Observing Habitable Worlds Near and Far

Margaret Turnbull - STScI

The Big Question: To what extent is the Universe *alive*?

What is "life?"

How does life originate?

Where is life found?

Is all life carbon/water based?

Is life "originating" on Earth now?

What is a "habitable" planet?

What is the range of complexity and diversity for life?

Can life spread between planets/stars?

Do we have cosmic ancestors/cousins?

Are there other inhabited planets in the Solar System?

Are there other technological civilizations?

What are the environmental limits of Earth-like life?

Is there a habitable "belt" within the Galaxy?

Why aren't clouds green?

The Big Question: To what extent is the Universe *alive*?

http://cmex.ihmc.us/VikingCD/Puzzle/Evolife.htm

Key Concept: Habitability

What is a "habitable" environment?

Life needs:

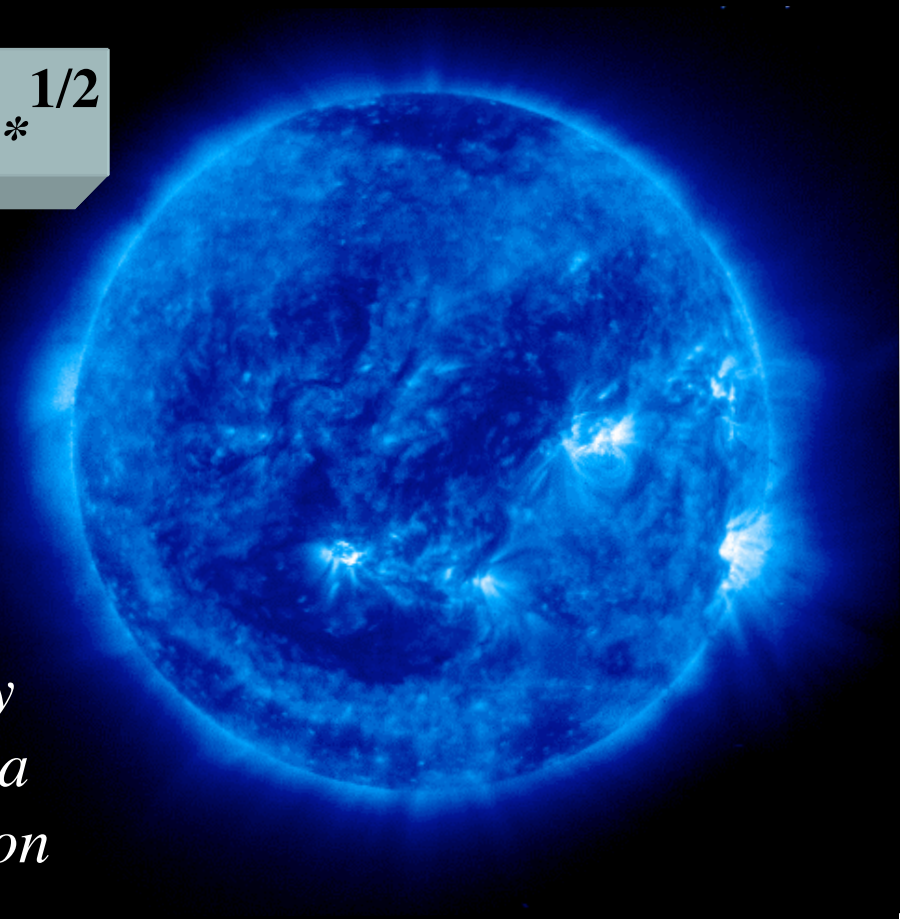
1. Raw materials: C, N, O, S, P...
2. An energy source: sunlight, geothermal
3. Liquid water
4. Time

the limiting factors on Earth

predictable factors for other planetary systems

Astrobiology: The Study of Habitable Zones

0.7 to 1.5 AU, $\propto L_*^{1/2}$



(In reality, HZ location depends on planet characteristics, too.)

(And actually there also is a dependence on stellar T_{eff}.)

Question

Which stars are the best stars around which to search for *habitable* planets and biosignatures?

Answer

It depends on the search strategy:

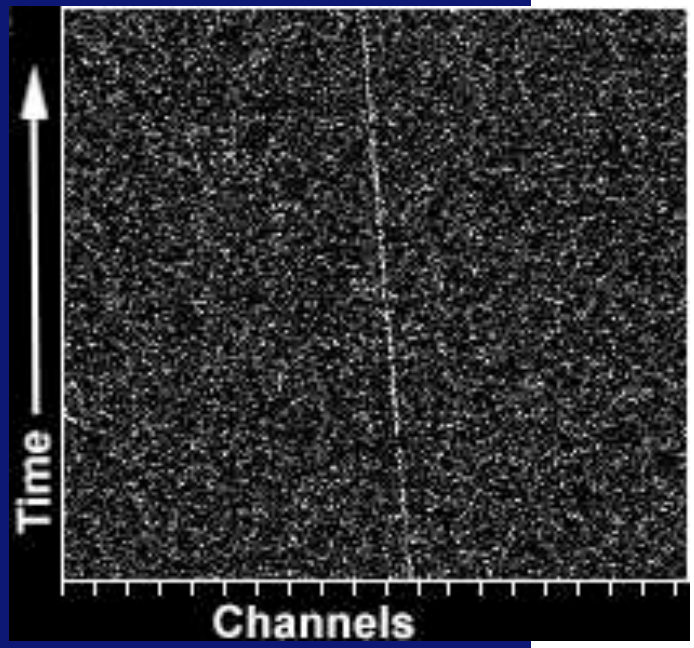
Is the burden of technology on *us* or *them*?

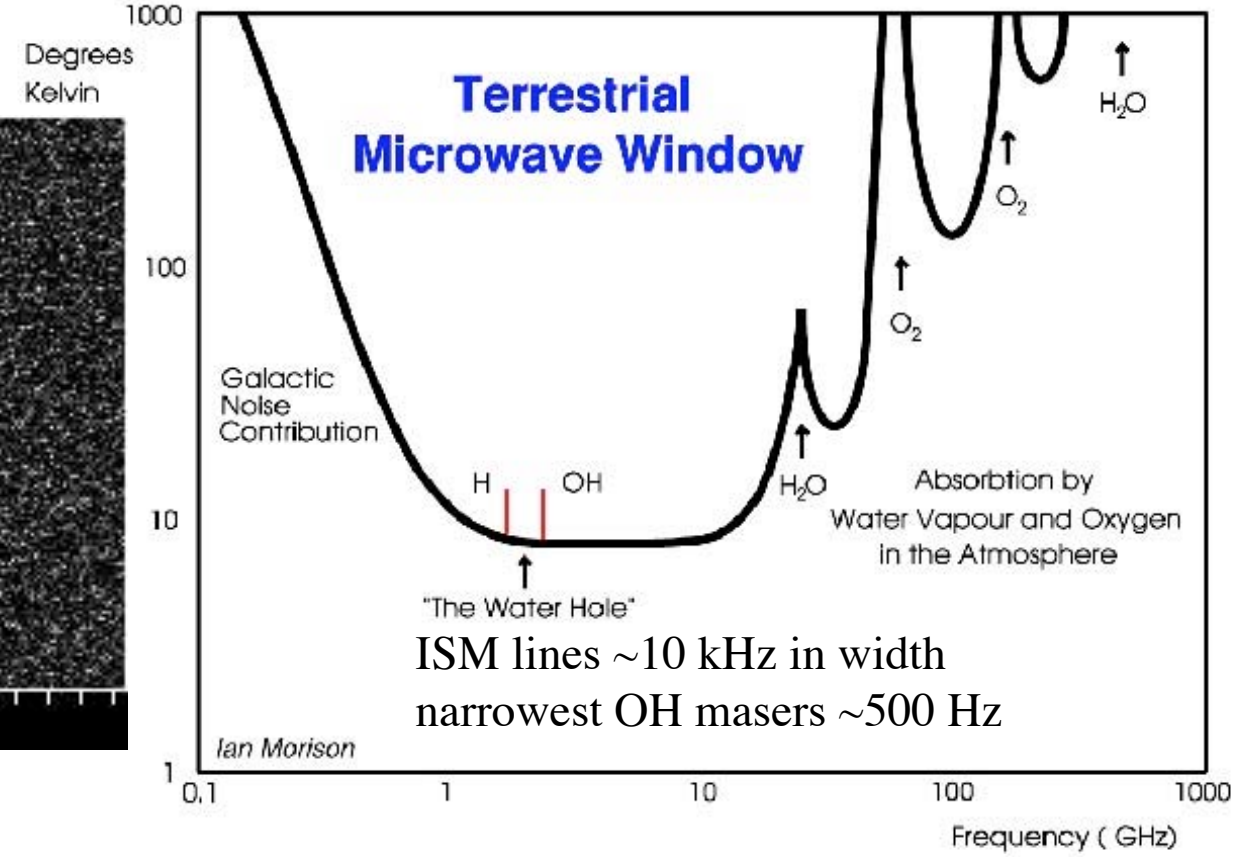
Two Case Studies: SETI vs TPF

SETI

Project Phoenix: A Targeted Search for Narrow-Band Microwave ET Signals

"Narrow-band"
< 300 Hz

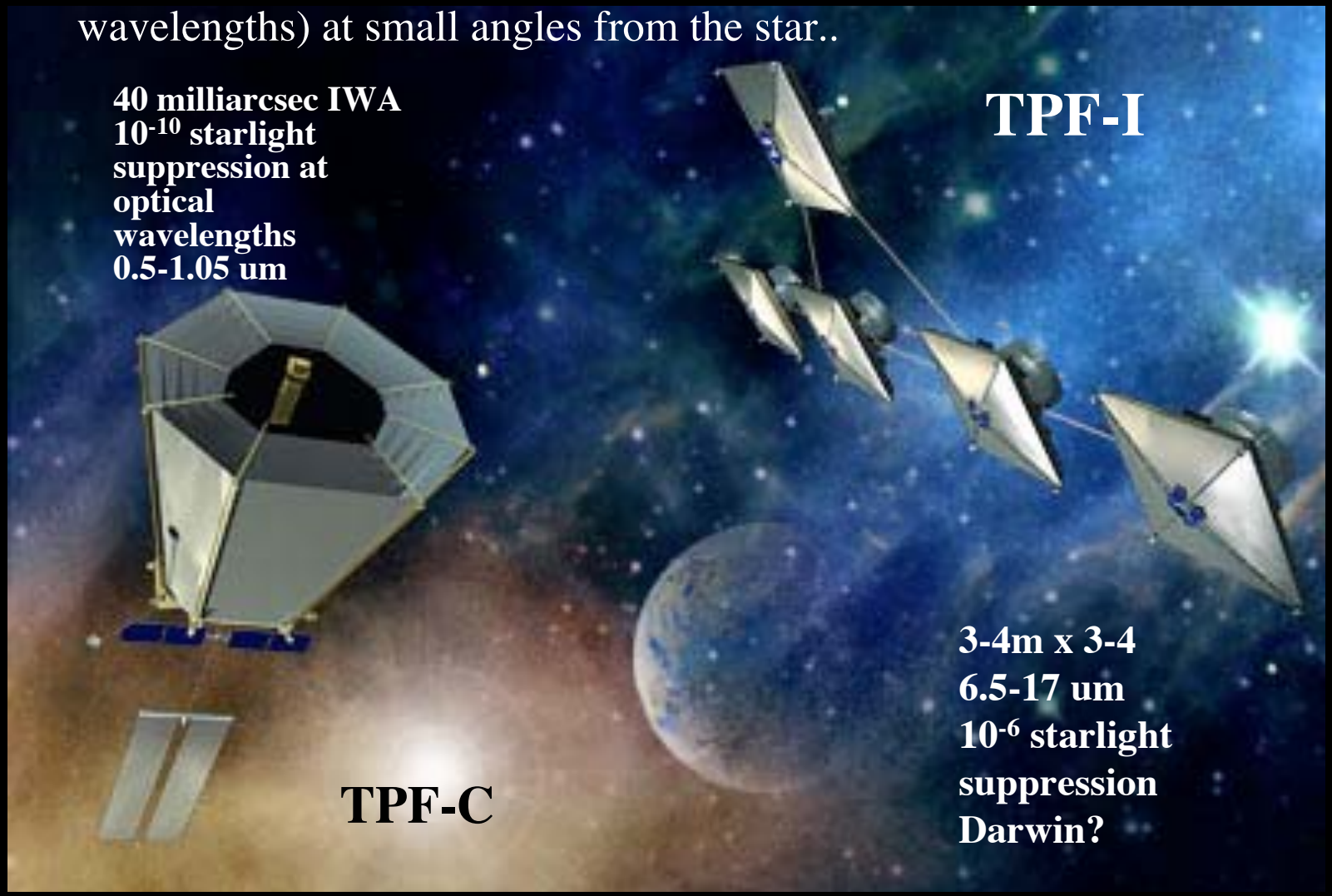




ISM lines ~10 kHz in width
narrowest OH masers ~500 Hz

The Terrestrial Planet Finder

The technology driver is the need to suppress starlight by a factor of 1 million (at mid-IR wavelengths) or 10 billion (at optical wavelengths) at small angles from the star..



Habitable Stellar Systems

A "habstar" has:

(1) A *habitable zone* that is *dynamically stable on a *timescale* that is comparable to the timescale of *global biosignature* production,**

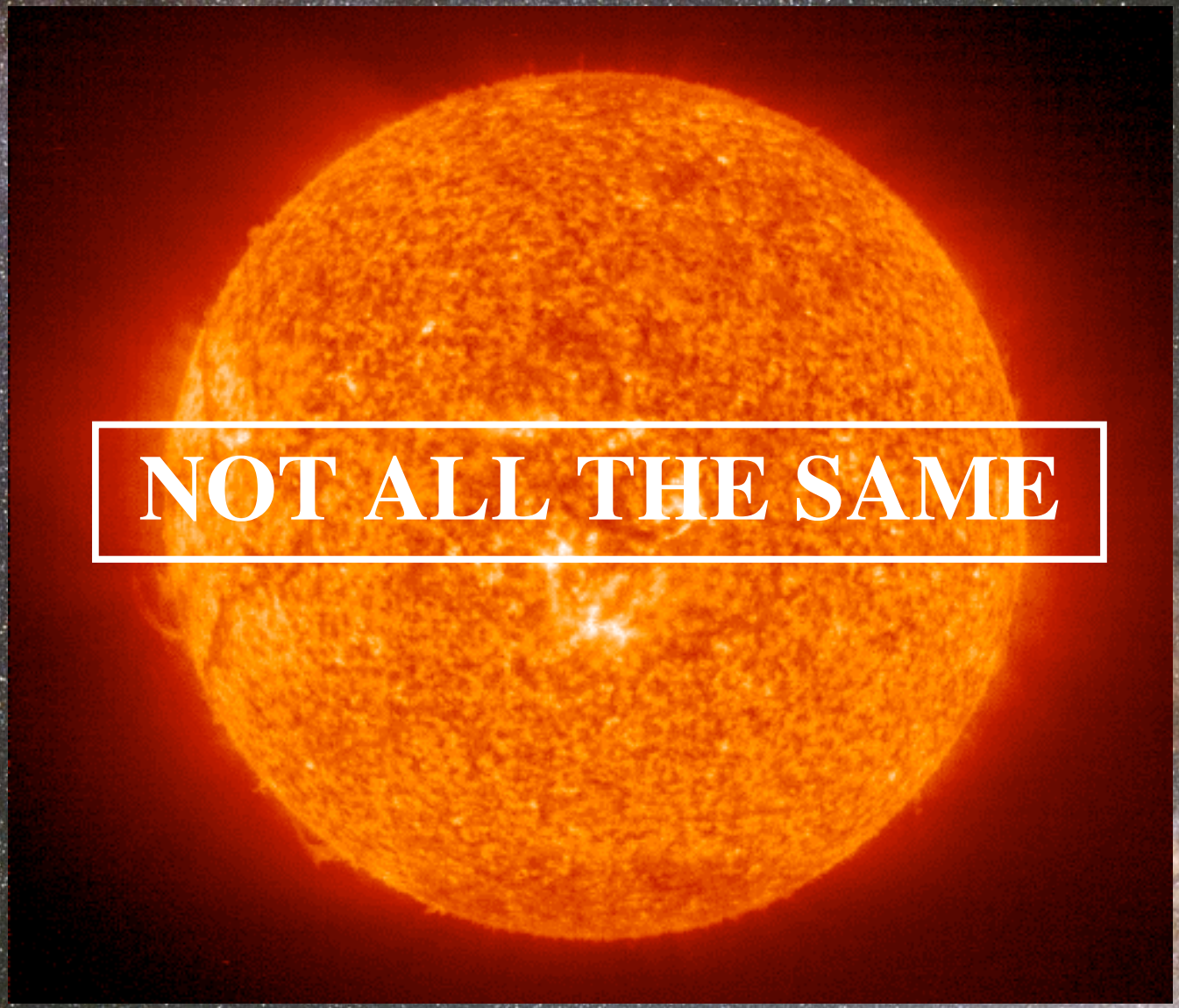
*** and does not overlap any major resonances w/companions**

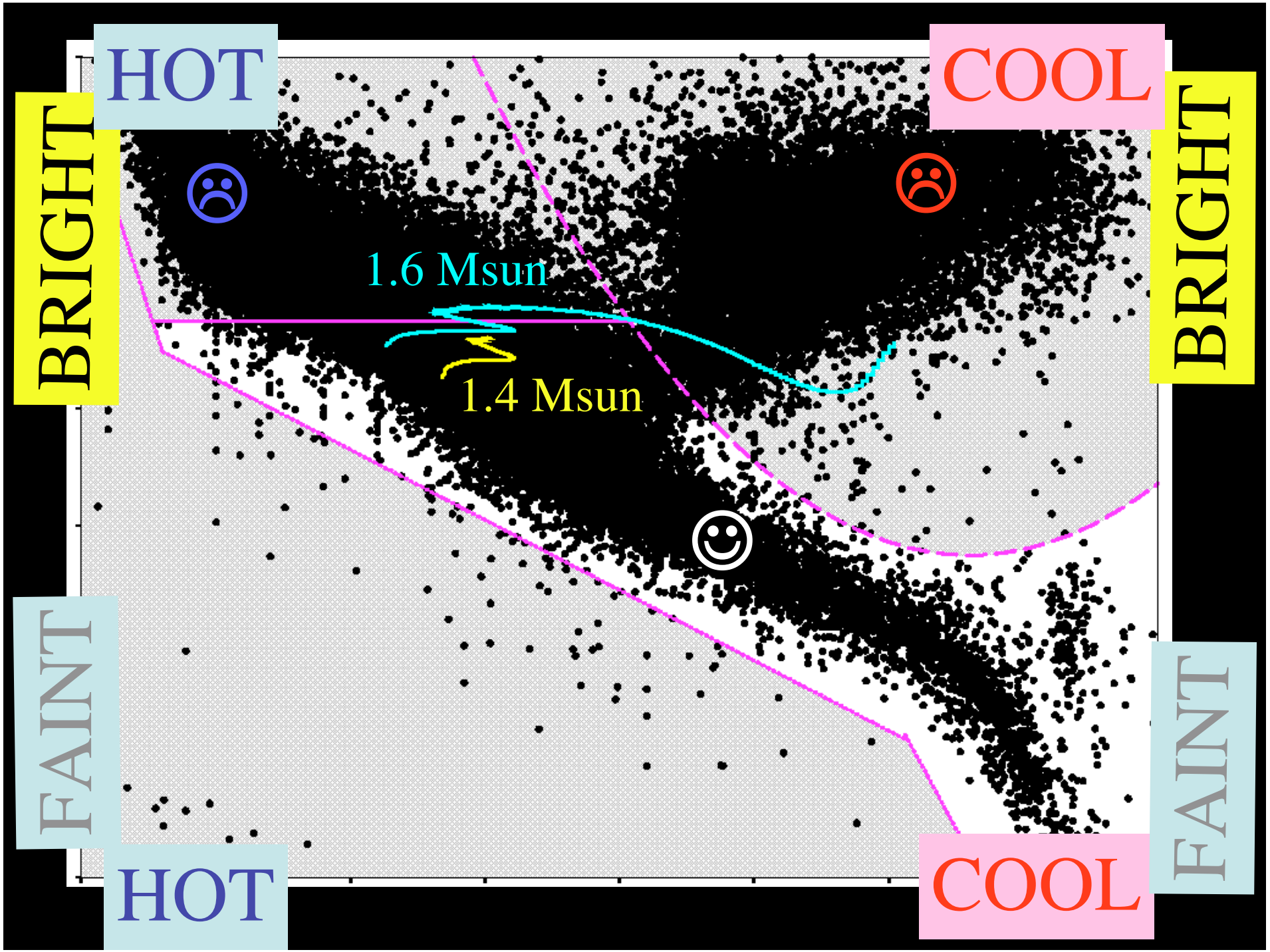
(2) A habitable zone that is *spatially static* on that same timescale, and

(3) A *metallicity* that is consistent with the existence of *terrestrial planets*.

