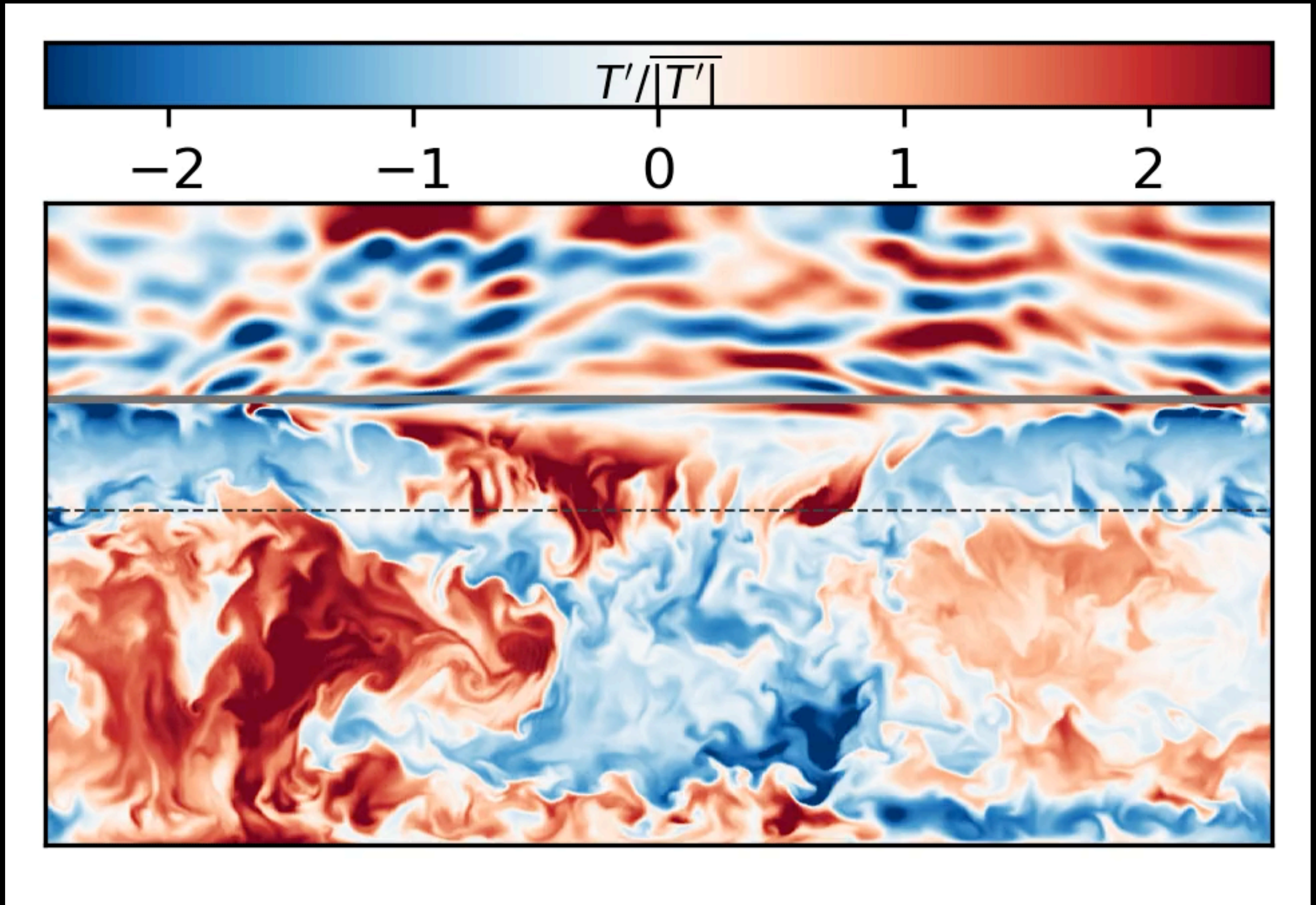
A modern mystery in stellar convection ... & Dedalus is a flexible tool.



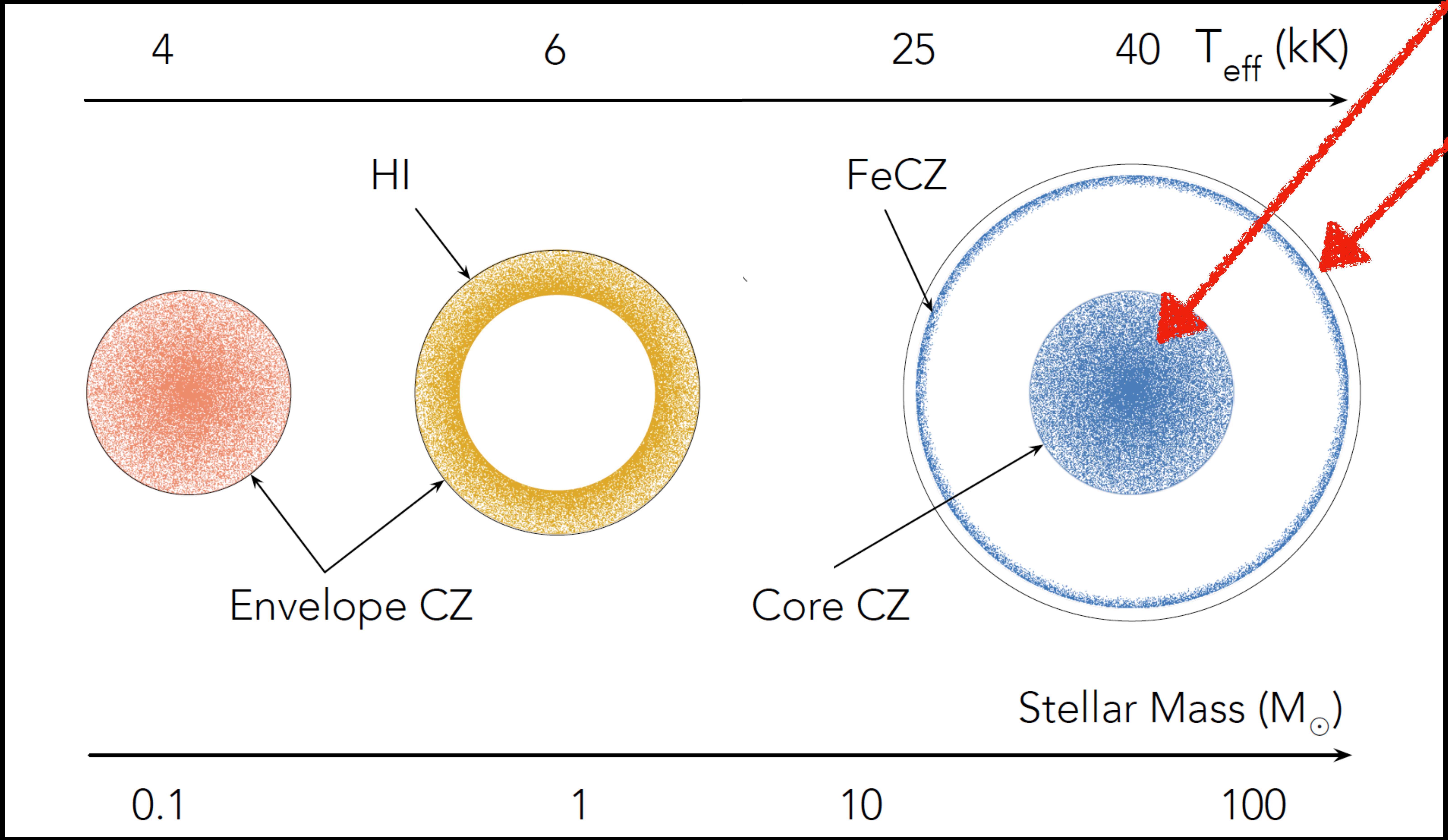
Evan Anders
CIERA Postdoctoral Fellow
Northwestern University

I am interested in convection.

I am interested in convection.

Convection happens in stars.

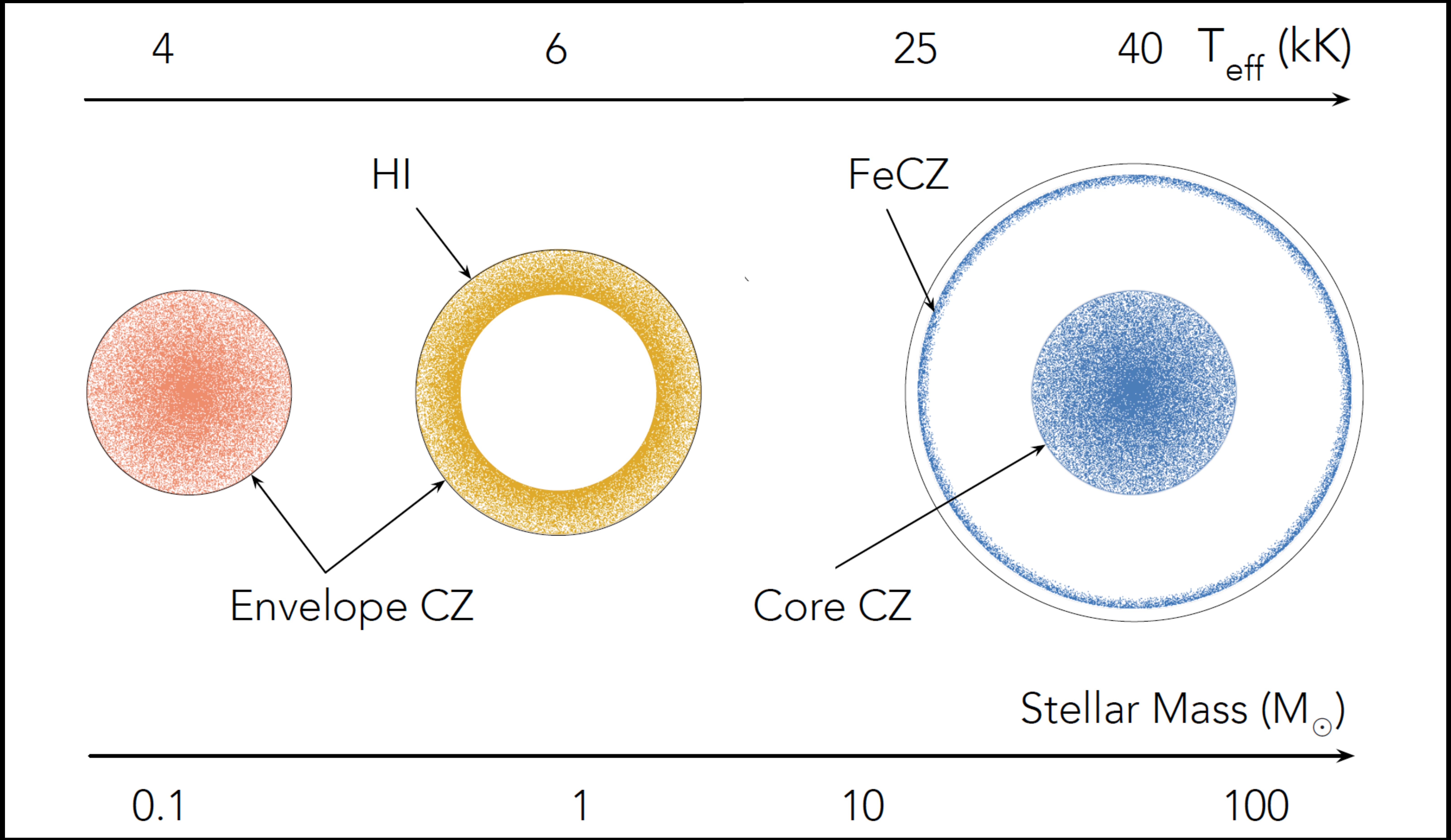
Shaded areas are convection



[Jermyn, Anders et al 2022 arxiv:2206.00011]

Stellar convection is diverse

It spans a broad range of your favorite fluid number.



E.g., the Rossby number

$$\mathrm{Ro} = \frac{\tau_{\mathrm{rot}}}{\tau_{\mathrm{conv}}}$$

Ro measures Rotational constraint.

Smaller Ro = rotation matters more.

[Jermyn, Anders et al 2022 arxiv:2206.00011]

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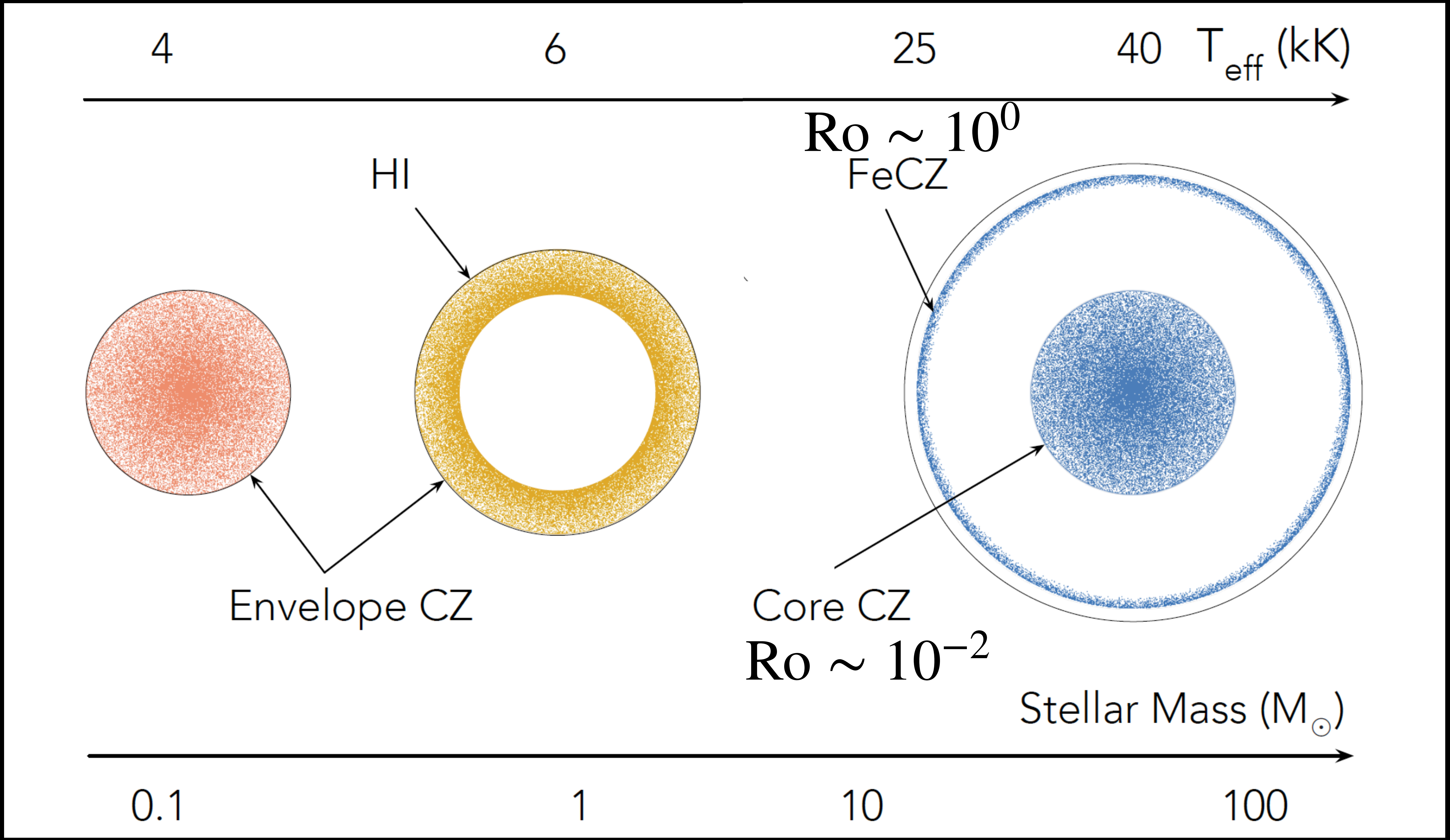

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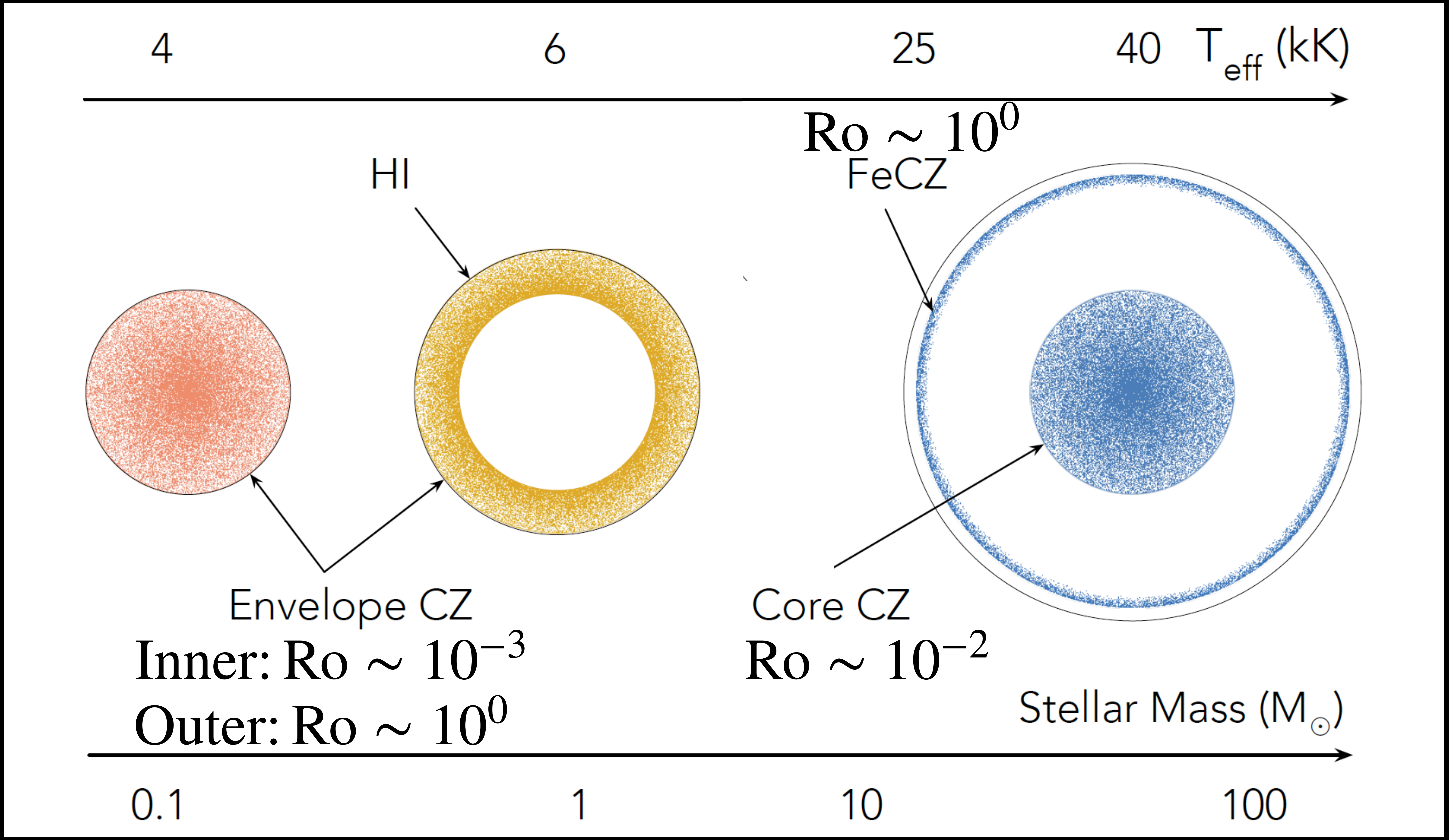

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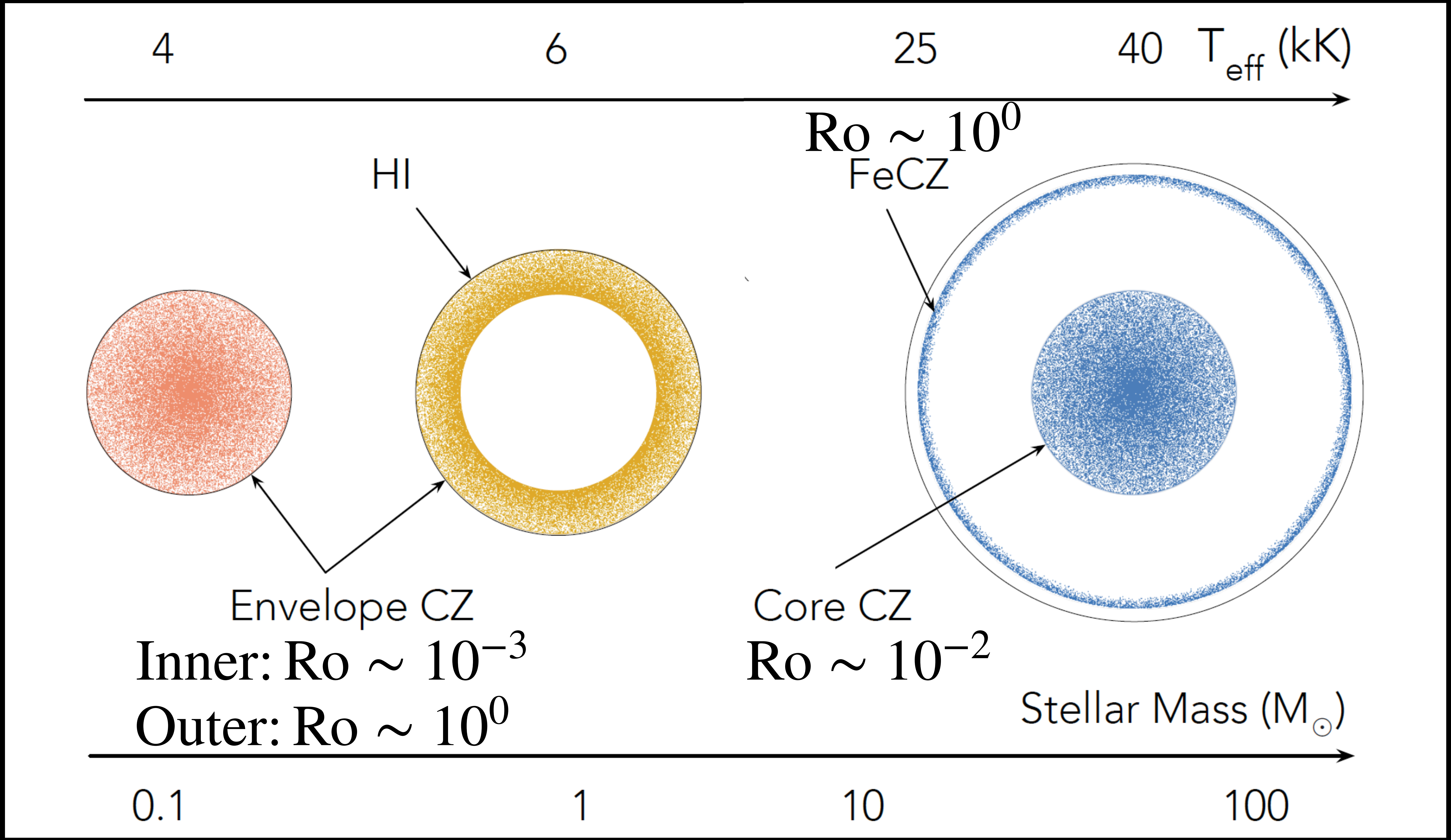


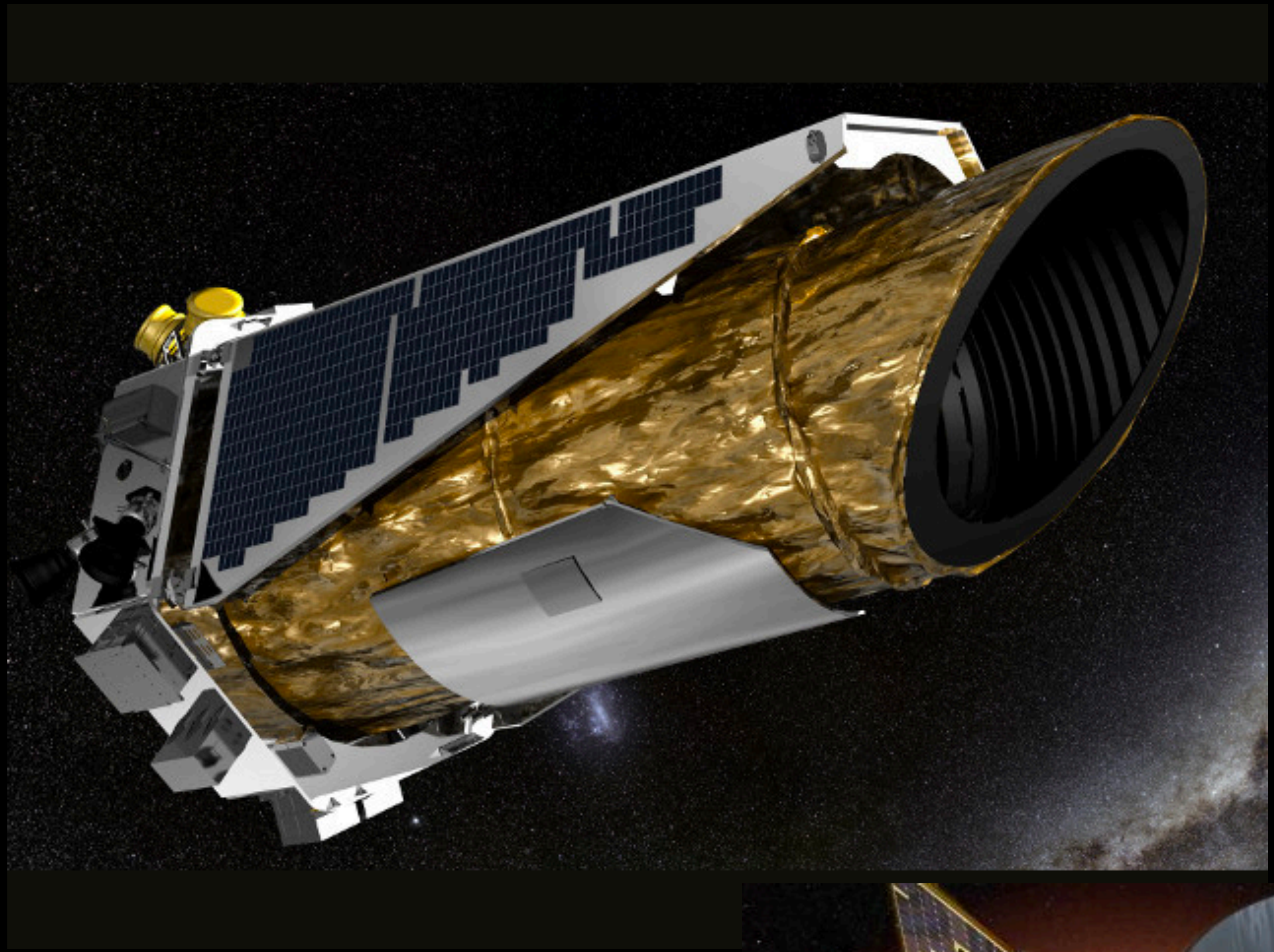
[Jermyn, Anders et al 2022 arxiv:2206.00011]

