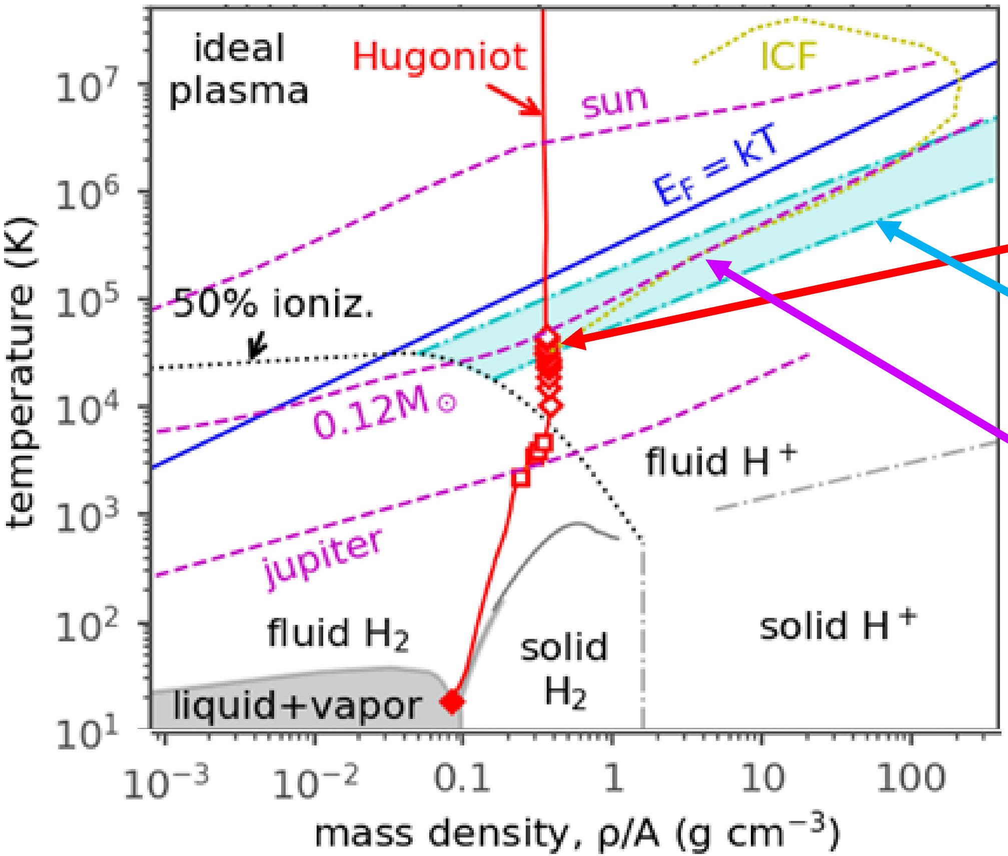
Hydrogen shock experiments and the structure of stars



Hydrogen phase diagram

1. Observed shock discrepancy
2. Conjectured regime of anomaly
3. Path of low-mass star (Proxima Centauri)

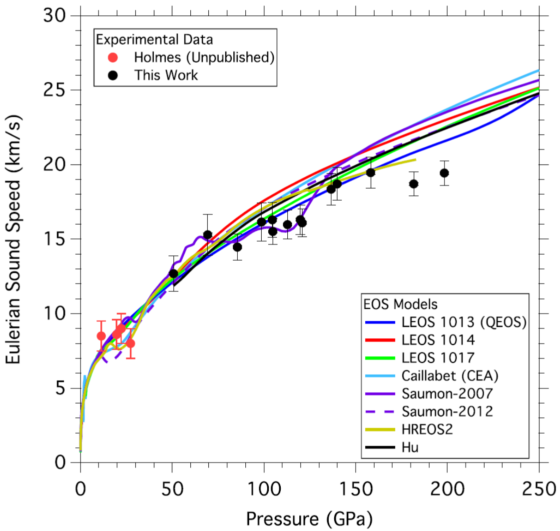
J. Ryan Rygg
University of Rochester
NIF User Group Meeting 2025

Outline

- Discrepancies between hydrogen shock experiments and theory
- A possible mechanism for the anomalous behavior
- Implications for stellar structure

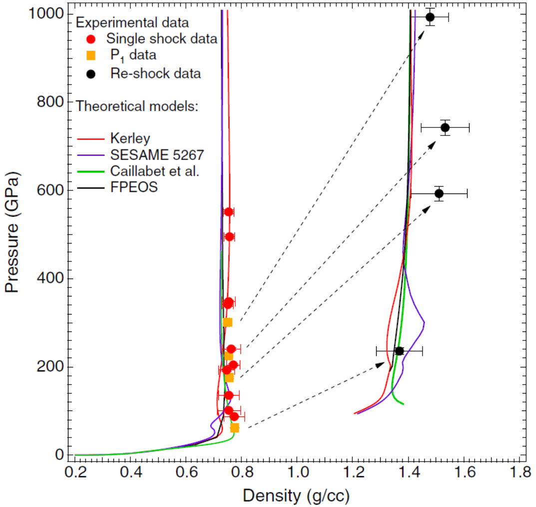
Three different experiments show unexpected behavior in deuterium shocked near 200 GPa

[1] sound speed



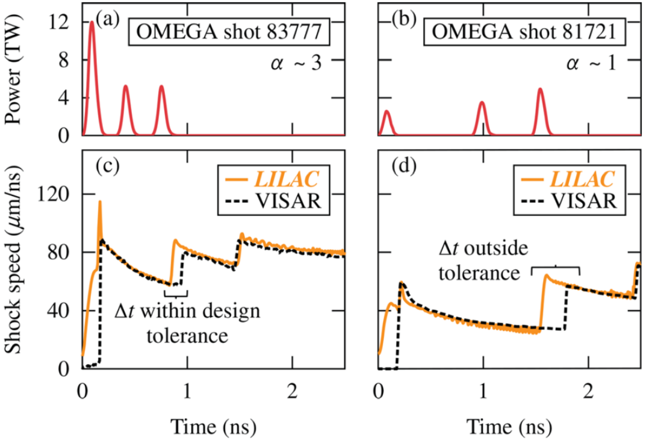
[1] D. E. Fratanduono et al POP (2019).

[2] reshock density



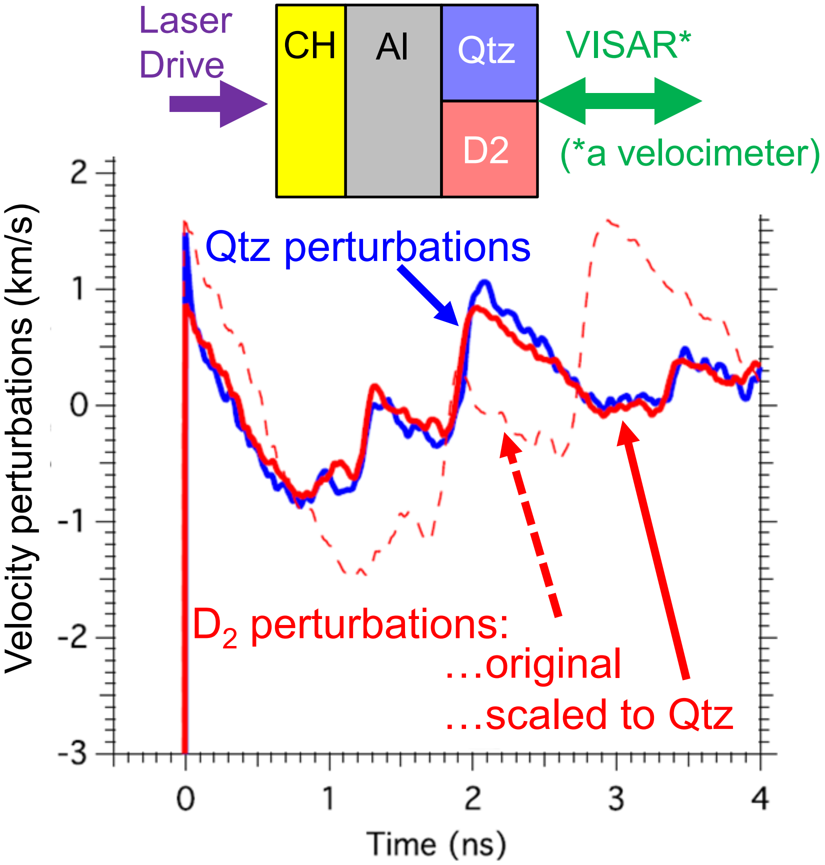
[2] A. Fernandez-Panella et al PRL (2019).

