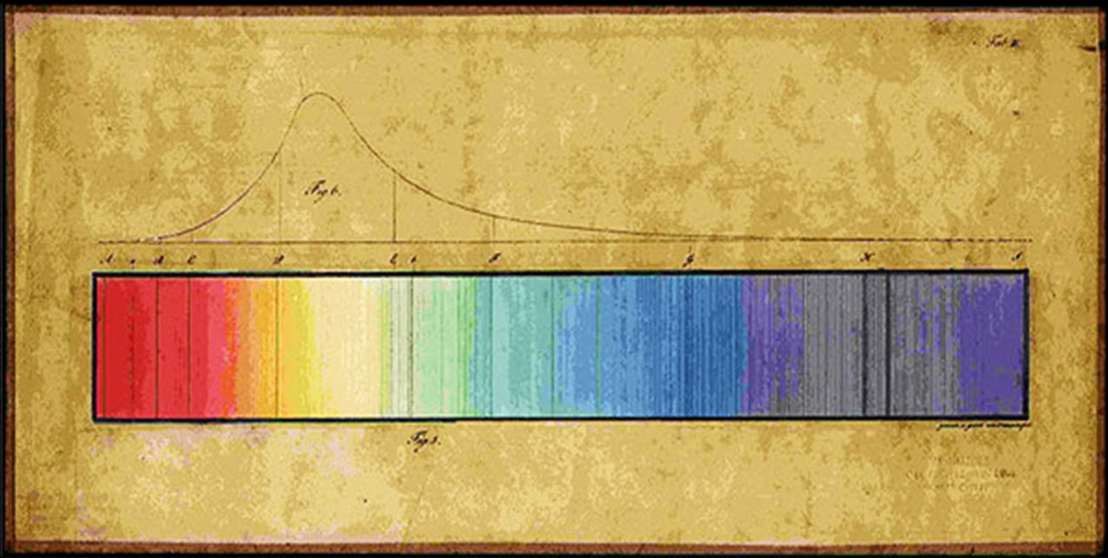
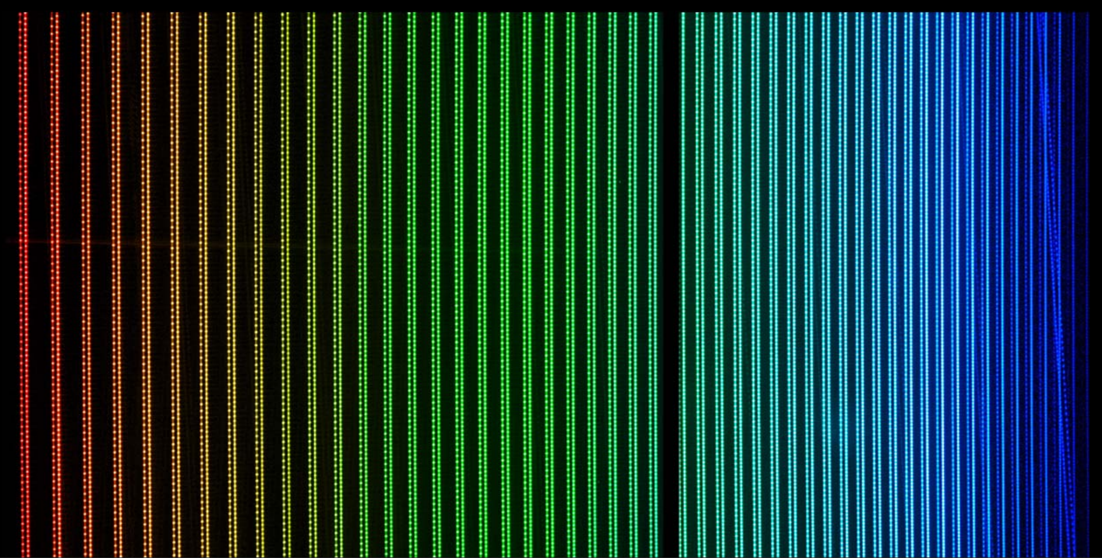




Fraunhofer's hand-colored map of the solar spectrum (ca. 1814; Deutsches Museum, München)

HARPS spectra of two laser frequency combs (ESO)

Spectral Fidelity

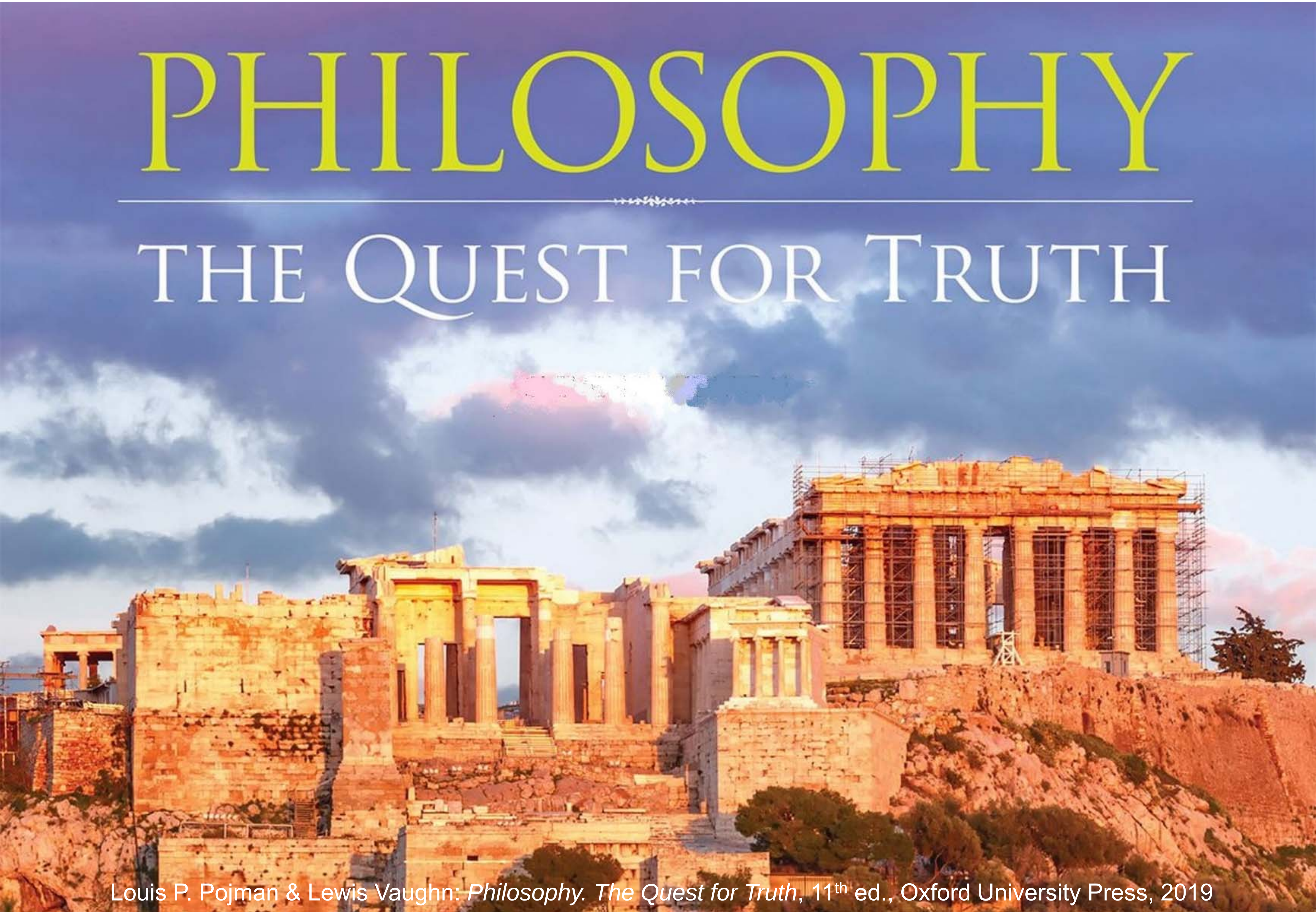
Opportunities, limitations, and future challenges

Dainis Dravins

Lund Observatory, Lund University, Sweden

www.astro.lu.se/~dainis

LUND UNIVERSITY



Louis P. Pojman & Lewis Vaughn: *Philosophy. The Quest for Truth*, 11th ed., Oxford University Press, 2019

What limits accuracy?

What requires S/N >>1000?

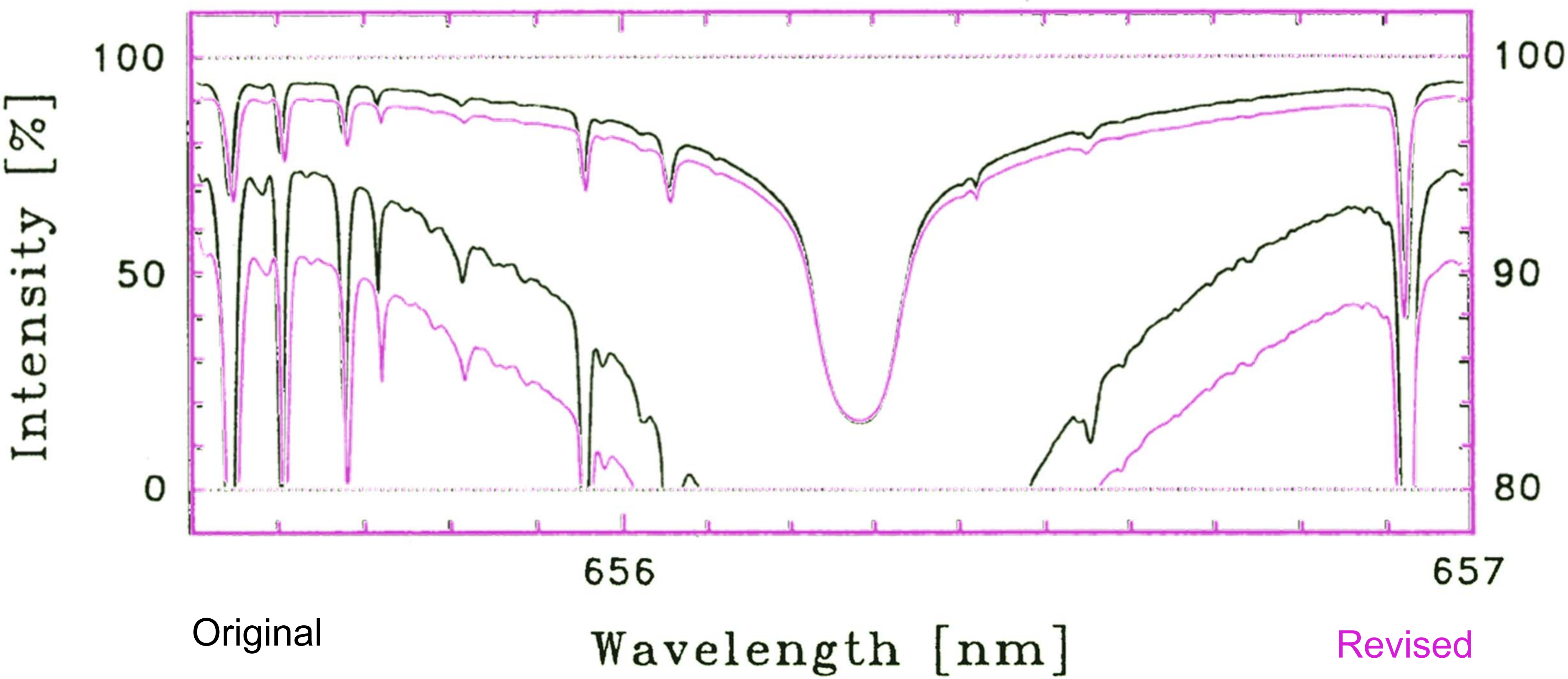
What requires $\lambda/\Delta\lambda$ = 1,000,000?

What requires post-CCD detectors?

What can still not be measured?

From precision to accuracy

Highest-precision atlases of the Solar spectrum



$\lambda/\Delta\lambda \approx 10^6$

S/N = 2000 or 20 ??

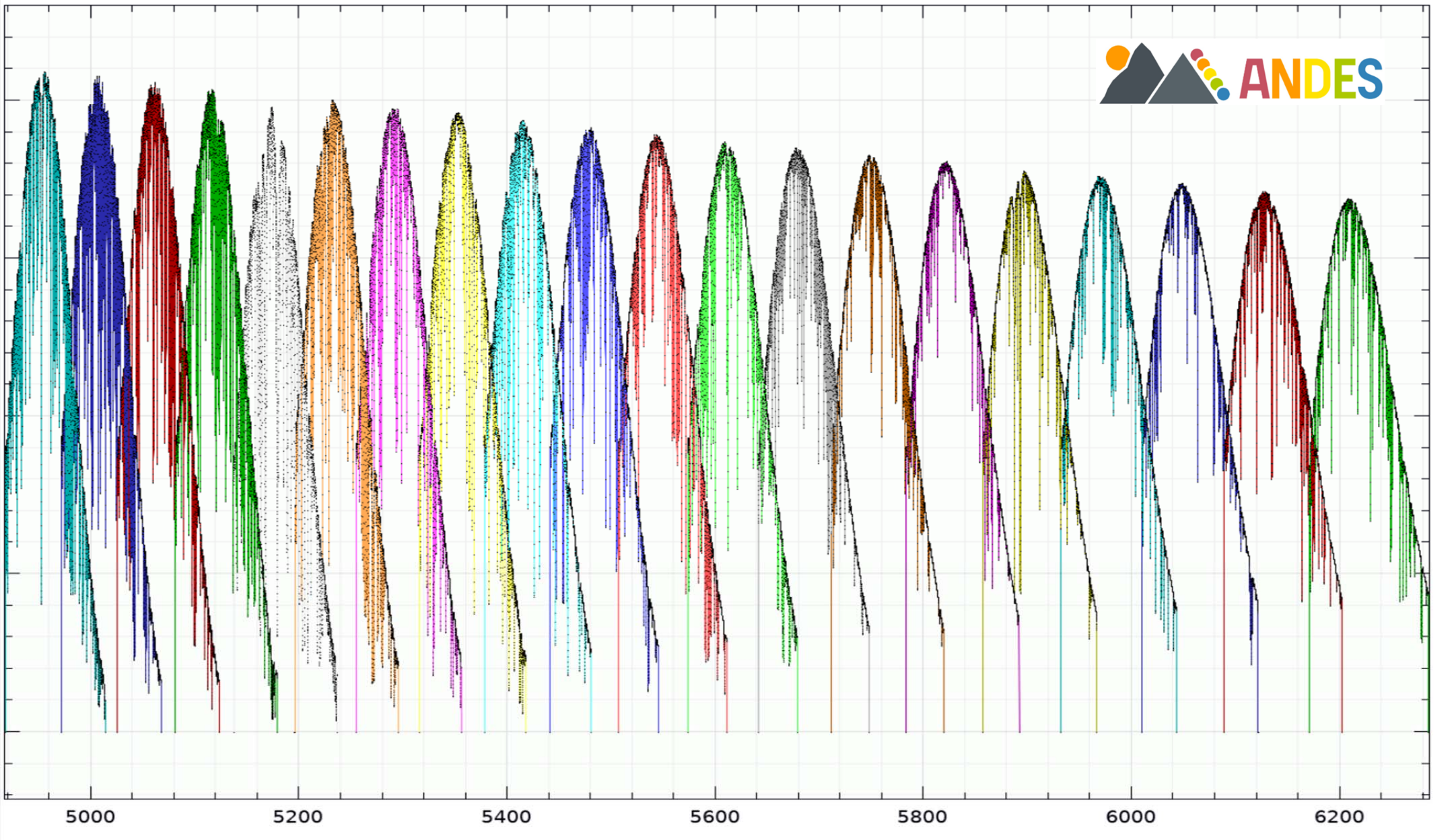
L.Delbouille, G.Roland, L.Neven

Atlas photométrique du spectre solaire de λ 3000 à λ 10000

Institut d'Astrophysique de l'Université de Liège, Observatoire Royal de Belgique, 1973-1988 – this revision 1979

What is limiting the fidelity ?