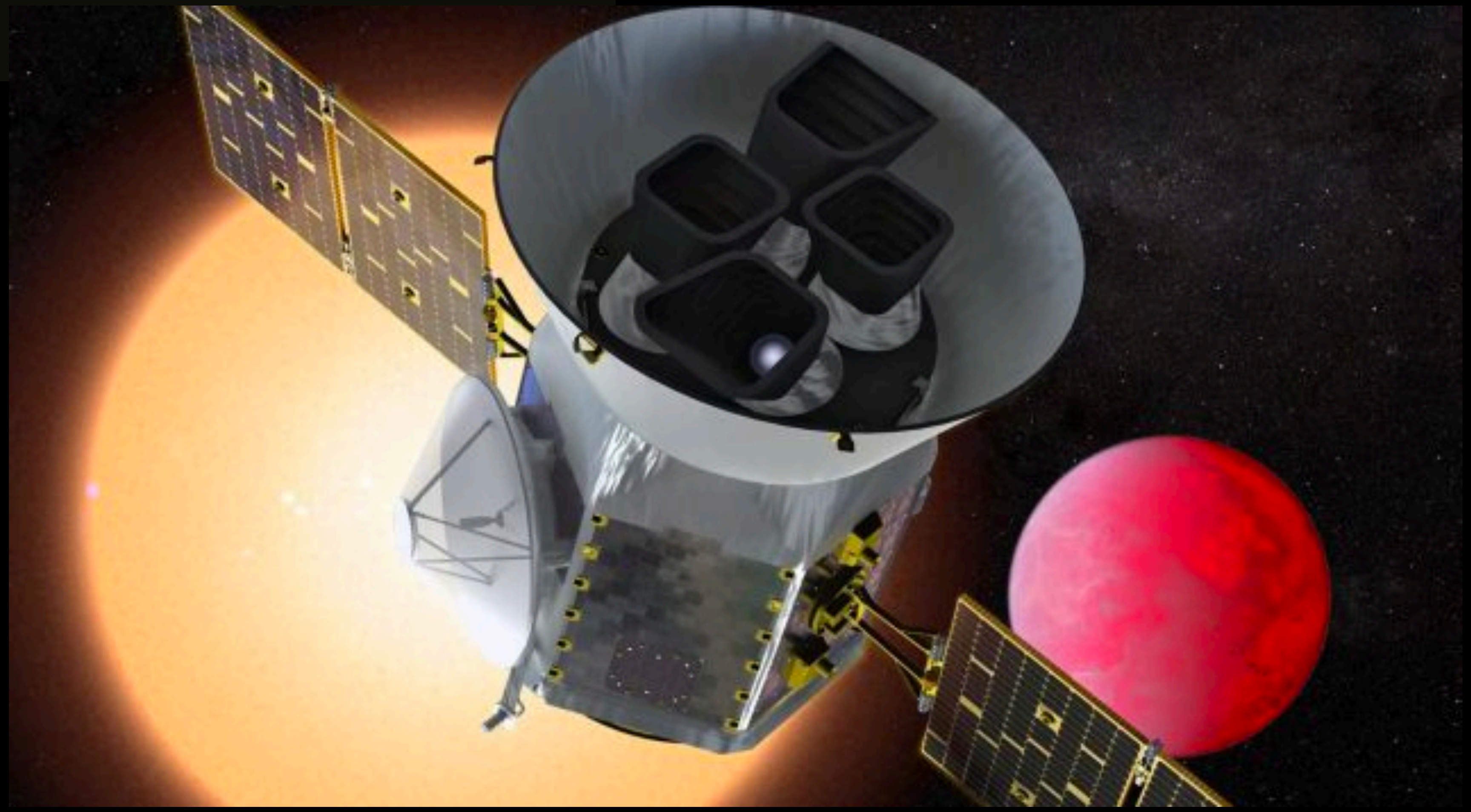
You can play this game with any non dimensional number.

Almost every regime is important in some star.

Why now?

Observations: Kepler, TESS, and (soon! 2026) PLATO

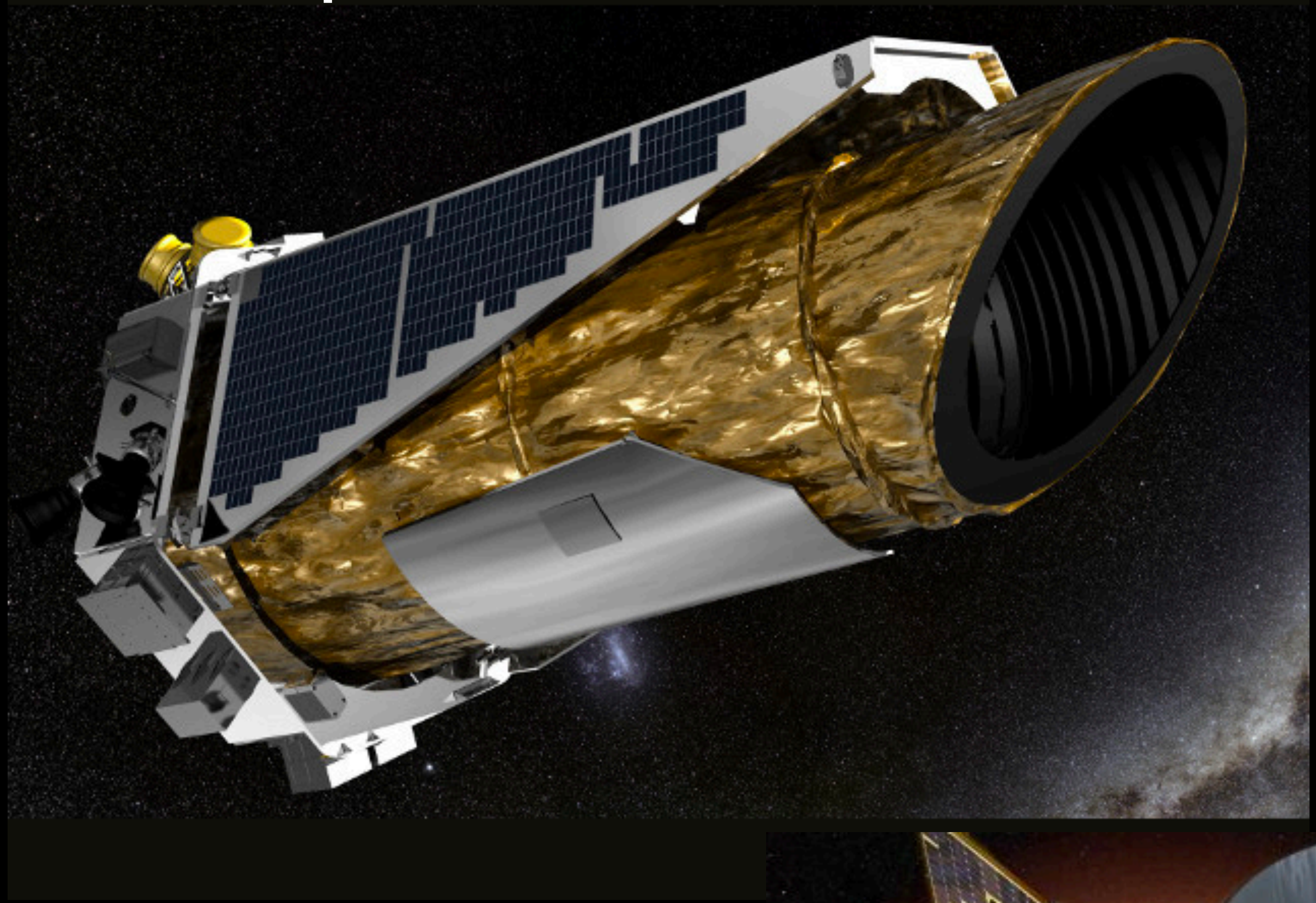




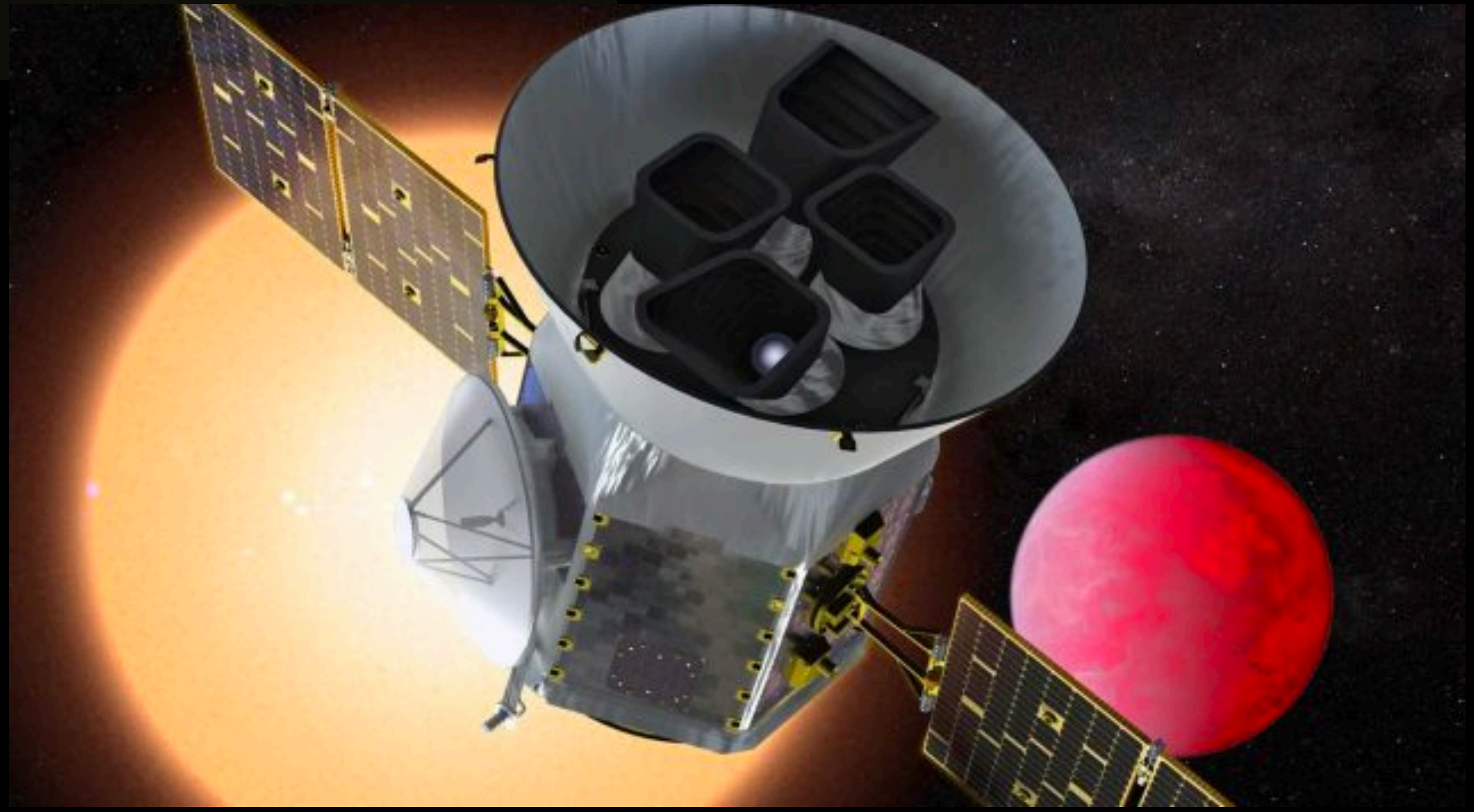
Why now?

But they're looking at *more* stars

Kepler: ~150,000 stars



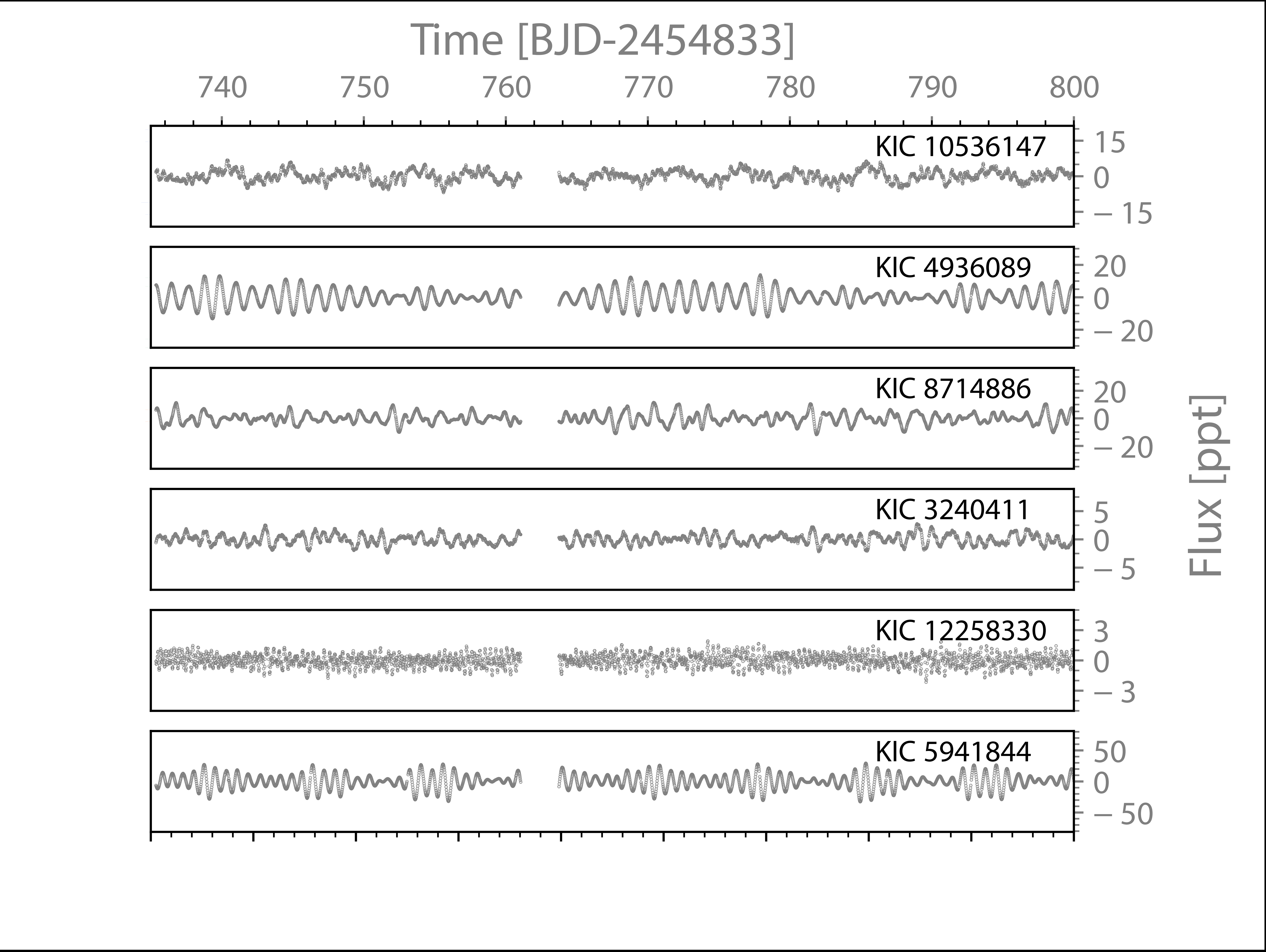
TESS: ~200,000 stars



PLATO: ~1 million stars

Asteroseismology

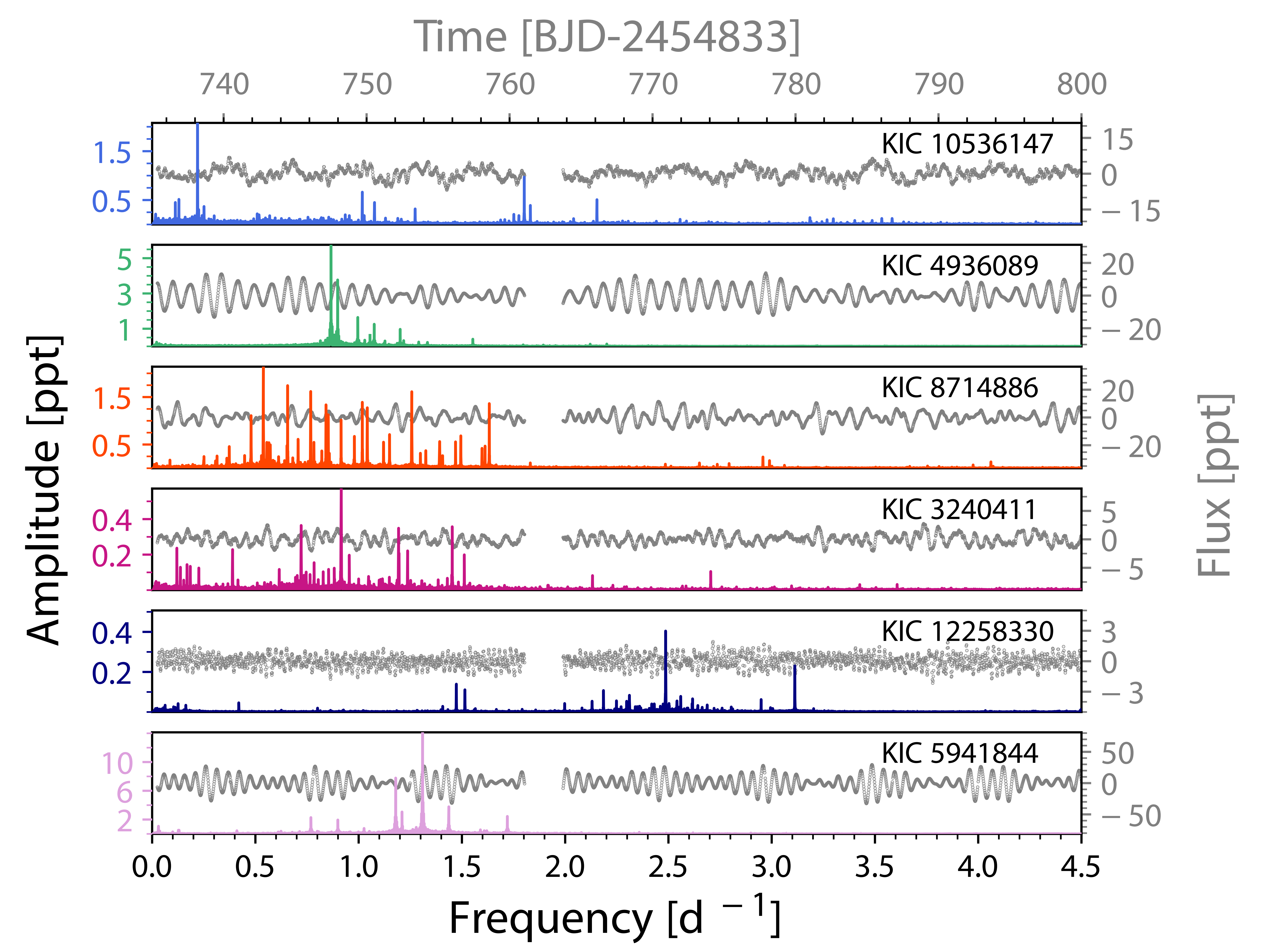
Stars “wiggle”



[Pedersen et al 2021, Nature Astron. 5 715-722]

Asteroseismology

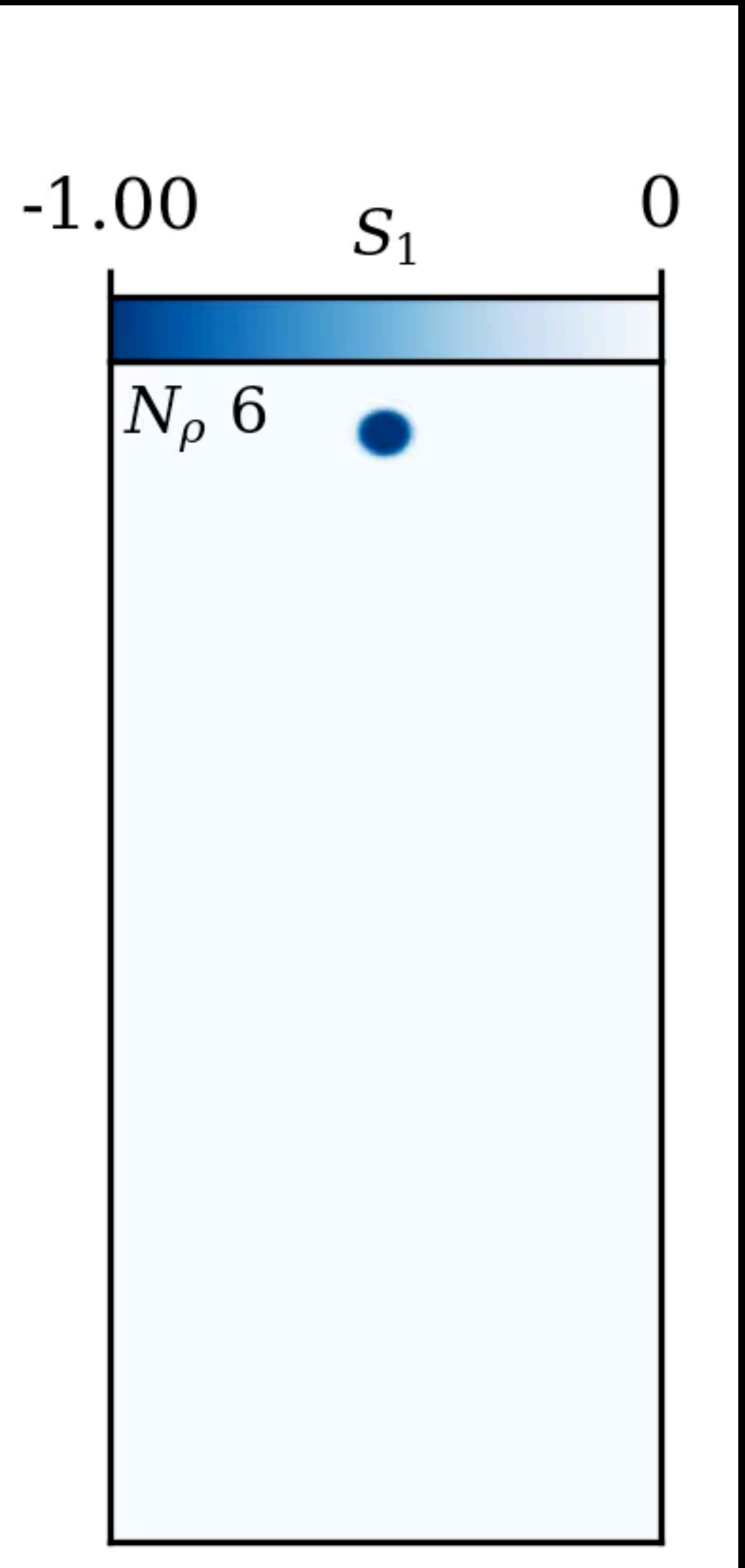
These wiggles are from waves that we can use to look inside of stars and discover "missing physics".



