# Massive Stars Evolution

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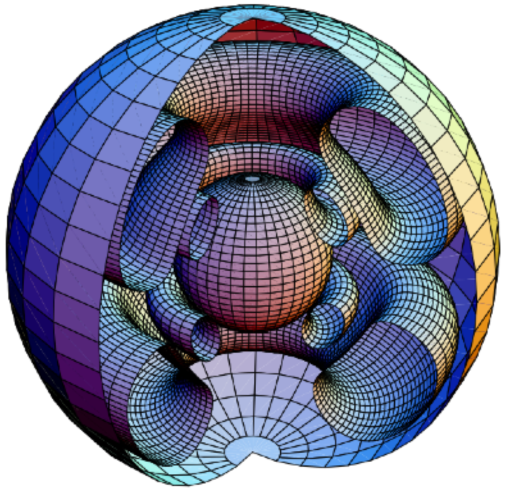
The evolution and death of massive stars is still an unsolved problem

# Massive Stars: Why so hard?



- Poorly constrained **Internal Physics**: overshooting, rotational mixing, convection in radiation dominated regions

- Large uncertainty in **Massloss**: clumping in line driven winds, cool winds, burps/eruptions

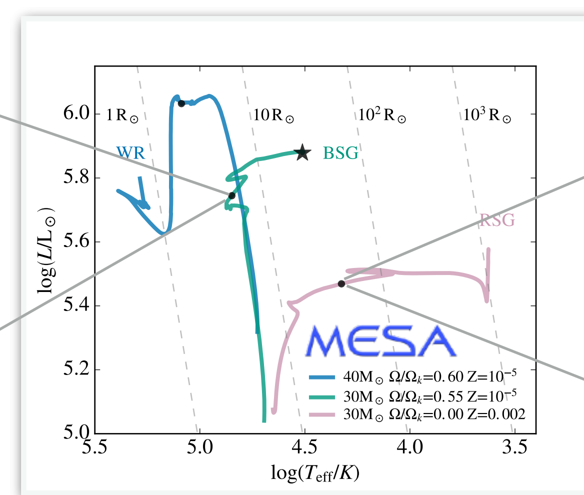
- **Multiplicity**: large binary fraction, poorly constrained and complex physics (mass transfer, common envelope evolution…)

# Massive Stars: Why so hard?

- Massive stars are rare (IMF + short lifetimes)
- Degeneracy of different internal physical processes hard to break using surface properties

# A new era of stellar physics

Unprecedented synergy between high precision, big data (in particular photometry and astrometry) and theory (in particular asteroseismology and 3D numerical simulations). Together with the advent of open source, community-driven stellar evolution codes like MESA, this is empowering a better scrutiny of established 1D results. With many exciting surprises…




# Open Questions:
# Massive Stars Evolution

# Massive Stars:
# The most uncertain physics

- Stability and energy transport
- Mass loss
- Rotation
- Magnetic Fields
- Binary interactions

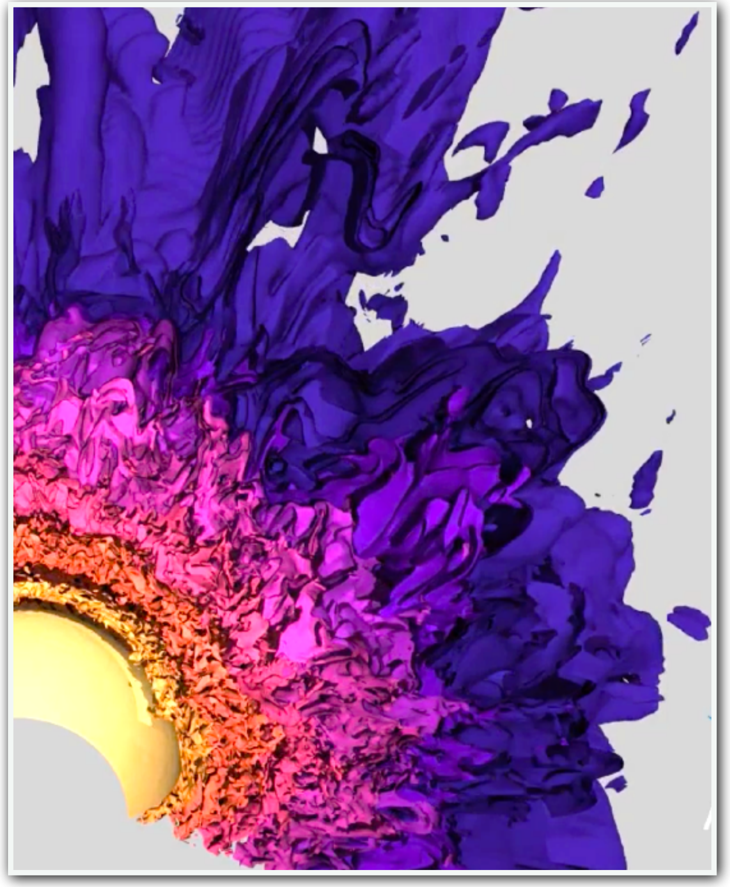
See Natasha, Ylva and Silvia’s talks

# Understanding Massive Stars

Most massive stars are in multiple systems, and it is clear that binary interactions are extremely important. However, these stars **evolve for a large fraction of their lives as ~single stars**.

The problem is that we do not understand many basic physical processes in single, massive stars.

Need to focus on understanding the basic physics first.



# Massive Stars:
# The most uncertain physics

- Stability and energy transport
- Mass loss
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- Magnetic Fields
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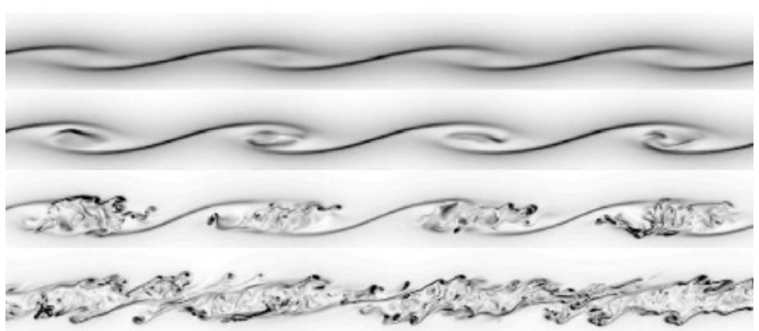
# Internal Rotation & Magnetism

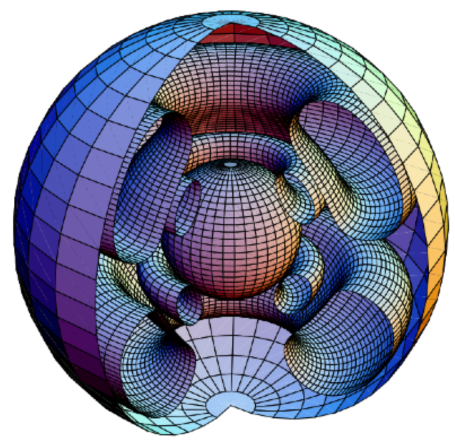
# Angular Momentum Transport

Different classes of mechanisms have been proposed:

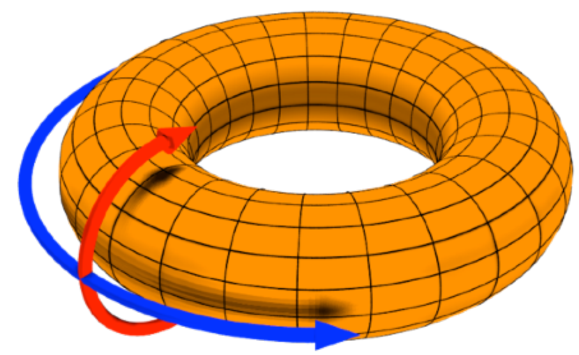
e.g. Heger et al. 2000



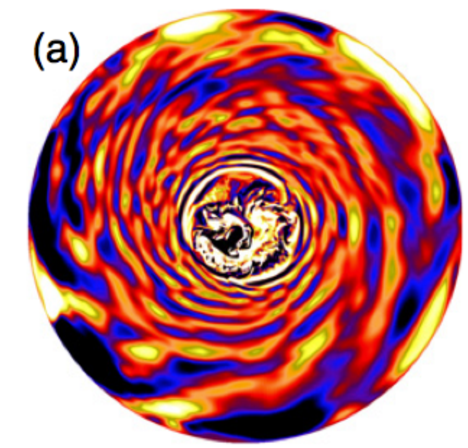
e.g Maeder & Meynet 2002



e.g. Spruit 2002



e.g. Rogers et al. 2013
Fuller et al. 2014, 2015

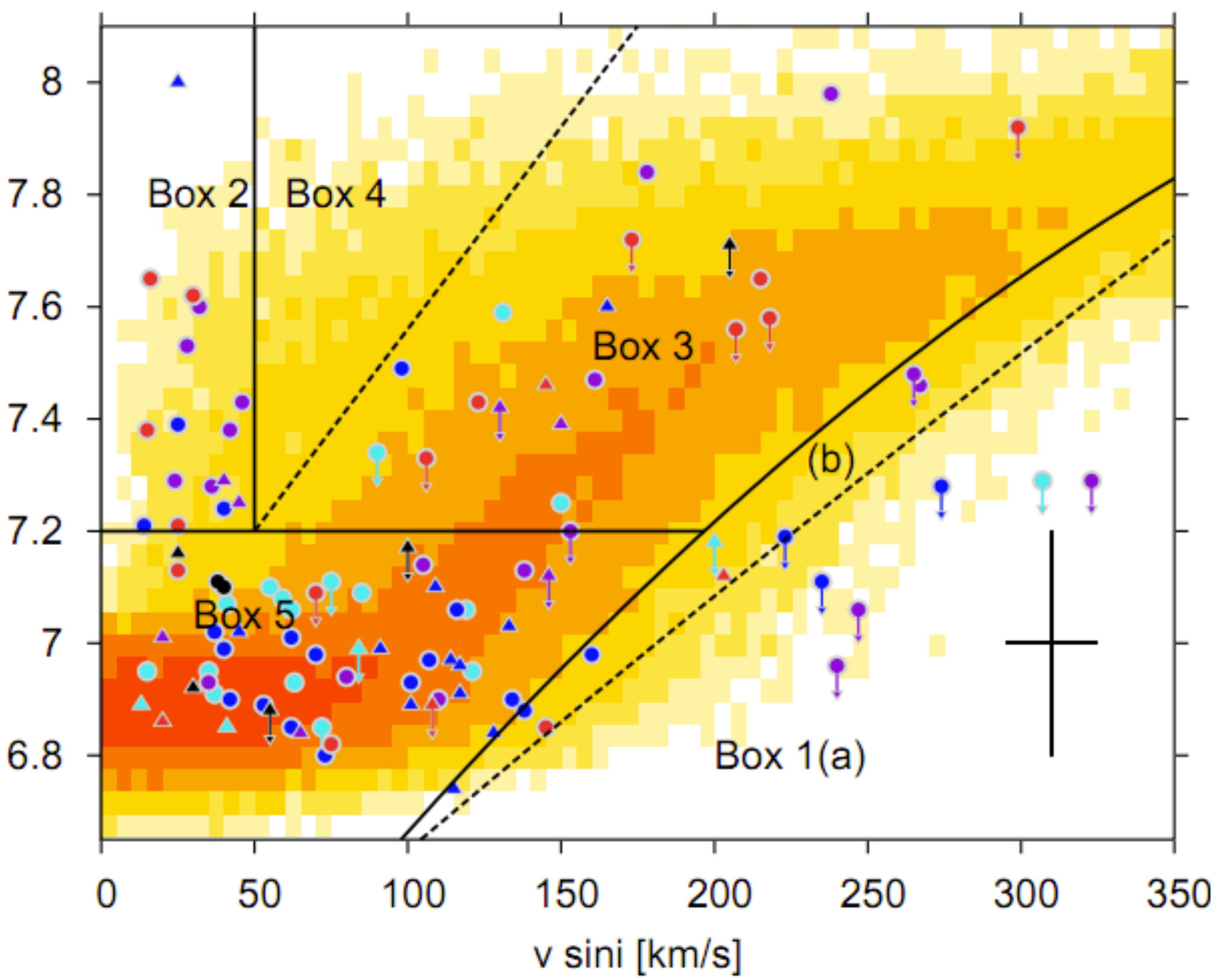



- Hydrodynamics instabilities
- Rotationally induced circulations
- **Magnetic torques**
- Internal gravity waves

Possible to treat the problem in 1D under the assumption of shellular rotation law

