Supernovae and Neutron Stars
Part II

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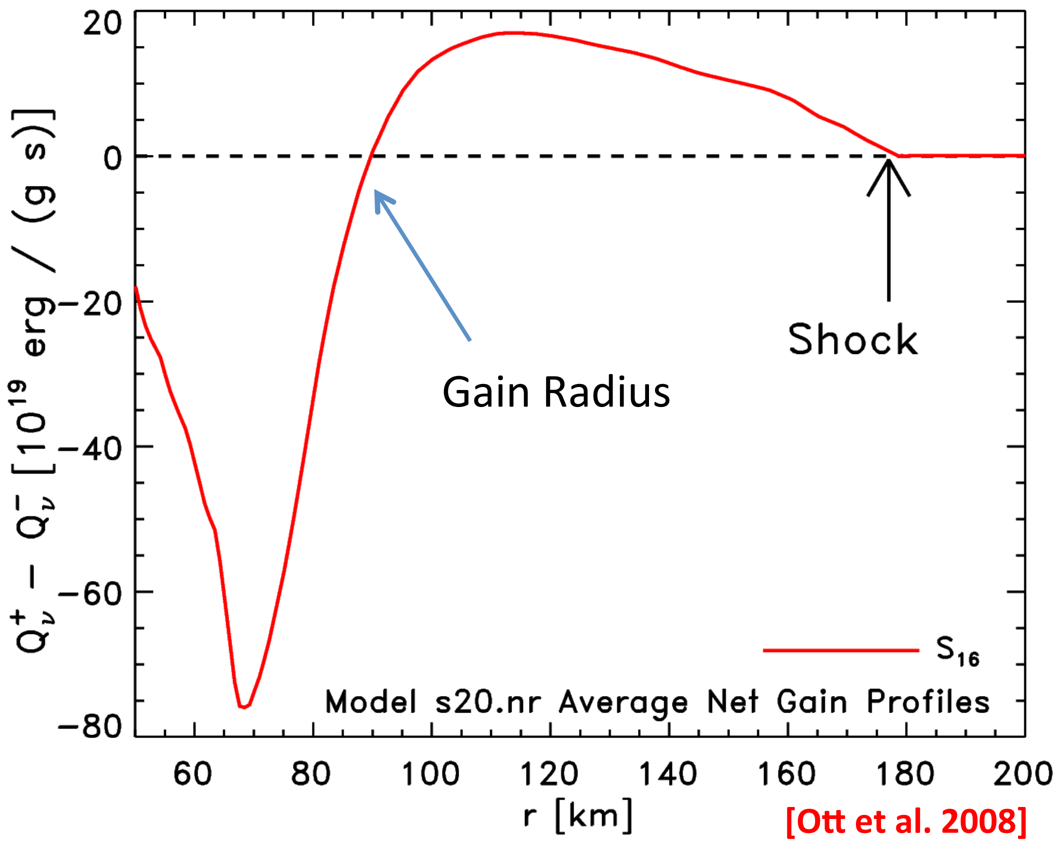
The Neutrino Mechanism

Neutrino cooling: $Q_\nu^- \propto T^6$

Neutrino heating: $Q_\nu^+ \propto L_\nu r^{-2} \langle \epsilon_\nu^2 \rangle$

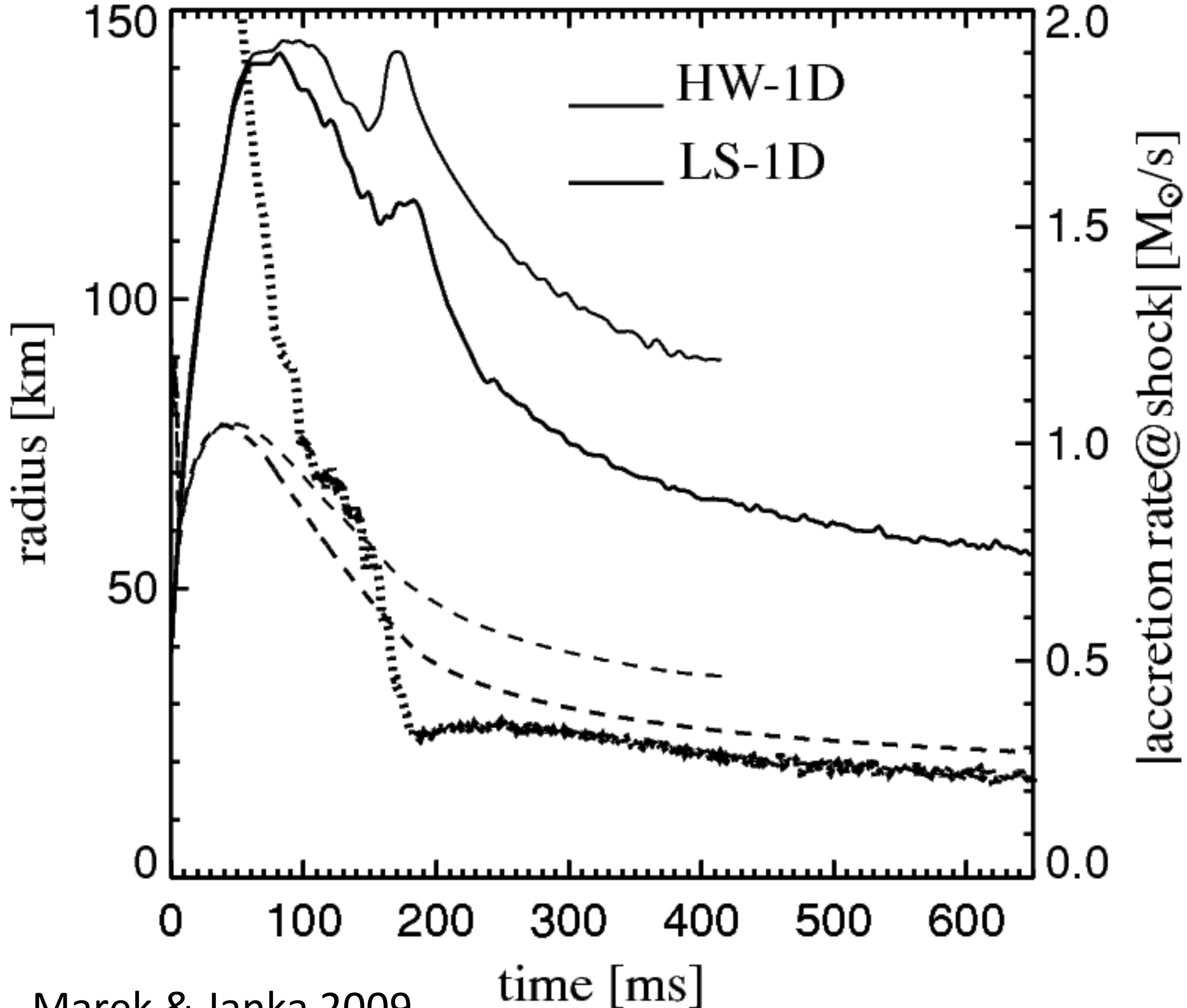
Net heating where: $Q_\nu^+ > Q_\nu^-$

- Neutrino-driven mechanism: Based on subtle imbalance between neutrino heating and cooling in postshock region.



[Ott et al. 2008]

Failure of the Neutrino Mechanism in 1D

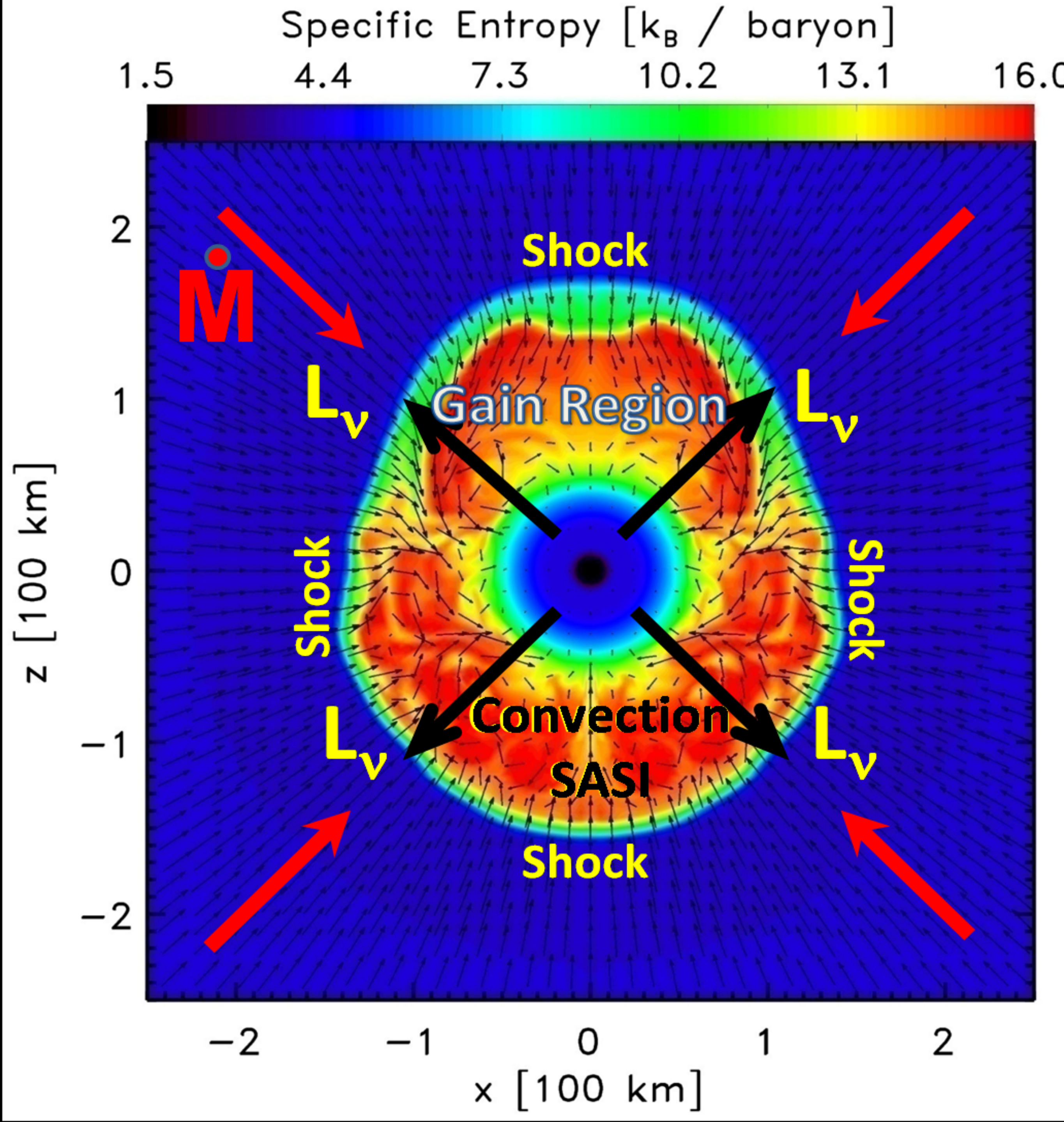


Marek & Janka 2009

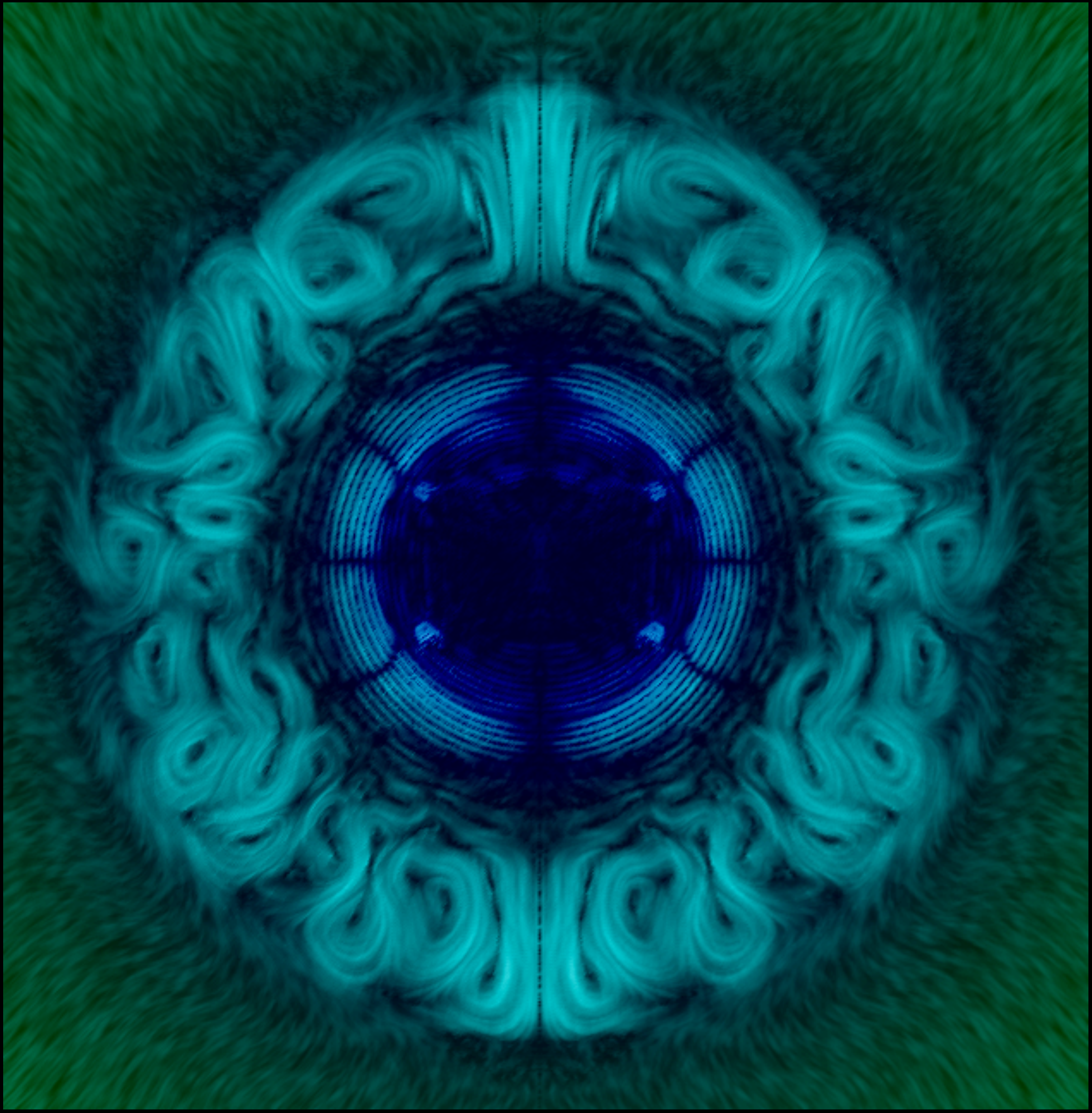
Anyway... What next?

