CONVECTION IN STARS

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OUTLINE

Part I

- Solar and stellar convection
- Astrophysical interest in convection

Part II

- Convection in A stars
- Simulations and models of convection
- Applications of such models for A stars

Solar and Stellar Convection I

- **Turbulent convection (Re, Ra $\gg$ 1)**
  - fluid stratified by gravitational force (top-bottom)

    $$\rho_{top} < \rho_{bottom}$$

  - heating at bottom and/or cooling at top

    $$T_{top} < T_{bottom}$$

  - consider small vertical ("upwards") perturbation
    - ➔ if ρ(displaced fluid) $<$ ρ(*environment*)
    - ➔ **buoyancy driven instability**
      (unstable due to 'large' ∇ T)

criterion first derived by K. Schwarzschild (1905)

$$\nabla > \nabla_{\mathbf{ad}}$$

Solar and Stellar Convection II

Stratoscope observations of solar granulation

M. Schwarzschild, ApJ 130, 345 (1959)

R.B. Leighton, ARA&A 1, 19 (1963)

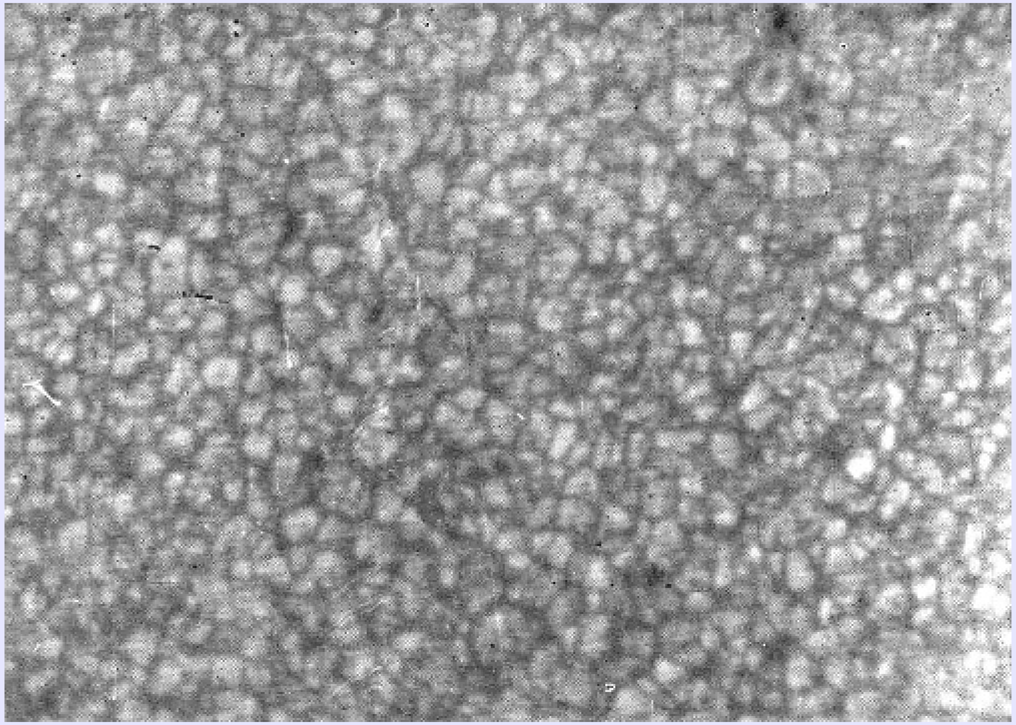


Fig. 1 upper part: frame 290, 25 Sep 1957

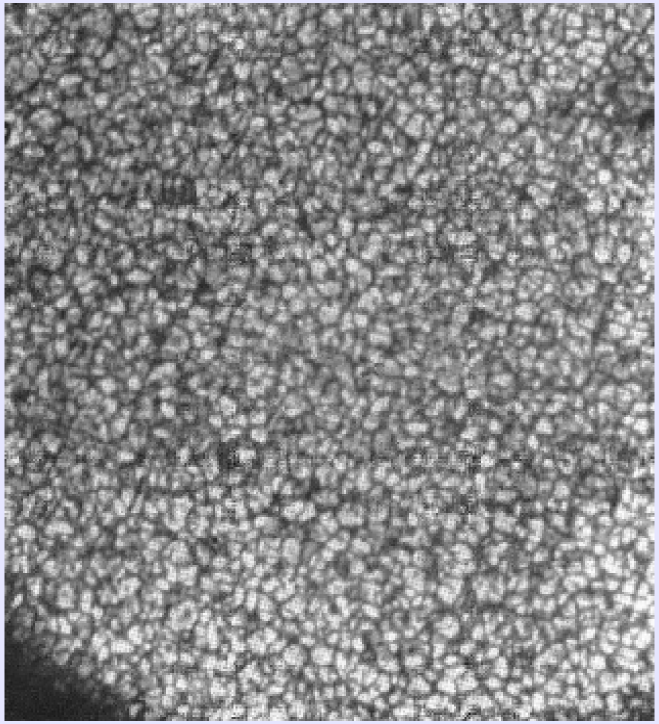


Fig. 1: frame 4759, 17 Aug 1959

Solar and Stellar Convection III

- **Convective instability in stars** ($\nabla > \nabla_{ad}$)
  - $\nabla_{rad} = (3\kappa_{ross} P L_r) / (16\pi a c G T^4 M_r)$
    - P=pressure, L_r=luminosity(r), M_r=mass inside radius r, T=temperature, κ_{ross}=Rosseland opacity
  - high opacity (ionisation of H I, He I/II, "Fe-peak")
    - in the sun and other cool stars
  - partial ionisation ➔ low γ (Unsöld 1931: solar H I zone)
  - high luminosity ($\varepsilon_c = dL_r/dM_r \sim L_r/M_r$ for small M_r)
    - in massive (hot) stars

  ➔ steep ∇ T (interacting with ∇_μ ➔ semi-convection)

  ➔ convective instability

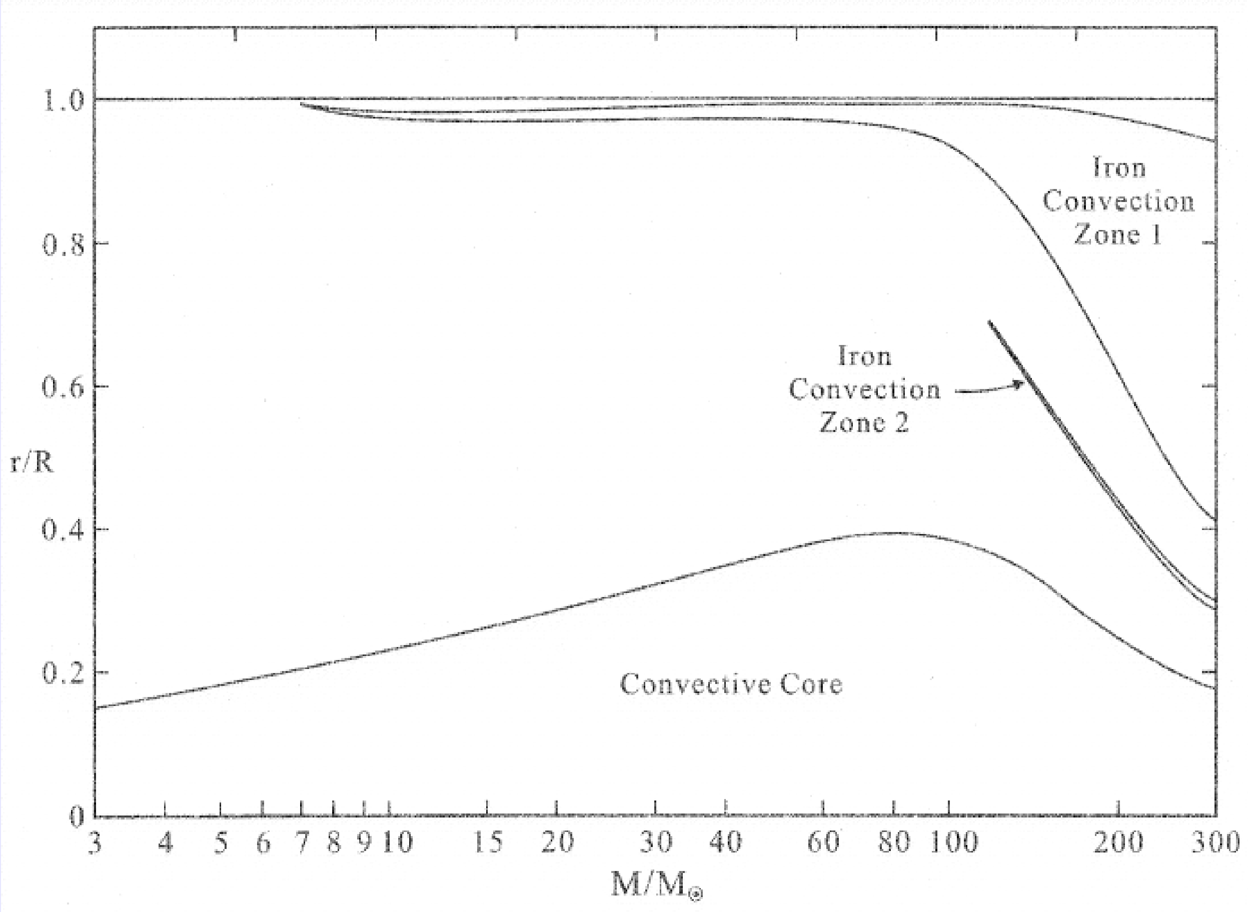
Solar and Stellar Convection IV

Massive stars at MS

Core convection beginning at ~ 1.2 $M_\odot$

opacity caused Fe convection zones

R.B. Stothers 2000, ApJ 530, L103



Solar and Stellar Convection V

- **Physics of stellar convection**
  - radiative losses, “low” viscous friction (very low $Pr=\nu/\chi$)
  - no boundary layers, “external” forces: **g**, magnetic field **B**
  - mean velocity gradient ∇ U (shear): rotation, pulsation
  - mean molecular weight gradient (Ledoux 1947: $\nabla - \nabla_{ad} > \nabla_{\mu}$)
    - Schwarzschild & Härm (1958): semi-convection (diffusive conv.)

      $\nabla > \nabla_{ad}$ “unstable” $\qquad \nabla_{\mu} > 0$ “stable”

      ➔ core convection of massive stars: $\nabla - \nabla_{ad} > (K_c/K_h)\, \nabla_{\mu}$
    - Stothers & Simon (1969), Ulrich (1972): salt-fingers (inverse μ-gradient, thermohaline conv., Stern 1960) ➔ CT1

      $\nabla < \nabla_{ad}$ “stable” $\qquad \nabla_{\mu} < 0$ “unstable”

      ➔ binary mass transfer, shell burning: $|\nabla_{\mu}| > (K_h/K_c)(\nabla_{ad}-\nabla)$

Astrophysical Interest I

Main effects of convection

– heat transport; mixing mechanism; couples to mean flow, **B**

Convective heat transfer influences

through temperature gradients, surface inhomogeneities

- emitted radiation, stellar atmospheres
  - photometric colours, line profiles, chromospheric activity
    ➔ uncertainty of secondary distance indicators
    (adding to the one already introduced by primary standards)
- stellar structure, stellar evolution
  - pre-main sequence tracks & post-main sequence evolution
  - main sequence location (stellar radii)
    ➔ mass determination, interpretation of observed HRD

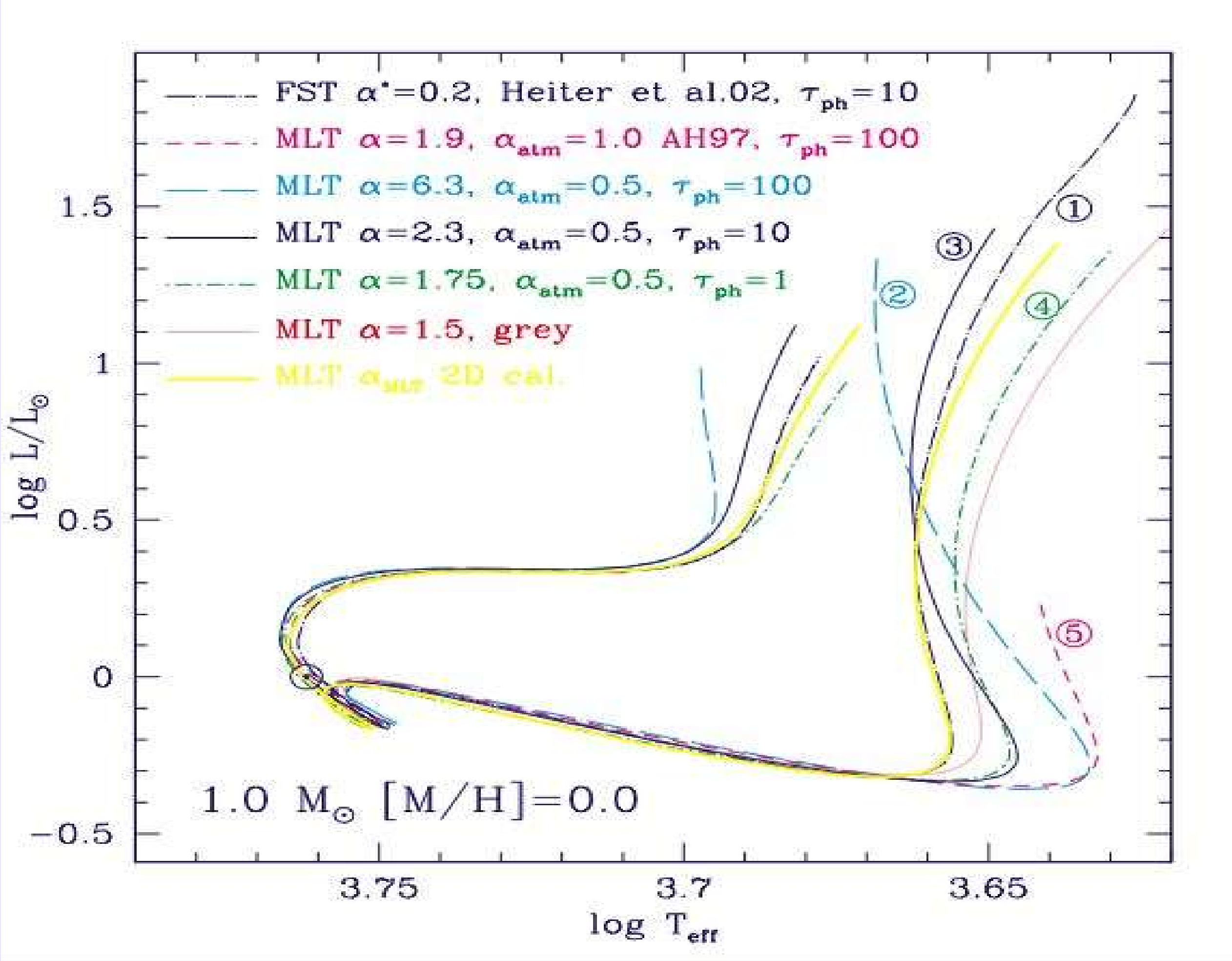
Astrophysical Interest II

Solar radius

T_{eff} along PMS and RGB

Solar models which "match" the present sun differ along its evolutionary track !

