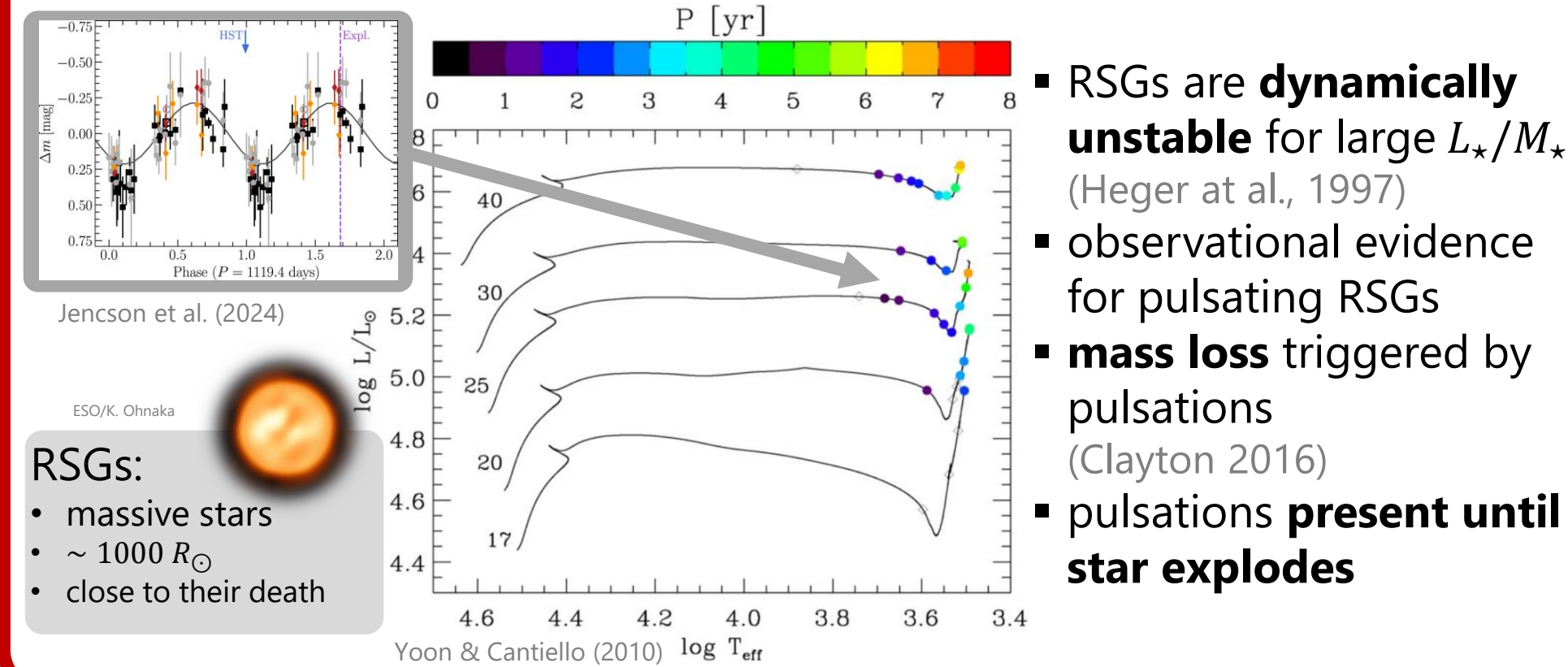# Pulsating Red Supergiants: A New Perspective on Type II