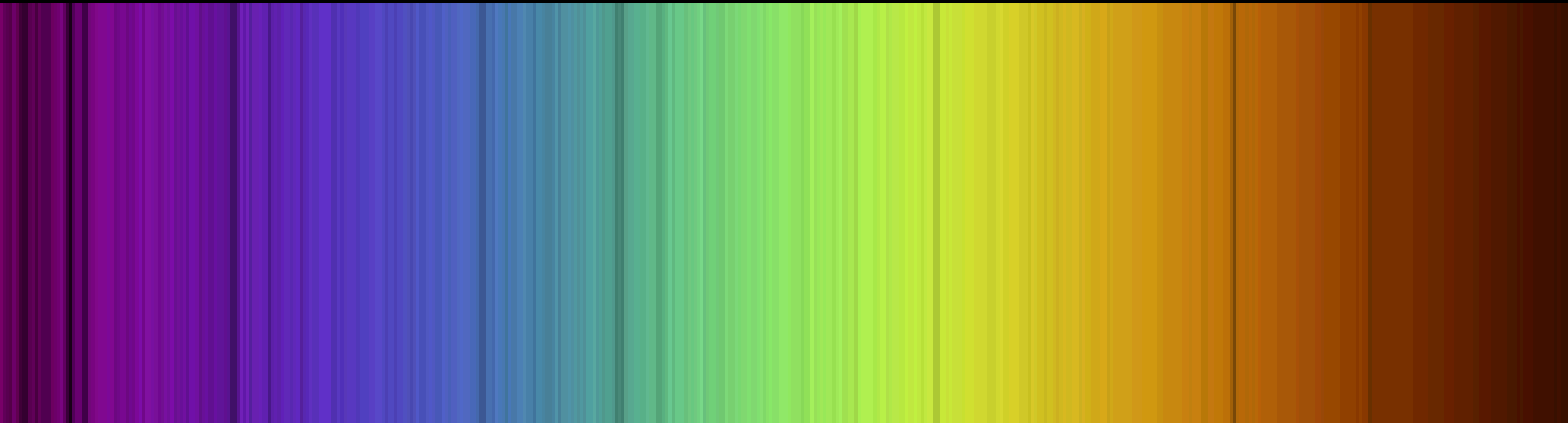
ESO Santiago, February 2012



Gravitational redshifts, and other wavelength shifts in stellar spectra

Dainis Dravins – Lund Observatory

www.astro.lu.se/~dainis

Exactly 100 years ago

Predicted effects by gravity on light

4. Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes; von A. Einstein.

Die Frage, ob die Ausbreitung des Lichtes durch die Schwere beinflußt wird, habe ich schon an einer vor 3 Jahren erschienenen Abhandlung zu beantworten gesucht.[1]) Ich komme auf dies Thema wieder zurück, weil mich meine damalige Darstellung des Gegenstandes nicht befriedigt, noch mehr aber, weil ich nun nachträglich einsehe, daß eine der wichtigsten Konsequenzen jener Betrachtung der experimentellen Prüfung zugänglich ist. Es ergibt sich nämlich, daß Lichtstrahlen, die in der Nähe der Sonne vorbeigehen, durch das Gravitationsfeld derselben nach der vorzubringenden Theorie eine Ablenkung erfahren, so daß eine scheinbare Vergrößerung des Winkelabstandes eines nahe an der Sonne erscheinenden Fixsternes von dieser im Betrage von fast einer Bogensekunde eintritt.

gegebenen Betrages. Es wäre dringend zu wünschen, daß sich Astronomen der hier aufgerollten Frage annähmen, auch wenn die im vorigen gegebenen Überlegungen ungenügend fundiert oder gar abenteuerlich erscheinen sollten. Denn abgesehen von jeder Theorie muß man sich fragen, ob mit den heutigen Mitteln ein Einfluß der Gravitationsfelder auf die Ausbreitung des Lichtes sich konstatieren läßt.

Prag, Juni 1911.

A.Einstein, *Annalen der Physik* **340**, 848 (1911)

- Historical perspectives
- Predicting gravitational redshift
- Unsuccessful searches
- Experimental confirmations
- Effects in “normal” stars?
- Other wavelength shifts
- Shifts across stellar disks

Already long before Einstein…

Predicting gravitational effects on light

PHILOSOPHICAL

TRANSACTIONS,

OF THE

ROYAL SOCIETY

OF

LONDON.

VOL. LXXIV. For the Year 1784.

PART I.

LONDON,

SOLD BY LOCKYER DAVIS, AND PETER ELMSLY,
PRINTERS TO THE ROYAL SOCIETY.

MDCCLXXXIV.

VII. *On the Means of diſcovering the Diſtance, Magnitude, &c. of the Fixed Stars, in conſequence of the Diminution of the Velocity of their Light, in caſe ſuch a Diminution ſhould be found to take place in any of them, and ſuch other Data ſhould be procured from Obſervations, as would be farther neceſſary for that Purpoſe. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendiſh, *Eſq. F. R. S. and A. S.*

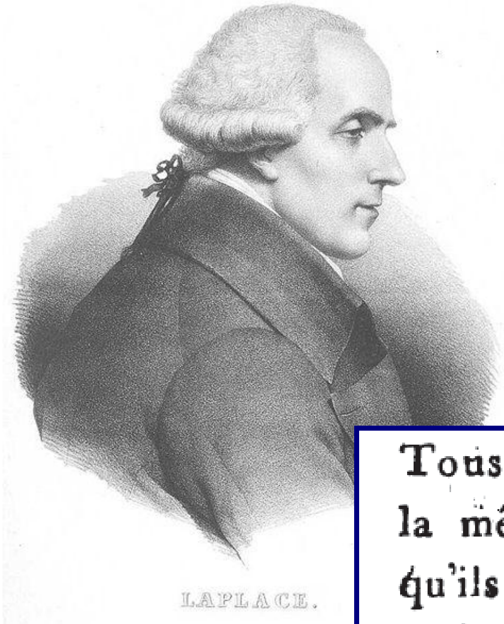
Read November 27, 1783.

DEAR SIR, Thornhill, May 26, 1783.

THE method, which I mentioned to you when I was laſt in London, by which it might perhaps be poſſible to find the diſtance, magnitude, and weight of ſome of the fixed ſtars, by means of the diminution of the velocity of their light, occurred to me ſoon after I wrote what is mentioned by Dr. PRIESTLEY in his Hiſtory of Optics, concerning the diminution of the velocity of light in conſequence of the attraction of the ſun; but the extreme difficulty, and perhaps impoſſibility, of procuring the other data neceſſary for this purpoſe appeared to me to be ſuch objections againſt the ſcheme, when I firſt thought of it, that I gave it then no farther conſideration. As ſome late obſervations, however, begin to give us a little more chance of procuring ſome at leaſt of theſe data, I thought it would not be amiſs, that aſtronomers ſhould be apprized of the method, I propoſe (which, as far as I know,

John Mitchell (1784)

Predicting gravitational effects on light



Pierre-Simon Laplace (1796)

Tous ces corps devenus invisibles, sont à la même place où ils ont été observés, puisqu'ils n'en ont point changé, durant leur apparition; il existe donc dans les espaces célestes, des corps obscurs aussi considérables, et peut être en aussi grand nombre, que les étoiles. Un astre lumineux de même densité que la terre, et dont le diamètre serait deux cents cinquante fois plus grand que celui du soleil, ne laisserait en vertu de son attraction, parvenir aucun de ses rayons jusqu'à nous; il est donc possible que les plus grands corps lumineux de l'univers, soient par cela même, invisibles. Une étoile qui, sans être de

EXPOSITION

DU SYSTÊME

DU MONDE,

PAR PIERRE-SIMON LAPLACE,
de l'Institut National de France, et
du Bureau des Longitudes.

TOME SECOND.

A PARIS,

De l'Imprimerie du CERCLE-SOCIAL, rue du
Théâtre Français, N°. 4.

L'AN IV DE LA RÉPUBLIQUE FRANÇAISE.

Verifying Einstein ?

Freundlich's attempts to verify relativity theory (I)

End of 1911–Oct. 1912: Examination of available plate data from solar eclipse expeditions for evidence of light deflection in the sun's gravitational field; plates not sharp enough.

1912–1913: Comments on possible daytime observations of stars near the sun; but too much scattered light.

1913: Analyses of binary stars: Test of the axiom $c =$ constant of the special theory of relativity versus Ritz's emission theory of light.

1914: Analysis of Fraunhofer-line measurements by Evershed (1913) and Fabry & Buisson [1910] with the view toward possible gravitational redshift; Results: redshift is present. But already in 1914 Schwarzschild publishes new data that rather speak against gravitational redshift.

1914: Expedition to the Crimea exclusively to verify light deflection during a solar eclipse; due to the outbreak of war, the members of the expeditions are taken into custody and their instruments confiscated.

Erwin Finlay Freundlich (1885-1964) worked to experimentally verify the predictions from Einstein's theory of relativity and the effects of gravity on light.

Klaus Hentschel: *Erwin Finlay Freundlich and Testing Einstein's Theory of Relativity*, Archive for History of Exact Sciences **47**, 243 (1994)

Freundlich's attempts to verify relativity theory (II)

Einsteinturm, Potsdam-Telegrafenberg

Feb. 1915: Refutation of v. SEELIGER's zodiacal light hypothesis as an explanation of anomalies in the planetary system; in Nov. 1915 EINSTEIN will explain the mercurial perihelion anomaly with his new theory.

1915ff.: Statistical investigations of redshift of fixed stars in relation to their spectral classification; observed redshifts are correlated with estimated mean masses and radii of the fixed stars. Results: redshift is present. But v. SEELIGER and LUDENDORFF accuse FREUNDLICH in the same year of technical errors and 'wishful thinking' [see the next section]. Repetition of these investigations: 1919, 1922, 1924, 1928, 1930.

1920–24: Building of the Einstein Tower, initially with the special aim of testing beyond any doubt the existence of redshift of the sun's spectral lines; while still in the construction stage, scope of analysis broadened – redshift never actually is confirmed beyond doubt at the EINSTEIN Tower.

1922: Solar eclipse expedition to Christmas Island, *re* light deflection.

1923: Solar eclipse expedition to Mexico, to test also for light deflection.

1926: Solar eclipse expedition to Bengkulen, South Sumatra, also *re* light deflection.

1929: Solar eclipse expedition to Takingeun, North Sumatra, to test also for light deflection; different from the preceding expeditions, for the first time good weather and successful procurement of observation data; the evaluation yields too large an effect of light deflection (2″.2 instead of 1″.75 at the sun's rim). (See Section 5).

1931ff.: Reanalysis of older data from other solar eclipse expeditions of 1922 and 1924 confirms the tendency: Light deflection is larger than predicted in the general theory of relativity.

1931–1965: Development of a phenomenological theory to explain the discrepancies between observations and the general relativity theory (photon-photon interaction)

Klaus Hentschel: *Erwin Finlay Freundlich and Testing Einstein's Theory of Relativity*, Archive for History of Exact Sciences **47**, 243 (1994)

Unethical falsifications in astronomy ?

Nature **306**, 727 (1983)

NATURE VOL. 306 22/29 DECEMBER 1983 COMMENTARY 727

Just how objective is science?

Norris S. Hetherington*

The supposed objectivity of science has come into question. Recent historical studies reveal instances in which scientific knowledge has not been strictly controlled by observation statements in turn established beyond reasonable doubt by rigorous scientific method. The scientific method has not always proven adequate; scientific observations have, at times, reflected personal biases.

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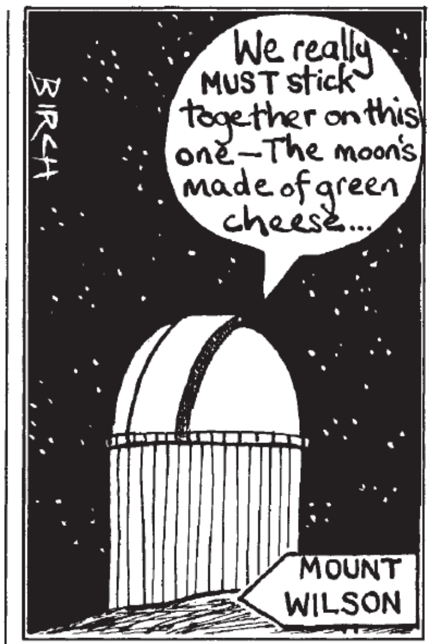


Sirius B redshift

A third Mount Wilson case, and one not involving van Maanen, is that of the purported measurement of the gravitational redshift of Sirius B[18]. The existence of such a redshift, even its amount, was predicted from relativity theory, and Arthur Eddington asked Walter Adams at Mount Wilson to attempt the measurement. That Adams did, finding almost exactly the amount predicted by Eddington.

Controversial interpretations of history

On the Redshift of Sirius B

Jesse L. Greenstein and J. B. Oke
Palomar Observatory and the Department of Astronomy, California Institute of Technology, Pasadena, CA 91125, USA

Harry Shipman
Department of Physics, University of Delaware, Newark, DE 19711, USA

QJRAS **26**, 279 (1985)

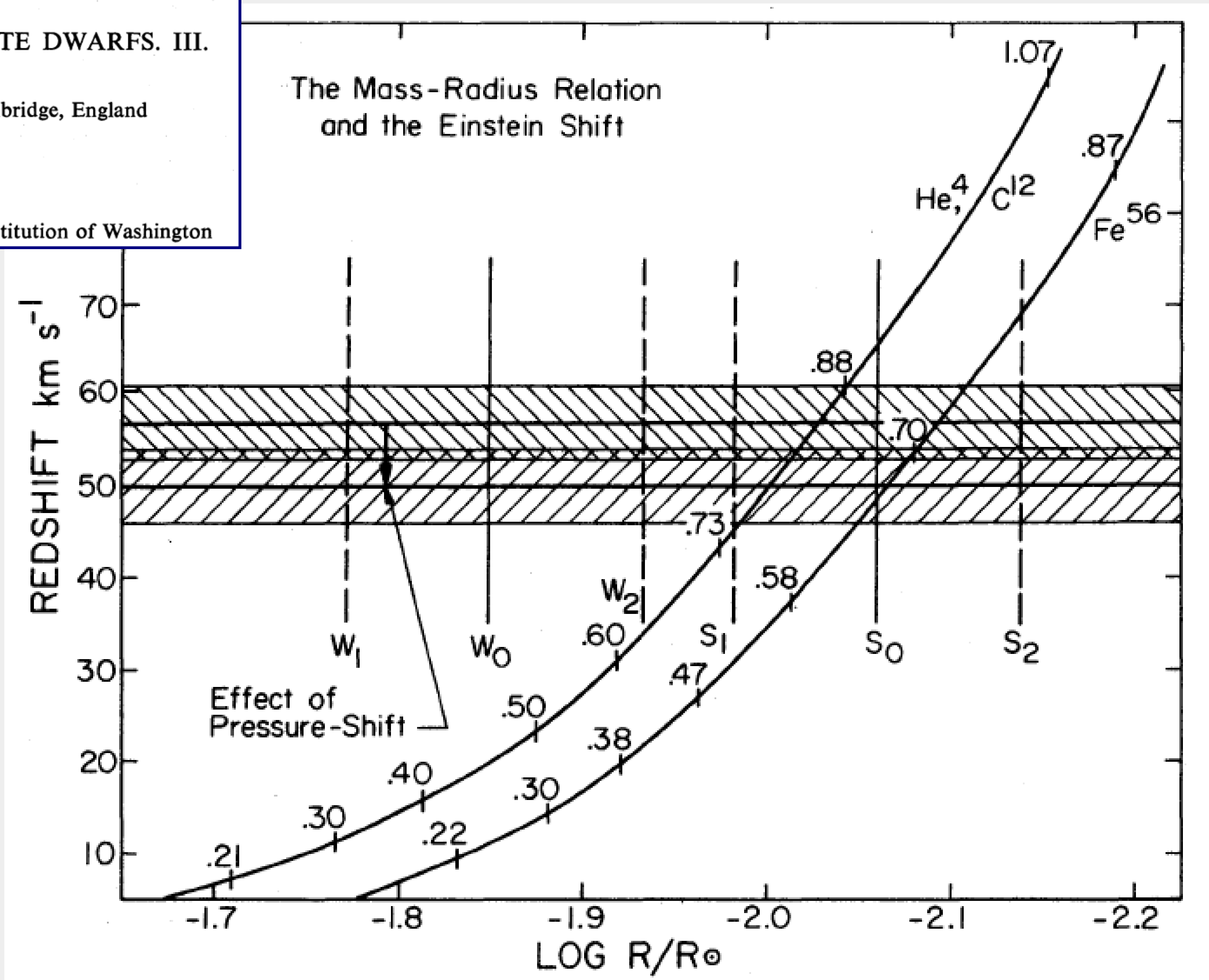
In such an unfortunate reordering of the past, three strong attacks by N.S.Hetherington (1, 2, 3) have attempted to create an image of a locale, the Mount Wilson Observatory, occupied by allegedly incompetent observers, who are also by implication scientifically dishonourable, finding 'too facilely what they expected to find'. Their major dramatic usefulness is 'in support of H.Bondi's argument (4) that observational work has been no less liable to erroneous conclusions than theoretical work, if indeed not more so'. Such exhumed Berkeleyan idealism would not be worth the notice of scientists, acting as scientists, however much it might stir controversies among historians. But the third of his attacks criticizes in 1980 work done by us in 1971, as well as that done at Mount Wilson in 1925. At stake is not only the scientific integrity of many good scientists, but the evidence for an important theory, relativistic degeneracy. The white dwarf Sirius B is now drawing closer to periastron and to its overwhelmingly bright primary, making a new experiment difficult or impossible in the near future.

