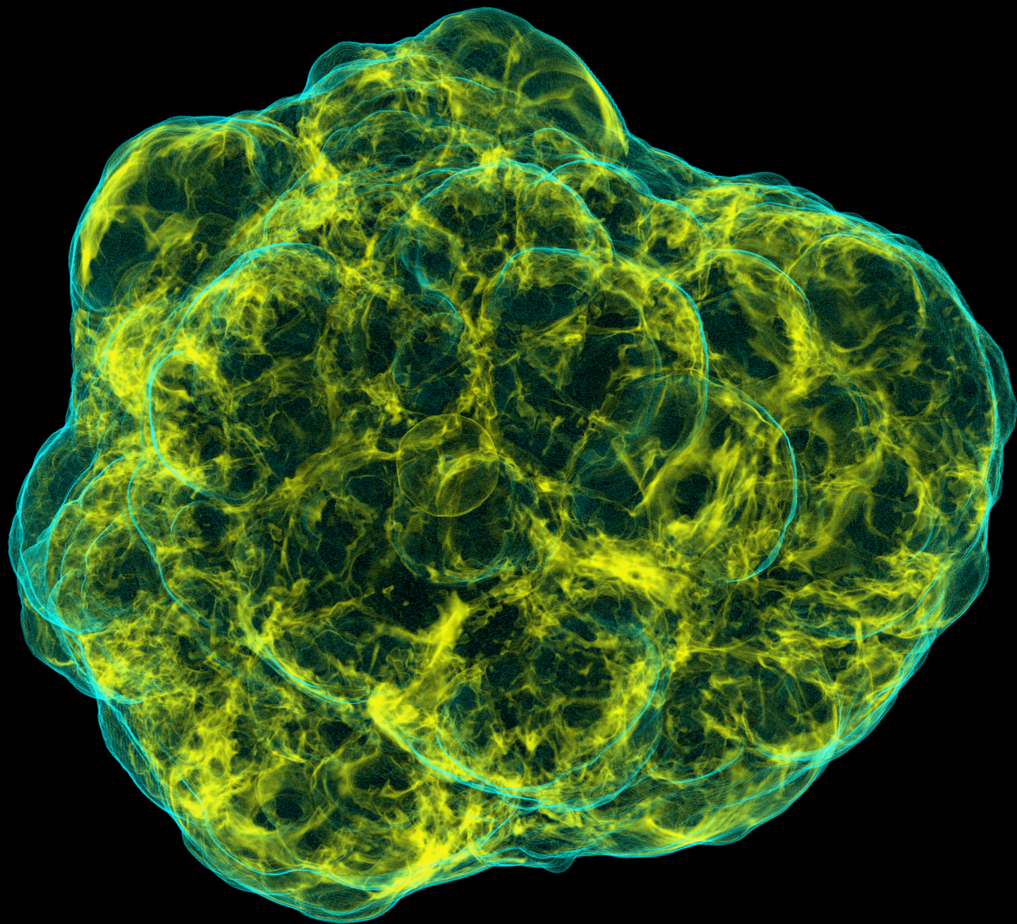
Supernova Neutrinos: A Review



Christian D. Ott

TAPIR, California Institute of Technology

With input and help from Luke Roberts (Caltech),
Evan O'Connor (NC State), Tobias Fischer (Wraclaw),
John Beacom (OSU), Mark Vagins (IPMU)

Caltech

BURKE INSTITUTE

IGPPS Los Alamos

NSF

Stellar Death & Supernova Explosions

- **~10 SN/s in the Universe**
- **~multiple SN/day discovered in photons**
- **~1 SN/50-100 yrs (?) in the Milky Way**
- **>1 SN/year within 10 Mpc**

Chandra

- **~20% thermonuclear SNe (Type Ia)**
  -> exploding white dwarfs
- **~80% core-collapse SNe (CCSNe, II, Ib,c)**
  -> exploding massive stars

G1.9+0.3
Explosion ~140 yrs ago.
@ 8 kpc in Sgr

Core-Collapse Supernovae:

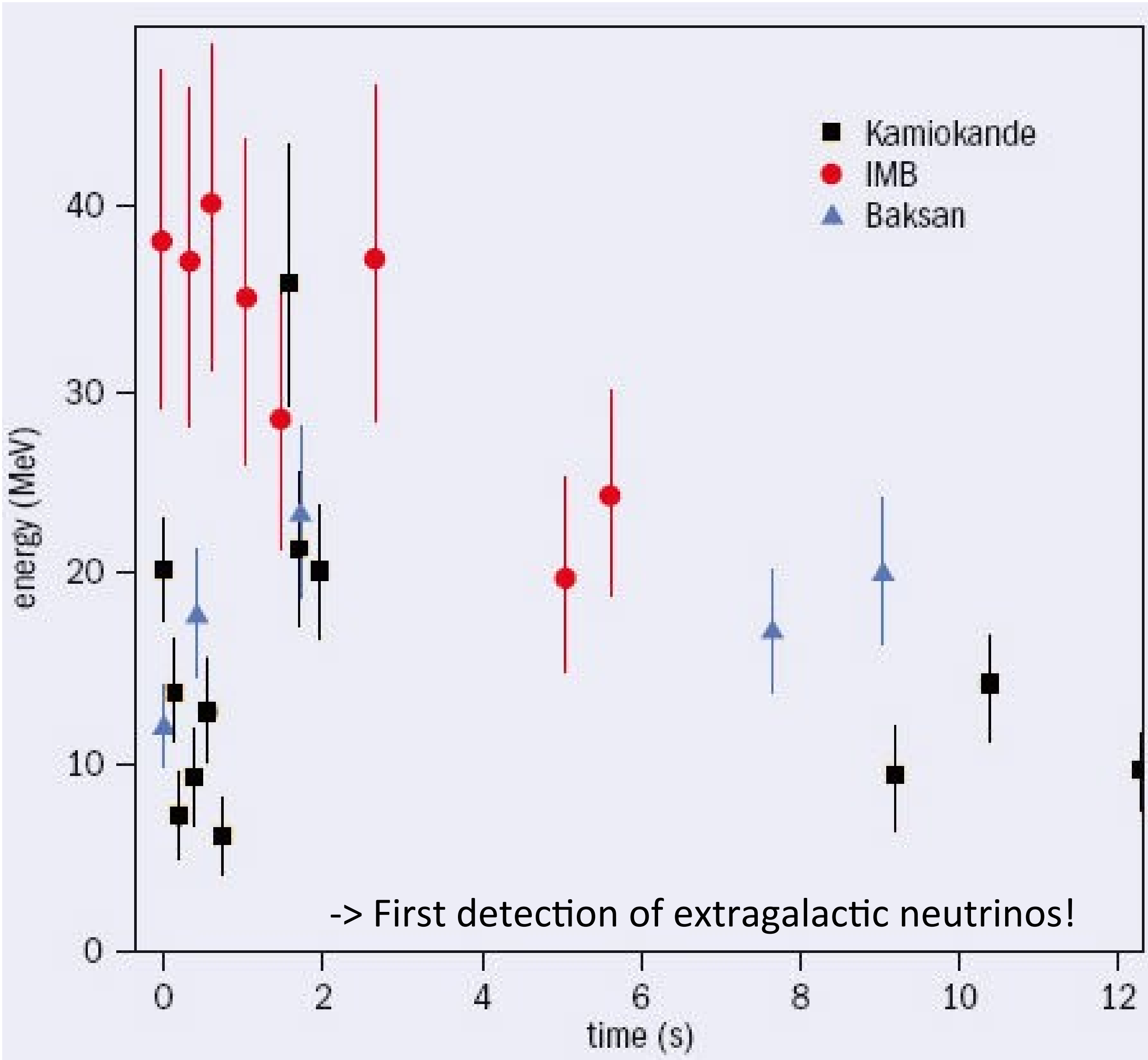
Explosions of Massive Stars $8M_\odot \lesssim M \lesssim 130M_\odot$

© Anglo-Australian Observatory

Supernova 1987A
Large Magellanic Cloud
Progenitor:
BSG Sanduleak -69° 220a, ≈18 M_{SUN}

SN 1987A: Neutrino Detection!

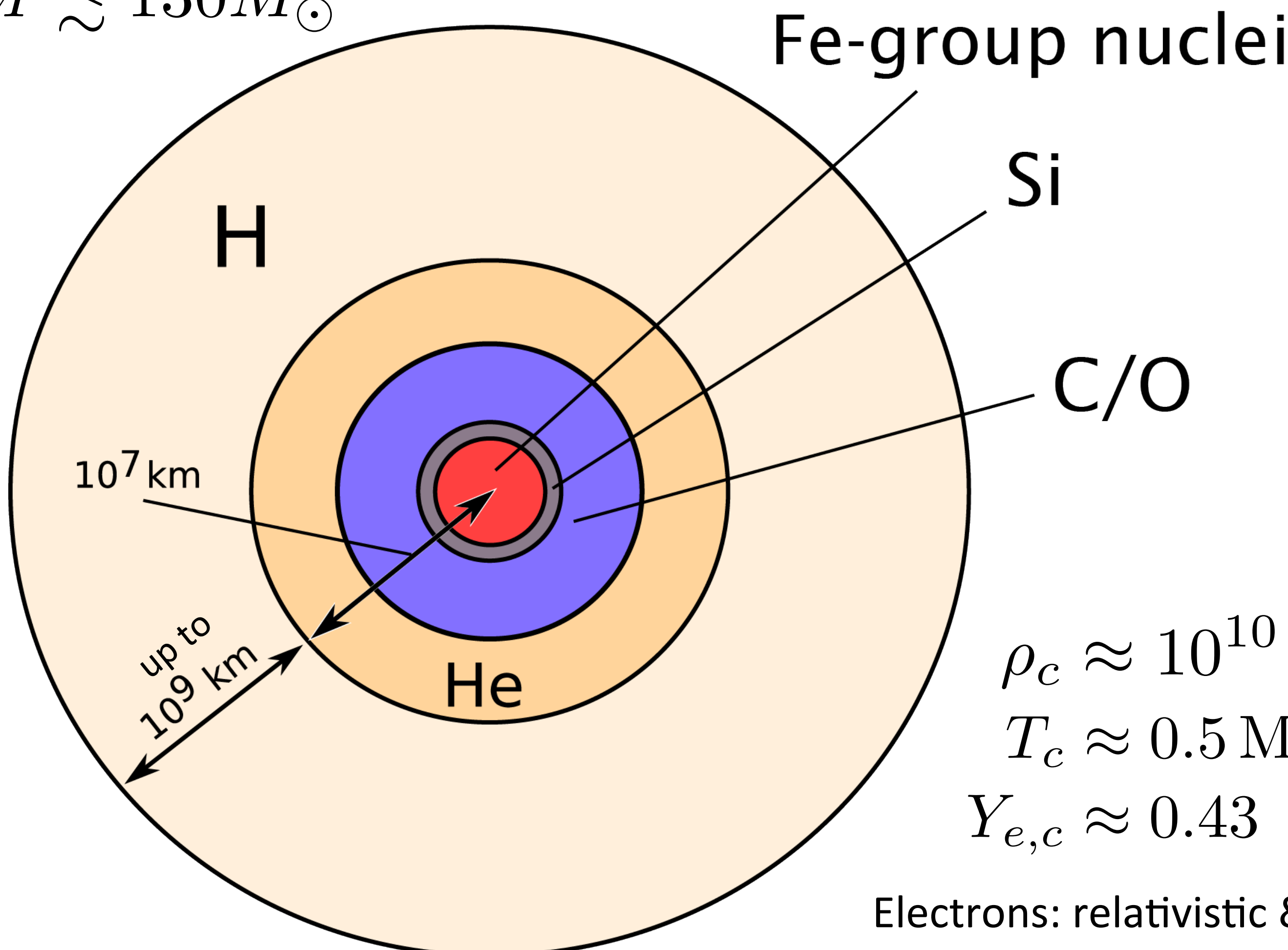
Hirata+87
Bionta+87
Alekseev+87



http://images.iop.org/objects/ccr/cern/47/1/28/CCEsup3_01-07.jpg

The Basic Theory of Core Collapse

$8M_\odot \lesssim M \lesssim 130M_\odot$



[not drawn to scale]

$\rho_c \approx 10^{10}\,\mathrm{g\,cm^{-3}}$

$T_c \approx 0.5\,\mathrm{MeV}$ (NSE)