- Why does the neutrino mechanism fail in 1D?
- Is dimensionality an issue? What is 1D missing?
  - Rotation and magnetohydrodynamics (MHD)
  - Convection/Turbulence
  - Other multi-D processes; e.g., pulsations

- First multi-D radiation-hydrodynamics simulations:
  - early to mid 1990s:
    Herant et al. 1994, Burrows et al. 1995, Janka & Müller 1996.



[Ott et al. 2008, Ott 2009 b]



Convection

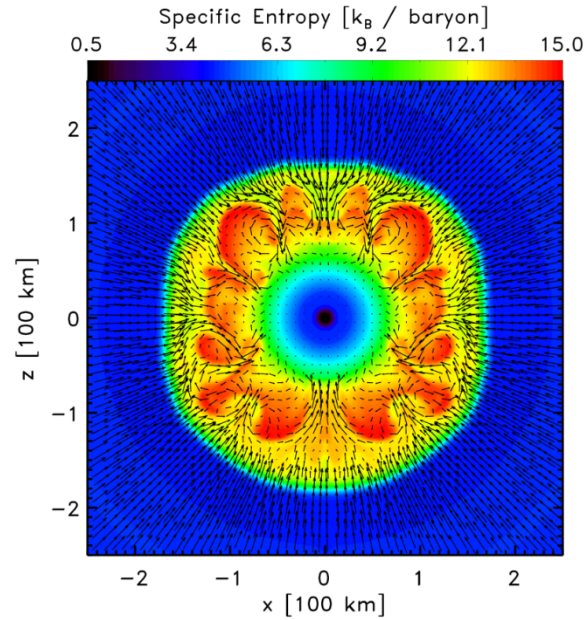
- Ledoux criterion for instability:

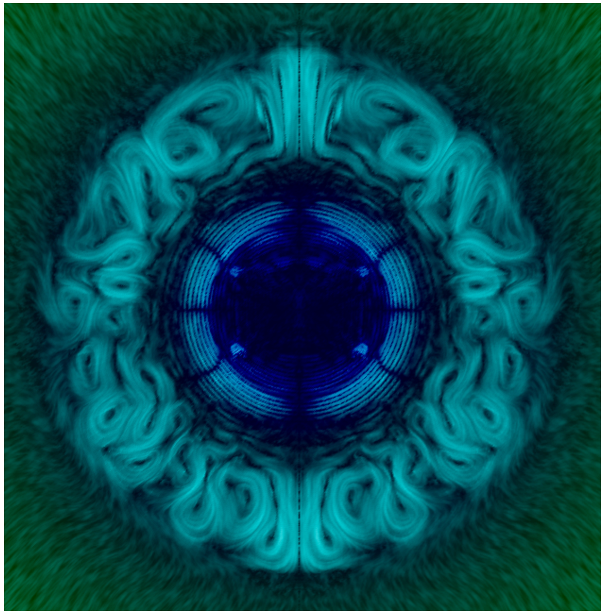
$$C_L \equiv \left(\frac{\partial \rho}{\partial s}\right)\Bigg|_{Y,p} \frac{ds}{dr} + \left(\frac{\partial \rho}{\partial Y}\right)\Bigg|_{s,p} \frac{dY}{dr}$$

< 0 **Entropy Gradient**

< 0 **Lepton Gradient**

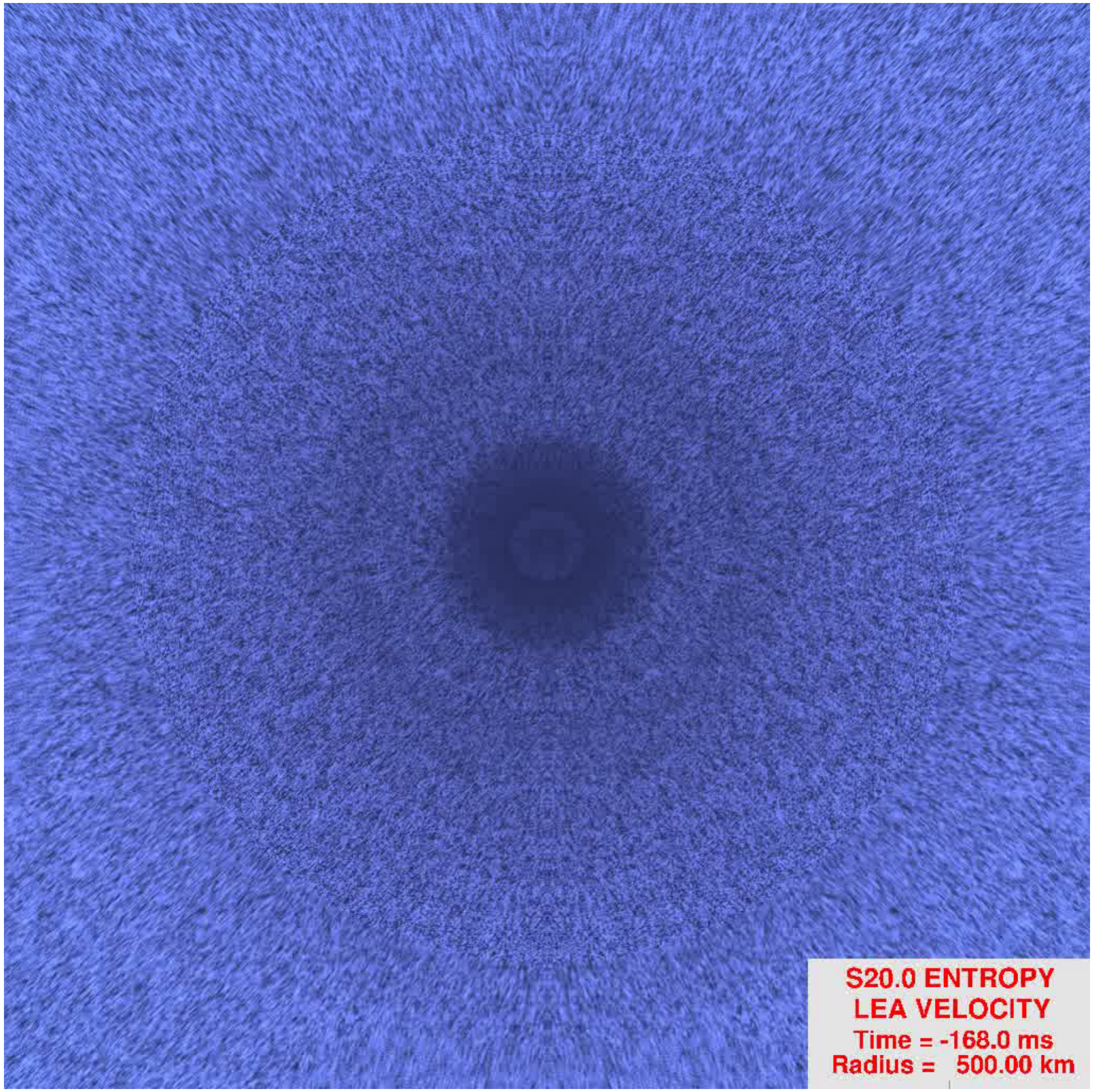
- $C_L > 0$ -> convective instability.
- Postbounce supernova cores:
  - Negative entropy gradient in postshock region -> convection
  - Negative entropy region inside the neutrinosphere in the PNS -> convection
- **Important effect of convection:**
  - "Dwell time" of material in the heating ("gain") region is increased -> leads to more favorable ratio $\tau_{advect} / \tau_{heat}$.





Standing Accretion Shock Instability

[Blondin et al. ‘03,’06; **Foglizzo et al. ‘06**, Scheck et al. ‘06, ‘07, Burrows et al. ‘06, ’07]

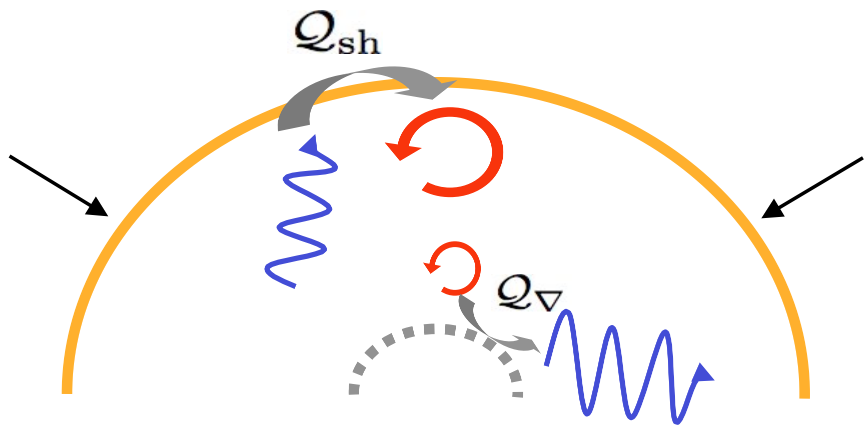


Advective-acoustic cycle drives shock instability.

Seen in simulations by all groups!

How does the SASI work?

for details: see, e.g., Fernandez & Thompson '09ab, Foglizzo+ '06, '07, Scheck+ '08, and many others



(Source: Foglizzo)

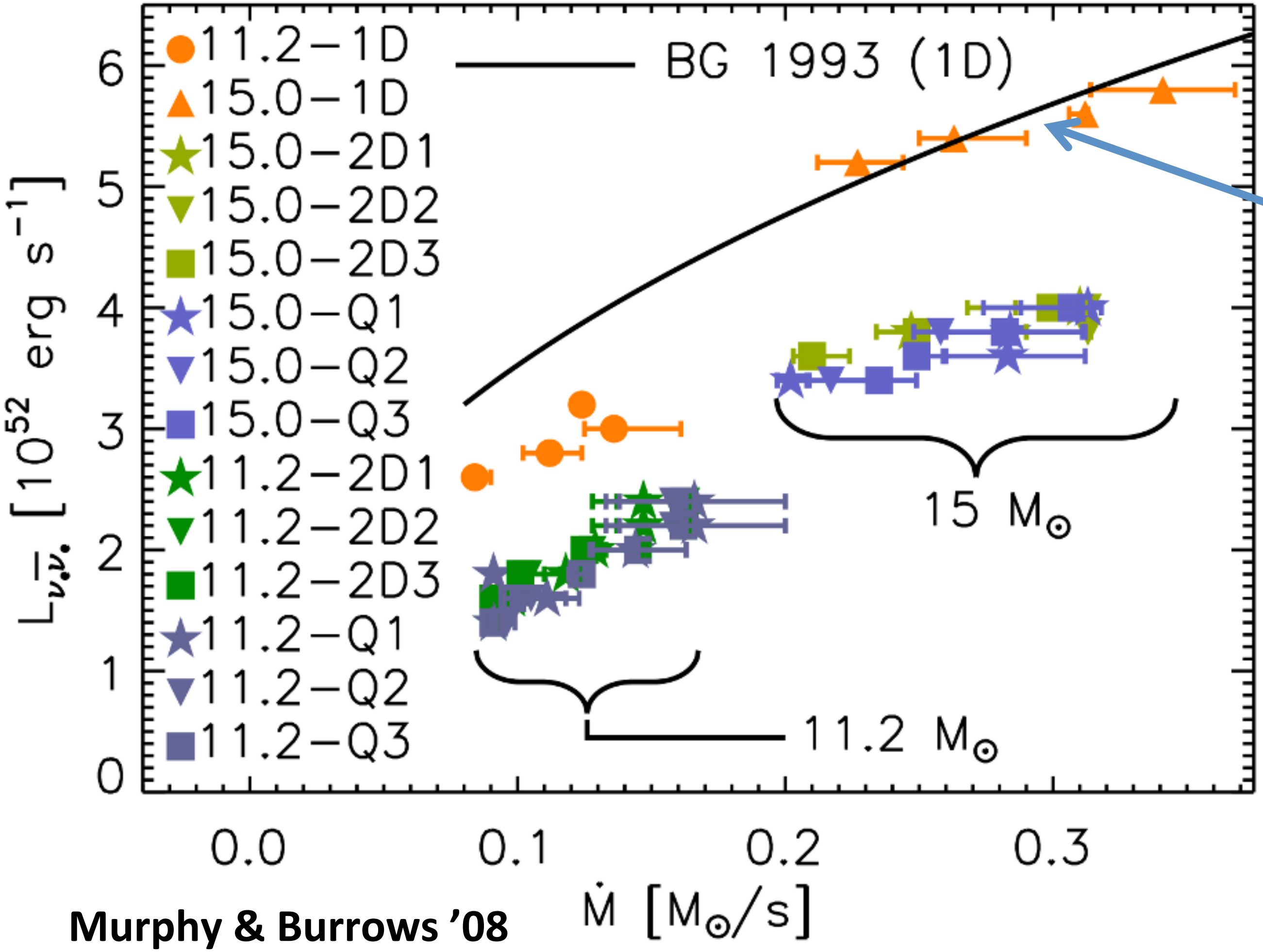
Advective-acoustic cycle.