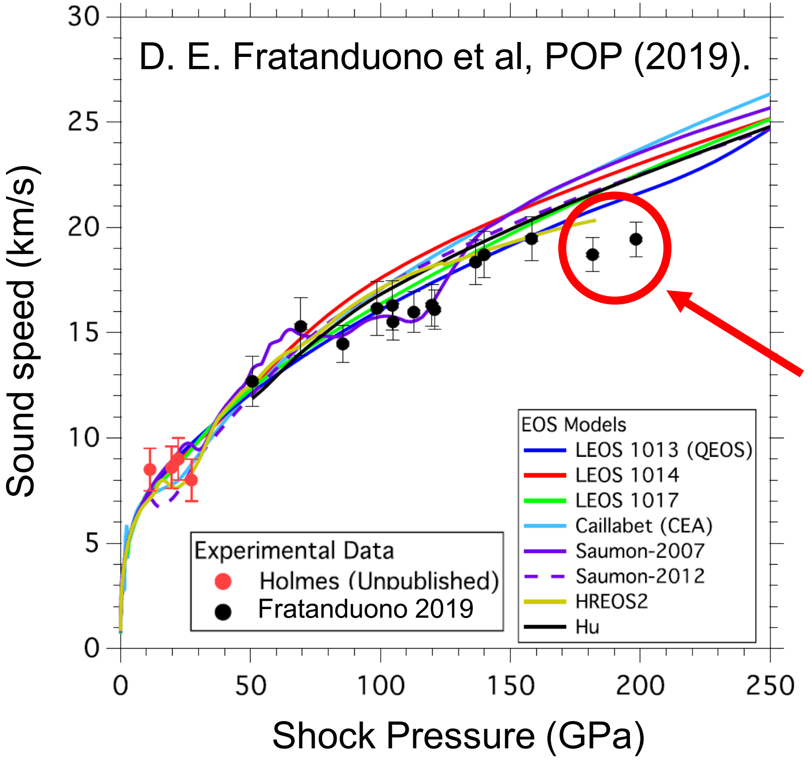
[3] shock coalescence time



[3] D. Cao et al POP (2018).

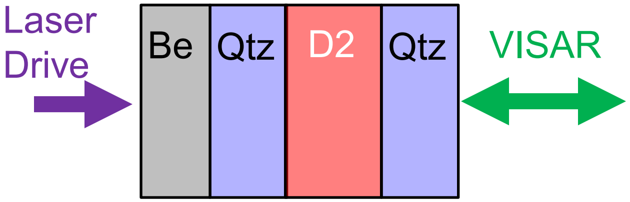
Experiment 1: sound speed in shocked deuterium

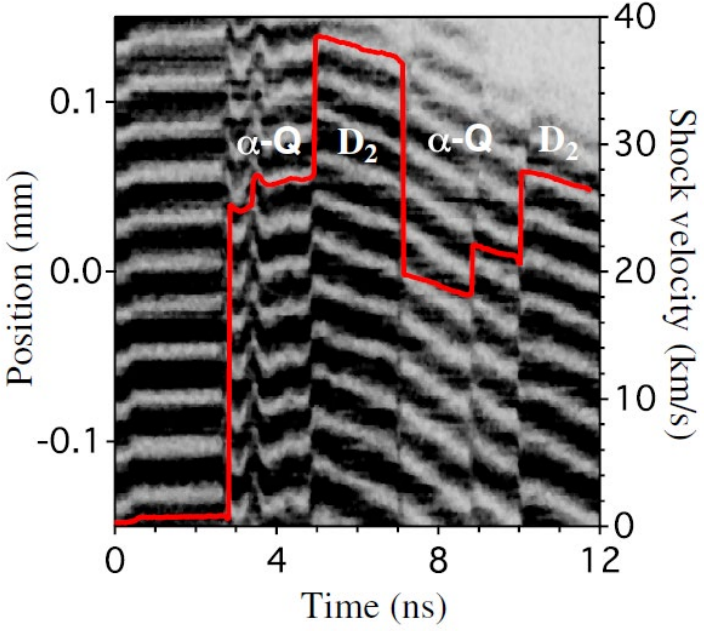




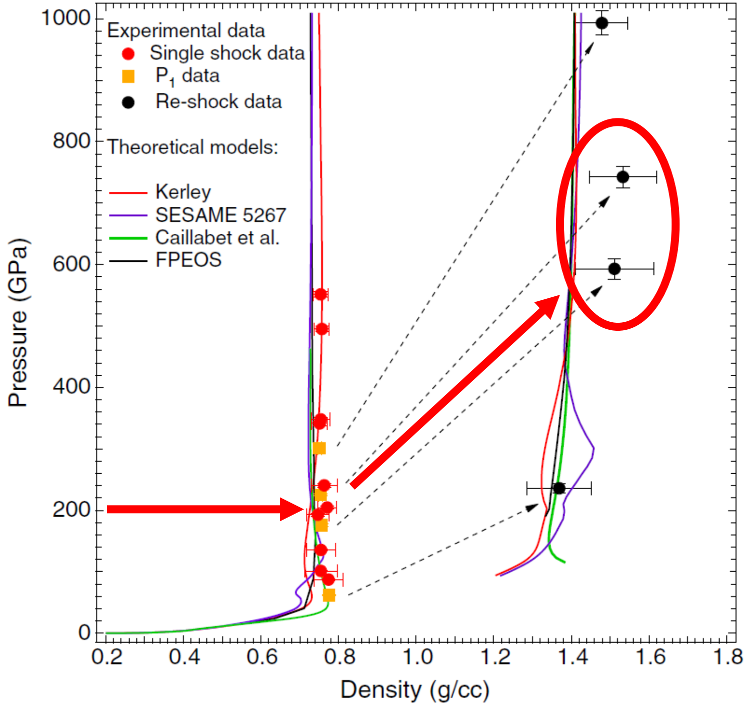
Sound speed in D_2 shocked to 200 GPa is lower than *all* theoretical models.

Experiment 2: reshock of deuterium on quartz



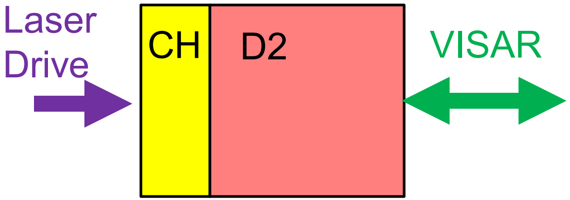


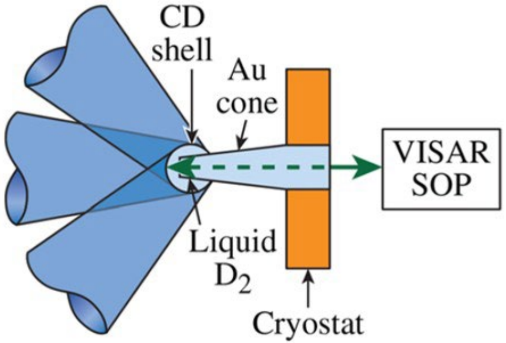
A. Fernandez-Panella et al, PRL (2019).