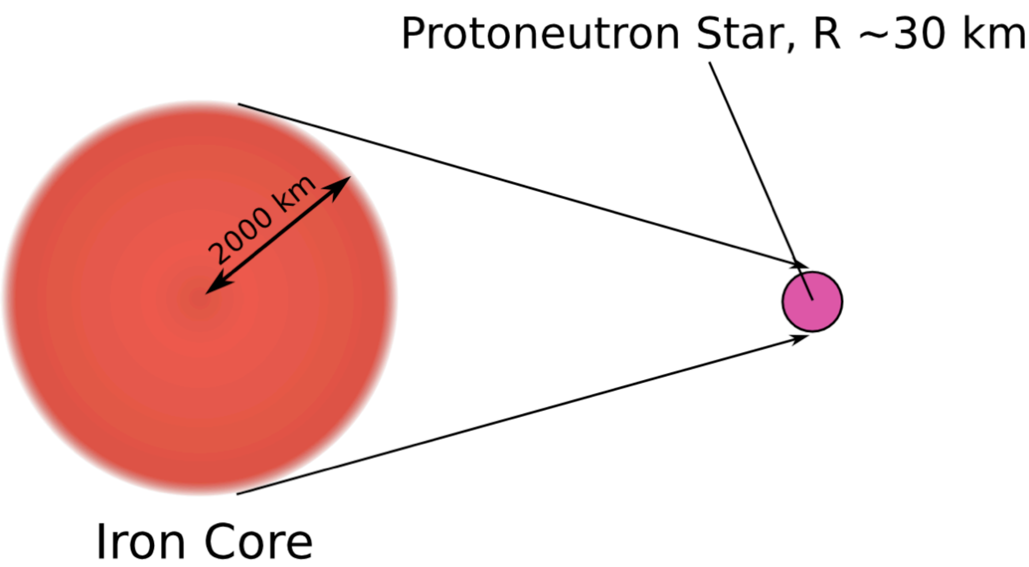
$Y_{e,c} \approx 0.43$

Electrons: relativistic & degenerate

$$M_{\mathrm{Ch}} \approx 1.44 \left(\frac{Y_e}{0.5}\right)^2 M_\odot$$

Effective Chandrasekhar mass

Core Collapse Basics

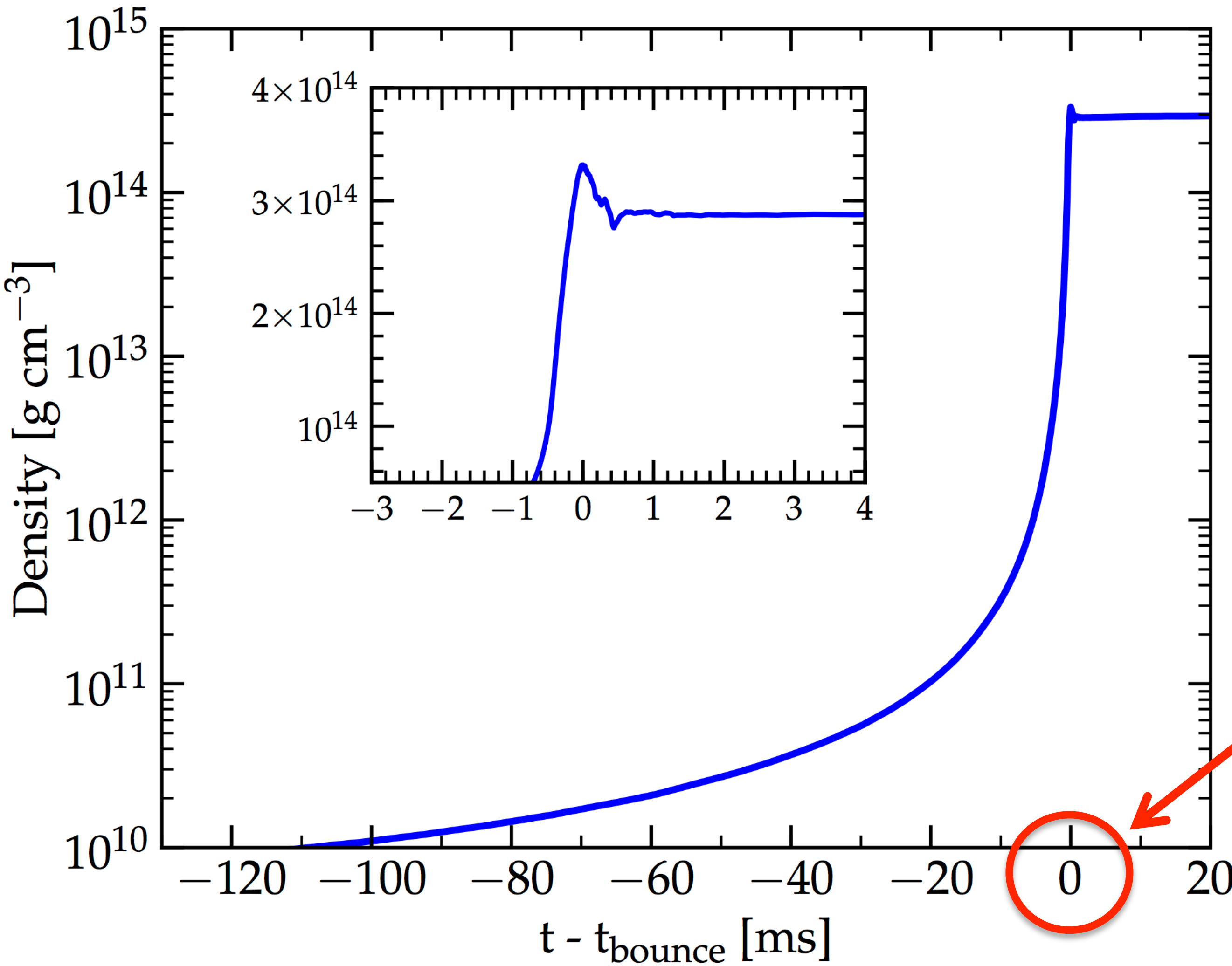


Nuclear equation of state (EOS) stiffens at nuclear density.

"**Core Bounce**"

Reviews:
Janka+12
Burrows 13

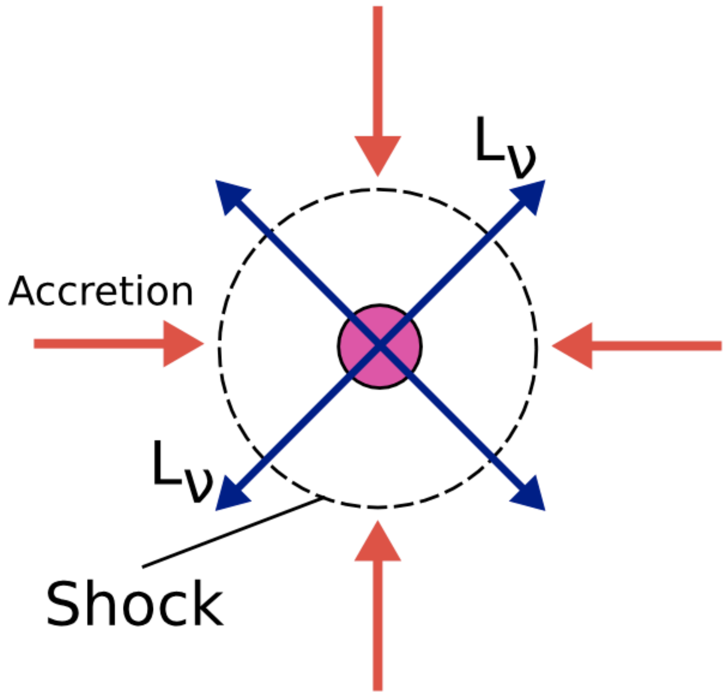
Collapse and Core "Bounce"



Stiff Nuclear **Equation of State** (EOS):
"**Core Bounce**"

Bounce:
t=0 for SN theorists.

Core Collapse Basics



"Core Bounce"

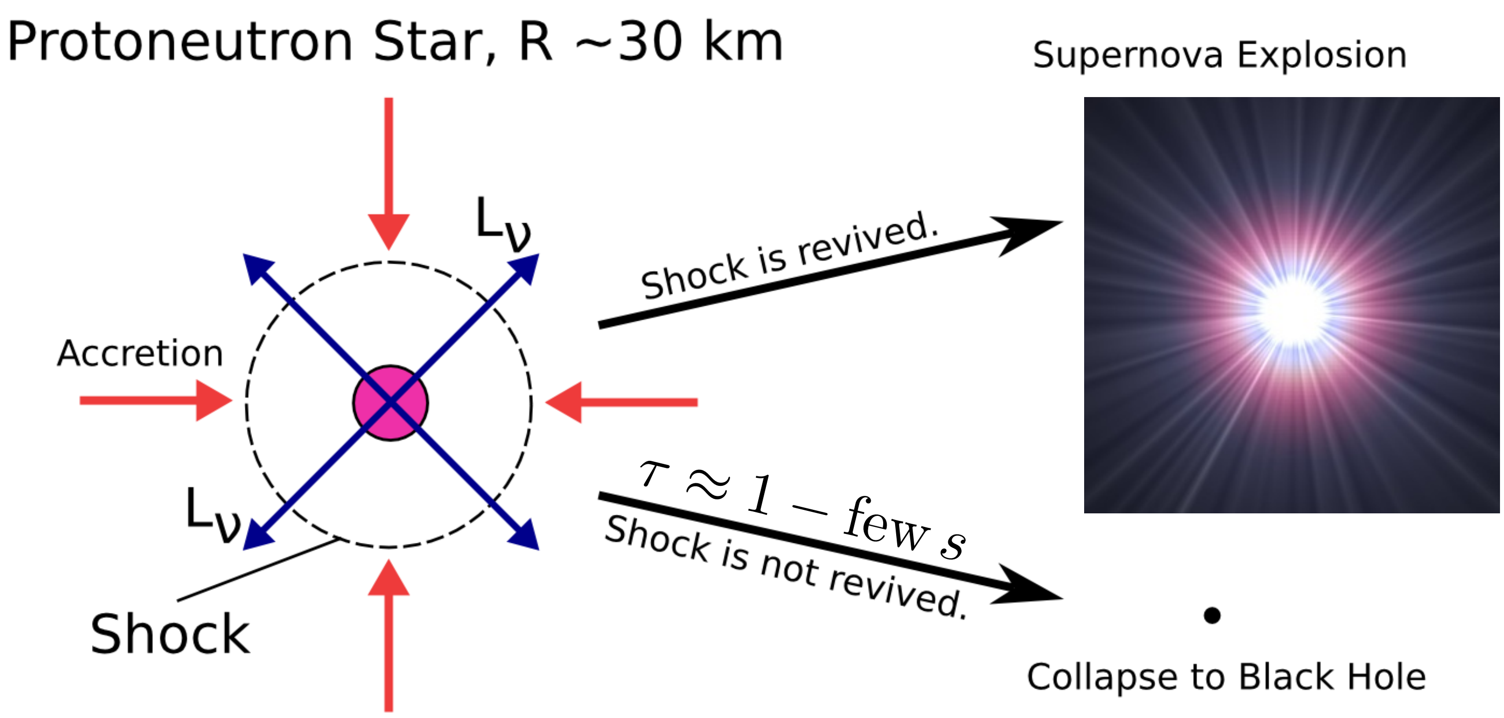
Inner core (~0.5 M_{Sun})
-> protoneutron star core.
Shock wave formed.

Outer core accretes onto shock & protoneutron star with O(1) $M_\odot$/s.

-> **Shock stalls at ~$\mathcal{O}$(100) km, must be "revived" to drive explosion.**

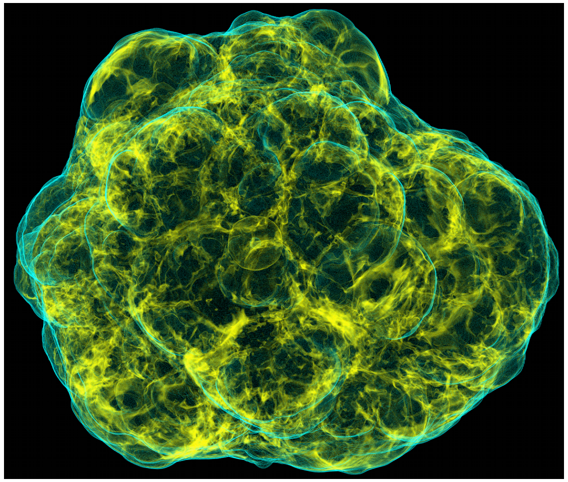
Reviews:
Janka+12
Burrows 13

"Postbounce" Evolution



Core-Collapse Supernovae & **Neutrinos**

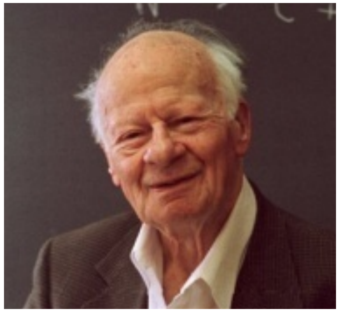
- CCSNe: *Neutrino-spewing gravity bombs*!



- Collapse to a neutron star:
  Gravitational energy release
  ~2–4 x 10^{53} erg = 200–400 [B]ethe

- ~10^{51} erg = 1 B kinetic and internal energy of the explosion.
  (Extreme cases: 10 B; "hypernova")

- 99% of the energy is radiated in neutrinos over tens of seconds in proto-NS cooling.
  ($L_\nu \approx L_{photon}$ of all stars in the universe!)



Hans Bethe

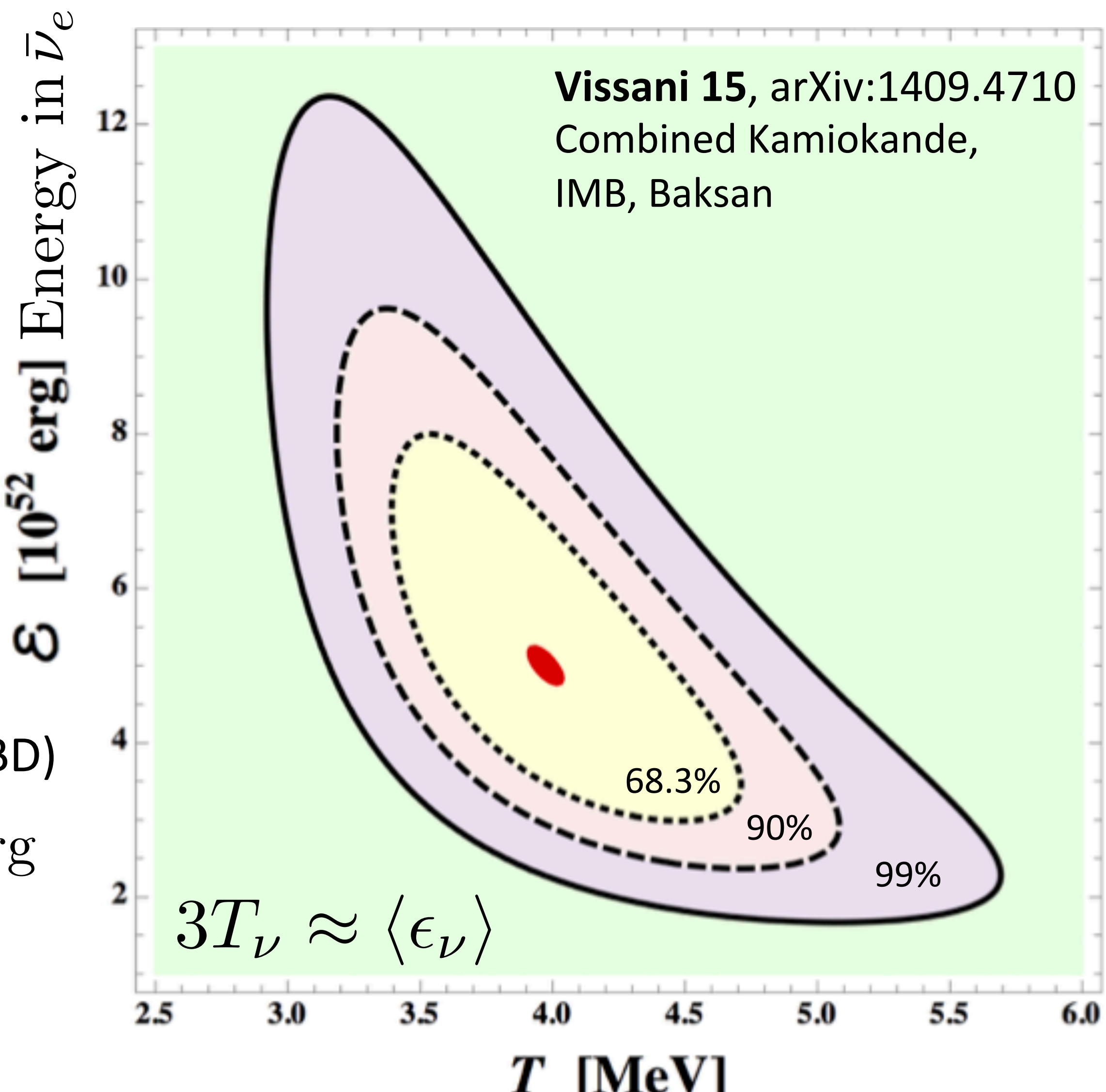
CCSNe: Neutrino-Spewing Gravity Bombs

SN 1987A

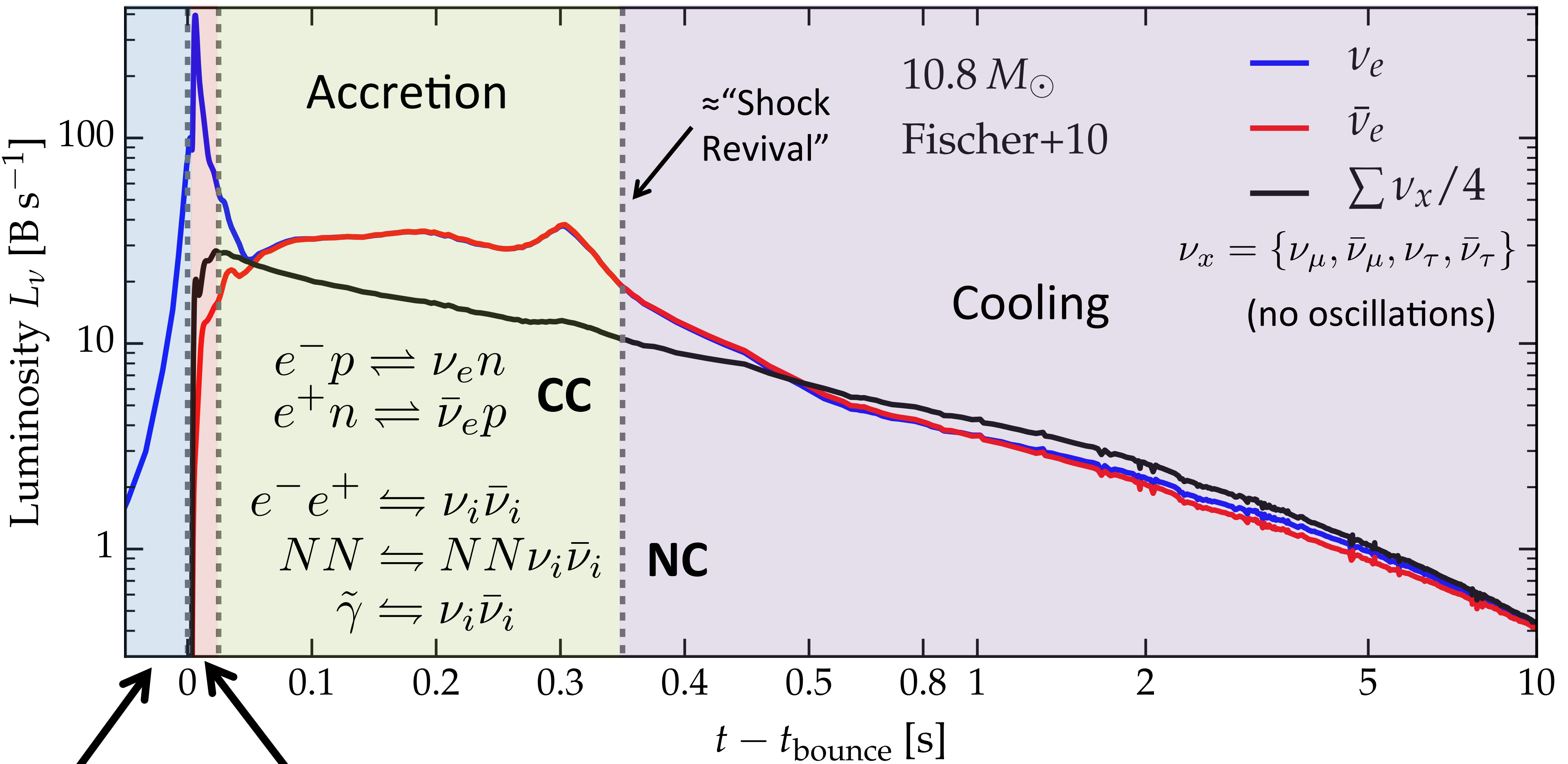
Kamiokande II, IMB, Baksan:

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad \text{(IBD)}$$

$$E_{\text{tot}} \approx 6\mathcal{E} \approx 3 \times 10^{53}\,\text{erg}$$



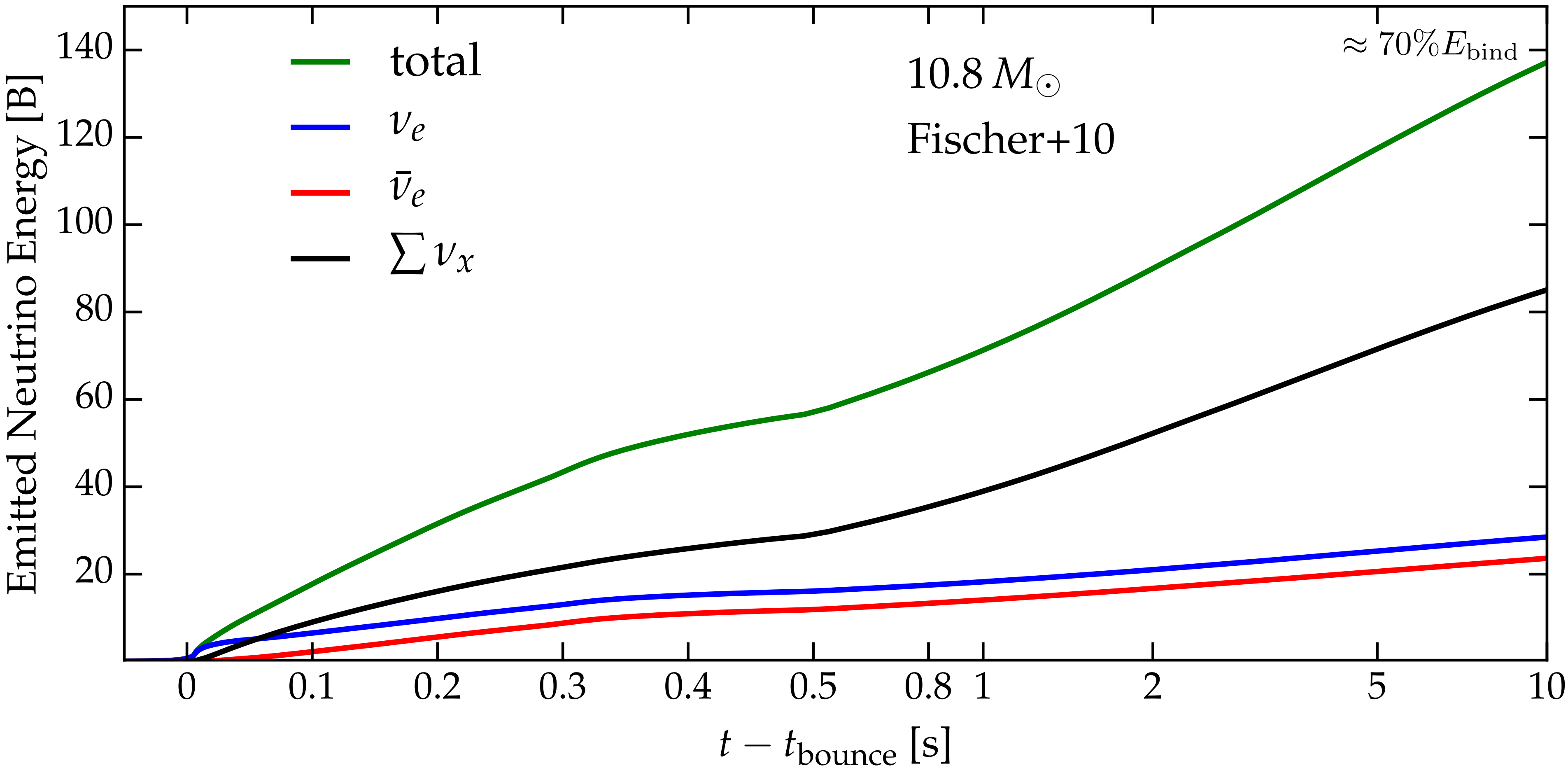
Supernova Neutrino "Lightcurves"



Collapse "Deleptonization Burst"

$$e^- + p \to n + \nu_e$$

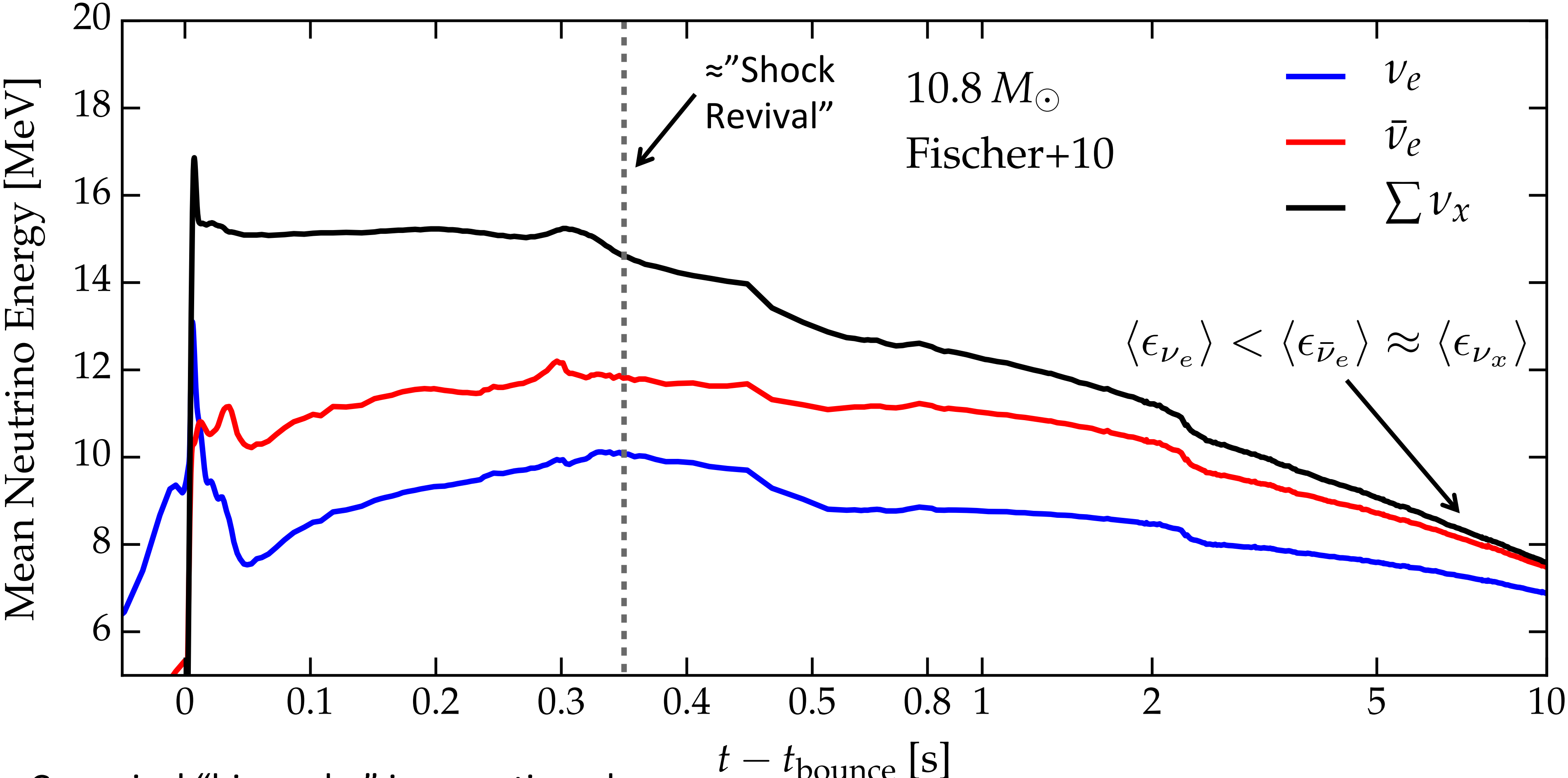
Neutrinos: Emitted Energy



$M_{\rm bary,NS} \approx 1.44\, M_\odot$ $M_{\rm grav,NS} \approx 1.33\, M_\odot$

$E_{\rm bind} \approx 2 \times 10^{53}$ erg

Neutrinos: Mean Energies



Canonical "hierarchy" in accretion phase:

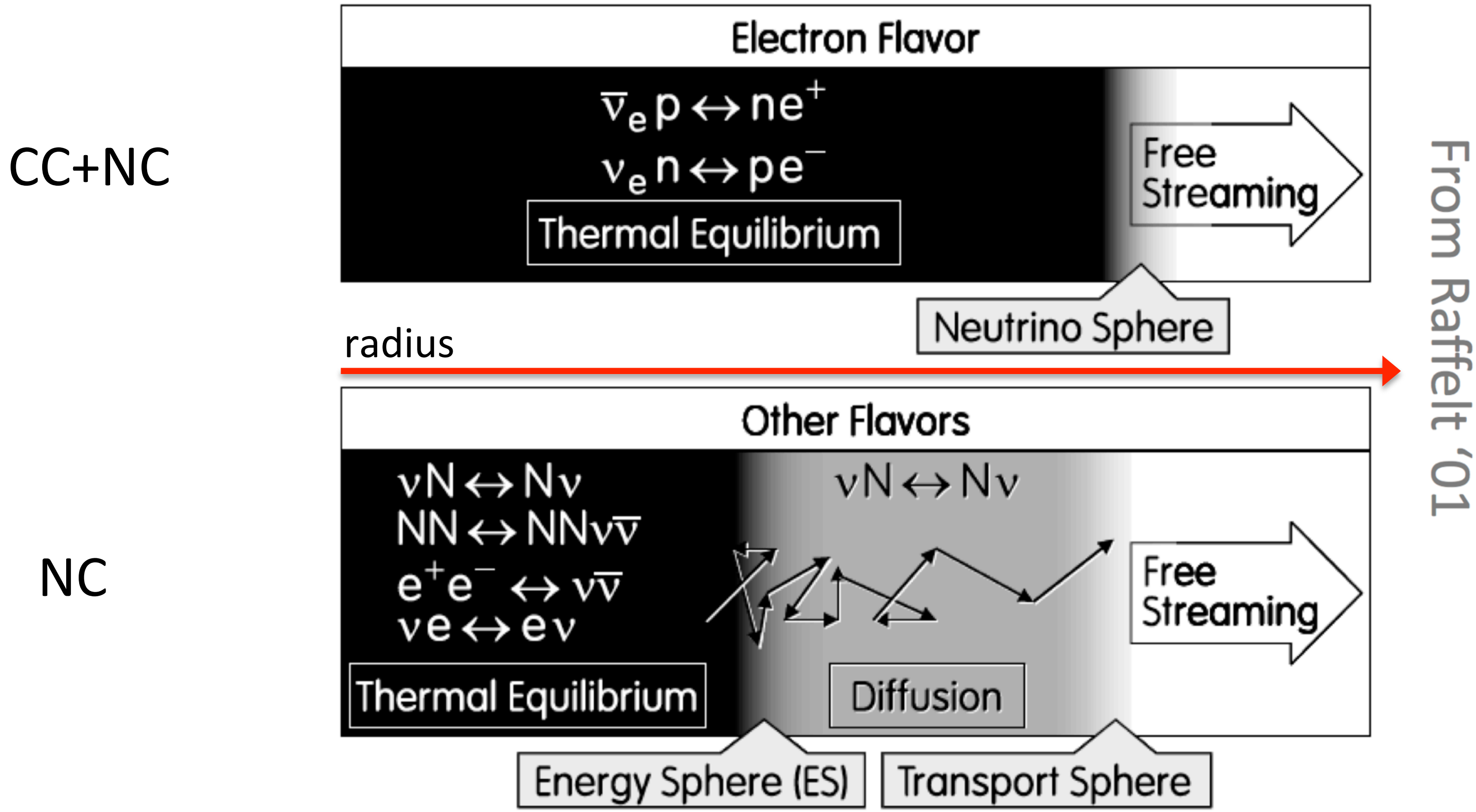
$$\langle \epsilon_{\nu_e} \rangle < \langle \epsilon_{\bar{\nu}_e} \rangle < \langle \epsilon_{\nu_x} \rangle$$

(at least at early times & lower-mass stars)

$$\langle \epsilon_{\nu_e} \rangle < \langle \epsilon_{\nu_x} \rangle \lesssim \langle \epsilon_{\bar{\nu}_e} \rangle$$

(late accretion phase, more massive stars)

Neutrinos: Spectrum Formation



$$\tau = \int \kappa ds \qquad \tau_{\mathrm{NS}} = 2/3$$

Spectra: Quasi-thermal, pinched (high-energy component downscattered)

Neutrinos: Spectra

Roberts 2012; also:
Burrows&Lattimer 86,
Pons+99, Keil+03,
Fischer+10,12, Hüdepohl+10,
Nakazato+13, Mirizzi+15

Fermi-Dirac:

$$f(\epsilon_\nu) \propto \epsilon_\nu^2 [1 + \exp(\epsilon_\nu / T - \eta)]^{-1}$$