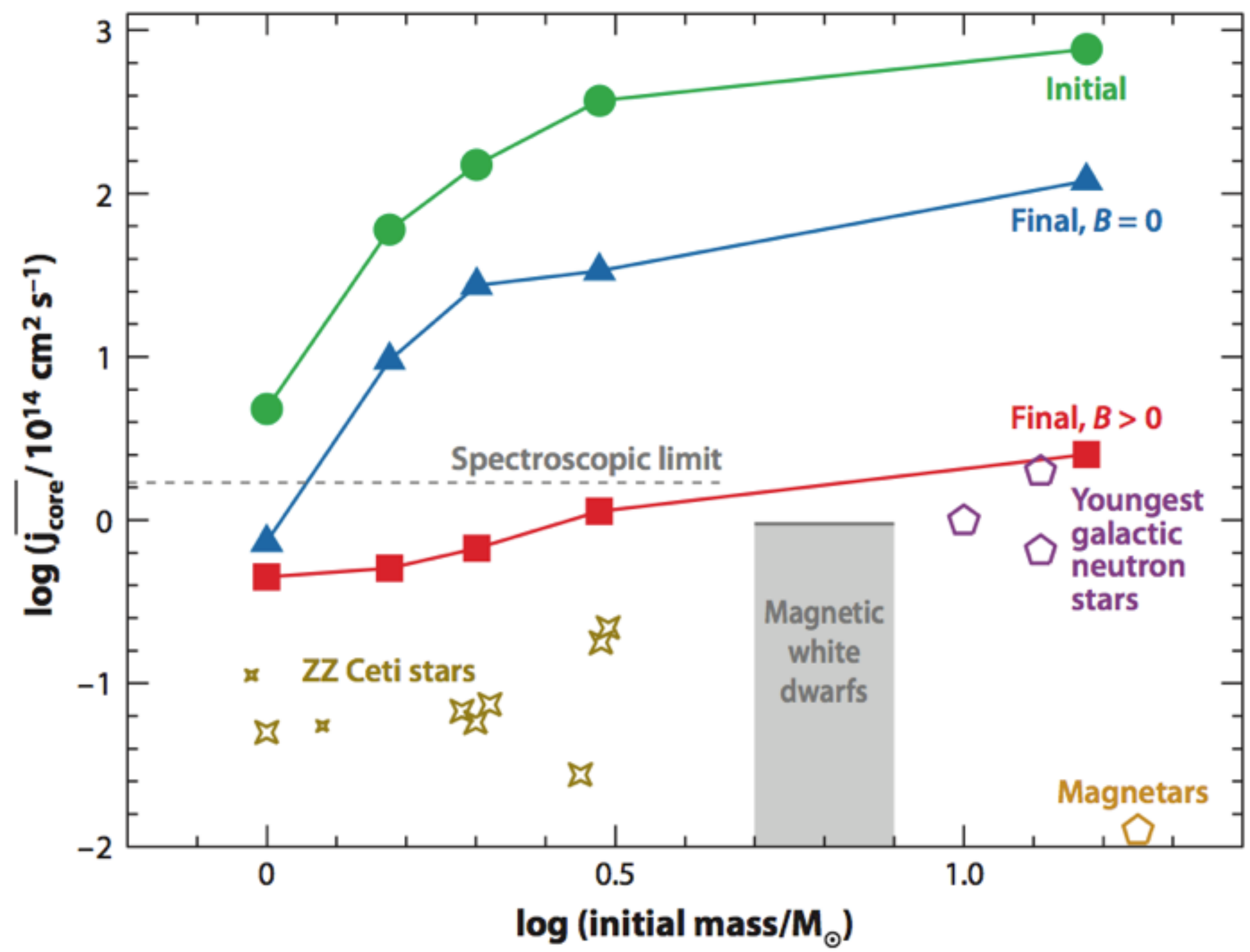
# Testing Physics of Stellar Rotation

e.g Brott et al. 2011



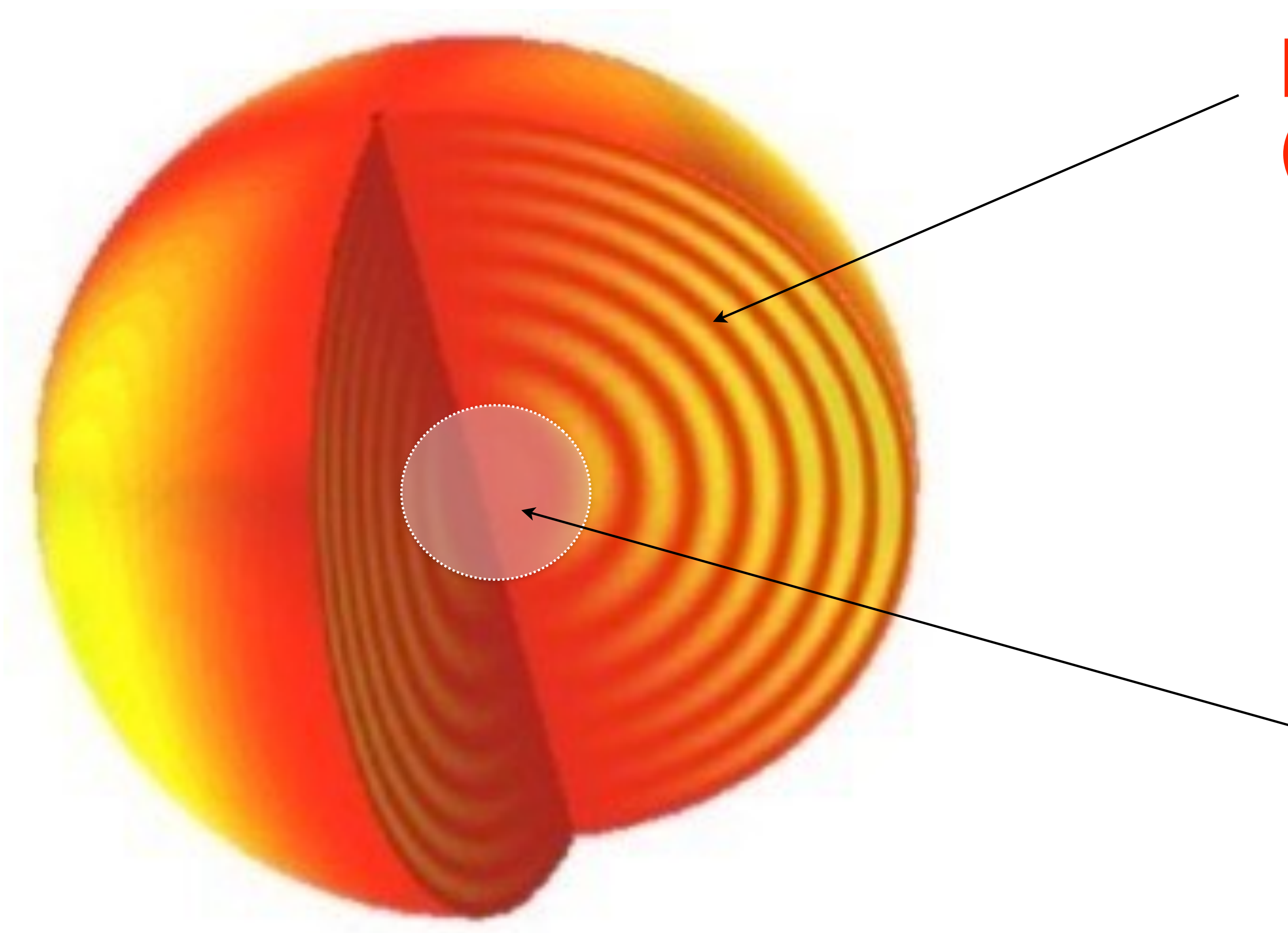

**Surface Abundances**

e.g Suijs et al. 2008



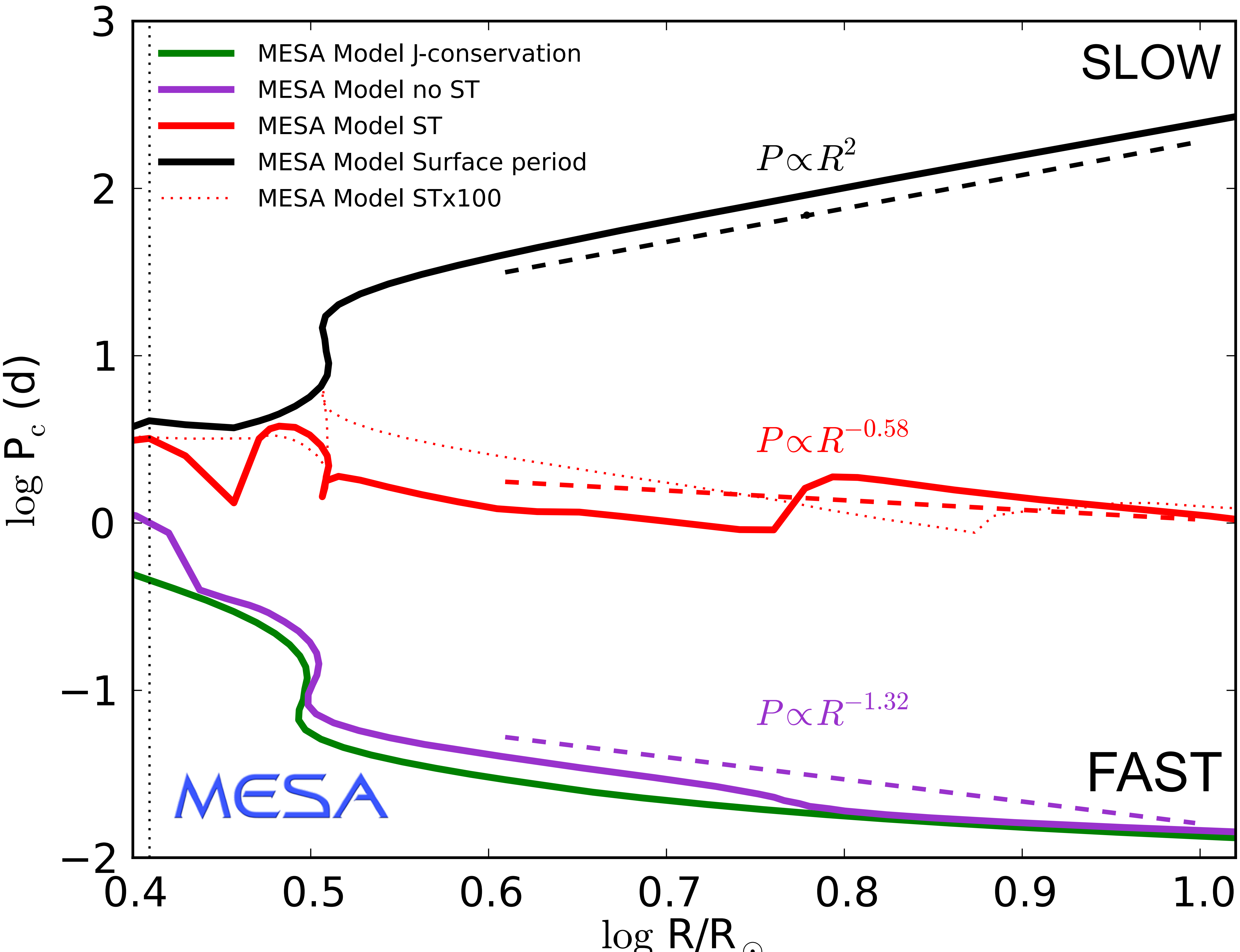

**Compact Remnants**

# Kepler
# Asteroseismology: Mixed Modes



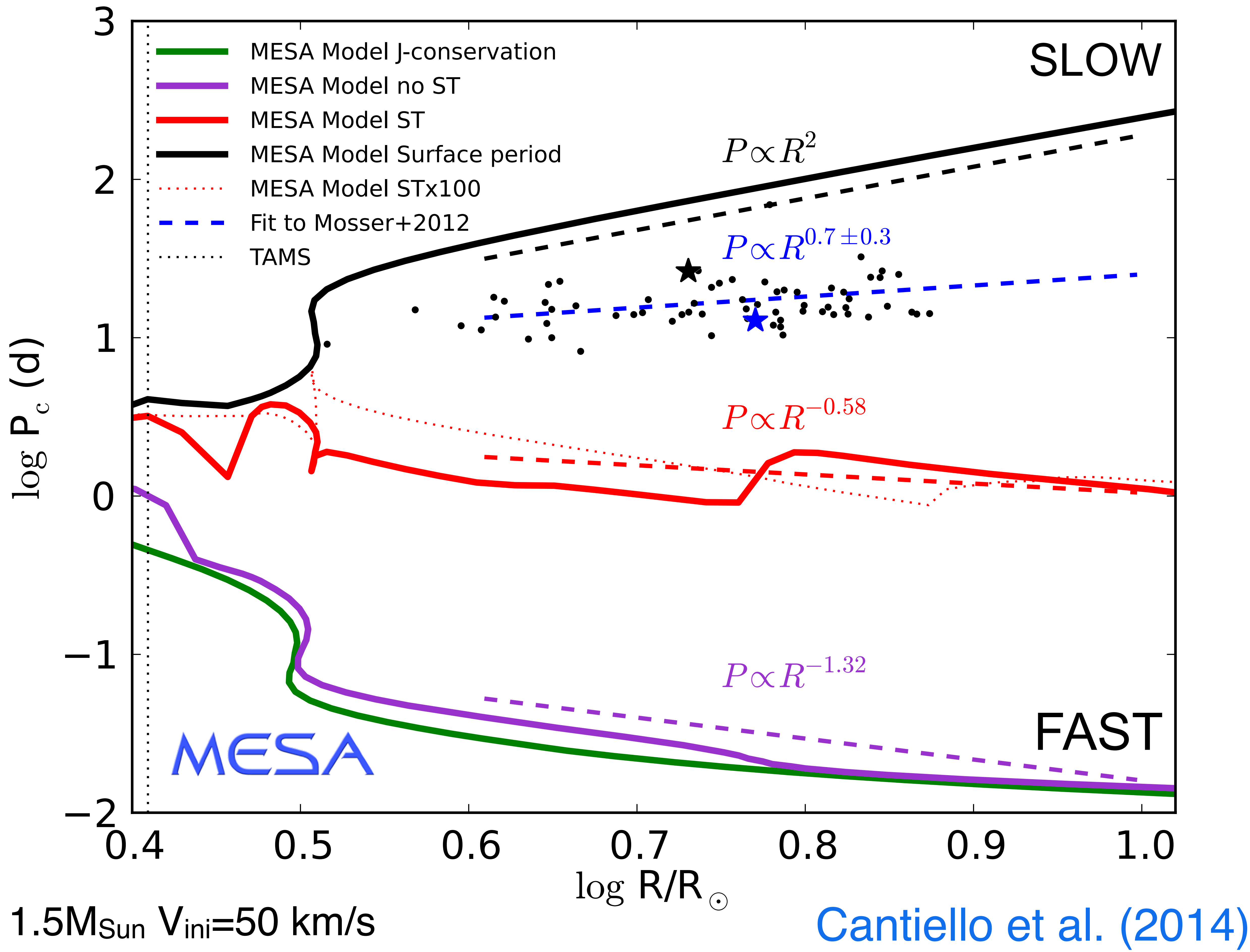

Since mixed modes live both as p-mode (in the envelope) and as g-mode (in the core), if observed at the surface their properties (e.g. rotational splitting) can give information about e.g. rotation rate in different regions of the star!