Fastest growing mode in linear analysis: l = 1

Non-linear saturation: sourcing of Kelvin-Helmholtz and Rayleigh-Taylor instability

SASI strongest if neutrino-driven convection absent, e.g., in idealized simulations w/o neutrino heating.

1D -> 2D



Murphy & Burrows '08

Simple analytic/ODE model of Burrows & Goshy 1993. "**Critical Curve**"

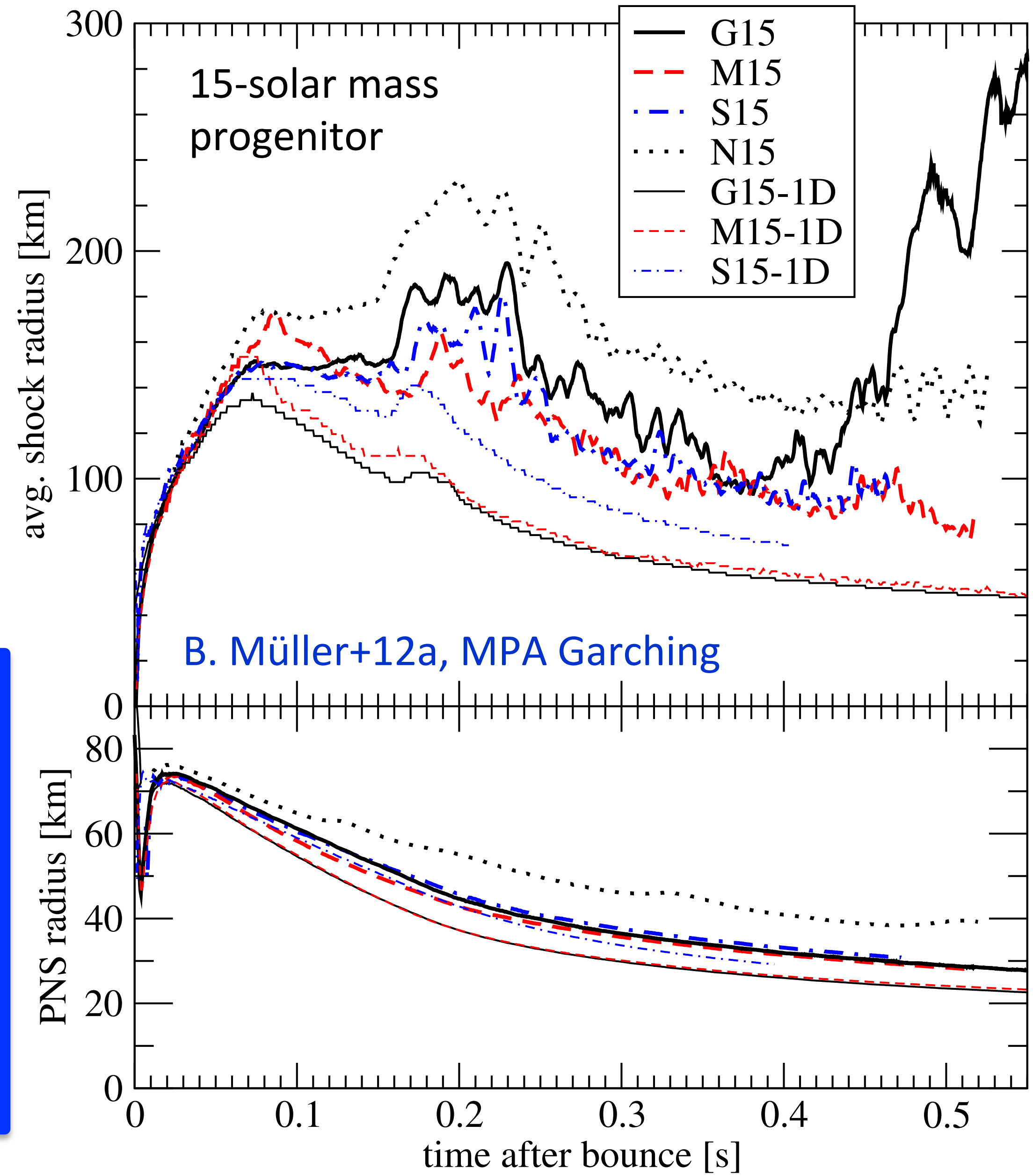
Results of 2D Simulations

Recent 2D work: Buras+06, Ott+08, Marek+09, Murphy+08, Suwa+10, Müller+12abc, Bruenn+12

Net effect of 2D:
"Dwell time" in heating region increases.

-> 2D models explode more easily.

2D explosions still marginal and sensitive to details:
- neutrino interactions
- GR vs. Newtonian
- different codes giving different results.



What are we missing?

Dimensionality?

2D -> 3D

Physics?

Missing Physics: Neutrino Oscillations!?

Neutrino Oscillations

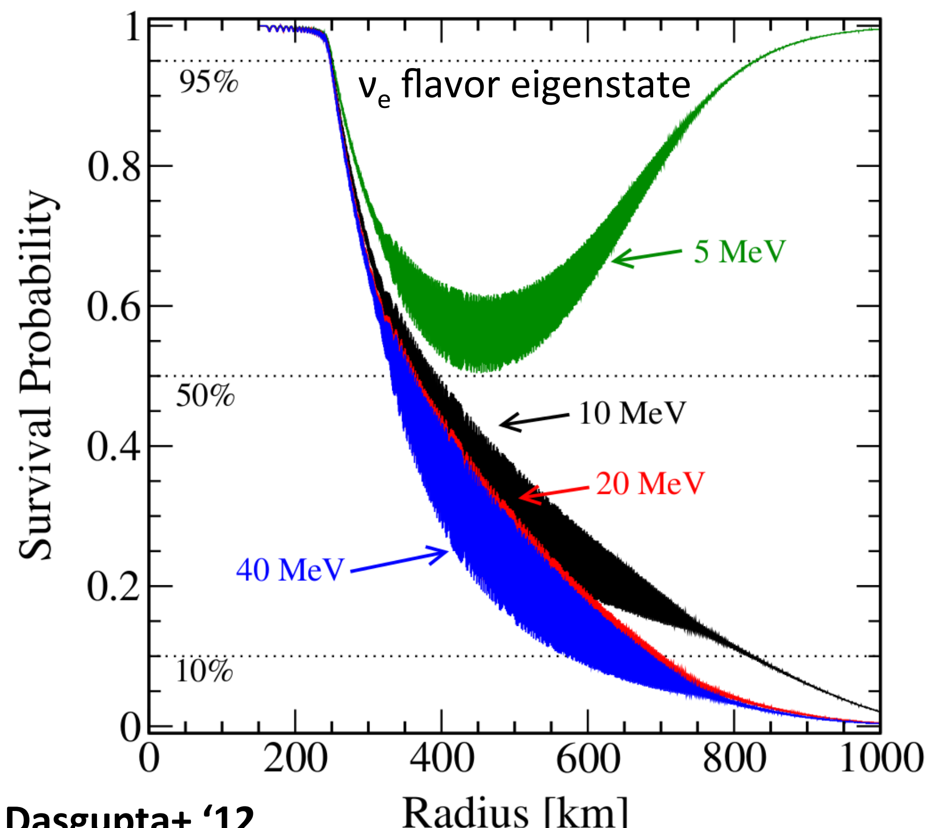
[Dasgupta, O'Connor, & Ott'12]

Georg Fuller's lecture!

- Multiple kinds of oscillations:
  - Vacuum oscillations
  - Mikheyev–Smirnov–Wolfenstein (MSW) effect: ν-e⁻ scattering
  - **New: Self-induced "collective" oscillations: ν-ν scattering**

[Pantaleone '92, Hannestad/Raffelt et al. '06, Duan/Fuller et al. '06-'10, Dasgupta/Dighe '07-'11]

- Collective oscillations need high neutrino density -> *near the core of a core-collapse supernova*.

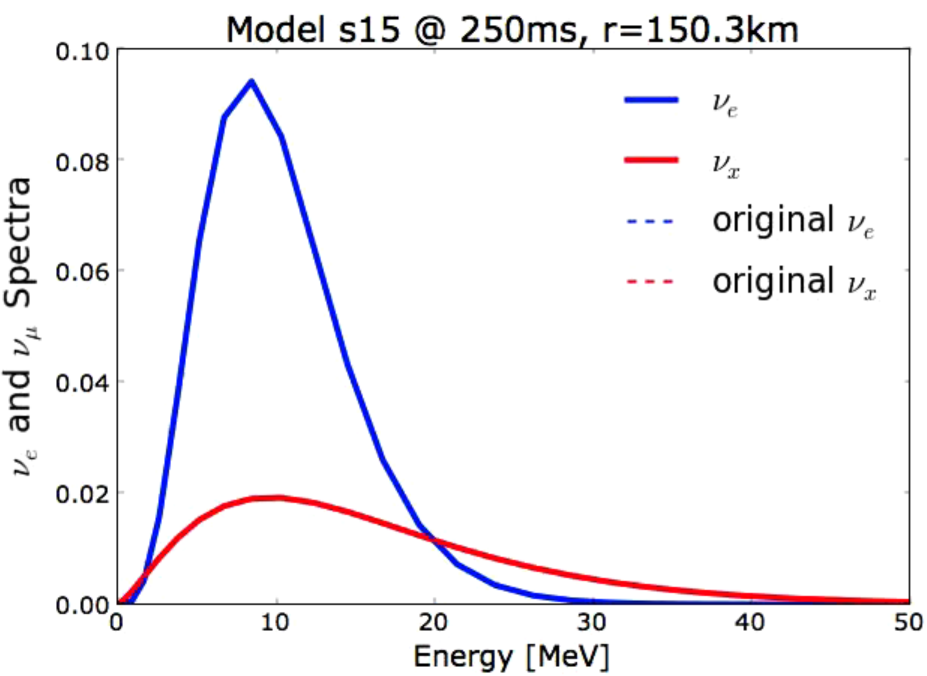


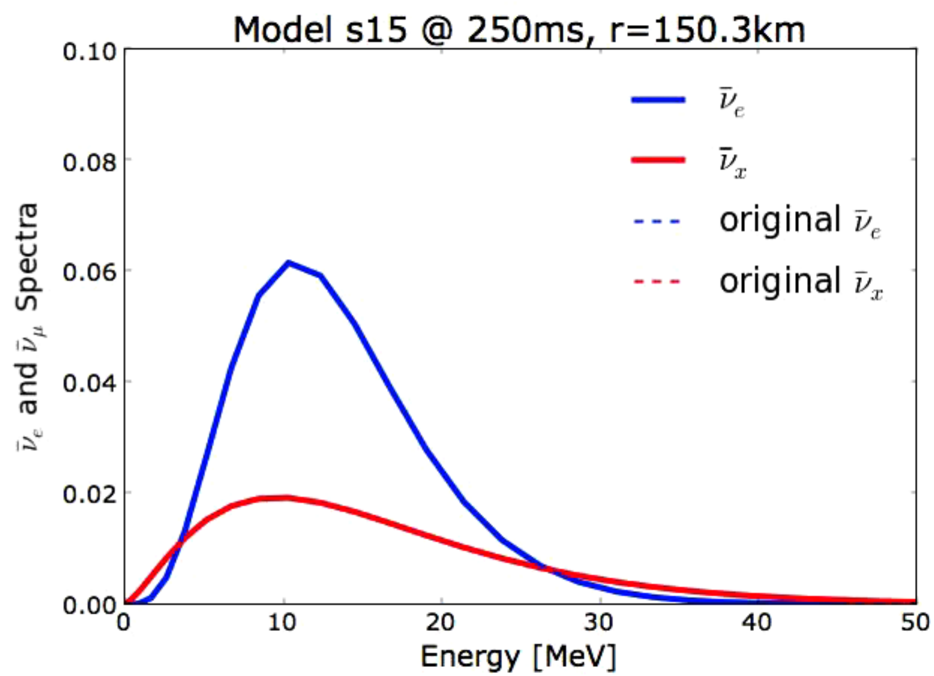
Dasgupta+ '12

Collective Oscillations

[**Dasgupta, O'Connor, & Ott 2012**]

- Example from Dasgupta, O'Connor & Ott '12 – single-angle, multi-energy, effective 2-flavor approach: ν_e, ν_x
- First oscillation calculation tagging on to 2D radiation-hydro simulations. Work in 1D by Hamburg & Munich groups.





