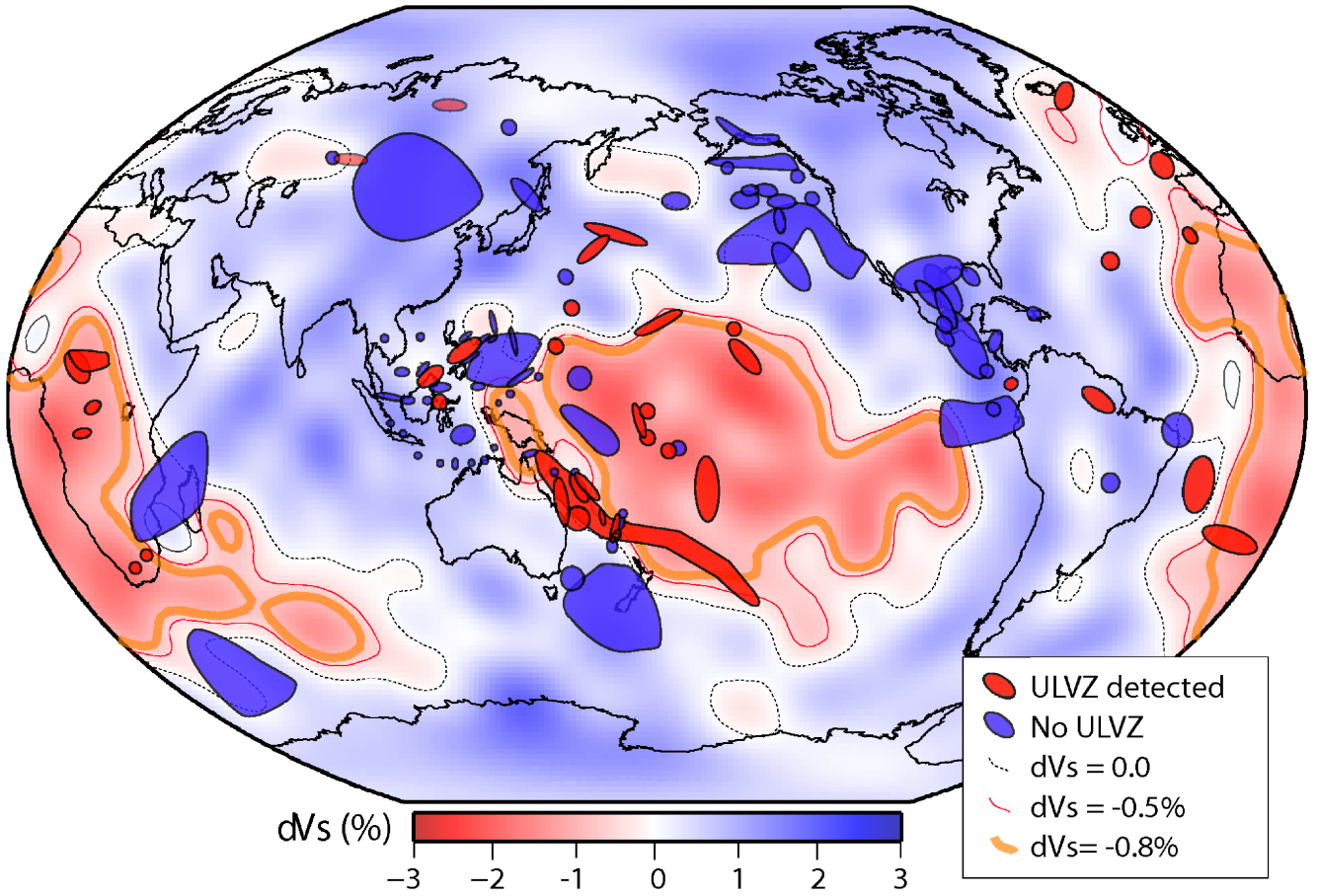
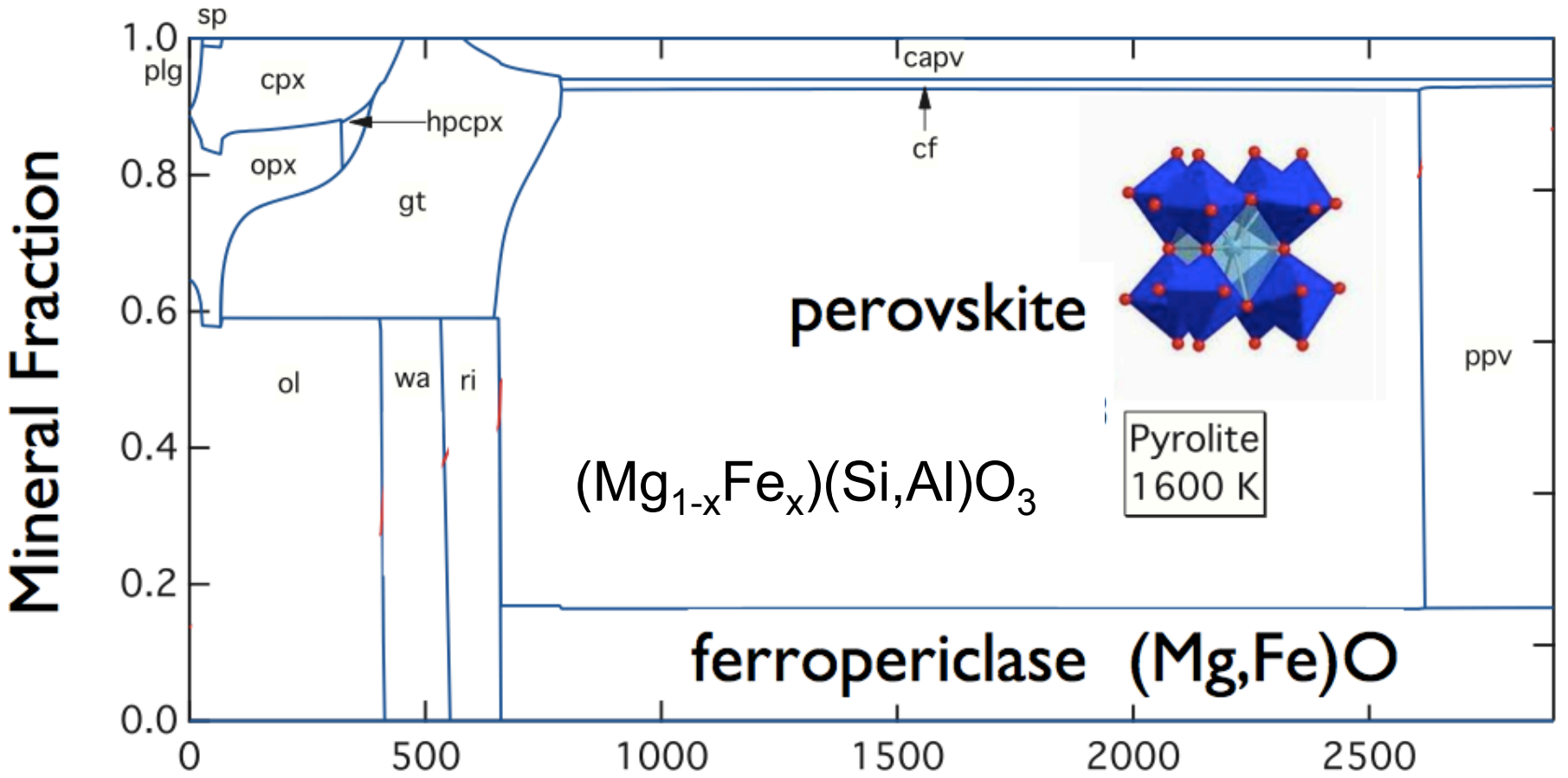
Distributions of ultra-low velocity zones (ULVZs)



McNamara *et al. EPSL* 2010

- Slow
  - ~10 to 30% drop in V_S
  - ~5 to 20% drop in V_P
- Variable
  - V_P/V_S range ~1 to 5
  - Not well-constrained
- Density Constrained?

Major minerals in Earth's mantle



Stixrude & Lithgow-Bertelloni (2005)

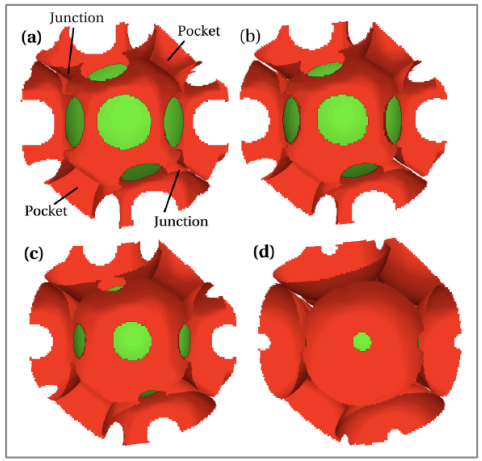
$0.05 \leq x \leq 0.35$

$Fe^{2+,3+}$
spin state

Explanations of low velocities in ULVZs

Partially Molten ULVZ

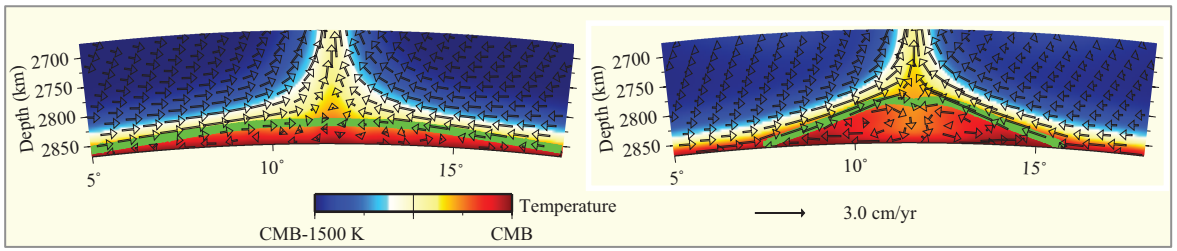
- Increased melt fraction → lower velocities
- How to make dense enough melts?
  - Shock melting on Mg-Fe silicates indicate melts are not dense enough to stick around (Thomas *et al.* 2012)
- How to maintain enough melt 10s of km high?



Wimert and Hier-Majumder, 2012

Solid ULVZ

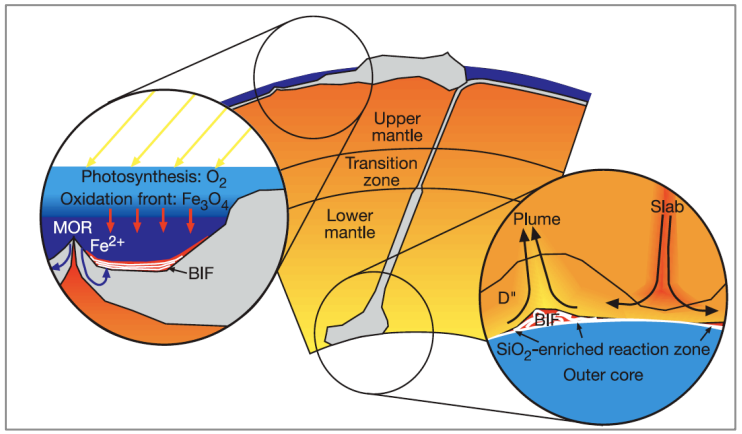
- Increased iron content → lower velocities
- Relationship between sound velocity and density?
  - Iron-rich post-perovskite (Mao *et al.*, 2004)
- How to decrease velocities without making it too dense?
  - Iron-rich (Mg,Fe)O (this study)



Bower *et al. EPSL* 2011

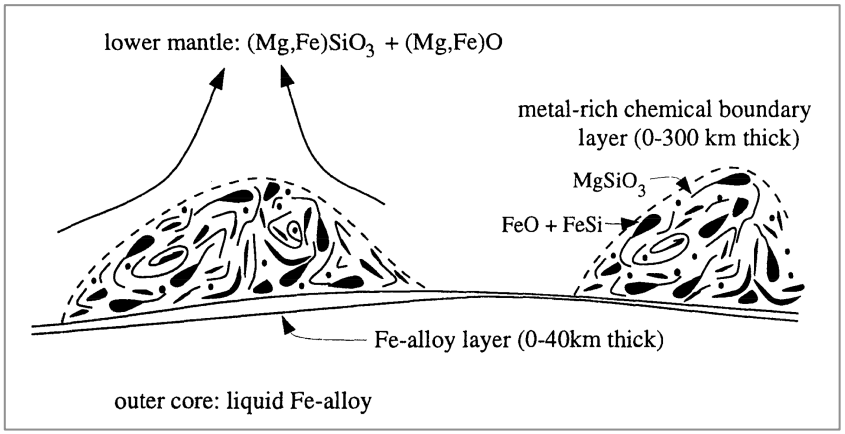
Formation mechanisms suggested for ULVZs

