Formation and Early Evolution
of
Ultra Low Mass Objects

Convective Radiation Fluid-Dynamics

Günther Wuchterl

Astrophysikalisches Insitut und Universitäts-Sternwarte Jena
wuchterl@astro.uni-jena.de
http://www.astro.uni-jena.de/wuchterl

When a dark cloud grows in the sky ...

... a wind will blow

(Omen, Enuma Anu Enil, 700 BC, Assurbanibal's library)

... stars and planets will form

The Question

How does a cloud look like after it became a star or brown dwarf?

What are the properties of a Bonnor-Ebert-sphere when it comes to rest after collapse and accretion, and it evolved into a star or brown dwarf?

The Answer ...

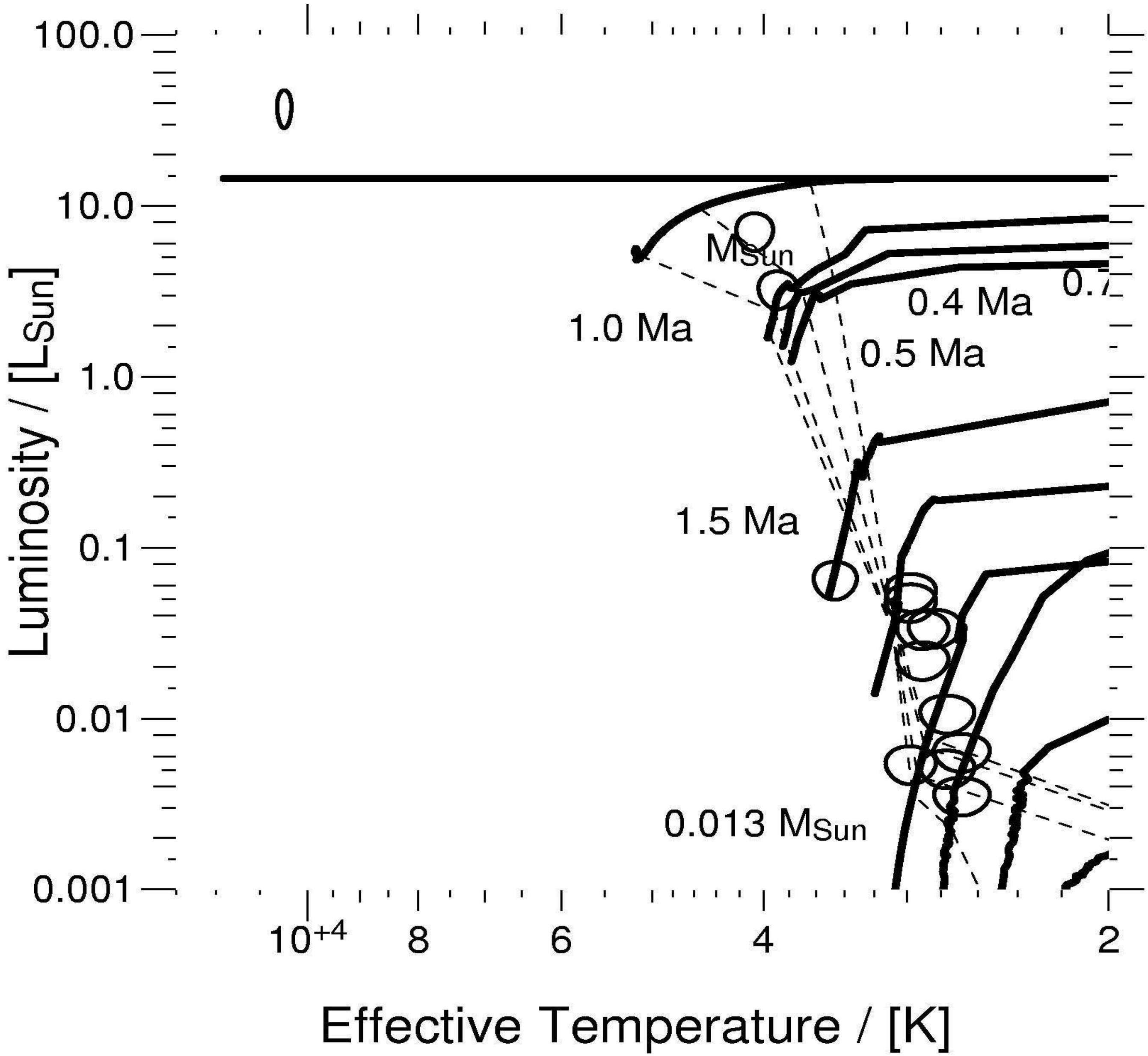
- Theoretically is easier for Ultra-Low Mass Objects.
- Collapse calculations now reach typically:

  100 Ma for planets

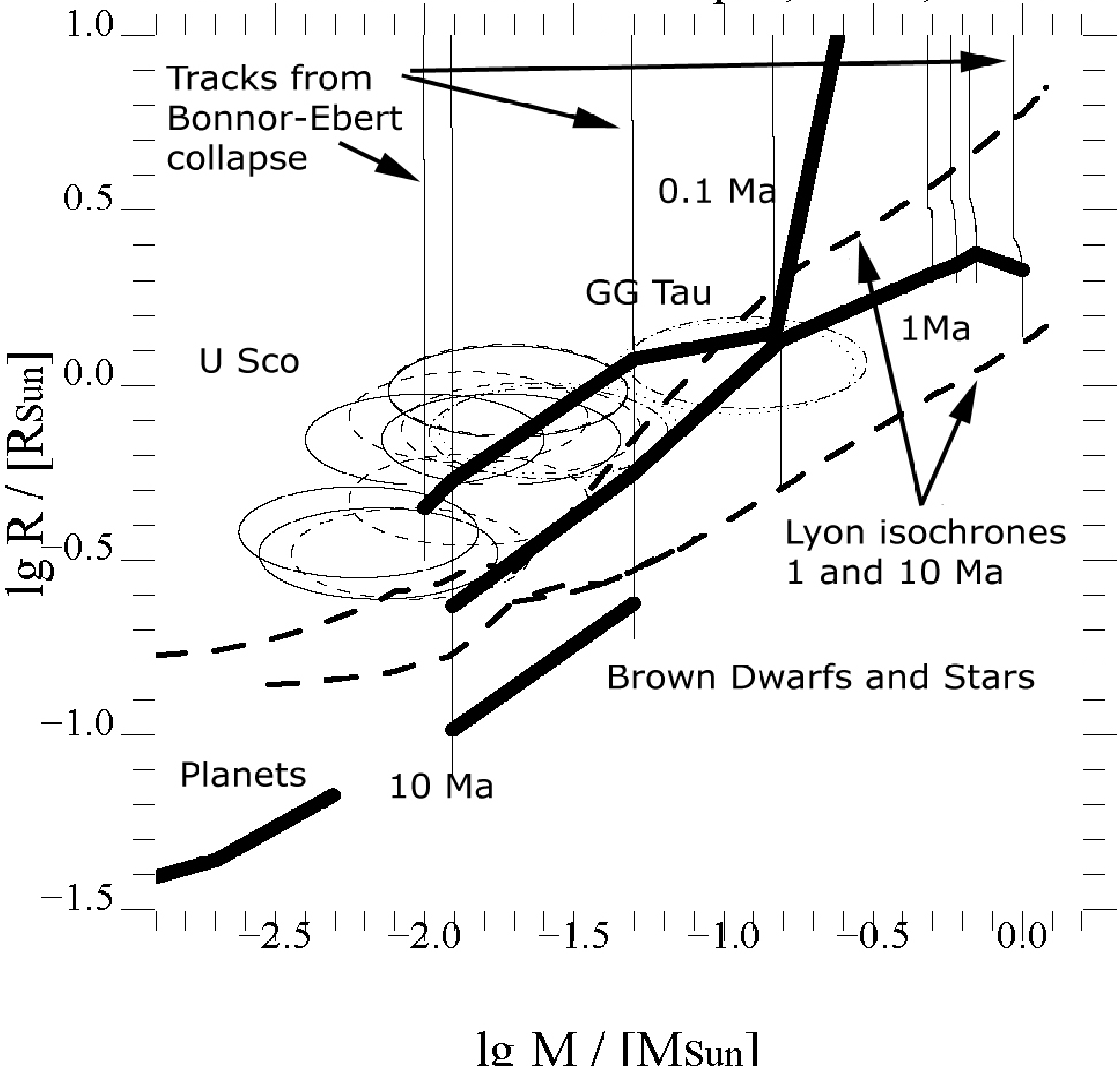
  10 Ma for brown dwarfs

  1 Ma for stars (up to 6 is feasible)

Chamaeleon Stars and ULM Objects



Mass−Radius relations: collapse, static, observed



What is different?

Convective Radiation Fluid-Dynamics of Formation

versus

Hydrostatics of large and hot gas spheres

Equations for self-gravitating radiating media with convection

10 G. Wuchterl and W.M. Tscharnuter: From clouds to stars Astron. Astrophys, **398**, 1081-1090, 2003

$$\frac{d}{dt}\left[\int_{V(t)} \varrho \, d\tau\right] + \int_{\partial V} \varrho (u_{\mathrm{rel}} \cdot dS) = 0 \,, \qquad \Delta M_r = \int_{V(t)} \varrho \, d\tau \,, \tag{A.2}$$

$$\frac{d}{dt}\left[\int_{V(t)} \varrho_D \, d\tau\right] + \int_{\partial V} [\varrho_D u_{\mathrm{rel}} + j_{\mathrm{D}}] \cdot dS = \int_{V(t)} \dot{\varrho}_D \, d\tau \,, \qquad \dot{\varrho}_{\mathrm{D}} = \frac{A_{\mathrm{D}}}{N_{\mathrm{L}} Q_{\mathrm{D}}} \varrho \epsilon^{D}_{\mathrm{nuc}} \,, \tag{A.3}$$

$$\frac{d}{dt}\left[\int_{V(t)} \varrho u \, d\tau\right] + \int_{\partial V} \varrho u (u_{\mathrm{rel}} \cdot dS) + \int_{V(t)} \left(\frac{\partial p}{\partial r} + \varrho \frac{G M_r}{r^2}\right) d\tau = C_M \,, \qquad C_M = \int_V \kappa \varrho \frac{F}{c} \, d\tau \,, \tag{A.4}$$

$$\frac{d}{dt}\left[\int_{V(t)} \varrho (e + \omega) \, d\tau\right] + \int_{\partial V} [\varrho (e+\omega) u_{\mathrm{rel}} + j_w] \cdot dS + \int_{V(t)} p \, \mathrm{div}\, u \, d\tau = -C_E + \int_{V(t)} \varrho \epsilon^{D}_{\mathrm{nuc}} \, d\tau \,, \tag{A.5}$$

$$\frac{d}{dt}\left[\int_{V(t)} E \, d\tau\right] + \int_{\partial V} [E u_{\mathrm{rel}} + F] \cdot dS + \int_{V(t)} P \, \mathrm{div}\, u \, d\tau = C_E \,, \qquad C_E = \int_V \kappa \varrho (4\pi S - cE) d\tau \,, \tag{A.6}$$

$$\frac{d}{dt}\left[\int_{V(t)} \frac{F}{c^2} \, d\tau\right] + \int_{\partial V} \frac{F}{c^2} (u_{\mathrm{rel}} \cdot dS) + \int_{V(t)} \left(\frac{\partial P}{\partial r} + \frac{F}{c^2} \frac{\partial u}{\partial r}\right) d\tau = -C_M \,, \qquad P = \frac{1}{3} E \,, \tag{A.7}$$

$$\frac{d}{dt}\left[\int_{V(t)} \varrho \omega \, d\tau\right] + \int_{\partial V} \varrho \omega u_{\mathrm{rel}} \cdot dS = \int_{V(t)} \left(S_\omega - \tilde{S}_\omega - D_{\mathrm{rad}}\right) d\tau \,, \qquad S_\omega = -\nabla_{\mathrm{s}} \frac{T}{P} \frac{\partial P}{\partial r} \Pi \,, \quad \tilde{S}_\omega = \frac{c_{\mathrm{D}}}{\Lambda} \omega^{3/2} \,, \tag{A.8}$$

$$j_{\mathrm{w}} = \varrho T \Pi \,, \quad \Pi = \frac{w}{T} u_c F_L \left[-\sqrt{3/2}\, \alpha_{\mathrm{S}} \Lambda \frac{T}{w} \frac{\partial s}{\partial r}\right] , \quad \frac{1}{\Lambda} = \frac{1}{\alpha_{\mathrm{ML}} H_p^{\mathrm{stat}}} + \frac{1}{\beta_r r} , \quad H_p^{\mathrm{stat}} = \frac{p}{\varrho} \frac{r^2}{G M_r} , \quad \tau_{\mathrm{rad}} = \frac{c_p \, \kappa \, \rho^2 \, \Lambda^2}{4\sigma \, T^3 \, \gamma_{\mathrm{R}}^2} \,, \tag{A.9}$$

$$\epsilon^{D}_{\mathrm{nuc}} = \frac{Q_{\mathrm{D}}}{\varrho} \tilde{r}_{{}^2\mathrm{H}(\mathrm{p},\gamma)^3\mathrm{He}} \,, \quad \tilde{r}_{{}^2\mathrm{H}(\mathrm{p},\gamma)^3\mathrm{He}} = \varrho_{\mathrm{p}} \frac{N_{\mathrm{L}}}{A_{\mathrm{p}}} \varrho_{\mathrm{D}} \frac{N_{\mathrm{L}}}{A_{\mathrm{D}}} \langle \sigma v \rangle_{{}^2\mathrm{H}(\mathrm{p},\gamma)^3\mathrm{He}} \,, \quad D_{\mathrm{rad}} = \frac{\omega}{\tau_{\mathrm{rad}}} \,, \quad j_{\mathrm{D}} = -\alpha_{\mathrm{M}} \Lambda \omega^{1/2} \varrho \frac{\partial c_{\mathrm{D}}}{\partial r} \,. \tag{A.10}$$