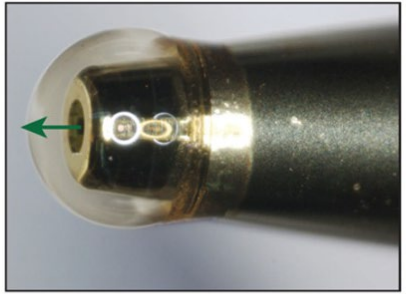


Deuterium shocked to 200 GPa reshocks to higher density than *all* theoretical models.

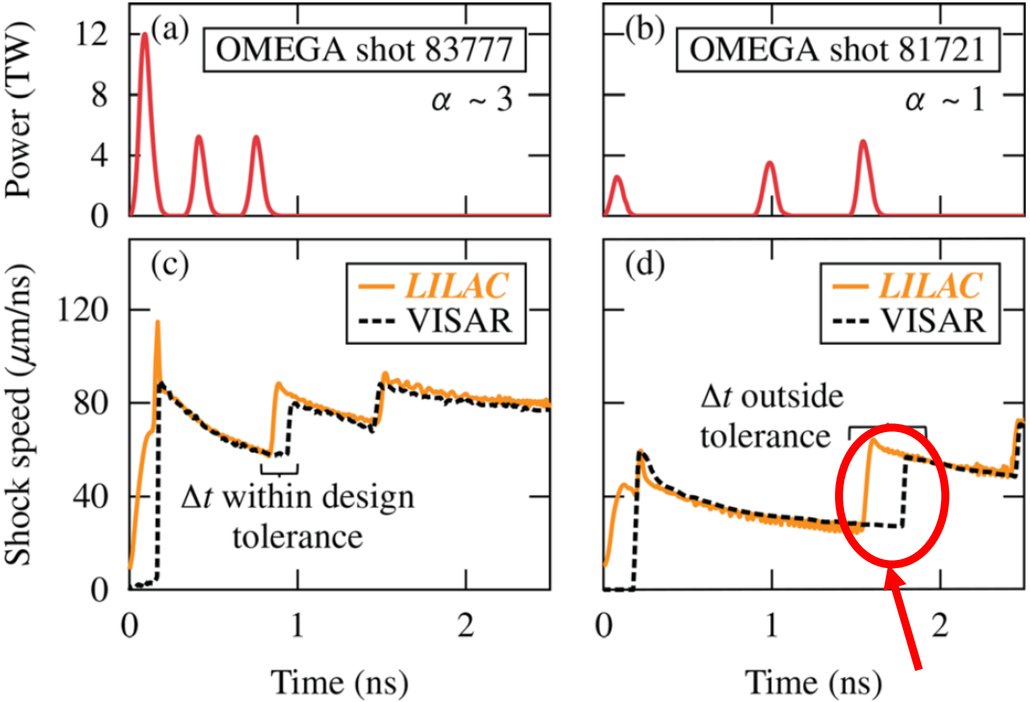
Experiment 3: shock coalescence in deuterium







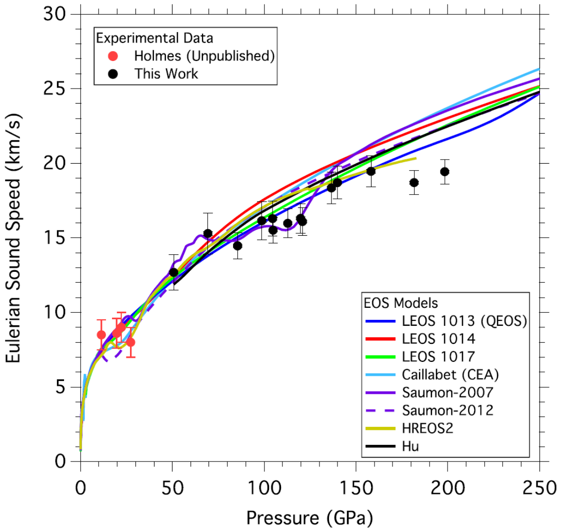
D. Cao et al, POP (2018).



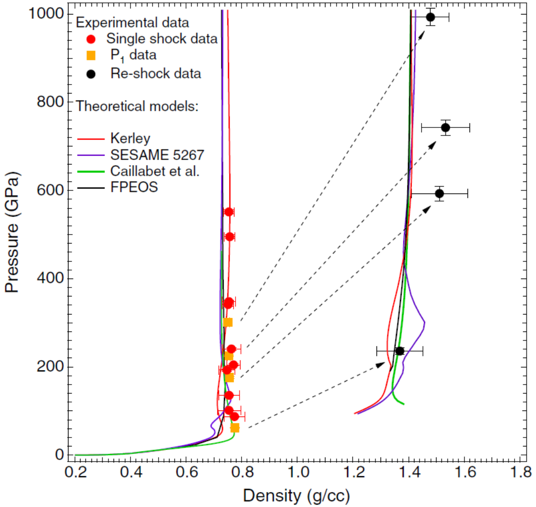
Shock coalescence is delayed compared to theory when first shock is ~40 km/s (200 GPa)

Three different experiments show unexpected behavior in deuterium shocked near 200 GPa

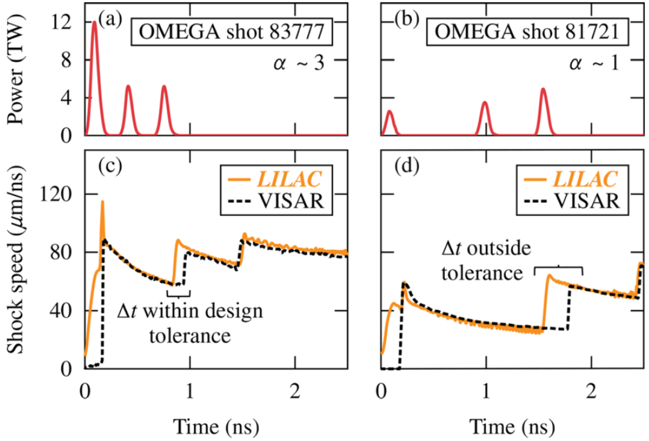
[1] sound speed



[2] reshock density



[3] shock coalescence time



Are the results of these different experiments consistent?
Are they connected?

Acoustic perturbation as the weak-shock limit

There are numerous ways to derive the sound speed c_s in a fluid. Let's look at the propagation of pressure perturbations moving at speed C.

Conservation of mass and momentum give

$$\rho_1 C = \rho_2 (C - u_2)$$
$$P_2 = P_1 + \rho_1 C u_2$$

These are the Rankine-Hugoniot "shock" equations.

Combine the equations, eliminate u_2, and solve for C

$$C^2 = \left(\frac{P_1}{\rho_1}\right) \frac{P_2/P_1 - 1}{1 - \rho_1/\rho_2}$$

Applies to the propagation of any pressure perturbation.