Habstars

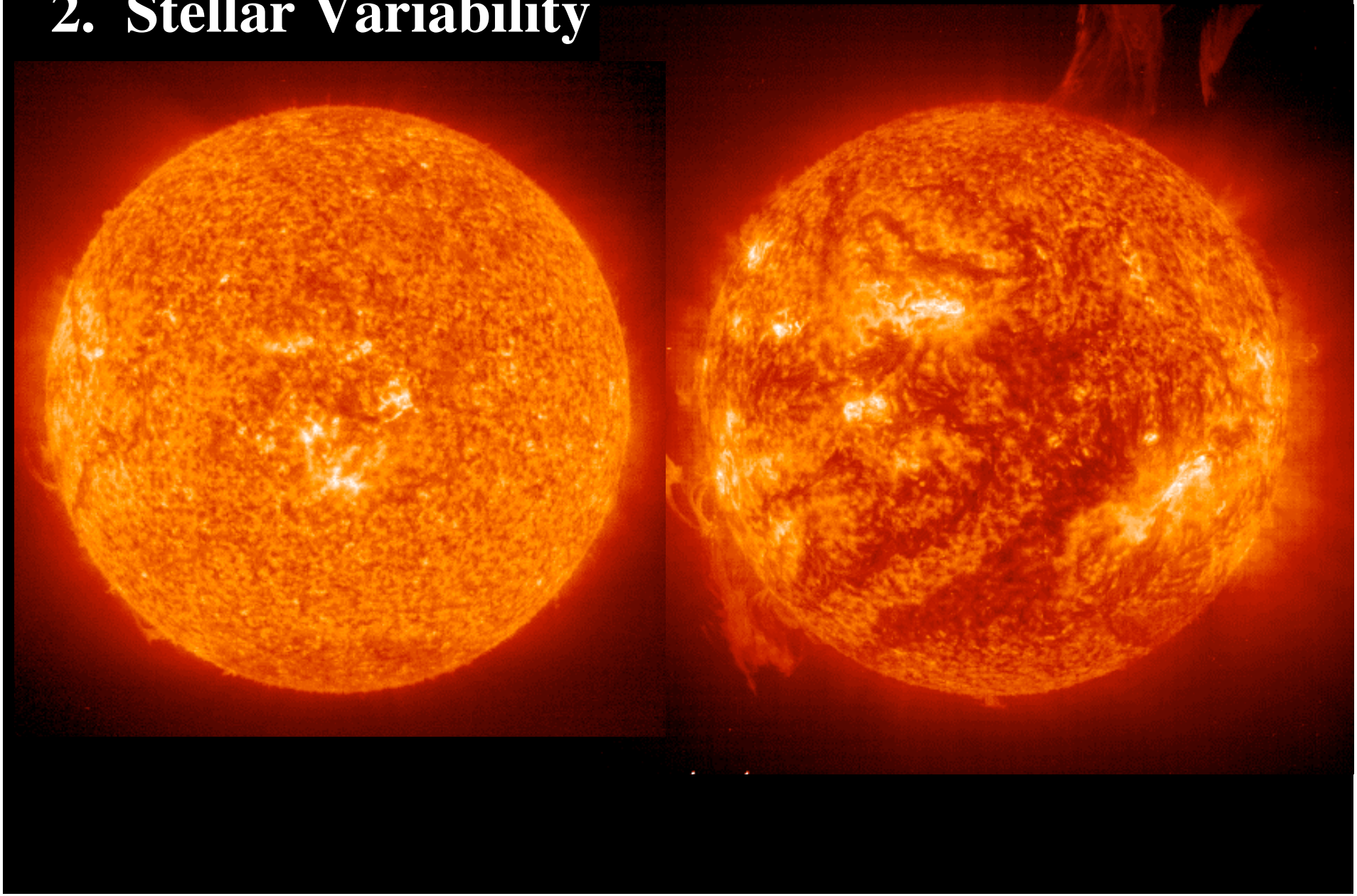
1. Timescales: Stellar Evolution, Minimum Age




HOT
COOL
BRIGHT
BRIGHT
1.6 Msun
1.4 Msun
FAINT
FAINT
HOT
COOL

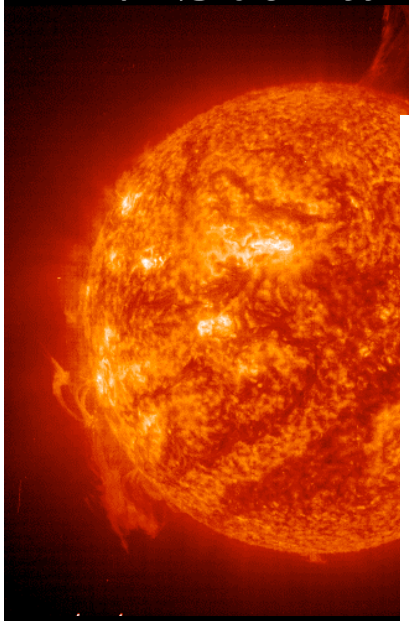
Habstars

2. Stellar Variability

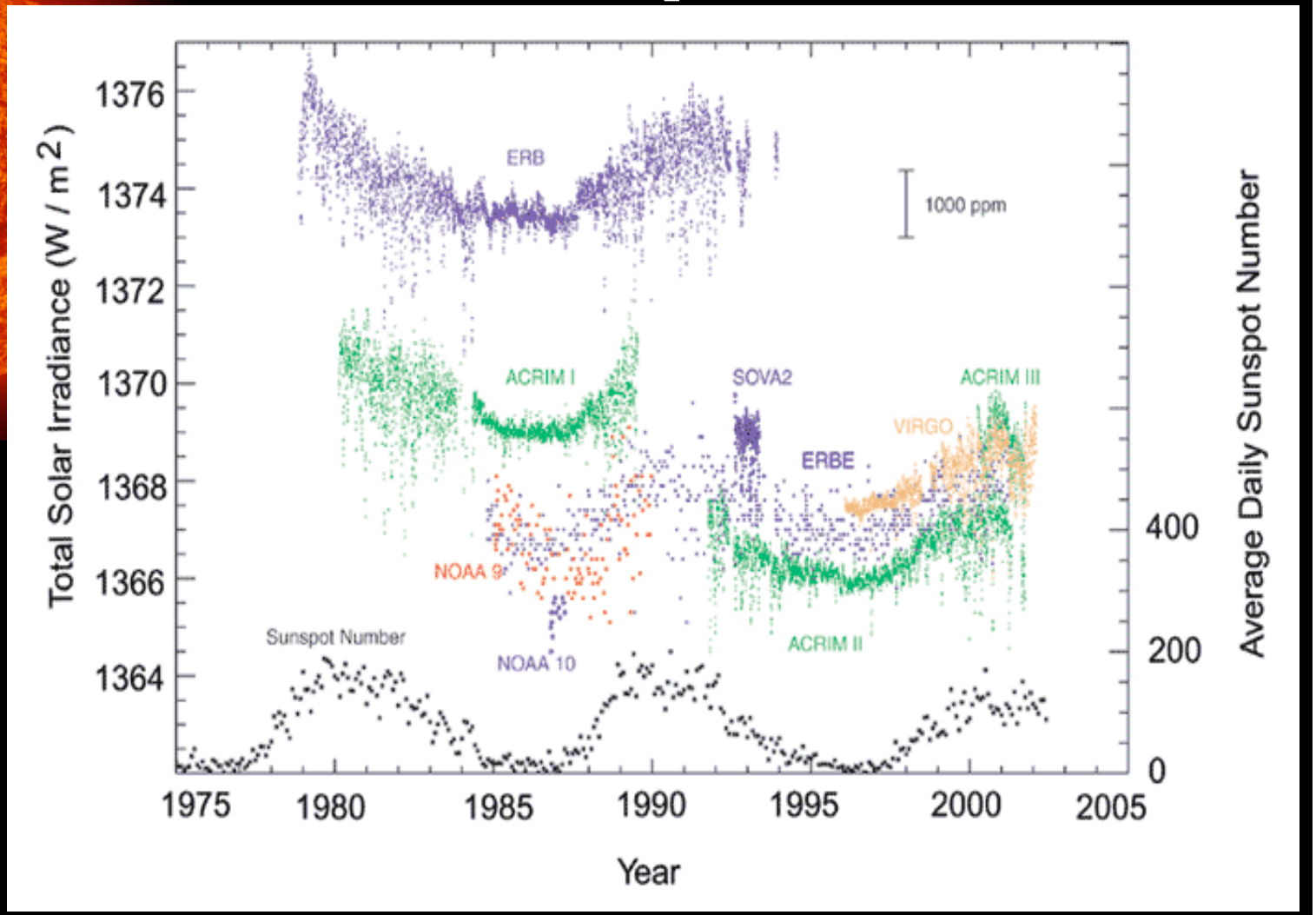


Habstars

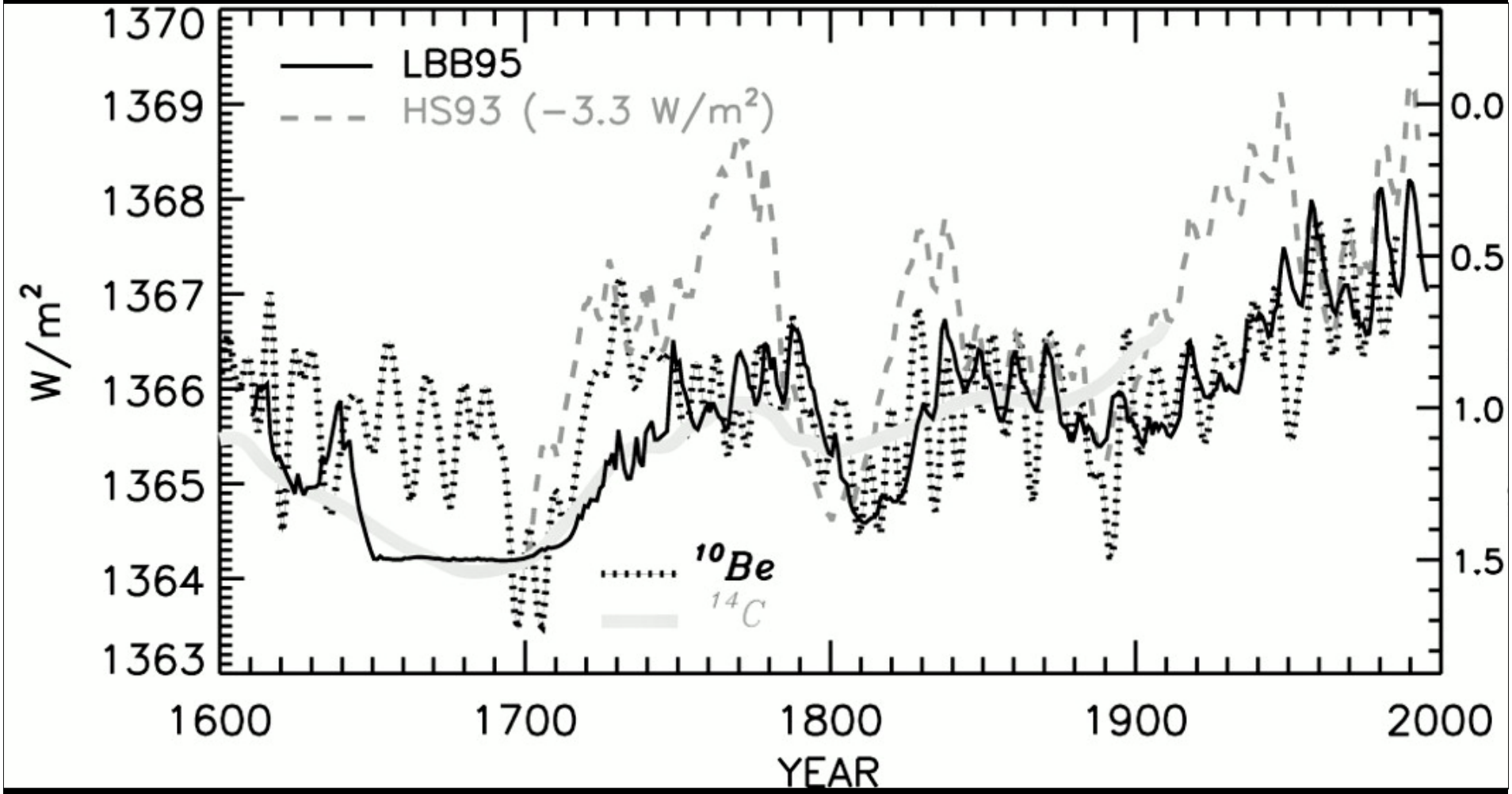
2. Stellar Variability



What combination of amplitude & timescale is OK?



