New Results in Core Collapse Supernova Theory

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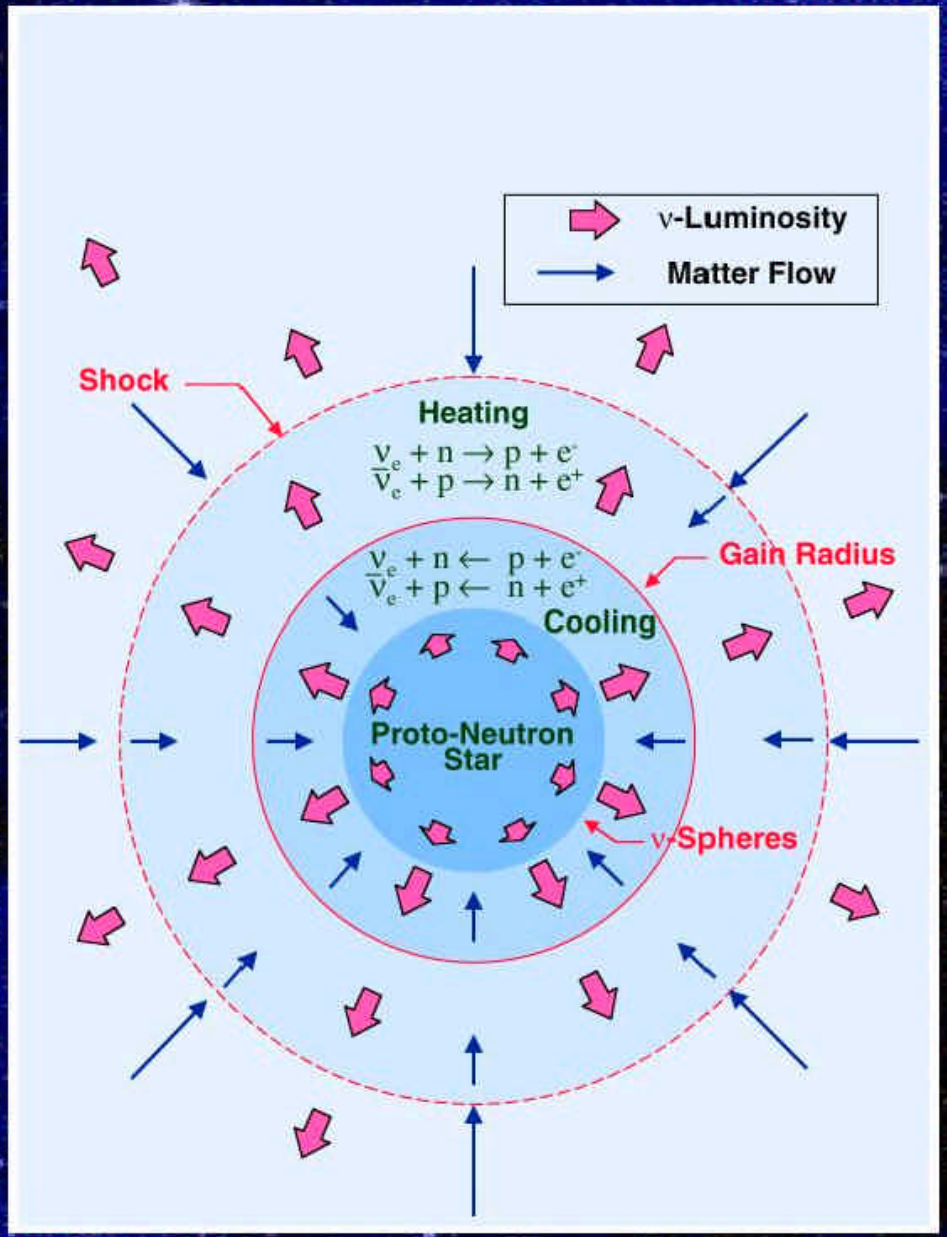
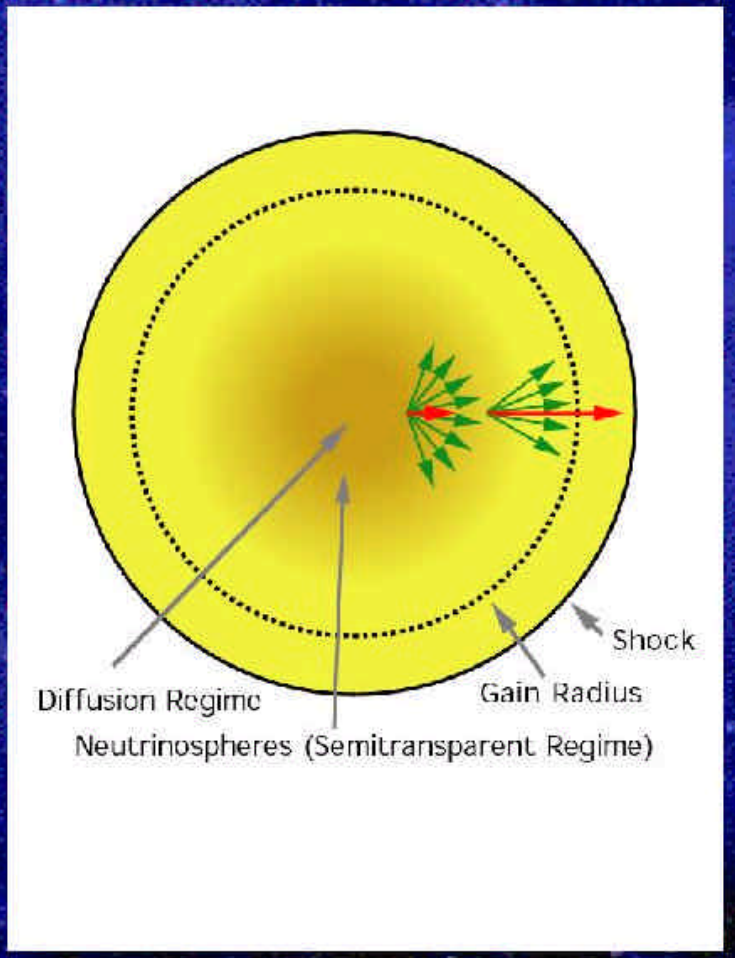
ORNL Supernova Group and Co.

