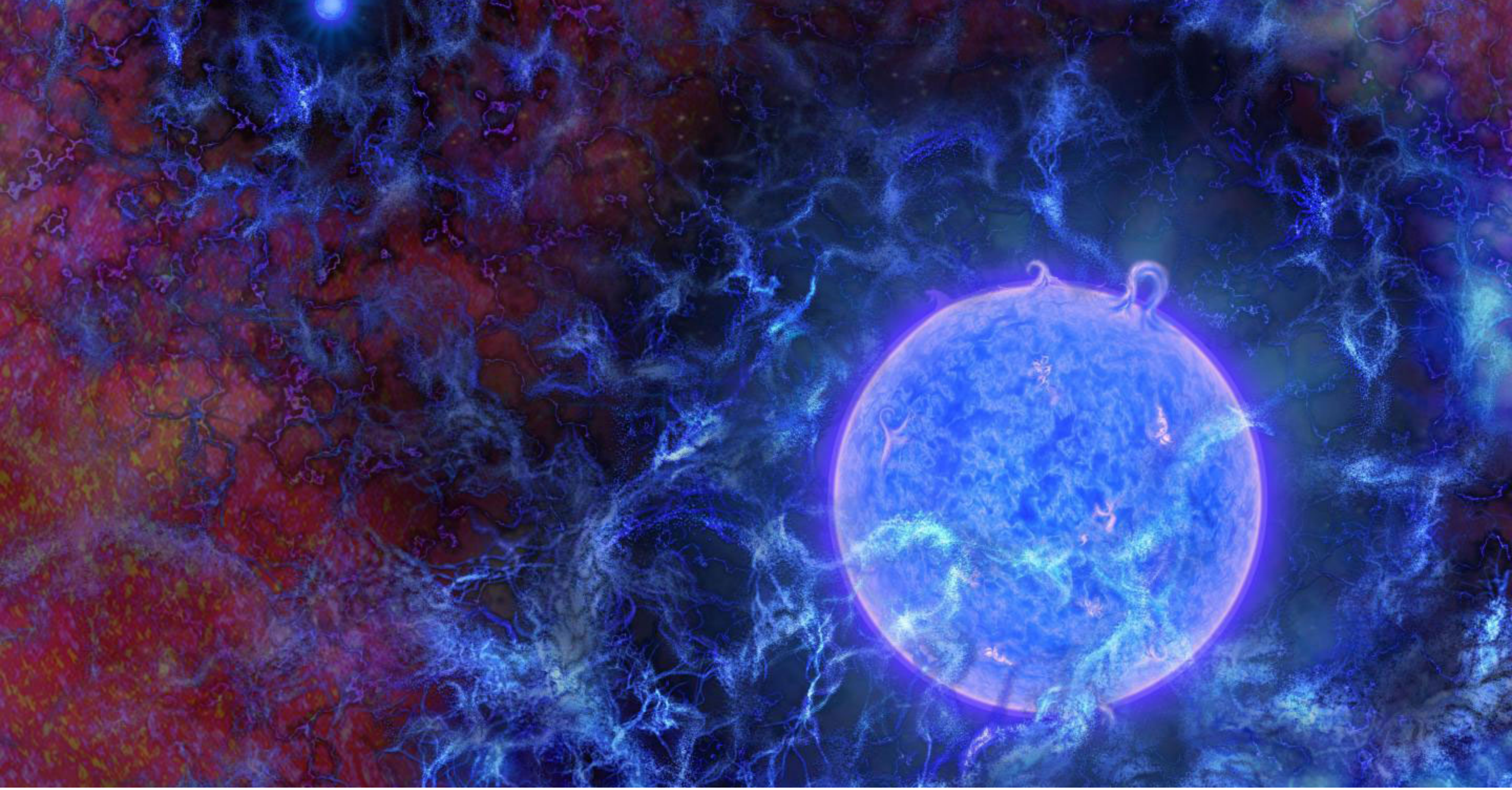


Stellar Physics: The New Era

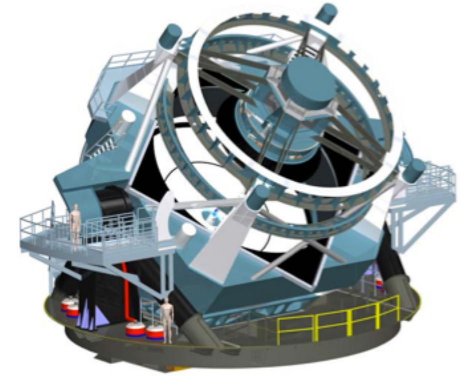
Matteo Cantiello [1,2]

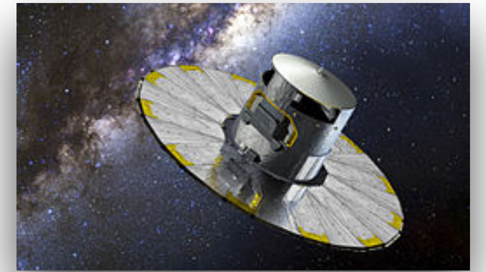
[1] CCA, Flatiron Institute
[2] Princeton University

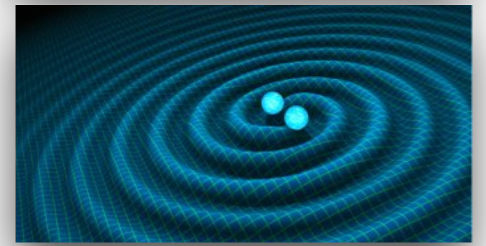
FLATIRON INSTITUTE
Division of Simons Foundation

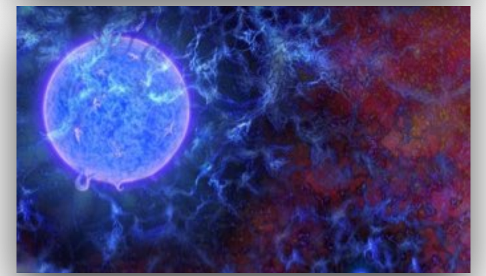
Exciting times for Stellar Physics

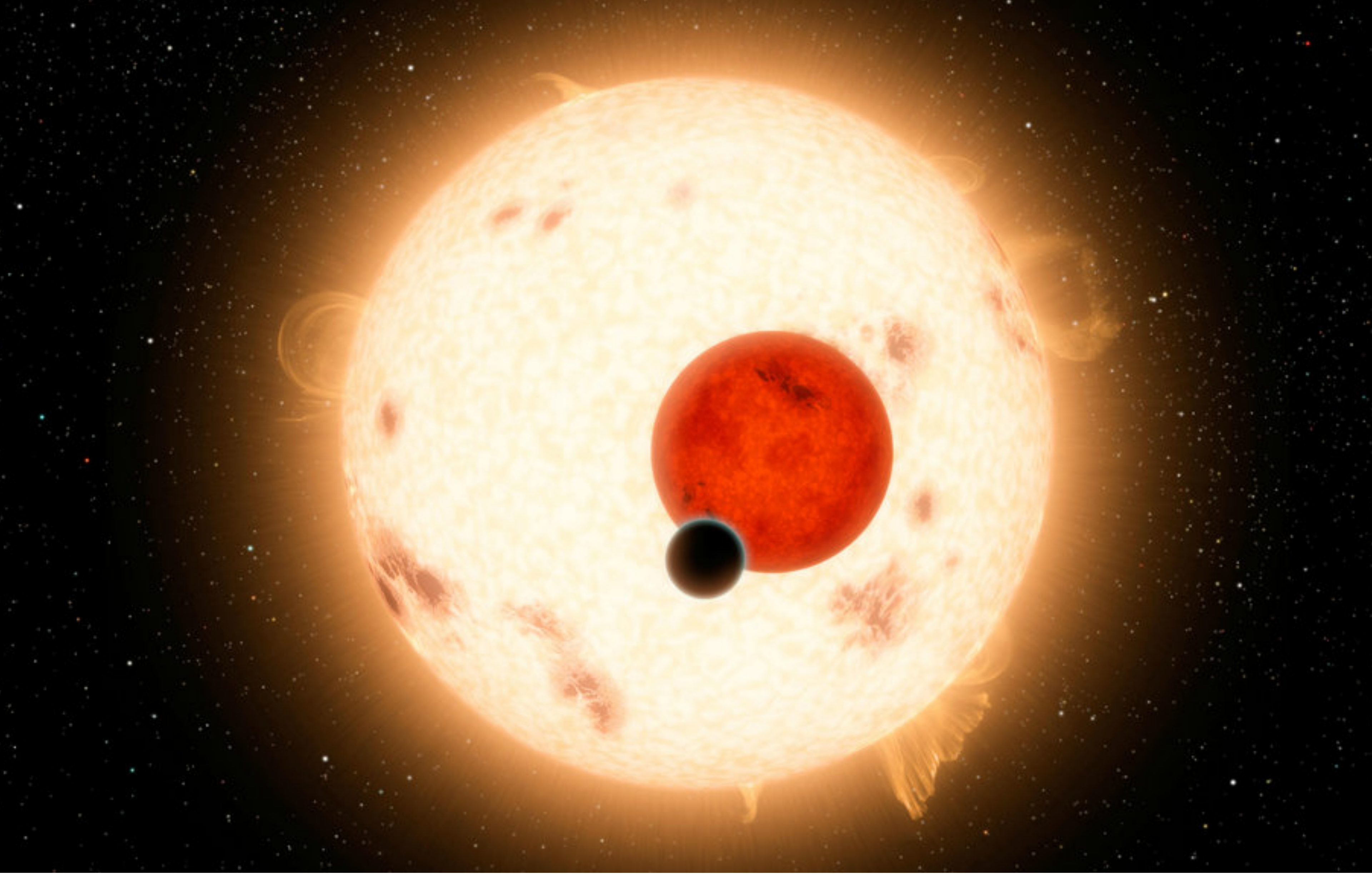
- Transient surveys unraveling unpredicted variety of explosive stellar deaths (e.g. PTF/ZTF, ASAS-SN, Pan-STARRS and soon LSST). We do not understand SN progenitors
- We are entering the era of high precision stellar physics (Kepler, BRITE, K2, GAIA, TESS, PLATO). Theory is lagging behind
- Dawn of GW-Astronomy! (LIGO/VIRGO)
- Probing the epoch of reionization / first stars? (EDGES / JWST)



