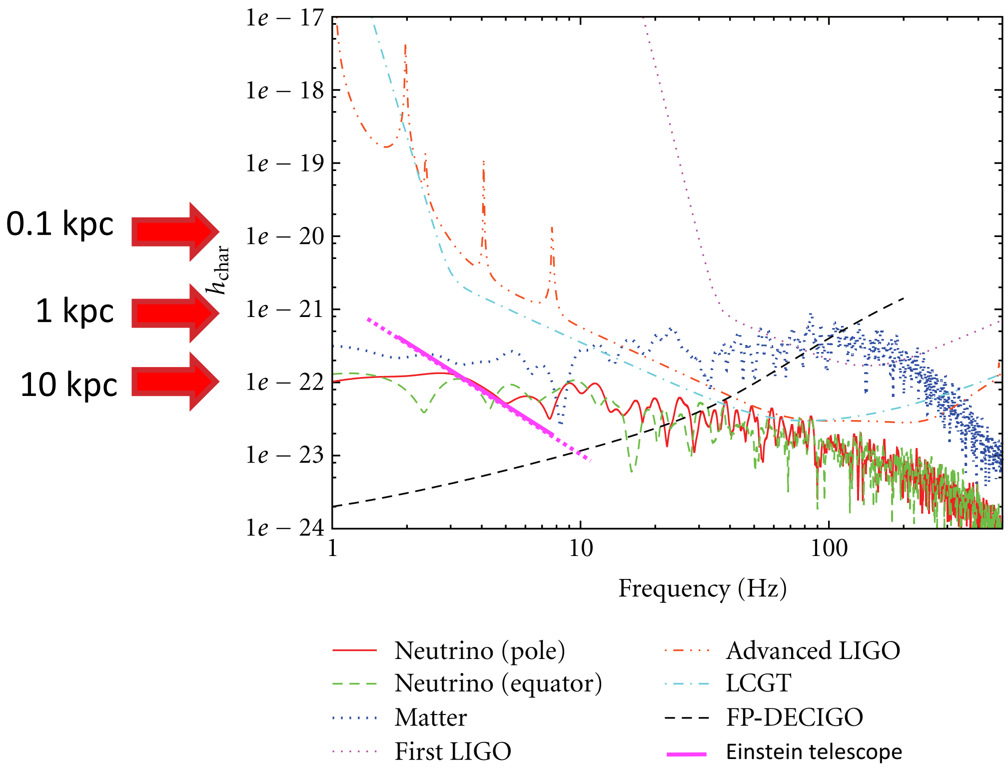
- Produces a low frequency signal in GW detectors

- GW signature:

$$\Delta h_\nu^{(\mathrm{mem})} \sim 7 \times 10^{-21} \left(\frac{10\,\mathrm{kpc}}{R} \right)$$

  - f < 10 Hz
  - Linear in 1/R

- *Detectable for near-Earth SN?*

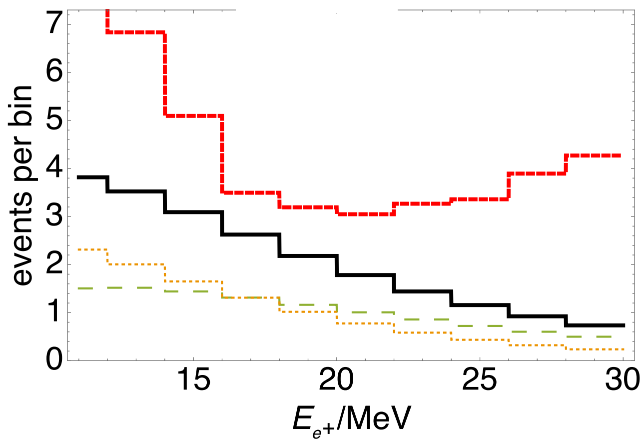


Adapted from Kotake et al., Adv.Astron. 2012 (2012) 428757

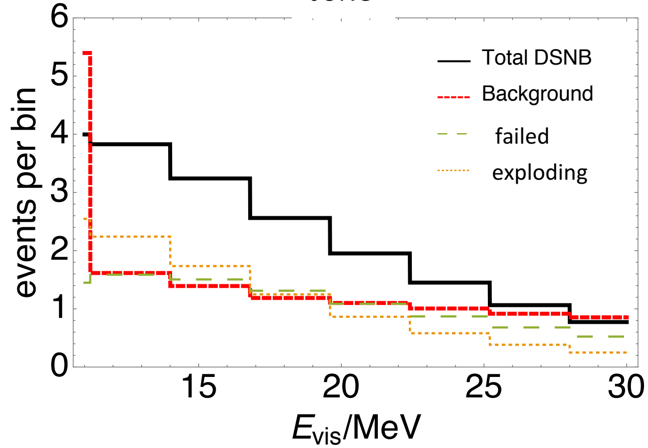
DSNB detectability

- Detectability:

SuperK-Gd



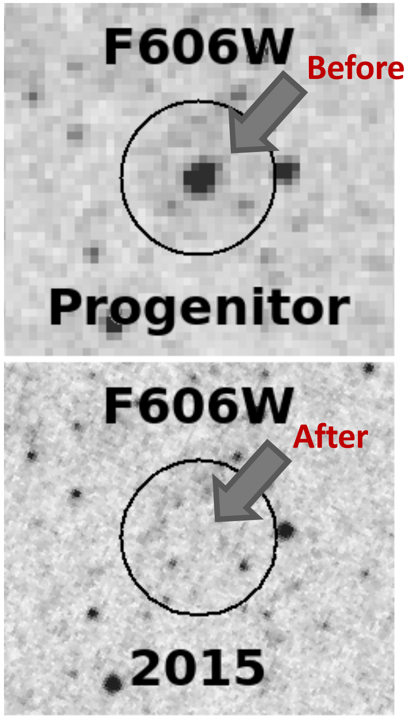
JUNO



A. Priya and CL, JCAP 1711 (2017) no.11, 031

Diversity: *failed* supernovae

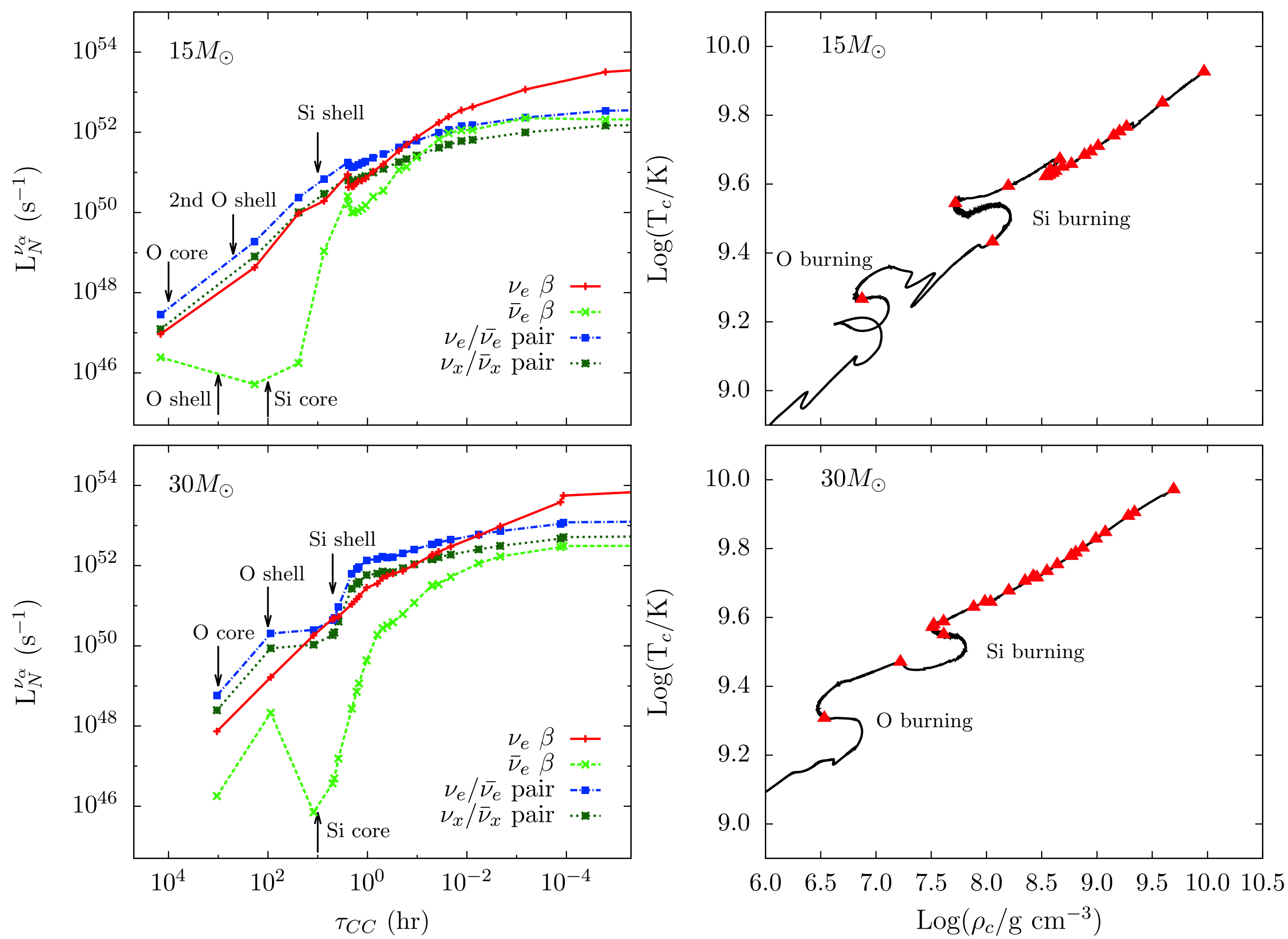
- Supported by:
  - numerical simulations
  - Problem of missing red supergiants
  - Evidence of a disappearing star (a “survey about nothing”)