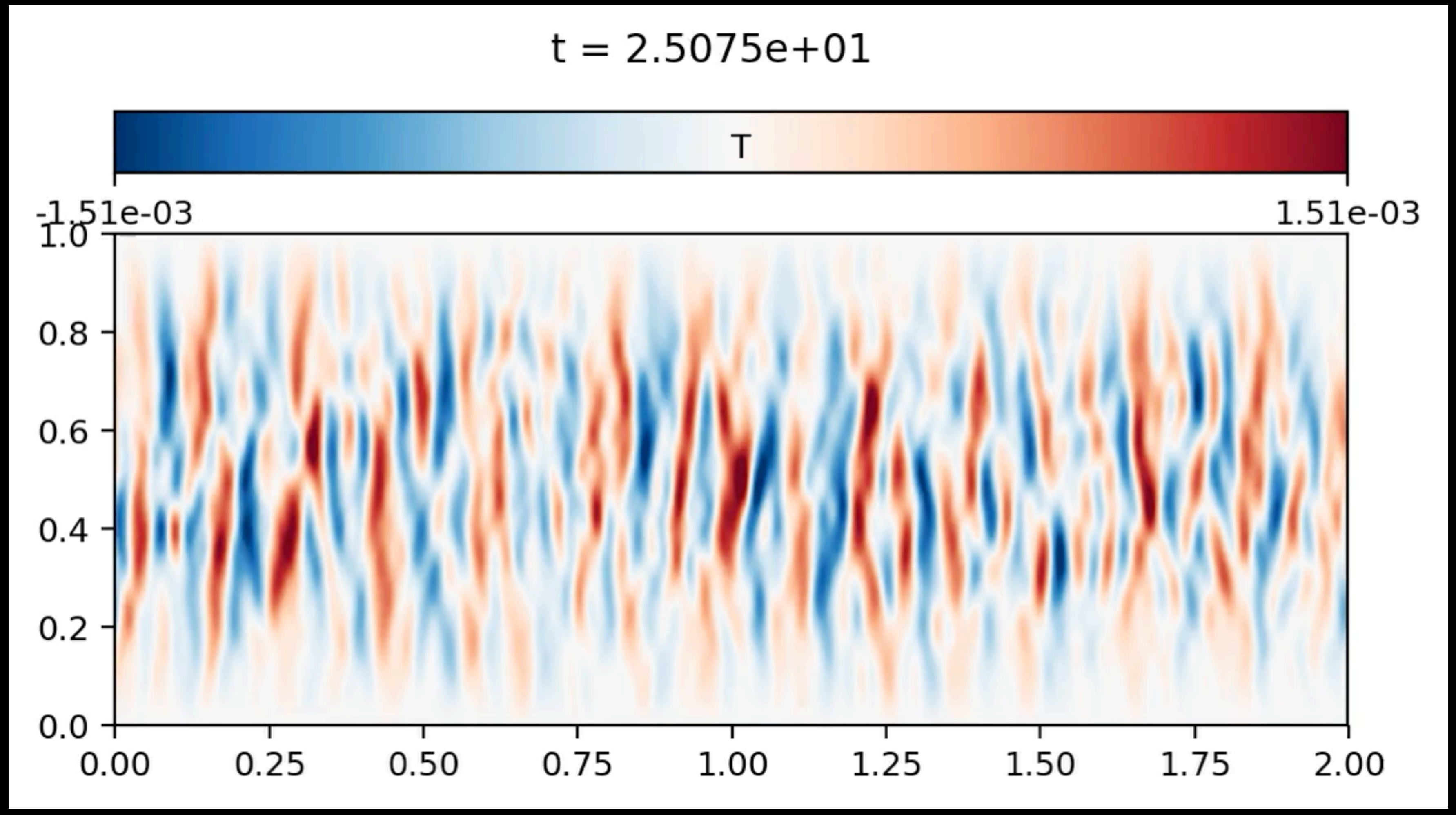
[Pedersen et al 2021, Nature Astron. 5 715-722]

My research studies the “missing physics”

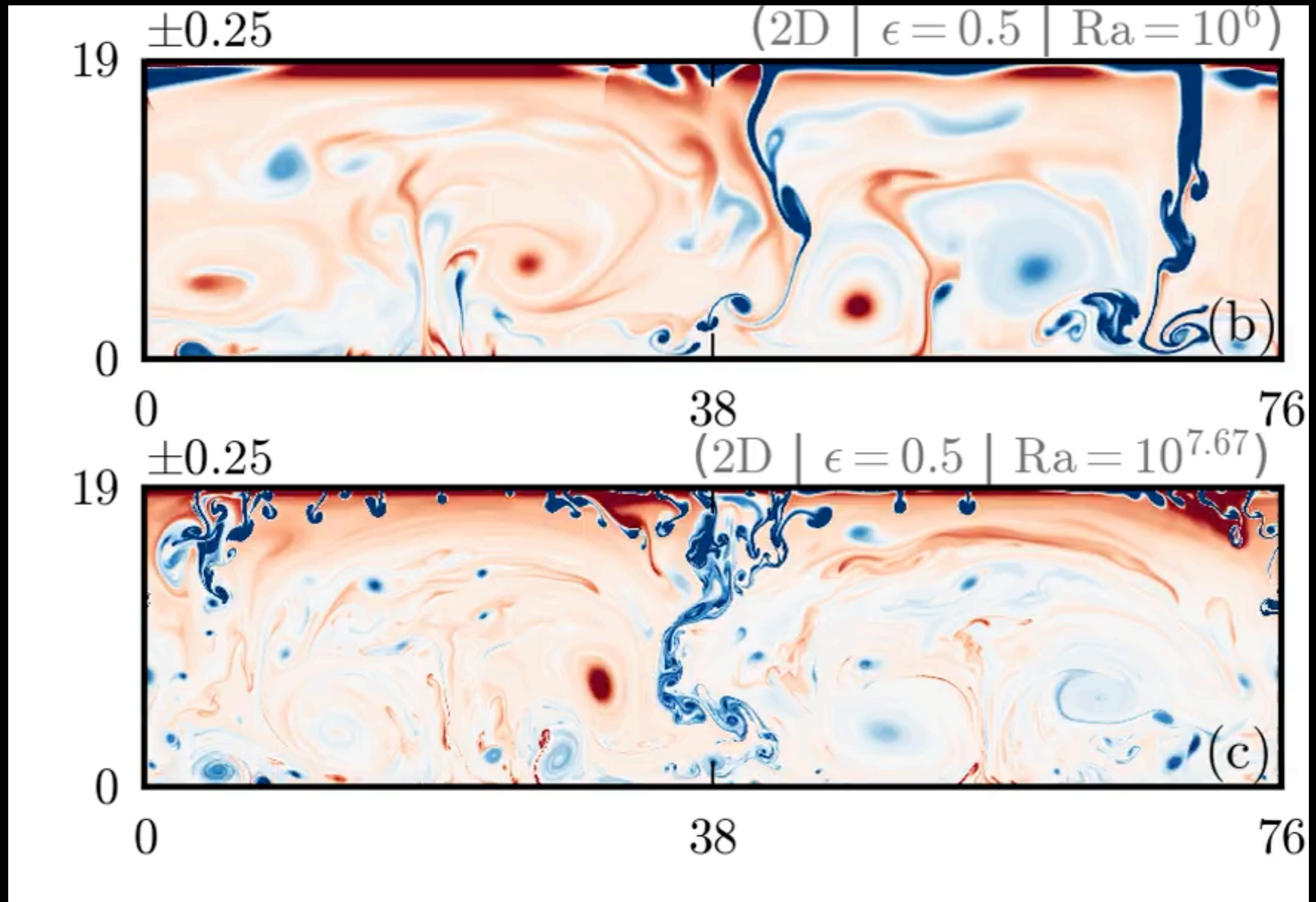
Smallest length scales
[Anders et al 2019 ApJ 884 65]



Disparate time scales
[Anders et al 2018 PRF 03 083502]
[Anders et al 2020 PRF 05 083501]



Density stratification
[Anders & Brown 2017 PRF 02 083501]



Methods paper: [Burns et al 2020 PRR 02 023068]
Eigentools: [Oishi et al 2021 JOSS 06 30790]

Dedalus is a programming language for PDEs

Very flexible; includes IVPs, BVPs, EVPs.

$$\nabla \cdot \vec{u} = 0$$
$$\partial_t \vec{u} + \vec{u} \cdot \nabla \vec{u} + \nabla \varpi = -T\vec{g} + \nu \nabla^2 \vec{u}$$
$$\partial_t T + \vec{u} \cdot \nabla T = \kappa(\nabla^2 T + Q)$$

Internally heated,
Boussinesq convection

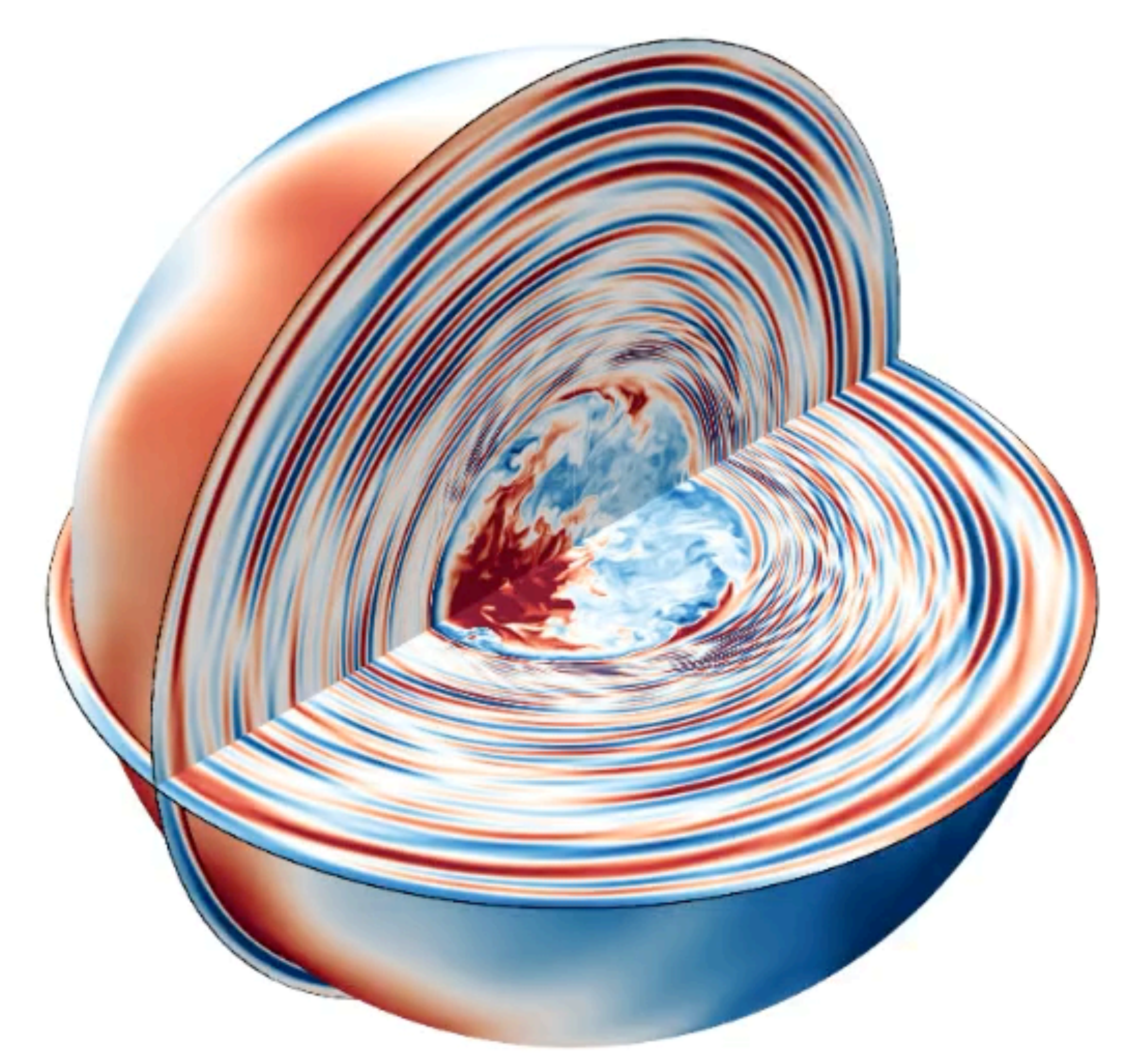
Dedalus form

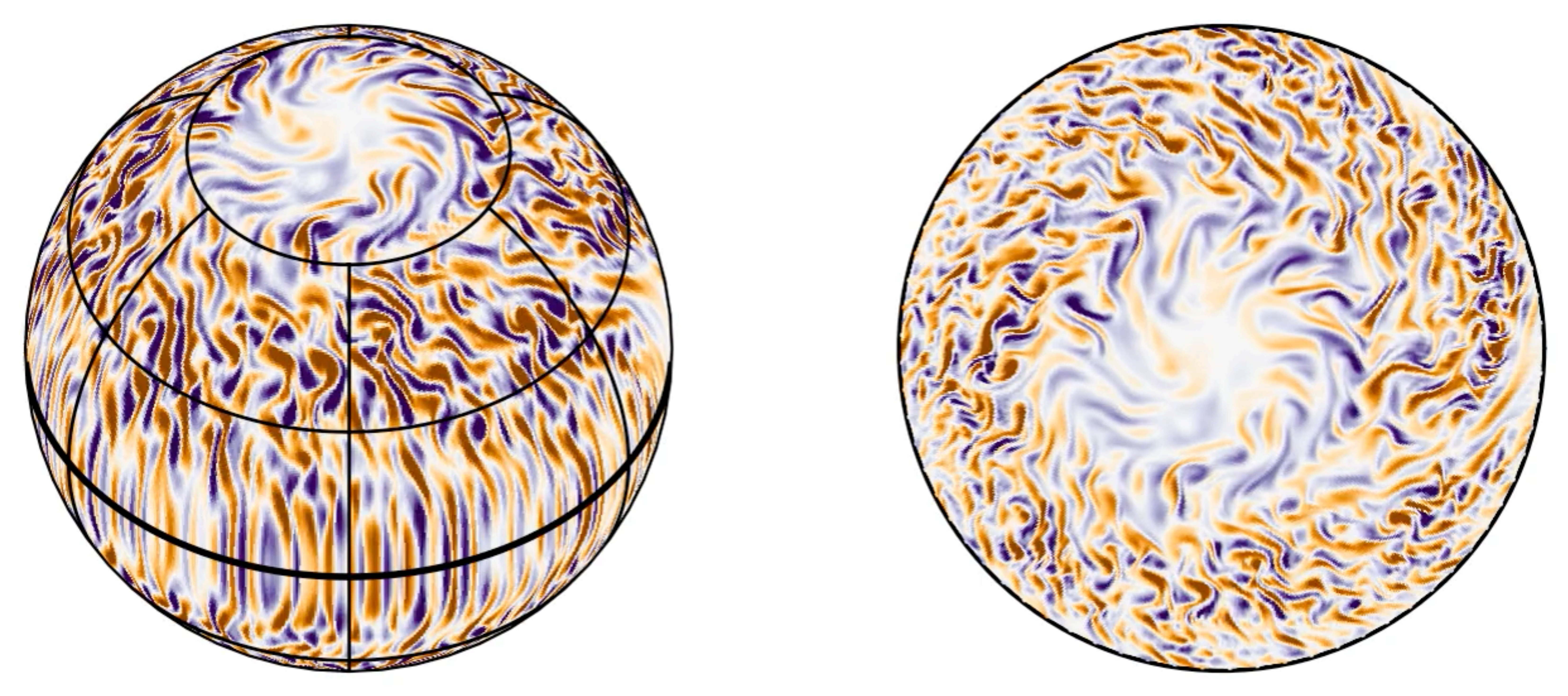
```
problem.add_equation("div(u) + tau_p = 0")
problem.add_equation("dt(u) - nu*lap(u) + grad(p) - r_vec*T + lift(tau_u) = - cross(curl(u),u)")
problem.add_equation("dt(T) - kappa*lap(T) + lift(tau_T) = - u@grad(T) + kappa*T_source")
```

Methods paper: [Burns et al 2020 PRR 02 023068]
Eigentools: [Oishi et al 2021 JOSS 06 30790]

Dedalus' many applications: Geo/Astro Convection

Convection / waves in stars

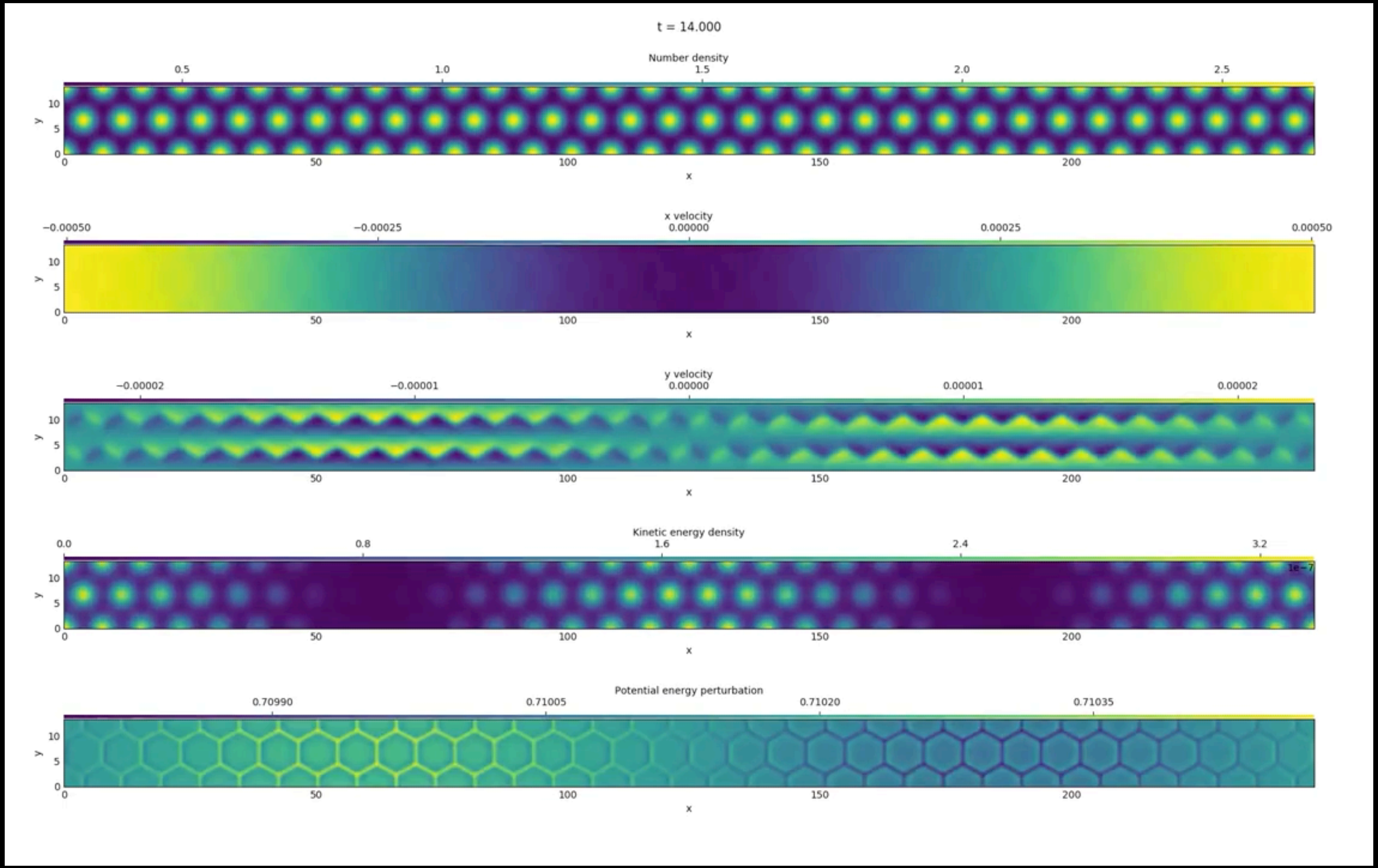




Rotationally-constrained convection in stars and planets

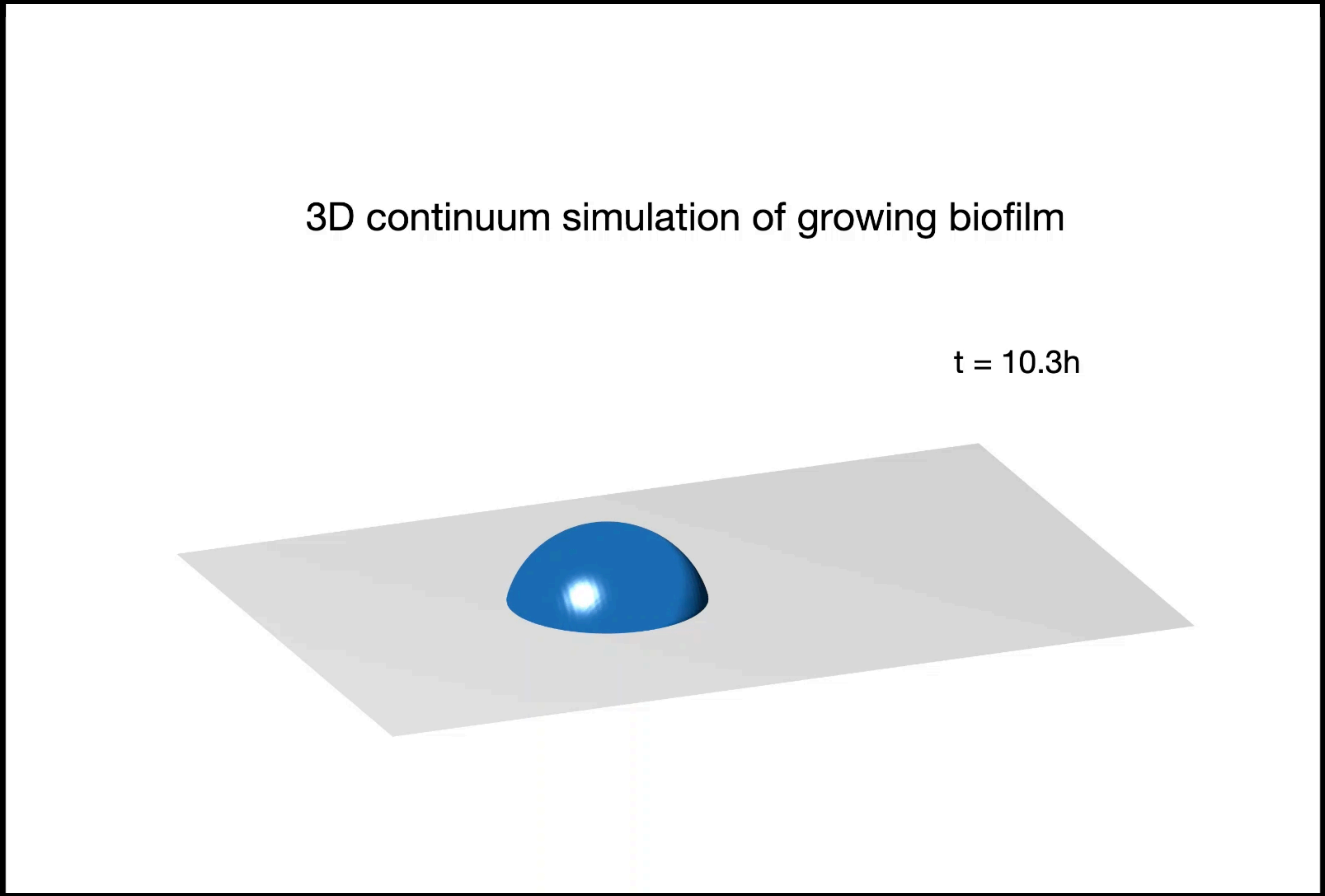
Dedalus' many applications: Quantum Fluids

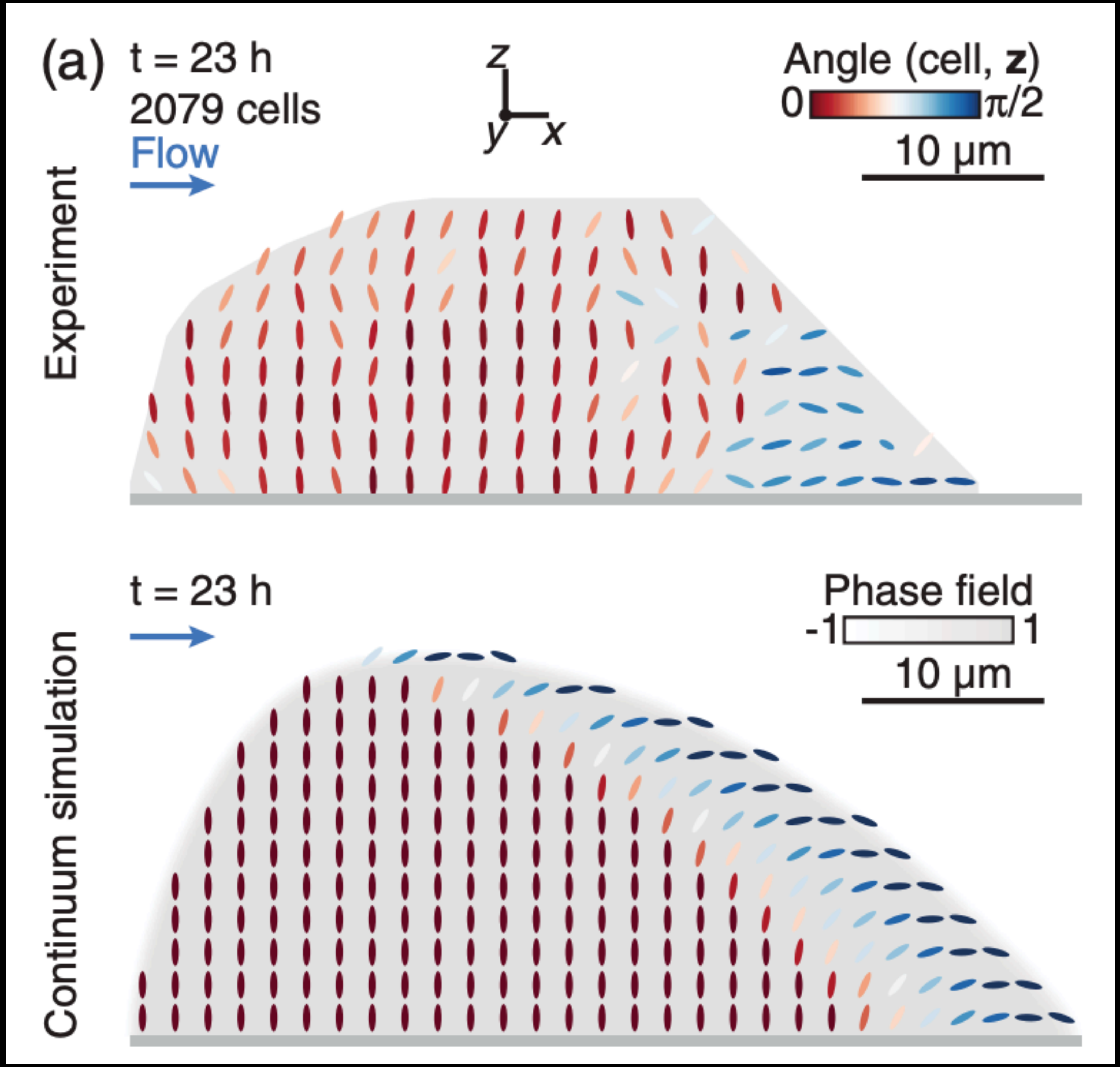
Sound wave dynamics in a supersolid



Generalized Gross-Pitaveskii Equation [Heinonen, Burns, Dunkel 2019 PRA 99 063621]

Dedalus' many applications: Biofluids





Rod-shaped
bacteria in a flow.