Dense, subducted material



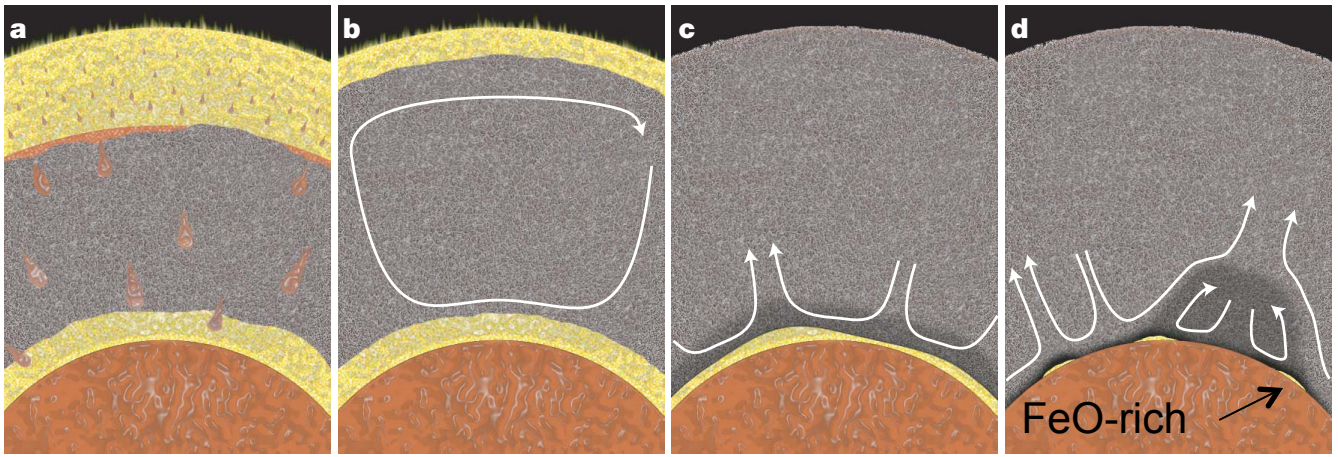
Dobson and Brodholt (2005)

Interaction with the core



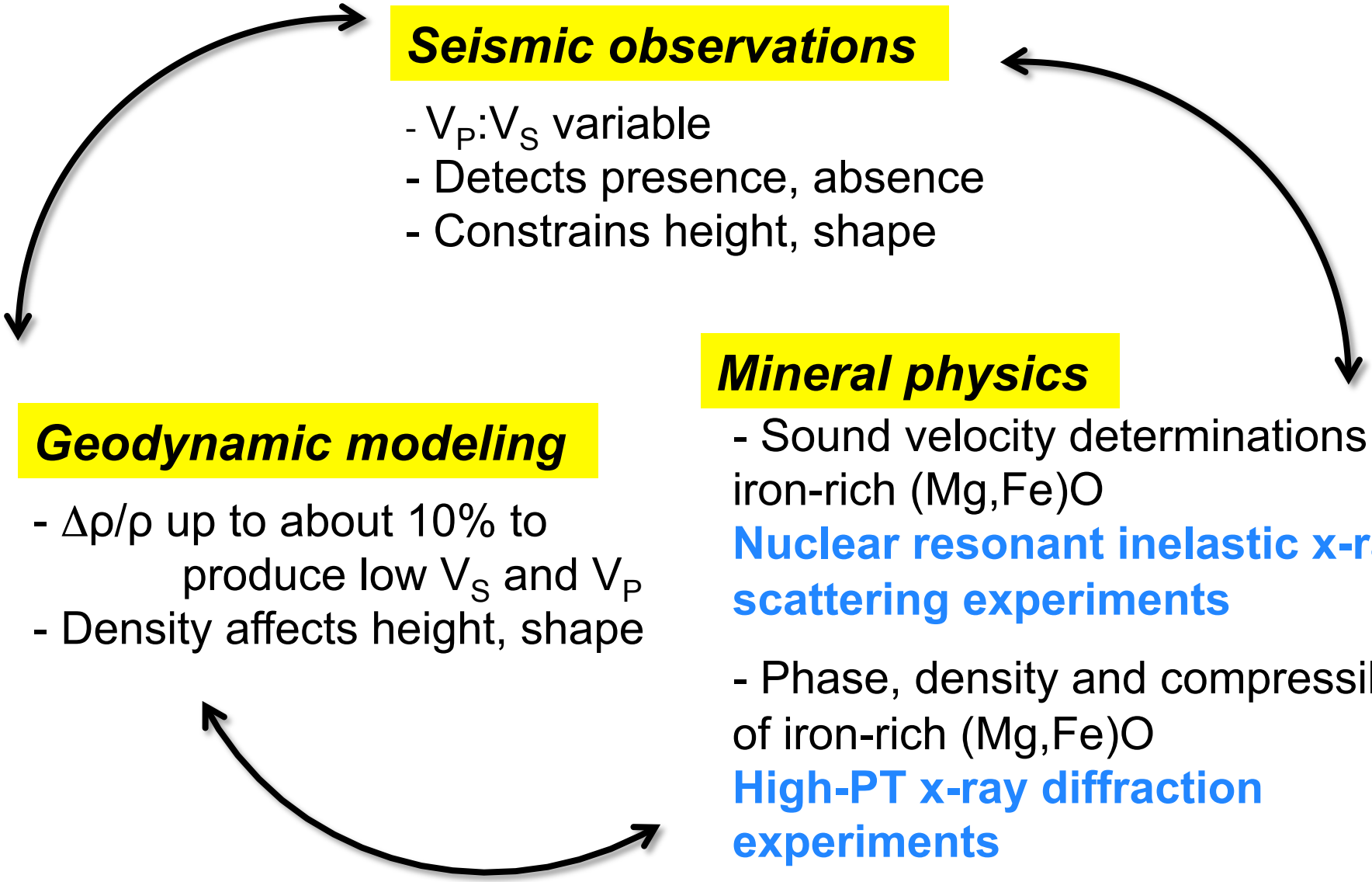
Manga and Jeanloz (1996)
Otsuka & Karato (2012)

Residues of a crystallizing magma ocean

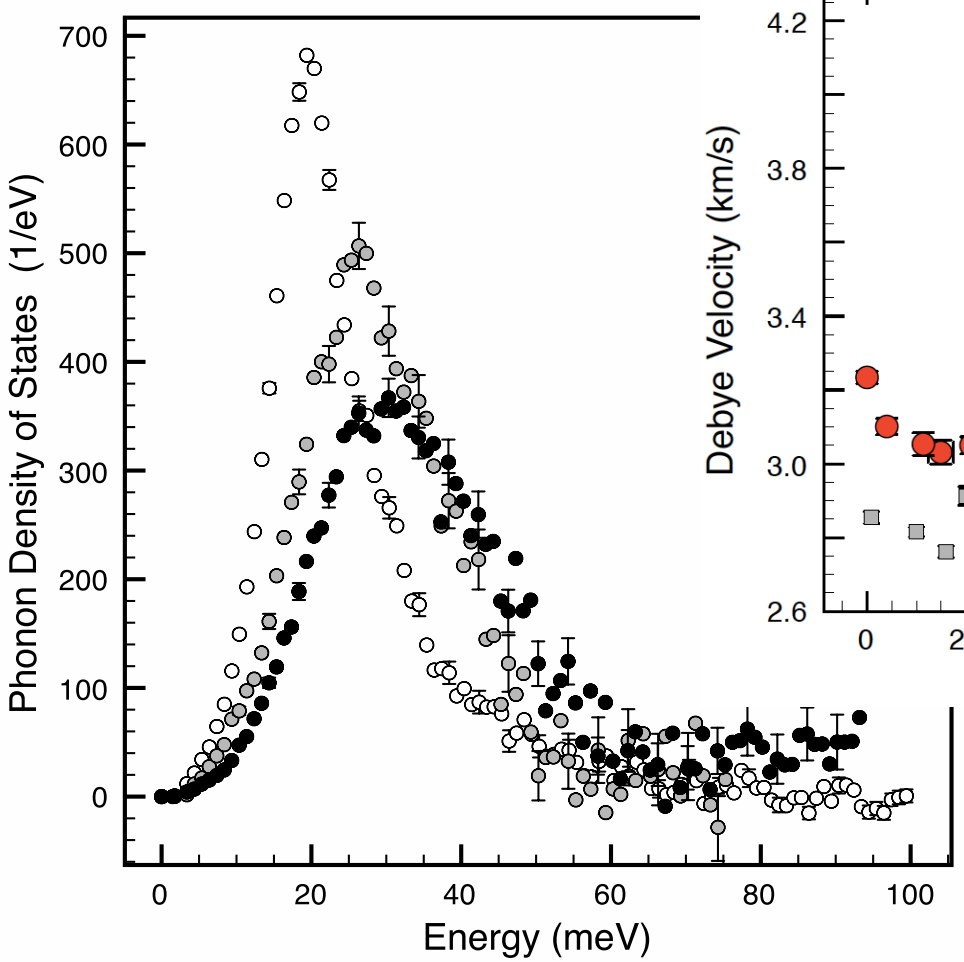


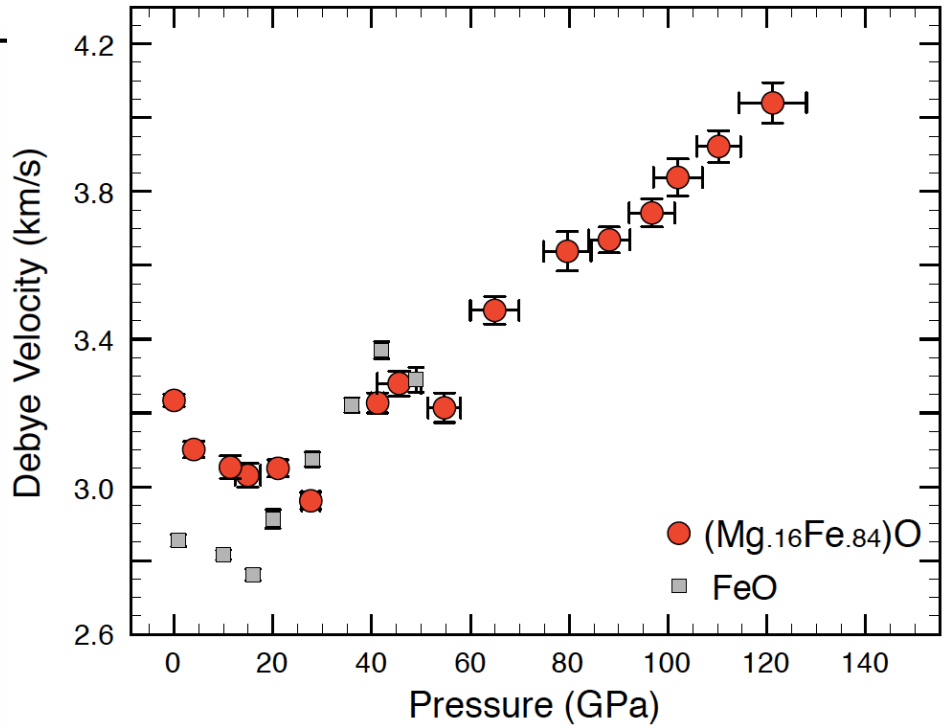
Labrosse et al. (2007)

Approach to investigate ULVZs



Partial phonon density of states of $(Mg_{0.16}Fe_{0.84})O$, "iron-rich"





Wicks, Jackson, Sturhahn. (*GRL* 2010)