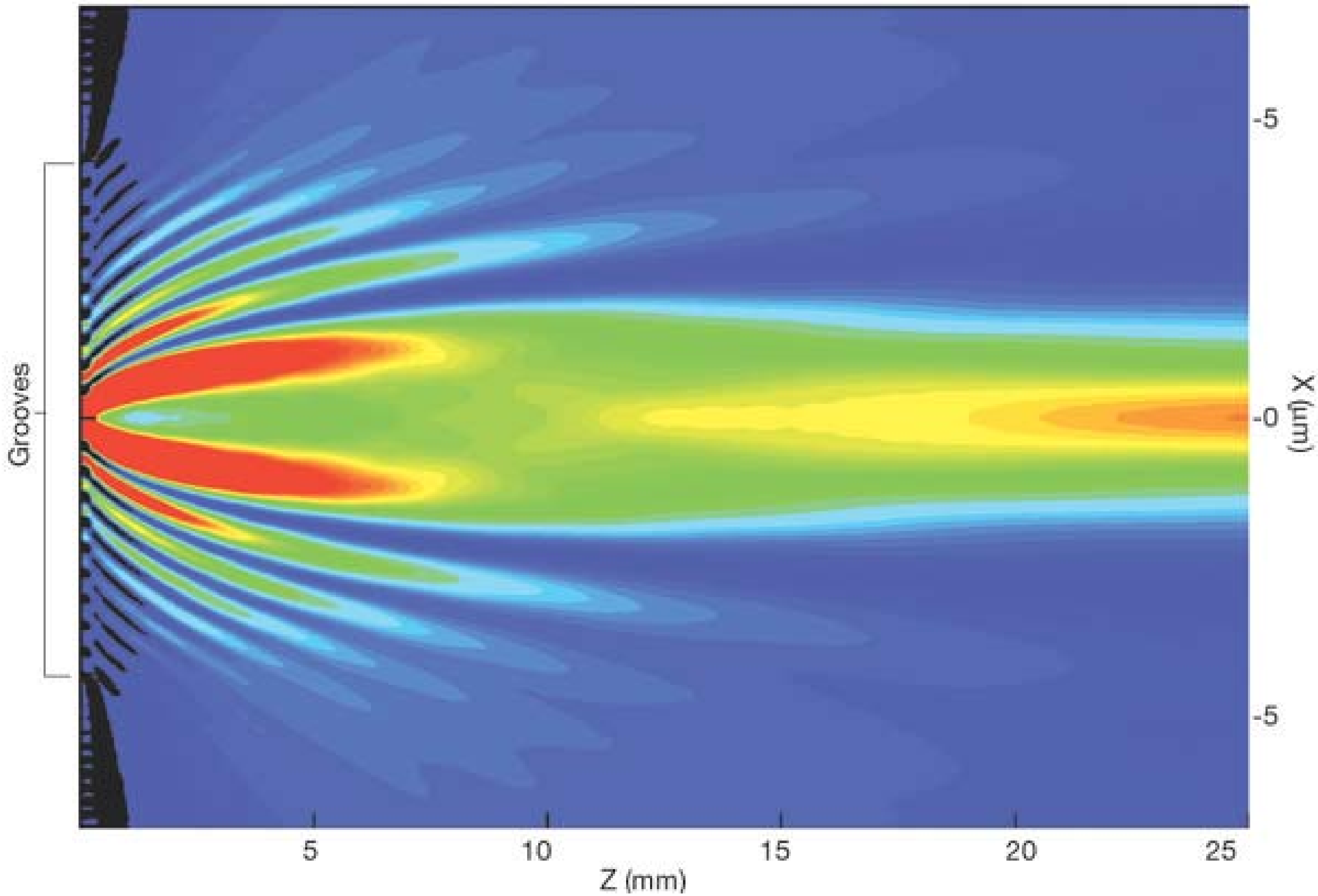
Continuum calibration issues



Simulated extracted solar spectrum from the ANDES spectrometer @ ELT

Michael Weber, Manfred Woche, Ilya Ilyin, Klaus G. Strassmeier, Ernesto Oliva:
ANDES, the high resolution spectrometer for the ELT: The UBV spectrograph module
Proc. SPIE **12184**, 1218439 (2022)

Grating physics is complex…

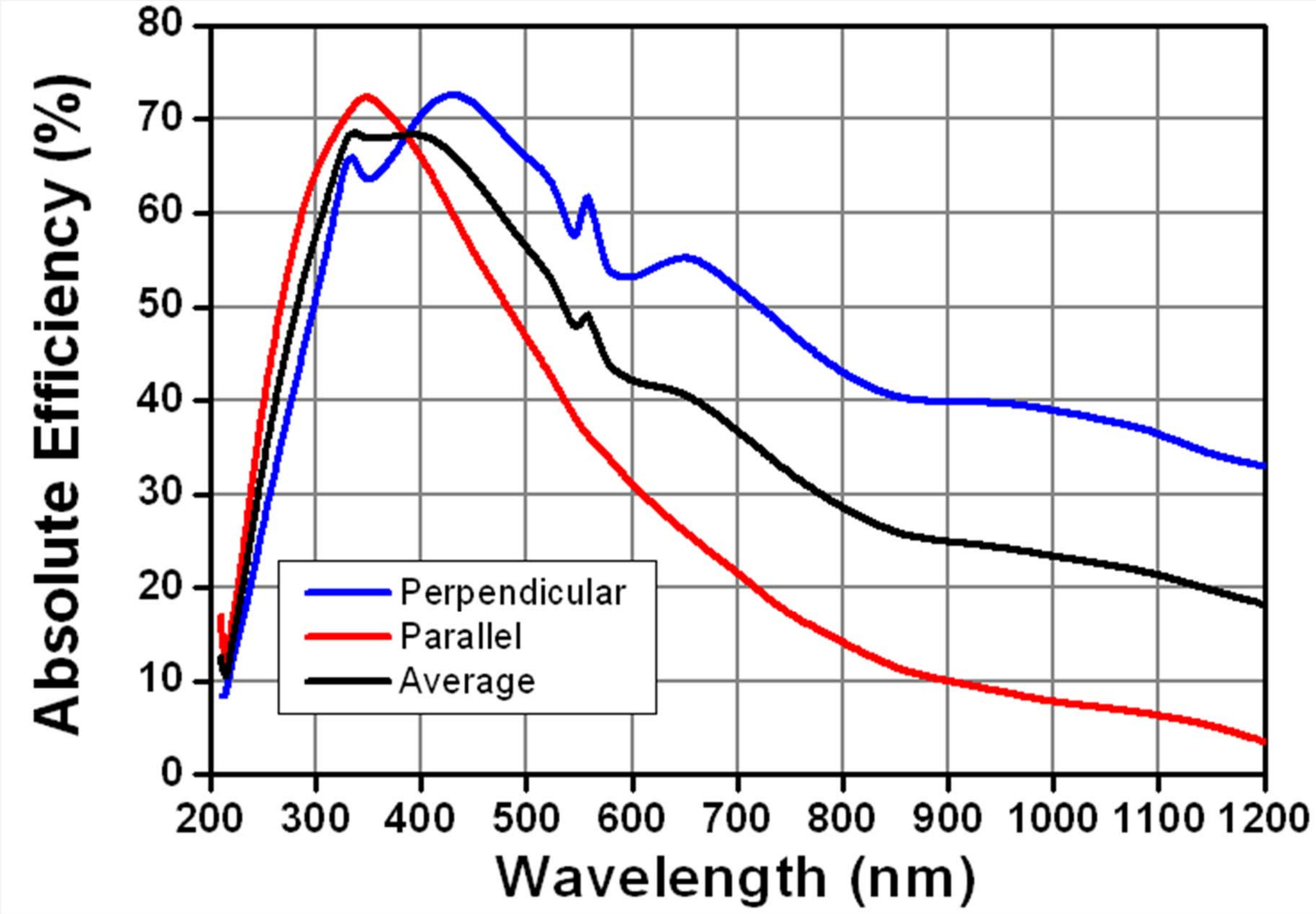


Calculated pattern of light emerging from a slit surrounded by an array of grooves

Simulation with 10 grooves on each side of the slit, each 40 nm wide and 100 nm deep, with period 500 nm. The plot shows the spatial dependence of the component of the Poynting vector along the radial direction for a wavelength of 560 nm (spectral transmission maximum). Blue denotes low intensity, and red high.

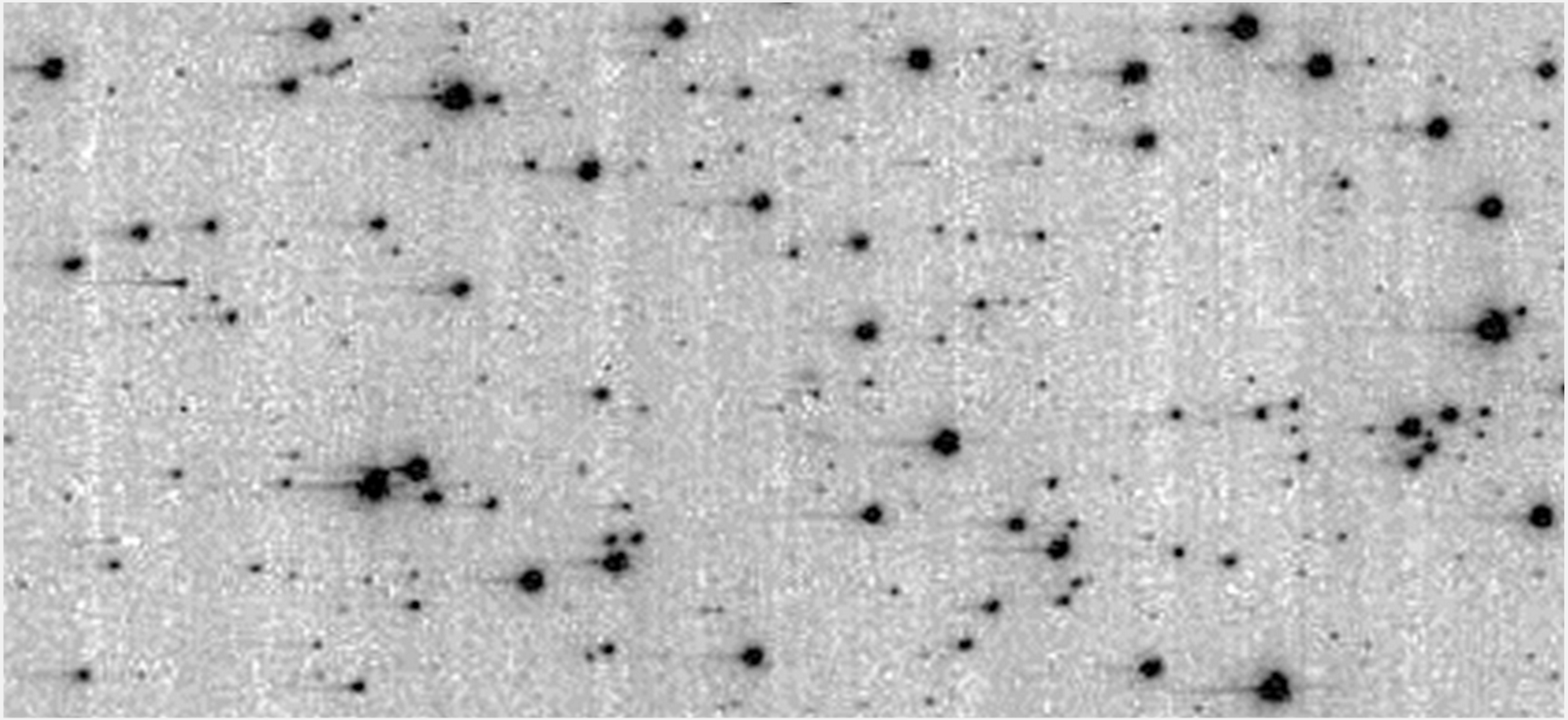
(W.L.Barnes, A.Dereux, T.W.Ebbesen: *Surface plasmon subwavelength optics,* Nature **424**, 824,2003)

Efficiency curves for diffraction gratings



Grating efficiency curves for a ruled diffraction gating in different linear polarizations
Blaze at 400 nm; 1200 grooves/mm (ThorLabs)

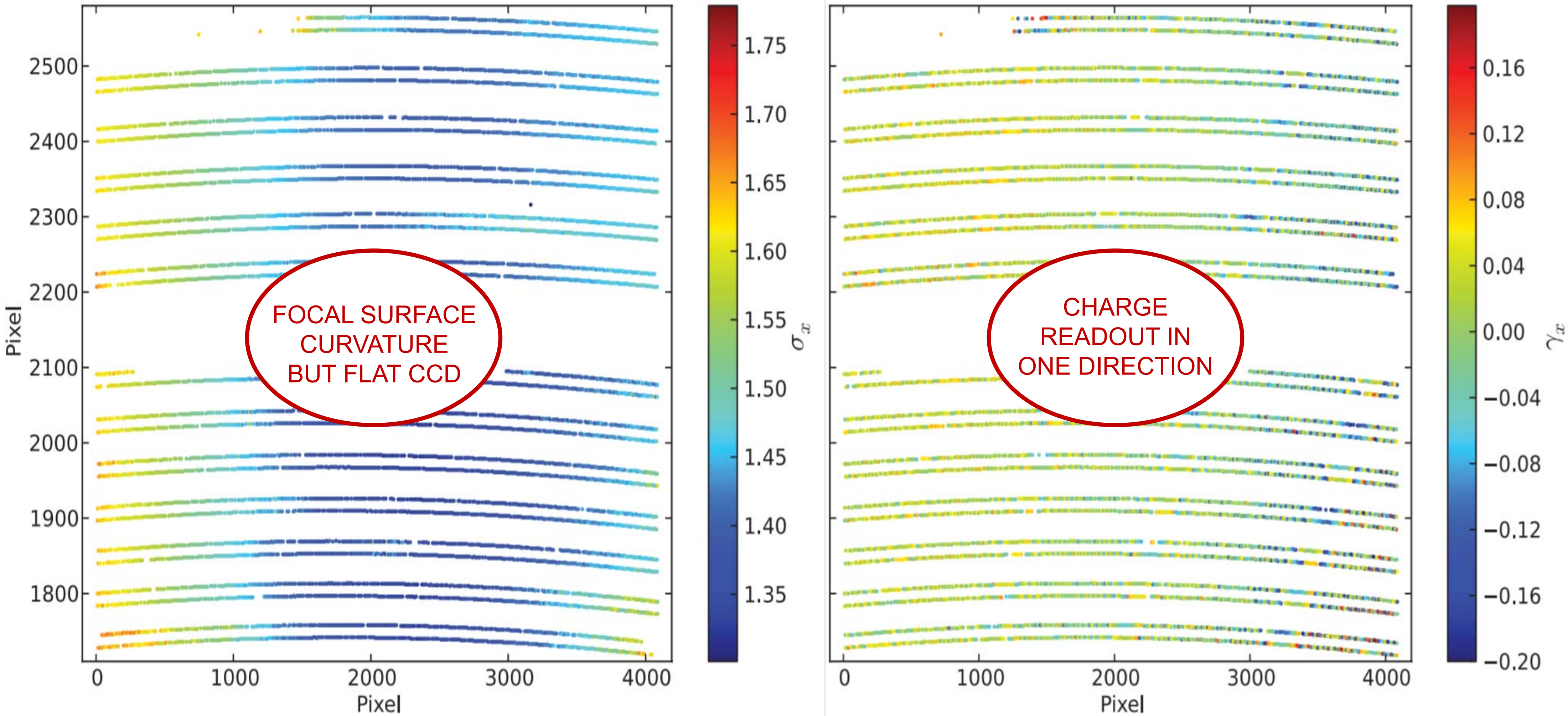
CCD limitations: Charge transfer [in]efficiency



ACS, Advanced Camera for Surveys on Hubble Space Telescope
A section of an exposure of 47 Tucanae
Trails extending from the stars indicate effects of *Charge Transfer Efficiency* in the detector

Hubble Space Telescope: ACS Data Handbook, `http://www.stsci.edu/hst/acs/documents/handbooks`

Spectrometer instrumental profiles: HARPS



Laser comb spectrum of unresolved lines on the HARPS detector.

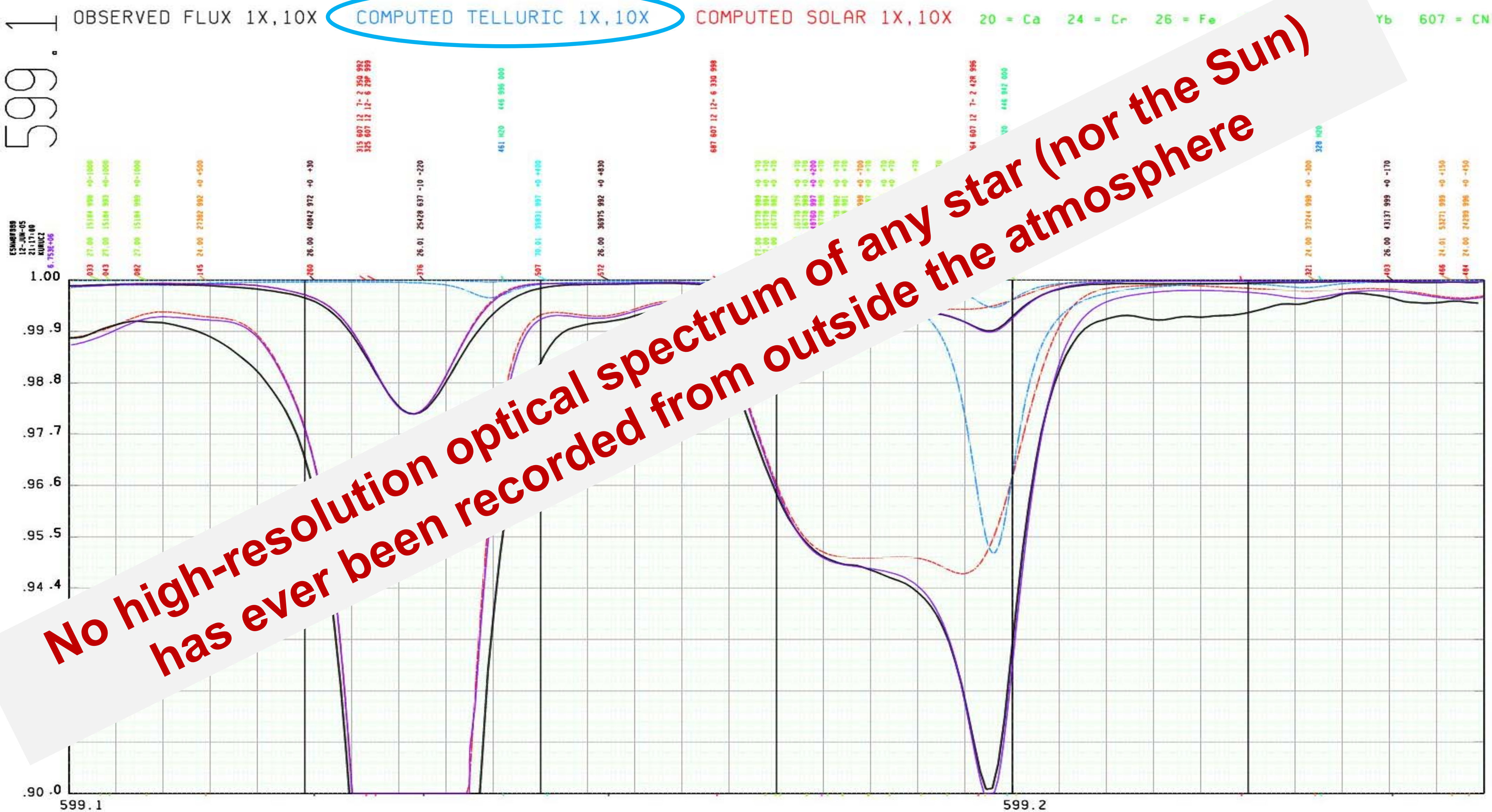
Left: Line width changes due to optical projection onto a flat CCD surface

Right: Line asymmetry (skewness) changes: presumably Charge Transfer Efficiency (CCD readout is off to the right). Asymmetry also depends also on the line intensity

F.Zhao, G.Lo Curto, L.Pasquini, G.Zhao: *Study of the HARPS Line Profile Using a Laser Frequency Comb,* IAU Symp. **293**, 407 (2014)