[Pearce et al 2019 PRL 123 258101]

I’m excited to use my expertise with this tool to work with all of you.

Uncertainties from mixing are huge

Uncertainties from mixing are huge

Main sequence

	$\delta\tau_{\mathrm{H}}$
$15\,\mathrm{M}_{\odot}$	24.38% (30.06%)

[Kaiser et al 2020, MNRAS 496 2]

Age uncertainty due to mixing prescriptions

Uncertainties from mixing are huge

Ouch

Main sequence

	$\delta\tau_{\mathrm{H}}$
15 $M_\odot$	24.38% (30.06%)

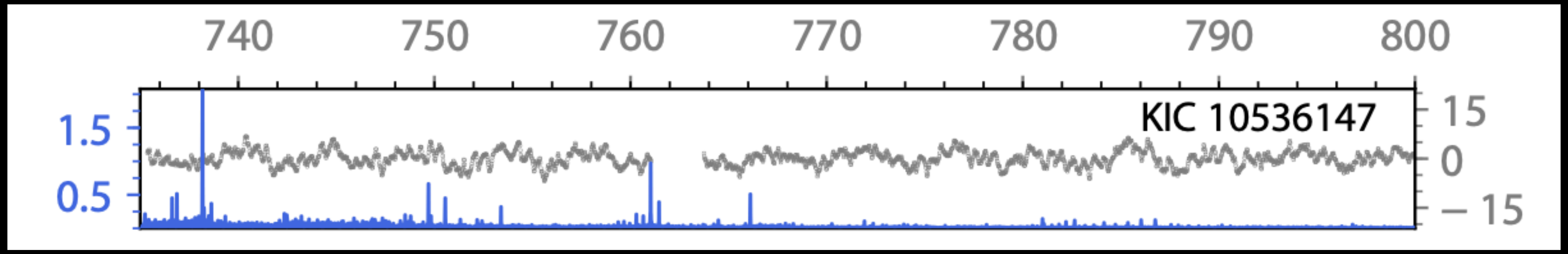
Blue supergiant

$\delta\tau_{\mathrm{BSG}}$
5800.0% (5800.0%)

[Kaiser et al 2020, MNRAS 496 2]

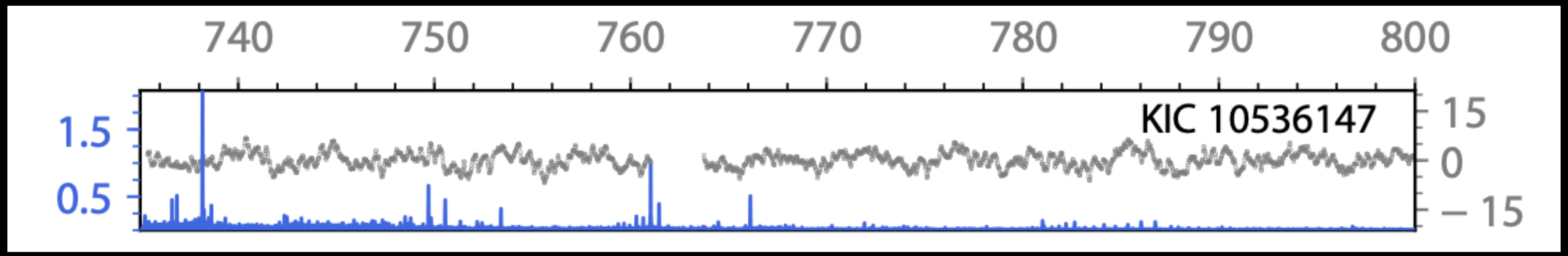
Age uncertainty due to mixing prescriptions

Asteroseismology puts empirical constraints on mixing

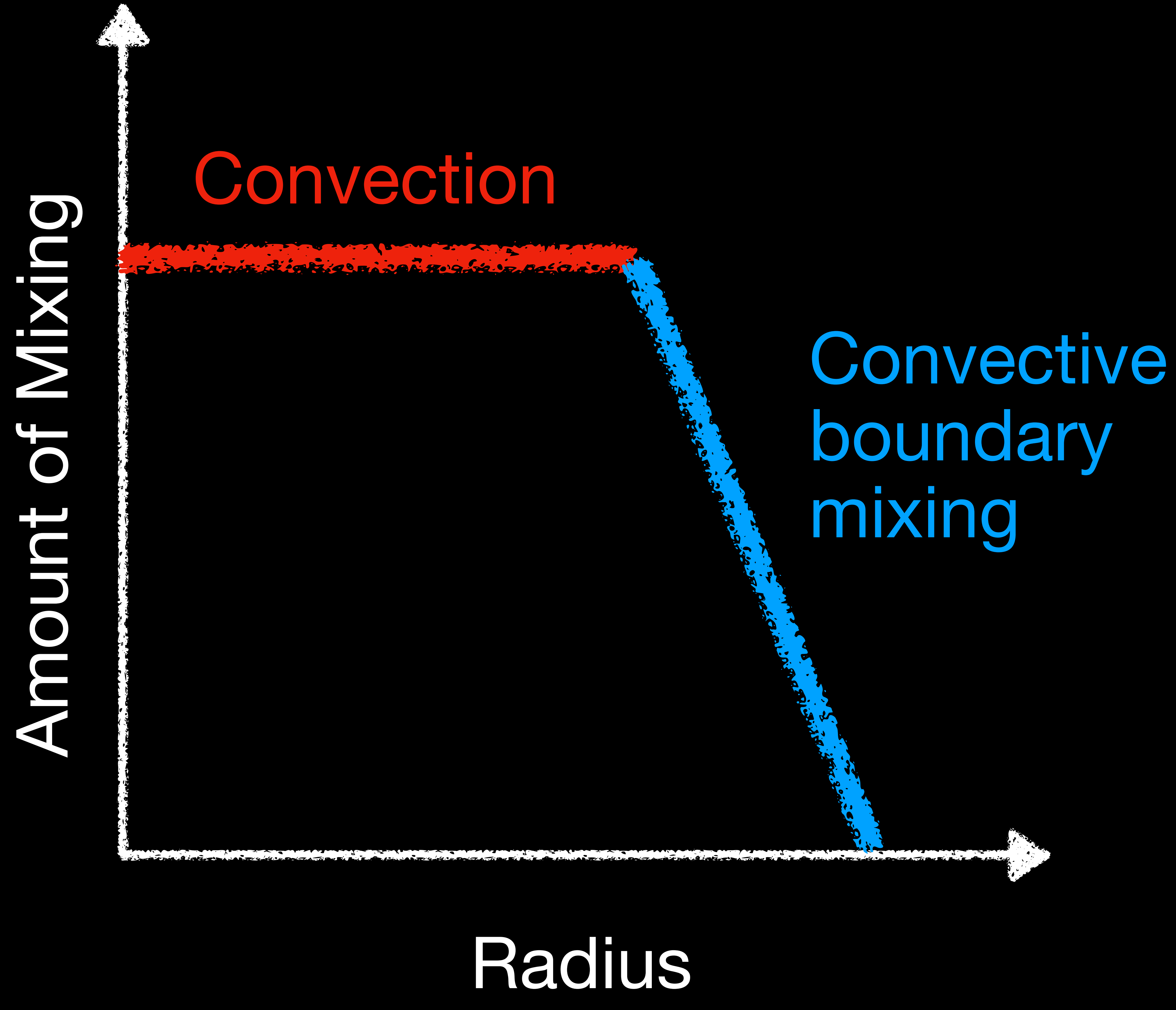


[Pedersen et al 2021, Nature Astron. 5 715-722]

Asteroseismology puts empirical constraints on mixing



Model 1: Convective Overshoot



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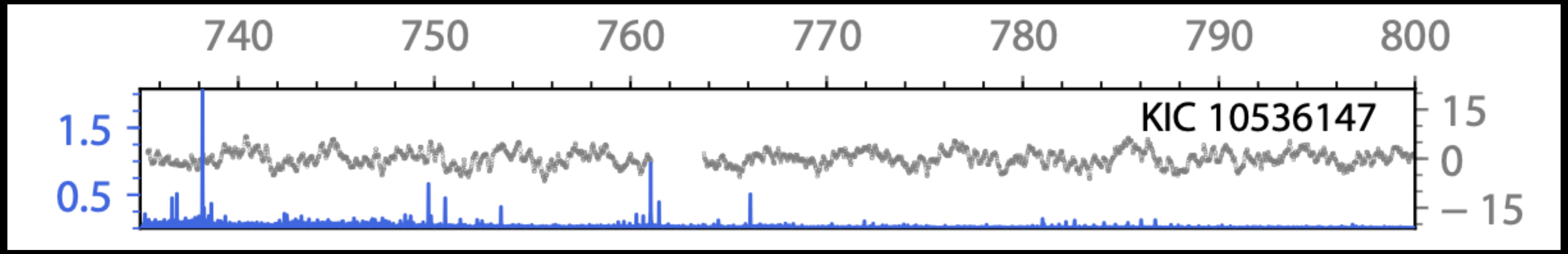
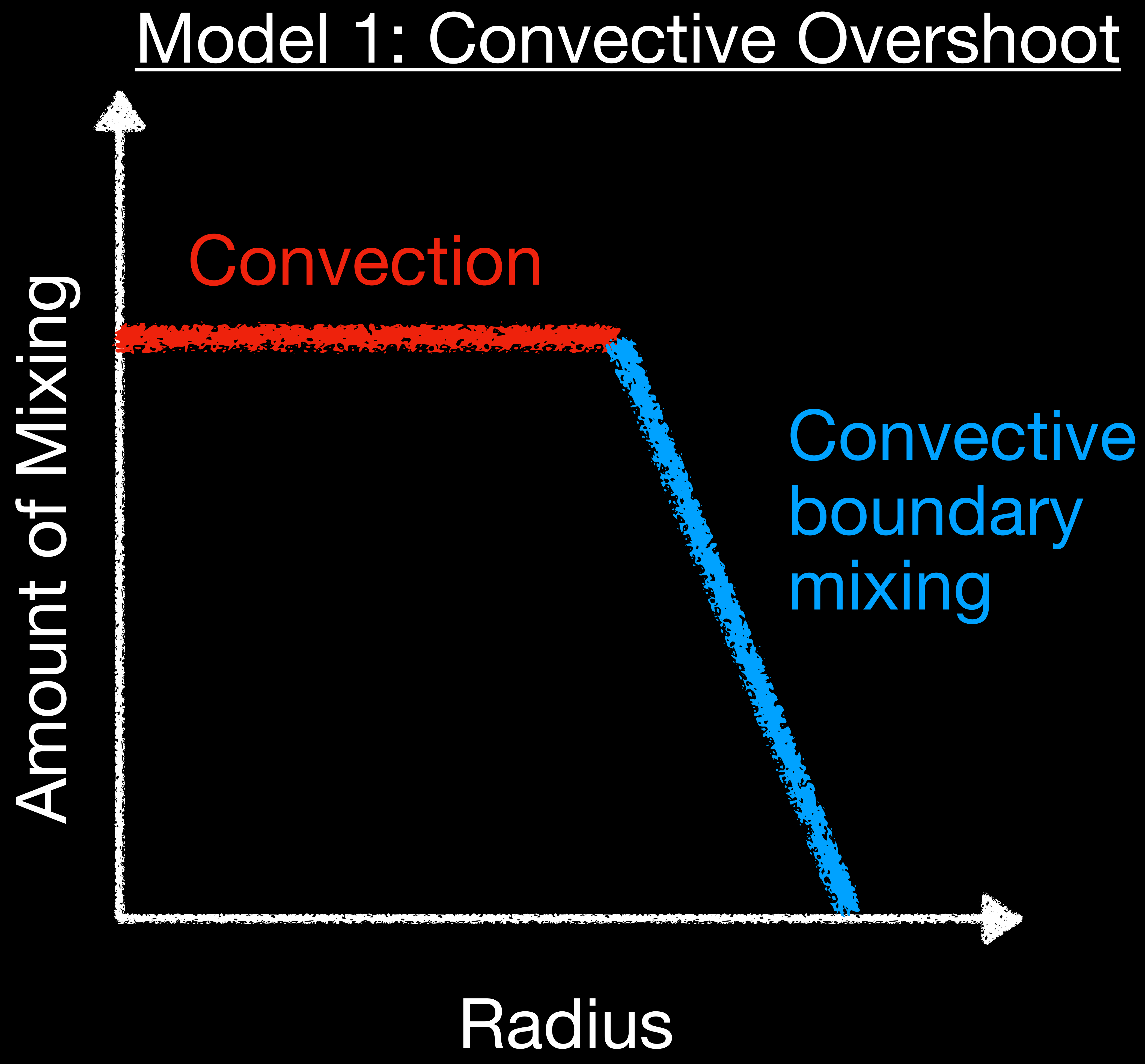
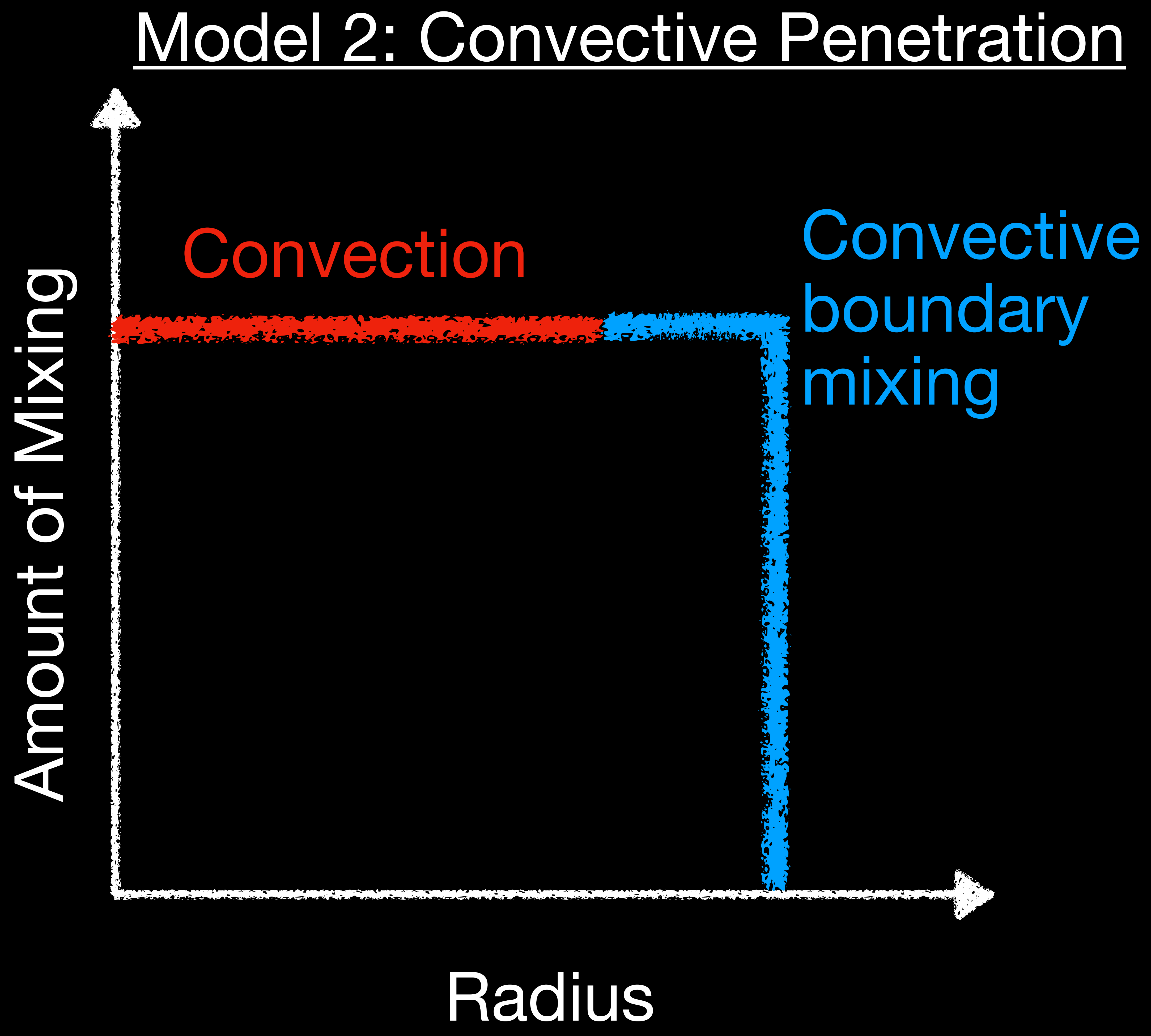


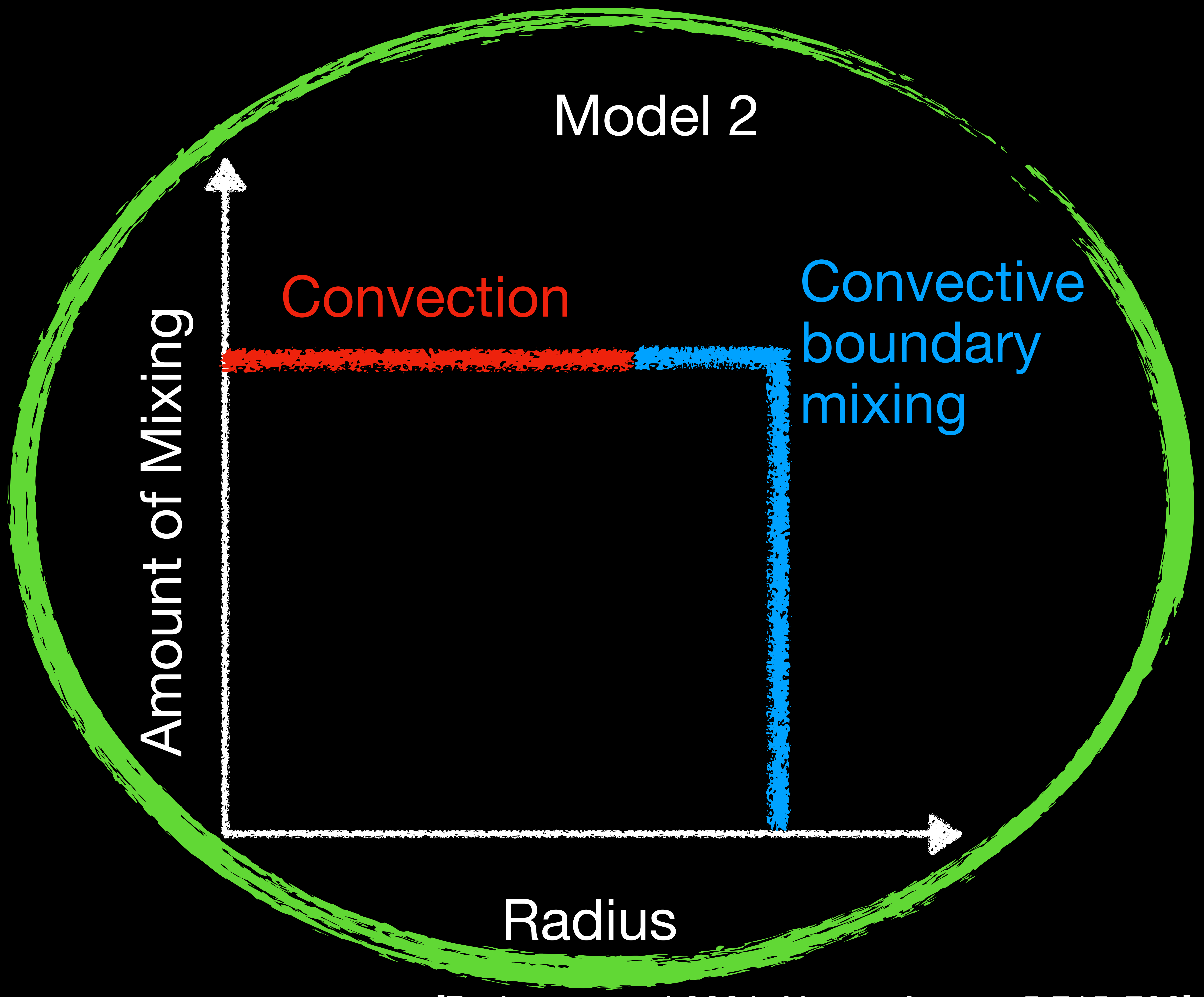




[Pedersen et al 2021, Nature Astron. 5 715-722]

Asteroseismology puts empirical constraints on mixing

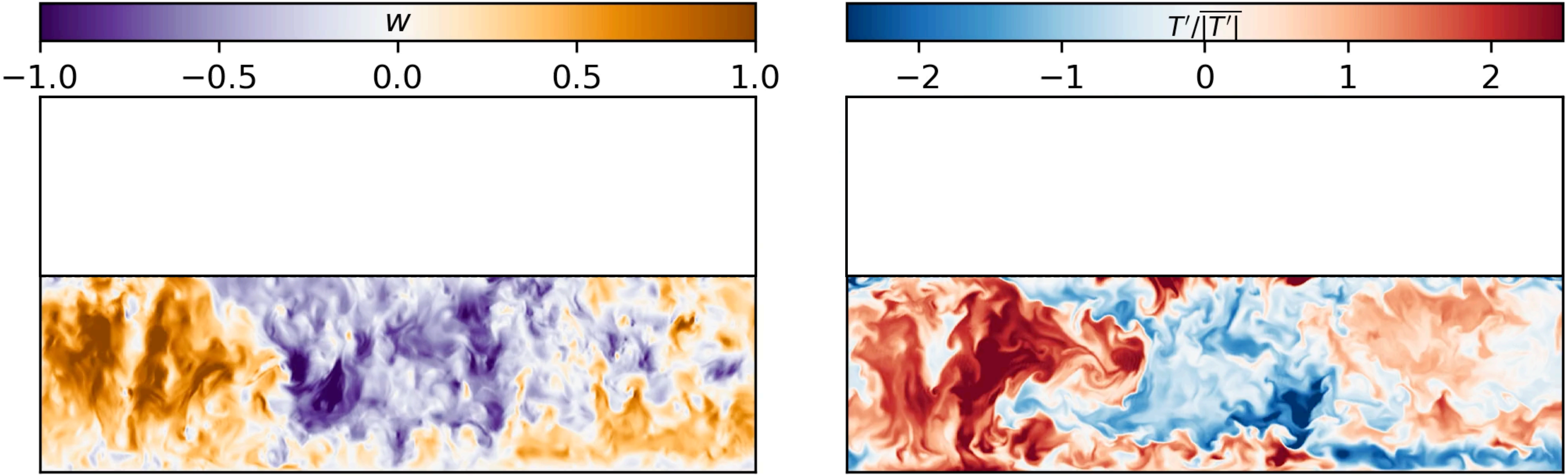
Preferred model



[Pedersen et al 2021, Nature Astron. 5 715-722]

Convection in a box

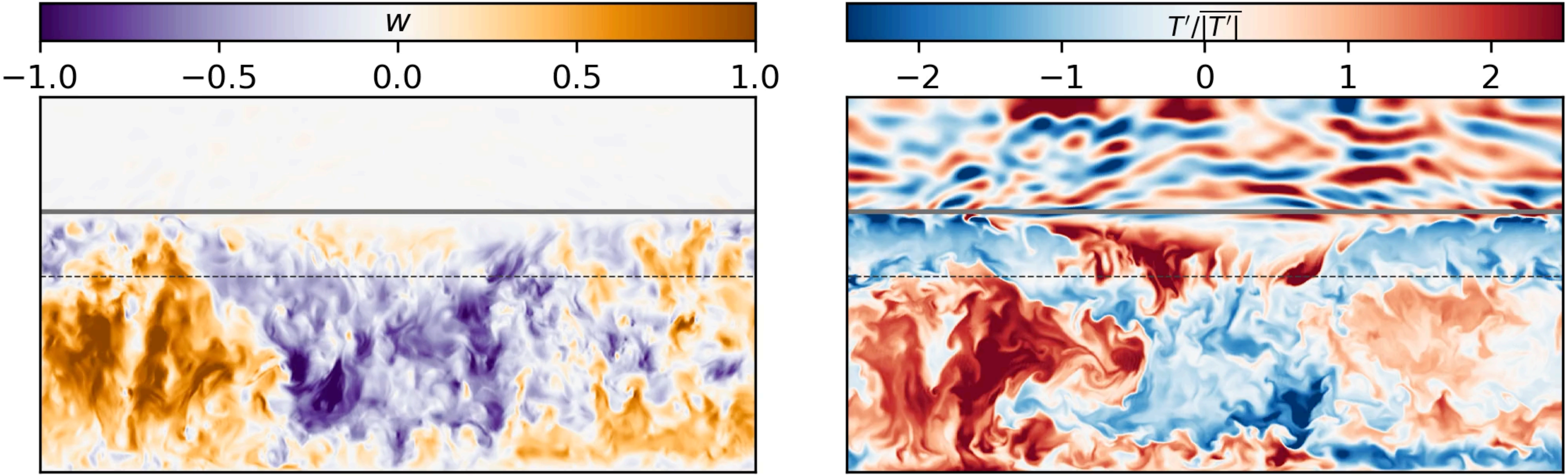
Widely studied, pretty well understood



[Anders et al 2022 ApJ 926 169]

Convection eats into an adjacent stable region

Our simulations look like what observers see in stars!



