SUPERNOVA NEUTRINOS - AN OVERVIEW

Cecilia Lunardini

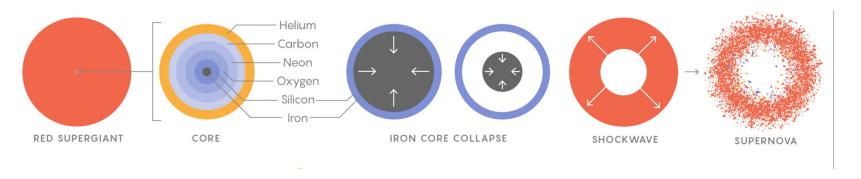Arizona State University

Contents

The theme:

What can we learn from future SN neutrino detections?

- Introduction: what we have learned so far

- Next 10-20 years: scenarios

  - Future low or high statistics detections

INTRODUCTION: WHAT WE HAVE LEARNED SO FAR

Stellar death: a core collapse supernova

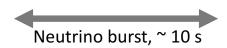Credit: Lucy Reading-Ikkanda/Quanta Magazine

Helium
Carbon
Neon
Oxygen
Silicon
Iron

RED SUPERGIANT   CORE   IRON CORE COLLAPSE   SHOCKWAVE   SUPERNOVA

time

Advanced stellar evolution

Loss of pressure; free fall; core formation

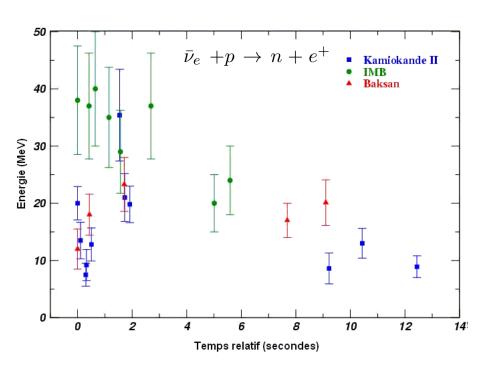Falling matter bounces; shockwave; *Cooling via neutrinos*

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

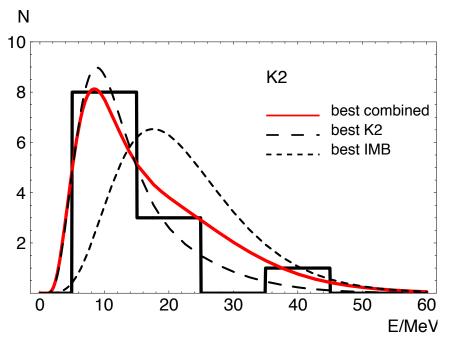Bionta et al., PRL 58,1987, Hirata et al., PRL 58,1987, Alekseev et al. JETP Lett. 45 (1987)

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

- ■ Kamiokande II
- ● IMB
- ▲ Baksan

Energie (MeV) vs Temps relatif (secondes)

K2

best combined
best K2
best IMB

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

Basic picture: 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
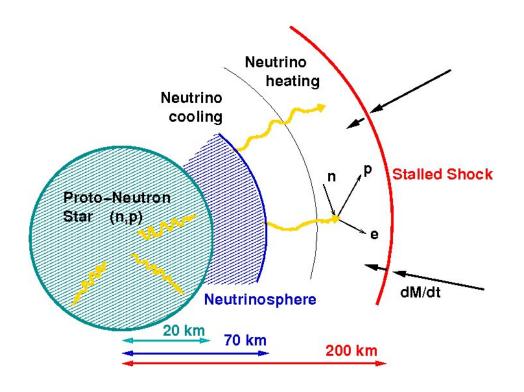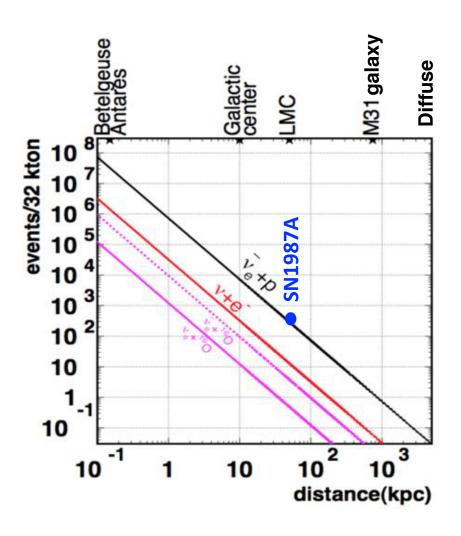 - Time ~ (size^2)/(mean free path) ~ 10 s
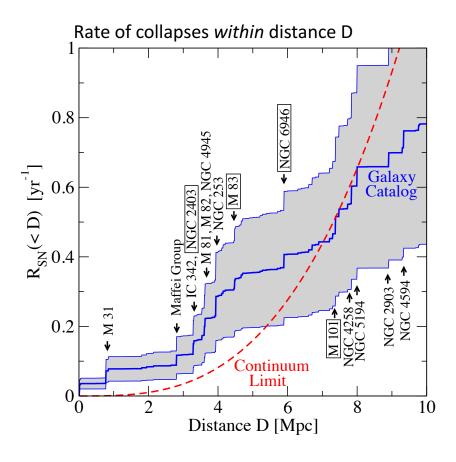