Adams et al., MNRAS, 468, 4, p. 4968-4981

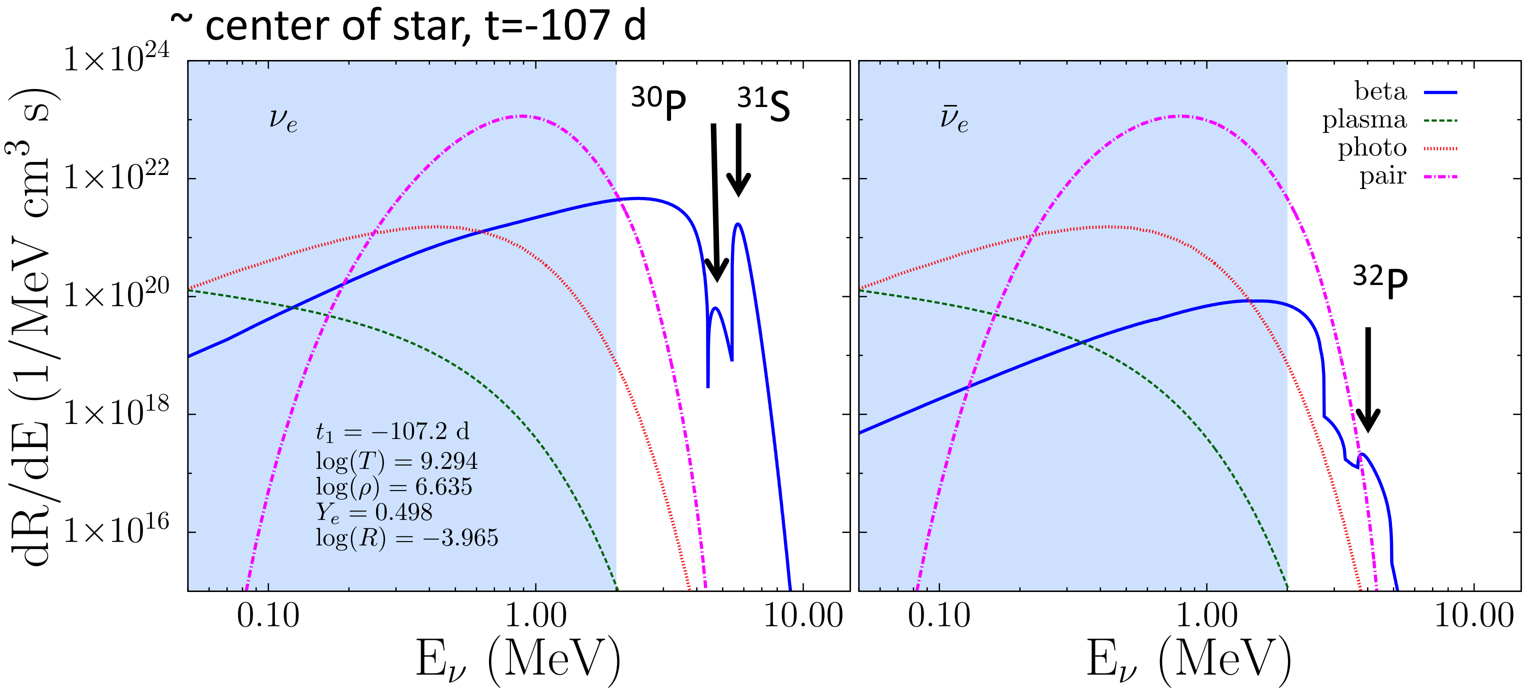
Horiuchi et al., MNRAS Lett. 445 (2014) L99
Kochanek, ApJ 785 (2014) 28
Kochanek et al. ApJ 684 (2008) 1336
Adams et al., MNRAS, 468, 4, p. 4968-4981

