THEORY AND PHENOMENOLOGY OF SUPERNOVA NEUTRINOS

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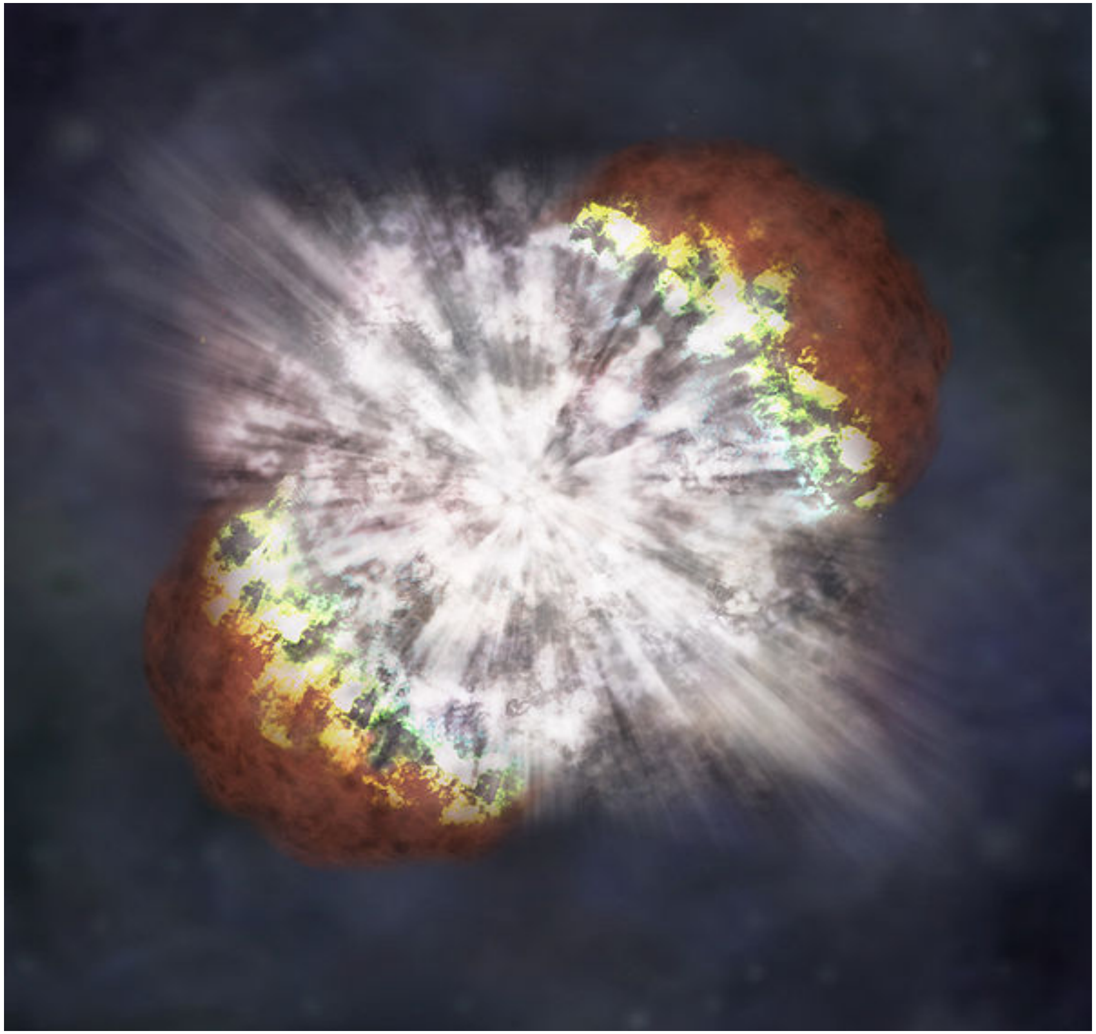
Topics

- Introduction
- Status and updates
  - Numerical simulations
  - Oscillations
  - Diffuse flux and mini-bursts
- Discussion: future directions

INTRODUCTION

Core collapse supernovae



Artist's impression of SN2006gy – credit: NASA/Getty Images

Core collapse : a neutrino event

- $M > 8\ M_{sun}$: death by core collapse
  - Gravitational collapse → bounce and shock → explosion
  - $E \approx 10^{53}$ ergs emitted, 99% in neutrinos & antineutrinos of all flavors

- Neutrinos are *direct* messengers
  - Diffuse from inner 50-200 Km
  - Only unambiguous tracers of core collapse

The *only* place today where neutrinos…

- Produce a macroscopic force
  - Re-launch a stalled shock

- Are thermalized

- Undergo four stages of oscillations
  - All masses and mixings contribute

- Have observable interaction with each other
  - Oscillation effects

- Quasi-thermal spectra

$$\langle E \rangle \sim 9 - 18 \ \ \mathrm{MeV}$$

- Hierarchy of energies
  - Different coupling to matter → different decoupling radii

$$\langle E \rangle_e \lesssim \langle E \rangle_{\bar{e}} \lesssim \langle E \rangle_x$$

$$(x = \mu, \tau)$$

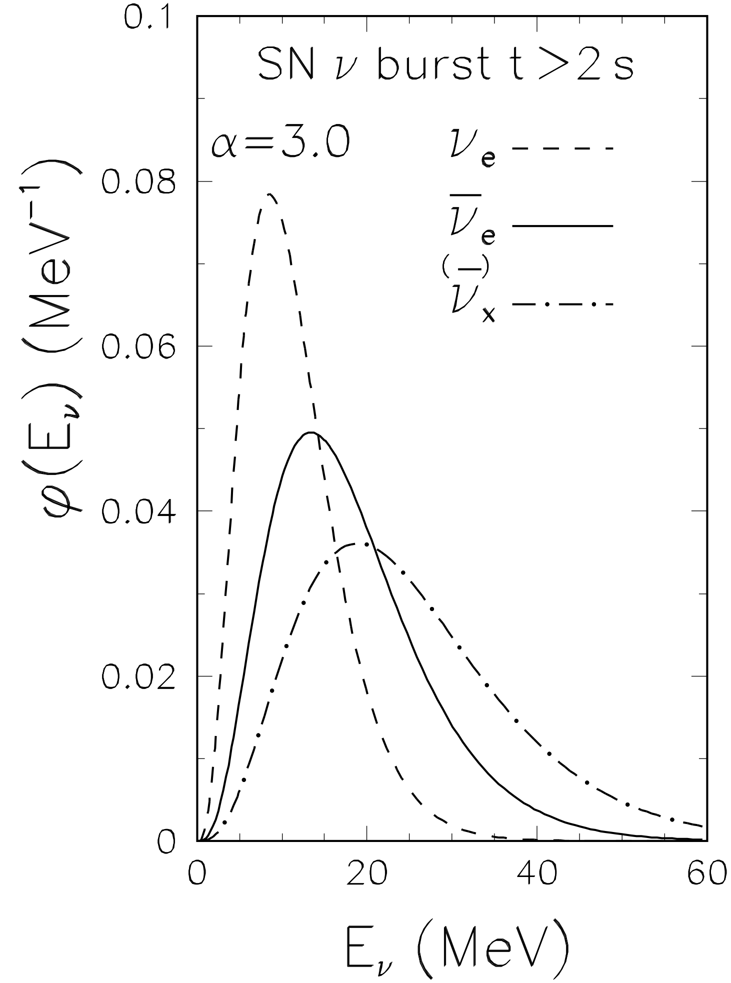
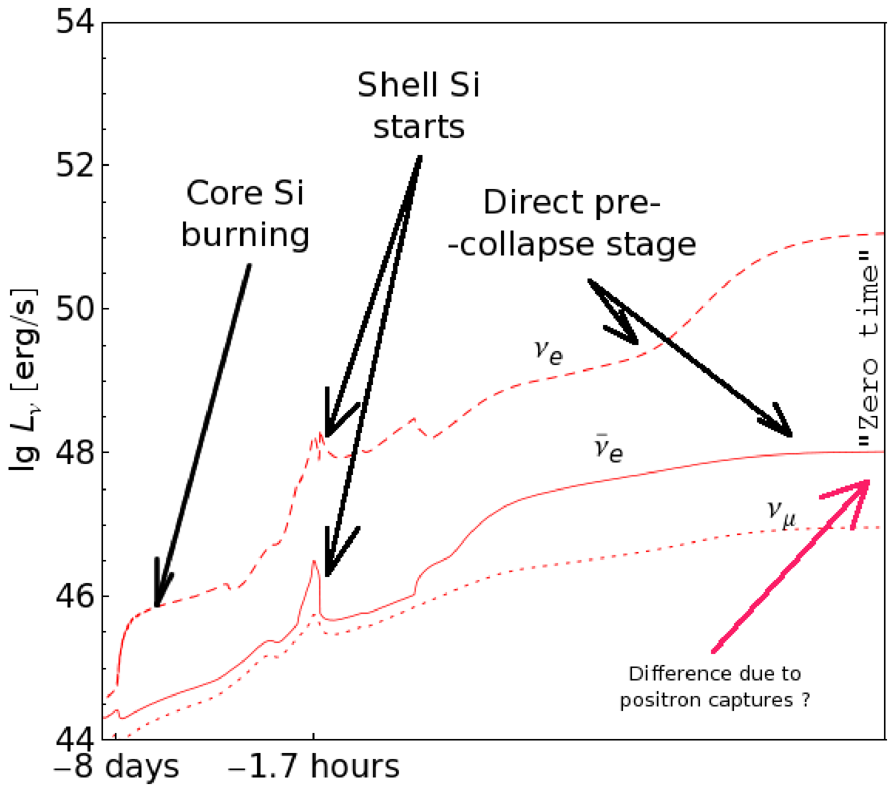
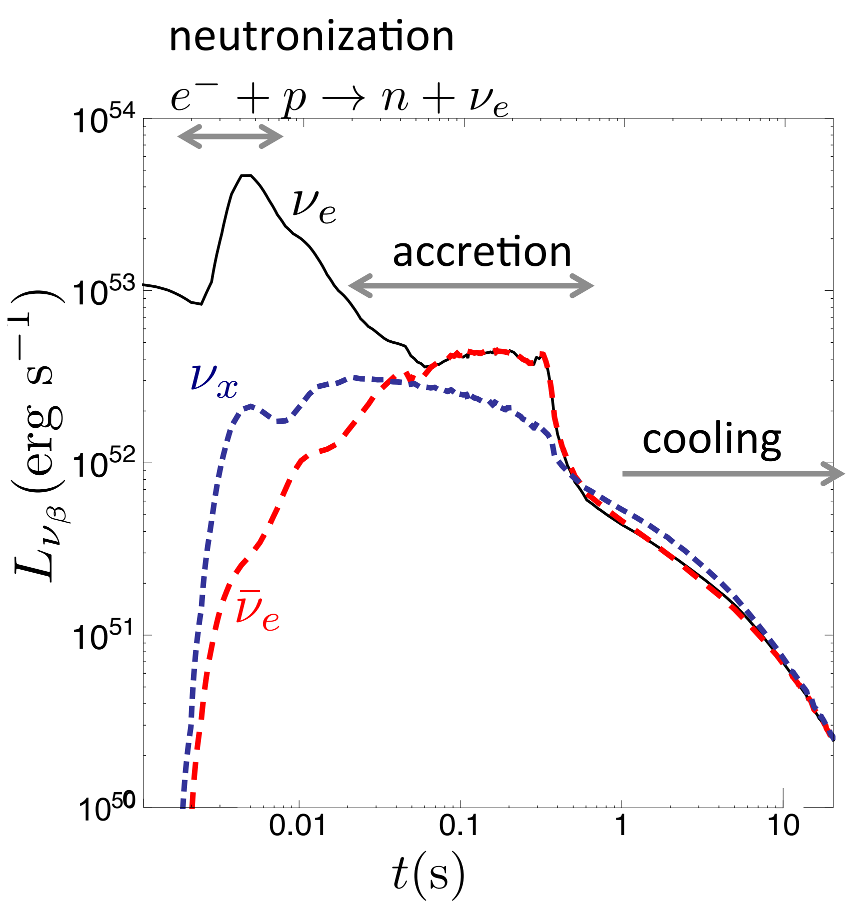


