# [FUND] Main Sequence and Subgiant stars

Creevey, Ligi, Shulyak,
Chiavassa, Bigot, Mourard, Nardetto, Thevenin, Petit,
Wittkowski, Le Boquin, Allard

Science Cases for Interferometry in the Visible: January 15-16 2015, Nice

# Science drivers

- Main sequence stars = huge % of observable Galaxy
- Fundamental parameters: mass, age, Teff, (exoplanet hosts, stellar populations)
- Activity and impact on Planetary characterisation
- Stellar interiors and evolution -> diffusion/rotation/magnetism
- Granulation and atmospheres, high precision abundances
- Chemical evolution of Galaxy (Teff scale /logg)
- Early Galaxy (metal-poor stars)
- Galactic populations (with seismology) .... LIST GOES ON

# Technical Summary

- Low/Medium spectral resolution + high A Res.

  **A** No time constraints (sizes, diameters, V2)

  **B** Time sensitive + time series (convection/planet detection, closure phases/imaging)

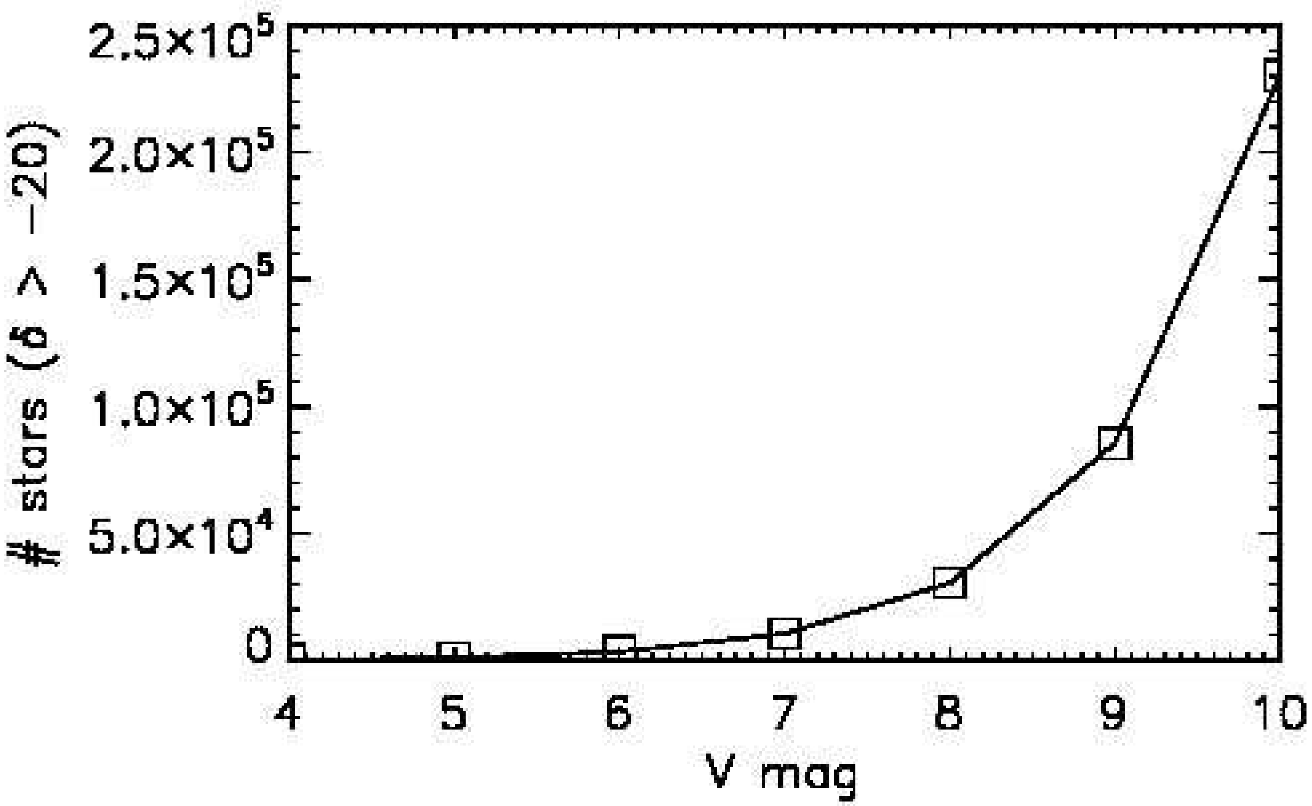
- **C** Medium/High spectral resolution + ang.res. > 0.1 mas (spots/limb-darkening V2, closure phases)

# A Sizes of stars

- V2 measurements down to 0.1 mas
- 4-6 hours good observations per star
- Little or no time constraint
- <2% precision (reasonable?)
- Limits:
  - 1 Rsolar for G5V @ V=6: θ=0.54 mas
  - V=7: θ=0.34 mas
- FRIEND: 0.3 mas = K star @ V=10

# Interest in going fainter

- #stars V<4 (decl > -20) = 378

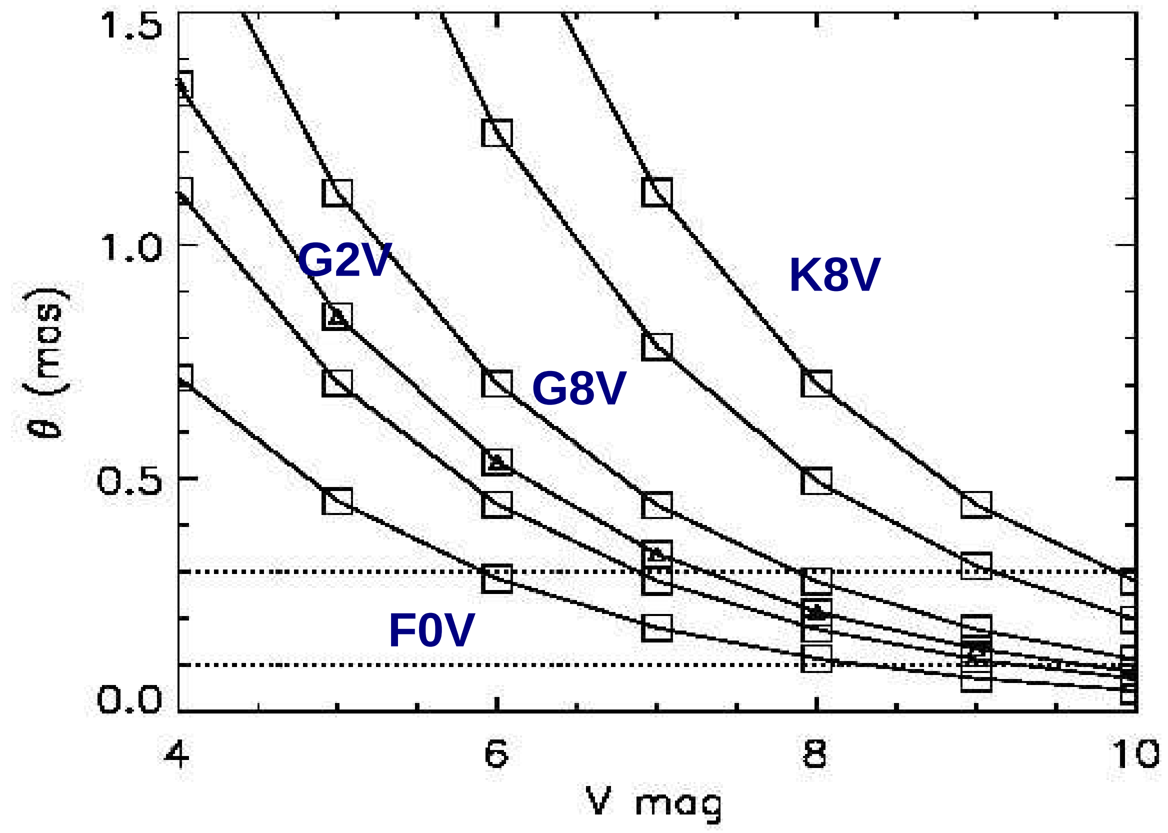


~60% more objects in whole sky

Data from SIMBAD database

# Interest in going fainter

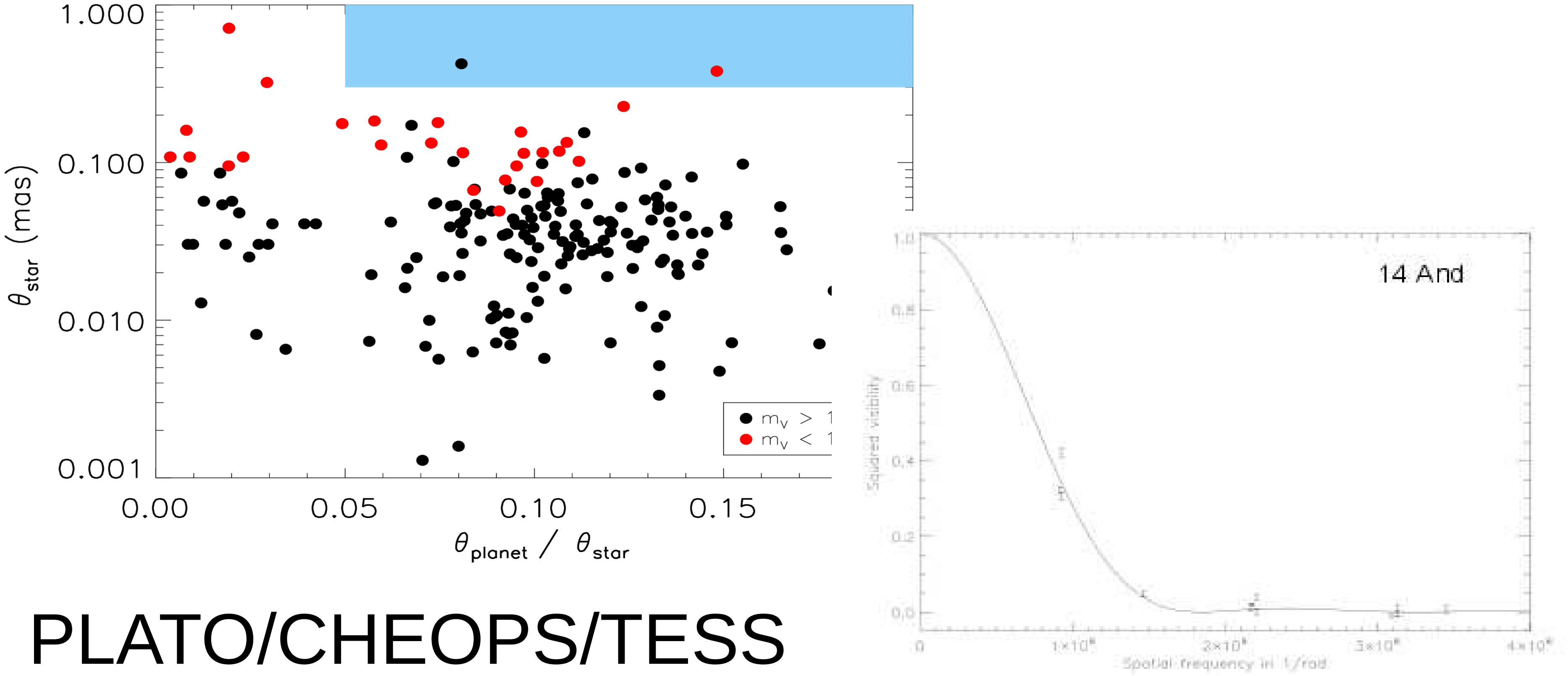
- Access later spectral types



Estimated angular diameter for ZAMS stars (not evolved)

