An Equation to Estimate the Probability of Identifying an Inhabited World Within the Next Decade

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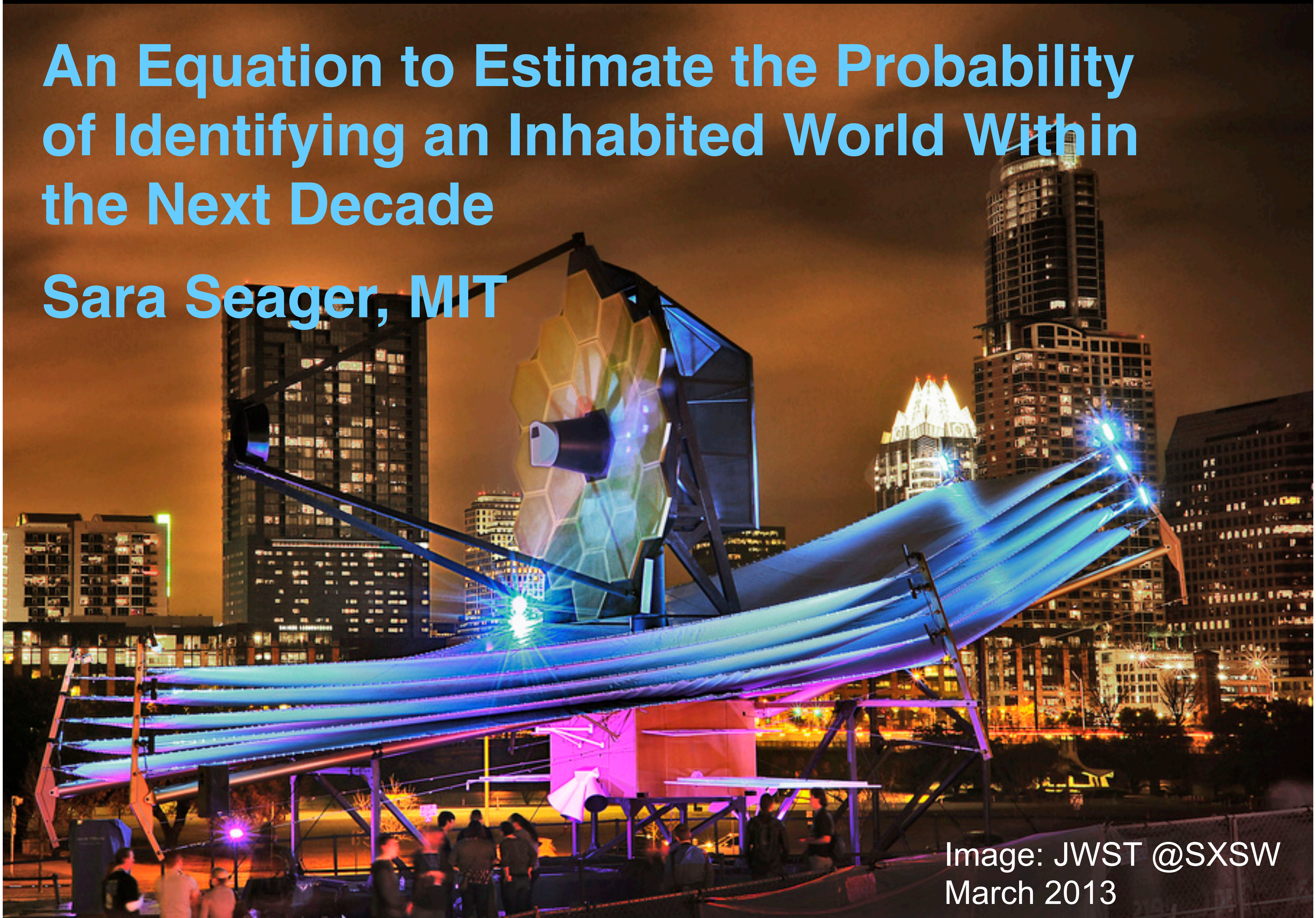

Image: JWST @SXSW
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$$N = N_* F_Q F_{HZ} F_O F_L F_S$$