Figure from Fogli et al., JCAP 0504 (2005) 002

Phases of neutrino emission



Odrzywolek & Heger, Acta Phys. Polon. 41 (2010)



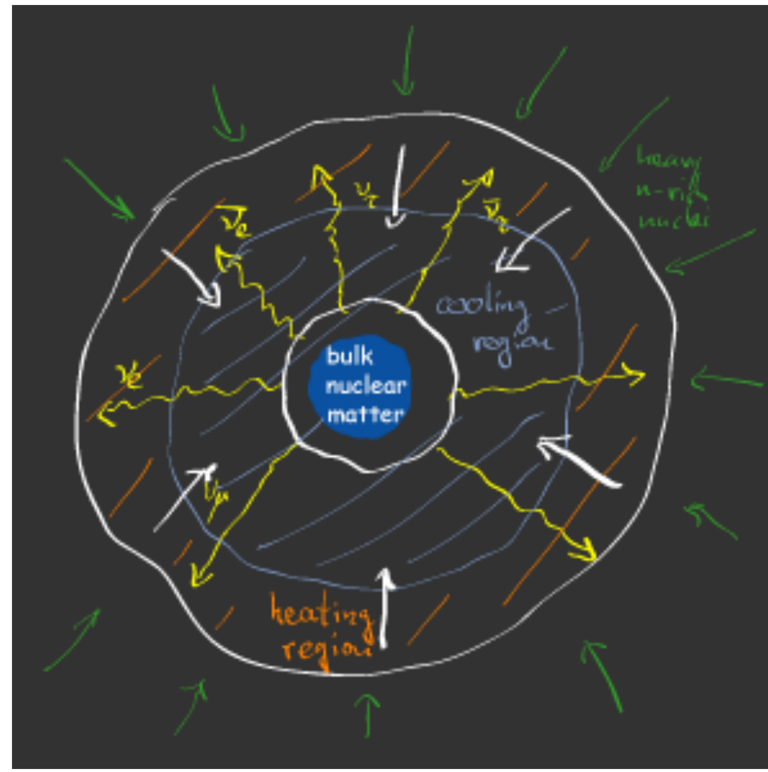
Fischer et al., A&A 517 (2010)

NUMERICAL SIMULATIONS

Neutrino fluxes

Neutrino-driven explosion in *multi-D*

- Multi-dimensionality is crucial
  - Convection, shock instabilities, …
- Second generation 2D (axisymmetric) simulations
  - Ab-initio, self-consistent, spectral neutrino transport
  - t<1 only available



from M. Liebendörfer's homepage

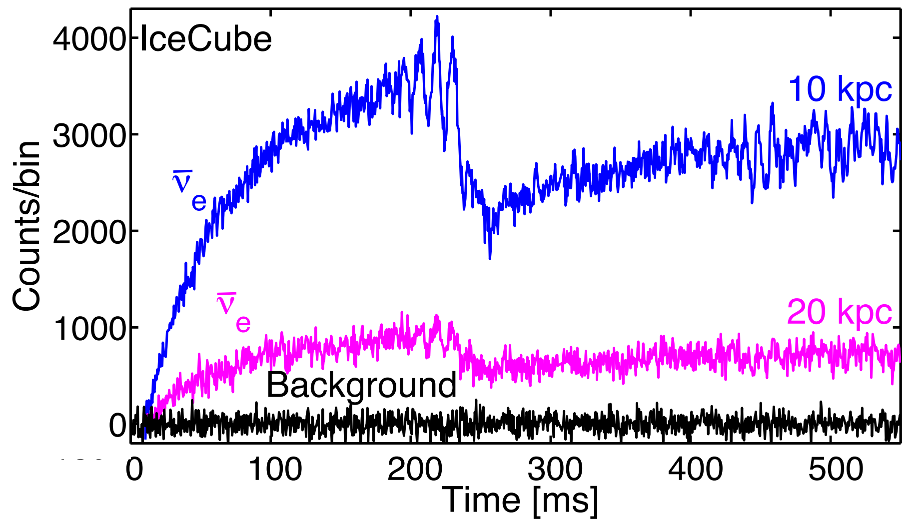
Paper	Type	D	Outcome	$t_{\rm end}(s)$
Mueller et al. (2012)	ν variable Eddington factor method	2D	$E_{\rm exp} \lesssim 0.2$ foe, $E_{\rm rec} \lesssim 0.2$ foe	0.8
Janka (2013)	ν variable Eddington factor ν method	3D	No explosion	0.35
Takiwaki et al. (2013)	IDSA ν scheme	2,3D	$E_{\rm exp} \lesssim 0.1$ foe in 3D	< 0.4 in 3D
Bruenn et al. (2013)	RbR+ approximation	2D	No explosion for $25 M_\odot$ success for $12,15,20 M_\odot$. Explosion energy $E_{\rm exp} \simeq 0.3 - 0.4$ foe	$0.5 - 0.8$
Couch & Ott (2013)	neutrino leakage scheme	3D	Core perturbations help shock revival	$\lesssim 0.3$
Couch & O'Connor (2013)	neutrino leakage scheme	2,3D	3D explodes less easily than 2D	< 0.5
Suwa et al. (2010)	IDSA ν scheme	2D	$E_{\rm exp} \lesssim 0.1$ foe	0.5
Suwa (2013)	IDSA ν scheme	2D	~ 0.1 foe	70
Dolence et al. (2014)	MGFLD	2D	No explosion	~ 0.6 s

Calculations with “realistic” neutrino transport, from Papish, Nordhouse and Soker, arXiv:1402.4362