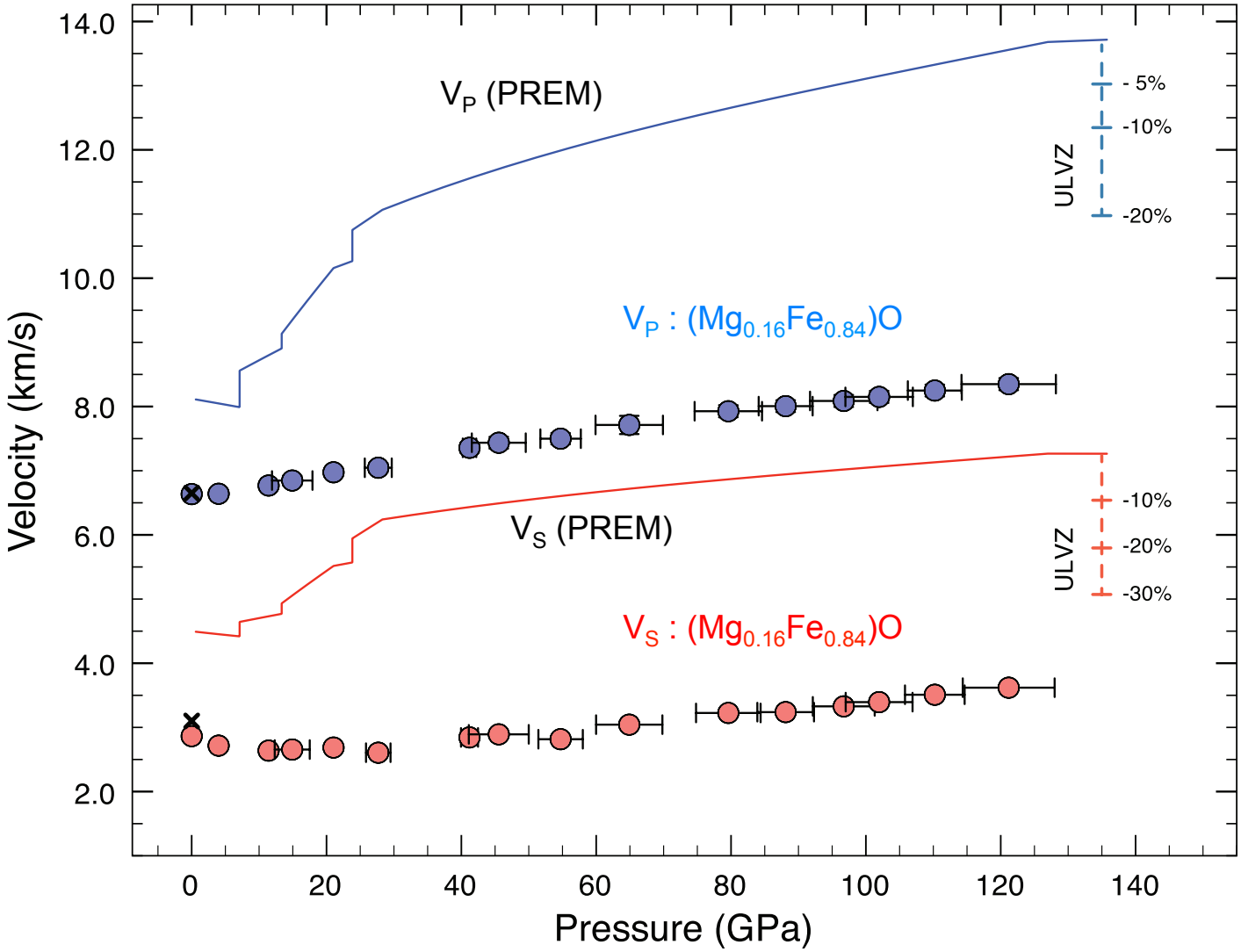
$$D(E \to 0) = \frac{m}{2\pi^2 \hbar^3 \rho} \frac{E^2}{v_D^3}$$

$$\frac{3}{V_D^3} = \frac{1}{V_P^3} + \frac{2}{V_S^3}$$

$$\frac{K_S}{\rho} = V_P^2 - \frac{4}{3} V_S^2$$

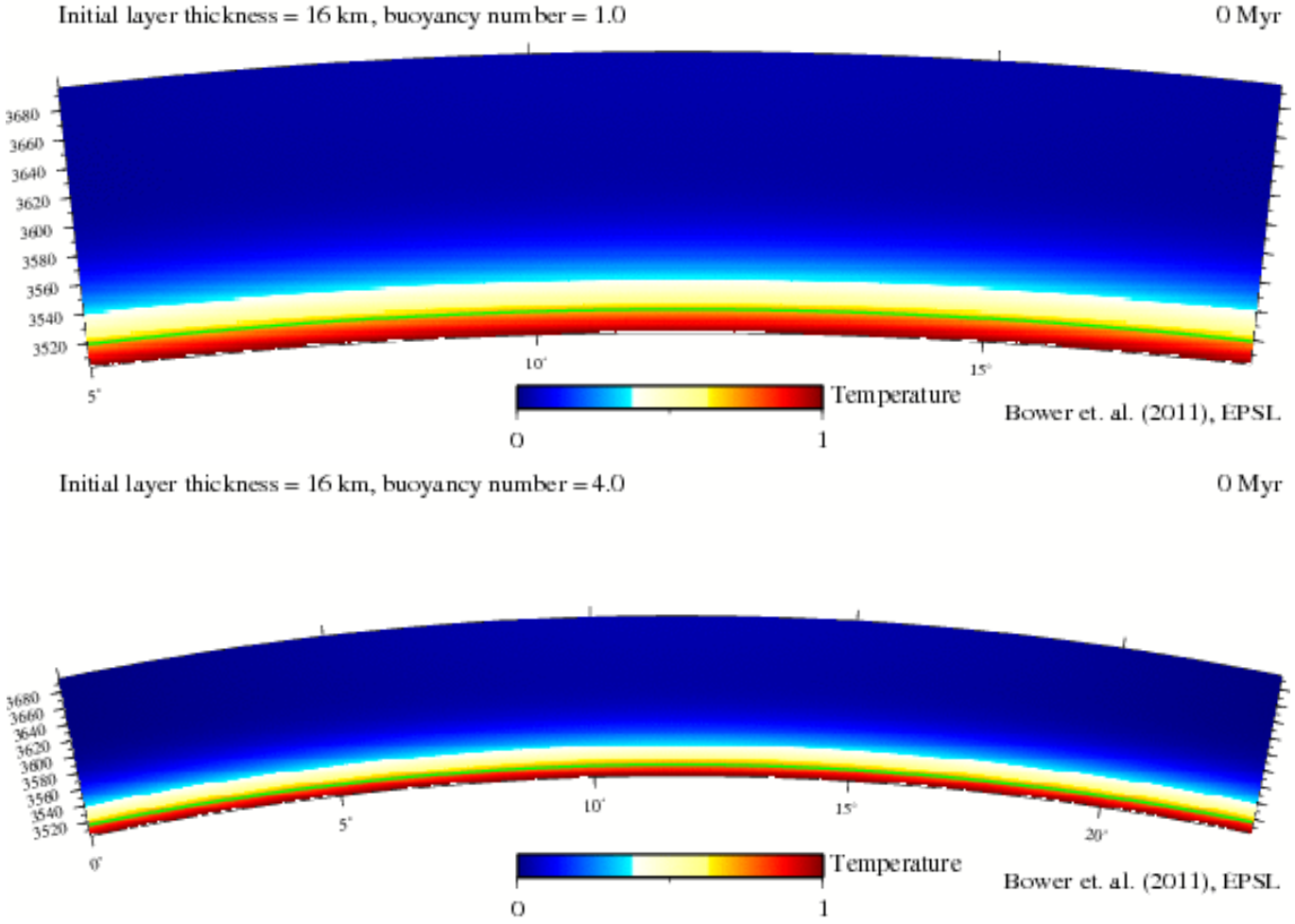
Software: PHOENIX
www.nrixs.com, Sturhahn,
Hyp. Int. 2000

Iron-rich (Mg,Fe)O: Very low sound velocities at pressures approaching Earth's CMB



Revised from Wicks *et al. GRL* 2010

Density of iron-rich (Mg,Fe)O-bearing chemical layer: Constrains buoyancy and shape of structures near Earth's core-mantle boundary

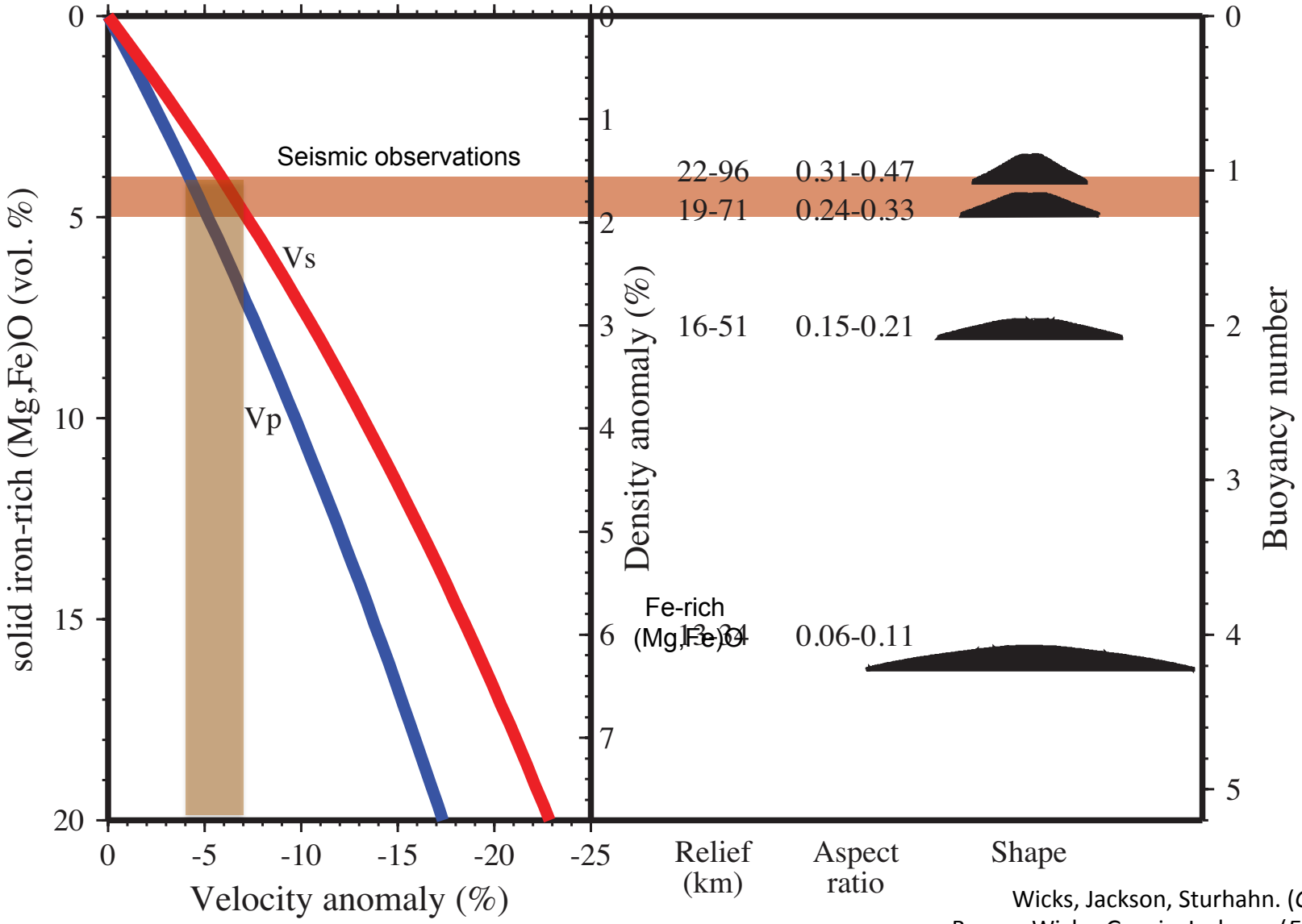


A few percent of iron-rich (Mg,Fe)O

About 10% of iron-rich (Mg,Fe)O

Bower, Wicks, Gurnis, and Jackson. *EPSL* 2011

Wave velocities and relief (shape) of iron-rich (Mg,Fe)O-bearing layer near Earth's core-mantle boundary