# 1. Planetary Systems

- Diameters of (transiting) exo-planet host stars

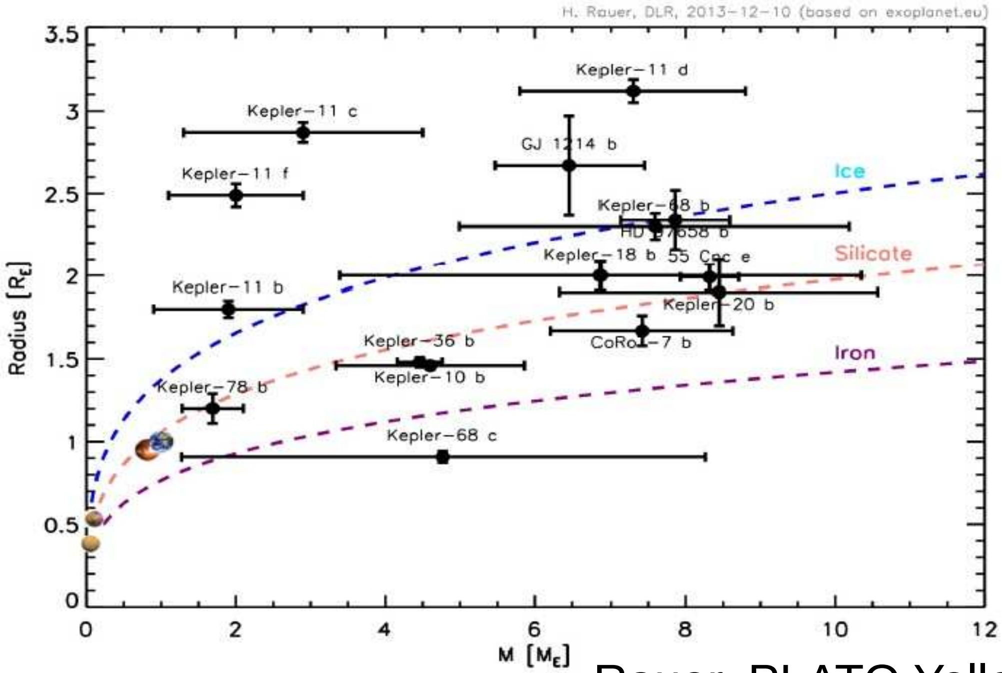


- PLATO/CHEOPS/TESS

Ligi et al. 2012

# 1. Planetary systems

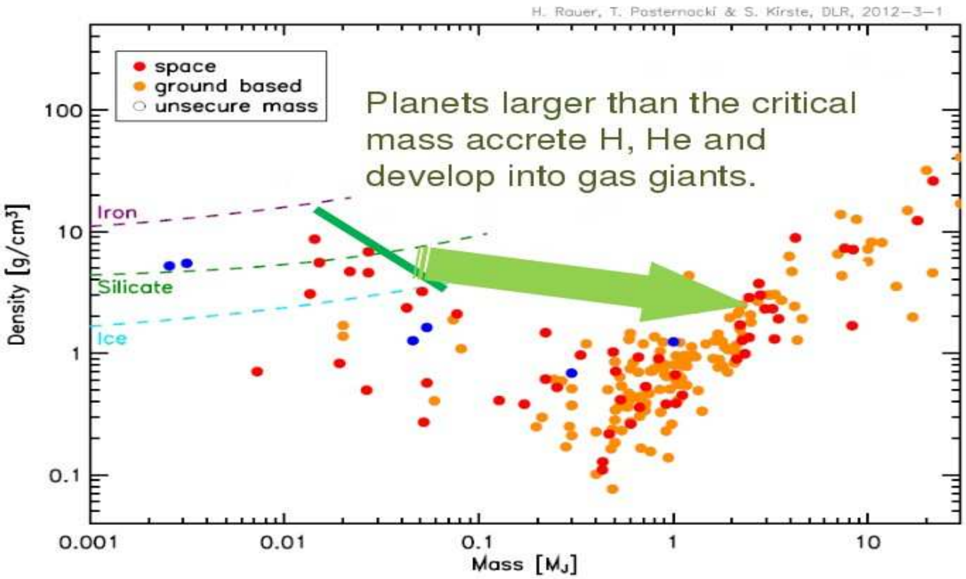
- Diameters of (transiting) exo-planet host stars
- Transit depth ~ Rp/Rstar
- Rp constrains bulk composition



Rauer, PLATO Yellow-Book

# 1. Planetary Systems

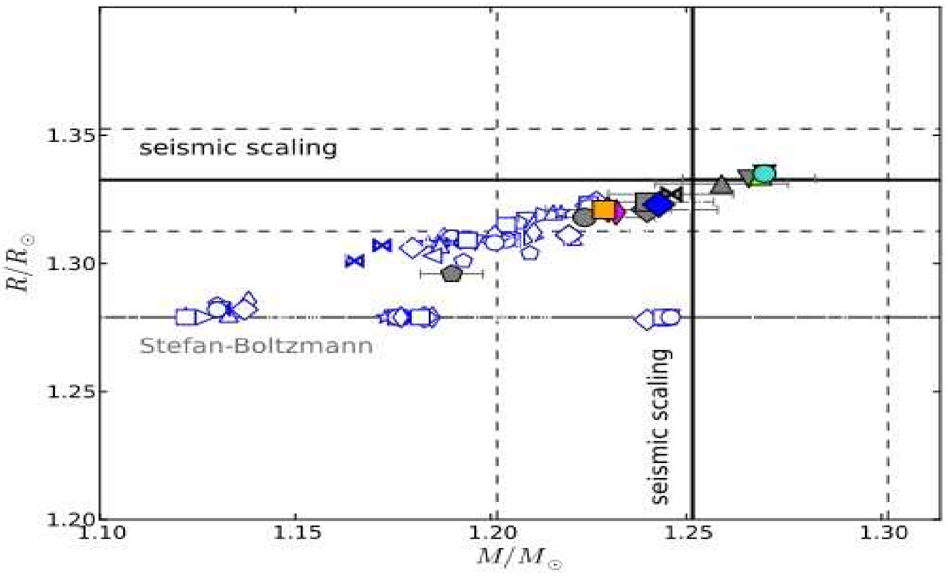
- Diameters of (transiting) exo-planet host stars
- Transit depth ~ Rp/Rstar
- Rp constrains bulk composition
- Evolution of planets



Rauer, PLATO Yellow-Book

# 1. Planetary Systems

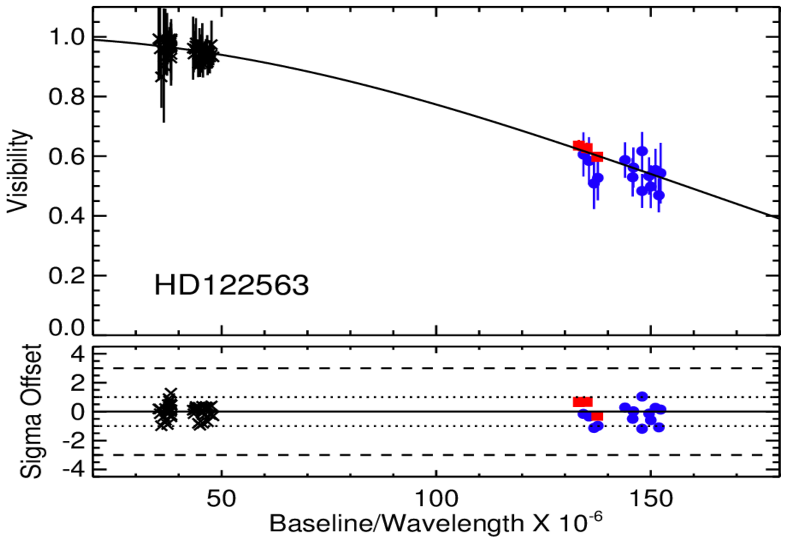
- Exoplanet host radii as constraints on the star's mass and age for transiting or RV
- Radius direct observable constraint on evolution
- Combined with seismic analysis, high precision mass and age



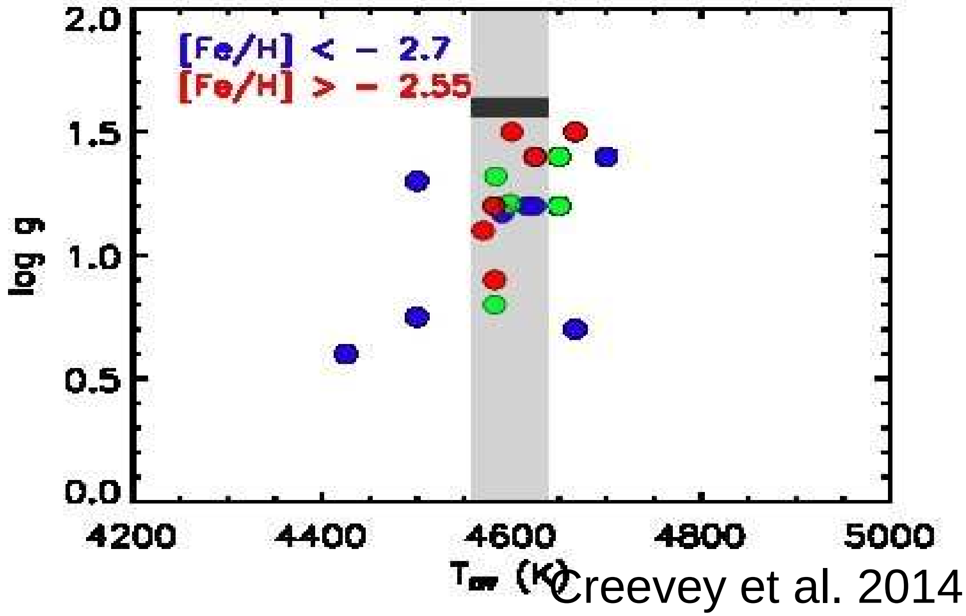
HD 52265 Lebreton & Goupil 2014

# 2. Metal-poor stars

- Effective temperatures + log g of metal-poor stars
- Poorly modeled atmospheres, difficult teff, logg thus abundances
- Today ~6 metal-poor measurable