Montalbán et al. 2004, A&A 416, 1081

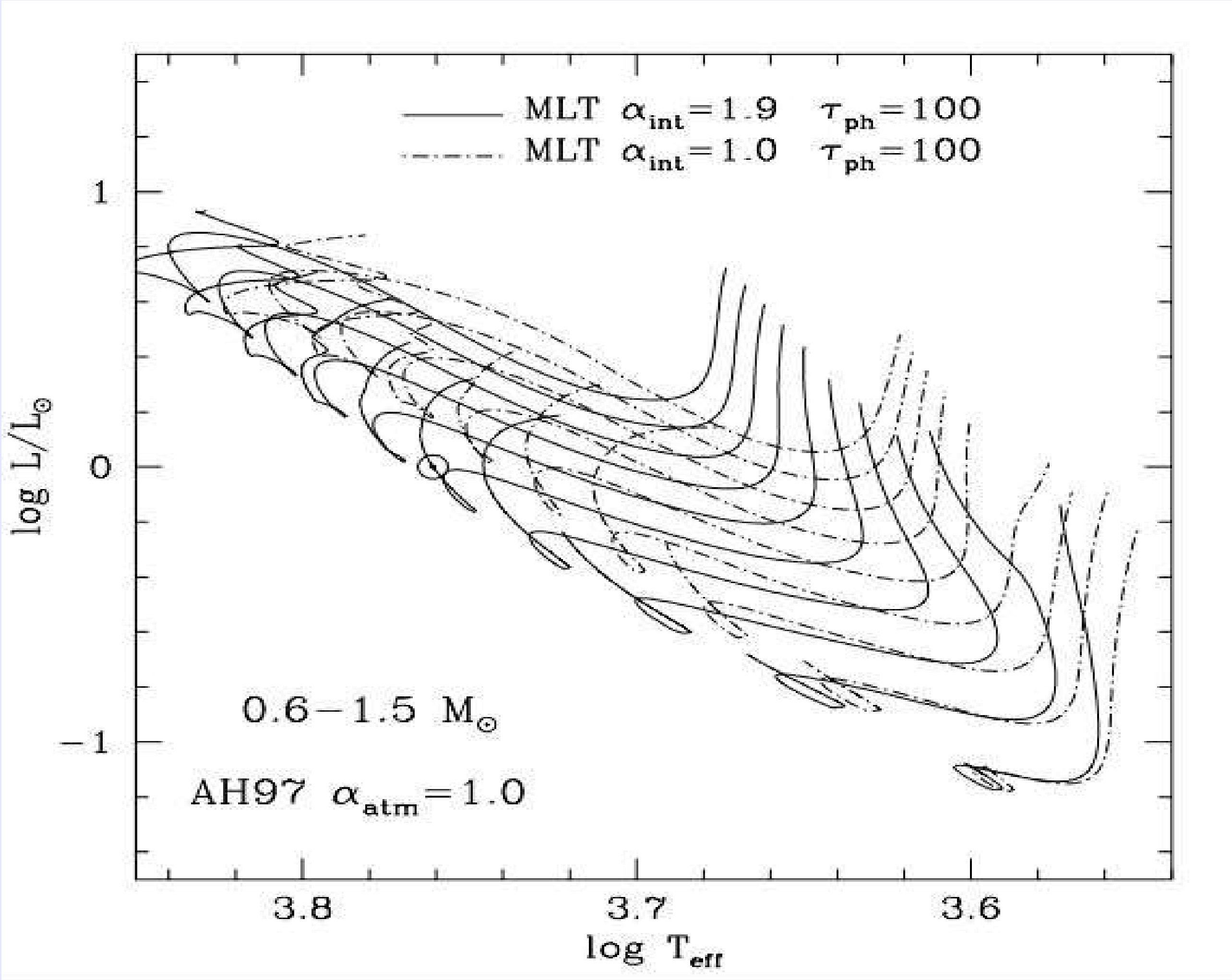


Astrophysical Interest III

PMS tracks

different convective efficiencies influence

- ZAMS location / radii
- PMS track shapes
- determined PMS masses



Montalbán et al. 2004, A&A 416, 1081

Astrophysical Interest IV

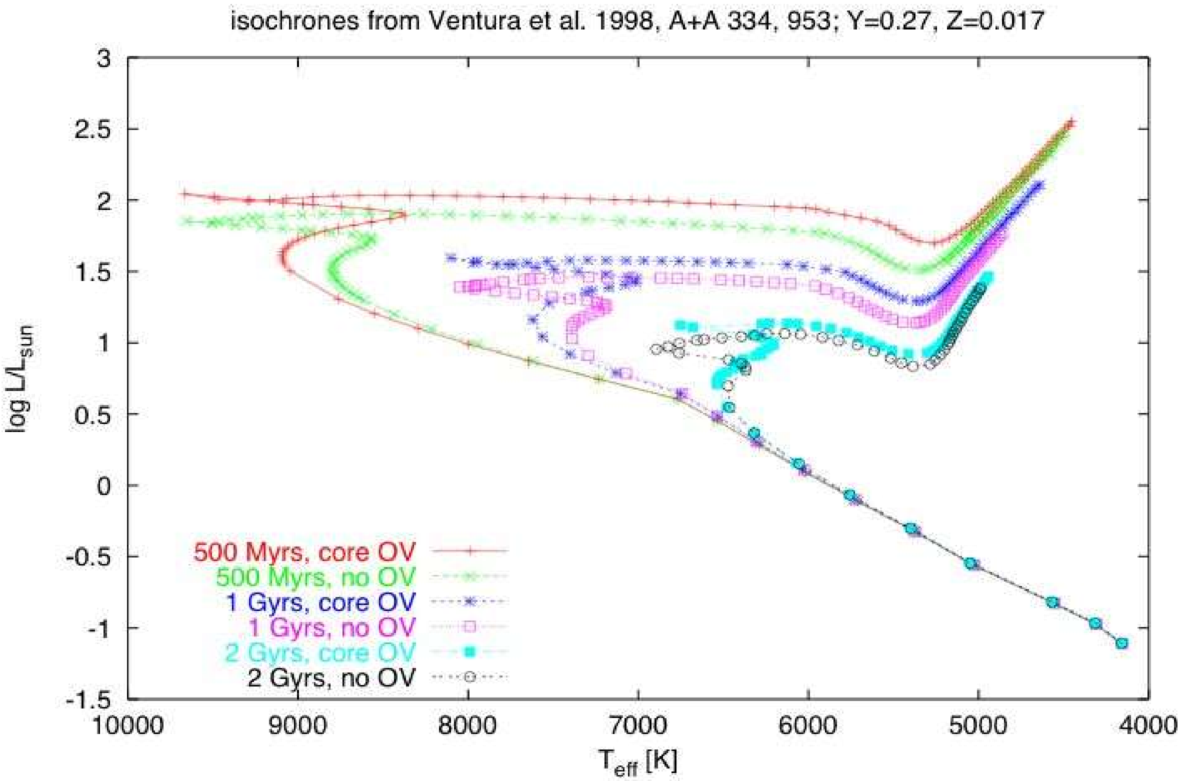
Convective mixing influences

via overshooting, semi-convection, concentration gradients

- evolution of convective cores ➔ stellar lifetimes
- chemical composition
  - convection zone depth and mixing: destruction of ^{7}Li ($T_b \sim 2.5 \times 10^6$ K)
- late stages of stellar evolution
  - H/He shell burning in final "LTP/VTLP" phases
    ➔ white dwarf returns to AGB structure (Sakurai's object)
  - structure and composition of progenitors of supernovae
    ➔ initial conditions for SN simulations
    - effects cosmological distance indicators, production of heavy elements, final fate of exploded / collapsed star, ...

Astrophysical Interest V

Main sequence life times / turn off



Effect of core OV (overshooting)

Galaxy evolution simulations for ages 0.5 – 2 Gyrs

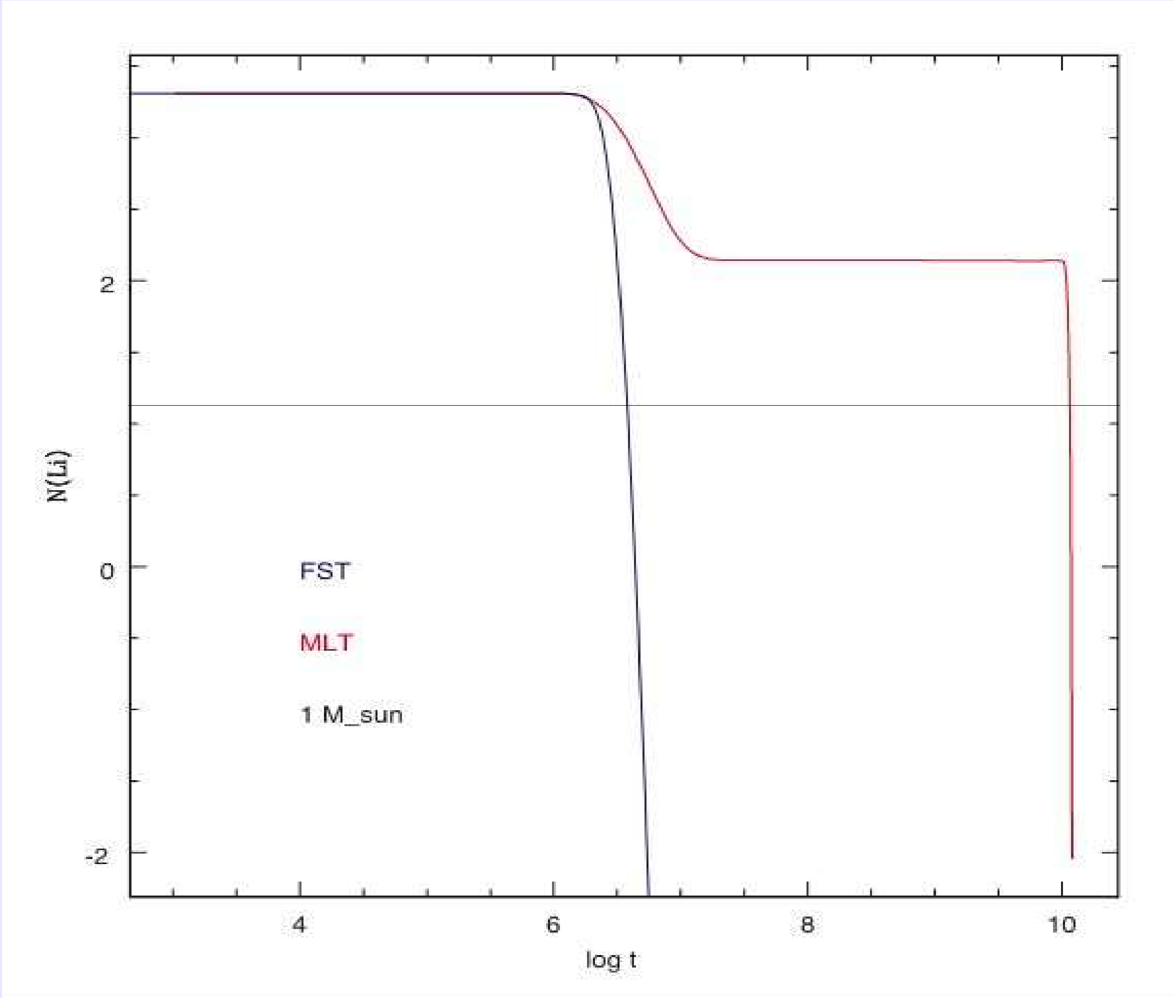
Astrophysical Interest VI

Li and Be abundances

[7]Li destruction due to mixing at and beyond the bottom of a deep convection zone

solar twin problem

Based on calculations by F. D'Antona, J. Montalbán 2003, A&A 412, 213



Astrophysical Interest VII

Coupling to mean fields (velocity, magnetic)

- **excitation and driving of pulsation**
  - **studied through non-linear pulsation calculations and asteroseismology**
- transport of angular momentum ➔ talk BIL1
  - stellar rotation rates ➔ effects on stellar evolution
- magnetic dynamos
  - solar / stellar activity ➔ chromospheric / coronal activity
    ➔ influence on solar / stellar wind
- solar cycle: 11 / 22 yr cycle, longterm cycle evolution

Astrophysical Interest VIII

Angular momentum transport in the sun

Helioseismological results on internal rotation rates ➔ L-transport
(Figure from P.A. Gilman 2000, Sol. Phys. 192, 27)

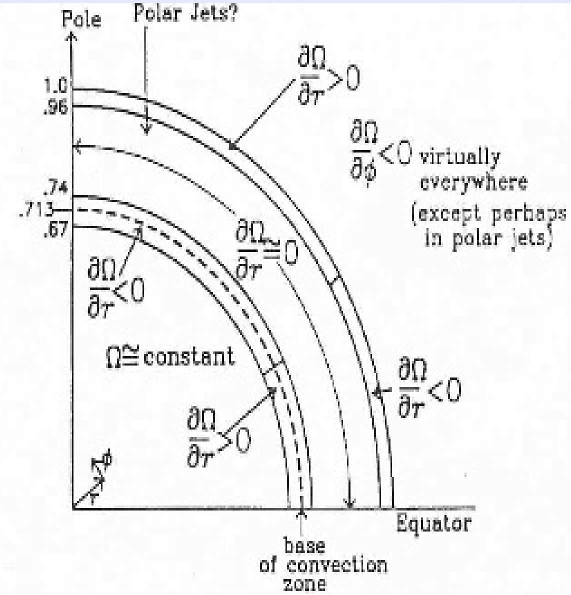


Figure 1. Schematic summary of latitudinal and radial gradients in rotation that have been inferred from helioseismic measurements.

