Finite T EOS

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Finite temperature EOS

Want more than EOS, want degrees of freedom/ composition of matter.

Low but nonzero T
Heat capacity, Neutrino emissivity and NS cooling (Case of MXB 1659)

Neutrinosphere in SN (and NS mergers) T~ 5-10 MeV, density~ 1/100 n_0
Clusters
Correlations and neutrino interactions (Simulate with cold atoms)
How to calculate: problems with Monte Carlo, Many-body perturbation theory
RPA gives consistent response for MFT EOS. Neutrino opacity should be consistent with EOS.

High temperature "hadronic" degrees of freedom
Muons, **pions**, Deltas
Thermally excited strangeness: Hyperons

Warm quark phases: Shear and bulk viscosity for post merger evolution.

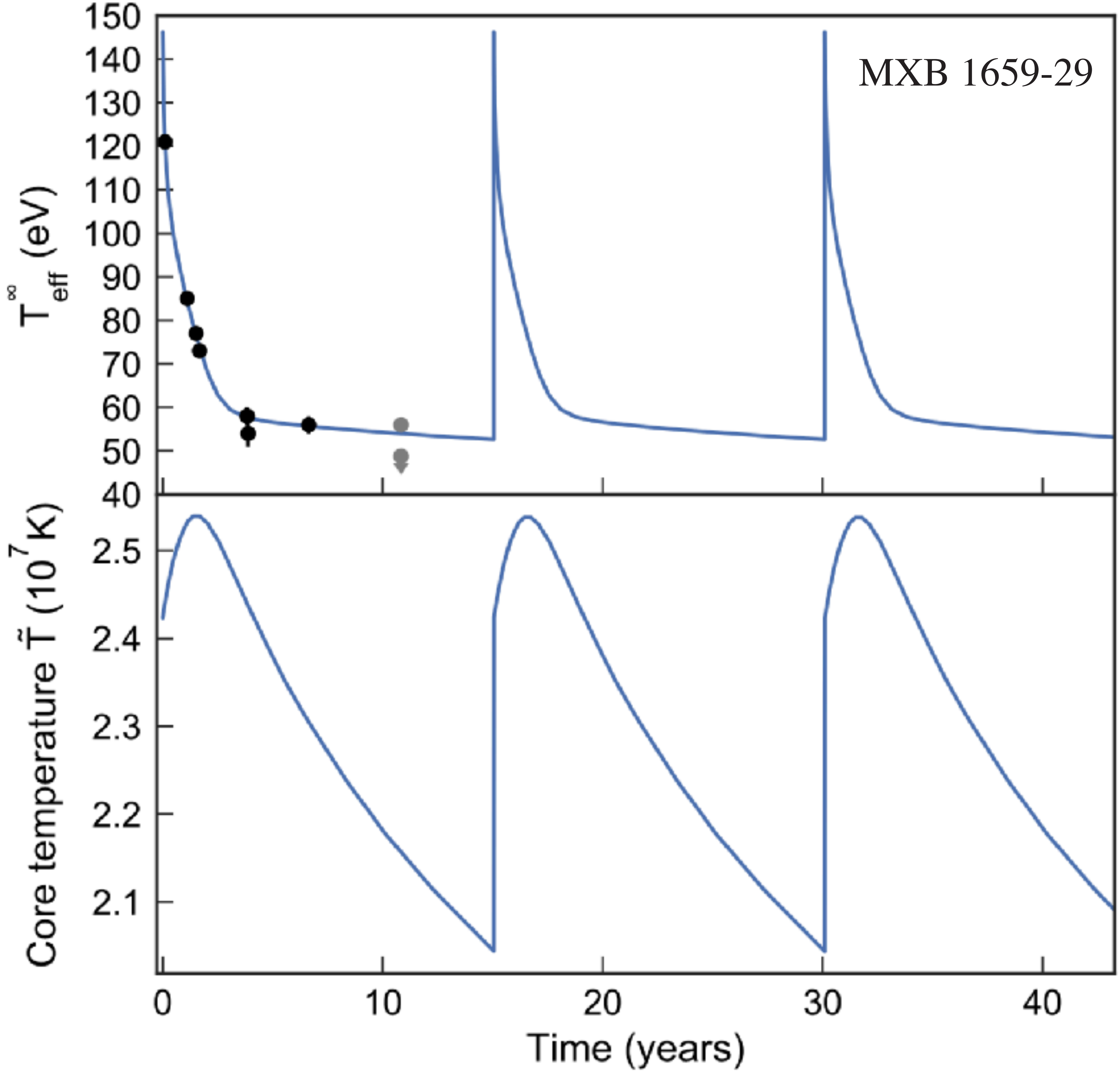
Neutron Star Cooling

- NS born hot in Supernovae and cool by neutrino emission from dense interior.
- **Normal cooling:** Most NS appear to cool by modified URCA process involving two correlated nucleons: n+n—>p+n+e+anti-nu, followed by e+p+n—>n+n+nu. Net result radiate anti-nu, nu pair each with ~kT energy.
- **Enhanced cooling:** If beta decay of single hadron possible cooling rate much higher: n—>p+e+anti-nu and then p+e—>n+nu. Called URCA process and needs large proton fraction.