Figure: Amol Dighe, talk at WHEPP XV, 2017

The future: beyond the basic picture

We need new data!

*Next SN neutrino detection.... **When**?*

High (low) statistics, low (high) probability

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

Ando, Beacom & Yuksel, PRL 95 (2005)

Within our lifetime....

Credit: ESA/Hubble, NASA

Guaranteed:
multiple SNe, (quasi-)diffuse flux

Credit: Anglo-Australian observatory
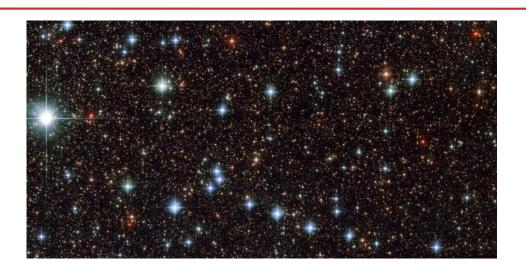
Possible:
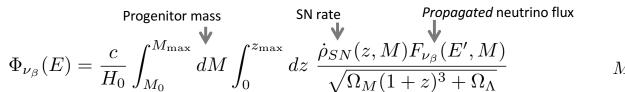single, galactic SN burst

Exceptional:
single, near-Earth
SN burst
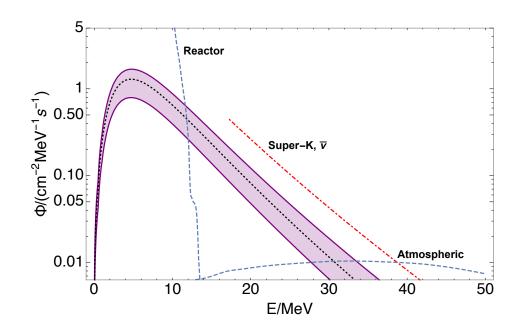
SmithsonianScience.org

GUARANTEED: (QUASI-)DIFFUSE FLUX

Diffuse Supernova Neutrino Background (DSNB)

- Whole sky flux; constant in time

$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0} \int_{M_0}^{M_{\max}} dM \int_0^{z_{\max}} dz \, \frac{\dot{\rho}_{SN}(z, M) F_{\nu_\beta}(E', M)}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}}$$

Progenitor mass → SN rate → *Propagated* neutrino flux

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

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

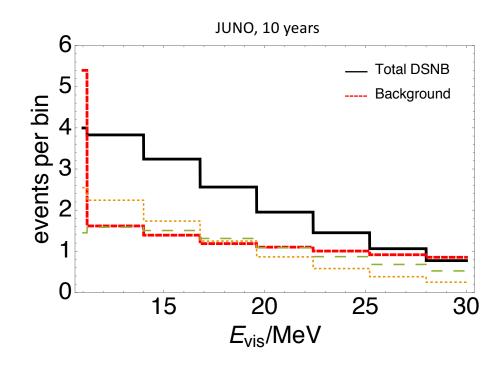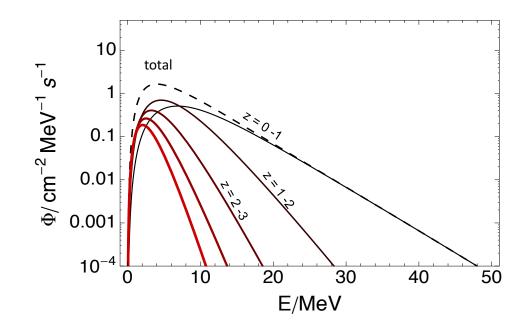- detection will change from exceptional to *routine*!

