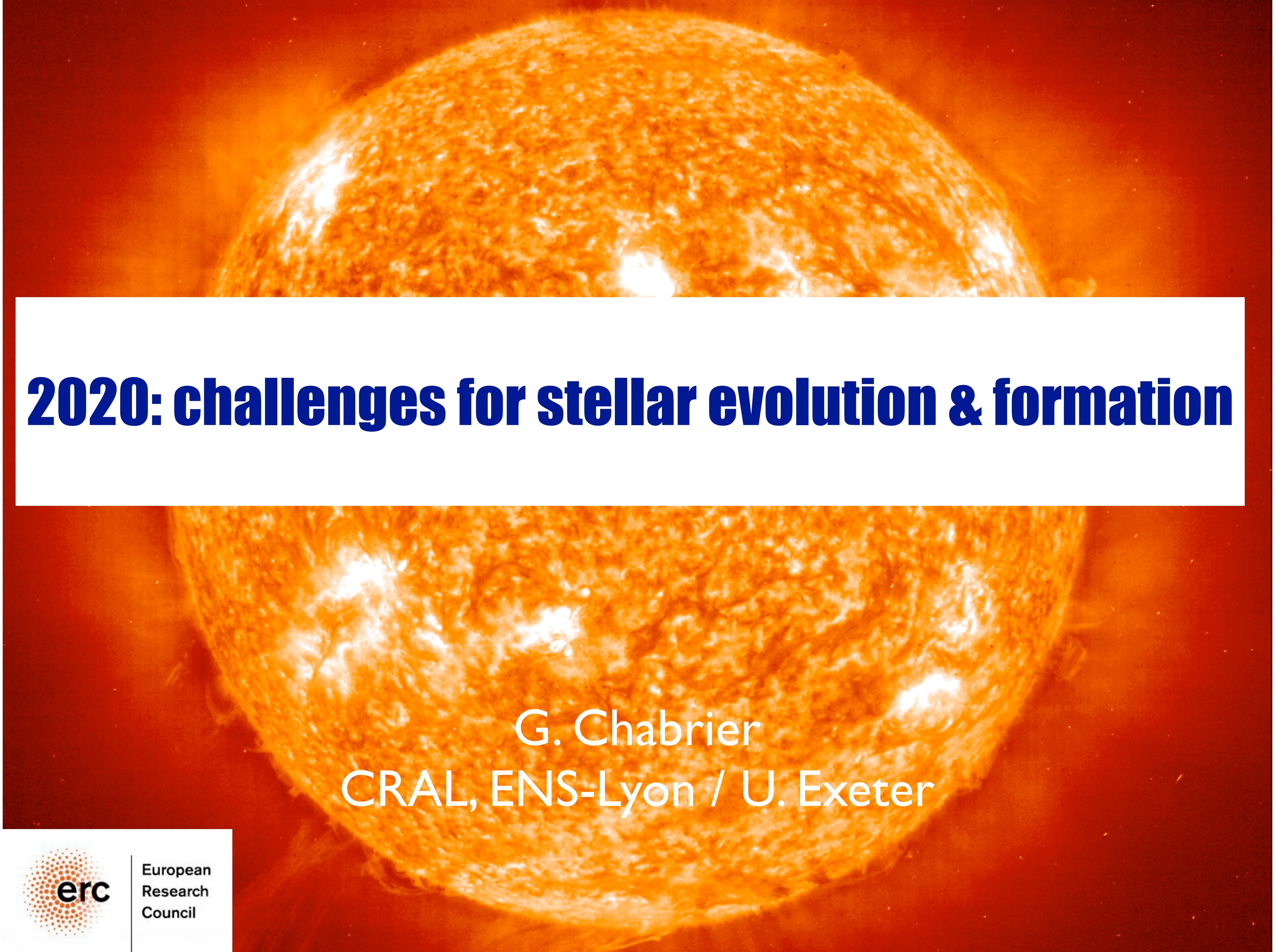

2020: challenges for stellar evolution & formation

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European
Research
Council

I) Transport properties

Understanding energy transport in stellar/planetary interiors (convection, turbulence, accretion,…)

Motivation for time-implicit multi-D simulations

Stellar physics/evolution rely on various processes characterised by very different time/length scales

Convection, pulsation, rotation, dynamo, nuclear burning, turbulence, radiation transport …

One-dimensional stellar evolution models: rely on **phenomenological** description of hydrodynamica processes:

☛ **Convection:** Mixing Length Theory

all substellar/stellar objects: a few M_{Jup} *to a few 100* $M_\odot$

☛ **Pulsation:** time-dependent convection models with several free parameters (up to 7 !)

radial/non-radial pulsators: Cepheids, RR-Lyrae, Delta Scuti, γ Doradus

☛ **Rotation:** formalism (Zahn 1992) with several free parameters

Mixing + transport of angular momentum: Sun, solar type stars, red giants, pre-SN stages (final yields, GRB's, hypernovae)

☛ **Magnetic fied:**

$$\mathcal{F}_r = \bar{\rho} r \sin\theta \left[-\nu r \frac{\partial}{\partial r}\left(\frac{\hat{v}_\phi}{r}\right) + \boxed{\widehat{v'_r v'_\phi}} + \hat{v}_r(\hat{v}_\phi + \Omega r \sin\theta) - \boxed{\frac{1}{4\pi\bar{\rho}}\widehat{B'_r B'_\phi}} - \frac{1}{4\pi\bar{\rho}}\hat{B}_r\hat{B}_\phi \right] \quad (21)$$

☛ **Accretion:** phenomenological description of mass/heat redistribution of accreted matter

Very early stages of evolution: from brown dwarfs → massive stars

☛ **Pre-SN stages**

one-D Phenomenological approaches have reached their limits

To match high quality data, we need **sophisticated** tools and models

Multi-dimensional models

- Anelastic approach: filter sound waves (ASH code)

Restricted to very low Mach number flows: convection in stellar cores ($M \lesssim 10^{-2}$)
not appropriate for most asteroseimological studies

- Compressible hydrodynamical codes (FLASH, DJEHUTY, PENCIL, ZEUS, ...)

☛ based on **explicit time integration**

$$\frac{du(t)}{dt} = f(u(t)) \qquad u^{n+1} = u^n + \Delta t f(u^n)$$

conditionally stable: $\Delta t < \Delta t_{stab}$

Time step is limited: $\boxed{\Delta t < \Delta t_{CFL} = \frac{\Delta x}{|u| + c_S}}$ **Courant-Friedrich-Lewy condition**

➡ Motivation for using **time-implicit methods**:

$$\frac{du(t)}{dt} = f(u(t)) \longrightarrow u^{n+1} = u^n + \Delta t f(u^{n+1})$$

unconditionally stable

No stability limit on the time-step

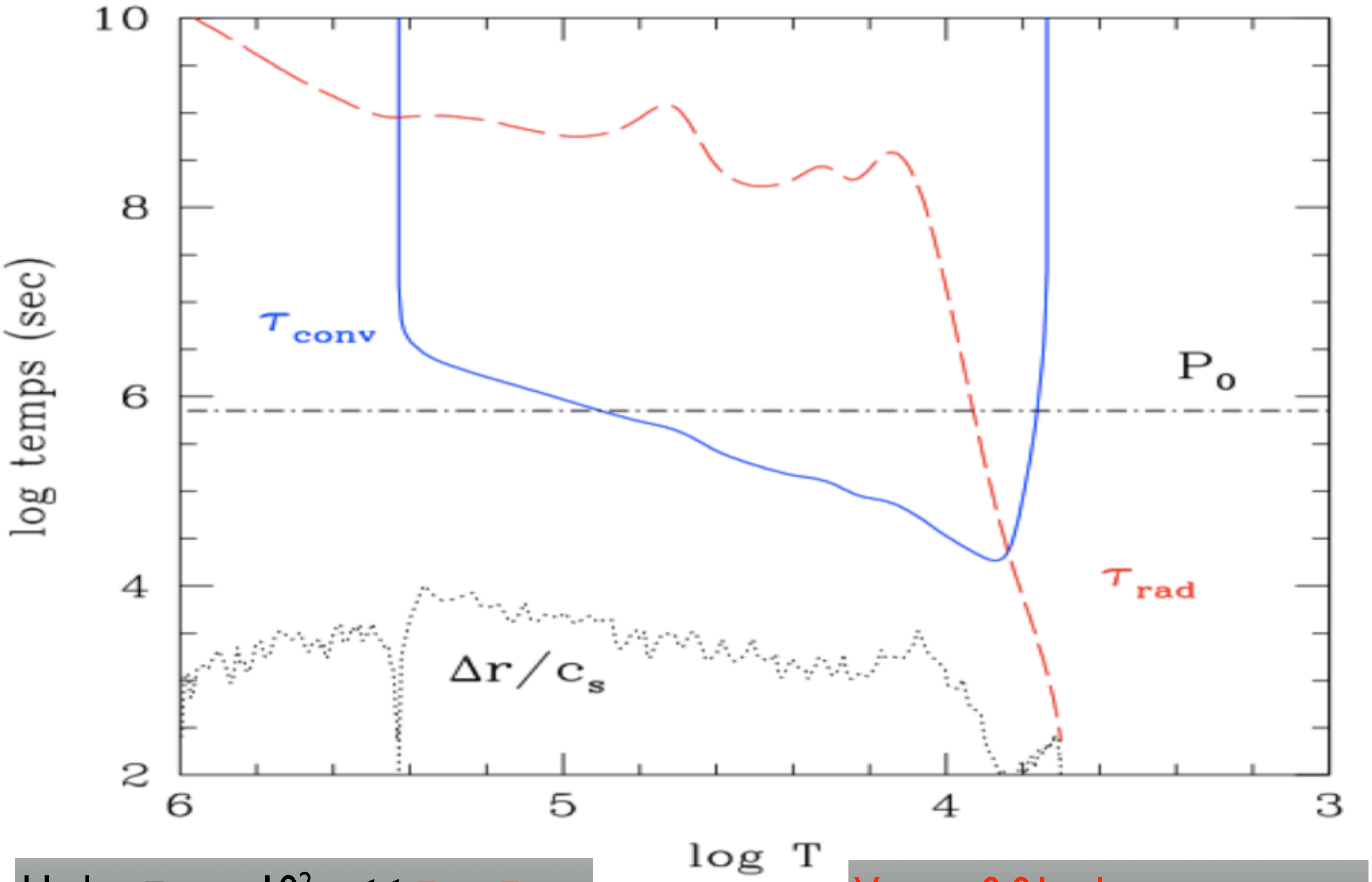
→ Appropriate methods to describe most of stellar physics problem:

$$\tau_{evol} = \tau_{therm}, \tau_{conv}, \tau_{rot}, \tau_{nuc} \gg \tau_{dyn}$$

adapted for problems with various stiff scales (e.g disparate timescales)