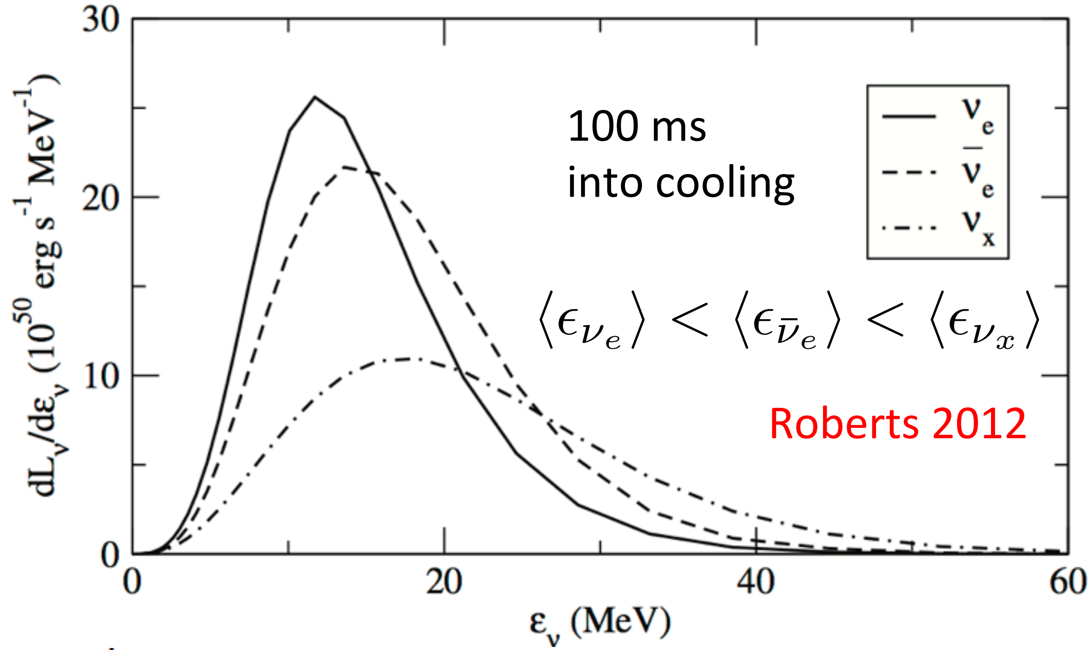
$$dL_\nu / d\epsilon_\nu = \epsilon_\nu f(\epsilon_\nu)$$

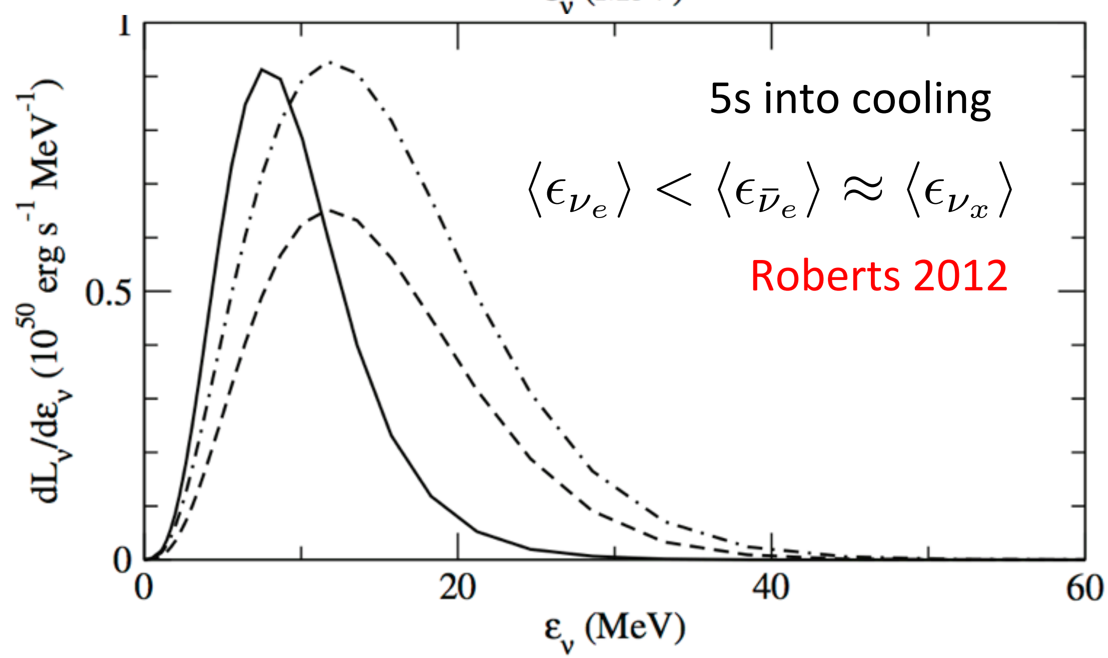
Keil+03:

$$f_\alpha(\epsilon_\nu) = \left(\frac{\epsilon_\nu}{\langle \epsilon_\nu \rangle} \right)^\alpha e^{-(\alpha+1)\epsilon_\nu / \langle \epsilon_\nu \rangle}$$

$$\frac{\langle \epsilon_\nu^2 \rangle}{\langle \epsilon_\nu \rangle^2} = \frac{2 + \alpha}{1 + \alpha}$$

α : Pinch Parameter
(time dependent)





What can Supernova Neutrinos do for you?

Revive the stalled shock! -> “Neutrino Mechanism”

Probe Stellar Structure

Probe Stellar-Mass Black Hole Formation

Probe Multi-Dimensional Supernova Dynamics

Bonus: ν-Driven Wind & (no) r-Process Nucleosynthesis (A>120)

Probe the Equation of State of Nuclear Matter

Reveal Neutrino Oscillation & Flavor Physics

(Constrain Exotic Particle Physics [Axions etc.]; see Raffelt ‘90, ‘12)

Probe the Supernova History of the Universe

Blowing up Stars: Neutrino Mechanism

Bethe & Wilson ’85; also see: Janka ‘01, Janka+ ’07

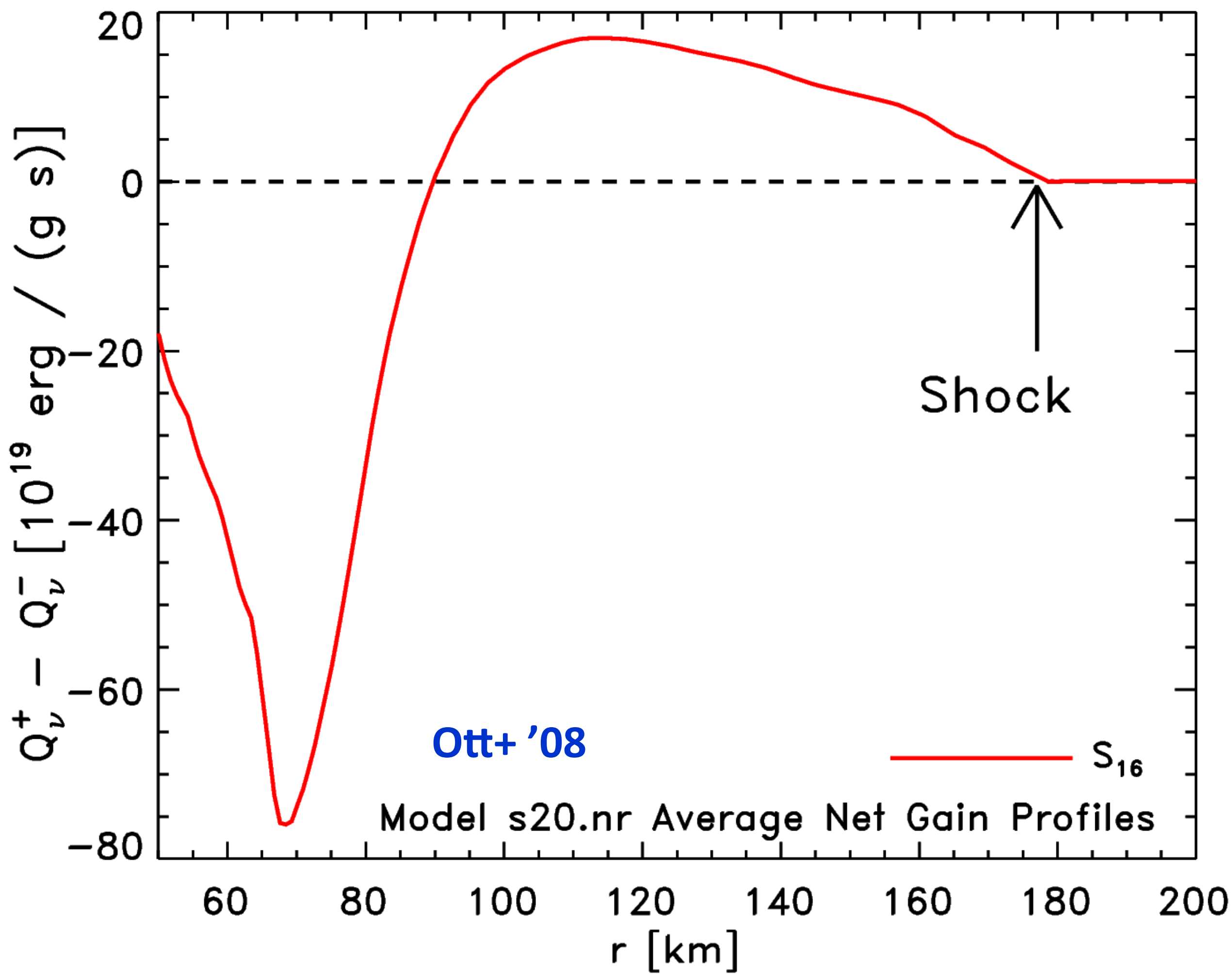
Cooling:

$$Q_\nu^- \propto T^6, T^9$$

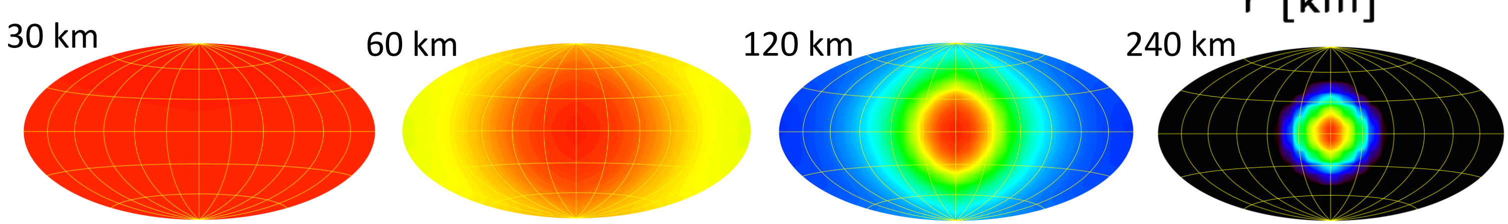
Heating:
charged-current absorption

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

$$Q_\nu^+ \propto \left\langle \frac{1}{\mathrm{F}_\nu} \right\rangle L_\nu r^{-2} \langle \epsilon_\nu^2 \rangle$$



Neutrino radiation field:



-6.18 ms

Ott+2013
Caltech,
full 3D & GR,
parameterized
neutrino heating

Multi-D
dynamics
essential.

1D explosions
fail.

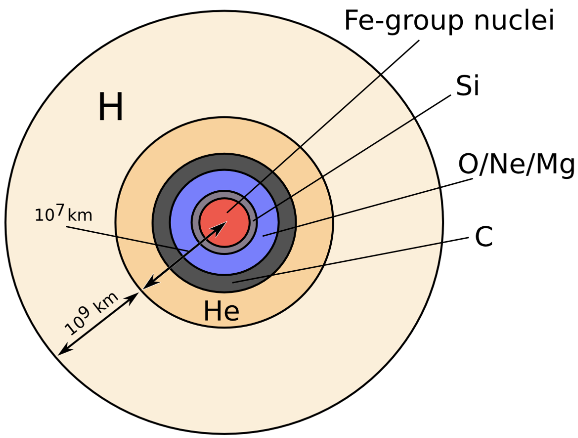
Much other work:
Hanke+13,
Melson+15ab,
Lentz+15,
Takiwaki+14,
Couch&O'Connor+14
Abdikamalov+14

Caltech

Probing Stellar Structure

- Neutrino signal in the **accretion phase** is determined by
  (1) the accretion rate of the stellar envelope and
  (2) the proto-NS core temperature.

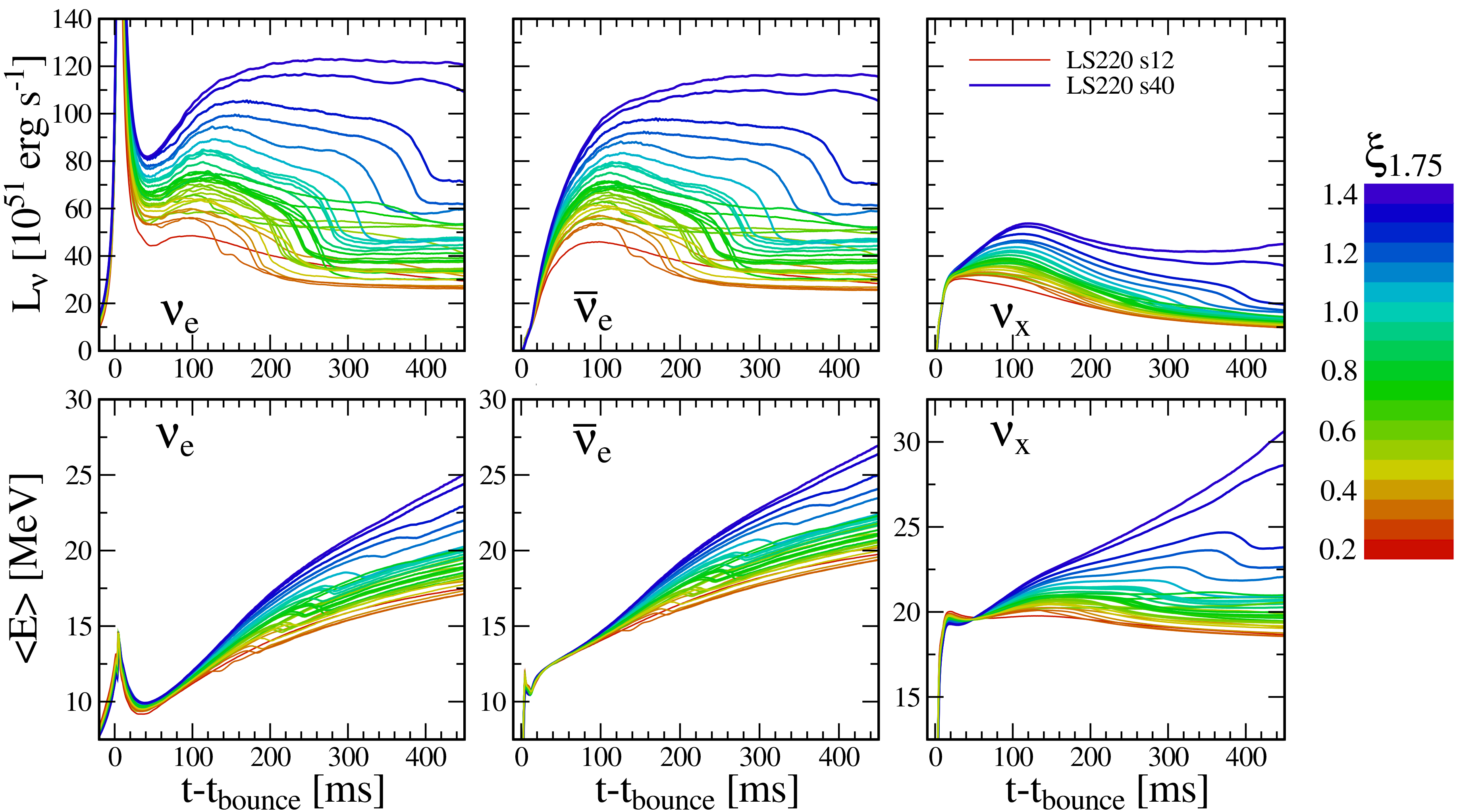
$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary}=M)/1000\,{\rm km}}\Big|_{t=t_{\rm bounce}}$$