(Beck et al. 2012, Mosser et al. 2012)



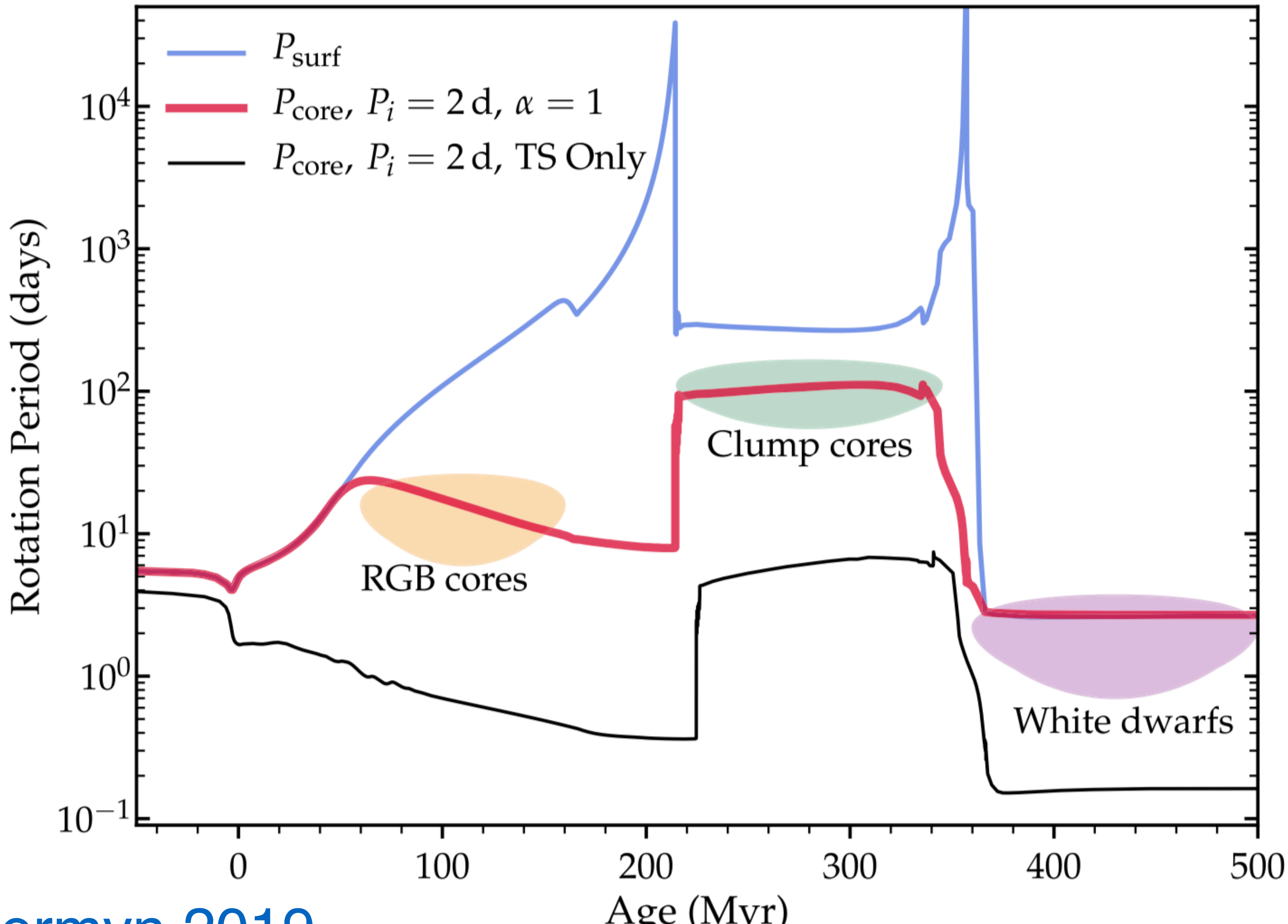

1.5$M_{Sun}$ $V_{ini}$=50 km/s

Cantiello et al. (2014)



MESA Model J-conservation
MESA Model no ST
MESA Model ST
MESA Model Surface period
MESA Model STx100
Fit to Mosser+2012
TAMS
SLOW
FAST
$P \propto R^2$
$P \propto R^{0.7 \pm 0.3}$
$P \propto R^{-0.58}$
$P \propto R^{-1.32}$
MESA
3
2
1
0
−1
−2
0.4
0.5
0.6
0.7
0.8
0.9
1.0
log $P_c$ (d)
log $R/R_\odot$
$1.5 M_{Sun}$ $V_{ini}$=50 km/s
Cantiello et al. (2014)

# New Prescription able to match the observations




Cores rotate ~10 times slower than with the old Spruit-Tayler prescription (Spruit 2002).

Fuller, Piro & Jermyn 2019

# Spin of Compact Remnants

Cores rotate ~10 times slower than with the old Spruit-Tayler prescription (Spruit 2002).

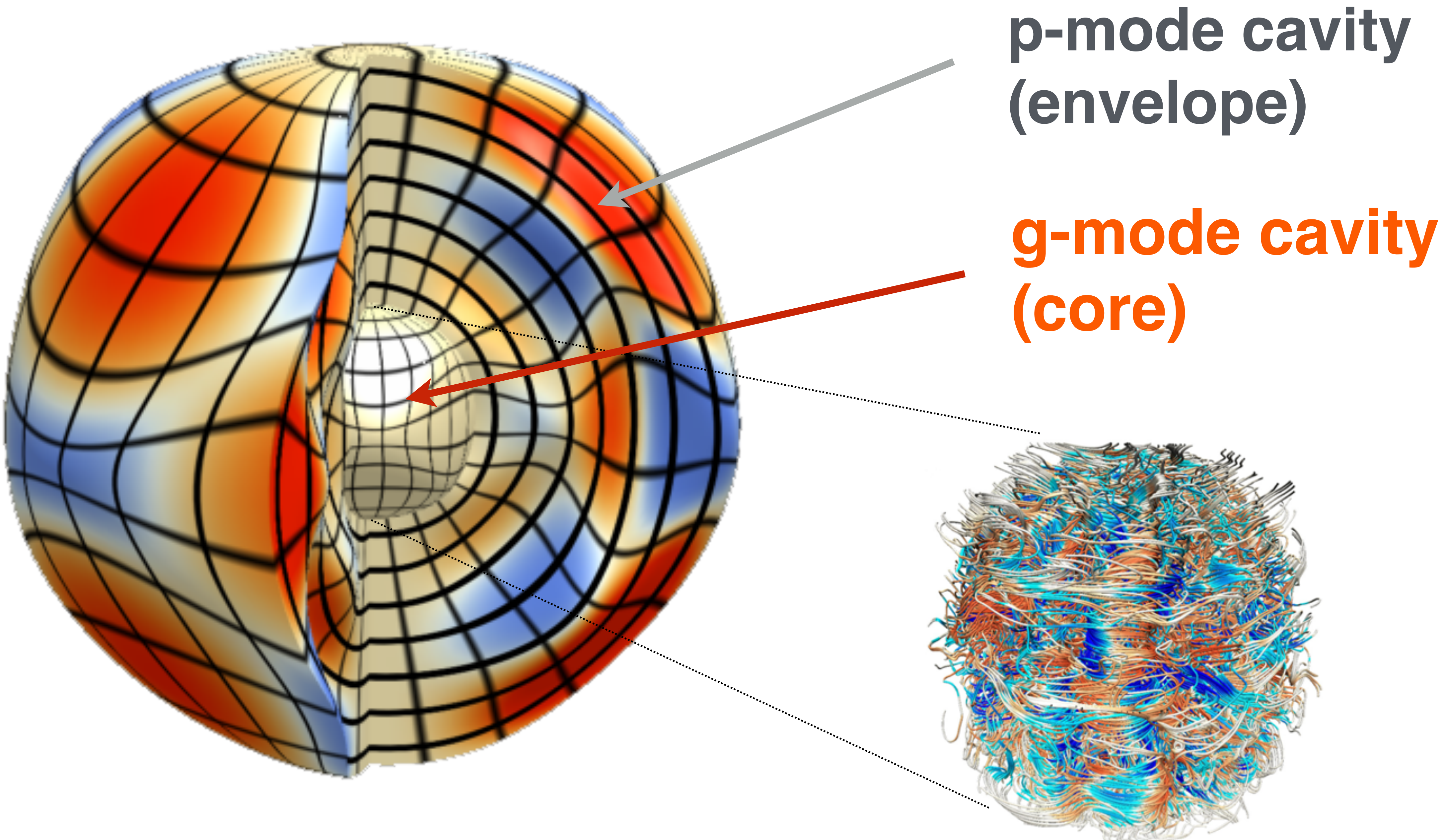
Fuller, Piro & Jermyn 2019

If this holds for massive stars as well, young compact remnants should spin very slowly (exception: chemically homogeneous evolution at low Z)

$$a_{BH} \sim 0$$

This might be consistent with most LIGO/Virgo detections, see Ben Farr's Talk. But see also Zackay+ 2019

# Possible Detection of Strong Internal Magnetic Fields Using




Fuller + Cantiello et al. (Science 2015)
Stello, Cantiello, Fuller et al. (Nature 2016)

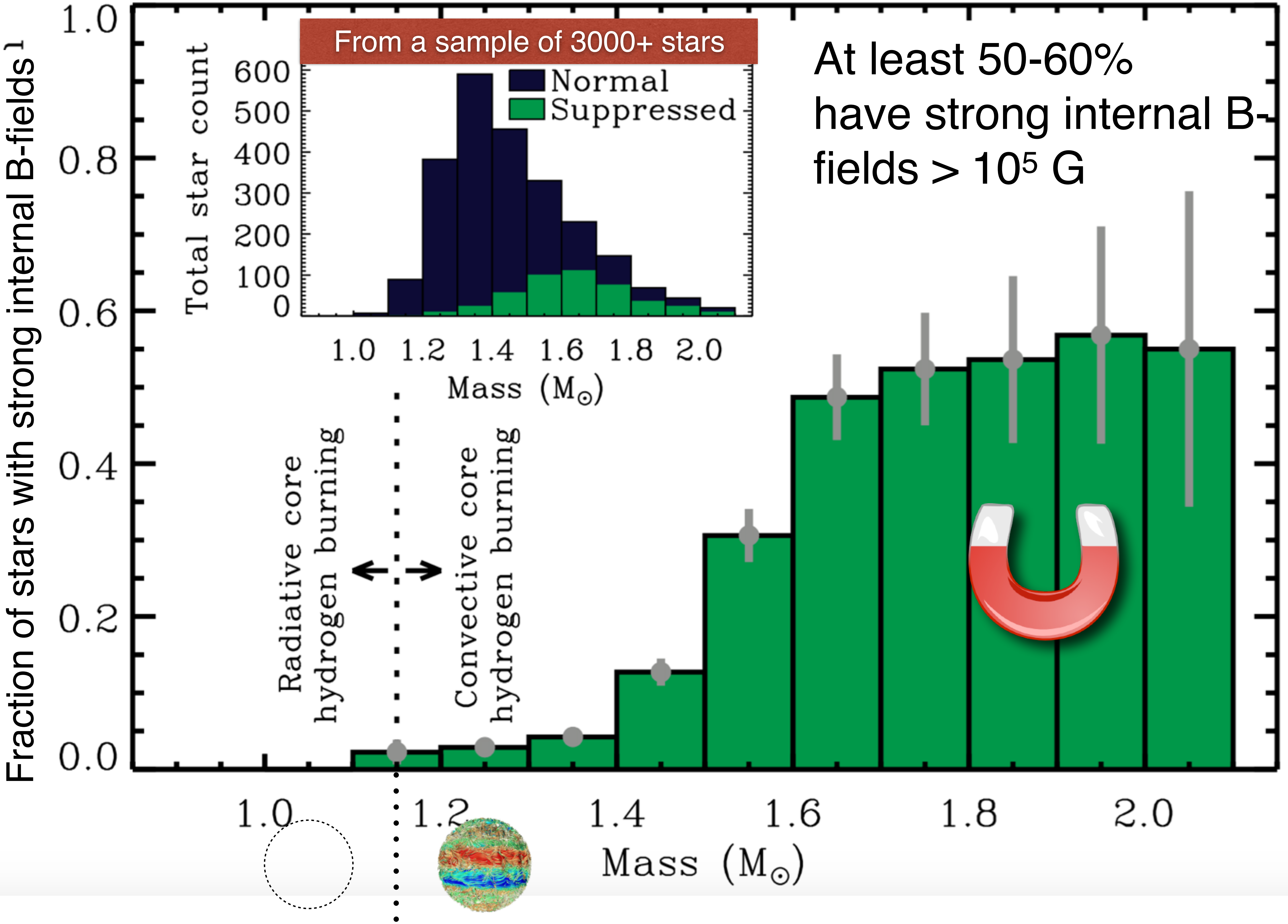
# In the presence of strong B-fields, magnetic tension forces can become comparable to buoyancy

Lorentz Force ~ Buoyancy Force

Critical Field Strength ~$10^5$ G

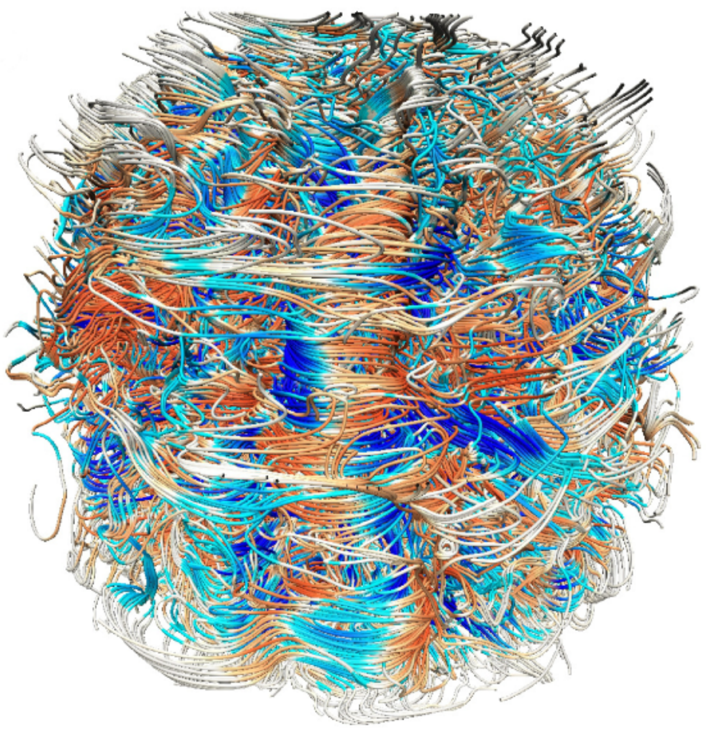
$$B_c = \sqrt{\frac{\pi\rho}{2}}\,\frac{\omega^2 r}{N}$$

Fuller + Cantiello et al. (Science 2015)
Lecoanet, Fuller, MC et al. (2016)
See also Loi & Papaloizou (2017,2018)