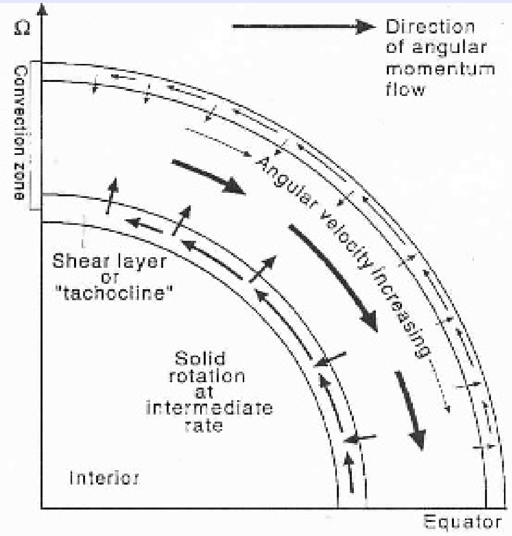
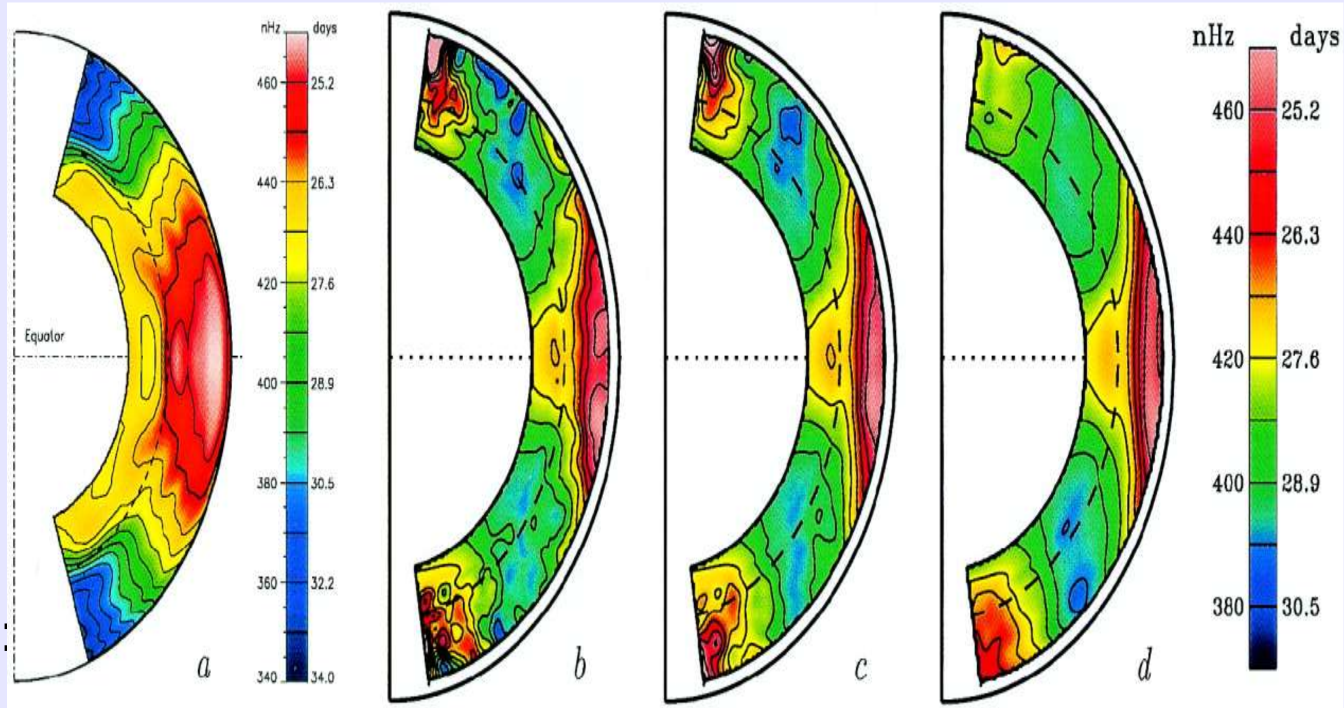


Figure 2. Schematic of the probable flow of angular momentum in the convection zone, tachocline, and photosphere that is consistent with, and may be responsible for, the rotation gradients summarized in Figure 1. Not shown are arrows depicting angular momentum being returned to high latitudes from low latitudes within the convection zone, by motions other than the convective drivers responsible for the equatorward transport.

Astrophysical Interest IX

Longitudinally averaged angular velocity profile



a) seismological "inversion" based on GONG satellite data

b-d) LES time averages: 1 time step, 1 rotation and 10 rotation periods

(M.S. Miesch et al. 2000, ApJ 532, 593)

Astrophysical Interest X

Sun spots

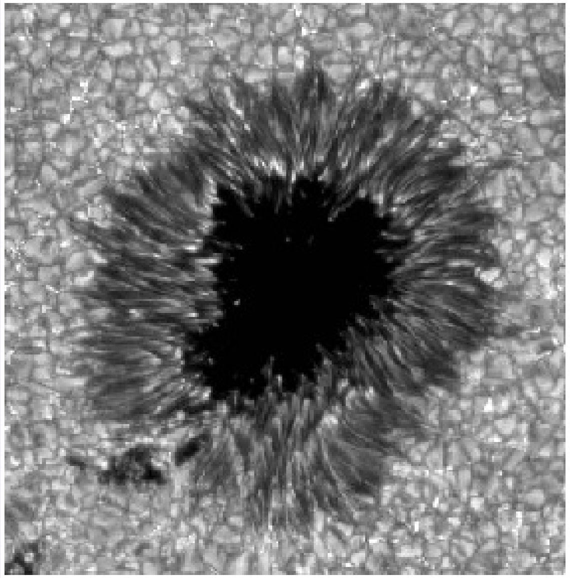
Figure: S.K. Solanki,
A&AR 11, 153 (2003)

L. Biermann
(1938, 1941)

T.G. Cowling
(1938, 1953)

→ convective
inhibition

Do magnetic fields always inhibit convection ?



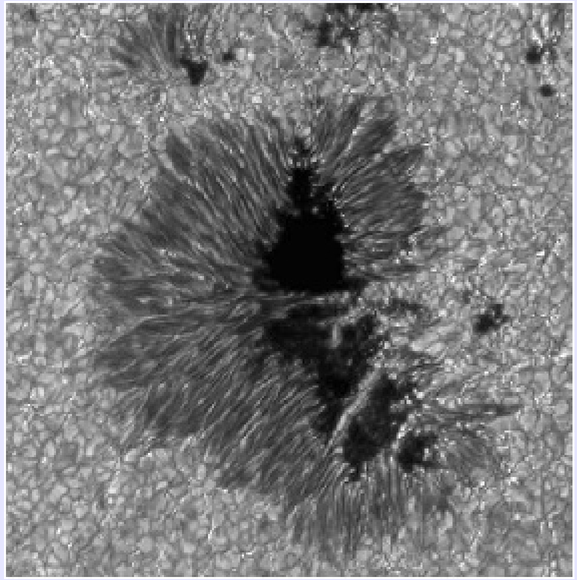


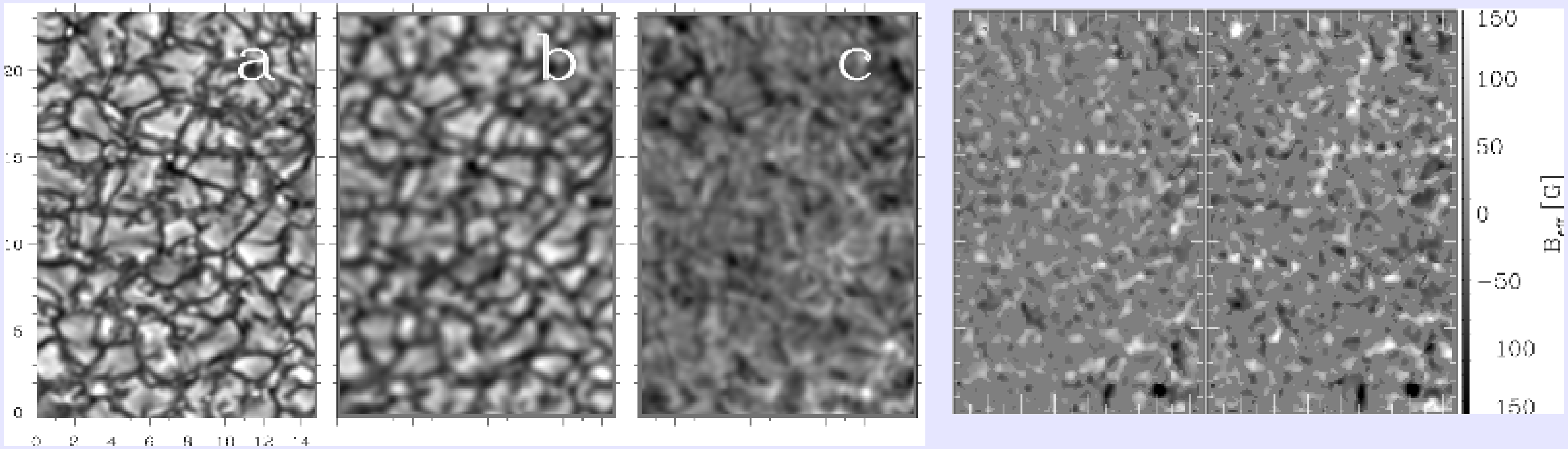
Fig. 1.1. Images recorded in a roughly 10 Å wide band centred on 4306 Å (g-band) of a relatively regular sunspot (*top*) and a more complex sunspot (*bottom*). The central, dark part of the sunspots is the umbra, the radially striated part is the penumbra. The surrounding bright cells with dark boundaries are granular convection cells. The upper sunspot has a maximum diameter of approximately 30000 km, the lower sunspot of roughly 50000 km (upper image courtesy of T. Berger; lower image taken by O. von der Lühe, M. Sailer, T. Rimmele).