ORNL-Centered Collaboration
DoE SDAC Program
15 Investigators
10 Institutions
Astrophysics, Nuclear Physics,
Computer Science, Visualization

Neutrino Heating Mechanism



Need Boltzmann Solution



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

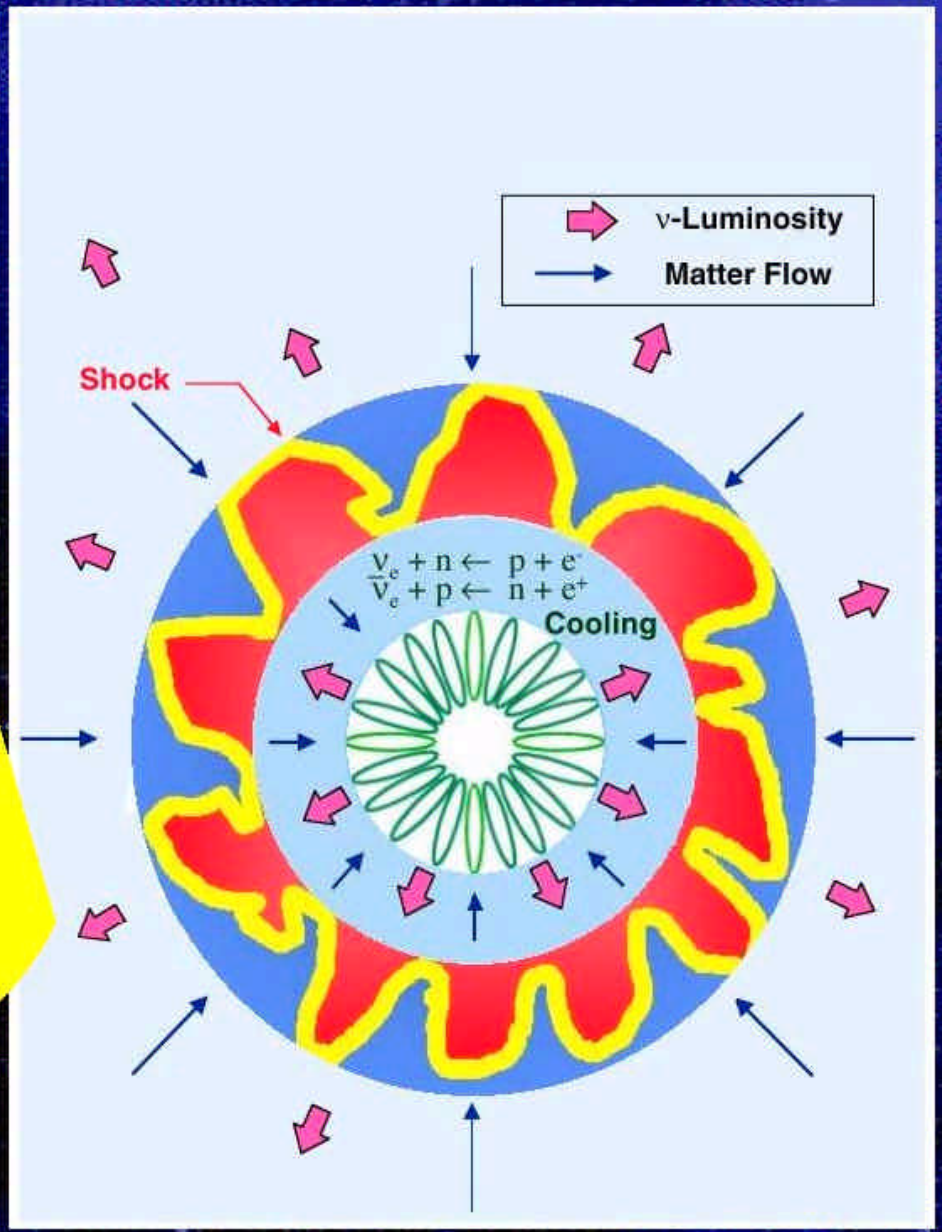
Decrease with Anisotropy

Approximations Used in the Past: e.g., MGFLD

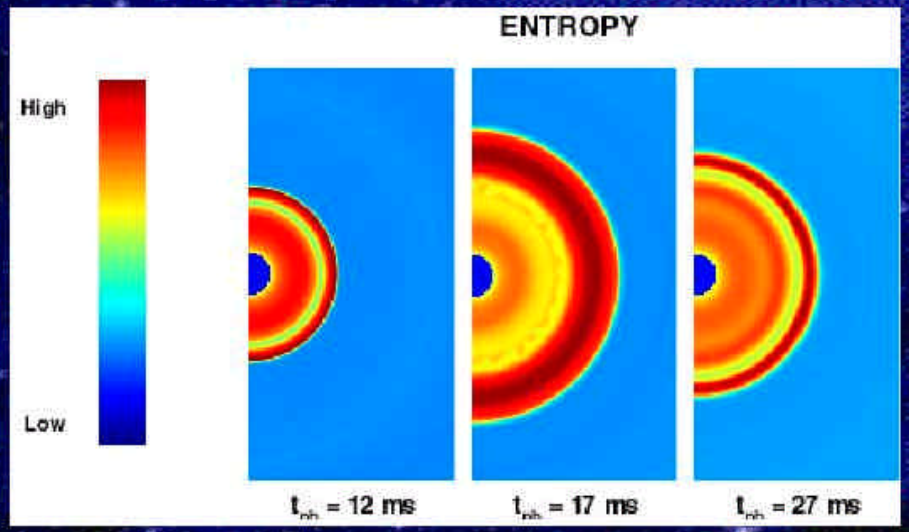
What About Convection?