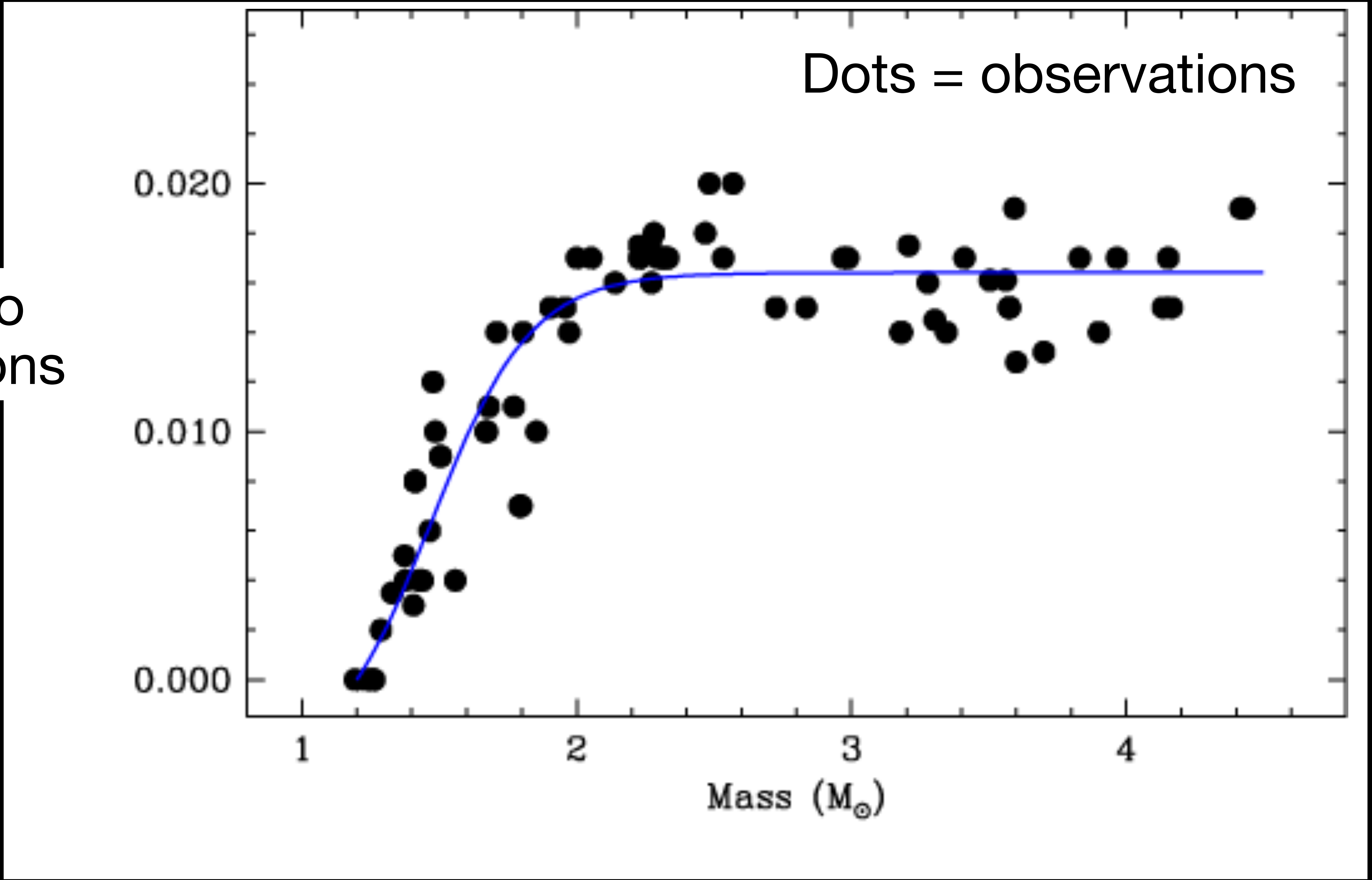
This is my most impactful work.

[Anders et al 2022 ApJ 926 169]

Upshot: Mixing in Eclipsing Binaries

Observed mass dependence

Mixing required to match observations

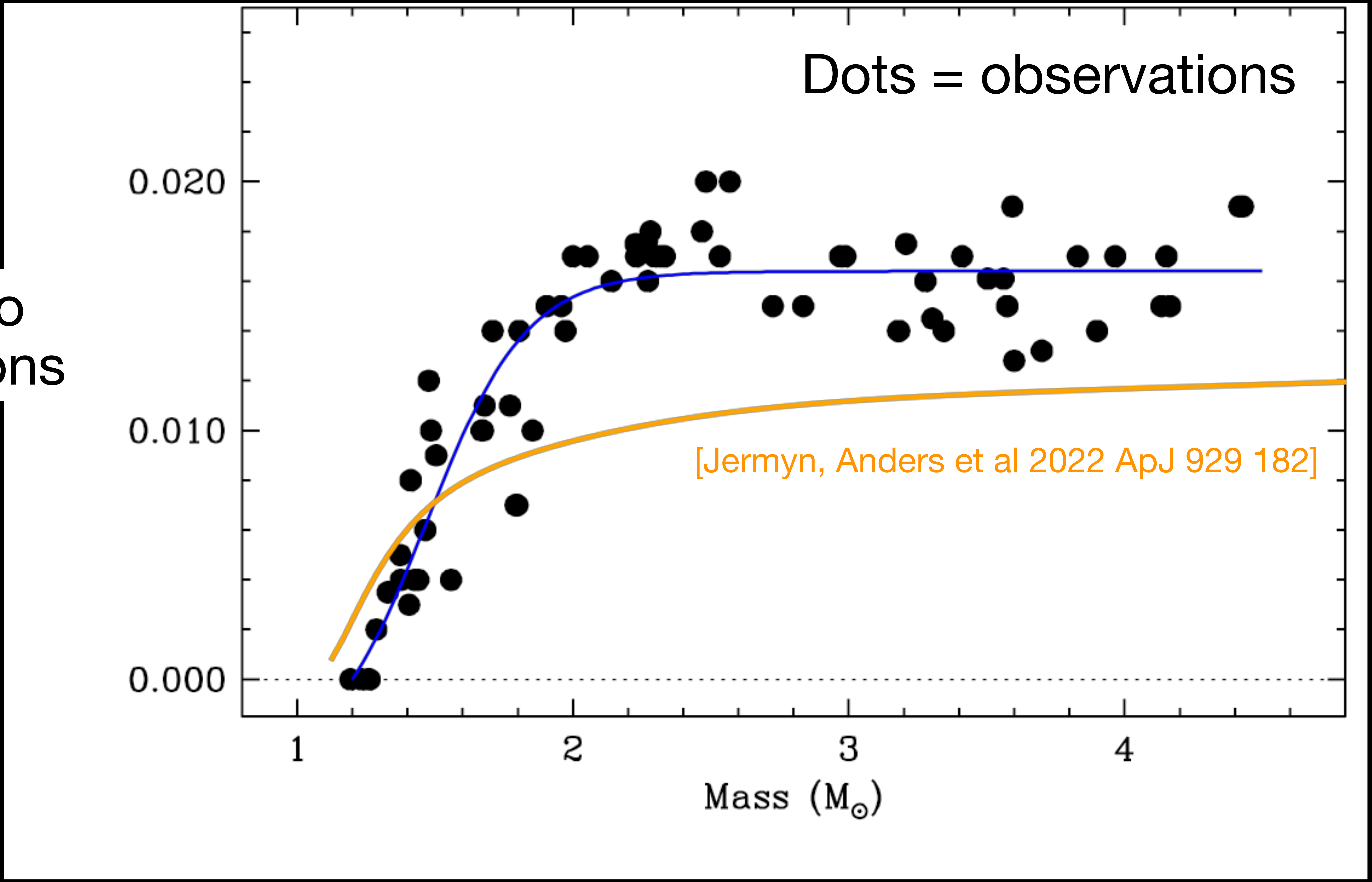


[Claret & Torres 2019 ApJ 876 134]

Upshot: Mixing in Eclipsing Binaries

New theory matches better at low mass; still more work to do!

Mixing required to match observations



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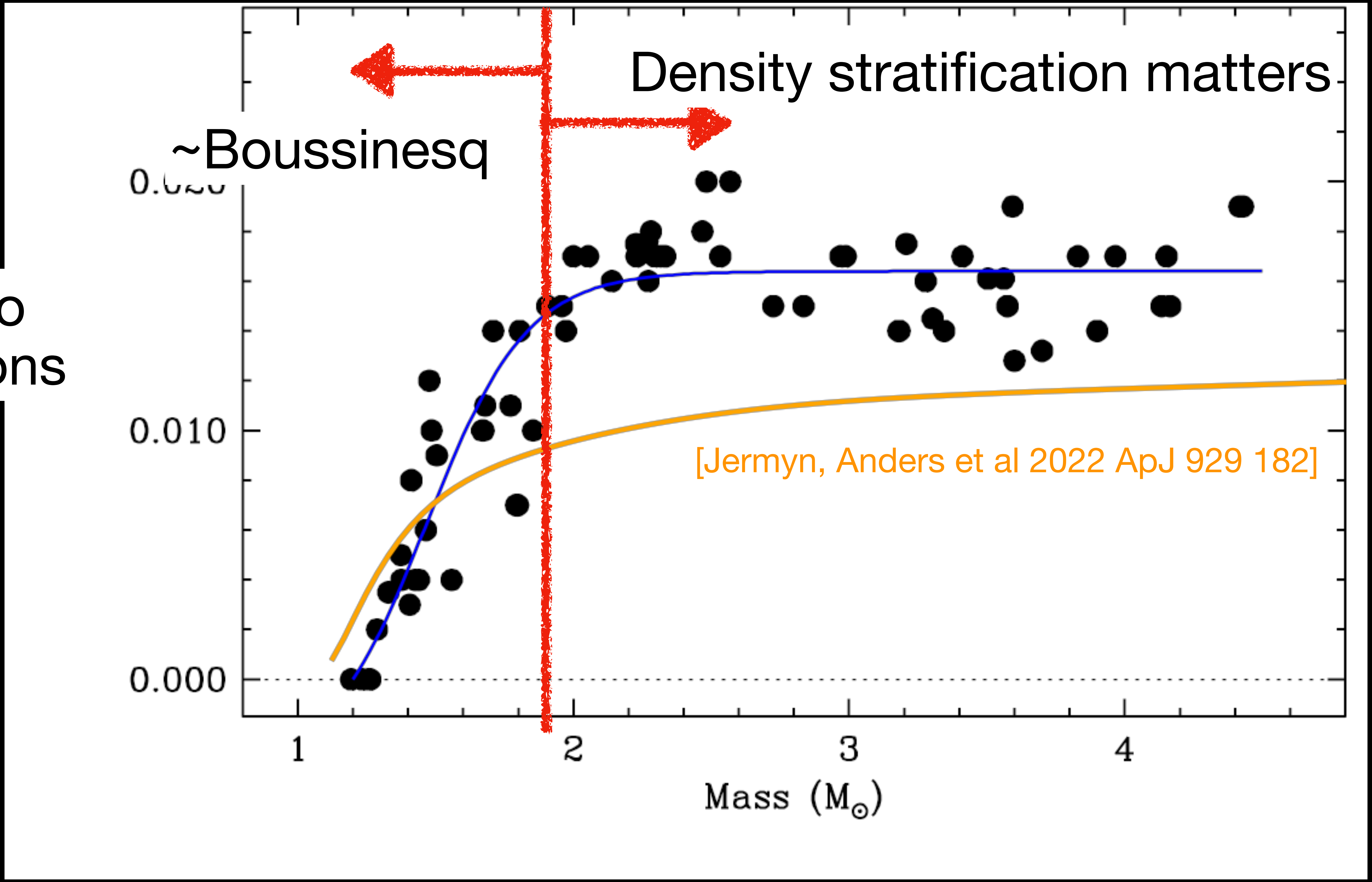
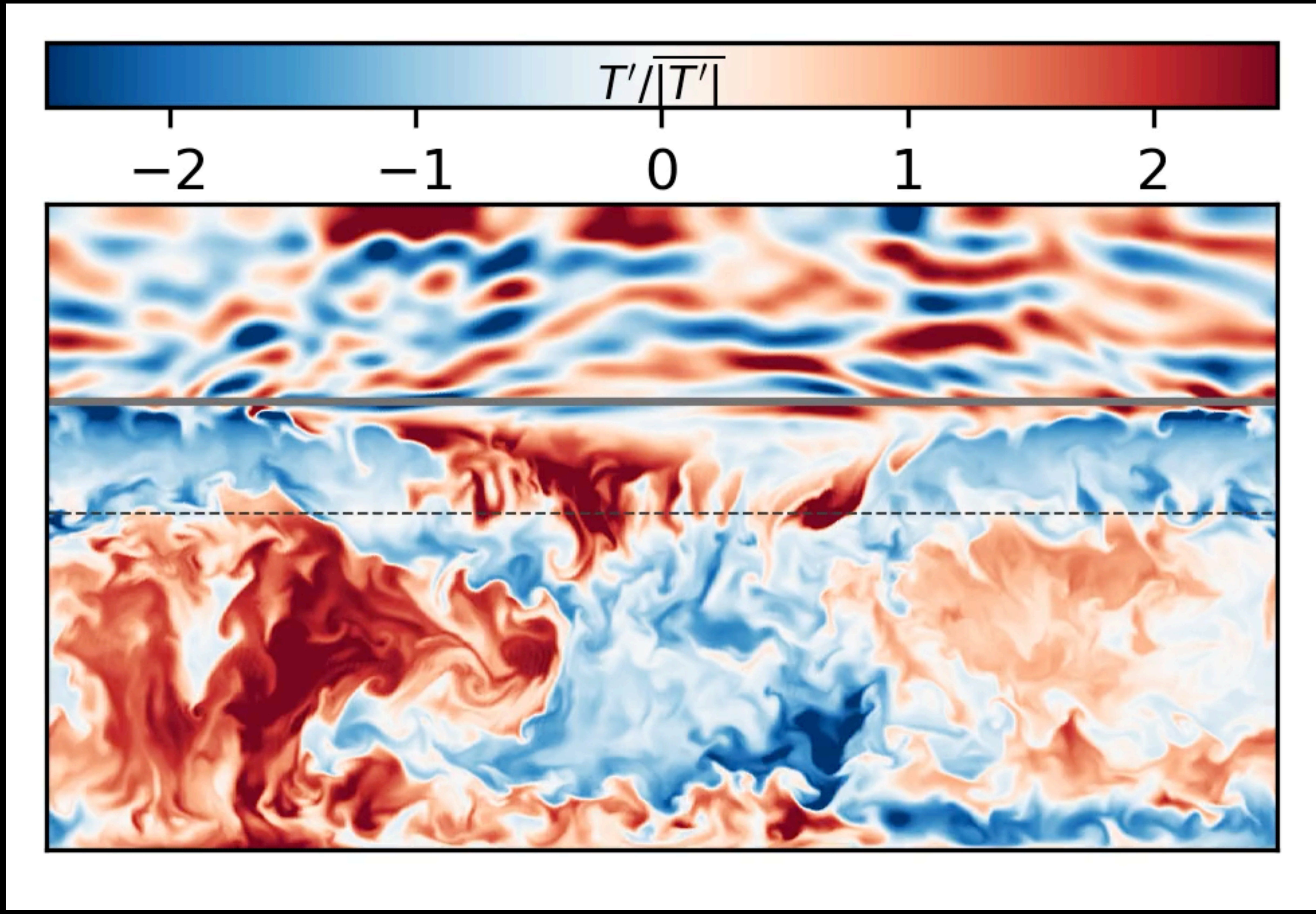


[Claret & Torres 2019 ApJ 876 134]

What's next?

1. Improve the theory of penetrative convection with more ingredients

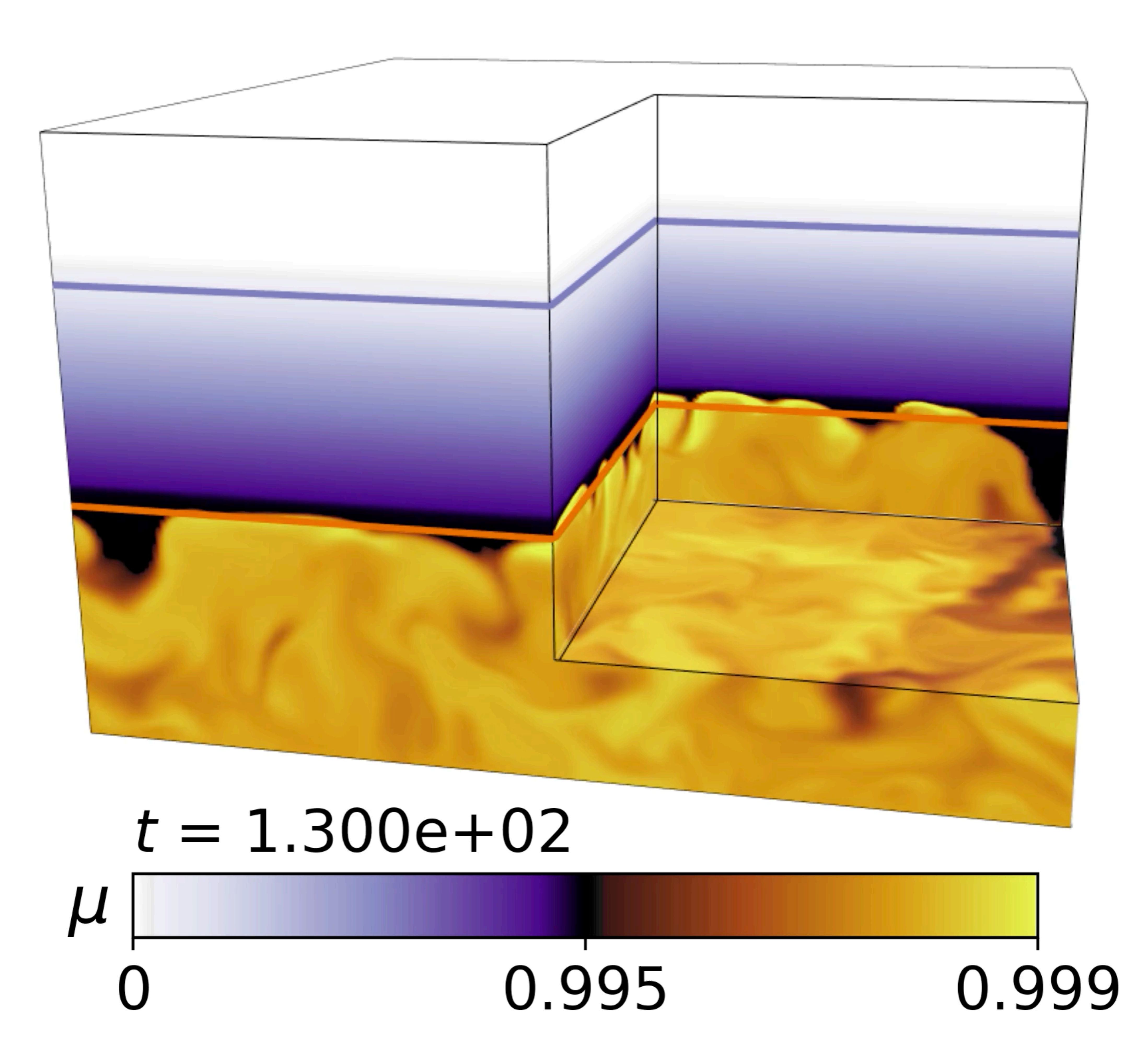
- Box -> sphere
- Boussinesq -> Compressible
  - (Sims, Theory)
- Self-consistent expected convective boundary



What’s next?

2. Answer other open boundary mixing questions

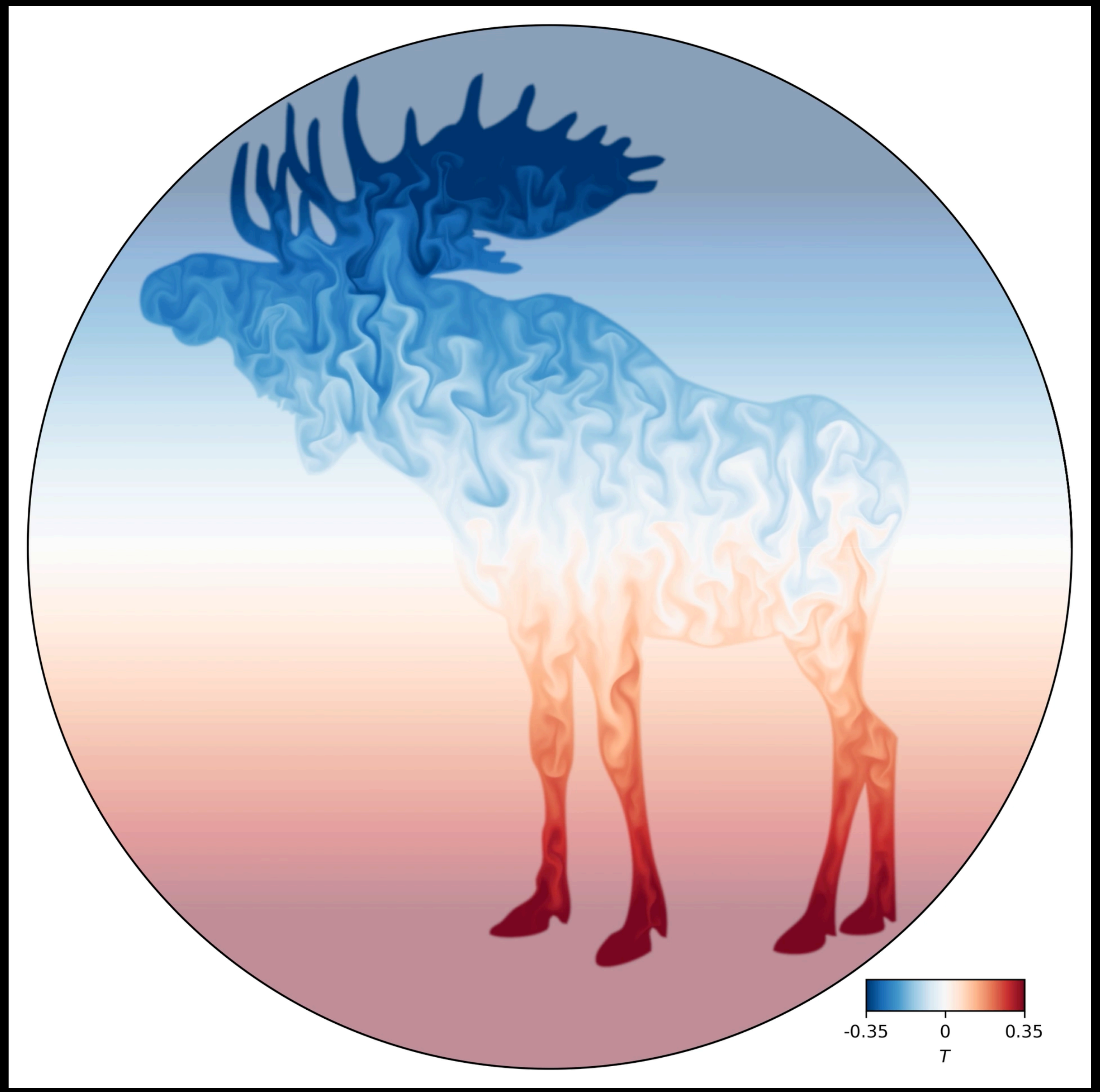
- Sometimes convection zones aren’t equilibrated!
  - Need to better understand **entrainment**
- Parameterize for 1D boundary modeling.
- Move prior studies to 3D, compressible, spherical geometry, etc, etc, etc…



[Anders et al 2022 ApJL 928 L10]

Summary

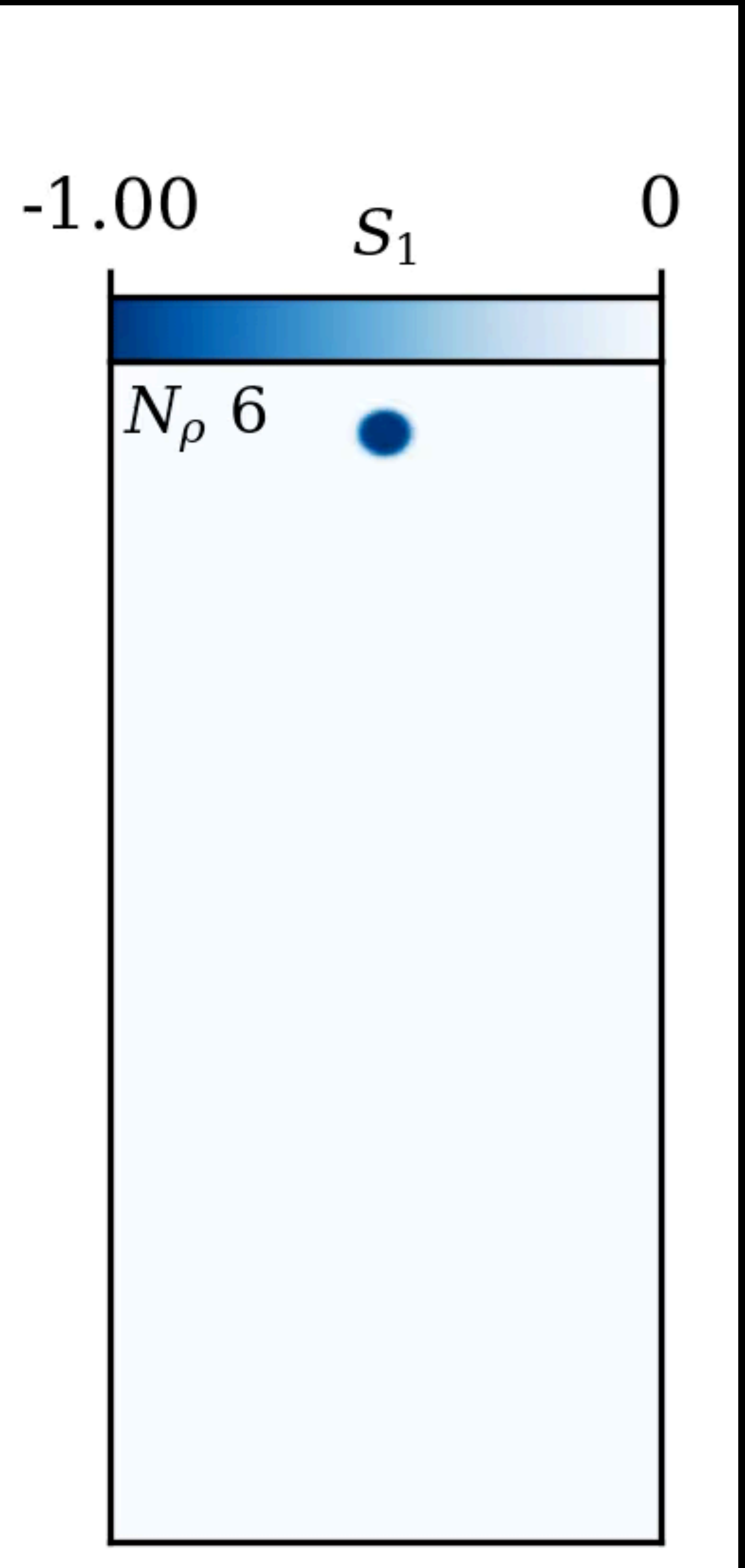
- It's an exciting time to be studying astrophysical fluid dynamics.
- I use Dedalus to study astro-fluids and am excited to collaborate with you all and apply it to other fields.
- My current and future research focus on improving theories of convective boundary mixing.