Actual gravitational redshift in white dwarfs

THE ASTROPHYSICAL JOURNAL, 177:441–452, 1972 October 15

THE EINSTEIN REDSHIFT IN WHITE DWARFS. III.

VIRGINIA TRIMBLE*
Institute of Theoretical Astronomy, Cambridge, England
AND
JESSE L. GREENSTEIN
Hale Observatories,
California Institute of Technology, Carnegie Institution of Washington

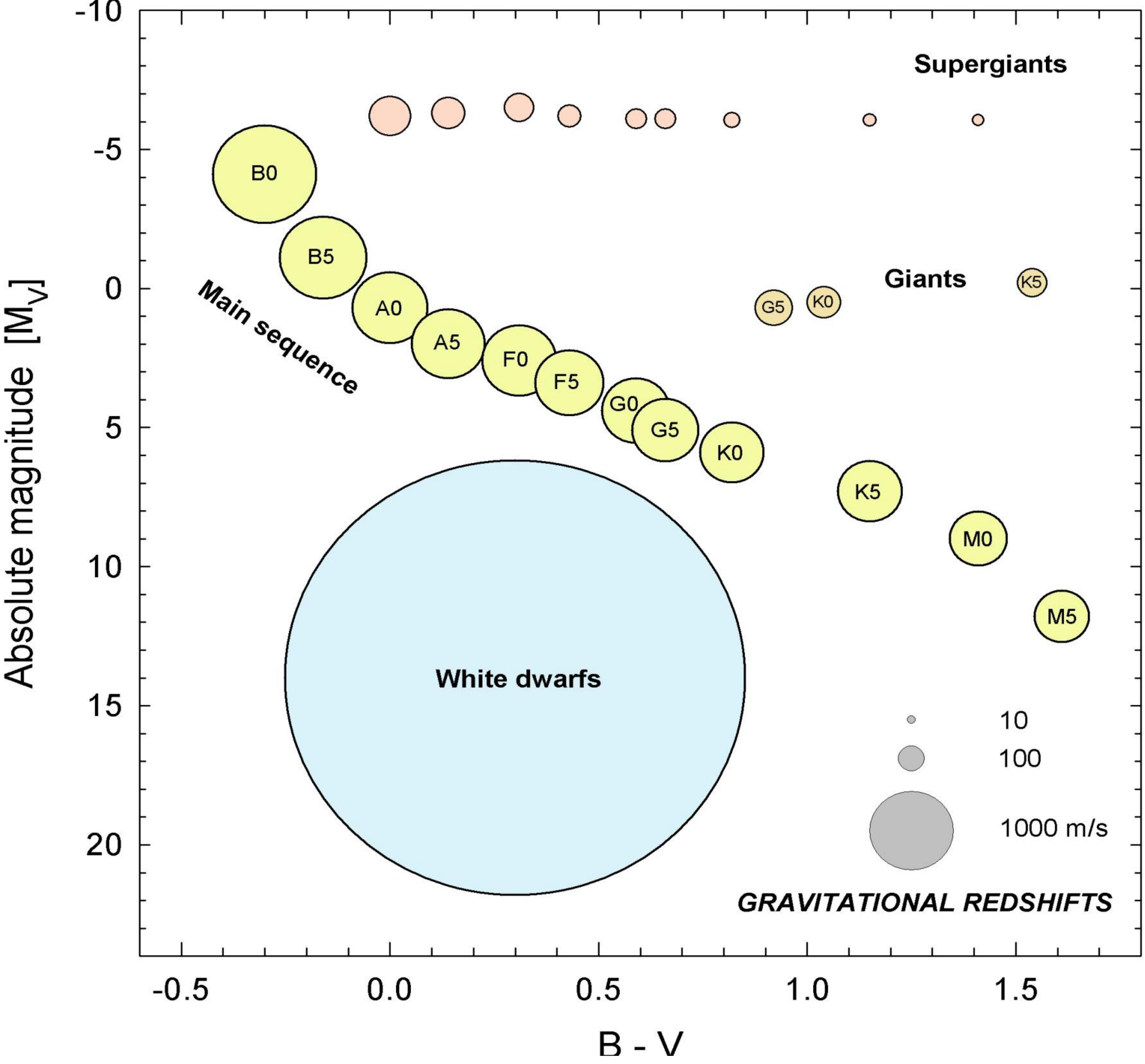


Stellar spectroscopy

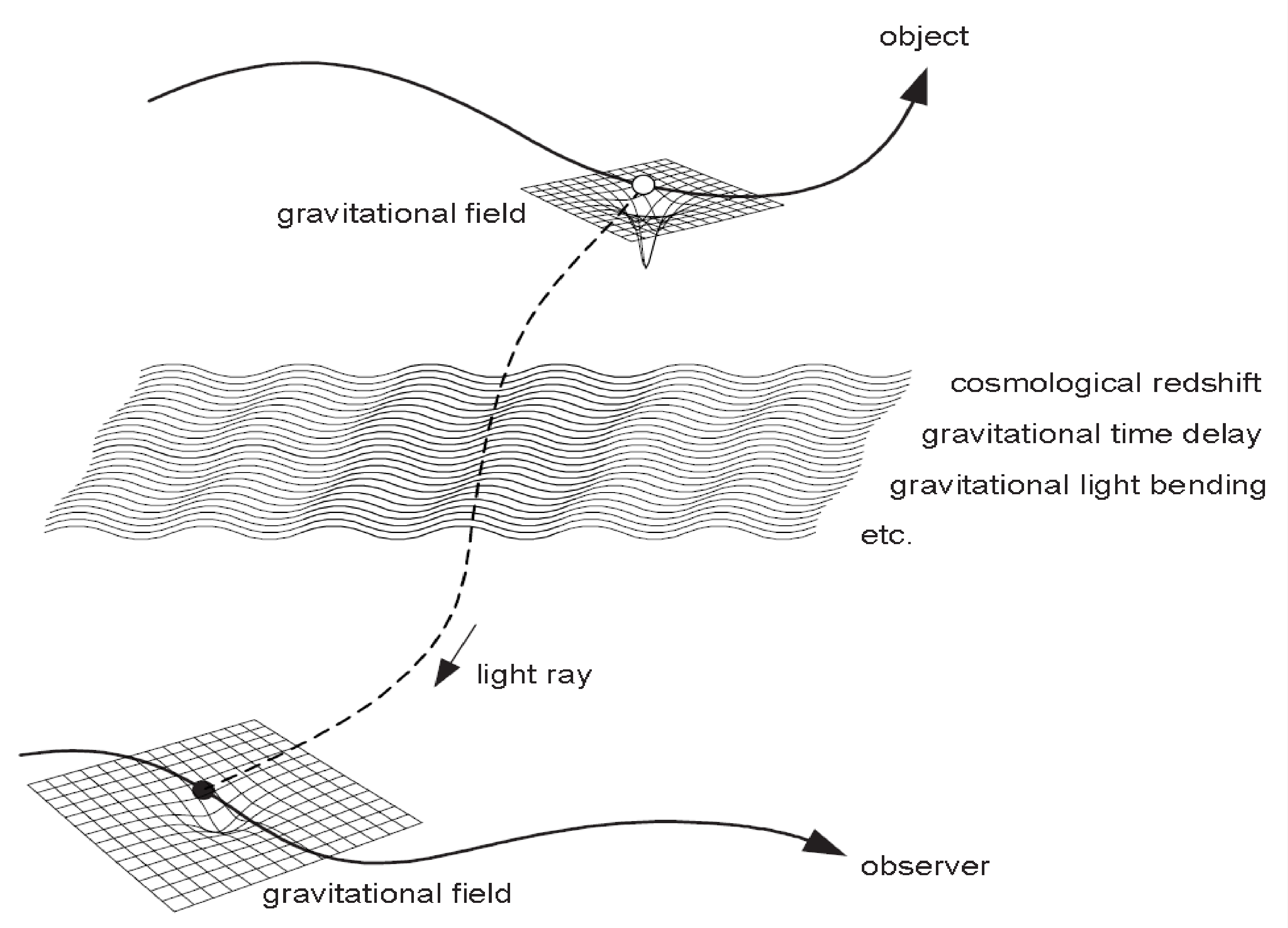
Expected gravitational redshifts

D. Dravins

IAU Symp. 210



Mechanisms causing wavelength shifts

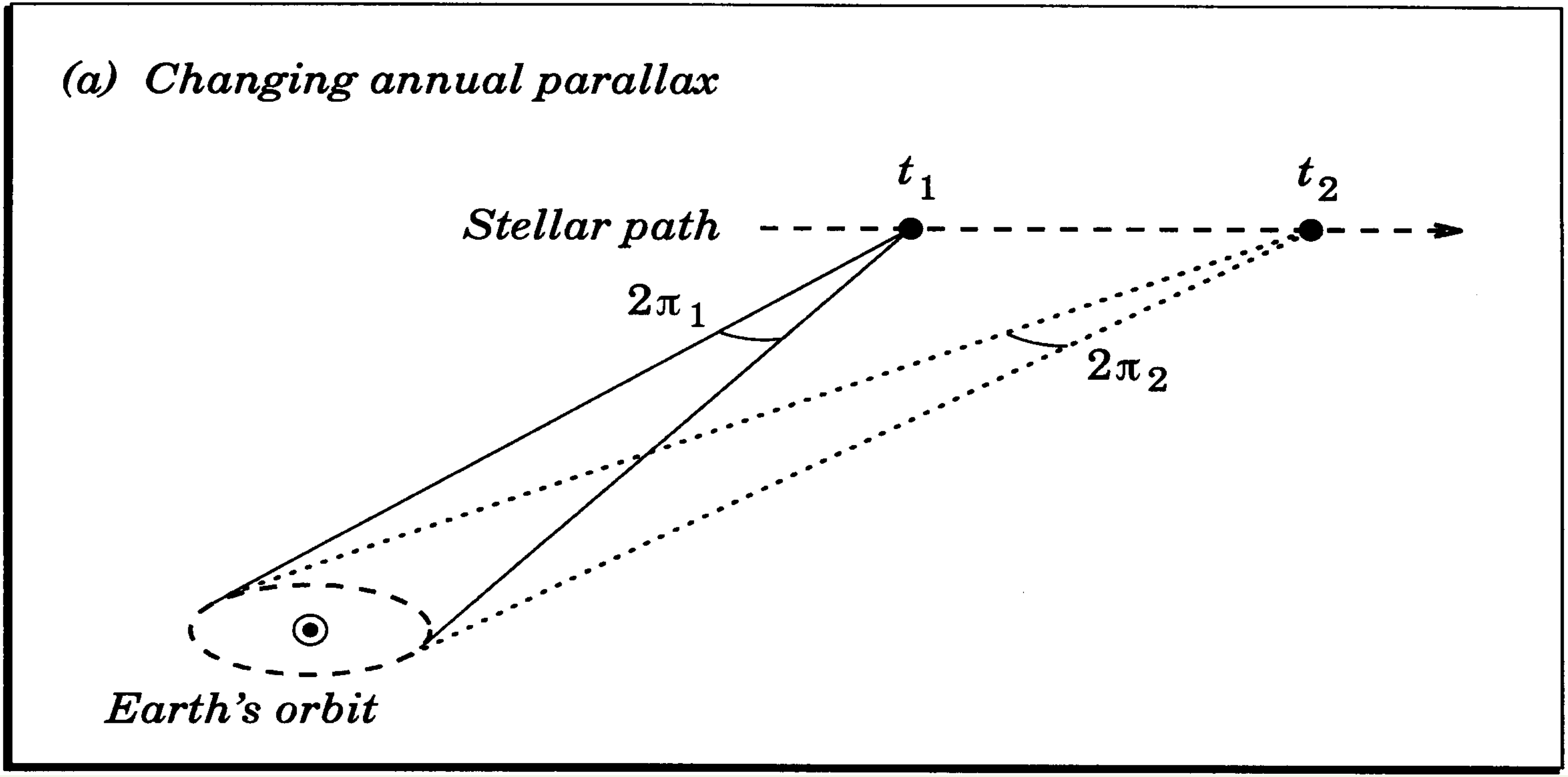


The process includes: motion of the object; its emission of an electromagnetic signal; its propagation through space; motion of the observer; and the reception of the signal.