Observing through the Earth’s atmosphere

Precision limits from telluric absorption

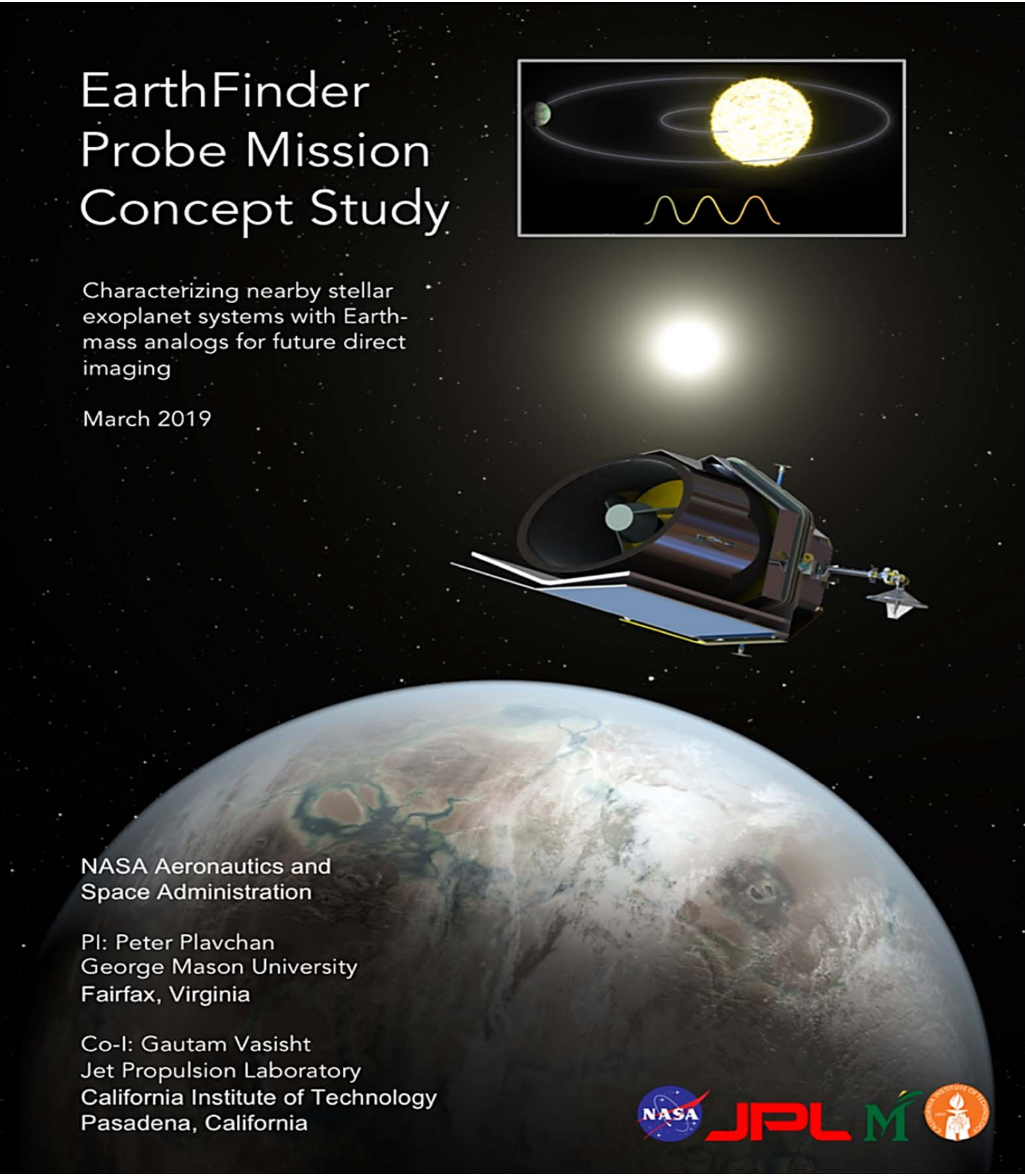


No high-resolution optical spectrum of any star (nor the Sun) has ever been recorded from outside the atmosphere

Example of a relatively empty region in the solar spectrum.
Telluric, synthetic, and observed spectra at normal, and 10× scale.

R.Kurucz: *New Atlases for Solar Flux, Irradiance, Central Intensity, and Limb Intensity*, Mem.Soc.Astr.It.Suppl. **8**, 189 (2005)

Going to space to avoid telluric absorption ??


EarthFinder Probe Mission Concept Study

Characterizing nearby stellar exoplanet systems with Earth-mass analogs for future direct imaging

March 2019

NASA Aeronautics and Space Administration

PI: Peter Plavchan
George Mason University
Fairfax, Virginia

Co-I: Gautam Vasisht
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

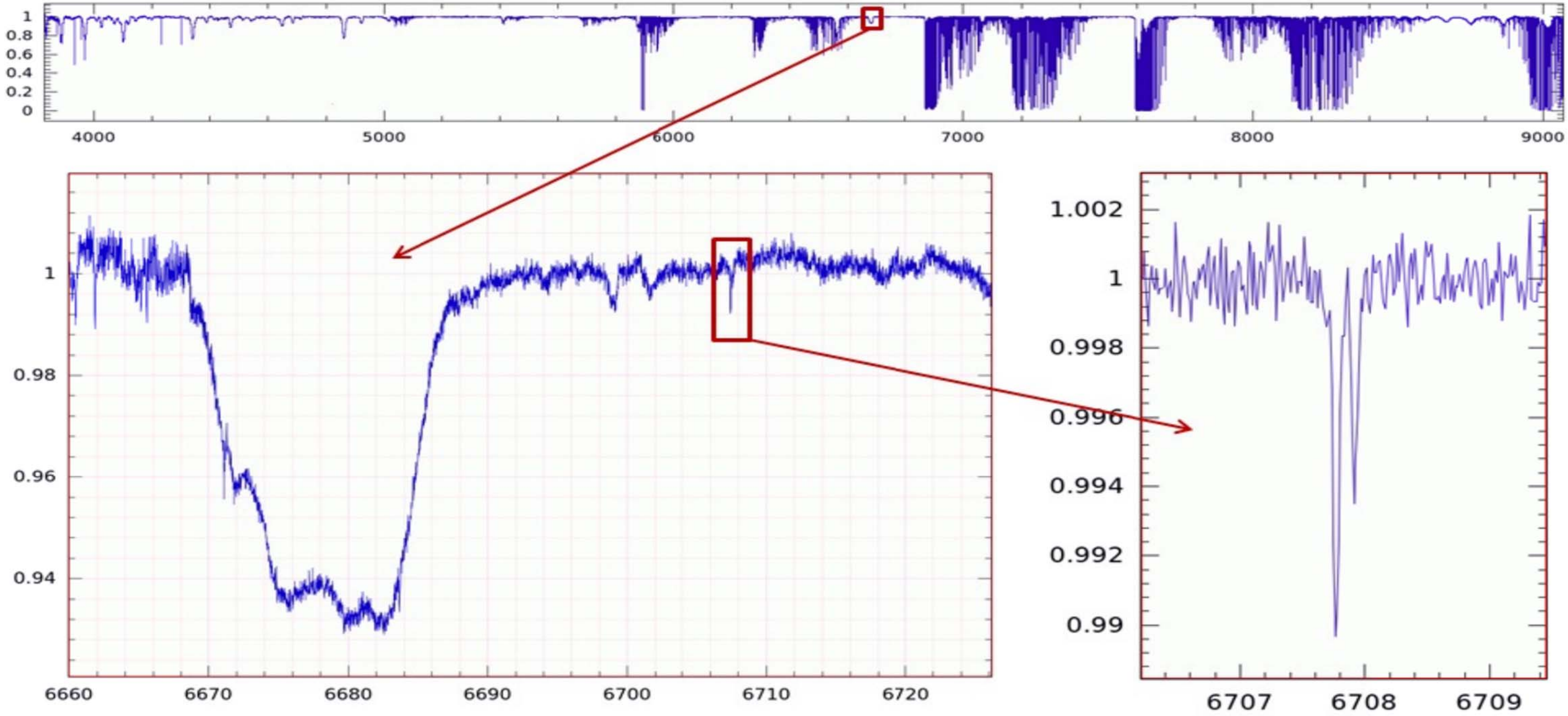
arXiv:2006.13428

Why do we want fidelity？

What requires S/N = 1,000?

PEPSI @ LBT

$\lambda/\Delta\lambda$ = 250,000, S/N = 1,800



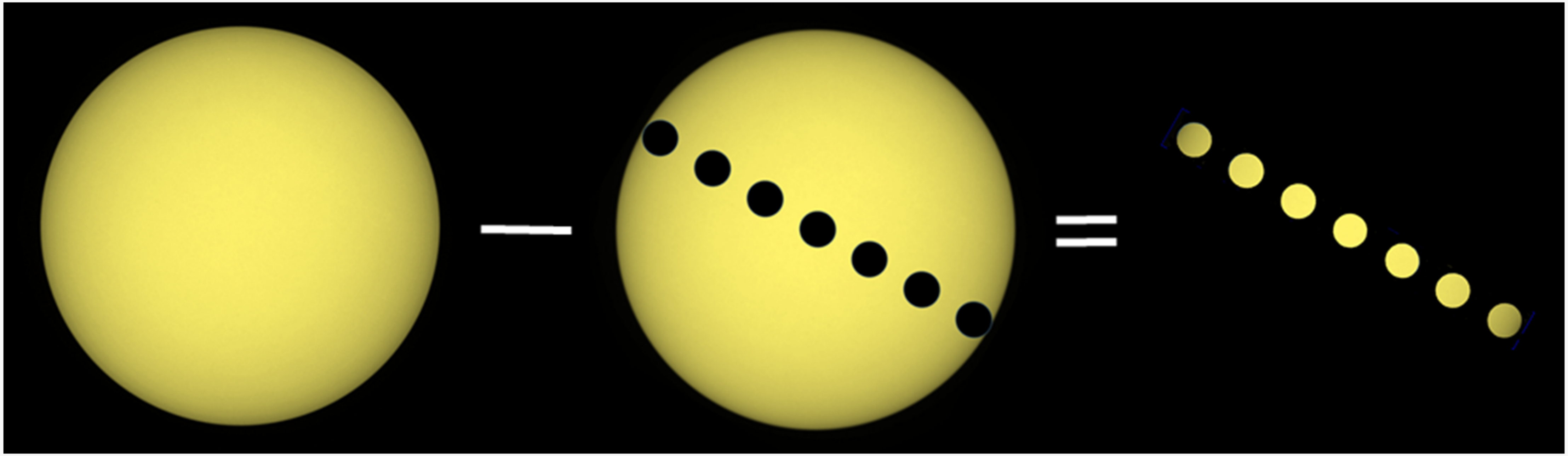
Interstellar lines in ζ Oph (O9 IV)

Left: Stellar He I 688 nm (deformed by non-radial pulsations)
Right: Resolved interstellar Li I doublet at 670.8 nm

K. Strassmeier, I. Ilyin, M. Weber, A. Järvinen, M. Woche, et al.: *Want a PEPSI? Performance status of the recently commissioned high resolution spectrograph and polarimeter for the 2x8.4m Large Binocular Telescope.* Proc.SPIE **10702**, 1070212 (2018)

What requires S/N = 10,000?

Spatially resolved spectra across stellar surfaces

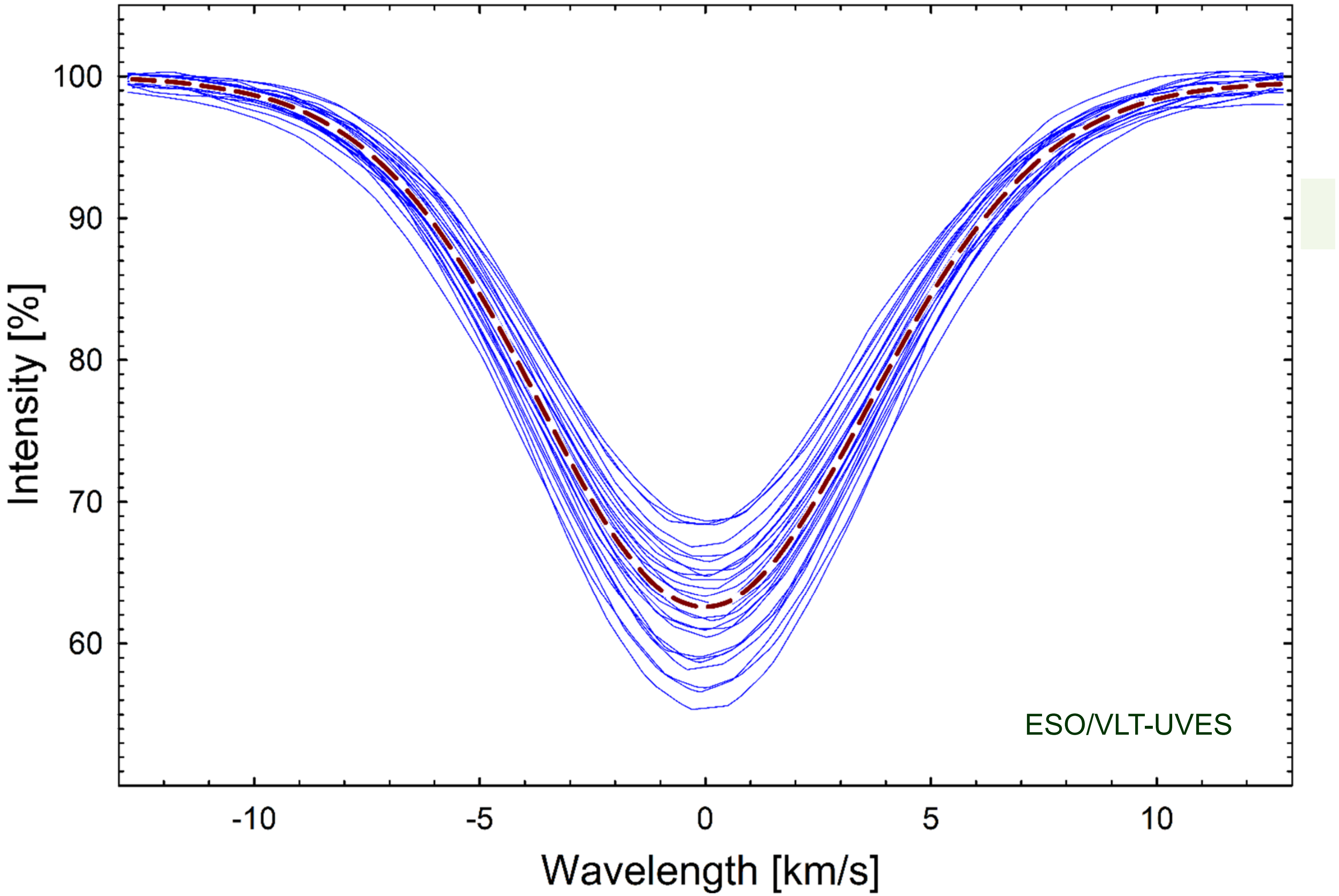


Differences during exoplanet transit reveal temporarily hidden stellar surface segments

Changing continuum flux measured by photometry, spectral changes by spectroscopy

D.Dravins, H.-G.Ludwig, E.Dahlén, H.Pazira: *Spatially resolved spectroscopy across stellar surfaces. I. Using exoplanet transits to analyze 3-D stellar atmospheres*
Astron.Astrophys. **605**, A90 (2017)

Averaging many photospheric Fe I lines

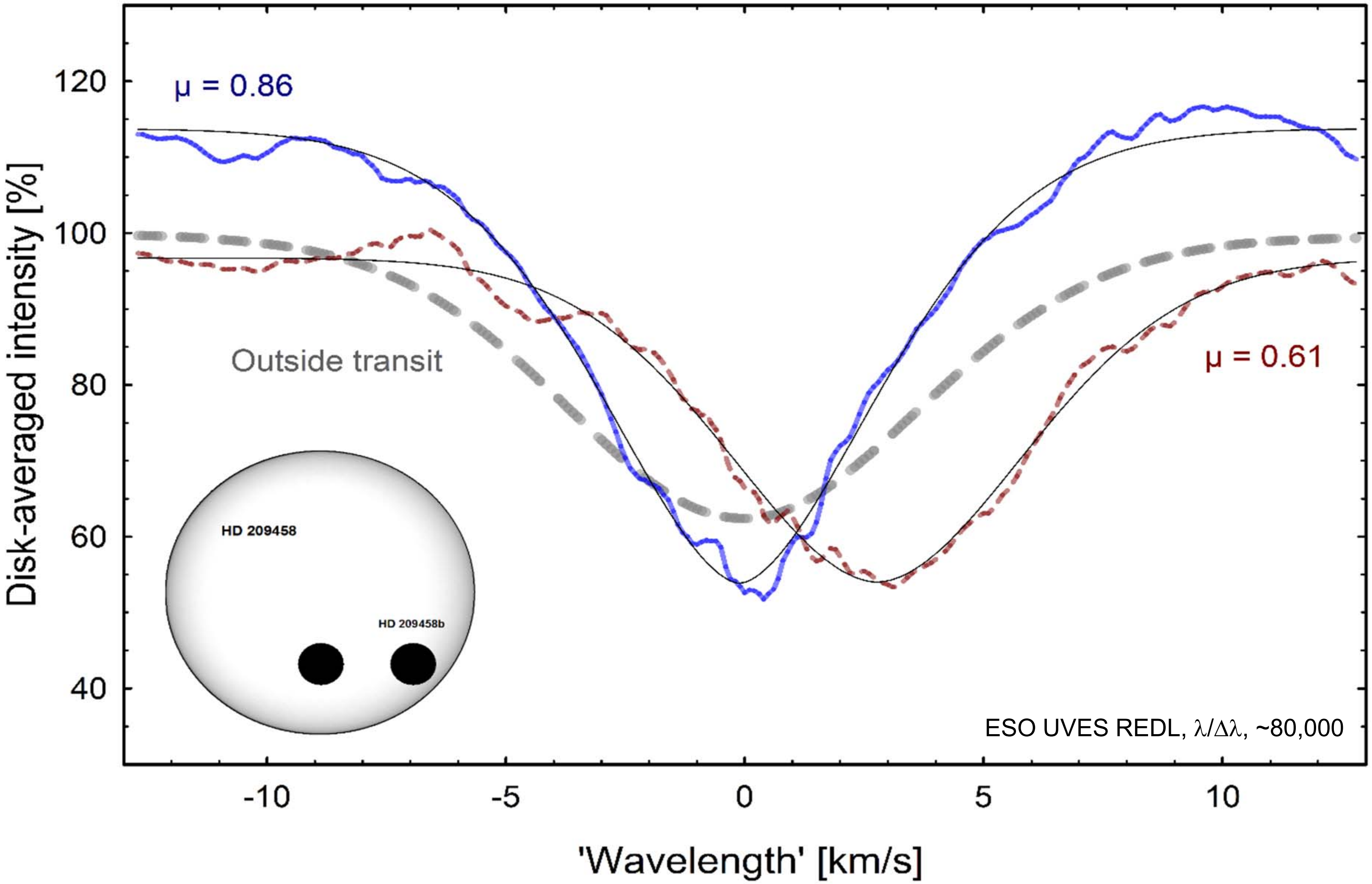


Photospheric Fe I lines of similar strengths in HD 209458 carry redundant information

Averaging multiple exposures gives a representative profile with $\lambda/\Delta\lambda \sim 80{,}000$, S/N $\sim 7{,}000$

D.Dravins, H.-G.Ludwig, E.Dahlén, H.Pazira: *Spatially resolved spectroscopy across stellar surfaces. II. High-resolution spectra across HD 209458 (G0 V)*
Astron.Astrophys. **605**, A91 (2017)

Retrieved line profiles across HD 209458 (G0 V)



Solid blue: near disk center, dashed brown: closer to limb.