Wicks, Jackson, Sturhahn. (*GRL* 2010)
Bower, Wicks, Gurnis, Jackson. (*EPSL* 2011)
Sun, Helmberger, Jackson, Clayton, Bower. (*EPSL* 2013)

Accessing terrestrial planetary cores

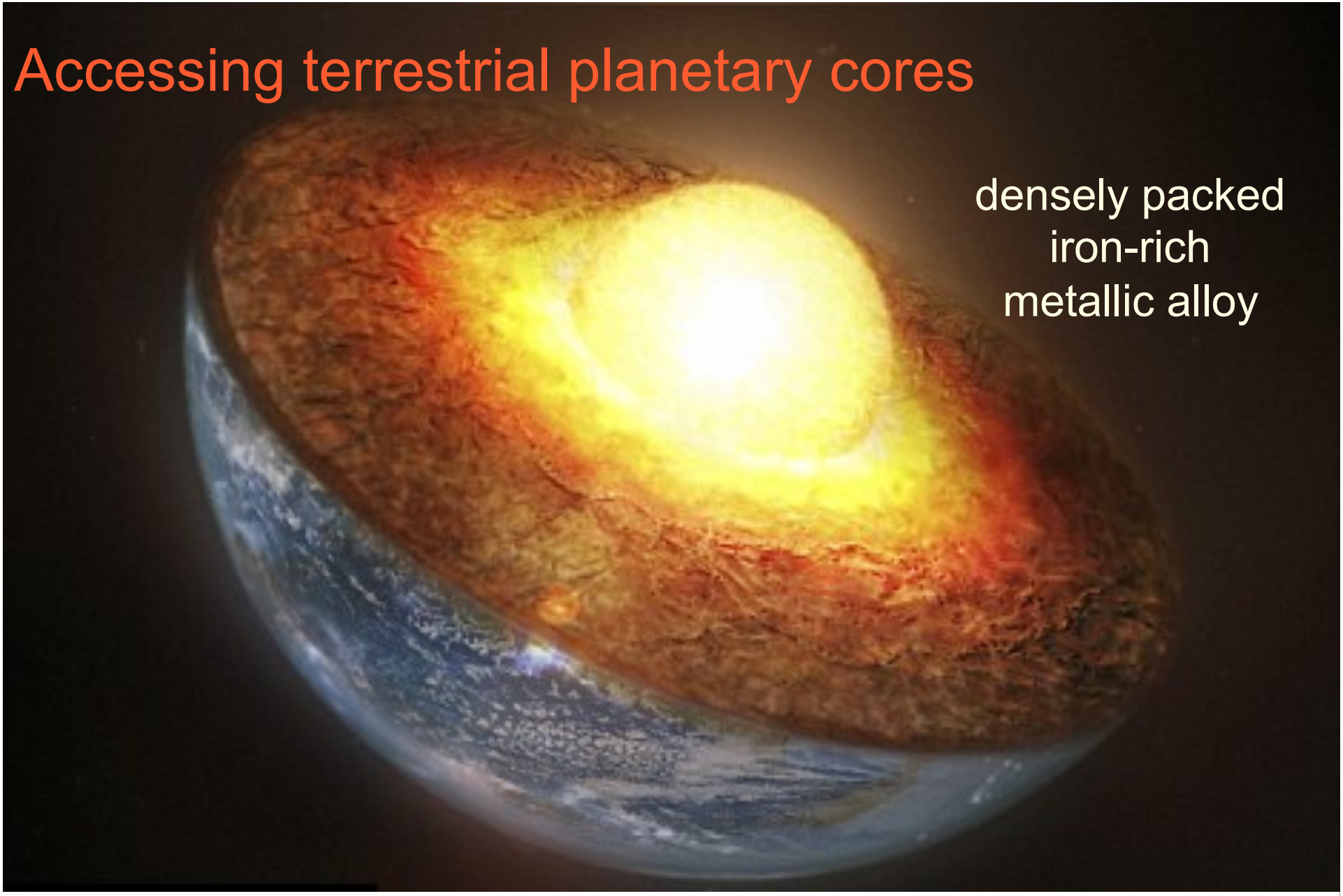
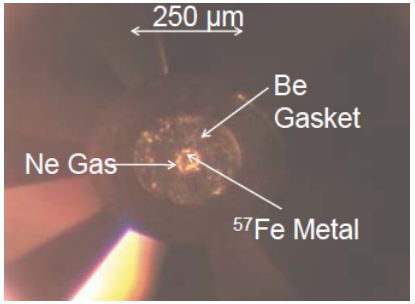
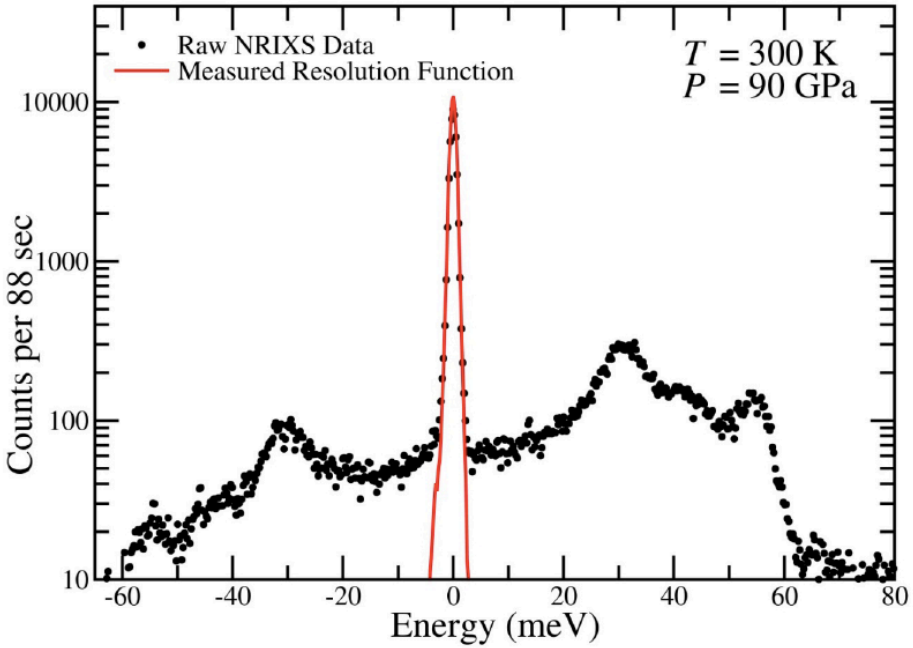


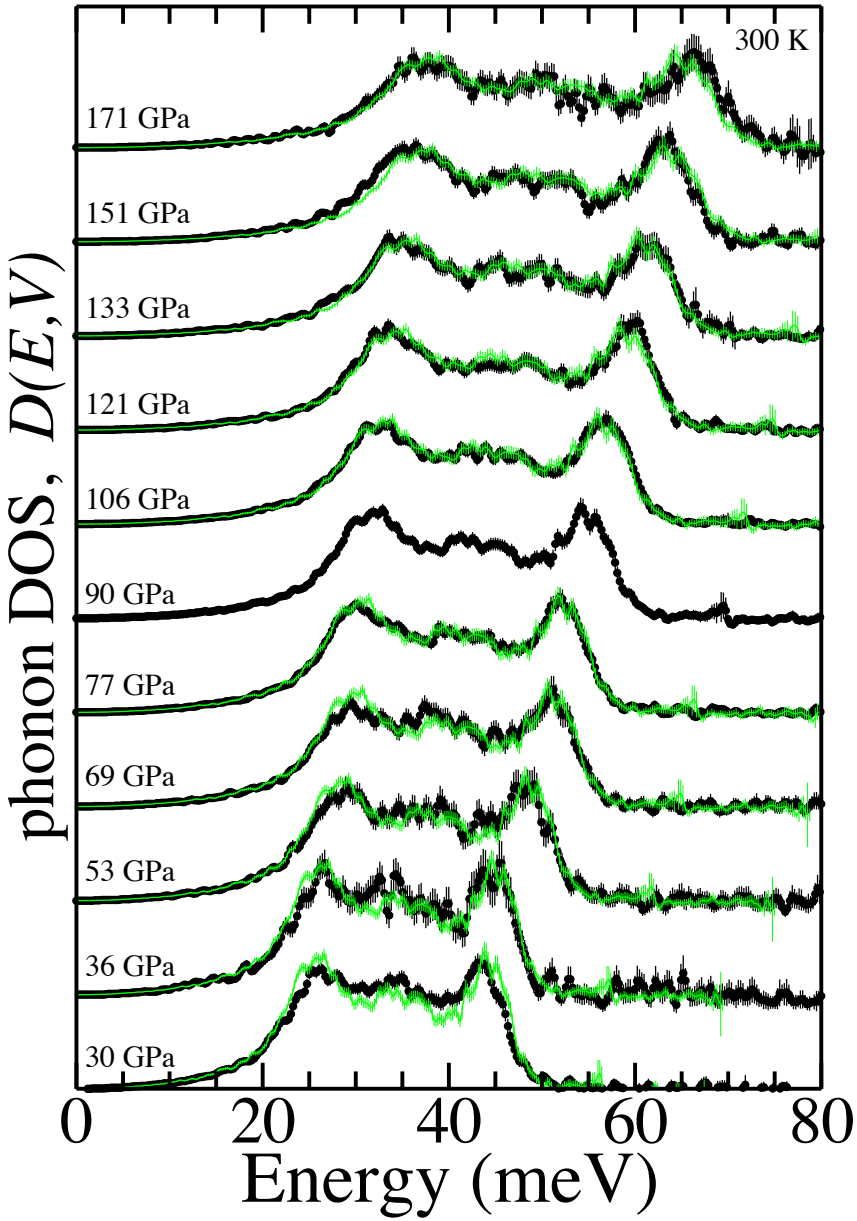
Image credit: Discovery Channel

Volume dependence of the phonon DOS for *hcp*-iron to outer core pressures



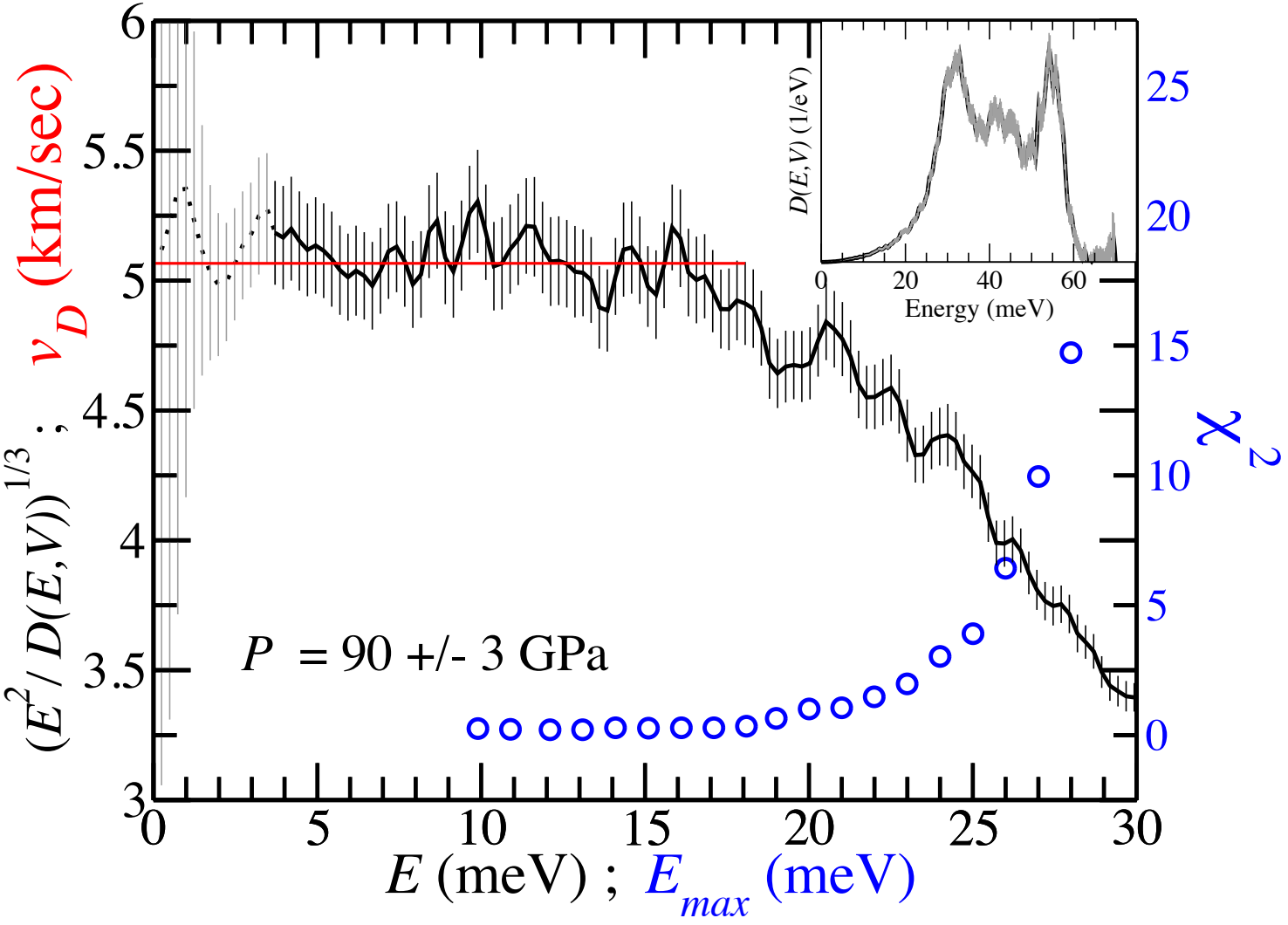


Fe sample loaded with neon
Pressure scale*: Dewaele et al. PRL* (2006)