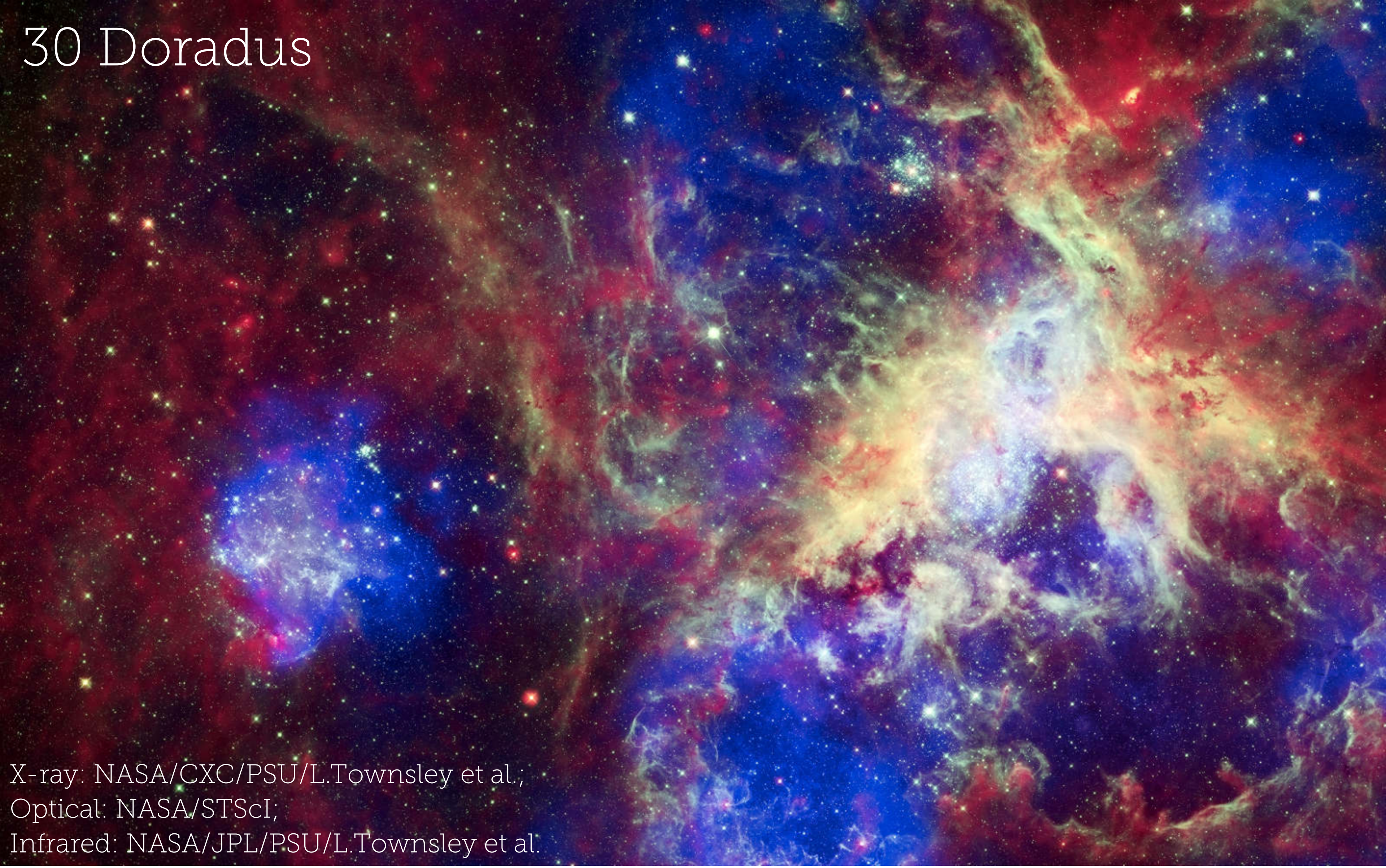








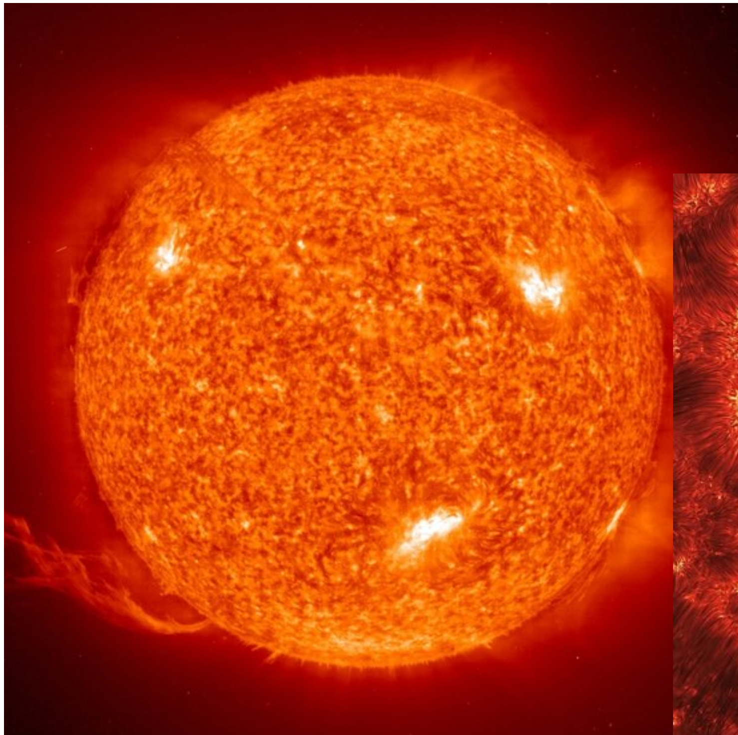
Know thy star, know thy planet

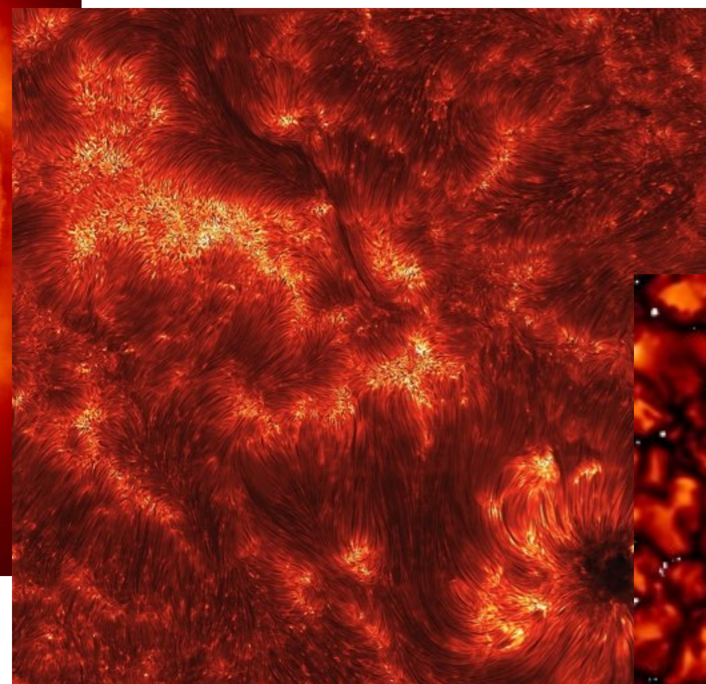


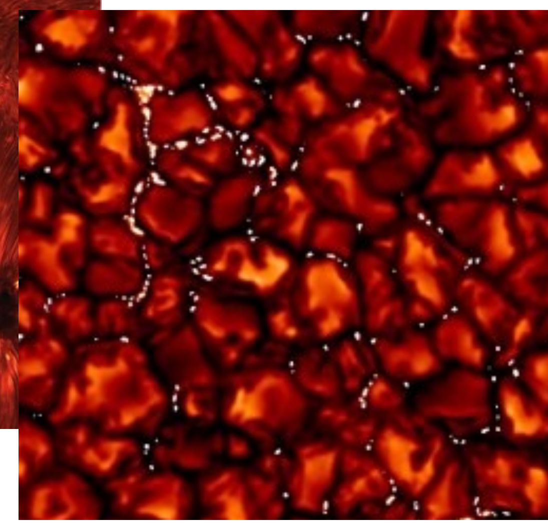
Reionization / Stellar Feedback. Chemical Evolution

Stellar Models

The Computational Challenge



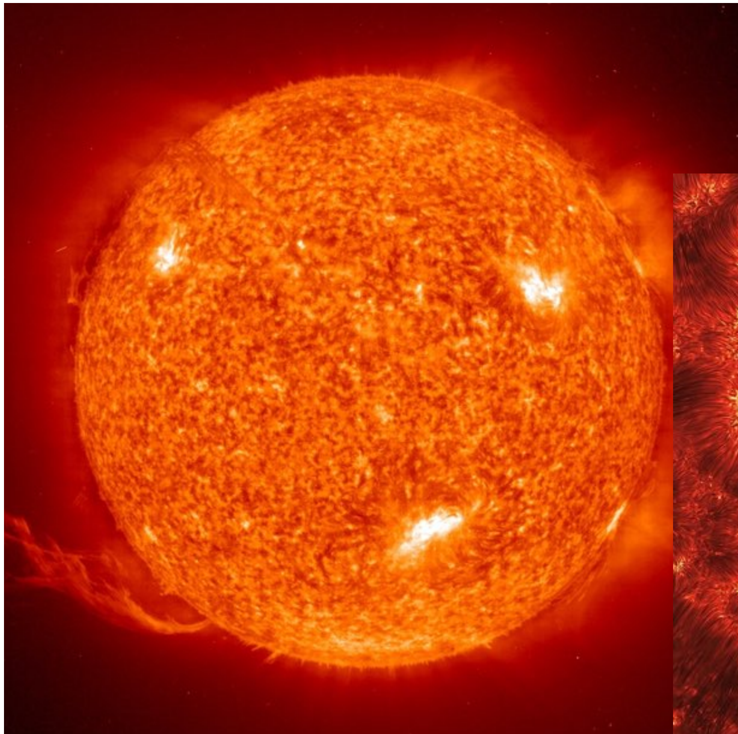


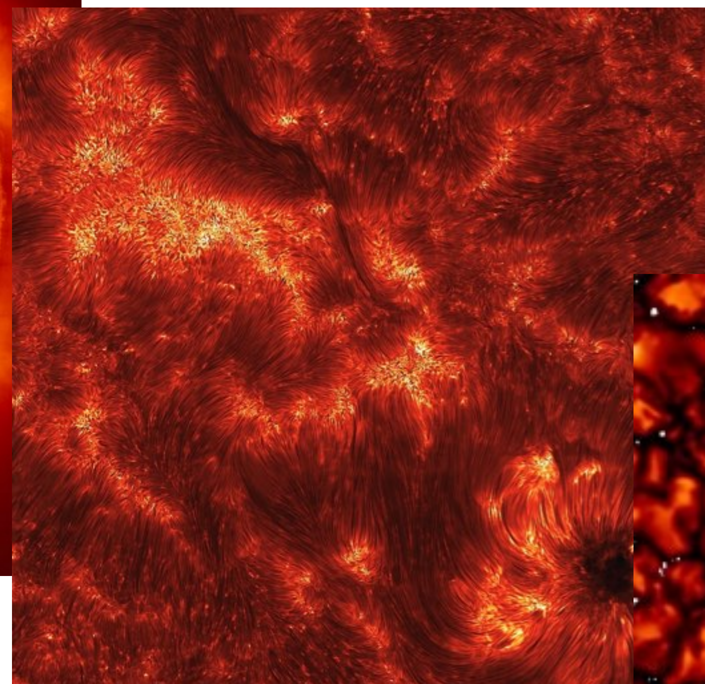


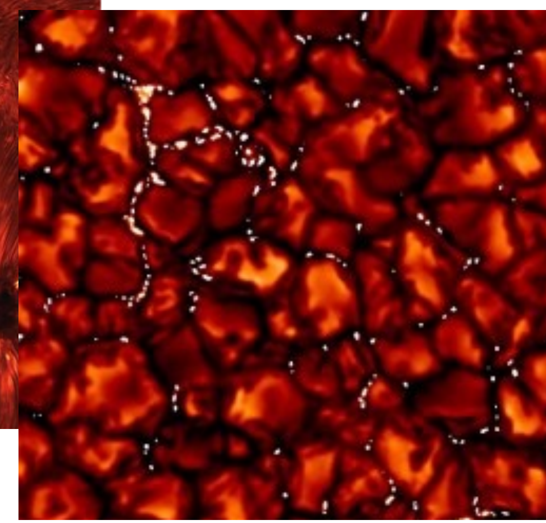
$$\frac{\ell_{\rm max}}{\ell_{\rm min}} \sim \mathrm{Re}^{3/4} \sim 3 \times 10^7$$

Ratio between largest and smallest scales can be related to the Reynolds number of the flow (assuming Kolmogorov)

The Computational Challenge







$$N = \left(\frac{\ell_{\rm max}}{\ell_{\rm min}}\right)^3 \sim 10^{22}$$

Number of cells to model a cubic region from the largest eddies down to the viscous damping scale (direct numerical simulation). See e.g. Meakin 2008

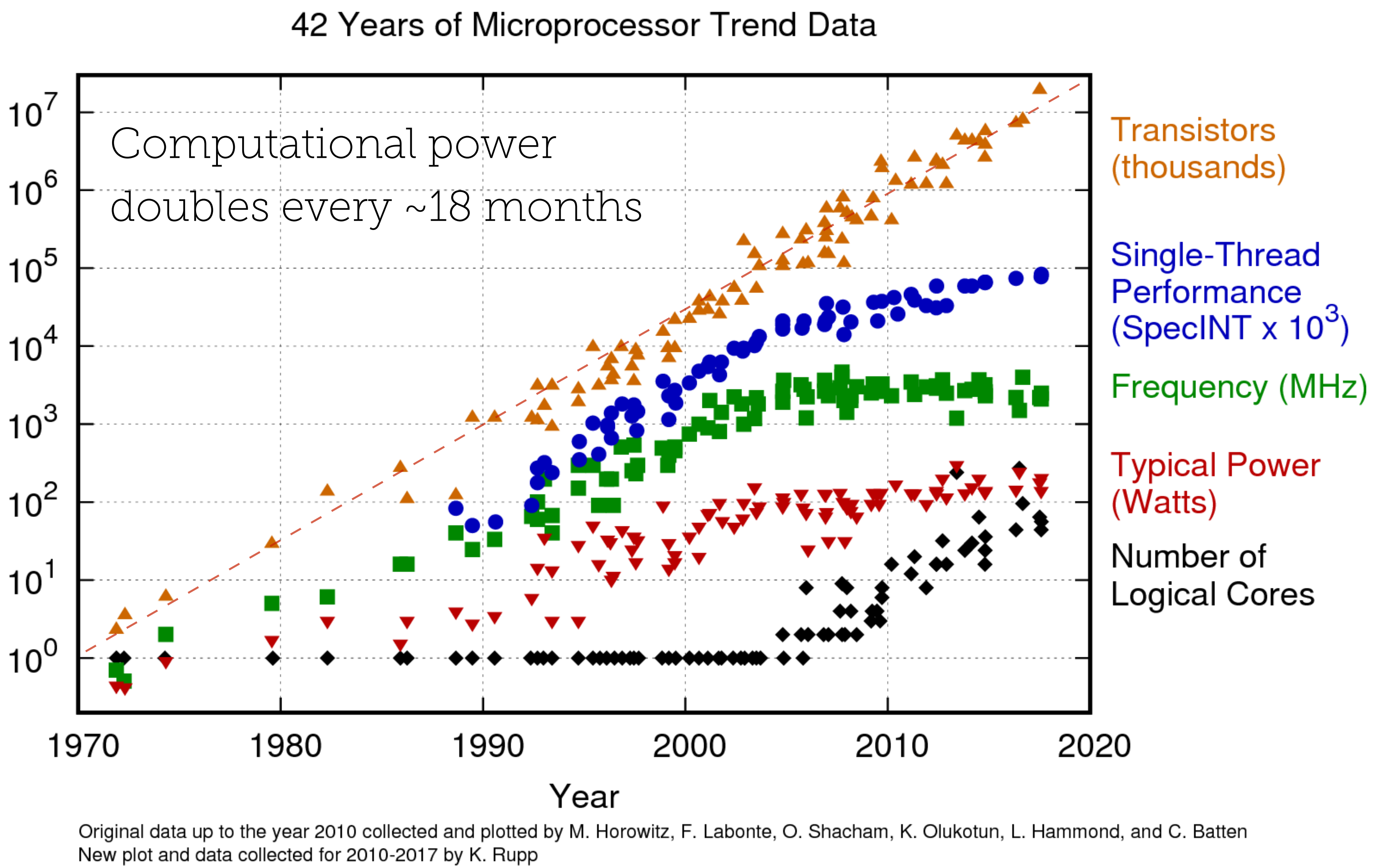
The Computational Challenge

Sunway-TaihuLight is currently the fastest supercomputer in the world (~10M Cpus, 93 petaFLOPS)

$$N = (8192)^3 \sim 5 \times 10^{11} \ll 10^{22}$$

Current largest hydrodynamic simulations on PetaFLOPS class machines. Still ~11 orders of magnitude away

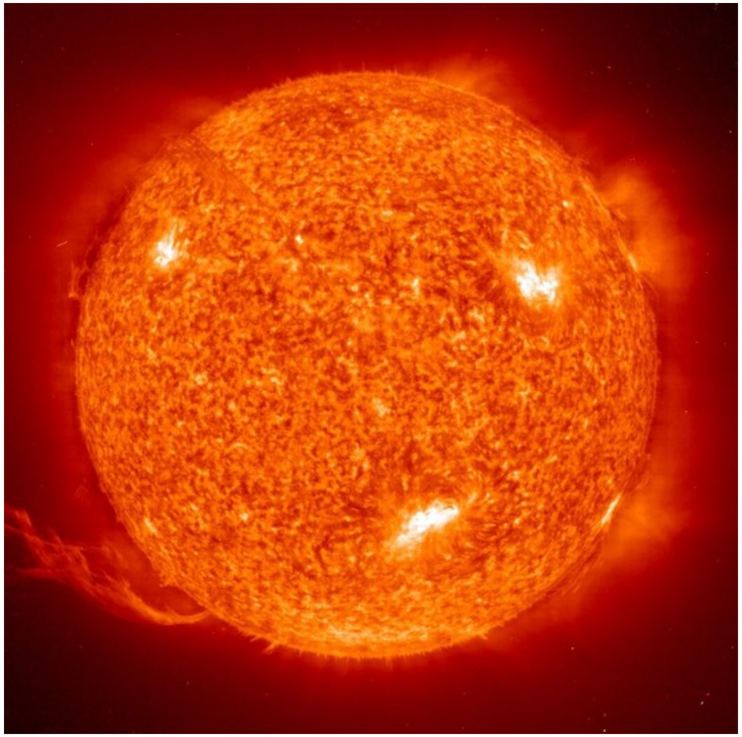
Moore's Law

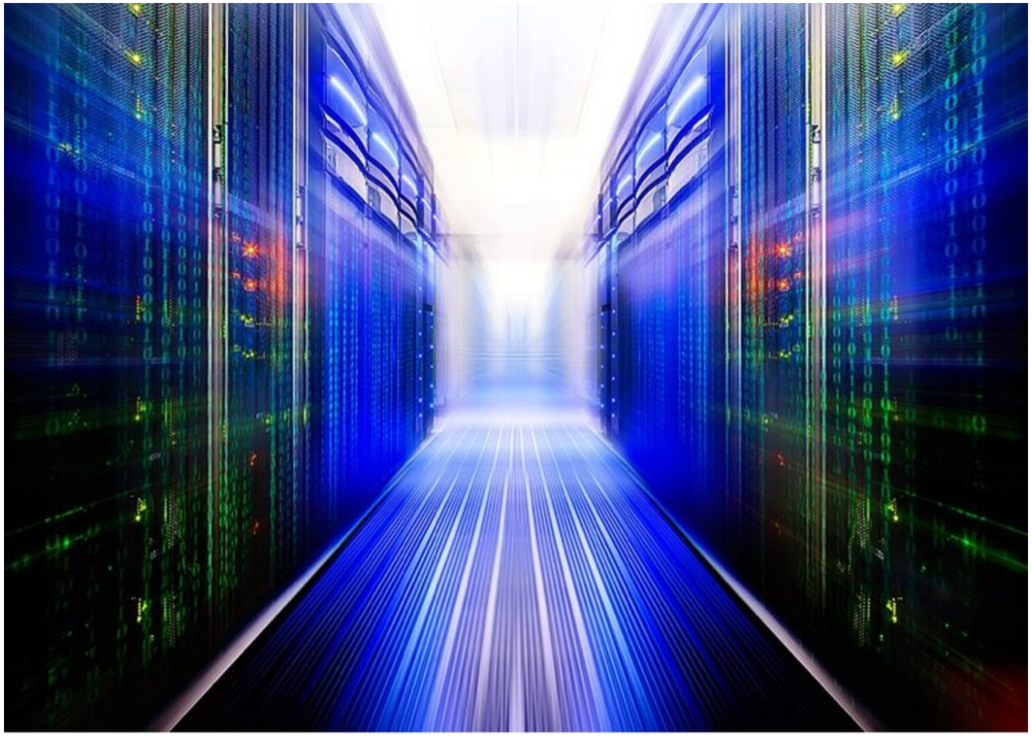

42 Years of Microprocessor Trend Data
Computational power
doubles every ~18 months
Transistors
(thousands)
Single-Thread
Performance
(SpecINT x 10^3)
Frequency (MHz)
Typical Power
(Watts)
Number of
Logical Cores
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
1970
1980
1990
2000
2010
2020
Year
Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

First DN Simulation of the Sun?