N	number of planets with detectable biosignature gases
N_*	number of stars within the sample
F_Q	fraction of quiet stars
F_{HZ}	fraction with rocky planets in the HZ
F_O	fraction of observable systems
F_L	fraction with life
F_S	fraction with detectable spectroscopic signatures

A "revised" Drake Equation
For any star types, any well defined survey

$$N = N_* F_Q F_{HZ} F_O F_L F_S$$

N	number of planets with detectable biosignature gases
N_*	number of M stars with $I < 13$
F_Q	fraction of quiet M stars
F_{HZ}	fraction with rocky planets in the HZ
F_O	fraction of observable=transiting systems observable with JWST
F_L	fraction with life
F_S	fraction with detectable spectroscopic signatures

For M stars: TESS/JWST

N_* Number of Stars

$$N = N_* F_Q F_{HZ} F_O F_L F_S$$

Term	M Stars
N_*	30,000

N_* should be those accessible to TESS and for planet-hosting stars accessible to atmosphere followup with *JWST*

- *I* mag < 13
- 30,000 to 50,000 stars
- Bochanski 2007; Reid and Hawley 2006

F_{HZ} Fraction of Stars in the HZ

$$N = N_* F_Q F_{HZ} F_O F_L F_S$$

Term	M Stars
N_*	30,000
F_Q	(0.2)
F_{HZ}	0.15

F_{HZ} for M stars comes from Kepler data from Dressing and Charbonneau 2013. The quiet star fraction is folded in here

F_O Fraction of Observable Systems

$$N = N_* F_Q F_{HZ} F_O F_L F_S$$

Term	M Stars
N_*	30,000
F_Q	(0.2)
F_{HZ}	0.15
F_O	0.01 x 0.1

F_O here means fraction of planets that transit and that are observable by *JWST*. Transiting planets are required for *JWST* atmosphere followup for small planets in the HZ