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)
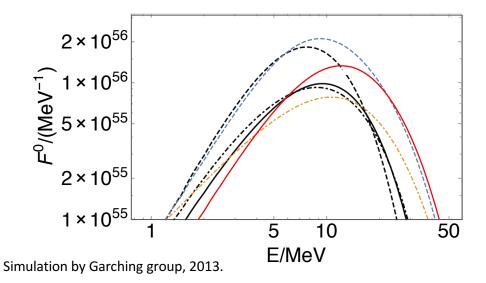An et al., J. Phys. G: Nucl.Part. Phys. 43 (2016) 030401.

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?
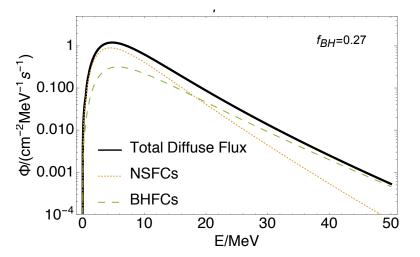 - Diversity of core collapses (ONeMg cores, black hole formation, …)

Neutrinos from a failed supernova

- collapse *directly* into a black hole, *no explosion!*
- Failed supernovae are *brighter* in neutrinos
  - 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

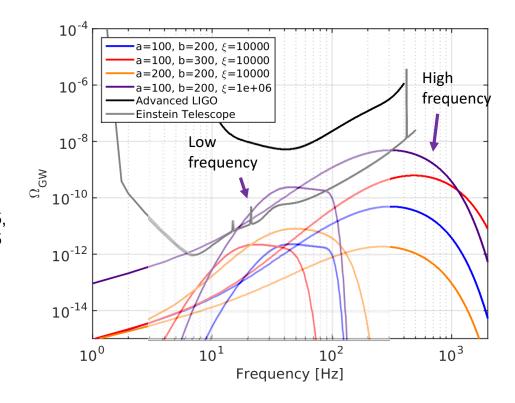Figures from A. Priya and CL, JCAP 1711 (2017) no.11, 031

See also: CL, PRL 102 (2009);
Lien et al., PRD81 (2010);
Keehn & CL, PRD85 (2012);
Mathews et al., arXiv:1405.0458

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: (NEAR-)GALACTIC SUPERNOVA

Proto-neutron star (PNS) evolution
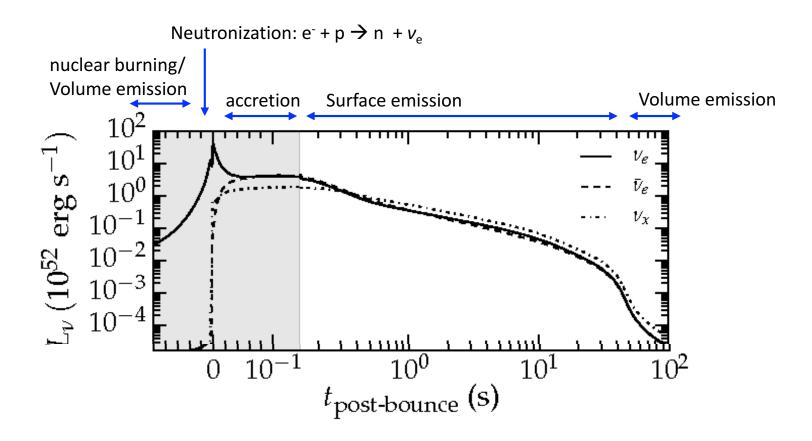
- Direct narrative of events at R < 200 Km

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

Accretion: Standing Accre

- 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)