Supernova Light Curve Diversity
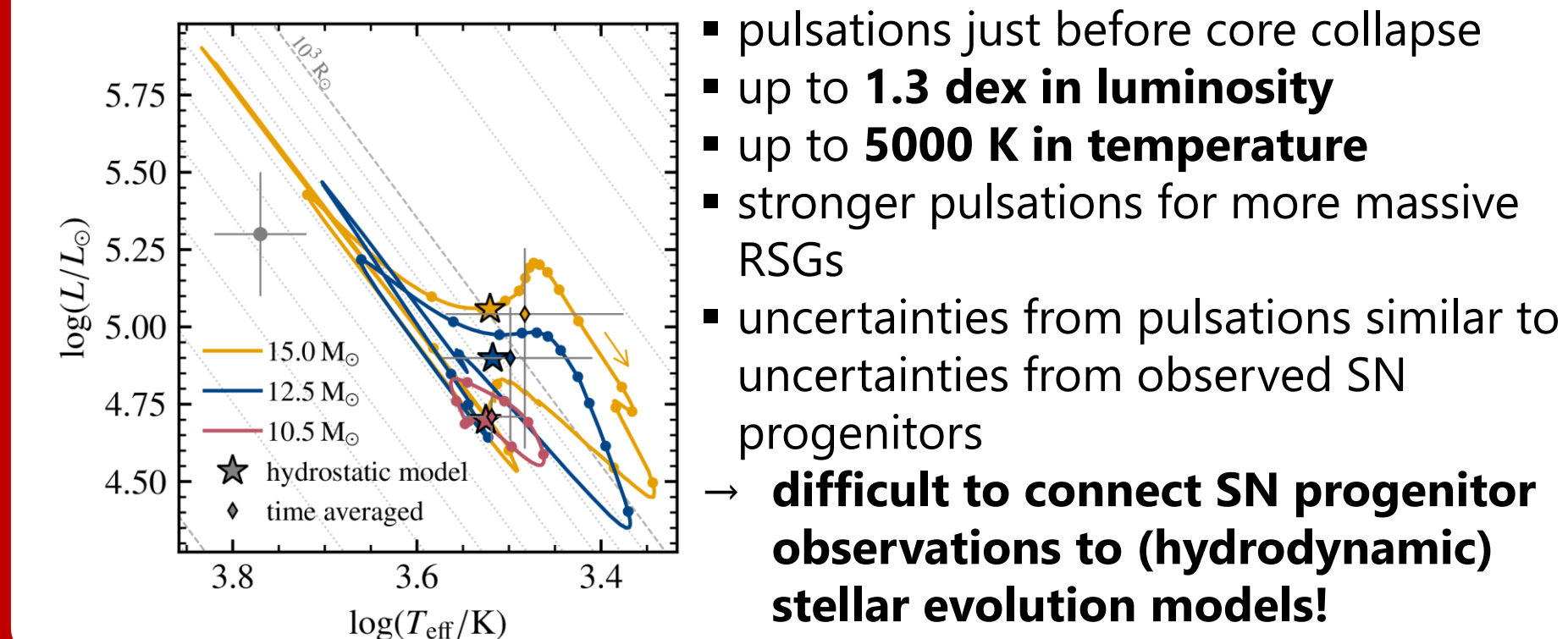
Vincent. A. Bronner, Eva