"compactness parameter" (O'Connor & Ott '11)

Rule of Thumb:
More compact progenitor
-> higher accretion rate & core temperature

Probing Stellar Structure

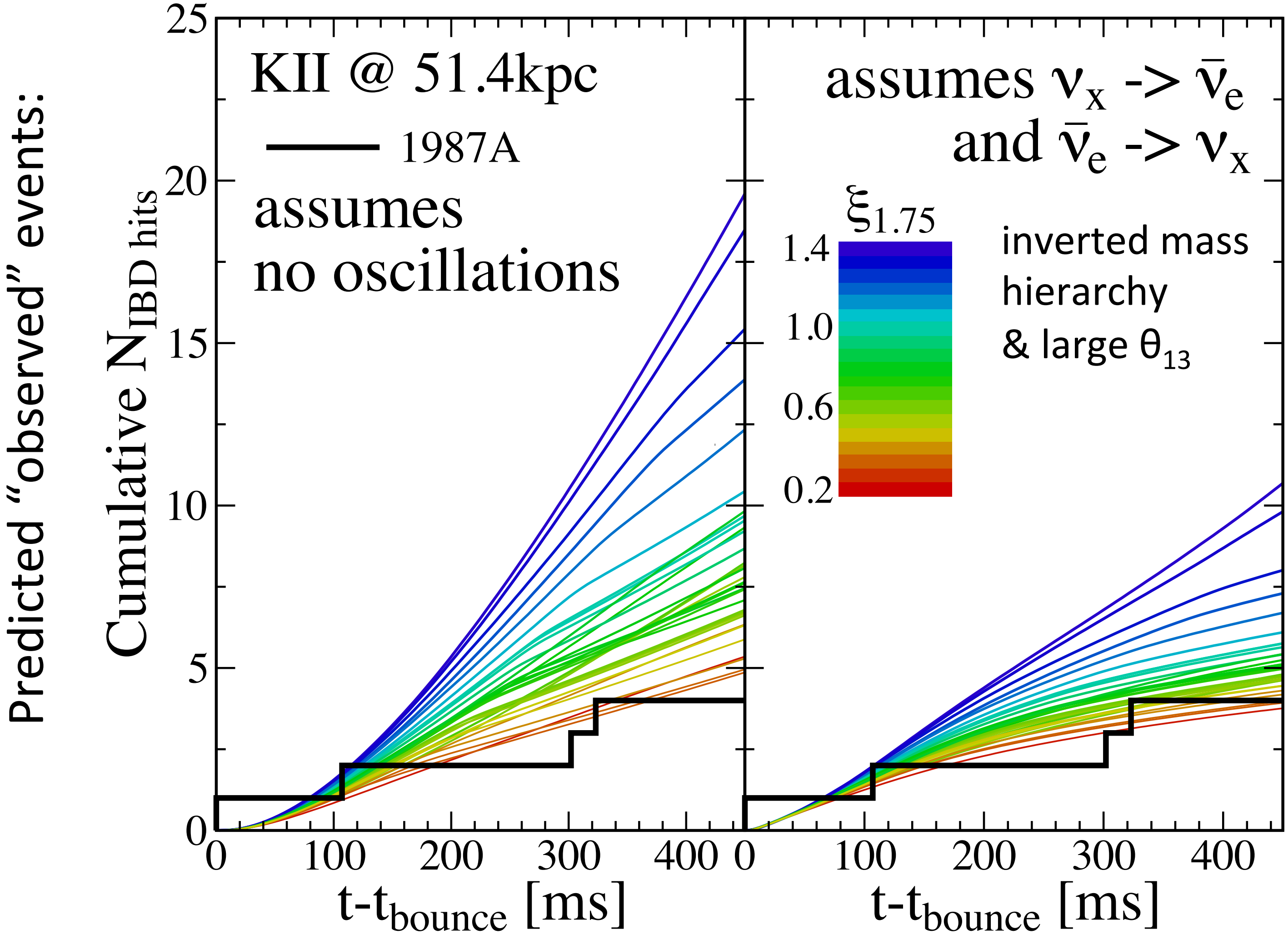


$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}}\bigg|_{t=t_{\rm bounce}}$$

O'Connor & Ott 13

Progenitor Structure of SN 1987A?

O'Connor & Ott 2013



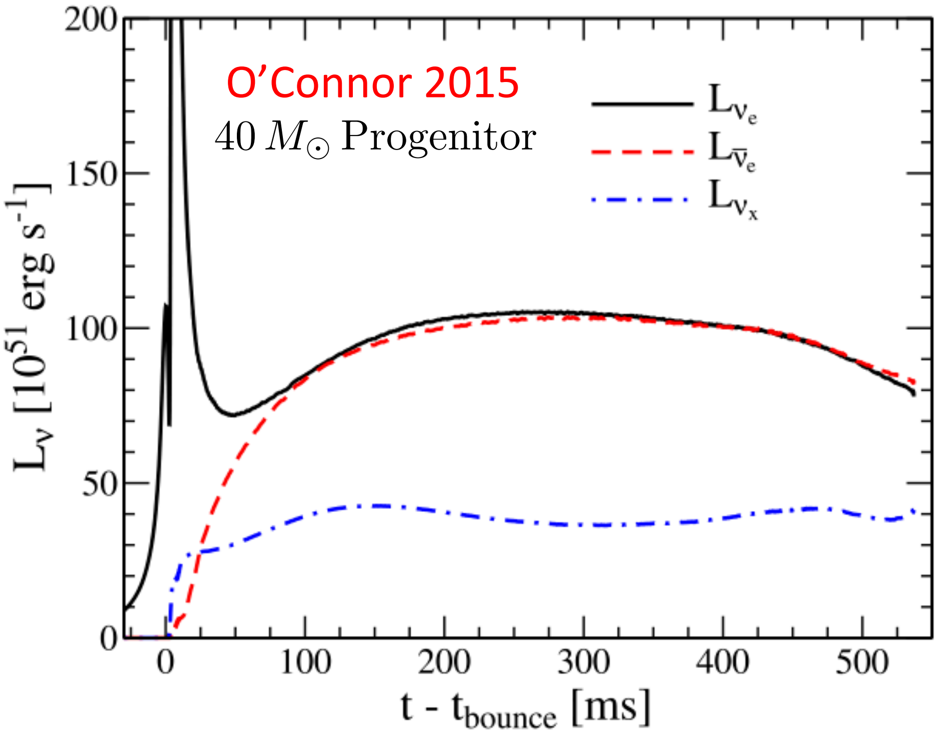
-> Potential Conclusion: **early explosion OR low-compactness progenitor core!**

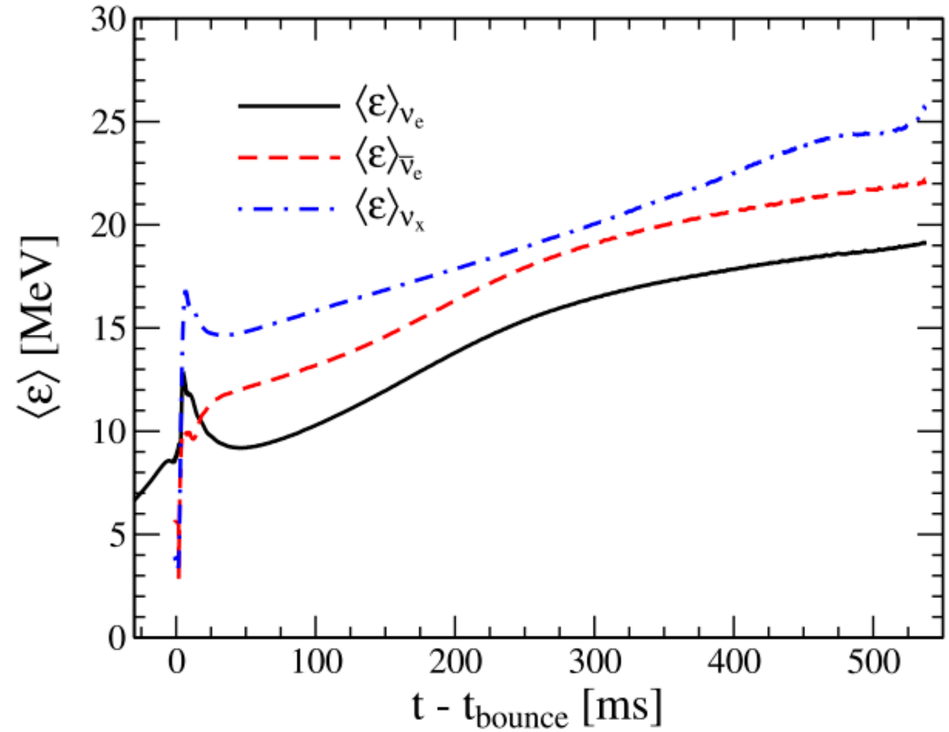
But: beware of small-number statistics!!

Probing Black Hole Formation

- BH-forming collapse: always proto-NS phase!
- Failure of explosion -> BH formation
- BH formation fraction? Up to 50%, but uncertain.

O'Connor & Ott 11,
Kochanek 15,
Clausen+15, Ertl+15

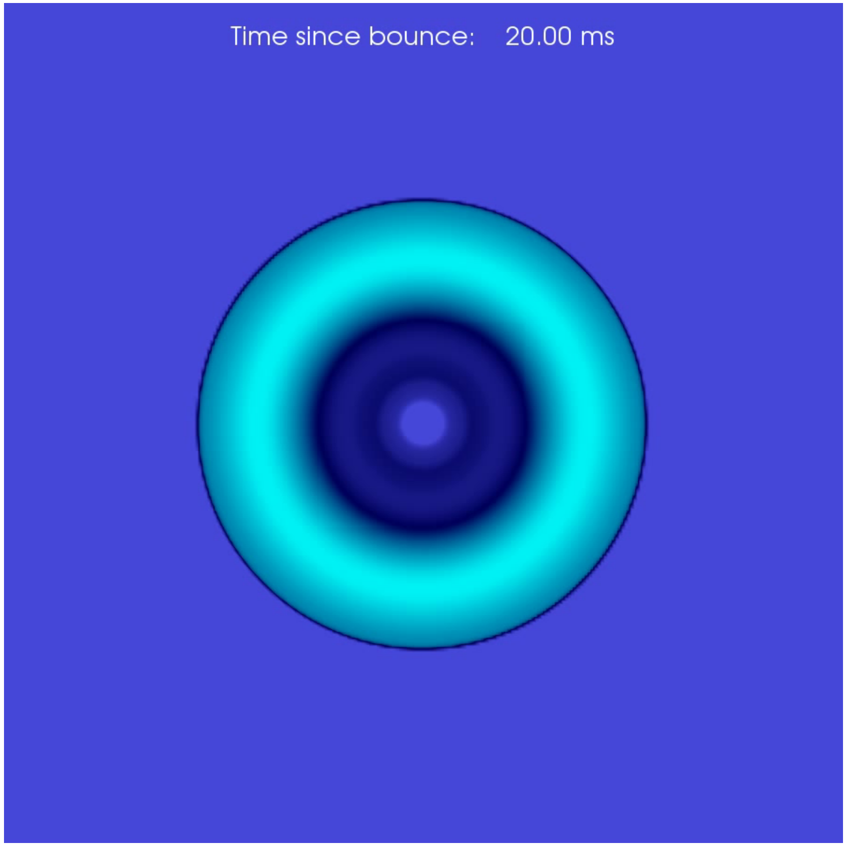


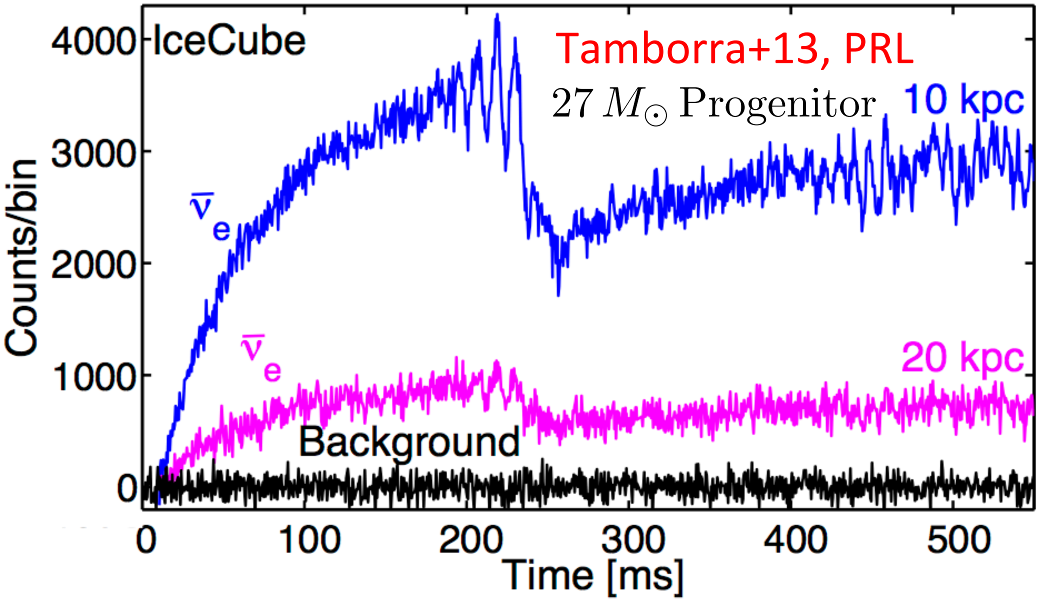


- Signature: high $<\varepsilon_\nu>$, abrupt termination at t < 1-3 s.
- ν emission set by accretion rate and nuclear equation of state.