F_L Fraction with Life

$$N = N_* F_Q F_{HZ} F_O F_L F_S$$

Term	M Stars
N_*	30,000
F_Q	(0.2)
F_{HZ}	0.15
F_O	0.001
F_L	1

F_L is purely speculative

F_S

Fraction with Detectable Spectrscopic Signature

$$N = N_* F_Q F_{HZ} F_O F_L F_S$$

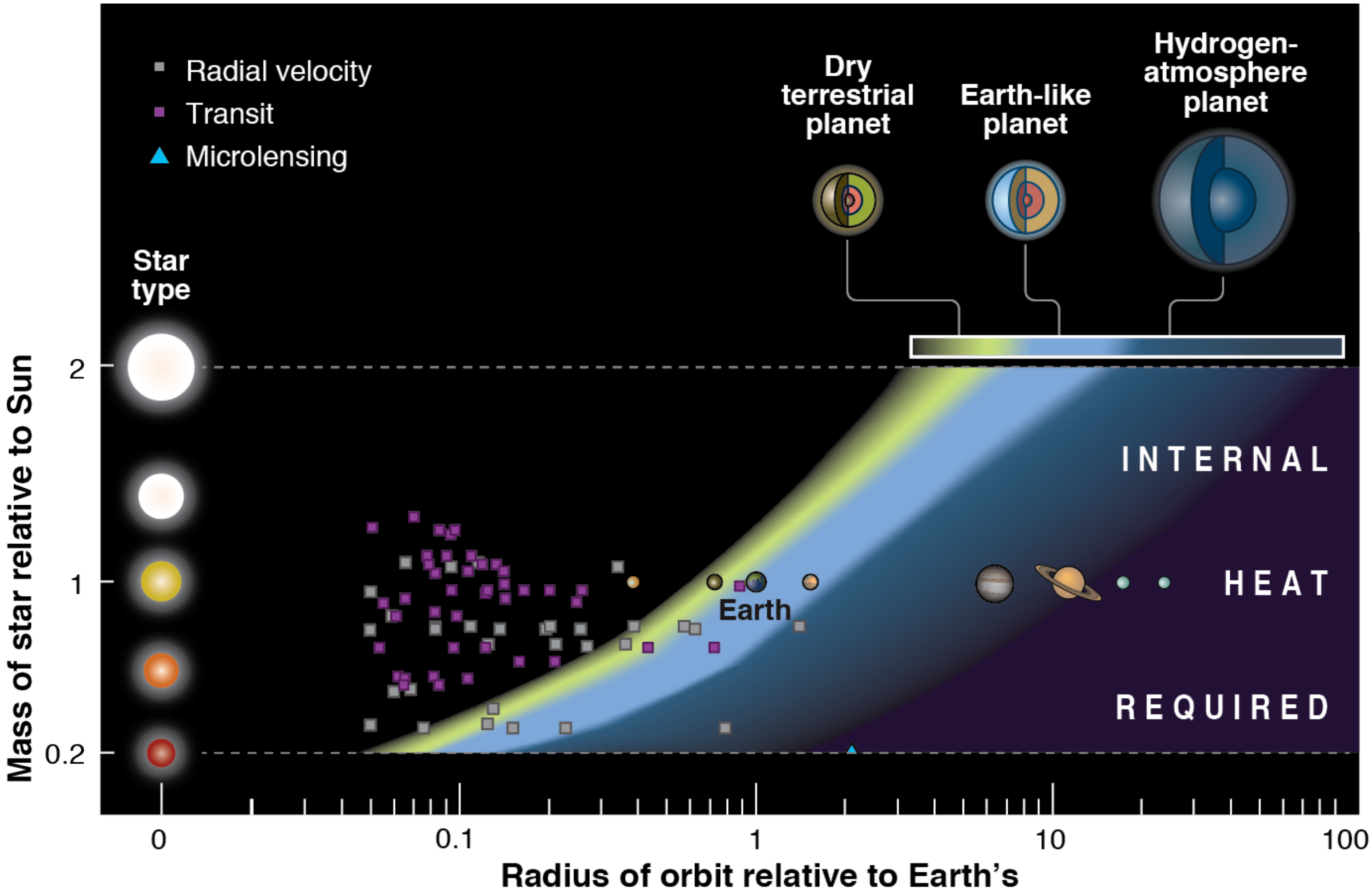
Term	M Stars
N_*	30,000
F_Q	(0.2)
F_{HZ}	0.15
F_O	0.001
F_L	1
F_S	0.5
$\boldsymbol{N}$	**2**

Does life generate a spectroscopic signature?