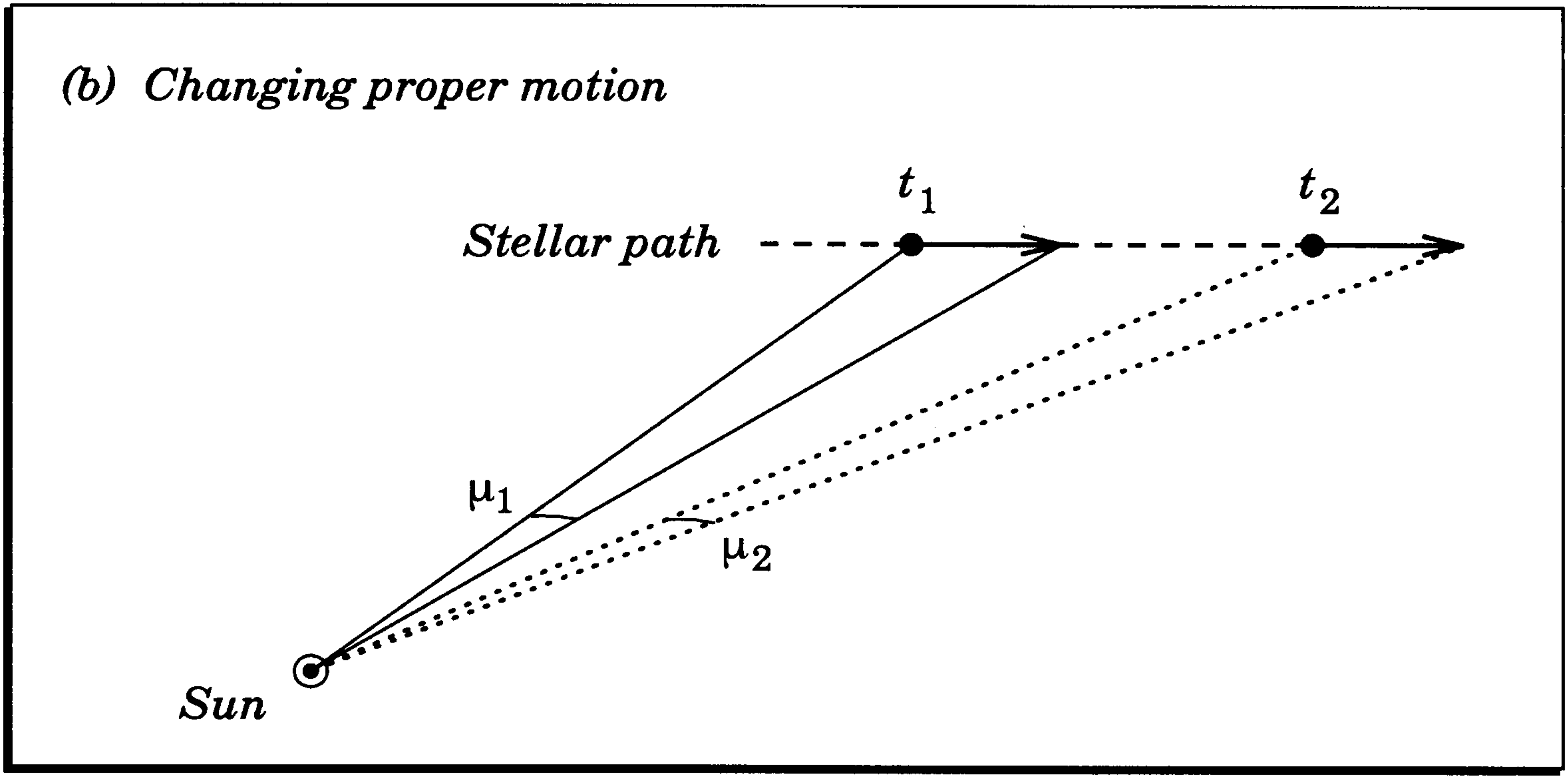
L.Lindegren & D.Dravins: *The fundamental definition of "radial velocity,* A&A **401**, 1185

Radial velocities without spectroscopy

Astrometric radial velocities I

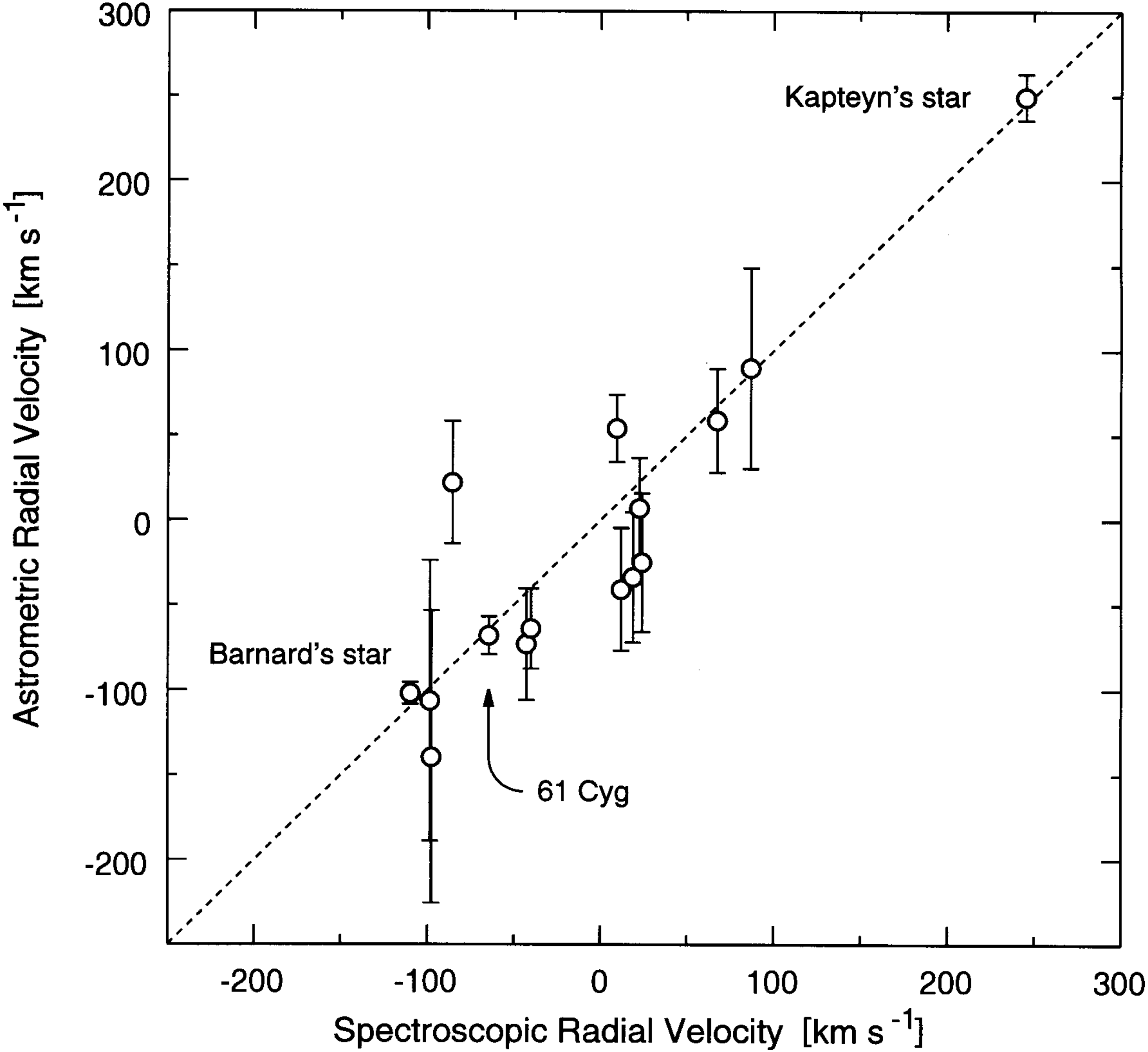


Astrometric radial velocities II



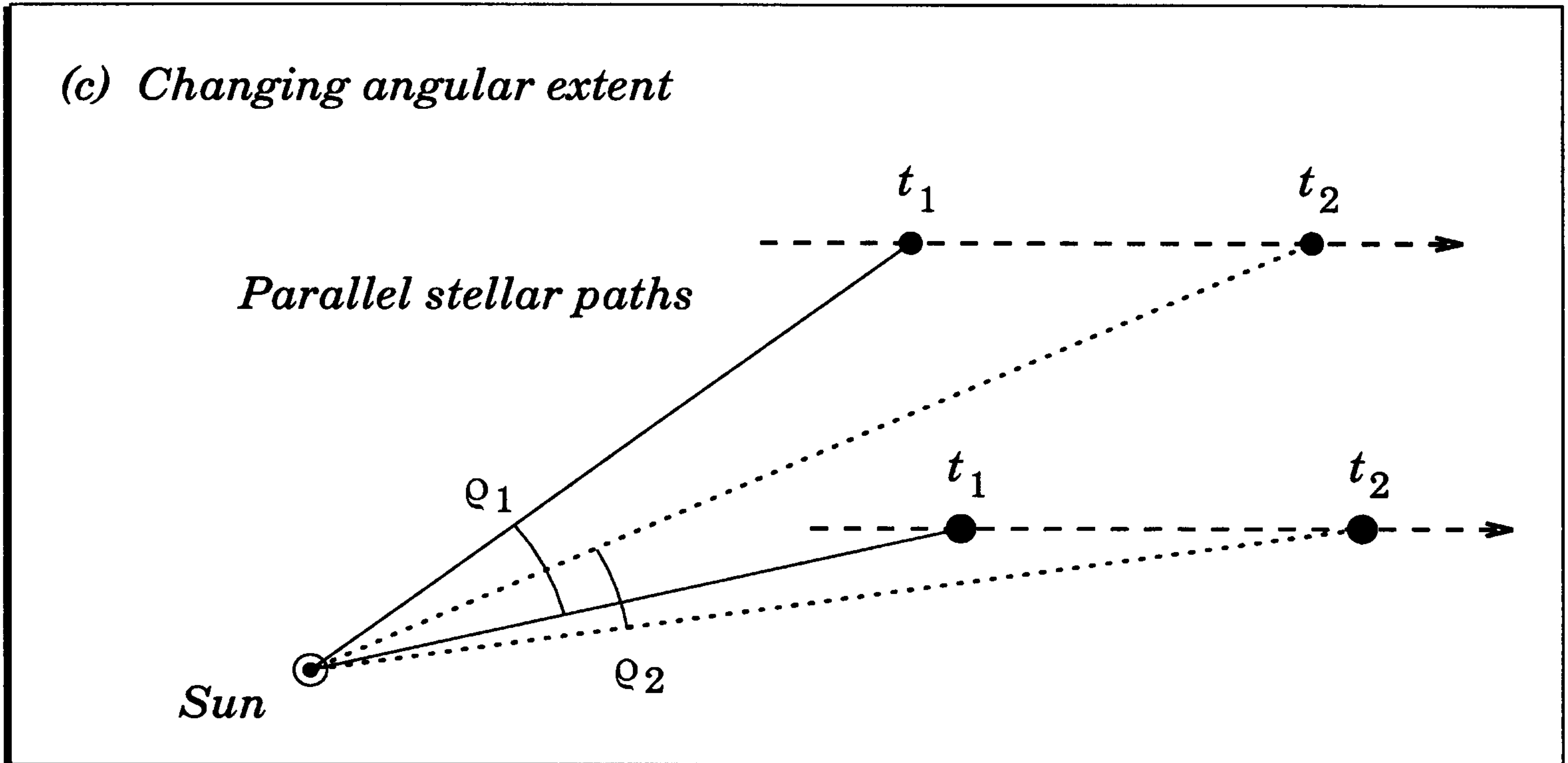
Dravins, Lindegren & Madsen, *A&A* 348, 1040

Astrometric radial velocities from perspective acceleration



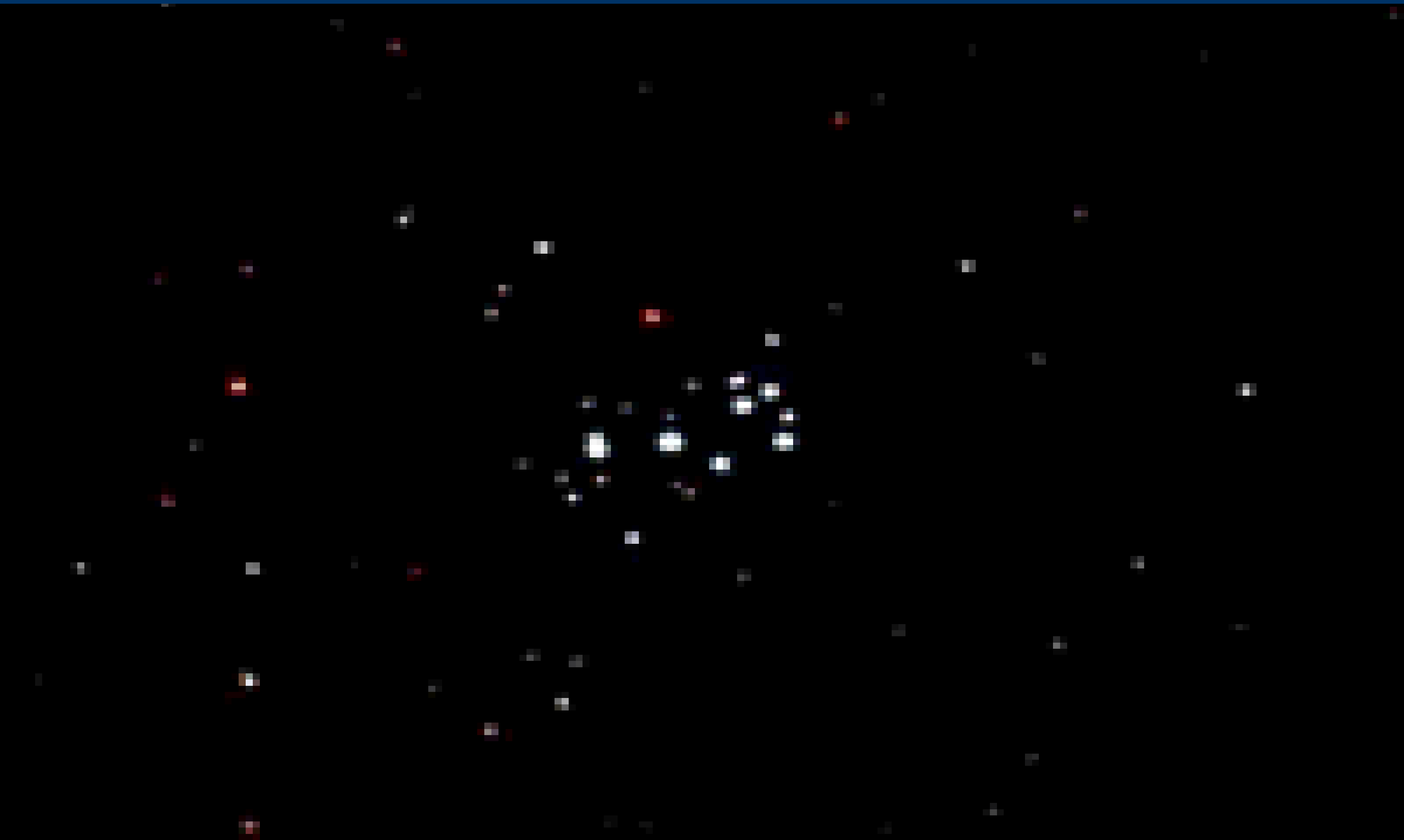
Dravins, Lindegren & Madsen, A&A 348, 1040