Probing Multi-Dimensional Supernova Dynamics

Adikamalov+15



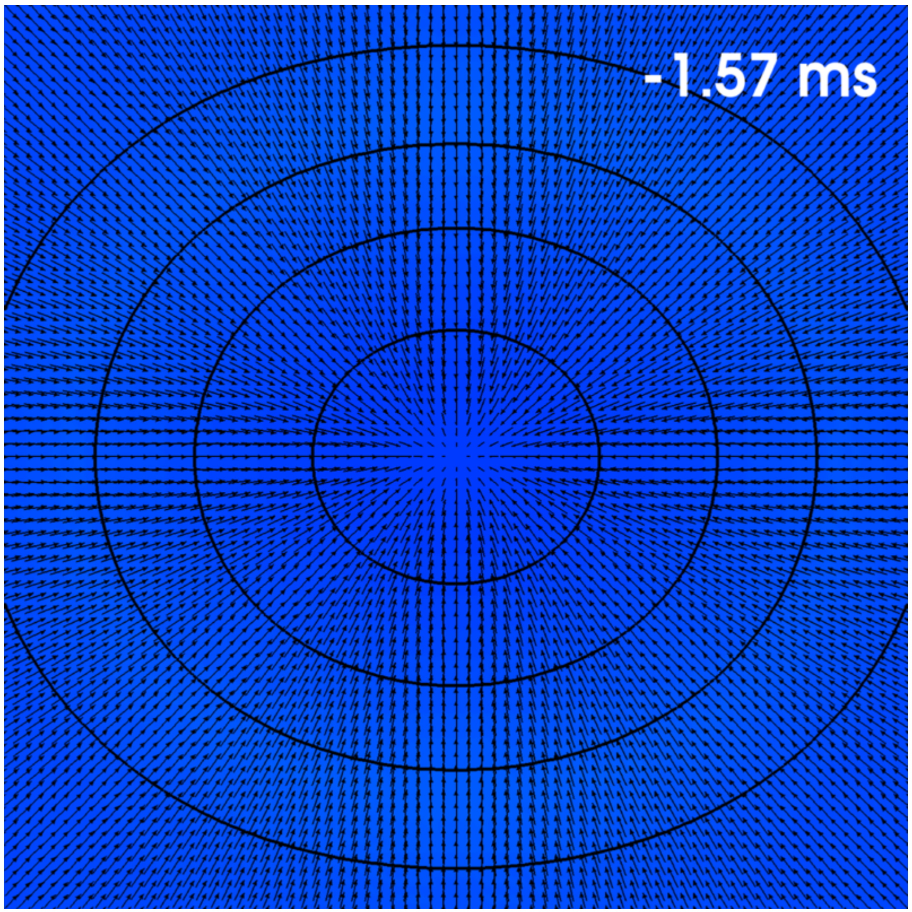


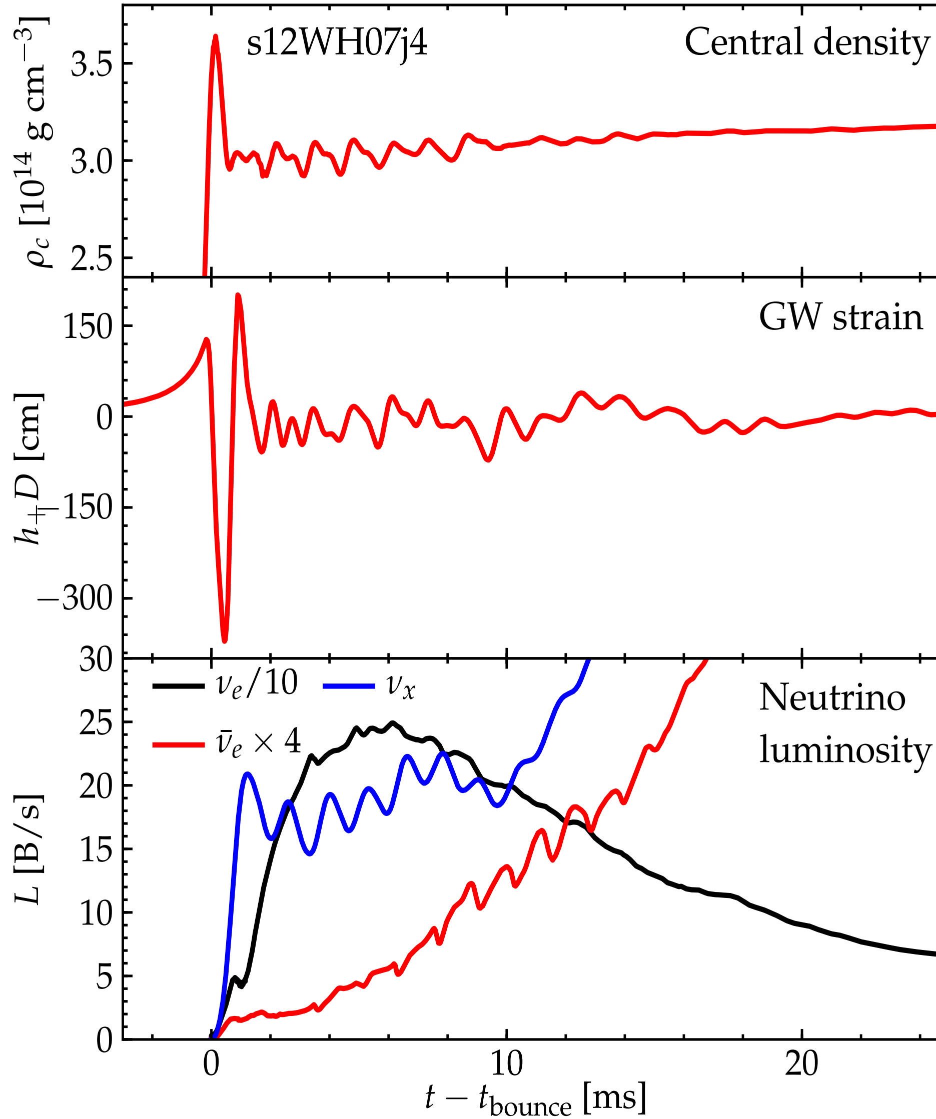
- Neutrino-driven convection & standing accretion shock instability (SASI) *modulate* neutrino signal.

Probing Multi-Dimensional Supernova Dynamics

- Rotating core collapse: Correlated neutrino and gravitational-wave signal.

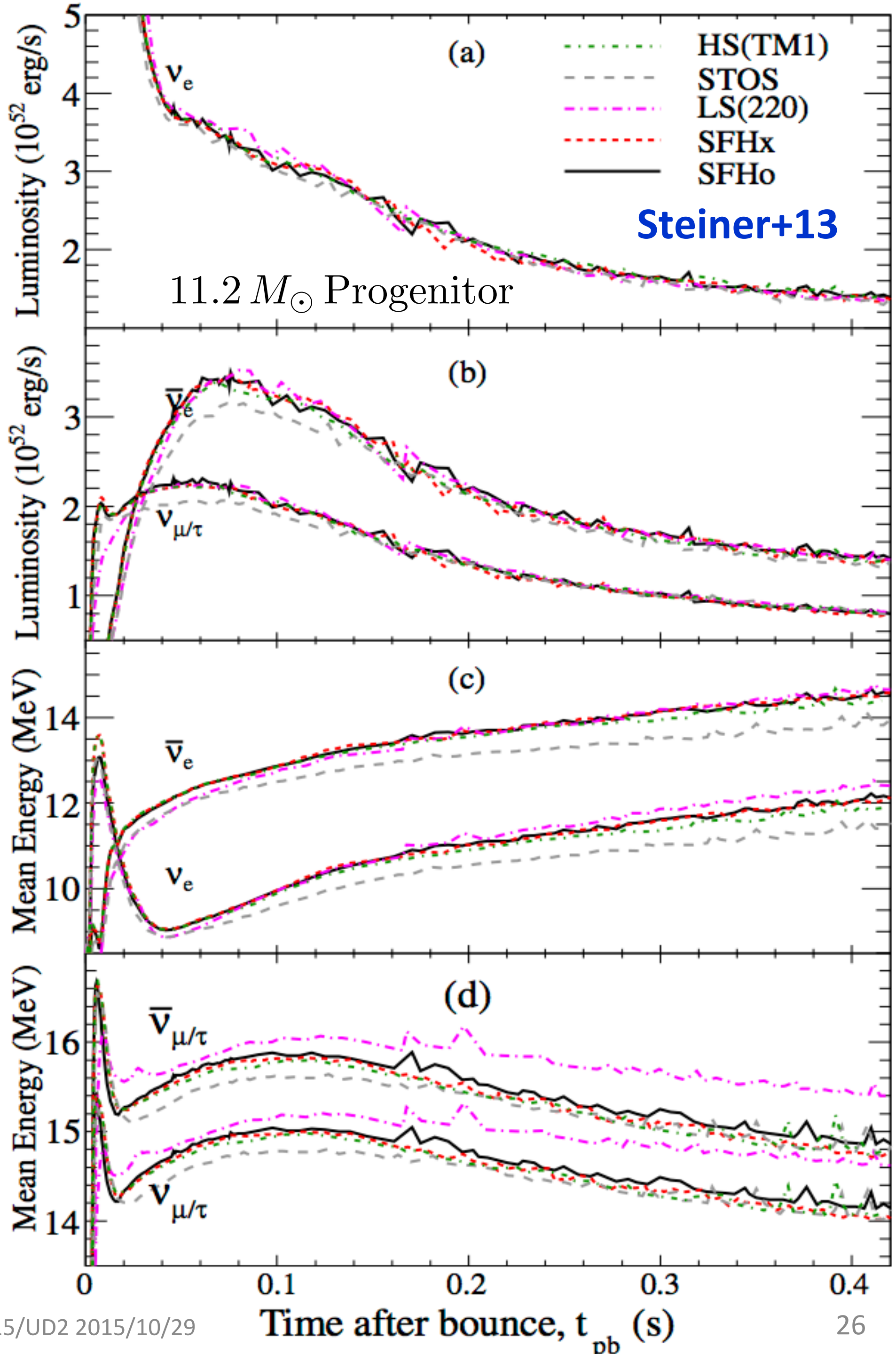
Ott+2012





Probing the Nuclear Equation of State

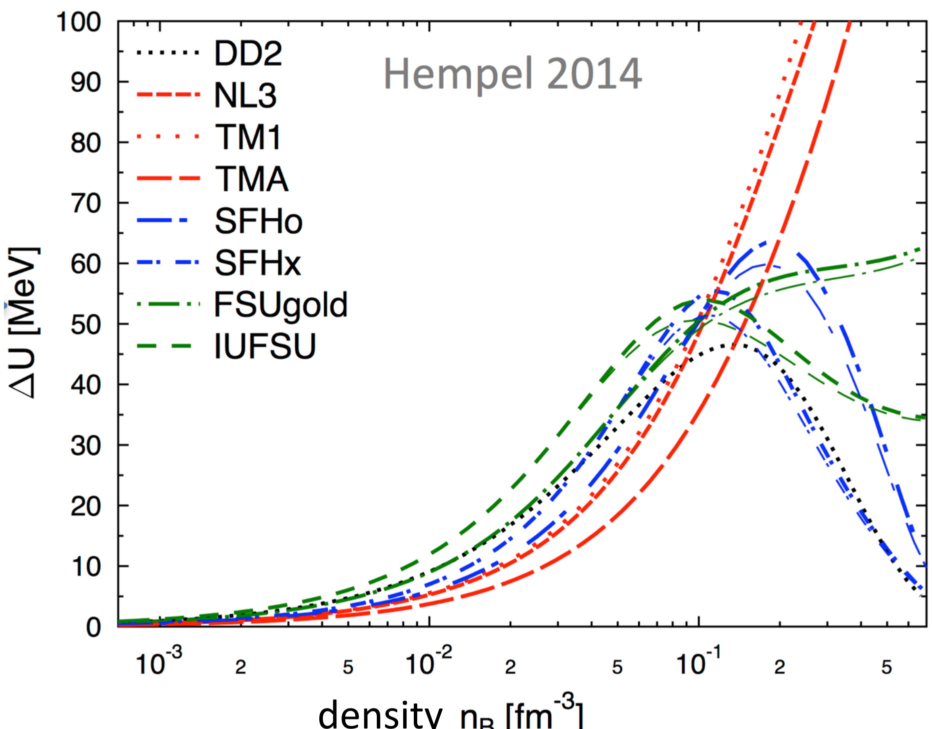
- High-density nuclear EOS uncertain ($\gtrsim$ 2-3 x 10^{14} g/cm^3, s ~ 1 kB/baryon)
- Limited experimental / astrophysical constraints. (Steiner+13,Lattimer&Steiner 14, Lattimer&Lim 13, Hebeler+13)
- ν Signal: Must disentangle progenitor, time of explosion, and EOS effects (O'Connor & Ott 13).
- Too few studies to make definite statements. (Mirizzi+15, Marek+09, Steiner+13, Hempel+12, Roberts+12)

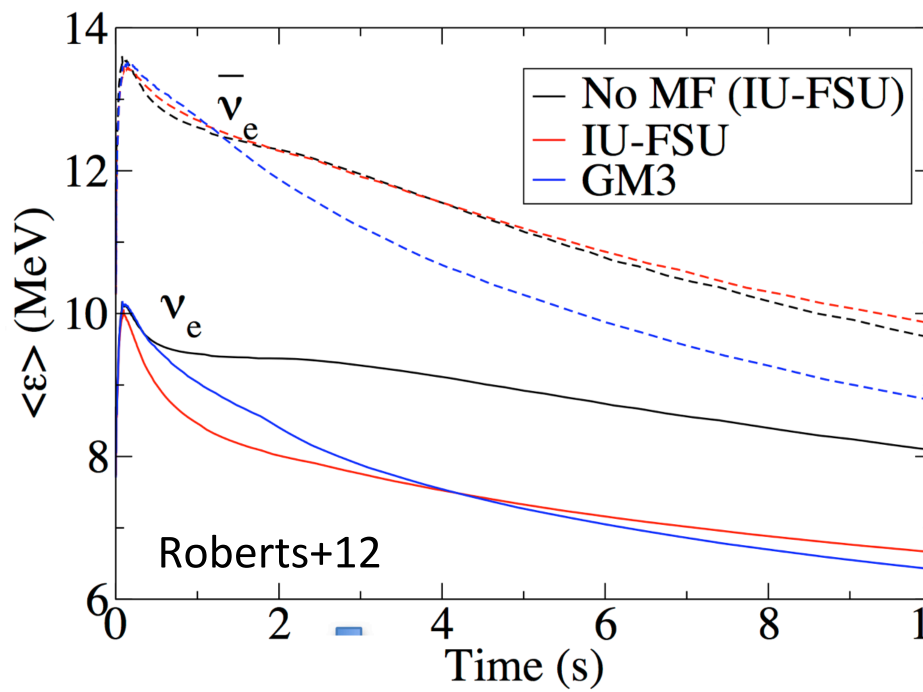


Probing the Nuclear Equation of State

(Reddy+98, Roberts+12, Horowitz+12, and others)

- Mean-field potentials of nucleons in proto-NS medium:
  -> energy shifts ΔU -> influence on charged-current reactions.
- ΔU sensitive to EOS model & parameters (symmetry energy!).
- Shifts of electron neutrino & antineutrino energies & luminosities. Changes deleptonization rate of proto-NS.





Supernova Neutrino Oscillations

(see, e.g., Mirizzi+15, Duan+10 for reviews)

Three flavors, three mass eigenstates: $|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$

$\delta m^2 = m_2^2 - m_1^2 > 0$ "solar"

$\Delta m^2 = \left| m_3^2 - \frac{m_1^2 + m_2^2}{2} \right|$ "atmospheric" (sign unknown)

$\delta m^2 \ll \Delta m^2$

Two possible mass hierarchies:

$$\mathrm{NH}: \quad m_3 > m_2 > m_1$$
$$\mathrm{IH}: \quad m_2 > m_1 > m_3$$

Mixing parameters (compiled by Mirizzi+15):

$$\Delta m^2 = (2.43^{+0.12}_{-0.13}) \times 10^{-3}\ \mathrm{eV}^2\ ,$$
$$\delta m^2 = (7.54^{+0.46}_{-0.39}) \times 10^{-5}\ \mathrm{eV}^2\ ,$$
$$\sin^2\theta_{12} = (3.08^{+0.17}_{-0.34}) \times 10^{-1},$$
$$\sin^2\theta_{23} = (4.37^{+1.15}_{-0.44}) \times 10^{-1}\ ,$$
$$\sin^2\theta_{13} = (2.34^{+0.40}_{-0.39}) \times 10^{-2}\ .$$

← Daya Bay, Reno 2012

Supernova Neutrino Oscillations

(see, e.g., Mirizzi+15, Duan+10 for reviews)

Multiple contributors: $\mathrm{H} = \mathrm{H}^{\mathrm{vac}} + \mathrm{H}^{\mathrm{MSW}} + \mathrm{H}^{\nu\nu}$