Astrophysical Interest XI

Observations of intergranular network

Fields of 50..150 G in magnetograms of intergranular lanes
of quiet solar regions (Domínguez Cerdeña et al. 2003, A&A 407, 741)

a – broad band, b – narrow band continuum; c, left plot: Fe I 6302.5; right: Fe I 6301.5



D.O. Gough, R.J. Tayler 1966, MNRAS 133, 85

Analytical stability results for several configurations with a vertical field component ➔ damping for field strengths > few kG

Convection in A stars I

- **Convection zones in A stars**
  - Existence of photospheric convection due to low γ (H I ionisation) predicted in 1933 by H. Siedentopf (Astron. Nachr. 247, 297)
- **Spectroscopic evidences**
  - Balmer line profiles (& photometry) ➔ talk CIL1
  - line bisectors
  - line profiles (R >70000, v sin(i) < 10 km/s, ➔ poster CP2)
  - chromospheric activity indicators (observed with FUSE) (disappear at T_{eff} ~ 8300 K for MS, Simon et al.2002, ApJ 579, 800)

➔ photospheric, convective velocity fields exist in A/Am stars (➔ topology fa: filamentary, ascending)

Convection in A stars II

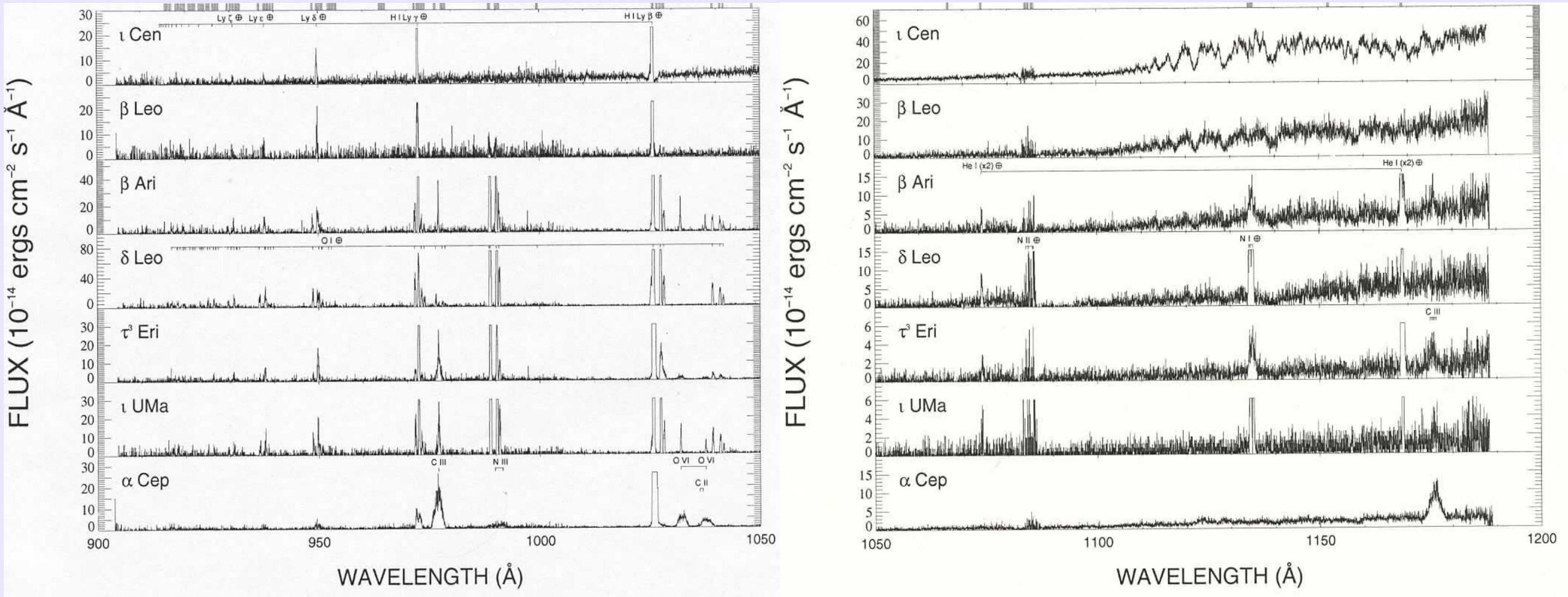


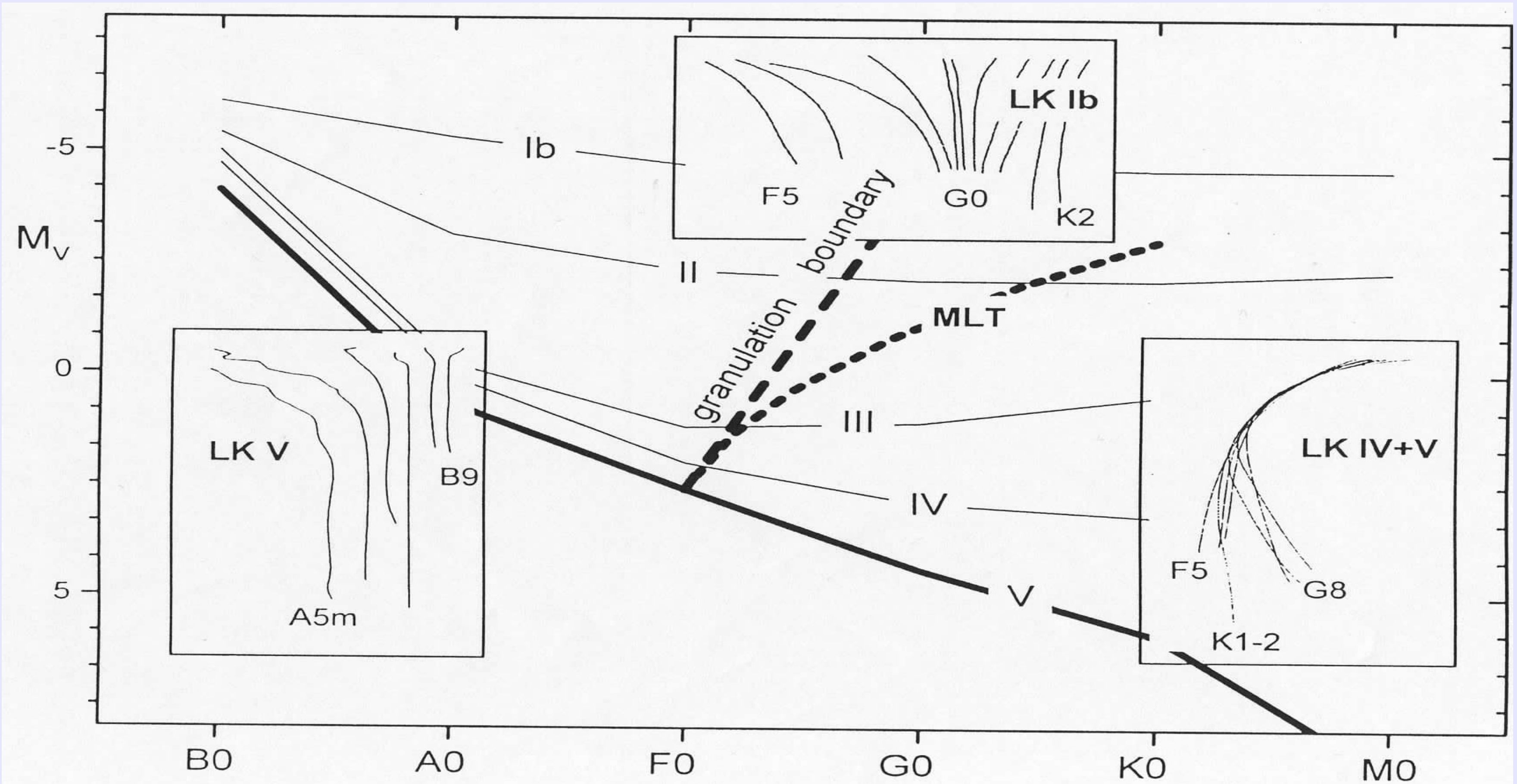
TABLE 1

STARS OBSERVED BY *FUSE*

Name	HD	HIP	Spectral Type	$v \sin i$ (km s^{-1})	V	$B-V$	π (mas)	M_v	$L_{bol}/L_\odot$	β	$b-y$	T_{eff} (K)
ι Cen	115892	65109	A2 Va	75	2.75	0.05	55.64	1.48	20.1	2.901	0.004	8630
β Leo	102647	57632	A3 Va	115	2.14	0.09	90.16	1.92	13.0	2.899	0.043	8590
β Ari	11636	8903	A4 V	70	2.64	0.13	54.74	1.33	21.9	2.879	0.059	8400
δ Leo	97603	54872	A4 IV	180	2.56	0.12	56.52	1.32	22.1	2.869	0.067	8300
τ^3 Eri.........	18978	14146	A4 V	120	4.09	0.16	37.85	1.98	12.0	2.858	0.091	8210
ι UMa	76644	44127	A7 IVn	140	3.14	0.19	68.32	2.31	8.8	2.843	0.104	8060
α Cep	203280	105199	A7 Vn	205	2.44	0.22	66.84	1.57	17.6	2.807	0.127	7840

Convection in A stars III

Line bisectors (data by D.F. Gray, J.D. Landstreet, as in Weiss & Kupka 1999)



Convection in A stars IV

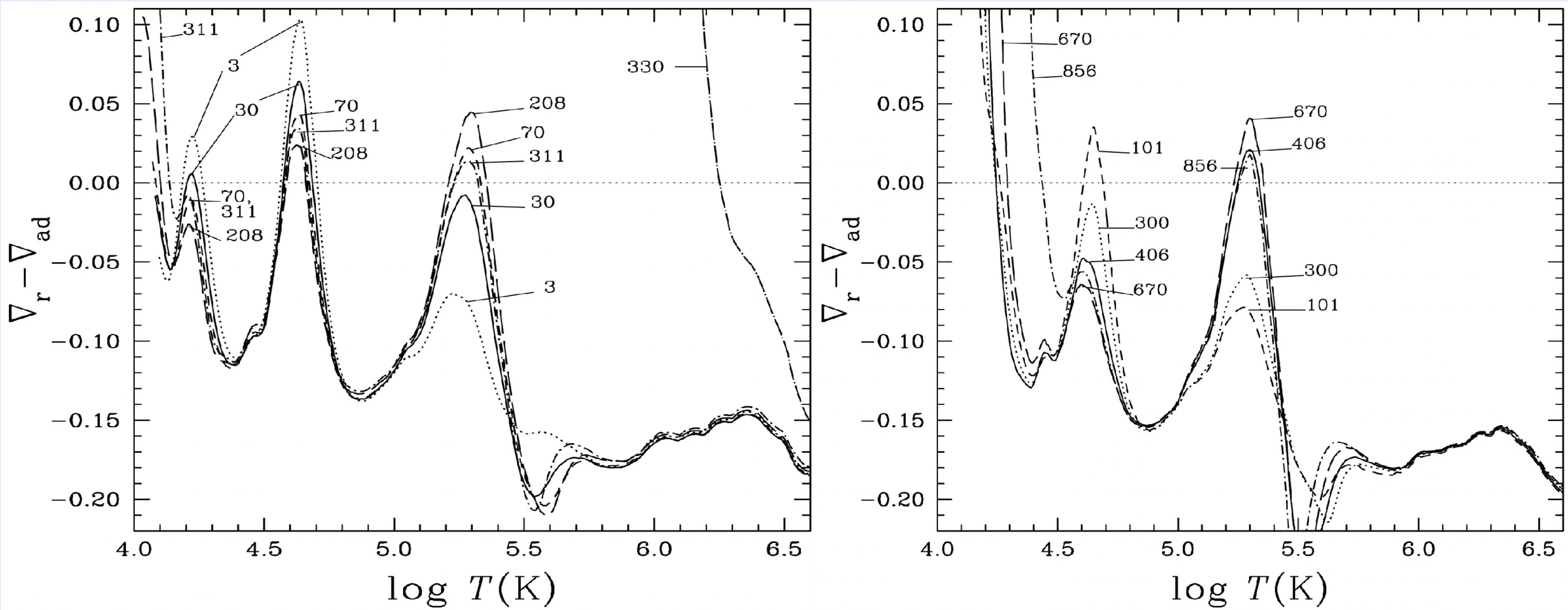
- **Envelope convection**
  - photospheric H I convection zone
    - opacity caused (+ γ-effect), gradually disappears for late B stars
    - surface velocity fields, effects on colours for late A stars
    - suppression due to strong magnetic fields ?
  - internal He I and He II convection zone
    - primarily a γ-effect, very weak (particularly He I)
    - He depletion → zones can disappear
  - Fe-group convection zone(s)
    - require(s) diffusion to accumulate enough Fe-peak ions

→ diffusion calculations and predictions (→ session D)

Convection in A stars V

Envelope convection zones in Am stars

Richer et al. 2000, ApJ 529, 338; Figures below: 3 $M_\odot$ and 2 $M_\odot$



Convection in A stars VI

- **Convective cores**
  - point of onset around 1.2 $M_\odot$
  - convective overshooting
    - cluster colour distribution
    - observational indicator: binary pairs MS turnoff
    - internal composition, evolution at late stages
  - influence of rotation ? (likewise for envelopes !)

    ➔ simulations presented in CT2
  - Possible dynamo mechanism ?

    ➔ simulations presented in CT2

Convection in A stars VII

- **Convective cores**

(figures courtesy I.W. Roxburgh)

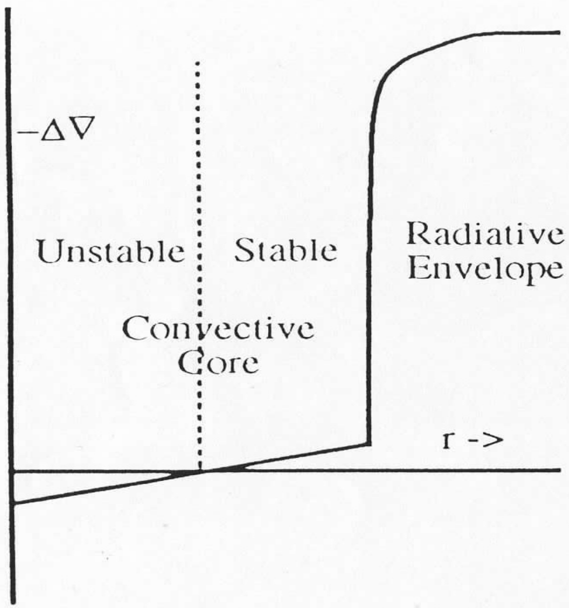


Fig. 1. Variation with radius of the superadiabatic gradient $\Delta\nabla$ in a Cowling model with overshooting. In the overshoot region $\Delta\nabla$ remains small and negative before adjusting to large negative values.