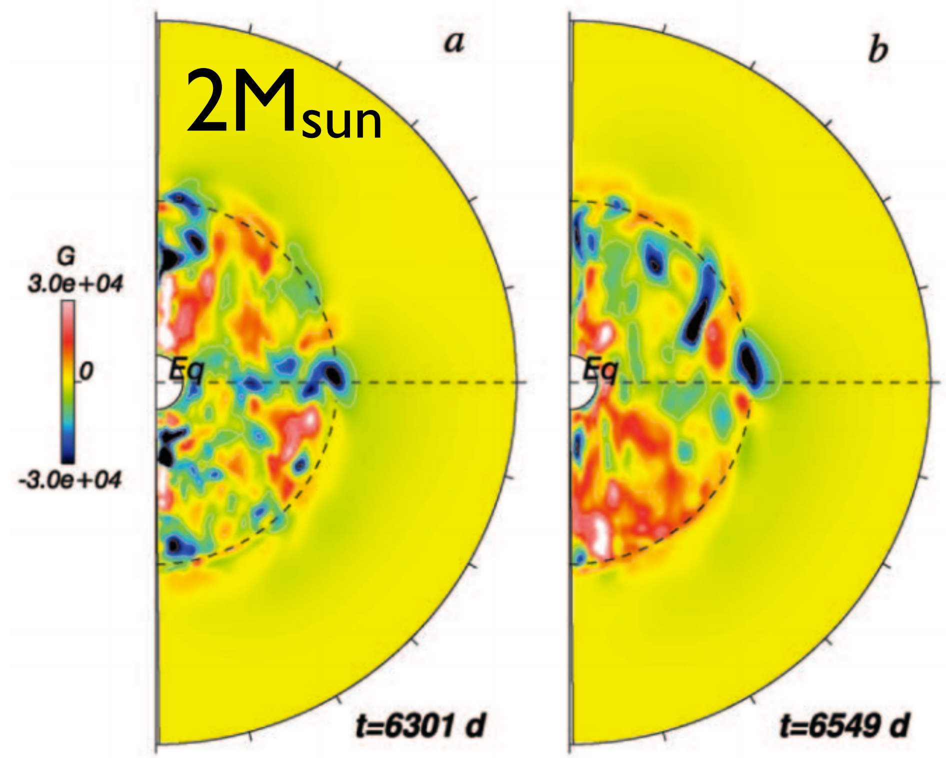



But See also Mosser et al. 2016

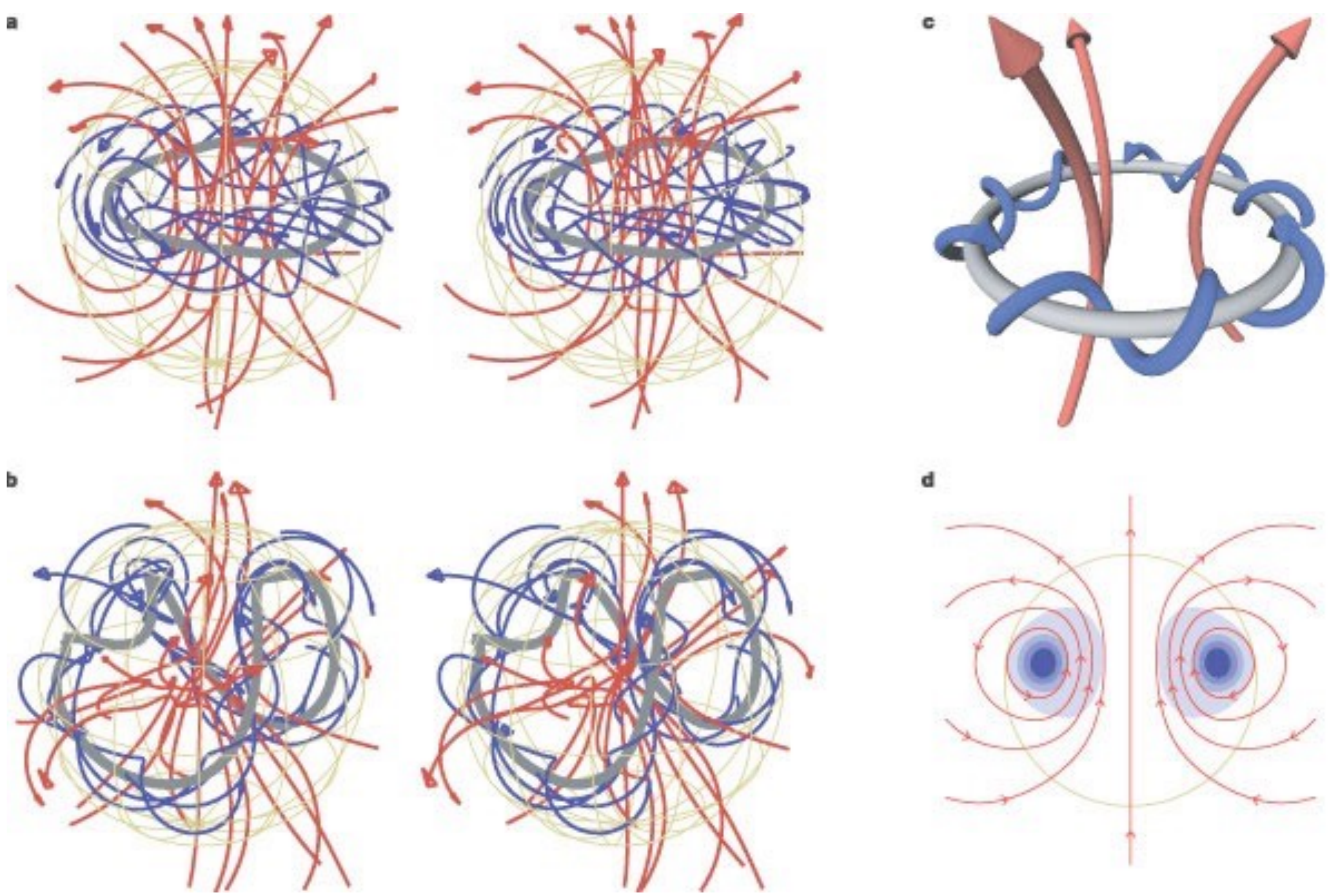
Stello, Cantiello, Fuller et al. (Nature 2016)



Augustson et al. 2016




Brun et al. 2005



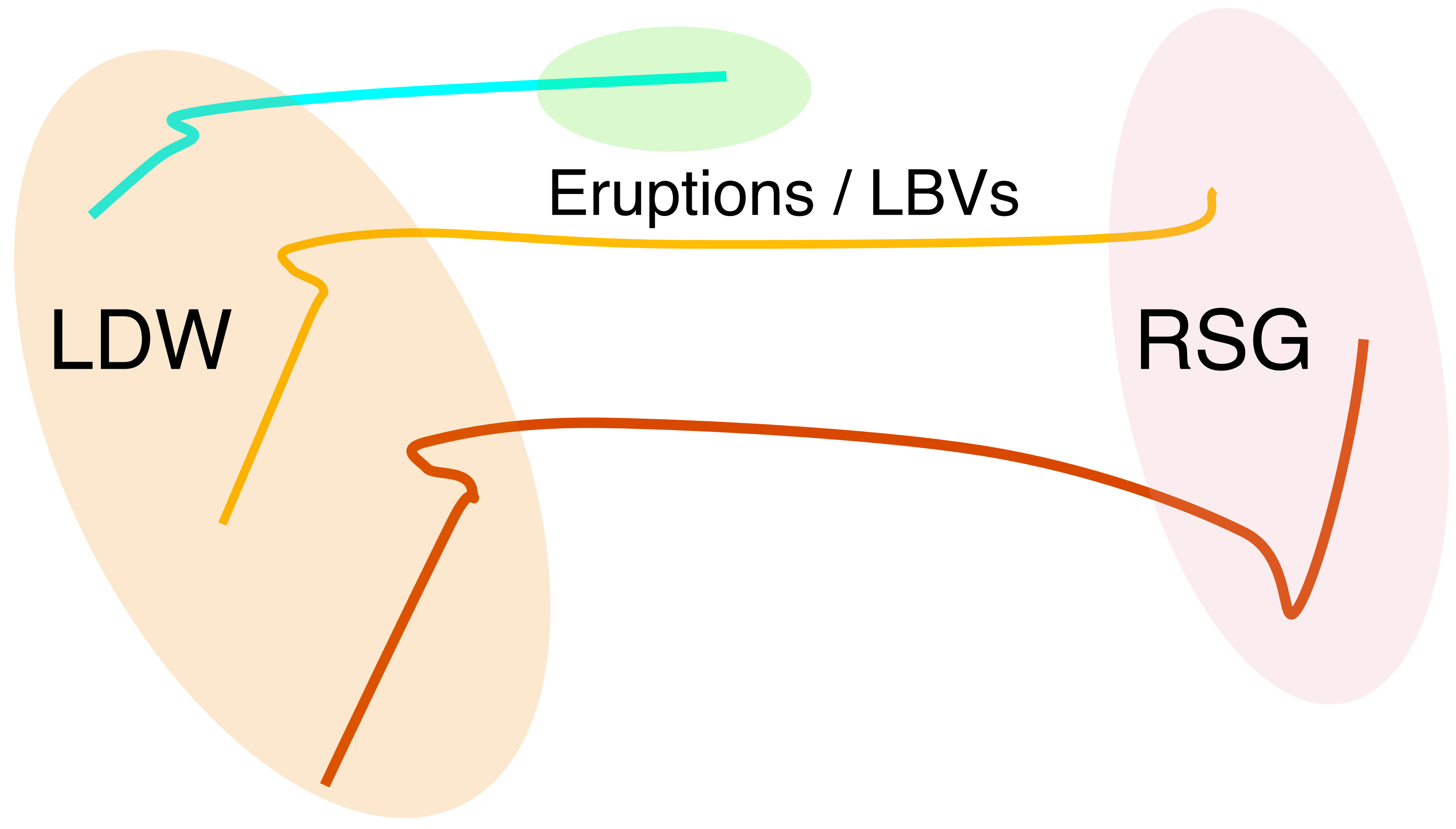

- Convective core dynamos on the MS: **$B_{eq}$~$10^5$ G**
- Magnetic field topology is complex
- Flux conservation can easily lead to B~$10^6$-$10^7$ G on the Red Giant Branch
- Stable magnetic configurations of interlocked poloidal+toroidal fields exist in radiative regions
- If conserved, strongly magnetized remnants

Prendergast 1956, Mestel 1984, Braithwaite & Nordlund 2006, Duez et al. 2010, Bonanno & Urpin 2008,2013

# Massive Stars:
# The most uncertain physics

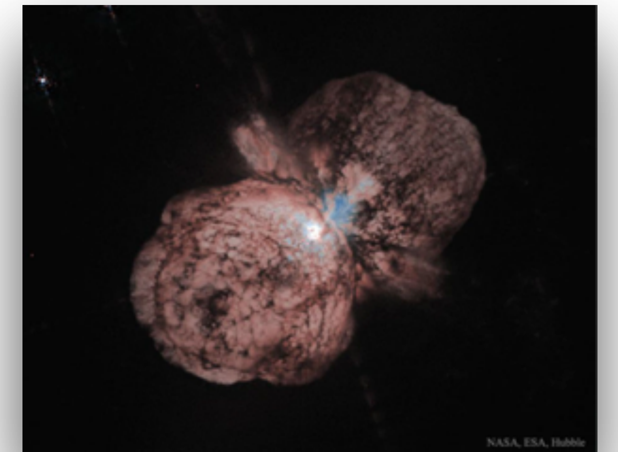
- Stability and energy transport
- Mass loss
- Rotation (Strong internal coupling)
- Magnetic Fields (Strong internal B-fields ubiquitous?)
- Binarity (Most massive stars are in binary systems!)

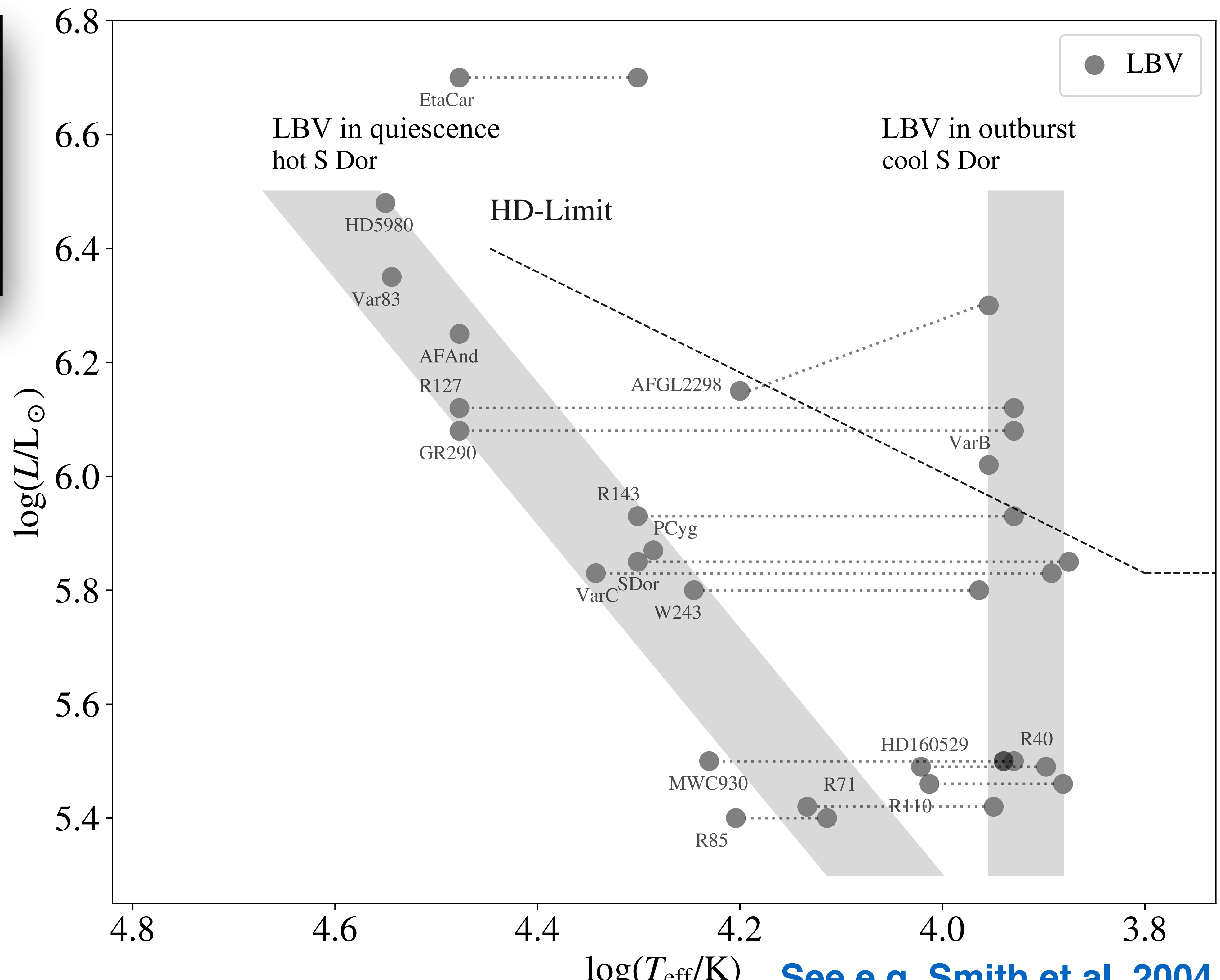
# Mass Loss




- **Line Driven Winds**: affected by wind clumping. Likely overestimated by a factor ~3. Z-dependent
- **Cool (RSG) winds**: Poorly understood. Poorly constrained observationally. Z-dependent?
- **Continuum-driven winds, eruptions**... Not understood