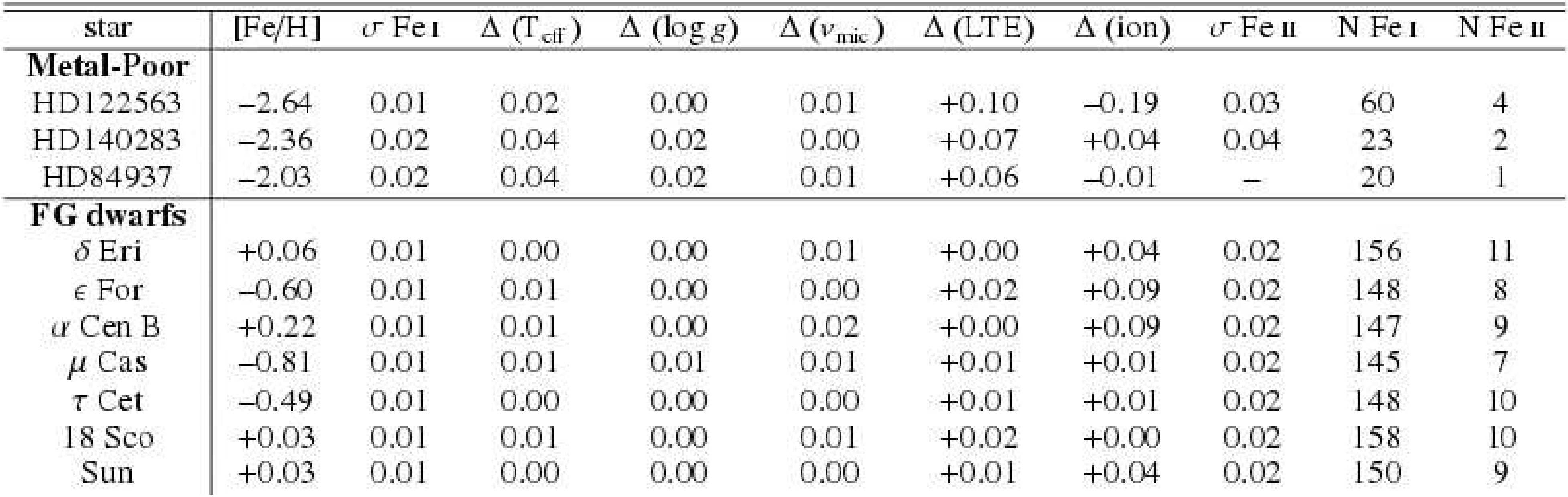
Creevey et al. 2012



Creevey et al. 2014

# 2. Metal-poor stars

- Benchmark metallicities and calibration of methods for fainter more distant stars
- Improvement of models (logg and Teff fixed)

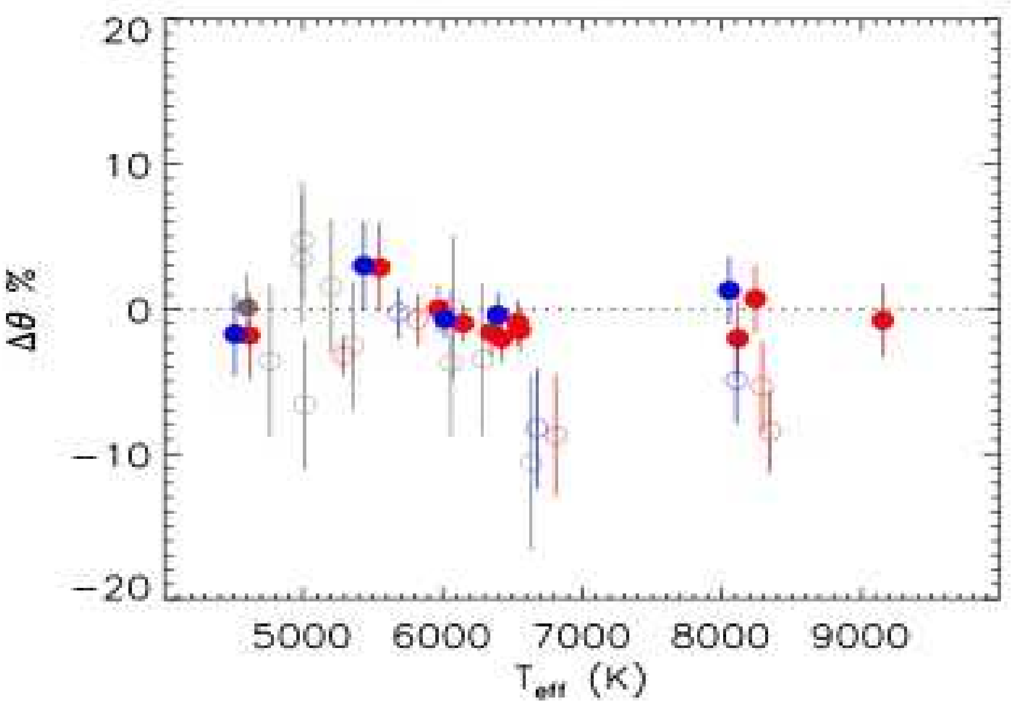


| star | [Fe/H] | $\sigma$ Fe I | $\Delta$ ($T_{\rm eff}$) | $\Delta$ ($\log g$) | $\Delta$ ($v_{\rm mic}$) | $\Delta$ (LTE) | $\Delta$ (ion) | $\sigma$ Fe II | N Fe I | N Fe II |
|---|---|---|---|---|---|---|---|---|---|---|
| **Metal-Poor** | | | | | | | | | | |
| HD122563 | –2.64 | 0.01 | 0.02 | 0.00 | 0.01 | +0.10 | –0.19 | 0.03 | 60 | 4 |
| HD140283 | –2.36 | 0.02 | 0.04 | 0.02 | 0.00 | +0.07 | +0.04 | 0.04 | 23 | 2 |
| HD84937 | –2.03 | 0.02 | 0.04 | 0.02 | 0.01 | +0.06 | –0.01 | – | 20 | 1 |
| **FG dwarfs** | | | | | | | | | | |
| $\delta$ Eri | +0.06 | 0.01 | 0.00 | 0.00 | 0.01 | +0.00 | +0.04 | 0.02 | 156 | 11 |
| $\epsilon$ For | –0.60 | 0.01 | 0.01 | 0.00 | 0.00 | +0.02 | +0.09 | 0.02 | 148 | 8 |
| $\alpha$ Cen B | +0.22 | 0.01 | 0.01 | 0.00 | 0.02 | +0.00 | +0.09 | 0.02 | 147 | 9 |
| $\mu$ Cas | –0.81 | 0.01 | 0.01 | 0.01 | 0.01 | +0.01 | +0.01 | 0.02 | 145 | 7 |
| $\tau$ Cet | –0.49 | 0.01 | 0.00 | 0.00 | 0.00 | +0.01 | +0.01 | 0.02 | 148 | 10 |
| 18 Sco | +0.03 | 0.01 | 0.01 | 0.00 | 0.01 | +0.02 | +0.00 | 0.02 | 158 | 10 |
| Sun | +0.03 | 0.01 | 0.00 | 0.00 | 0.00 | +0.01 | +0.04 | 0.02 | 150 | 9 |

Jofre et al. 2014

# 2. Metal-poor stars

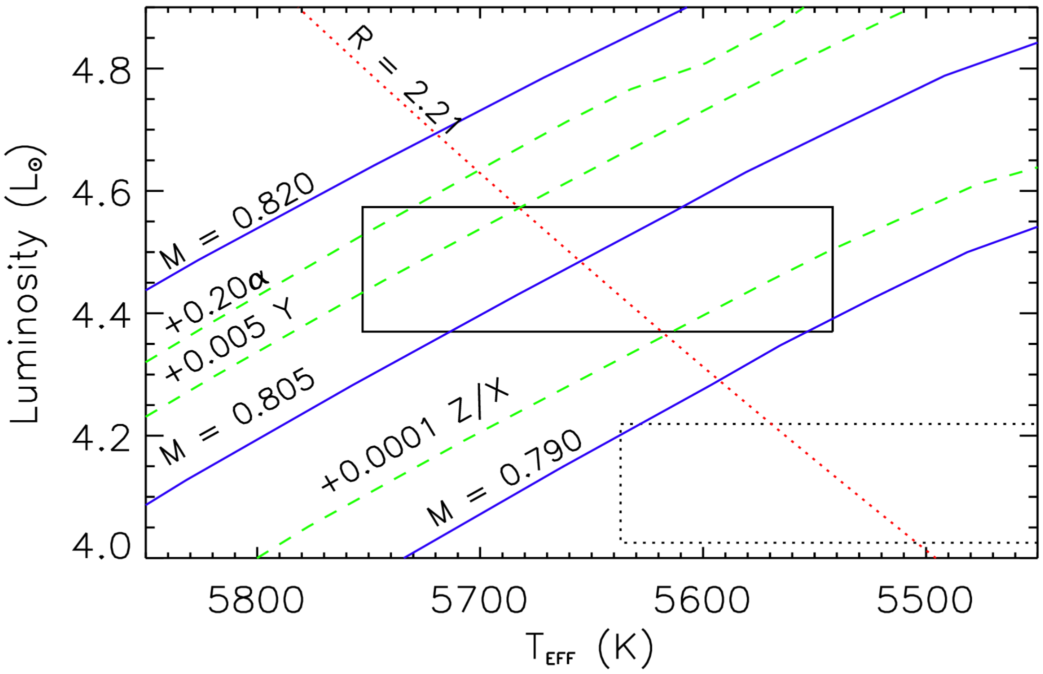
- 1% precisions in Effective temperature scale
- Infra-red flux method validated with interferometric measurements