Spatially resolved lines are not rotationally broadened and are deeper than the disk average.

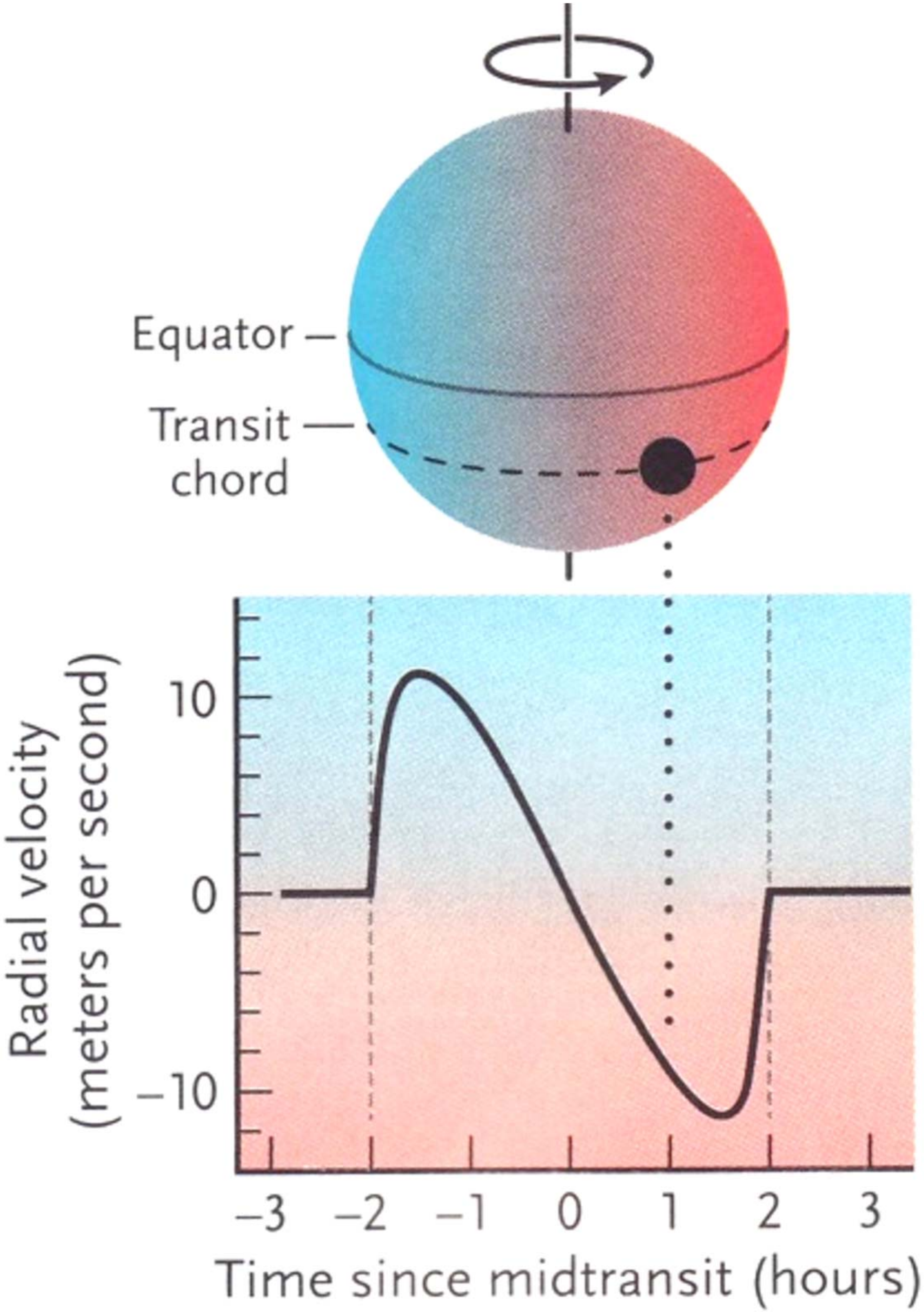
Wavelength shift during transit illustrates stellar rotation and prograde orbital motion of the exoplanet.

Planet size and positions on the stellar disk are to scale.

D.Dravins, H.-G.Ludwig, E.Dahlén, H.Pazira: *Spatially resolved spectroscopy across stellar surfaces. II. High-resolution spectra across HD 209458 (G0 V)*
Astron.Astrophys. **605**, A91 (2017)

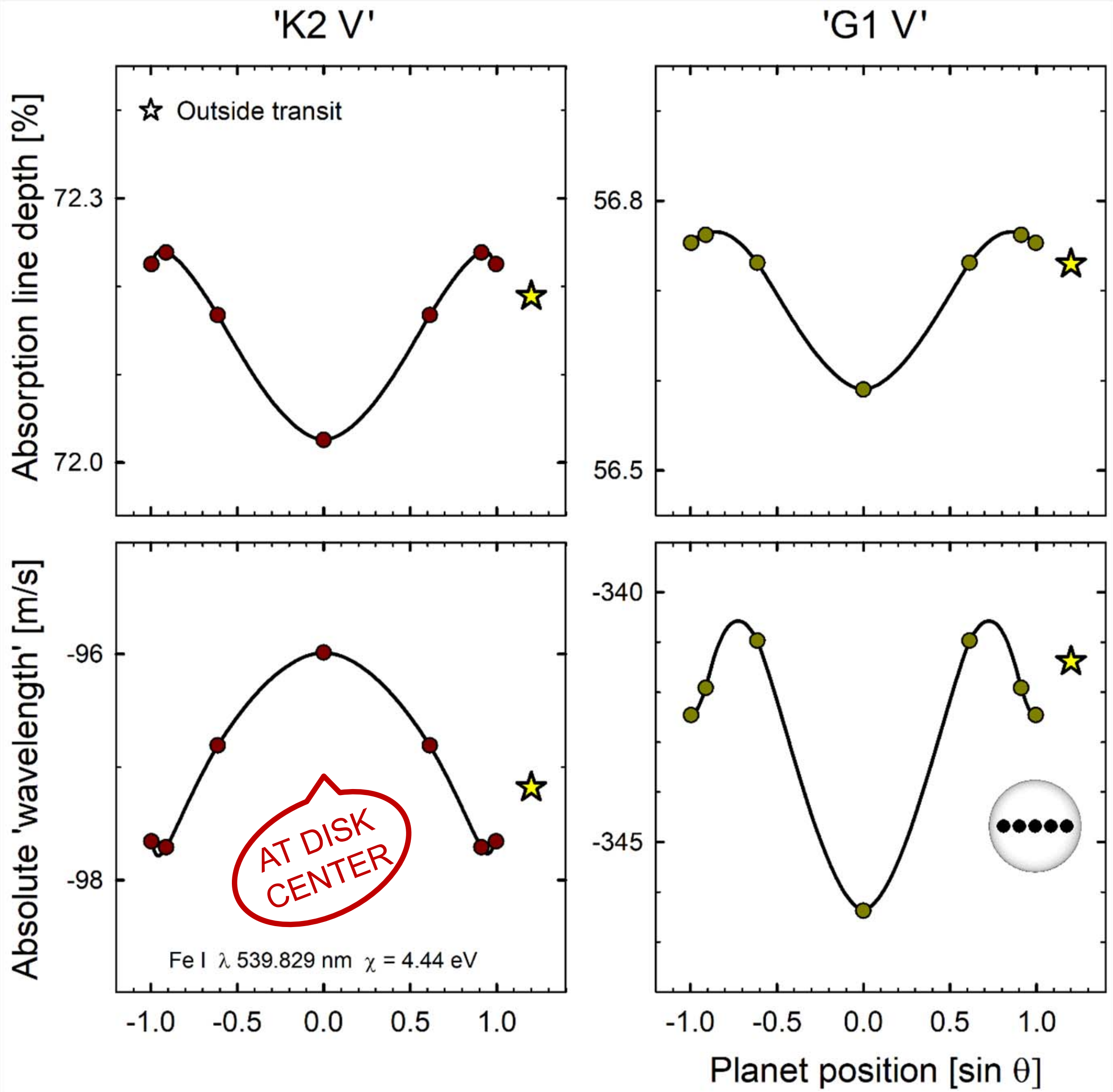
Exoplanet transits: Stellar center-to-limb line profile changes

Classical Rossiter-McLaughlin effect



Analogies to the Rossiter-McLaughlin effect

Exoplanet transit signatures



Changes during exoplanet transit, caused by center-to-limb line profile changes, in absence of stellar rotation

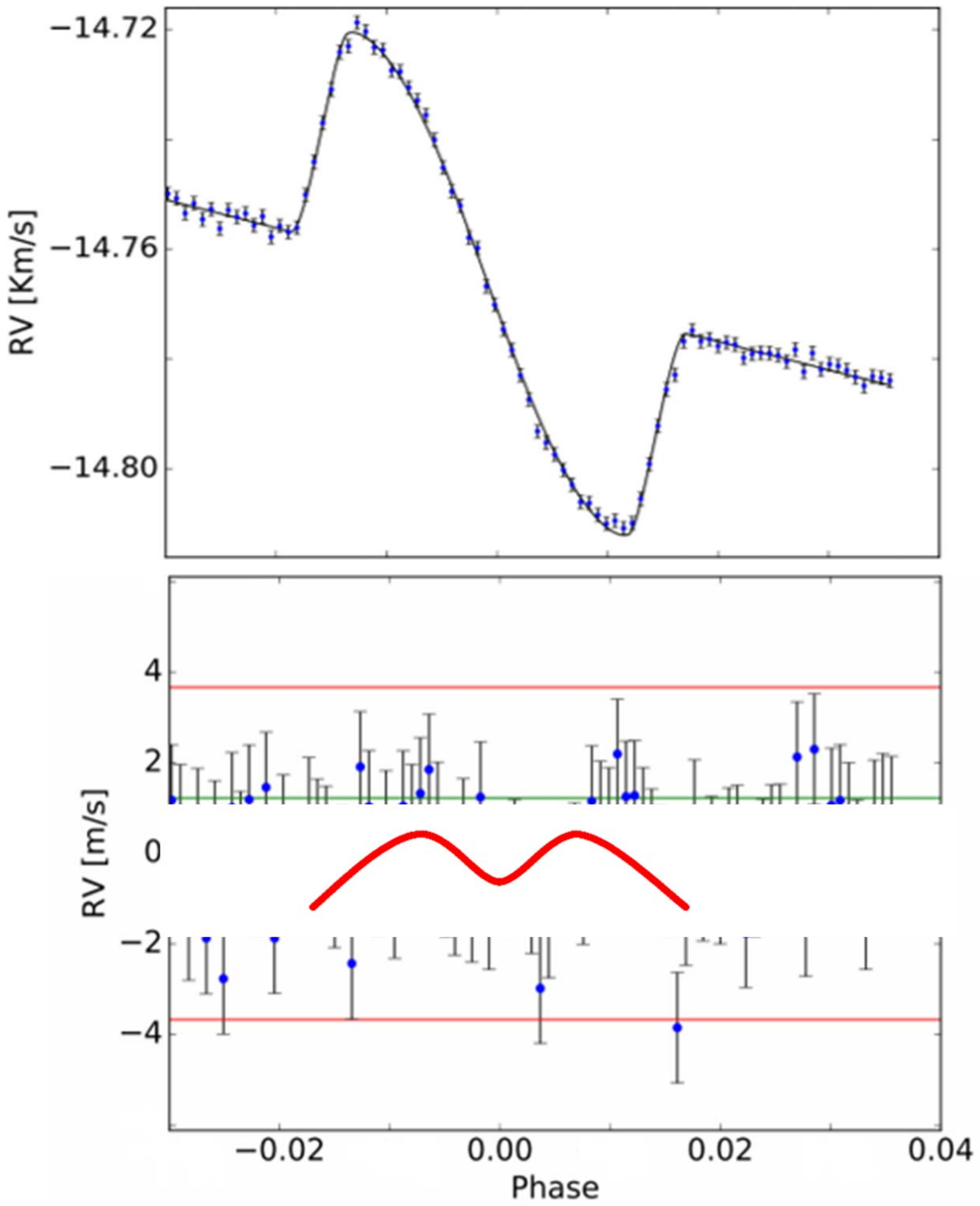
Modeled transit across a stellar diameter of an exoplanet covering 1.5% of the stellar disk

Star symbols denote full-disk values outside transit.

Wavelength shifts are absolute but gravitational redshifts are neglected

D.Dravins, H.-G.Ludwig, B.Freytag: *Spatially resolved spectroscopy across stellar surfaces. V. Observational prospects: Toward Earth-like exoplanet detection*
Astron.Astrophys. **649**, A17 (2021)

Observed effects across HD 209458 at $\lambda/\Delta\lambda = 140{,}000$



ESPRESSO transit observations vs. orbital phase

Top: Rossiter–McLaughlin curves and best-fit models

Bottom: Residuals from best fit for the night with best S/N

N.C.Santos et al.:
Broadband transmission spectroscopy of HD 209458b with ESPRESSO: evidence for Na, TiO, or both?
Astron. Astrophys. **644**, A51 (2020)

Overlay: Predicted radial-velocity signature, caused by intrinsic changes of the line asymmetry and convective wavelength shift when going from stellar disk center toward the limb.

For medium-strong Fe I lines, a maximum redshift of some m/s, about halfway between disk center and the limb is expected, seemingly consistent with the observed R-M deviations.

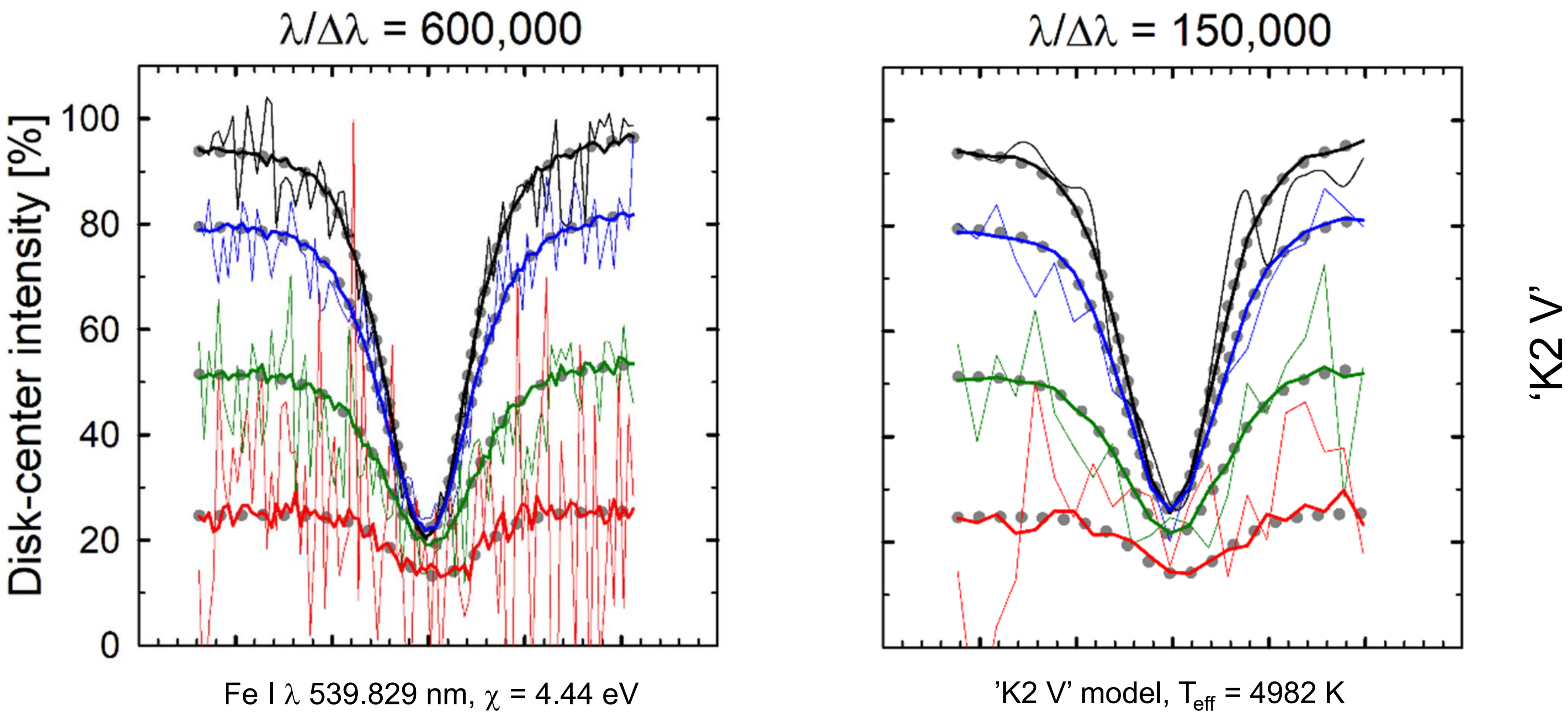
Overlay modeling:

D.Dravins, H.-G.Ludwig, B.Freytag: *Spatially resolved spectroscopy across stellar surfaces. V. Observational prospects: Toward Earth-like exoplanet detection,* Astron.Astrophys. **649**, A17 (2021)

D.Dravins, H.-G.Ludwig, in preparation (2023)

What could be done with S/N = 100,000?