# Unstable Massive Stars: Luminous Blue Variables (LBVs)



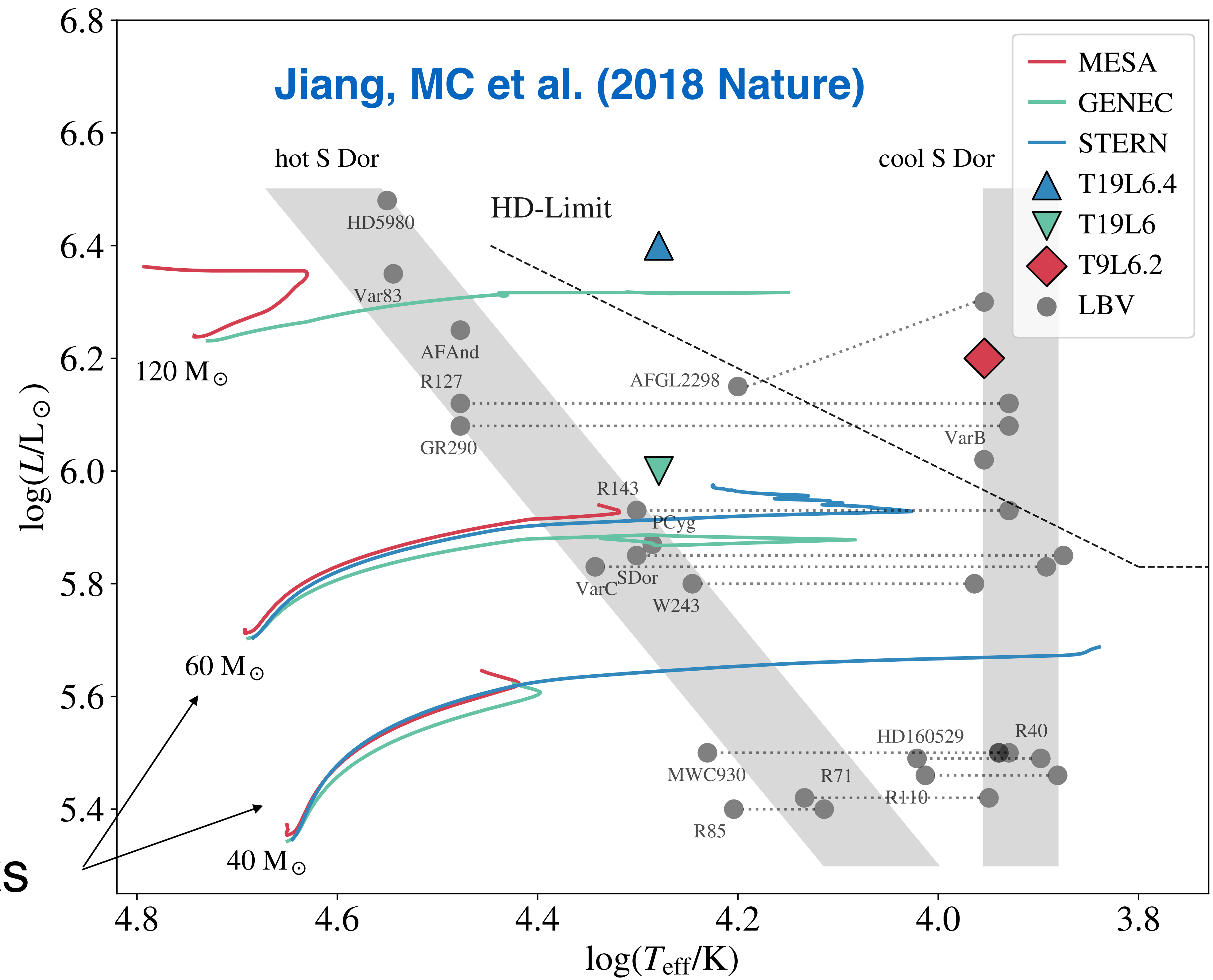




See e.g. Smith et al. 2004

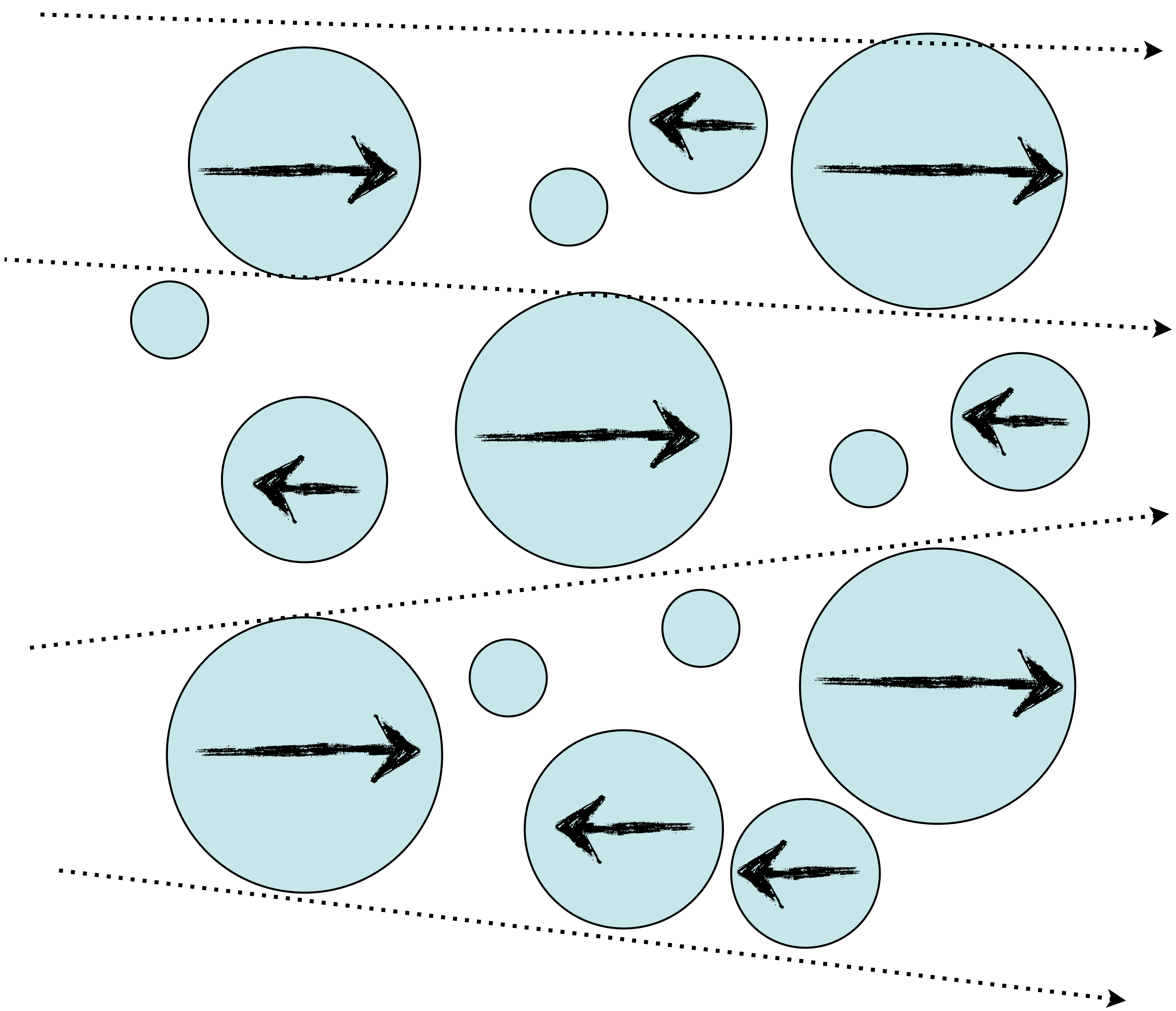
# Unstable Massive Stars: Luminous Blue Variables (LBVs)

Polygons: Location of 3D models

1D Stellar Evolution Tracks



# Different regimes in Radiation Dominated Convection



Diff Rad Flux

Advection Flux
(“convection”…)

$$F_{\rm dif} \sim \frac{a_r T^4 c}{\tau}$$

$$F_{\rm adv} \sim c_s a_r T^4$$

Critical optical depth

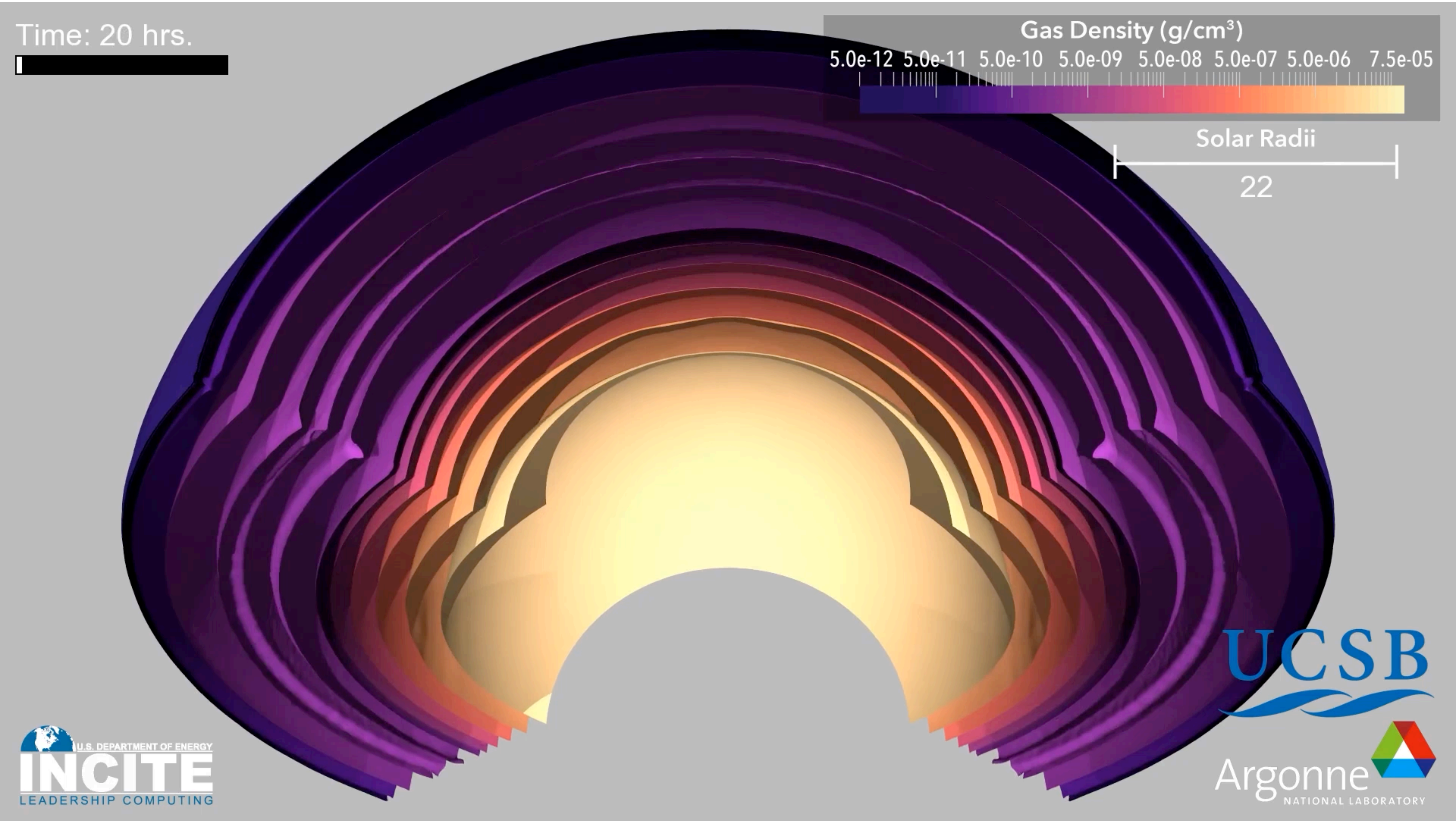
$$\tau_c = c/c_s$$

Optical depth where radiation diffusion timescale = dynamical timescale

**Jiang, MC et al. 2015**

Mixing Length Theory not supposed to work!