Neutrino-Driven Convection
- ➢Boost Shock Radius
- ➢Boost Neutrino Heating

Proto-Neutron Star Convection
- ➢Boost Neutrino Luminosities

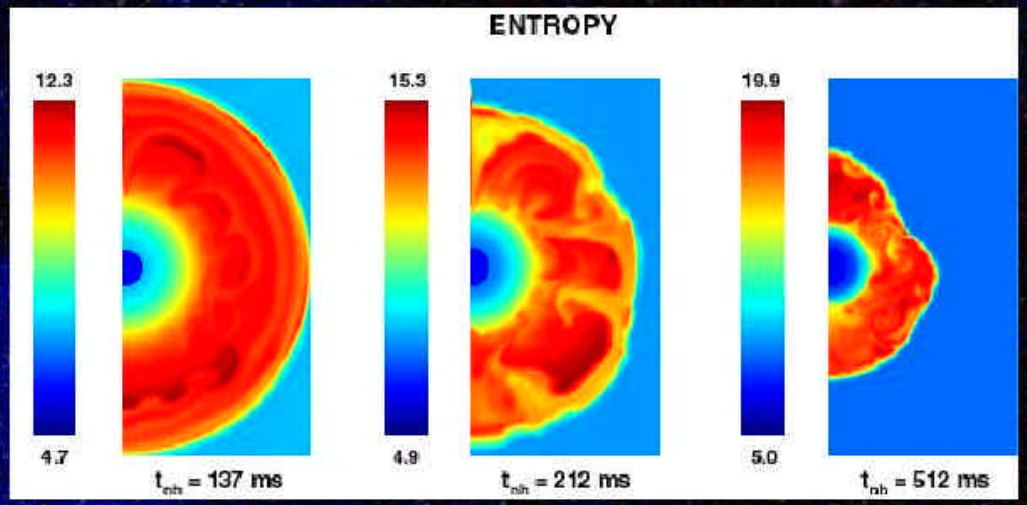


Proto-Neutron Star Convection



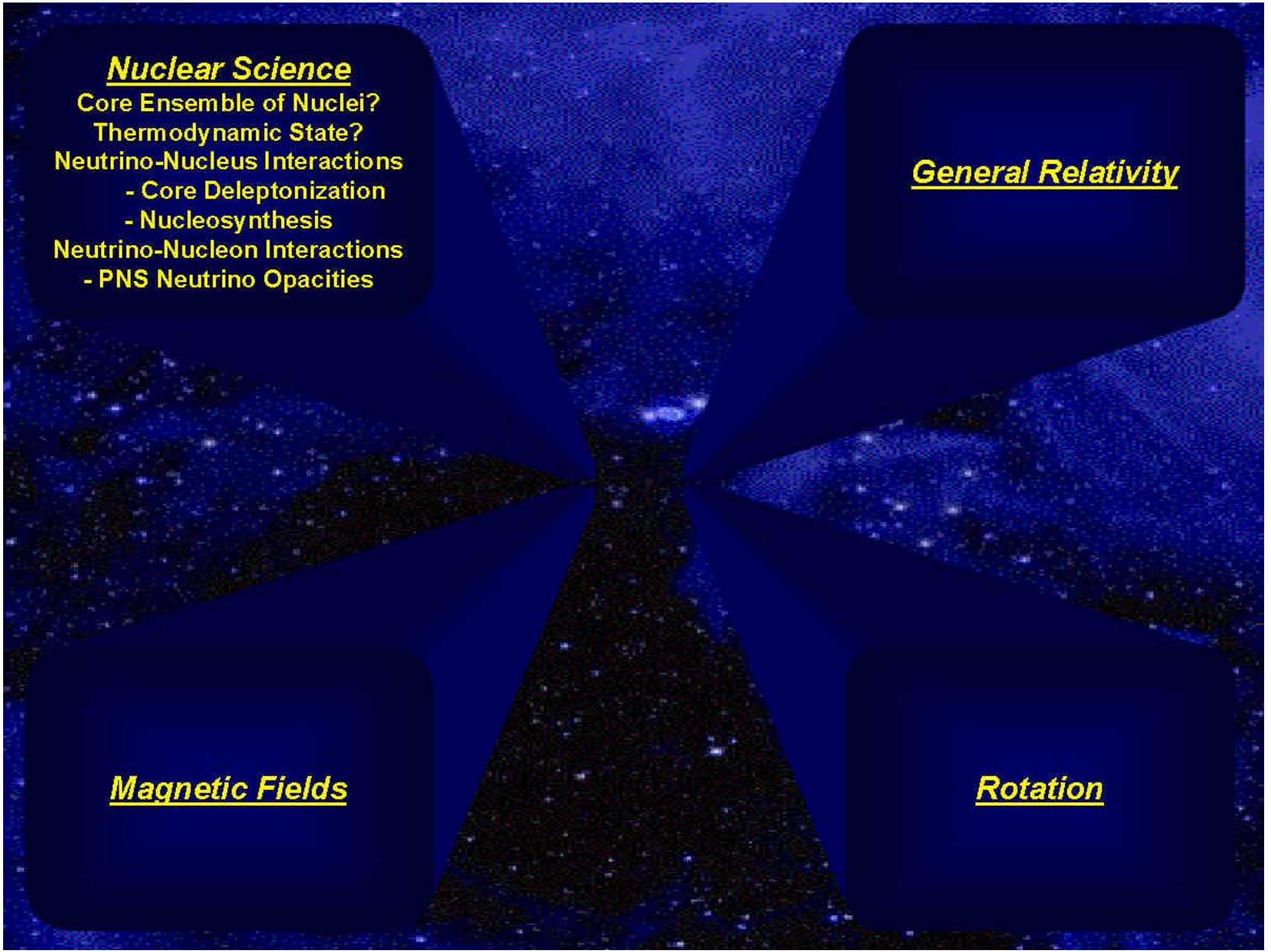
Radiation Hydrodynamics Problem
Requires 3D MG Transport
Existence and Vigor Uncertain

Neutrino-Driven Convection



3D Character Uncertain
3D for Convecting, Rotating Flows
Impact on Mechanism Uncertain
2D Simulations Suggestive

Mezzacappa *et al.*, *Ap.J.* 493, 848 (1998)
Mezzacappa *et al.*, *Ap.J.*, 495, 911 (1998)