Time step choice is driven by accuracy and physical considerations

Characteristic timescales in the envelope of a Cepheid type star (radial pulsator - 5 $M_\odot$, T_{eff}=5500K)



Hydro τ_{CFL} ~ 10^2 s << τ_{rad} ; τ_{conv}

τ_{rad} ~ 10^{10} s - 10^2 s

τ_{conv} ~ 10^5 s - 10^7 s

1/10 - 10 x Period

V_{conv} ~ 0.01 - 1 c_{sound}

Period: 10^6 s (10 days)

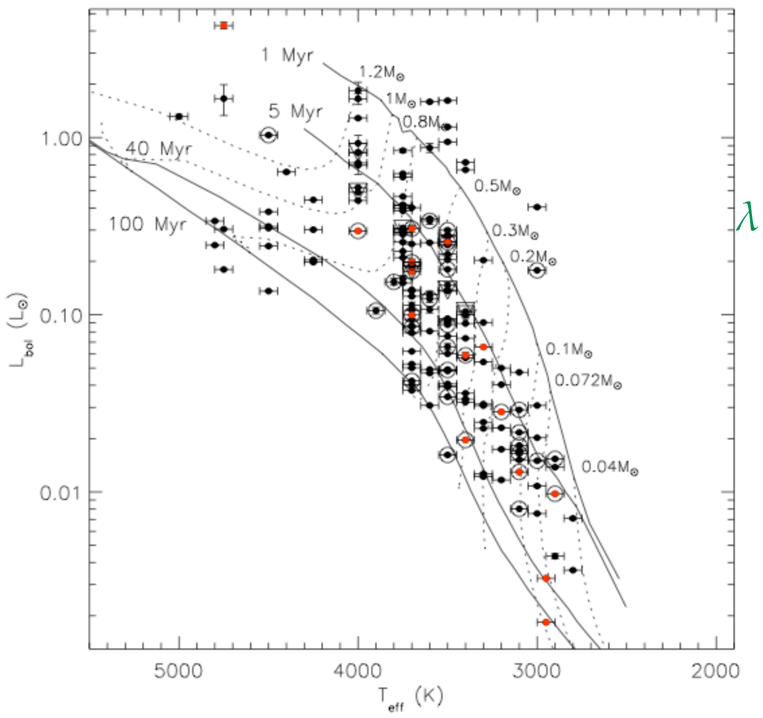
Growth rate: ~ 1000 x Period

Early stages of accretion history

Spread in the HRD:

Well know problem: spread in Teff-L diagram of young cluster members (1-10 Myr)

Age spread?



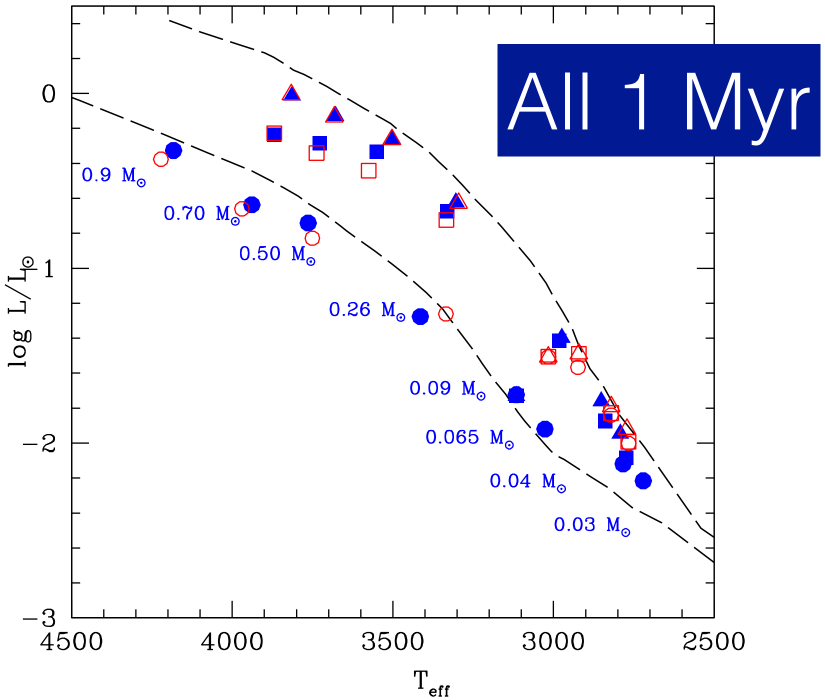
Bayo et al. 2011
λ Orionis (~5Myr)

➝**Accretion at early stages of evolution** can affect the evolution **even after a few Myr** and produce the observed HRD spread

$$t_{acc} = \frac{M}{\dot{M}} \ll t_{KH}$$

⇒ **No need to invoke an age spread**

(Baraffe et al.2009, 2010, 2012)



large (compressible) convective zones

Convection in a red giant

5 M_{sol} T_{eff}=4500 K

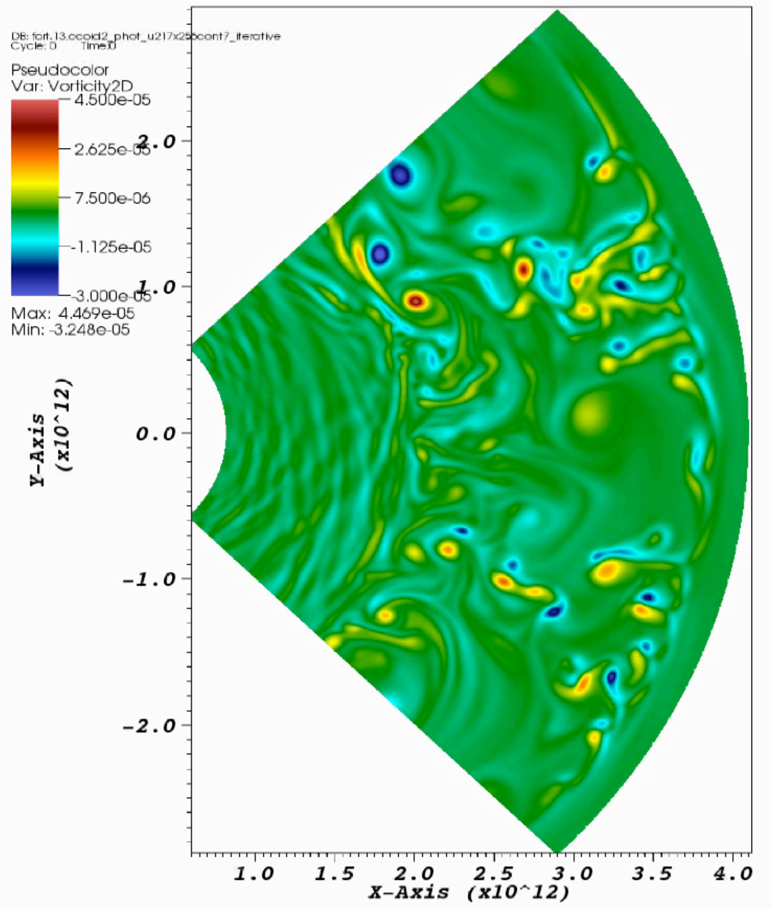
R_{conv} = 0.80 R_{star}

CFL_{hydro} ~ 100

Convection in a young Sun (~Myr)