Casagrande et al. 2014

# 2. Metal-poor stars

- Ages of the oldest stars



Creevey et al. 2014

# 2. Metal-poor stars

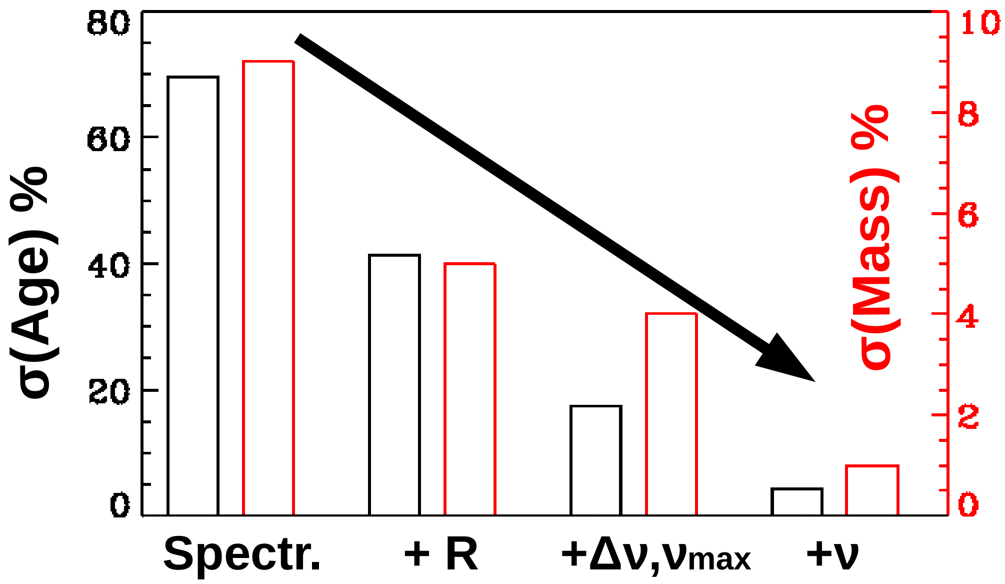
- Today ~6 metal-poor measurable
- FRIEND (V<10) + 8 stars
- >0.2 mas + 13 stars
- >0.15 mas + 21 stars
- >0.1 mas + 27 stars  (catalogue Giridhar et al.)

# 3 Stellar Physics

- Improving stellar models (structure, evolution, atmospheres) with consequences for all aspects of astrophysics, e.g. [M/H],age
- 1D mixing-length parameter, initial helium abundance, age
- Modelling spectral lines
- Better abundances, e.g. Li, for constraint on diffusion processes
- Applications: -> better ages!

# 4. Asteroseismology+Interferometry

- Age + Mass



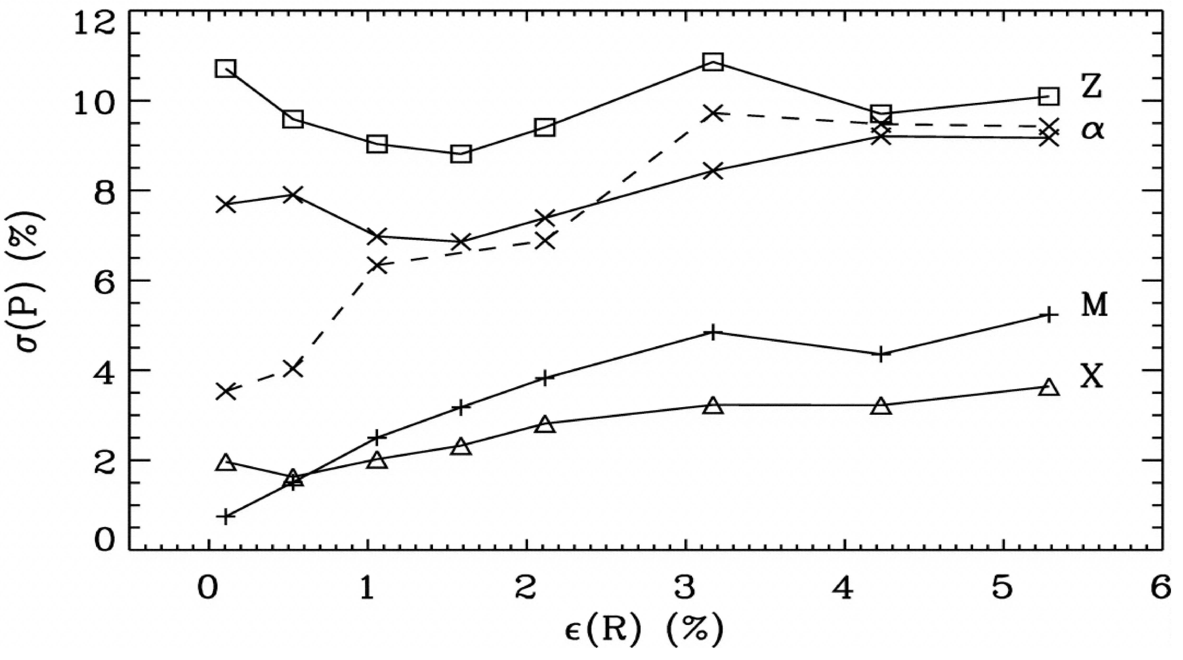
Creevey et al.

# 4. Asteroseismology+Interferometry

- Age + Mass
- Mixing-length parameter 'observationally' constrained
- Consequence

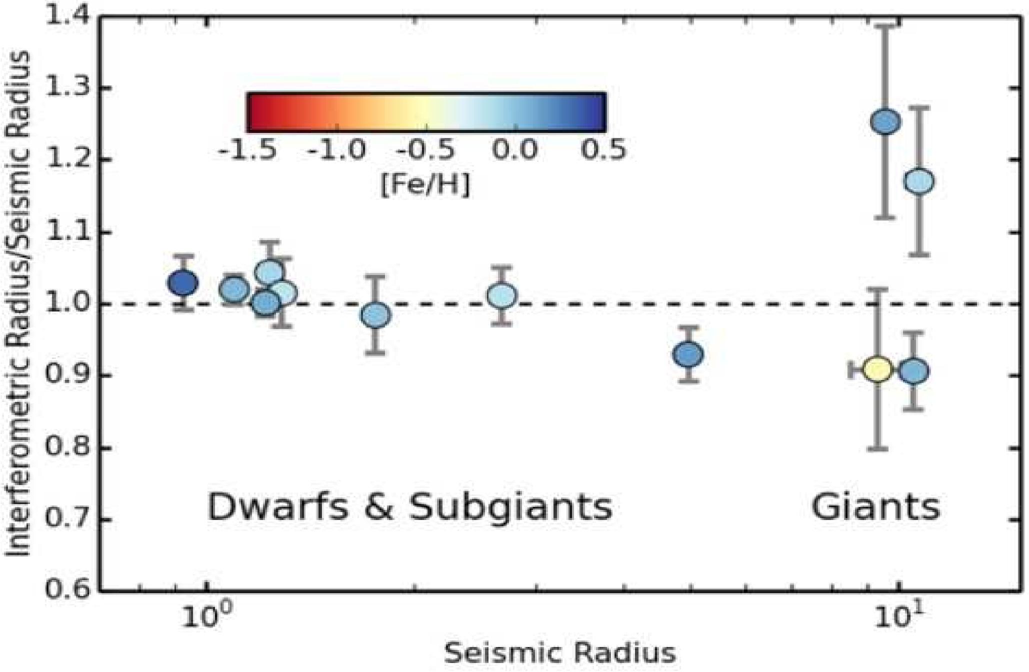
  for initial helium

  abundance



# 4. Asteroseismology+Interferometry

- Validation of seismic laws which predict M & R

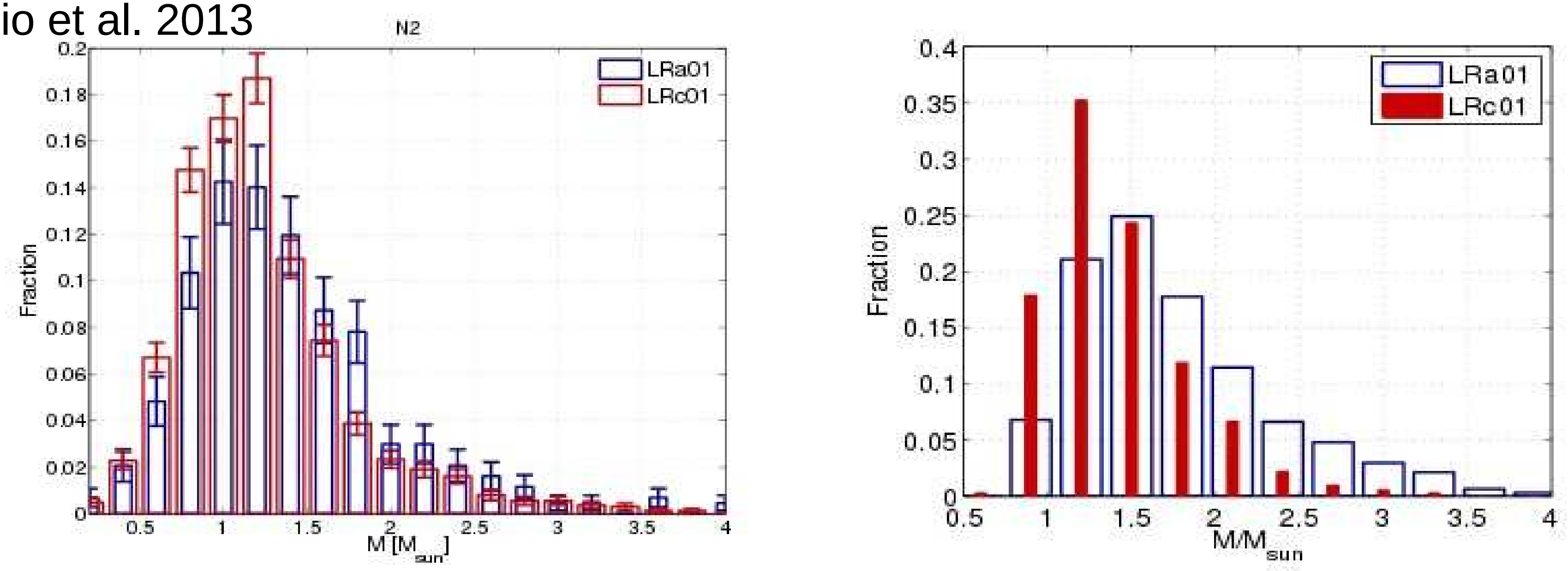


Huber et al.