Towards 3D : Standing Accretion Shock Instability

- Deformation, sloshing of shock front
  - Affects ν emission rate

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



Tamborra et al., arXiv:1307.7936

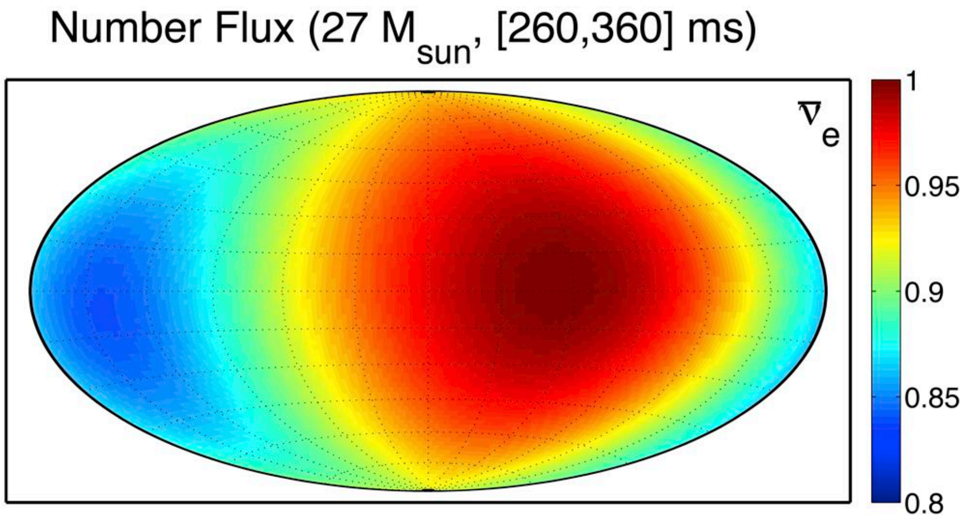
- Strong in 3D with detailed neutrino transport

Tamborra et al., arXiv:1307.7936
See also Lund et al., PRD 82, (2010), PRD 86, (2012)

Lepton-number Emission Self-sustained Asymmetry

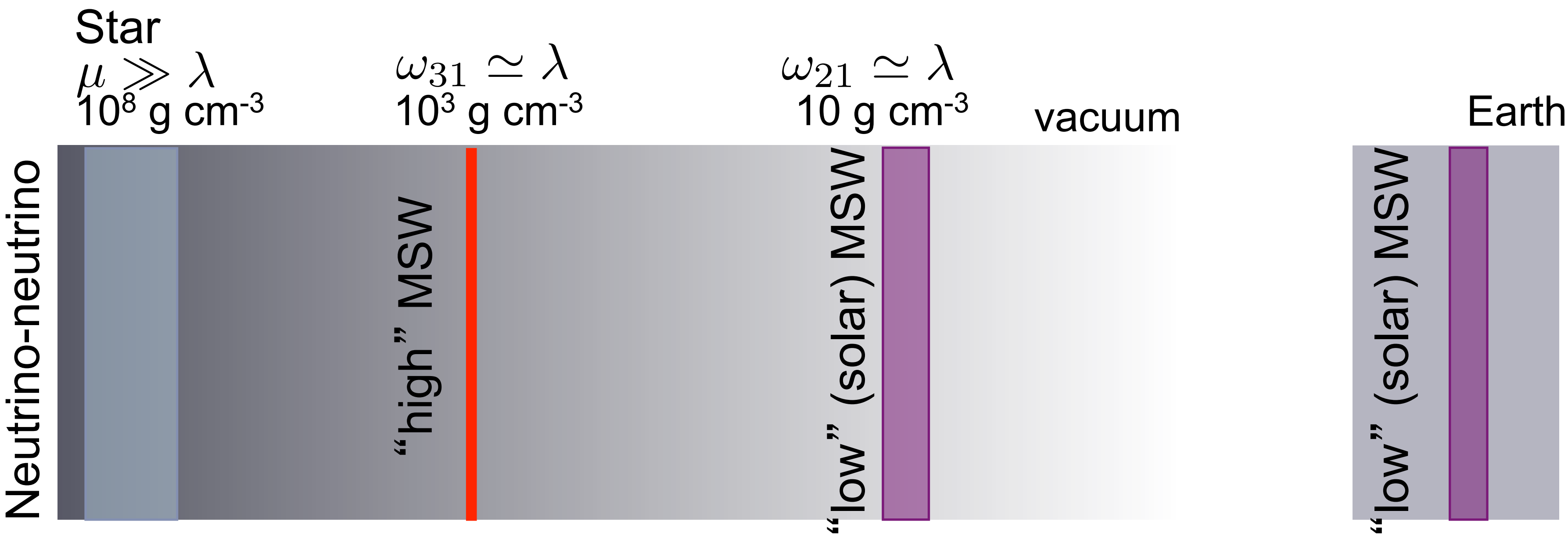
- $N(\nu_e) - N(\bar{\nu}_e)$ has (quasi-)dipolar form
  - Possible implications on r-process, oscillations

Tamborra et al.,arXiv:1402.5418



PHENOMENOLOGY OF OSCILLATIONS

Unique interplay of frequencies



- Kinetic $\omega_{ij} = \Delta m^2_{ij}/2E$
- ν-e potential $\lambda = \sqrt{2} G_F n_e \propto R^{-3}$
- ν-ν potential $\mu \simeq \sqrt{2} G_F n_\nu^{\text{eff}} \propto R^{-4}$

Wolfenstein, PRD 17 1978, Mikheyev & Smirnov, Yad. Fiz. 42, 1985

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

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

- 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)

Contributors by affiliation

UC San Diego, U. Minnesota, Los Alamos Natl. Lab., Northwestern U., North Carolina State, U. of Washington (INT), Ohio State U., U. Wisconsin, U. of New Mexico

Tata Inst. , Harish-Chandra Res. Inst., Saha Inst.

APC Paris, Valencia U., Max Planck Munich, Bari U., INFN Bari, Hamburg/DESY, GRAPPA Amsterdam, INR Moscow, ICTP Trieste

Linearized stability analysis

- Linearized equation for flavor-changing parameter
  - $|S|^2 + |s|^2 = 1$, $|S|^2 \ll 1$, $\theta \ll 1$

$$S_{swap} = \begin{pmatrix} s & S \\ S^* & -s \end{pmatrix} \qquad P(\nu_e \to \nu_e) = \frac{1}{2}(1+s) \qquad -1 \le s \le 1$$

$$i\partial_r S = (\omega + u\bar{\lambda})S - \mu \int d\Gamma' \left[u + u' - 2\sqrt{uu'}\cos(\varphi - \varphi')\right] g' S'$$

- Solve eigenvalue equation for frequency: $S = Q_\Omega e^{i\Omega t}$

$$\Im m(\Omega) = \begin{cases} < 0 & \textbf{instability}, \text{strong conversion} \\ > 0 & \text{damping} \end{cases}$$

Banerjee, Dighe, Raffelt, PRD 84, (2011), Sarikas et al., PRD 85 (2012), arxiv:1109.3601

Pre-cooling phases

- Neutronization peak, accretion phase (Fe-core SNe)
  - High matter density suppresses collective effects → *MSW-driven oscillations dominate*

Chakraborty et al., PRL 107, (2011), PRD 84 (2011)
Dasgupta, O'Connor & Ott, PRD85 (2012)

- $\sin^2 \theta_{13} = 0.02$ drives *adiabatic* MSW resonance
  - complete flavor permutation
    - neutrino channel for NH → hotter ν_e spectrum
    - antineutrino channel for IH → hotter $\bar{\nu}_e$ spectrum

Dighe & Smirnov, PRD 62 (2000), CL & Smirnov, JCAP 0306 (2003)