# 3D Athena++, Radiation HD (VET)




Jiang, MC et al. (2018 Nature)

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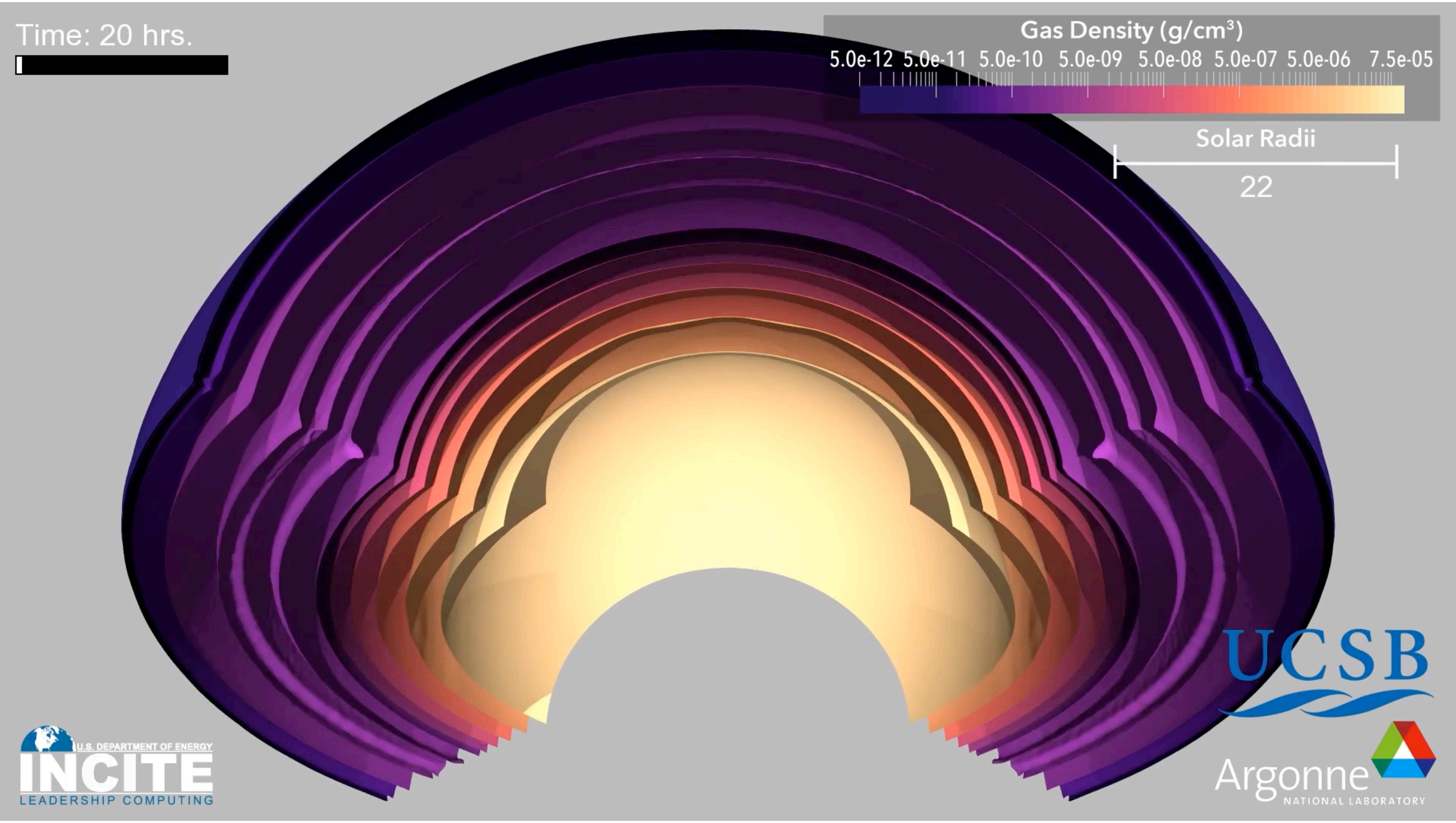


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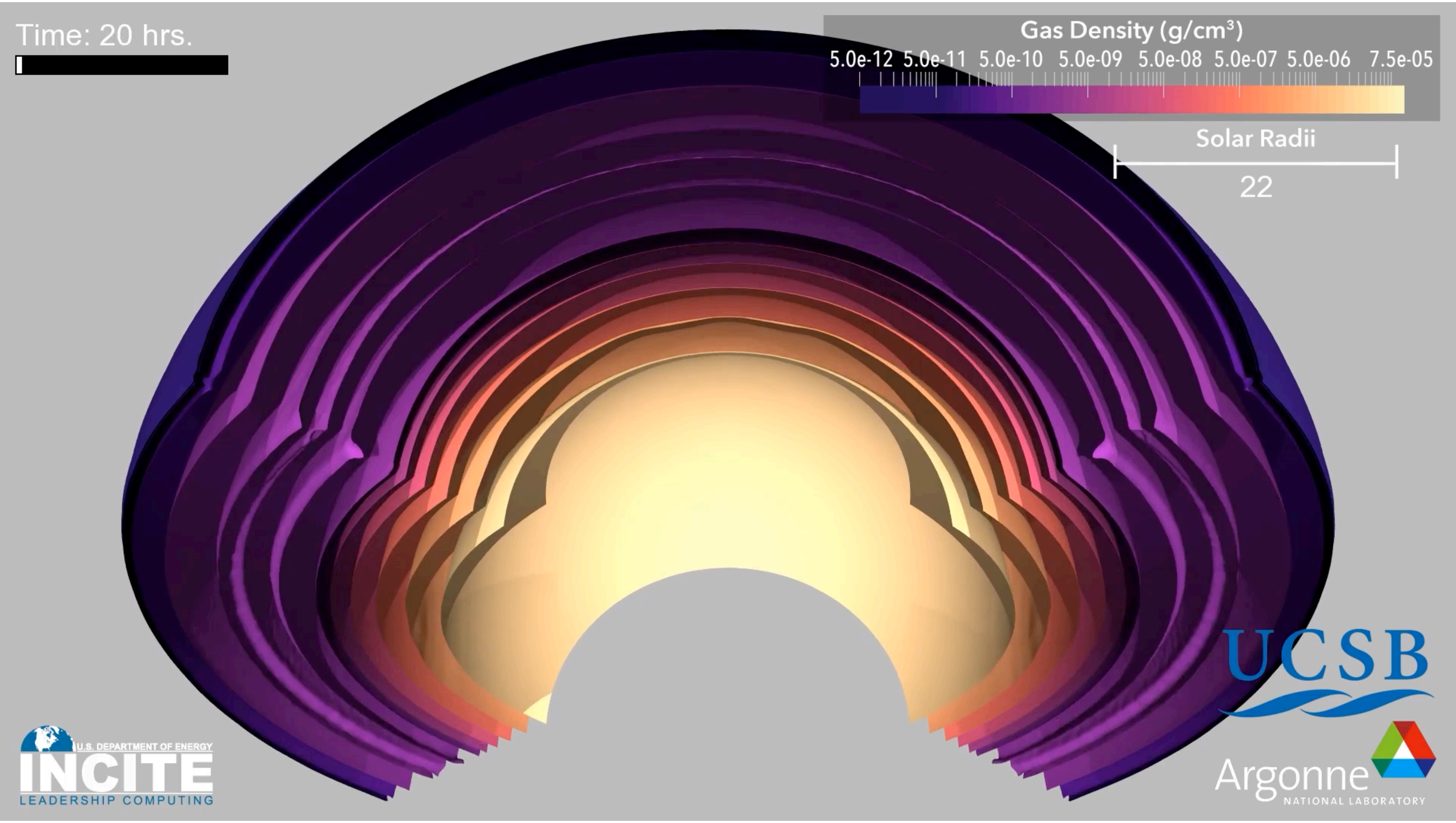
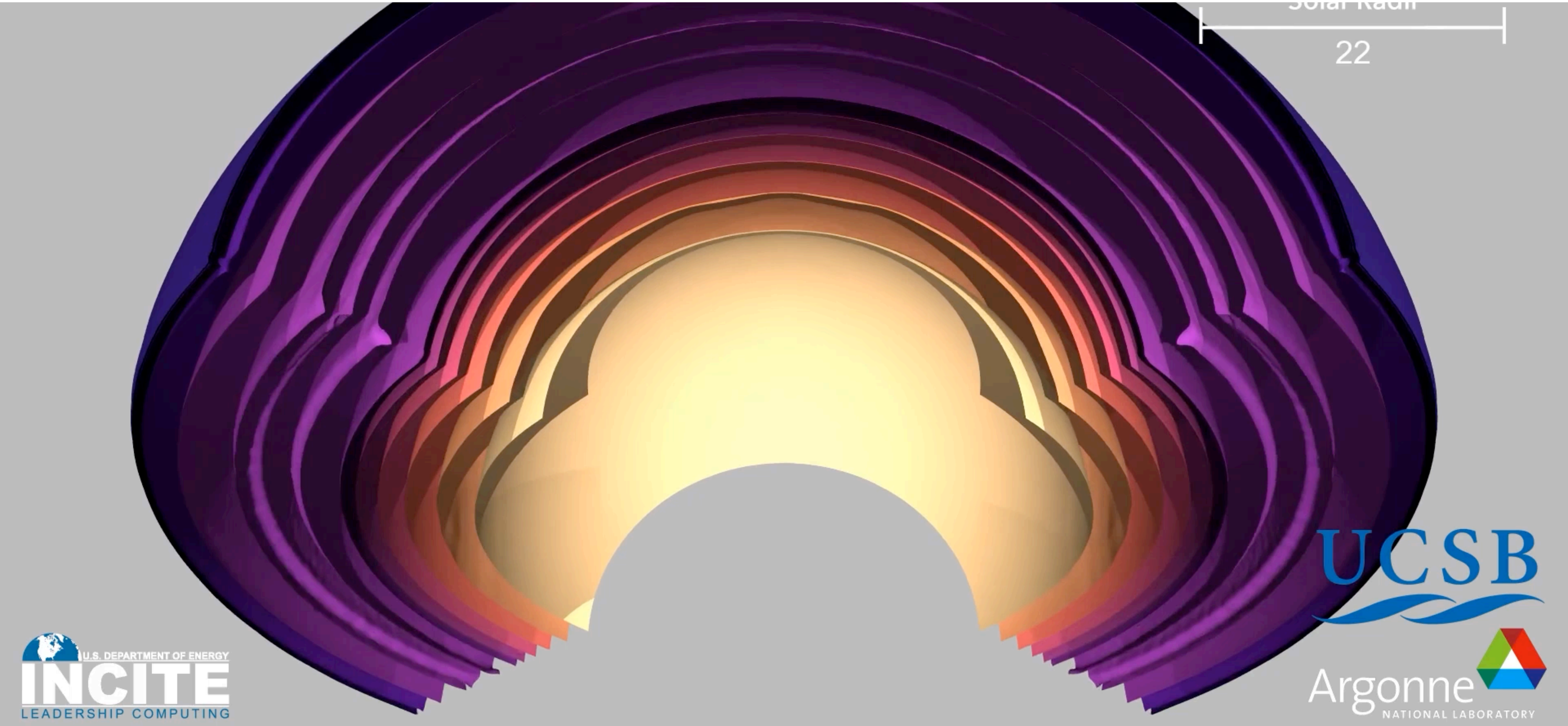



Jiang, MC et al. (2018 Nature)

$$\approx 5 \times 10^{-6} M_{\odot}/\mathrm{yr}$$

(not including line driving)