We appear stuck with a terracentric view of biosignature gases

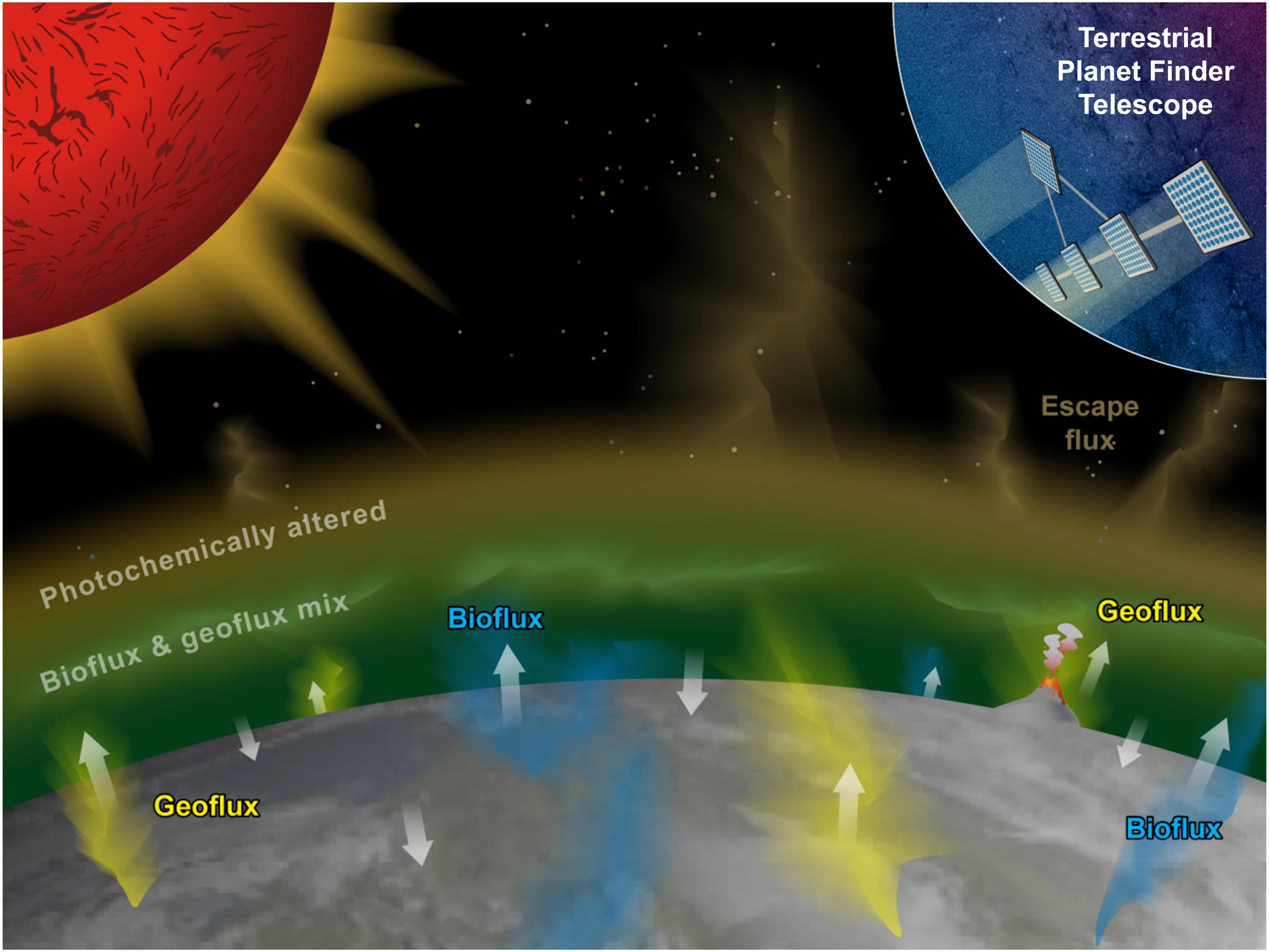
“Nothing would be more tragic in the … exploration of space than to encounter alien life and fail to recognize it” NRC report 2007

The Habitable Zone



Seager, *Science* 2013

Inner edge: Zsom, Seager, de Wit, arXiv: 1304.3714



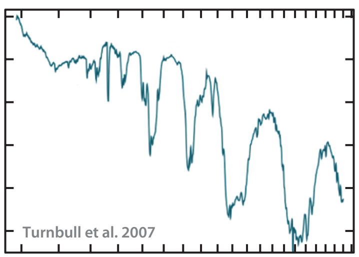
Terrestrial
Planet Finder
Telescope
Escape
flux
Photochemically altered
Bioflux & geoflux mix
Bioflux
Geoflux
Geoflux
Bioflux

Biomass Model as a Plausibility Check for Biosignature Gases

***Hypothesis*: biosignature gas to be evaluated**

Step 1: *Determine atmospheric gas concentration*

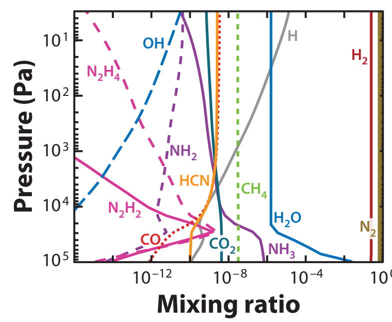
Planetary scenario:
P, T, base chemistry



Compute minimal spectral feature needed for detection

Gas concentration needed for detection

Step 2: *Determine related gas surface flux*



Atmosphere photochemistry model

Source flux necessary to maintain the detectable gas concentration

Step 3: *Determine related biomass*

$$CO_2 + H_2 \longrightarrow CH_4 + H_2O$$

$$\Delta G = \Delta G^o - RT\ln(Q_t)$$

$$\Sigma_B = \Delta G \left[\frac{F_S}{P_{m_e}} \right]$$

Thermodynamic model predicts necessary biomass

Is biomass needed to generate a detectable spectrum a plausible biomass?