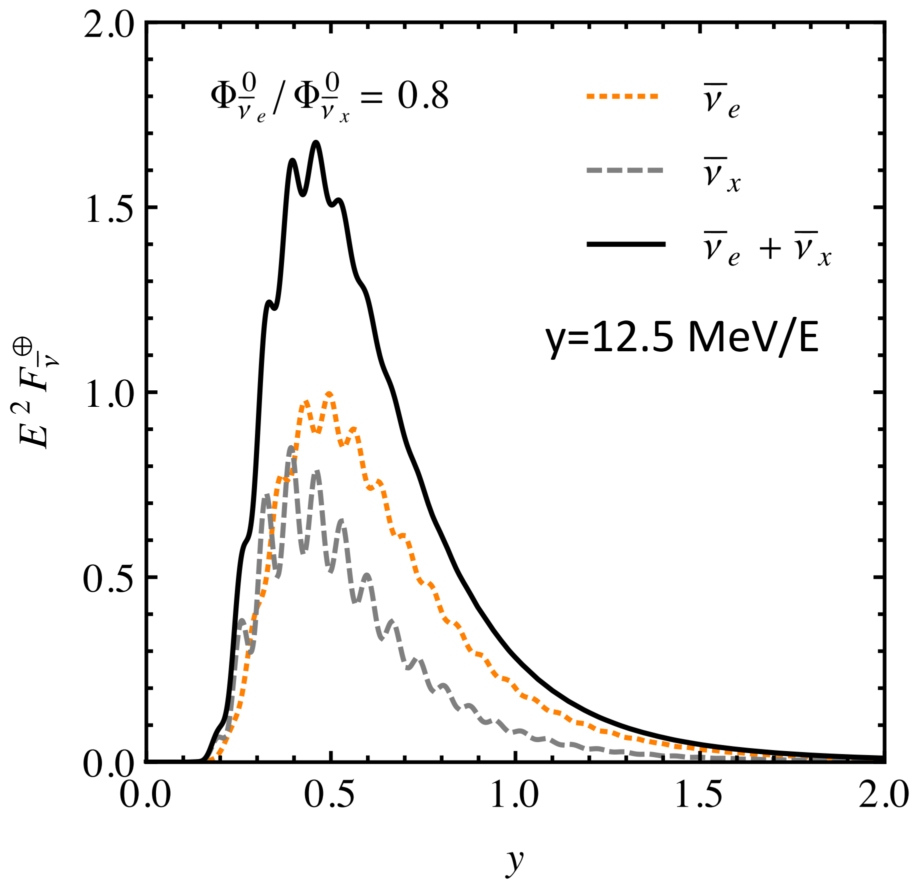
Robust signatures of mass hierarchy

- NH : disappearance of neutronization peak

Gil Botella & Rubbia, JCAP 0310 (2003)
Kachelriess et al., PRD71 (2005)

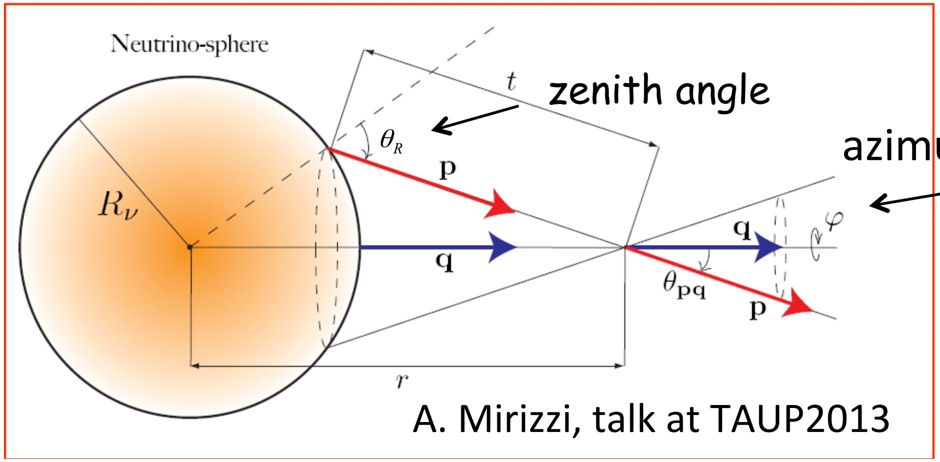
- Oscillations in the Earth
  - $\bar{\nu}_e$ *only* for NH
  - ν_e *only* for IH
  - 5-10% effect, needs good energy resolution

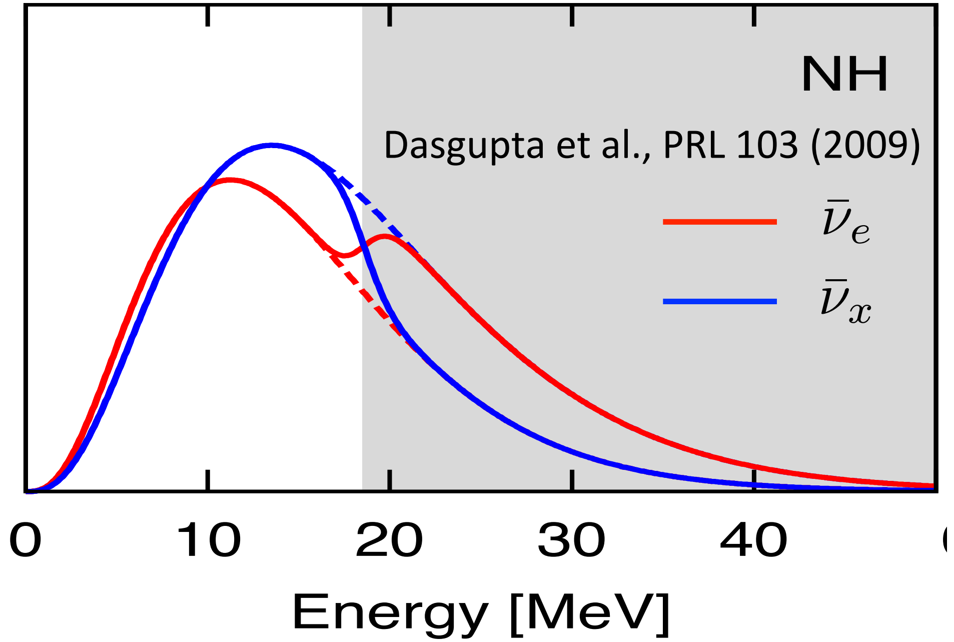
Borriello et al., Phys.Rev. D86 (2012)



Cooling phase: collective effects

- Azimuthal symmetry: Multi-Zenith-Angle instability
  - include angular distribution of emission
  - spectral splits
    - IH more unstable

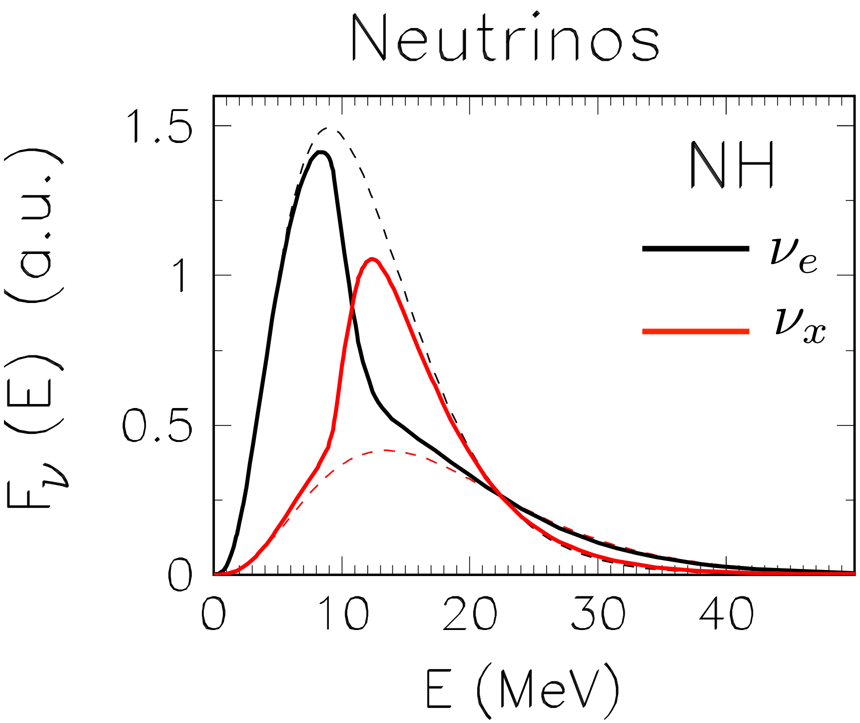




Relaxing azimuthal symmetry

- New Multi-Azimuthal Angle instability
  - New splits in NH

- Initial symmetry is (spontaneously) broken
  - Symmetric initial conditions → asymmetric solution



Raffelt, Sarikas & de Sousa Seixas, PRL 111, (2013)
Mirizzi,PRD 88 (2013), Mirizzi, arXiv:1308.5255
See also Mangano, Mirizzi & Saviano, PRD89 (2014)

Turbulence, interdisciplinary ramifications, …

- collective + MSW + turbulence

Lund & Kneller, PRD 88, 023008 (2013),
Borriello et al.,arXiv:1310.7488

- collective oscillations and r-process

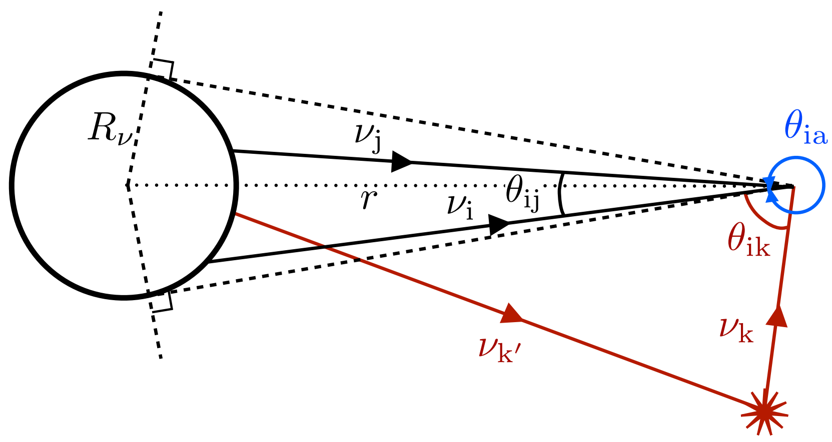
Duan et al., J. Phys. G 38 (2011)