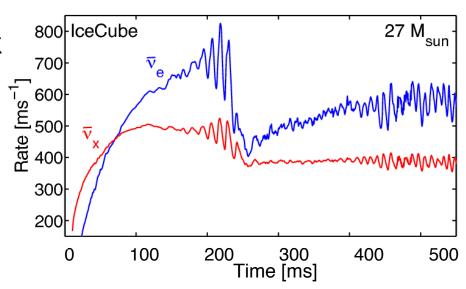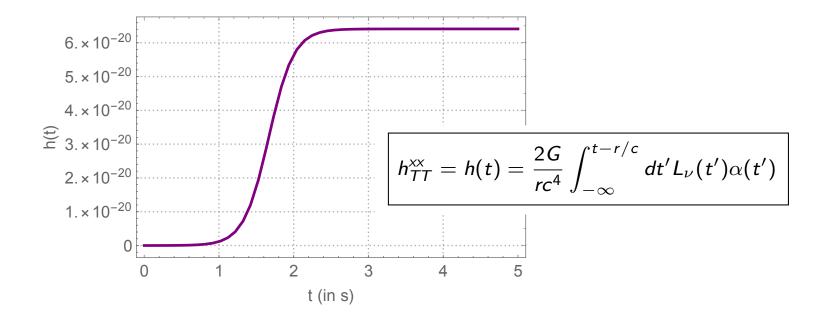- Strong in 3D with detailed neutrino transport

Figure from Tamborra et al., arXiv:1307.7936

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

multi-messenger: the GW memory of SN neutrinos

- a permanent distortion of the local space time metric
  - due to anisotropic matter/energy emission

$$h_{TT}^{xx} = h(t) = \frac{2G}{rc^4} \int_{-\infty}^{t-r/c} dt' \, L_\nu(t') \alpha(t')$$

- emission timescale t ~ O(10) s → sub-Hz scale
  - promising for future Deci-Hz detectors!

Zel'dovich and Polnarev, Sov. Astron. 18 (1974) 17.
Braginskii and Thorne, Nature 327 (1987) 123.
Epstein, Astrophys. J. 223 (1978) 1037.
Turner, Nature 274 (1978) 565.
M. Favata, Class. Quant. Grav. 27 (2010) 084036

Probing near-core dynamics: anisotropy

$$\alpha(t) = \frac{1}{L_\nu(t)} \int_{4\pi} d\Omega' \ \Psi(\vartheta', \varphi') \ \frac{dL_\nu(\Omega', t)}{d\Omega'}$$

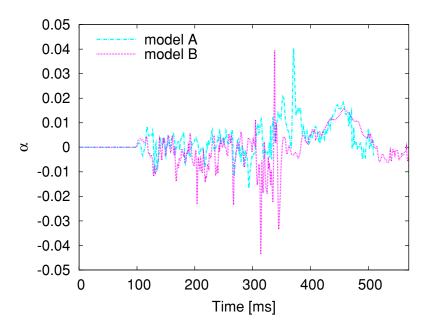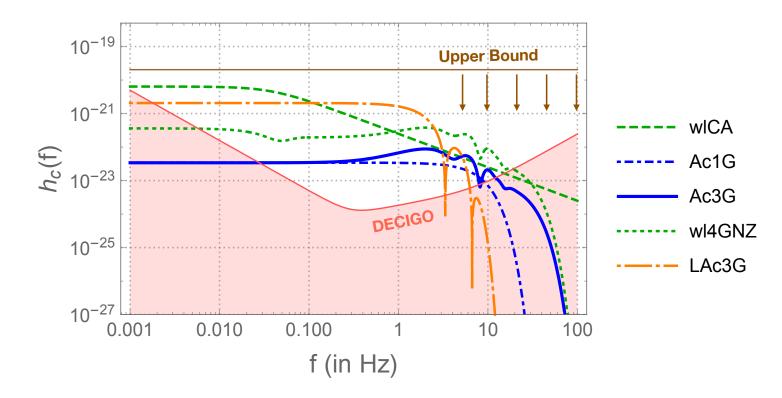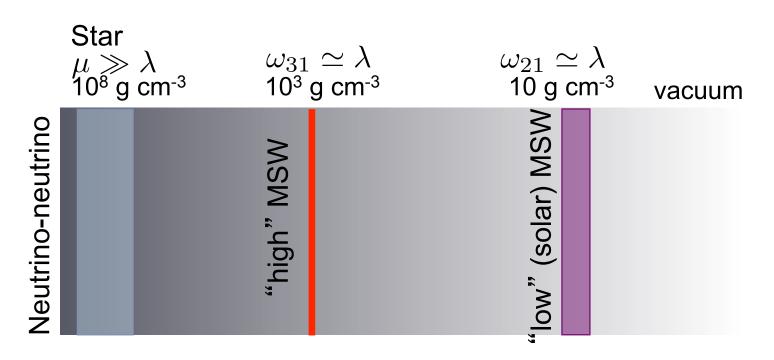develops during accretion, due to convection and SASI