Biomass Model Estimate

$$P_{m_e} \approx \Delta G \, R$$

- The minimum maintenance energy rate [kJ/g/s]
- Empirically measured in the lab
- Tijuis et al. 1993

$$P_{m_e} = A \exp\left[\frac{-E_A}{RT}\right]$$

- Gibbs Free energy yield [kJ/mole]

- Gas production rate [mole/g/s]
- Measured for lab cultures

Biomass Model Estimate

$$P_{m_e} \approx \Delta G\, R$$

R [mole/g/s] can be broken down into relevant quantities

$$F_{source} \approx R\, \Sigma_B$$

F_{source}: biosignature surface flux [mole/m^2/s] would be derived from future exoplanet observations, considering photochemistry

$$\Sigma_B \approx \frac{\Delta G\, F_{source}}{P_{m_e}}$$

Σ_B: biomass surface density [g/m^2]

Cold Haber World: NH_3

- Cold Haber World $3H_2 + N_2 \rightarrow 2NH_3$
  - NH_3 as a biosignature gas on an 90% H_2-10% N_2 planet with life enzymatically catalyzing the N_2 bond
  - NH_3 has a short lifetime and requires a surface flux for production in thin atmospheres
  - Detectable NH_3 around a quiet M star with 3.3 ppm, $F_{source} = 2 \times 10^{13}$ molecules/m^2/s, ΔG and $\Sigma_B \sim 3 \times 10^{-5}$ g/m^2

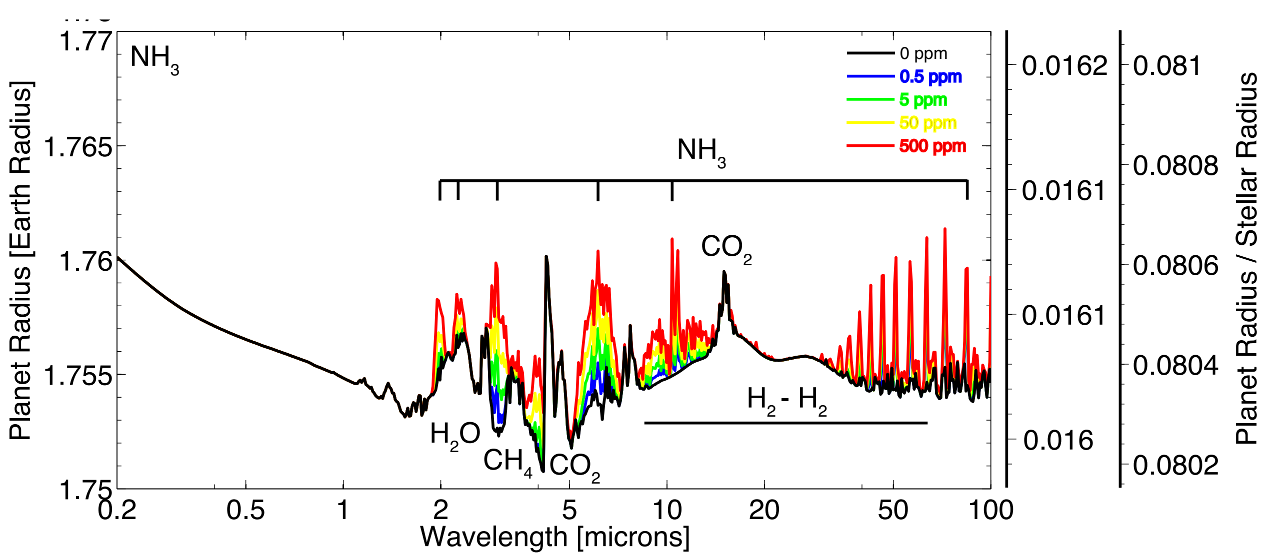


Figure shows synthetic transmission spectra for a 10 Earth mass, 1.75 Earth radius planet orbiting a quiet M5 dwarf star Seager et al. submitted to ApJ