Laplace, Fabian R. N. Schneider, Philipp Podsiadlowski
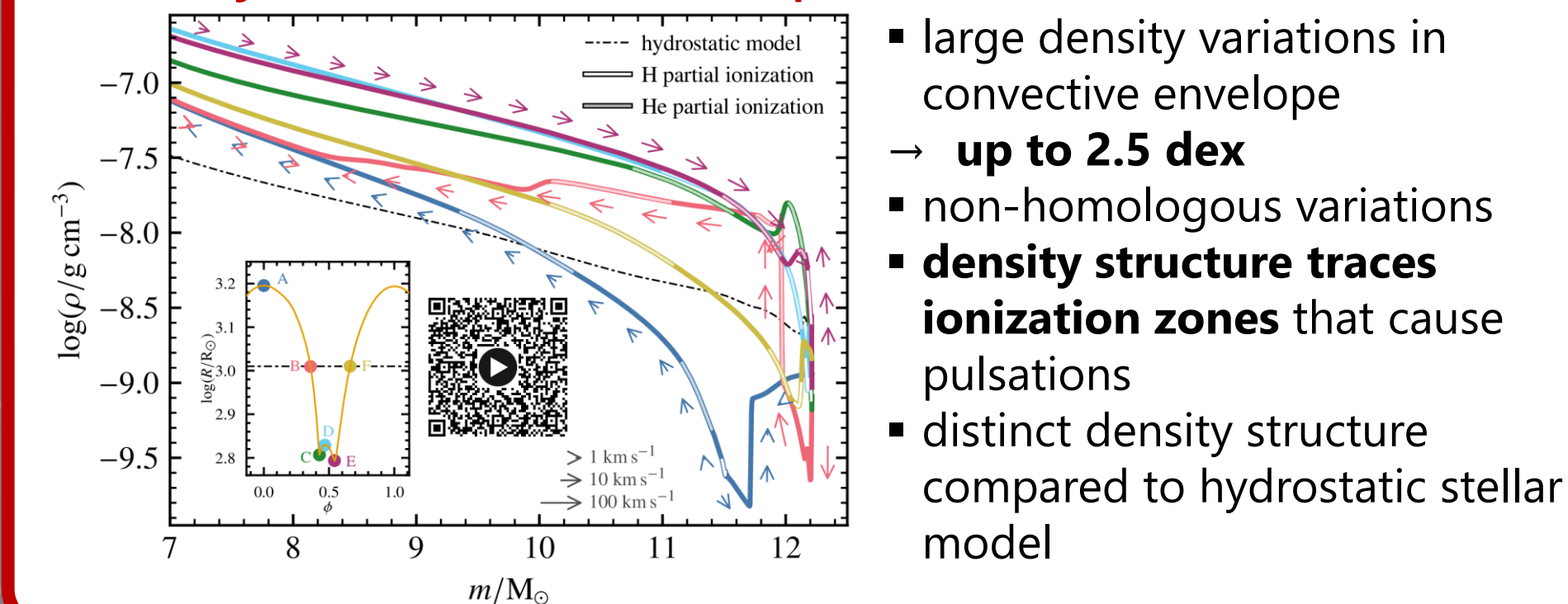