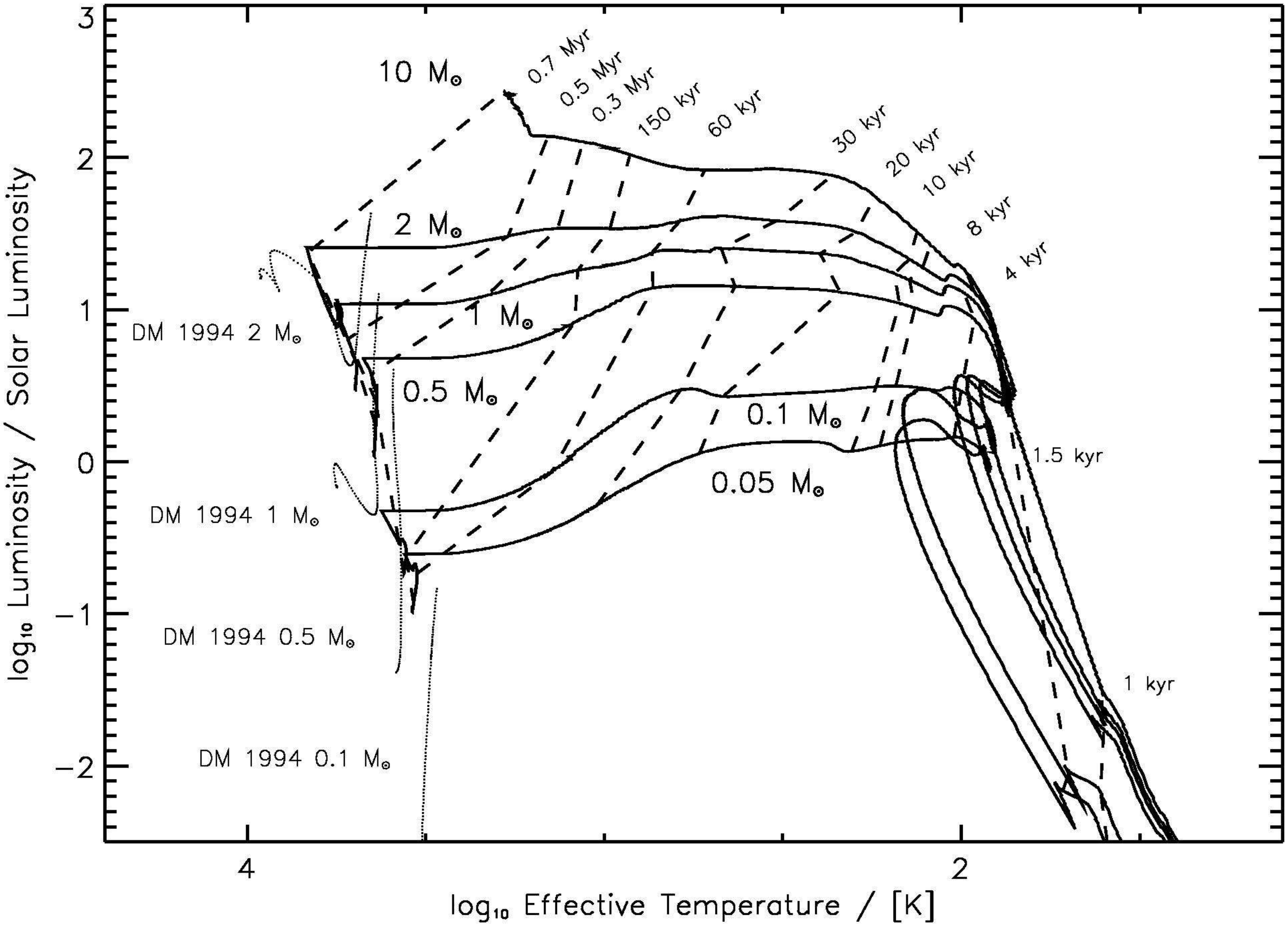
Zero Age

- Clouds have no history
- Pre-main sequence: history and age
- Pre-main sequence: towards thermal equilib.
- Energy-balance controls evolution
- Pre-requisite: thermal reservoir
- First formation of the reservoir: age=0
- Occurs when cloud centre optically thick

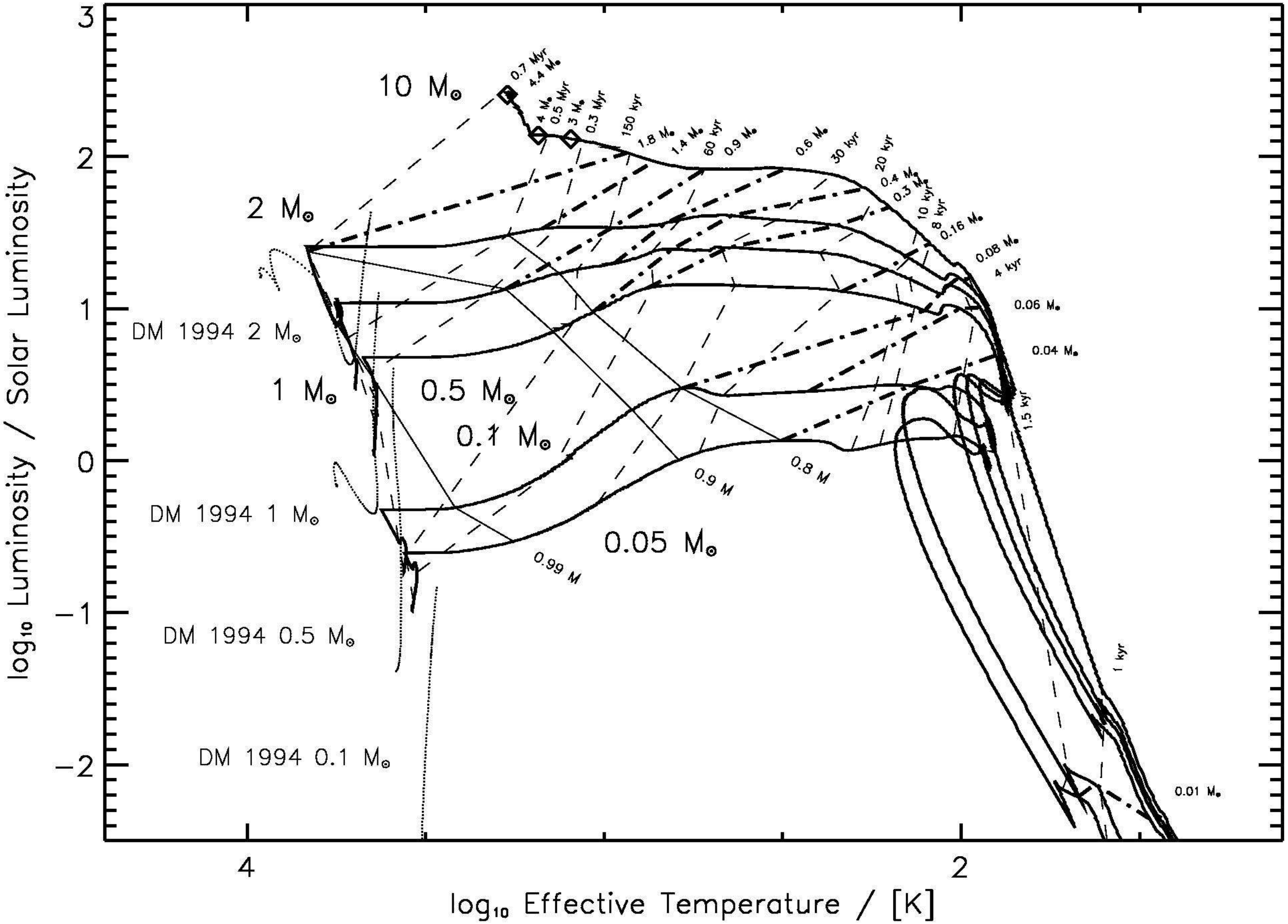
Collapse Remarks

- Free-fall time << PMS-time (thermal relax.),
- Inertia+gravity driven collapse produces thermal imprint,
- That imprint is an accretion profile for T,
- Opacity limit results in similar embryo mass for all cloud masses,
- Depending on mass, embryos are more or less embedded --> ULMO have no main accretion phase.