(Assuming Moore's law)

$1.5 \log_2 10^{11}$ ~55 years from now





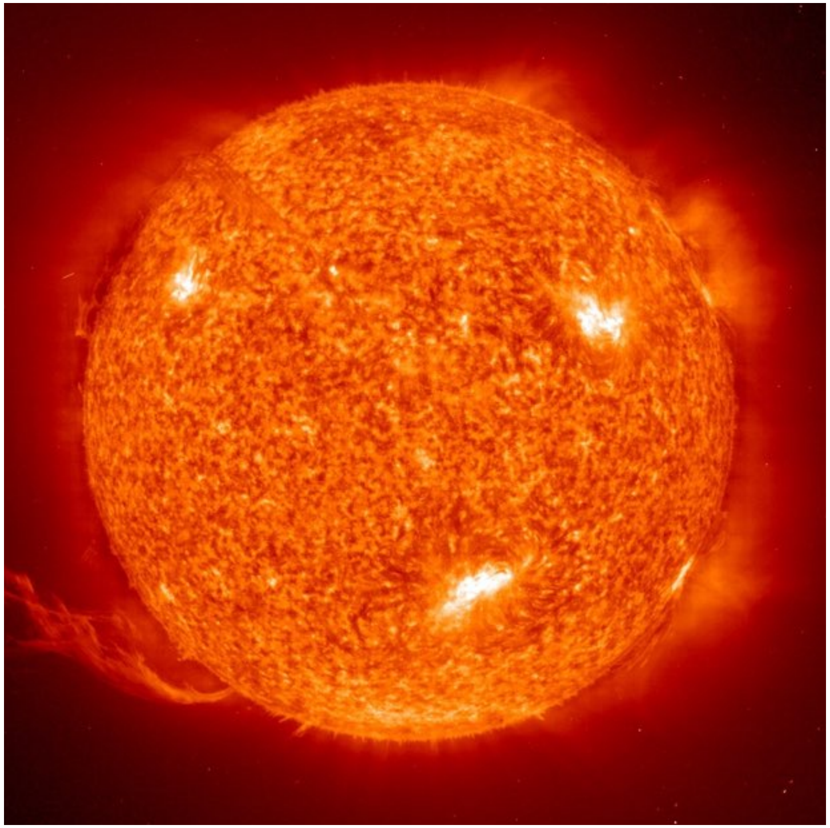
It's worse than that...

Not only the spatial dynamical range is huge, but the hierarchy of relevant timescale also poses an immense challenge (~10^{15} time steps to simulate full evolution!)

$$t_{\rm dyn} \equiv \left(\frac{R_\odot^3}{GM_\odot}\right)^{1/2} \approx 1600\,{\rm s}$$

$$t_{\rm KH} \approx \frac{GM_\odot^2/R_\odot}{L_\odot} \approx 3 \times 10^7\,{\rm yr}$$

$$t_{\rm nuc} = \frac{0.007 M_\odot c^2}{L_\odot} \approx 10^{11}\,{\rm yr}$$



It’s worse than that…

Not only the spatial dynamical range is huge, but the hierarchy of relevant timescale poses an immense challenge too (~10^{15} time steps to simulate full evolution!)

On ~Dynamical Timescale

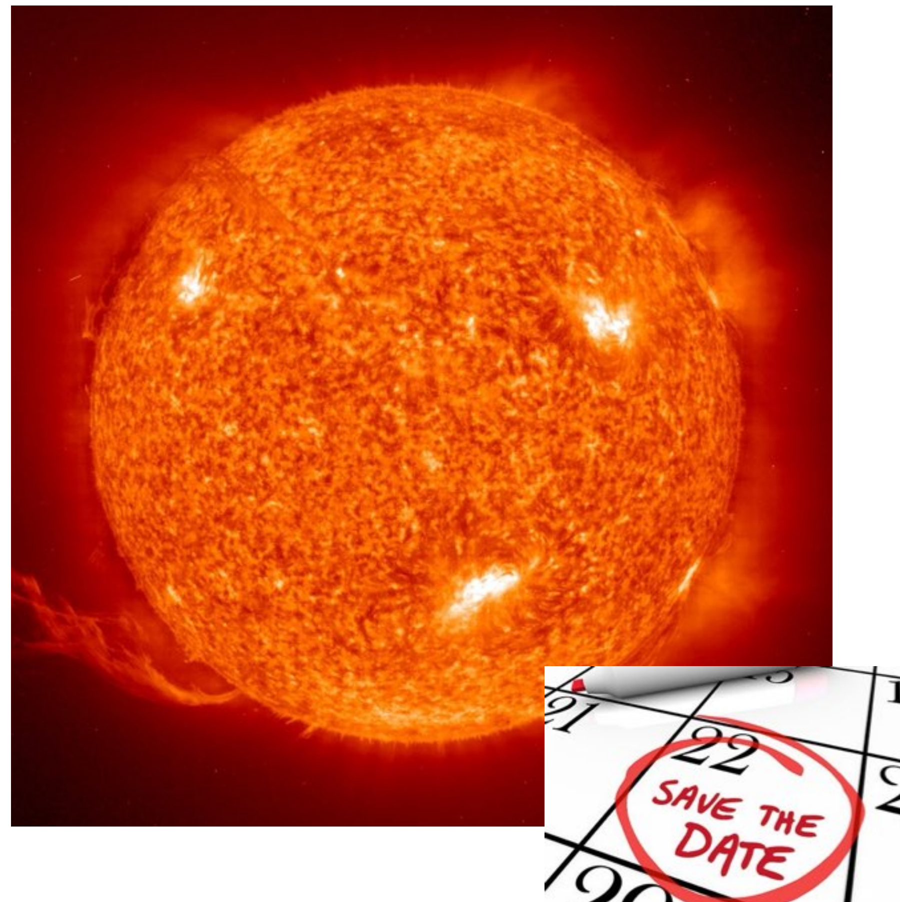
~ year 2075

On ~Thermal Timescale

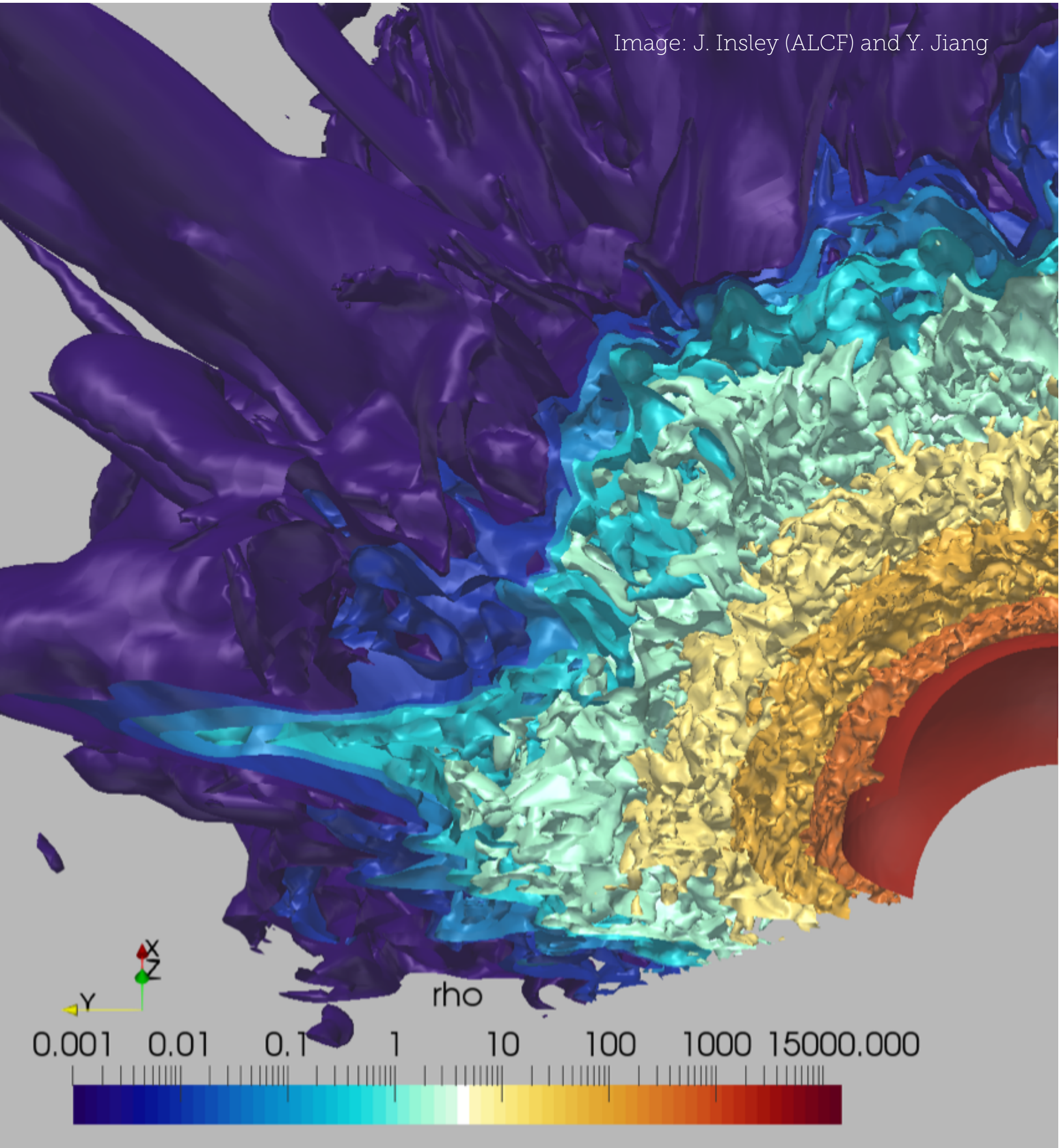
~ year 2120

Full Evolution

~ year 2145



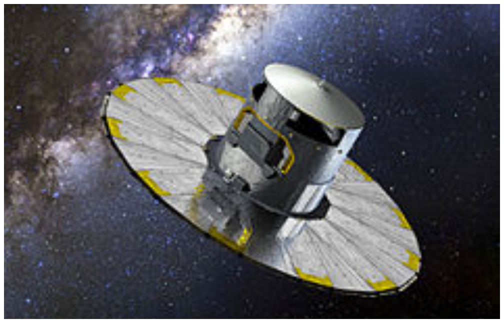
Models are still useful!

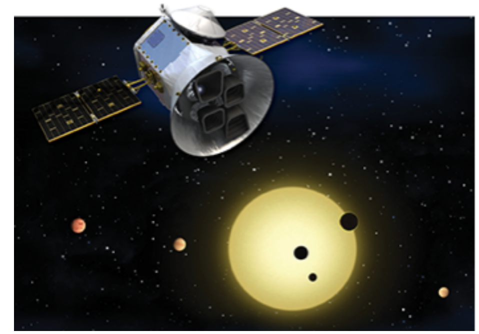


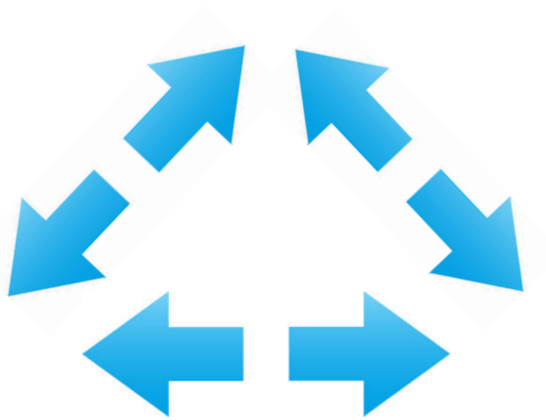
It is likely that many of the resulting flow features captured by incompletely resolved numerical hydro calculations are still robust/ useful to understand real astrophysical situations.

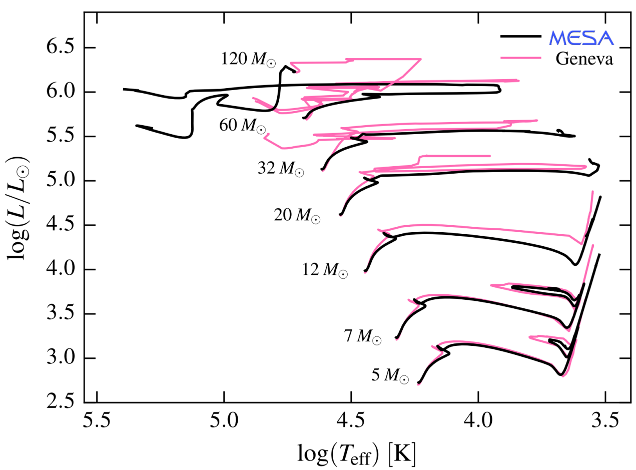
Particular attention to MHD calculations!

High precision big data

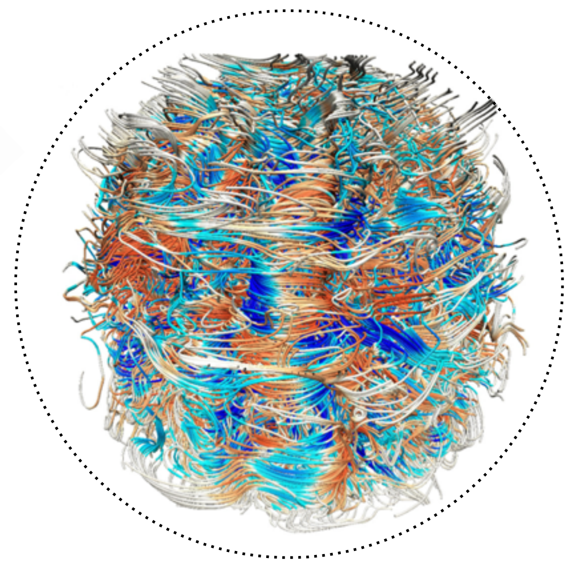






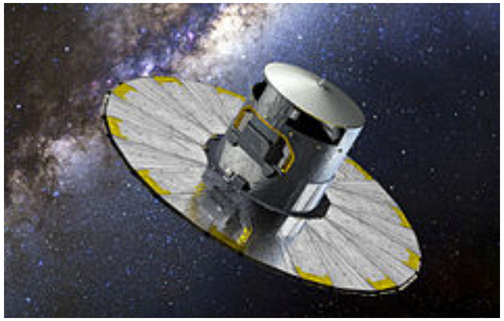


1D Calculations

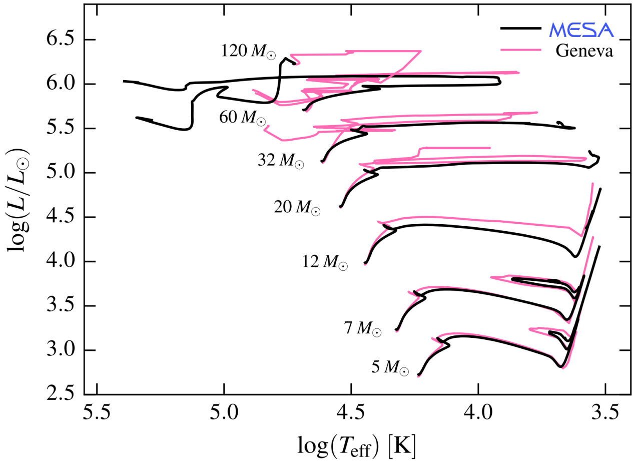


3D Calculations

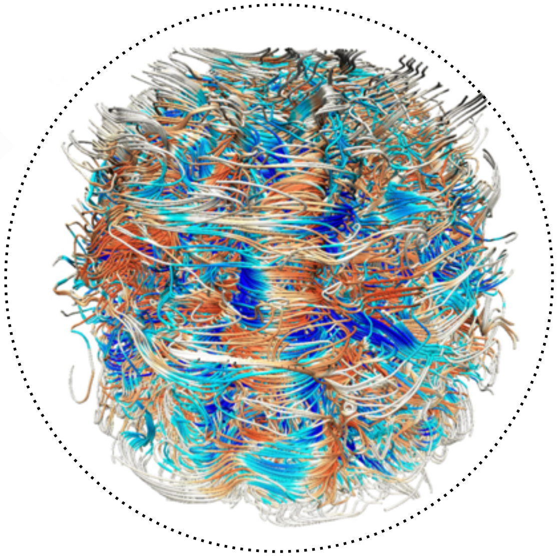
High precision big data



TESS Launching today!