For isentropic perturbations in the weak-perturbation $(P_2 - P_1 \rightarrow 0)$ limit

$$c_s = \left(\frac{\partial P}{\partial \rho}\right)_S^{1/2}$$

Sound speed c_s corresponds to the slope of the isentrope in pressure-density space

Sound speed and the adiabatic index

The sound speed is an equation of state (EOS) derivative that is also related to the adiabatic index or “ratio of heat capacities”.

$$c_s = \left(\frac{\partial P}{\partial \rho}\right)_S^{1/2} = \left(\gamma_1 \frac{P}{\rho}\right)_S^{1/2}$$

For an ideal material, there is a single adiabatic index, but for non-ideal conditions such as warm dense matter (WDM), deviations arise due to the nature of the non-ideality.

$$\gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_S$$

First adiabatic index (related to sound speed)

$$1 - \frac{1}{\gamma_2} = \left(\frac{\partial \ln T}{\partial \ln P}\right)_S$$

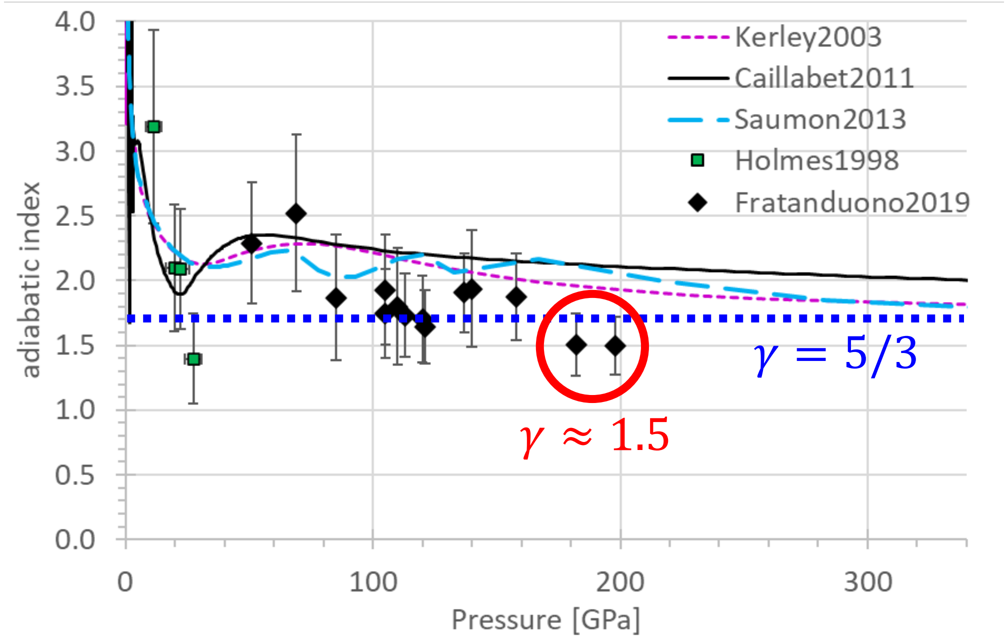
Second adiabatic index (related to adiabatic gradient and convection)

$$\gamma_3 - 1 = \left(\frac{\partial \ln T}{\partial \ln \rho}\right)_S$$

Third adiabatic index (related to Gruneisen parameter and shocks)

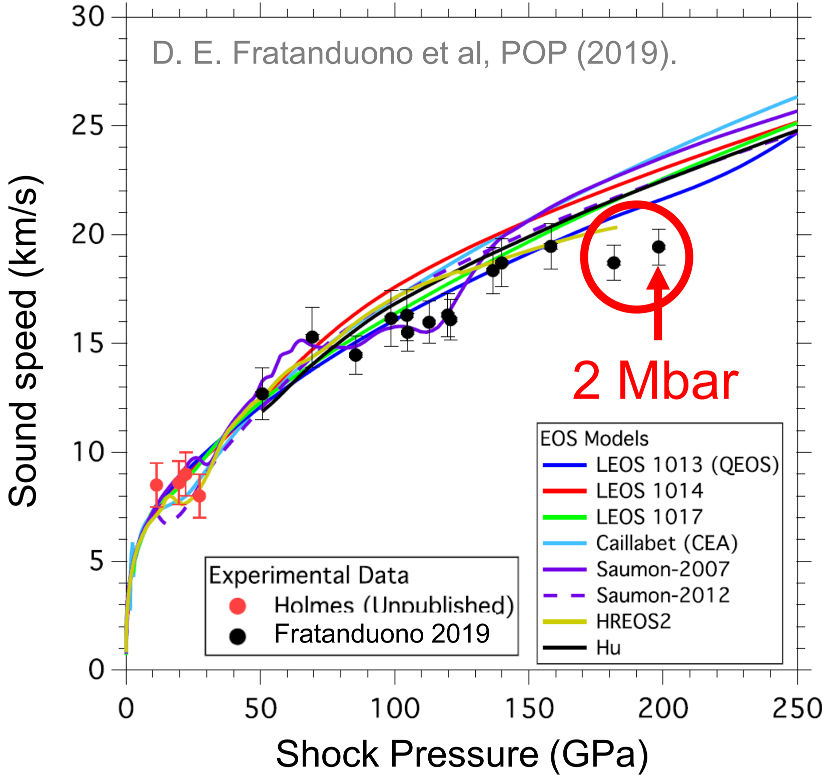
Again, $\gamma_1 = \gamma_2 = \gamma_3$ for an ideal material, but they remain connected for WDM and other non-ideal states.

Anomalous sound speed measurements suggest that the adiabatic index of the models is too high at 2 Mbar



$\gamma = 5/3$

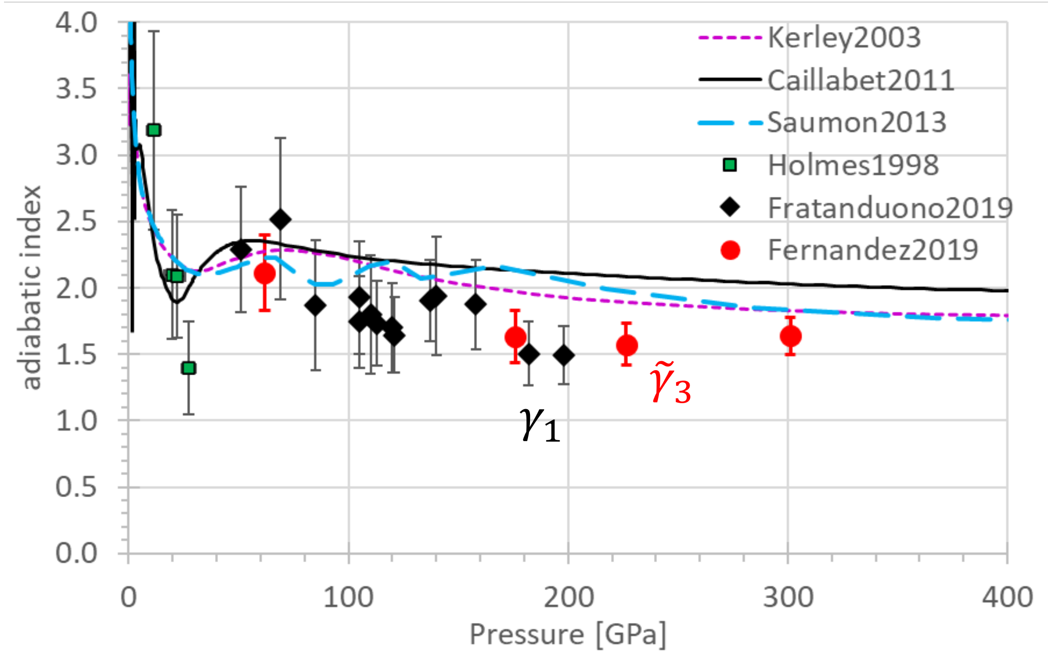
$\gamma \approx 1.5$



D. E. Fratanduono et al, POP (2019).

2 Mbar

Higher reshock compression implies lower (3rd) adiabatic index, consistent with sound speed results