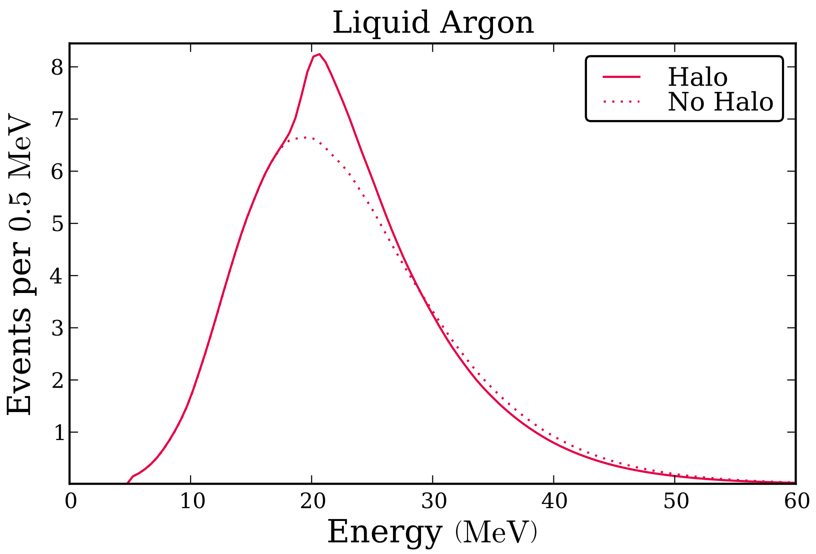
- collective oscillations and shock-revival

Dasgupta, O'Connor & Ott, PRD85 (2012)

Other new effects: the halo

- rescattered flux incident at large angle
  - $< 10^{-4}$ fraction
  - possible spectral swaps
    - ONeMg SN, neutronization flux



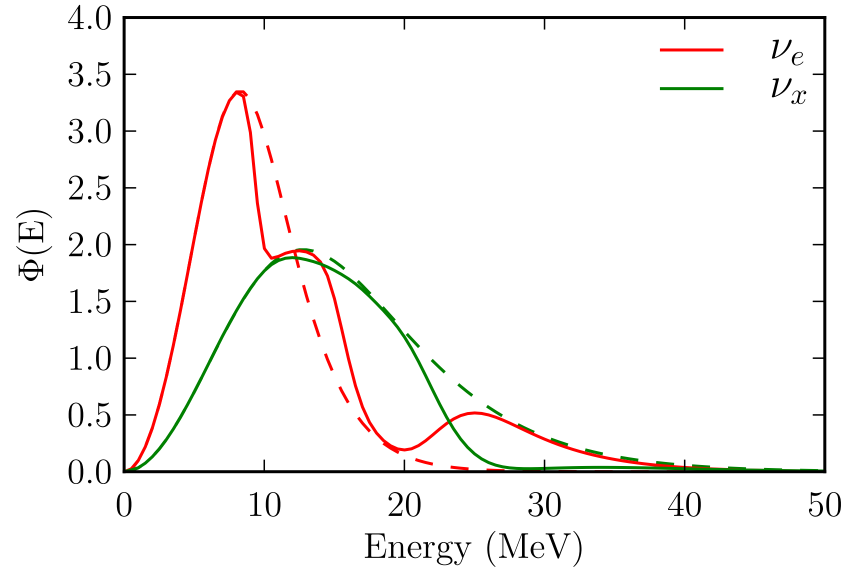


Cherry et al., PRL 108 (2012), Cherry et al., PRD87 (2013) Sarikas et al., PRD85 (2012)

Transition magnetic moment

- Neutrino → antineutrino collective oscillations

- Sensitive to *Standard Model* Majorana transition magnetic moment



$$|\mu_{ij}| = \begin{pmatrix} 0 & [0, 3.1] & [0, 3.3] \\ [0, 3.1] & 0 & [0, 7.2] \\ [0, 3.3] & [0, 7.2] & 0 \end{pmatrix} \times 10^{-24}\ \mu_B$$

De Gouvea & Shalgar, JCAP 1210 (2012), JCAP 1304 (2013)

New approaches: formalisms

- QFT-based derivation of evolution equations
  - Consistent inclusion of refraction and collision terms
  - New "spin coherence" term, $\propto \frac{m}{E} V \quad : \quad \nu \to \bar{\nu}$ conversion?

Vlasenko, Fuller, Cirigliano, PRD89 (2014)

- Lagrange polynomials, many body techniques, chaos theory,…

Baldo & Palmisano,arXiv:1202.2243
Volpe, Vaananen & Espinoza, PRD87 (2013)
Hansen & Hannestad, arXiv:1404.3833

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

Guaranteed : whole-sky flux

- Galactic SN : high statistics, but *very rare*
  - N~ 10^4 events, ~ 0.01/year

- Low statistic but *guaranteed:*
  - ***Mini-bursts*** : SNe at few Mpc, N~2-3, ~ 1/year

Kistler et al., PRD **83**, 2008, CL & Yang, PRD84 (2011)

  - ***Diffuse Supernova Neutrino Background (DSNB)*** : cosmological flux, constant in time

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

DSNB : probing the SN population

- SN statistics
  - typical parameters? Common phenomena?
- Cosmological supernovae
  - History of core collapse?
- SN diversity: rare types
  - Failed SN, ONeMg SNe, PopIII, supermassive stars, …

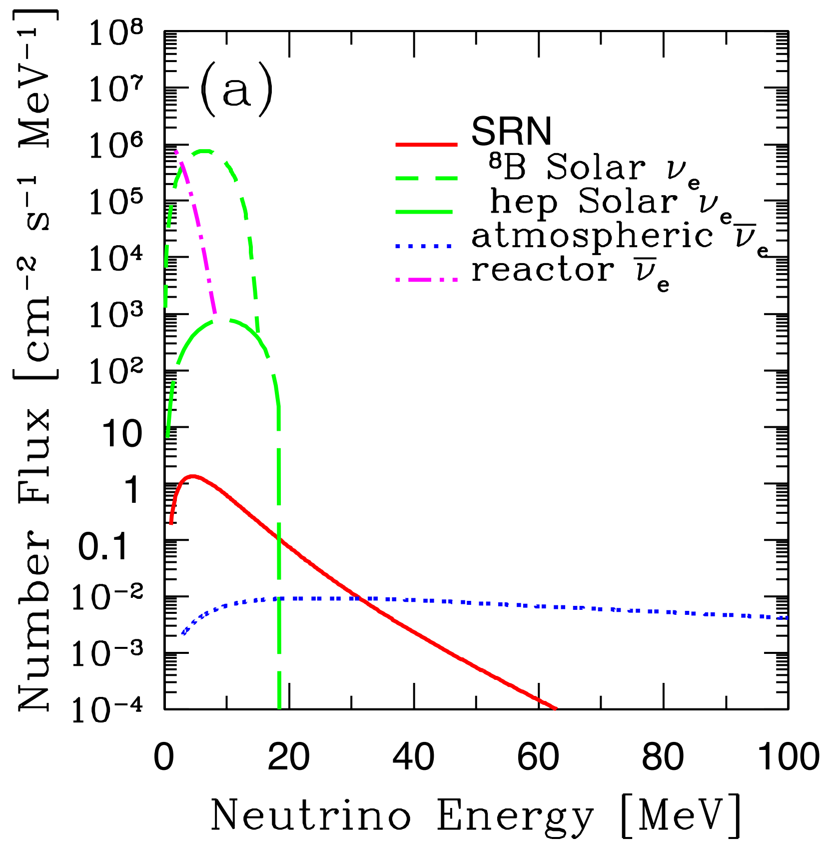
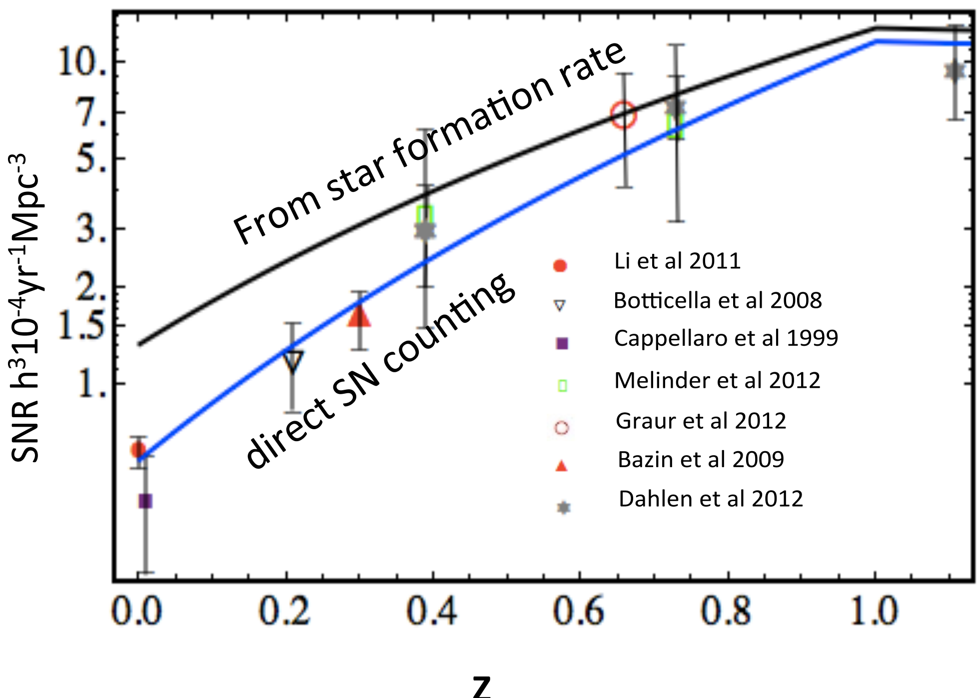