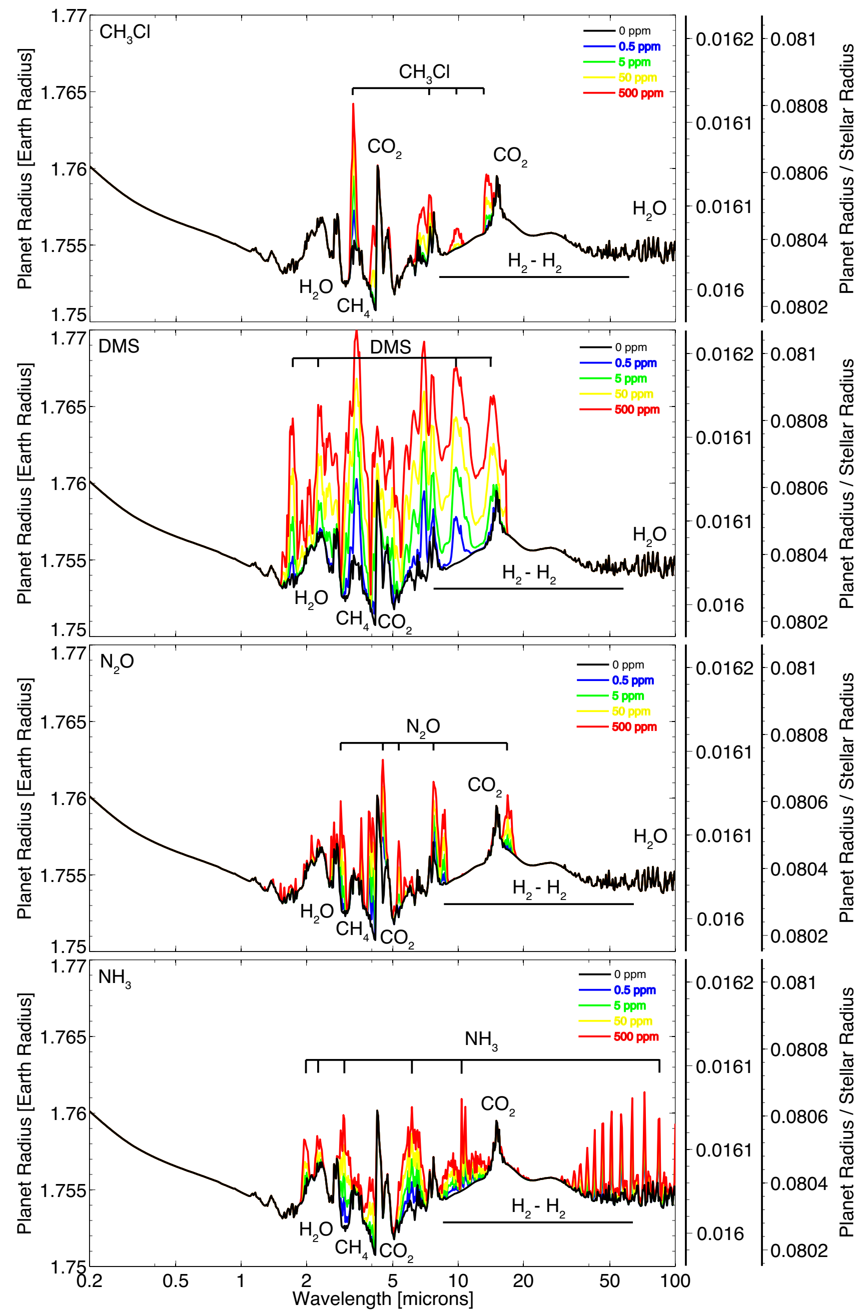
Biosignature Gases in H_2 Atmospheres

Proof of concept that biosignature gases can accumulate in an H_2-rich atmosphere