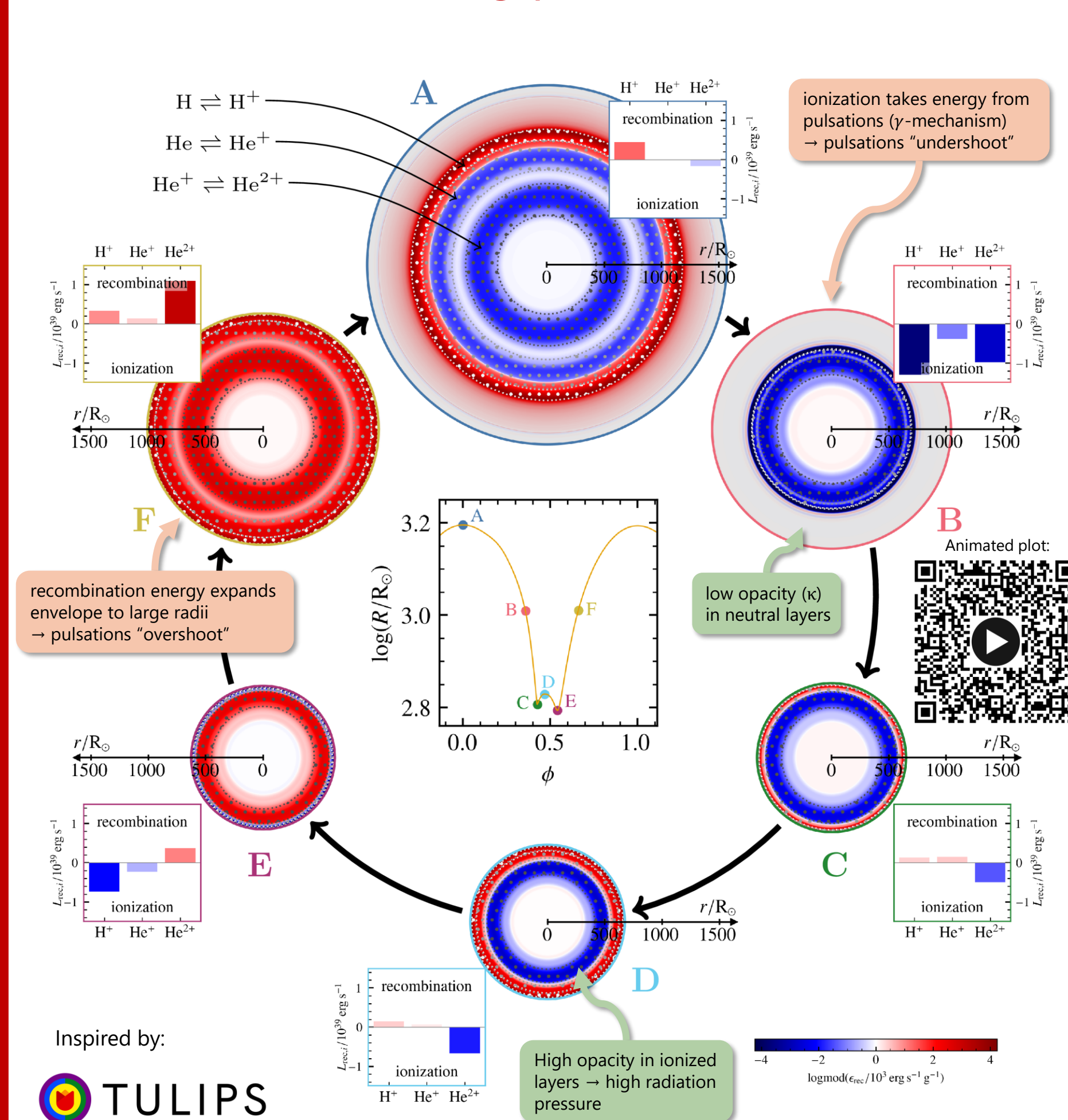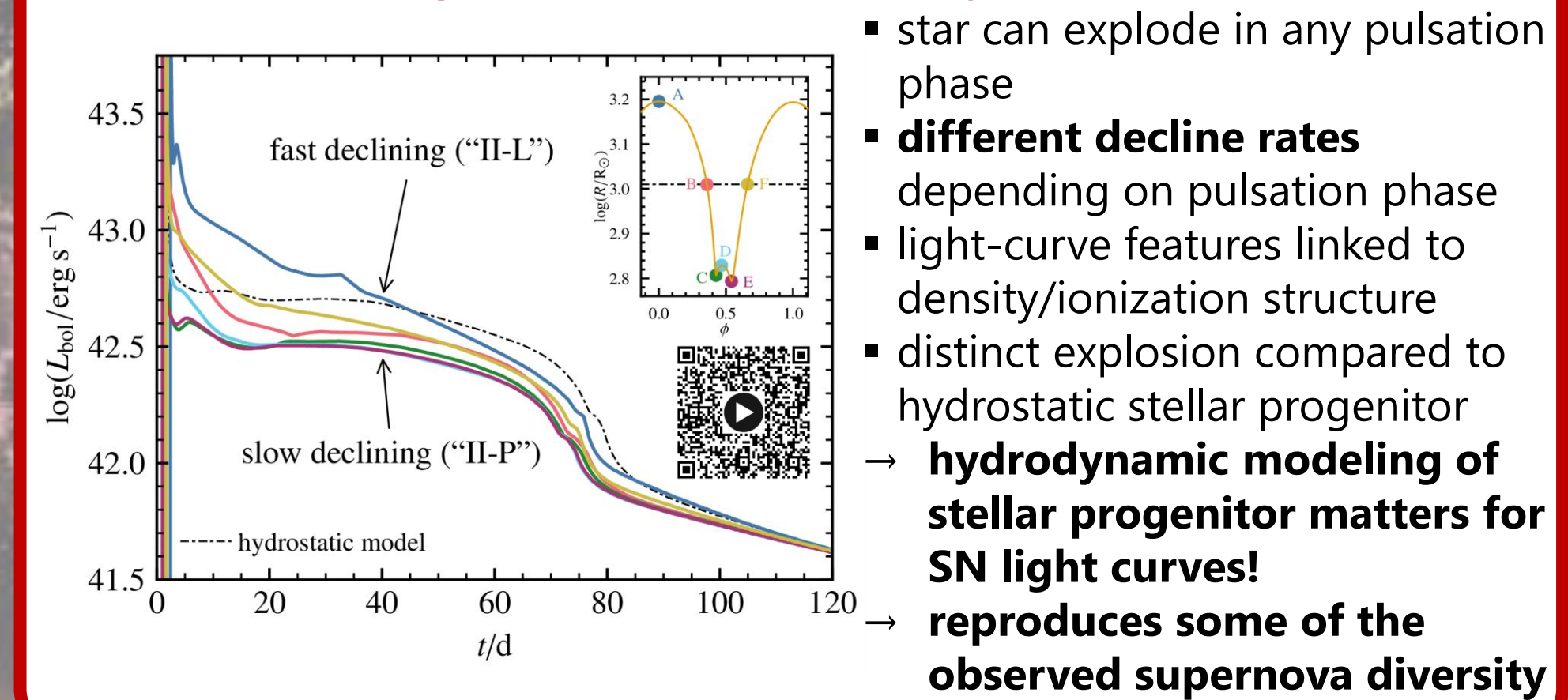
Pulsating red supergiants (RSGs)