# 4. Asteroseismology+Interferometry

- Validation of seismic laws
- Application to Galactic archaeology

Miglio et al. 2013



Mass distribution of Two Corot fields: left observations, right simulations

# 4. Asteroseismology+Interferometry

- TESS and PLATO!!  + Gaia

# 5. Surface Brightness

- Surface brightness relations, esp. Metal-poor and giants
- Gaia delivering distance
- “observational” radius for 1 billion stars!

# 6 Binaries

- Detached Binaries, preferably eclipsing and SB2s: solve full orbit, known M, R
  - Interior physics, e.g. core overshooting

# Technical Summary

- Low/Medium spectral resolution + high A Res.

  **A** No time constraints   (sizes, diameters, V2)

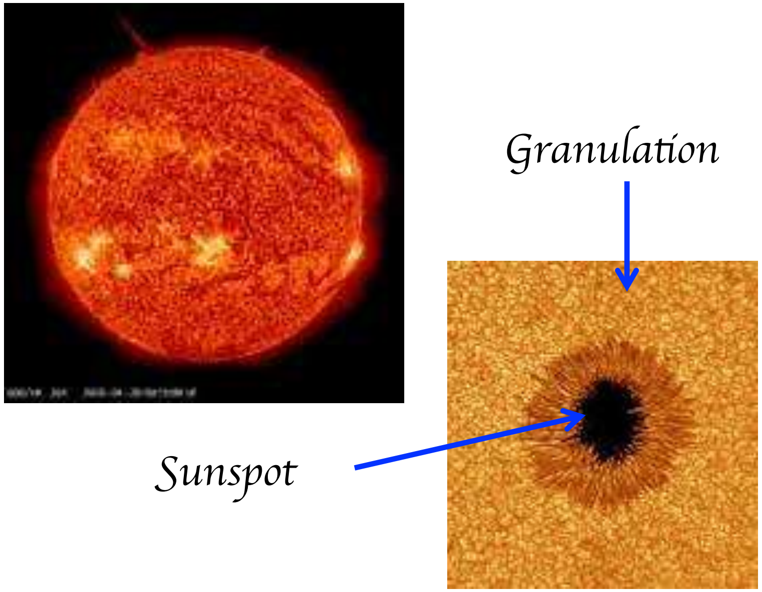
  **B** Time sensitive + time series  (convection/planet det, closure phases/imaging)

- **C** Medium/High spectral resolution + ang.res. > 0.1 mas (spots/limb-darkening  V2, closure phases)

# EXOPLANETS AND STELLAR ACTIVITY

Stellar activity:
- magnetic (dark) spots
- convection paterns (granulation)

causes difficulties for:
- stellar parameters determination
- (transiting) exoplanet characterization.

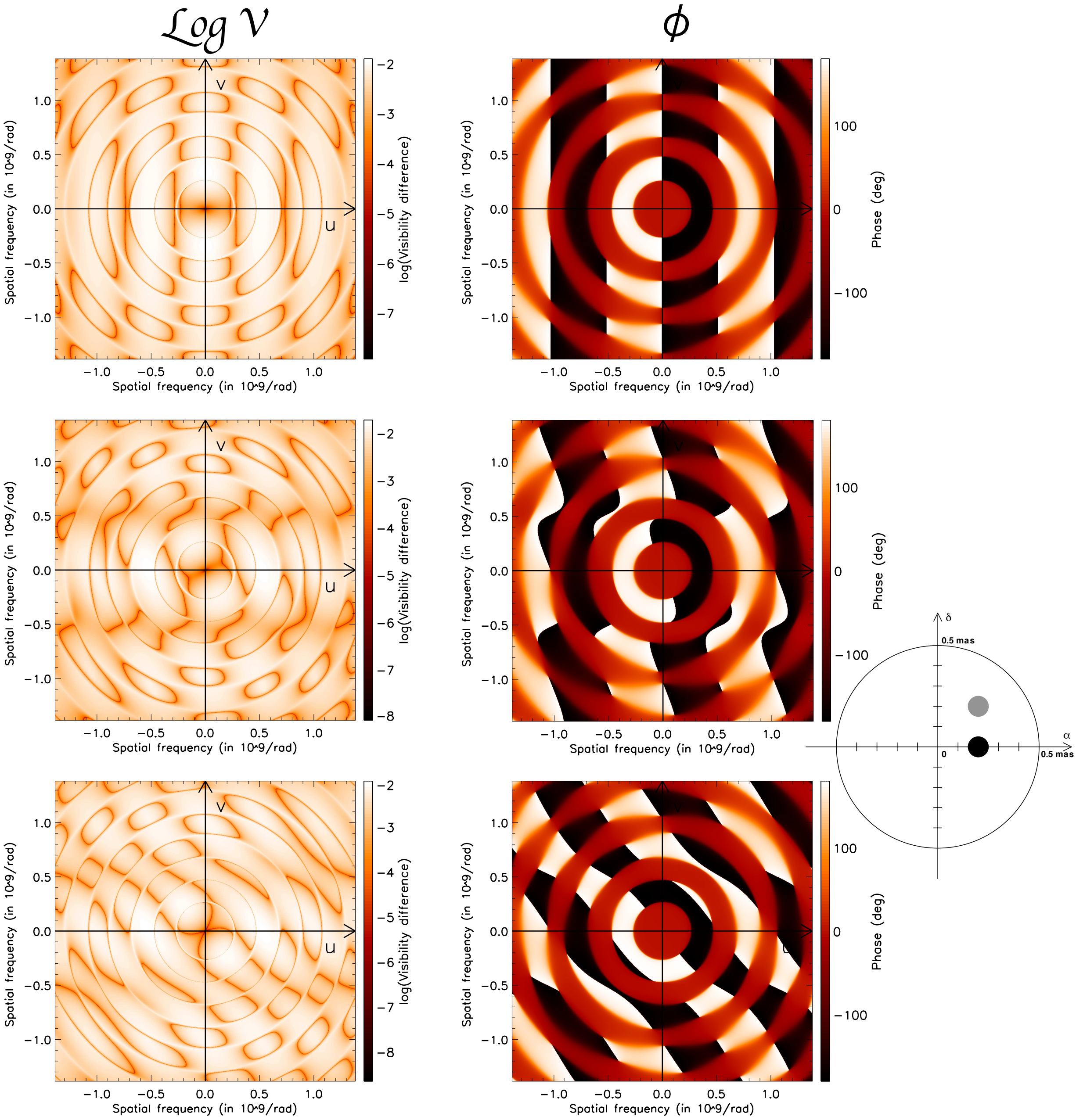


Interferometry = high angular resolution technique, same wavelength as RV and transit measurements.

How can interferometry help for exoplanet characterization?

# EXOPLANETS AND STELLAR ACTIVITY

**SPOTS**
(Ligi et al. 2014)



Star
+ 0.1 mas exoplanet

Star
+ 0.1 mas exoplanet
+ 0.1 mas spot

Star
+ 0.05 mas exoplanet
+ 0.1 mas spot

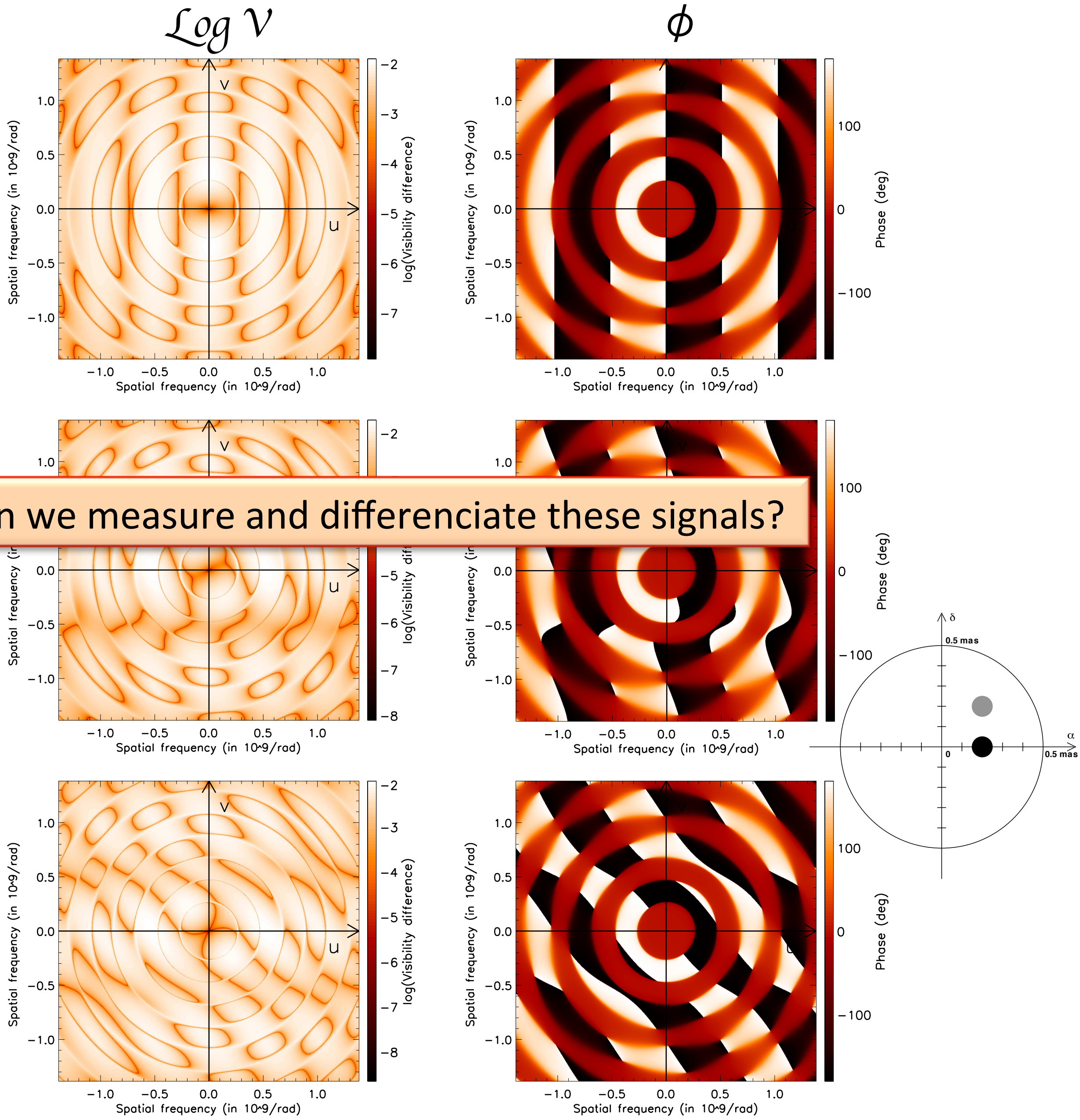
# EXOPLANETS AND STELLAR ACTIVITY

**SPOTS**
(Ligi et al. 2014)

Star
+ 0.1 mas exoplanet

Star
+ 0.1 mas exoplanet
+ 0.1 mas spot

Star
+ 0.05 mas exoplanet
+ 0.1 mas spot



How can we measure and differenciate these signals?