fig. from Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951

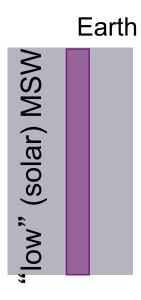See also Muller, Janka and Wongwathanarat, Astron. Astrophys. 537 (2012)

Detectable at future Deci-Hz interferometers

$h_c(f) \equiv 2f|\tilde{h}(f)|$ ($\tilde{h}$: Fourier transform)
A- and LA- : anisotropy in accretion phase only ;
w- : anisotropy is non-zero throughout
(D=10 kpc)

M. Mukhopadhyay, C. Cardona and CL, JCAP 07 (2021), 055

Oscillations: *unique* interplay of frequencies

Star
$\mu \gg \lambda$
10^8 g cm^{-3}

$\omega_{31} \simeq \lambda$
10^3 g cm^{-3}

$\omega_{21} \simeq \lambda$
10 g cm^{-3}

vacuum

Earth

Neutrino-neutrino

"high" MSW

"low" (solar) MSW

"low" (solar) MSW

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

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

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

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

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

Vacuum + matter + self-interaction

$$H_E = H_E^{\mathrm{vac}} + H_E^{\mathrm{m}} + H_E^{\nu\nu}$$

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

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

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

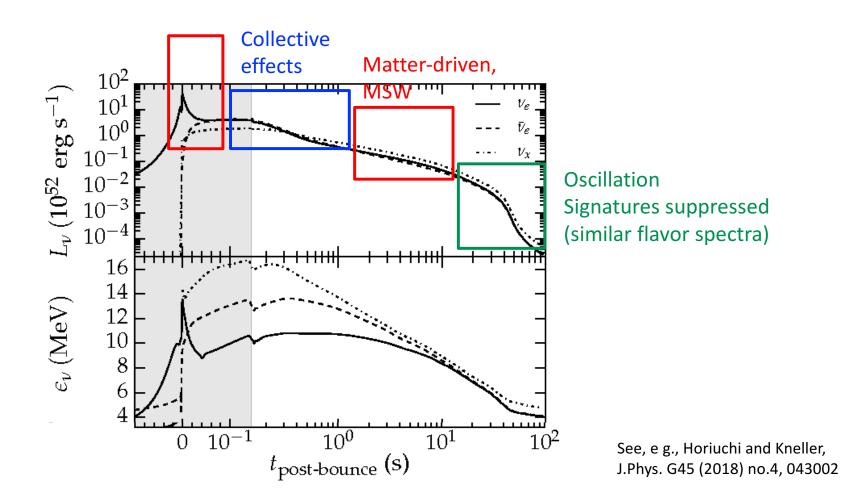θ angle between incident momenta

$$\Delta m_{31}^2 > 0 \quad \text{normal hierarchy, NH}$$
$$\Delta m_{31}^2 < 0 \quad \text{inverted hierarchy, IH}$$

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

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
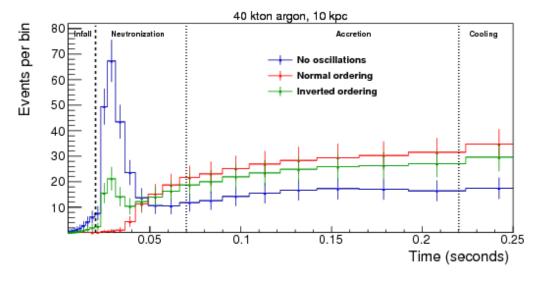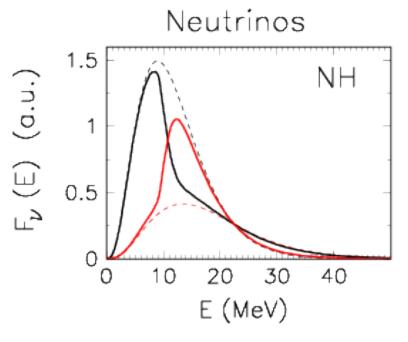due to θ_{13}-driven MSW resonance,
For Normal mass hierarchy
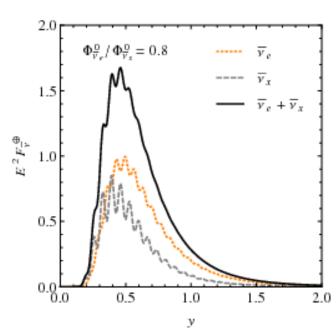