Habstars



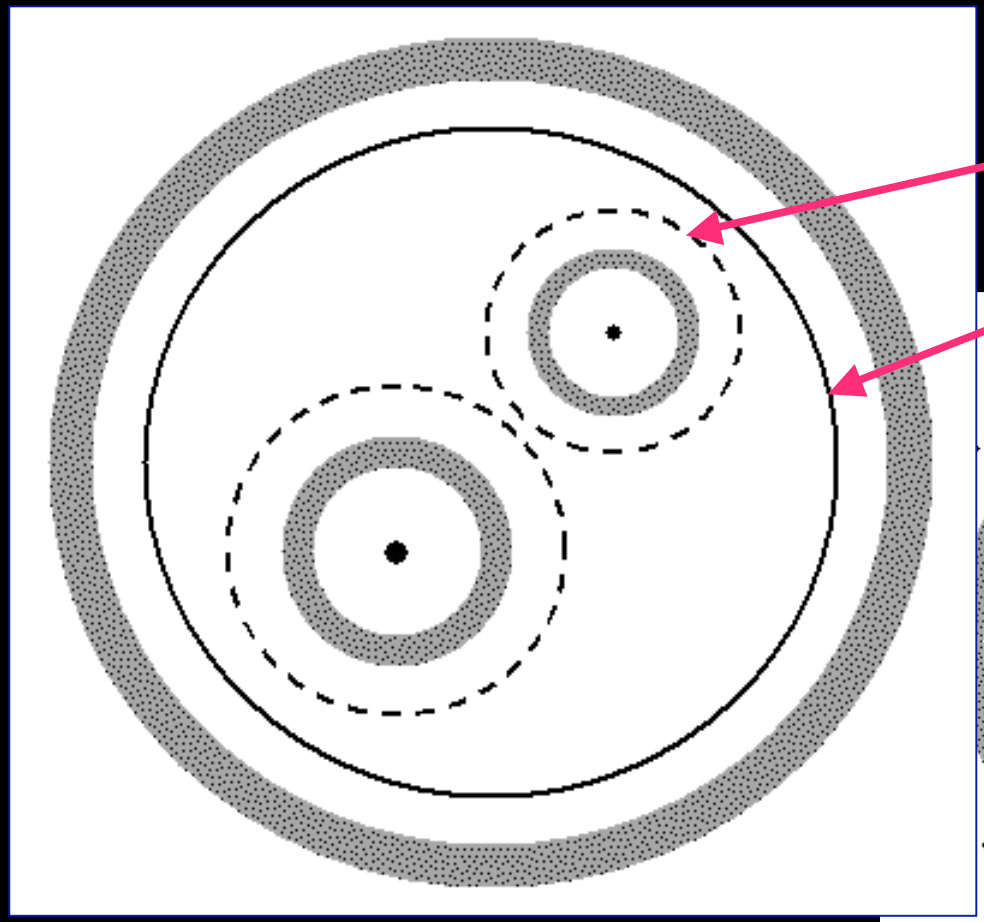
Lean 1997, ARA&A, 35, 33

Wilson & Hudson 1991, Nature, 351, 42

Tkachuck 1983, Origins, 10, 51

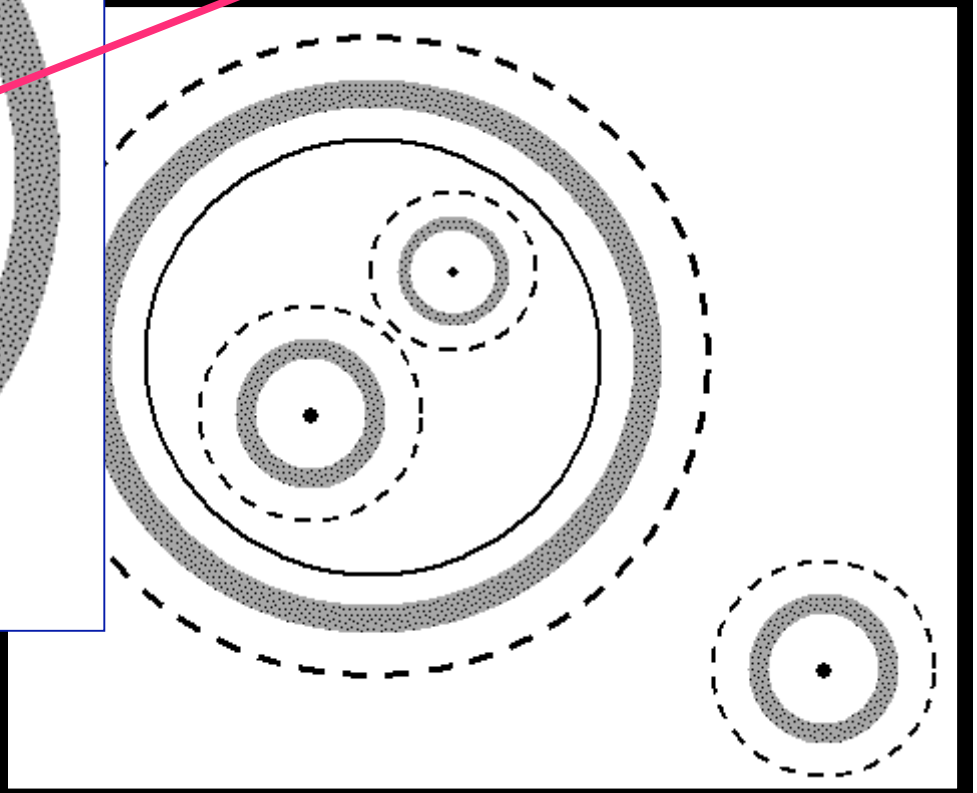
Habstars

3. Stability: Stellar Companions



Safe *interior* to here

Safe *exterior* to here



Habstars

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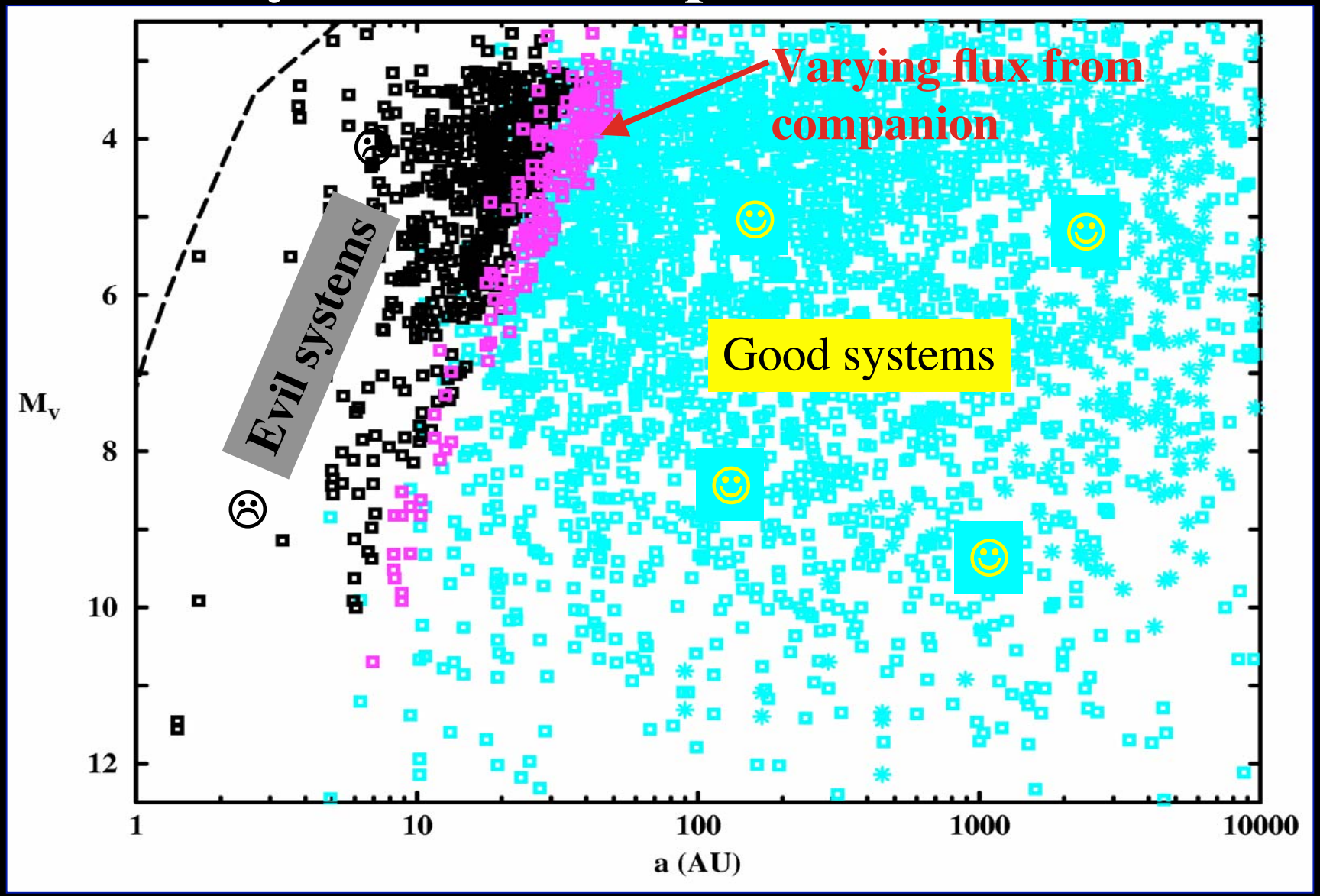
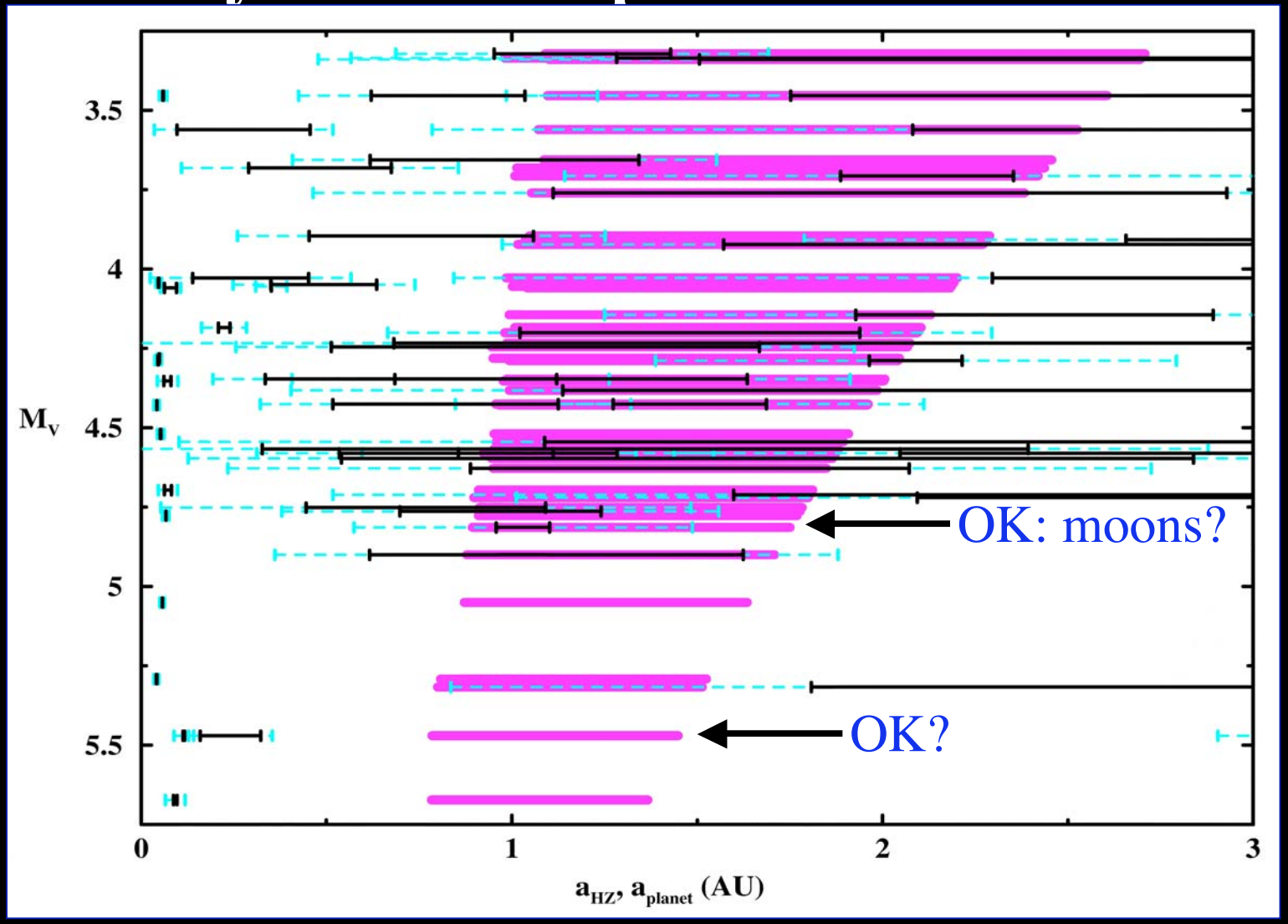


Habstars

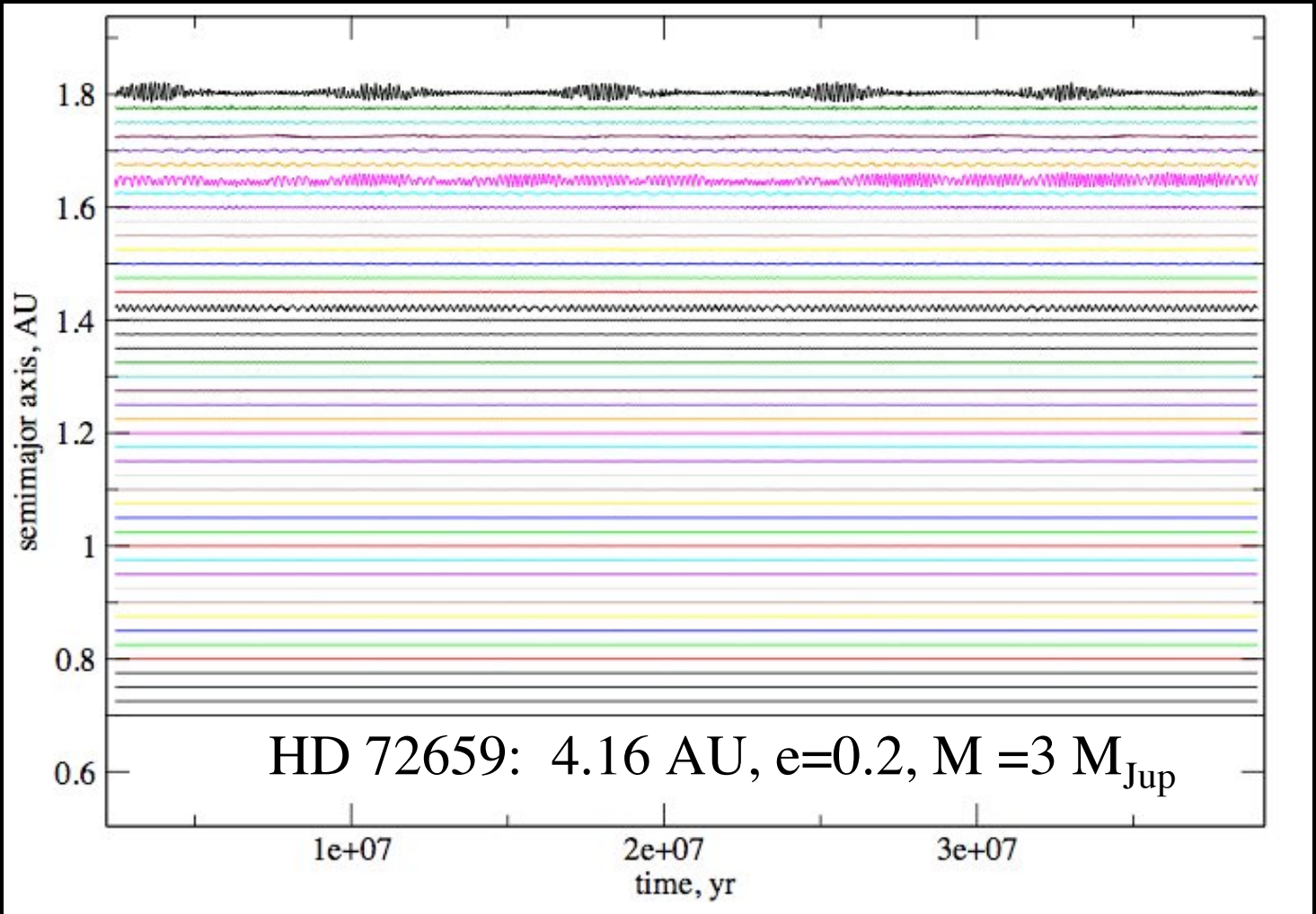
3. Stability: Giant Exoplanet Orbits



=> about 1/3 of known EGP systems are OK

Habstars

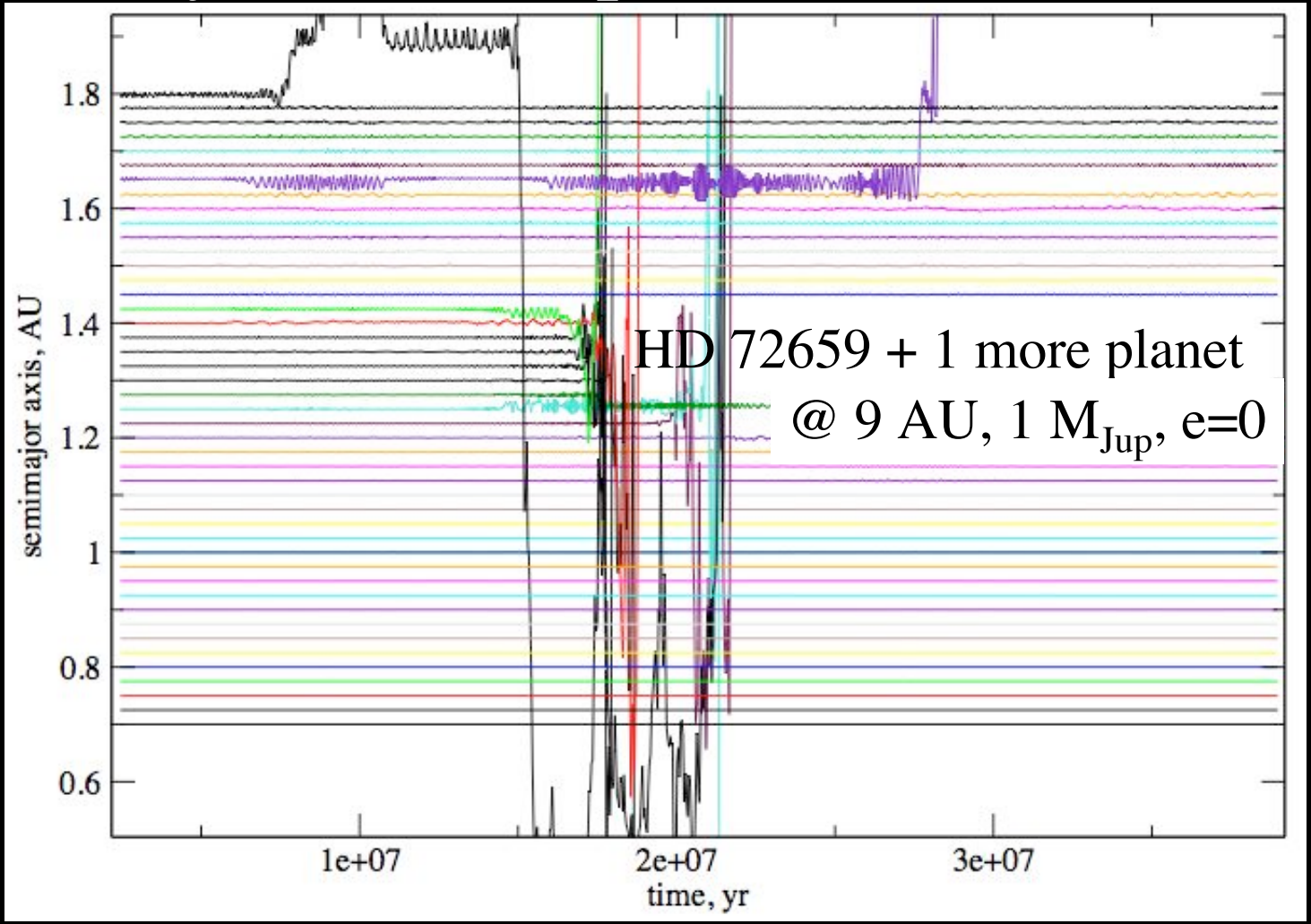
3. Stability: Giant Exoplanet Orbits



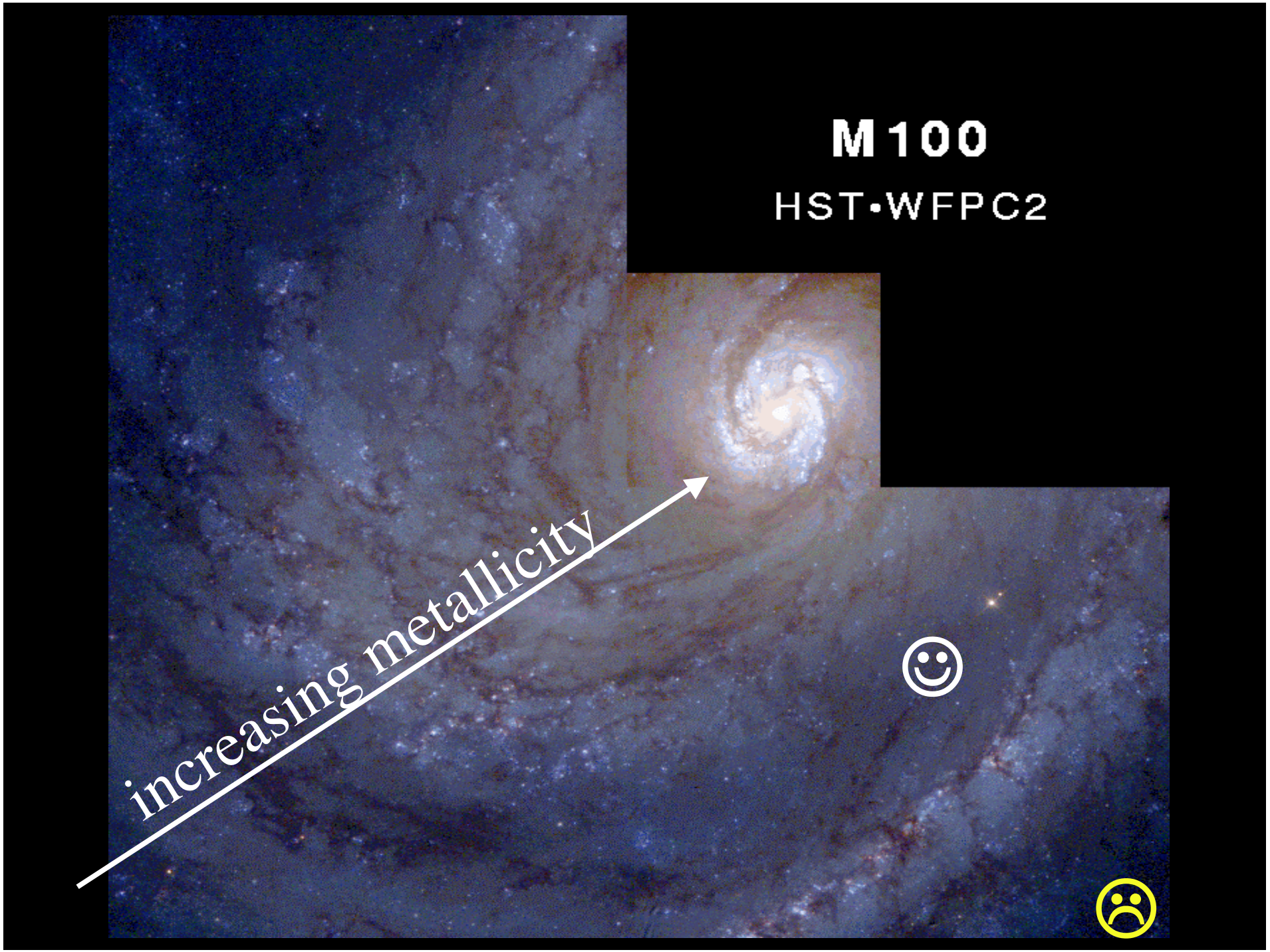
This system looks OK. However....