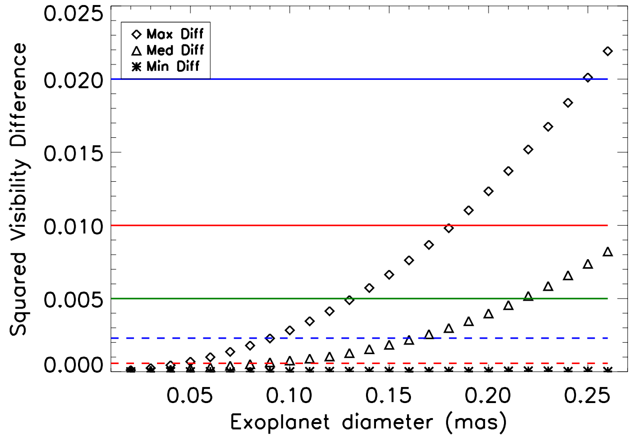
# EXOPLANETS AND STELLAR ACTIVITY

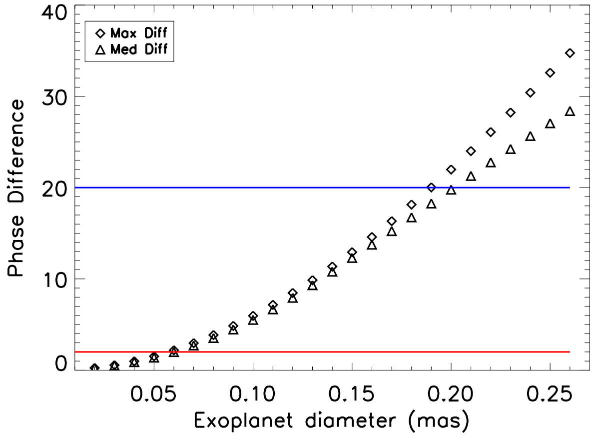
**SPOTS**
(Ligi et al. 2014)

Baseline length

0.04 mas-exoplanet with 190 m-baseline
Signal of 2° in phases, S/N = 5 (at best)

Accuracy





*Spat. freq =3.4.10$^{8}$ (1/rad) (2$^{nd}$ lobe)*

Instrumental capabilities

| Instrument | $V^2$ accuracy | CP accuracy | Ref. |
|---|---|---|---|
| VEGA/CHARA | 1 – 2% | - | 1 |
| FLUOR/CHARA | 0.3% | - | 2 |
| JouFLU/CHARA | 0.1%$^{*}$ | - | 3 |
|  | 1% | - | 4 |
| VISION/NPOI | 5 – 20%$^{**}$ | 1 – 10° | 5 |
| CLIMB/CHARA | 5% | 0.1° | 6 |
| CLASSIC/CHARA | 5% | - | 7 |
| PAVO/CHARA | ∼ 5% | 5° | 8 |
| MIRC/CHARA | ∼ 2% | < 1° | 9 |
|  | - | 0.1 – 0.2 | 10, 11, 12 |
| AMBER/VLTI | - | 0.20 – 0.37 | 13 |
| PIONIER/VLTI | - | 0.25 – 3° | 14 |
|  | 3 – 15% | 0.5° | 15 |
| GRAVITY/VLTI | - | 1 | 16 |
| MATISSE/VLTI | 1.6 – 2.3% | < 1.16 | 17 |

*Competition between angular resolution and sensitivity*

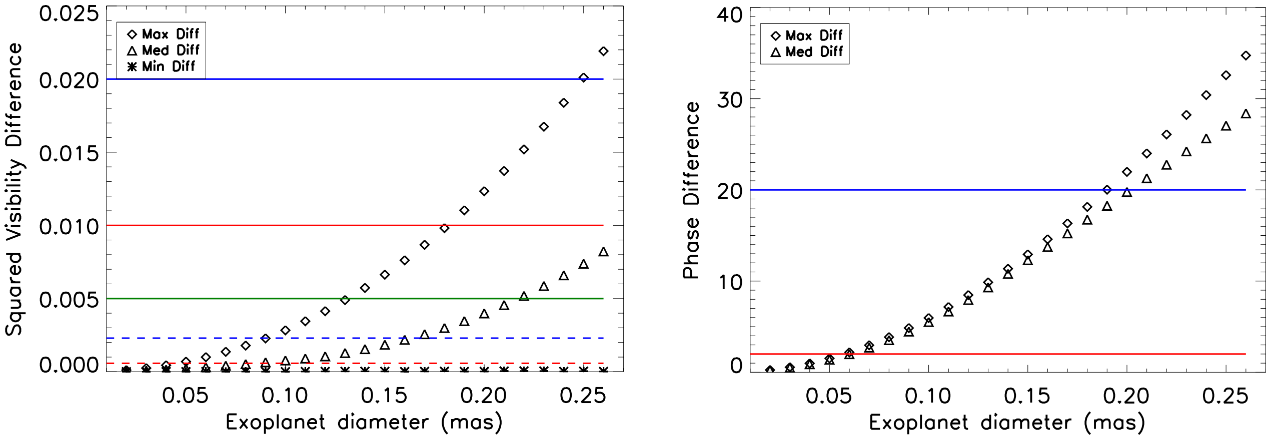
# EXOPLANETS AND STELLAR ACTIVITY

**SPOTS**
(Ligi et al. 2014)

Baseline length

0.04 ✔ -exoplanet with 190 m-baseline
Signa OK in phases, S/N = 5 (at best)

Accuracy



*Spat. freq =3.4.$10^8$ (1/rad) ($2^{nd}$ lobe)*

Instrumental capabilities

| Instrument | $V^2$ accuracy | CP accuracy | Ref. |
|---|---|---|---|
| VEGA/CHARA | 1 – 2% | - | 1 |
| FLUOR/CHARA | 0.3% | - | 2 |
| JouFLU/CHARA | 0.1%$^*$ | - | 3 |
| | 1% | - | 4 |
| VISION/NPOI | 5 – 20%$^{**}$ | 1 – 10° | 5 |
| CLIMB/CHARA | 5% | 0.1° | 6 |
| CLASSIC/CHARA | 5% | - | 7 |
| PAVO/CHARA | ~ 5% | 5° | 8 |
| MIRC/CHARA | ~ 2% | < 1° | 9 |
| | - | 0.1 – 0.2 | 10, 11, 12 |
| AMBER/VLTI | - | 0.20 – 0.37 | 13 |
| PIONIER/VLTI | - | 0.25 – 3° | 14 |
| | 3 – 15% | 0.5° | 15 |
| GRAVITY/VLTI | - | 1 | 16 |
| MATISSE/VLTI | 1.6 – 2.3% | < 1.16 | 17 |

*Competition between angular resolution and sensitivity*

# EXOPLANETS AND STELLAR ACTIVITY

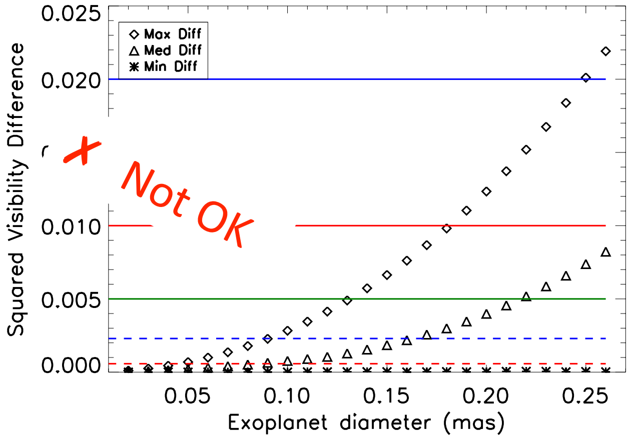
**SPOTS**
(Ligi et al. 2014)

Baseline length

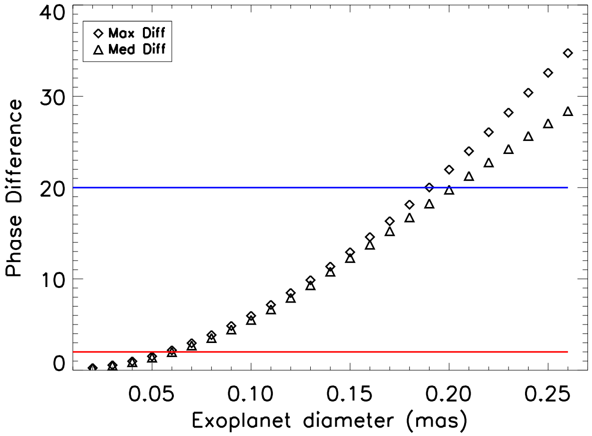
0.04 -exoplanet with 190 m-baseline
Signa ✔ OK in phases, S/N = 5 (at best)

Accuracy

*Spat. freq =3.4.10$^8$ (1/rad) (2$^{nd}$ lobe)*



✗ Not OK



Instrumental capabilities

| Instrument | $V^2$ accuracy | CP accuracy | Ref. |
|---|---|---|---|
| VEGA/CHARA | 1 – 2% | - | 1 |
| FLUOR/CHARA | 0.3% | - | 2 |
| JouFLU/CHARA | 0.1%* | - | 3 |
| | 1% | - | 4 |
| VISION/NPOI | 5 – 20%** | 1 – 10° | 5 |
| CLIMB/CHARA | 5% | 0.1° | 6 |
| CLASSIC/CHARA | 5% | - | 7 |
| PAVO/CHARA | ~ 5% | 5° | 8 |
| MIRC/CHARA | ~ 2% | < 1° | 9 |
| | - | 0.1 – 0.2 | 10, 11, 12 |
| AMBER/VLTI | - | 0.20 – 0.37 | 13 |
| PIONIER/VLTI | - | 0.25 – 3° | 14 |
| | 3 – 15% | 0.5° | 15 |
| GRAVITY/VLTI | - | 1 | 16 |
| MATISSE/VLTI | 1.6 – 2.3% | < 1.16 | 17 |