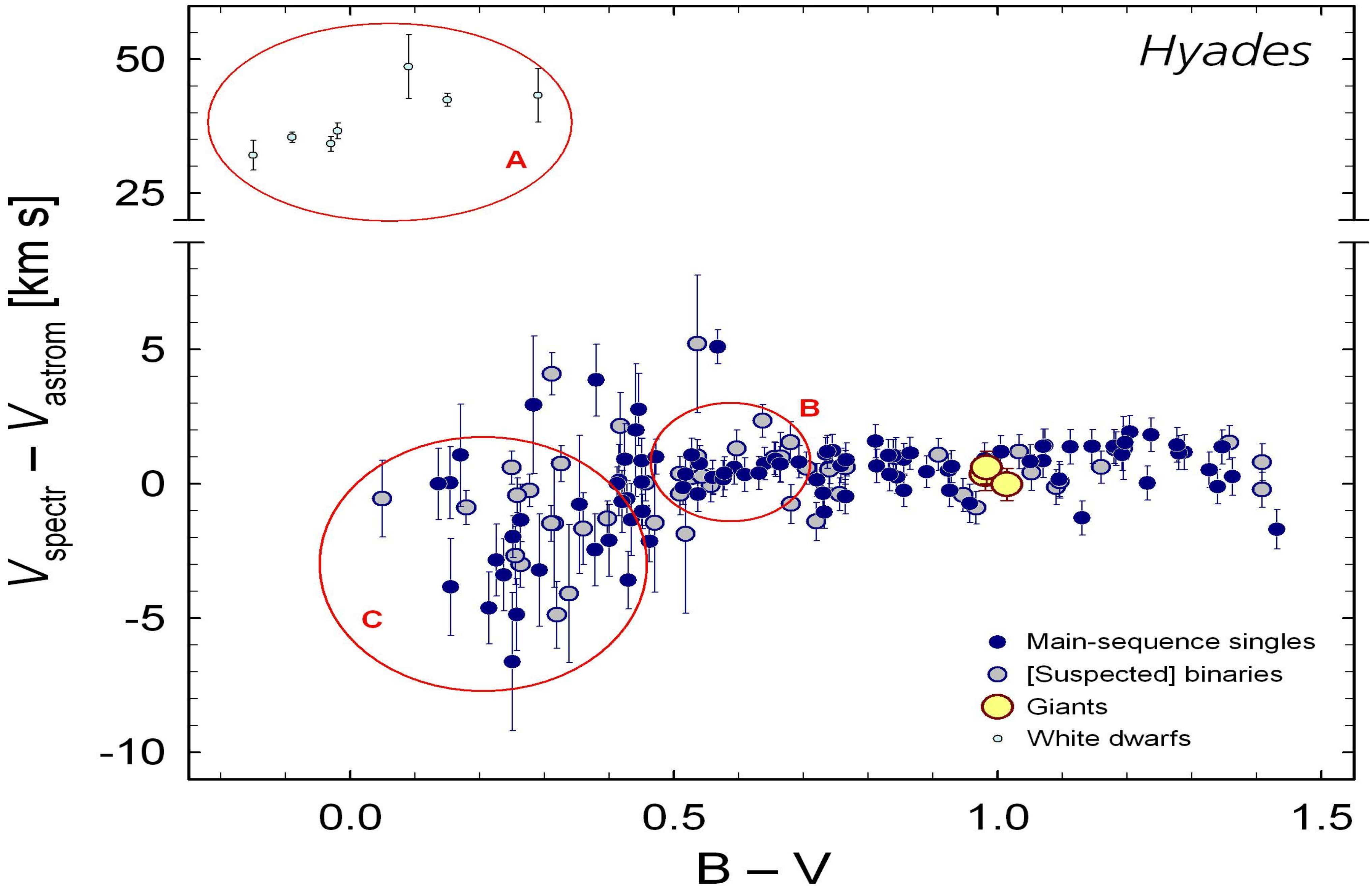
Astrometric radial velocities III



Pleiades from Hipparcos

Proper motions over 120,000 years





Hyades lineshifts *Madsen, Dravins & Lindegren, A&A* ***381***, *446*

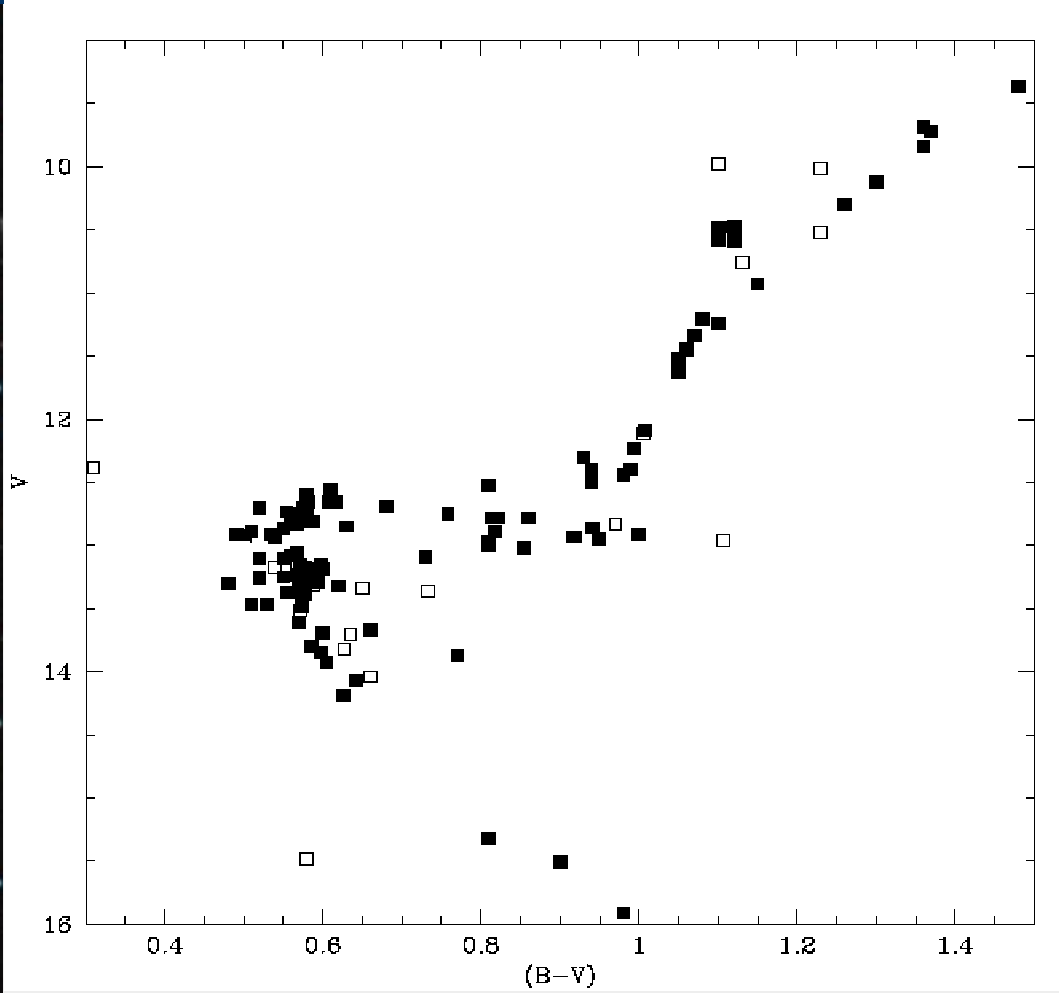
Differential velocities within open clusters

M67

Dean Jacobsen, astrophoto.net

Searching for gravitational redshifts in M67

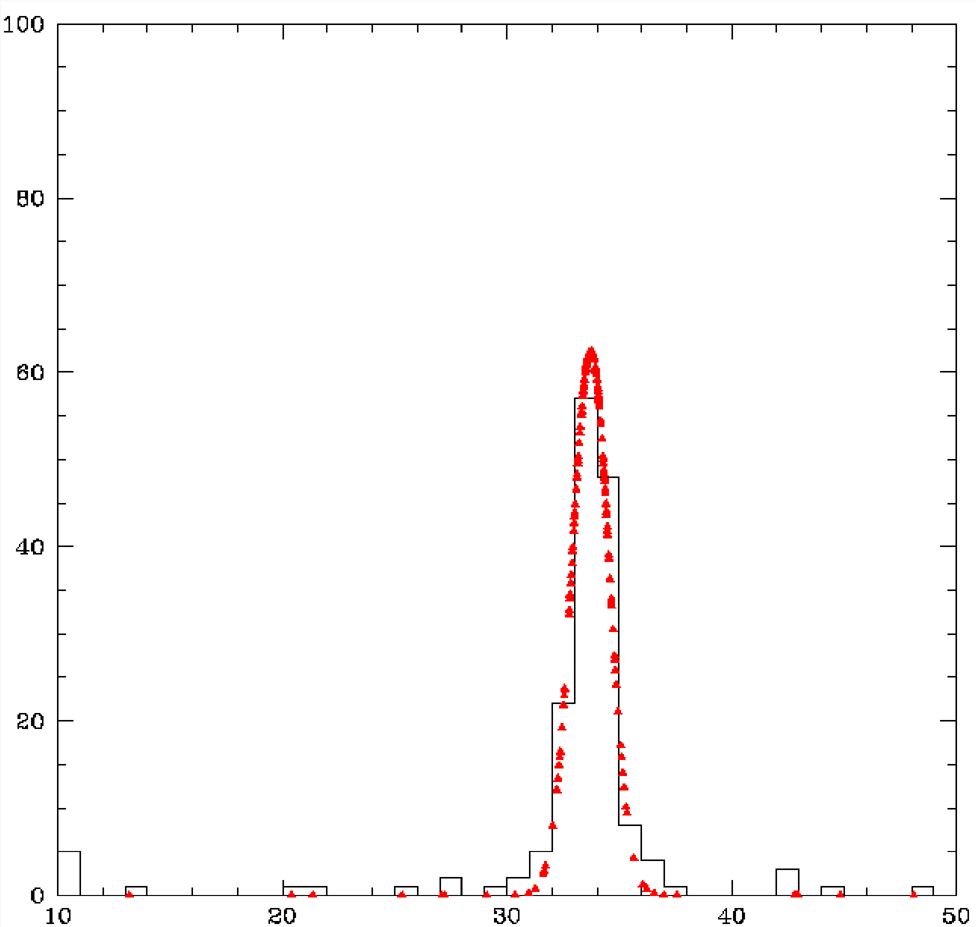
M67 (NGC 2682) open cluster in Cancer contains some 500 stars;
age about 2.6 Gy, distance 850 pc.



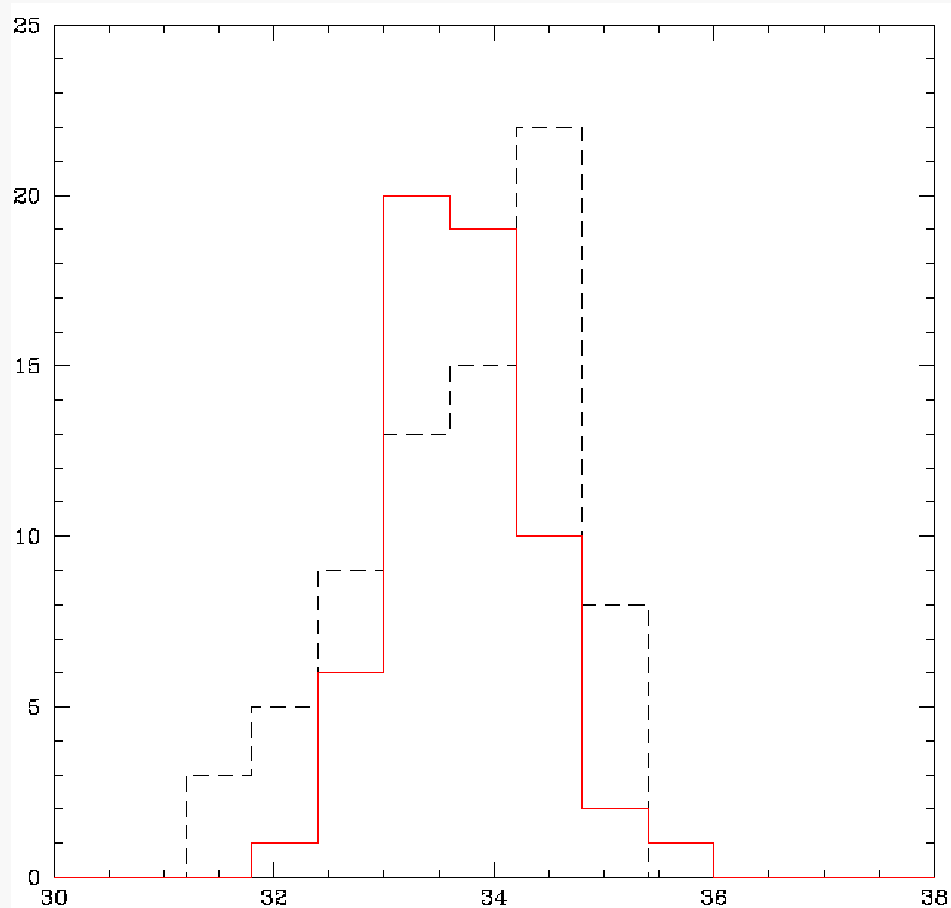
M67 color-magnitude diagram with well-developed giant branch.
Filled squares denote single stars.

L.Pasquini, C.Melo, C.Chavero, D.Dravins, H.-G.Ludwig, P.Bonifacio, R.De La Reza:
Gravitational redshifts in main-sequence and giant stars, A&A **526**, A127 (2011)

Searching for gravitational redshifts in M67



Radial velocities in M67 with a superposed Gaussian centered on Vr = 33.73, σ = 0.83 km s^{-1}

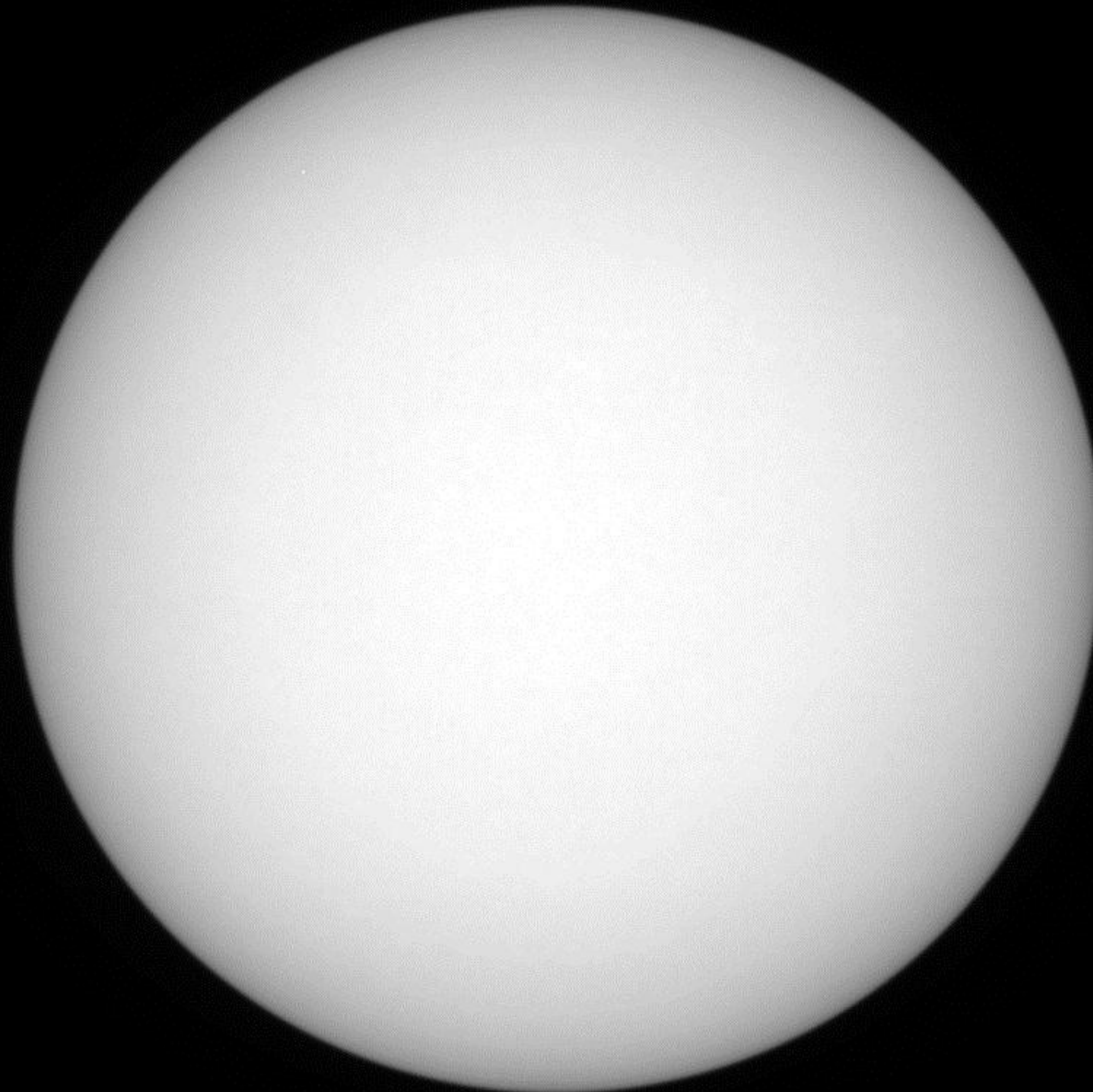


Radial velocities in M67:
No difference seen between giants (red) and dwarfs (dashed)