Relevant potentials:

kinetic (vacuum) $\omega_{ij} = \Delta m_{ij}^2 / 2E$

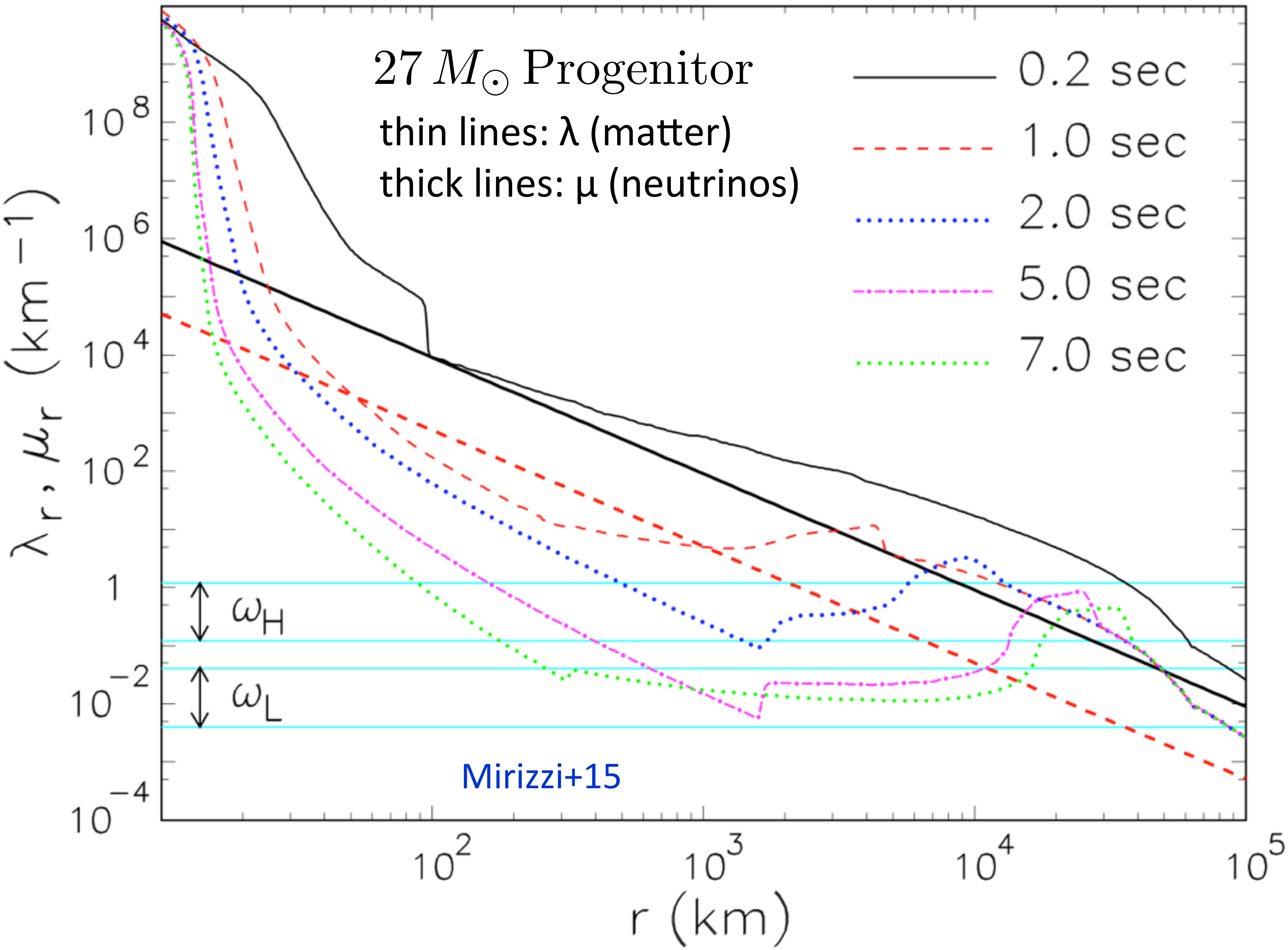
MSW: ν – e $\lambda = \sqrt{2} G_F n_e \propto R^{-3}$

Self-induced: ν – ν $\mu \simeq \sqrt{2} G_F n_\nu^{\mathrm{eff}} \propto R^{-4}$ if $\mu \gg \lambda$

(Pantaleone 92 + much work since 2006 – see Duan+10 & Mirizzi+15)

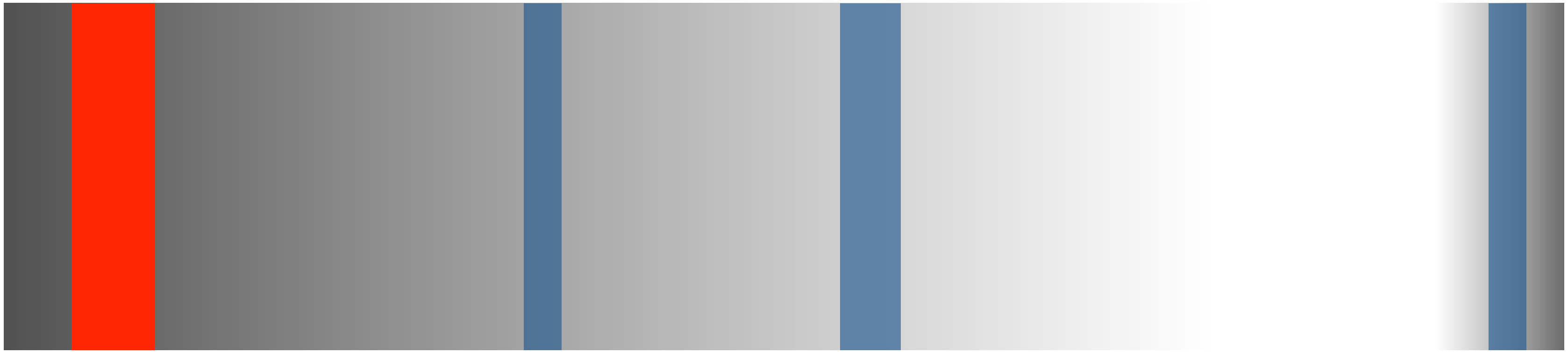
Supernova Neutrino Oscillations

(see, e.g., Mirizzi+15, Duan+10 for reviews)



Supernova Neutrino Oscillations

(see, e.g., Mirizzi+15, Duan+10 for reviews)



$\mu \gg \lambda$

$10^9 - 10^7\,\mathrm{g\,cm^{-3}}$

$r \lesssim 10^3\,\mathrm{km}$

Self-Induced

(likely)

suppressed in accretion phase

$\omega_{31} \simeq \lambda$

$10^3\,\mathrm{g\,cm^{-3}}$

MSW
H Resonance

$\omega_{21} \simeq \lambda$

$1 - 10\,\mathrm{g\,cm^{-3}}$

MSW
L Resonance

$\omega_{21} \simeq \lambda$

$1 - 10\,\mathrm{g\,cm^{-3}}$

MSW
L Resonance

(figure inspired by C. Lunardini)

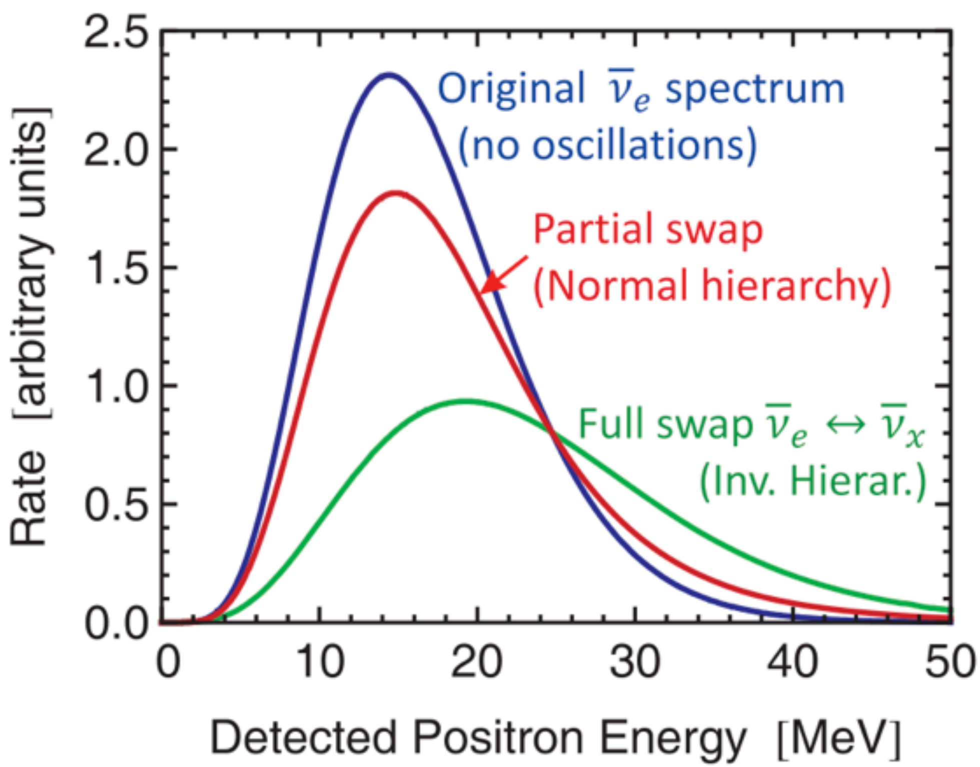
SN ν Oscillations: Simplest Scenario

(see, e.g., Mirizzi+15, Duan+10 for reviews)

- No self-induced oscillations, no Earth effects, adiabatic evolution.
  Survival probabilities:

Normal Hierarchy: $(P_{ee}, \bar{P}_{ee}) = (0, \cos^2\theta_{12})$

Inverted Hierarchy: $(P_{ee}, \bar{P}_{ee}) = (\sin^2\theta_{12}, 0)$



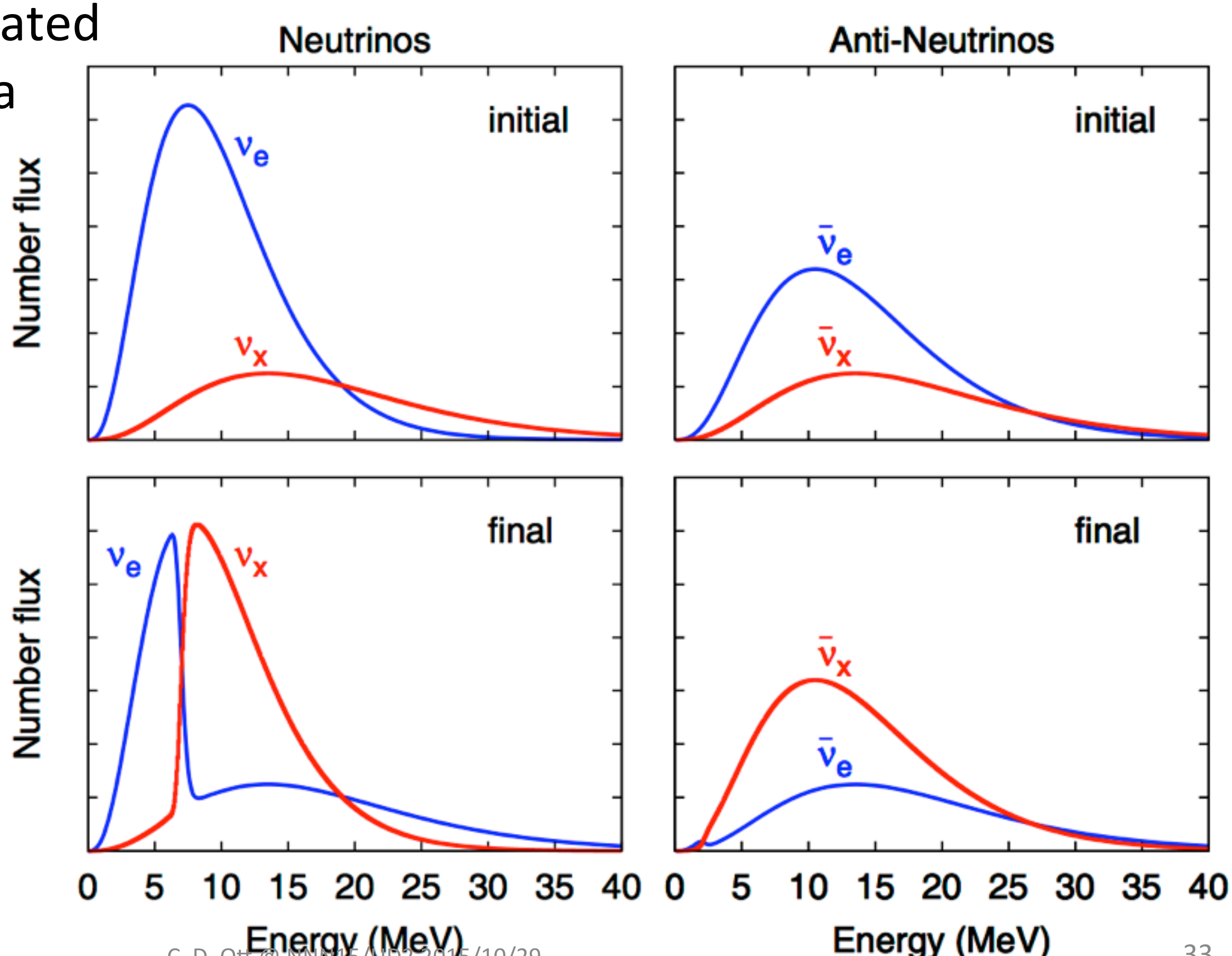
Raffelt 12

Complications:
Shocks, turbulence

Self-Induced "Collective" Oscillations:

(see, e.g., Mirizzi+15, Duan+10 for reviews)

- **Inverted hierarchy**: spectral splits & swaps
- Provided: no matter suppression (μ>>λ), non-zero flux asymmetry.
- Various other complicated oscillation phenomena possible (see Mirizzi+15).



Inferring the Neutrino Mass Hierarchy

(see, e.g., Mirizzi+15, Raffelt 12 for reviews)

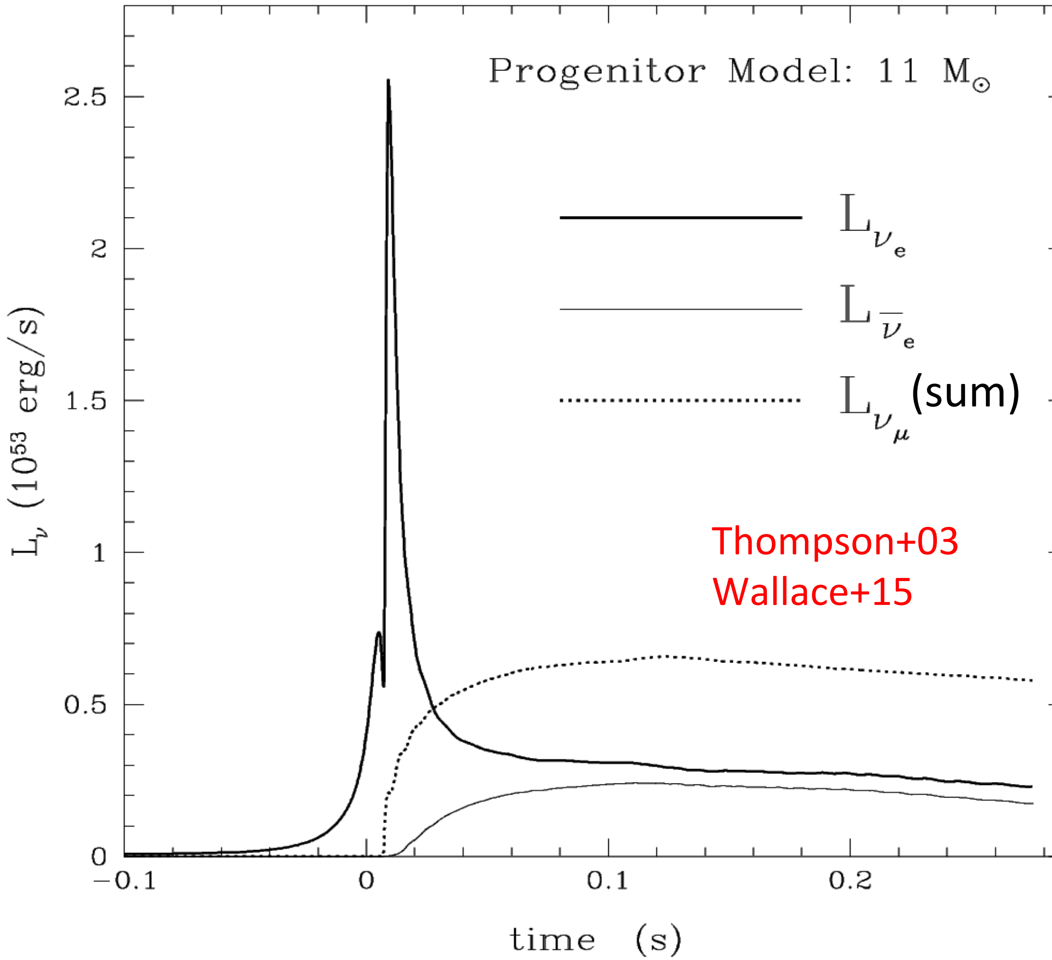
- **Normal Hierarchy**: $(P_{ee}, \bar{P}_{ee}) = (0, \cos^2\theta_{12})$
  -> Deleptonization burst in ν_e goes away!