Bonnor-Ebert collapse



Isopleths


10 M$_\odot$
0.7 Myr
4.4 M$_\odot$
4 M$_\odot$
0.5 Myr
3 M$_\odot$
0.3 Myr
150 kyr
1.8 M$_\odot$
1.4 M$_\odot$
60 kyr
0.9 M$_\odot$
0.6 M$_\odot$
30 kyr
20 kyr
0.4 M$_\odot$
0.3 M$_\odot$
10 kyr
8 kyr
0.16 M$_\odot$
0.08 M$_\odot$
4 kyr
0.06 M$_\odot$
0.04 M$_\odot$
1.5 kyr
1 kyr
0.01 M$_\odot$
2 M$_\odot$
DM 1994 2 M$_\odot$
1 M$_\odot$
0.5 M$_\odot$
0.1 M$_\odot$
DM 1994 1 M$_\odot$
0.05 M$_\odot$
0.9 M
0.8 M
0.99 M
DM 1994 0.5 M$_\odot$
DM 1994 0.1 M$_\odot$
3
2
1
0
−1
−2
4
2
log$_{10}$ Luminosity / Solar Luminosity
log$_{10}$ Effective Temperature / [K]

Comparing to early-hydrostatics

Solar Case, Brown Dwarf, Planet

The Classics: Hayashi-Line

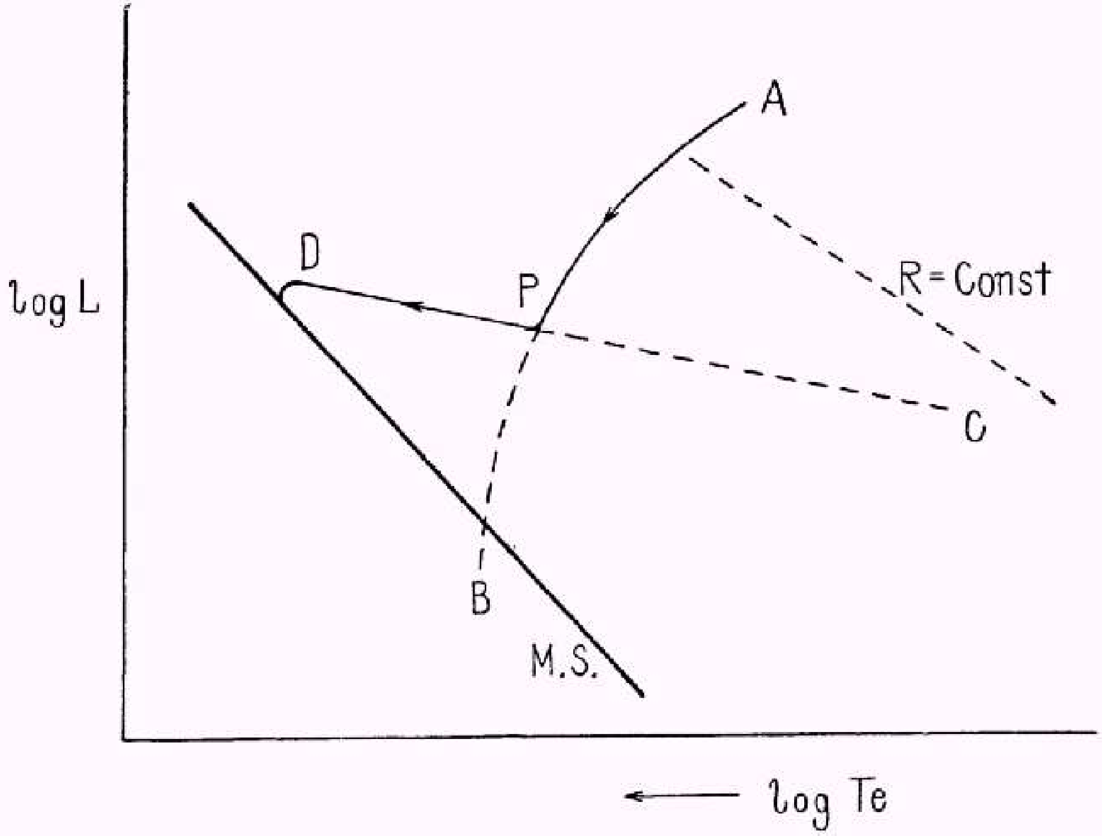
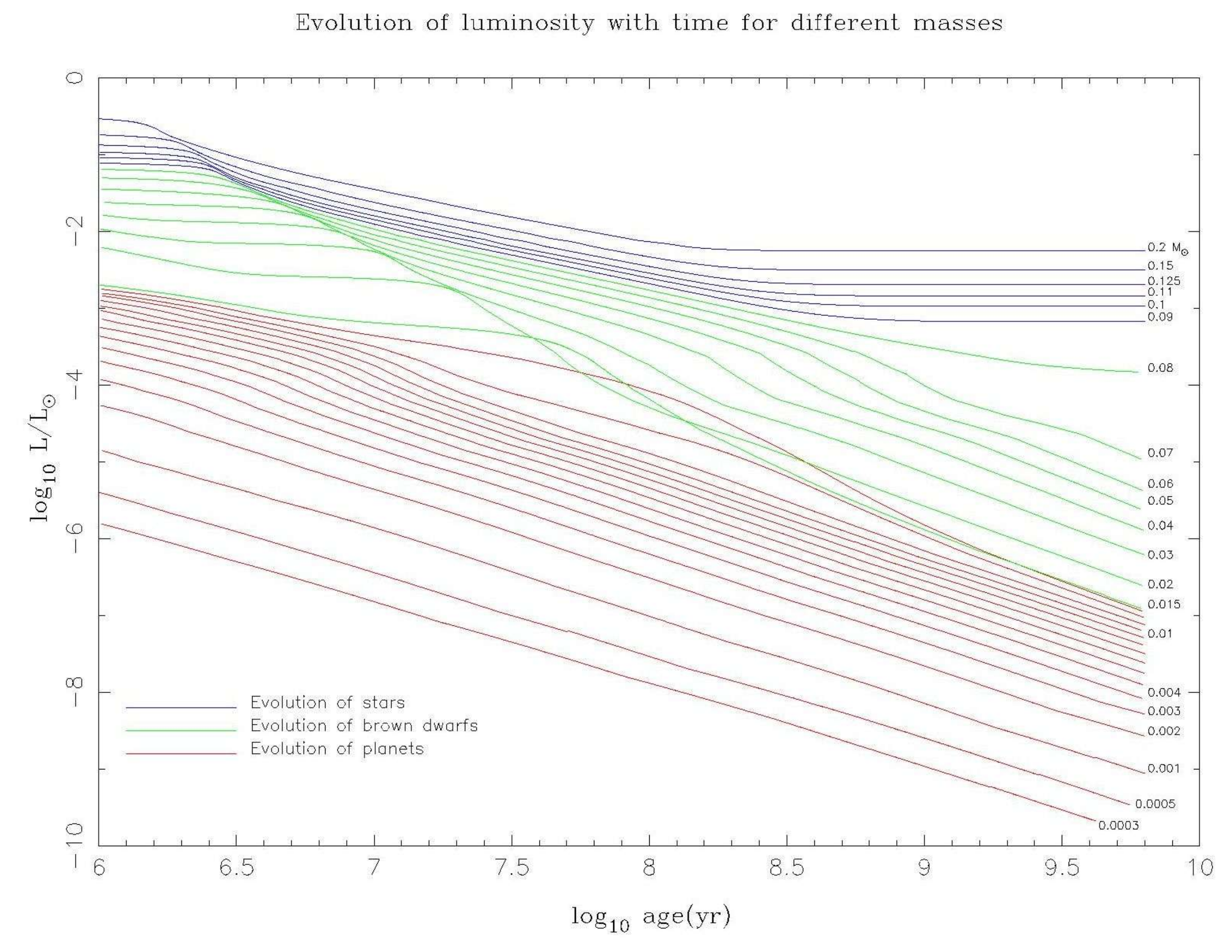