MXB 1659

- Is first star with well measured temperature that needs enhanced cooling.
- Enhanced cooling could be URCA (if large proton fraction) or beta decay of hyperons, quarks, or meson condensates.
- Large proton fraction requires large symmetry energy at high density.

D. Page, A. Cumming, E. Brown, CJH… Phys. Rev. Lett. **120**, 182701 (2018)



MXB 1659-29
T_{eff}^{∞} (eV)
Core temperature $\tilde{T}$ (10^7 K)
Time (years)
150
140
130
120
110
100
90
80
70
60
50
40
2.5
2.4
2.3
2.2
2.1
0
10
20
30
40

Simulate SN in Lab with cold atoms

- Nucleon-nucleon correlations at low neutrino sphere density dominate by large neutron scattering length.
- Can tune scattering length of cold atoms in lab by adjusting magnetic field.
- Neutrinos have large spin coupling to nucleons (axial current). Measure spin response of cold atoms with spin dependent brag spectroscopy.

Can the spin response of a unitary gas help a supernova explode?

- Well posed question.

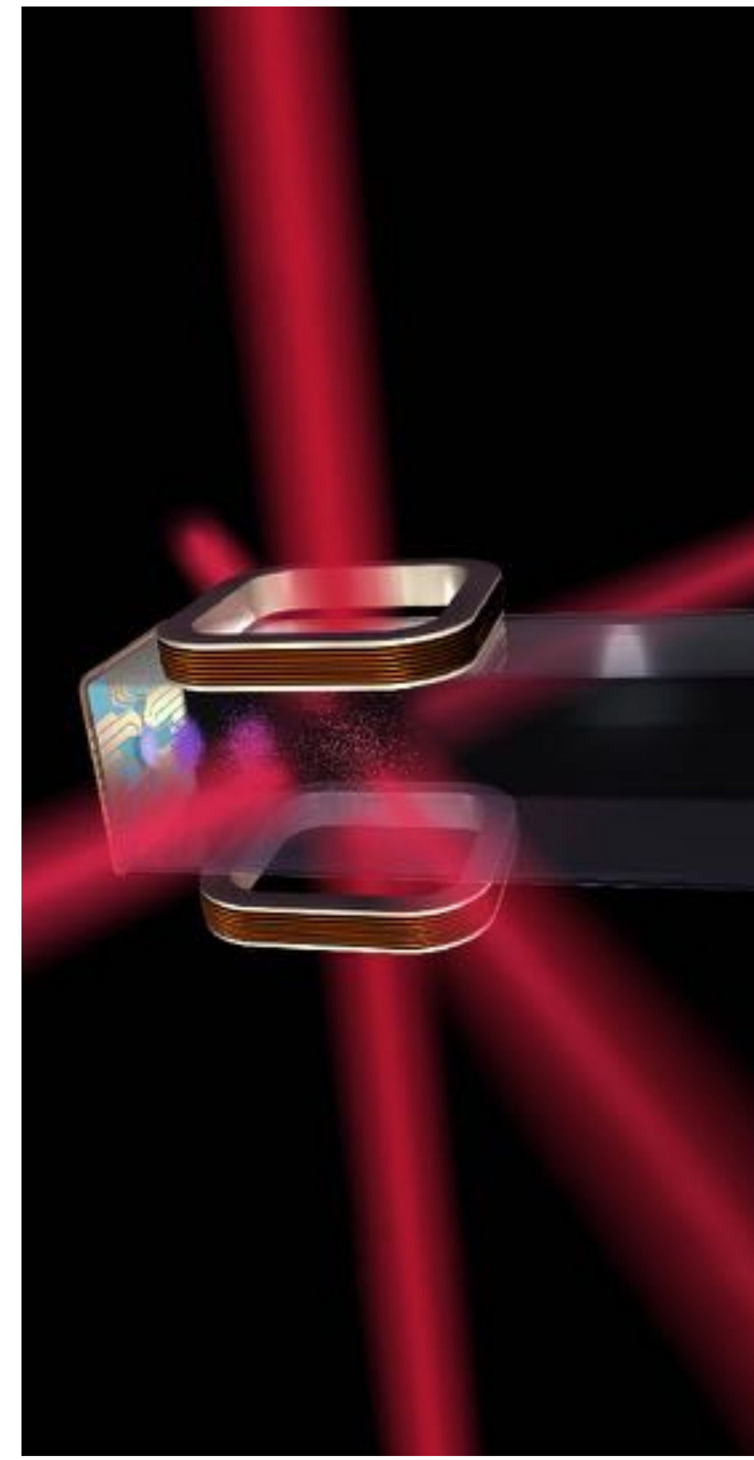
- Helpful to think of neutrinos interacting with a unitary gas as a special reference system for nuclear matter. Better to model neutrinosphere region as a unitary gas instead of a free (Fermi) gas as is often done.