- In most detectors: ν_e detectable via

  $$\nu + e \rightarrow e + \nu$$

  but at low rates.
  In NH: factor ~7 reduction of early e-scattering signal.

- Ideal: detector sensitive to ν_e (liquid argon, lead, iron)

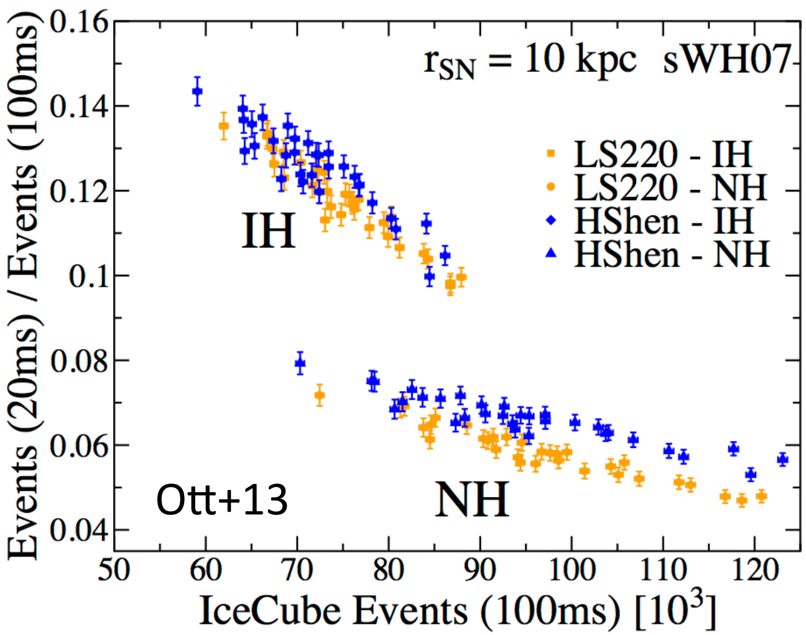


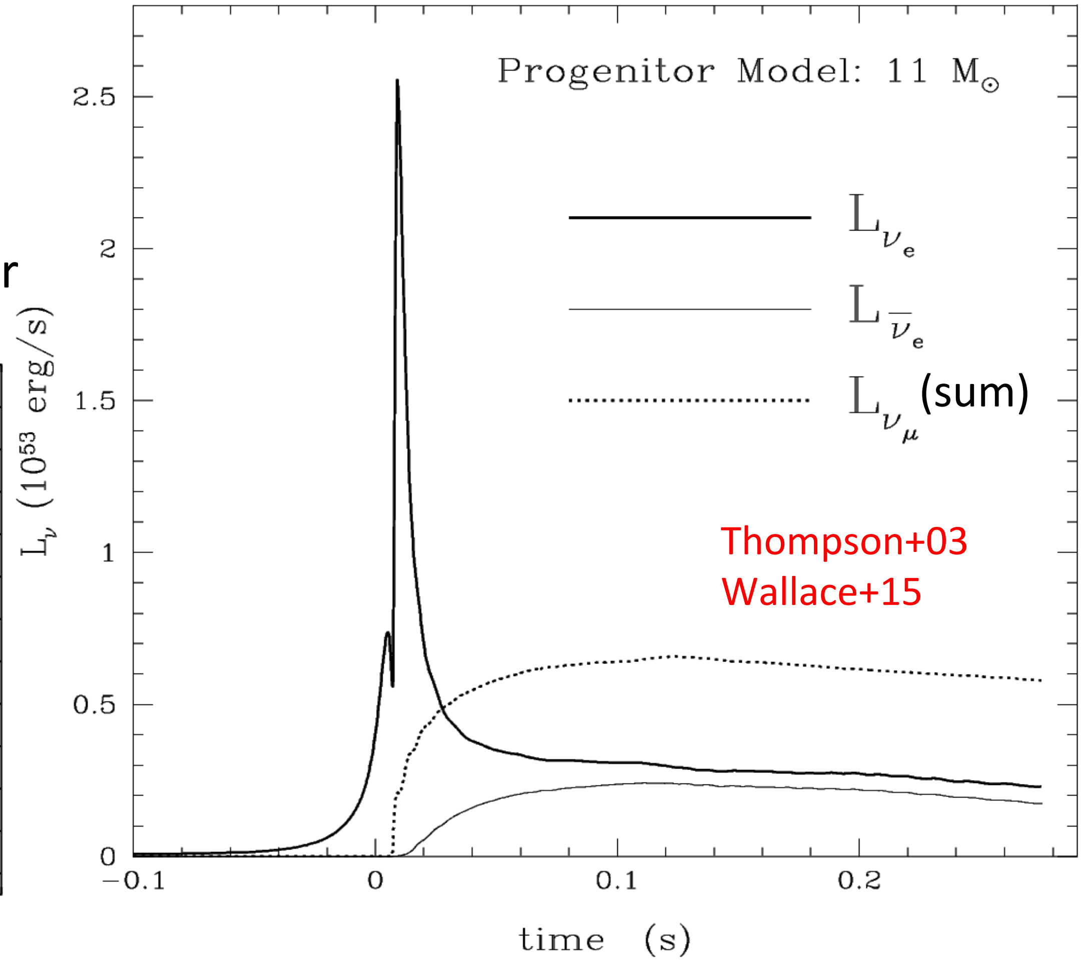
Inferring the Neutrino Mass Hierarchy

(see, e.g., Mirizzi+15, Raffelt 12 for reviews)

- **Inverted Hierarchy**: $(P_{ee}, \bar{P}_{ee}) = (\sin^2\theta_{12}, 0)$
  -> $\bar{\nu}_e \rightarrow \bar{\nu}_x$

- Exploit difference in signal rise times.
  Serpico+12, Ott+13
  Independent of EOS and progenitor





Supernova Neutrinos
without the annoying wait!

(Mark Vagins)

Diffuse Supernovae Neutrino Background
(DSNB)

The Diffuse Supernova Neutrino Background (DSNB)

Reviews: Beacom ARNP 2010 , Mirizzi+15

N >> 1 : **Burst** | N ~ 1 : **Mini-Burst** | N << 1 : **DSNB**

Universe is flooded by SN neutrinos!

$E_{DSNB} \approx E_{EBL} \approx 10\%\ E_{CMB}$

Credit:
John Beacom

Rate ~ 0.01/yr | Rate ~ 1/yr | Rate ~ 10^8/yr

high statistics, all flavors | object identity, burst variety | cosmic rate, average emission

The Diffuse Supernova Neutrino Background (DSNB)

Reviews: Beacom ARNP 2010 , Mirizzi+15

Signal rate spectrum in measured energy

SN Rate (astronomy, known))

$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu)\int_0^\infty \left[(1+z)\,\varphi[E_\nu(1+z)]\right]\left[R_{SN}(z)\right]\left[\left|\frac{c\,dt}{dz}\right|dz\right]$$

detector capabilities (known)

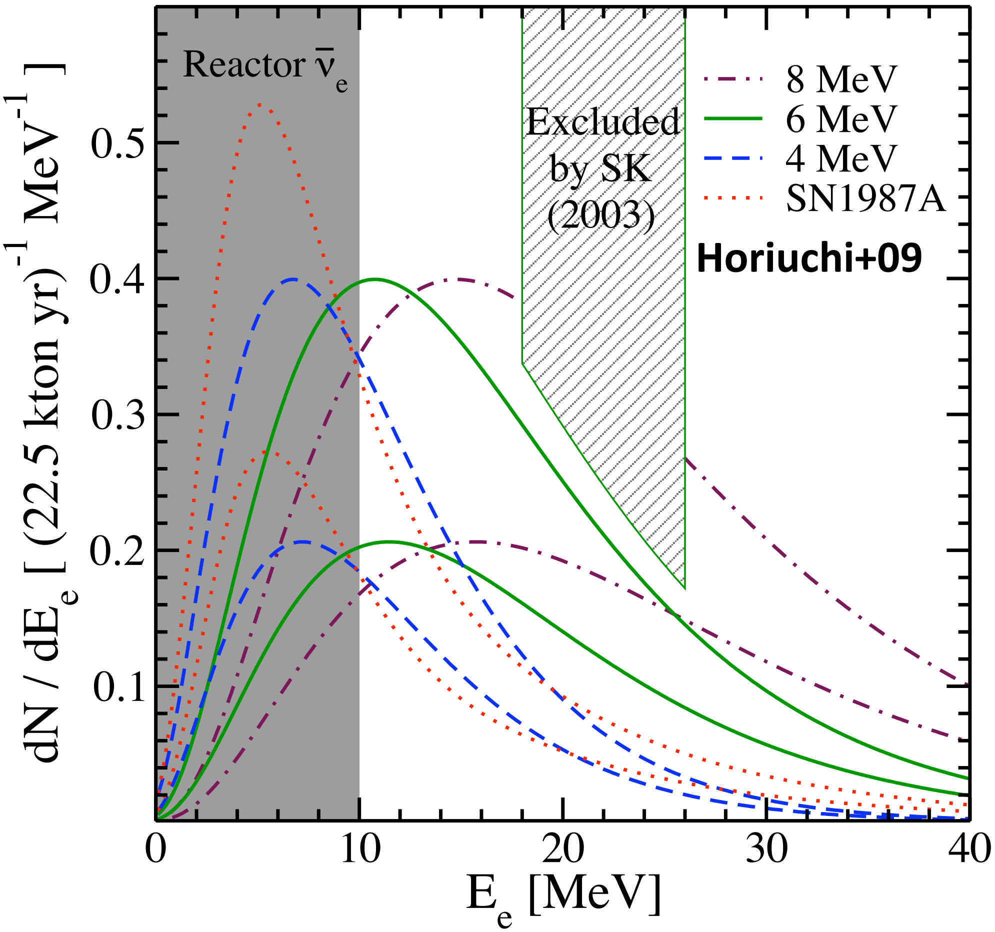
avg. SN ν spectrum (want!)

Cosmology (known)

- DNSB ν spectrum: redshifted *average* SN ν spectrum
- Will reveal relevance of “normal” core-collapse SNe vs. “special” events (BH formation, low-mass progenitors, supermassive stars...)

The Diffuse Supernova Neutrino Background (DSNB)

Reviews: Beacom ARNP 2010 , Mirizzi+15

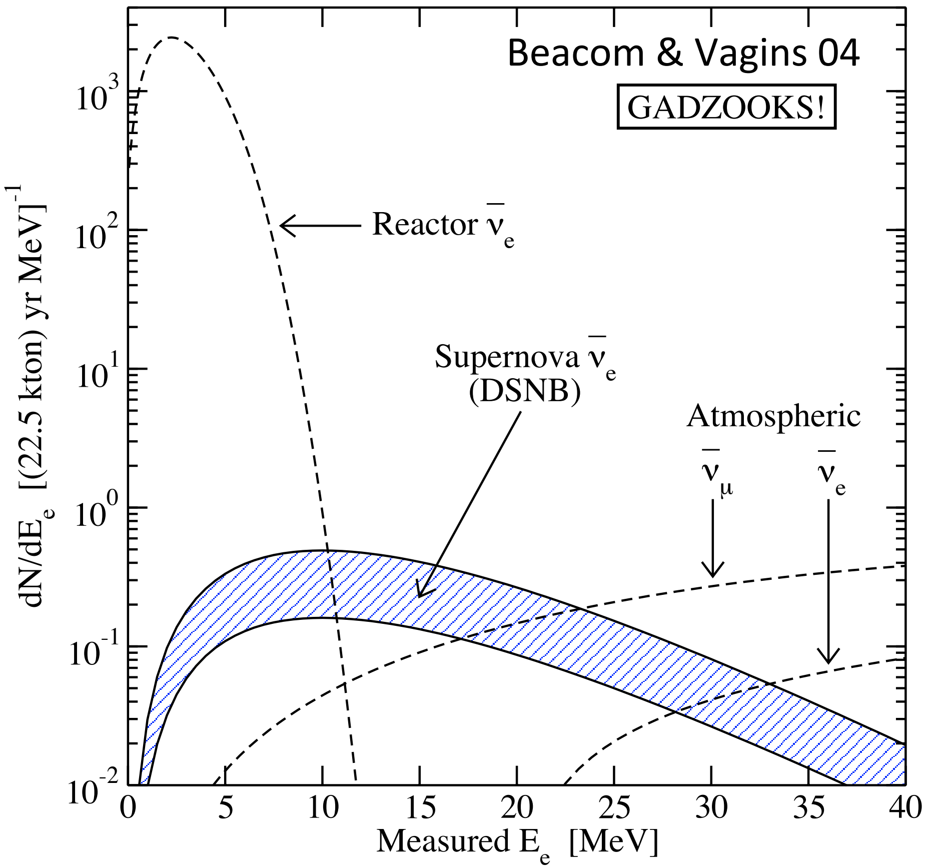


Bands indicate uncertainty from cosmic supernova rate

Must reduce background!

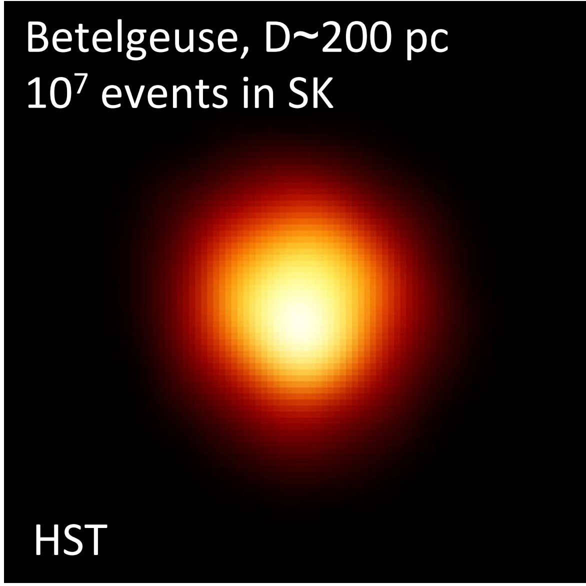
-> Use gadolinium to tag IBD events with 8 MeV photon cascade.

-> M. Vagins's Wednesday talk.



Concluding Remarks

The next galactic
Core-Collapse Supernova
has already exploded!



- Core-collapse SN neutrinos are powerful messengers and probes of astrophysics and fundamental physics.
- Supernova theorists & phenomenologists have got work to do! Not yet "ready" for the next galactic core-collapse supernova.
- Gadolinium-doped SuperK 2018/19: DSNB, pre-SN neutrinos, + much more
- More details in recent reviews on Supernova Neutrinos:
  Mirizzi+15, arXiv:1508.00785 (broad)
  Vissani 15, arXiv:1409.4710 (SN 1987A)
  Scholberg 12, arXiv:1205.6003 (detection)