Figure from K. Scholberg, J.Phys. G45 (2018) no.1

Spectral splits due to collective effects

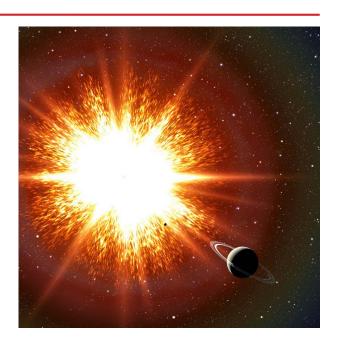Figure from Chakraborty and Mirizzi,
PRD90 (2014) no.3, 033004

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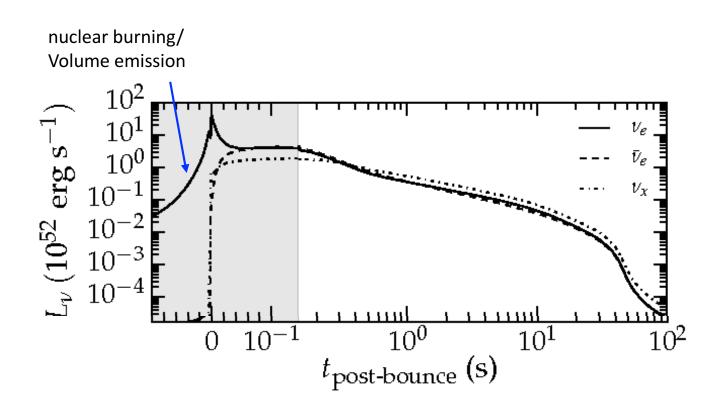in the θ_{12}-driven MSW resonance

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

EXCEPTIONAL: NEAR-EARTH SUPERNOVA

Pre-supernova neutrinos!

The last months of stellar evolution

- ## Last stages of fusion chain

  - rapid evolution of isotopic composition

  - increase of core density, temperature

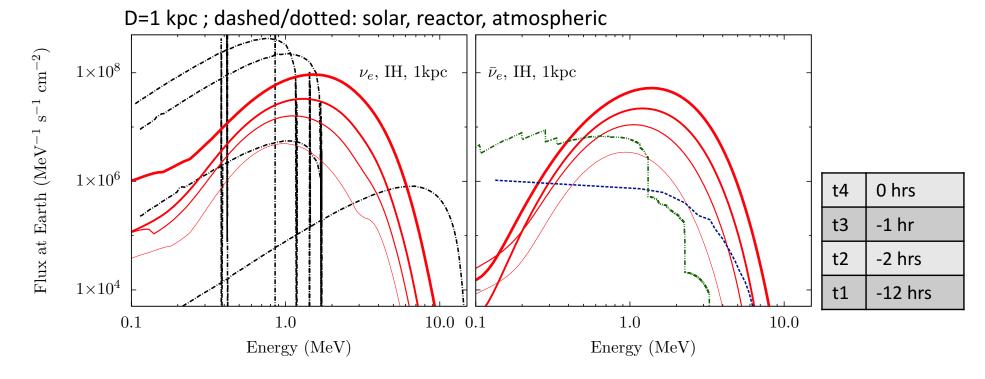 - *increase of neutrino emission*

    - *detectable!*

Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

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

Detectability

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

Flux at Earth (MeV^{-1} s^{-1} cm^{-2})

ν_e, IH, 1kpc

$\bar{\nu}_e$, IH, 1kpc

Energy (MeV)

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

Early alert!