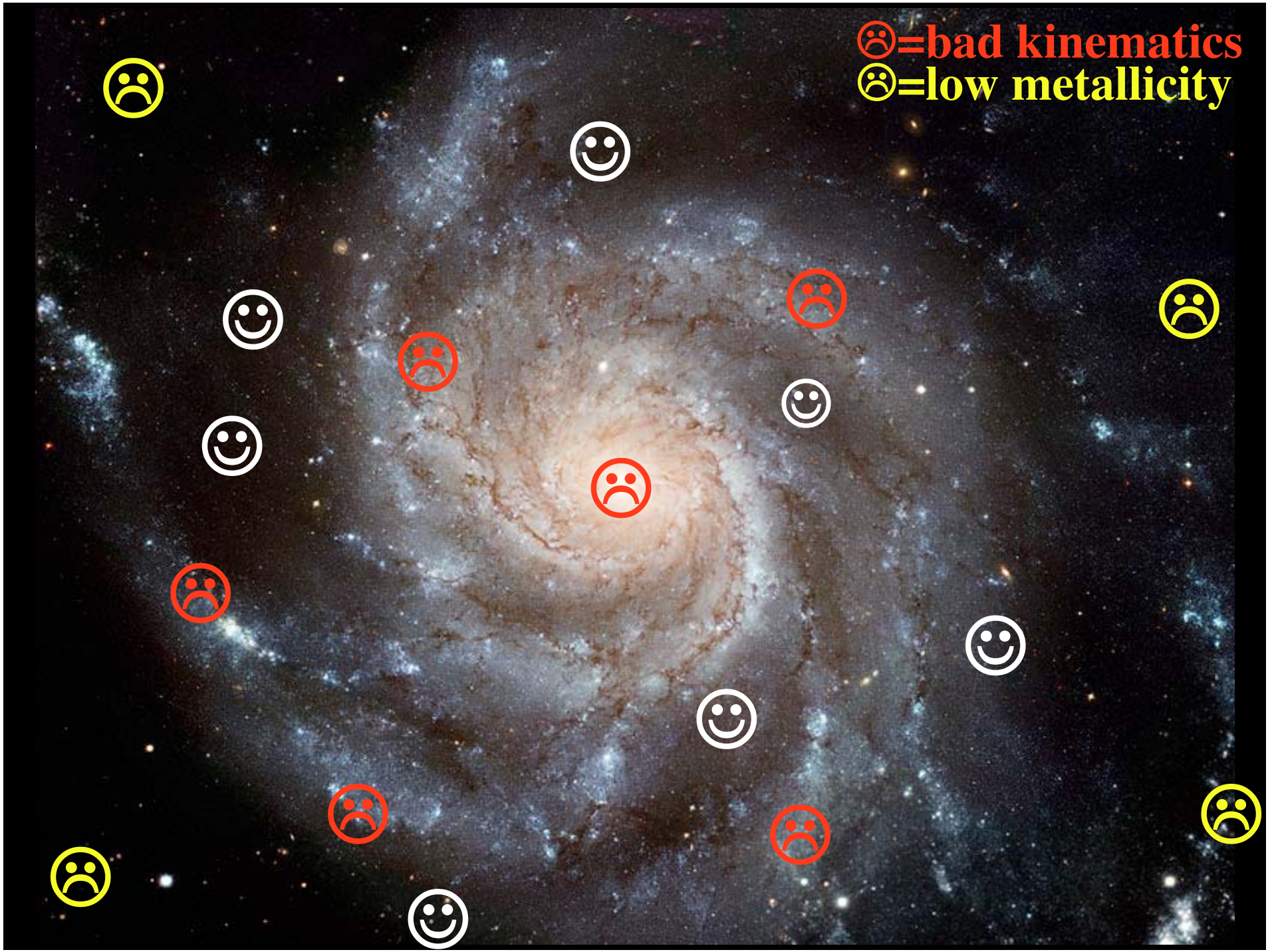
Habstars

3. Stability: Giant Exoplanet Orbits



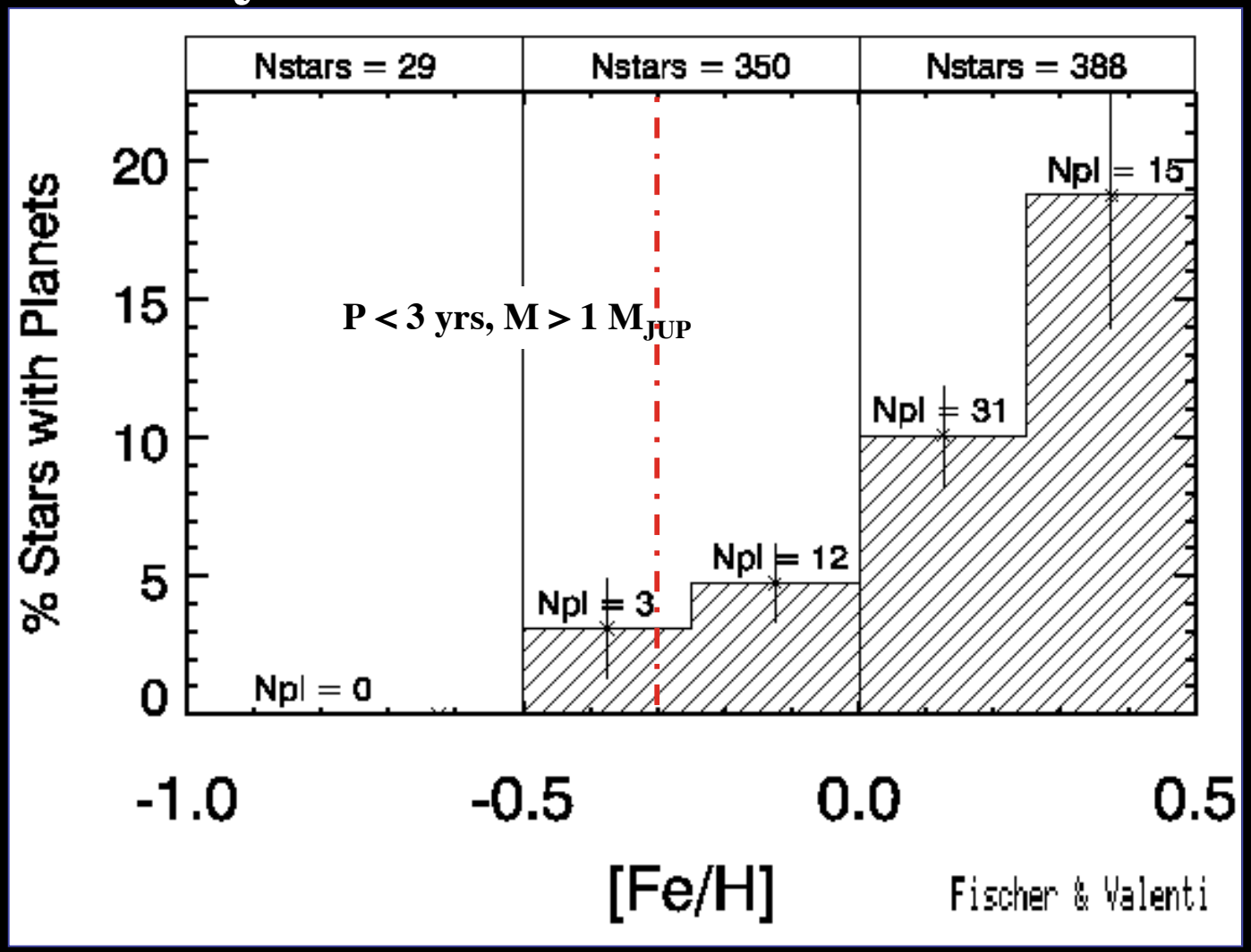
...if *more* giant planets orbit further out, NOT OK!


M100
HST•WFPC2
increasing metallicity


☹=bad kinematics
☹=low metallicity

Habstars

4. Metallicity



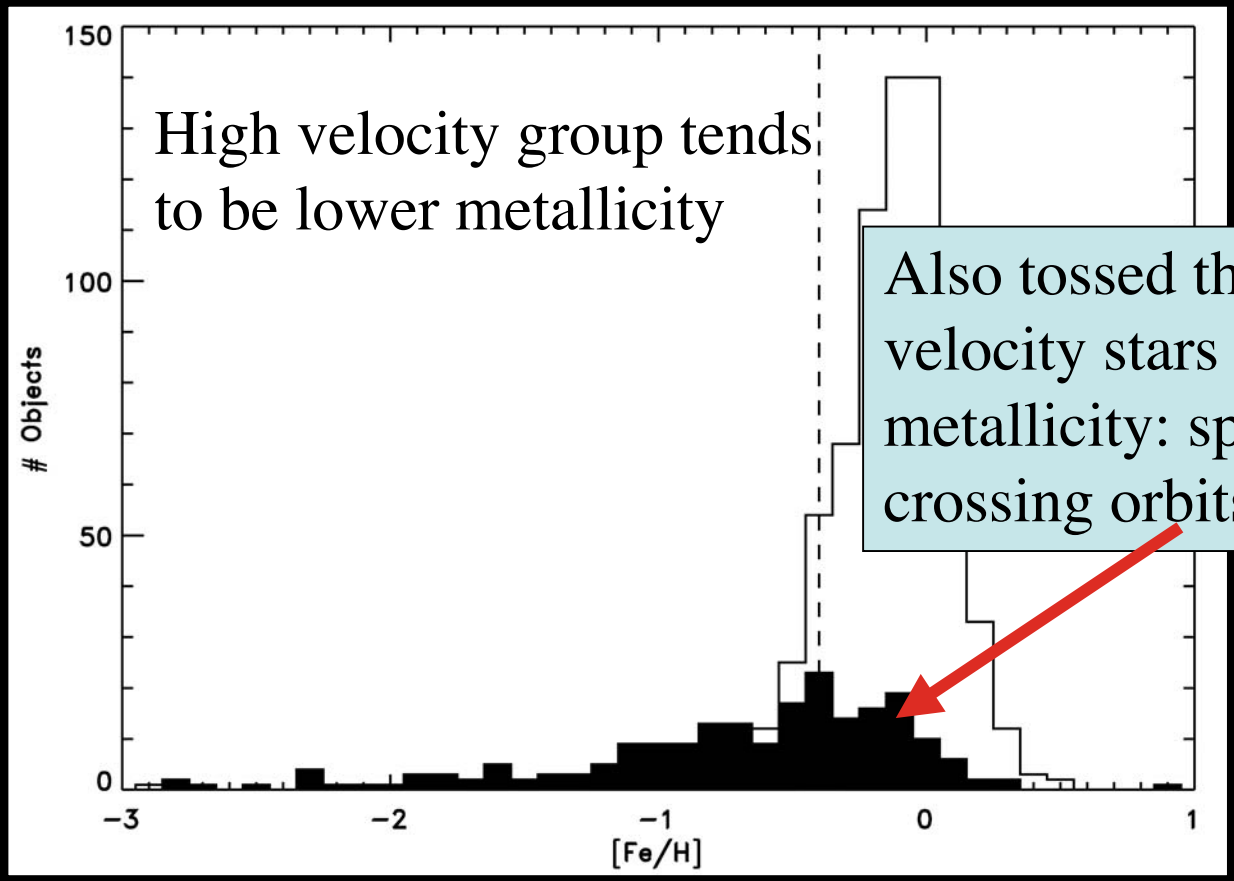
Does this trend persist for longer orbital periods?

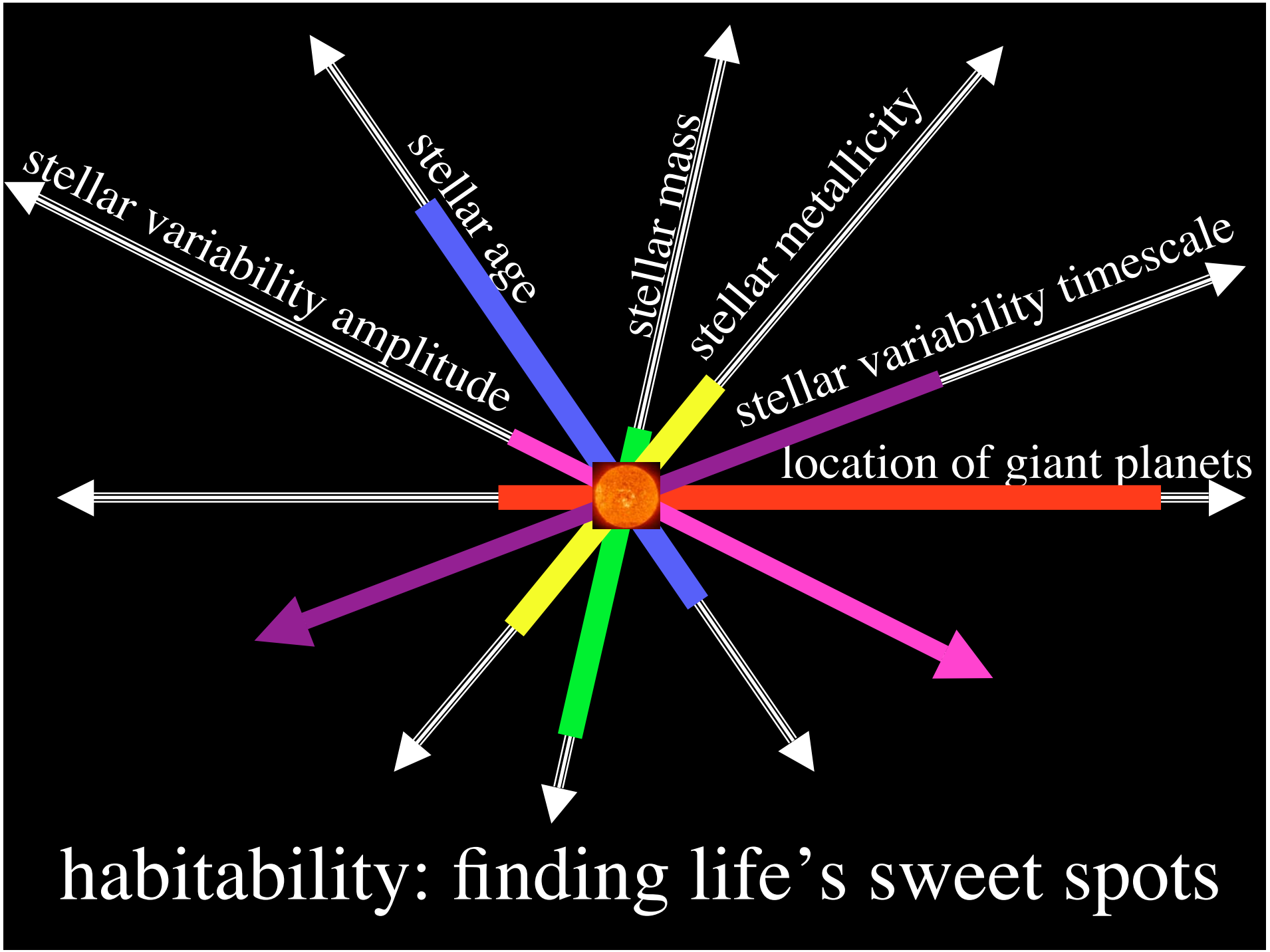
Does this trend persist for terrestrial planets?

Habstars

5. Kinematics

Kinematics and Galactic Habitability

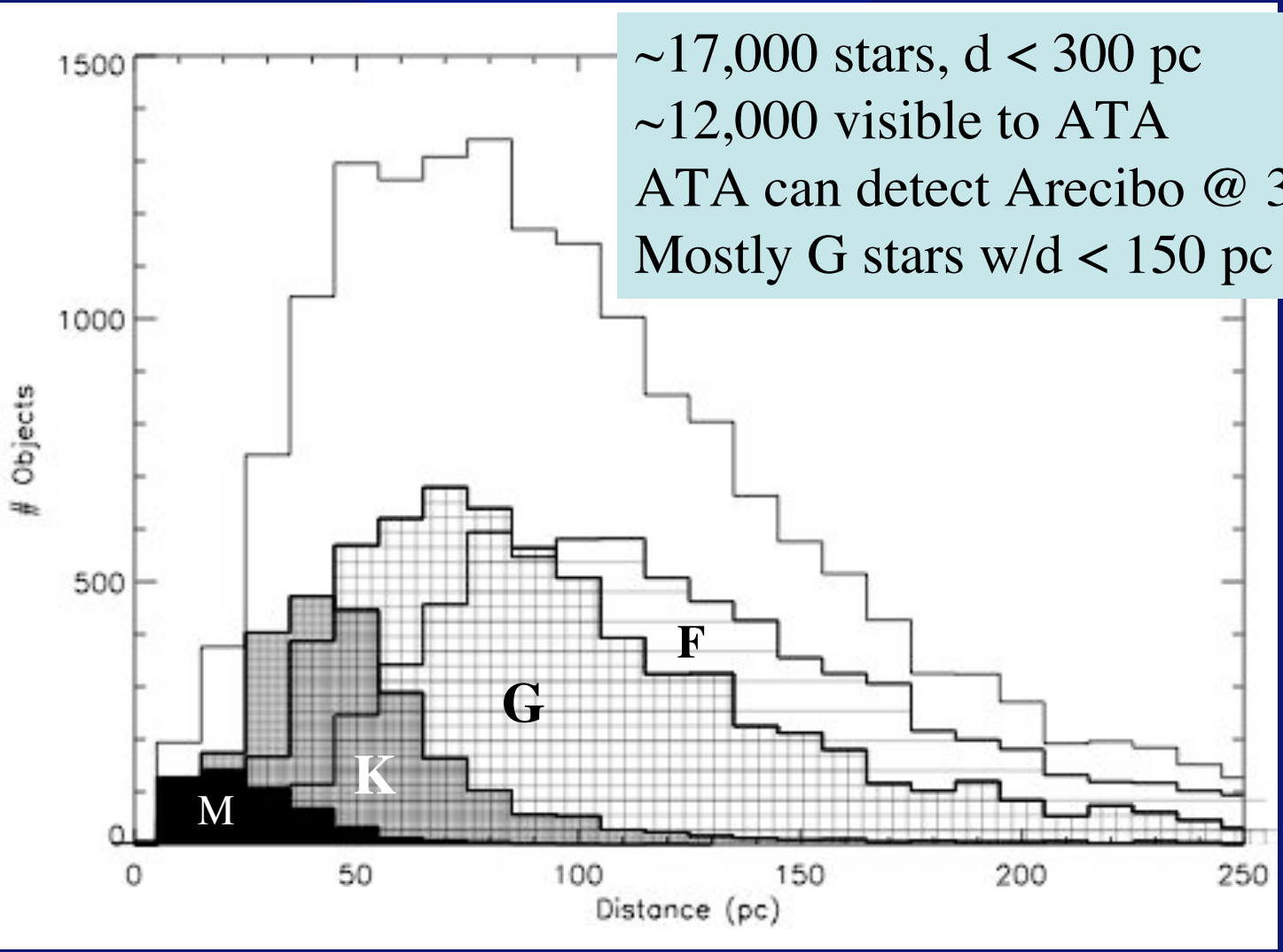




habitability: finding life's sweet spots

A New Target List for SETI

Finally: HabCat



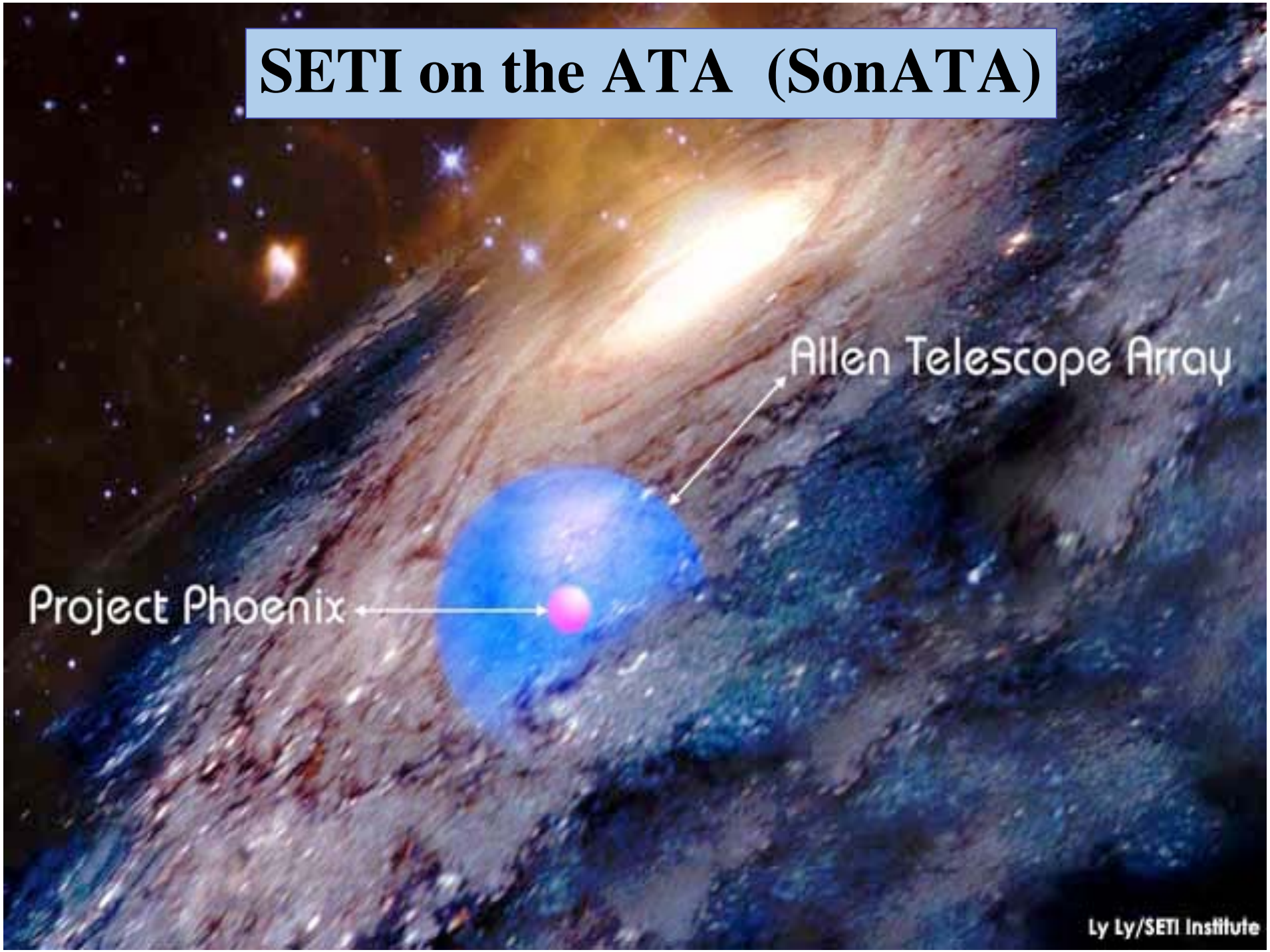
~17,000 stars, d < 300 pc
~12,000 visible to ATA
ATA can detect Arecibo @ 300pc
Mostly G stars w/d < 150 pc