…And sometimes I study Moosinesq convection.
[Anders et al 2022 arxiv: 2204.00002]

My research studies the "missing physics"

Smallest length scales
[Anders et al 2019 ApJ 884 65]



Disparate time scales
[Anders et al 2018 PRF 03 083502]
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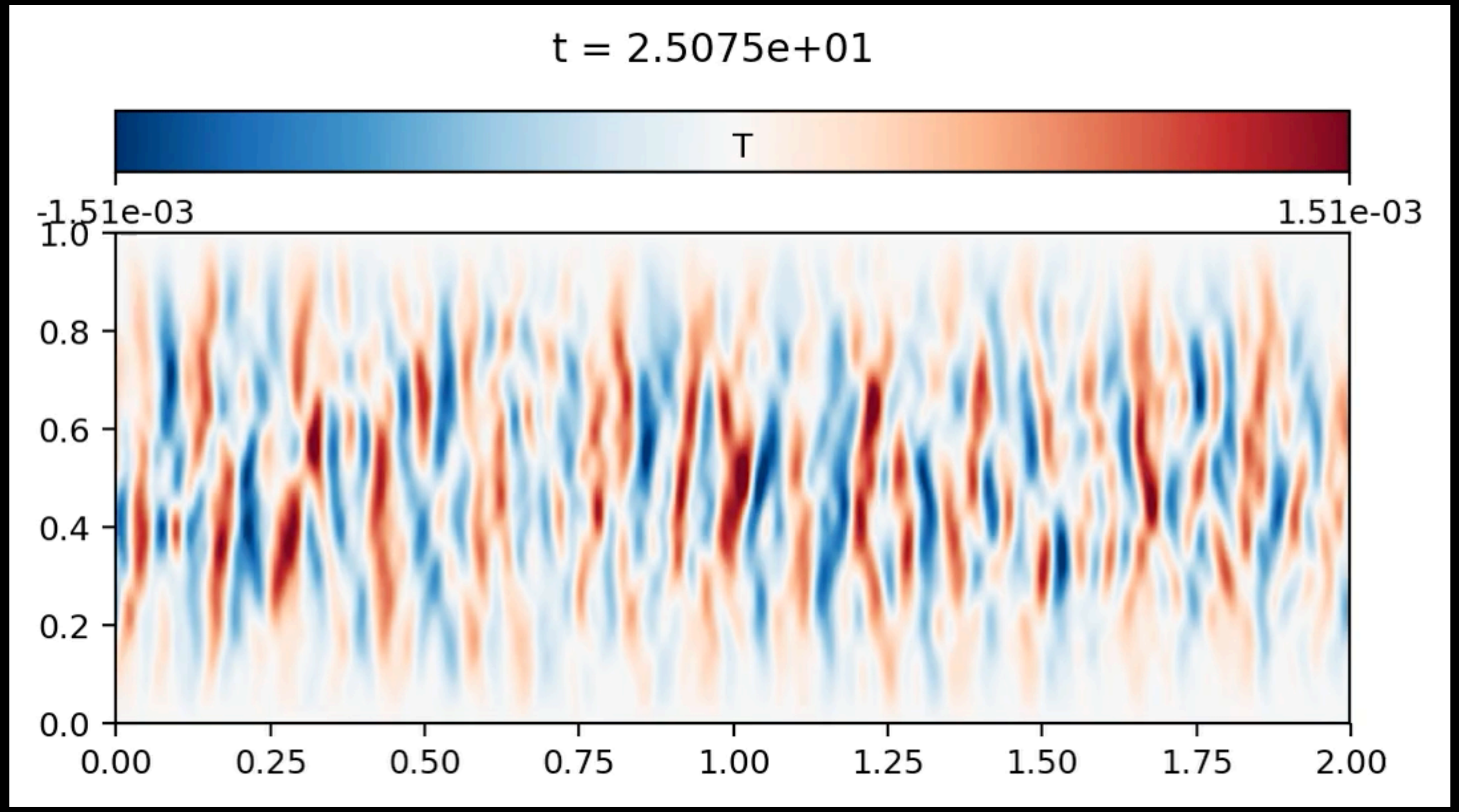
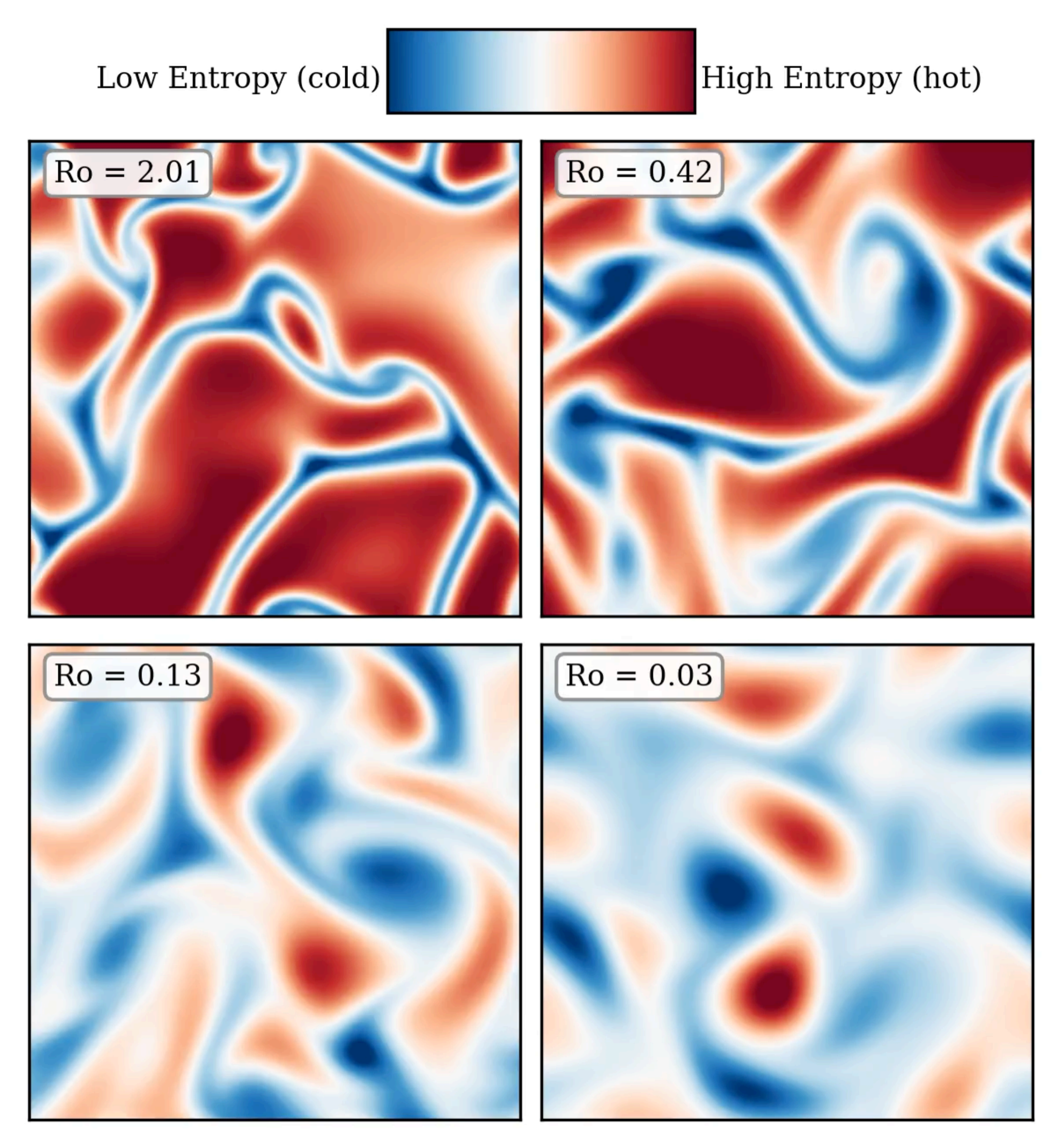
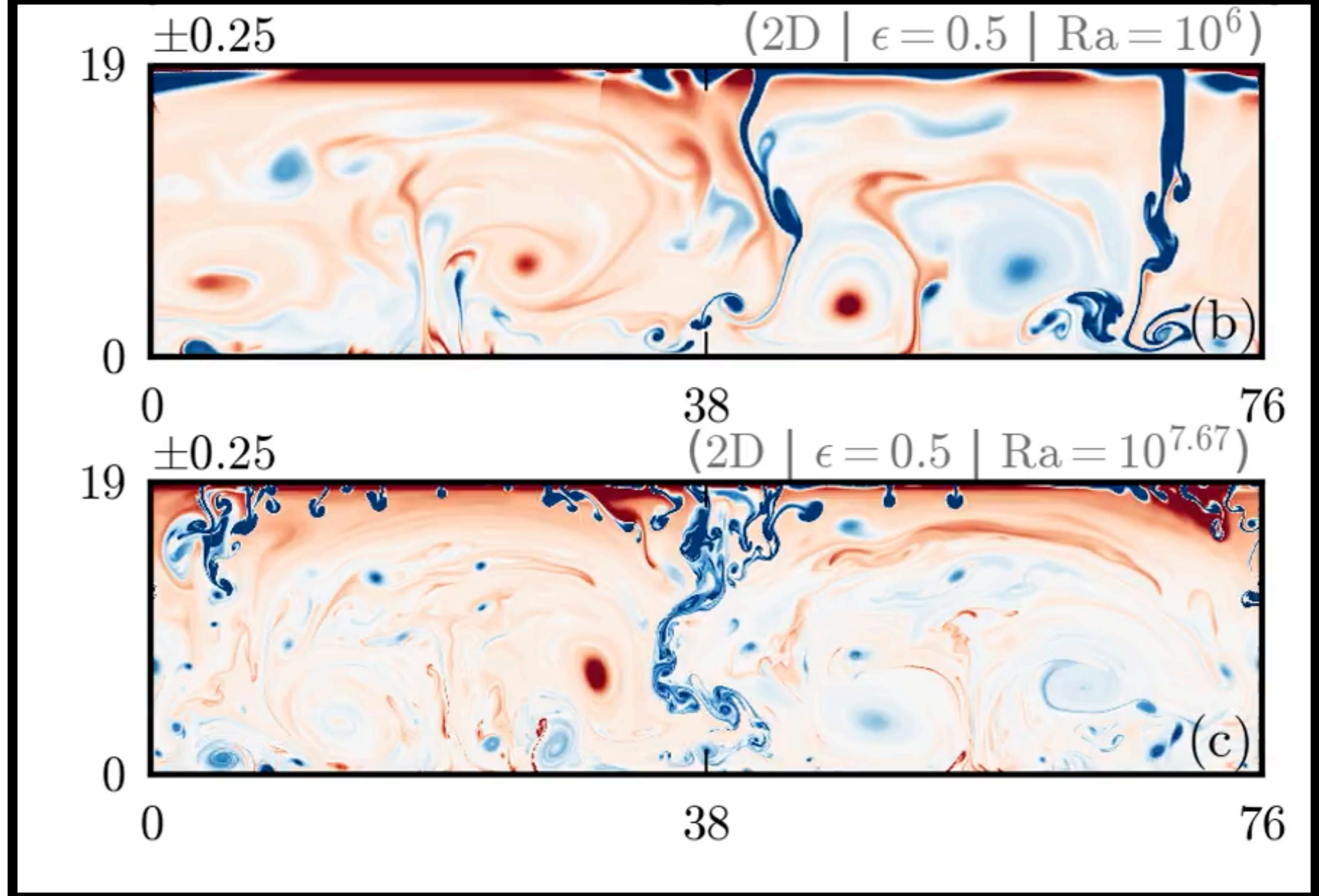


Rotation + stratification
[Anders et al 2019 ApJ 872 138]

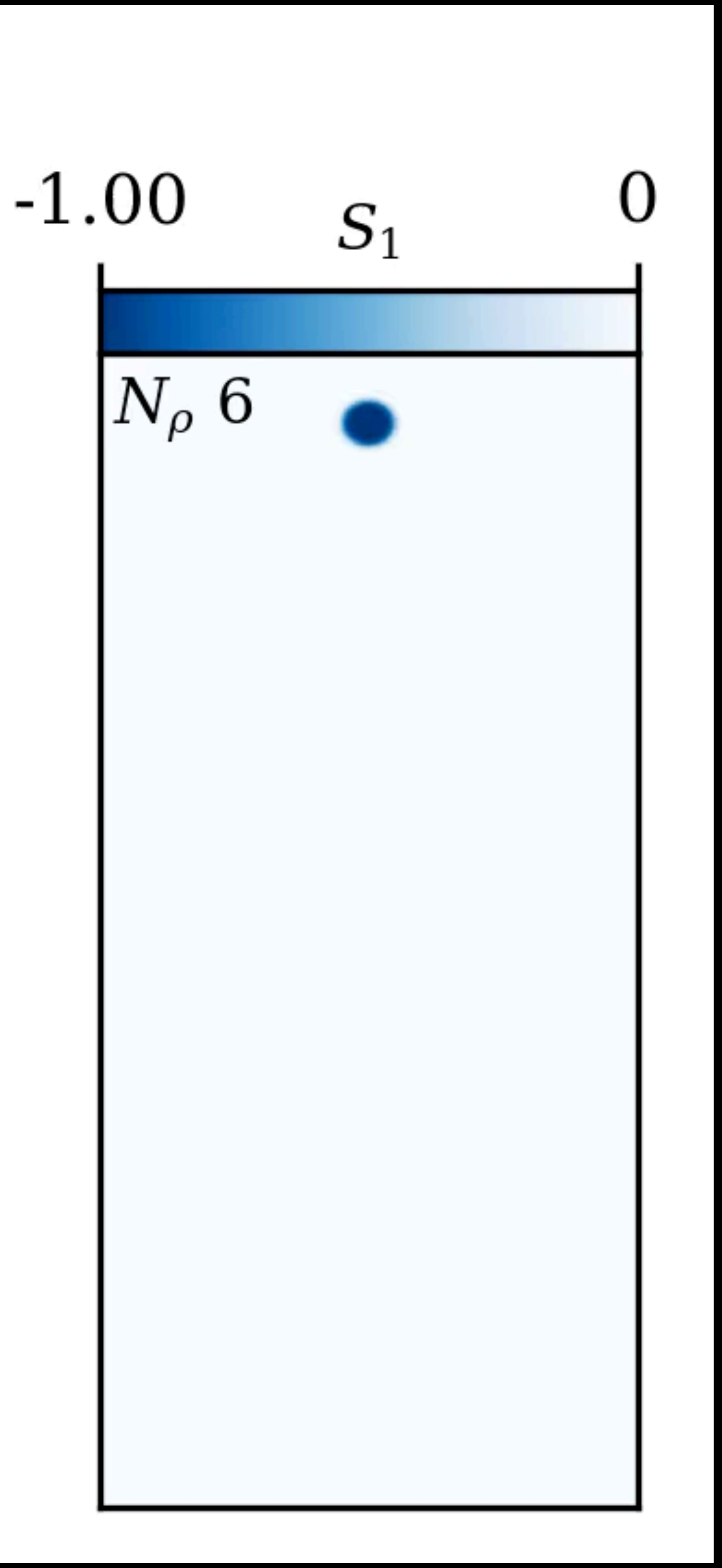




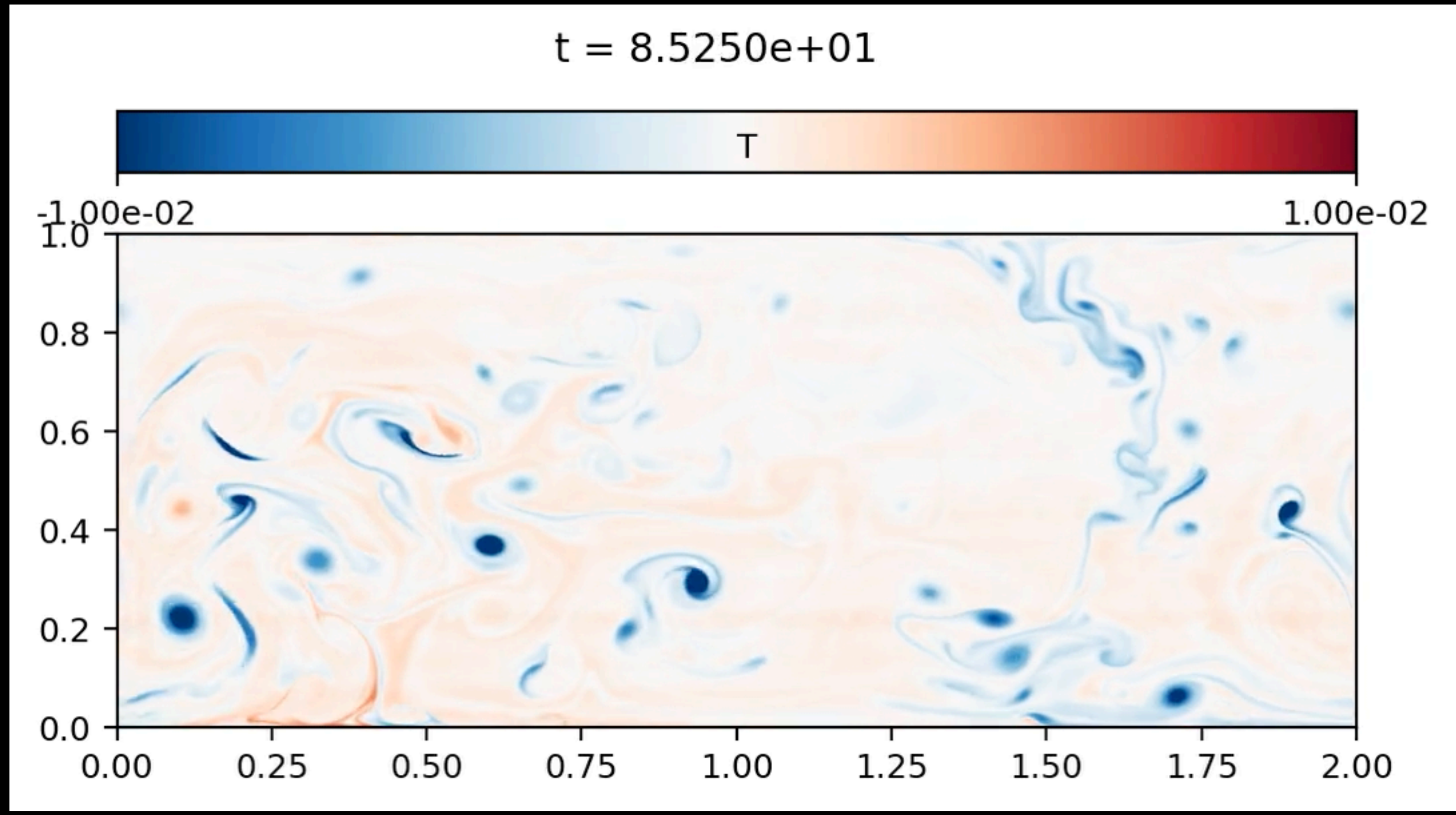
Density stratification
[Anders & Brown 2017 PRF 02 083501]

Dedalus' many applications: Education

MMath and MPhys projects

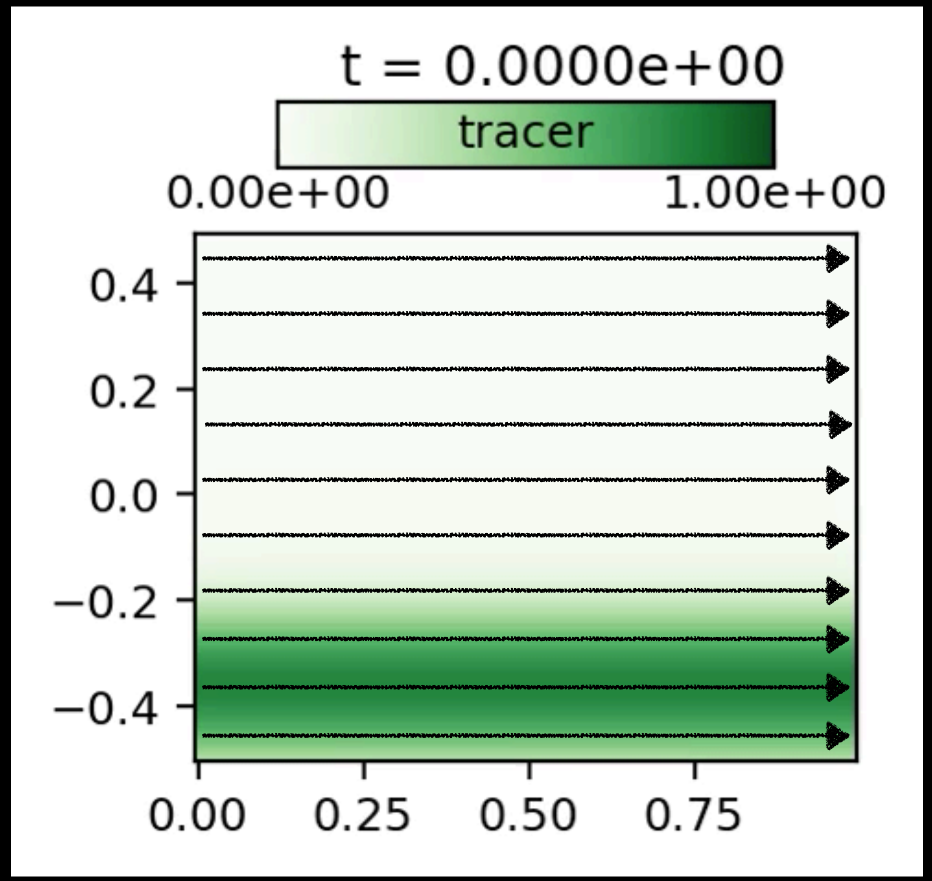


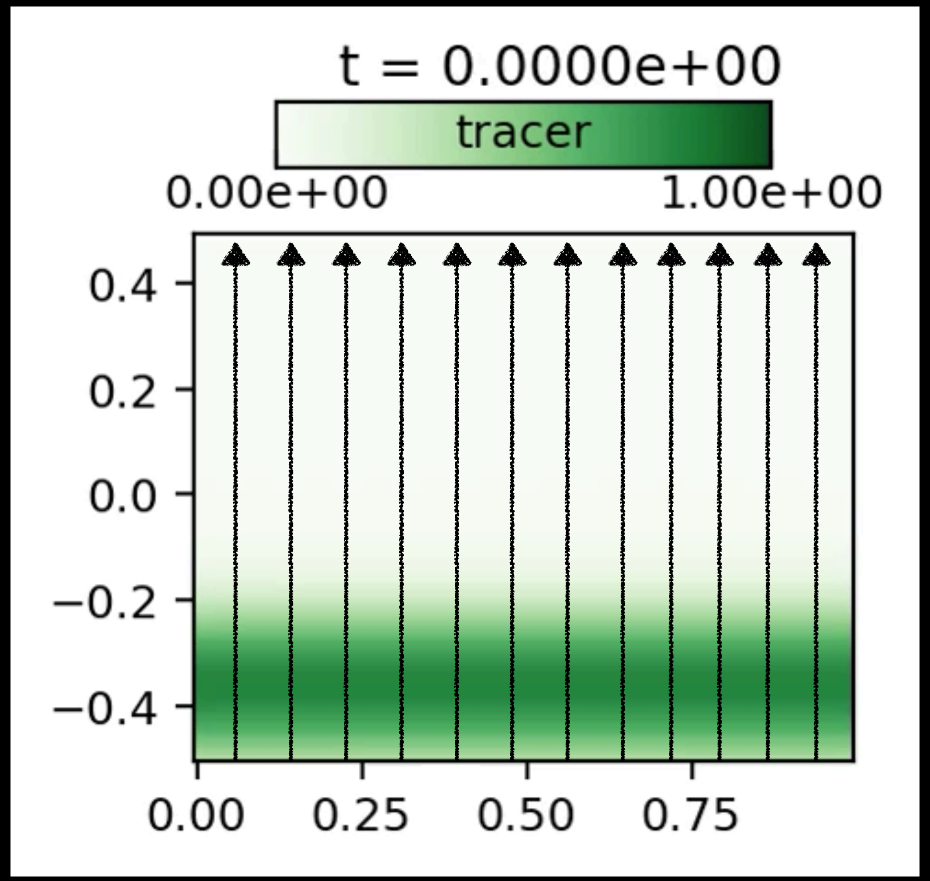
Single convective events:
Thermals or plumes



Rayleigh-Benard Convection

Classroom examples





What sets the size of a PZ?