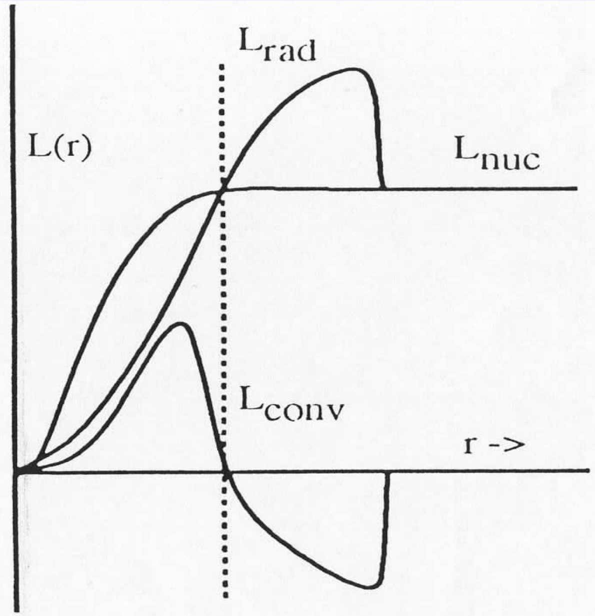


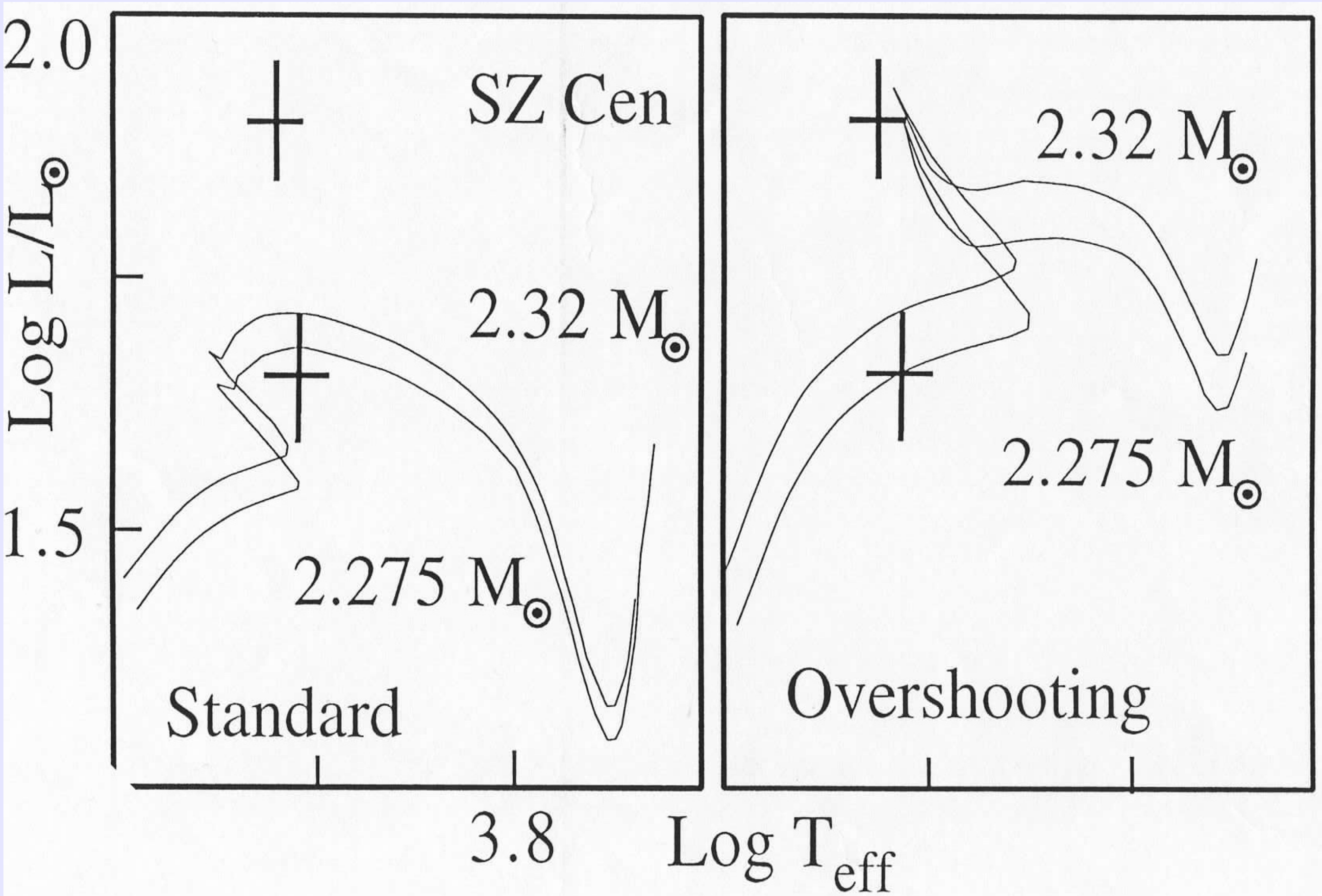
Fig. 2. Variation with radius of the luminosities L_{rad}, L_{conv}, and the total luminosity L_{nuc}. L_{conv} goes negative in the overshoot region so that L_{rad} exceeds the total luminosity L_{nuc}.

Convection in A stars VIII

Matching of binary pairs near turn off

implications on overshooting of convective cores

(figure courtesy I.W. Roxburgh)



Simulations and Models I

Why not "just solve Navier-Stokes equations" for stars ?

- **Problem P1: High Re number flows**

	Sun	Earth (PBL)	Oceans (circulation)
L	~ 180,000 km	~ 1 km	~ few 10^3 km
l_d	~ 1…10 cm	~ 1 mm	~ 1 mm
Re	~ 10^{10}... 10^{14}	~ 10^8	~ 10^{12}
Pr	~ 10^{-6} ... 10^{-10}	~ 0.7	~ 6

- **Problem P2: long time scales involved**
  Sun: few sec - minutes - 1 month - ~10^6 a
  Oceans: ~0.1 sec - few decades - > ~10^2 a

Simulations and Models II

- **Averages**
  - volume average interpretation of *f(t,x,y,z)* to compute most important length scales

    ➔ Large Eddy Simulations (LES)

    (numerical simulations with realistic microphysics)

    A-Stars: ➔ CIL2, CT2, CT3
  - ensemble average interpretation of *f(t,x,y,z)* to compute *<f(t,x,y,z)>*, ...

    ➔ Convection (& Turbulence) Models

    ➔ F_{conv} (heat flux), P_{turb} (turbulent pressure), v_{rms} (flow velocity)

    No rigorous theory exists for this approach ! ➔ CKNS, CP1

Simulations and Models III

Solar Convection Zone Physics

- quasi-stationary convective shell in a rotating sphere
  - density stratification: ~(0.2 / 3.2×10^{-7}) ~625,000:1
  - temperature stratification: ~(2.15×10^{6} / 6200) ~350:1
  - depth ~ 30% of solar radius, Ma ~ 10^{-4}
  - Ro ~ 0.1, differential rotation ➔ magnetic fields, solar cycle & activity
- size of granulation structures at the surface ≪ r:
  D ~ 1100 km ➔ ~2 million granules on solar surface
  - $v_{conv} \sim 0.3\, v_{sound}$ (~ 2...3 km s^{-1}), Ro ~ 300 ➔ rotation effects indirect
  - cooling of gas at the surface (radiation into space)
    ➔ convective instability due to large ∇ T
    ➔ *cooling from above* ➔ downwards sinking "drafts"

Simulations and Models IV

LES simulation:

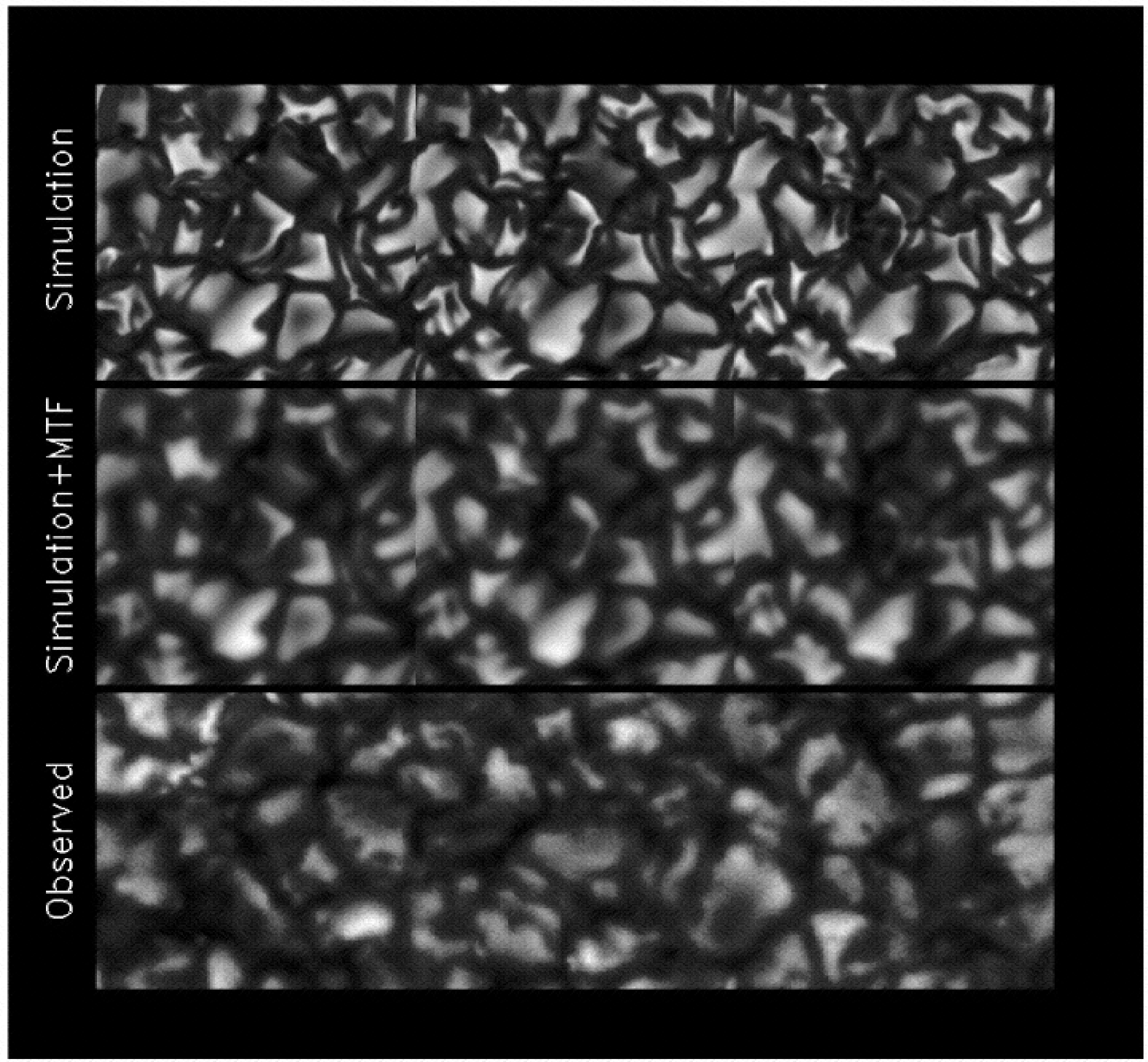
R.F. Stein, Å. Nordlund
Astrophys. Jour. 499, 914 (1998)

resolution: 253 × 253 × 163
(6 Mm × 6 Mm × 3 Mm)

intensity at CH G band (visual)
smoothed with telescope
modulation transfer function

Observations:

La Palma Swedish
Vacuum solar telesope,
3 slides
separated by 1 min each



Simulations and Models V

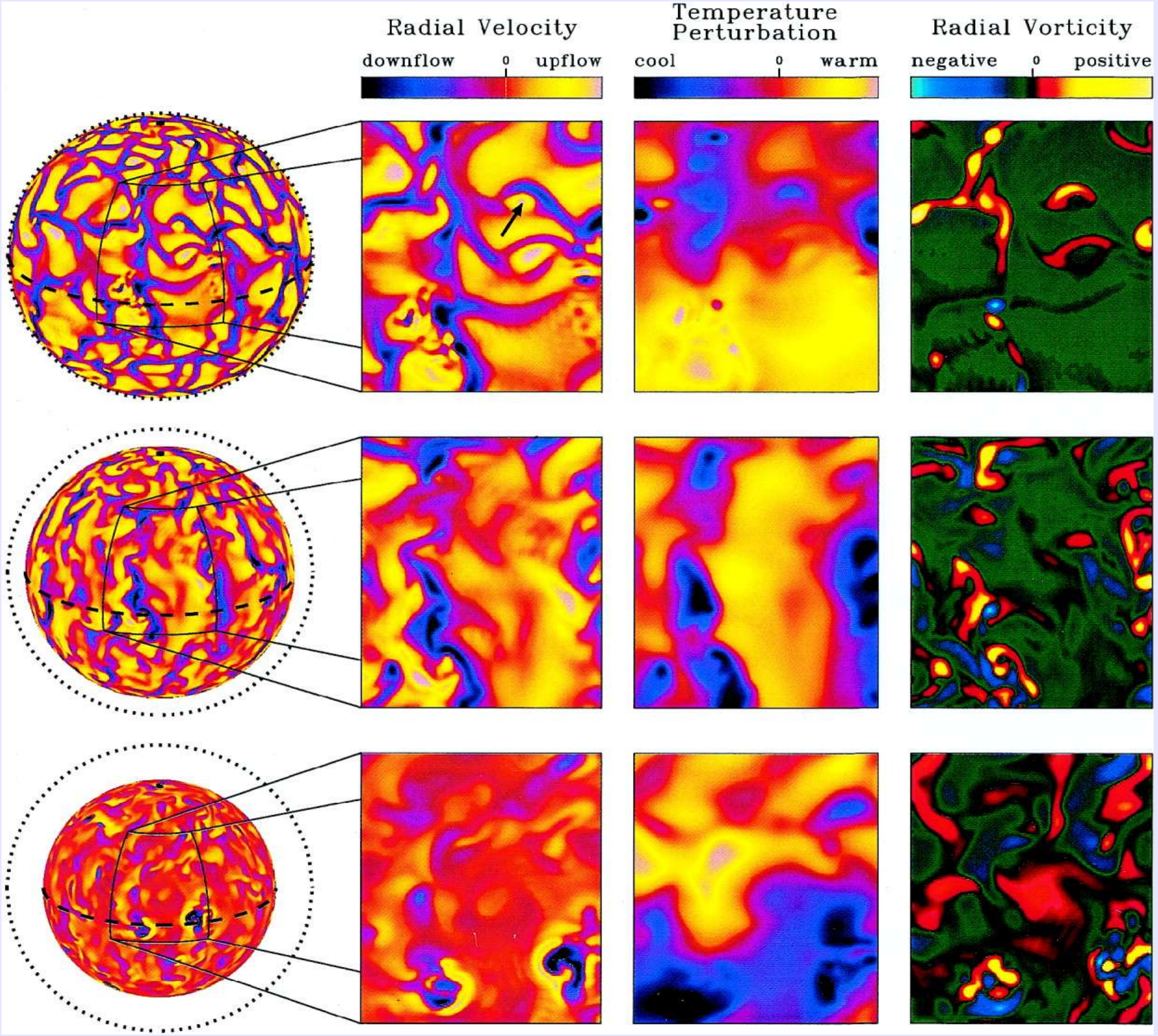
LES simulation:

M.S. Miesch et al.
ApJ 532, 593 (2000)

$98 \times 256 \times 512$ (r,θ,φ)
$0.62\ R_{sun} - 0.96\ R_{sun}$

top row: upper zone
mid row: centre
bottom: overshooting

Note varying colour scale!