Retrieving spatially resolved spectra



Simulated reconstructions from transit of an exoplanet covering 1.5% of a stellar disk

Spectral resolutions: λ/Δλ = 600,000 & 150,000

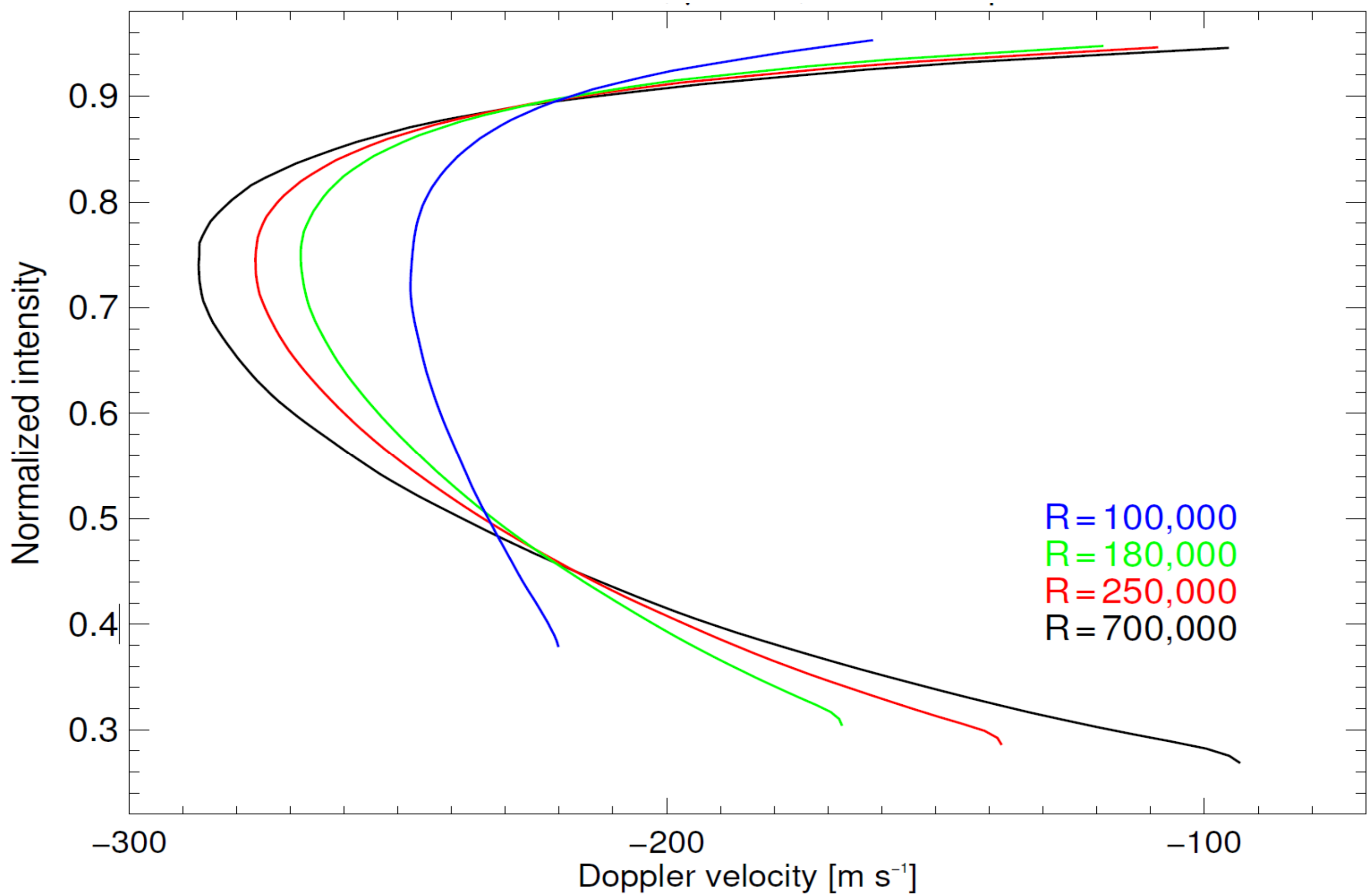
Photometric S/N = 10,000 (thin lines), S/N = 100,000 (bold). Noise-free original: gray dots.
From top down: μ = 1, 0.79, 0.41, 0.09

D.Dravins, H.-G.Ludwig, B.Freytag: *Spatially resolved spectroscopy across stellar surfaces. V. Observational prospects: Toward Earth-like exoplanet detection*
Astron.Astrophys. **649**, A17 (2021)

What requires $\lambda/\Delta\lambda$ = 1,000,000?

Need for hyper-high spectral resolution

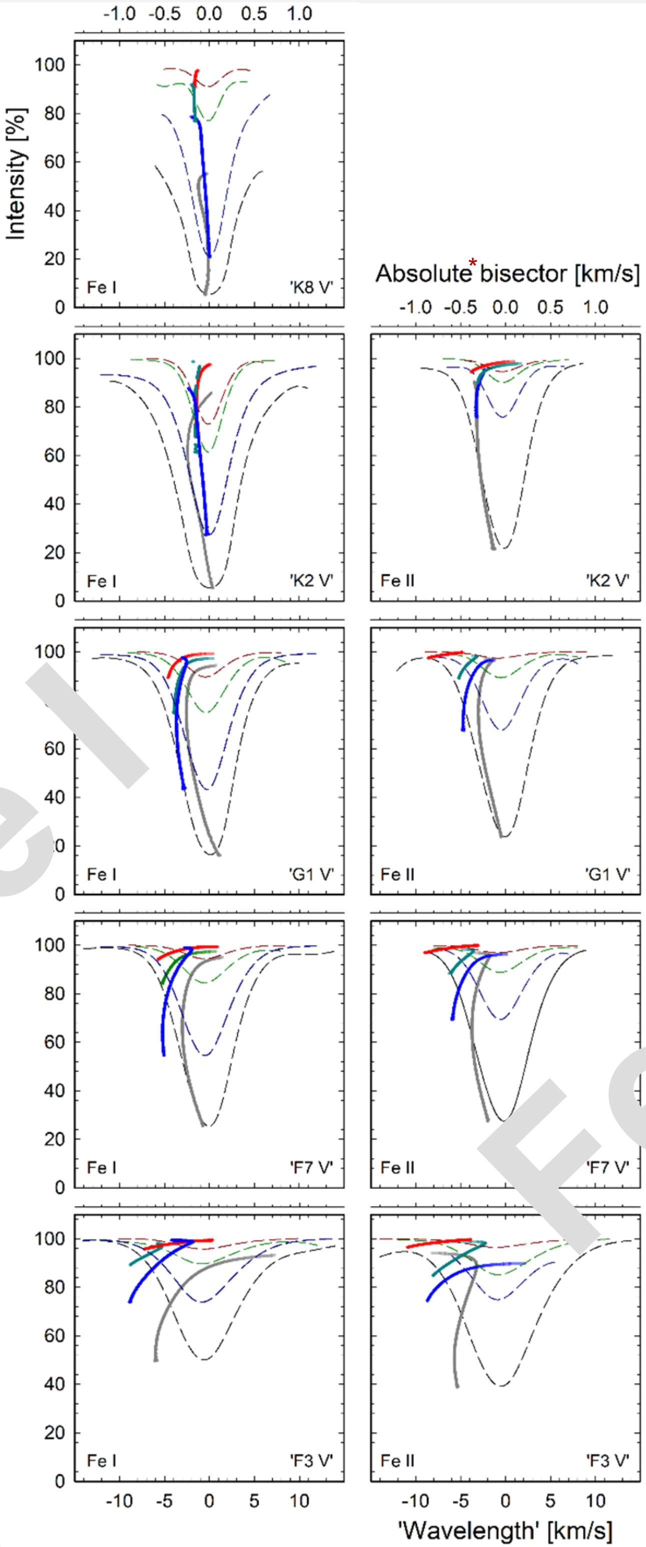
Solar spectral lines observed at different $\lambda/\Delta\lambda$



Bisector changes with spectral resolution

Fe I 525.02084 nm for $\lambda/\Delta\lambda$ = 700,000 (black) to 100,000 (blue)

J.Löhner-Böttcher, W.Schmidt, R.Schlichenmaier, T.Steinmetz, R.Holzwarth: *Convective blueshifts in the solar atmosphere. III. High-accuracy observations of spectral lines in the visible,* Astron.Astrophys. **624**, A57 (2019)



Bisectors for different spectral types

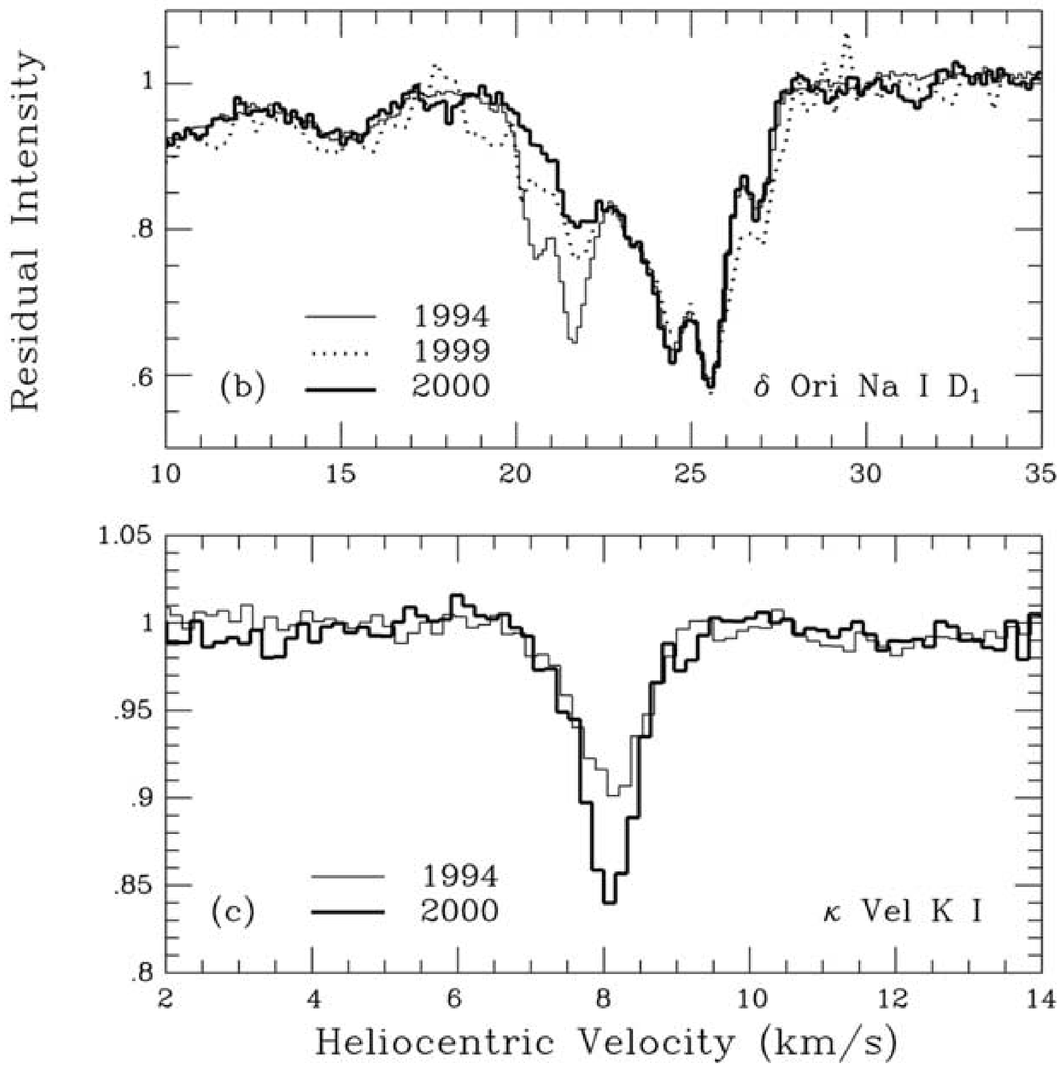
Synthetic line profiles and bisectors in integrated starlight

$\lambda / \Delta\lambda \approx 1{,}100{,}000$

D.Dravins, H.-G.Ludwig, B.Freytag:
Spatially resolved spectroscopy across stellar surfaces. IV. F, G, & K-stars: Synthetic 3-D spectra at hyper-high resolution
Astron.Astrophys. **649**, A16 (2021)

Interstellar line variability

Ultra High-Resolution Facility @ AAT, $\lambda/\Delta\lambda = 940,000$



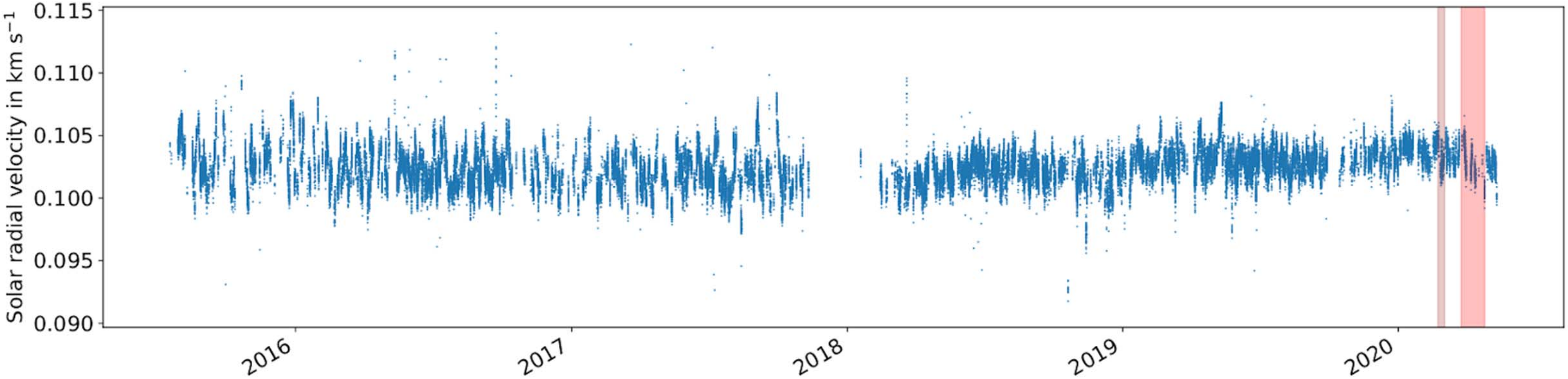
Variable interstellar lines, also resolving the Na I D_1 hyperfine structure (separation 1.08 km/s)

Variation over years imply scales on 10-100 AU

I.A.Crawford: *Variable Interstellar Absorption Lines: A Brief Review*, Astrophys.Space Sci. **285**, 661 (2003)

Temporal microvariability

Radial velocity jittering of the Sun



Solar apparent radial velocity at 5-minute cadence, corrected for barycentric motion and differential extinction

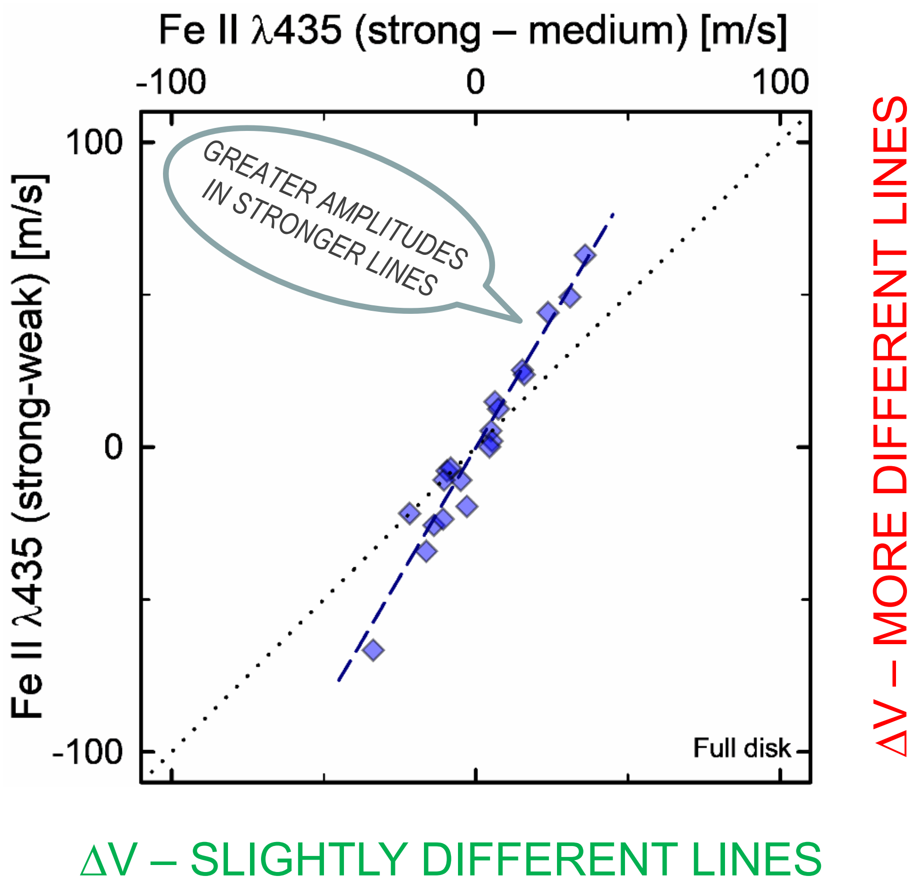
Colored bars indicate the 2020 Calima sandstorm and the COVID-19 lock-down. (Credit: A.Collier Cameron)

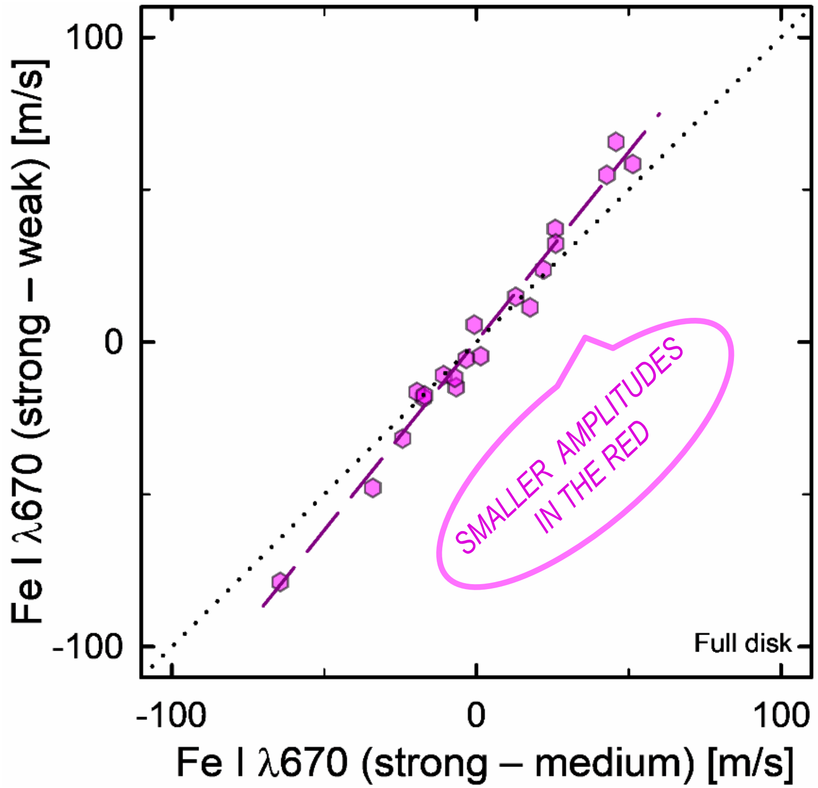
Telescopio Nazionale Galileo (TNG)
Roque de los Muchachos, La Palma