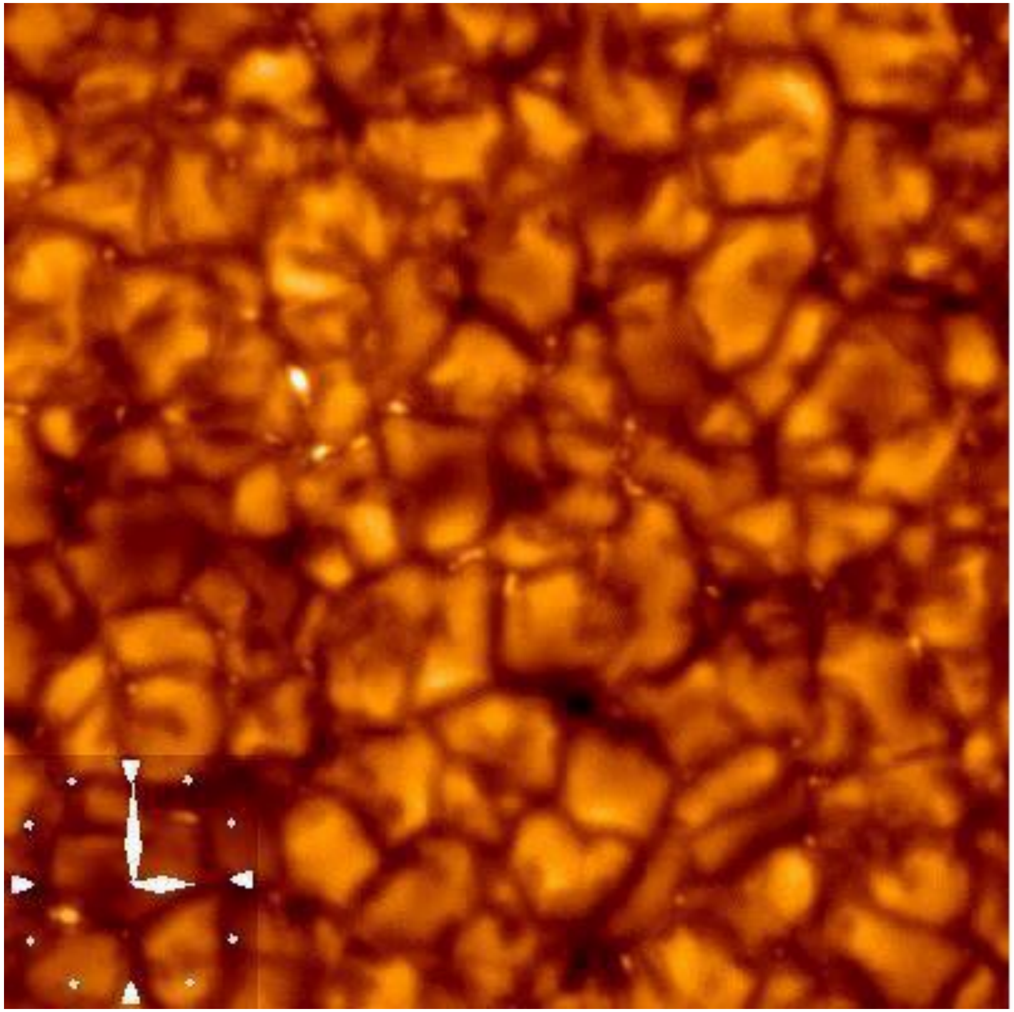
L.Pasquini, C.Melo, C.Chavero, D.Dravins, H.-G.Ludwig, P.Bonifacio, R.De La Reza:
Gravitational redshifts in main-sequence and giant stars, A&A **526**, A127 (2011)

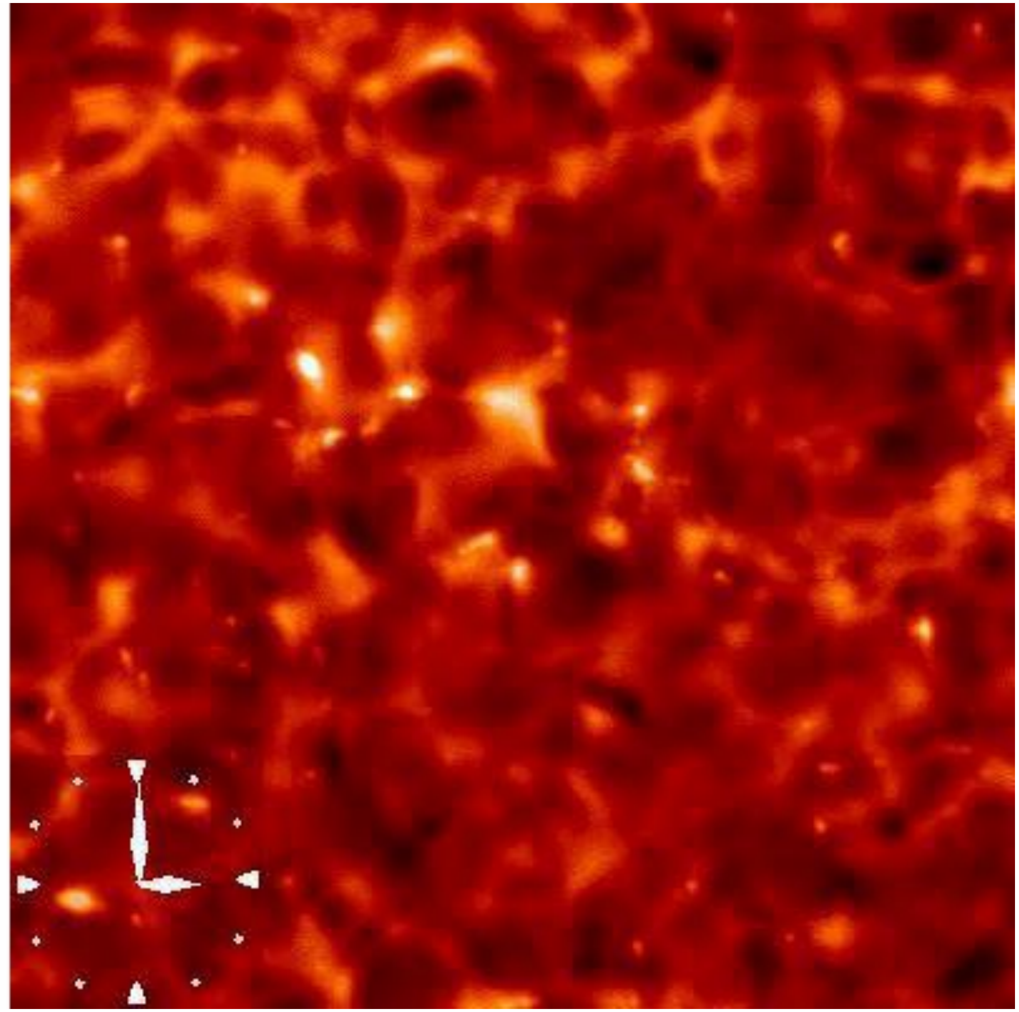
Real line formation

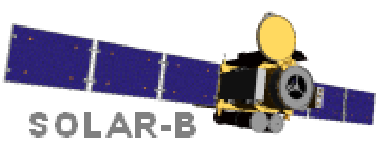
AN "IDEAL" STAR ?



Solar disk
June 12, 2009
GONG/Teide

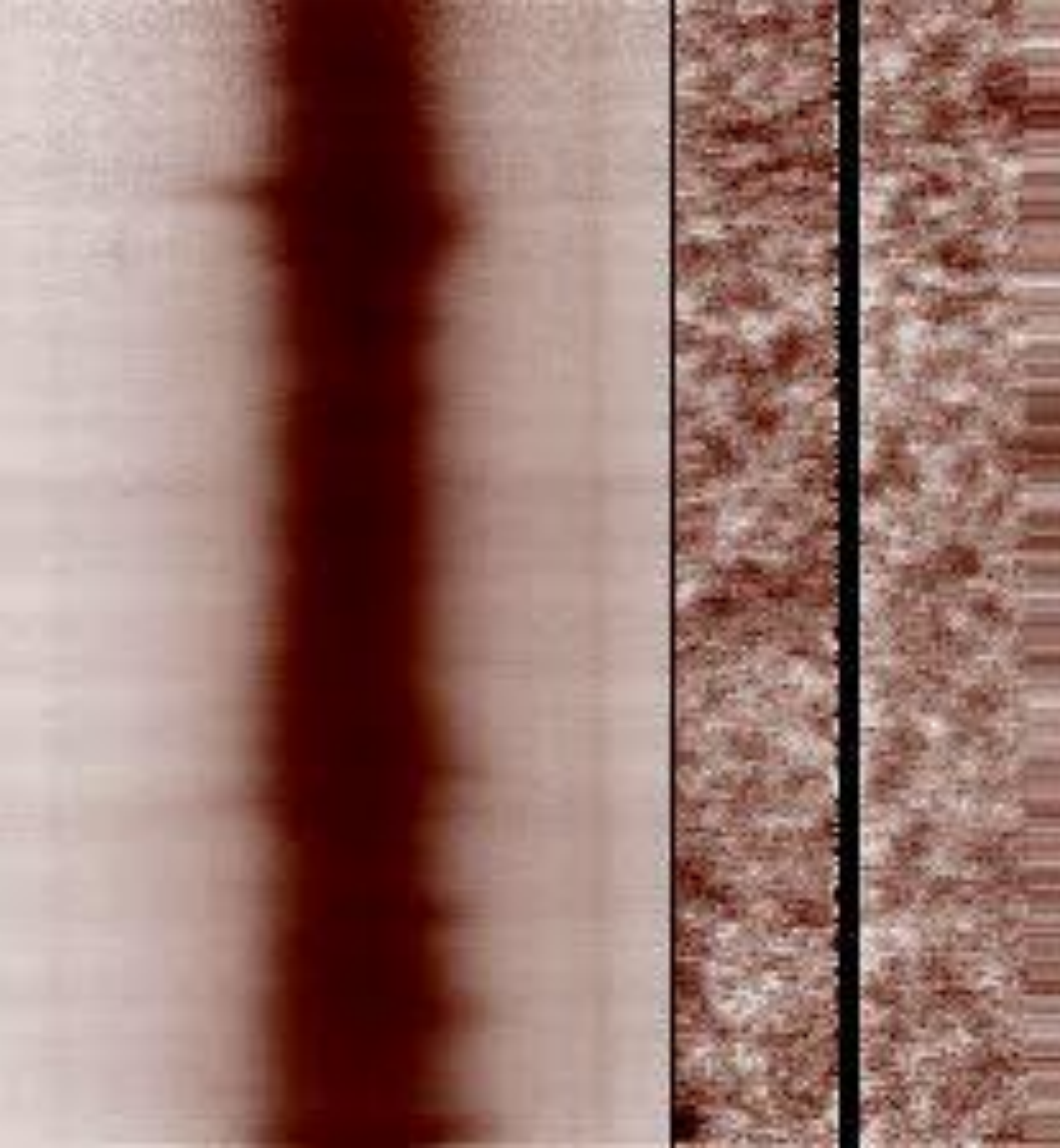






Solar Optical Telescope on board *HINODE* (Solar-B)

G-band (430nm) & Ca II H (397nm) movies



Spectral scan
across the solar surface.