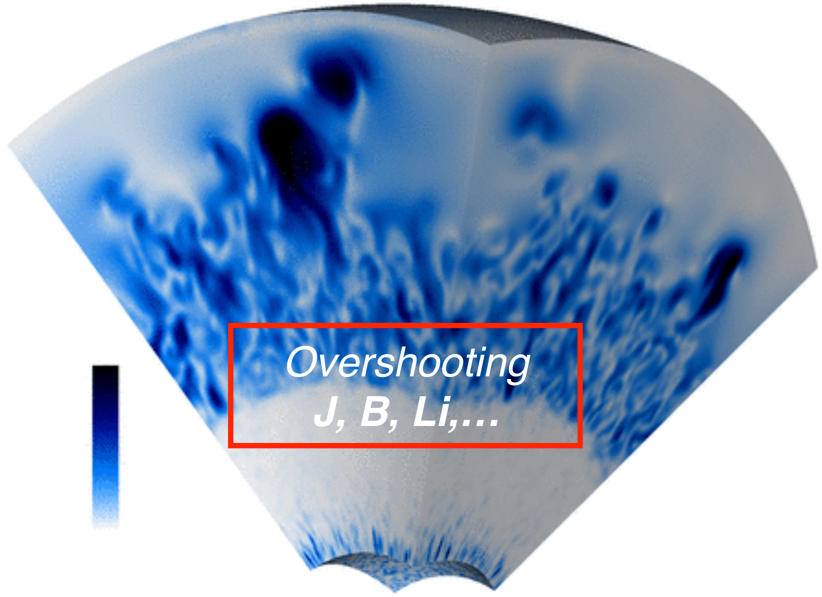
R_{conv} = 0.60 R_{star}

large convective zone



$\Delta t \sim 2.10^4$ s ~ 0.23 d

t ~ 13 years stellar time



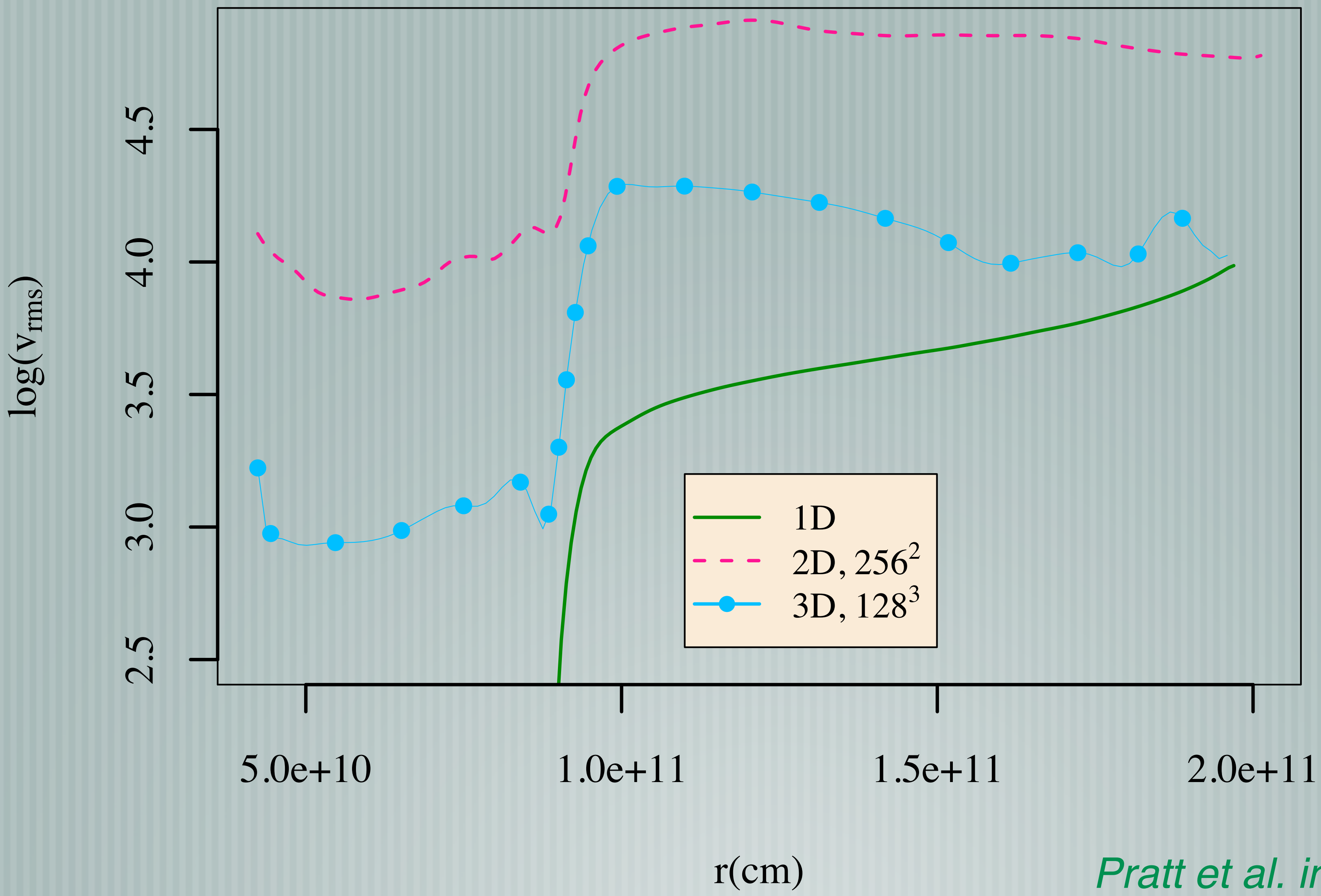
Overshooting

J, B, Li,…

Viallet et al. ’11, ‘13

Pratt et al. in prep

Comparison v_{conv} (MLT, 1D) vs $<v_{rms}^2>^{1/2}$ (2D and 3D) for a young Sun



Pratt et al. in prep

convective turnover timescale (~l/Vrms) -> magnetic braking (torque) *(Matt et al '15)*

II) Magnetic field

Dynamo generation, interaction convection-magnetic field

Effect of rotation

$$LMS : v_{rot} \geq 10\, km\, s^{-1} \quad t_{conv} \sim \frac{H_P}{v_{conv}} \sim 10^6 - 10^7\, s \Rightarrow Ro = \frac{P}{t_{conv}} \leq 0.1$$

$$\text{Rapidly rotating body} : 2\rho\boldsymbol{\Omega} \times \mathbf{u} = \nabla p \Rightarrow (\boldsymbol{\Omega} \cdot \nabla)\mathbf{u} = 0$$

Taylor-Proudman theorem: velocity uniform along the rotation axis => convective motions = **columnar patterns** with a charactristic length scale perpendicular to the rotation axis << the one parallel to the rotation axis (~ R) **=> Reduces the efficiency of large-scale thermal convection to transport the internal heat flux**

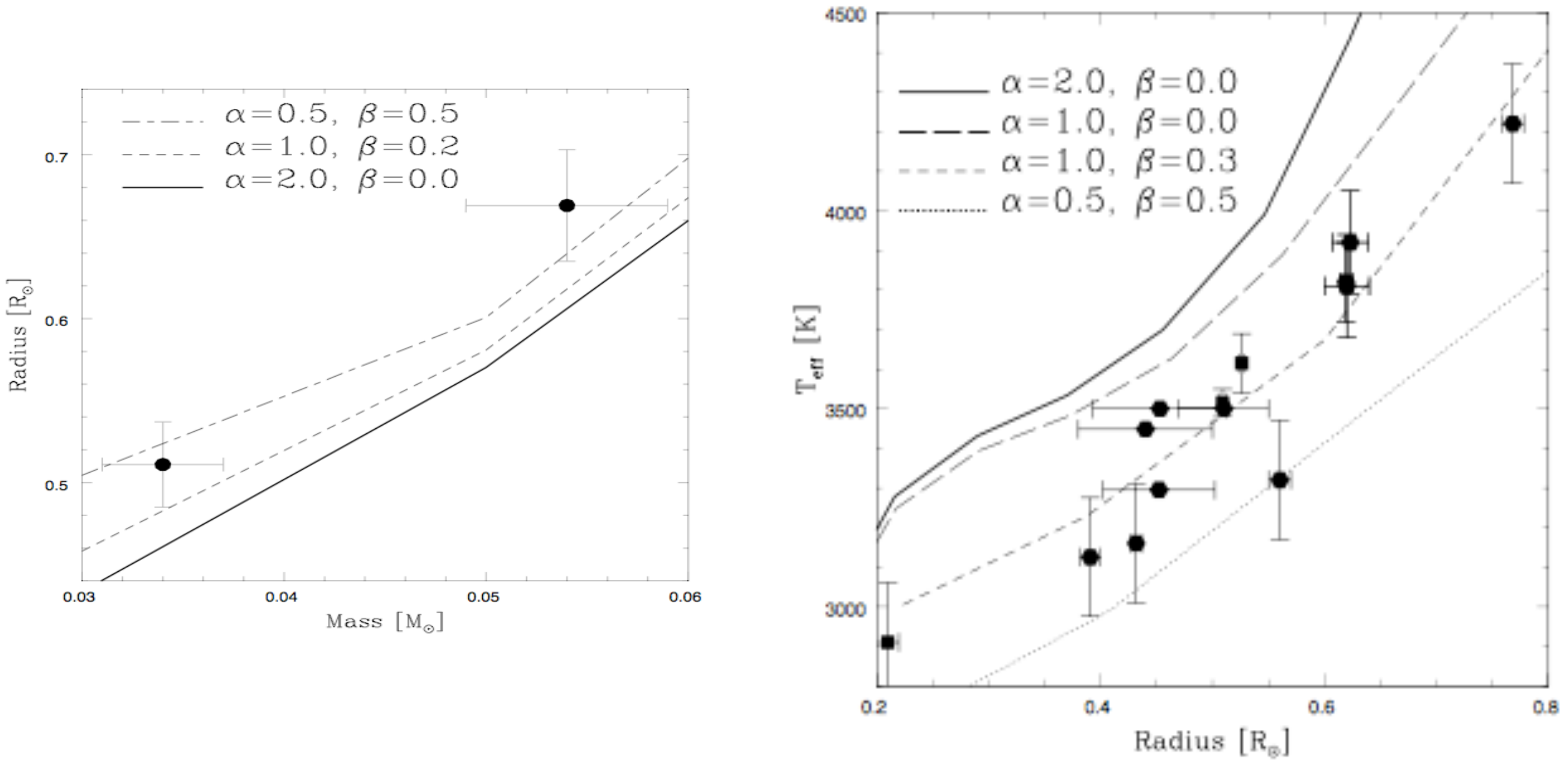
Effect of magnetic field

$$Rm = \frac{v_{conv} R}{\eta} \gg 100 \ \rightarrow \ B_{eq} \approx (8\pi\bar{\rho}\eta\Omega)^{1/2} \sim \mathrm{kG}$$

$$\frac{B^2}{4\pi l} \approx \rho g \delta(\nabla - \nabla_{ad})$$

Effect of rotation and/or magnetic field -> inhibates large-scale convection => α=l/Hp < 1

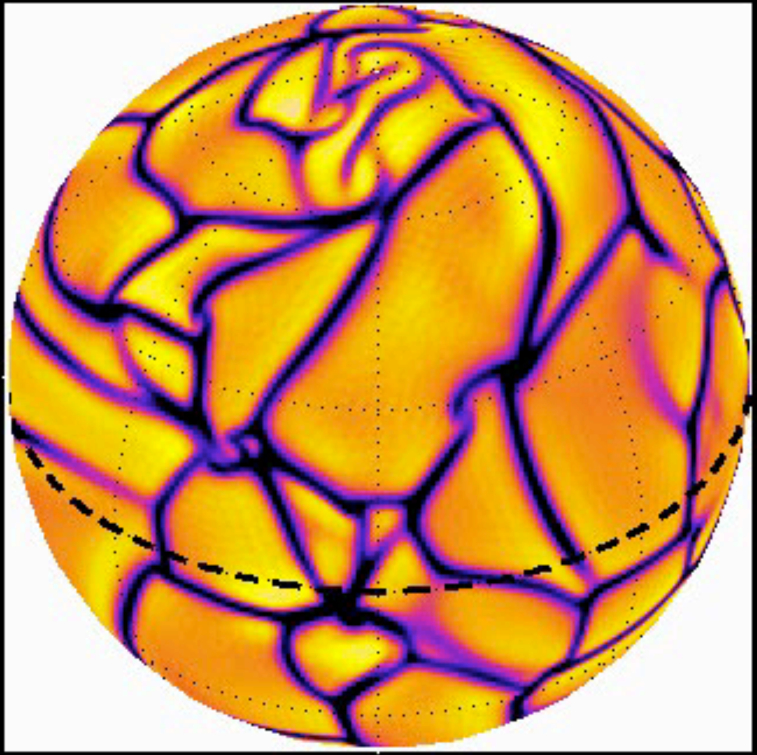
☛ **possible explanation for the eclipsing BD binary of Stassun et al. 2006** ***(Chabrier et al. 2007)***