fig. from Ando & Sato, New J.Phys. 6 (2004)

Calculating the DSNB

SN rate — *Propagated* neutrino flux — Progenitor mass

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



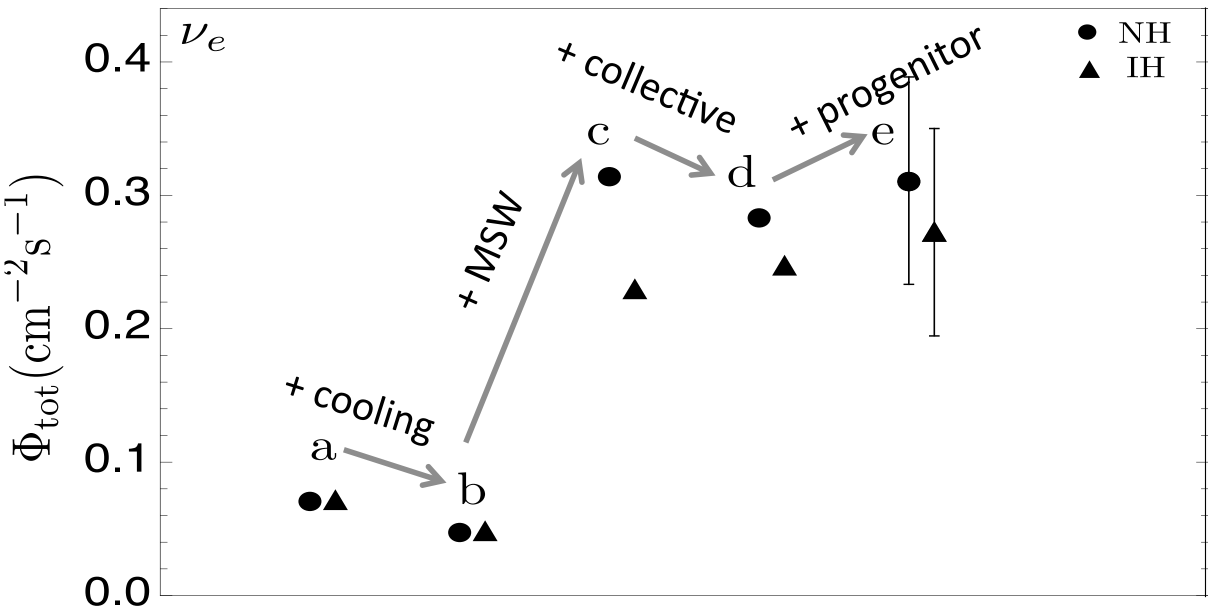
$$M_0 \simeq 8M_{sun}$$
$$M_{max} \simeq 125M_{sun}$$

Hopkins and Beacom, ApJ. 651 (2006), Horiuchi et al., ApJ 738 (2011)

Including multiple effects

- Accretion-, MSW-dominated
  - Other effects ~10%

C.L. and I. Tamborra, JCAP 1207 (2012)
[fluxes from 1D code: Fischer et al., A&A 517 (2010)]

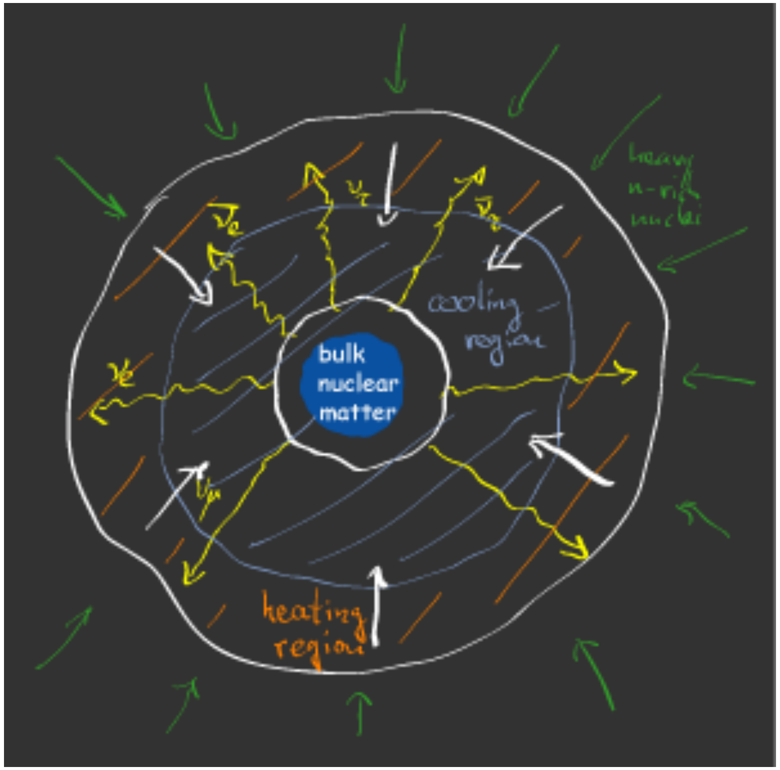


Mathews et al., arXiv:1405.0458

SUMMARY
FUTURE DIRECTIONS

Uncovering the complexity

- Still understanding the microphysics
  - collective oscillations, neutrino imprint of 3D effects
- Exploring the diversity of phenomena
  - phases of neutrino emission, SN types, …
- Mapping the parameter space
  - progenitor masses, equations of state, SN rate



from M. Liebendörfer's homepage

Possible future directions

- stronger focus on neutrinos in numerical simulations
  - detailed cooling phase, pre-supernova, …
- towards complete description of oscillation effects
  - consistent, unified theory
  - disentangling signatures of different effects: possible? Potential?
- stronger interdisciplinary focus
  - neutrinos as probes of SN physics, star formation, interplay with gravity waves, nuclear physics


Thank you!

BACKUP

Cosmological SN rate

- Proportional to star formation rate
  - Distribution of star masses at birth $\eta(M) \propto M^{-2.35}$

$$\dot{\rho}_{SN}(z,M) = \frac{\eta(M)}{\int_{0.5M_{sun}}^{M_{\max}} dM\ \ M\eta(M)}\dot{\rho}_\star(z)$$

$$\dot{\rho}_\star \propto \begin{cases} (1+z)^{3.28} & z<1 \\ (1+z)^{-0.26} & 1<z<4.5 \\ (1+z)^{-7.8} & 4.5<z \end{cases} .$$

Hopkins and Beacom, ApJ. 651 (2006)