Spectral swaps!

Movie by Evan O'Connor

Impact of Collective Oscillations

[Dasgupta, O'Connor, & Ott '12]

- **What is the effect on the CCSN mechanism?**

Neutrino heating:

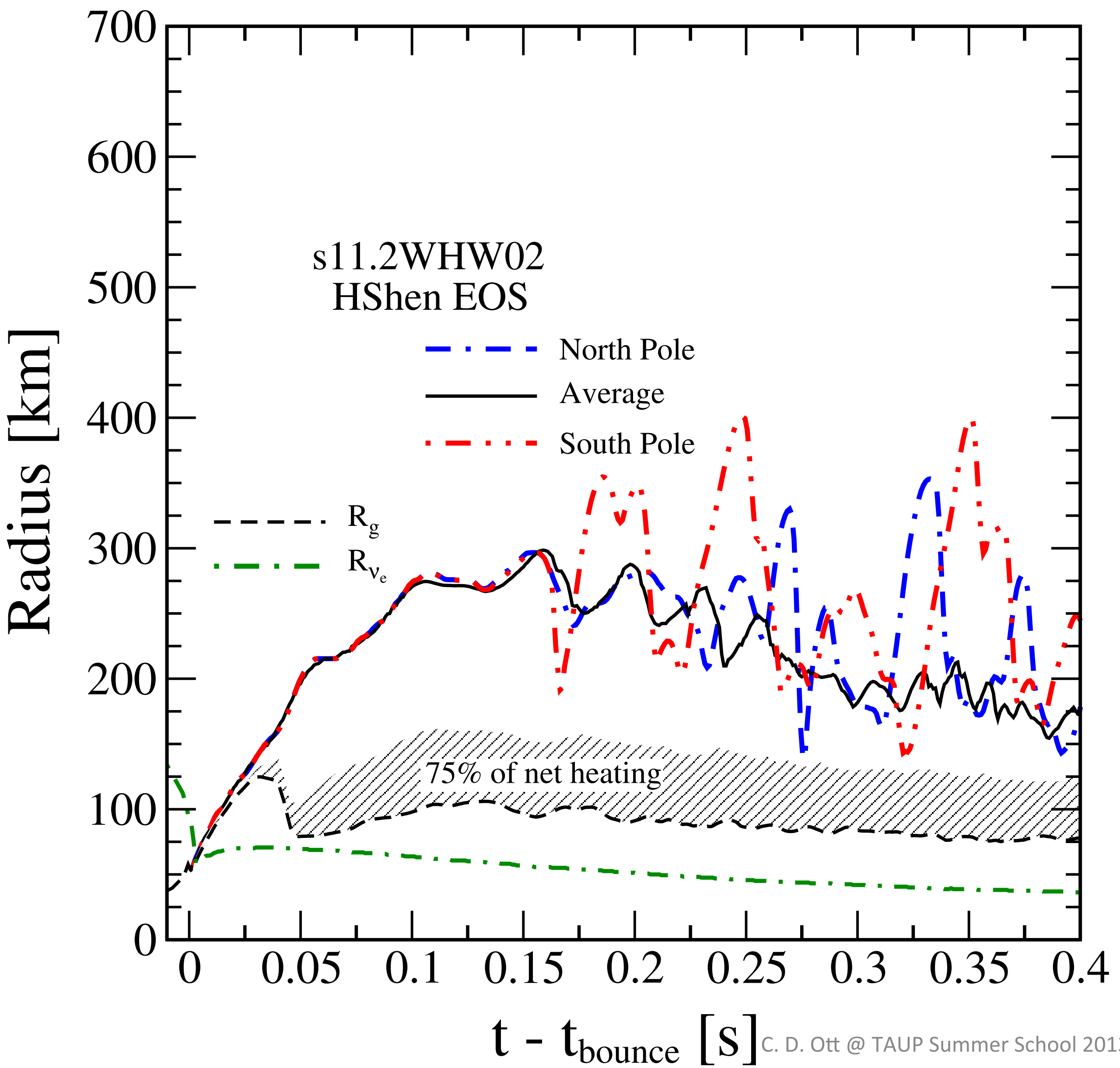
$$Q_\nu^+ = \frac{X_n}{\lambda_0^a} \frac{L_{\nu_e}}{4\pi r^2} \langle E_{\nu_e}^2 \rangle \left\langle \frac{1}{\mathsf{F}} \right\rangle + \frac{X_p}{\bar{\lambda}_0^a} \frac{L_{\bar{\nu}_e}}{4\pi r^2} \langle E_{\bar{\nu}_e}^2 \rangle \left\langle \frac{1}{\bar{\mathsf{F}}} \right\rangle$$

Messer et al. '98
Janka '01

- **Basic idea**: swap of ν_e/ν_x and anti-ν_e/anti-ν_x spectra
  -> **harder ν_e/anti-ν_e spectra** -> increased heating.
- Key prerequisite:
  Oscillations must occur below shock radius,
  ideally below gain radius.

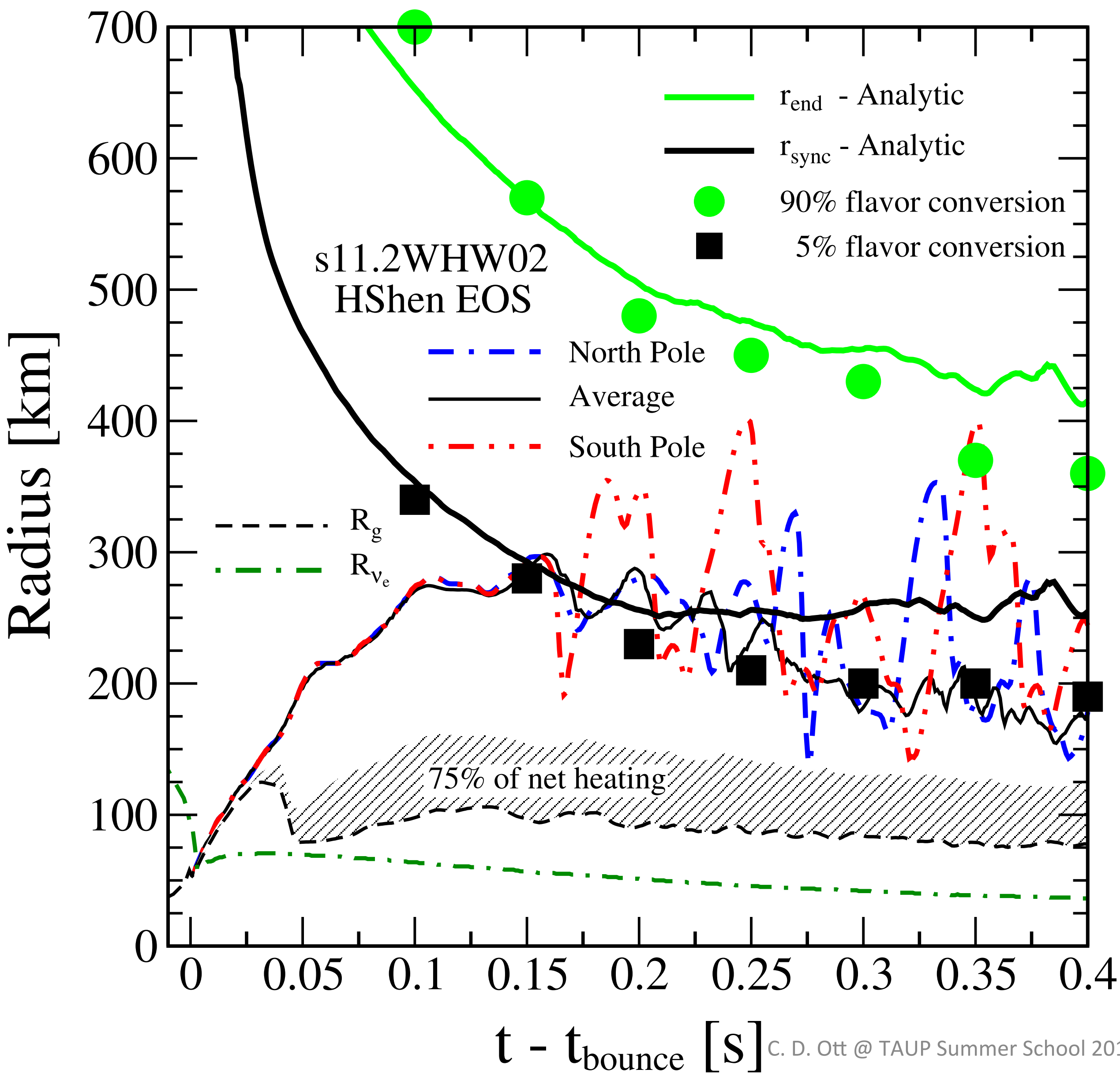
Impact of Collective Oscillations (2)

[Dasgupta, O'Connor, & Ott '12]



Impact of Collective Oscillations (3)

[Dasgupta, O'Connor, & Ott '12]



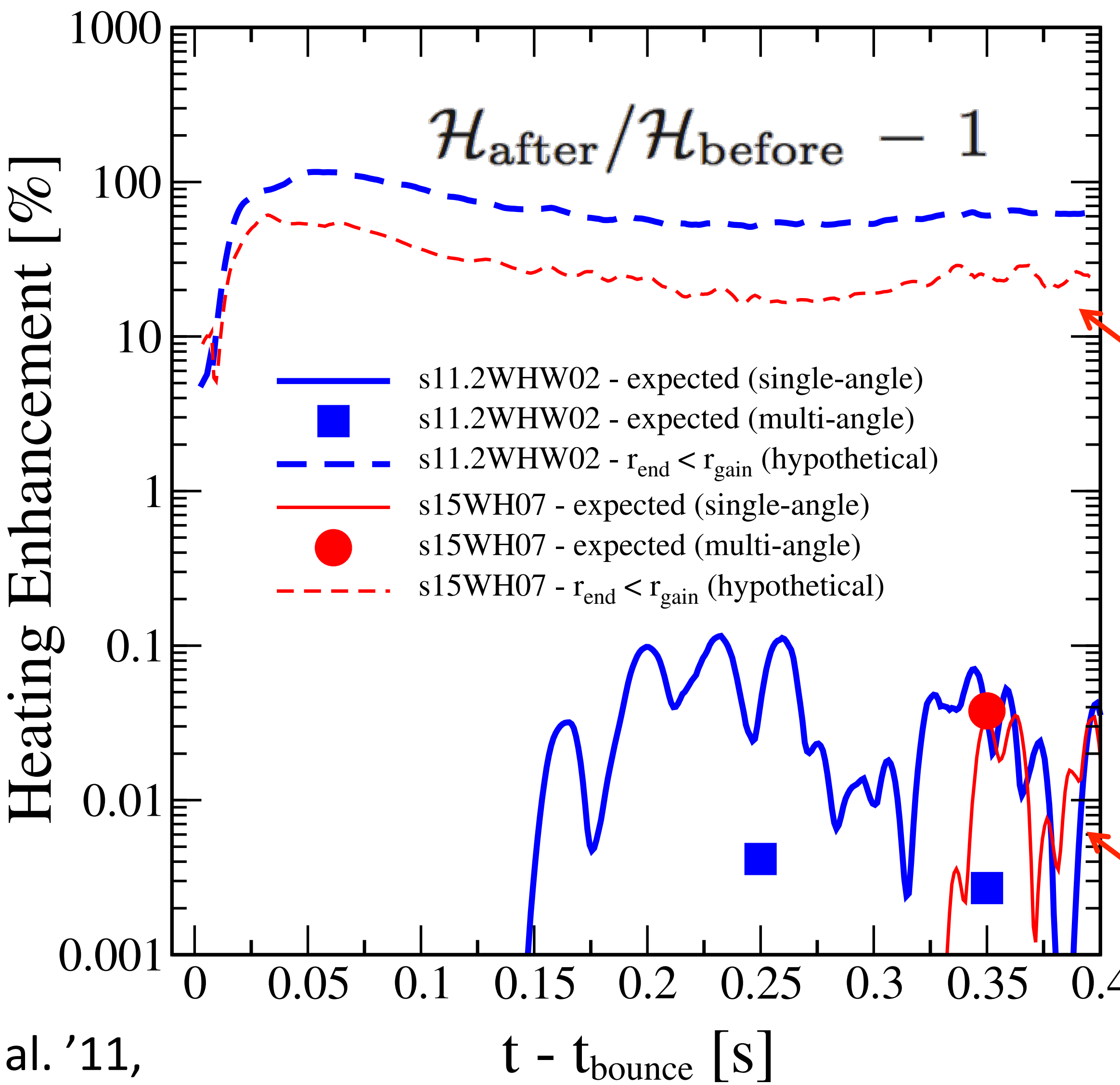
Analytic & numerical oscillation calculations based on 2D radiation fields

See also:
Chakraborty et al. '11ab
Suwa et al. '11
Pejcha et al. '11

Heating Enhancement?