Presupernova evolution



- β-processes important in detectable window!
- few isotopes contribute to most of signal
  - Importance of medium-mass species: Al, P, Na, Ne,…

K .M. Patton. C. Lunardini, R. Farmer and F. X. Timmes,
ApJ 851 (2017) no.1, 6 ; ApJ. 840 (2017) no.1, 2



- Main contributing isotopes :

t (hrs)	total ν_e	E=2 MeV ν_e
-12.01	^{55}Co, ^{53}Fe, ^{56}Ni, ^{54}Fe, ^{57}Ni	^{55}Co, ^{56}Ni, ^{57}Ni, ^{54}Fe, ^{52}Fe
-2.2	^{54}Fe, ^{55}Fe, ^{55}Co, ^{53}Fe, ^{57}Co	^{55}Fe, ^{55}Co, ^{54}Fe, ^{57}Co, ^{57}Ni
-0.99	^{55}Fe, ^{54}Fe, ^{56}Ni, ^{57}Co, ^{55}Co	^{55}Fe, ^{55}Co, ^{57}Co, ^{54}Fe, ^{56}Ni
0	^{55}Fe, ^{56}Fe, ^{1}H, ^{57}Fe, ^{54}Mn	^{55}Fe, ^{1}H, ^{56}Fe, ^{57}Fe, ^{54}Fe

t (hrs)	total $\bar{\nu}_e$	E=2 MeV $\bar{\nu}_e$
-12.01	^{28}Al, ^{24}Na, ^{27}Mg, ^{60}Co, ^{31}Si	^{28}Al, ^{24}Na, ^{60}Co, ^{32}P, ^{23}Ne
-2.2	^{28}Al, ^{56}Mn, ^{27}Mg, ^{60}Co, ^{54}Mn	^{28}Al, ^{56}Mn, ^{60}Co, ^{55}Mn, ^{54}Mn
-0.99	^{56}Mn, ^{60}Co, ^{28}Al, ^{52}V, ^{55}Mn	^{56}Mn, ^{60}Co, ^{28}Al, ^{52}V, ^{55}Mn
0	^{56}Mn, ^{62}Co, ^{55}Cr, ^{52}V, ^{53}V	^{56}Mn, ^{62}Co, ^{55}Cr, ^{52}V, ^{53}V

Number of events (preliminary)

2 hours pre-collapse, D = 1 kpc (for Betelgeuse : multiply by 25)

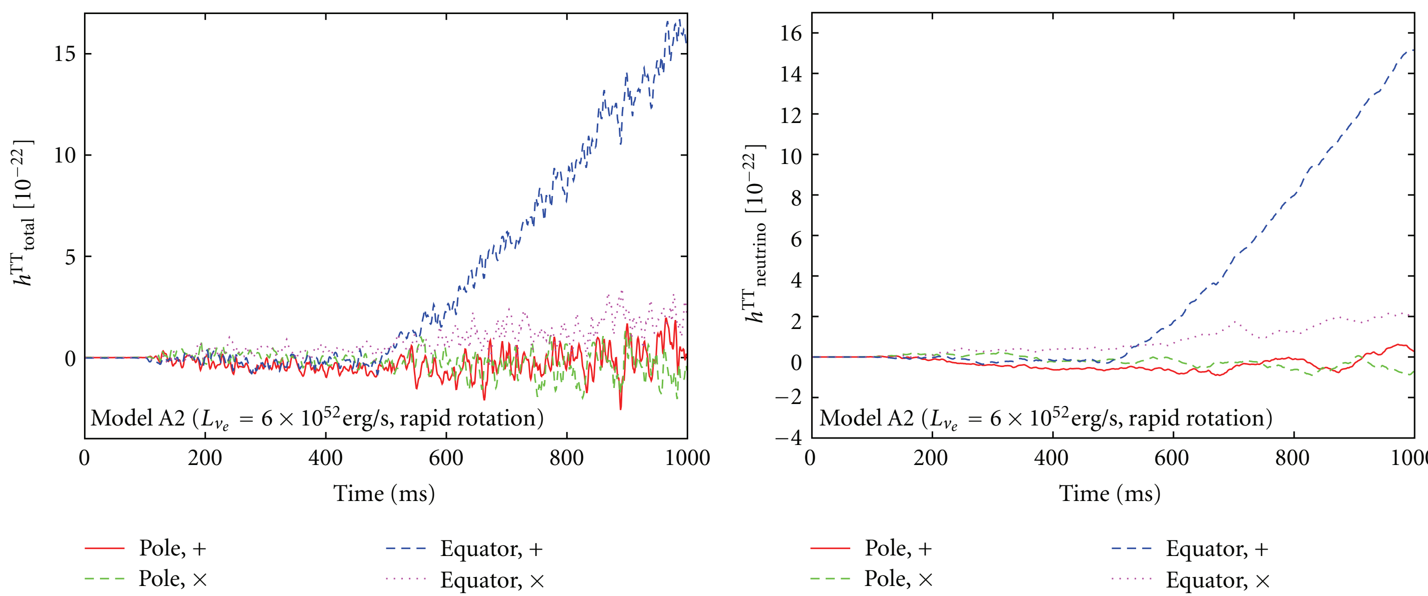
detector	composition	mass	interval	N_β^{el}	N^{el}	N_β^{CC}	N^{CC}	$N^{tot} = N^{el} + N^{CC}$
JUNO	C_nH_{2n}	17 kt	$E_e \geq 0.5$ MeV	9.3 [4.1]	39.0 [28.8]	0 [0]	12.3 [36.9]	51.3 [65.8]
SuperKamiokande	H_2O	22.5 kt	$E_e \geq 4.5$ MeV	0.11 [0.04]	0.17 [0.08]	0 [0]	0.65 [1.9]	0.82 [2.0]
DUNE	LAr	40 kt	$E \geq 5$ MeV	0.07 0.03	0.1 0.05	0.64 [0.04]	0.91 [0.17]	1.0 [0.22]