1D Calculations



3D Calculations

Open Questions:
Internal Rotation & Magnetism

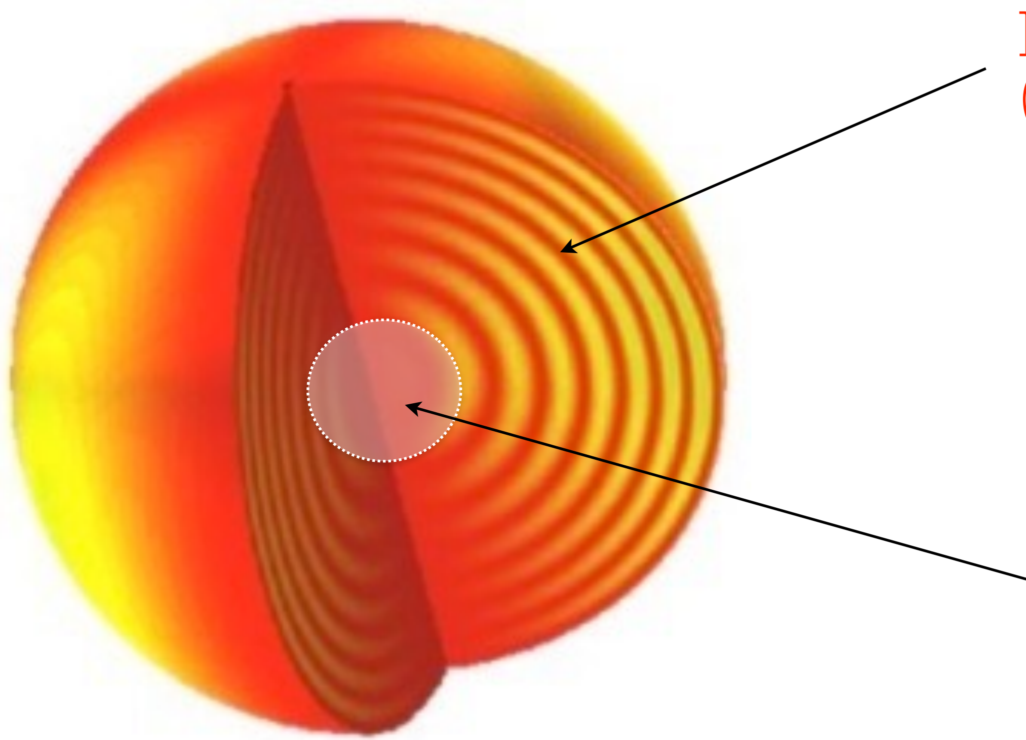
Probing Stellar Interiors

"It would seem that the deep interior of the Sun and stars is less accessible to scientific investigation than any other region of the universe"

Sir Arthur Eddington, 1926

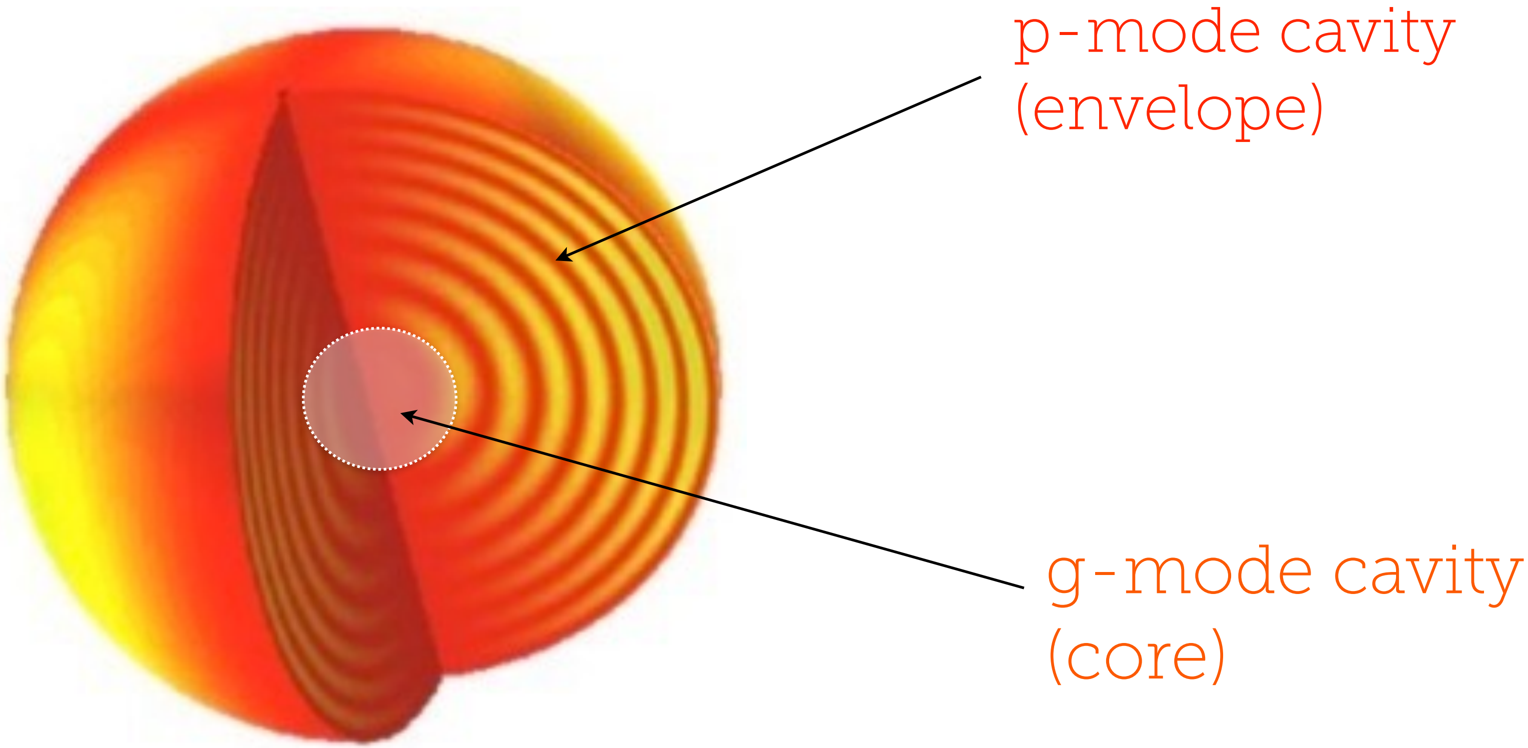
Seems to prevent the possibility of measuring important internal properties of stars, like rotation and magnetism (essential to e.g. understand some endpoint of stellar evolution, SLSNe, GRBs etc)

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 rotational splitting can give informations about e.g. rotation rate in different regions of the star! Done for red giants (Beck et al. 2012, Mosser et al. 2012)

Asteroseismology: Mixed Modes



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

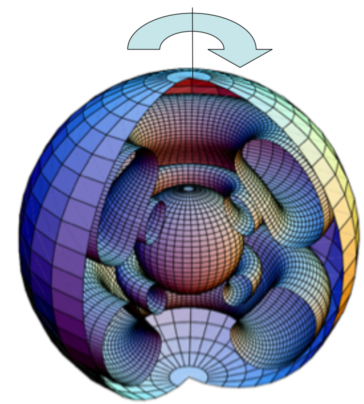
See Saskia Hekker's Talk

What the observations say?

Asteroseismology now allows to probe the deep interiors of stars

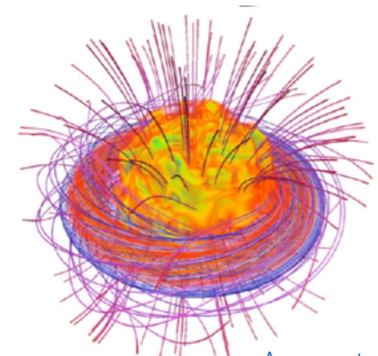
Important results:

* Internal J-transport not fully understood Cantiello et al. (2014) Large coupling core-envelope seems required. Most compact objects should be slowly-rotating



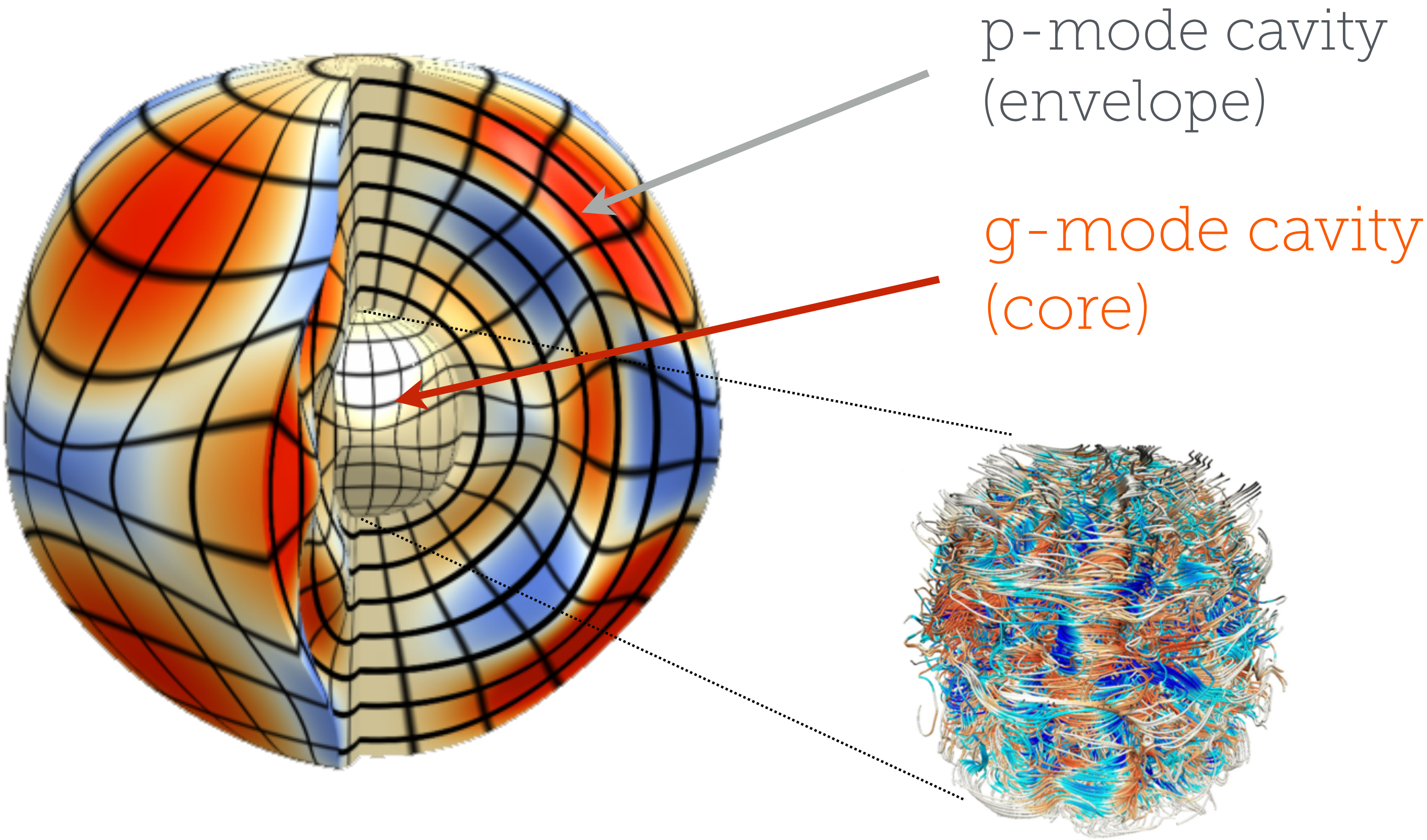
Maeder & Meynet

* Strong core B-fields potentially ubiquitous in stars above $\sim 1.5 M_{Sun}$ Fuller, MC et al. (2015), Stello, MC et al. (2016)



Augustson

Mixed Modes interacting with B-Fields



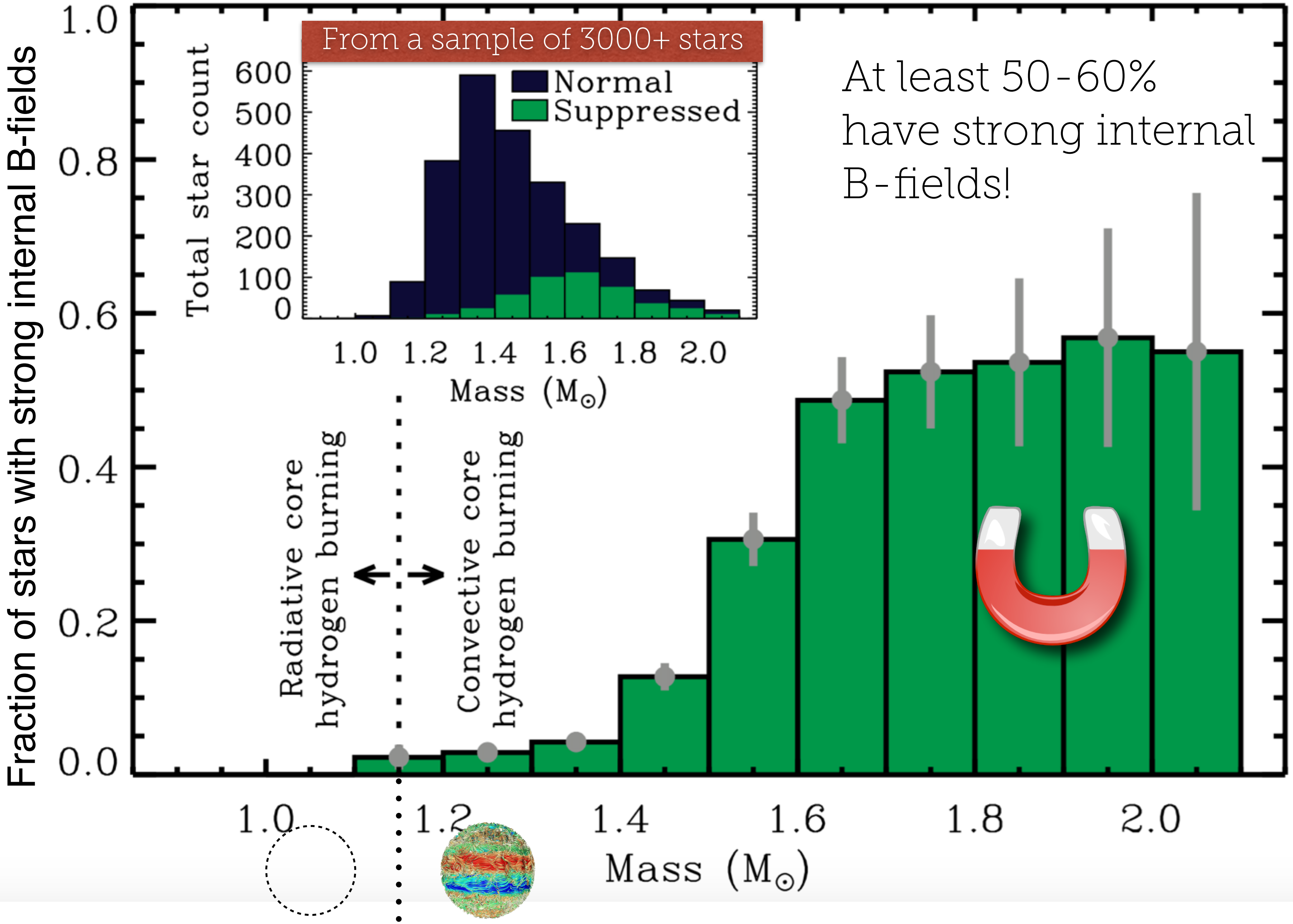
In the presence of strong B-fields, magnetic tension forces can become comparable to buoyancy