# Our simulations can naturally reproduce the HRD location and mass loss properties of (some) LBVs during outburst




**Jiang, MC et al. (2018 Nature)**

$$\approx 5 \times 10^{-6} M_{\odot}/\mathrm{yr}$$

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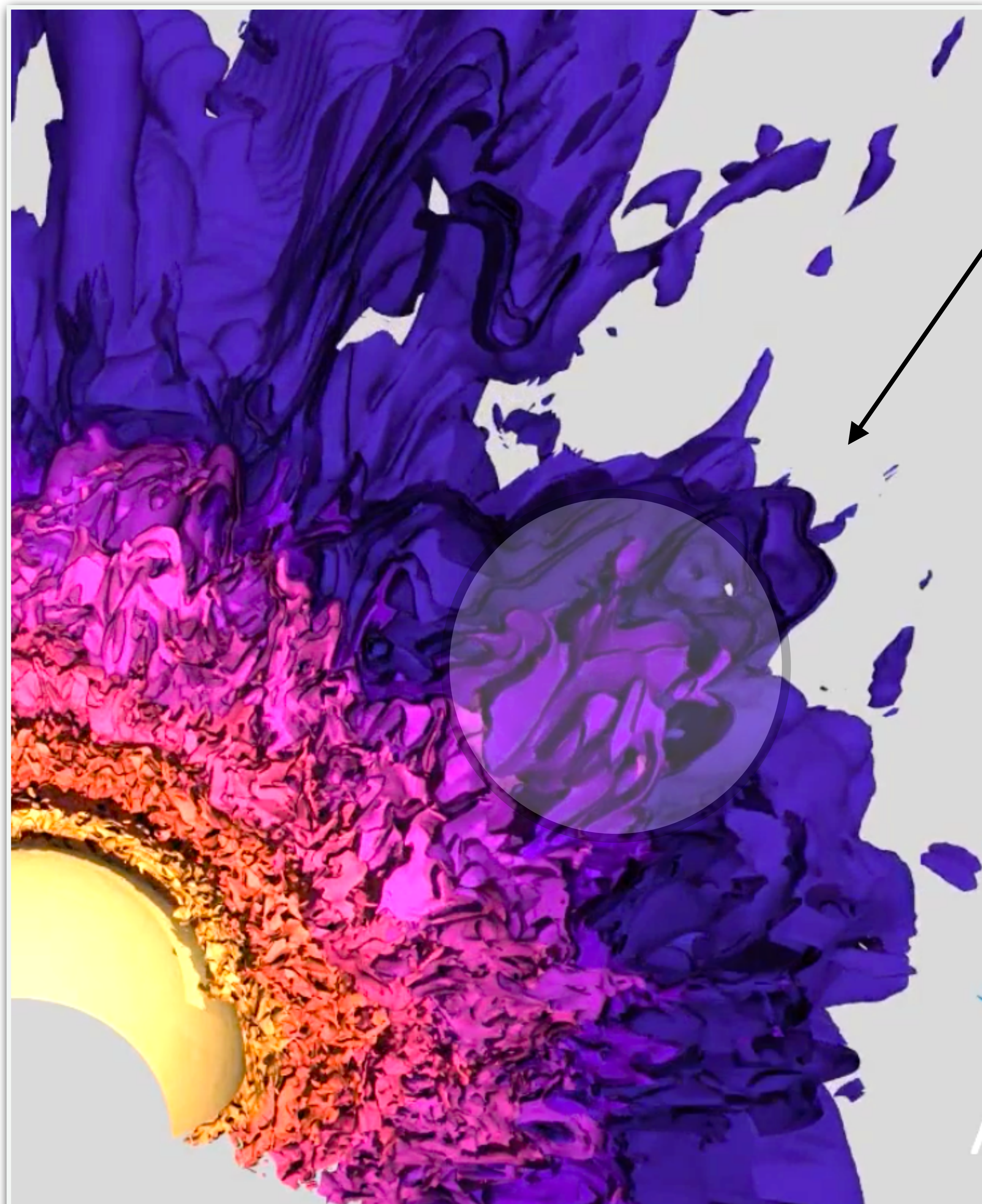
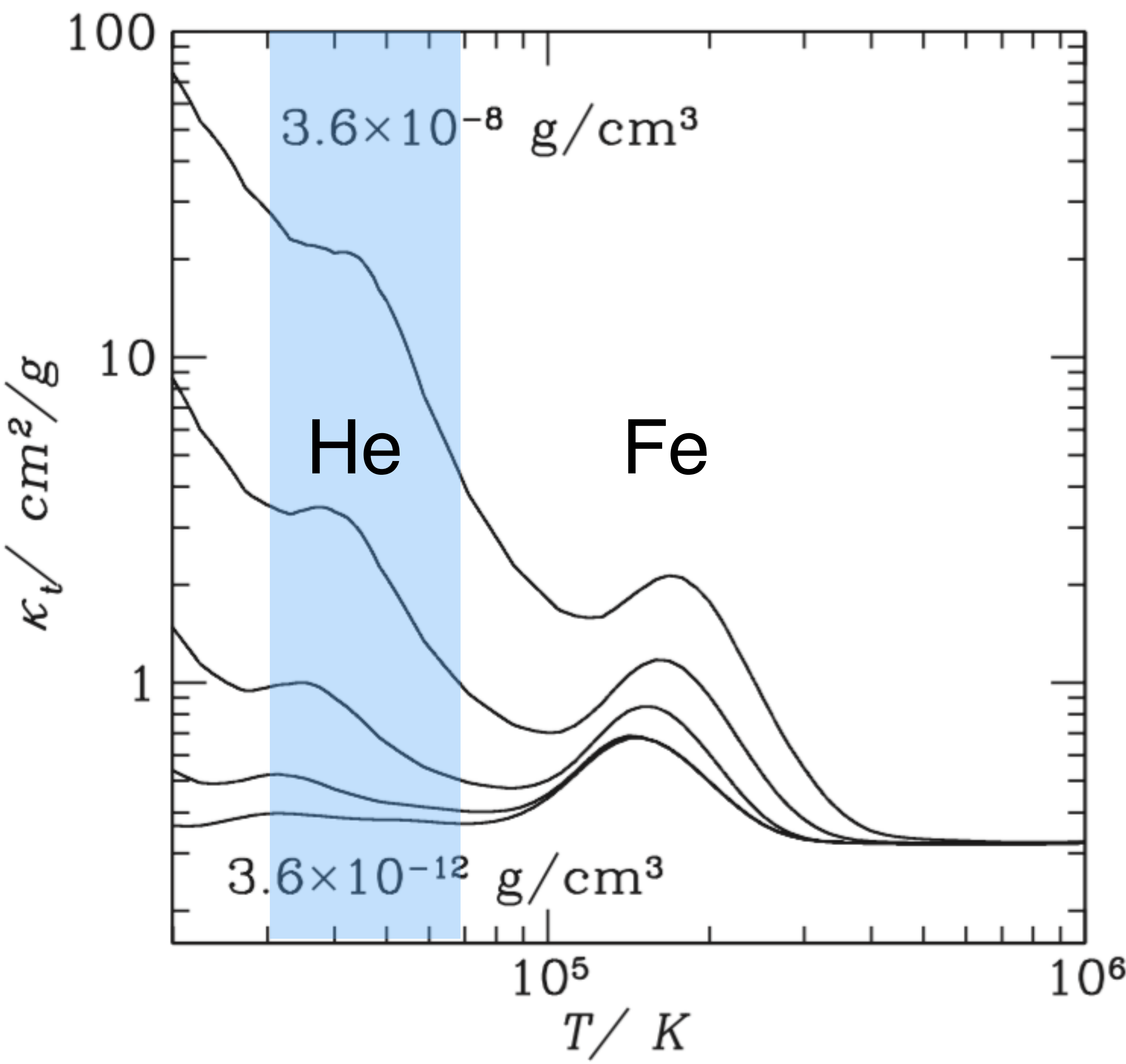
# The role of He opacity peak

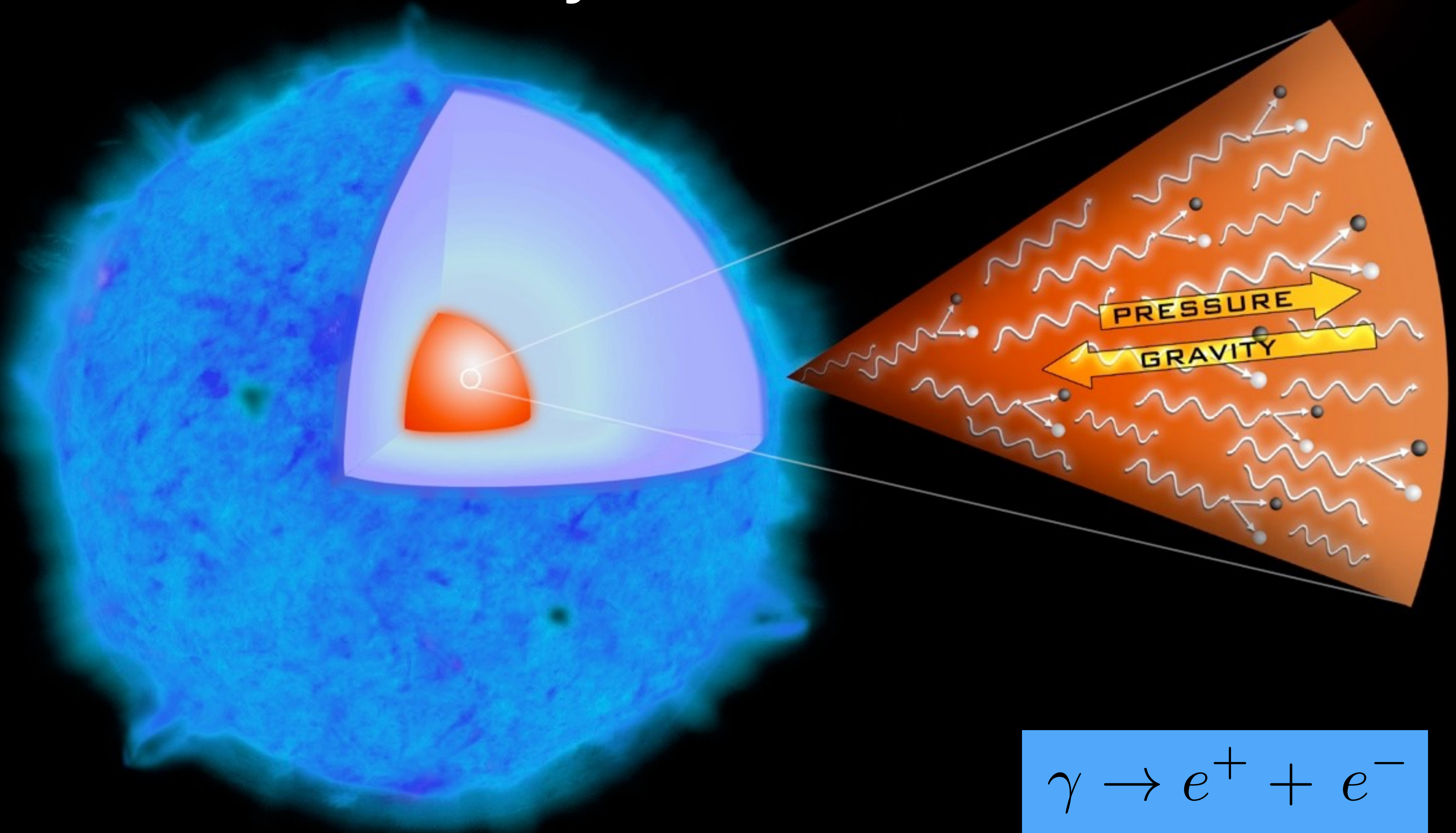


High density clumps rise, expand and cool, reaching low temperatures and relatively high densities. High He opacity



# Pair Instability

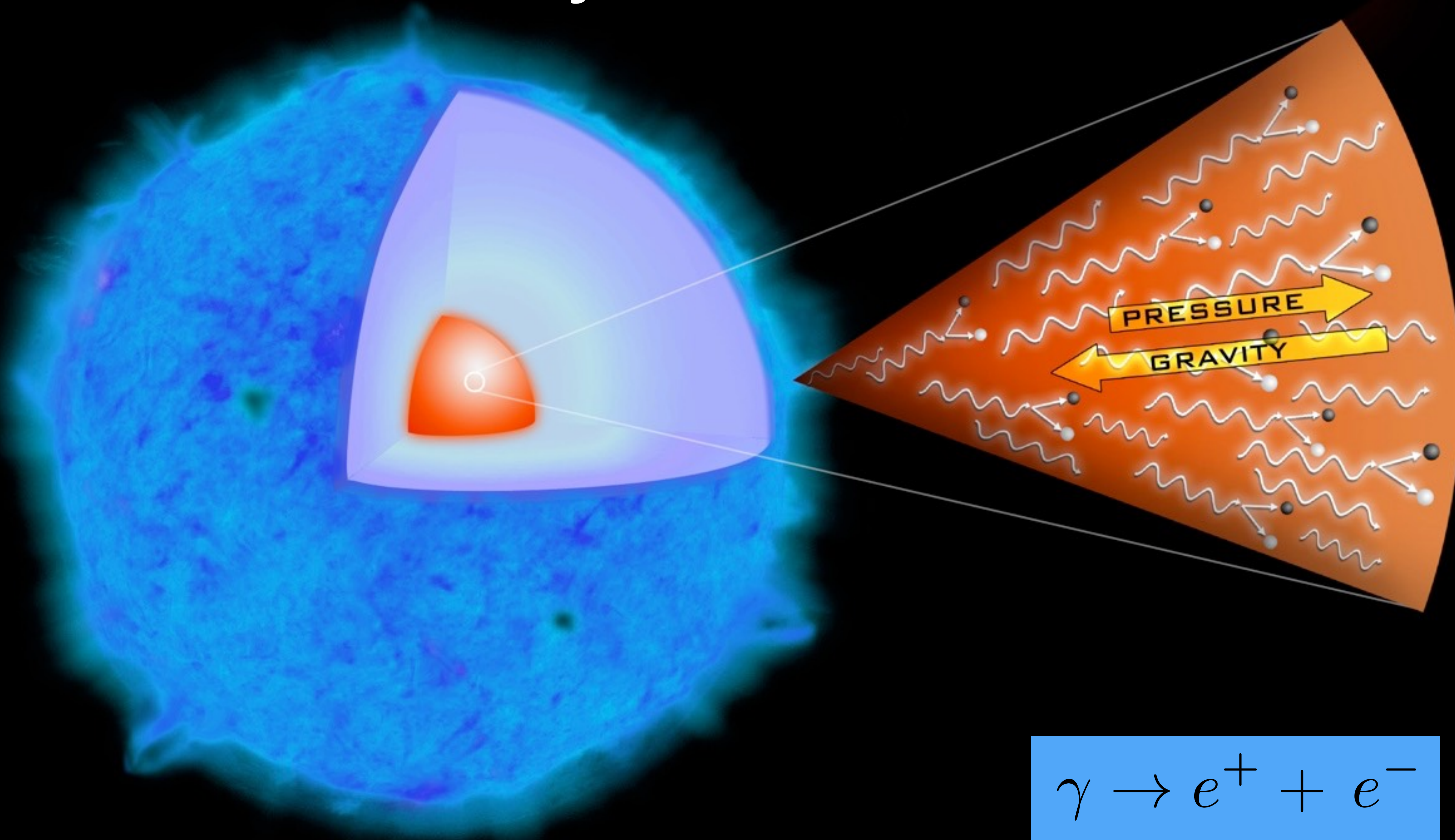
# Pair Instability




$$\gamma \rightarrow e^{+} + e^{-}$$

NASA/CXC/M

# Pair Instability




$$\gamma \rightarrow e^+ + e^-$$

$$\kappa T \approx h\nu > 2m_e c^2 \Rightarrow T > 10^9 K$$

NASA/CXC/M

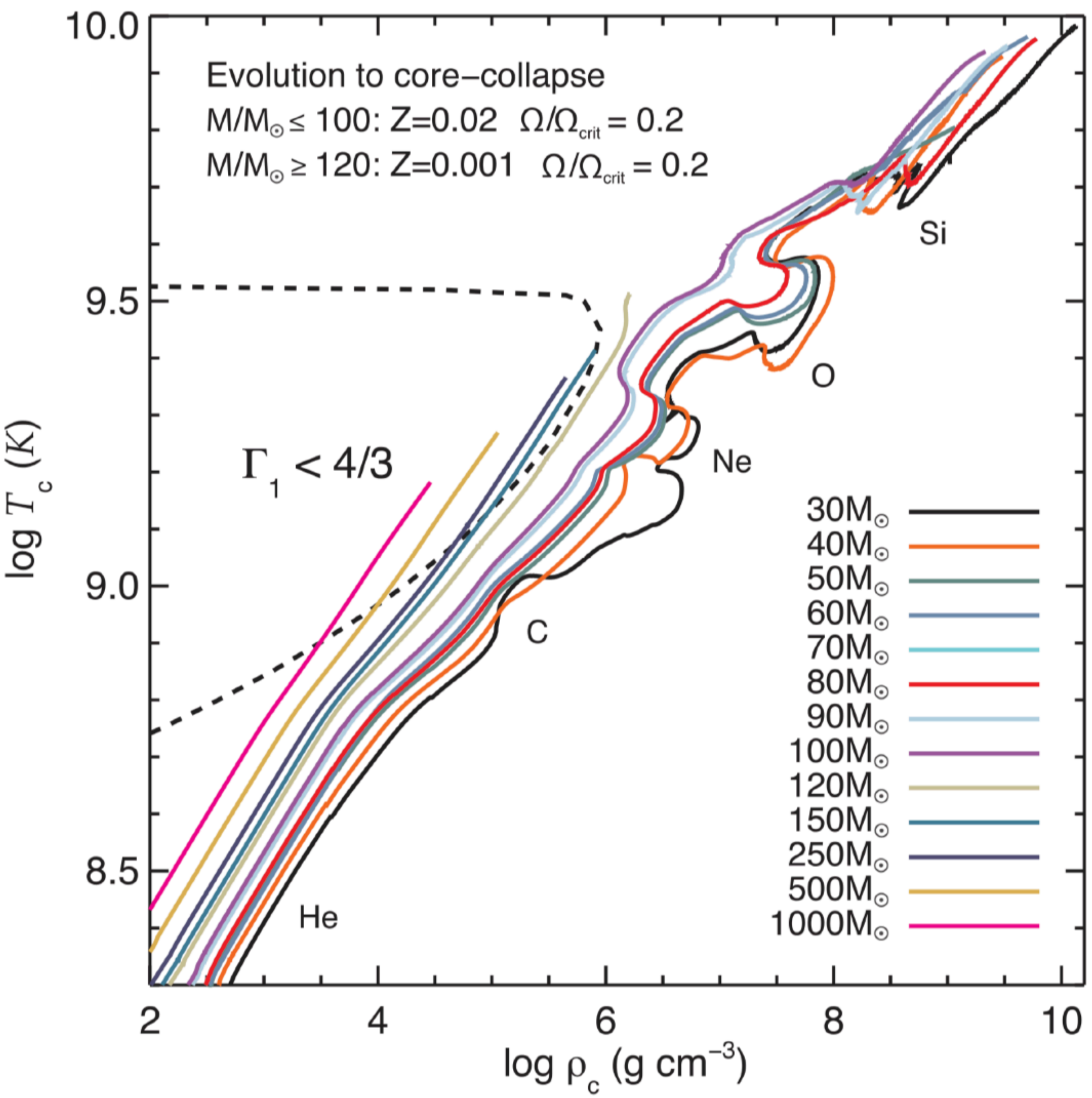
# Pair Instability

$$\gamma \rightarrow e^{+} + e^{-}$$

Since Massive stars are radiation dominated they are prone to become dynamically unstable