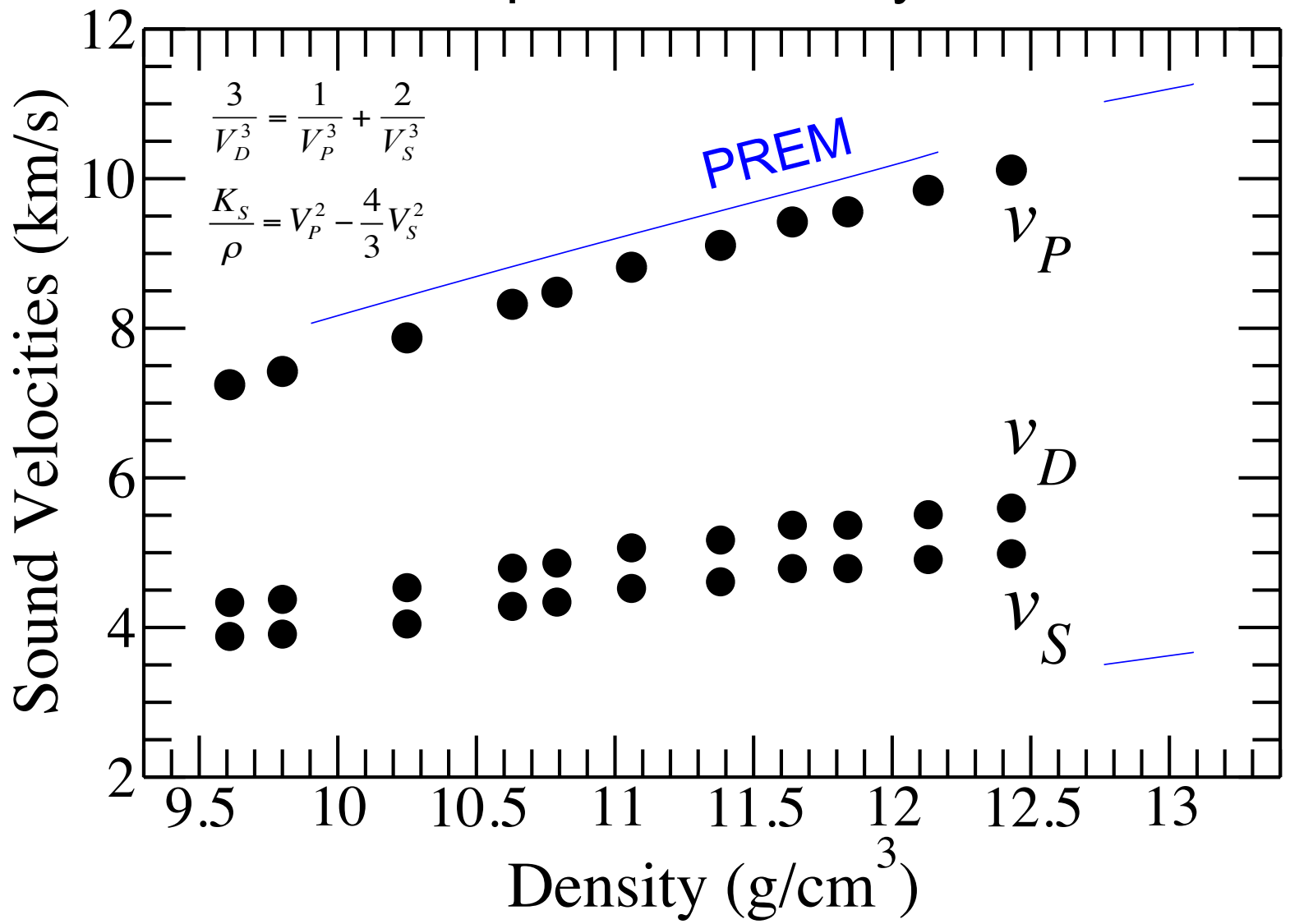
Murphy *et al. GRL* (2011); Murphy *et al. PEPI* (2011);
Murphy *et al. JGR* (2013)

Determination of the Debye sound velocity of *hcp*-iron from the measured phonon density of states



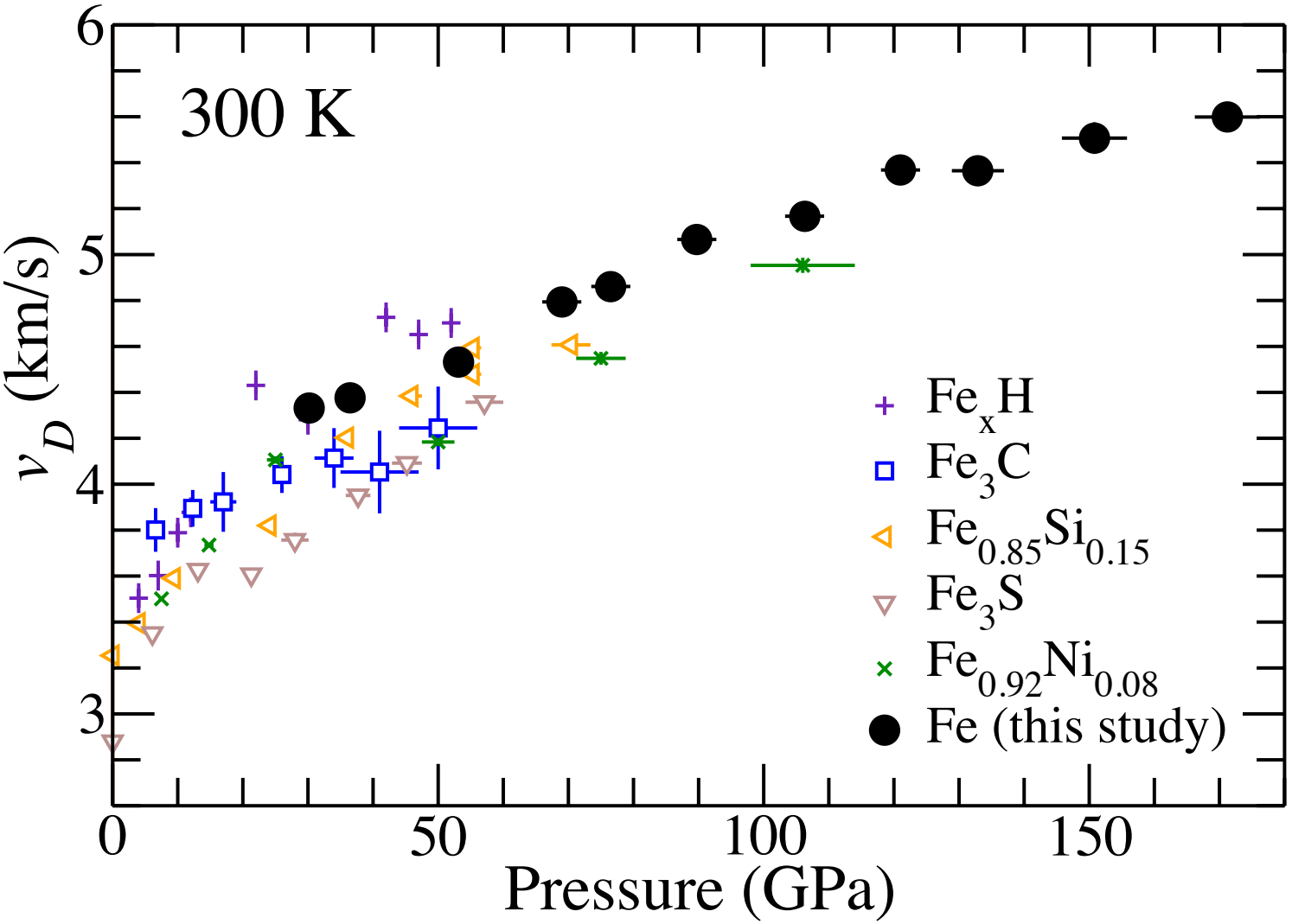
Jackson & Sturhahn, *GSA mono.* 2007
Murphy *et al. JGR* 2013

Sound velocities of *hcp*-iron from the measured phonon density of states



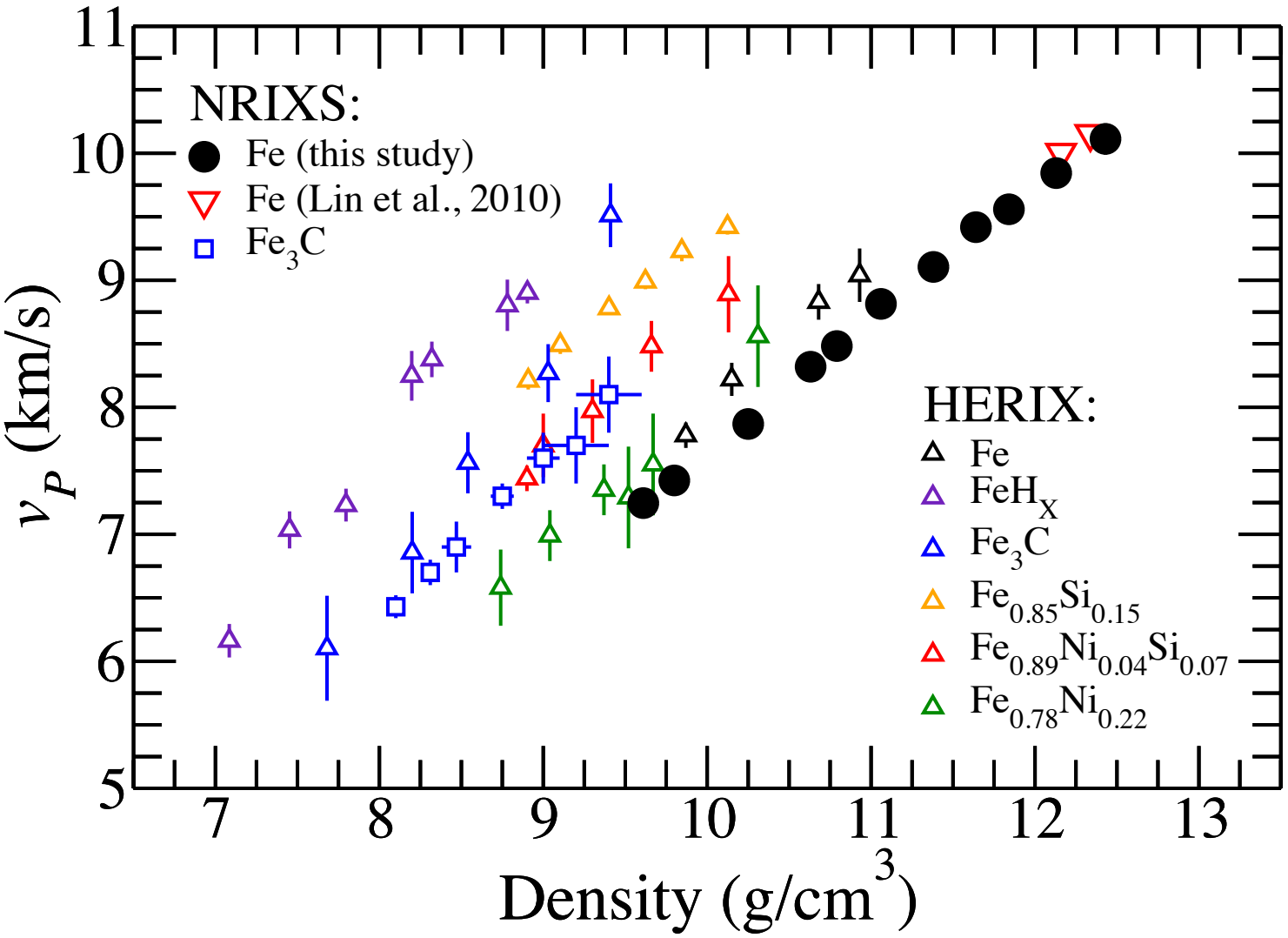
Murphy, Jackson, Sturhahn. *JGR*, 2013

Debye sound velocities of *hcp*-iron and iron-alloys from nuclear resonant inelastic x-ray scattering measurements