The Rankine-Hugoniot energy relation is:

$$E_2 - E_1 = \frac{1}{2}(P_2 + P_1)\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right)$$

Thermodynamic identities allow us to obtain an equivalent expression for γ_3 related to the Hugoniot relation.

$$\gamma_3 - 1 = \left(\frac{\partial \ln T}{\partial \ln \rho}\right)_S = \frac{1}{\rho}\left(\frac{\partial P}{\partial E}\right)_\rho$$

For slowly-varying γ, we can deduce an effective adiabatic index $\tilde{\gamma}_3$ [Hicks et al 2009],

$$(\gamma_3 - 1)(E_2 - E_1) = \left(\frac{P_2}{\rho_2} - \frac{P_1}{\rho_1}\right)$$

(This is the 3rd adiabatic index γ_3, related to but not identical to γ_1)

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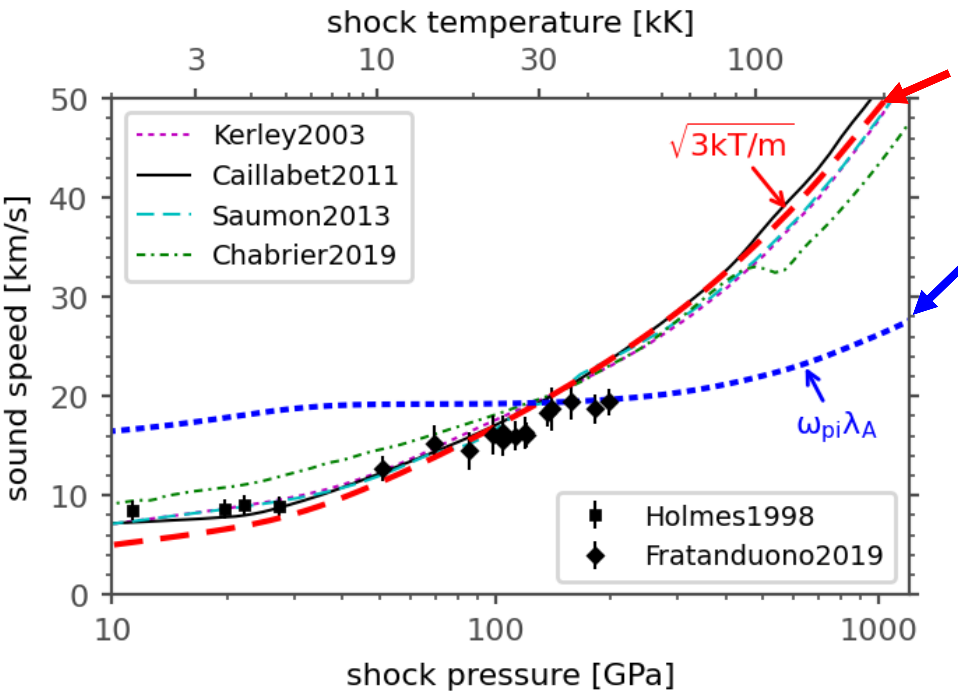
- A possible mechanism for the anomalous behavior
- Implications for stellar structure

What’s the mechanism for the anomalous sound speed? Perhaps an ion-acoustic resonance



Sound speed due to thermal pressure

Ion acoustic wave group and phase velocity*

$$\omega_{pi}\lambda_A = \sqrt{\frac{kT}{m_i}}\left(\left[1+\left(\frac{2}{3}\Theta\right)^2\right]^{-0.5} + \frac{1}{1+3\Gamma_{ii}}\right)^{-1/2}$$

Corrections for WDM:

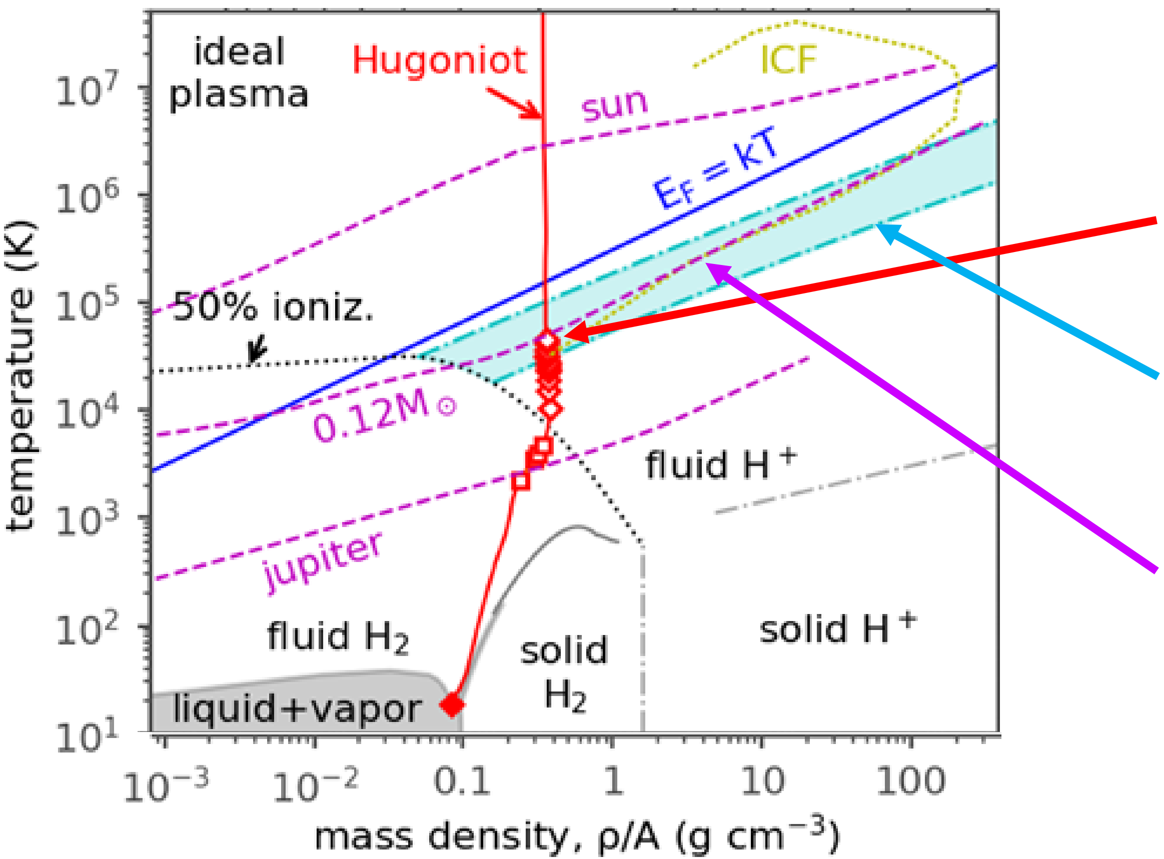
Degeneracy: $\Theta = \frac{E_F}{kT} = \frac{\hbar^2}{2m_e kT}\left(3\pi^2 n_e\right)^{2/3}$

Coupling: $\Gamma_{ii} = \frac{E_{Ci}}{kT} = \frac{(Ze)^2}{4\pi\varepsilon_0 kT}\left(\frac{4\pi}{3}n_i\right)^{1/3}$

This mechanism allows us to predict the thermodynamic conditions where this anomalous behavior will occur.