el = elastic scattering on electrons
CC = Charged Current on nuclei
β = contribution of neutrinos from beta processes

.. = results for IH
[..] = results for NH

GW neutrino memory

$$h^{TT}_{+,\mathrm{eq}}(t) = \frac{2G}{c^4 D} \int_{-\infty}^{t-D/c} \alpha(t') L_\nu(t') dt' \ ,$$

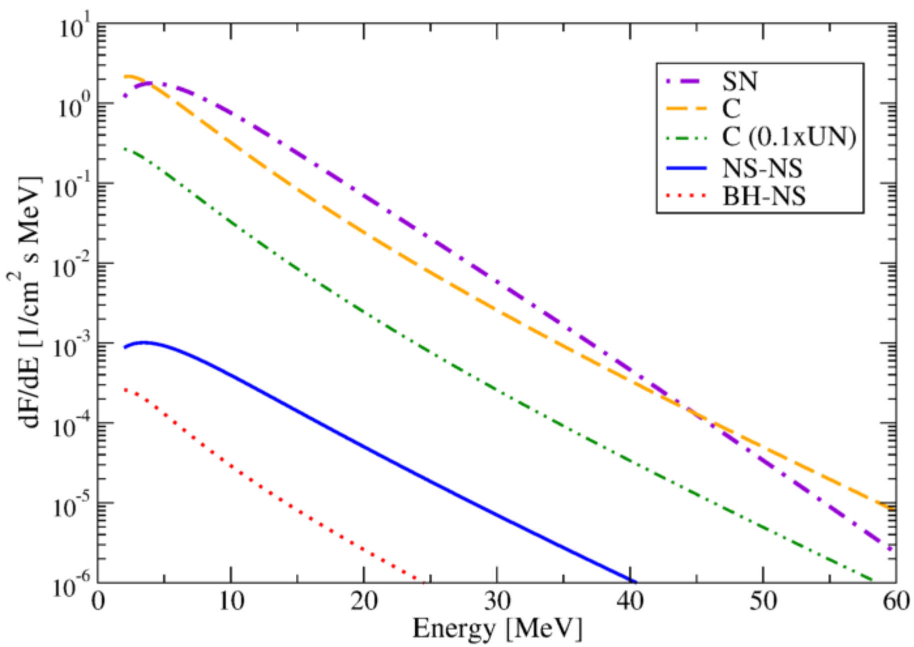


from Kotake et al., Adv.Astron. 2012 (2012) 428757

Daughters of SN: collapsars, mergers

- Neutrinos from cooling of accretion disks due to
  - Failed SN with fast rotation (collapsars)
  - Neutron Star-Neutron Star mergers
  - Neutron Star-Black hole mergers

- Contribution to diffuse flux can be high in extreme cases



Schilbach, Caballero and McLaughlin, arXiv:1808.03627
Kyutoku and Kashiyama, PRD97, 2018