FIG. 1. Schematic track for contracting stars with given mass and chemical composition. The curve CPD shows the track calculated by LEVEE, SALPETER and HENYEY et. al. and APB shows a curve with $E=45$, the right region of which is forbidden for the existence of the quasi-static solutions.

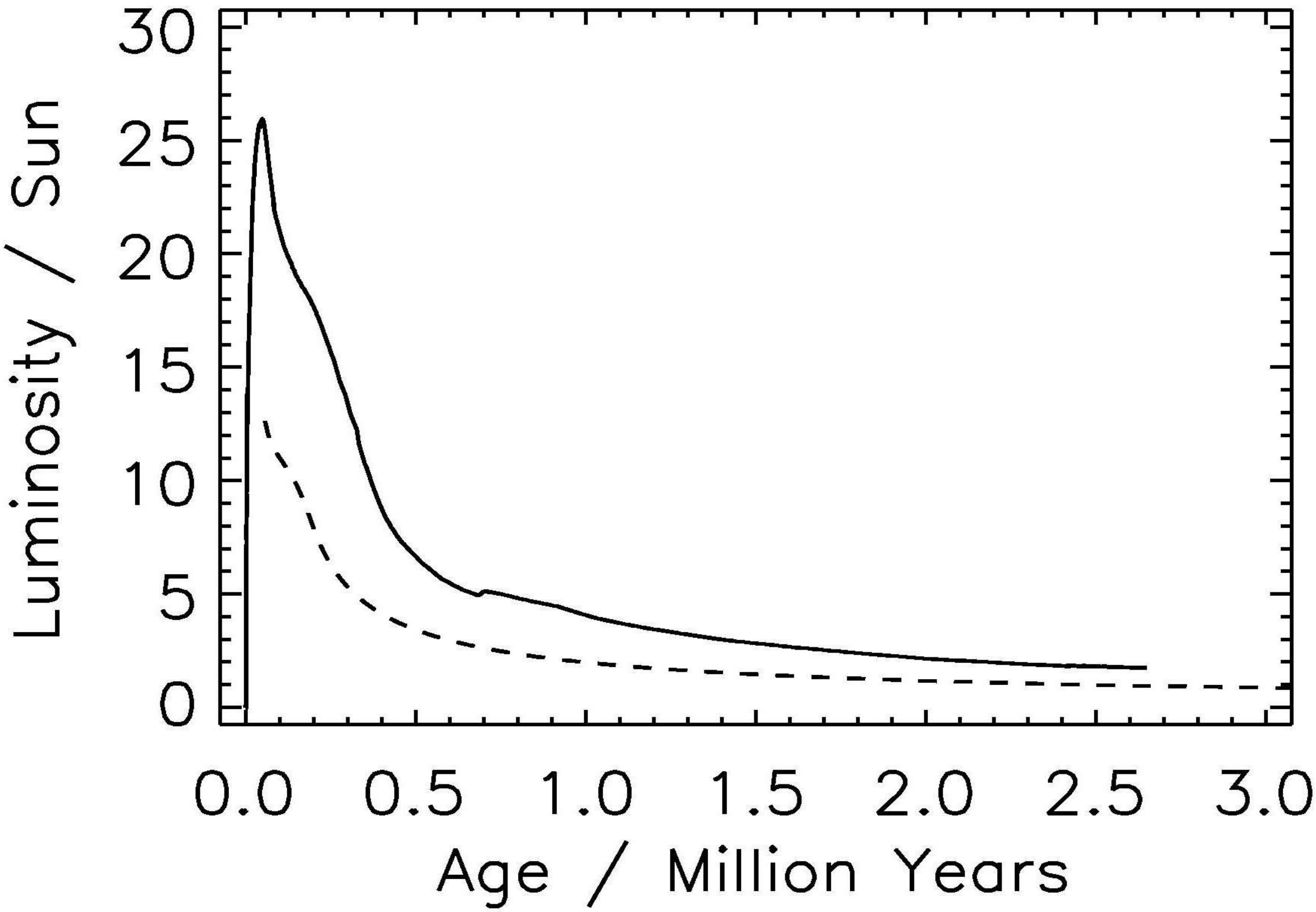
Hayashi 1961

Hydrostatic, fully convective

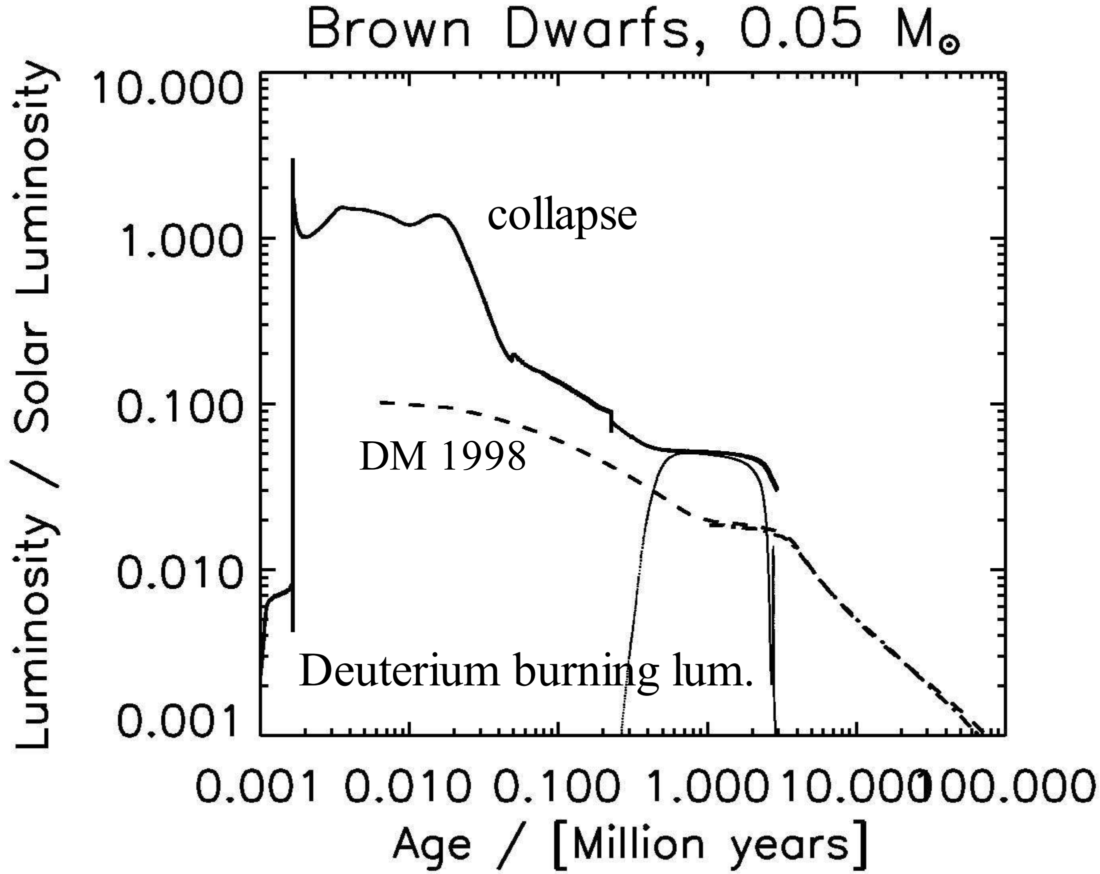


Burrows et al. 1993/97

Solar mass: Collapse vs. Static