Lorentz Force ~ Buoyancy Force

➡ Critical Field Strength

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

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)

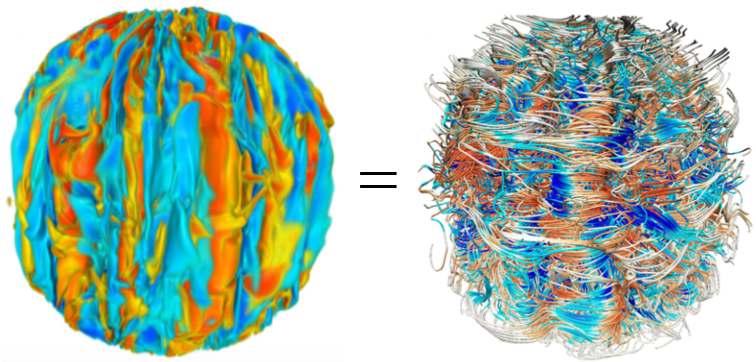
B-Fields 101

MHD Sims: Courtesy of K.Augustson

See Cantiello et al. 2016 for more...

B-Fields 101

Energy Equipartition



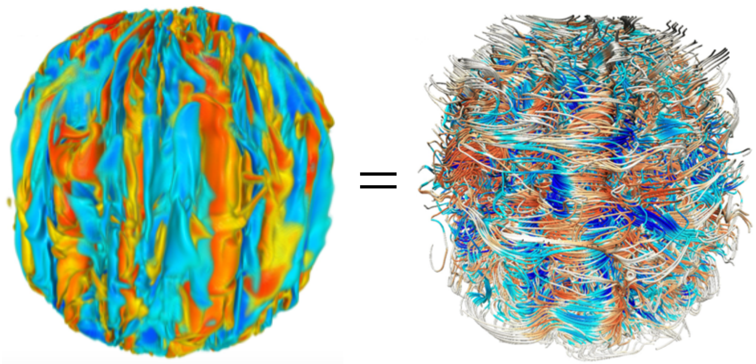
$$\frac{1}{2}\rho v_{\rm con}^2 \simeq \frac{B_{\rm eq}^2}{8\pi}$$

MHD Sims: Courtesy of K.Augustson

See Cantiello et al. 2016 for more...

B-Fields 101

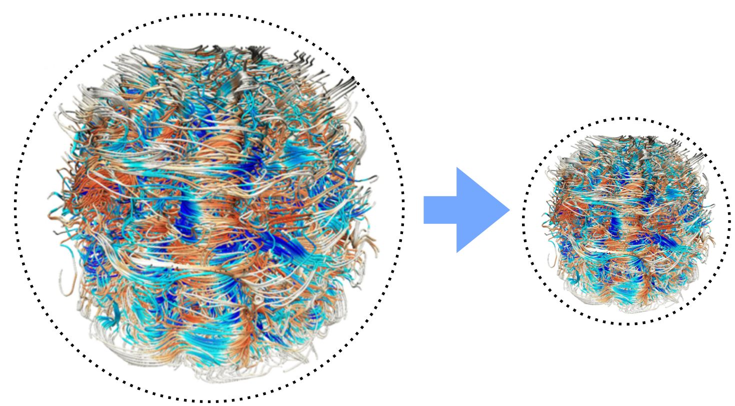
Energy Equipartition



$$\frac{1}{2}\rho v_{\rm con}^2 \simeq \frac{B_{\rm eq}^2}{8\pi}$$

Magnetic Flux

Freezing & Conservation



$$B_{\rm RG} = B_{\rm MS}\left(\frac{r_{\rm MS}}{r_{\rm RG}}\right)^2$$

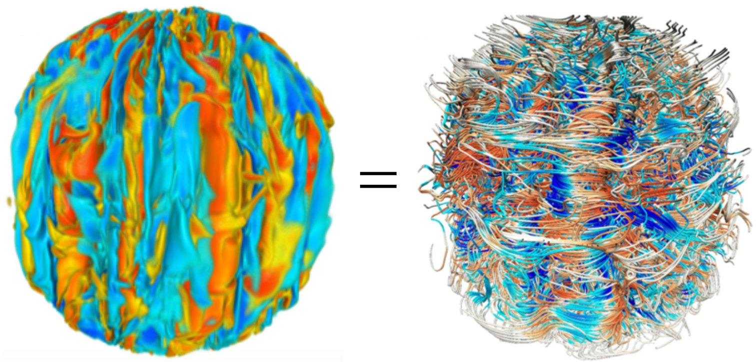
Magnetar-level fields possible/common!

MHD Sims: Courtesy of K.Augustson

See Cantiello et al. 2016 for more...

B-Fields 101

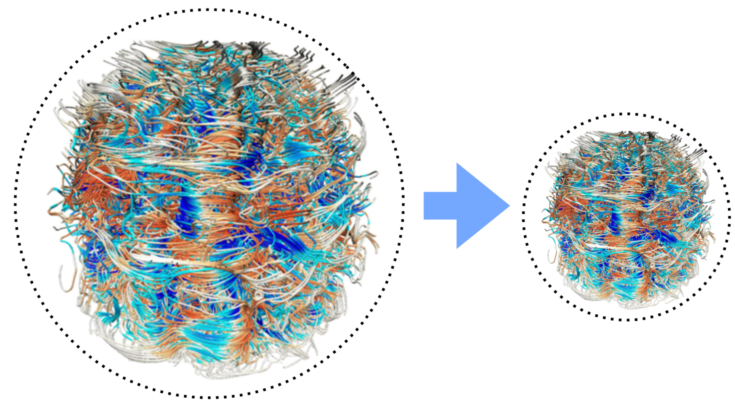
Energy Equipartition



$$\frac{1}{2}\rho v_{\rm con}^2 \simeq \frac{B_{\rm eq}^2}{8\pi}$$

B-Fields can also be inherited during stellar formation (e.g. Mark Morris' talk)

Magnetic Flux
Freezing & Conservation

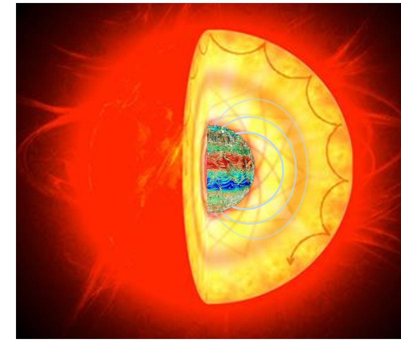


$$B_{\rm RG} = B_{\rm MS}\left(\frac{r_{\rm MS}}{r_{\rm RG}}\right)^2$$

Magnetar-level fields possible/common!

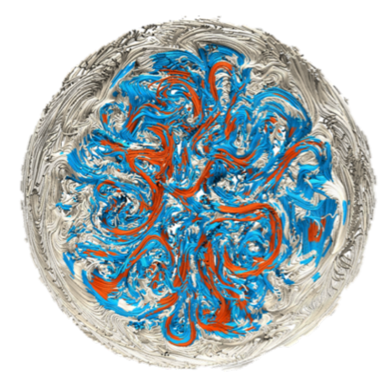
Conclusions (I)

- Novel asteroseismic technique allows to reveal the presence of strong internal magnetic fields in thousand red giants



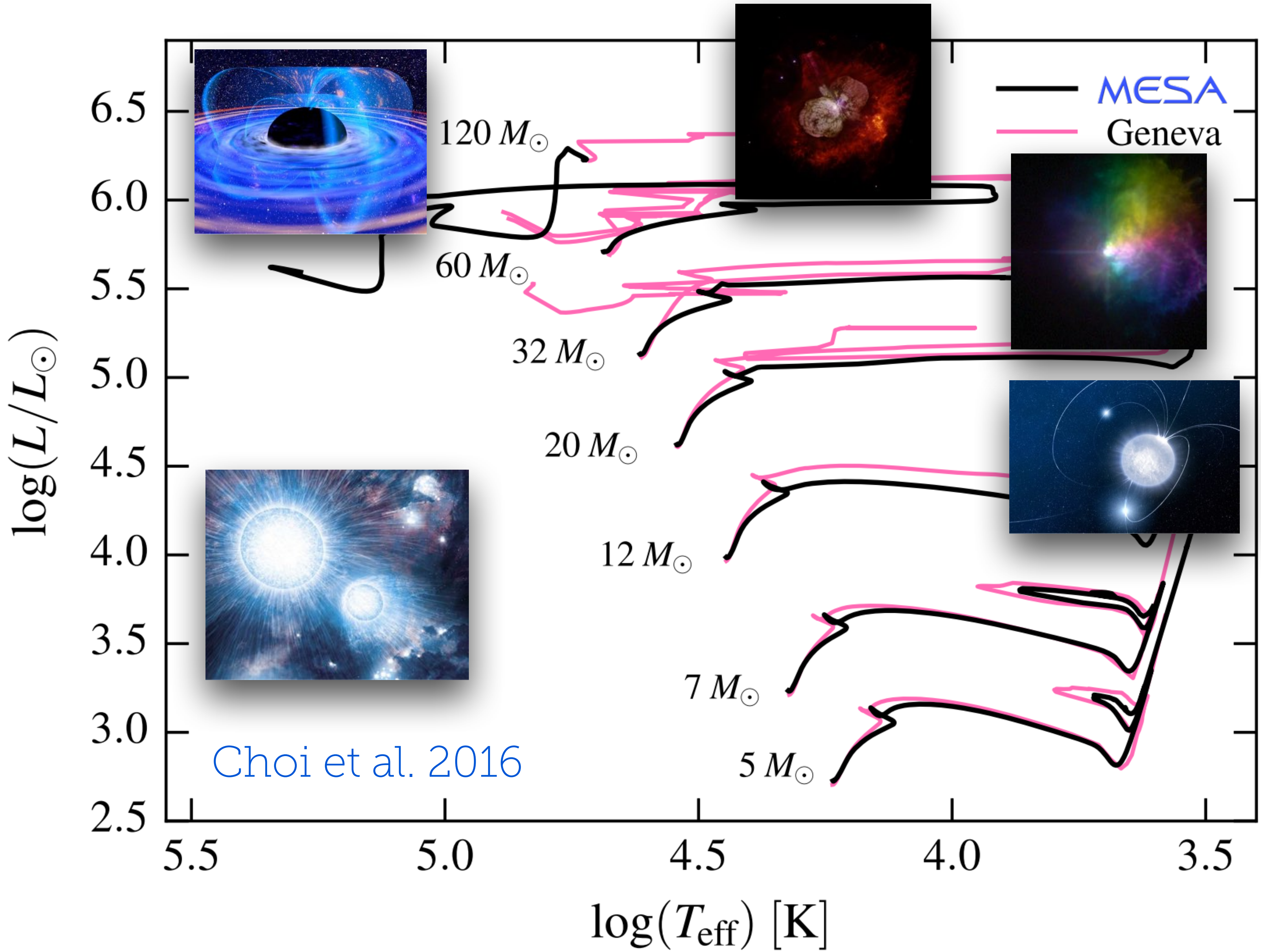
- Fields of roughly 10^5 G are very common in the core of stars with $M>1.5M_{Sun}$

- These fields are likely dynamo generated in the star's convective core during the main sequence

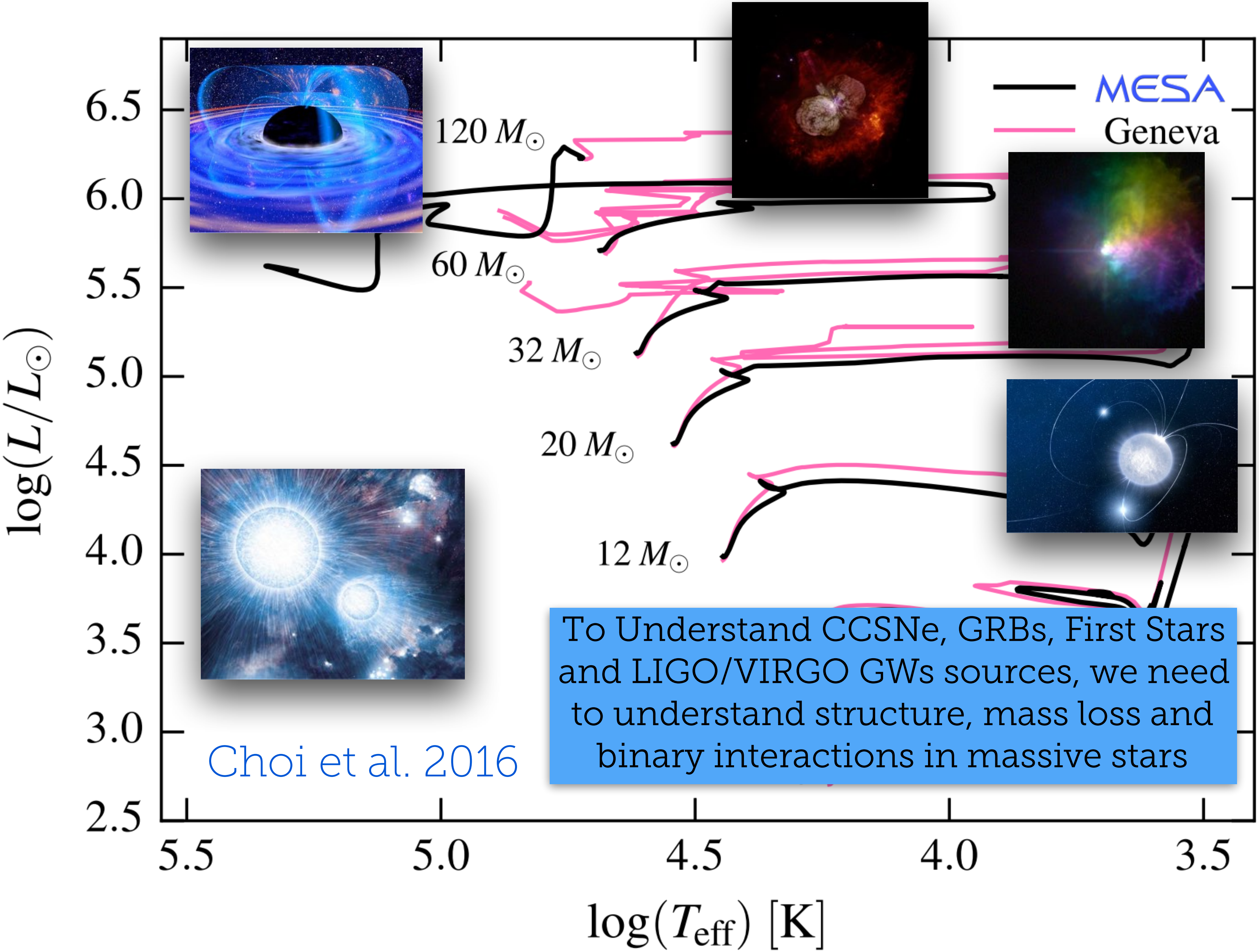


Courtesy: Kyle Augustson

Open Questions:
Massive Stars Evolution



MESA
Geneva
120 $M_\odot$
60 $M_\odot$
32 $M_\odot$
20 $M_\odot$
12 $M_\odot$
7 $M_\odot$
5 $M_\odot$
Choi et al. 2016
$\log(L/L_\odot)$
$\log(T_{\rm eff})$ [K]
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
5.5
5.0
4.5
4.0
3.5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$\log(T_{\rm eff})$ [K]
Choi et al. 2016
To Understand CCSNe, GRBs, First Stars and LIGO/VIRGO GWs sources, we need to understand structure, mass loss and binary interactions in massive stars