*Competition between angular resolution and sensitivity*

# EXOPLANETS AND STELLAR ACTIVITY

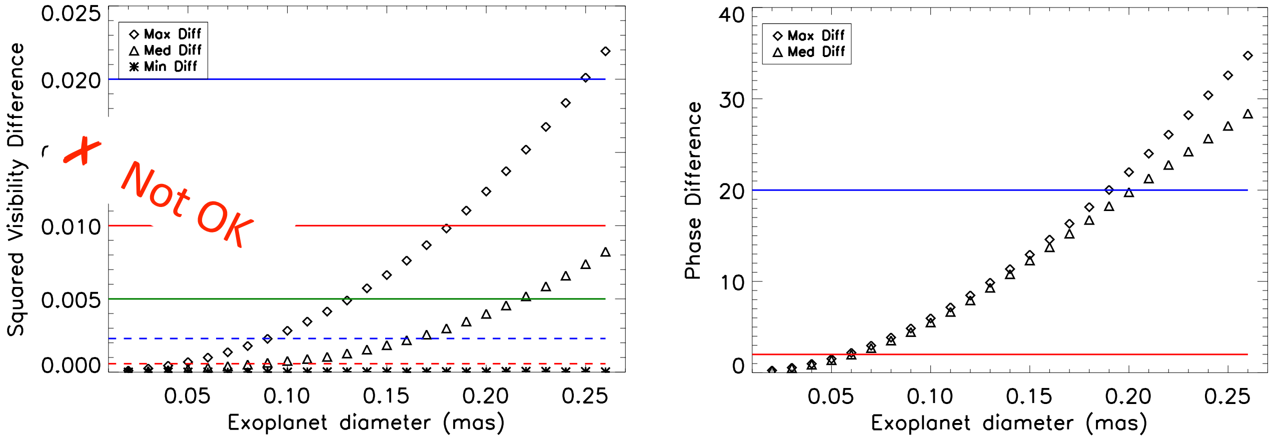
**SPOTS**
(Ligi et al. 2014)

Baseline length

0.04 -exoplanet with 190 m-baseline
Signa in phases, S/N = 5 (at best)

✔ OK

Accuracy



✗ Not OK

*Spat. freq =3.4.10$^{8}$ (1/rad) (2$^{nd}$ lobe)*

Instrumental capabilities

| Instrument | $V^2$ accuracy | CP accuracy | Ref. |
|---|---|---|---|
| VEGA/CHARA | 1 – 2% | - | 1 |
| FLUOR/CHARA | 0.3% | - | 2 |
| JouFLU/CHARA | 0.1%* | - | 3 |
|  | 1% | - | 4 |
| VIS N/NPOI | 5 – 20%** | 1 – 10° | 5 |
| CI ARA | 5% | 0.1° | 6 |
| CL A | 5% | - | 7 |
| PAVO/CI | ~ 5% | 5° | 8 |
| MIRC/CHAR | ~ 2% | < 1° | 9 |
|  | - | 0.1 – 0.2 | 10, 11, 12 |
| AMBER/VLTI | - | 0.20 – 0.37 | 13 |
| PIONIER/VLTI | - | 0.25 – 3° | 14 |
|  | 3 – 15% | 0.5° | 15 |
| GRAVITY/VLTI | - | 1 | 16 |
| MATISSE/VLTI | 1.6 – 2.3% | < 1.16 | 17 |

✗ Not OK

*Competition between angular resolution and sensitivity*

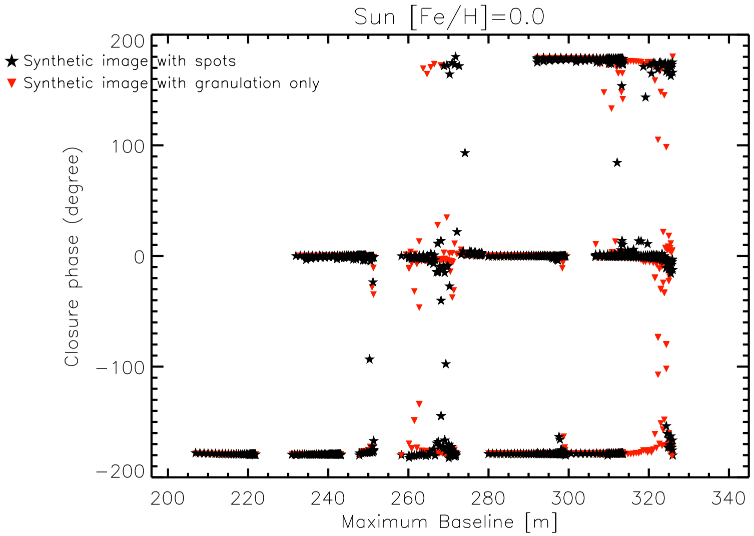
# EXOPLANETS AND STELLAR ACTIVITY

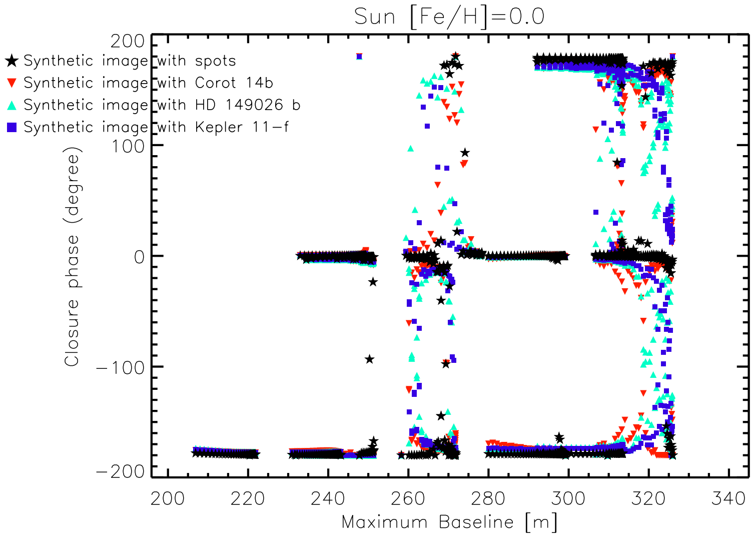
## GRANULATION
(Chiavassa et al. 2014)

- 3D simulations – Stagger grid
- Effects on closure phases (CP)

Impact of granulation
Impact of spots
Impact of exoplanets

Example with Procyon and β Com:
➔ MIRC is the most suitable instrument (good uv coverage and long baselines): 16.4° in the 5th lobe on CP
➔ VEGA: <1° in the 2nd lobe



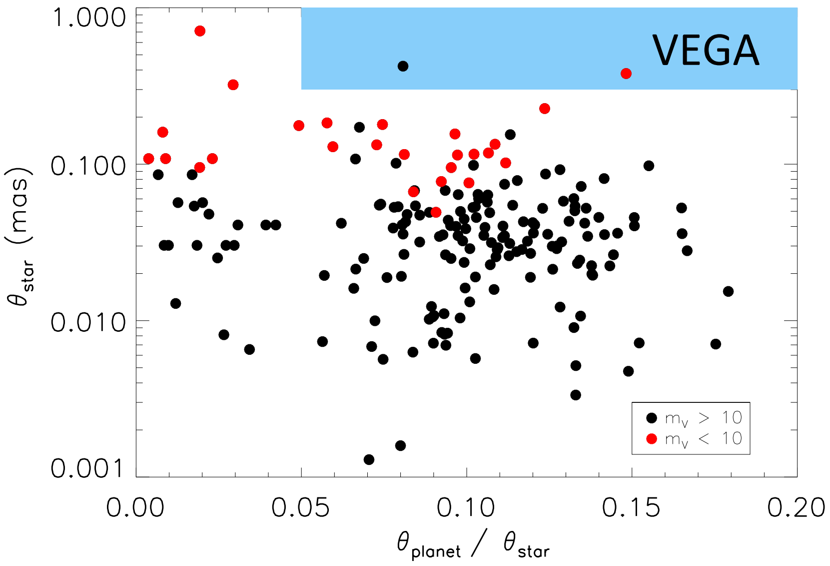


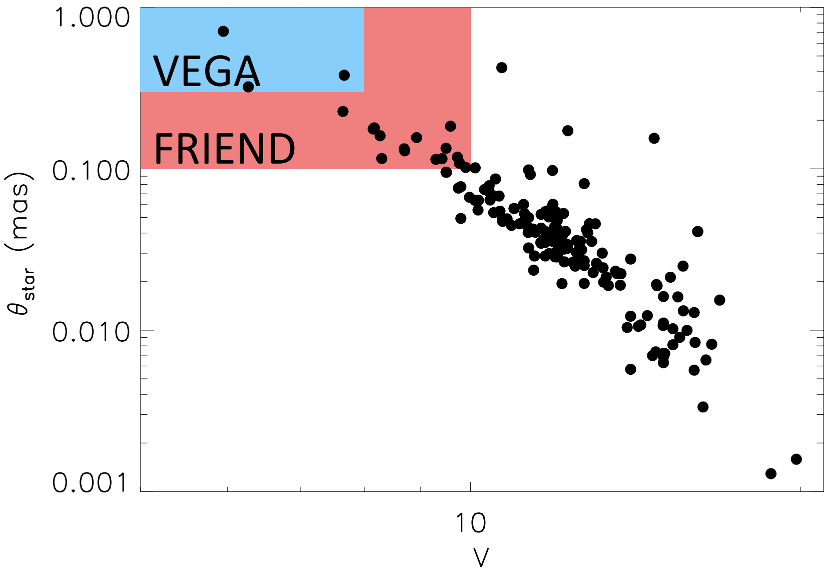
# EXOPLANETS AND STELLAR ACTIVITY

Conclusions:

- Baseline length should be enough to detect small enough planets (at visible wavelengths)
- But need to improve by a factor 10 instrumental accuracy to characterize them.

- Need measurements from the 3rd lobe of visibility for granulation 2nd lobe for exoplanets ➔ visible and near infrared wavelengths.
- Spot and exoplanet signals are mixed up but can be differenciated at optical wavelengths and at different phases of the transit.
- Limitation in magnitude for transiting exoplanet host stars: need targets!
  ➔ PLATO 2.0





# Science Case 7&8

- **B** Roxanne: planet detections and characterising granulation
- **C** Denis: stellar spots and magnetic activity

# Spots on main-sequence stars

## Interferometry and MS stars

- CP stars with abundance spots (look bright or dark depending on wavelength and spectral lines). Spectral types: B – F, slow rotation (at least at later spectral types). Some have fields up to $\approx$ 30 kG (strongest fields among MS stars!)
- There are many more sun-like stars and M dwarfs that possess temperature and magnetic spots.