SETI on the ATA (SonATA)

1 - From 10^2 (Phoenix) to 10^3 or 10^4 stars per year
2 - Simultaneous SETI and radio astronomy
3 - Nulling and independent tracking of RFI sources

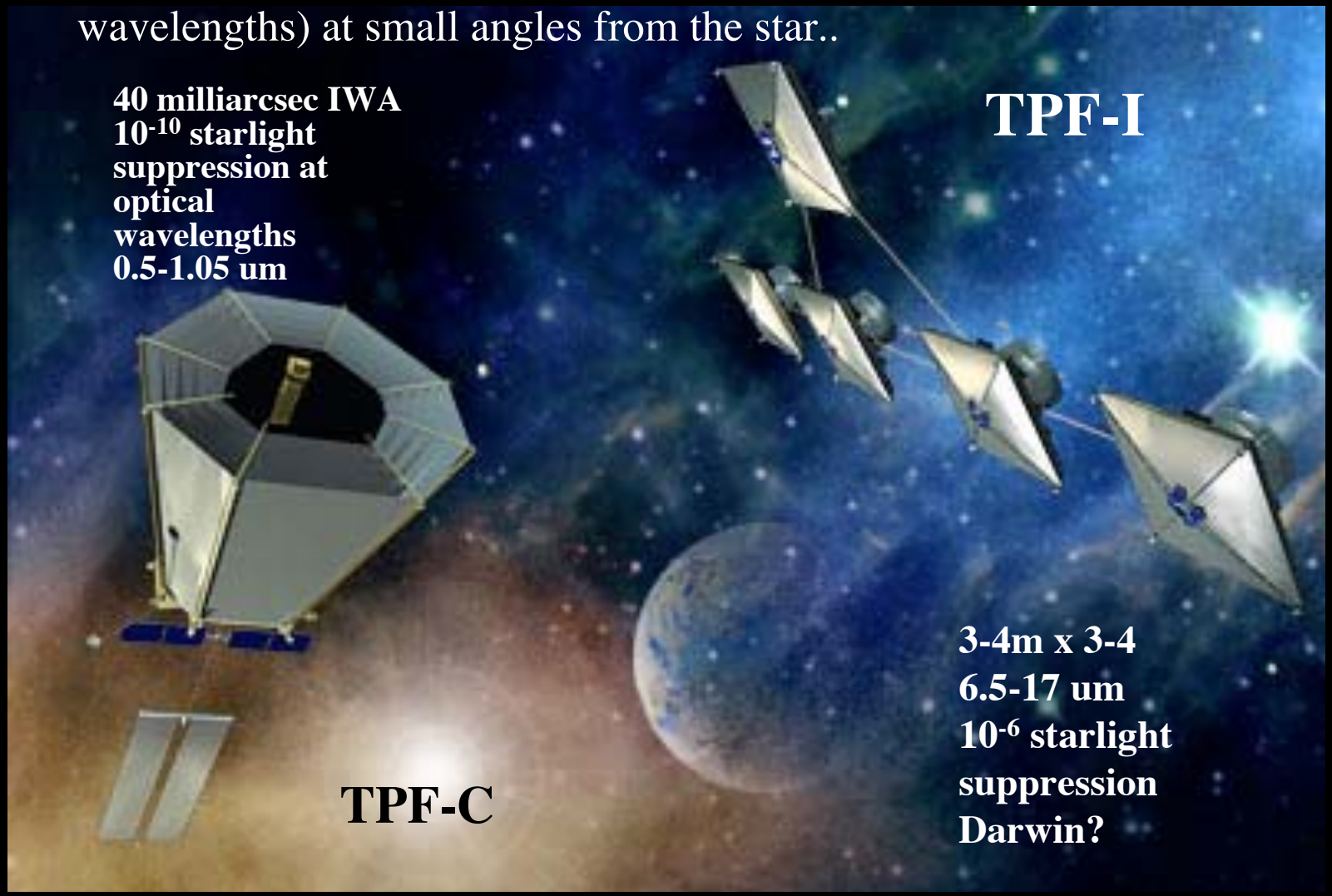
350 dishes, 0.5-11 GHz, 24/7 SETI

6.1 m


SETI on the ATA (SonATA)
Allen Telescope Array
Project Phoenix
Ly Ly/SETI Institute

The Terrestrial Planet Finder

The technology driver is the need to suppress starlight by a factor of 1 million (at mid-IR wavelengths) or 10 billion (at optical wavelengths) at small angles from the star..



How do we Choose TPF Targets?

- Want to have a conclusion in the case of a null result.
- We are potentially paying 600 million dollars per target.
- But how picky can we be before we have no stars left?
  - There are 479 habstars within 30 parsecs

Choosing TPF Targets

Instrumental Constraints

NOTES:

1. **angular HZ size depends on...**

stellar apparent magnitude!

5th mag -> 100 mas

6th mag -> 50 mas

7th mag -> 30 mas

Engineers say: $3\lambda/D \sim 40$ mas is doable

-> 6.5th (IHZ)-7th(OHZ) mag or brighter stars

Choosing TPF Targets

Instrumental Constraints

NOTES:

2. planet brightness depends on...
$1/(\text{distance})^2$

10 pc -> 30th mag

33 pc -> 32.5th mag

3. planet *fractional* brightness depends on...

$1/L_*$

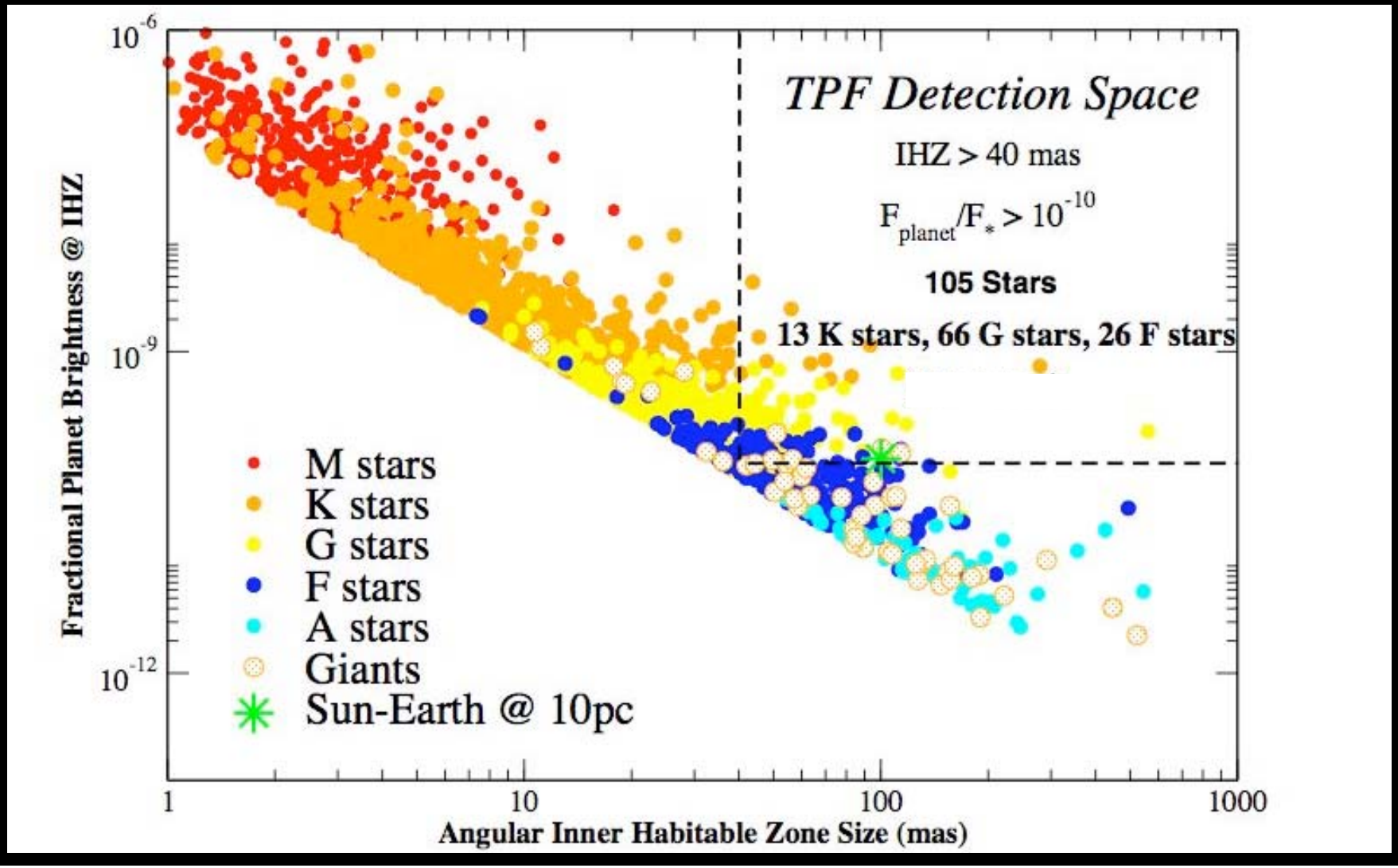
Engineers say: 10^{-10} is doable

-> ~2.5 L_{sun} for inner HZ

-> ~ 0.5 L_{sun} for outer HZ

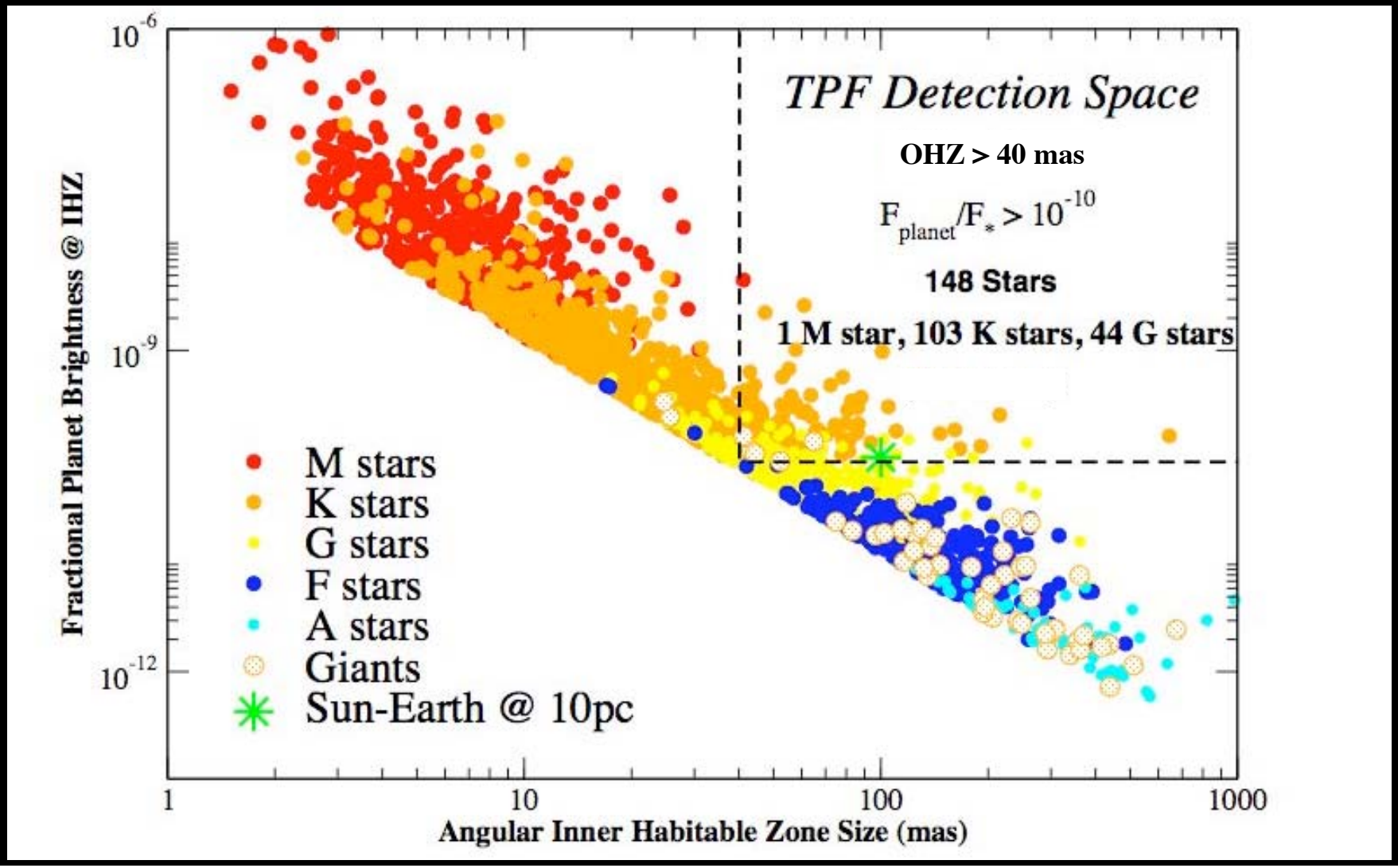
Choosing TPF Targets

Approach #2: Instrumental Approach

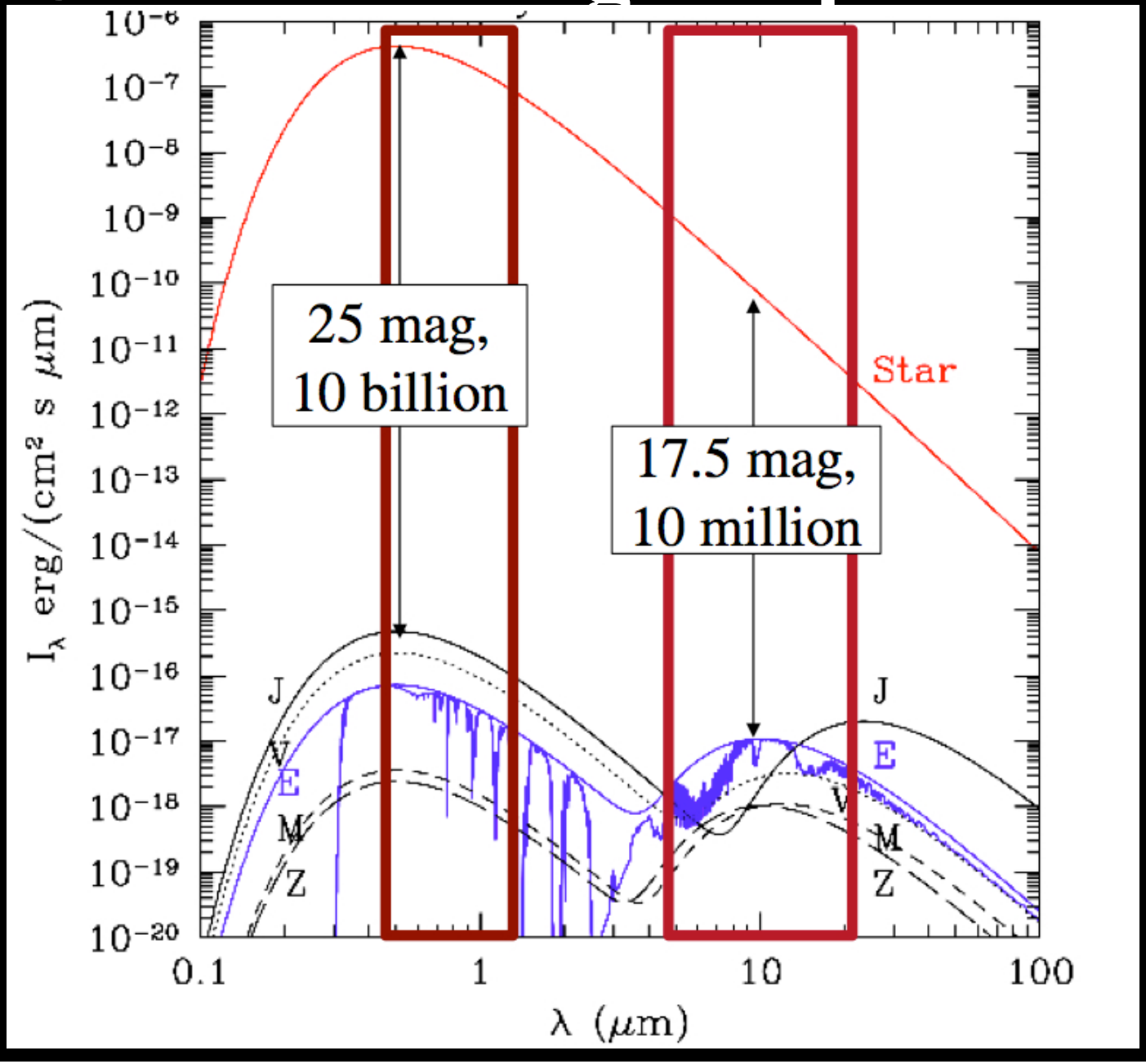


Choosing TPF Targets

Approach #2: Instrumental Approach



Characterizing Exoplanets



Characterizing Exoplanets

Optical Wavelengths: Atmos. AND Surface Signatures

What does the Earth look like (spectrally) at optical wavelengths?

We have no appropriate LEO/GEO satellite data for these wavelengths...

Characterizing Exoplanets

Optical Wavelengths

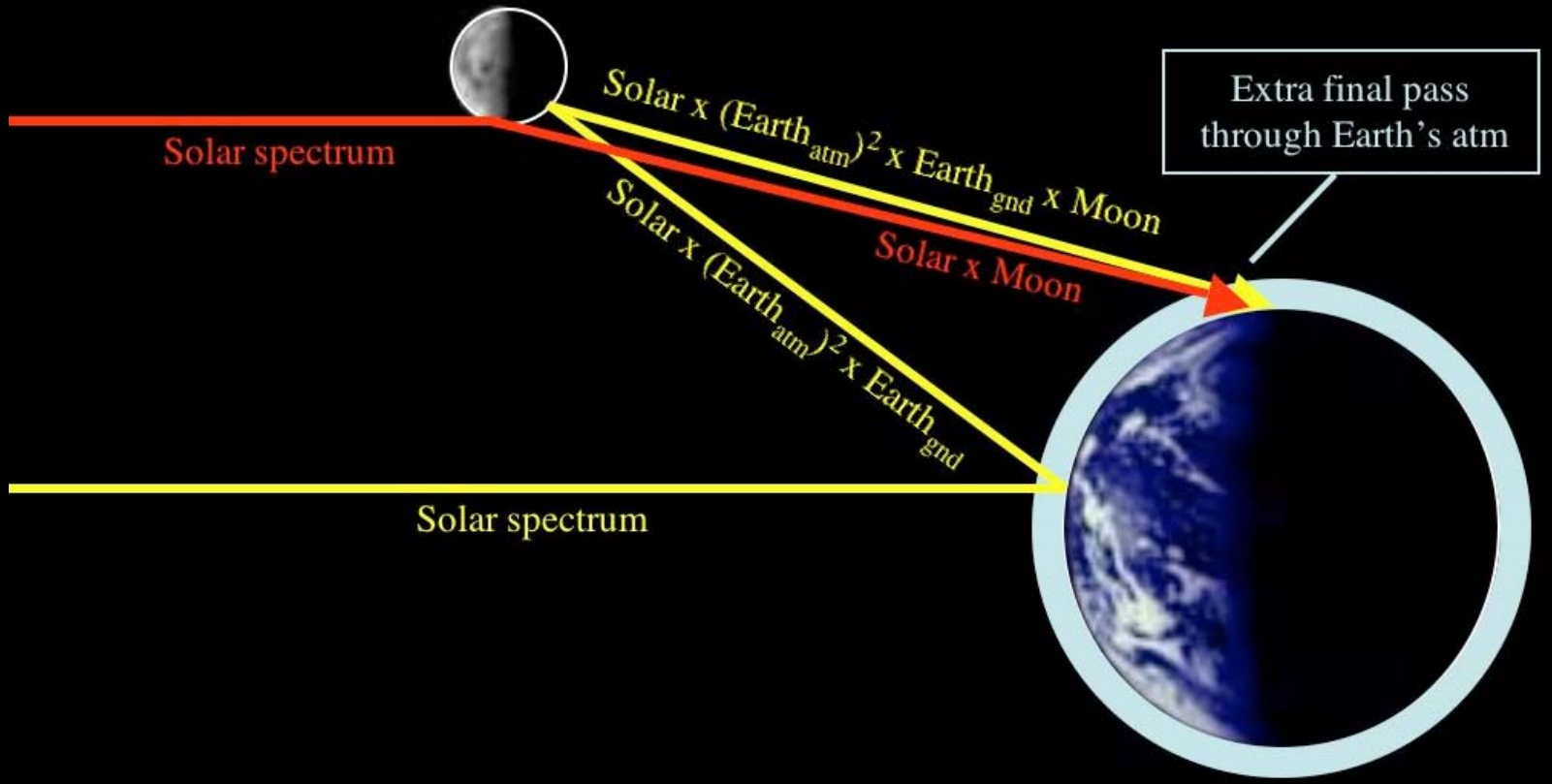
What does the Earth look like (spectrally) at optical wavelengths?