Pair-production lowers the adiabatic index and leads to a thermonuclear runaway (PISN), or strong pulsations (PPISN)

Mass of the He core largely determines if a star undergoes PI

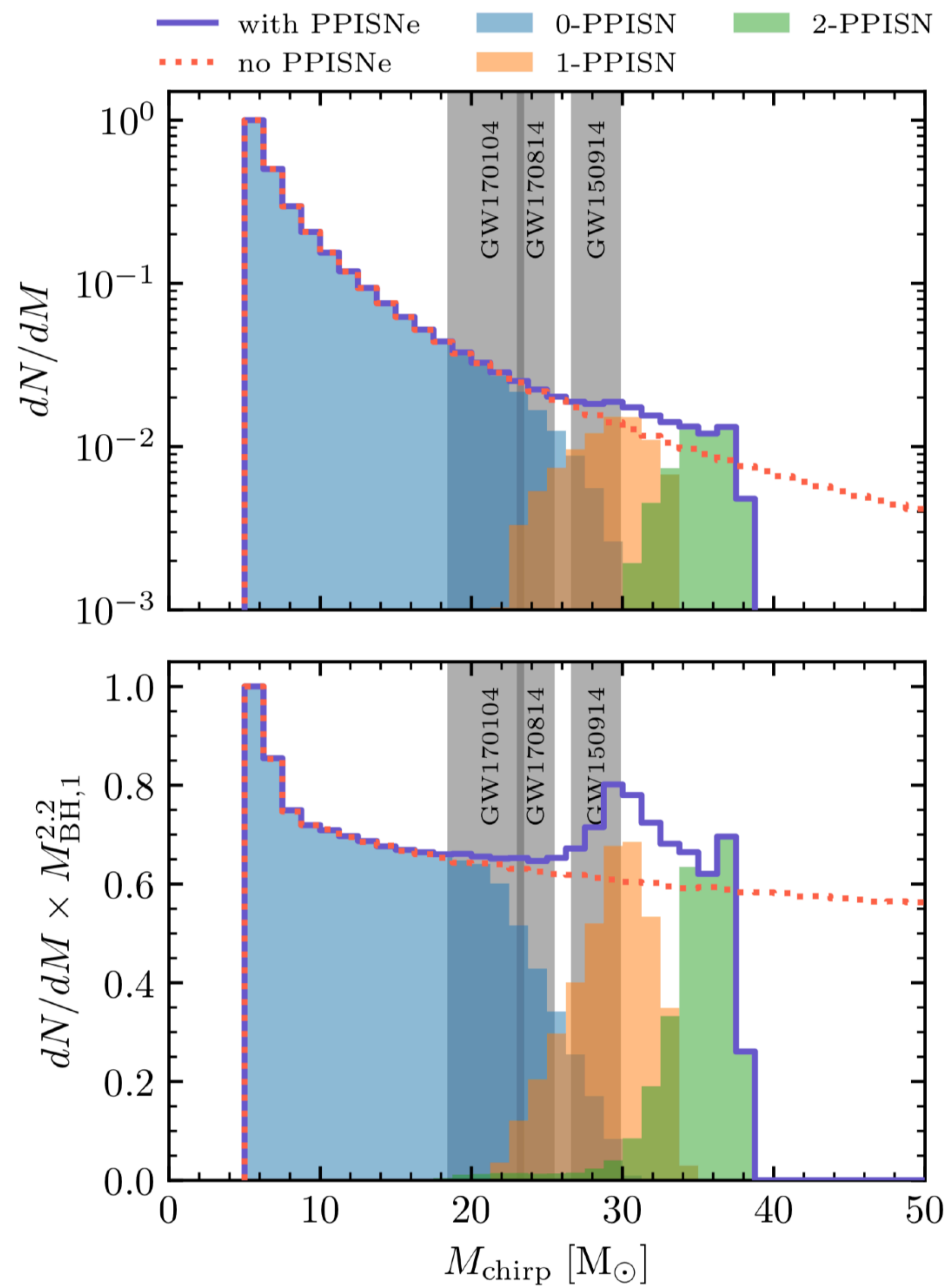



**Paxton et al. 2013**

**E.g.: Barkat+ 1967, Woosley & Weaver 1986, Langer+ 2007, Heger & Woosley 2002, Yoshida+ 2016, Woosley 2017, Marchant+ 2019**

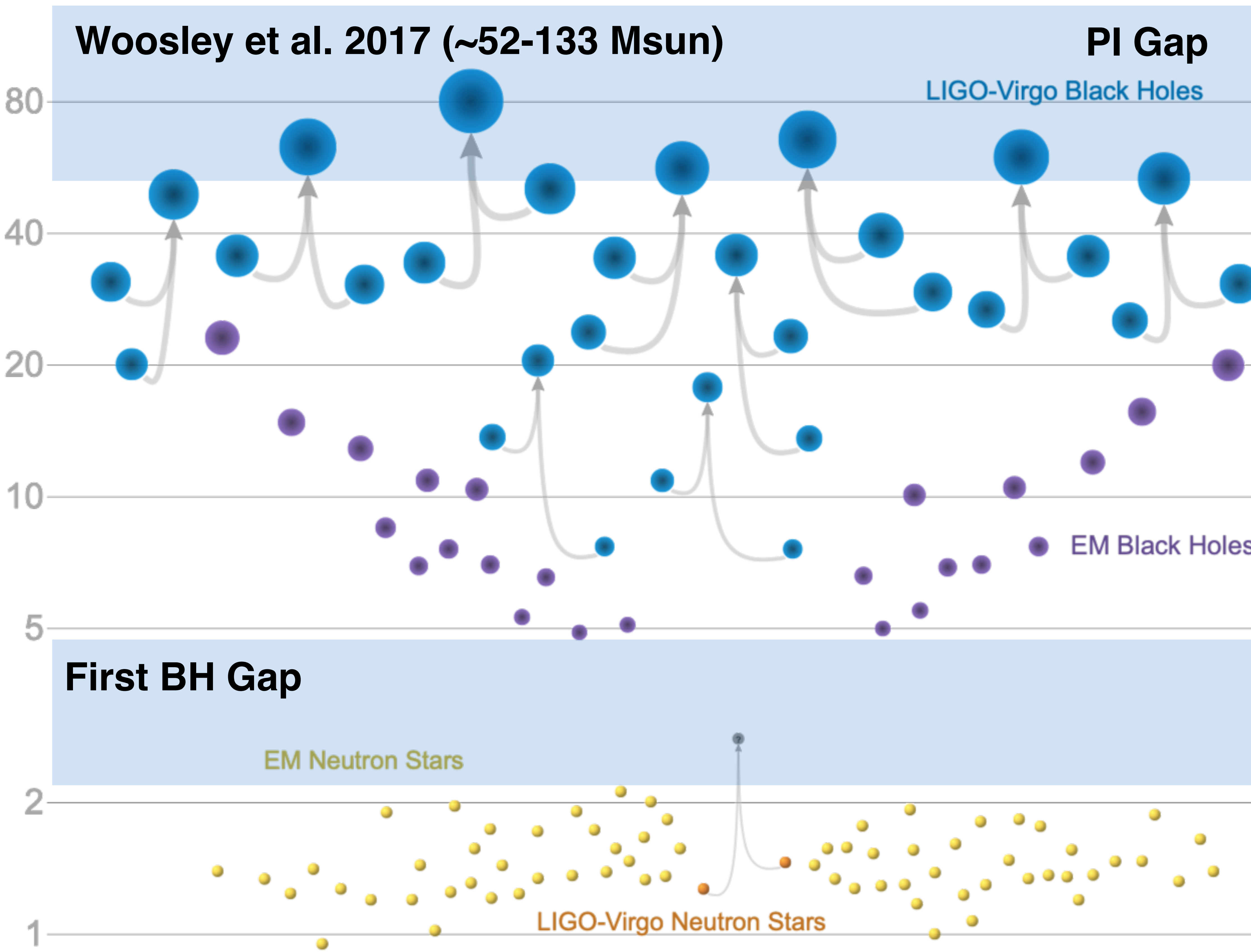
# PISN Gap and PPISN pileup

“No black holes between 52 and 133 $M_{Sun}$ are expected from stellar evolution in close binaries”
Woosley 2017




Marchant et al. 2019

# BH Mass Gaps




See Chris' Talk

Credit: LIGO/Virgo/Northwestern Frank Elavsky

# Conclusions

1. Massive stars evolution still very uncertain. Even for single stars
2. Despite uncertainties, most compact remnants are expected to rotate very slowly. Many might be strongly magnetized
3. Mass loss biggest uncertainty. First 3D global radiation hydro calculations used to study stability and mass loss in very luminous stars
4. Physics of PISN and PPISN fairly well understood. Prediction for a gap in BH masses between ~50-130 Msun

# Thanks!

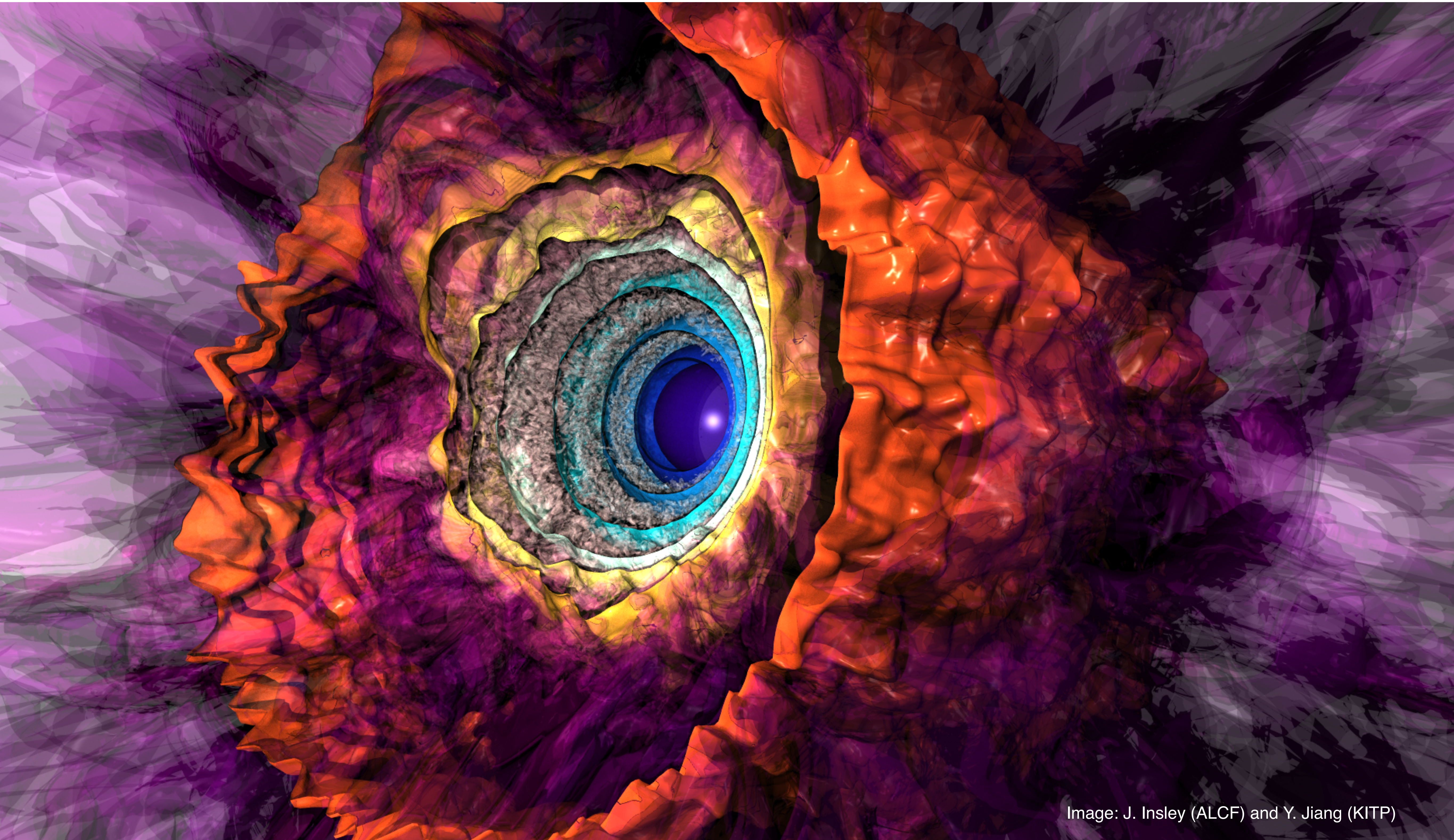


Image: J. Insley (ALCF) and Y. Jiang (KITP)