Simulations and Models VI

Drawbacks of the simulation approach

- too high computational costs (CFL ~ u_{flow}, c_{sound}) for
  - integral properties (GAIA survey: spectra for millions of stars)
  - models of complete physical systems: the sun, cluster of stars, and their long term evolution
- for realistic flows: uncertainties due to
  - small scale properties: particularly in case of shear flow and/or convectively stable stratification (overshooting)
  - boundary conditions / configurations (magnetic field...)
  - idealised microphysics and filtering methods introduced to make simulations of stellar interiors convection affordable
- statistical interpretation ➔ long run time / many runs

Simulations and Models VII

Drawbacks of the modelling approach

– if tested for one type of flow and a range of Re, Pr,...

➔ *it may not work for other cases !*

– homogeneous turbulence: rather general model exists

(V.M. Canuto & M.S. Dubovikov, Phys. Fluids 8, 571 (1996))

~100 tests (lab data, simulations) successfully passed

– but astrophysical and geophysical flows are inhomogeneous (boundary conditions, compressibility, phase transitions, radiation, …)

➔ *extensions have to be tested* with observed data and simulations

➔ *as of now limited to restricted classes of problems or of low accuracy*

– new geophysical models explicitly account for topology, ...

Simulations and Models VIII

- **Local and non-local models**
  - *non-linearity* and *non-locality* of the NSE/their solutions ➔ moment expansion ➔ equations for moments form an infinite hierarchy ➔ additional ("closure") assumptions necessary
  - local models: F_{conv} = f [local mean structure], ...
    MLT (Biermann 1932), FST (CM/CGM), ...
  - non-local models: differential equations for low order moments (F_{conv} , ...), closed at higher order
    Xiong (1978, 1985, 1997), Canuto (1992/93/97/98,2001)
  - *testing strategy: calibrate once, check for others (LES, observations), no "tuning" later on*

Applications I

- **Stellar envelope computations**
  - non-local (Reynolds stress) model Canuto et al. (1992, '93, '94, '98, 2001) (most sophisticated model available 3 years ago)
  - realistic microphysics: EOS $P(\rho,T)$, opacities
  - spherical geometry, adaptive grid
  - 200 grid points (mass shells) from τ_{Ross}~10^{-3} to $T(R)$~10^{5} K
  - placed within sufficiently deep stable boundary layers
  - for A-type stars along the main sequence with various metallicites, and for models along an "evolutionary track"
    (Kupka & Montgomery 2002, MNRAS 330, L6)
  - for DA and DB type white dwarfs (DA: 100% H, DB: 100% He)
    (Montgomery & Kupka 2004, MNRAS 350, 267)

Applications II

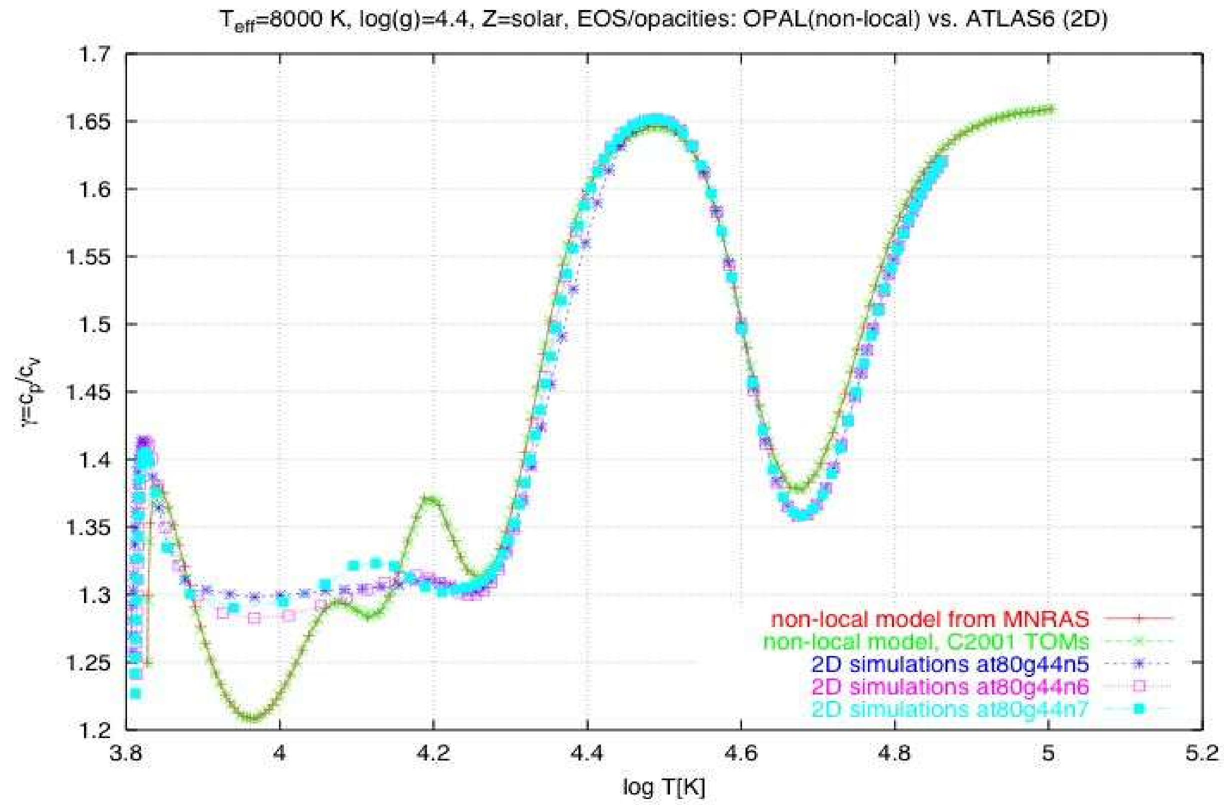
- **Results for A4 V to A9 V (T_{eff} 8500 K ... 7200 K)**
  - slow merging of H I/He I & He II instability zones
  - efficient convection sets in only for late A stars
    - implied from photometry and 2D simulations
  - high photospheric velocities ($v(\tau_{surf})$~3-4 km s^{-1})
    - from spectroscopy and 2D simulations (obtained: ~1.5-2 km s^{-1})
  - *interaction of He I & He II instability zones*
    - connected in terms of the velocity field
    - "separated" in terms of F_{conv}, temperature field (in the sense of becoming very small inbetween)
    - supported by 2D simulations

Applications III

Differences of "old" and "new" EOS in H I & He I zones

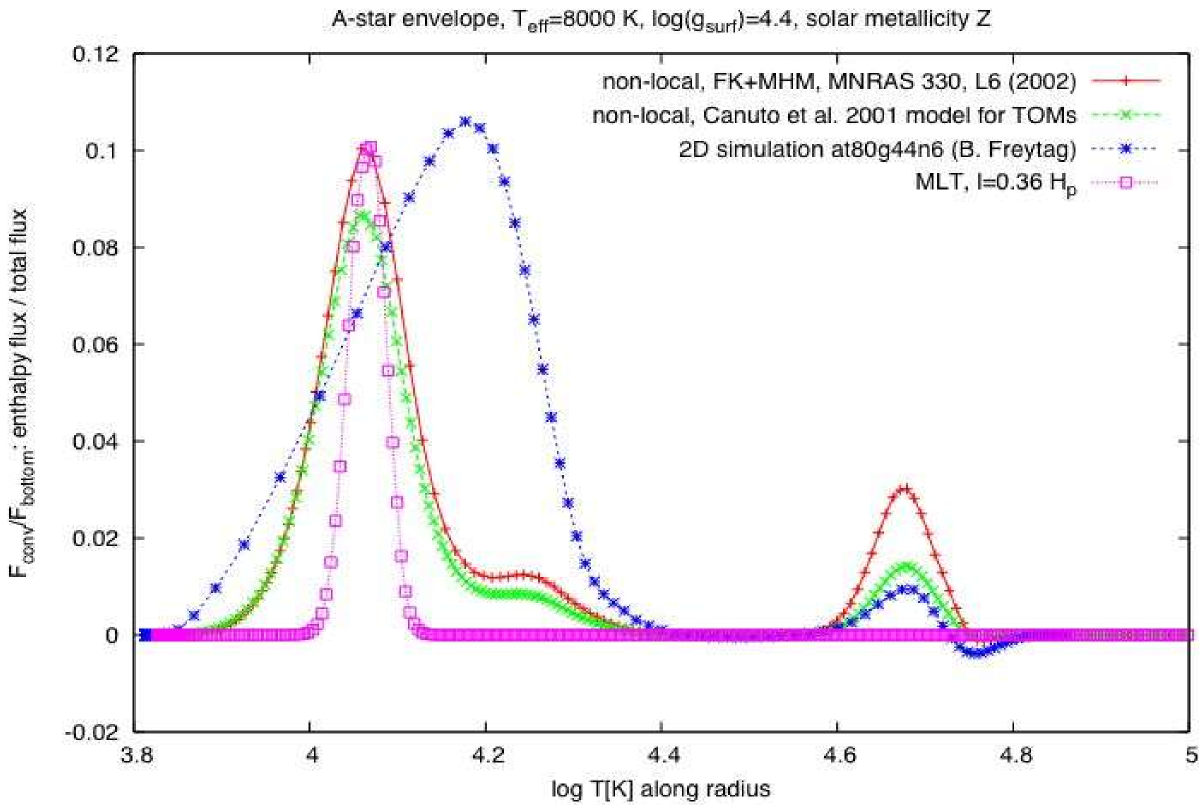
➔ interpretation of differences requires some caution...

limits comparison in Kupka & Montgomery 2002, MNRAS 330, L6



Applications IV

Convective flux in units of input flux for an A4 V to A5 V star



2D simulations, MLT & non-local model

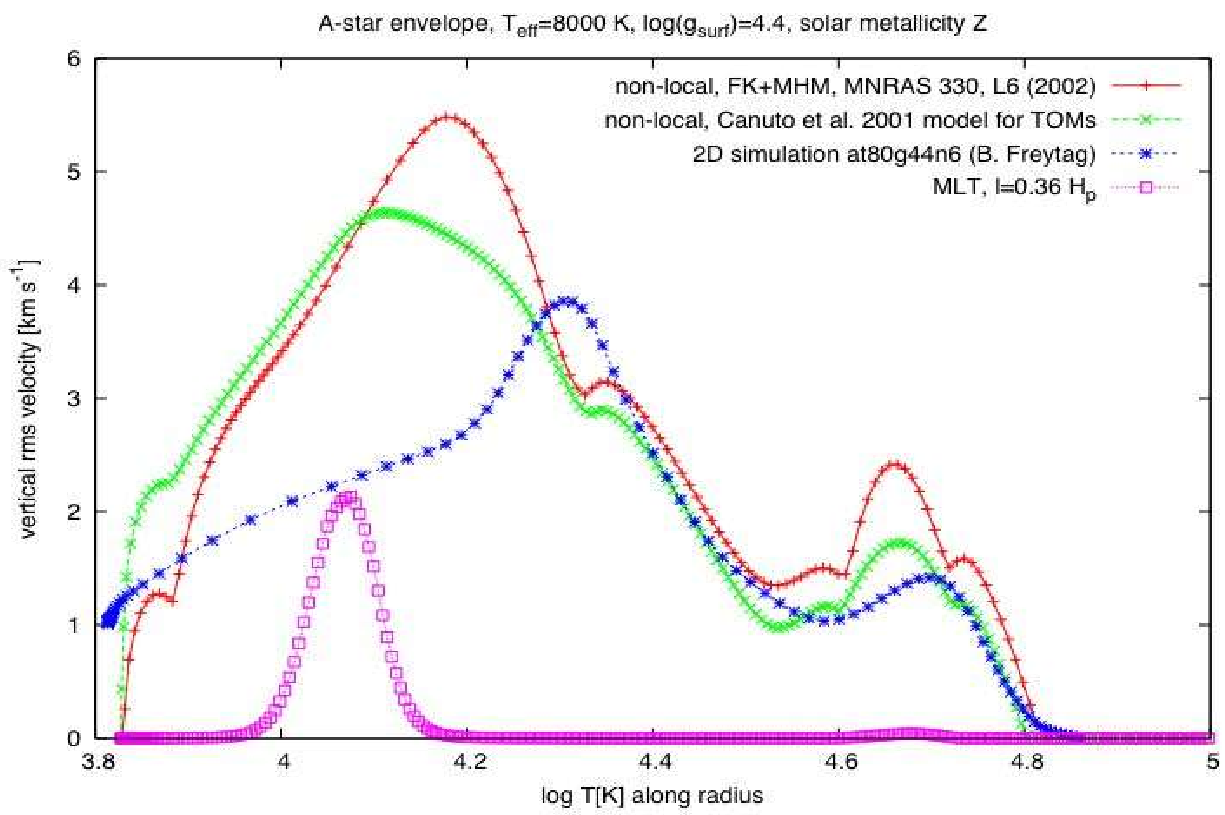
results discussed in Kupka & Montgomery 2002, MNRAS 330, L6