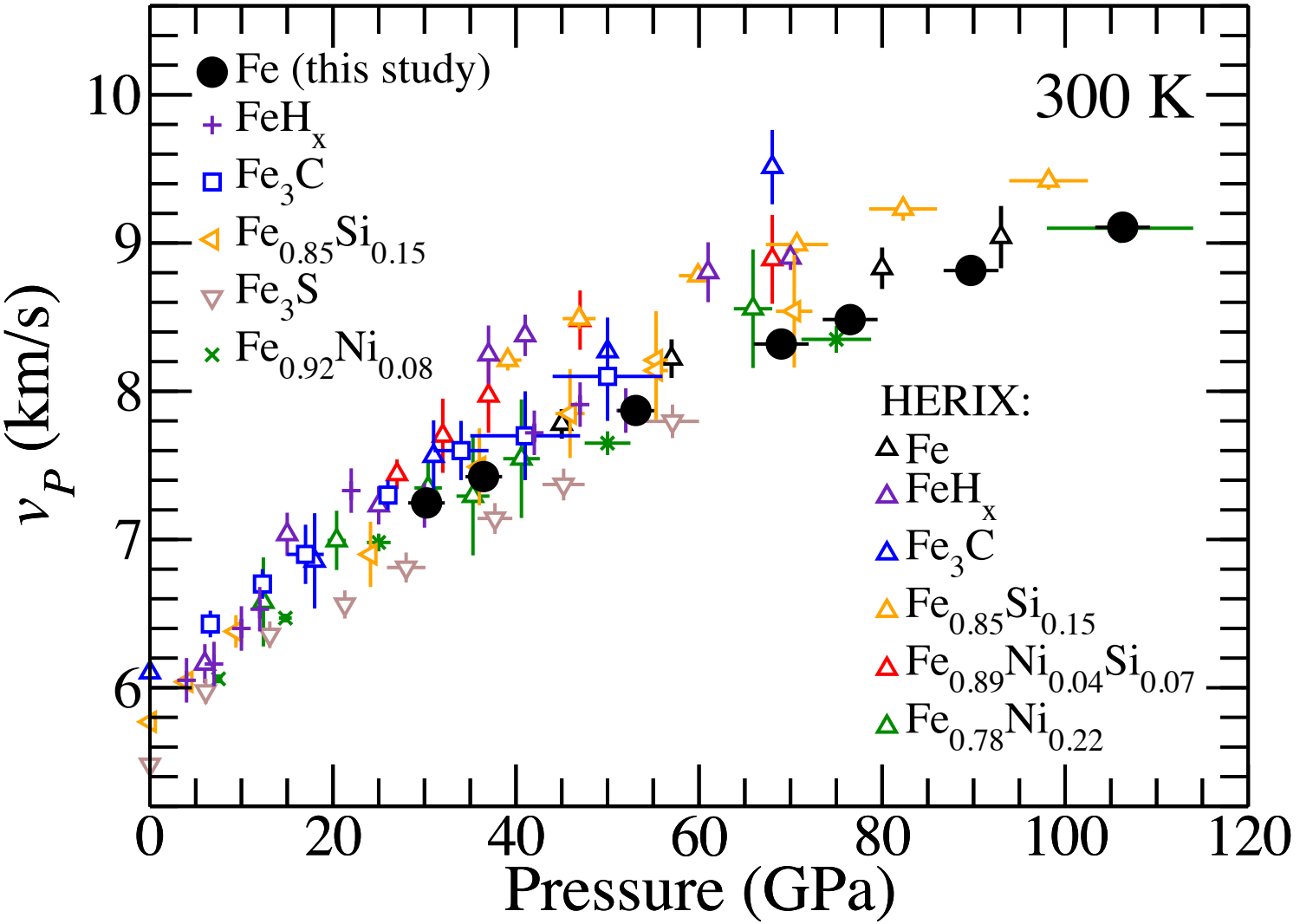
Murphy, Jackson, Sturhahn. *JGR*, 2013

Compressional wave velocities of *hcp*-iron and iron-alloys from inelastic x-ray scattering measurements



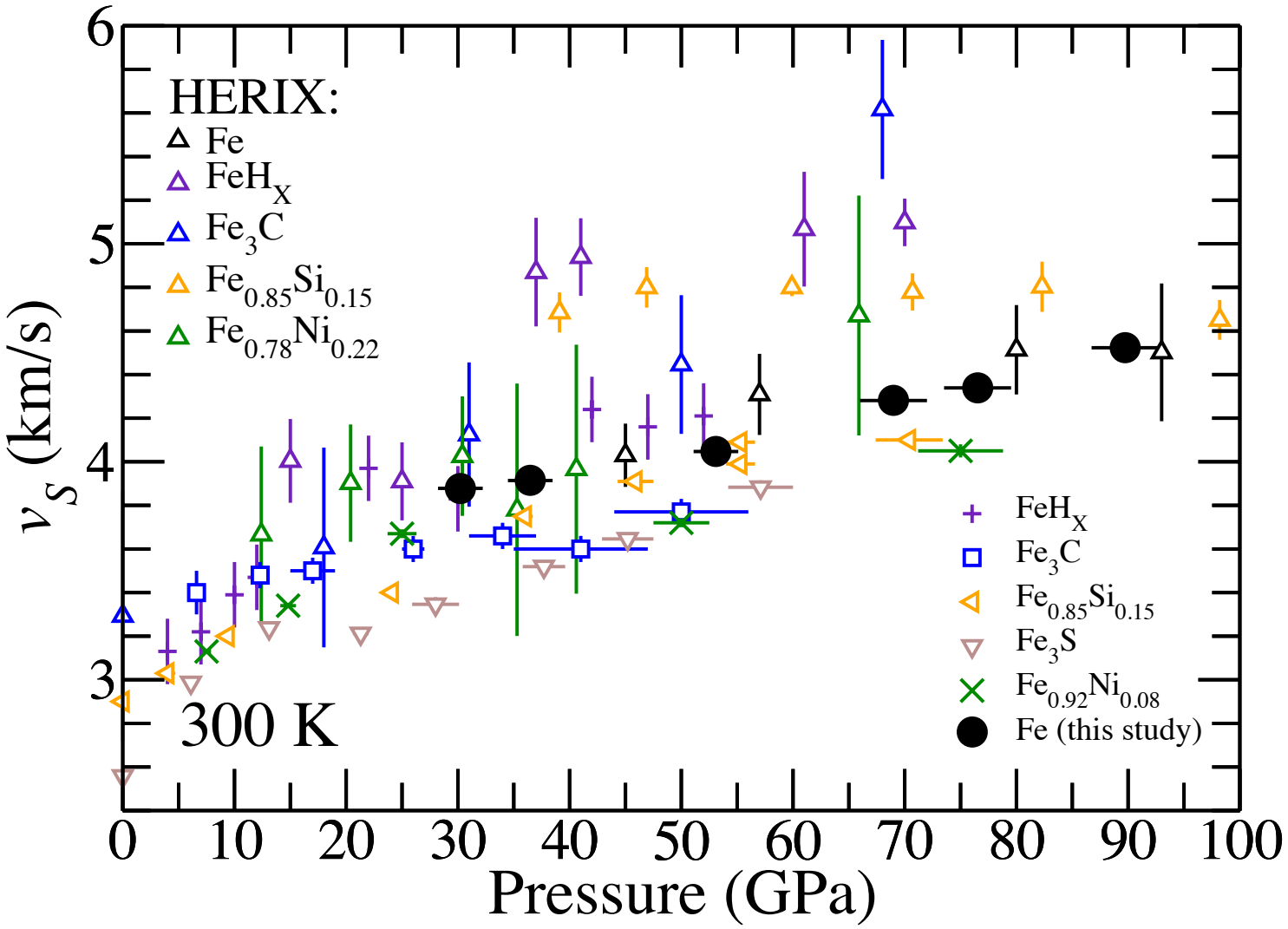
Murphy, Jackson, Sturhahn. JGR, 2013

Compressional wave velocities of *hcp*-iron and iron-alloys from inelastic x-ray scattering measurements



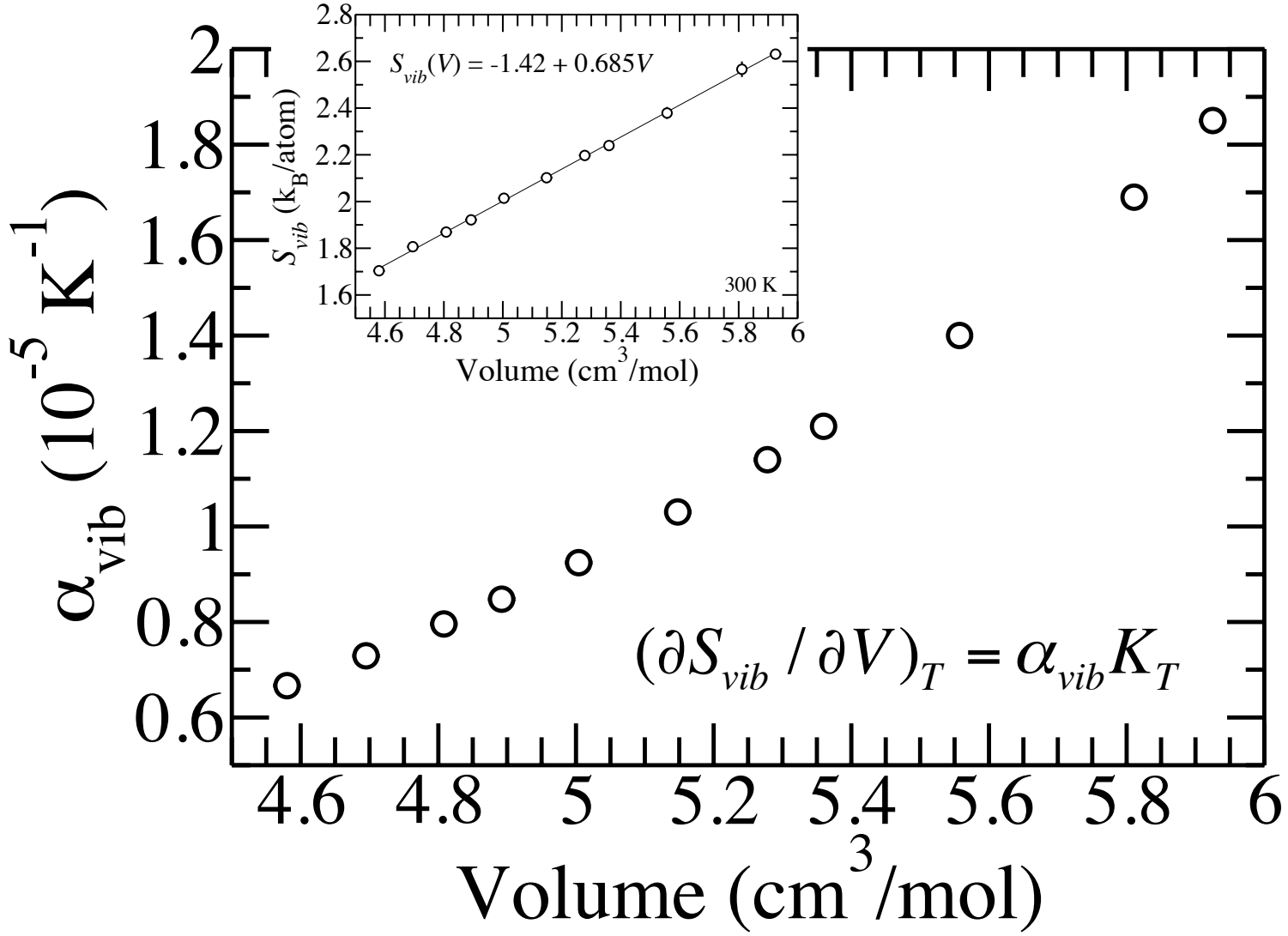
Murphy, Jackson, Sturhahn. JGR, 2013

Shear wave velocities of *hcp*-iron and iron-alloys from inelastic x-ray scattering measurements