[Dasgupta, O'Connor, & Ott '12]

Progenitors:
11.2 M_{Sun}
15 M_{Sun}
Woosley et al. '02



optimistic guess by Suwa et al. (wrong!)

results from actual calculations

See also Suwa et al. '11, Chakraborty et al. '11ab

Heating Enhancement?

[Dasgupta, O'Connor, & Ott '12]

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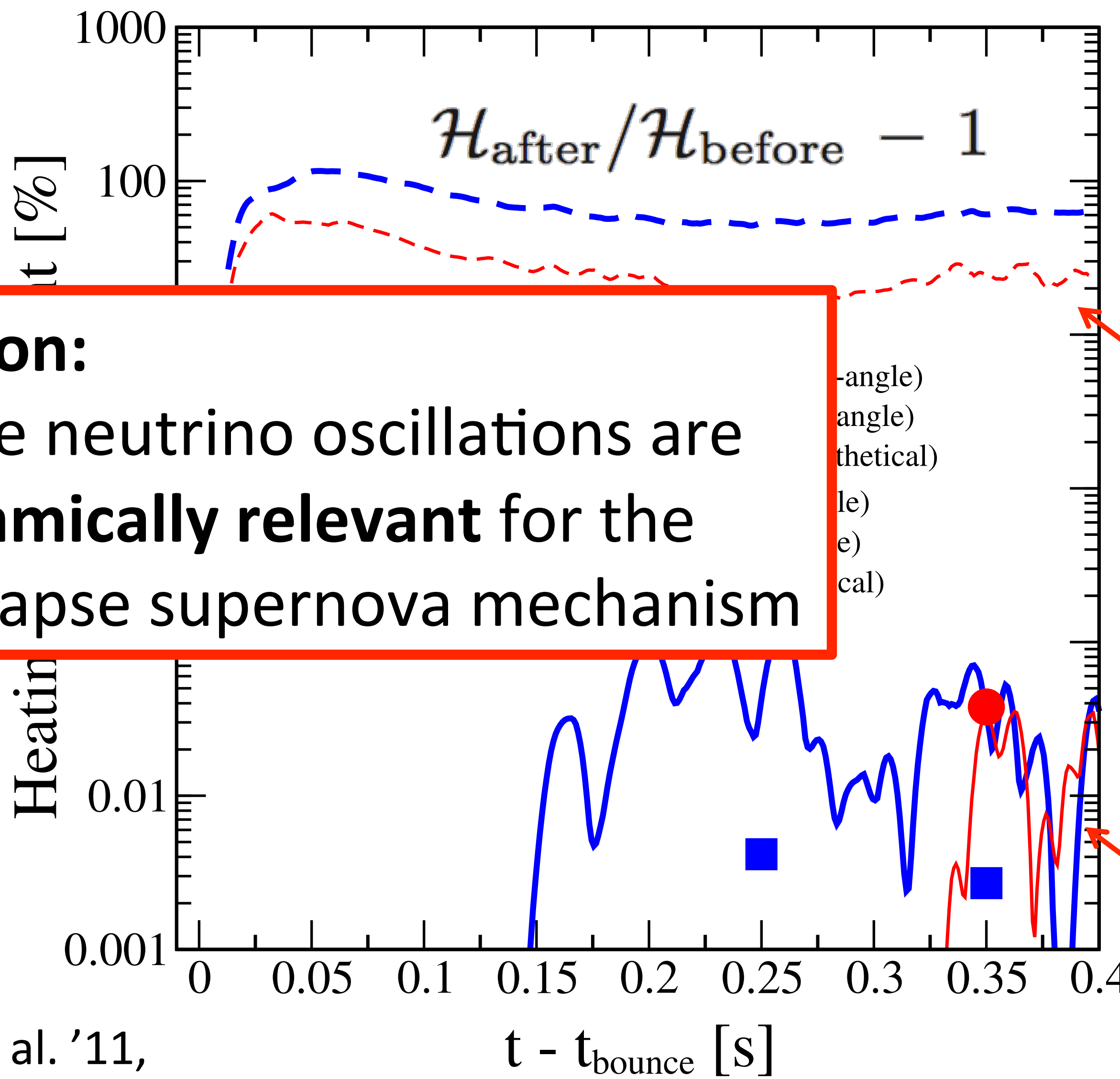


Conclusion:
Collective neutrino oscillations are **not dynamically relevant** for the core-collapse supernova mechanism

optimistic guess by Suwa et al. (wrong!)

results from actual calculations

See also Suwa et al. '11, Chakraborty et al. '11ab

Interlude: Other Candidate Mechanisms

Magnetorotational Mechanism

-> see next slide!

Magneto-viscous/sonic Mechanism

[Akiyama+'03, Thompson+ '05, Suzuki+'08, Obergaulinger+'11]

-> viscous heating by the magnetorotational instability [MRI];
-> and/or dissipation of Alfven waves.

Phase-Transition Induced Mechanism

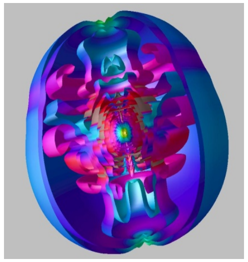
[e.g., Sagert +'09]

-> hadron-quark phase transition, leading to second collapse and bounce of protoneutron star + shock -> explosion;
-> requires soft equation of state, now disfavored.

Acoustic Mechanism

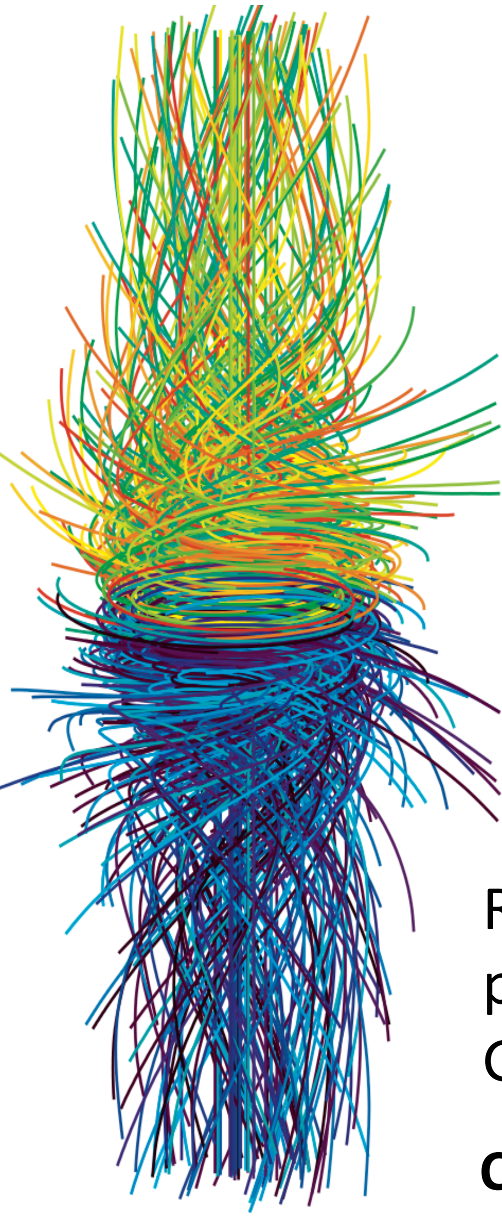
[e.g., Burrows+'06,'07, Ott+'06, Weinberg&Quataert'08]

-> excitation of protoneutron star pulsations, damping via sound waves that become shocks & dissipate -> explosion;
-> disfavored: non-linear mode couplings limit amplitudes, amplification seen only by one group.



Magnetorotational Mechanism

[LeBlanc & Wilson 70, Bisnovatyi-Kogan 70,
Burrows+ 07, Cerda-Duran+07, Takiwaki & Kotake 11, Winteler+ 12]



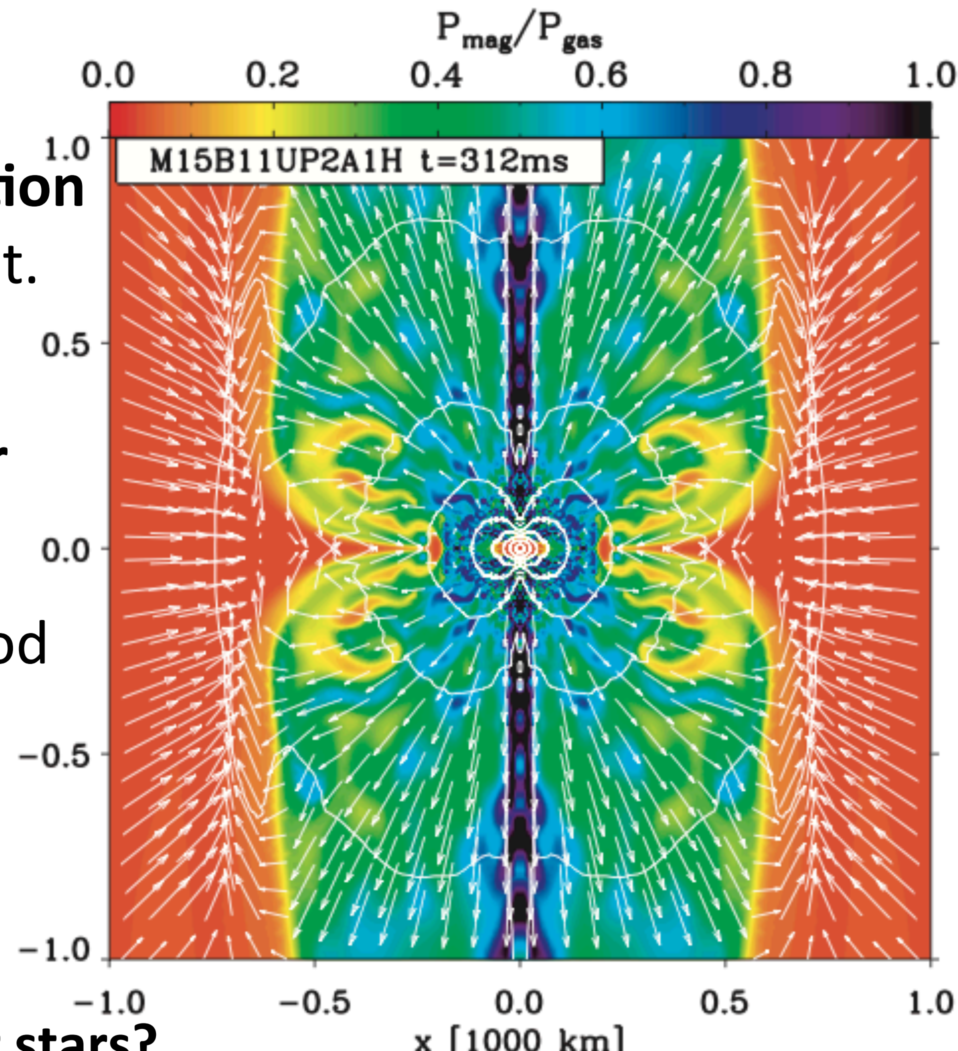
Burrows+07

Rapid Rotation +
B-field amplification
(need magnetorot. Instability [MRI])