- Measurements improving rapidly
  - Subdominant uncertainty on the DSNB

Linearized stability analysis

$$S_{swap} = \begin{pmatrix} s & S \\ S^* & -s \end{pmatrix} \qquad P(\nu_e \to \nu_e) = \frac{1}{2}(1+s) \qquad -1 \leq s \leq 1$$

$$i\partial_r S = (\omega + u\bar{\lambda})S - \mu \int d\Gamma' \left[u + u' - 2\sqrt{uu'}\cos(\varphi - \varphi')\right] g' S'$$

$$S(r,\omega,u,\varphi) \;=\; Q_\Omega(\omega,u,\varphi)\, e^{-i\Omega r}$$

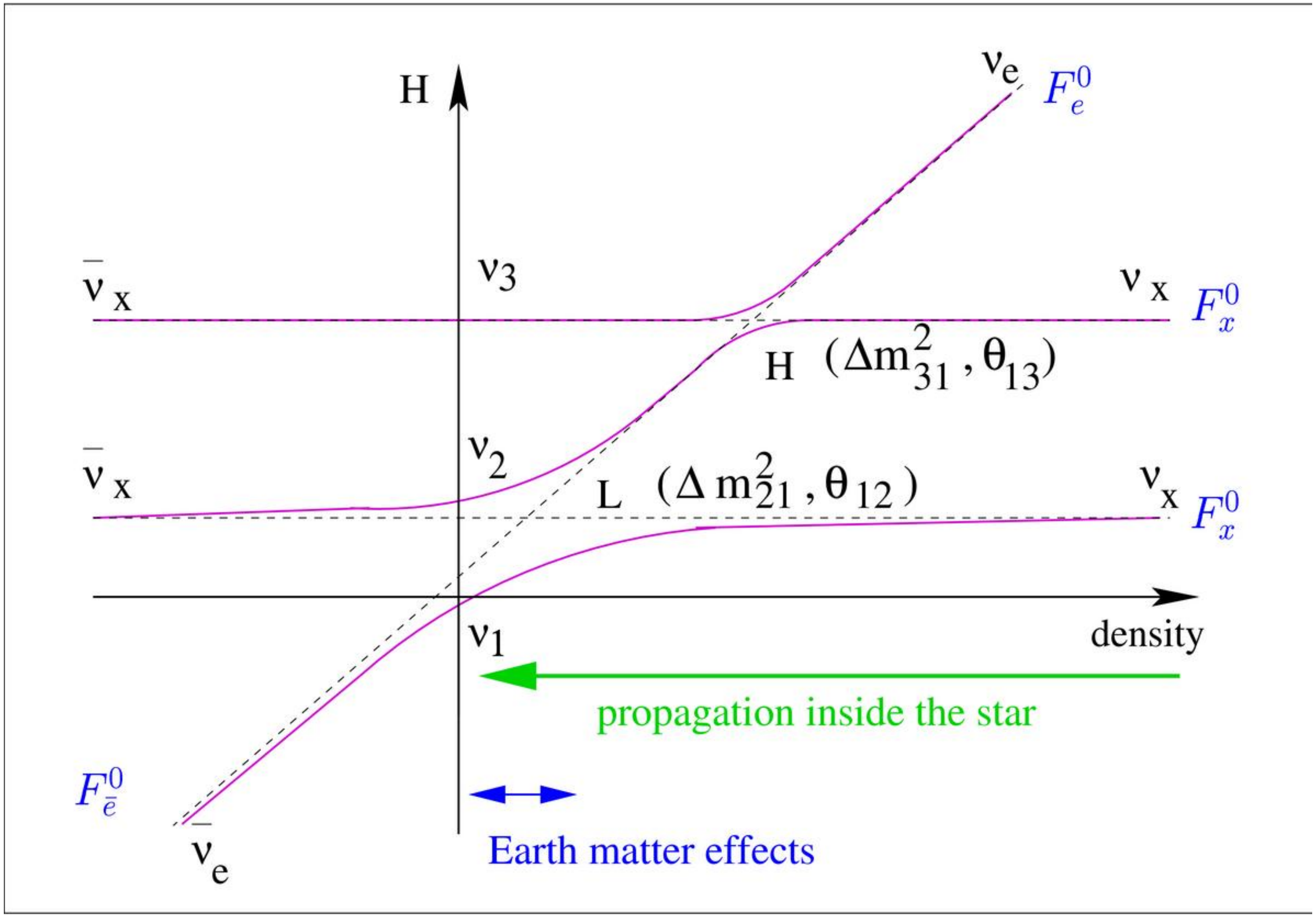
$$(\omega + u\bar{\lambda} - \Omega)Q_\Omega = \mu \int d\Gamma' \left[u + u' - 2\sqrt{uu'}\cos(\varphi - \varphi')\right] g' Q'_\Omega$$