Data release: X. Dumusque et al.: *Three Years of HARPS-N High-Resolution Spectroscopy and Precise Radial Velocity Data for the Sun*, Astron.Astrophys. **648**, A103 (2021)

Solar telescope feeding the HARPS-N spectrometer (credit: D.Phillips)

Velocity jittering due to solar granulation



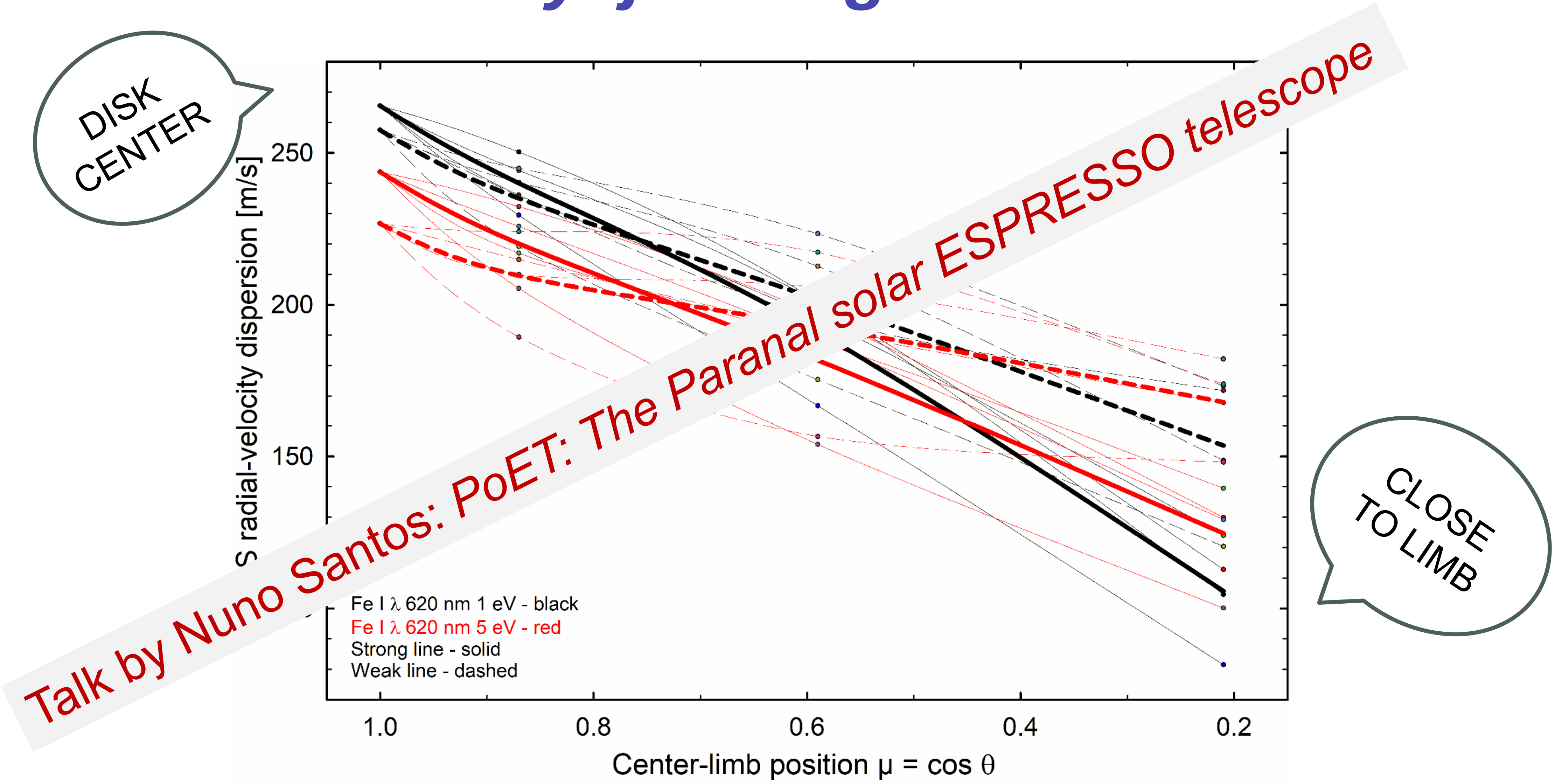


Radial-velocity excursions are greater for stronger and for ionized lines, decreasing at longer wavelengths

Numbers [m/s] refer to a small simulation area; for full-disk Sun, divide by ~150-200: amplitude ~2 m/s

D.Dravins, H.-G.Ludwig: *Solar photospheric spectrum microvariability. I. Theoretical searches for proxies of radial-velocity jittering*
Astron.Astrophys., accepted (2023), arXiv:2308.10937

‘Radial velocity’ jittering across solar disk

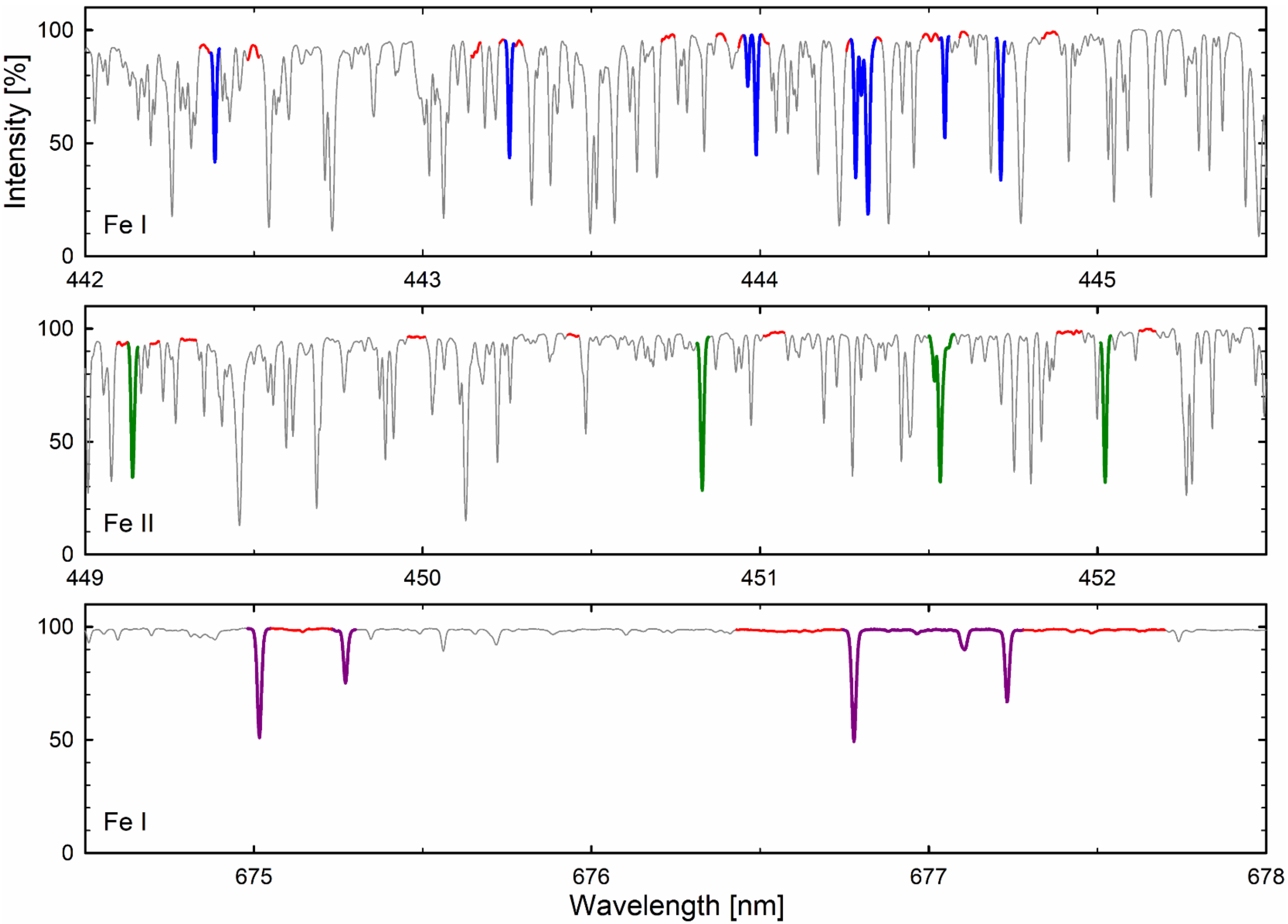


Theoretically predicted jittering of Fe I λ 620 nm lines due to granulation

D.Dravins, H.-G.Ludwig: *Solar photospheric spectrum microvariability. I. Theoretical searches for proxies of radial-velocity jittering*
Astron.Astrophys., accepted (2023), arXiv:2308.10937

Extreme precision radial-velocity spectrometers enable extreme precision stellar spectroscopy

Fe I and Fe II lines @ HARPS-North



Selected Fe lines in different spectral regions

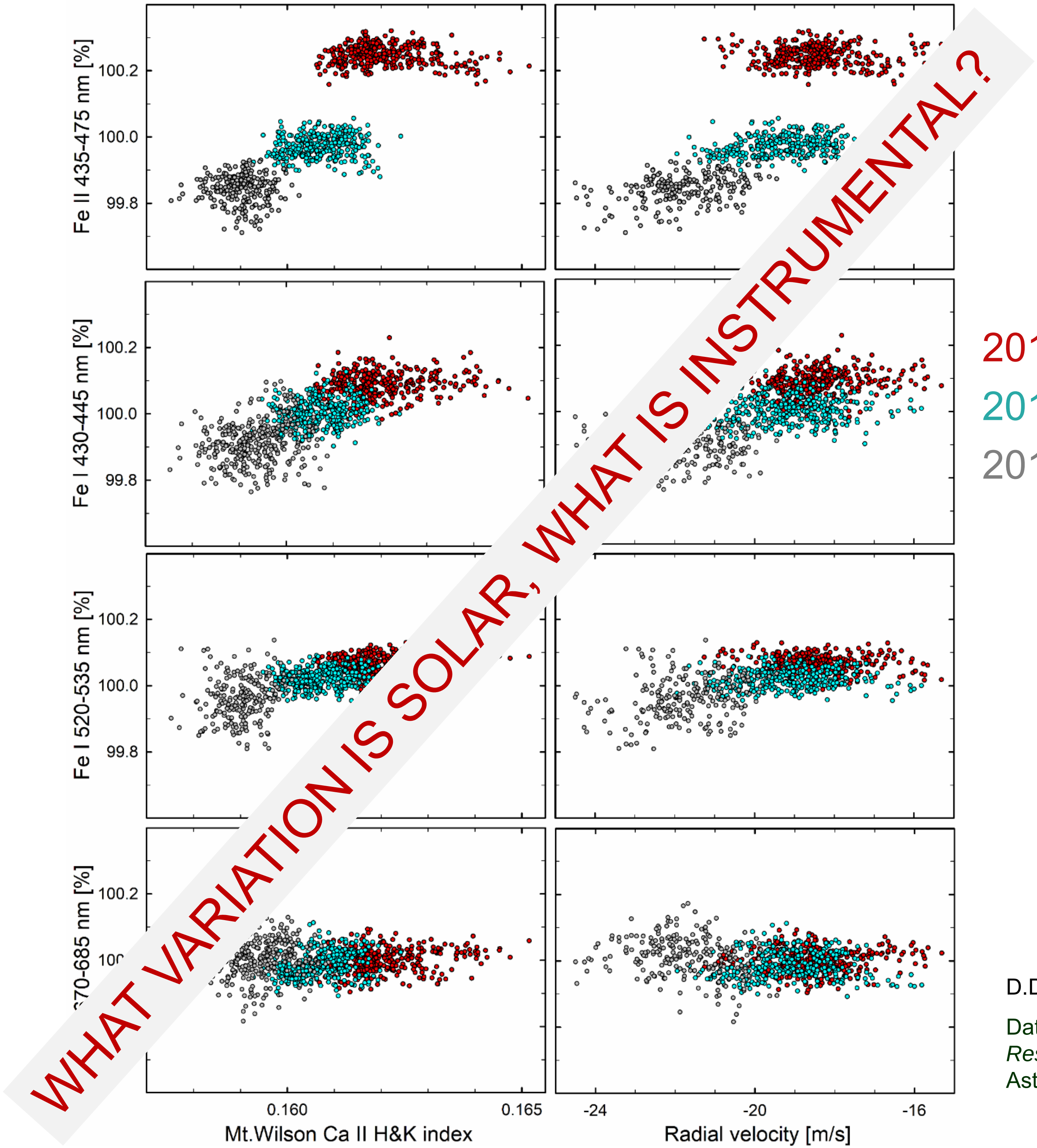
Red: Reference “continua”

Thin: 100-exposure average

D.Dravins, H.-G.Ludwig, *to be submitted* (2023)

Data from X.Dumusque et al.: *Three Years of HARPS-N High-Resolution Spectroscopy and Precise Radial Velocity Data for the Sun*
Astron.Astrophys. **648**, A103 (2021)

Fe line fluxes
@ HARPS-North



2016
2017
2018

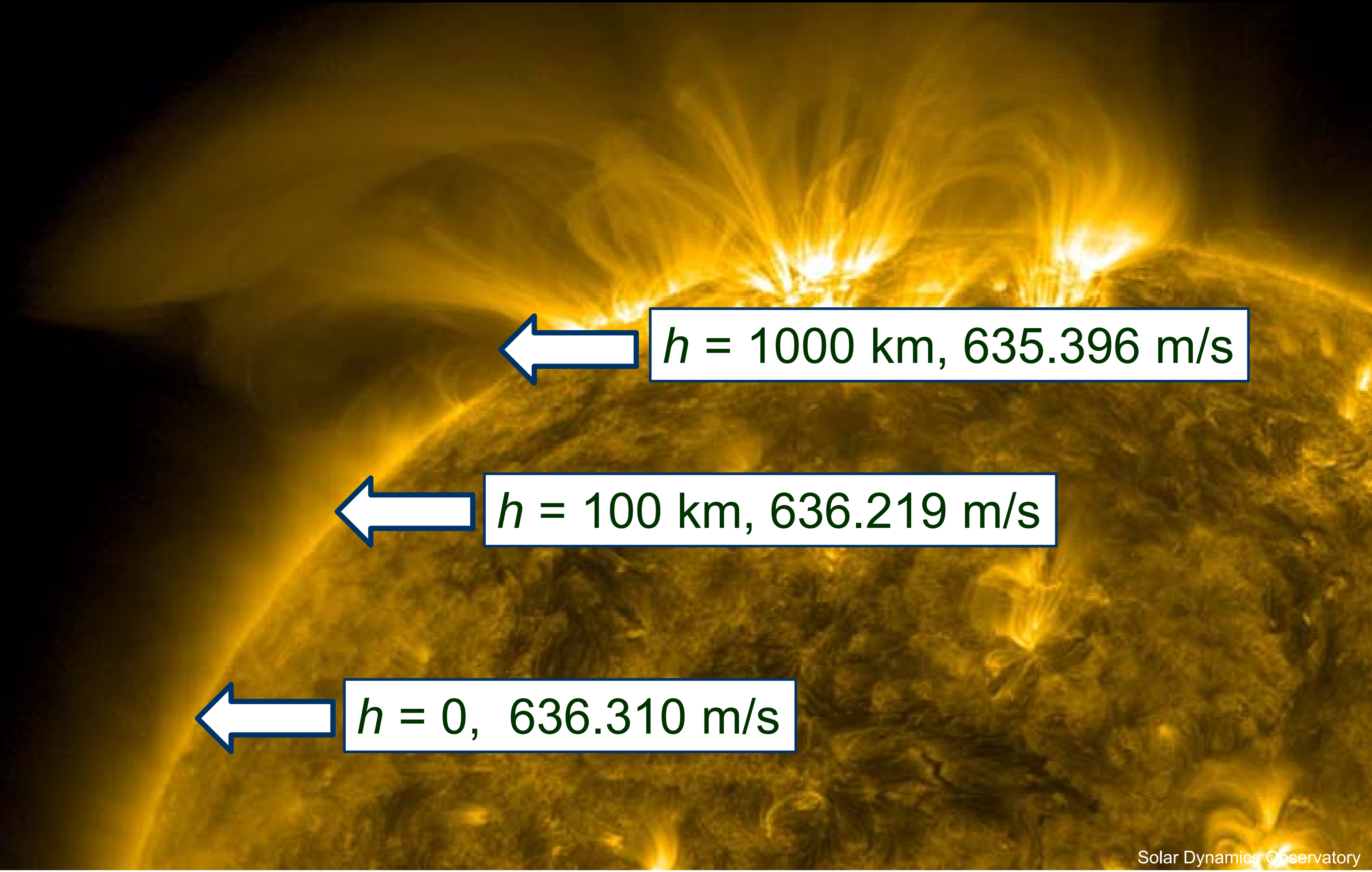
Fe I and Fe II fluxes vs. Ca II H & K (left); vs. radial velocity (right)

D.Dravins, H.-G.Ludwig, *to be submitted* (2023)

Data from X.Dumusque et al.: *Three Years of HARPS-N High-Resolution Spectroscopy and Precise Radial Velocity Data for the Sun* Astron.Astrophys. **648**, A103 (2021)

What requires cm/s radial-velocities?