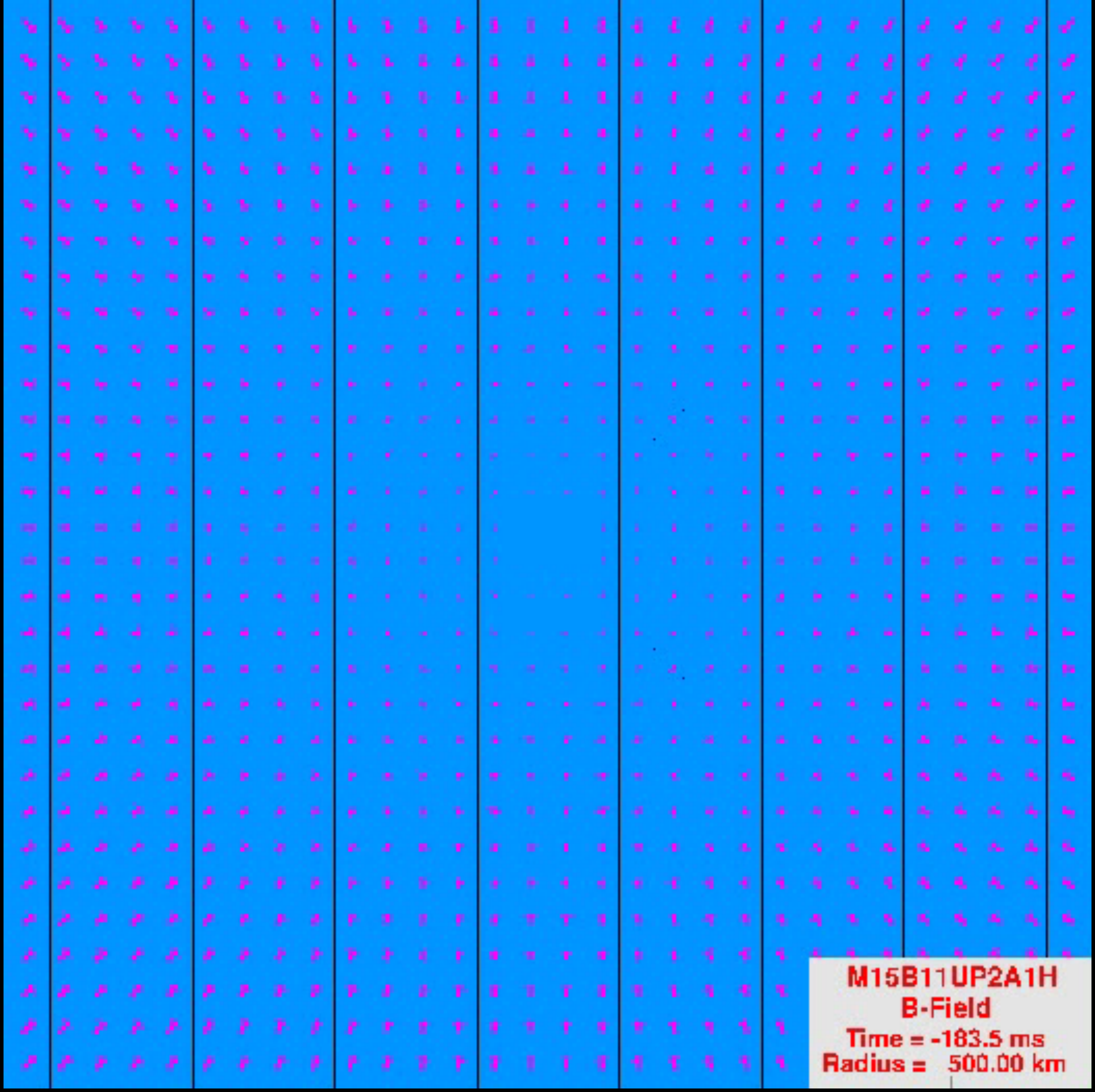
Energetic bipolar explosions.

Results in ms-period proto-magnetar.
GRB connection?

Caveat: Need high core spin; only in very few progenitor stars?



Burrows+07



Burrows+'07

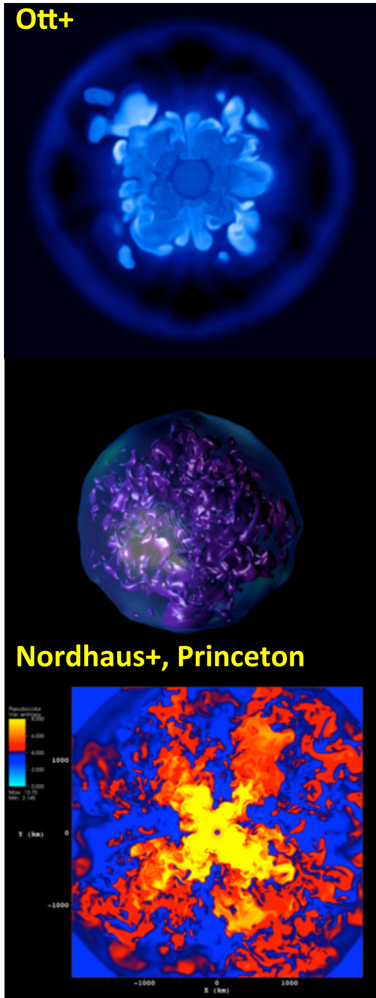
The Frontier: 3D Core-Collapse Supernovae

- 1D -> 2D: neutrino heating more efficient, some models explode.
- 2D -> 3D: (1) Character of turbulence changes;
  energy cascades to small scales (large scales in 2D).
  (2) Additional degree of freedom:
  nonaxisymmetric flow.

- **Is the neutrino mechanism robust in 3D?**

- **Computational challenge**:
  - **Multi-scale**: Resolve 10 m (turbulence) - 10000 km (outer core)
  - **Multi-physics**: GR, MHD, neutrinos, nuclear EOS, nuclear reactions
  - 3D estimates: Memory footprint: ~10-100 Terabytes
    Total # of floating point operations: ~10^5 Petaflops

  -> Approximations must be made!



Ott+13, ApJ

rendered by S. Drasco

Ott+13,
ApJ

-6.18 ms

rendered by
S. Drasco

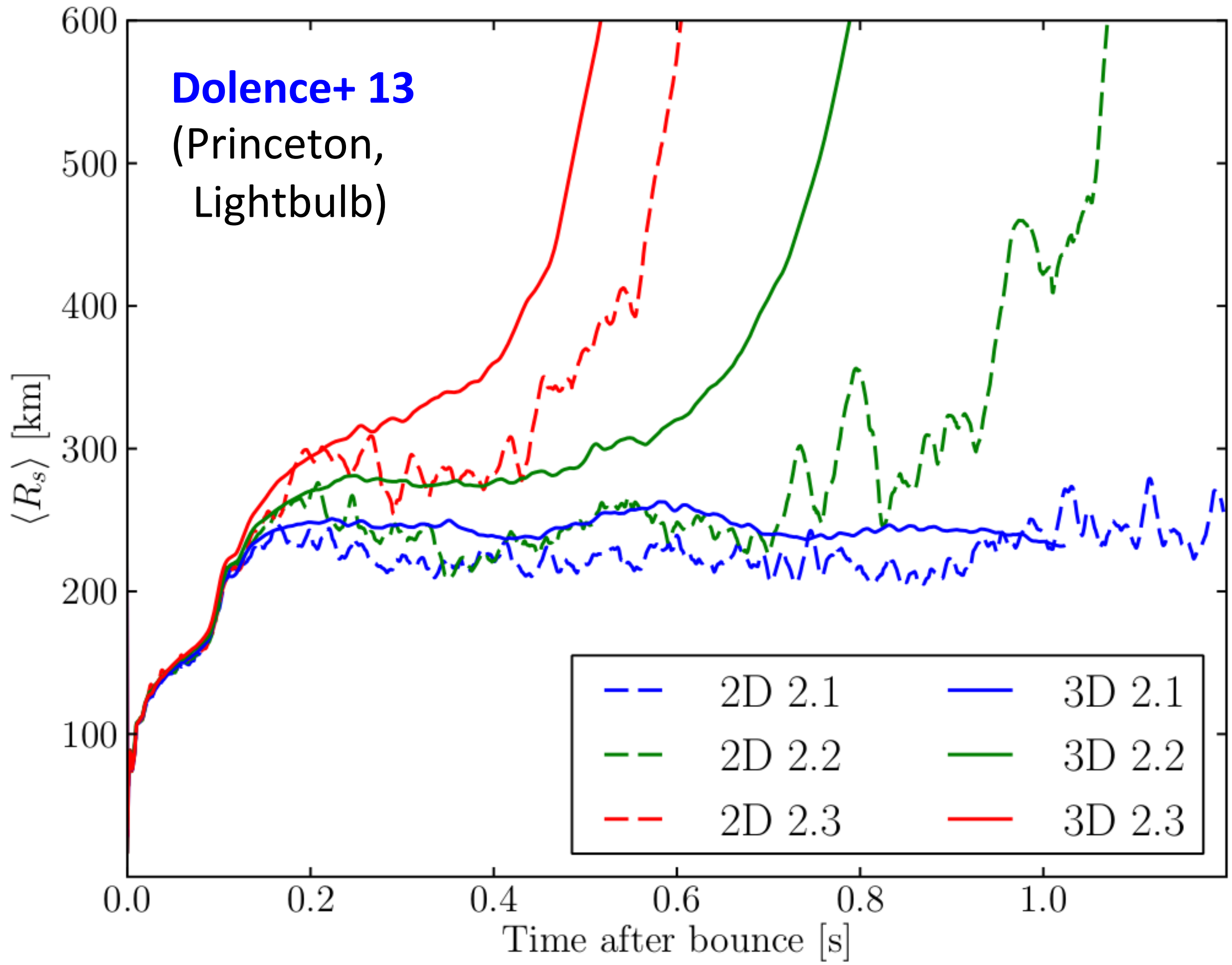
Results of current 3D Simulations

Does 3D help the explosion?

Yes:

Explosions start earlier in 3D

Nordhaus+10,
Burrows+12,
Dolence+13,
Takiwaki+12

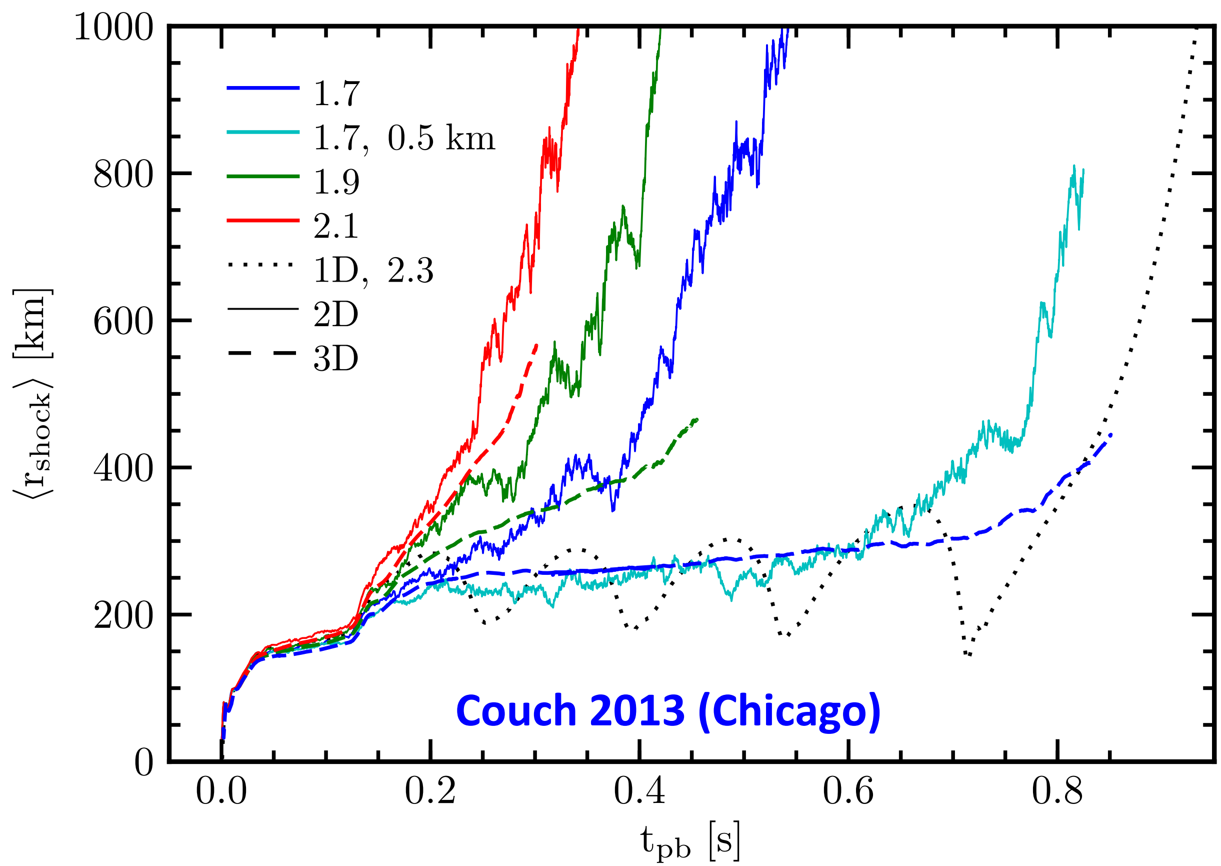


Results of current 3D Simulations

Does 3D help the explosion?

No:

Hanke+12,13 (Garching)
Couch 13 (Chicago)
3D simulations explode later than 2D ones.



Explanation(s)?