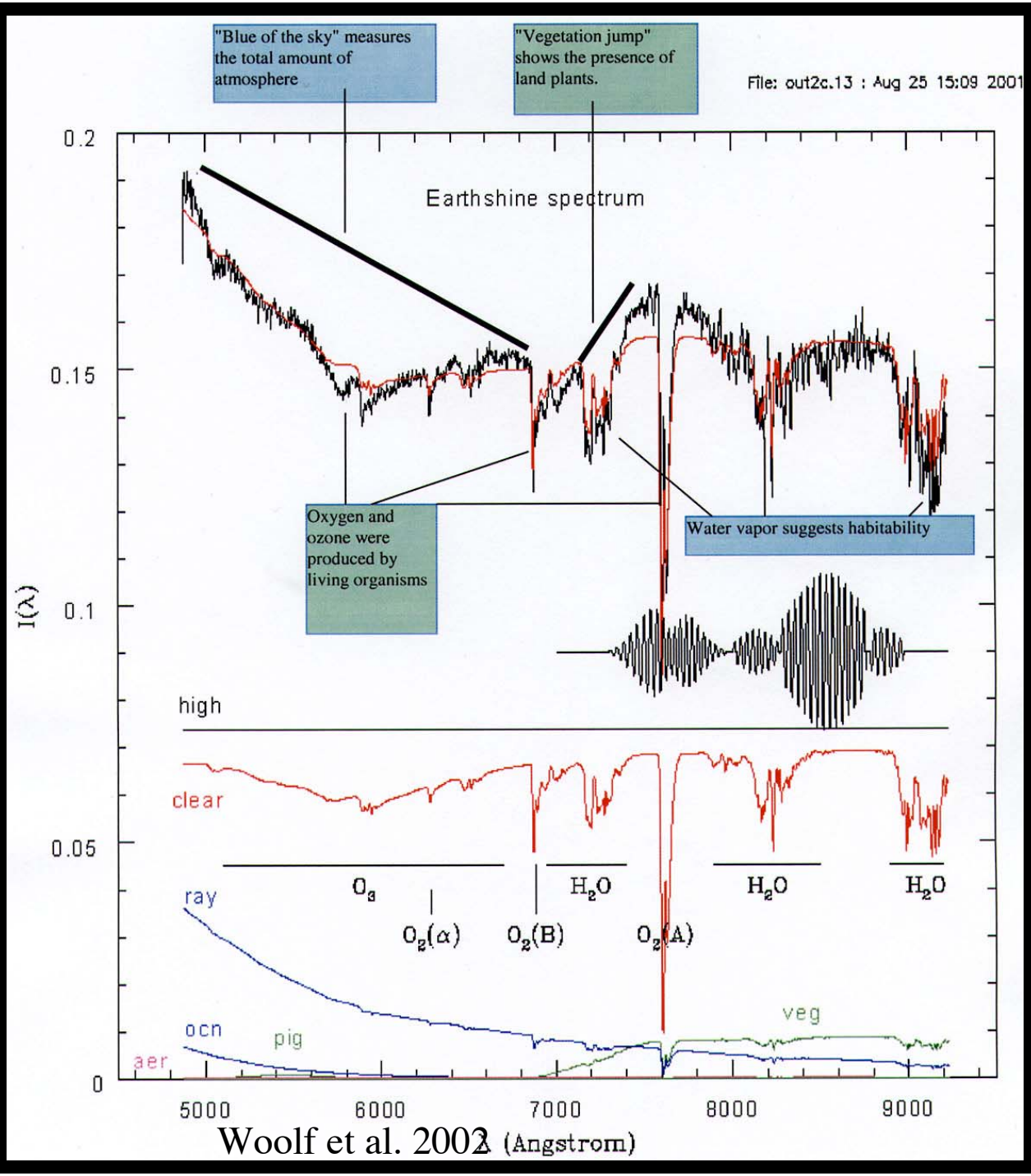
So far, the best indication comes from ground-based observations.

Earthshine contains the reflection spectrum of the whole visible Earth and is spatially unresolved, as an extrasolar planet would be for TPF

Characterizing Exoplanets

Optical Wavelengths

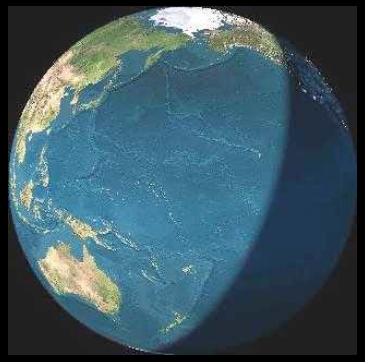


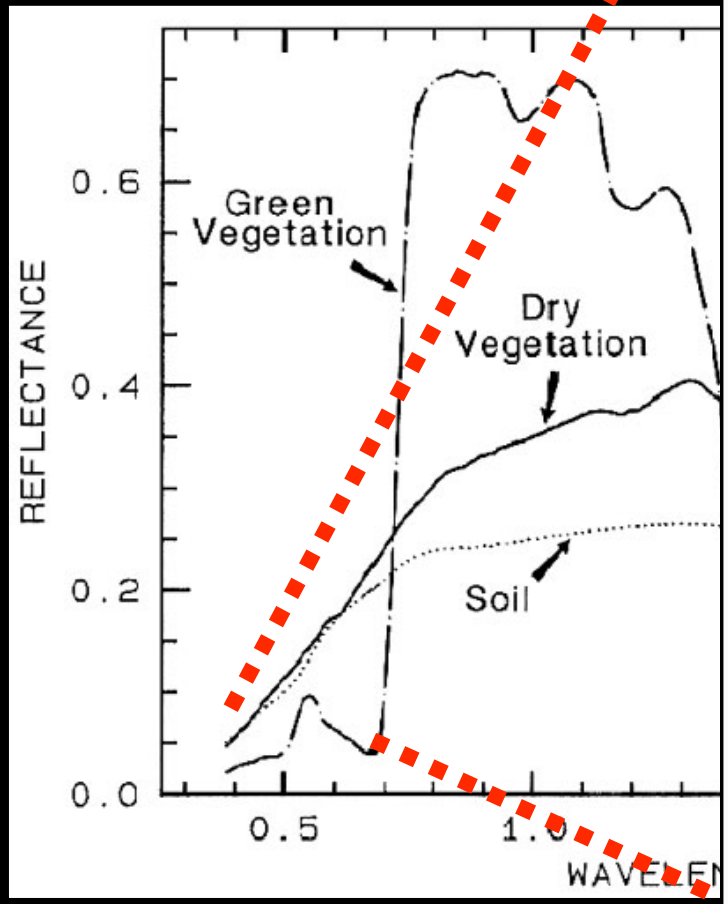


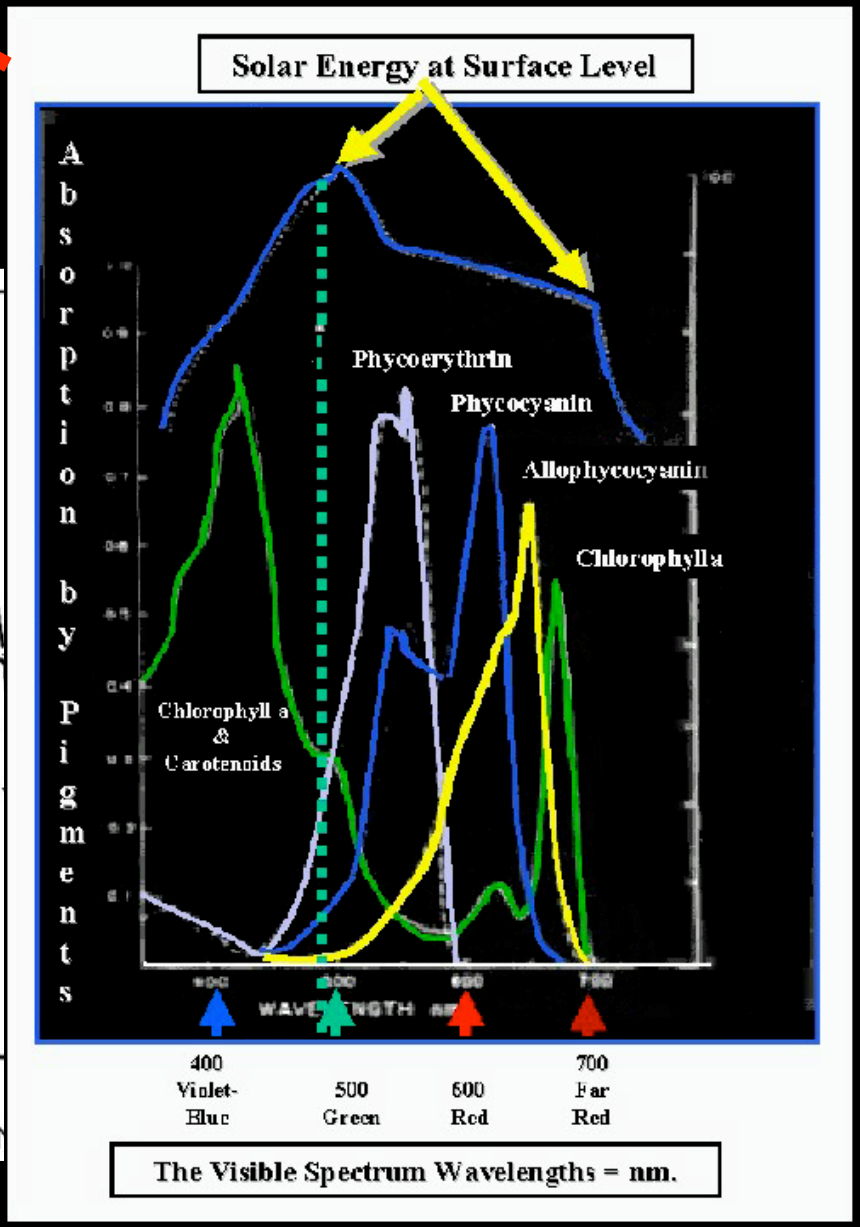
Woolf et al. 2002

90-inch data, Kitt Peak

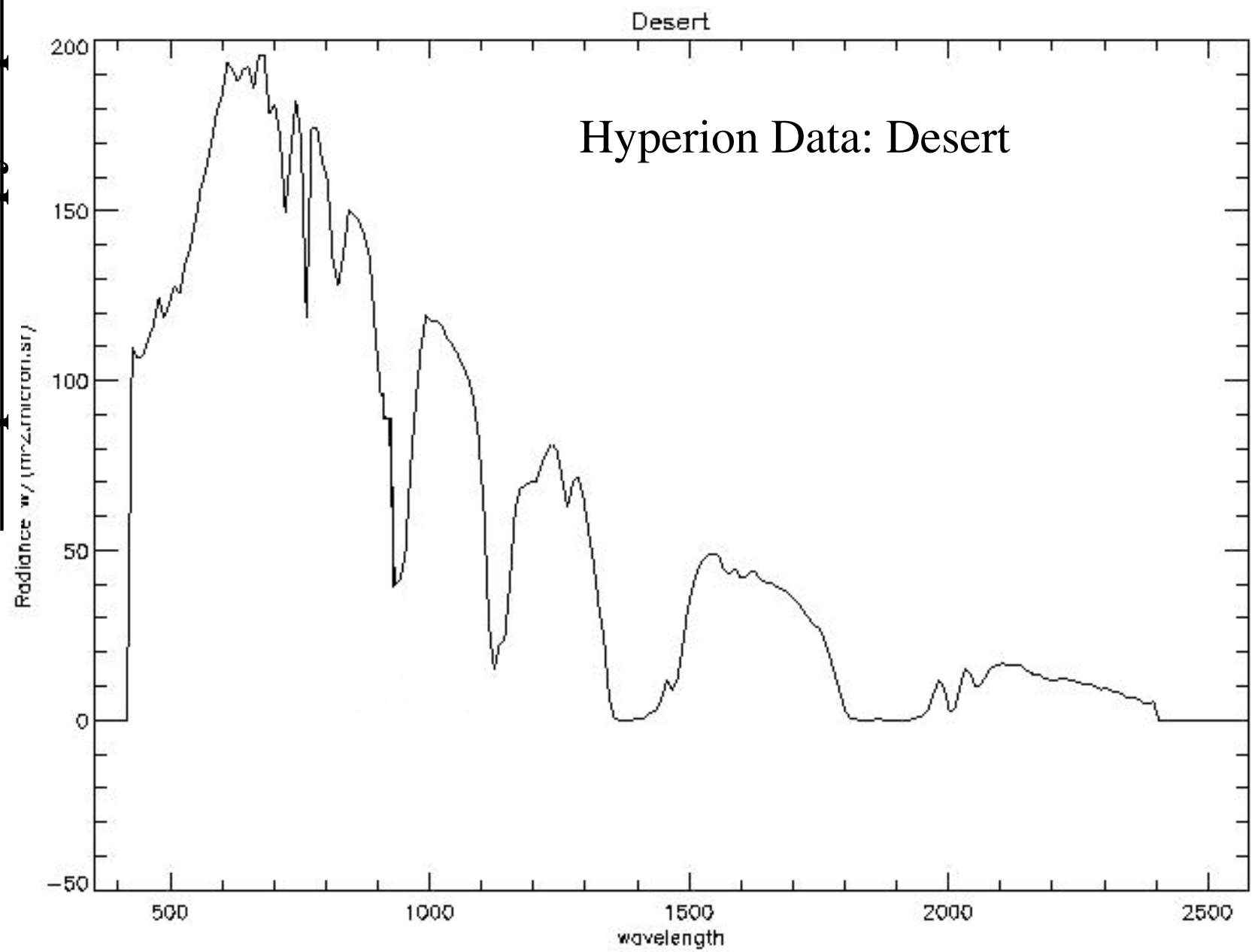
Tinetti et al 2006: Red-edge was indeed detected




REFLECTANCE
0.6
0.4
0.2
0.0
0.5
Green Vegetation
Dry Vegetation
Soil


Solar Energy at Surface Level
Absorption by Pigments
Phycoerythrin
Phycocyanin
Allophycocyanin
Chlorophylla
Chlorophyll a & Carotenoids
400 Violet-Blue
500 Green
600 Red
700 Far Red
The Visible Spectrum Wavelengths = nm.