Collapse towards a brown dwarf

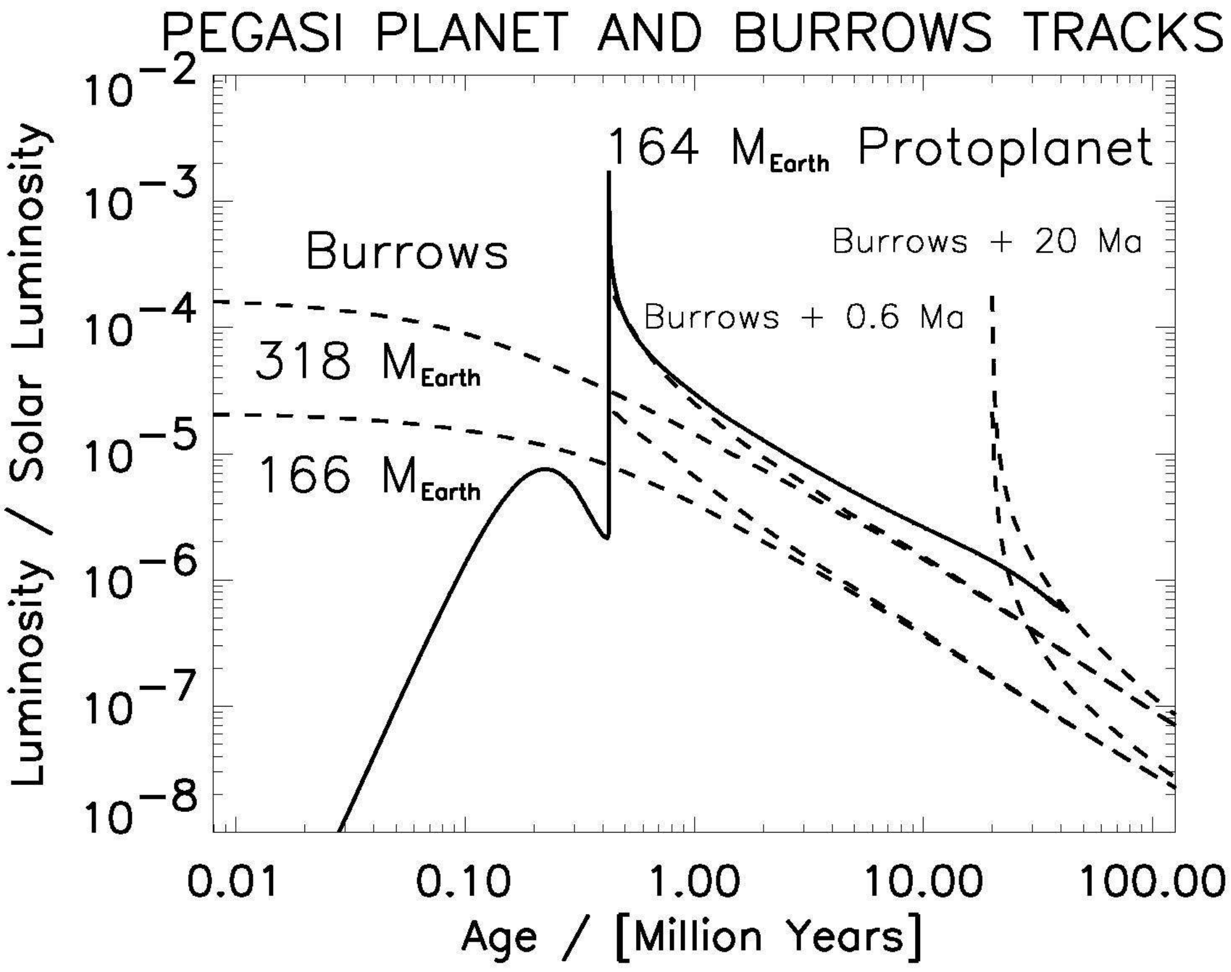


Collapse after „From Clouds to Stars“, Wuchterl and Tscharnuter 2003, A&A

Evolution of young brown dwarfs

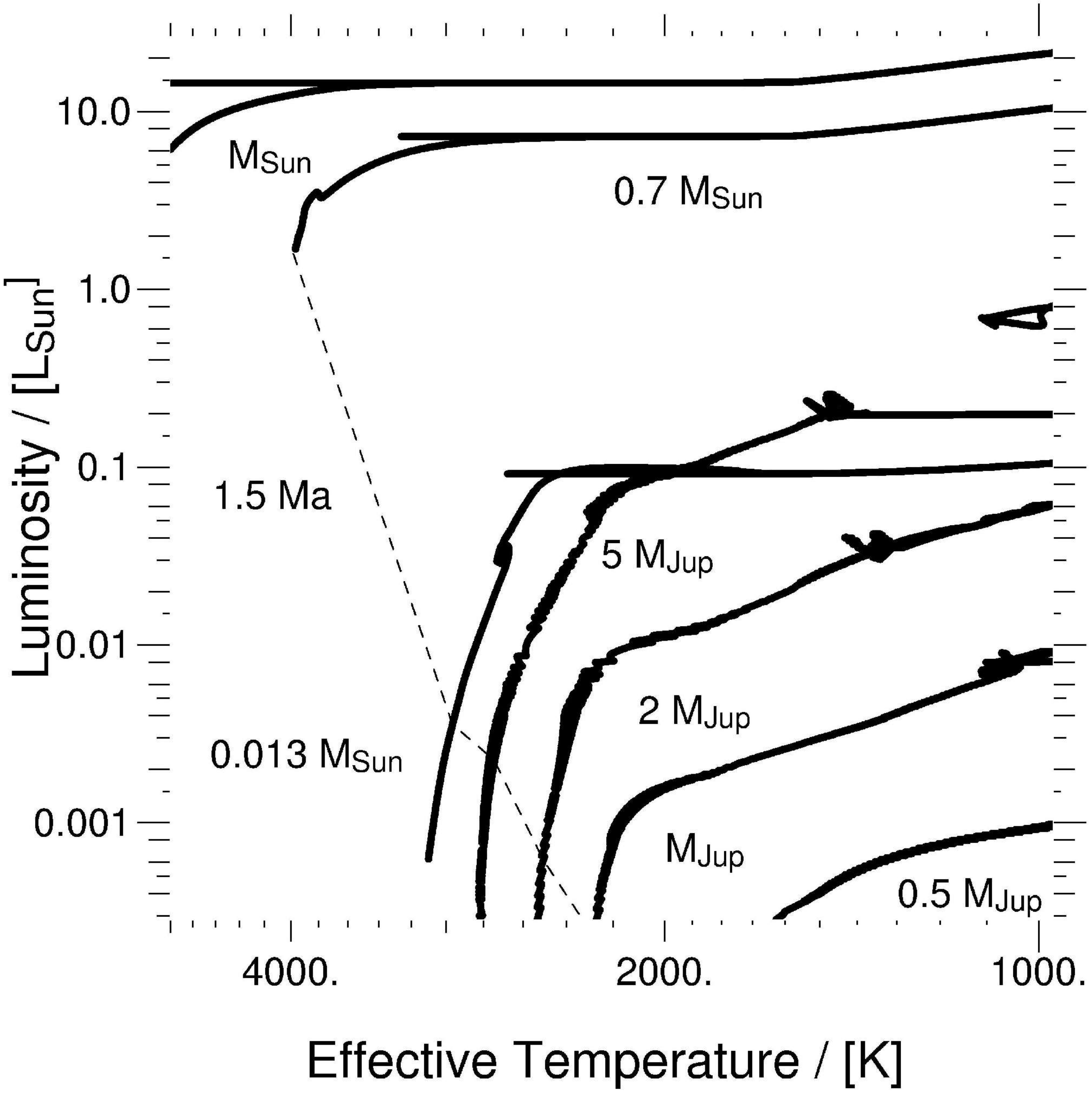
- Collapse results in radiative core
- D-burning starts in shell-source
- 100% of luminosity – „D-main-sequence“?
- D-burning makes brown dwarfs fully convective
- Approach to fully convective, static evolutionary „Hayashi“ tracks at 10 Ma