Nuclear Science
Core Ensemble of Nuclei?
Thermodynamic State?
Neutrino-Nucleus Interactions
- Core Deleptonization
- Nucleosynthesis
Neutrino-Nucleon Interactions
- PNS Neutrino Opacities
General Relativity
Magnetic Fields
Rotation

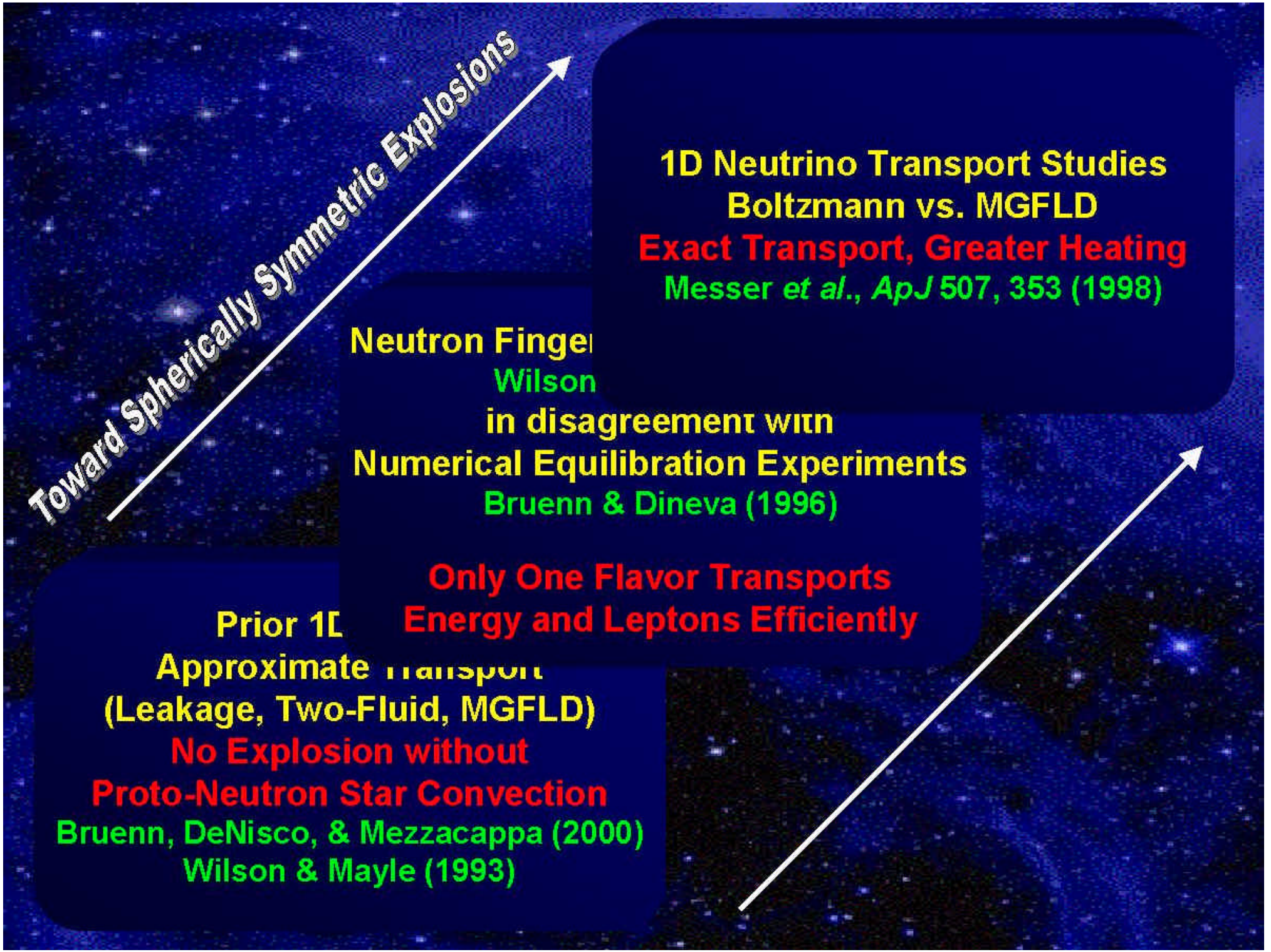
Fundamental Questions Remain

- What is the *Recipe for Explosion?*

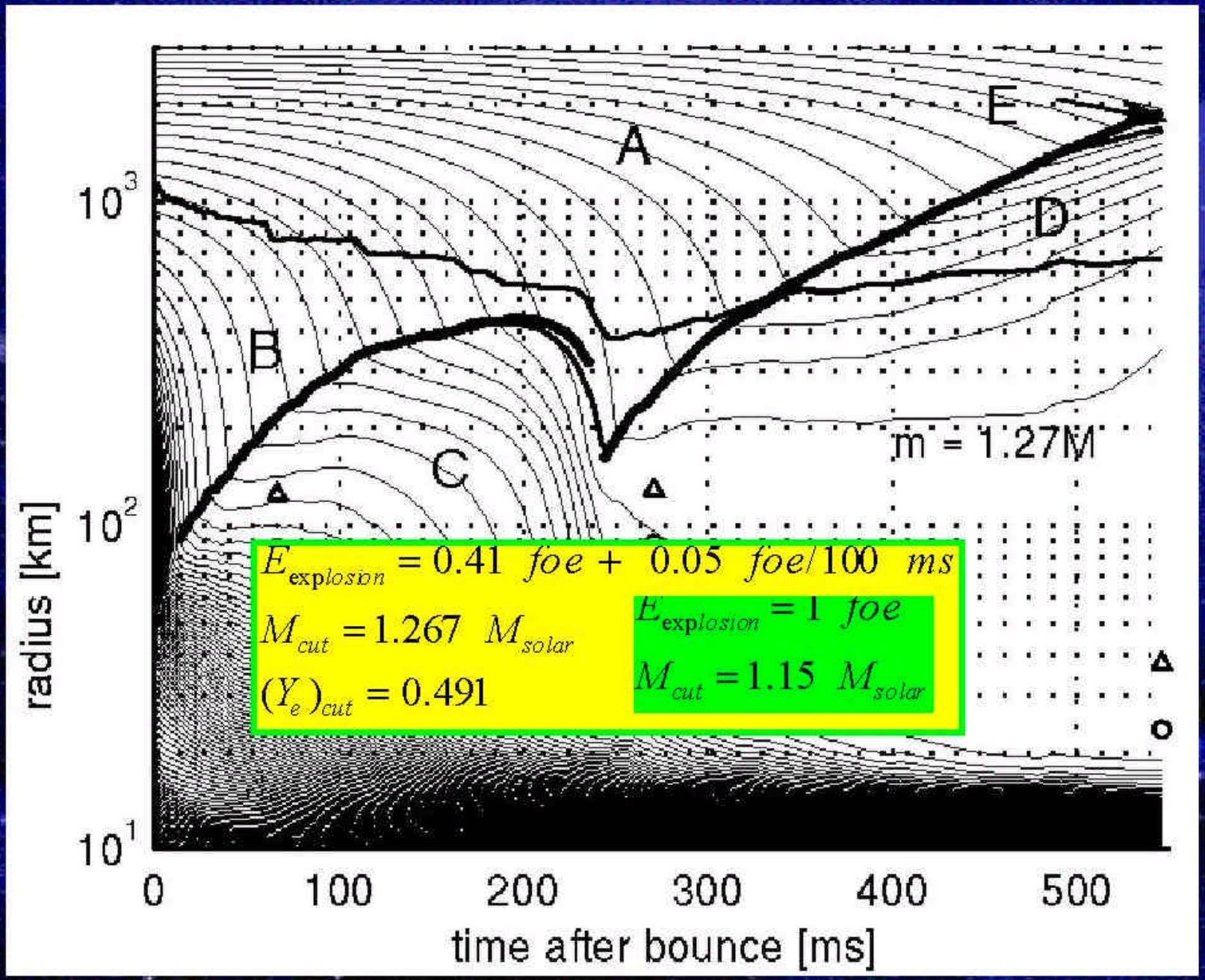
Is the neutrino heating sufficient, or are multidimensional effects such as convection and rotation required?

Can the fundamental observable, explosion, be reproduced in spherically symmetric models?

Explosion Mechanism
Explosion Observables
Related but Distinct


Toward Spherically Symmetric Explosions
1D Neutrino Transport Studies
Boltzmann vs. MGFLD
Exact Transport, Greater Heating
Messer et al., ApJ 507, 353 (1998)
Neutron Finge
Wilson
in disagreement with
Numerical Equilibration Experiments
Bruenn & Dineva (1996)
Only One Flavor Transports
Energy and Leptons Efficiently
Prior 1D
Approximate Transport
(Leakage, Two-Fluid, MGFLD)
No Explosion without
Proto-Neutron Star Convection
Bruenn, DeNisco, & Mezzacappa (2000)
Wilson & Mayle (1993)