- Many theoretical results for a unitary gas and many **experimental results** for cold atoms.

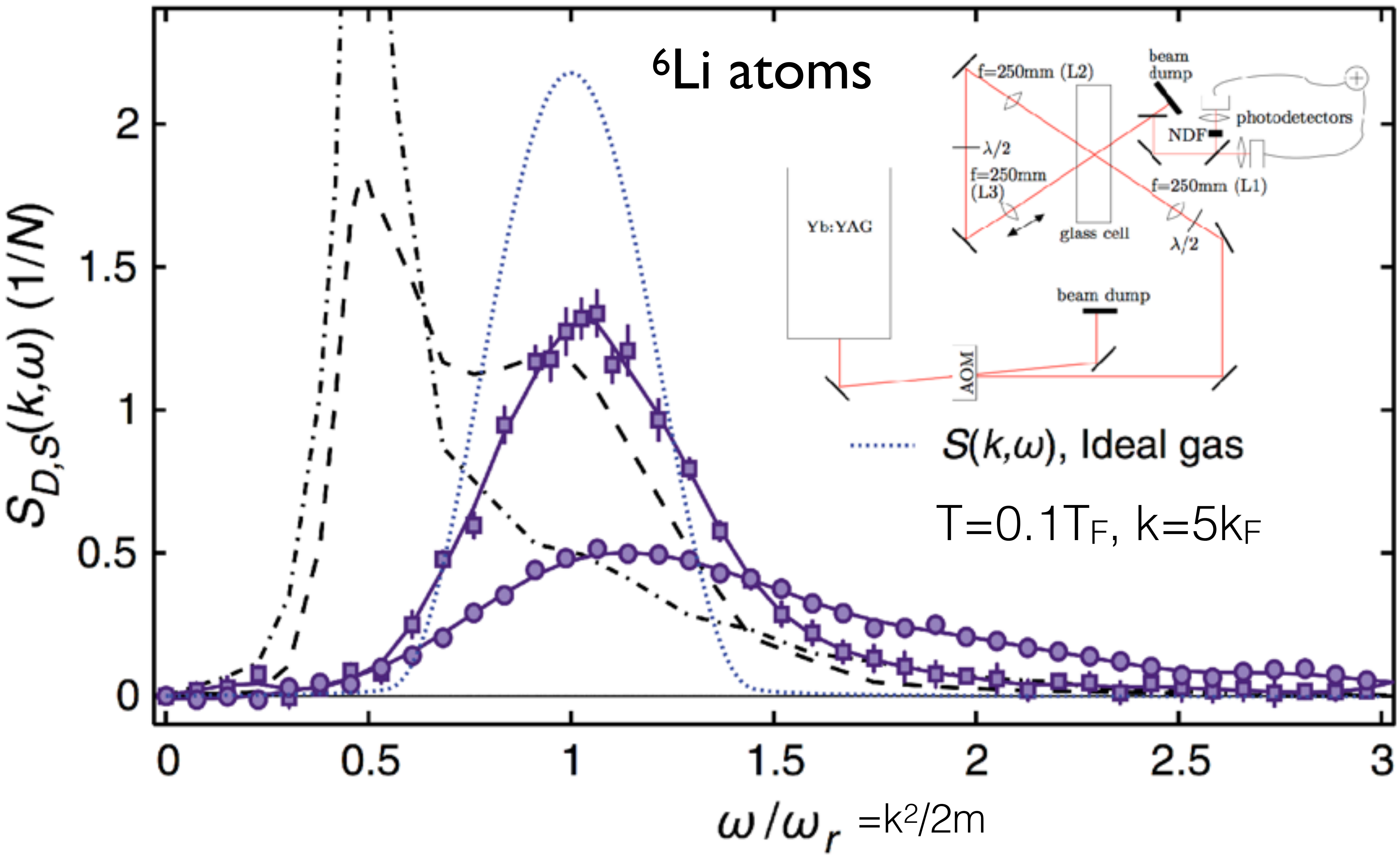
- Spin response <1 reduces scattering opacity.