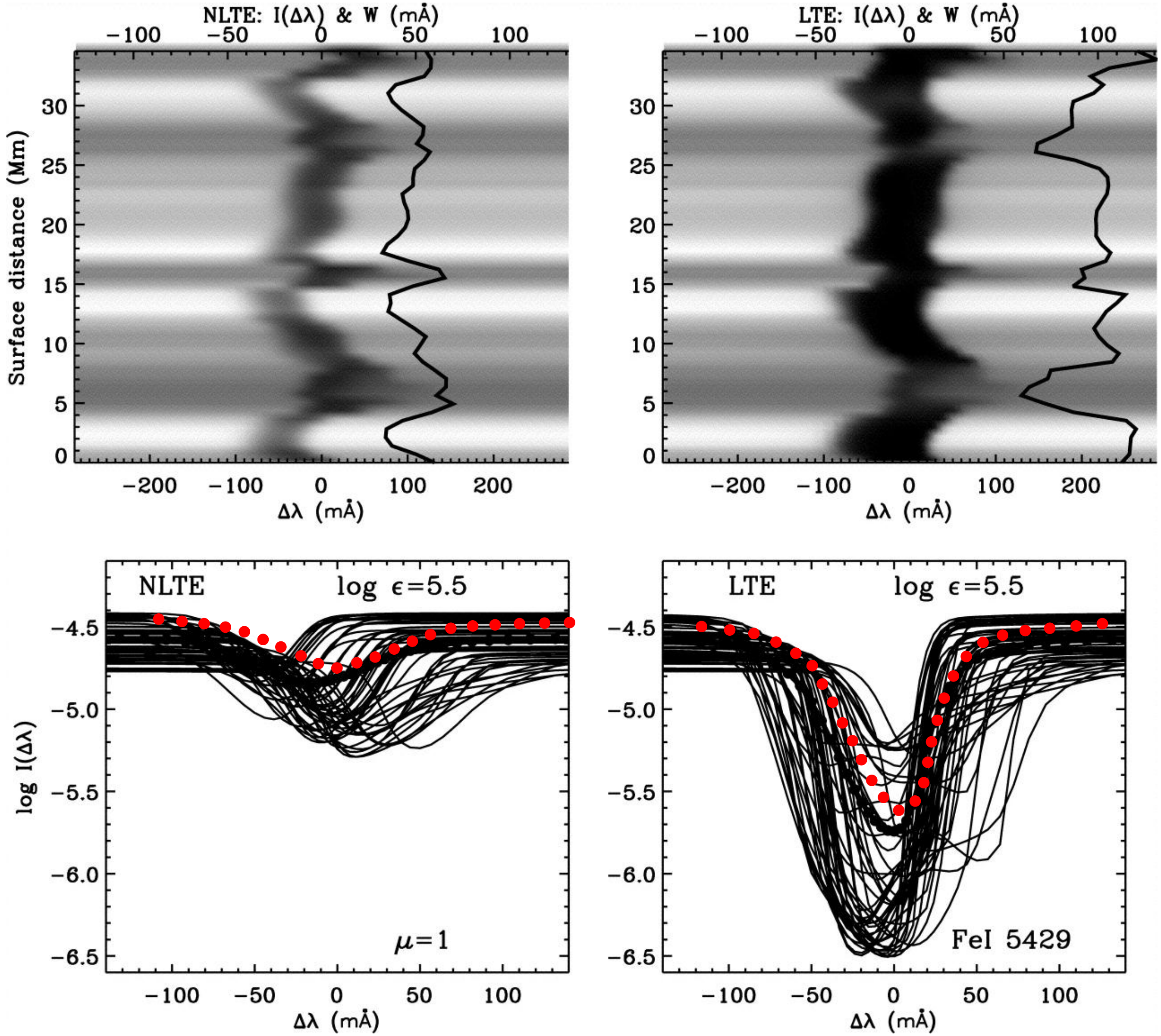
Left: H-alpha line

Right: Slit-jaw image

Big Bear Solar Observatory

“Wiggly” spectral lines of stellar granulation

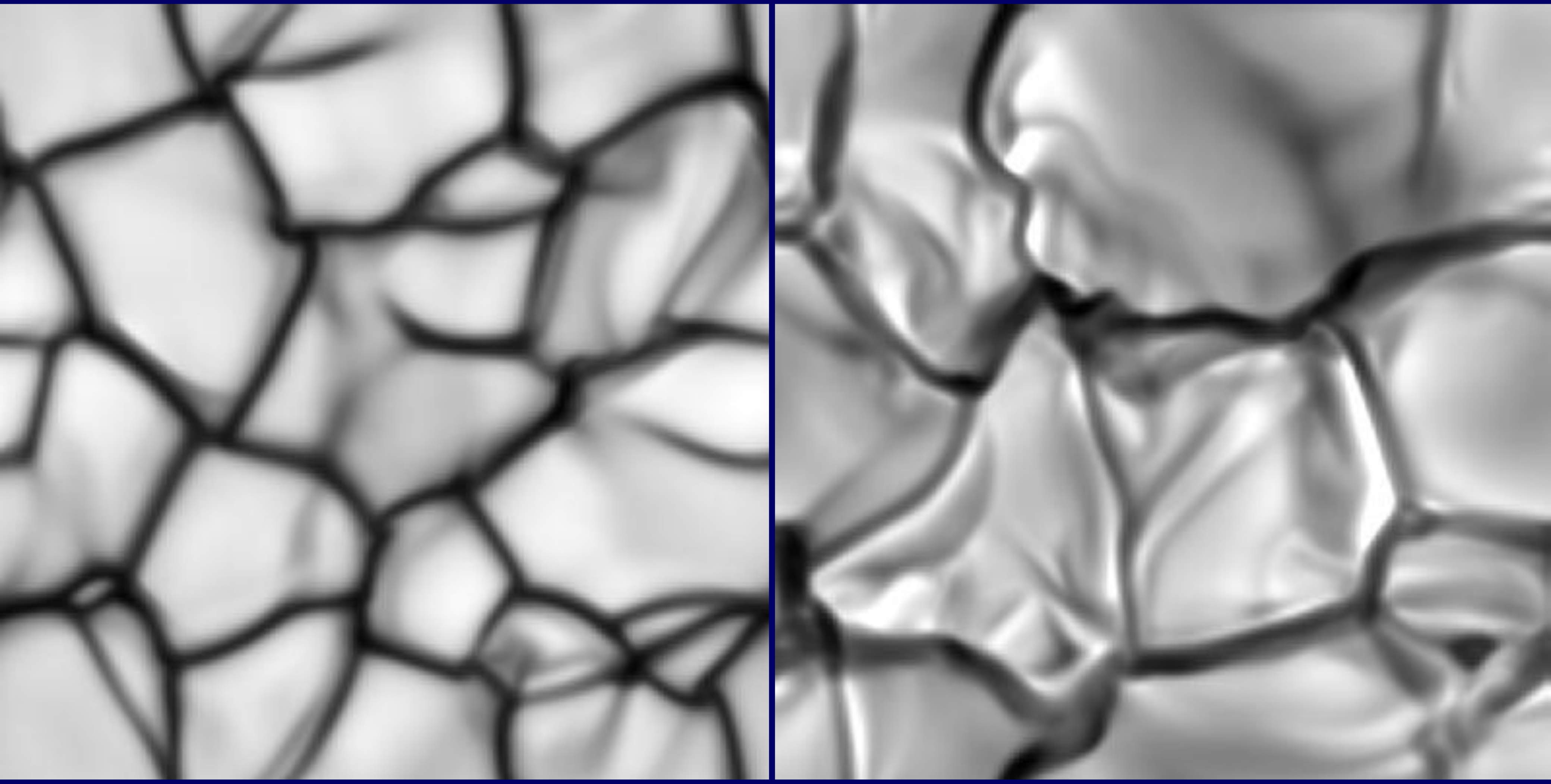
(modeled)



Disk-center Fe I profiles from 3-D hydrodynamic model of the metal-poor star HD 140283 in NLTE and LTE.
Top: Synthetic “wiggly-line” spectra across stellar surface. Curves show equivalent widths W along the slit.
Bottom: Spatially resolved profiles; average is red-dotted.
N.G.Shchukina, J.Trujillo Bueno, M.Asplund, *Astrophys.J.* **618**, 939 (2005)

Cool-star granulation causes convective lineshifts on order 300 m/s

STELLAR CONVECTION – White dwarf vs. Red giant



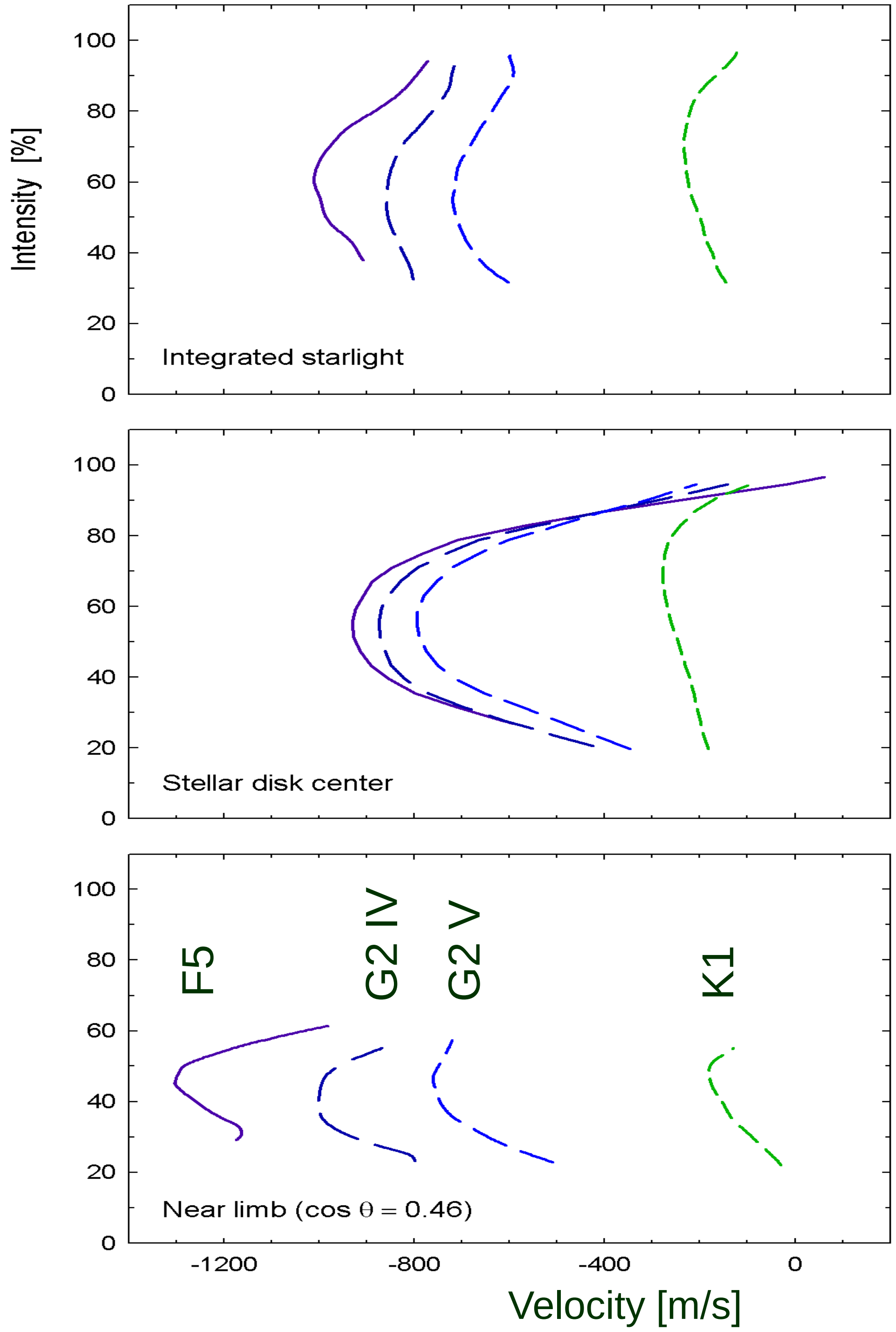
Snapshots of emergent intensity during granular evolution on a 12,000 K white dwarf (left) and a 3,800 K red giant. Horizontal areas differ by dozen orders of magnitude: 7x7 km^2 for the white dwarf, and 23x23 R_{Sun}^2 for the giant. (H.-G. Ludwig)

Bisectors of the same spectral line in different stars

Adapted from

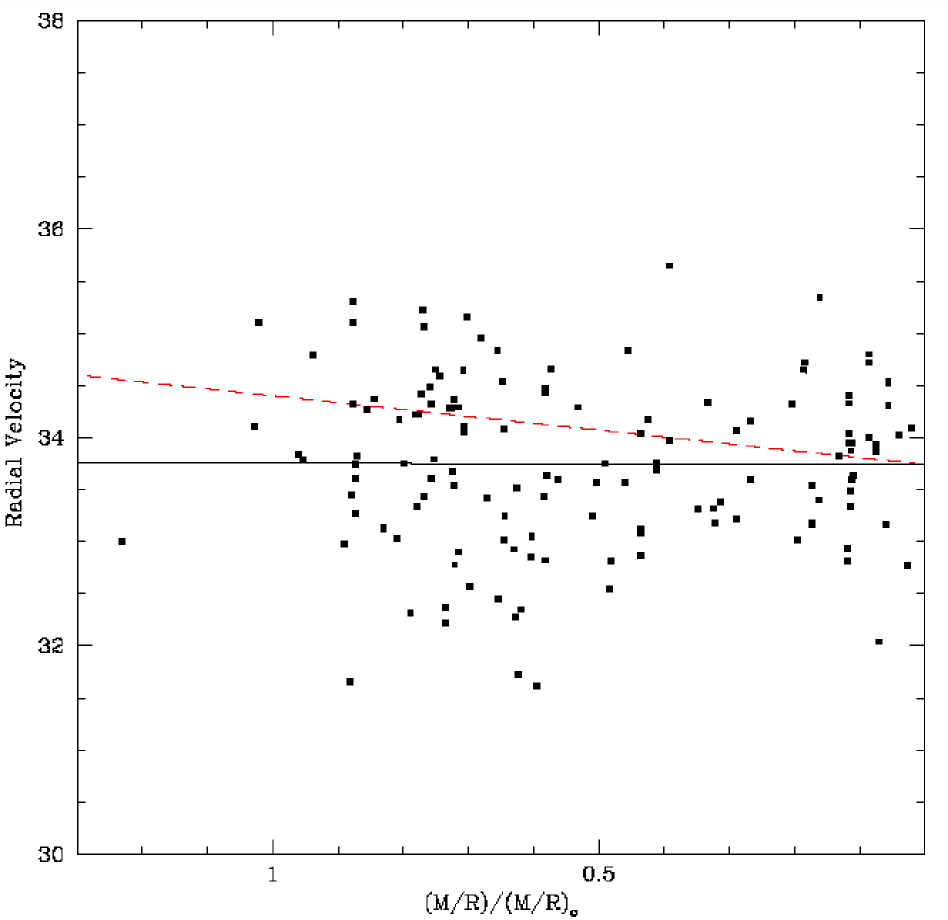
Dravins & Nordlund, A&A 228, 203

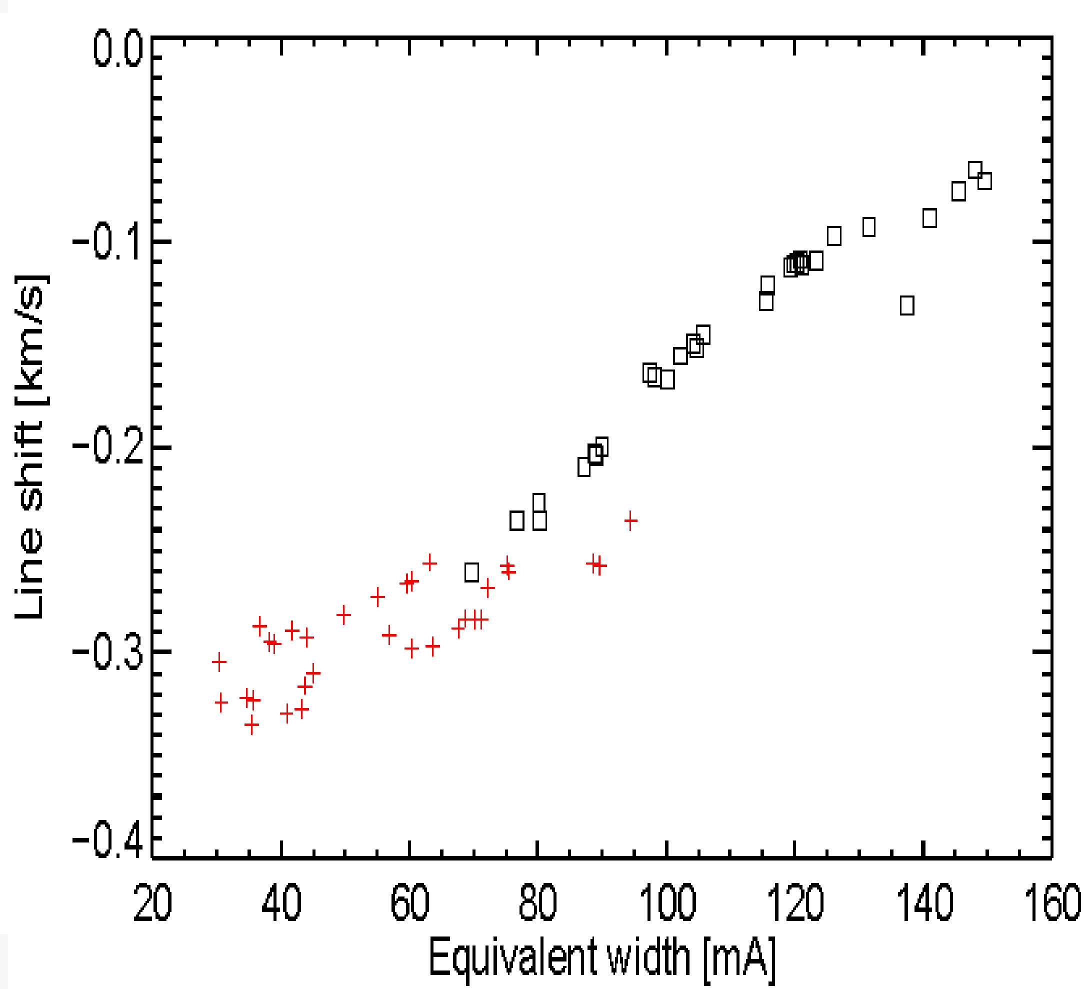
From left:
Procyon (F5 IV-V),
Beta Hyi (G2 IV),
Alpha Cen A (G2 V),
Alpha Cen B (K1 V).



In stars with "corrugated" surfaces, convective blueshifts increase towards the stellar limb

Searching for gravitational redshifts in M67



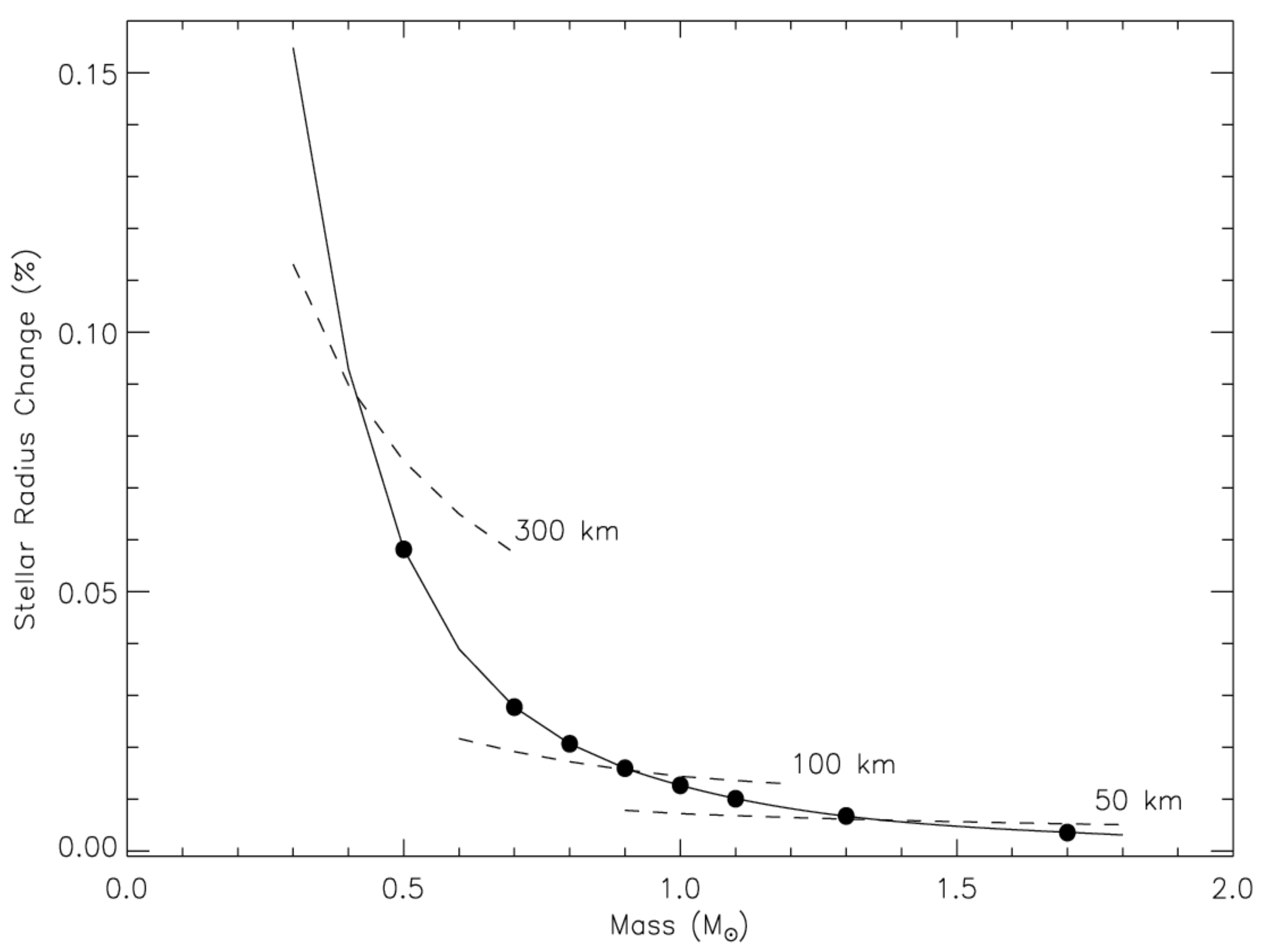


Gravitational redshift predictions vs. mass/radius ratio (M/R) (dashed red) do not agree with observations.