Collapse formation-dynamics vs. hydrostatic and hot

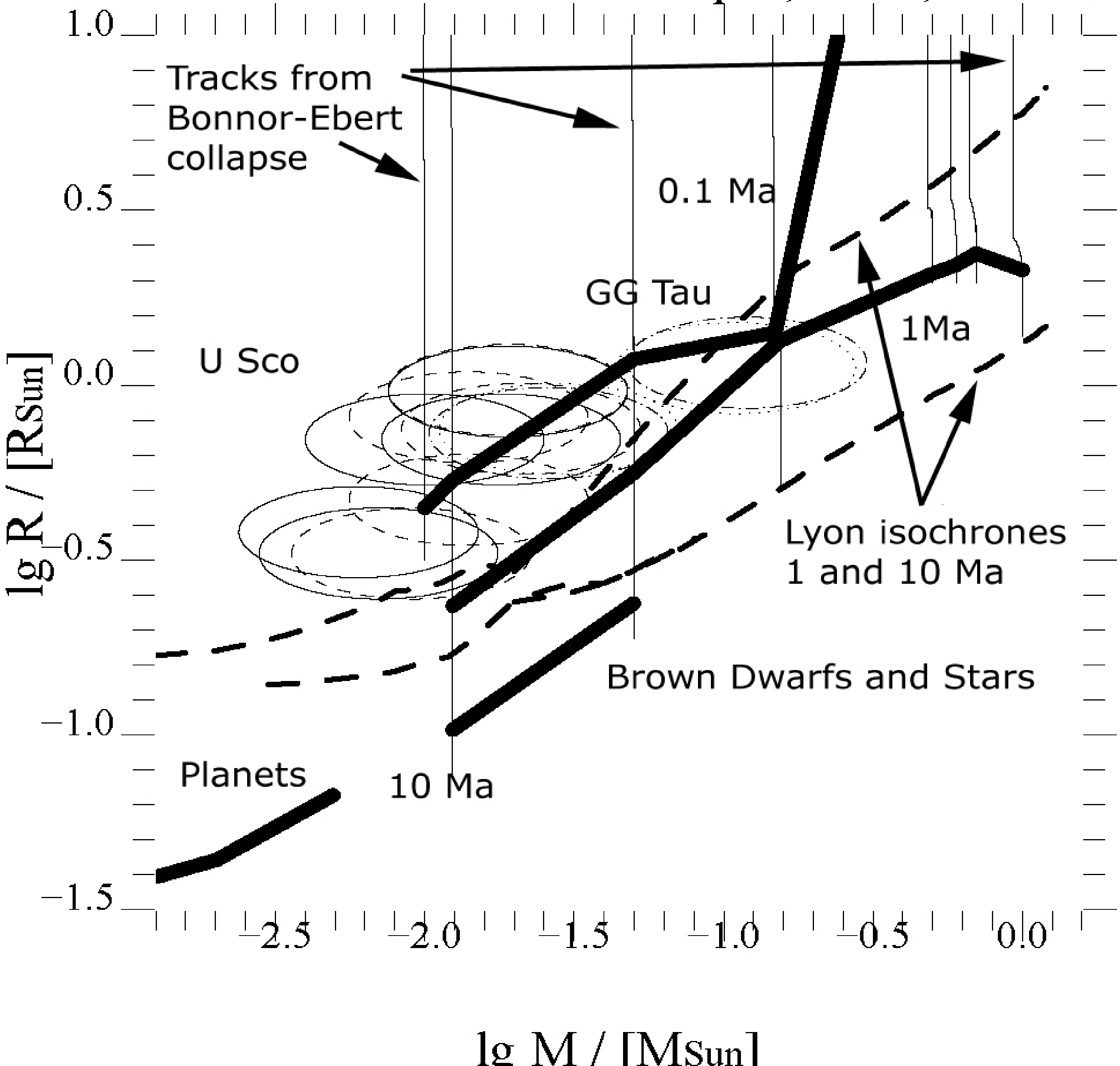


Putting it all together

Evolution of Substellar Objects and GQ Lupi's planet



Mass−Radius relations: collapse, static, observed



Accretion thermal profile controls early evolution

- Off- center temperature maximum leads to radiative core + convective envelope,
- D-burns in a shell,
- Depending on mass, D burns:
  + During accretion for stars,
  + At final mass for brown dwarfs,
  + “Delayed” for low mass brown dwarfs.

A note on the gap to planets

- Bonnor-Ebert collapse changes qualitatively between 10 and 5 Jupiter masses,
- First cores stay around and hesitate to collapse (opacity limit),
- Objects up to 5 Jupiter masses form easily the planet way: core first, then envelope capture.