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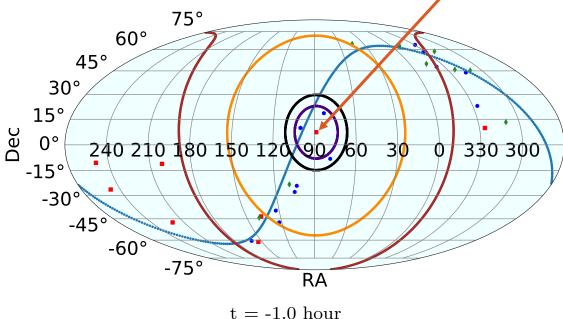 - Alert governments/public (?)

Progenitor identification: pointing

- Sensitivity up to 1 kpc; angular error ~70° from $p^{+} + \overline{\nu}_e \to e^{+} + n^{0}$

  - Need ~10 kt liquid scintillator detector (JUNO)

  - Can provide shortlist of 4-10 candidates, about 1 hour prior to collapse

- Possible long term improvements:

  - ~30° with THEIA (100 kt)

  - ~10° with LS+Lithium

$$t = -1.0 \text{ hour}$$

Mukhopadhyay, CL, Timmes and Zuber, Astrophys.J. 899 (2020) 2, 153

Direct probe of advanced stellar evolution

- Evolution of temperature, density
  - ν from thermal processes

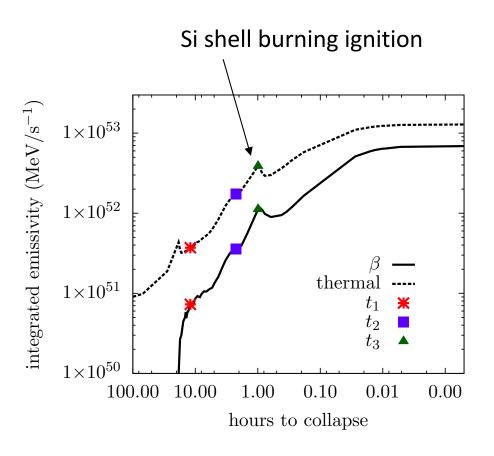 $$\gamma^* \rightarrow \nu_\alpha + \overline{\nu}_\alpha$$
  $$e^{\pm} + \gamma \rightarrow e^{\pm} + \nu_\alpha + \overline{\nu}_\alpha$$
  $$e^+ + e^- \rightarrow \nu_\alpha + \overline{\nu}_\alpha$$

- isotopic evolution
  - ν from beta processes

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

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

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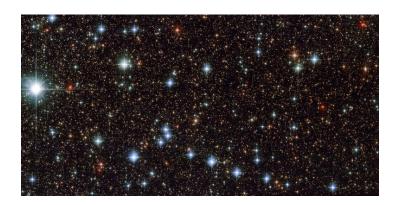
K .M. Patton. C. Lunardini, R. Farmer and F. X. Timmes, ApJ 851 (2017) no.1, 6 ; ApJ. 840 (2017) no.1, 2

CONCLUSIONS AND OPEN QUESTIONS
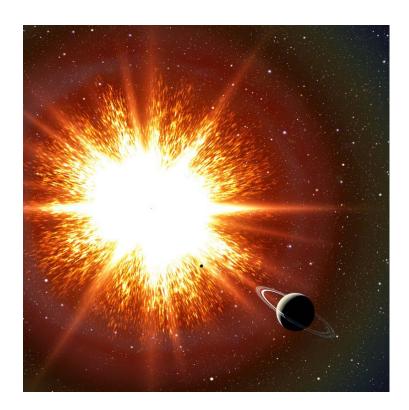
The future is bright for SN neutrinos

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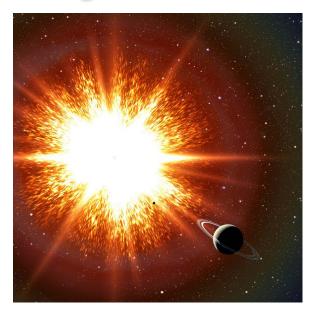
- Betelgeuse could collapse at any time
  - You will have a few hours to prepare for the show
  - Watch terminal stellar evolution in real time

Thank you!

BACKUP