- Effect may be important even at low $\sim 10^{12}$ g/cm^3 densities because of the large scattering length.

- Probably helps 2D (and 3D?) simulations explode perhaps somewhat earlier???

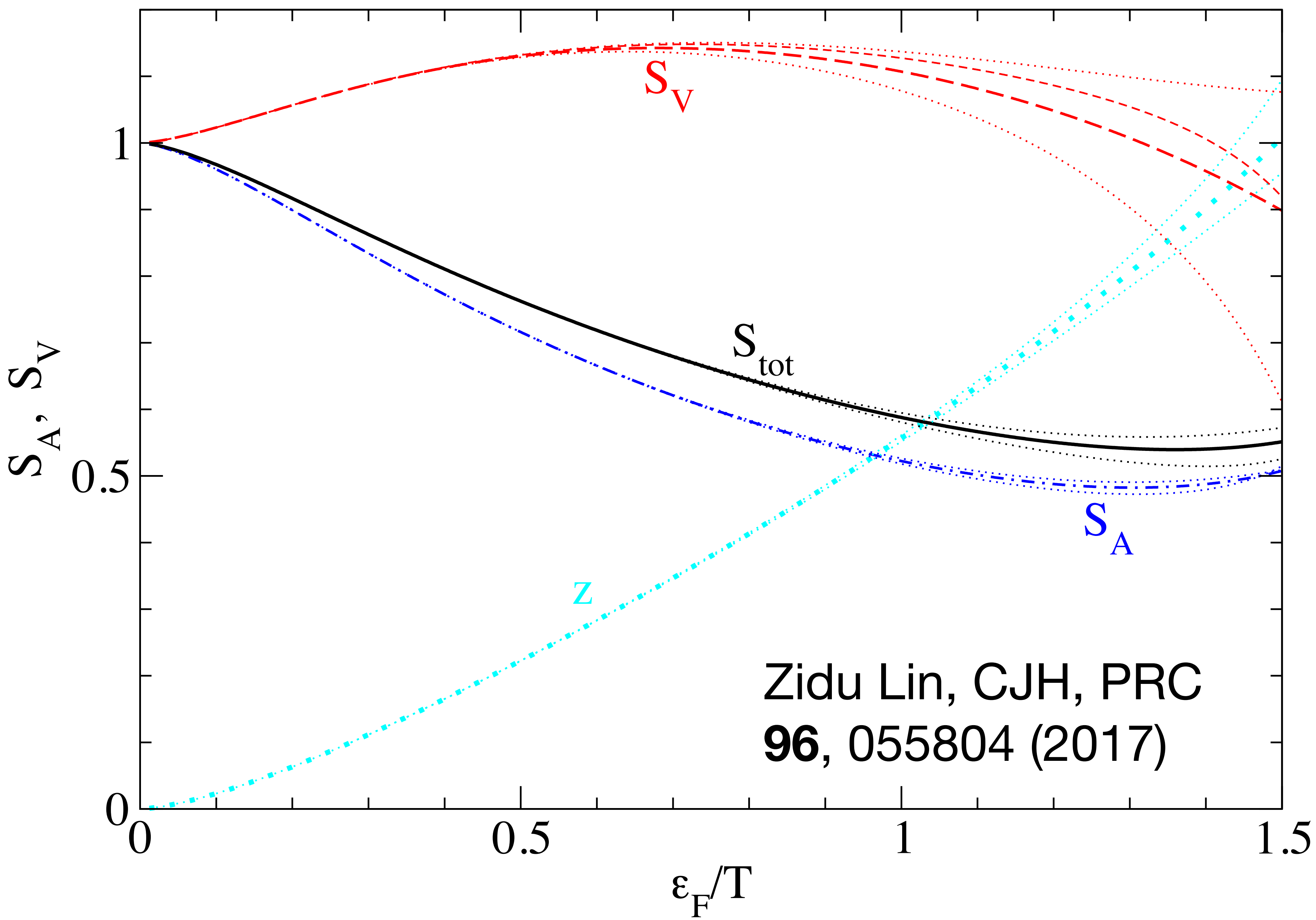


Dynamic Spin Response of a Strongly Interacting Fermi Gas [S. Hoinka, PRL **109**, 050403]