Massive Stars:
The most uncertain physics

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

Silvia Toonen's Talk

Massive Stars: The most uncertain physics

- Stability and energy transport
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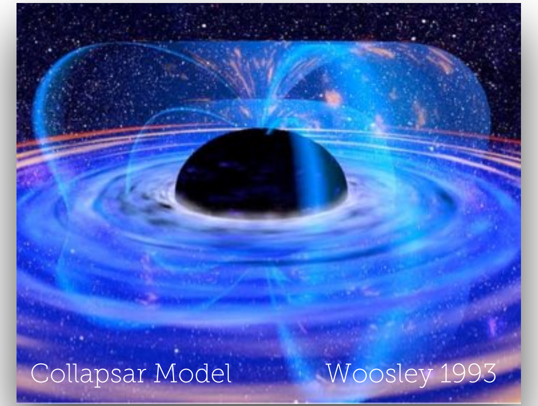
Silvia Toonen's Talk

Massive Stars: Rotation & Magnetic Fields

- The final rotation rate and magnetization of stellar cores are important for the physics of central engines (SLSNe, LGRBs…)

- Current models for angular momentum transport relies on 1D diffusion approximation of some (local) physical mechanisms.

- Large scale magnetic fields are usually not included



See e.g. Paxton+ 2013

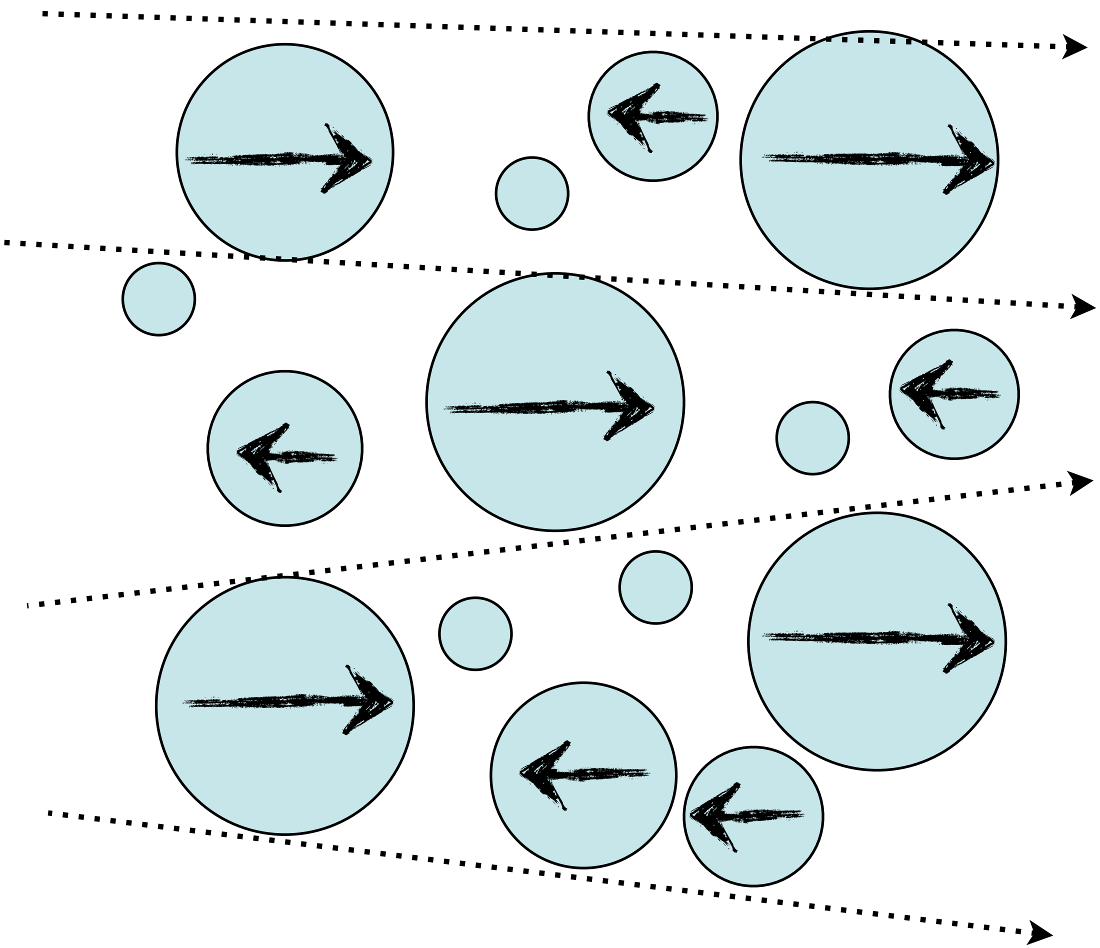
Massive Stars:
The most uncertain physics

- Stability and energy transport
- Mass loss
- Rotation (Strong internal coupling not fully understood)
- Magnetic Fields (Strong internal B-fields ubiquitous?)
- Binarity (Most massive stars are in binary systems!)

Massive Star Envelopes

- Massive stars can develop radiation dominated, loosely bound envelopes
  e.g Joss et al. 1973, Paxton et al. 2013
- In 1D models such super Eddington envelopes are characterized by:
  - Superadiabatic Convection
  - Density Inversions (e.g. Grafener et al. 2012)
  - Gas Pressure Inversions
  - Envelope Inflation (e.g. Sanyal et al. 2015)
- What about 3D?

Different regimes in Radiation Dominated Convection



Diff Rad Flux

Advection Flux
("convection"...)

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

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

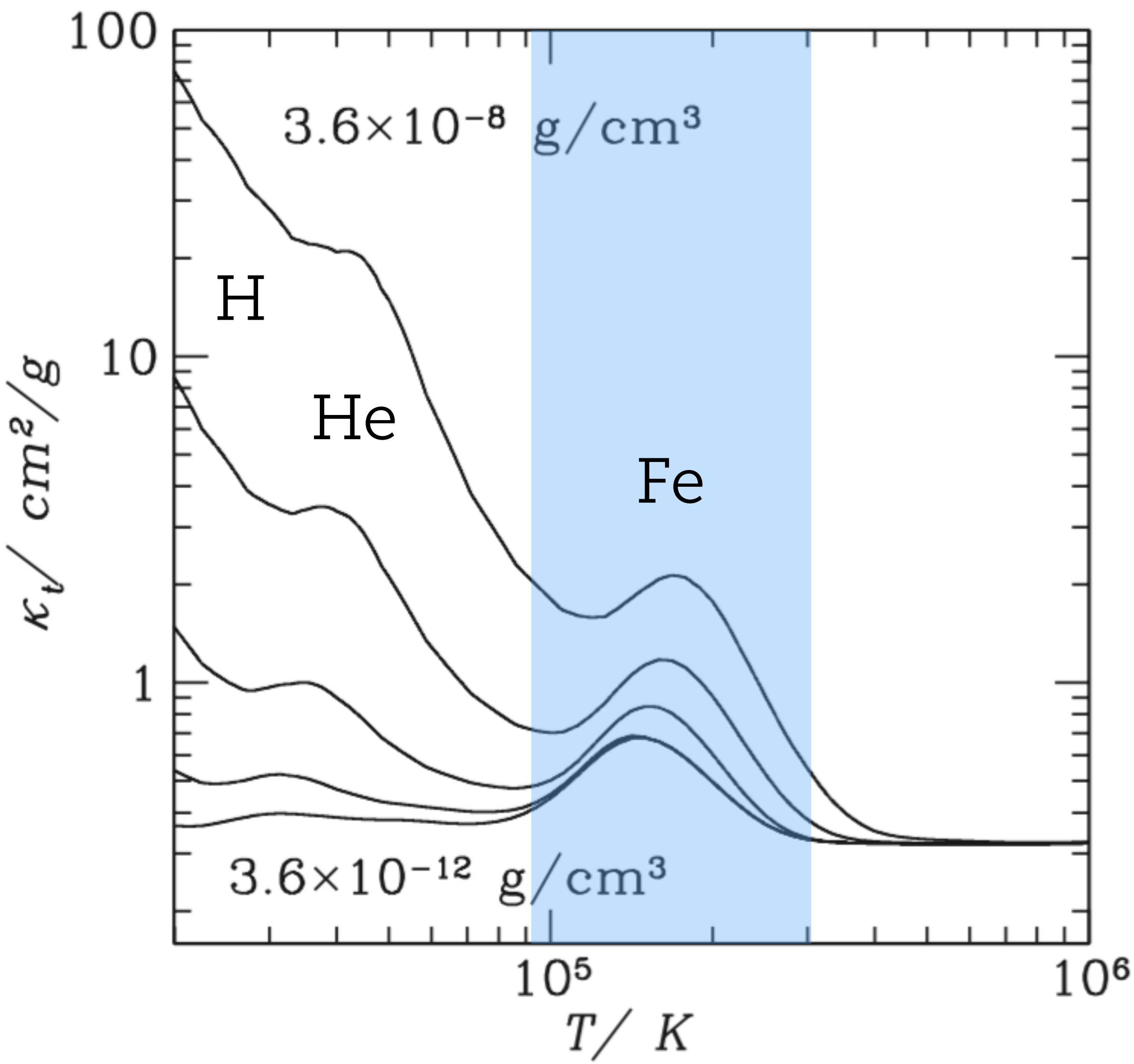
Critical optical depth

$$\tau_c = c/c_s$$

Optical depth where
radiation diffusion timescale
= dynamical timescale

Mixing Length Theory not supposed to work!

