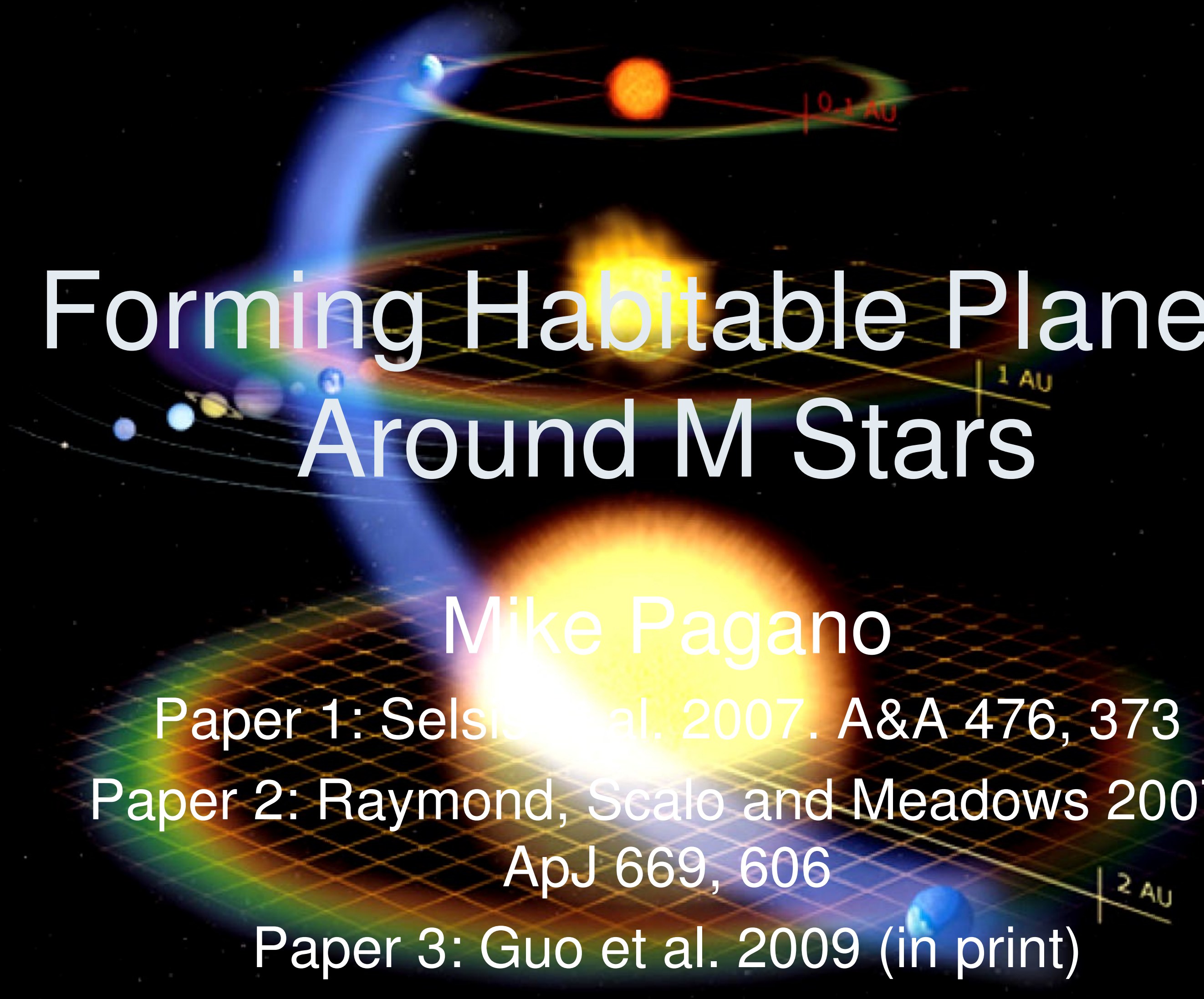


Forming Habitable Planets Around M Stars

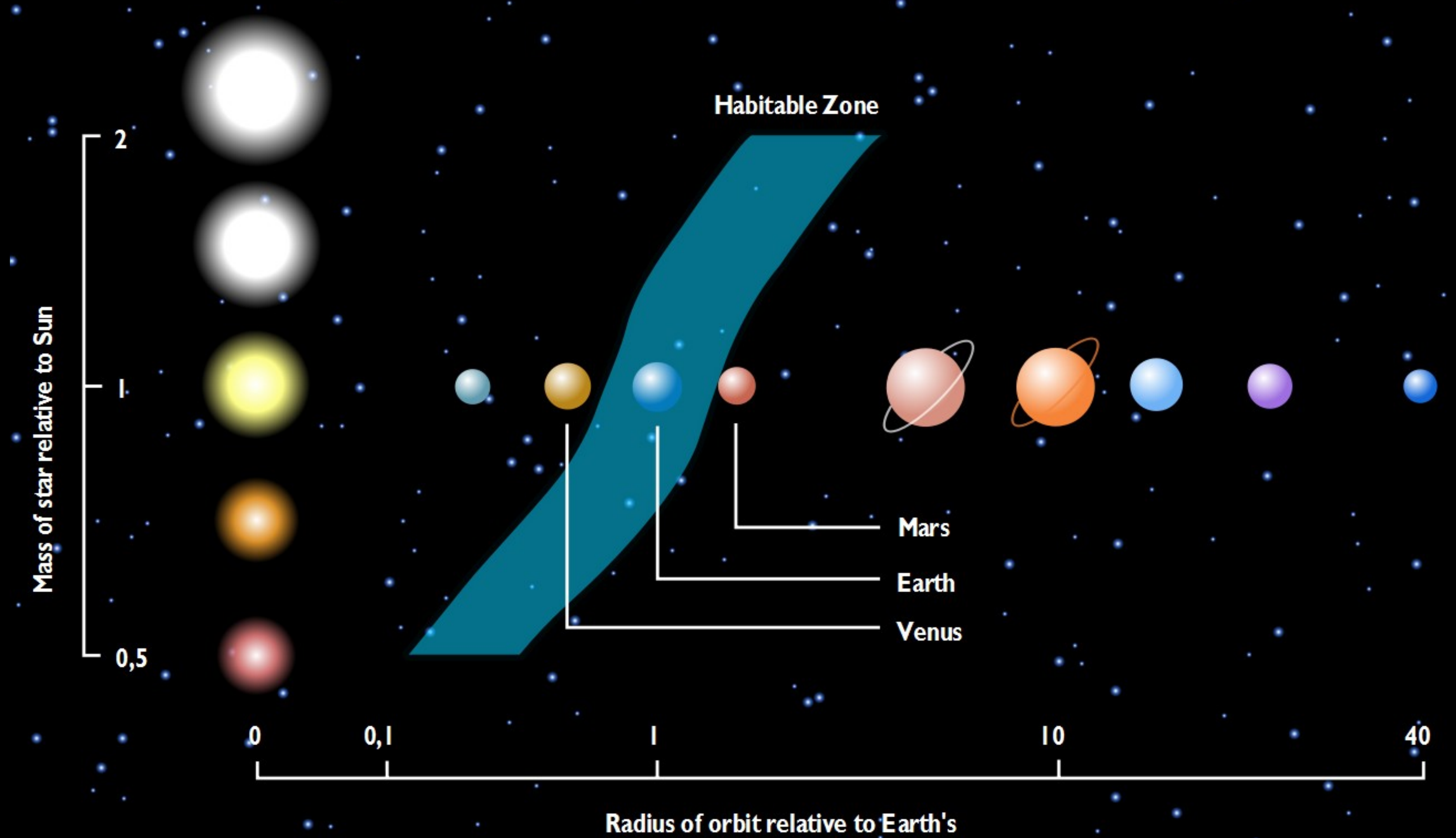
Mike Pagano