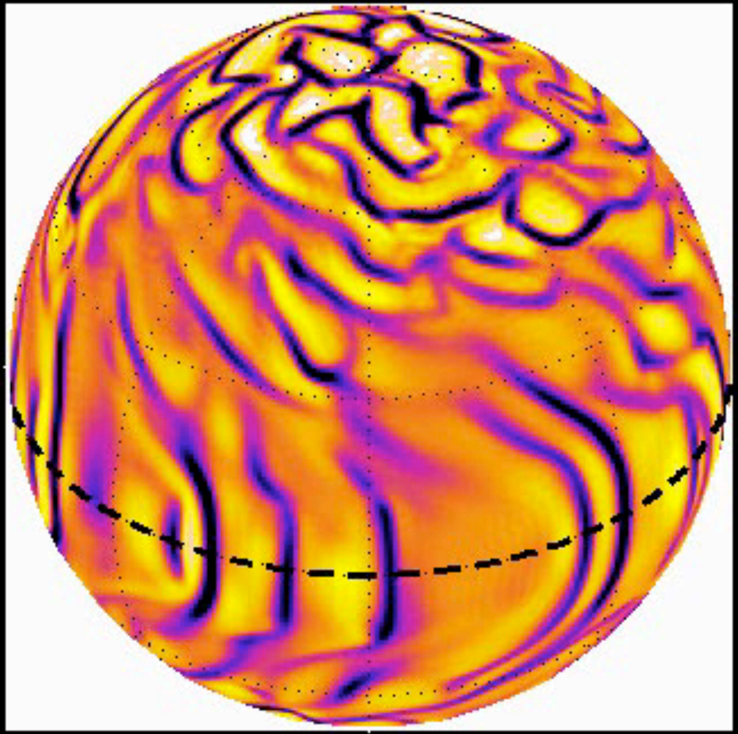


3D HD simulations: Rotation of fully convective objects

Radial velocity Vr on a surface near the top of a simulation of a slowly rotating M-dwarf. Up flows are reddish down flows are blue-ish.

Same, but in a more rapidly rotating simulation (10x faster)
The rotation has organised the convection into organised rolls.
(Interior rotation profile constant on cylinders, reflects the Taylor-Proudman constraint)



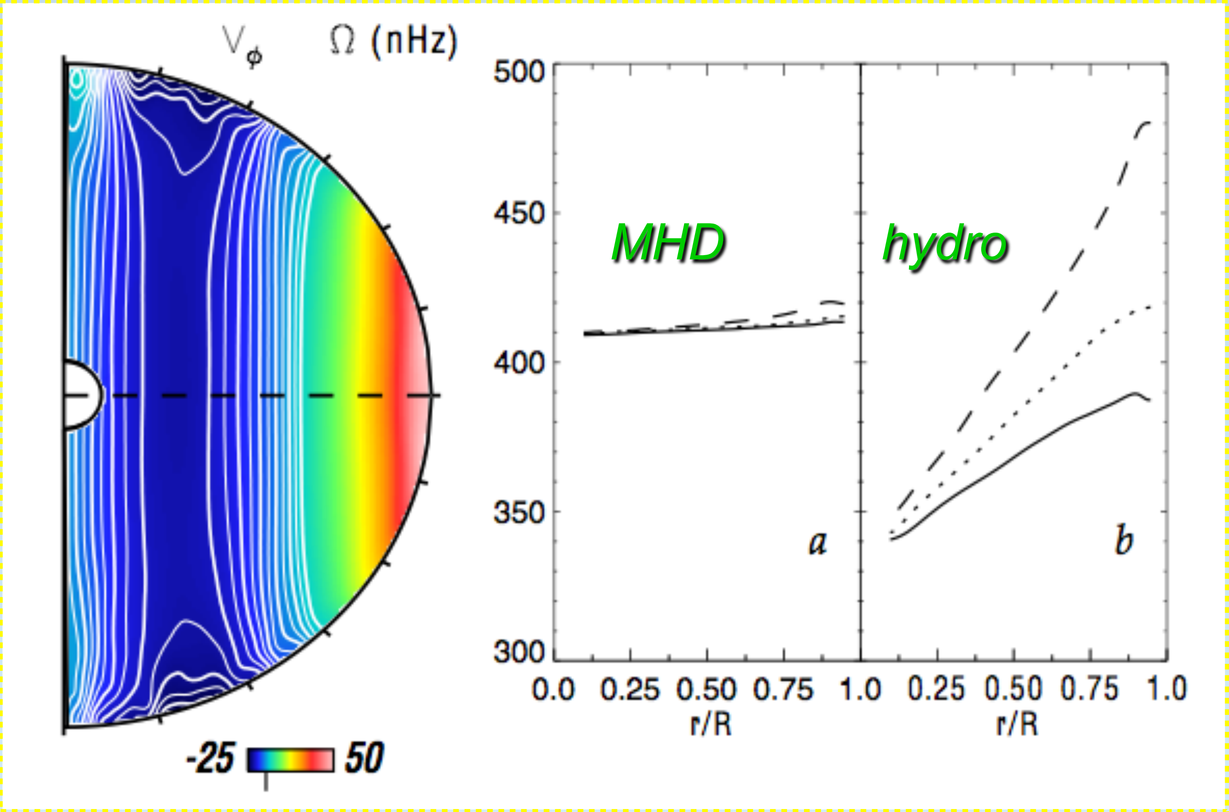


M. Browning , in prep

3D MHD simulations

- Development of differential rotation strongly affected by magnetic fields
- Magnetic field also impact the convective flows
  weakening of the convection (along the lines of Chabrier et al. 2007)

Quenching Differential Rotation



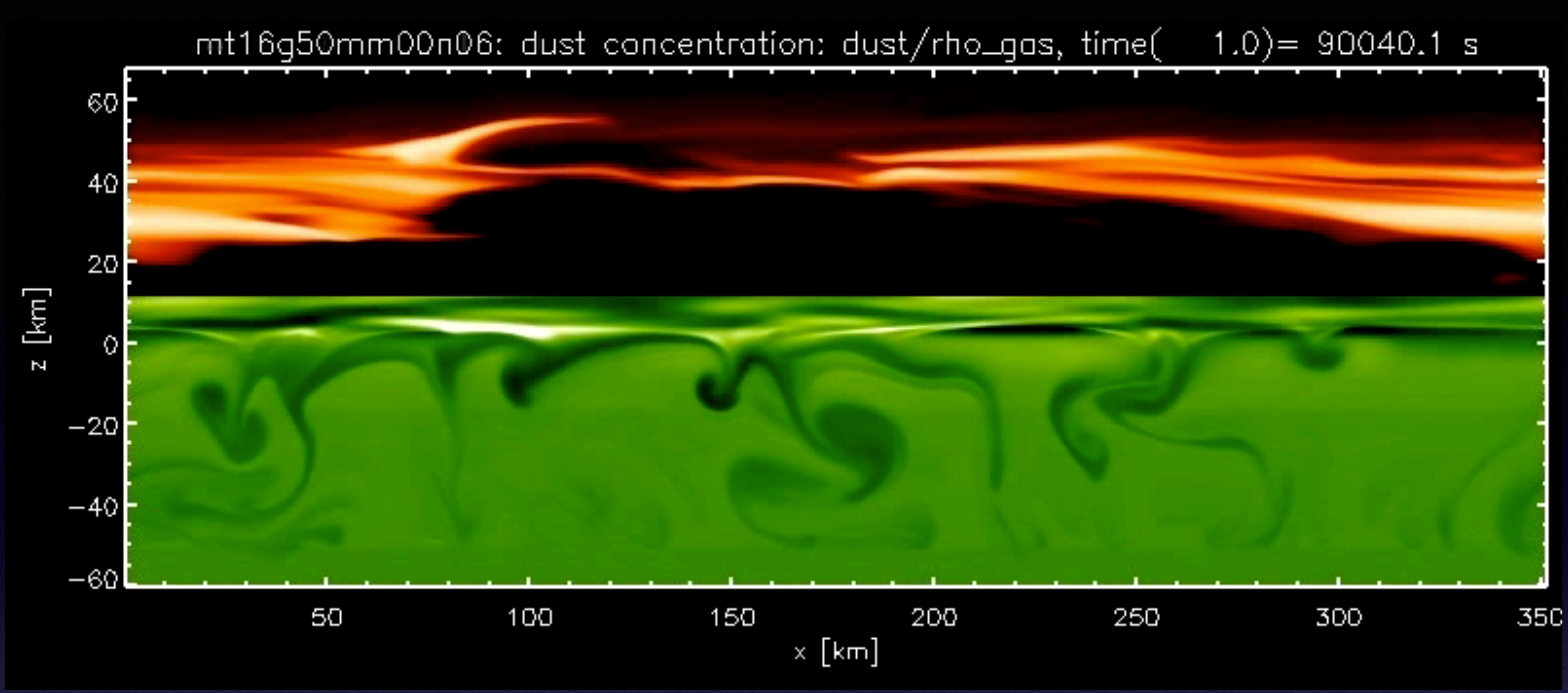
Differential rotation established in hydro, reduced in MHD

(*Browning 2008*)

At lower ME, find less quenching of differential rotation

III) Atmospheric processes in cool atmospheres

Radiation-hydrodynamics, grain formation, non-equilibrium chemistry
(cool giants, cool dwarfs, brown dwarfs, exoplanets)