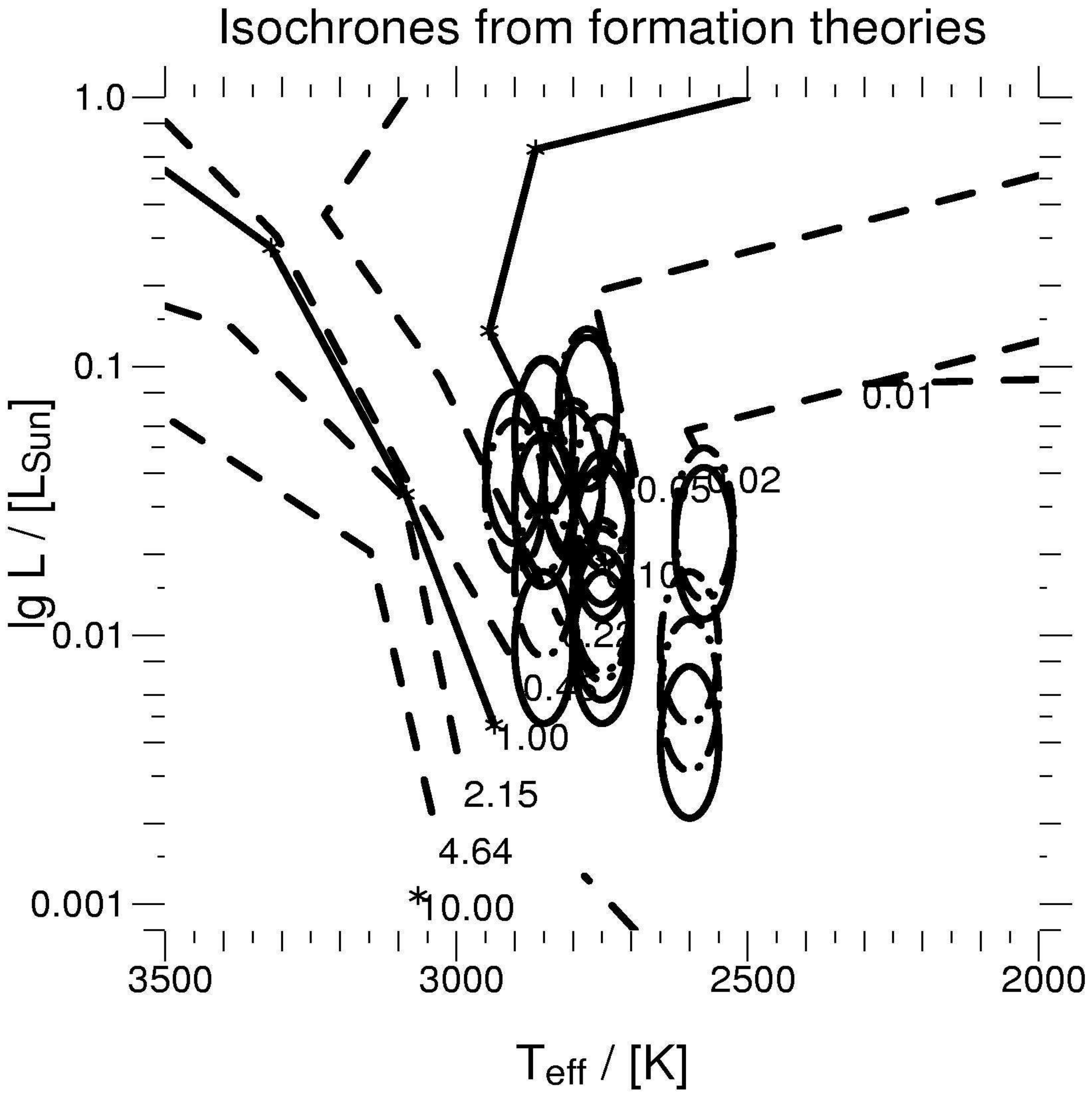
Collapse controlled early evolution

Observational Consequences

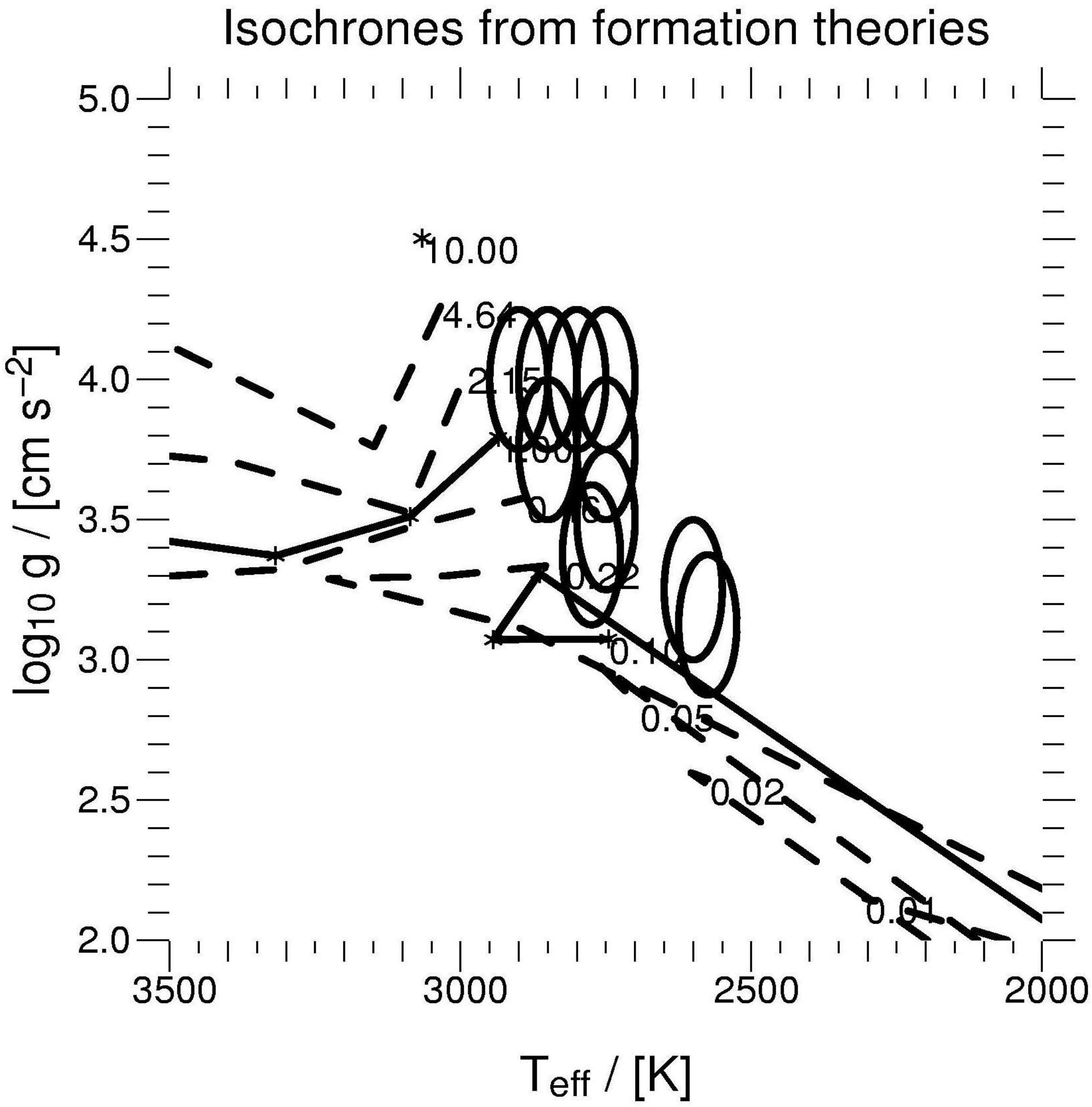
- No “birthline” for stars,
- Brief D-main sequence for intermediate mass brown dwarfs,
- Deuterium burning amplifies the effects of accretion by modulating early contraction,
- Thus leading to an observationally noticeable shift in the D-isochrone-feature between collapse and static tracks.

Bonnor-Ebert vs. fragmentation

- Differences in embedded phases
- More luminous at appearance
- After 1 Mio years: agreement
- But differences to the static picture
- Deuterium burnt
- Core radiative
- Twice as bright, 500 K hotter



HRD
Bonnor-Ebert
Isochrones
+
Basri-Mohanty
Properties



Kiel
Bonnor-Ebert
Isochrones
+
Basri-Mohanty
Properties

Hayashi was right ....

... for brown dwarfs only.