-> Hanke+12: Higher resolution makes it harder to explode in 3D. Consequence of turbulent cascade? (answer not clear)

Summary: 3D Simulations

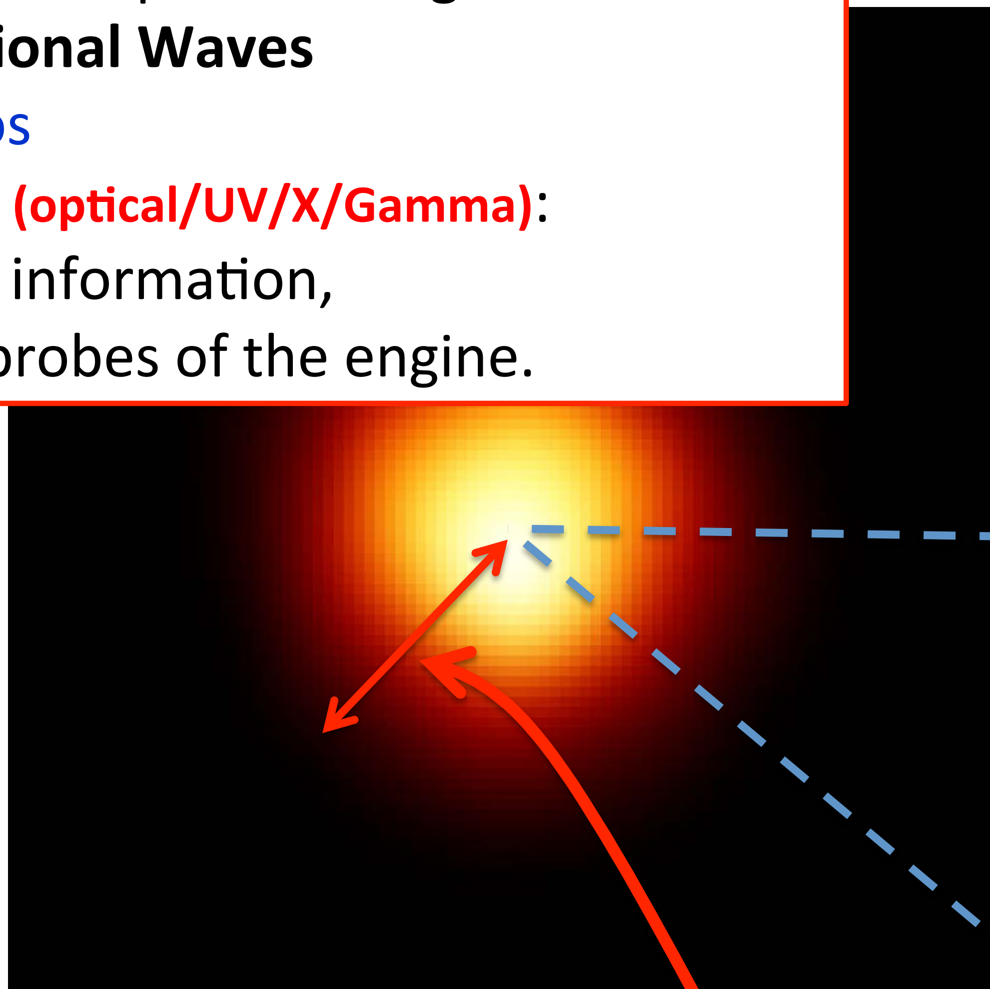
- Qualitative change in the dynamics from 2D to 3D: SASI and convection both change.
- Current simulations are either **parameterized** or underresolved or both.
- Not yet clear if 3D alone can lead to robust explosions.
  - Current simulations may be too incomplete / approximate.
  - Physics may be missing.
- In the near future (this year / next year):
  Well resolved 3D neutrino radiation hydro simulations
  -> Will be in a position to make more reliable statements.
- **See TAUP 2013 Conference for updates!**
  -> Talks by Janka, Kotake, Abdikamalov, and others.

Observing the CCSN Mechanism

Probing the "Supernova Engine"
- **Gravitational Waves**
- Neutrinos

EM waves (optical/UV/X/Gamma):
secondary information,
late-time probes of the engine.

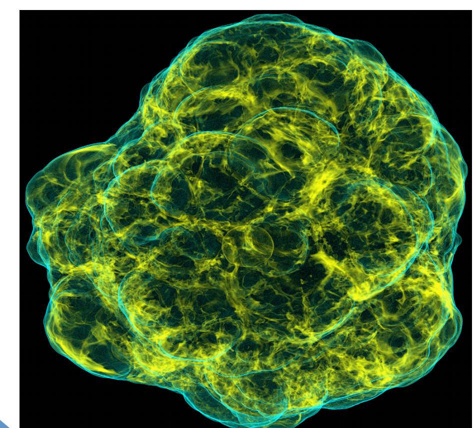
Red Supergiant
Betelgeuse
D ~200 pc



HST

800 million km

Supernova "Central Engine"



300 km

Core-Collapse Supernova Neutrinos

- Emission: Charged current & neutral current weak interactions.

$$\nu_e, \nu_\mu, \nu_\tau$$ + mixing (George Fuller's lecture)

$$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \quad \epsilon_\nu \sim 10\,\mathrm{MeV}$$

- Detection: (see Scholberg '12)

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

-> primary reaction in Water Cherenkov detectors like Super-K & IceCube.

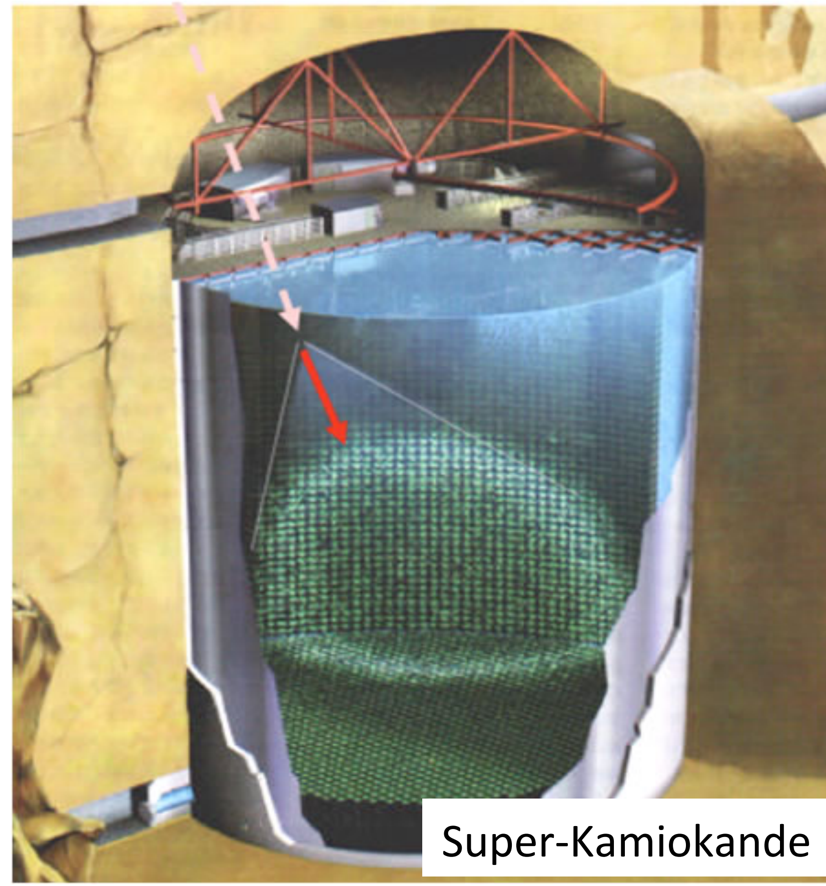
Other relevant interactions:

$$\nu_x + e^- \to \nu_x + e^-$$

$$\nu_e + (N, Z) \to (N-1, Z+1) + e^-$$

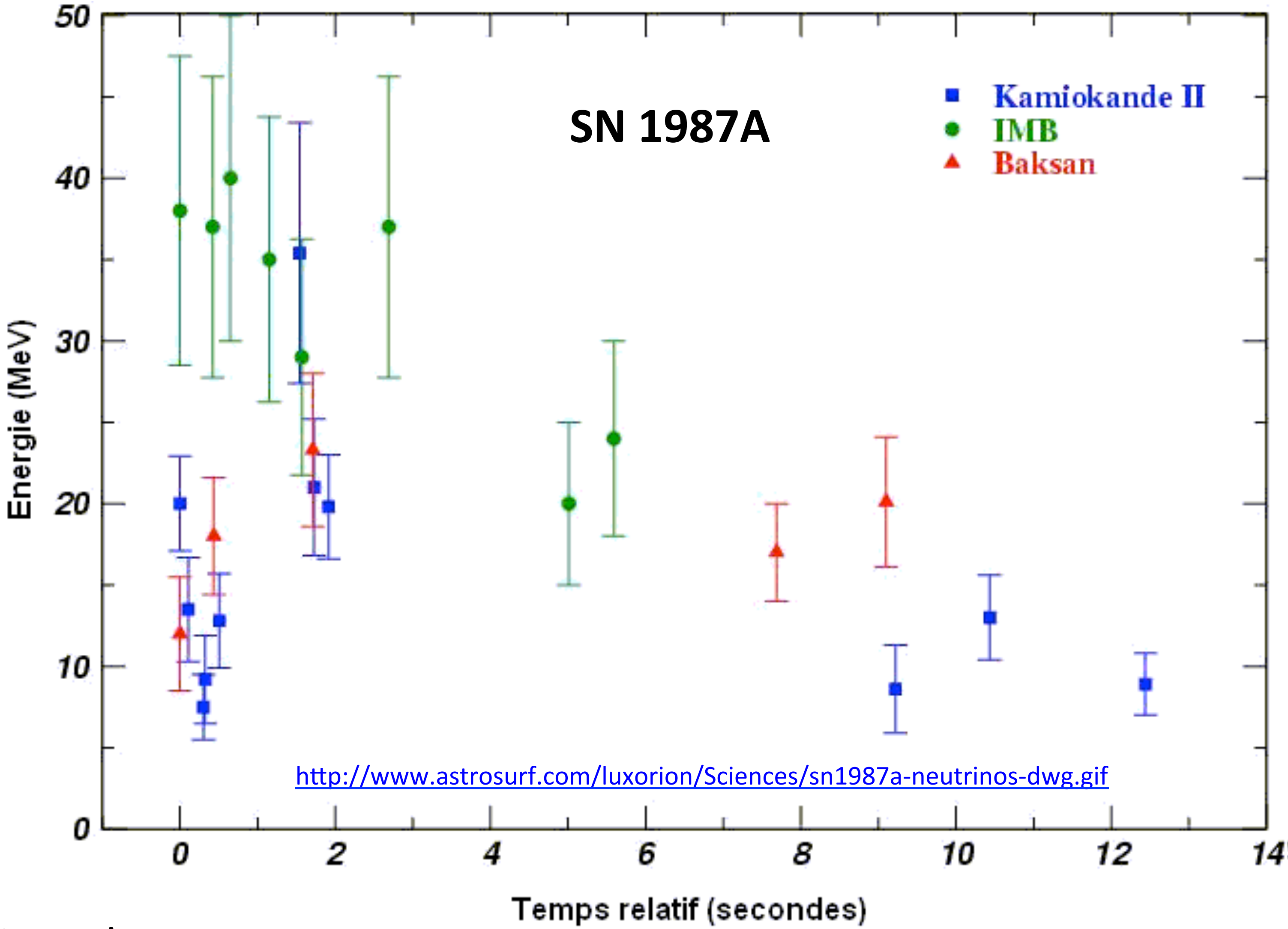
$$\bar{\nu}_e + (N, Z) \to (N-1, Z-1) + e^+$$

Water Cherenkov, liquid scintillator, liquid argon, lead detectors.



Most detectors will provide flux and spectral information.

Core-Collapse Supernova Neutrinos



3 emission phases:

(1) Neutronization burst, (2) Accretion Phase (~0.5s), (3) Cooling Phase (10+s)

Core-Collapse Supernova Neutrinos

Expected # of neutrino events for a galactic (10 kpc) supernova.

Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980-present
LVD	C_nH_{2n}	1	Italy	300	1992-present
Super-Kamiokande	H_2O	32	Japan	7,000	1996-present
KamLAND	C_nH_{2n}	1	Japan	300	2002-present
MiniBooNE*	C_nH_{2n}	0.7	USA	200	2002-present
Borexino	C_nH_{2n}	0.3	Italy	100	2005-present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007-present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE*	Ar	0.17	USA	17	Near future
NOνA*	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

Scholberg 2012

What to do with Supernova Neutrinos?

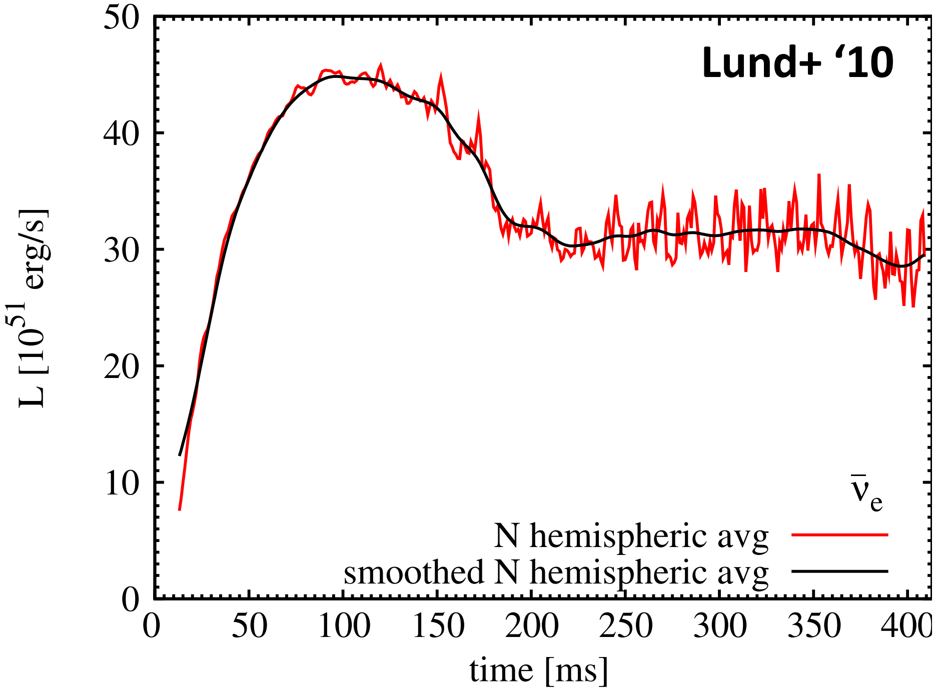
- **Neutrinos probe thermodynamics and dynamics of the supernova**. From luminosity & spectrum, learn about:
  - Protoneutron star mass & structure.
  - Nuclear equation of state.
  - Accretion rate.
  - Supernova dynamics.