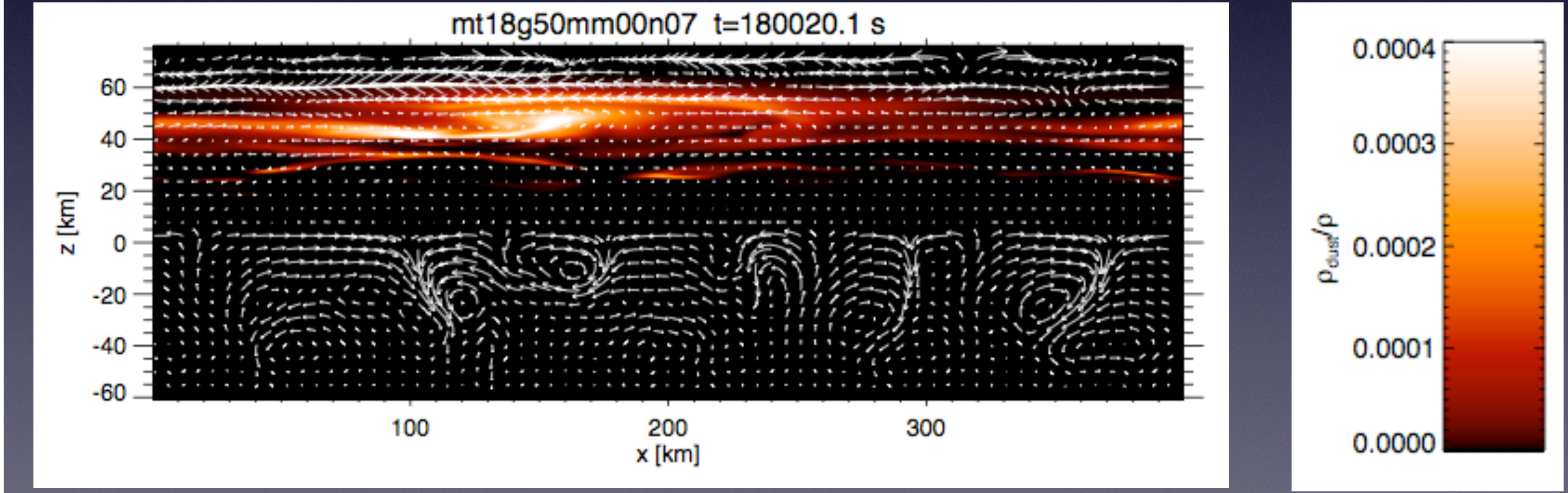
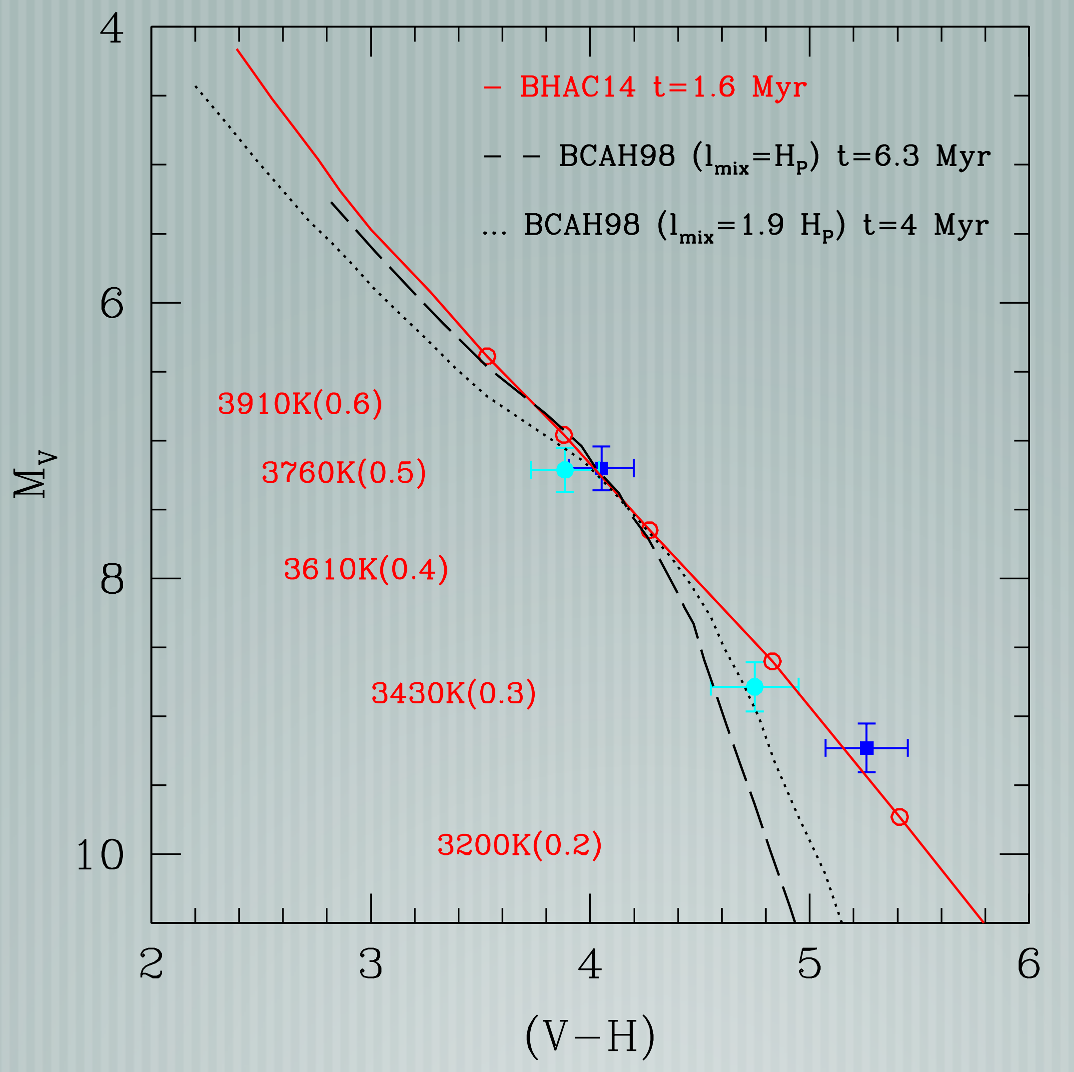


Fig. 1. This snapshot from a brown dwarf simulation with $T_{\mathrm{eff}} = 1858$ K, log $g = 5$ shows the velocity field as pseudo-streamlines, color-coded according to the dust concentration. The flow in the lower part is due to the surface granulation of the stellar convection zone. The top is dominated by gravity waves.

(Freytag et al. 2013)

☛ Better agreement for LMS (MKG types)

(Baraffe, Homeier, Allard, Chabrier, 2015, sub.)



quadruple system LkCa

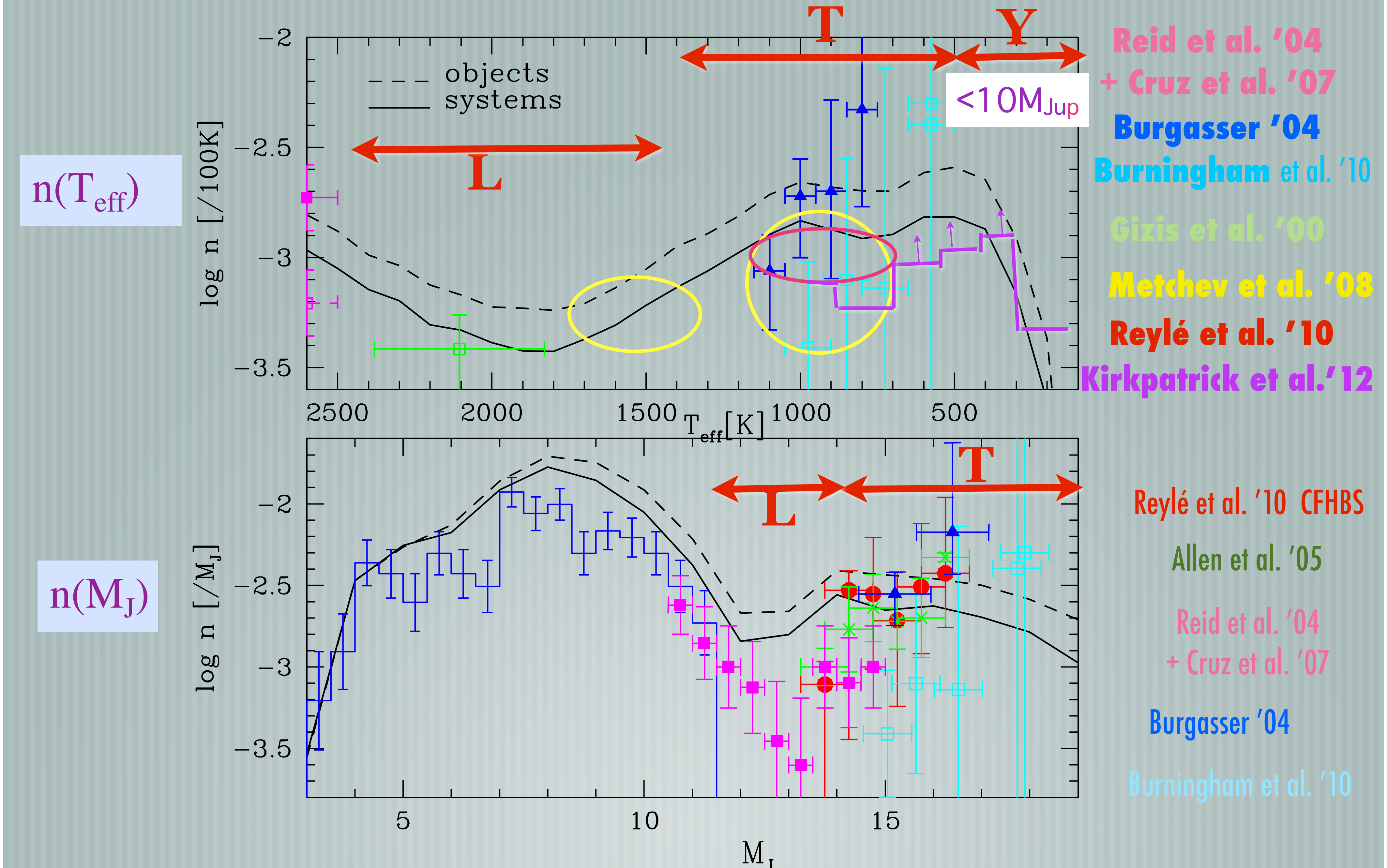
(Torres et al. 2013)