2. Spectroscopy: Optical



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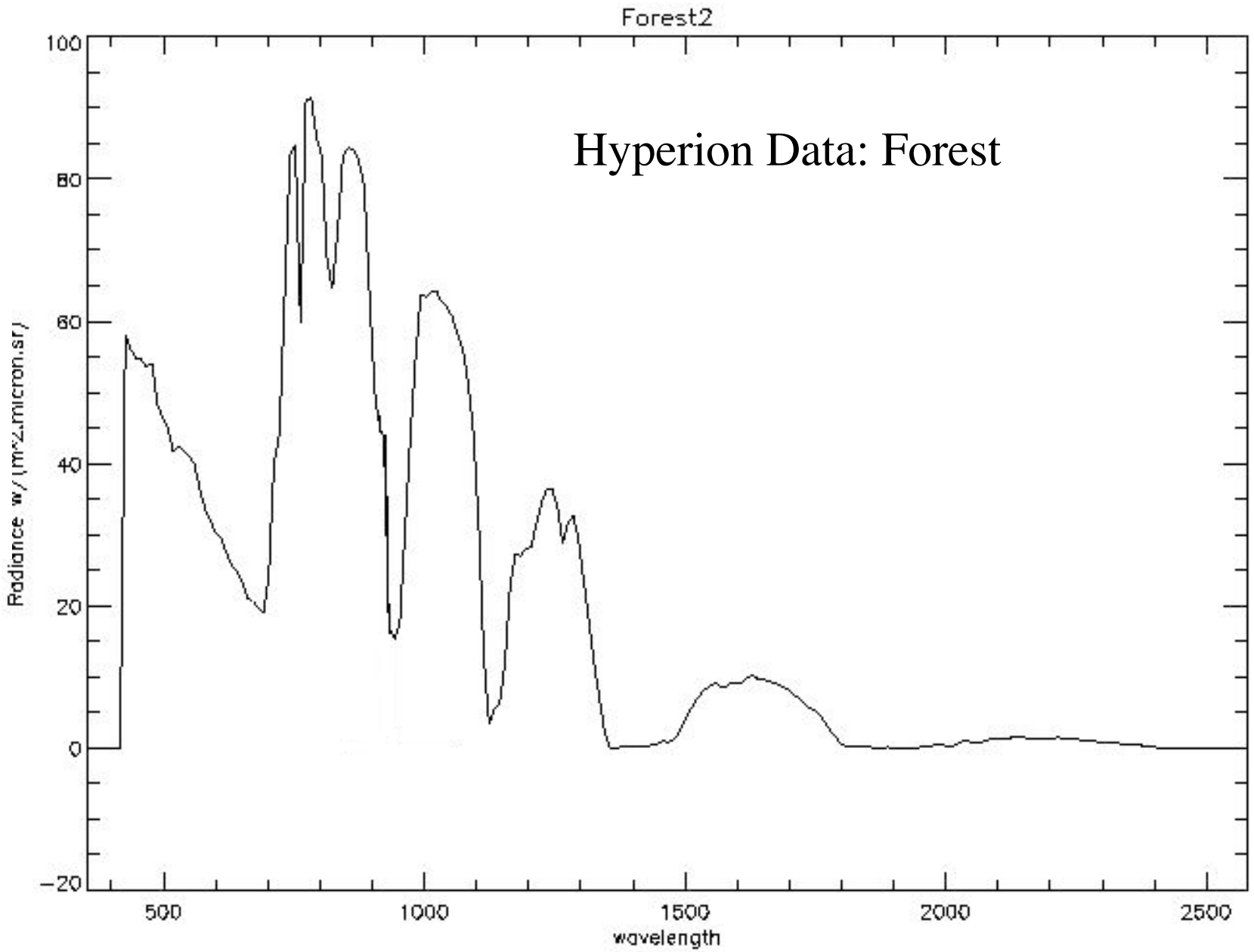
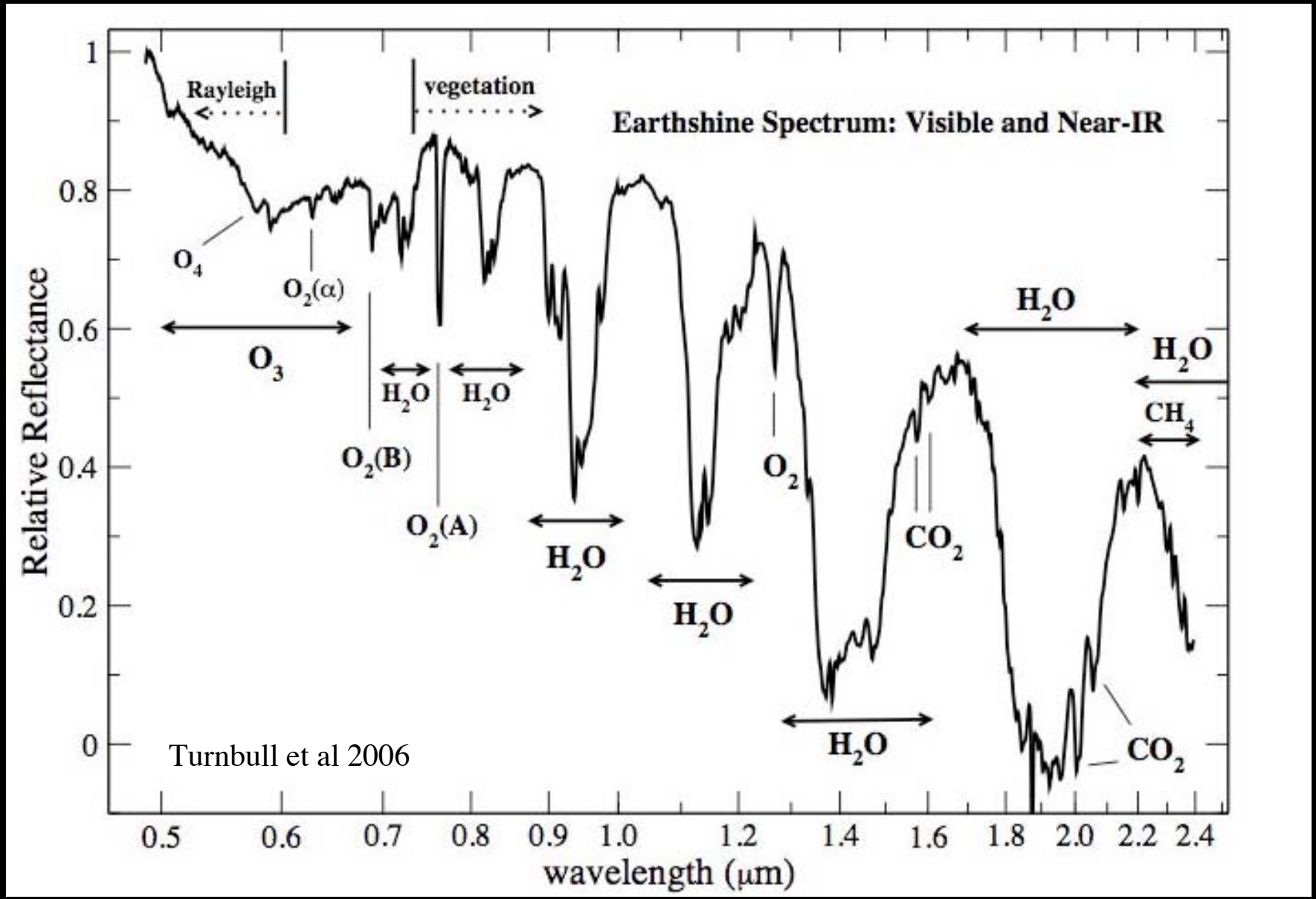
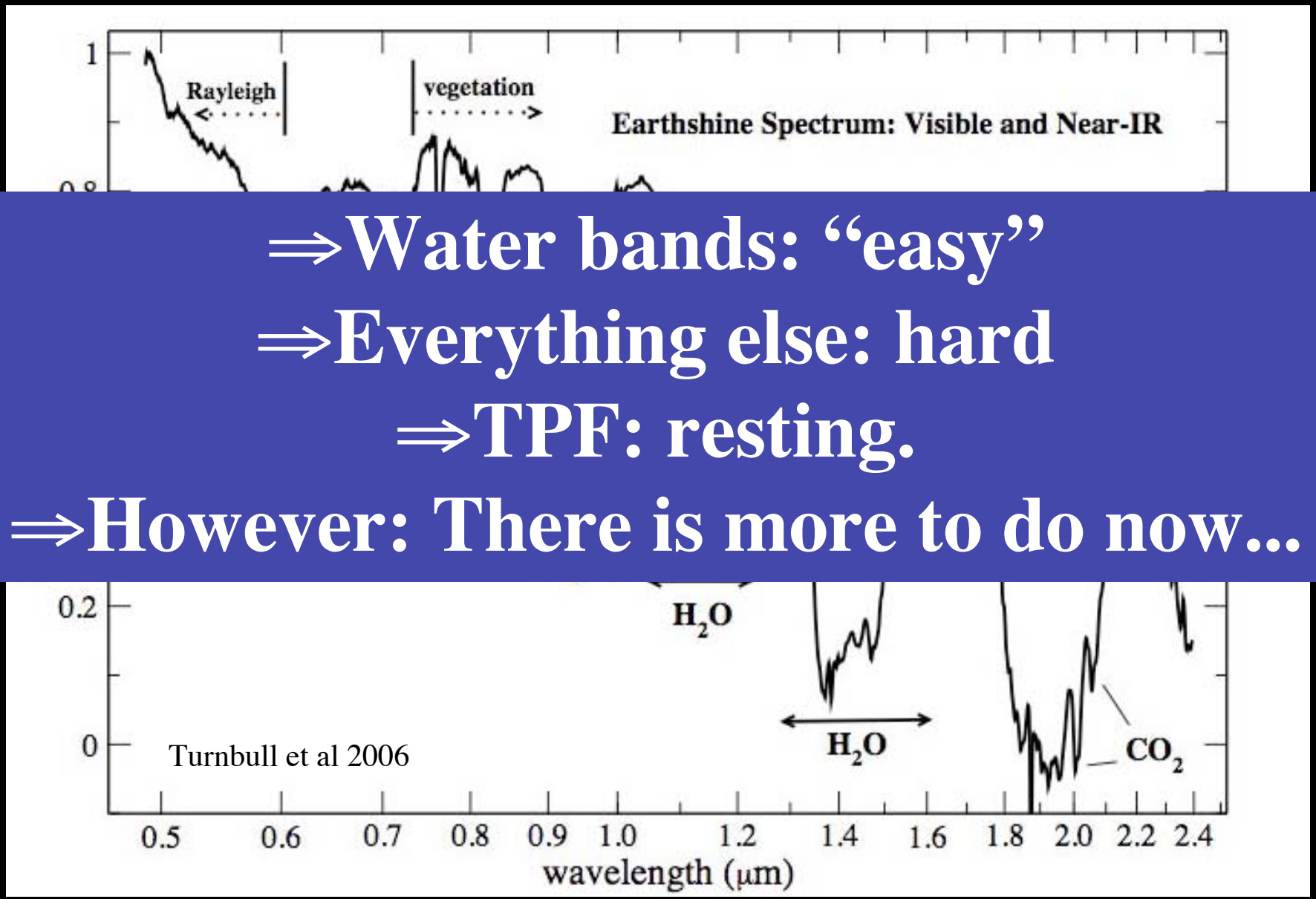


Optical and NIR Wavelengths



Optical and NIR Wavelengths



⇒Water bands: "easy"

⇒Everything else: hard

⇒TPF: resting.

⇒However: There is more to do now...

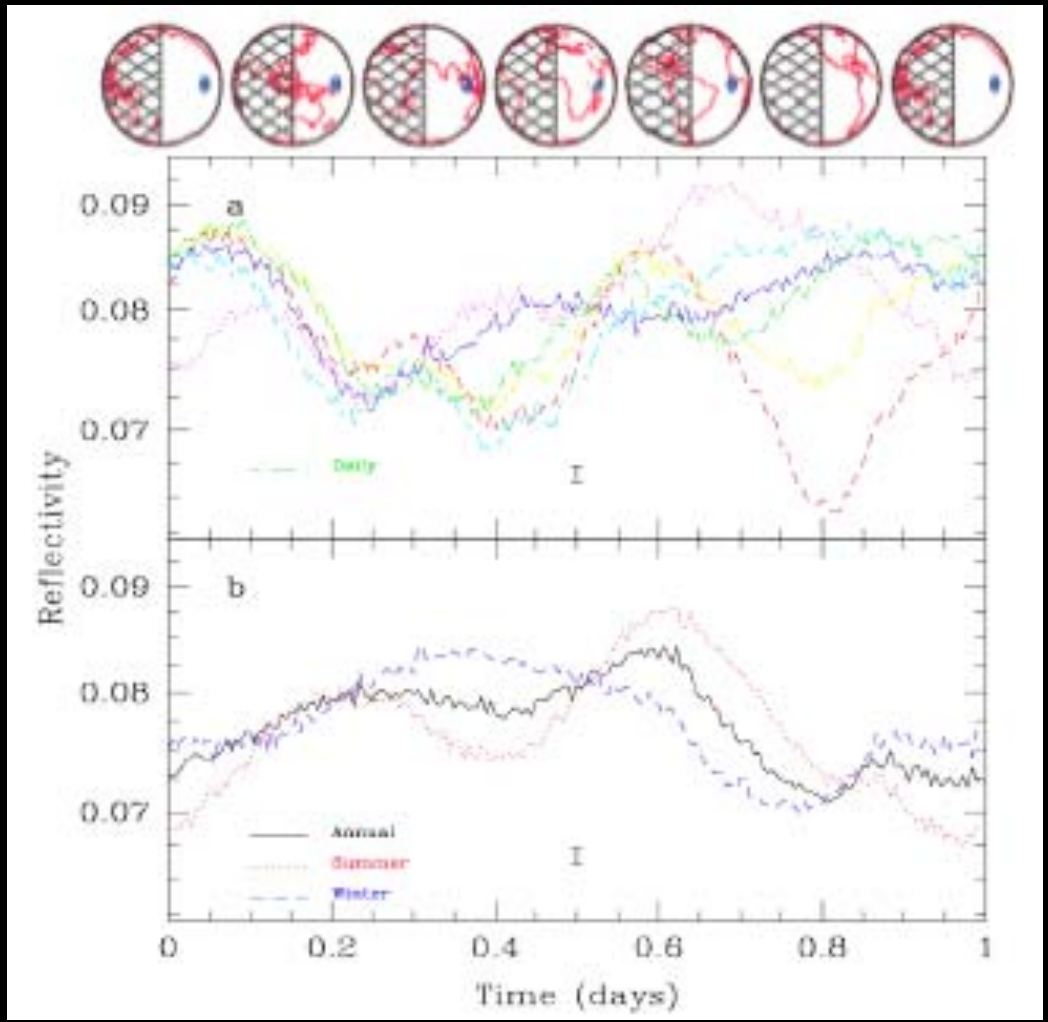
What does our planet look like from space?

Change over time may be the key to spatially characterizing planets via spatially unresolved signals

What does our planet look like from space?

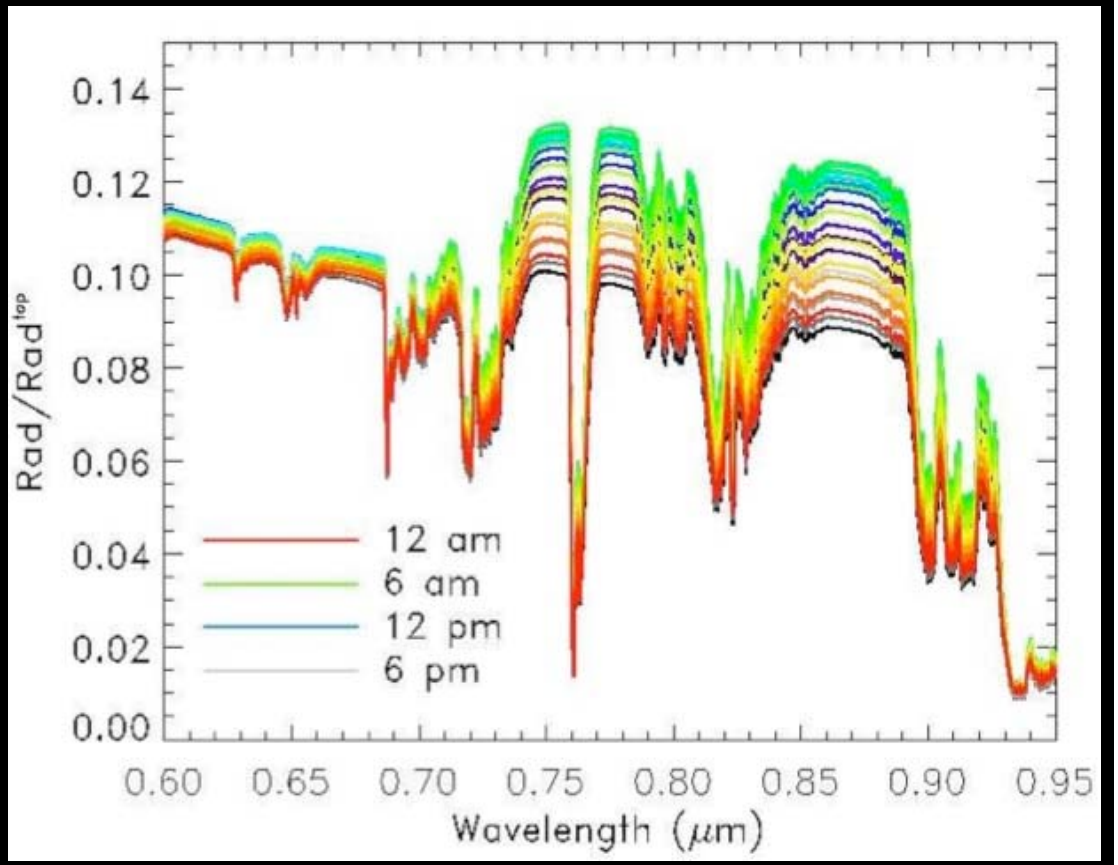
Change over time may be the key to spatially characterizing planets via spatially unresolved signals

⇒Photometric changes ~ 30% (Ford, Seager & Turner 2003)



What does our planet look like from space?

Change over time **may be the key to spatially characterizing planets via spatially unresolved signals**

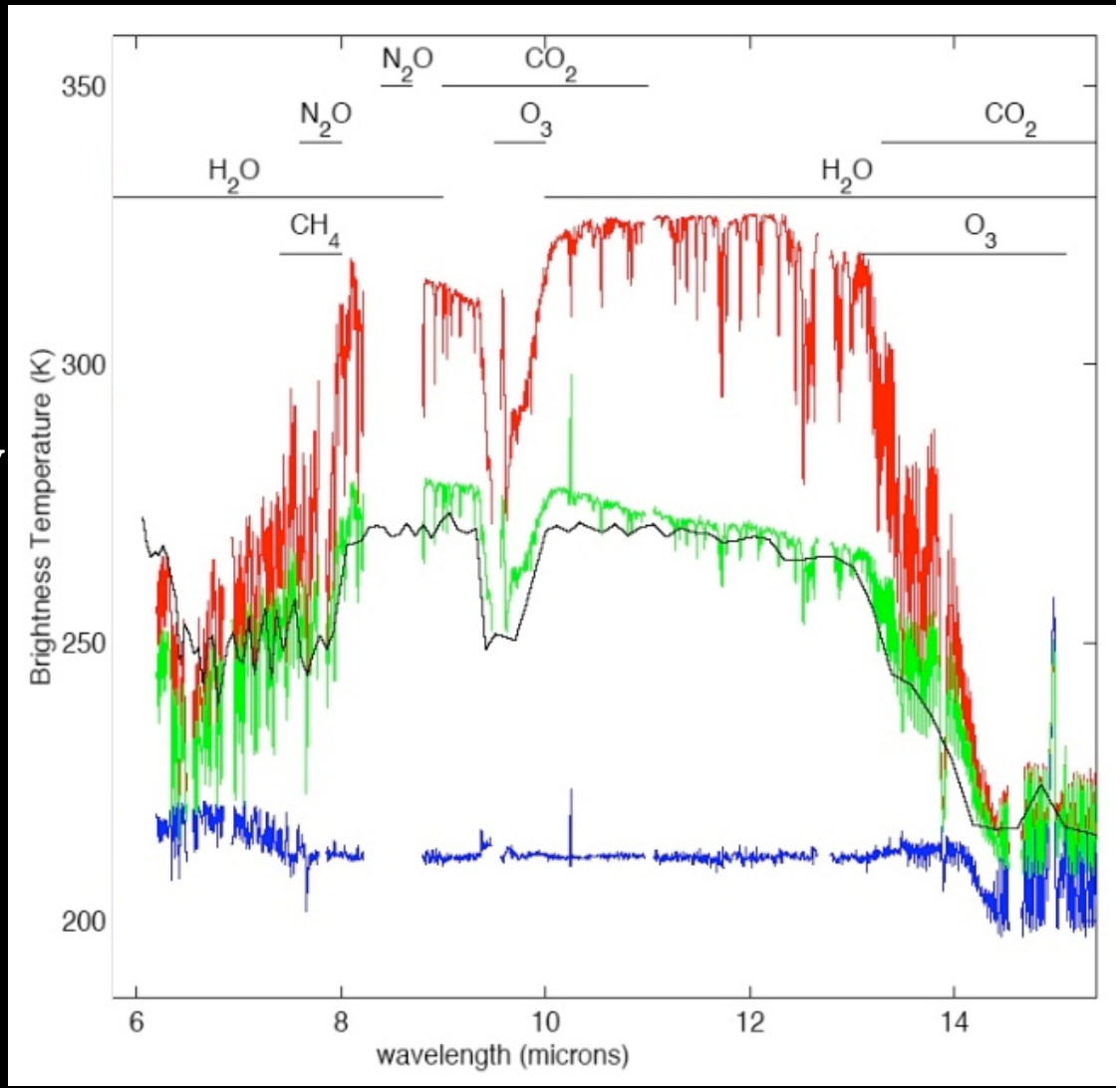


⇒Red edge variations ~30%
(Tinetti et al 2006)

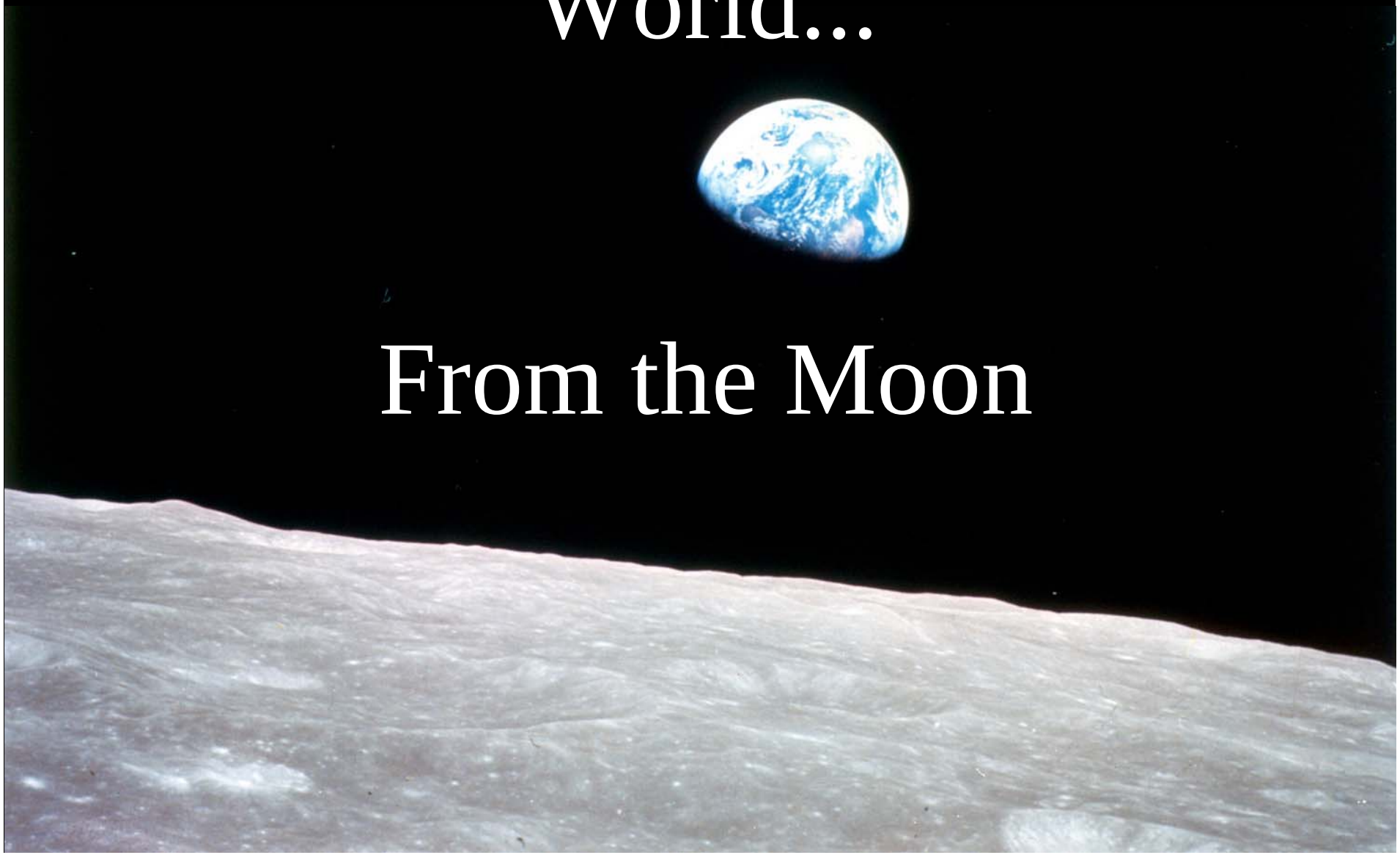
What does our planet look like from space?