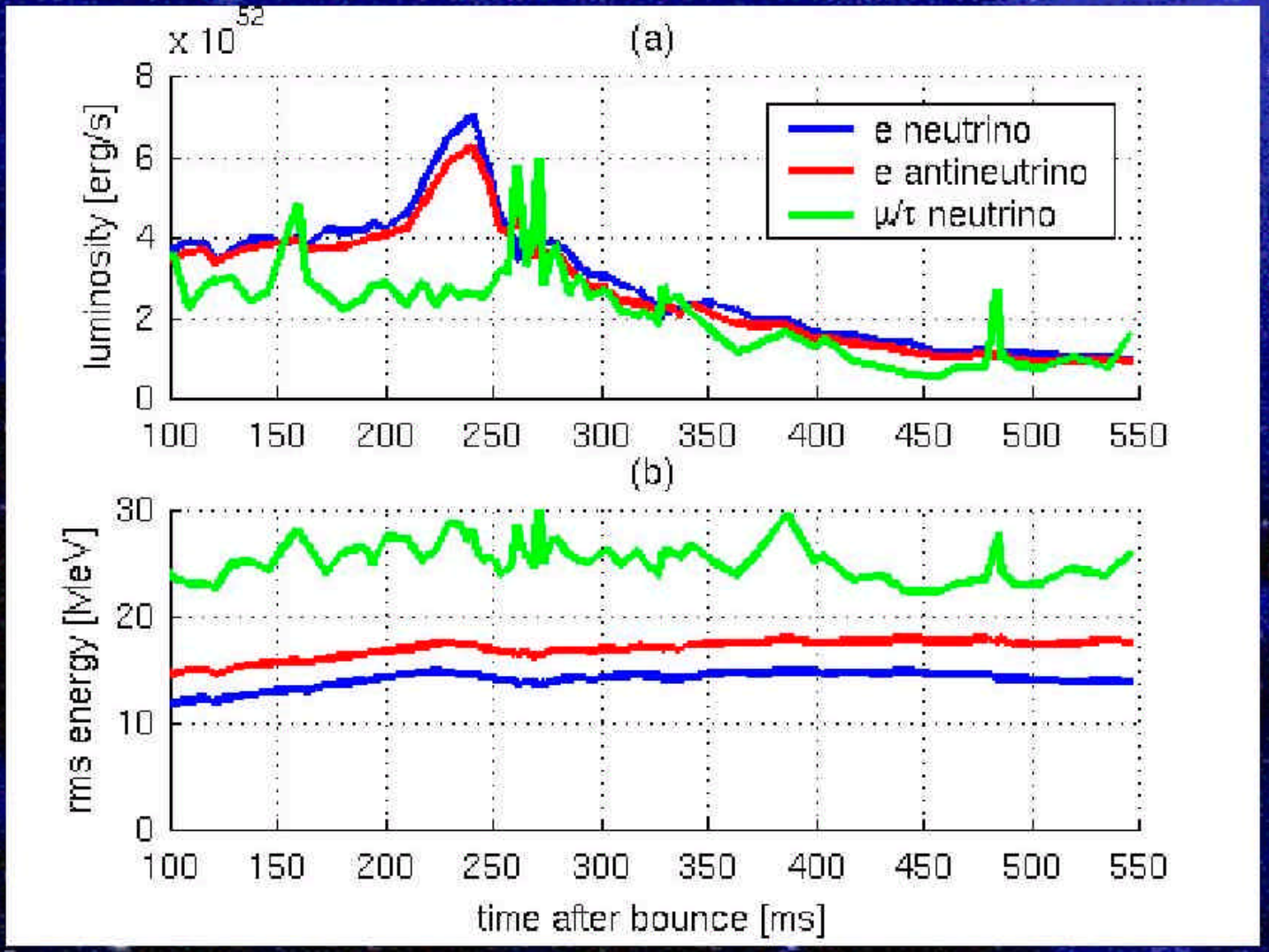
Spherically Symmetric Explosion



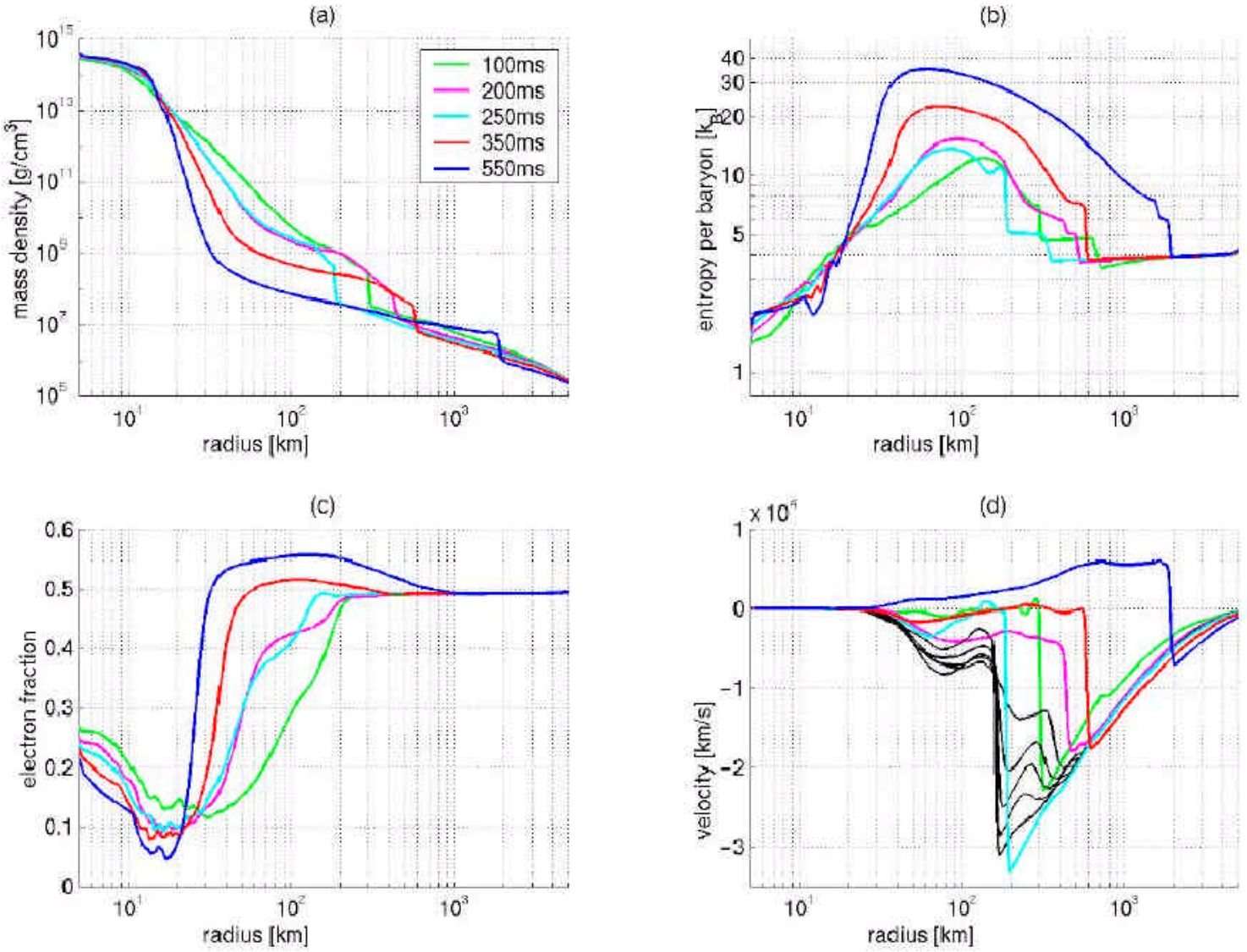
Mezzacappa *et al.*, *PRL*, submitted (astro-ph/0005366)

Liebendoerfer *et al.*, *PRL*, in preparation

Luminosities
RMS Energies



Core Profiles



AGILE-BOLTZTRAN

ADAPTIVE MESH
GENERAL RELATIVISTIC
BOLTZMANN TRANSPORT SOLVER

Liebendoerfer (2000)

Mezzacappa and Bruenn (1993)
Mezzacappa and Messer (1998)
Liebendoerfer (2000)

Supernova Nucleosynthesis

- **R-Process and Neutrino Nucleosynthesis**

Conclusions

First simulations with Boltzmann (vs. approximate) neutrino transport.
- Energetic explosions sans convection!
- Will our results extend to other progenitors?

Beginning to answer fundamental questions in supernova theory.
- What is the recipe for explosion?
- Are 3D phenomena needed?

A "solution" to the supernova problem (ascertaining the explosion mechanism) and understanding supernova phenomenology (kicks, polarization, bullets, etc.) will require a systematic effort.

Qualitative change in 1D models when Boltzmann transport used.
Required level of sophistication for all models: 1D, 2D, and 3D.

General Relativistic Radiation Hydrodynamics Code: AGILE-BOLTZTRAN
- Explosion Mechanism
- Accurate Neutrino Signatures (e.g., Neutrino Bursts)
- Supernova Nucleosynthesis