- **☛ Important for the determination of the age of young clusters**
- **☛ Important for the characterisation of planets around M-dwarfs (SPIROU, SPHERE, PLATO)**

IV) Star / Brown dwarf / Planet formation

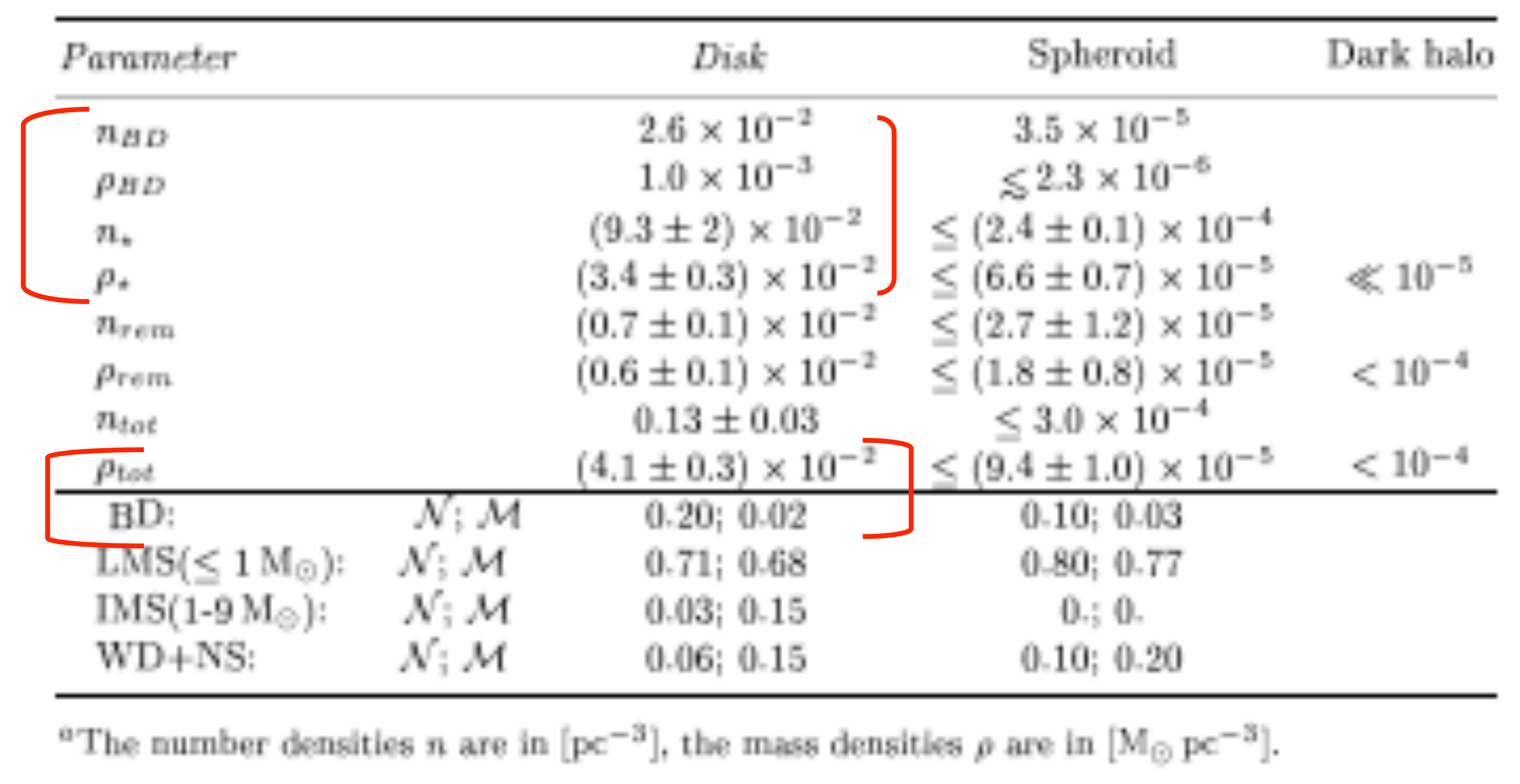
(Dominant) formation mechanisms, stellar/BD IMF, Galactic (baryonic) census

Brown dwarf mass function



Chabrier, 2003, 2005; see PPVI review Chabrier et al. ArXiv, in press

$n_{BD} \approx n_{MS}/3 \approx \mathbf{0.03\ pc^{-3}}$
$\rho_{BD} \approx \rho_{MS}/30 \approx \mathbf{0.001\ M_{sol} pc^{-3}}$

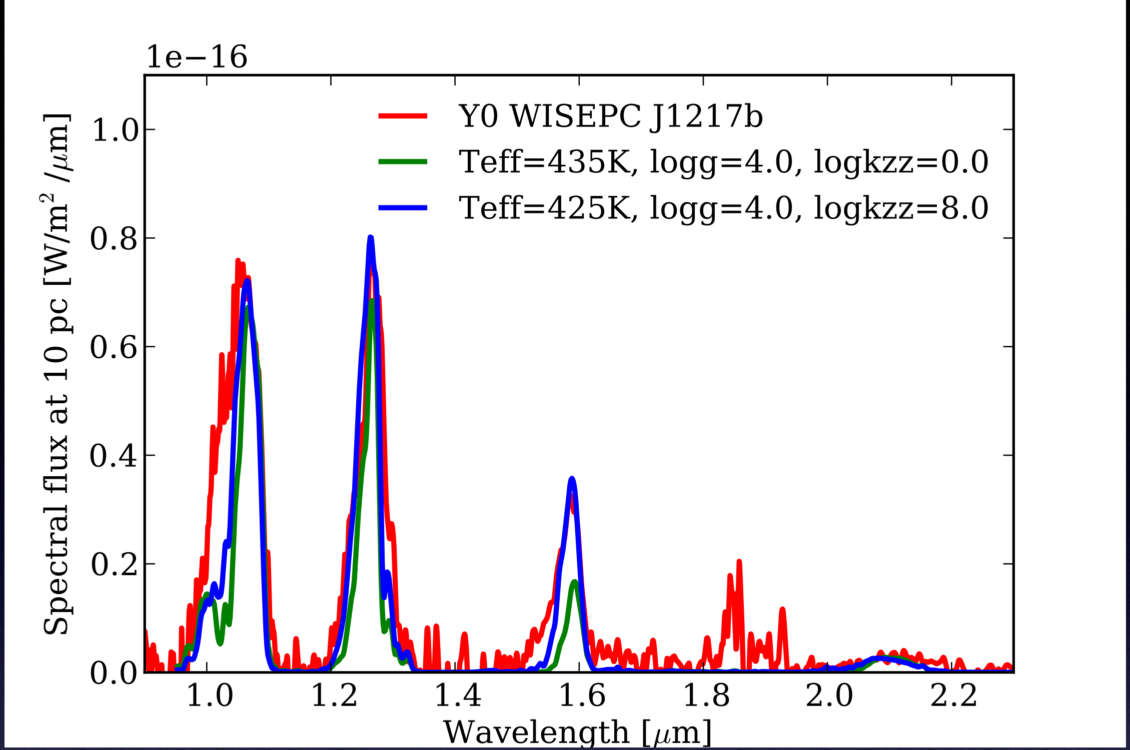


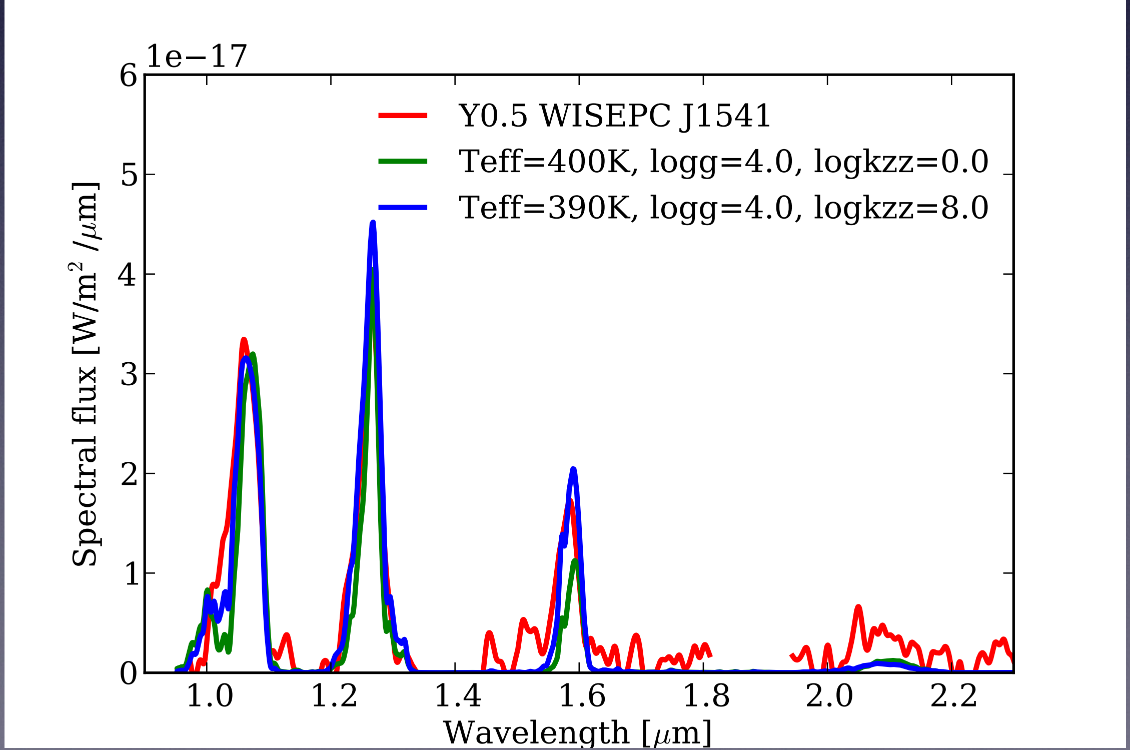
Parameter		*Disk*	Spheroid	Dark halo
n_{BD}		2.6×10^{-2}	3.5×10^{-5}	
ρ_{BD}		1.0×10^{-3}	$\lesssim 2.3 \times 10^{-6}$	
n_*		$(9.3 \pm 2) \times 10^{-2}$	$\lesssim (2.4 \pm 0.1) \times 10^{-4}$	
ρ_*		$(3.4 \pm 0.3) \times 10^{-2}$	$\lesssim (6.6 \pm 0.7) \times 10^{-5}$	$\ll 10^{-5}$
n_{rem}		$(0.7 \pm 0.1) \times 10^{-2}$	$\lesssim (2.7 \pm 1.2) \times 10^{-5}$	
ρ_{rem}		$(0.6 \pm 0.1) \times 10^{-2}$	$\lesssim (1.8 \pm 0.8) \times 10^{-5}$	$< 10^{-4}$
n_{tot}		0.13 ± 0.03	$\lesssim 3.0 \times 10^{-4}$	
ρ_{tot}		$(4.1 \pm 0.3) \times 10^{-2}$	$\lesssim (9.4 \pm 1.0) \times 10^{-5}$	$< 10^{-4}$
BD:	$\mathcal{N}$; $\mathcal{M}$	0.20; 0.02	0.10; 0.03	
LMS($\lesssim 1\,M_\odot$):	$\mathcal{N}$; $\mathcal{M}$	0.71; 0.68	0.80; 0.77	
IMS(1-9 $M_\odot$):	$\mathcal{N}$; $\mathcal{M}$	0.03; 0.15	0.; 0.	
WD+NS:	$\mathcal{N}$; $\mathcal{M}$	0.06; 0.15	0.10; 0.20	