Ω complex → Instability

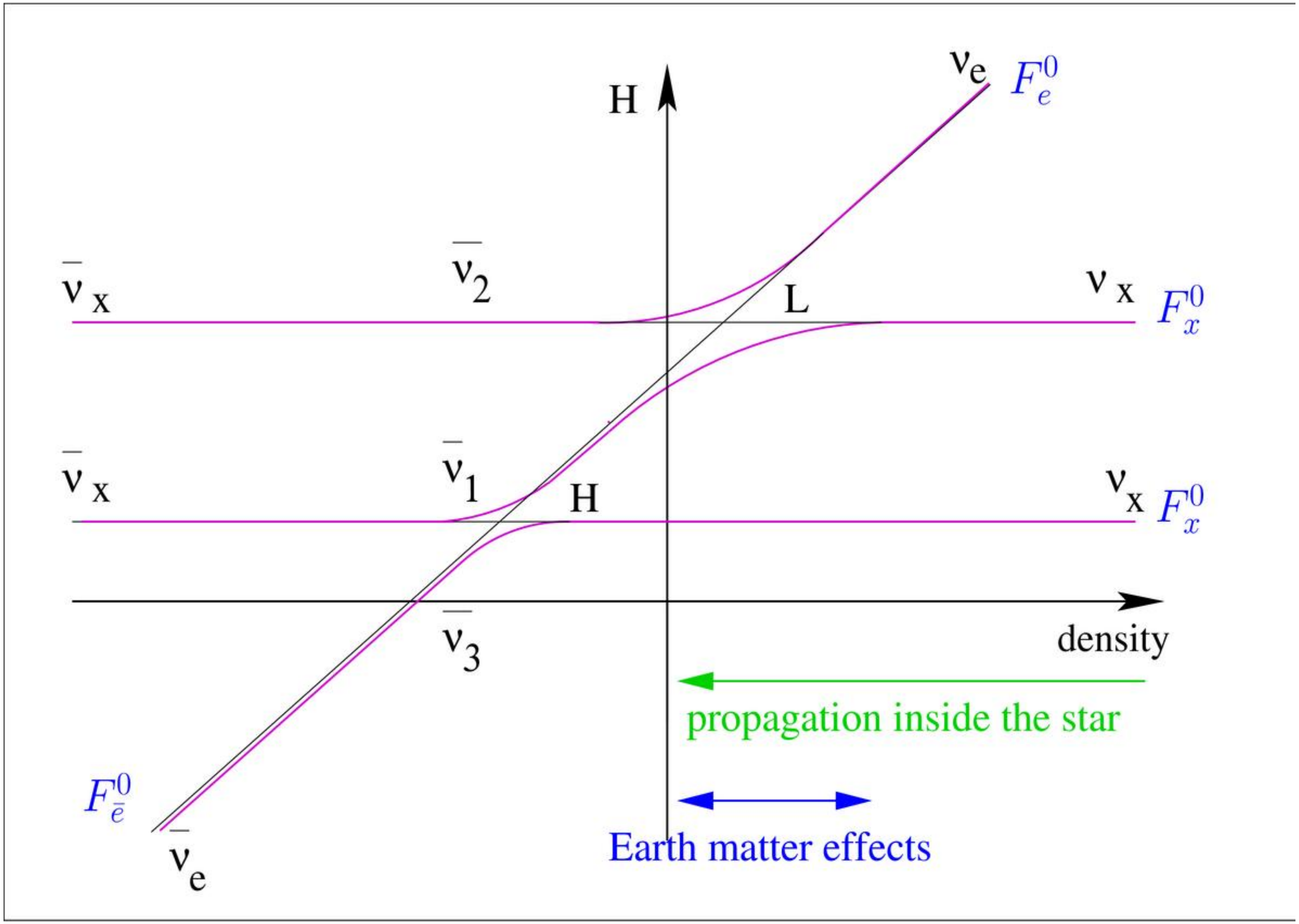
Im(Ω) > 0 *runaway, strong conversion*

Im(Ω) < 0 suppression of oscillations

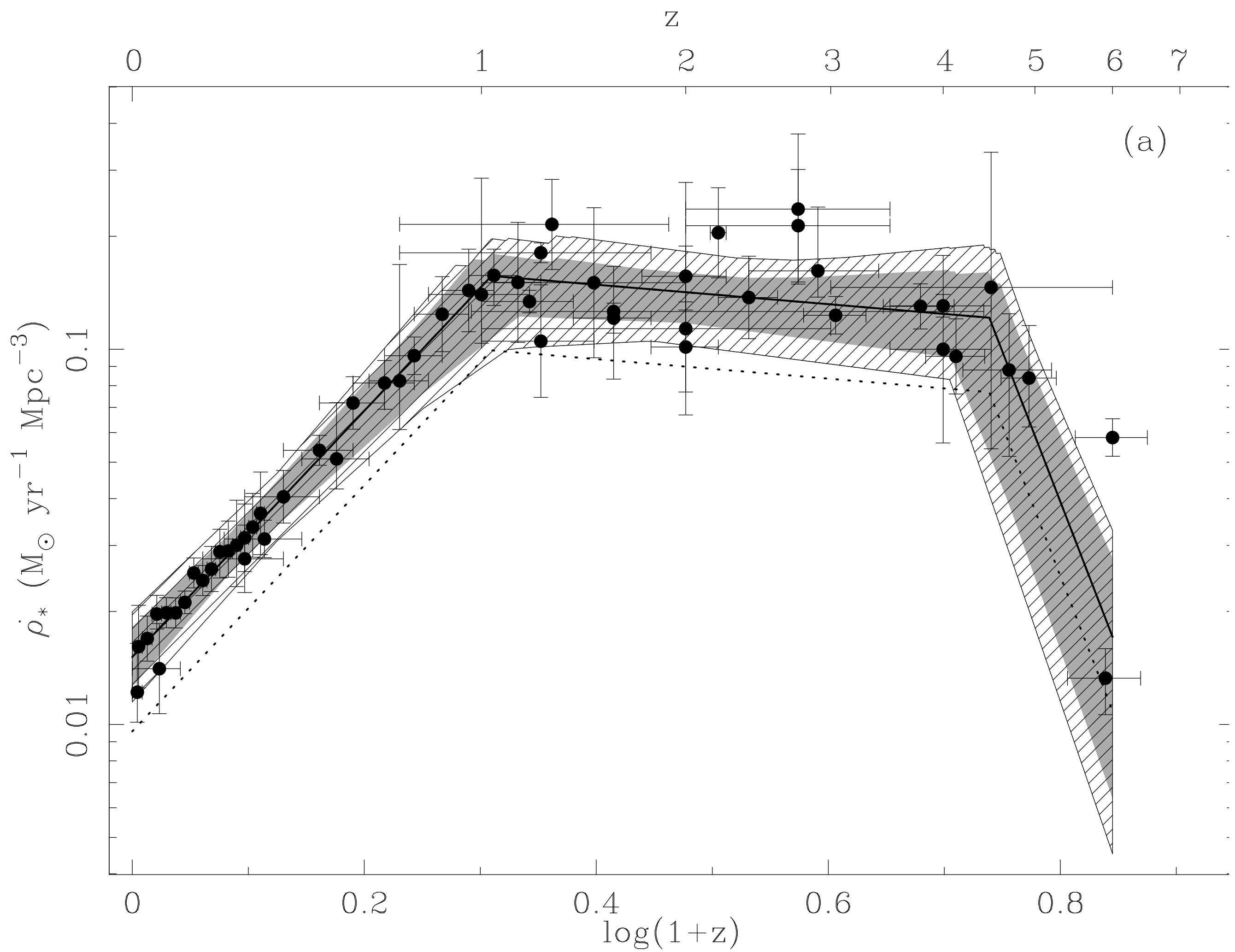
Normal hierarchy



Inverted hierarchy



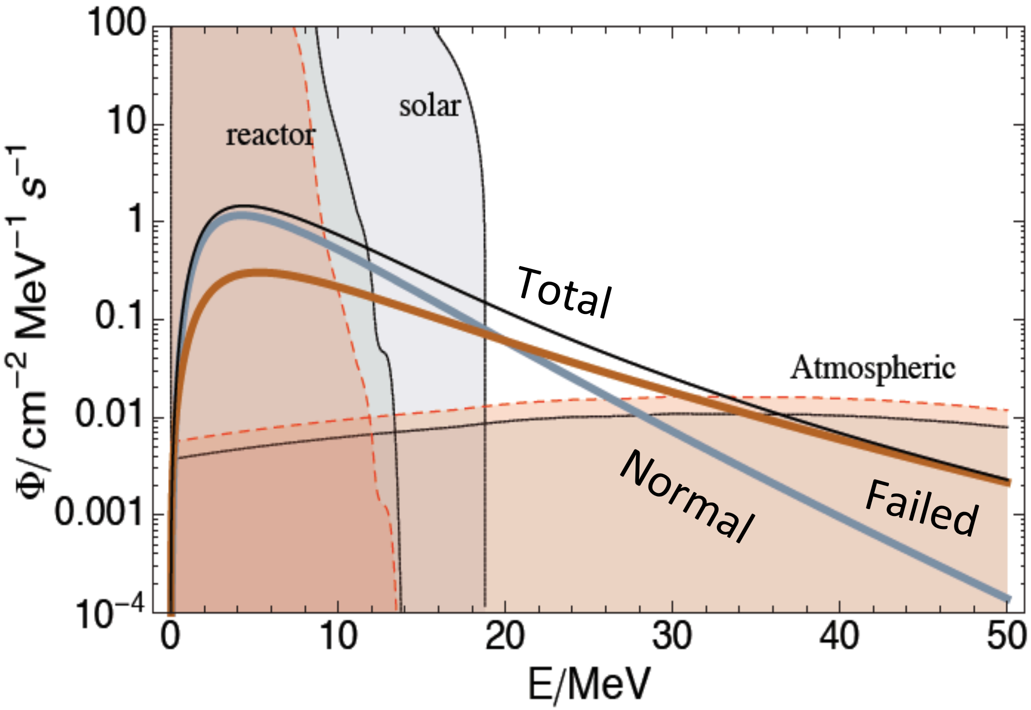
Star formation rate



Hopkins and Beacom, ApJ. 651 (2006)

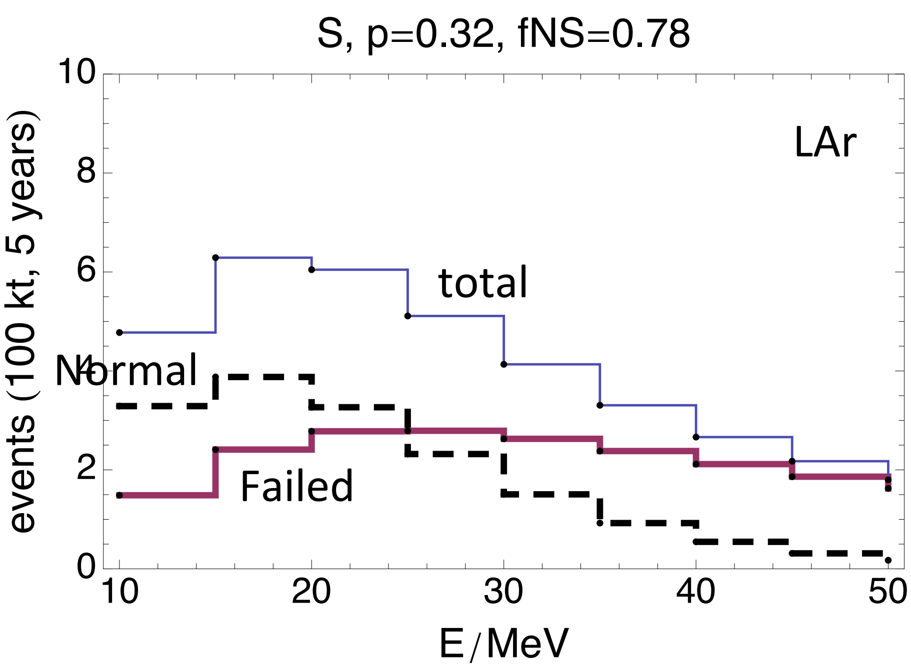
Including failed and ONeMg-core SN

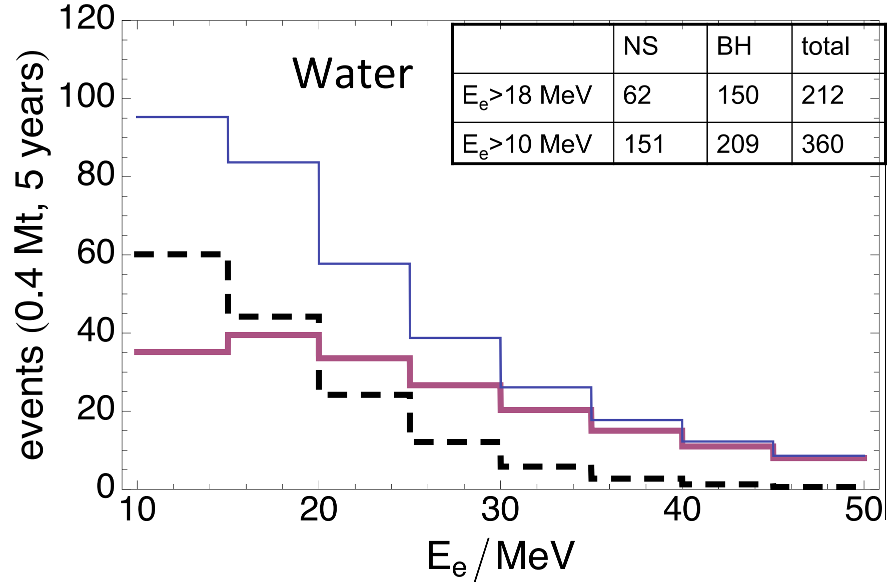
- Failed/dark SNe might appear



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

DSNB Event rates





	NS	BH	total
E_e>18 MeV	62	150	212
E_e>10 MeV	151	209	360