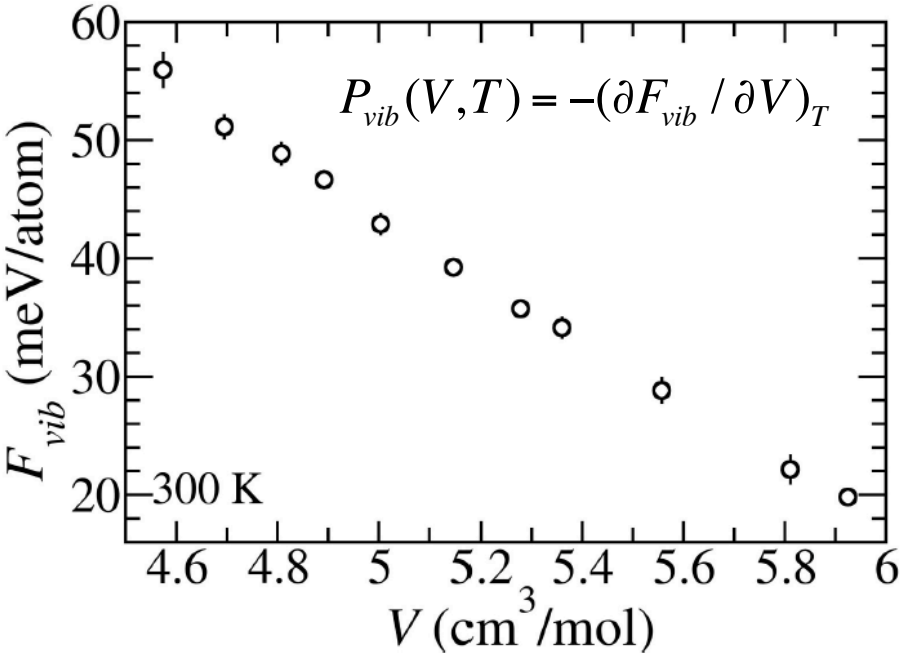
Murphy, Jackson, Sturhahn. *JGR*, 2013

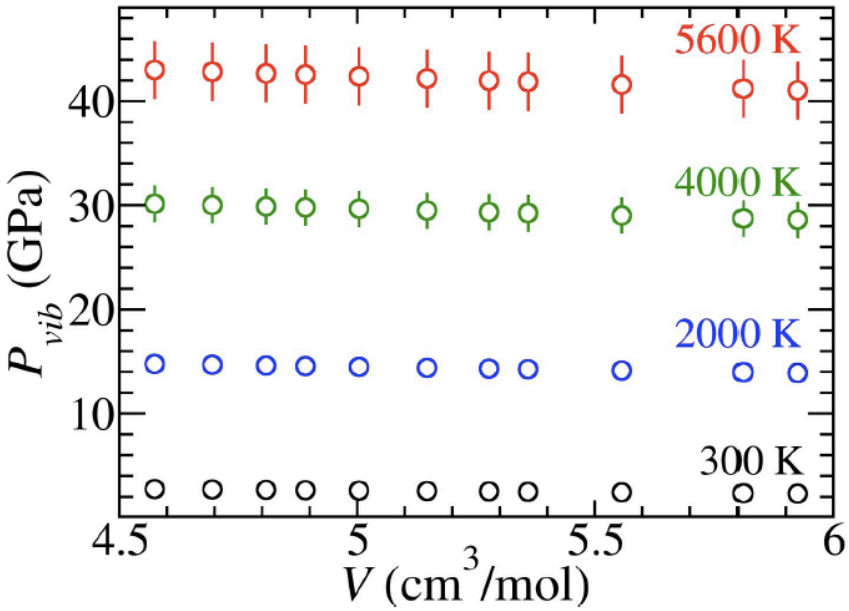
Thermal expansion of *hcp*-iron from the measured volume-dependence of vibrational entropy

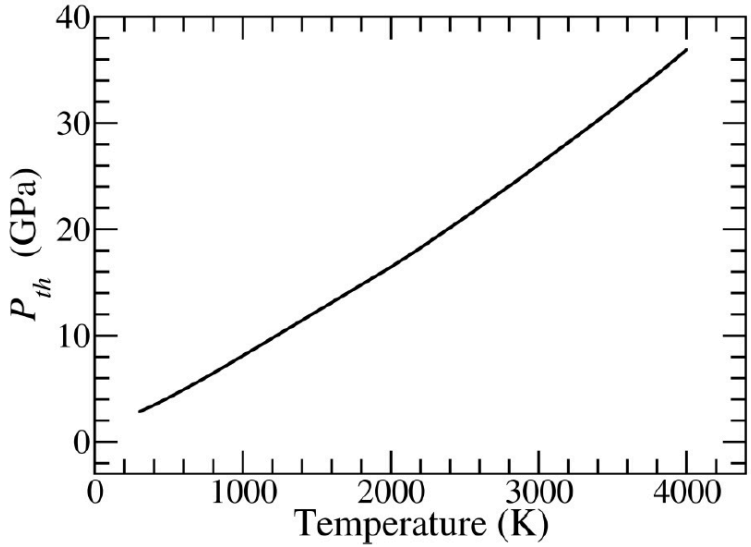


Murphy, Jackson, Sturhahn. *JGR*, 2013

Thermal pressure from the measured volume dependence of *hcp*-iron's vibrational free energy







$$P_{th} = P_{vib}^{h} + P_{vib}^{anh} + P_{el}$$

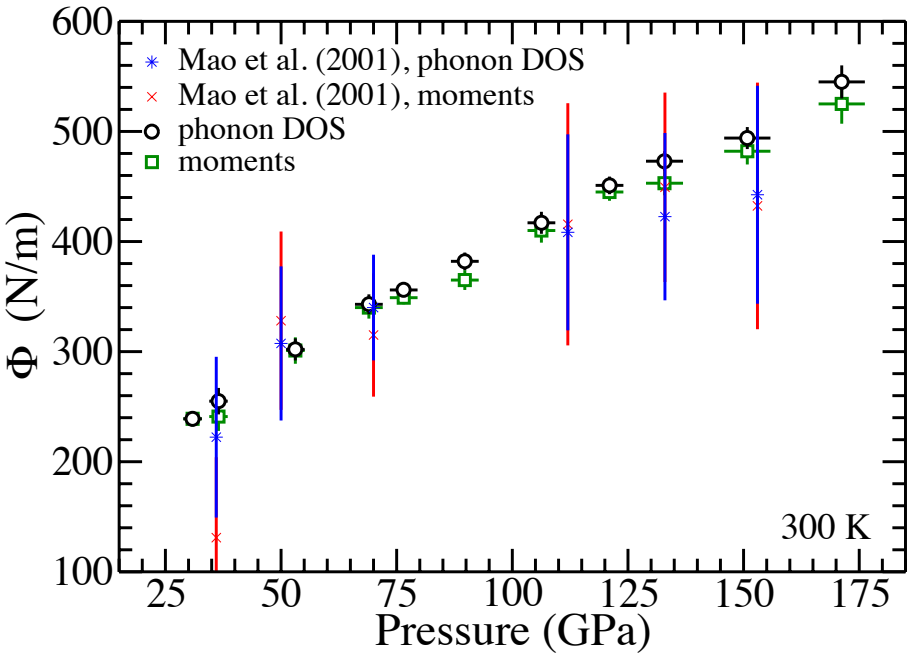
Dewaele *et al. PRL* (2006)

Murphy *et al. PEPI* (2011)

$$\rho_{ICB}^{hcp-Fe} = 13.50 \pm 0.03 \quad g/cm^3$$

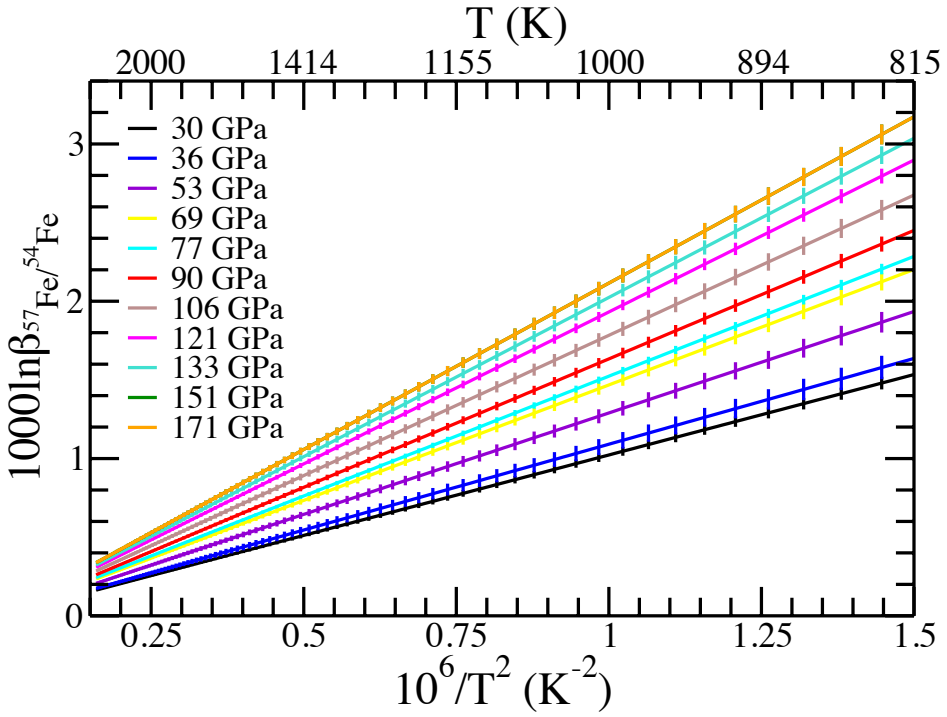
$$\Rightarrow 5.5 \pm 0.2\%$$

Isotope fractionation factors of *hcp*-iron from the measured force constants



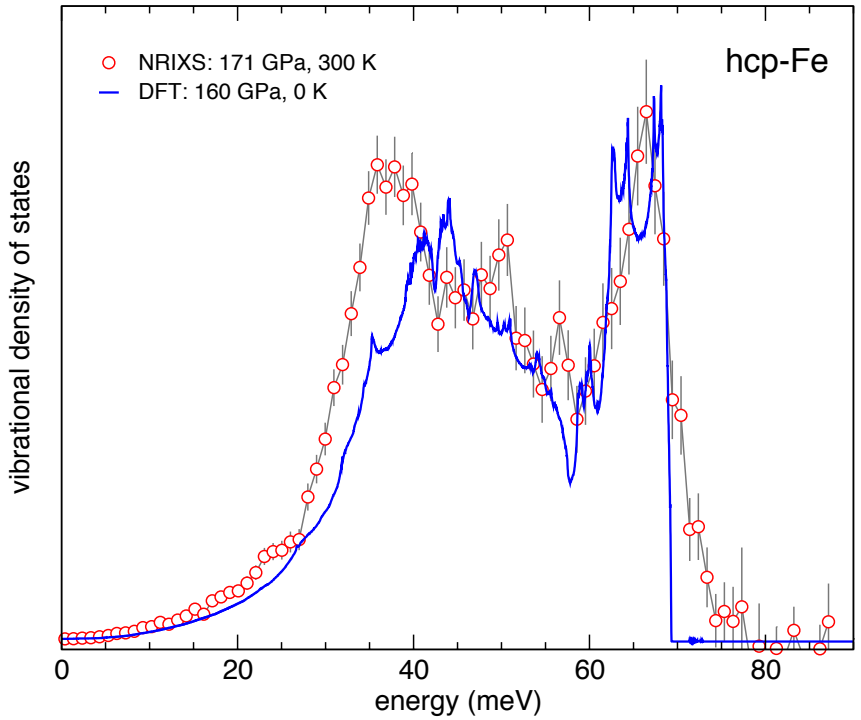
$$\Phi = \frac{k^2}{2E_R^2}\int \left(E - E_R\right)^3 S(E)\,dE$$

$$\ln \beta(V,T) = -\frac{\Delta m \hbar^2 \Phi(V,T)}{m m^* 8 (k_B T)^2}$$



Murphy, Jackson, Sturhahn. *JGR*, 2013

Combining density functional theory with measured data:



Collaboration with R. Caracas (ENS Lyon)

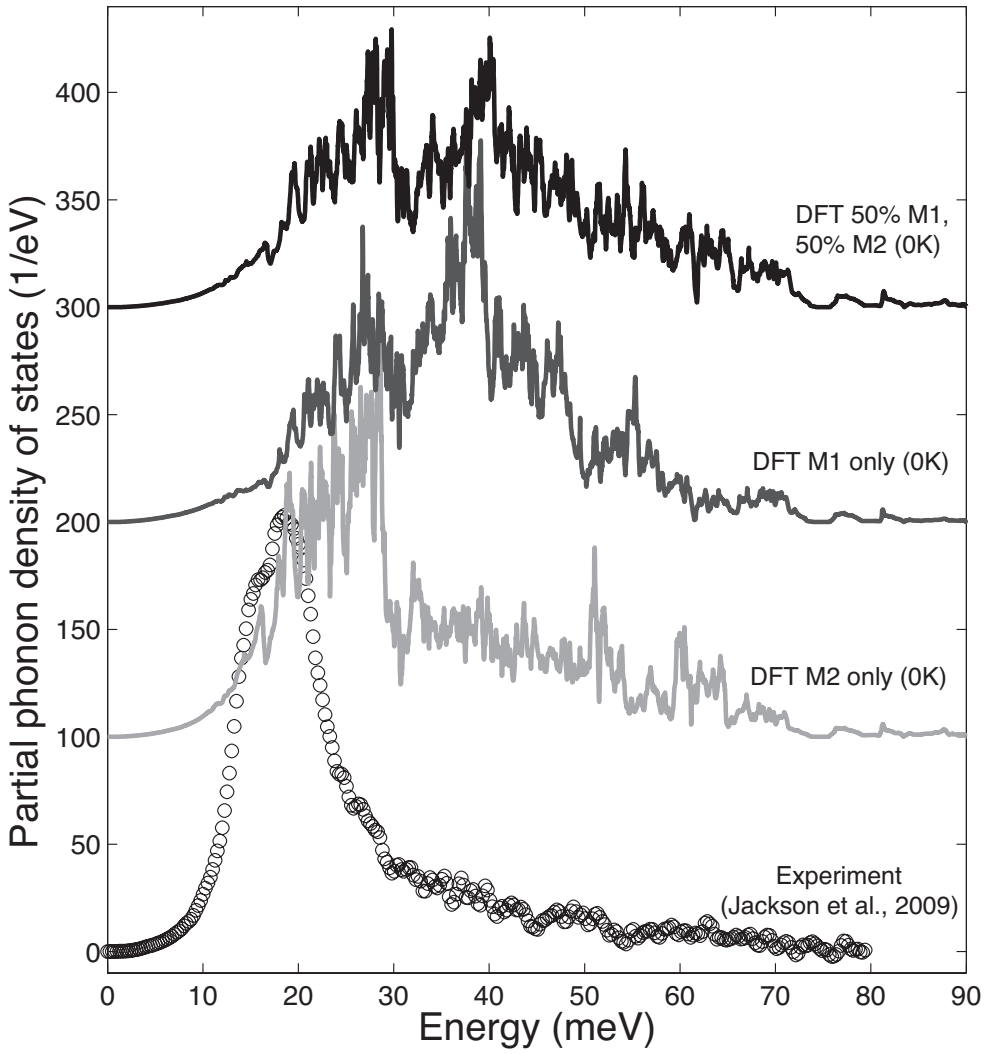
Candidate core alloys

- **Thermal equations of state**

Independent of theory:

- **V_P and V_S**
- **Iron isotope β-factors**

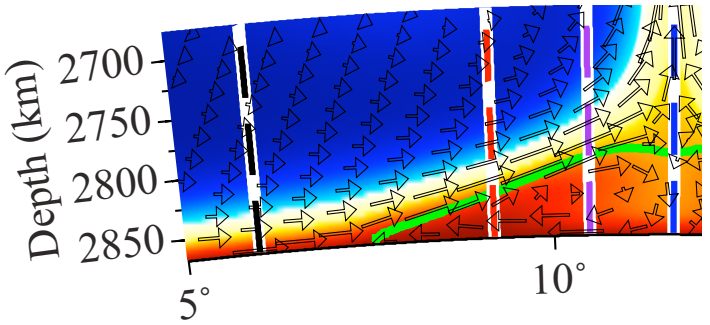
$(Mg_{0.98}Fe_{0.02})(Mg_{0.76}Fe_{0.24})Si_2O_6$
enstatite



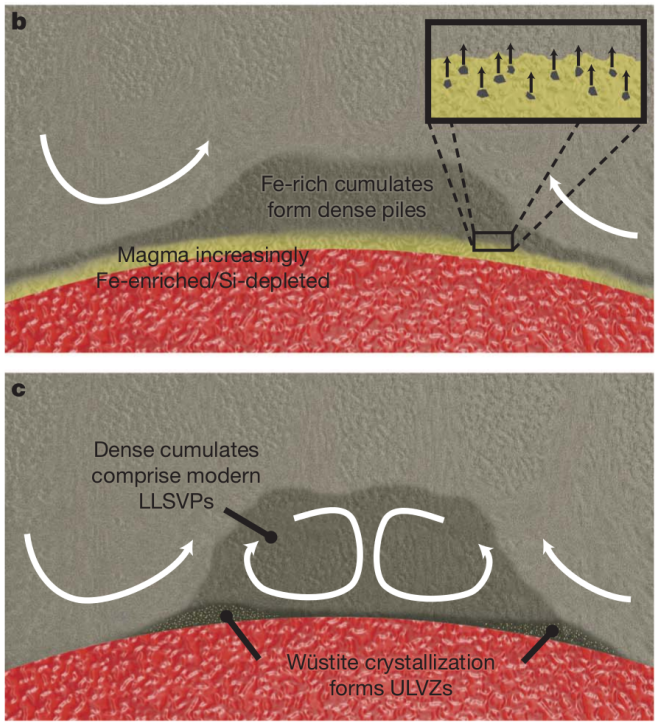
(Zhang, Jackson, Caracas, *et al. 2013)*

Conclusions

- Enstatite, an upper mantle mineral, exhibits shear softening near a pressure-induced phase transition

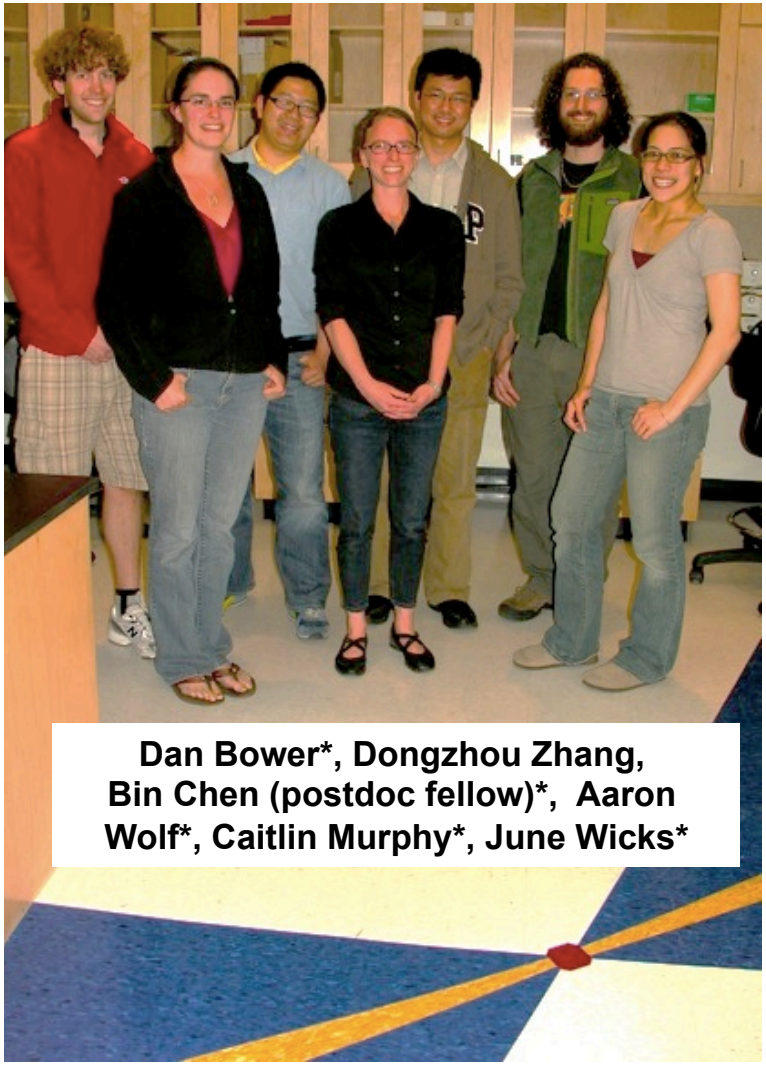


- Sound velocities and density of iron-rich (Mg,Fe)O provides a plausible explanation of heterogeneous patches at Earth's core-mantle boundary
  - Distinct, matches seismic observations
  - Could be a residue of a deep magma ocean

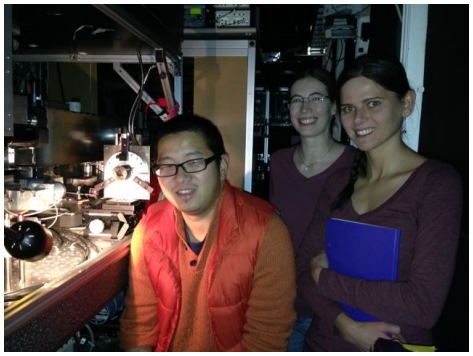


- Sound velocities of thermoelasticity of iron-alloys, together with seismic observations, will help constrain the composition of Earth's core

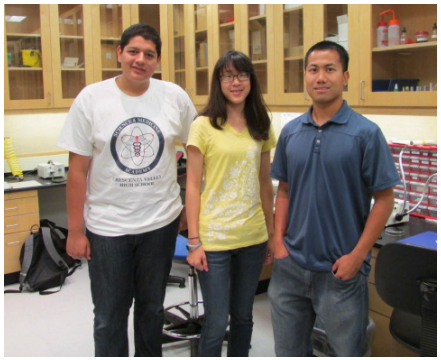
Acknowledgements



Dan Bower*, Dongzhou Zhang, Bin Chen (postdoc fellow)*, Aaron Wolf*, Caitlin Murphy*, June Wicks*



Rachel Miller Natalia Solomatova



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GSE-CARS (Sector 13): V. Prakapenka and P. Dera

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Aaron Wolf: *now a Turner Postdoc Fellow at Univ. of Michigan*
Caitlin Murphy: *now a Carnegie Postdoc Fellow at the Geophysical Laboratory*
June Wicks: *now a Hess Postdoc Fellow at Princeton*
YoungHee Kim, *now Asst. Prof. at Seoul National Univ.*
Zhongwen Zhan, *now Asst. Prof. at UT Austin*

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Thank You!