[a] The number densities n are in [pc^{-3}], the mass densities ρ are in [$M_\odot$ pc^{-3}].

$N_{BD}/N_* = 1/4 - 1/3$ WISE (now !)~1/5

Chabrier ASSL, 2005





Tremblin et al., in prep.

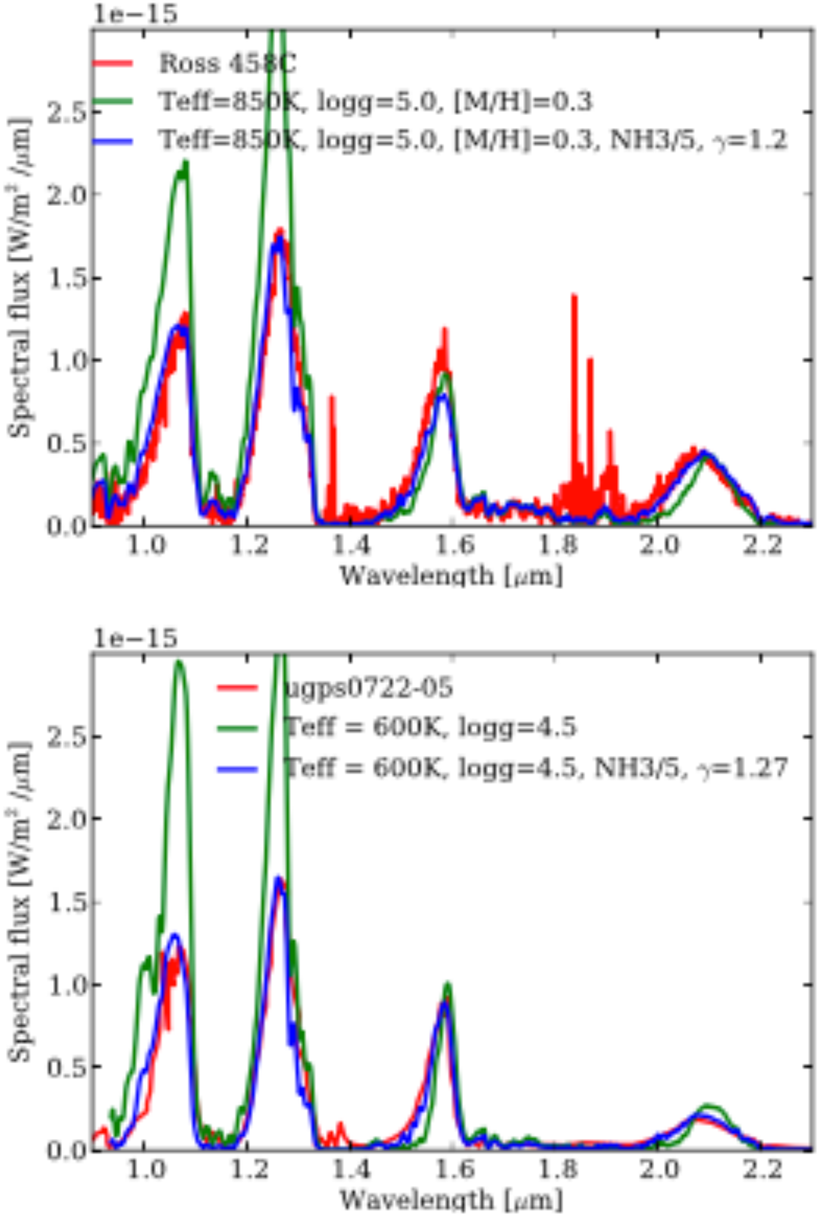
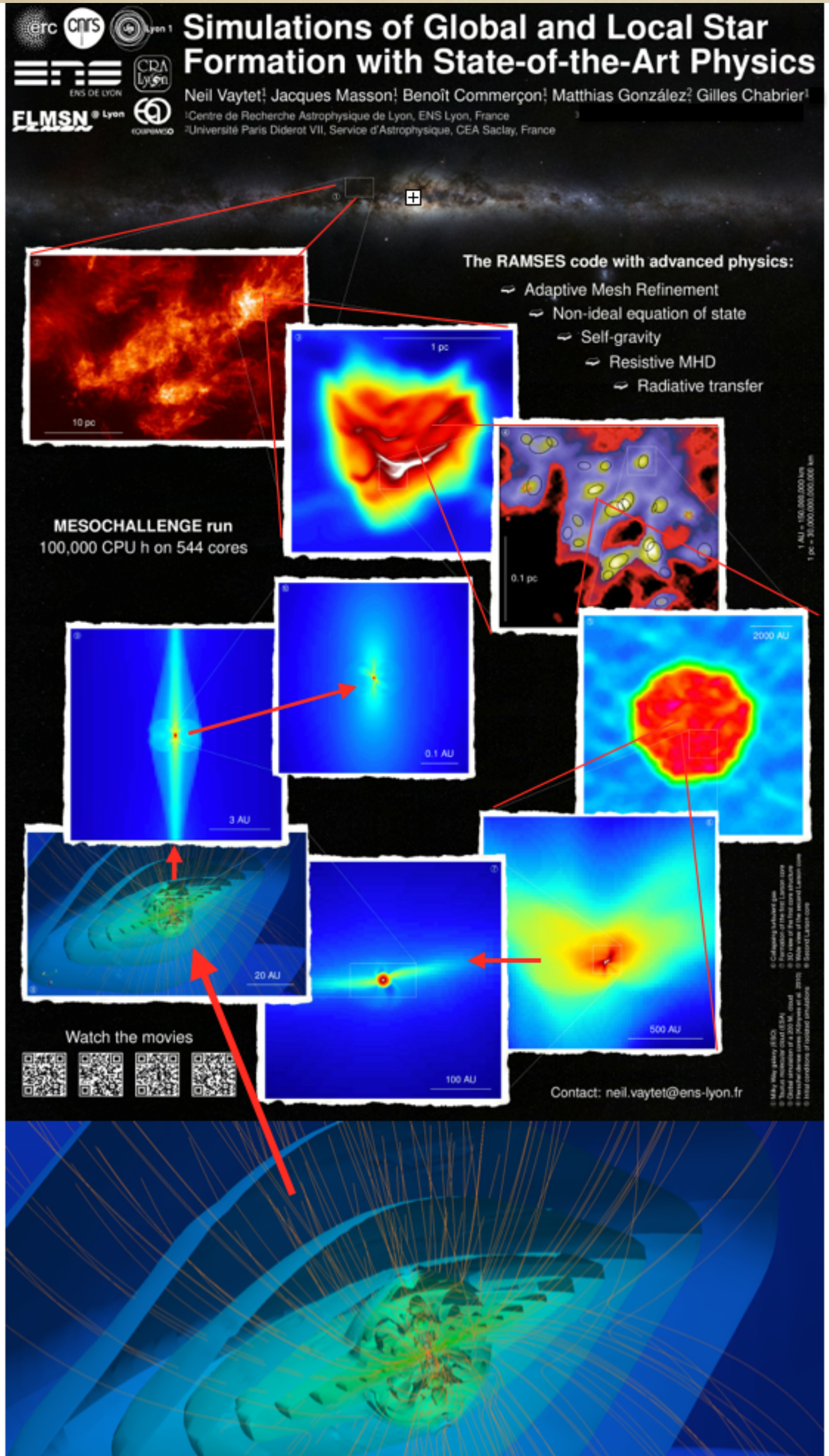


Fig. 2. Top: spectral flux of Ross 458C in red compared to a cloudless model (green) and with cooler deep layers (blue). Bottom: similar models for the spectral flux of UGPS 0722-05.