Calculated convective wavelength shifts for Fe I lines in dwarf (red crosses) and giant models (squares).

L.Pasquini, C.Melo, C.Chavero, D.Dravins, H.-G.Ludwig, P.Bonifacio, R.De La Reza: *Gravitational redshifts in main-sequence and giant stars*, A&A **526**, A127 (2011)

Variable gravitational redshift in variable stars?

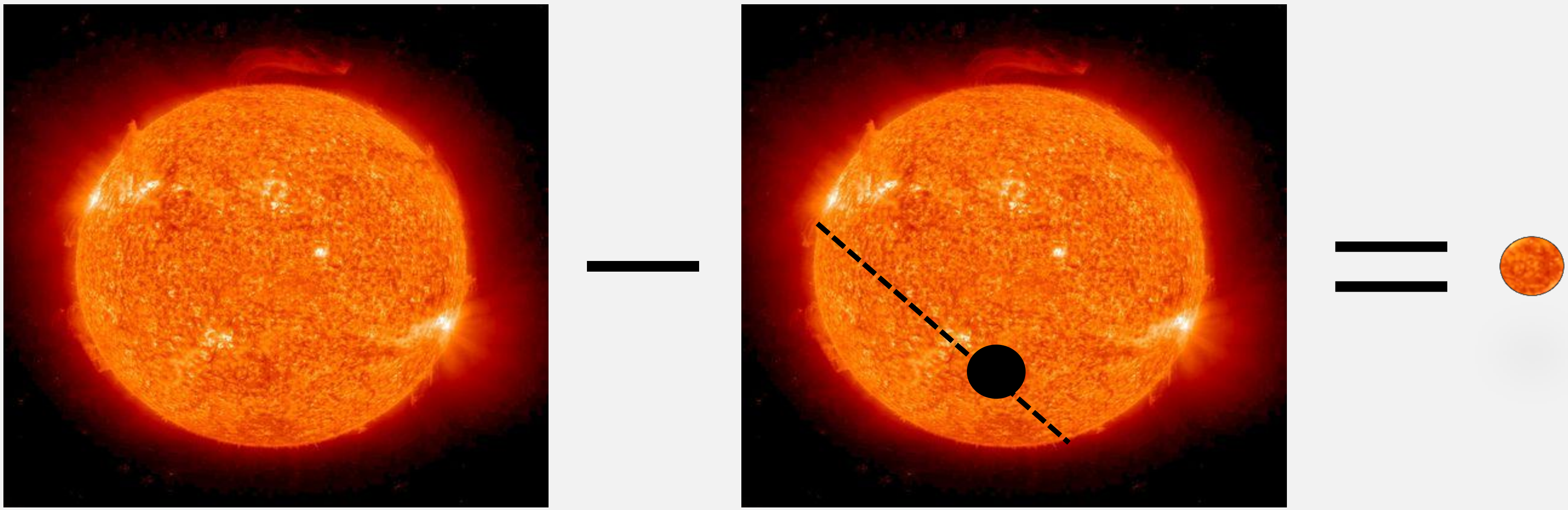


H.M.Cegla, C.A.Watson, T.R.Marsh, S.Shelyag, V.Moulds, S.Littlefair, M.Mathioudakis, D.Pollacco, X.Bonfils ***Stellar jitter from variable gravitational redshift: Implications for radial velocity confirmation of habitable exoplanets,*** MNRAS Lett. (2012)

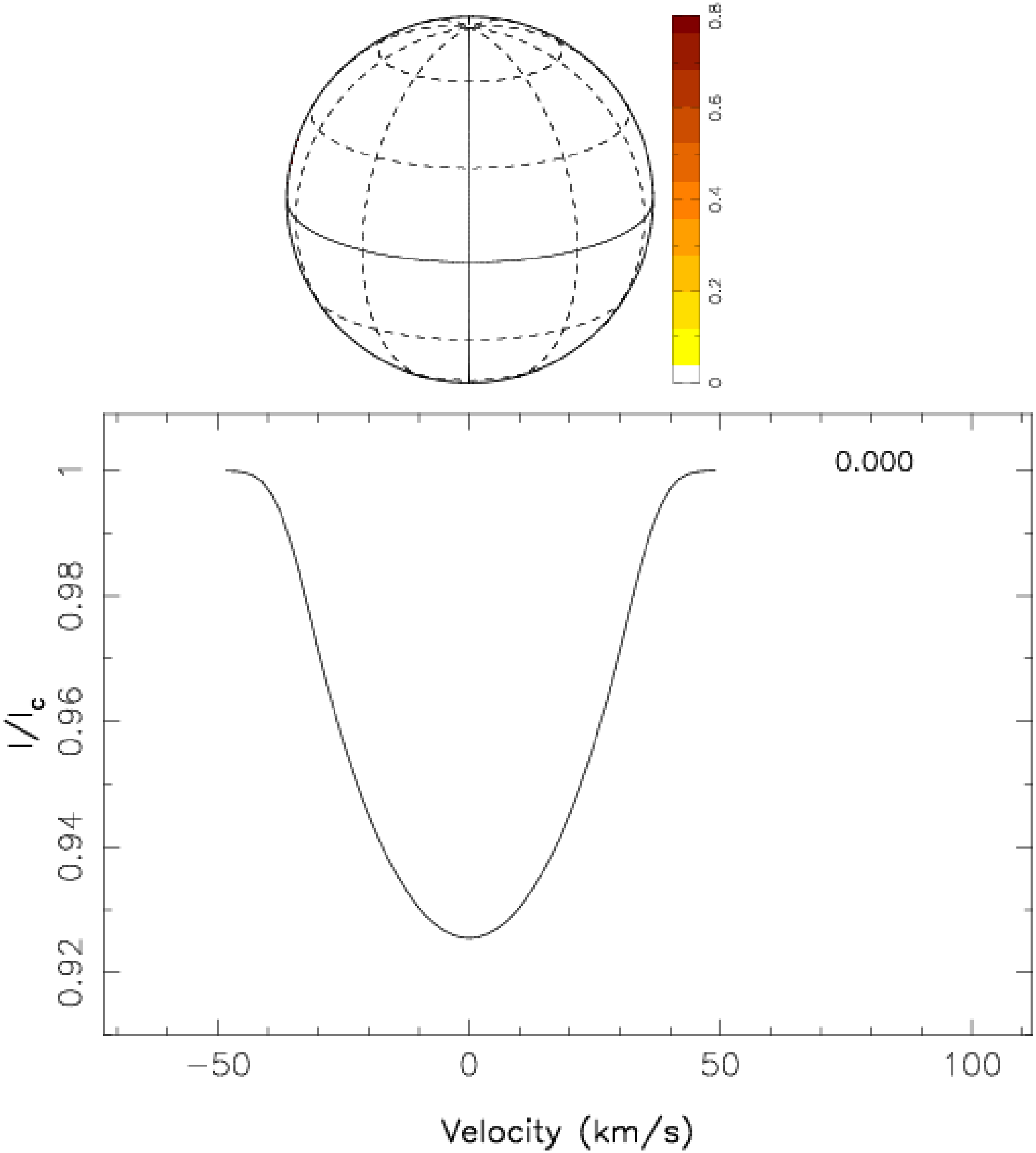
Stellar radius changes required to induce a δV_{grav} equivalent to an Earth-twin RV signal. Circles represent (right to left) spectral types: F0, F5, G0, G2, G5, K0, K5 and M0. Dashed curves represent stellar radius variations of 50, 100 and 300 km

Spatially resolved spectroscopy across stellar surfaces

Exoplanet transit



Selecting a small portion of the stellar disk

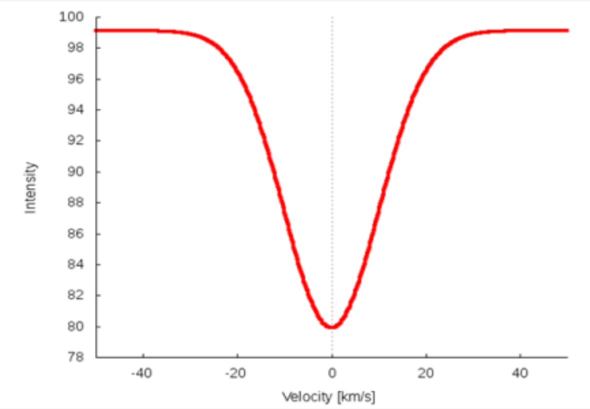


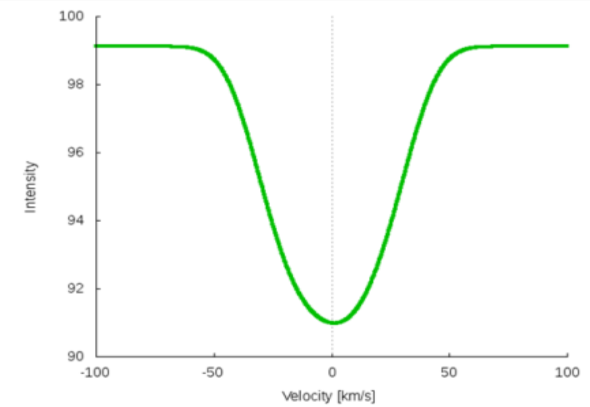
Doppler imaging of stellar surfaces

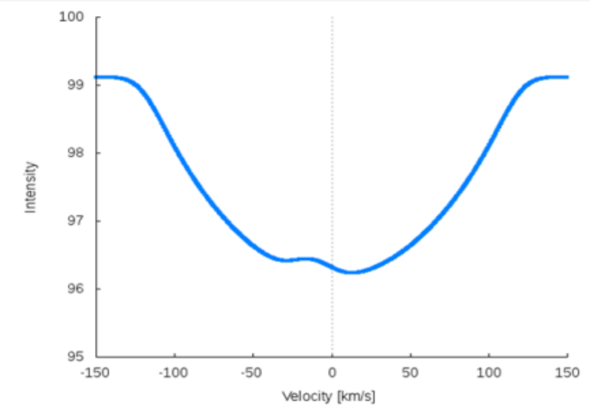
For a star with a dark spot close to the equator, spectral line profiles are affected throughout their whole Width, as the spot is carried around the star by rotation.

(Jean-François Donati)