Take the kinetic energy equation,

$$\frac{\partial \mathscr{K}}{\partial t} + \nabla \cdot \left(\overrightarrow{\mathscr{F}} \right) = \mathscr{B} - \Phi$$

[Zahn 1991 A&A 252 179]

[Roxburgh 1989 A&A 211 361]

What sets the size of a PZ?

Volume average (over CZ + PZ) & assume time stationary

$$\cancel{\frac{\partial \mathscr{K}}{\partial t}} + \cancel{\nabla \cdot \left(\overrightarrow{\mathscr{F}} \right)} = \mathscr{B} - \Phi$$

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Volume average (over CZ + PZ) & assume time stationary

$$\cancel{\frac{\partial \mathcal{K}}{\partial t}} + \cancel{\nabla \cdot \left(\overrightarrow{\mathcal{F}} \right)} = \mathcal{B} - \Phi$$

$$\iiint \mathcal{B}\, dV = \iiint \Phi\, dV$$

Buoyant work balances viscous losses.

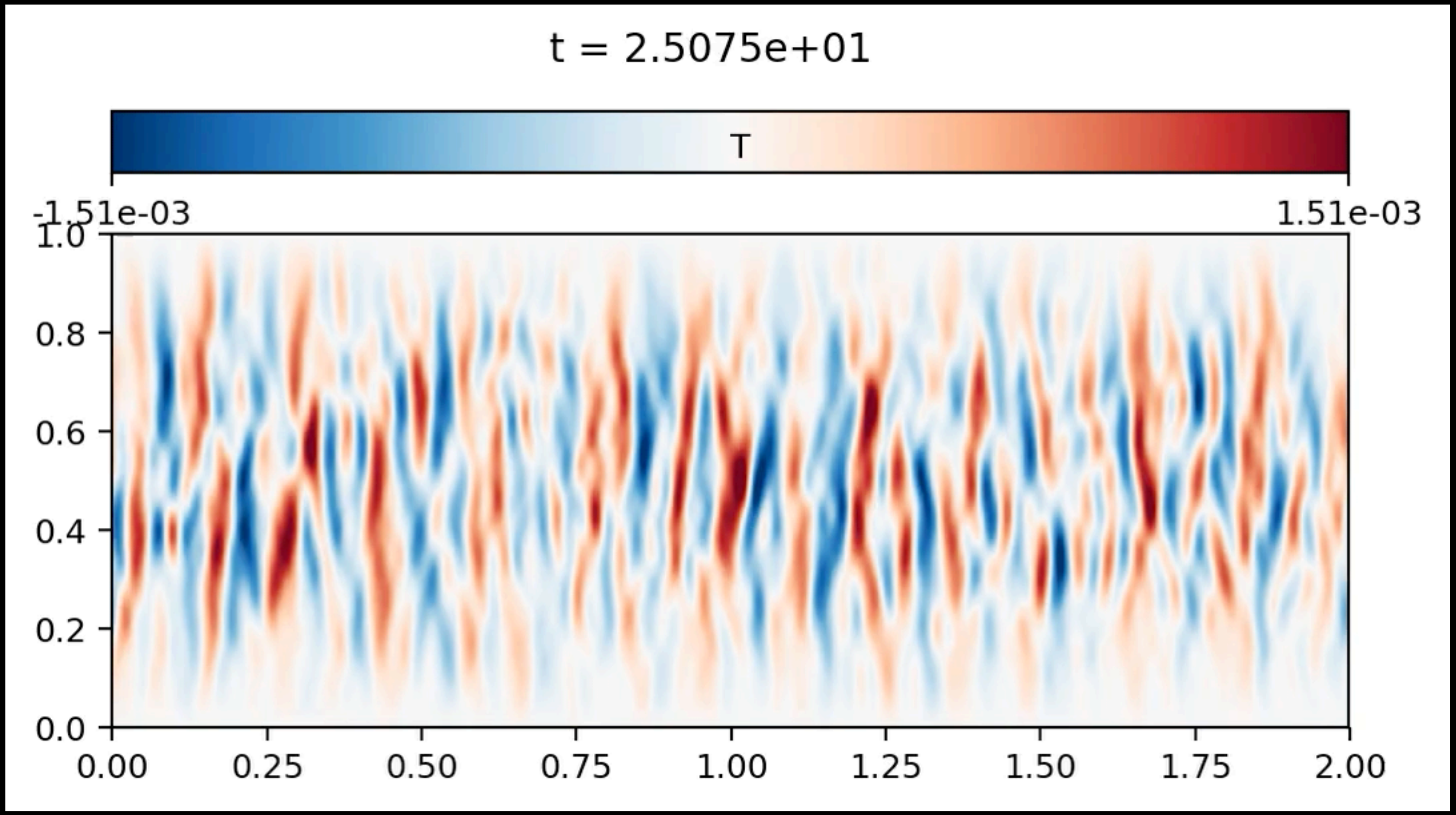
[Zahn 1991 A&A 252 179]

[Roxburgh 1989 A&A 211 361]

What's next?

3. Expand accelerated evolution experiments

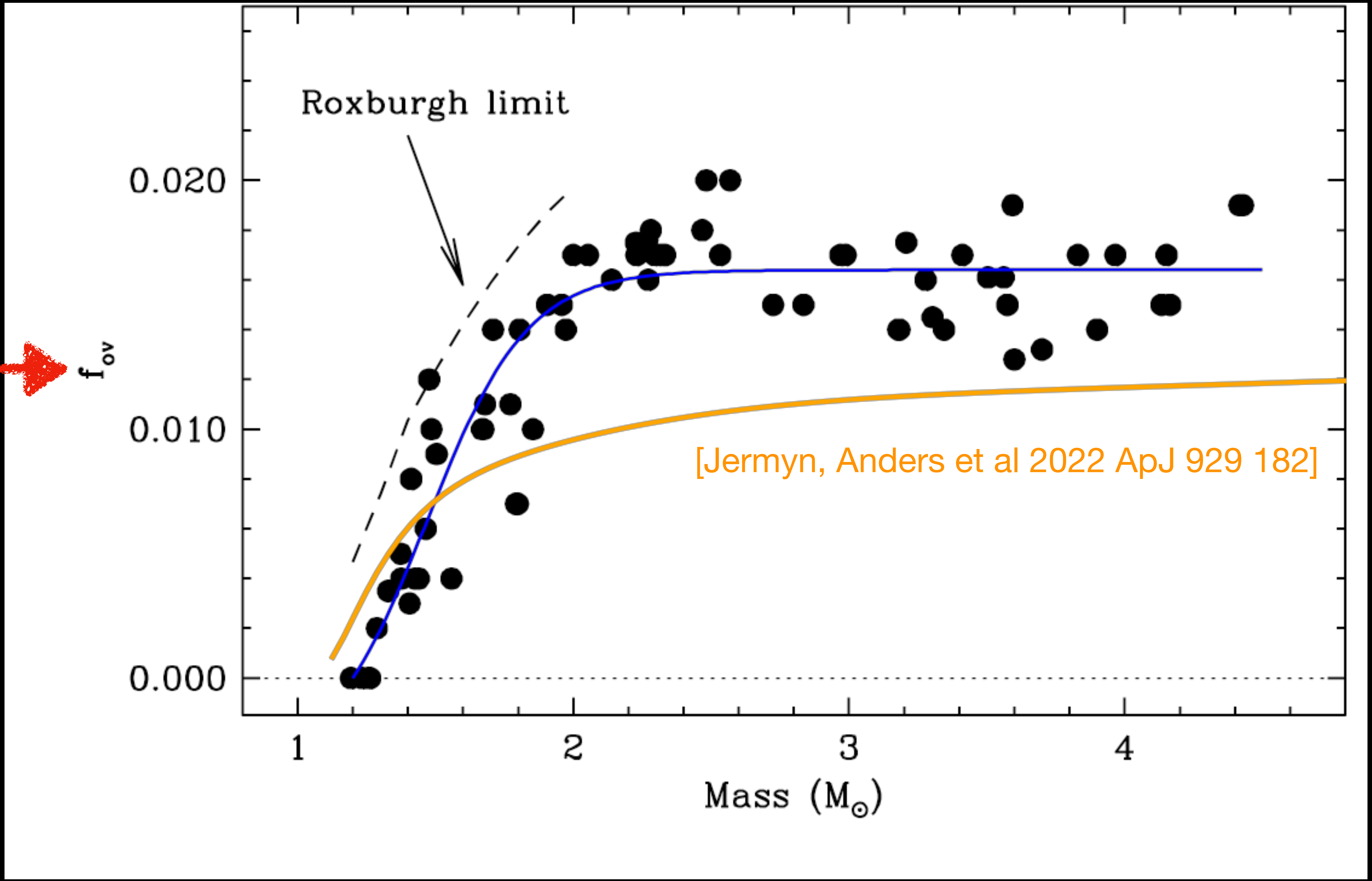
- Equilibrating a convection zone takes a long time. Unclear what happens when you have:
  - Convective layer + stable layer
  - Composition fields & irreversible mixing
- Possibly can use these methods for mean flows (e.g., differential rotation) and vector fields (angular momentum)



Upshot: Mixing in Eclipsing Binaries

Roxburgh limit uniformly over-predicts.

Mixing required to match observations



[Claret & Torres 2019 ApJ 876 134]

What sets the size of a PZ?

Buoyant work

$$\iiint \mathscr{B}\, dV$$

Positive in the CZ

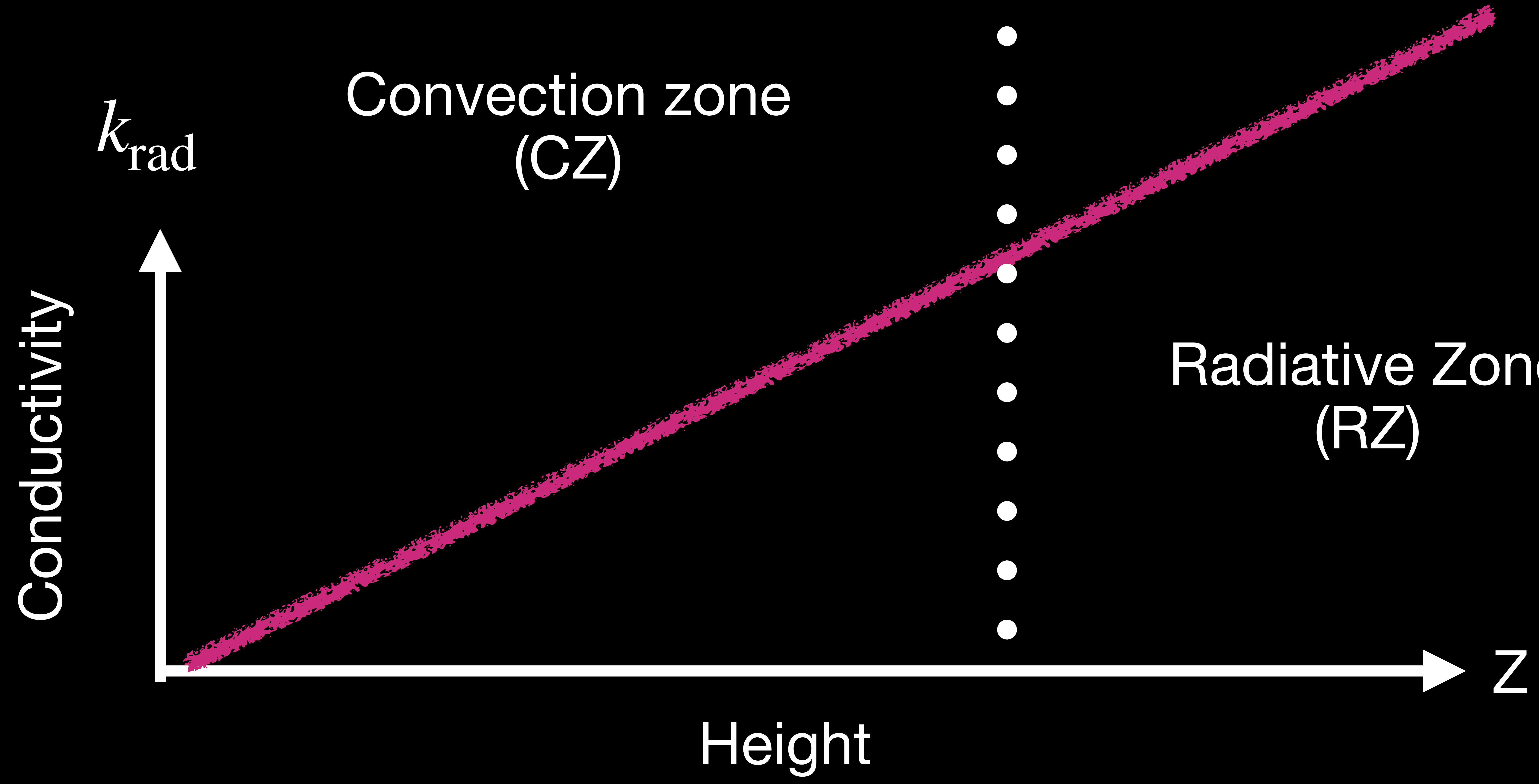
Negative in the PZ

Viscous Dissipation

$$\iiint \Phi\, dV \longrightarrow$$

Positive everywhere

Why is there a convective boundary?



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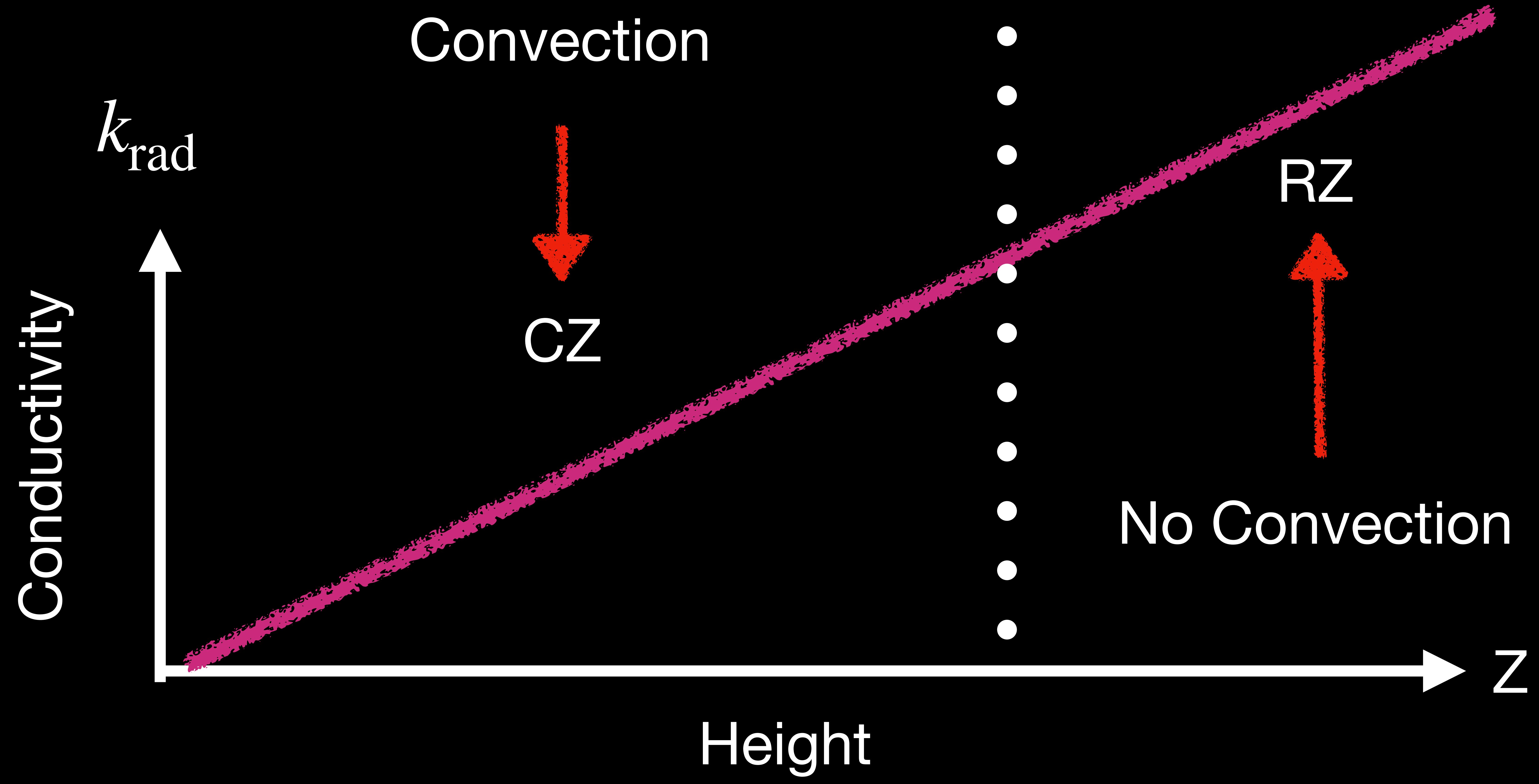

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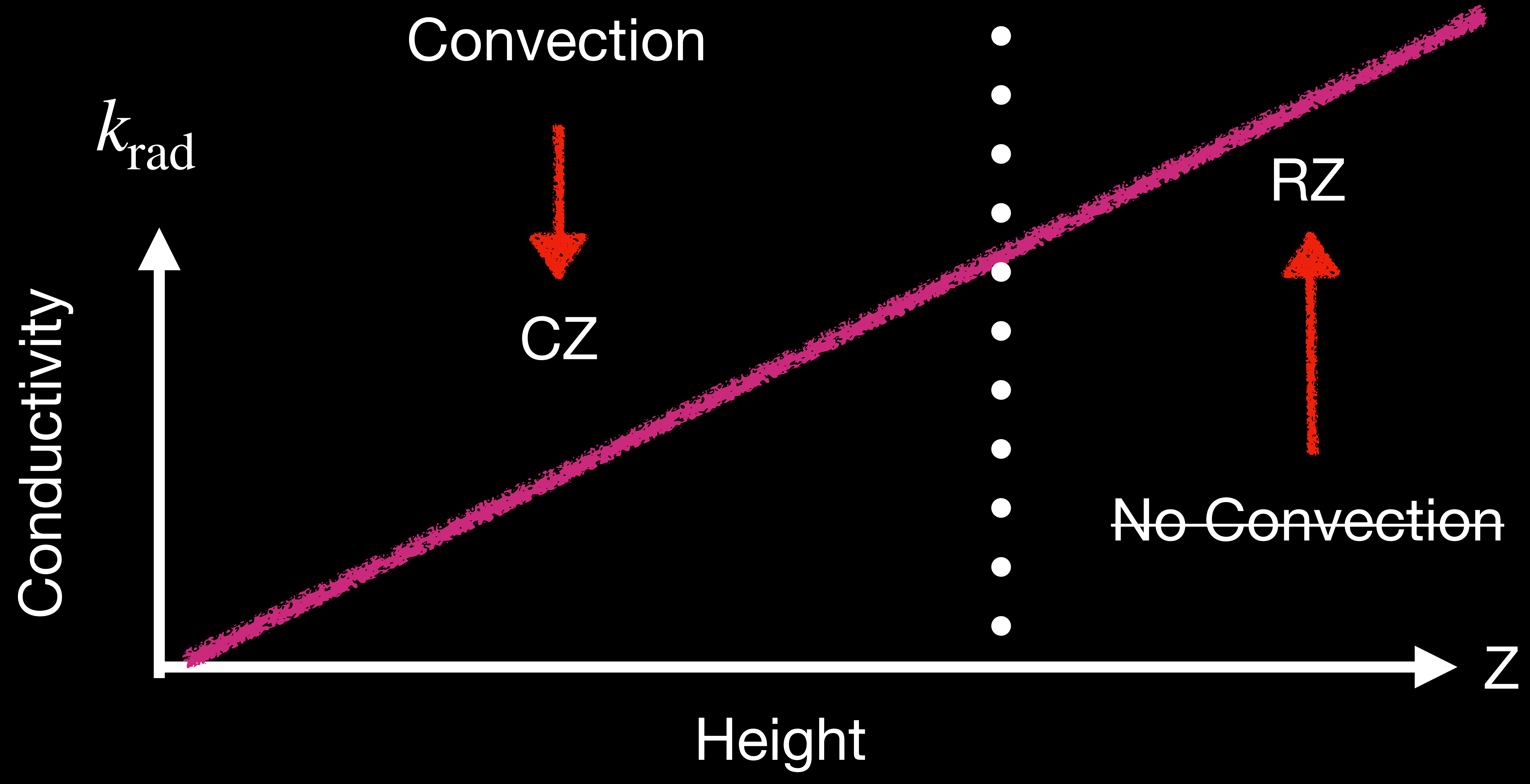