Change over time may be the key to spatially characterizing planets via spatially unresolved signals

⇒Thermal variations ~50% (Hearty et al 2007) AIRS data



Characterizing A Living World...



From the Moon

A Few Take-home Lessons:

The moon is fine for astronomy,
but not necessarily better than space.

Challenges are present (dust, radiation,
thermal fluctuations) but surmountable.

If we go to the moon, it will
NOT be so that we can do astrophysics.

A Few Take-home Lessons:

Whether and how we conduct
astrophysics on the moon
will depend on events which we can
inform but not control or predict.

TPF probably needs to be a space mission.

Now is the time to identify sexy, simple
astrophysics that can be carried out from
the moon in the “near” term.

FOR EXAMPLE...

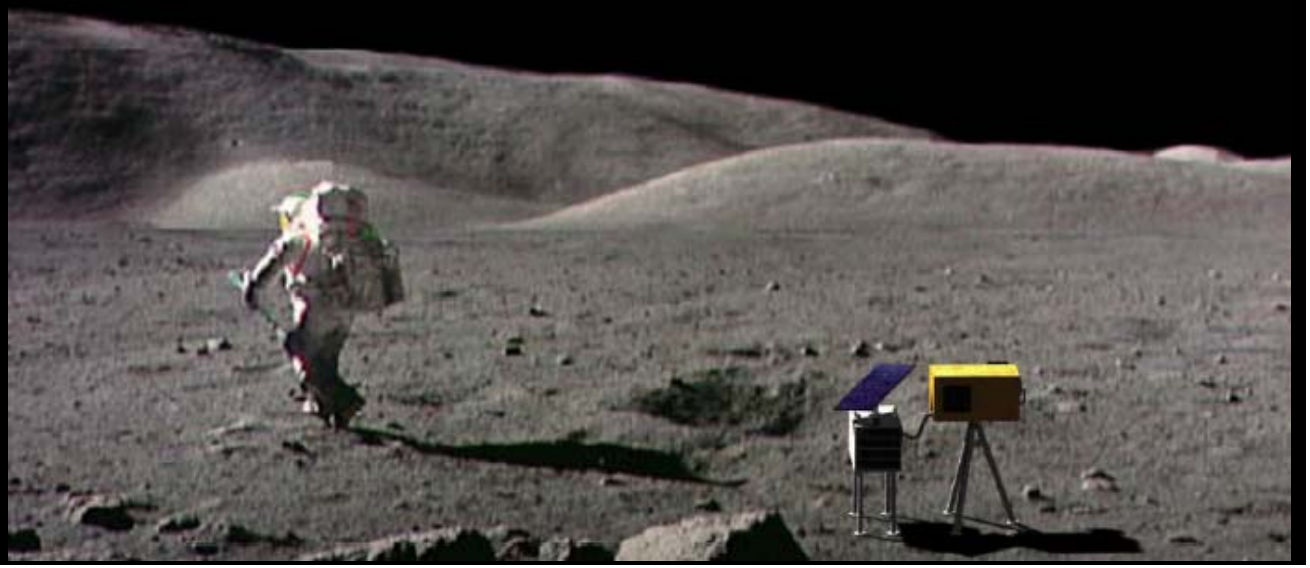
A Concept for TPF Prep Science from the Moon

(STScI's NASA "LSSO" Proposal)

ALIVE: Autonomous Lunar Investigation of the Variable Earth

Characterizing Earth's Habitability and Bio Signatures

PI: Margaret Turnbull, STScI



The ALIVE Idea:

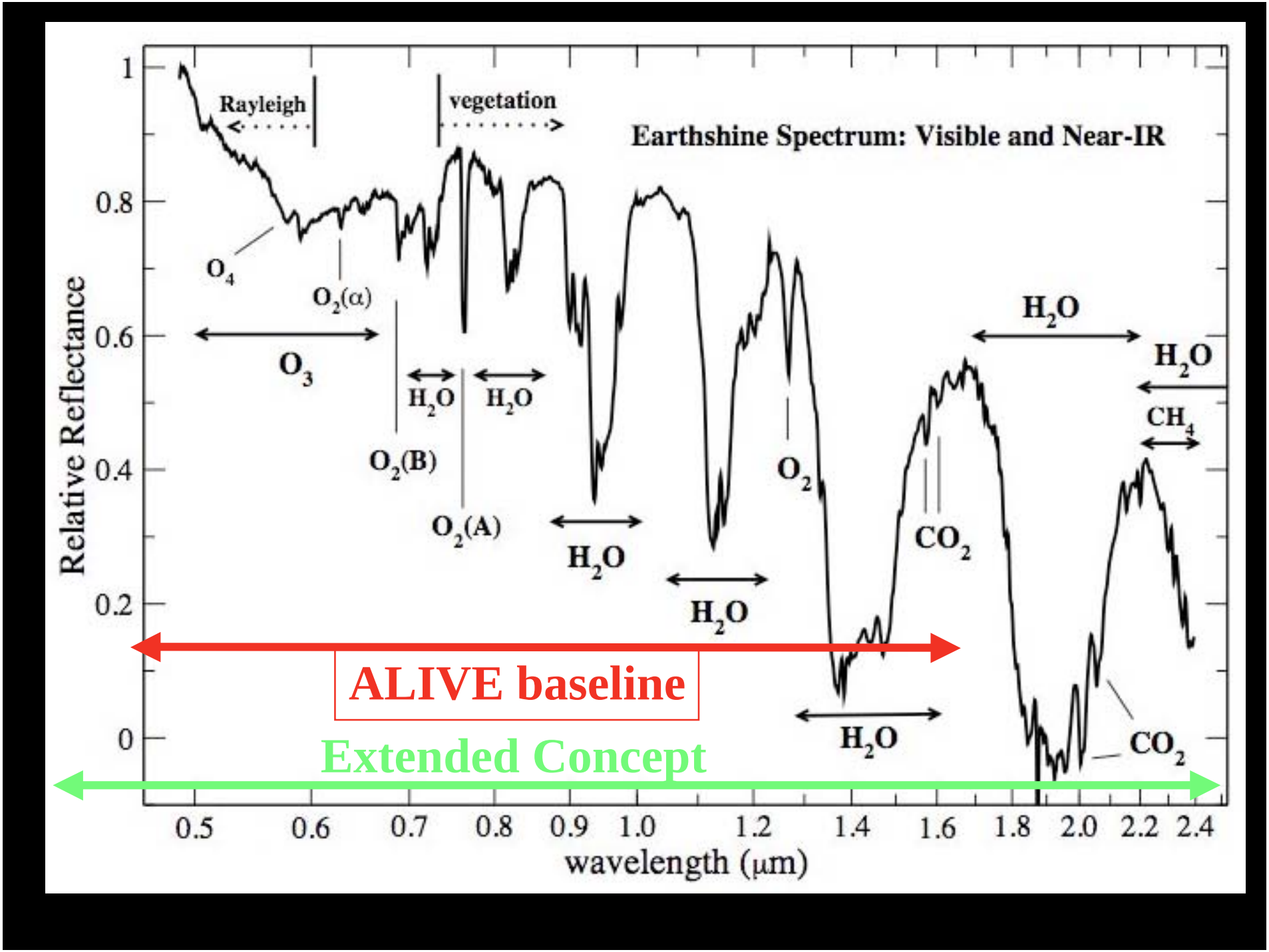
Characterize Terrestrial Change.

Do photometry, spectroscopy, and polarimetry of the Earth on an hourly basis for as long as possible in optical and near-IR wavelengths (possibly UV and thermal IR as well).

-Small telescope, Astronaut deployable

-Autonomously functioning after that

-Study change due to rotation, phases, seasons...solar cycles??

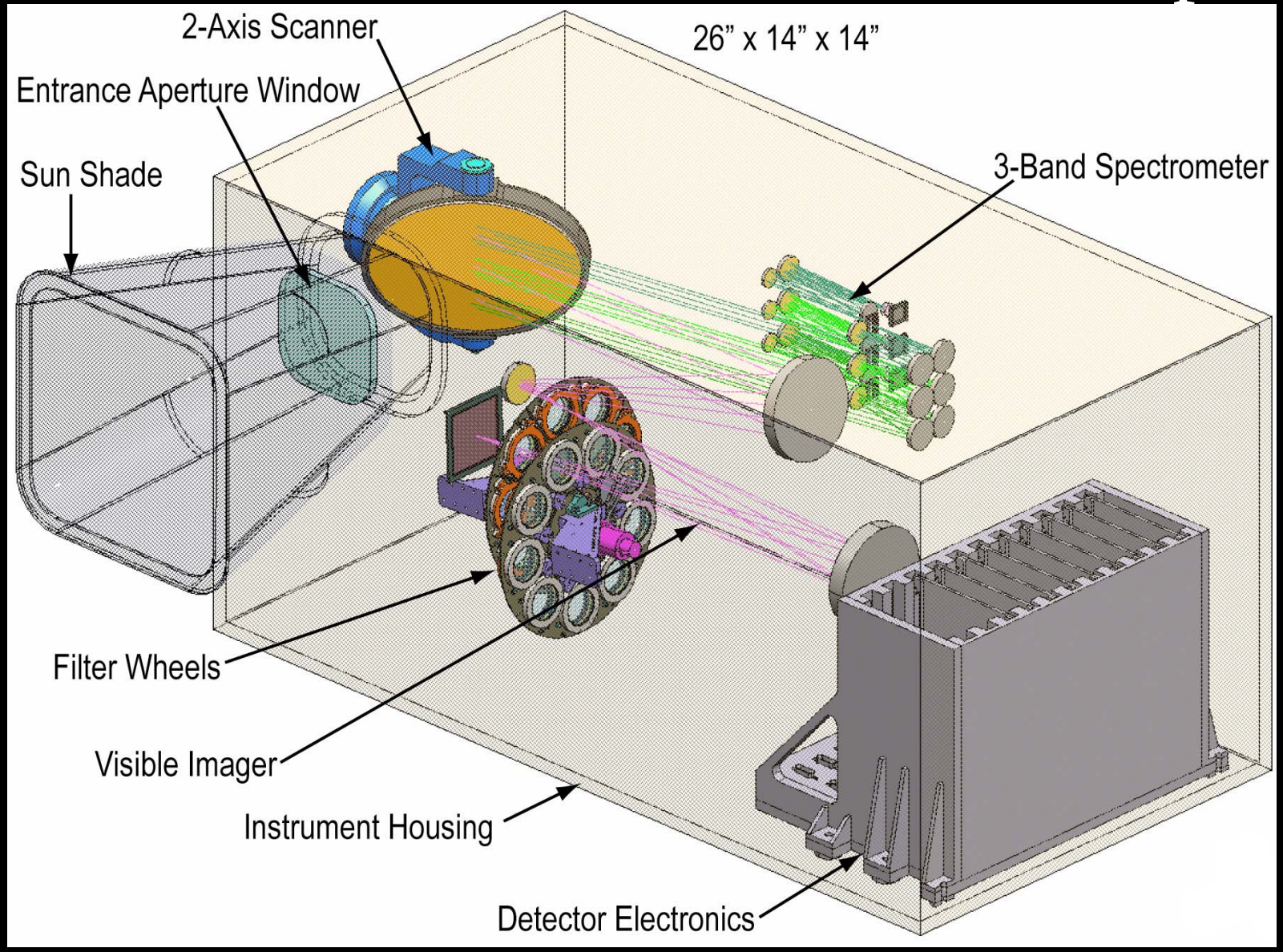

Earthshine Spectrum: Visible and Near-IR
Rayleigh
vegetation
Relative Reflectance
wavelength (μm)
O4
O2(α)
O3
H2O
H2O
O2(B)
O2(A)
H2O
H2O
O2
H2O
CO2
H2O
H2O
CH4
CO2
ALIVE baseline
Extended Concept

The ALIVE Idea:

Use spatially resolved measurements in conjunction with models to find out:

To what extent can we characterize unknown worlds, given a spatially unresolved signal?

The ALIVE Instrument Concept



ALIVE and Earth Science

The modern environmental movement was born of the Apollo missions.

ALIVE and Earth Science

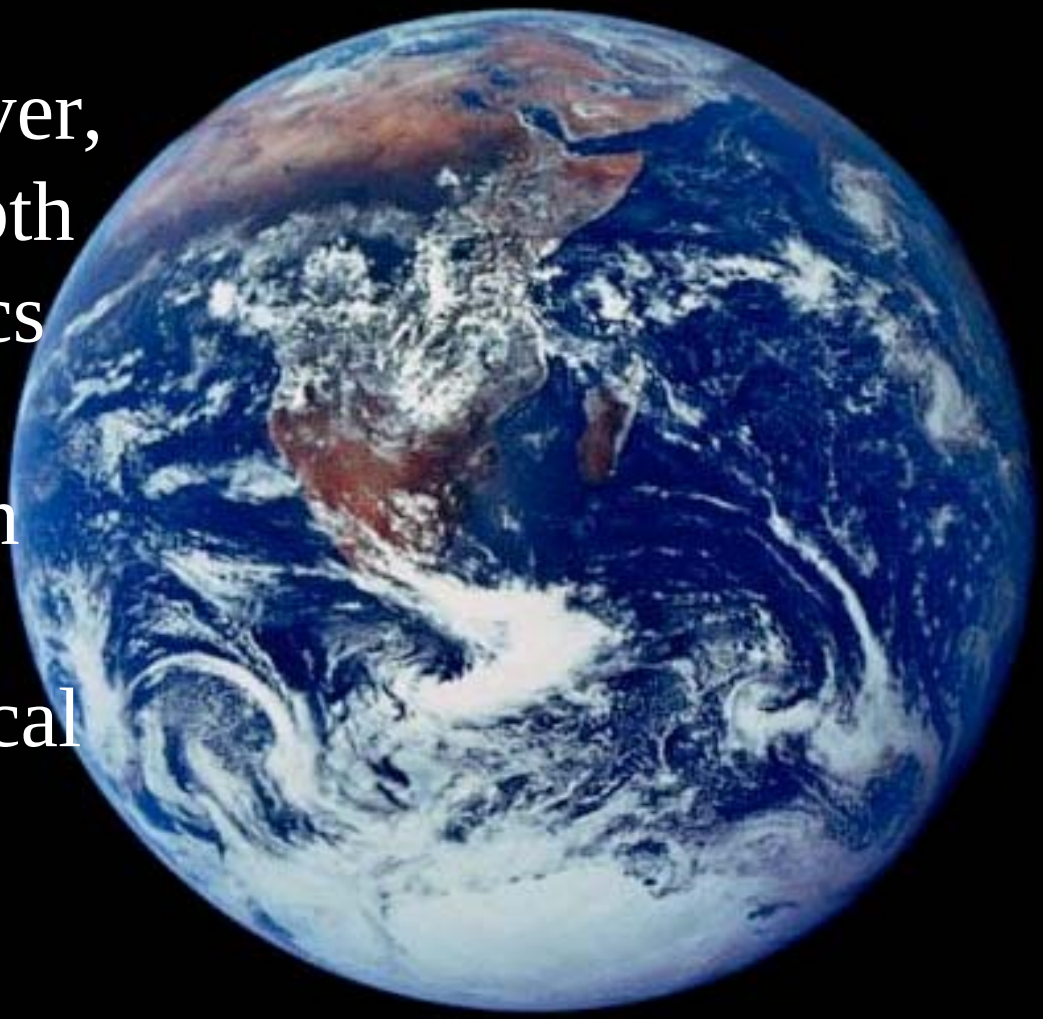
During “Full Earth”, what we lose in relevance to exoplanets we gain in relevance to geoclimatology.

ALIVE and Earth Science

"Hot spot" observations
-spectral separation b/w ground + plants enhanced
-probe canopy structure as the earth turns
-vegetation abundance and health

ALIVE and Earth Science

Limb-to-limb cloudcover, albedo, and optical depth
=>derive microphysics of clouds
=>needed to constrain Earth's albedo and thermal emission, critical for climate models



ALIVE and Earth Science

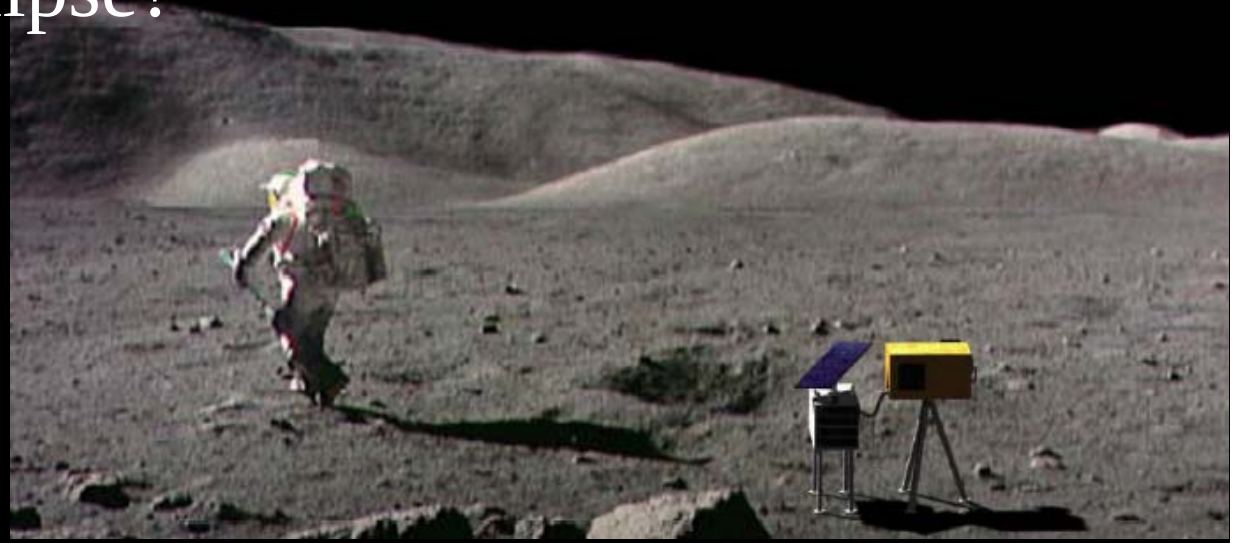
Obtain time- and space-resolved column measurements for greenhouse gases produced by natural and anthropogenic sources (CO_2, CO, CH_4)

ALIVE and Earth Science

Extension into the UV:
Cloud transmittance and absorption,
surface UV radiation,
time- and space-resolved measurements of ozone, aerosols, NO_2
=> also critical to understanding Earth's energy balance

Cost/benefit trades to be investigated:

-wavelength resolution reqs (R~250)
-wavelength range (UV? thermal?)
-spatial res reqs (~10km/100km)
-power (RTGs? solar? batteries?)
-location of deployment (poles?)
-thermal control, dust mitigation
-operations during lunar night?
-observe during eclipse?
-night-time sigs?



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Lunar Environmentalism

-> Apollo, Earthshine, ALIVE: continuing to use the moon to learn about Earth

-> A Lunar Base: An opportunity to learn about sustainable living (learn from Antarctic mistakes/successes)

-> "Magnificent desolation": worth preserving??

Lunar Environmentalism

Keep the moon "wild"...