Star/Brown dwarf formation



Simulations of Global and Local Star Formation with State-of-the-Art Physics

Neil Vaytet[1], Jacques Masson[1], Benoît Commerçon[1], Matthias González[2], Gilles Chabrier[1]

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[2]Université Paris Diderot VII, Service d'Astrophysique, CEA Saclay, France
[3][redacted]

The RAMSES code with advanced physics:

- Adaptive Mesh Refinement
- Non-ideal equation of state
- Self-gravity
- Resistive MHD
- Radiative transfer

MESOCHALLENGE run
100,000 CPU h on 544 cores

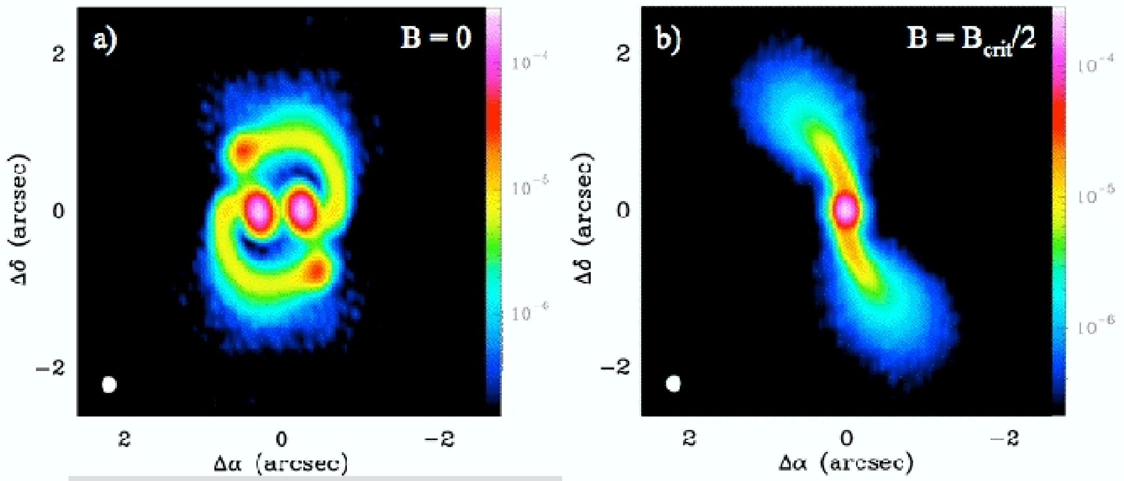
Watch the movies

Contact: neil.vaytet@ens-lyon.fr

Can we test these ideas ?

ALMA will offer the spatial resolution required

Synthetic observations done with the ALMA simulator
Included in the Gildas software



Commerçon et al. 2012

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II) Magnetic field

Dynamo generation, interaction convection-magnetic field

III) Atmospheric processes in cool atmospheres

Radiation-hydrodynamics, grain formation, non-equilibrium chemistry (cool giants, cool dwarfs, brown dwarfs, exoplanets)

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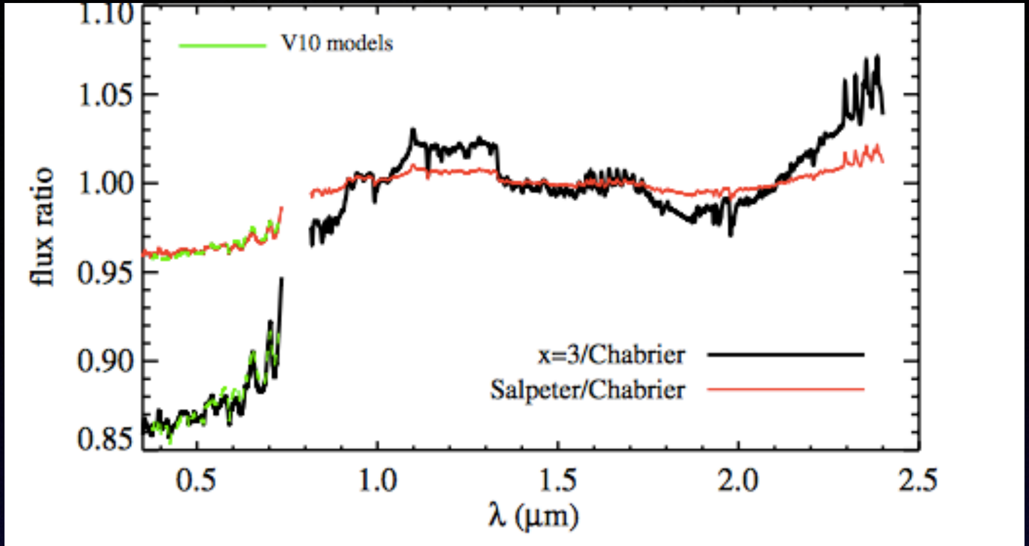
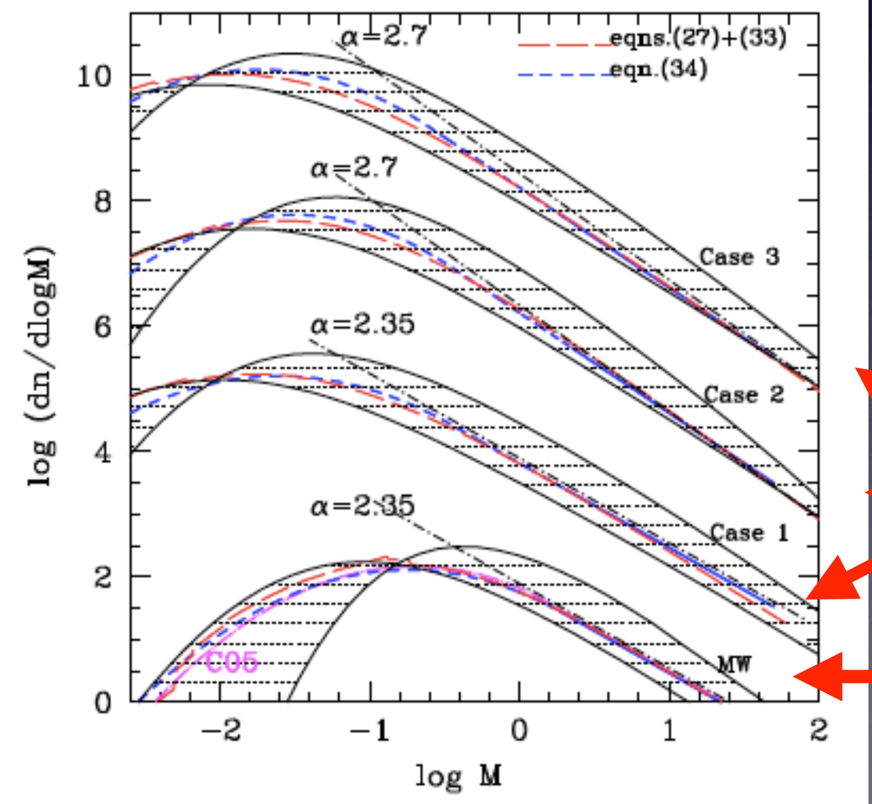


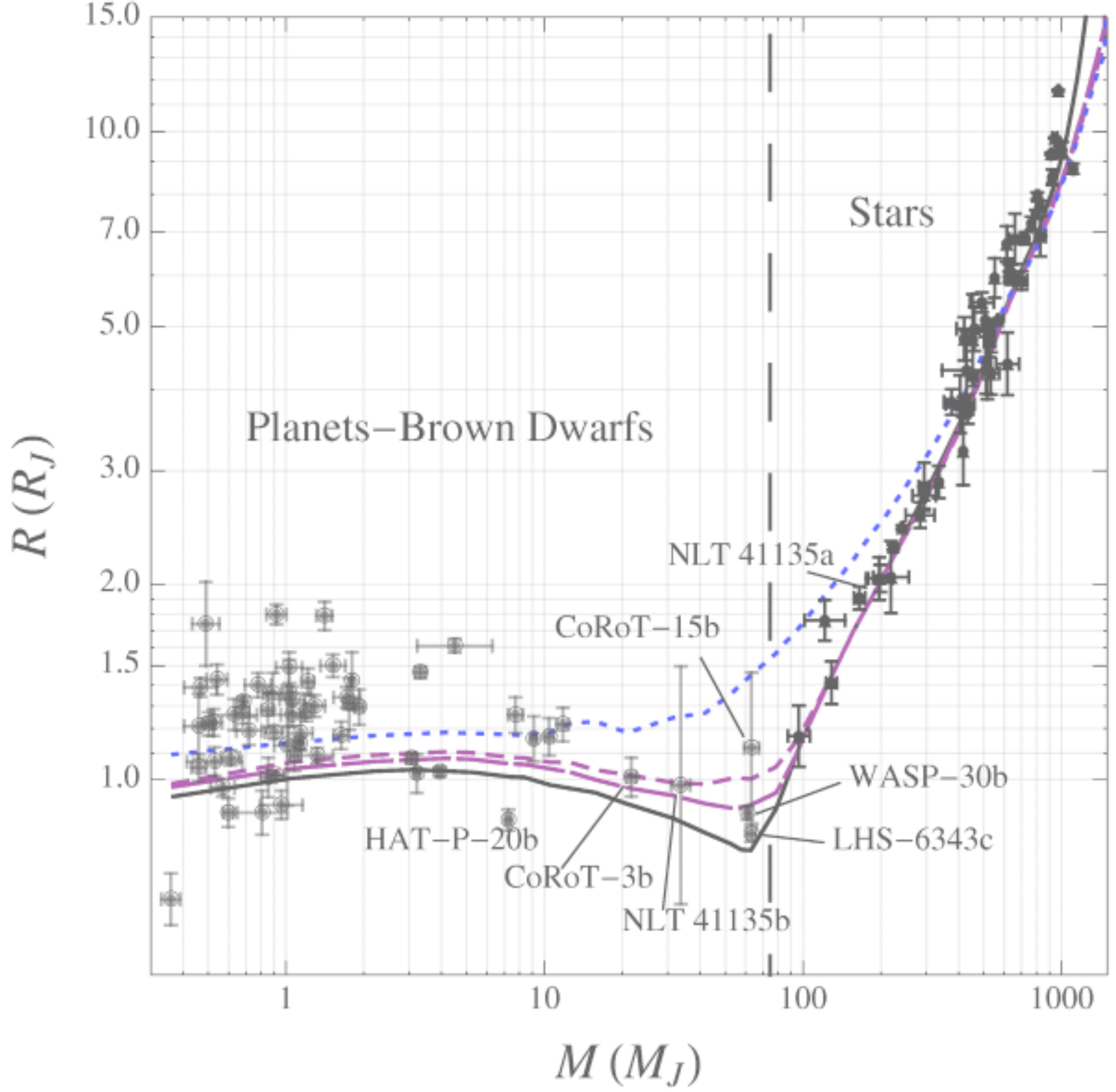
Conroy, van Dokkum et al.



ETGs

MW

Chabrier, Hennebelle & Charlot, 2014



15.0
10.0
7.0
5.0
3.0
2.0
1.5
1.0
$R\ (R_J)$
Stars
Planets−Brown Dwarfs
NLT 41135a
CoRoT−15b
WASP−30b
LHS−6343c
HAT−P−20b
CoRoT−3b
NLT 41135b
1
10
100
1000
$M\ (M_J)$