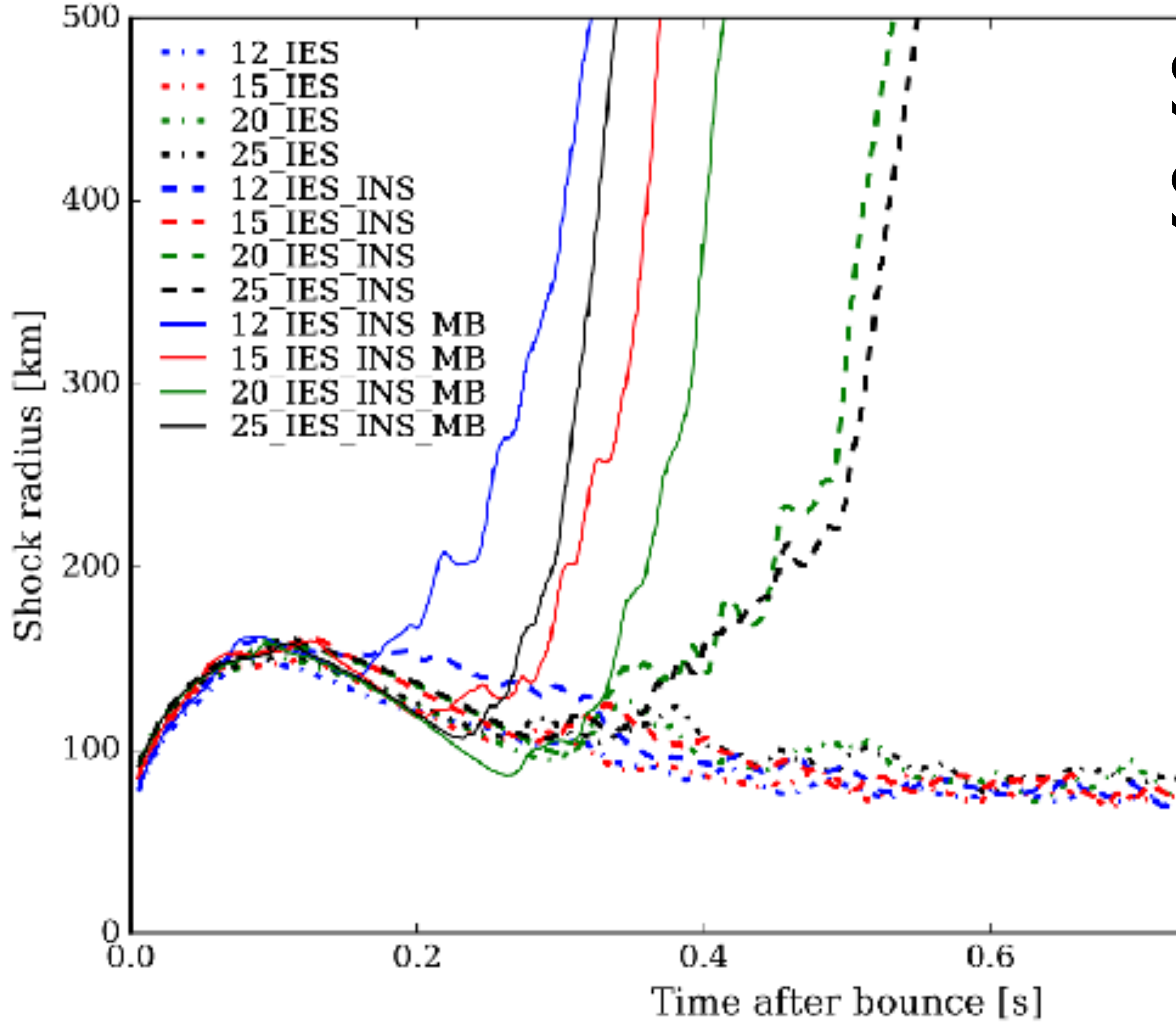


$S_A(k,w)$ is solid line and squares, while dashed line is $S_V(k,w)$.
Static structure factors: $S_V(k) = \int dw S_V(k,w)$, $S_A(k) = \int dw S_A(k,w)$