Gravitational redshift within the solar atmosphere



Line asymmetries and convective wavelength shifts

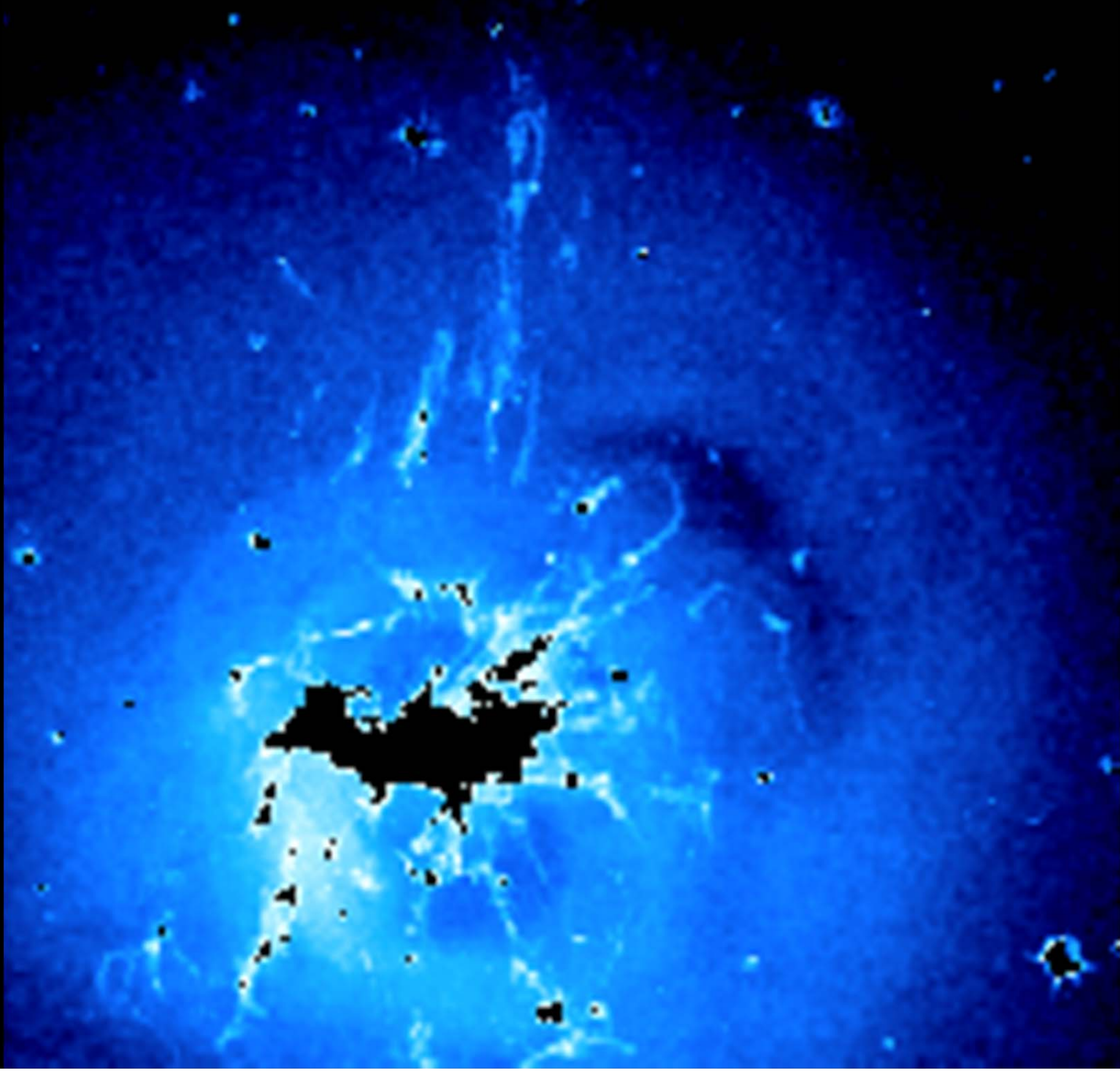
Intergalactic convection

Perseus cluster core in X-rays
overlaid with Hα image

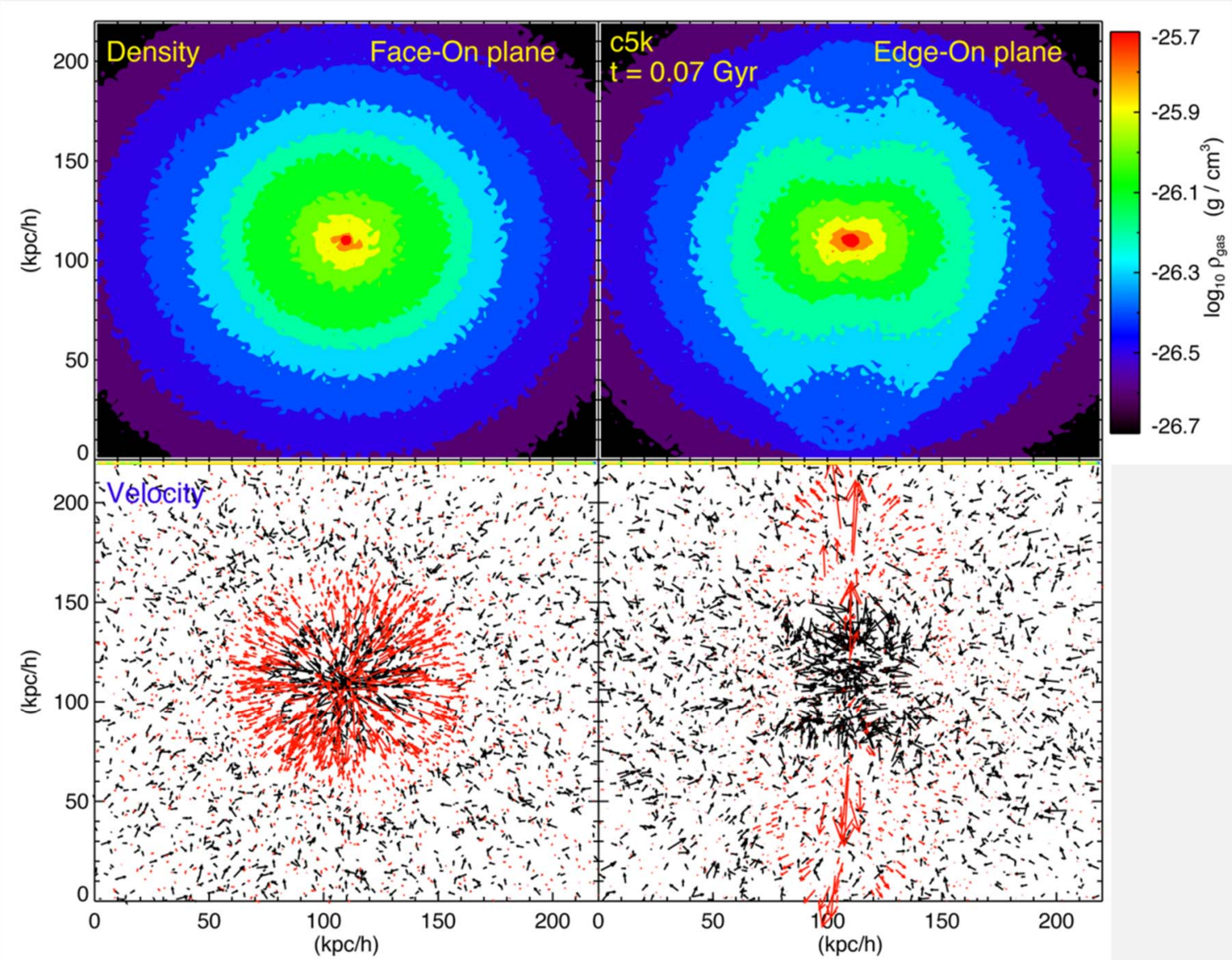
Arc-shaped Hα filaments suggest
vortex-like flows

Image is 96 kpc on the side

Reynolds et al.: *Buoyant radio-lobes in a viscous intracluster medium*, *MNRAS* **357**, 242 (2005)



Intergalactic convection



AGN feedback, modeled with smoothed-particle hydrodynamics

A black hole at the cluster center ejects energetic hot gas

Fast wind shocks slower-moving gas, bubble-like outflows propagate out to a distance of a few 100 kpc.

Inclusion of cold gas accretion produces a duty cycle of the AGN with a periodicity of ~100 Myr.

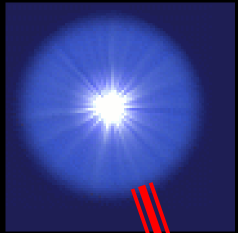
Top: 2D projection of gas kinematics face-on and edge-on for a (200 kpc/h)^3 volume around the cluster center

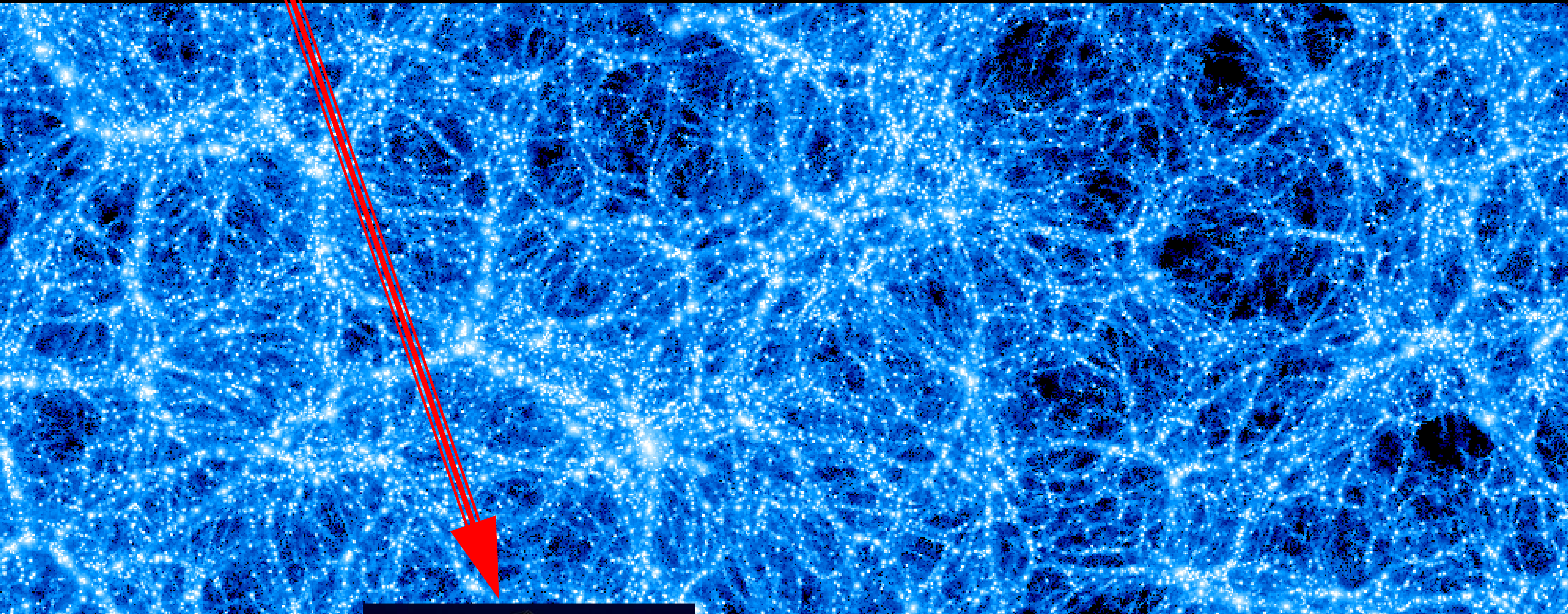
Bottom: Velocity vectors with outflow ($v_r > 0$) marked red, and inflow black

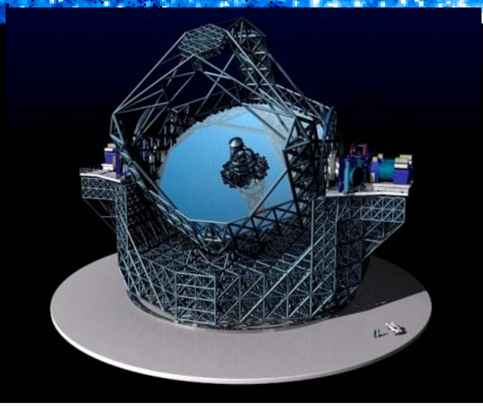
P.Barai et al.: *Kinetic AGN feedback effects on cluster cool cores simulated using SPH*. MNRAS **461**, 1548 (2016)

Observing the intergalactic medium

QSO







Cosmological 3-D hydrodynamic simulation.
Density map; each bright point is a group of galaxies evolved within CDM cosmology.
Image width = 400 Mpc.
(James Wadsley)

Toward the post-CCD era in spectroscopy

CCD: Current standard for digital imaging

Nobel prize in physics 2009

George E. Smith & Willard S. Boyle

"for the invention of an imaging semiconductor circuit – the CCD sensor"

Original discovery made at AT&T Bell Labs in 1969

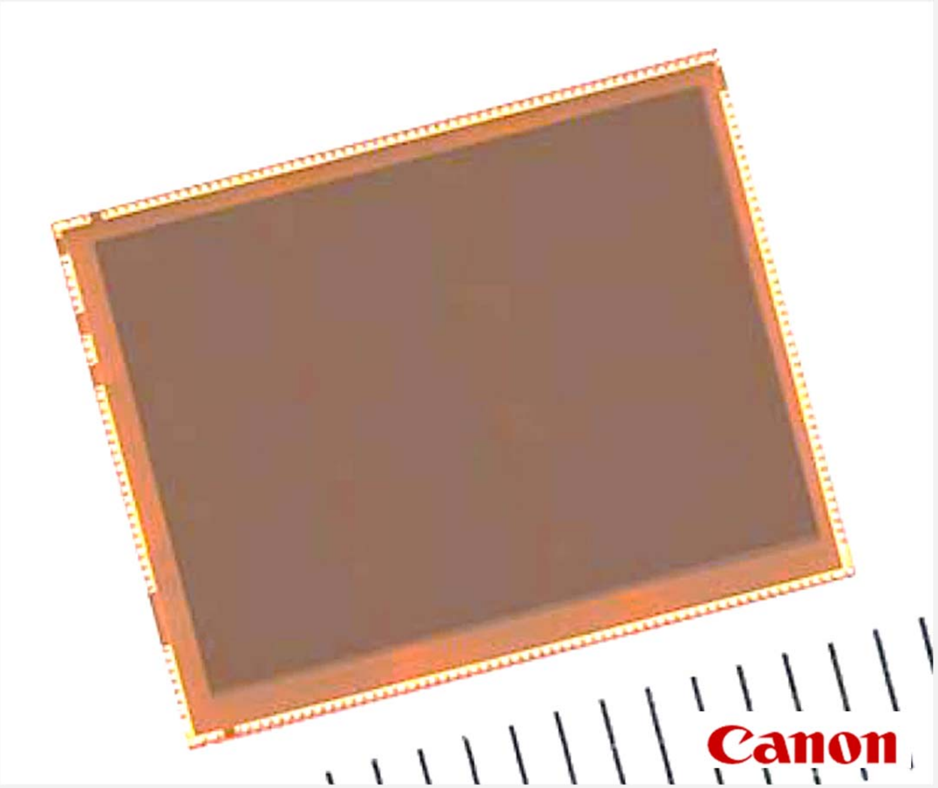
Toward the post-CCD era in spectroscopy

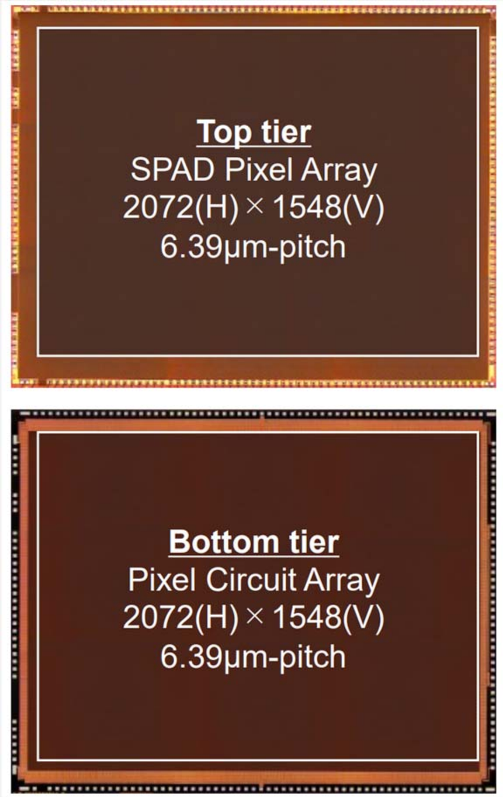
CCD limitations

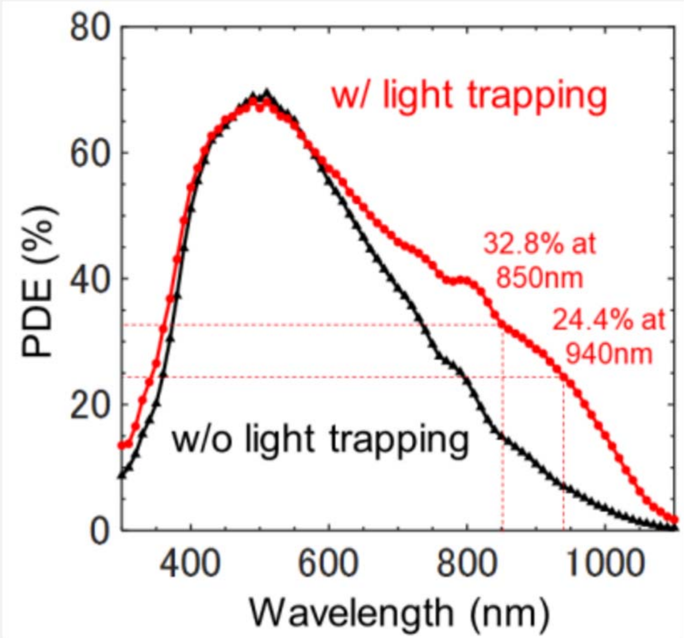
No high time resolution

No photon counting

SPAD array (Single Photon Avalanche Diode)