Applications V

Vertical rms velocity for an A4 V - A5 V star

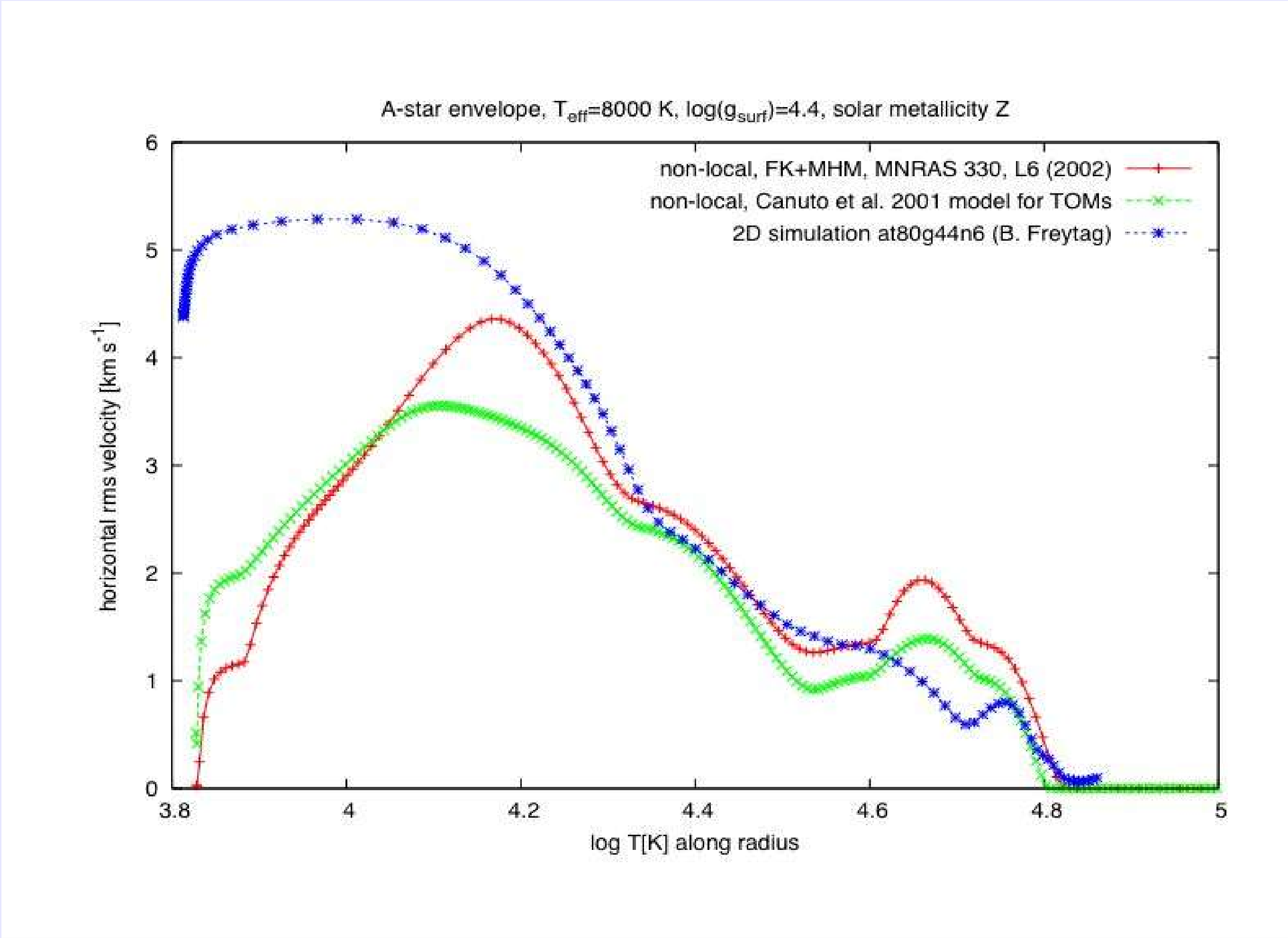
2D simulations, MLT & non-local model

results discussed in Kupka & Montgomery 2002, MNRAS 330, L6



Applications VI

Horizontal rms velocity for an A4 V - A5 V star



2D simulations & non-local model

results discussed in Kupka & Montgomery 2002, MNRAS 330, L6

Applications VII

- **Results for A4 V to A9 V part II**
  - photospheric *$S_w > 0$, filling factor < 1/2*
    - consistent with observed line profiles
  - *overshooting below He II zone*
    - along MS ~0.45 H_p ...0.6 H_p (below limit from 2D simulations)
  - MLT α to recover maximum of F_{conv} in H I zone:
    - for T_{eff} = 8000 K ... ~0.4, for T_{eff} = 7100 K ... ~1.0
    - different set of α (>1.5) required for He II zone
    - in full agreement with 2D simulations
  - similar for other metallicities, ...

Applications VIII

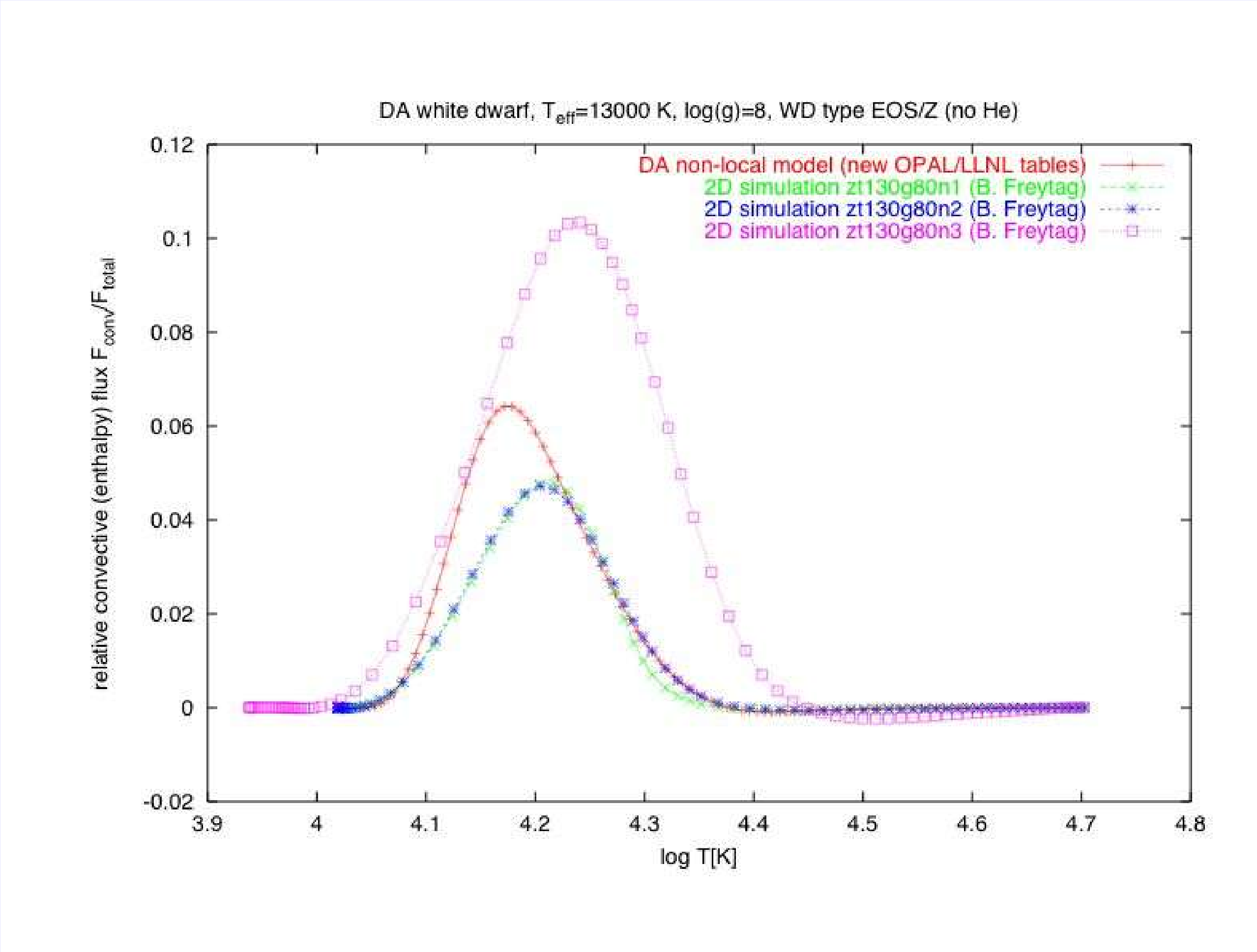
- **For DA white dwarfs, T_{eff} 12200 K …13400 K**
  - H I convection zone with large overshoot around
    - effective MLT: α ~1.7 (as in 2D simulations !)
    - OV below containing 10x above lying mass (2D simulations: 100x)
    - photospheric velocities: τ_{surf} ~4-5 km s^{-1} (Ma ~ 1/3, ~2D simulations)
- **For DB white dwarfs, T_{eff} 28000 K … 35000 K**
  - for < 30000 K: two strongly coupled zones (He I + He II)
  - for > 30000 K: single He II convection zone
    - but no suitable data from simulations for tests...
- **Velocity "bumps" already indicate limitations...**