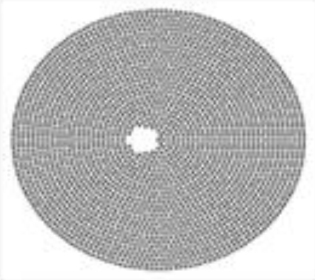
Spatially resolved stellar spectroscopy

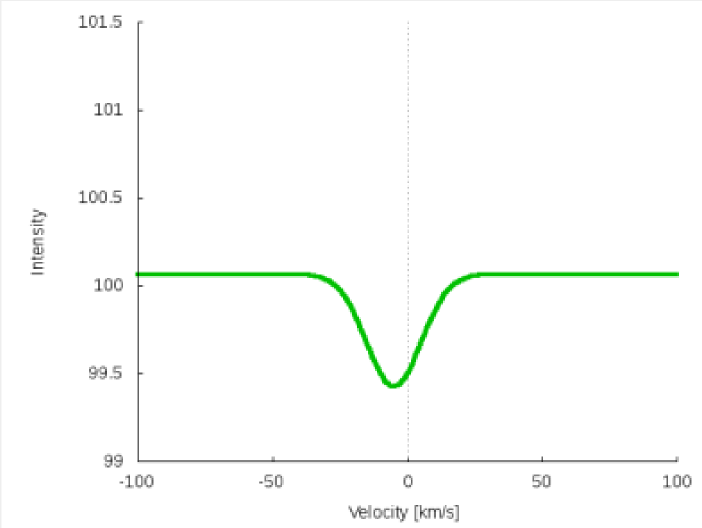






$$\frac{\textit{Planet position}}{\textit{Star radius}} = -0.1$$

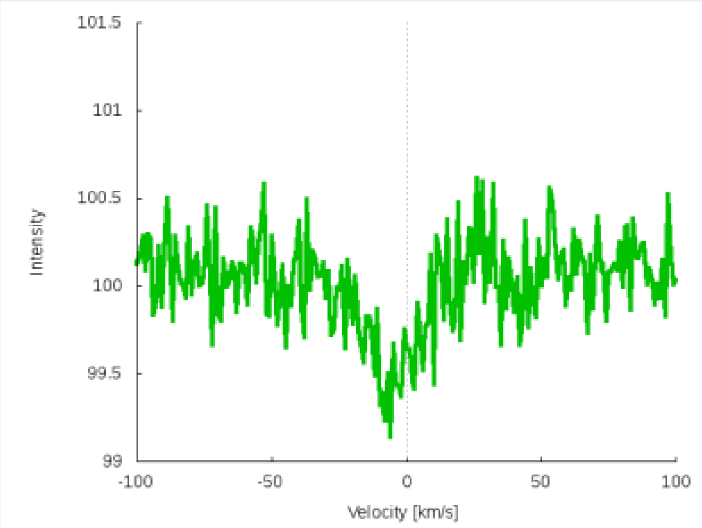




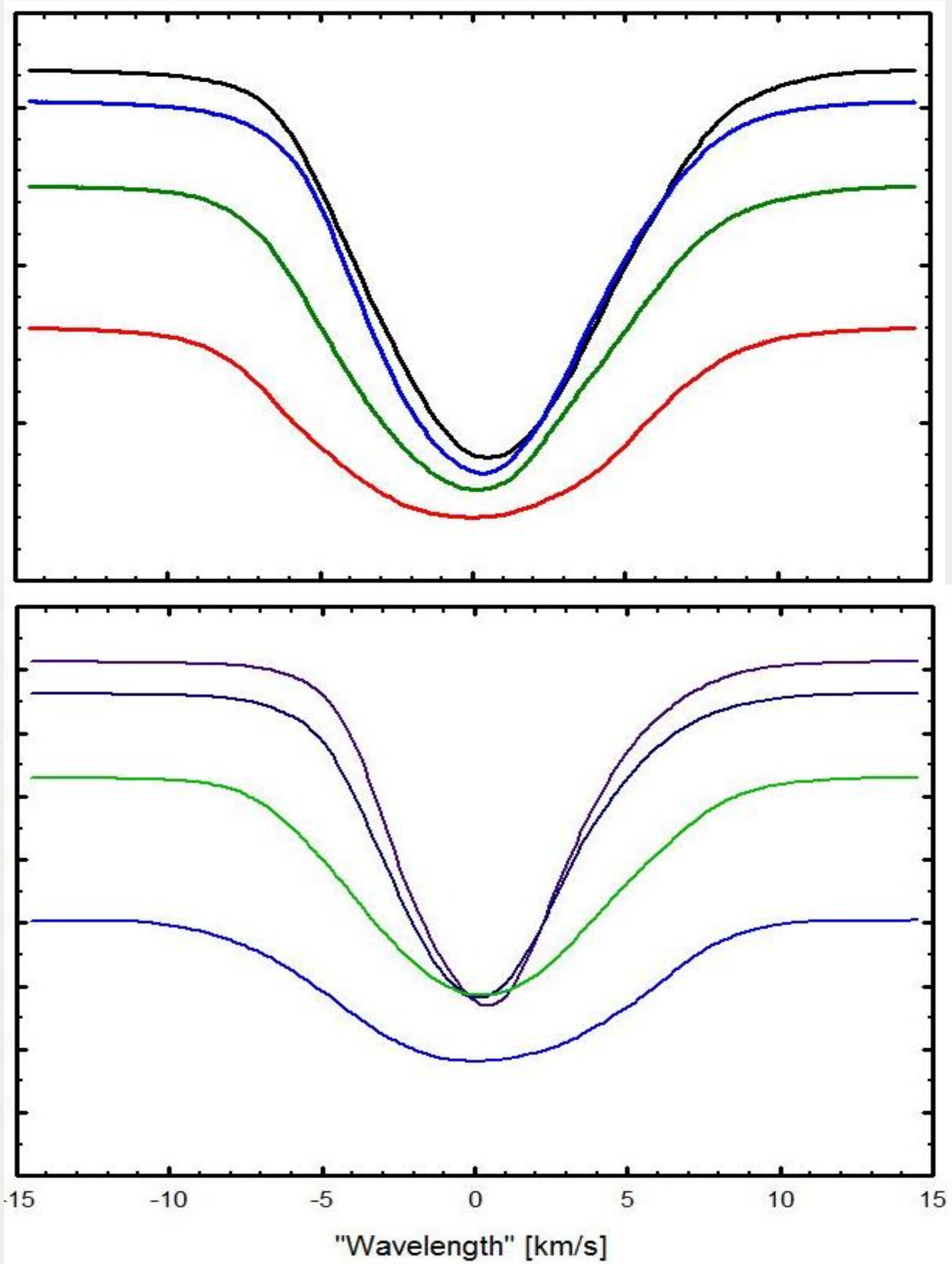
Left: Integrated line profiles
V_{rot} = 2, 40, 120 km/s

Right: Line behind planet
Top: Noise-free
Bottom: S/N = 300, R=300,000

(*Hiva Pazira,* Lund Observatory)



Spatially resolved stellar spectroscopy



Synthetic line profiles across stellar disks

Examples of synthetic line profiles from hydrodynamic 3-D stellar atmospheres.

Curves are profiles for different positions on the stellar disk, at some instant in time.

Black curves are at disk-center; lower intensities of other curves reflect the limb darkening.

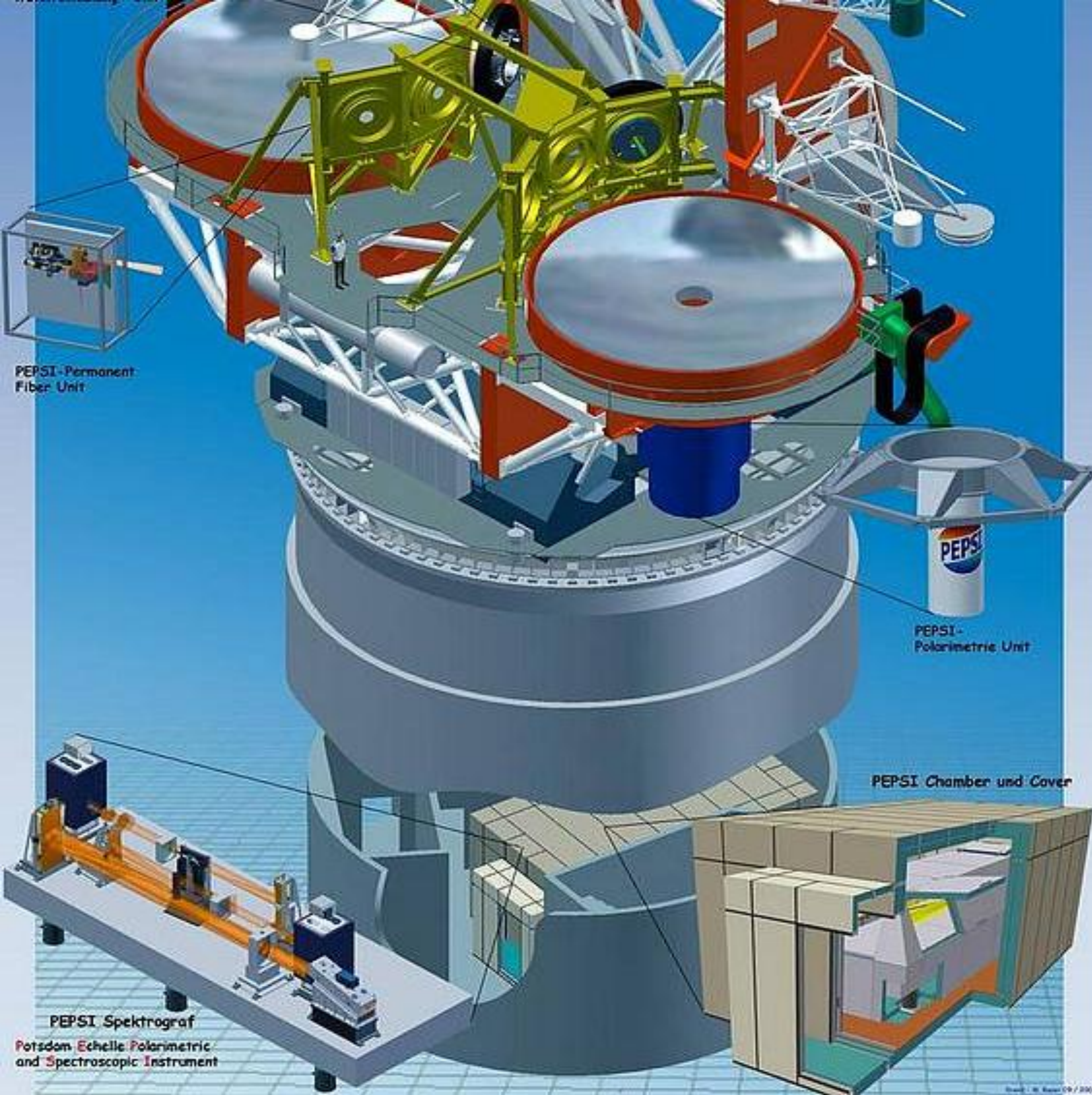
Top: Solar model; Fe I, λ 620 nm, χ 1 eV.
Bottom: Giant model; Fe I, λ 620 nm, χ 3 eV.

Disk locations $\cos\theta = \mu = 1, 0.87, 0.59, 0.21$.

Simulation by Hans-Günter Ludwig
(Landessternwarte Heidelberg)

Visual high-resolution spectrometers at 8-10 m telescopes

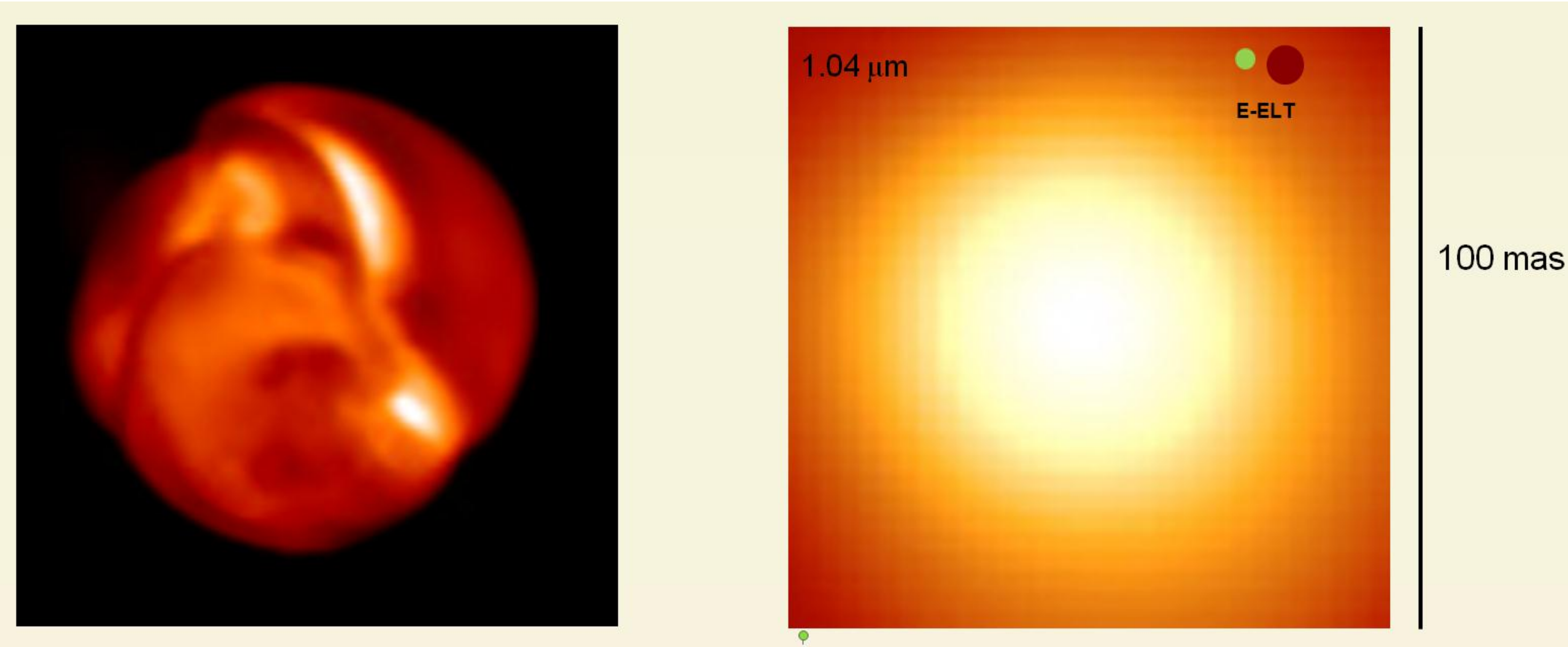
Telescope	**SALT** 	**Keck I** 	**VLT Kueyen** 	**HET** 	**Subaru** 	**LBT** 
Diameter [m]	10	10	8.2	9.2	8.2	2 × 8.4
Spectrometer	**HRS**	**HIRES**	**UVES**	**HRS**	**HDS**	**PEPSI**
Maximum R	65,000	84,000	110,000	120,000	160,000	320,000
Wavelengths [µm]	0.37– 0.89	0.3 – 1.0	0.3 – 1.1	0.39 – 1.1	0.3 – 1.0	0.38 – 0.91



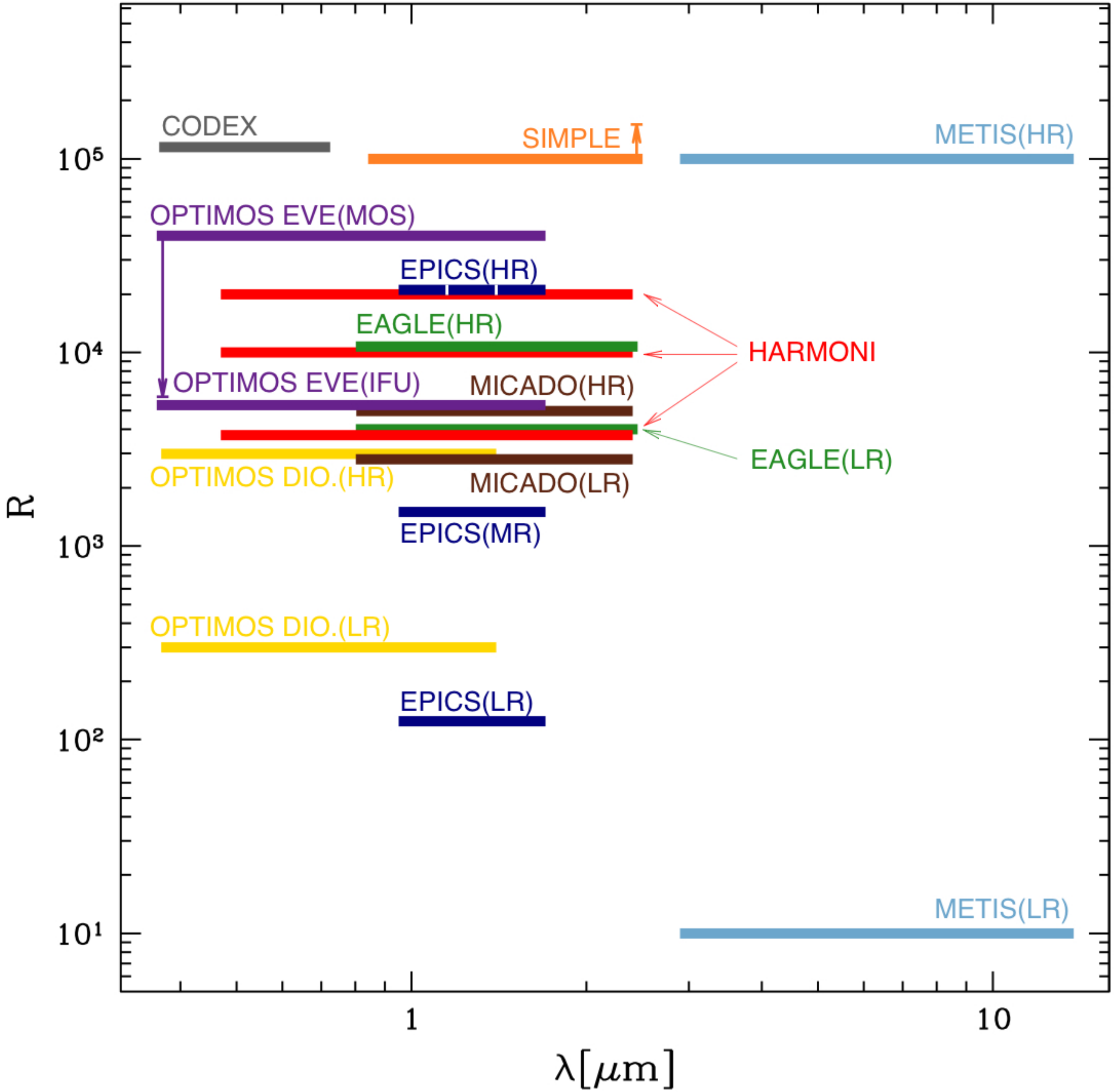
***Potsdam Echelle Polarimetric and Spectroscopic Instrument* @ Large Binocular Telescope**

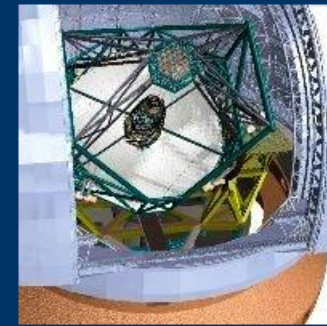
PEPSI

Spatially resolved spectroscopy with ELTs



Left: Hydrodynamic simulation of the supergiant Betelgeuse (B.Freytag)
Right: Betelgeuse imaged with ESO's 8.2 m VLT (Kervella et al., A&A, **504**, 115)
Top right: 40-m E-ELT diffraction limits at 550 nm & 1.04 µm..





Resolving power and spectral range of proposed E-ELT spectrographs

Grand challenge:
Design an efficient
R = 1,000,000
high-fidelity
spectrometer for E-ELT!

THE END