## Interferometry and MS stars

The application of interferometry to main-sequence (MS) stars is still limited to only brightest objects (closest and/or largest MS stars can be easily resolved – measuring stellar sizes).

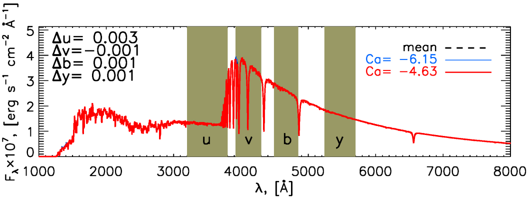
Detailed studies of surface morphology remain challenging.

# Spot detection with interferometry

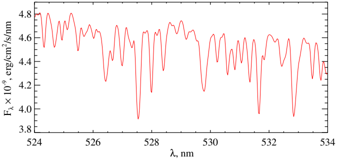
- Interferometry is a new independent method to study spotted surfaces of stars.
- Widely used Doppler Imaging explicitely assumes that the line profile variability is due to spots only, thus the true intensity contrast may be affected by other effects (local magnetic fields, inaccuracies in atomic data, etc.). Interferometry thus will provide an important supplementary information about spot locations and contrast.
- Interferometry is the only method to resolve spots in slowly rotating CP stars for which no Doppler Imaging possible.

# Why Visual?

More light

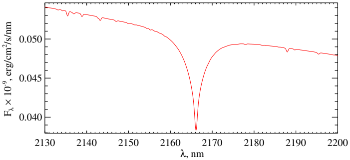


V



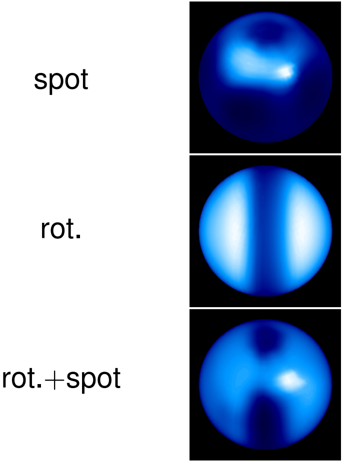
More features

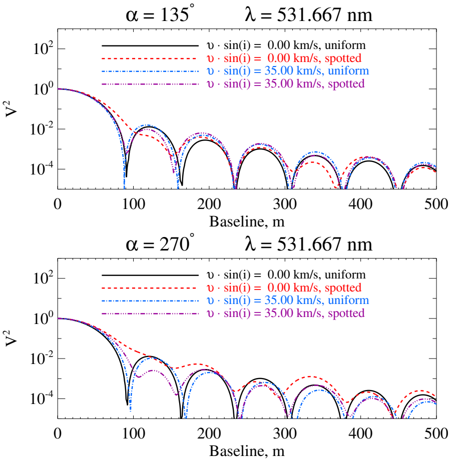
IR



# Why Sensitivity?

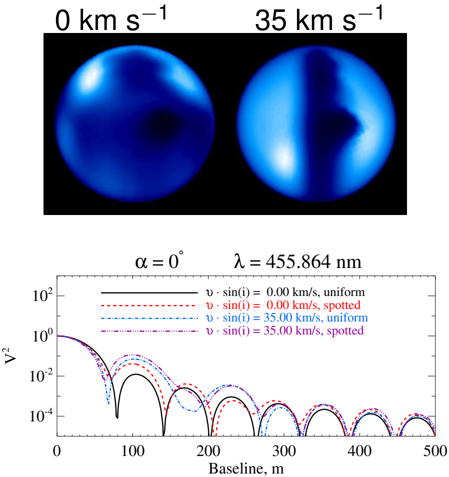
We want to go to lower $V^2$ to disantangle rotation/spots and/or simultaneos observations at different PA's are needed.

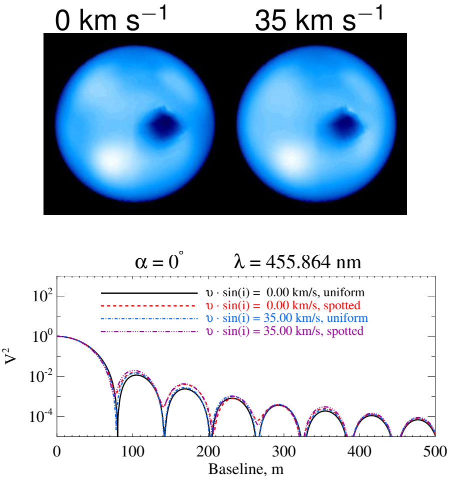




# Why Resolution?

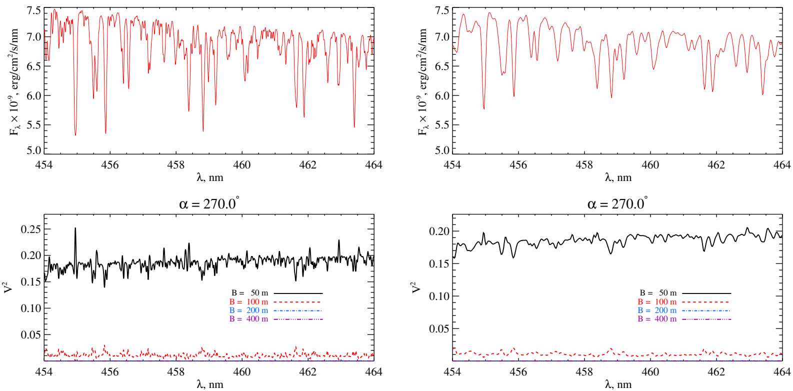
Resolution influences the intensity contrast which is essential for definite spot detection.





## Visibility vs. wavelength

High resolution results in more features. Potantially important at low $V^2$ and low SN.



$R = 30\,000$ $R = 6\,000$

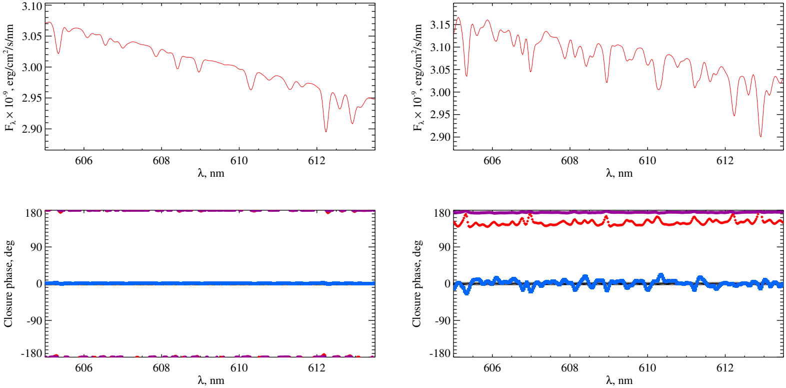
● $B = 50$m, ● $B = 100$m, ● $B = 200$m, ● $B = 400$m

## Why Closure Phase?

CP allows to uniquely disantangle rotation and spots at certain configurations.

Not spotted

Spotted

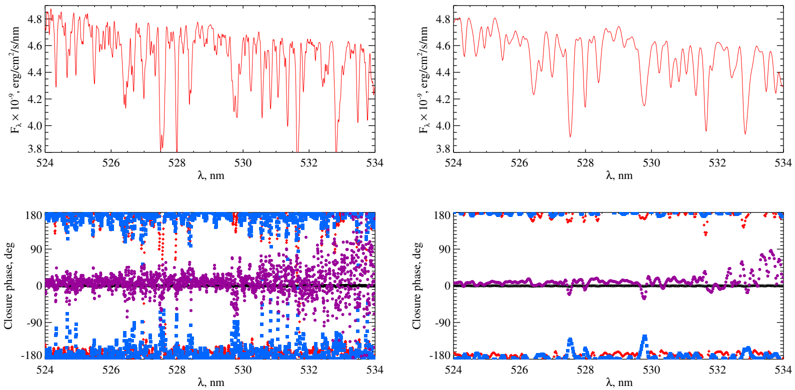


+ $B_{max} = 56.5$m, ♦ $B_{max} = 141.4$m, ■ $B_{max} = 254.6$m, ● $B_{max} = 452.6$m

# Why Closure Phase?

CP provides rich information at high resolution.

$R = 30\,000$ $\qquad$ $R = 6\,000$



$+$ $B_{max} = 56.5$m, ♦ $B_{max} = 141.4$m, ■ $B_{max} = 254.6$m, • $B_{max} = 452.6$m

## Summary

- Visual is the best region to hunt for spots. In this region, the intensity contrast is higher in spectral lines of spotted elements thus providing most easy way to detect and characterize them both from the analysis of $V^2$ and CP.
- Spots can be detected already at a first visibility slob in strong spectral features.
- Disentangling spots and rotation: $V^2 < 0.3$ + high $R$ + visual domain + several PA's. Alternative: wavelength dispersed closure phases.

## Summary

- An instrument with the spectral resolution around 6 000 like AMBER or GRAVITY but baselines longer than 180 m would be able to measure rotation, and also rotation+spots.
- For most CP stars their $\theta < 1$ mas. Baselines of hundreds of meters and detectors sensitive to values of $V^2 < 10^{-2}$ are required.
- Baseline length is crutial. Example: among selected 203 CP stars 157 are visible at VLTI location, and several of them could be observed if VLTI had $B_{\max} > 300$ m. Alternatively, there are two objects that could be observed already with available maximum baseline of 140 m but detectors operating in visual were needed.
- Improved interferometric facilities will provide a unique possibility to study spots on slowly rotating CP stars for which no Doppler Imaging possible or complicated.

## Summary

Studying of surface inhomogenities is important for:

- understanding CP star phenomena;
- stellar magnetism;
- particle diffusion theories;
- activity on low-mass stars;
- …

Interferometry+polarimetry is going to be a VERY powerful tool for many classes of MS stars.

# Comments/Questions

- Binaries: detached preferable eclipsing and SB2s.
- Ideally down to 0.1 mas
- How low in lambda? 400 too blue for 'red' stars
- How long can baselines go? Ideally >1km
- How precise can we get a diameter with V2~0.8? (observation time and sensitivity)
- Other Science cases: magnetic inflation of cool, rapidly-rotating stars, limb-darkening
- ROTATION --- Fx comment, I didn't discuss this