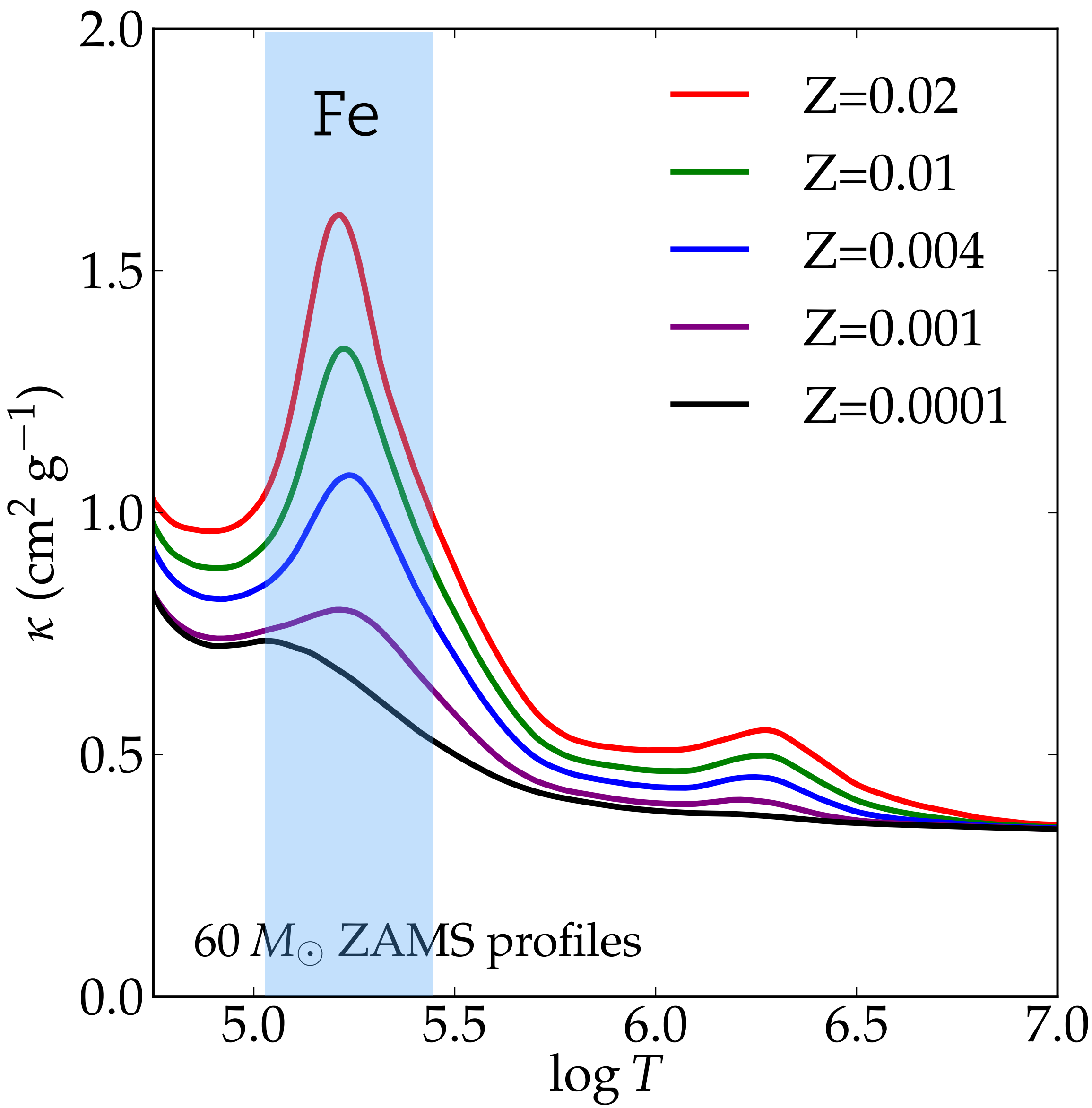
The Opacity



Jiang, MC et al. 2015

At fixed density around Iron Opacity peak.
Neighboring lines: x10 in rho

The Opacity: Iron Peak

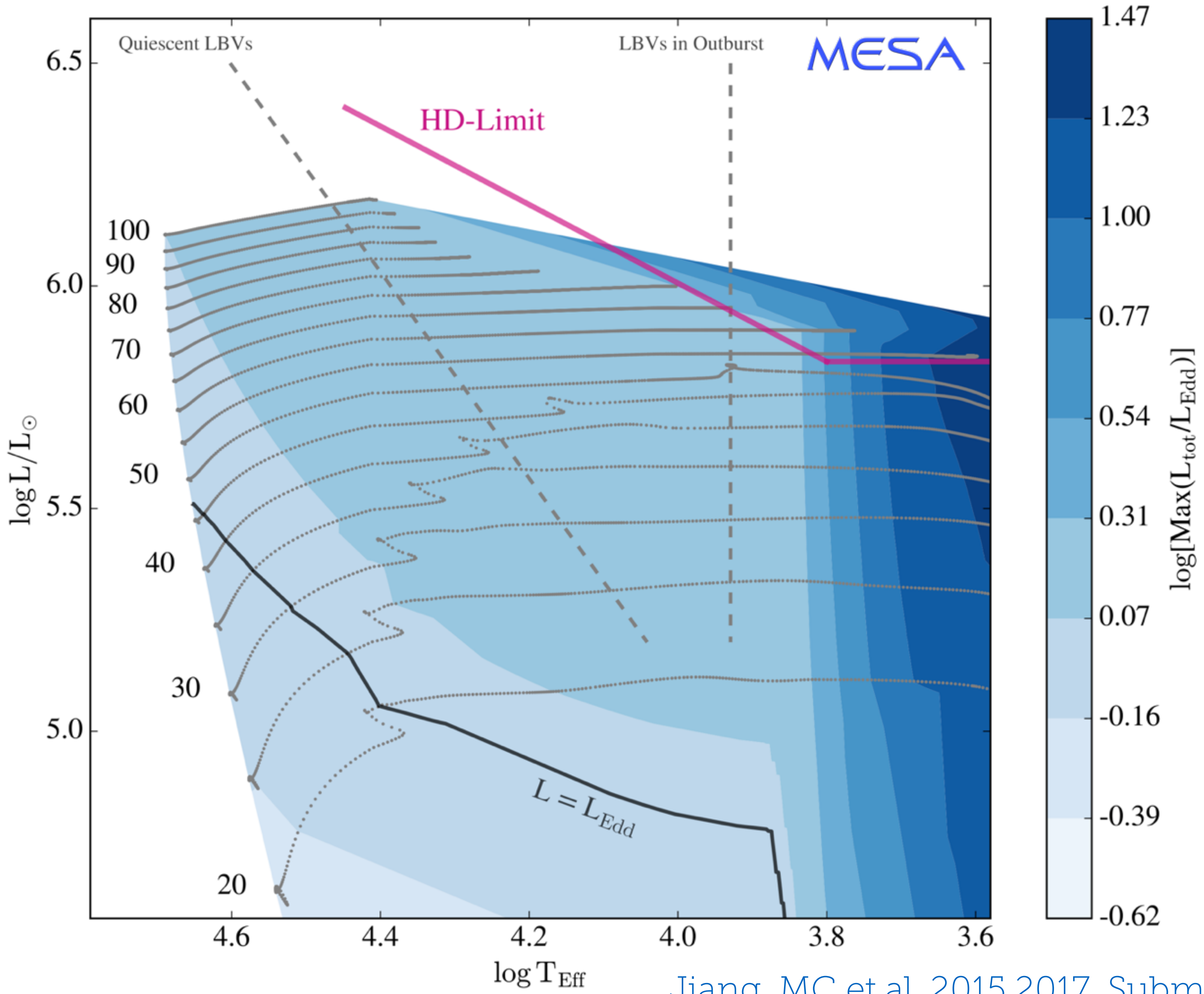


Paxton, MC et al. 2015
Cantiello et al. 2009
Iglesias & Rogers 1996

Strong Metallicity Dependence (Pop III)

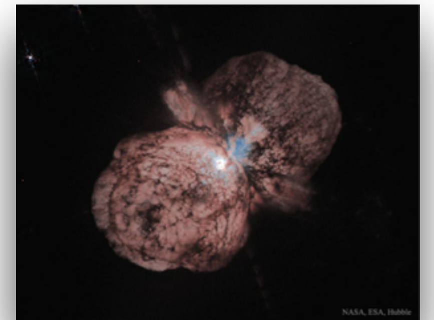
3D Radiation Hydro Calculations:

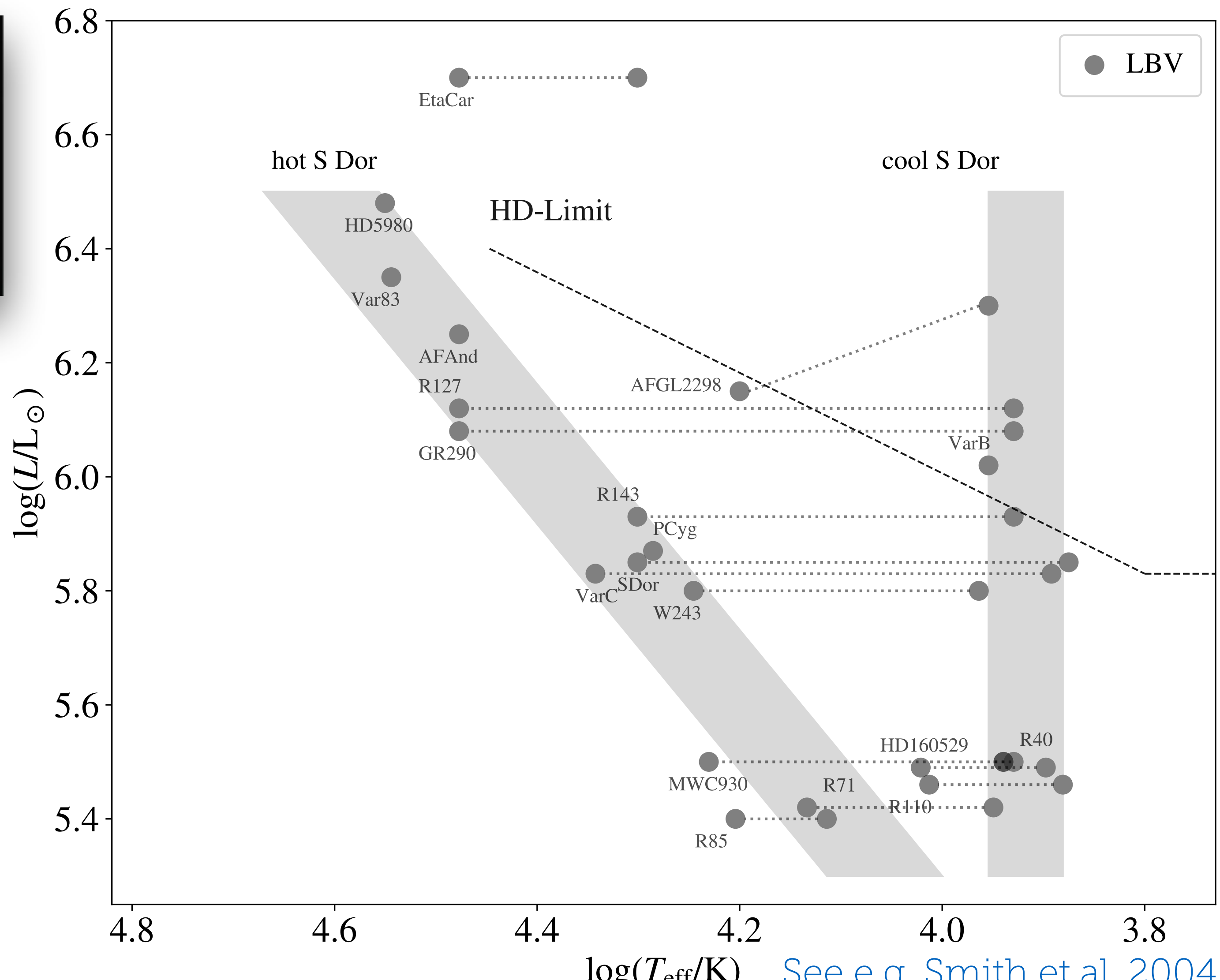
Global Calculations and Mass Loss



Jiang, MC et al. 2015,2017, Submitted

Unstable Massive Stars: Luminous Blue Variables (LBVs)

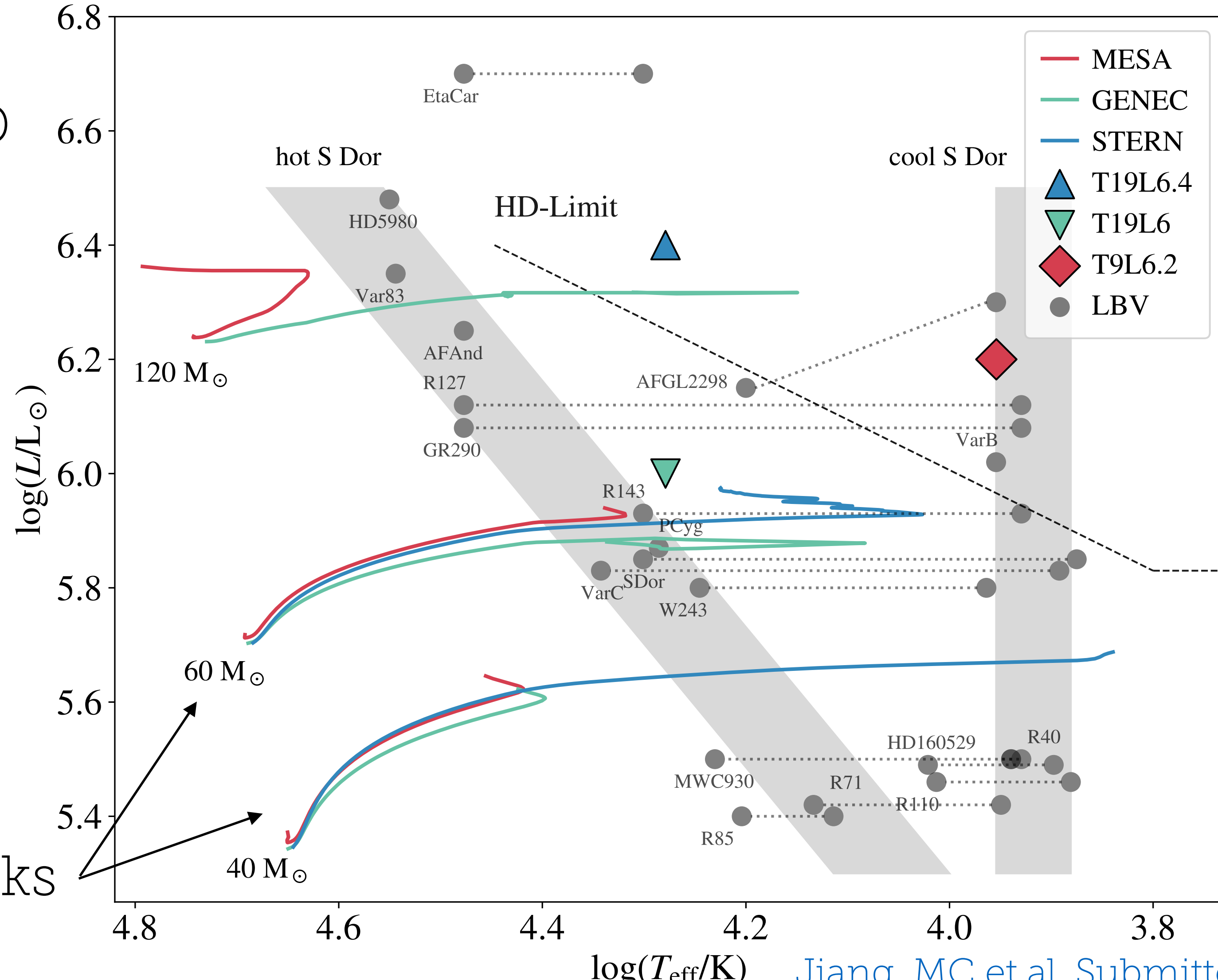




See e.g. Smith et al. 2004

Unstable Massive Stars: Luminous Blue Variables (LBVs)