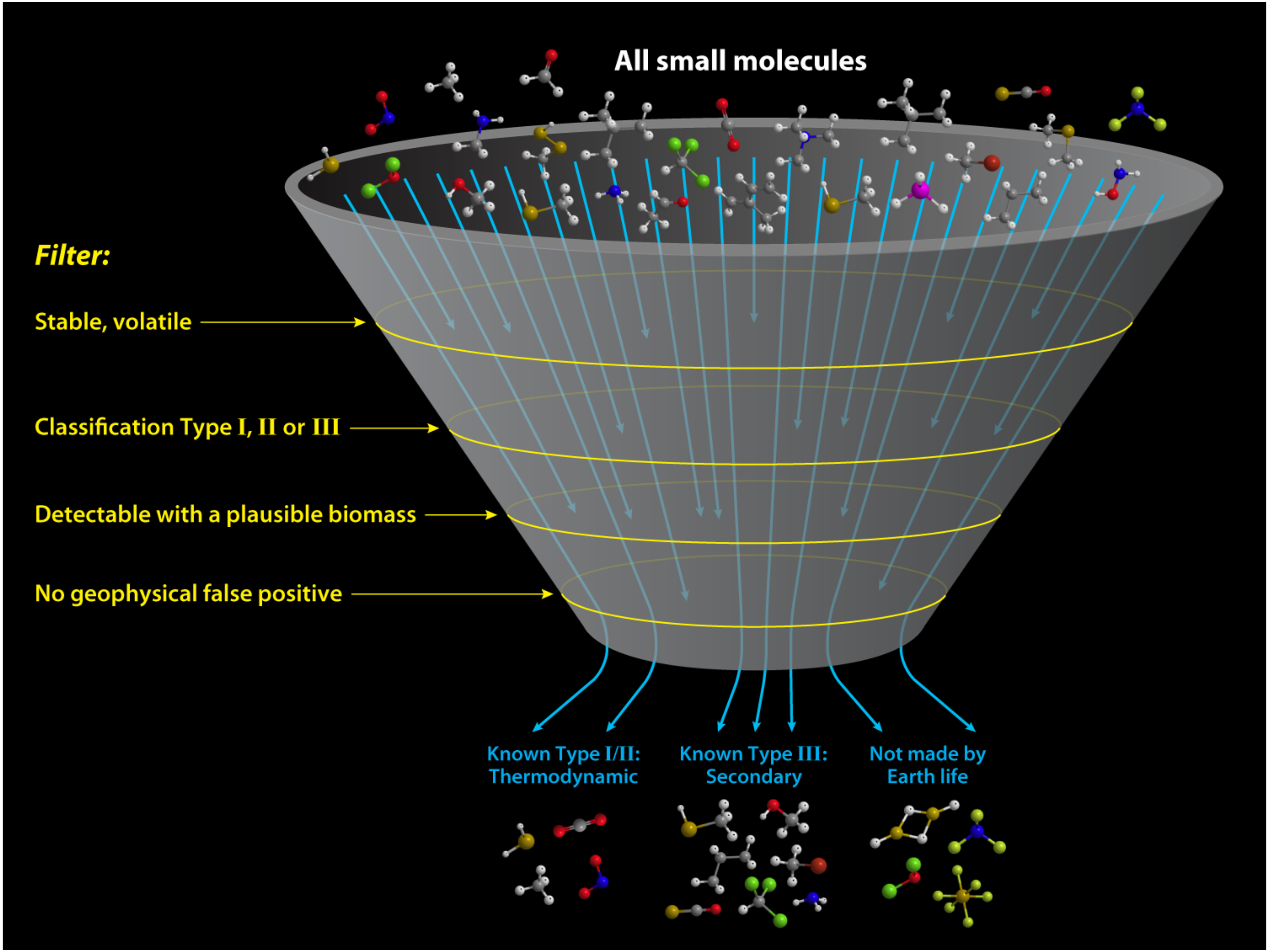
H is the dominant reactive species (akin to OH)

The low UV environments of quiet M stars are most favorable

Examples studied shown in Fig.



Seager, Bains, Hu submitted to ApJ



All small molecules
Filter:
Stable, volatile
Classification Type I, II or III
Detectable with a plausible biomass
No geophysical false positive
Known Type I/II: Thermodynamic
Known Type III: Secondary
Not made by Earth life

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F_O	0.001
F_L	1
F_S	0.5
N	**2**

"It's not going to be easy but we can dream"
Dave Latham