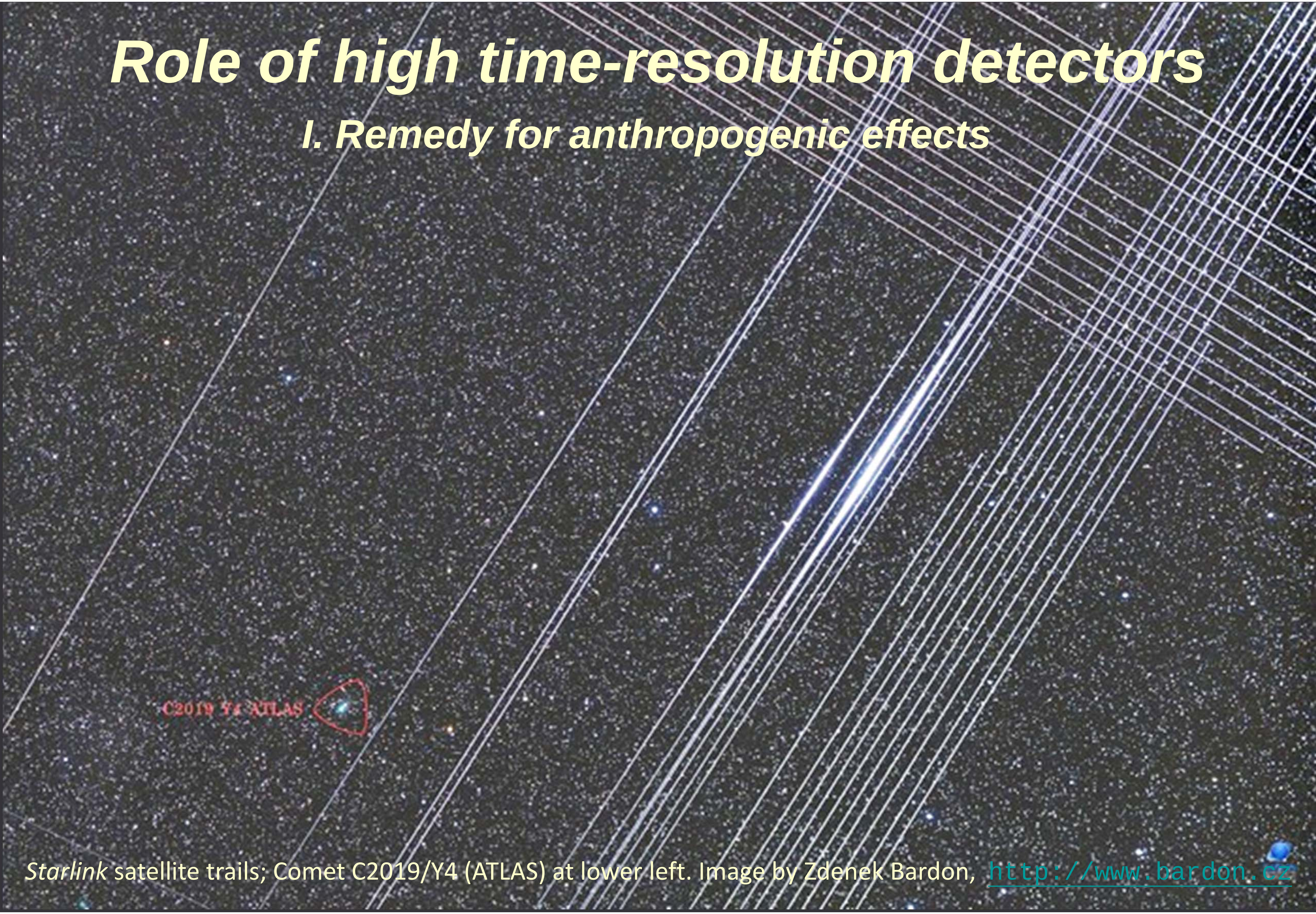
13.2 mm × 9.9 mm^2 3.2 Megapixel SPAD sensor array

Timing jitter 100 ps, zero read noise, maximum Photon Detection Efficiency 69%

K. Morimoto et al.: *3.2 Megapixel 3D-Stacked Charge Focusing SPAD for Low-Light Imaging and Depth Sensing*
IEEE International Electron Devices Meeting, p. 20.2.1 (2021)

Role of high time-resolution detectors

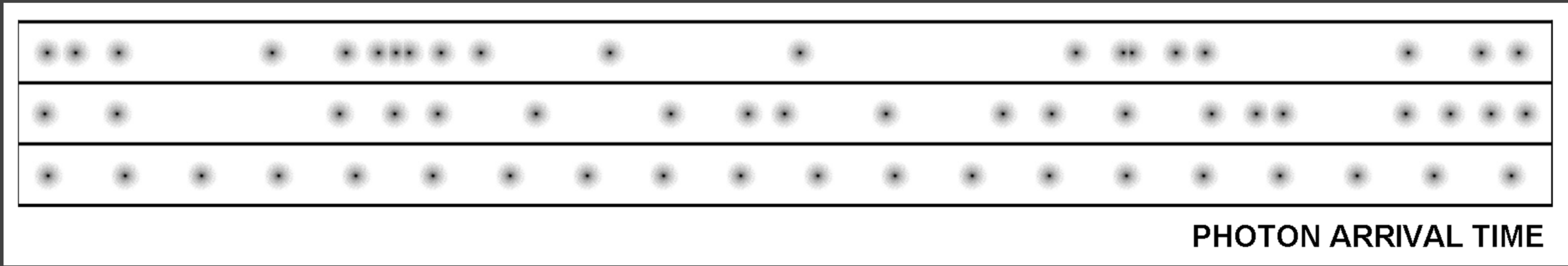
I. Remedy for anthropogenic effects



Starlink satellite trails; Comet C2019/Y4 (ATLAS) at lower left. Image by Zdenek Bardon, http://www.bardon.cz

Role of high time-resolution detectors

II. Quantum-optical statistics of photon streams



Top: Bunched photons (Bose-Einstein; ‘quantum-random’)

Center: Antibunched photons (like fermions)

Bottom: Coherent and uniformly spaced (like ideal laser)

D.Dravins: *Photonic astronomy and quantum optics*, in D.Phelan et al., eds. *High Time Resolution Astrophysics*, p.95 (2008)

Toward the post-CCD era in spectroscopy

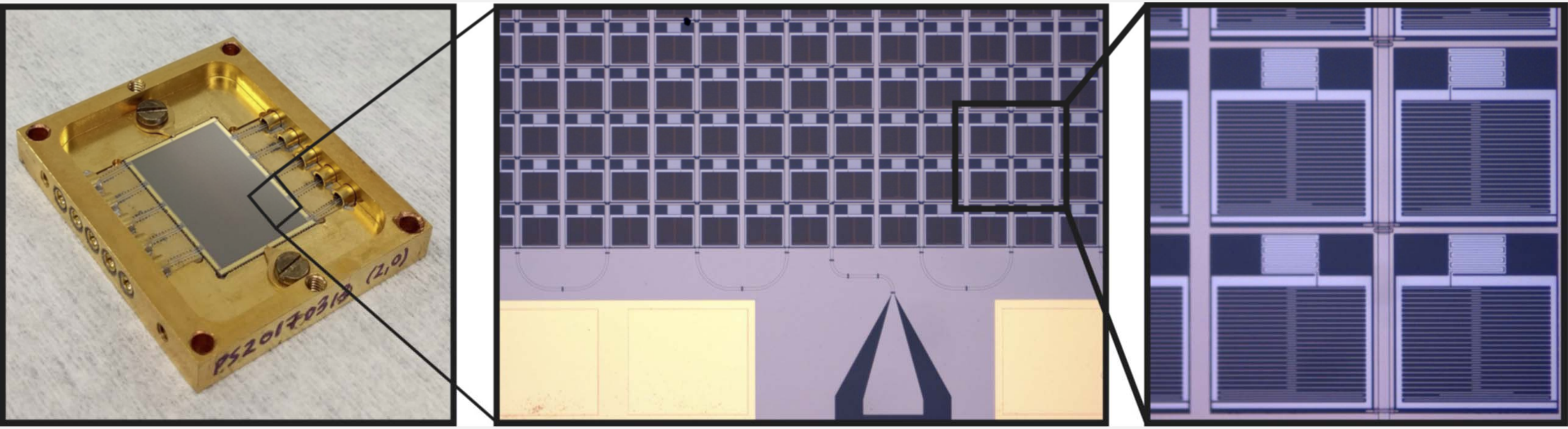
CCD limitations

No high time resolution

No photon counting

No energy resolution

MKIDs, Microwave Kinetic Inductance Detectors

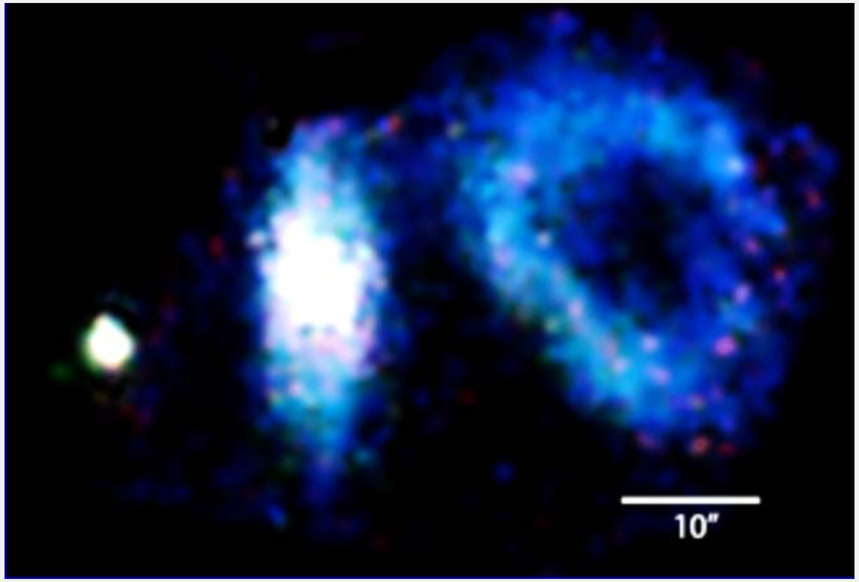


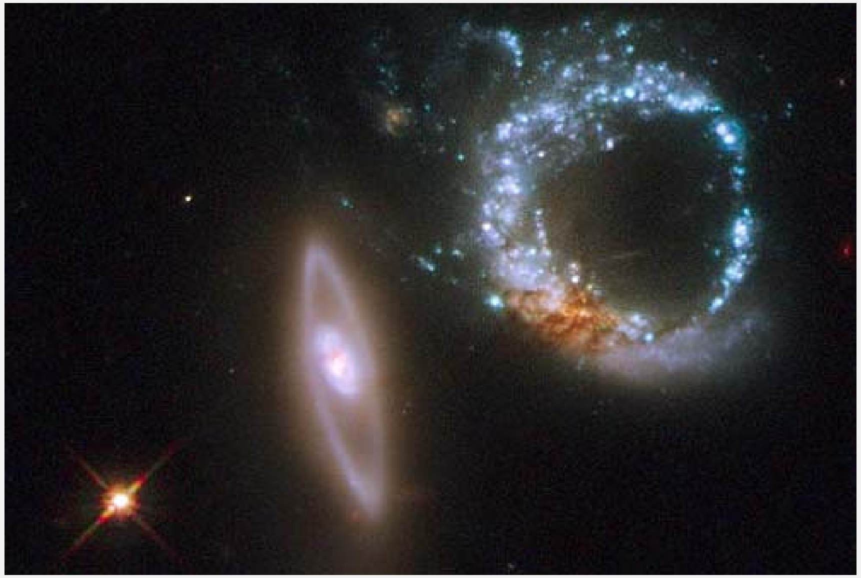
Left: 10,000-pixel MKID array for the DARKNESS instrument on Palomar 200” Hale telescope

Center & Right: Meandered patches are the photosensitive inductors,
sparse sections are capacitors giving each MKID a unique resonant frequency.
A microlens array boosts the effective fill factor to 90%.

B.A.Mazin et al.: “*Optical and Near-IR Microwave Kinetic Inductance Detectors (MKIDs) in the 2020s*”, ASTRO 2020 White Paper, arXiv:1908.02775, 2019

MKIDs, Microwave Kinetic Inductance Detectors





Interacting pair of ring galaxies - Arp147

Left: With the MKID camera *ARCONS* at the Palomar 200" telescope. (Mazin lab, UCSB)

Right: With HST, assembled from three filters on WFPC2. (`http://hubblesite.org`)

But, wait…

What information is still missing?

Toward the post-CCD era in spectroscopy

CCD limitations

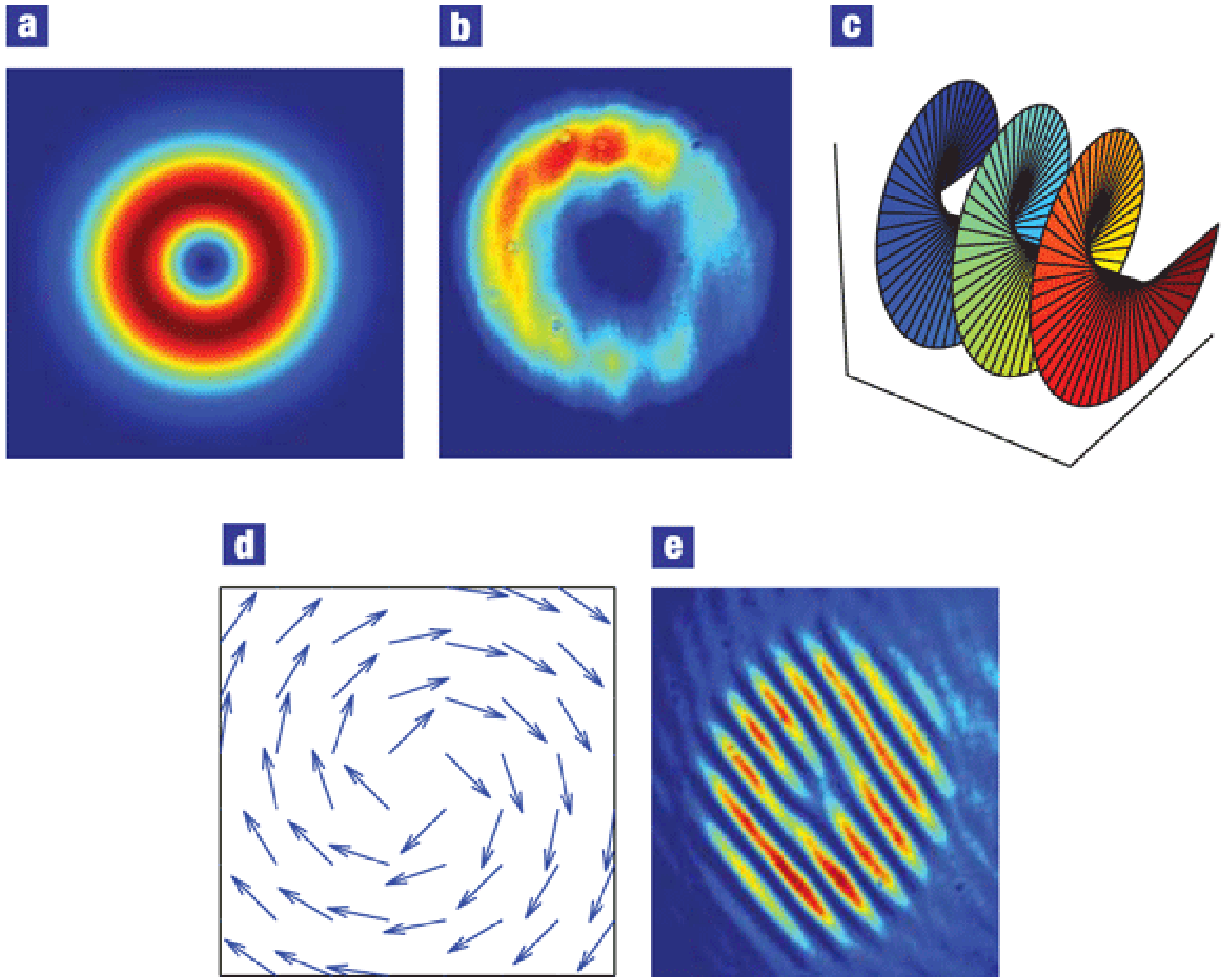
No high time resolution

No photon counting

No energy resolution

No polarization resolution

No photon orbital momentum



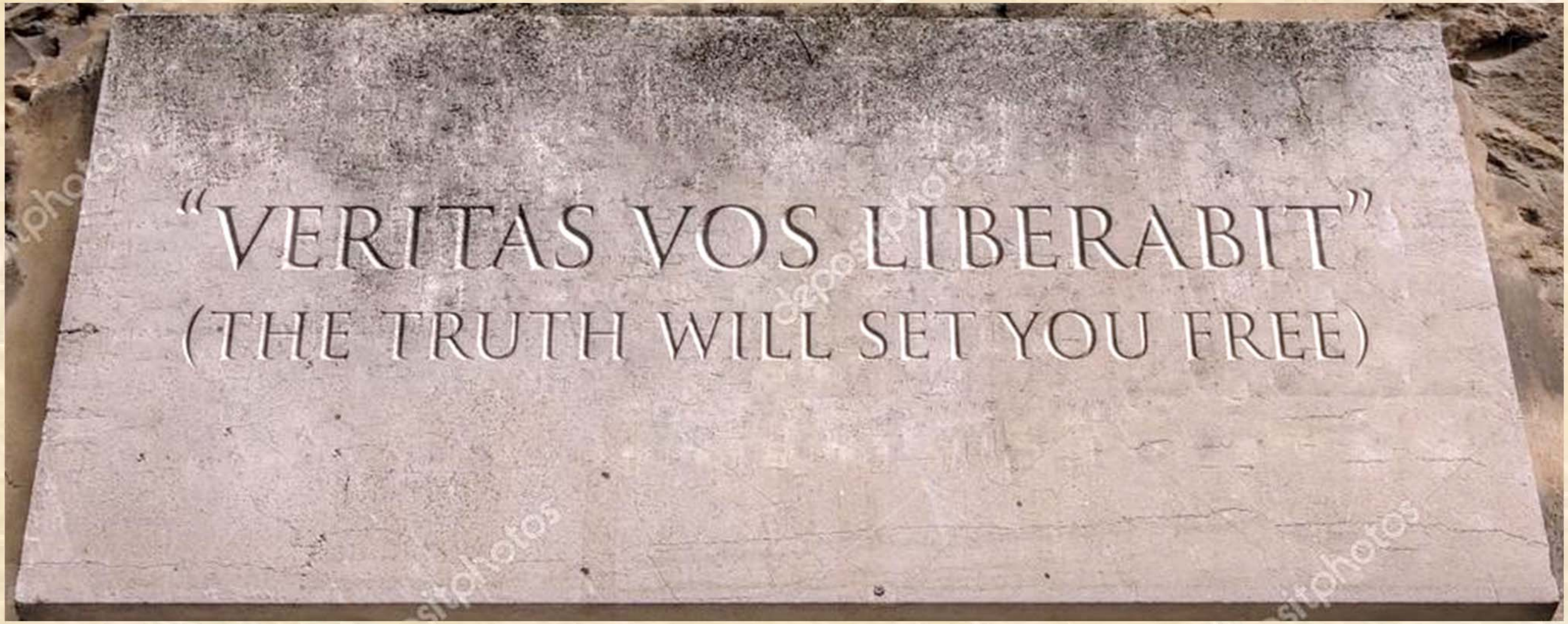
Light with photon orbital angular momentum

Transverse intensity patterns of a light beam; **a**: theoretical; **b**: experimental
c: Phase twists around the central dark spot, producing a staircase-like phase wavefront
d: Local momentum mimics a tornado or vortex fluid – “optical vortices”
e: Interference pattern for m = 1, revealed by the fork-like structure.

G.Molina-Terriza, J.P.Torres & Ll.Torner: *Twisted Photons*, Nature Physics **3**, 305 (2007)

Bottom line:

High-fidelity spectroscopy, combined with quantum optics, remains a challenge for ELT and beyond



THE

END