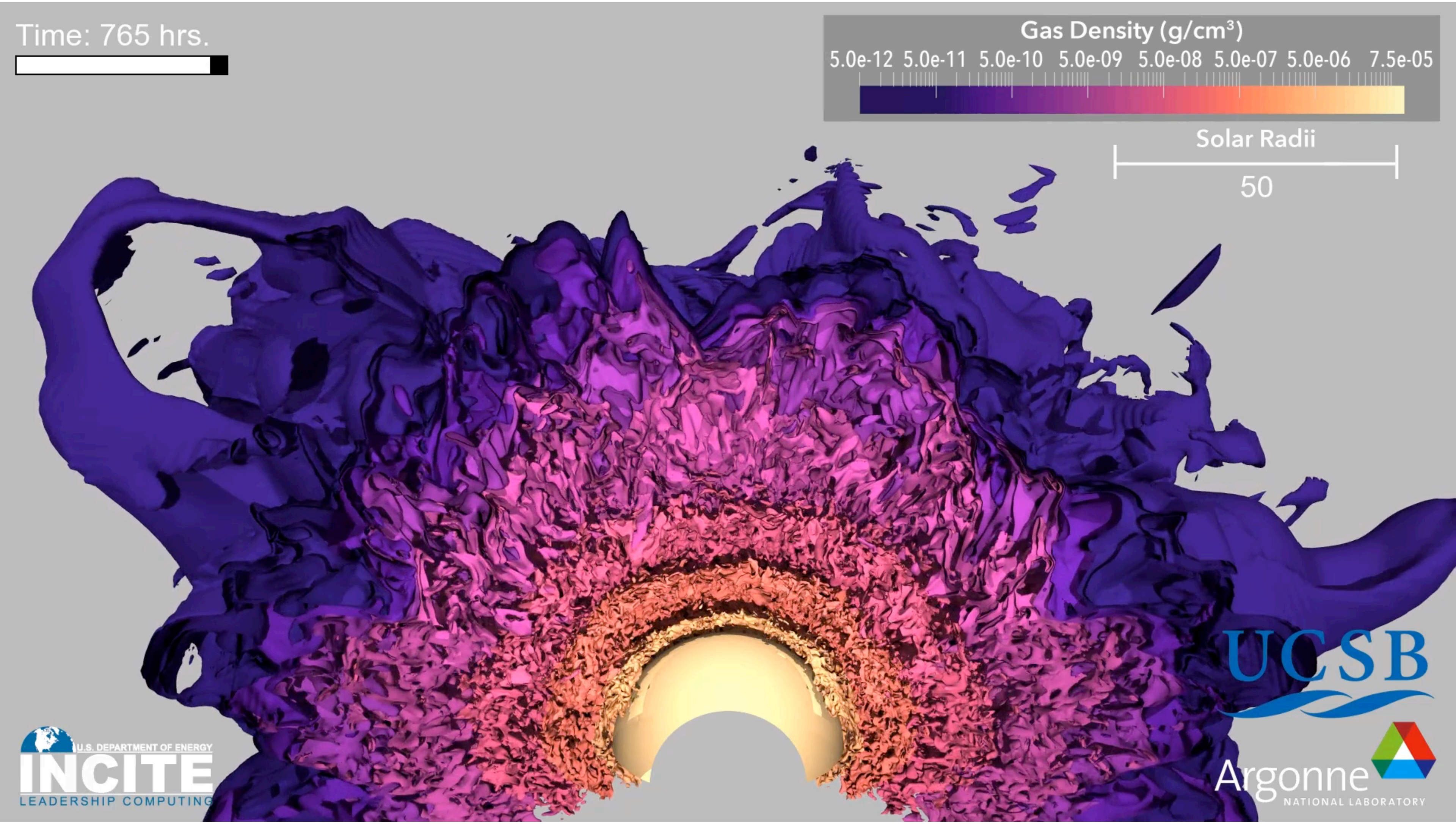
Polygons: Location of 3D models



1D Stellar Evolution Tracks

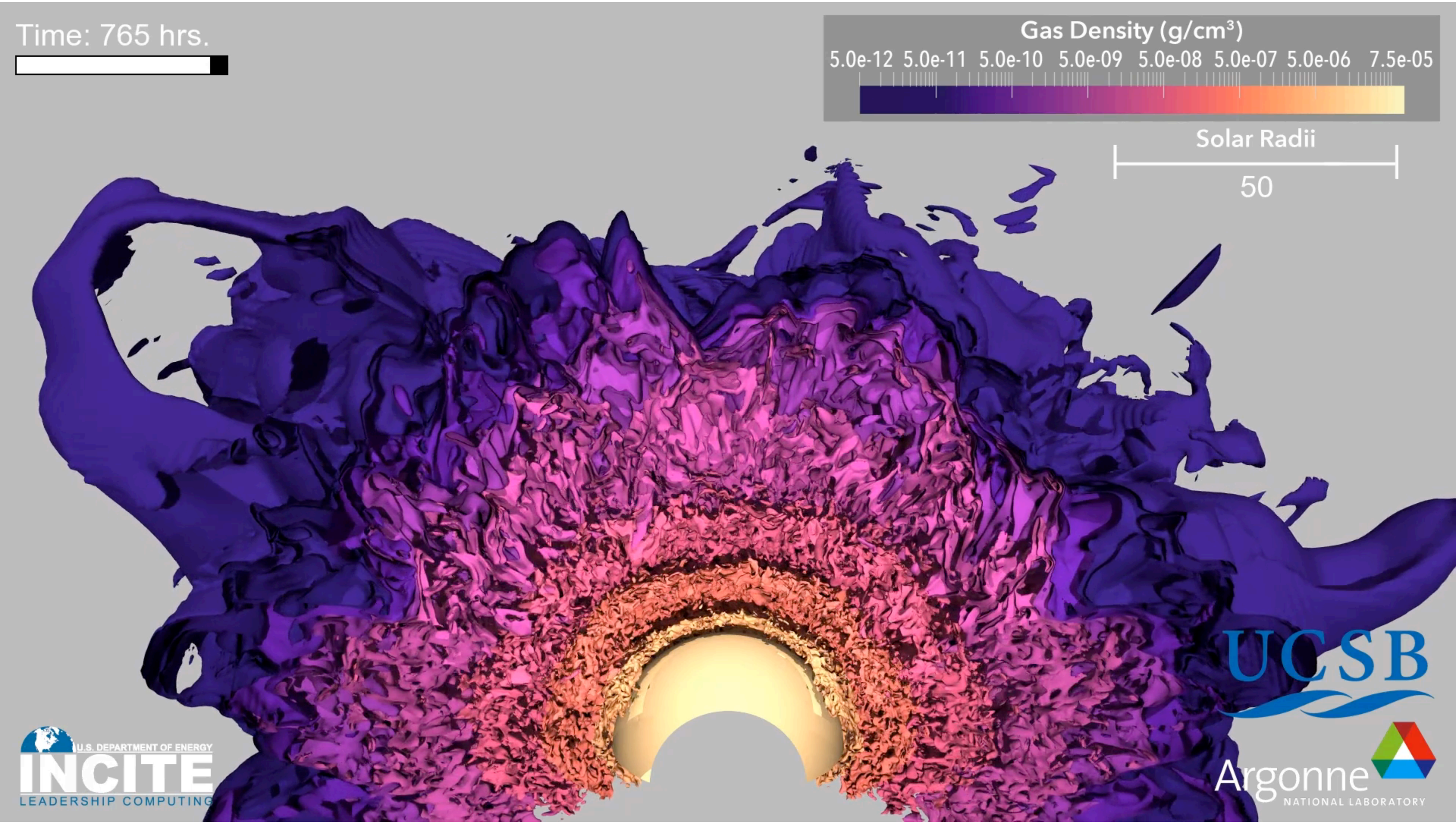
Jiang, MC et al. Submitted

3D Athena++, Radiation HD (VET)



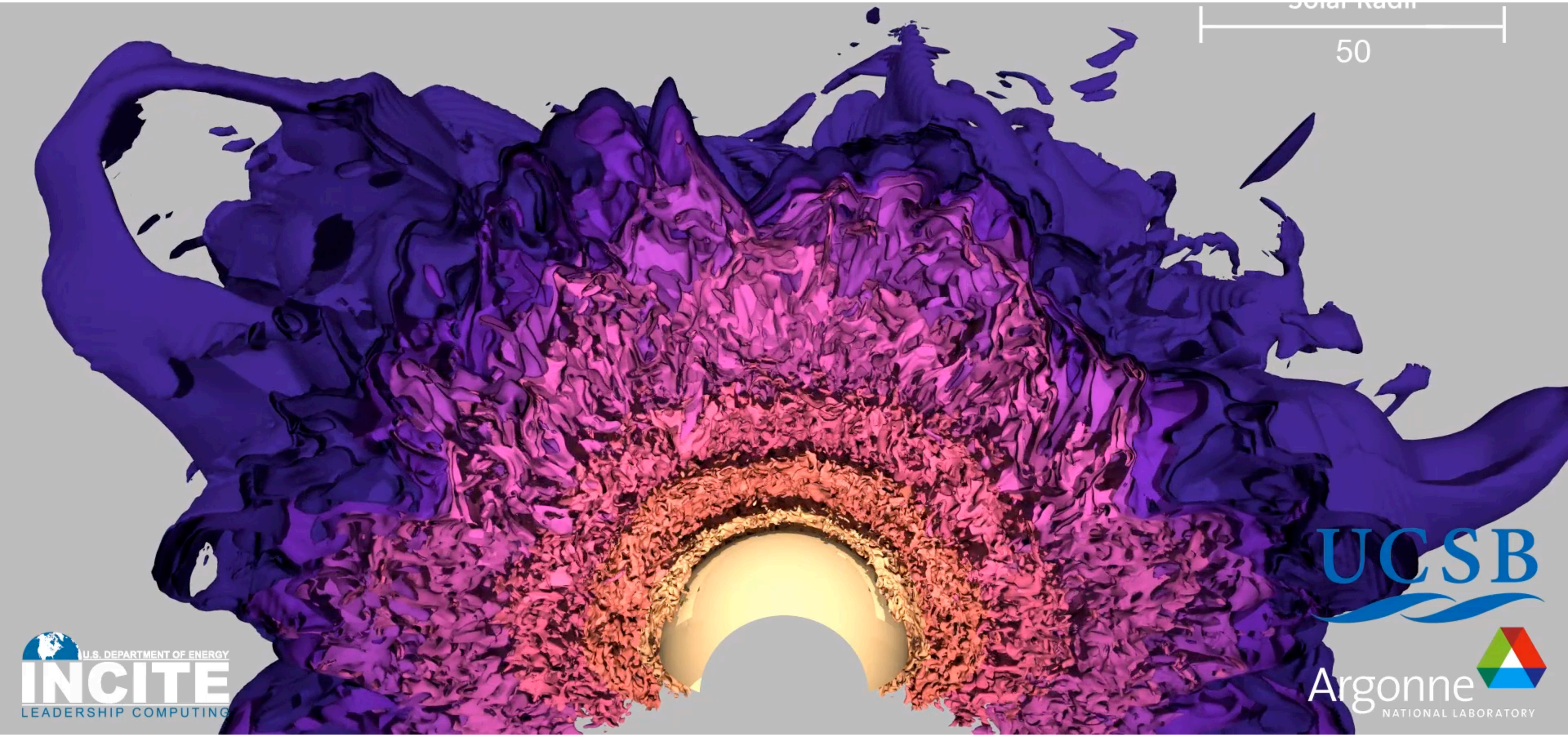
Jiang, MC et al. (Submitted)

3D Athena++, Radiation HD (VET)



Jiang, MC et al. (Submitted)

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



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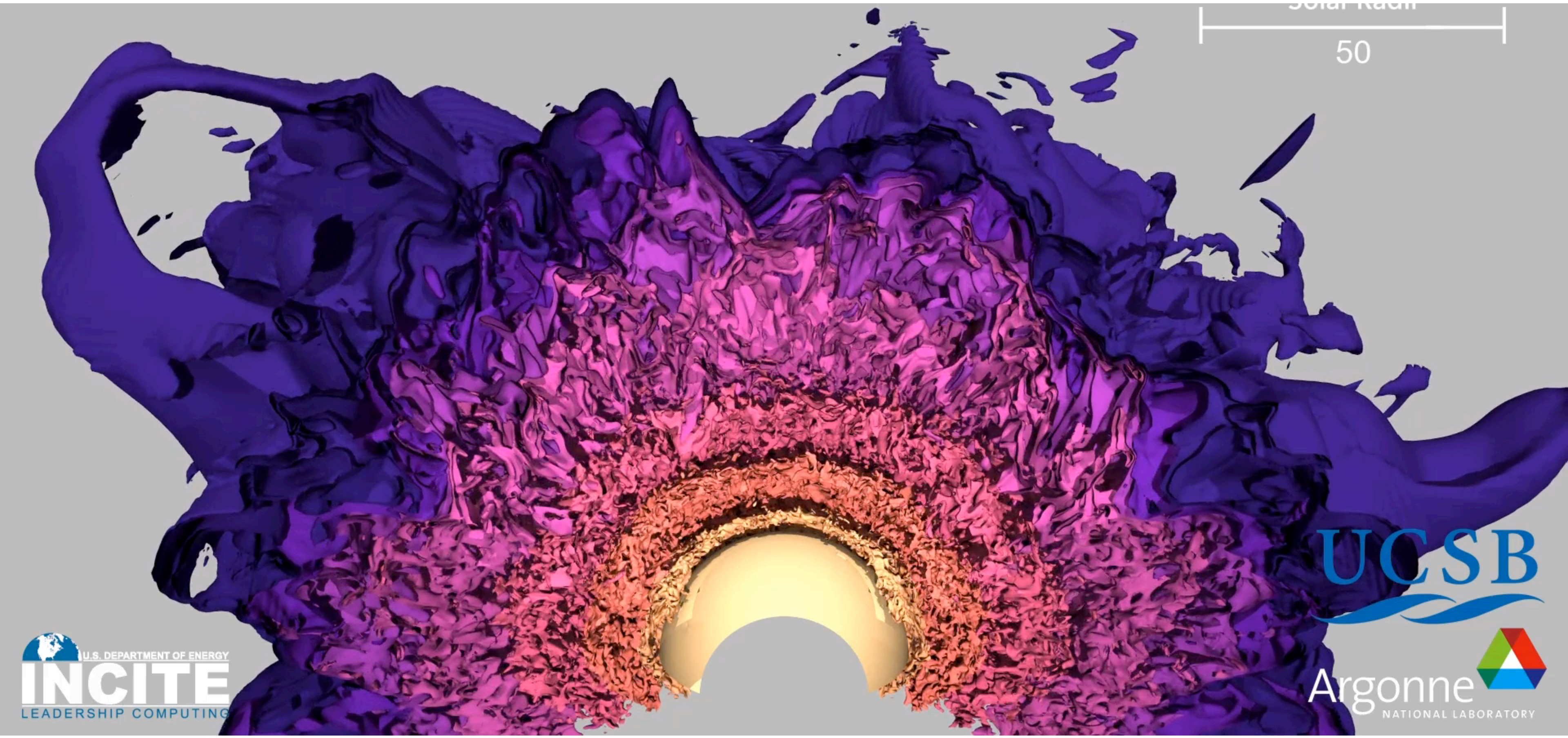

Jiang, MC et al. (Submitted)

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

Conclusions (II)

1. Massive stars evolution still very uncertain
2. Angular momentum transport and internal magnetization very important to understand transients/remnants properties
3. Largest source of uncertainties comes from our lack of understanding of envelope energy transport and mass loss
4. First 3D global radiation hydro calculations used to study the stability and mass loss of very luminous stars. One step closer to understanding mysterious LBVs

Thanks!

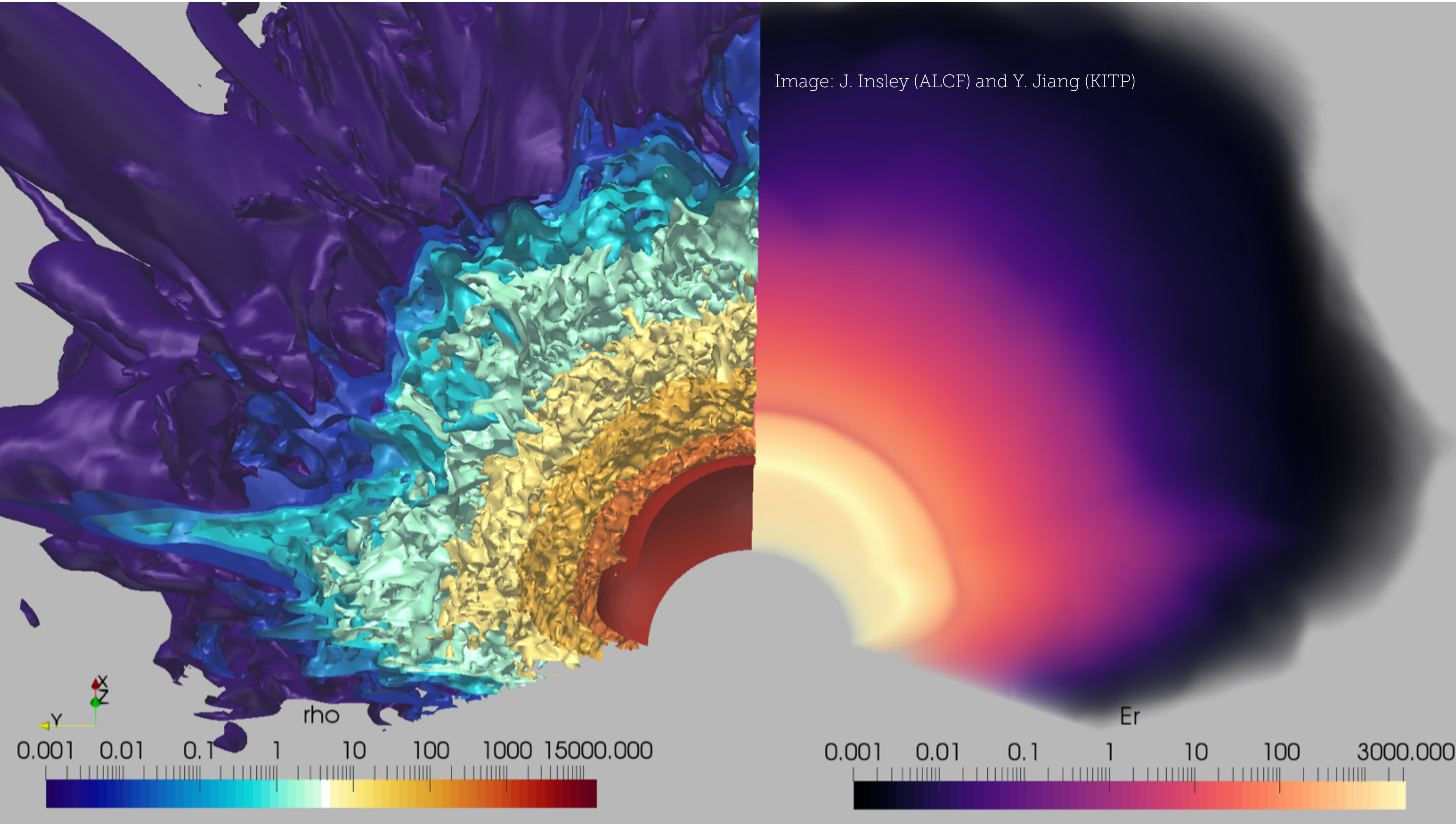
Image: J. Insley (ALCF) and Y. Jiang (KITP)
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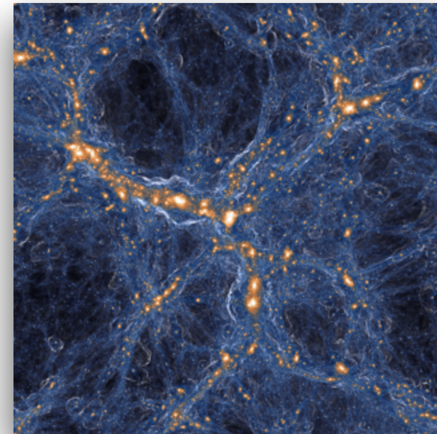



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