Jencson et al. (2024)

ESO/K. Ohnaka

RSGs:
- massive stars
- $\sim 1000\, R_\odot$
- close to their death

Yoon & Cantiello (2010)

- RSGs are **dynamically unstable** for large $L_\star/M_\star$ (Heger at al., 1997)
- observational evidence for pulsating RSGs
- **mass loss** triggered by pulsations (Clayton 2016)
- pulsations **present until star explodes**

Pulsations in Hertzsprung-Russell diagram

- 15.0 $M_\odot$
- 12.5 $M_\odot$
- 10.5 $M_\odot$
- ★ hydrostatic model
- ◆ time averaged

- pulsations just before core collapse
- up to **1.3 dex in luminosity**
- up to **5000 K in temperature**
- stronger pulsations for more massive RSGs
- uncertainties from pulsations similar to uncertainties from observed SN progenitors
→ **difficult to connect SN progenitor observations to (hydrodynamic) stellar evolution models!**

Density variations from pulsations

- hydrostatic model
- H partial ionization
- He partial ionization

- large density variations in convective envelope
→ **up to 2.5 dex**
- non-homologous variations
- **density structure traces ionization zones** that cause pulsations
- distinct density structure compared to hydrostatic stellar model

$\kappa\gamma$-mechanism driving pulsations

$H \rightleftharpoons H^+$
$He \rightleftharpoons He^+$
$He^+ \rightleftharpoons He^{2+}$

ionization takes energy from pulsations (γ-mechanism)
→ pulsations "undershoot"

low opacity (κ) in neutral layers

recombination energy expands envelope to large radii
→ pulsations "overshoot"

High opacity in ionized layers → high radiation pressure

Animated plot:

$\log(\epsilon_{mc}/10^3\,\mathrm{erg\,s^{-1}\,g^{-1}})$

Inspired by:

TULIPS
Tool for Understanding the Lives, Interiors, and Physics of Stars

2 new papers on arXiv this Monday

HITS — Heidelberg Institute for Theoretical Studies

European Research Council — Established by the European Commission

TEL-STARS

UNIVERSITÄT HEIDELBERG — ZUKUNFT SEIT 1386

Supernova light-curve diversity

fast declining ("II-L")

slow declining ("II-P")

hydrostatic model

- star can explode in any pulsation phase
- **different decline rates** depending on pulsation phase
- light-curve features linked to density/ionization structure
- distinct explosion compared to hydrostatic stellar progenitor
→ **hydrodynamic modeling of stellar progenitor matters for SN light curves!**
→ reproduces some of the observed supernova diversity

Modeling SN 2023ixf with pulsating progenitor

stellar progenitor of SN 2023ixf in M101 (6.9 Mpc)

Qin et al. (2024)

Supernova light curve

- Hydrostatic model
- Without CSM
- With CSM
- Zimmerman+2024
- Singh+2024

Gutiérrez+2017a

$\phi_{exp} = 0.36, R_{ext} = 4000\,R_\odot, \dot{M} = 1\,M_\odot\,\mathrm{yr}^{-1}$,
$E = 0.9\,\mathrm{B}, M_{Ni} = 0.055\,M_\odot, M_b = 12.09\,M_\odot$

Progenitor light curve

- 15 $M_\odot$: 3.6 μm
- 15 $M_\odot$: 4.5 μm
- Spitzer: 3.6 μm
- Spitzer: 4.5 μm

$\tau_0 = 22.7$
$P = 1133\,\mathrm{d}$
$\phi_{exp} = 0.92$
$\chi^2_{red} = 1.07$

- progenitor light curve **well reproduced by pulsating, dust-enshrouded RSG**
- supernova light curve well reproduced by pulsating RSG in **contracting phase**
- circum-stellar material (CSM) needed to reproduce early-time light curve
→ **CSM from pulsations**