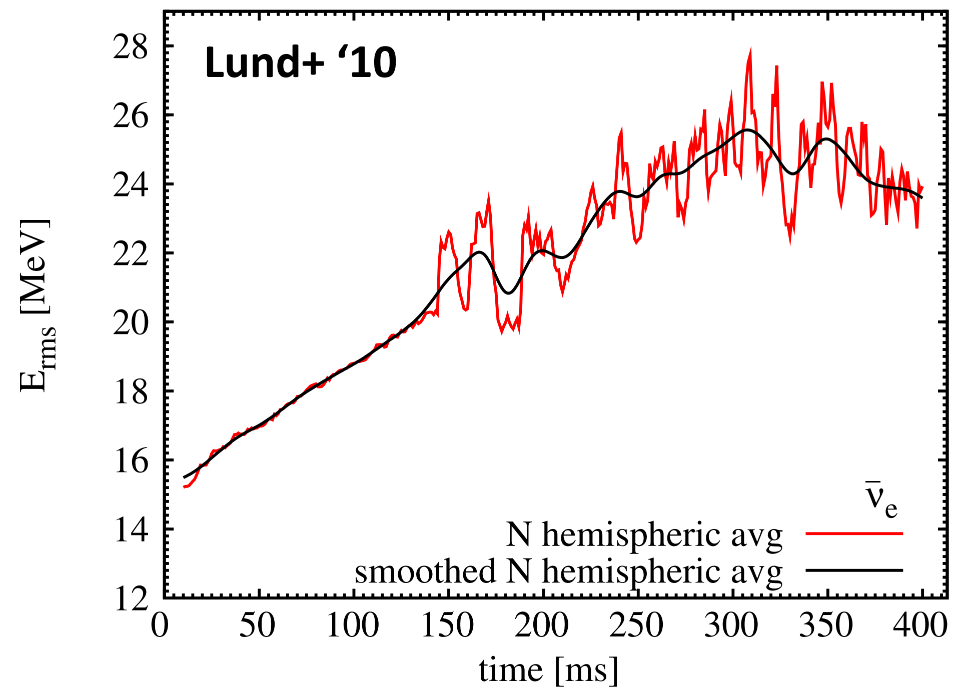
- **Probe uncertain/new neutrino physics**:
  - Mass hierarchy.
  - Collective oscillations.
  - MSW oscillations.
  - New/exotic physics.

George Fuller's lecture

http://www.particlezoo.net/

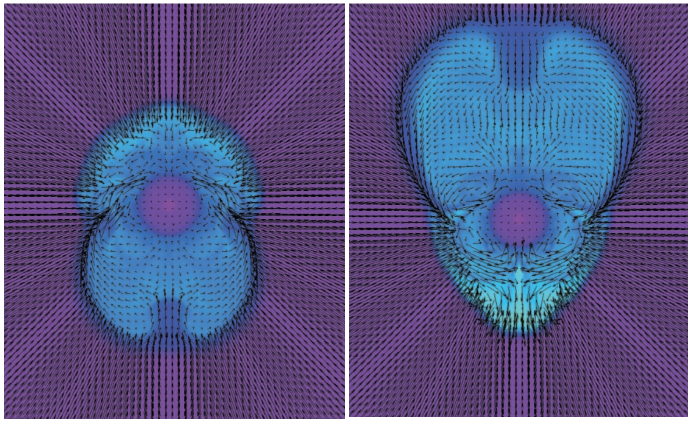
Neutrino Signature of Convections/SASI





See: Ott+ '08, Marek & Janka '09, Lund+ '10, '12, Brandt +'11

- Neutrino signal can be used to probe supernova dynamics.
- Lund et al. '10:
  IceCube can detect SASI for galactic event.



Neutrino Probes of Stellar Structure

- Pre-SN massive star structure is uncertain.
- Neutrino signal in the pre-explosion phase is determined by (1) the accretion rate of the stellar envelope and (2) by the core temperature of the collapsing star.

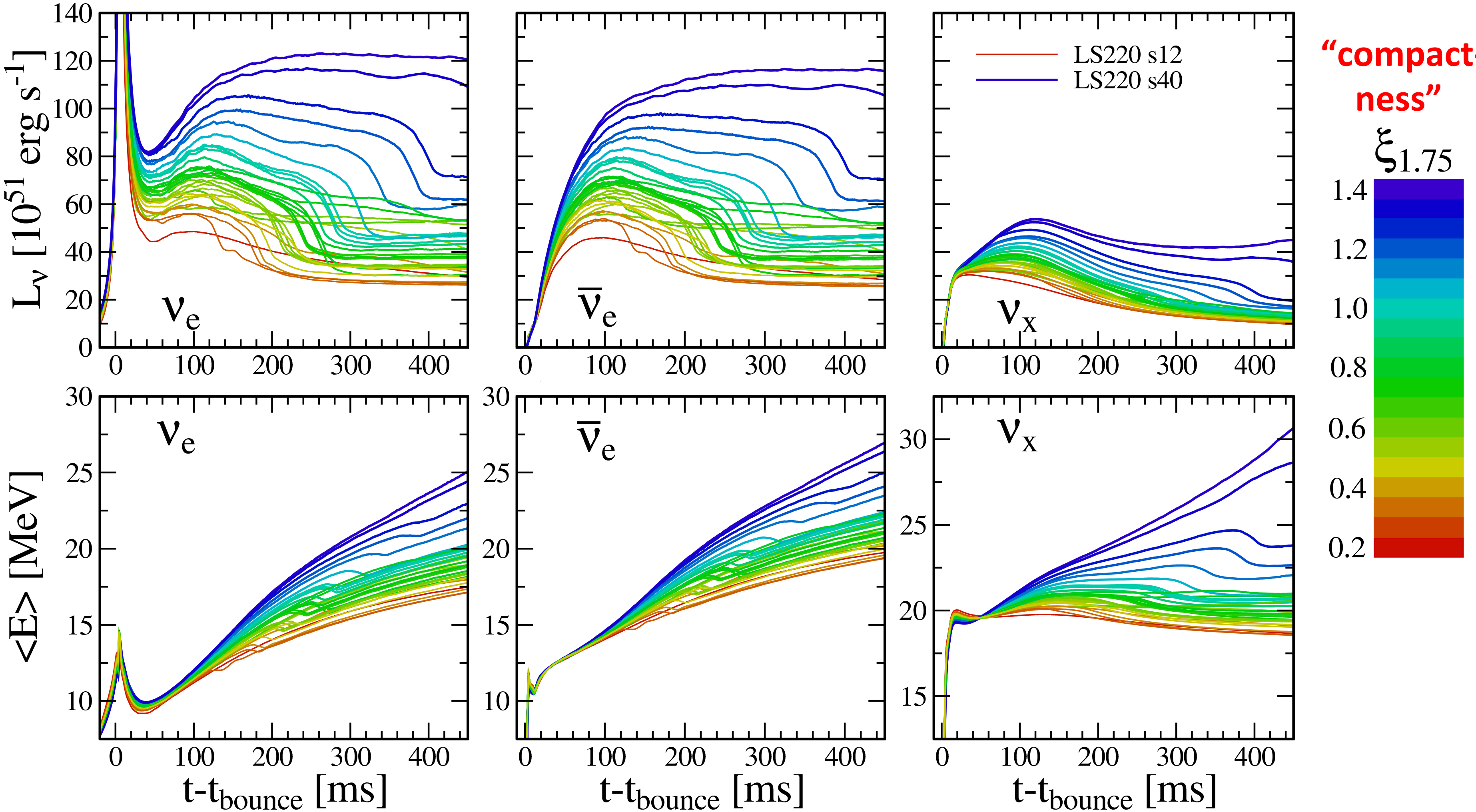
Parameter encapsulating both (1) and (2):

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

"compactness parameter" measured at bounce.
(O'Connor & Ott '11)

Probing Stellar Structure with Pre-Explosion Neutrinos

O'Connor & Ott '13, ApJ

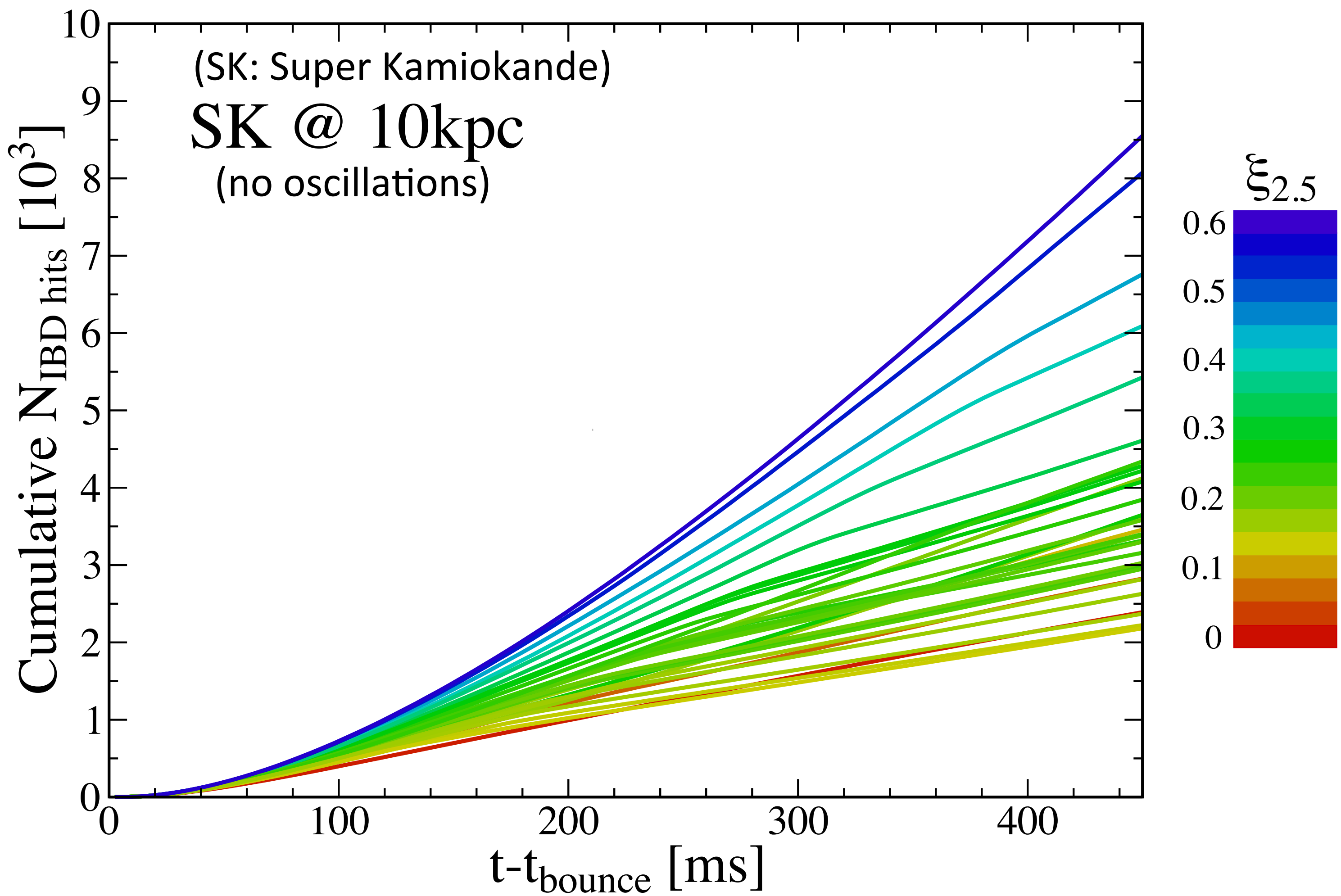


- Consider pre-explosion phase: clean, "collective oscillations" suppressed(?)

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

Probing Stellar Structure with Pre-Explosion Neutrinos

O'Connor & Ott '13, ApJ



- Expected inverse beta decay events in Super-K using SNOwGLoBES (Scholberg '12). http://www.phy.duke.edu/~schol/snowglobes

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

Progenitor Structure of SN 1987A

O'Connor & Ott '13

Comparison with early phase of the observed SN 1987A neutrino signal.

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

But: beware of small-number statistics!!