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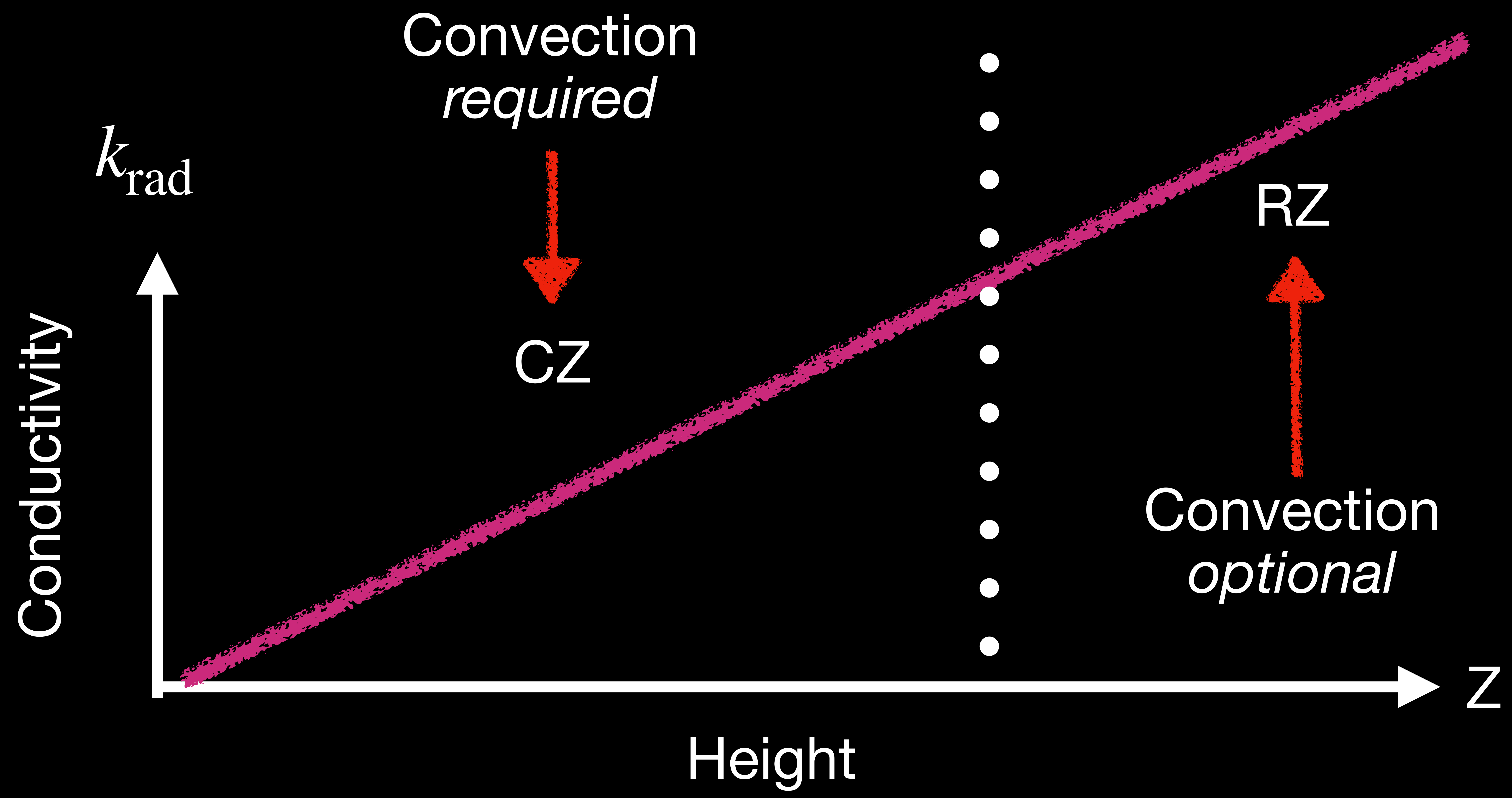
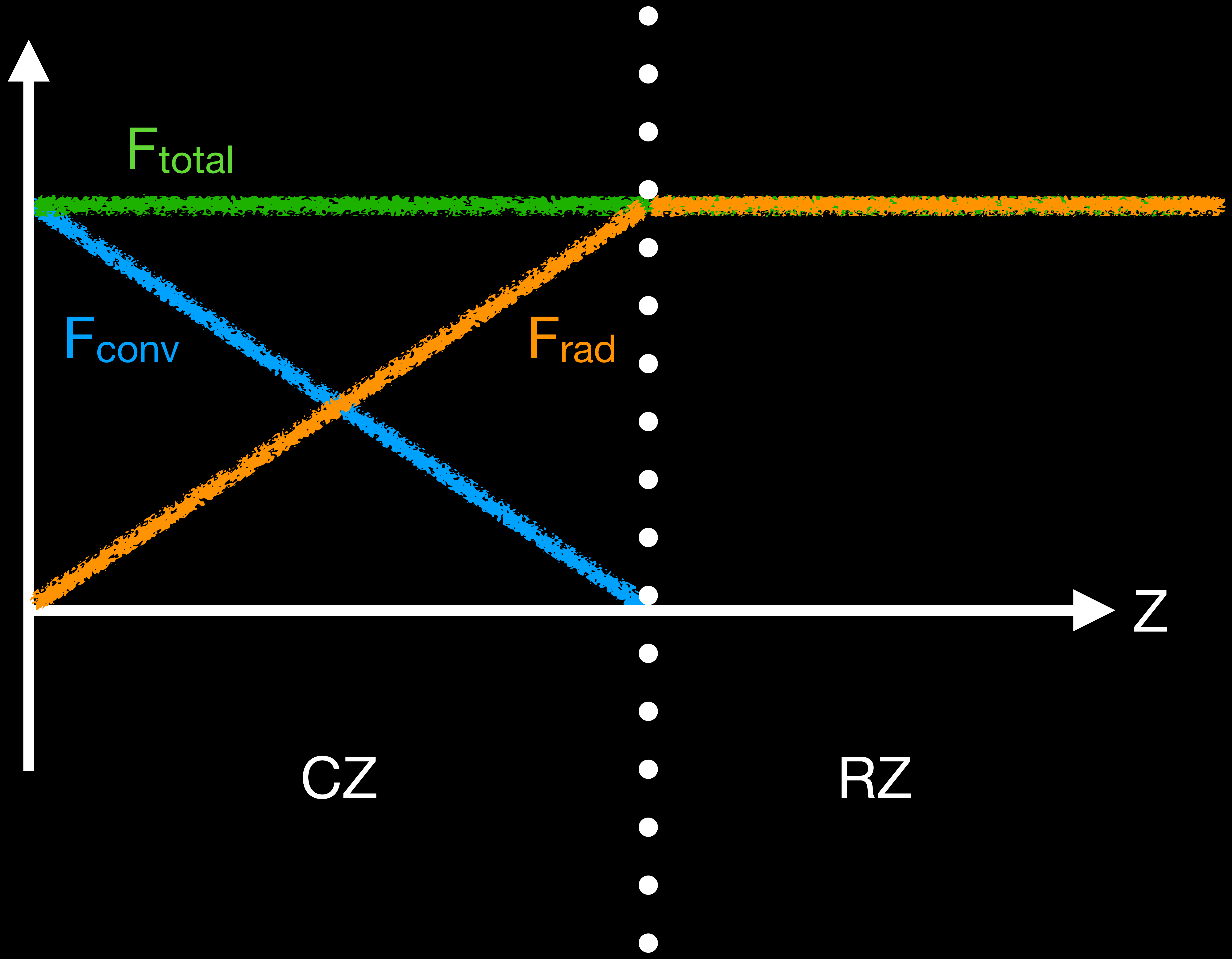
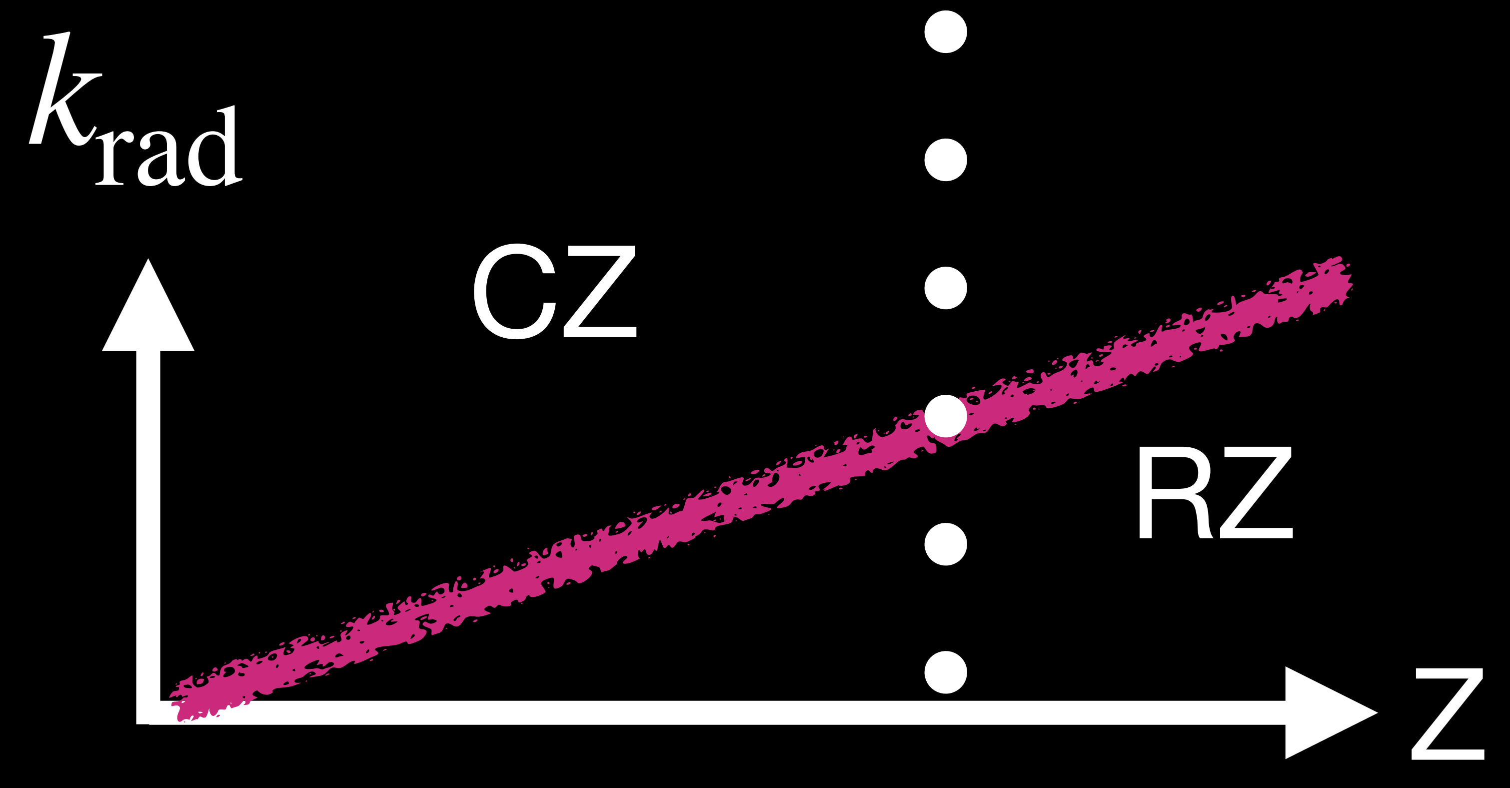
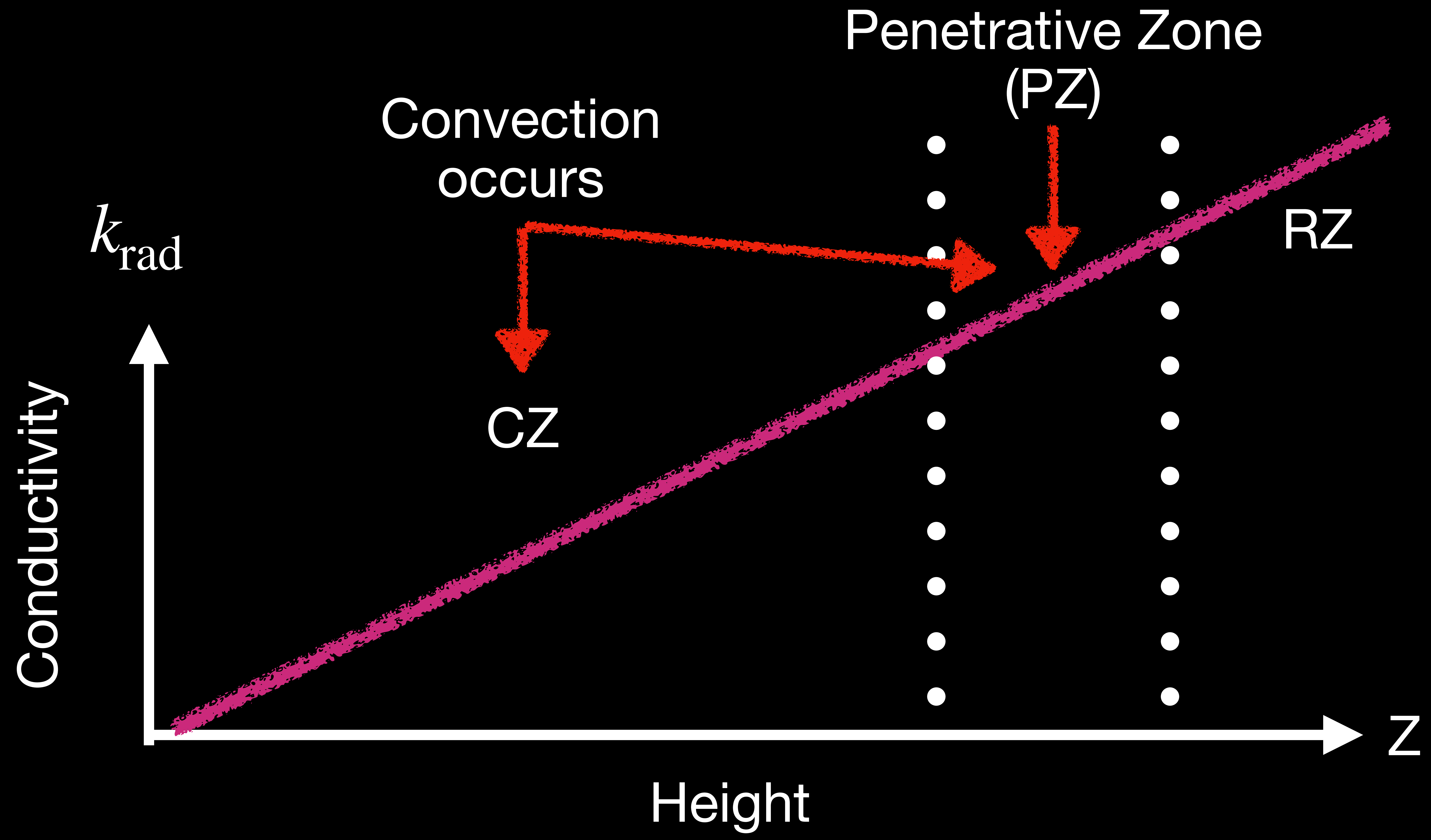


Fluxes and Stability

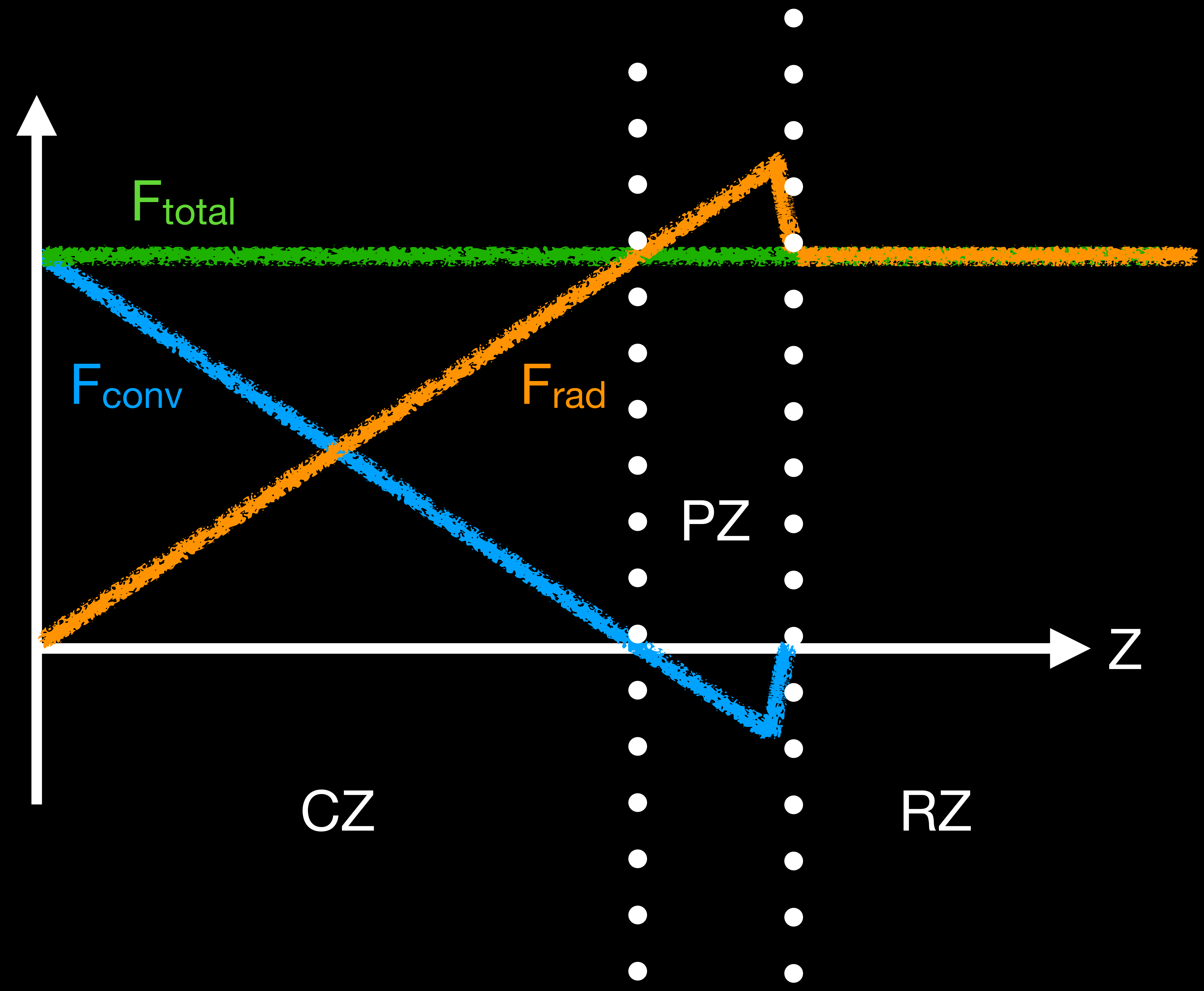


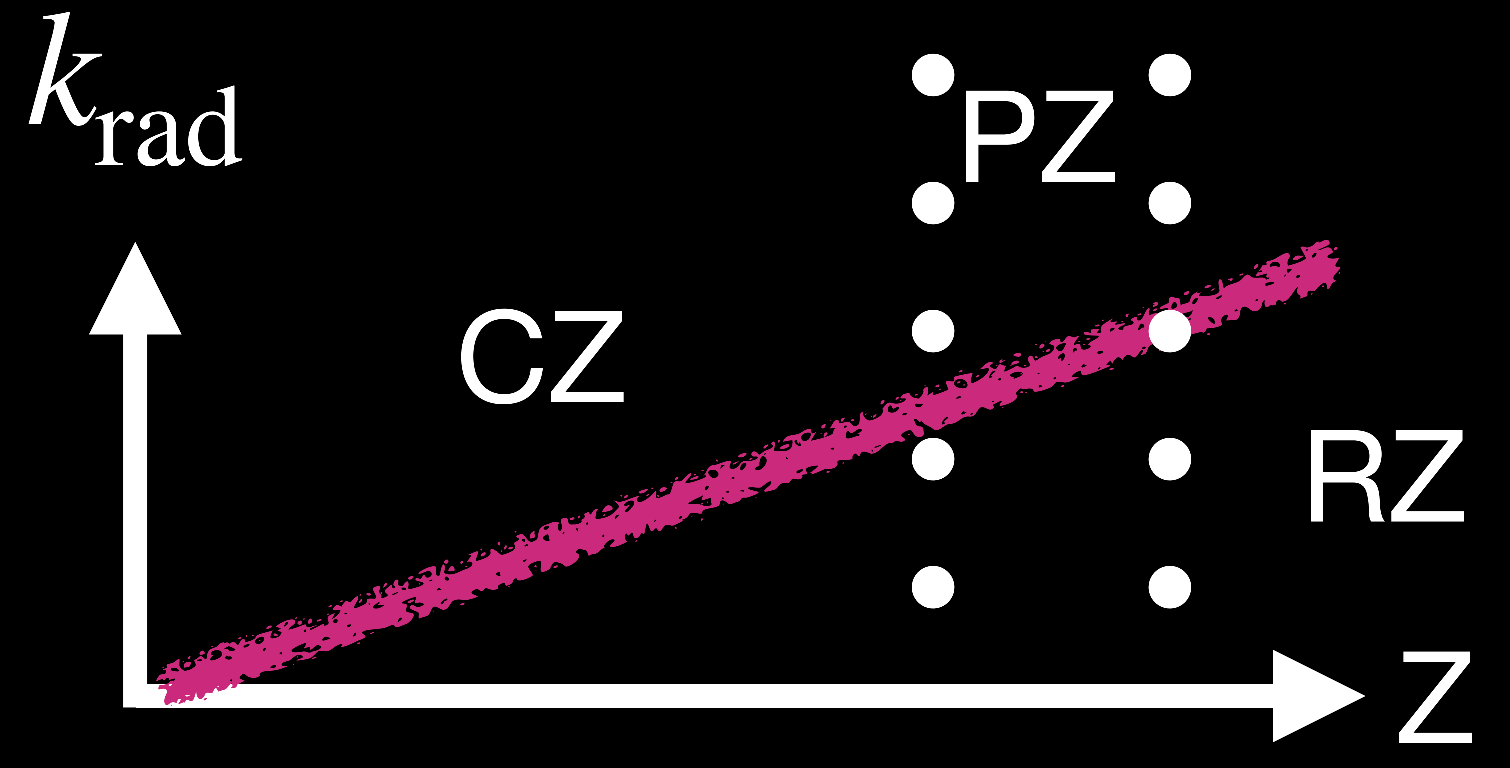


What is penetrative convection?



Fluxes and Stability - with a PZ

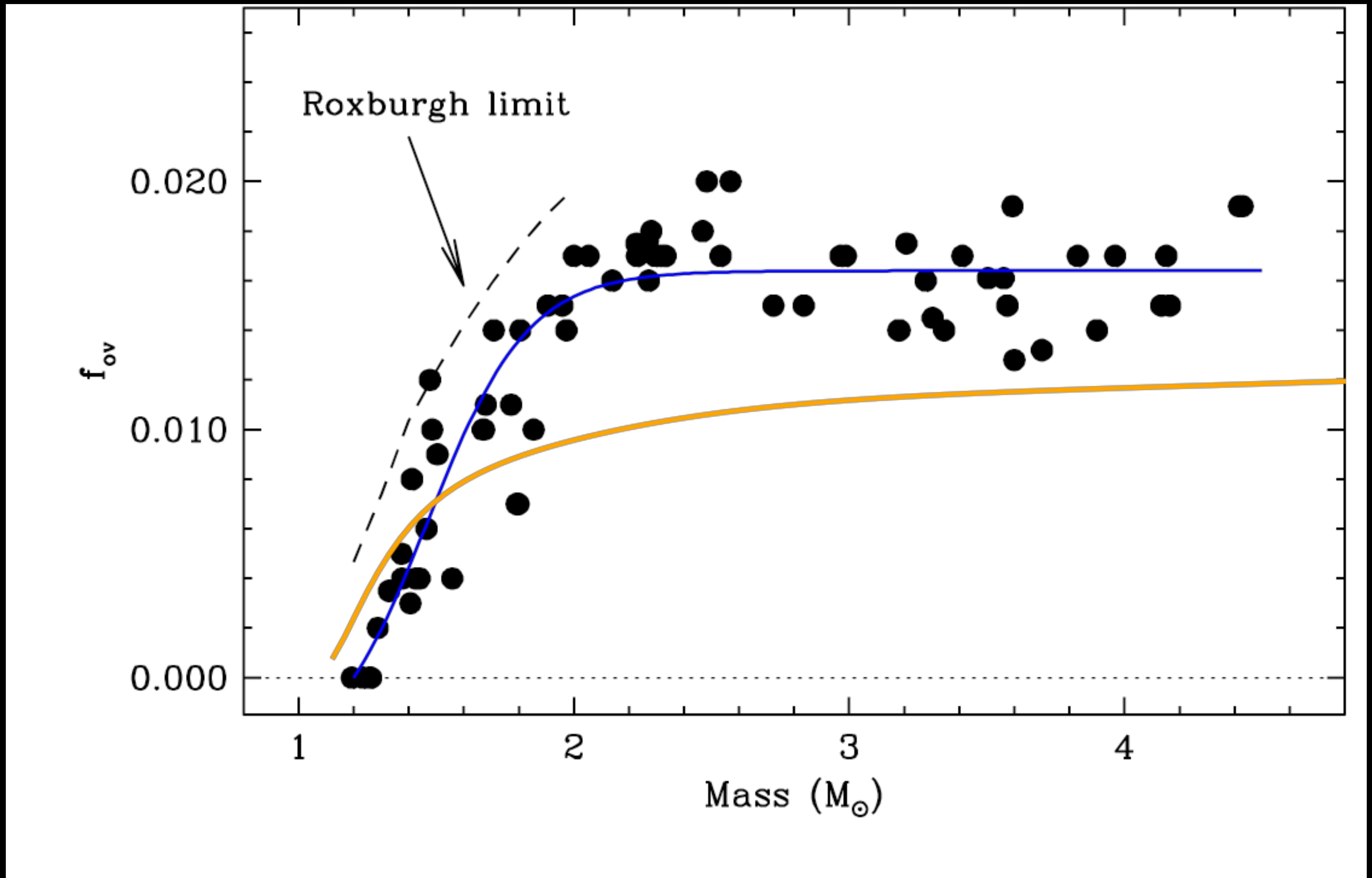




What's next?

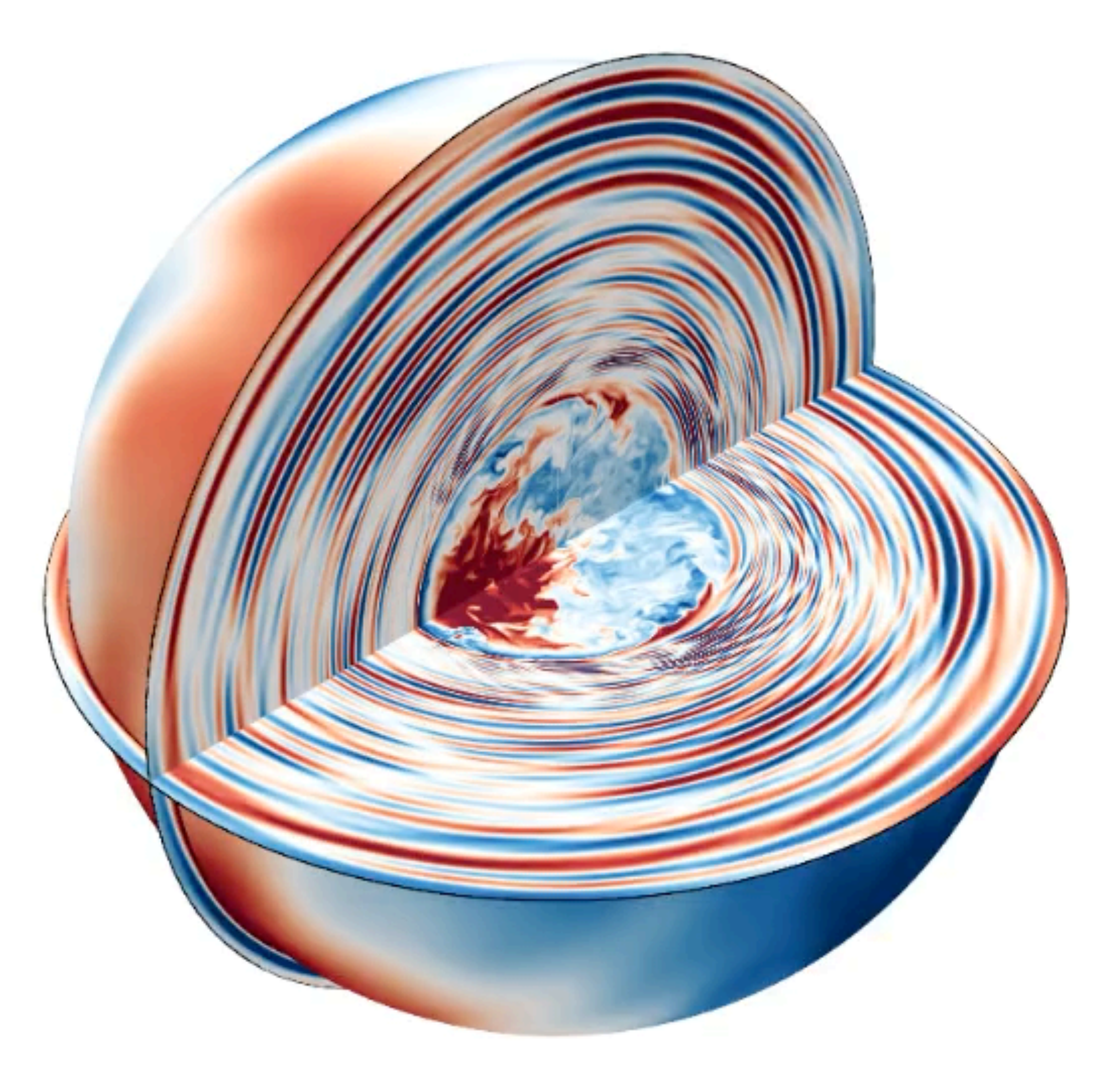
2. Understand penetrative convection in stars

- Incorporate into 1D models self-consistently
    - Understand implications for stellar lifetimes, remnants, etc
- Demonstrate validity of theory in a grid of 3D hydro models based on stars of different masses
    - Why does the mass change the fluid dynamics? / Rotation?



What’s next?

4. Internal gravity waves in massive stars



- First spectral fully compressible simulations that include r = 0 coordinate singularity.
- Determine the effects of rotation on observed signal
- Understand how stiffness changes wave properties
- Understand how damping changes observable signals

$$S = \frac{N_{RZ}}{(u/\ell)}$$