Applications IX

Convective flux in units of input flux for a hot DA white dwarf

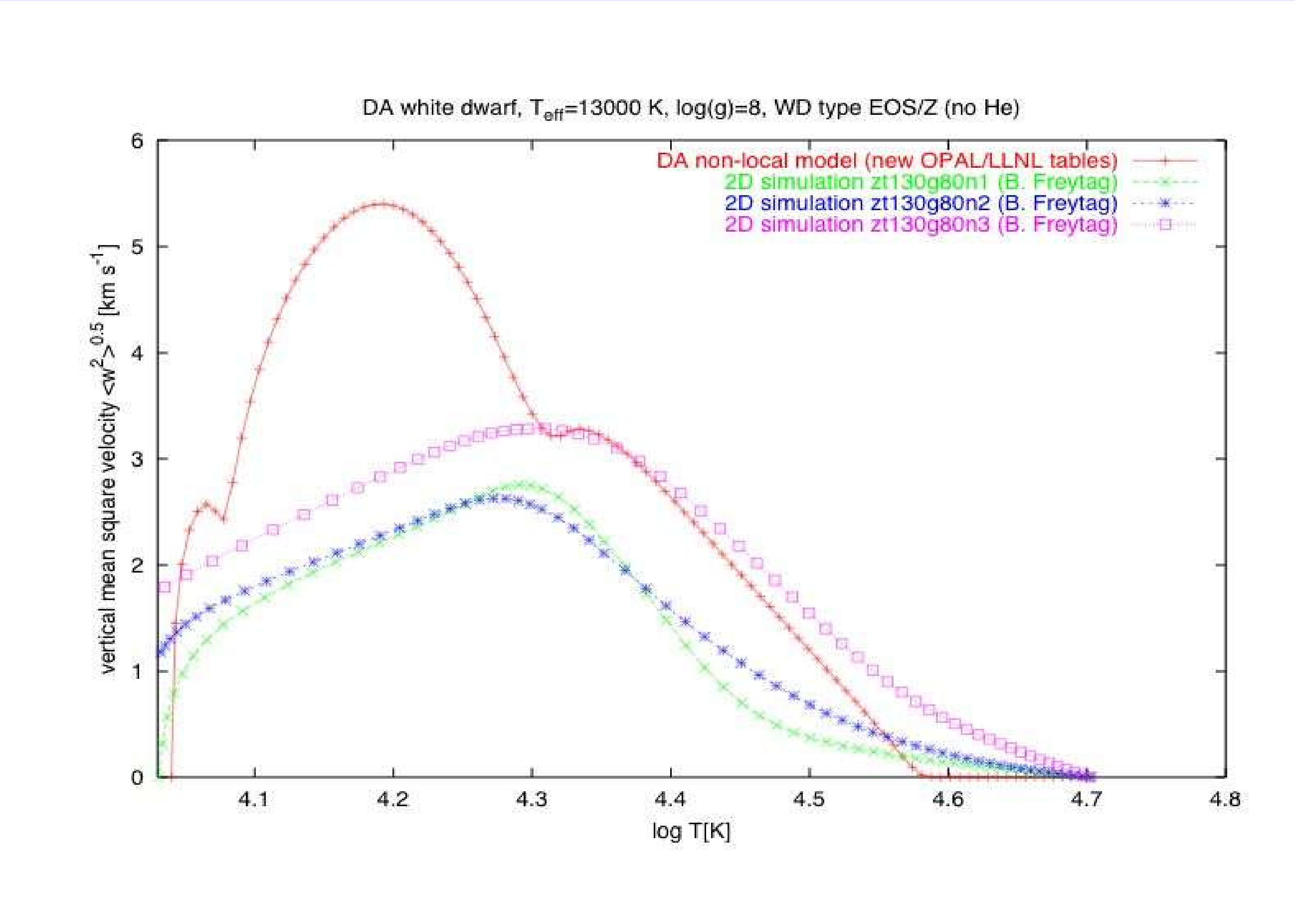
2D simulations, MLT & non-local model

results discussed in Montgomery & Kupka 2004, MNRAS 350, 267



Applications X

Vertical rms velocity for a hot DA white dwarf

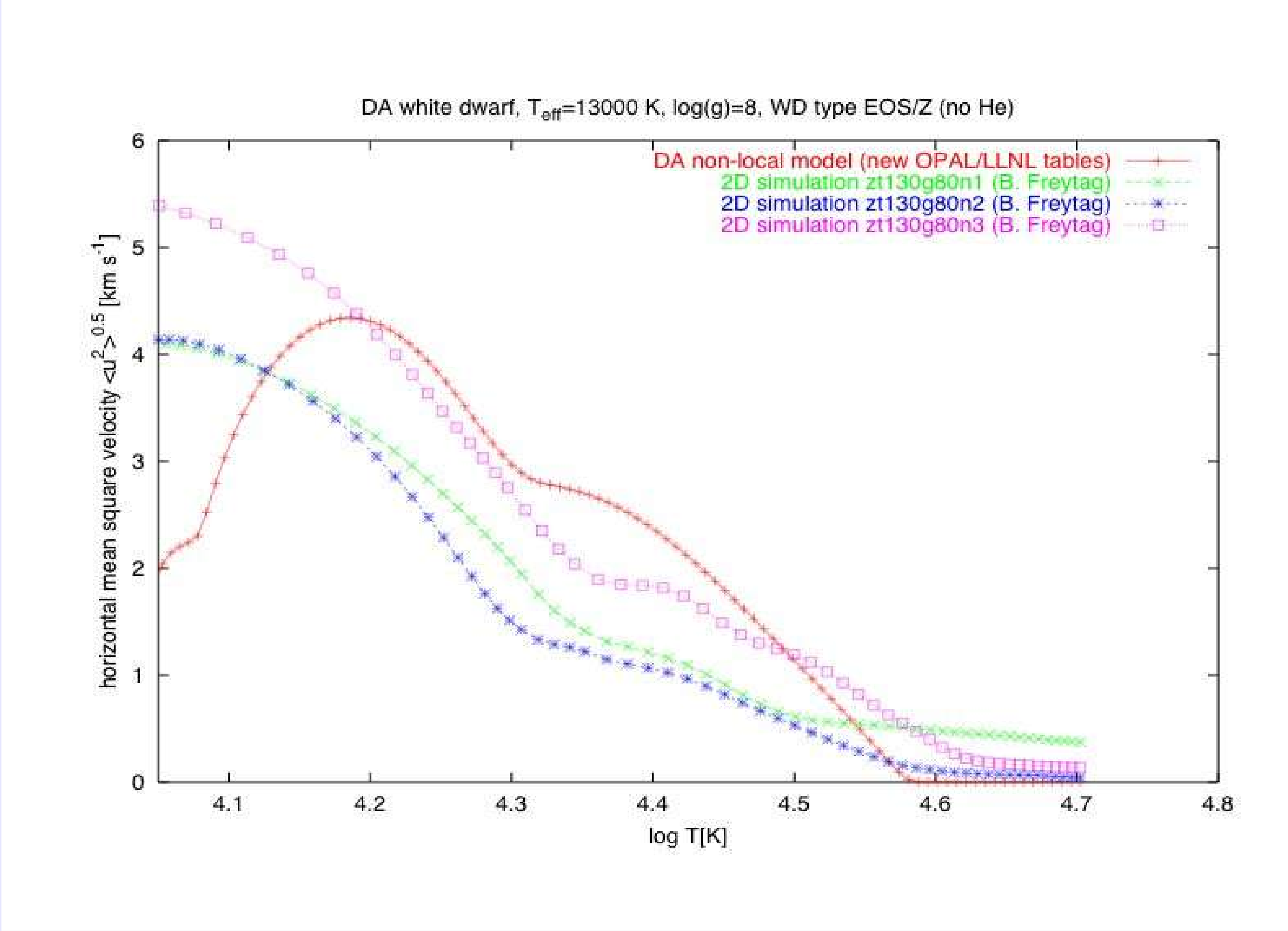


2D simulations, MLT & non-local model

results discussed in Montgomery & Kupka 2004, MNRAS 350, 267

Applications XI

Horizontal rms velocity for a hot DA white dwarf



2D simulations & non-local model

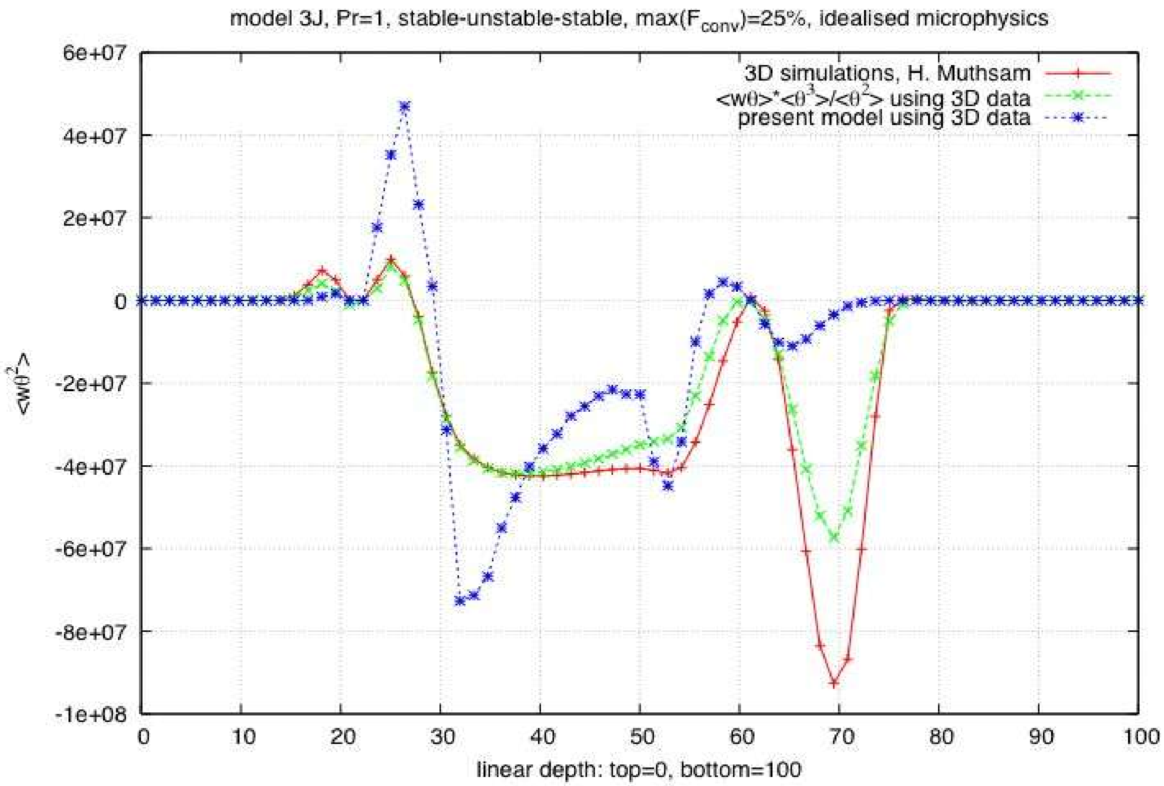
results discussed in Montgomery & Kupka 2004, MNRAS 350, 267

Applications XII

- **For deep convection zones such as in the sun...**
  - comparison with simulations
    - model cannot reproduce higher (third) order moments
  - analysis recovers: previous cases had small skewness
  - solar granulation simulations, deep/adiabatic convection:
    - models have to cope with varying & large skewness
  - large skewness related to flow topology
    - result of boundary conditions and non-locality
    - leads to inhomogeneity of the flow: up-/downdrafts
  - a "more universal" model should account for that...

Applications XIII

Flux of temperature fluctuations for an "A-star like" convection zone

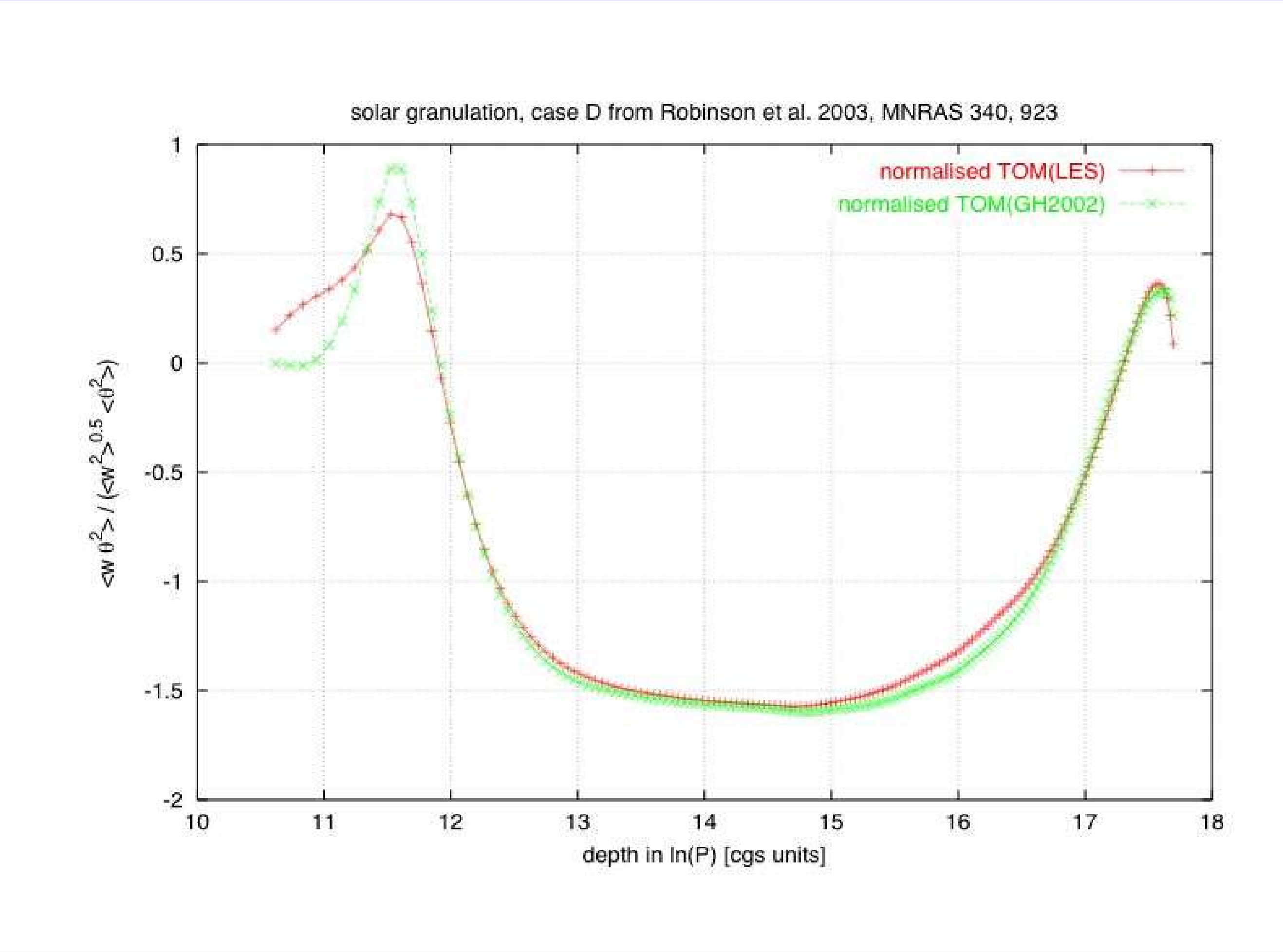


3D simulations, GH 2002 model, previous model

simulation data from Muthsam et al. 1995, A&A 293, 127

Applications XIV

Flux of temperature fluctuations for solar granulation



3D simulations & GH 2002 model

simulation data courtesy F.J. Robinson, see Robinson et al. 2003, MNRAS 340, 923

Applications XV

- **Gryanik/Hartmann model**
  - from analysis of PBL (planetary boundary layer) aircraft data
  - coherent structures
    - contribute most to higher order moments ➔ skewness
  - “ballistic limit” (up-/downdrafts) ➔ large skewness
  - assumes a linear interpolation
    - between quasi-Gaussian limit for zero skewness (previous model)
    - and the ballistic limit

      ➔ yields expressions for closing model at 4th order
  - a model requires tests ➔ aircraft & LES data for PBL

    ➔ results are surprisingly good...

(V.M. Gryanik, J. Hartmann, 2002, J. Atm. Sci. 59, 2729)

Applications XVI

- **Summary of test results so far**
  - model performs as well for solar granulation as for the PBL (and likewise for simulation data by Muthsam, Chan & Sofia; ocean data)
  - differences to PBL such as
    - compressibility, EOS/microphysics, boundary conditions
      ➔ are not so important...
  - some shortcomings
    - performance when coupled to complete model ? Currently tested...
    - less good in OV / superadiabatic layer: flow topology changes...
    - accuracy: order of magnitude better, but “5%” remains impossible
    - quite a bit more expensive (number of DEs) than previous models

...THE END