*WDM screening from Stanton+Murillo, PRE (2016)

Anomalous behavior relevant to some low-mass stars



Hydrogen phase diagram

1. Observed shock sound speed discrepancy
2. Conjectured regime of anomaly (electrostatic wave)
3. Path of low-mass star (Proxima Centauri)

Outline

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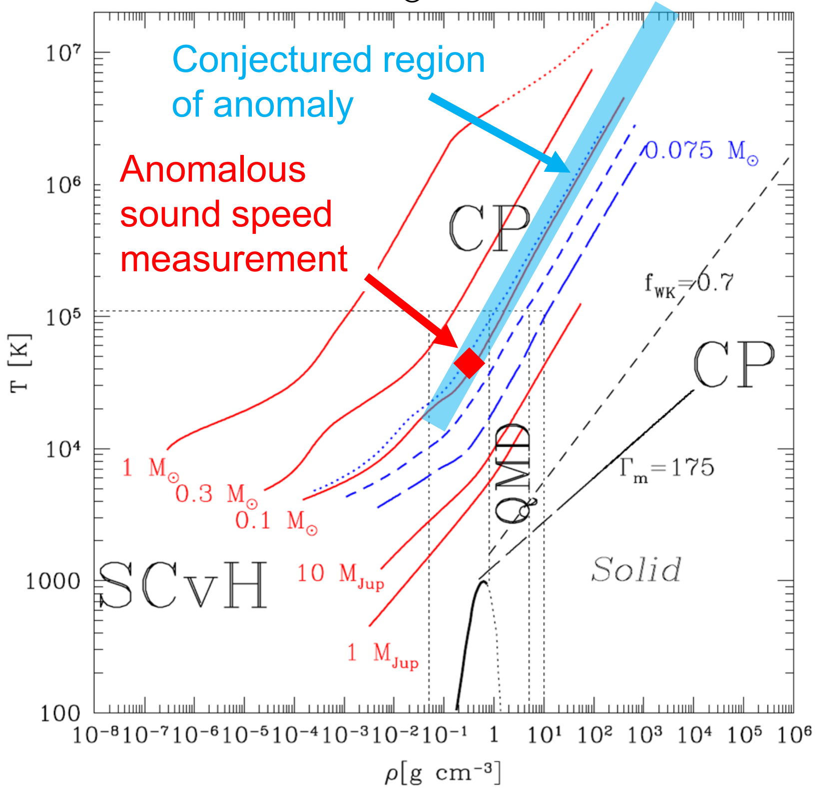
The observed anomaly and conjectured extension intersect with some low-mass main sequence stars

Interiors of 0.1-1 $M_\odot$ main sequence stars*



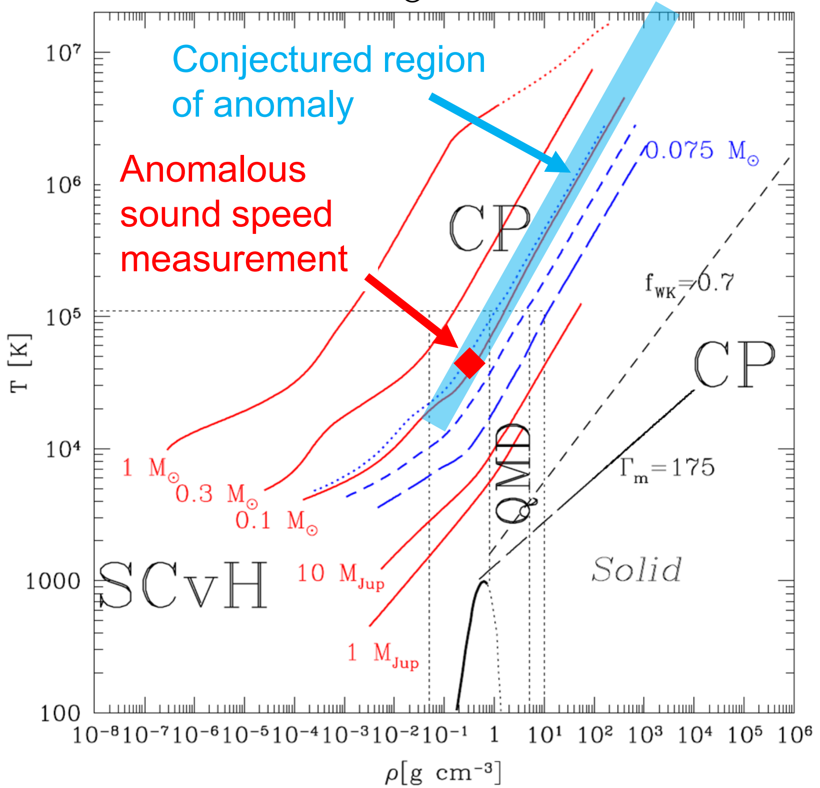
Conjectured region of anomaly

Anomalous sound speed measurement

*G. Chabrier et al, AA (2023)

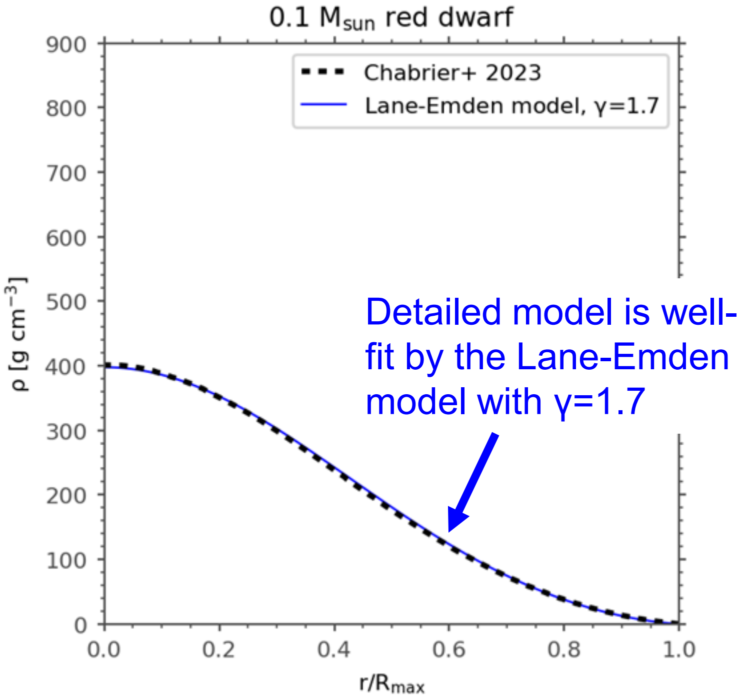
The overall structure of these fully-convective low-mass stars is well fit with a simple Lane-Emden model