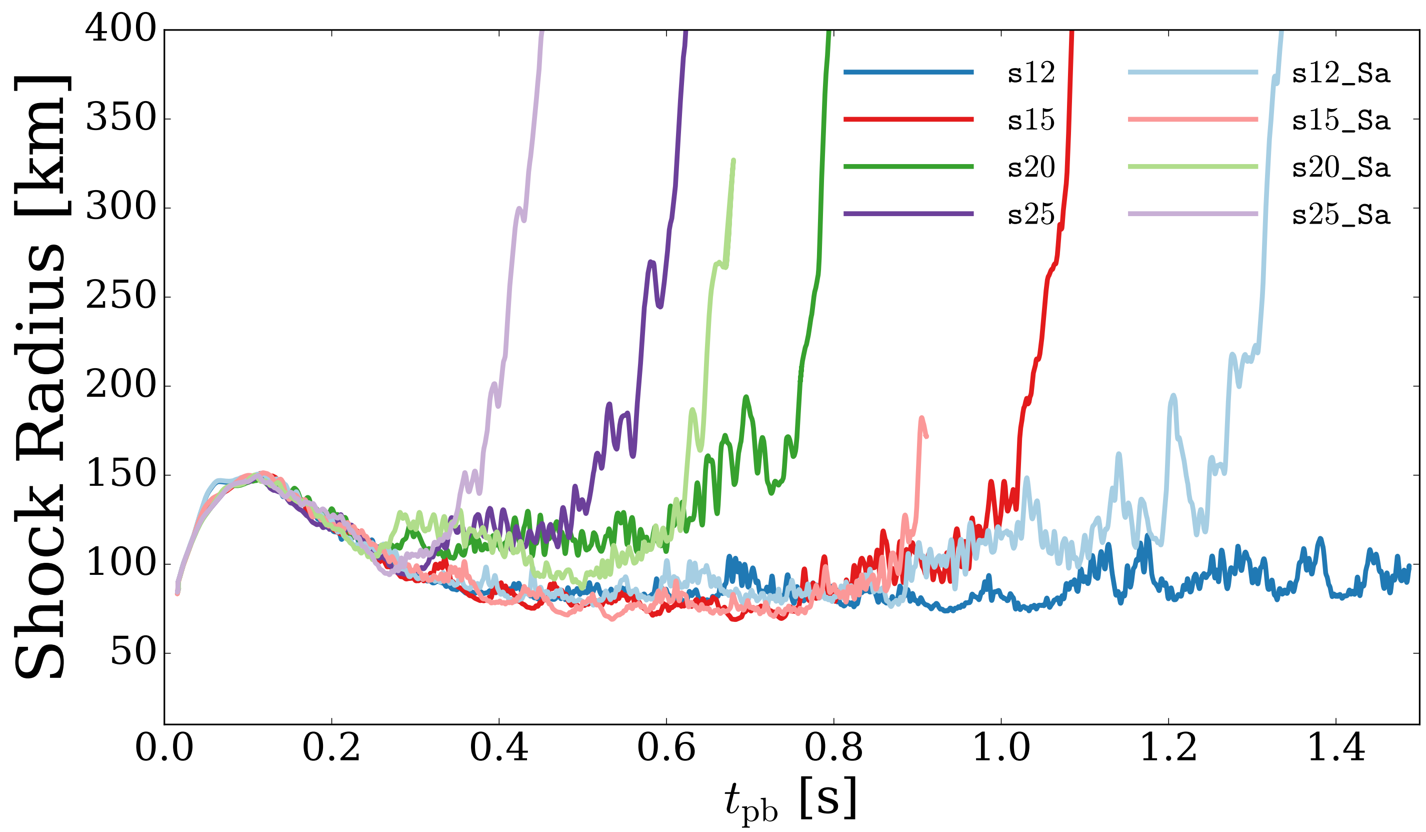
4th order Unitary results



Shock radius vs time for 2D SN simulations



All 2-D SN simulations by Burrows et al [arXiv: 1611.05859] with correlations (S_A<1) explode (solid lines) while 12 and 15 M_{sun} stars fail to explode, and 20, 25 M_{sun} explode later, without correlations (S_A=1).



Preliminary 2D SN simulations by Evan O'Connor for 12 to 25 M_{sun} stars explode earlier (lighter color) if correlations (S_A<1) included.

Sensitivity of SN dynamics motivates better treatments of neutrino interactions and NN correlations.