Interiors of 0.1-1 $M_\odot$ main sequence stars*



Conjectured region of anomaly

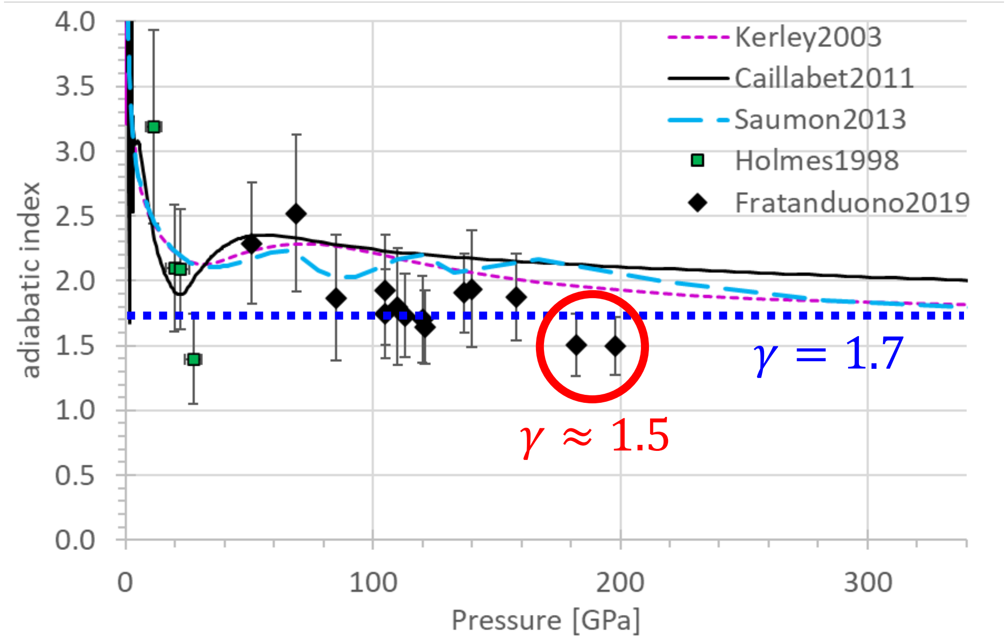
Anomalous sound speed measurement



Detailed model is well-fit by the Lane-Emden model with $\gamma=1.7$

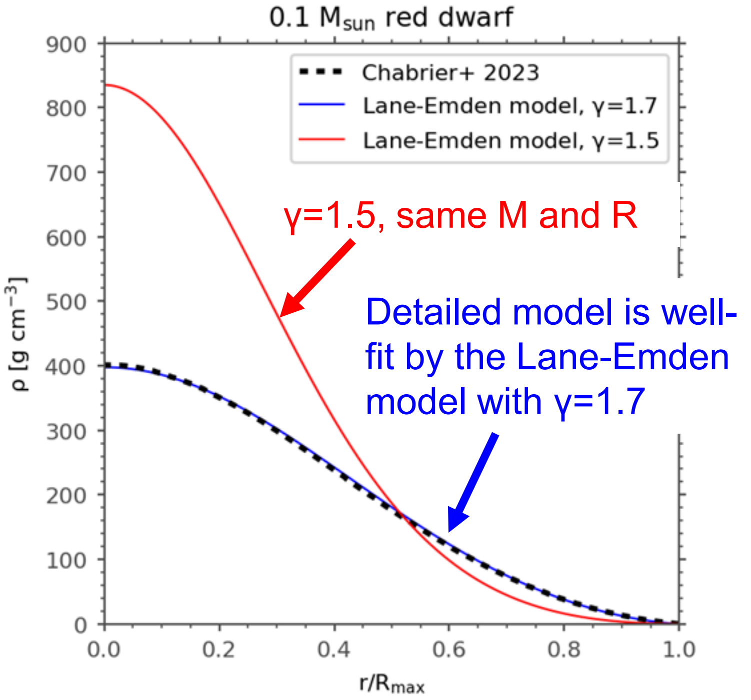
*G. Chabrier et al, AA (2023)

Even a slightly lower adiabatic index has profound impact on the internal structure



$\gamma = 1.7$

$\gamma \approx 1.5$



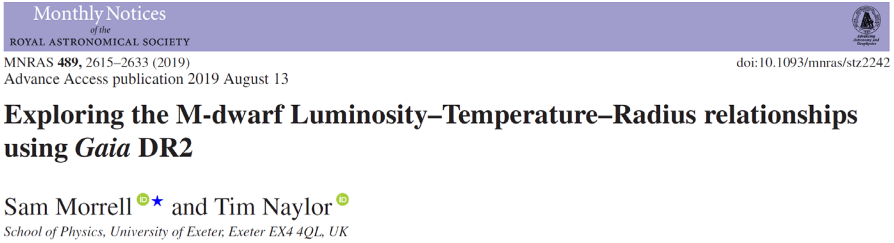
γ=1.5, same M and R

Detailed model is well-fit by the Lane-Emden model with γ=1.7

Incorrect EOS can be compensated by adjusting other model parameters, e.g., opacity, ionization, reactivity, etc

*G. Chabrier et al, AA (2023)

Can better γ resolve discrepancies in low-mass stars?

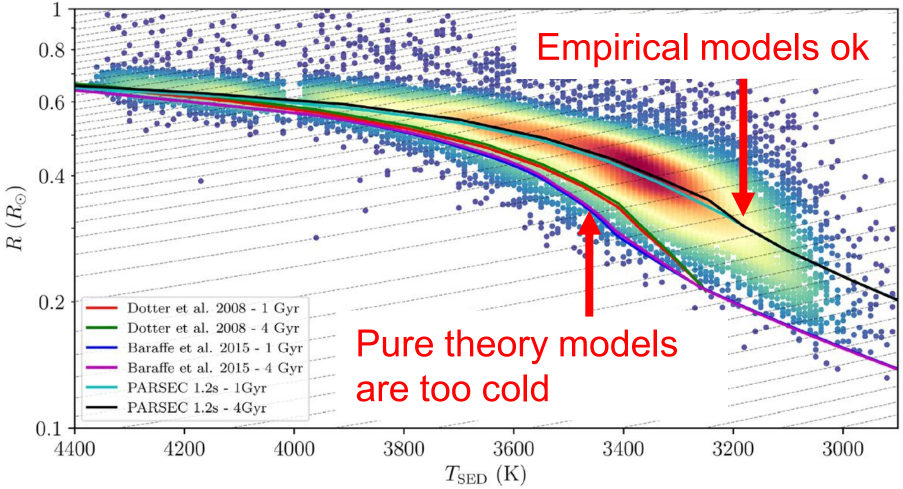


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **489,** 2615–2633 (2019) doi:10.1093/mnras/stz2242
Advance Access publication 2019 August 13

Exploring the M-dwarf Luminosity–Temperature–Radius relationships using *Gaia* DR2

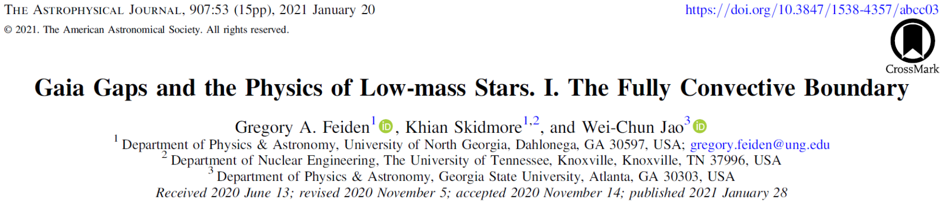
Sam Morrell ★ and Tim Naylor
School of Physics, University of Exeter, Exeter EX4 4QL, UK

ABSTRACT: There is growing evidence that M-dwarf stars suffer radius inflation when compared to theoretical models, suggesting that models are missing some key physics required to completely describe stars at effective temperatures less than about 4000 K….



Empirical models ok

Pure theory models are too cold

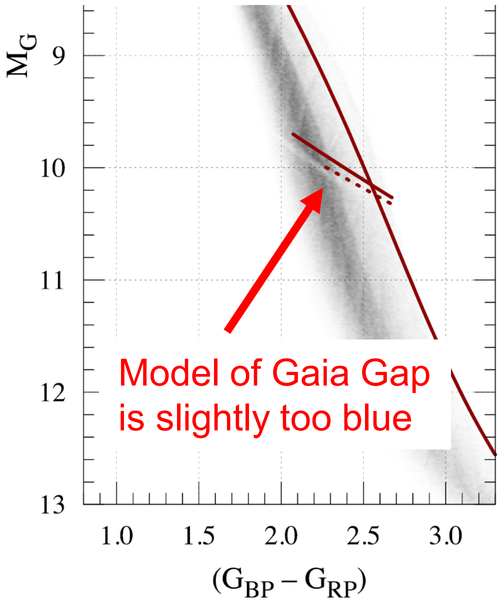


The Astrophysical Journal, 907:53 (15pp), 2021 January 20 https://doi.org/10.3847/1538-4357/abcc03

Gaia Gaps and the Physics of Low-mass Stars. I. The Fully Convective Boundary

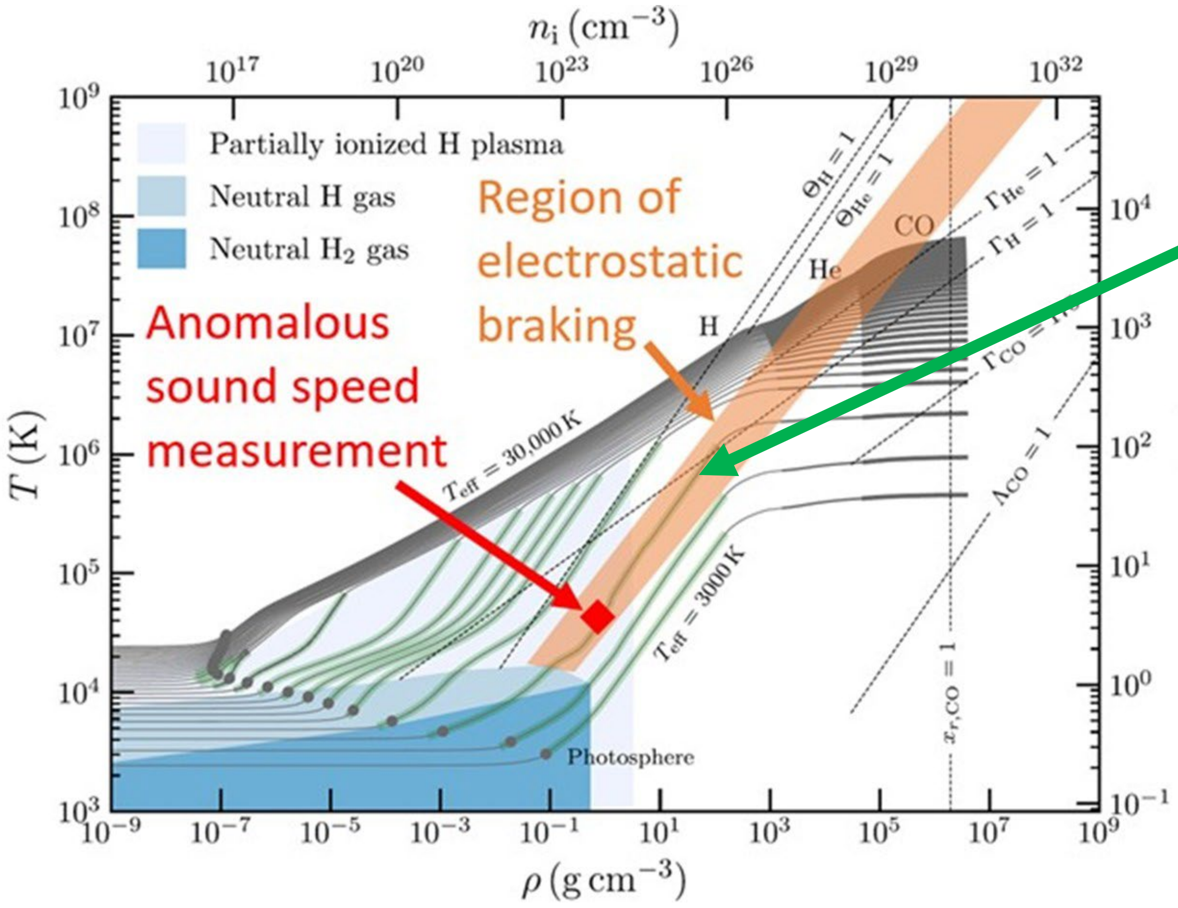
Gregory A. Feiden[1], Khian Skidmore[1,2], and Wei-Chun Jao[3]
[1] Department of Physics & Astronomy, University of North Georgia, Dahlonega, GA 30597, USA; gregory.feiden@ung.edu
[2] Department of Nuclear Engineering, The University of Tennessee, Knoxville, Knoxville, TN 37996, USA
[3] Department of Physics & Astronomy, Georgia State University, Atlanta, GA 30303, USA
Received 2020 June 13; revised 2020 November 5; accepted 2020 November 14; published 2021 January 28

ABSTRACT…While qualitatively similar, the synthetic gap is approximately 0.2 magnitudes bluer, and when this color offset is accounted for, it is 0.16 magnitudes brighter than the observed gap. Our results reveal that the Gaia M-dwarf gap is sensitive to conditions within cores of M-dwarf stars, making the gap a powerful tool for testing the physics of M-dwarf stars and potentially using M dwarfs to understand the local star formation history.



Model of Gaia Gap is slightly too blue

Anomalous sound speed affects white dwarf cooling



Region of electrostatic braking

Anomalous sound speed measurement

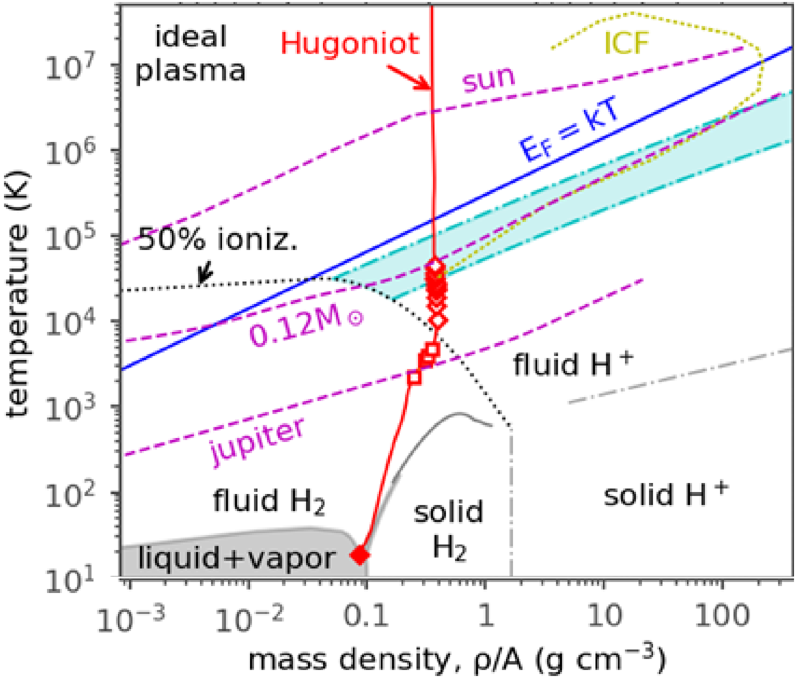
Green: structure and cooling dominated by convection

Convective profile tied to 2nd adiabatic index:

$$1-\frac{1}{\gamma_2}=\left(\frac{\partial \ln T}{\partial \ln P}\right)_S$$

D. Saumon et al, Phys, Rep (2023).

Better understanding can be achieved combining laser experiments, theory models, and astronomy observations



- Laser shock experiments have revealed a systematic difference with *all* theoretical hydrogen equation of state (EOS) models
- These thermodynamic conditions intersect many astrophysical objects such as red and white dwarf stars
- Such an EOS discrepancy suggests it is worthwhile to revisit the assumptions used to construct our models for stellar structure and evolution

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