Paper 1: Selsis et al. 2007. A&A 476, 373

Paper 2: Raymond, Scalo and Meadows 2007. ApJ 669, 606

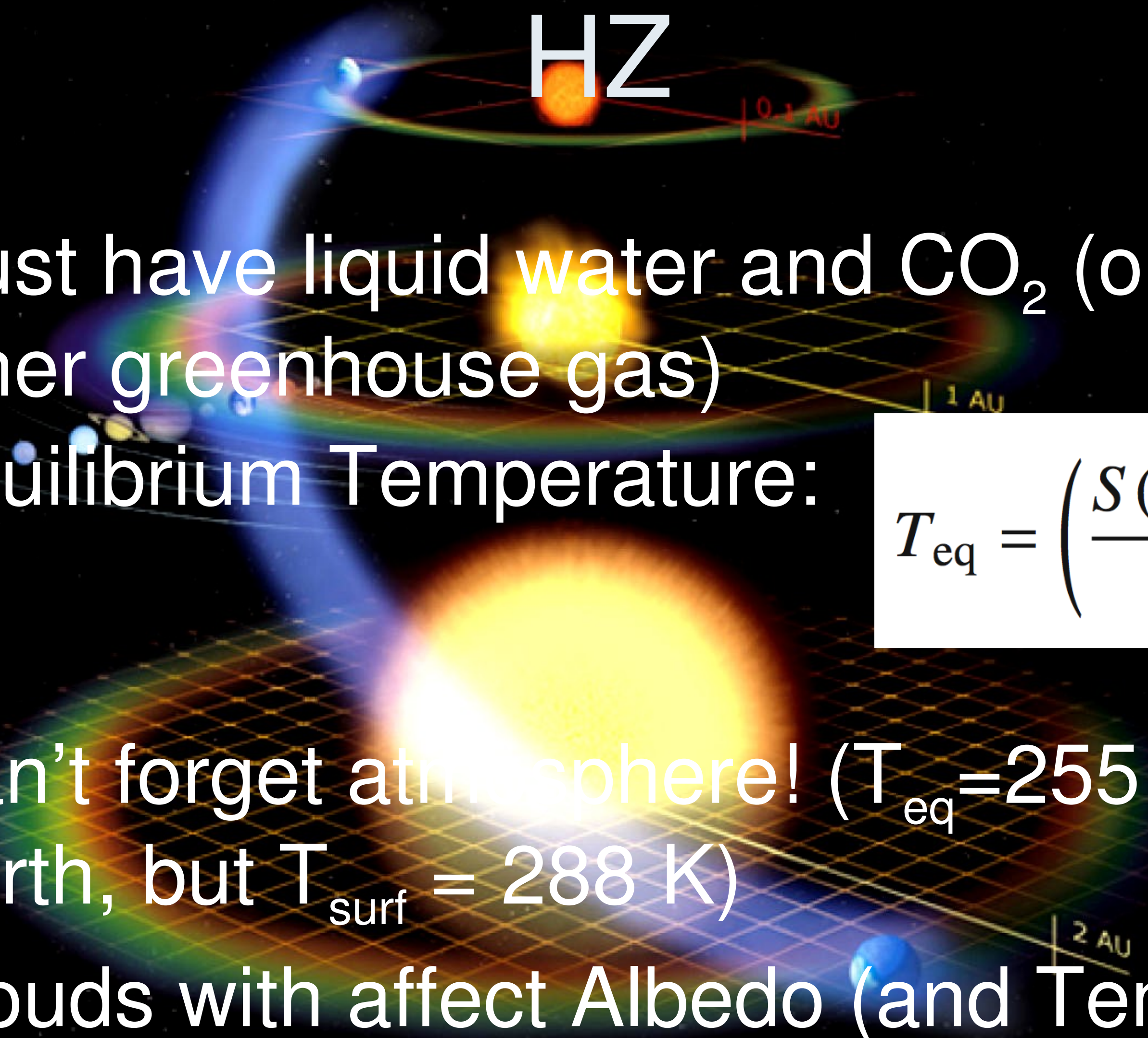
Paper 3: Guo et al. 2009 (in print)

What is a HZ?



Habitable Zone
Mass of star relative to Sun
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

HZ



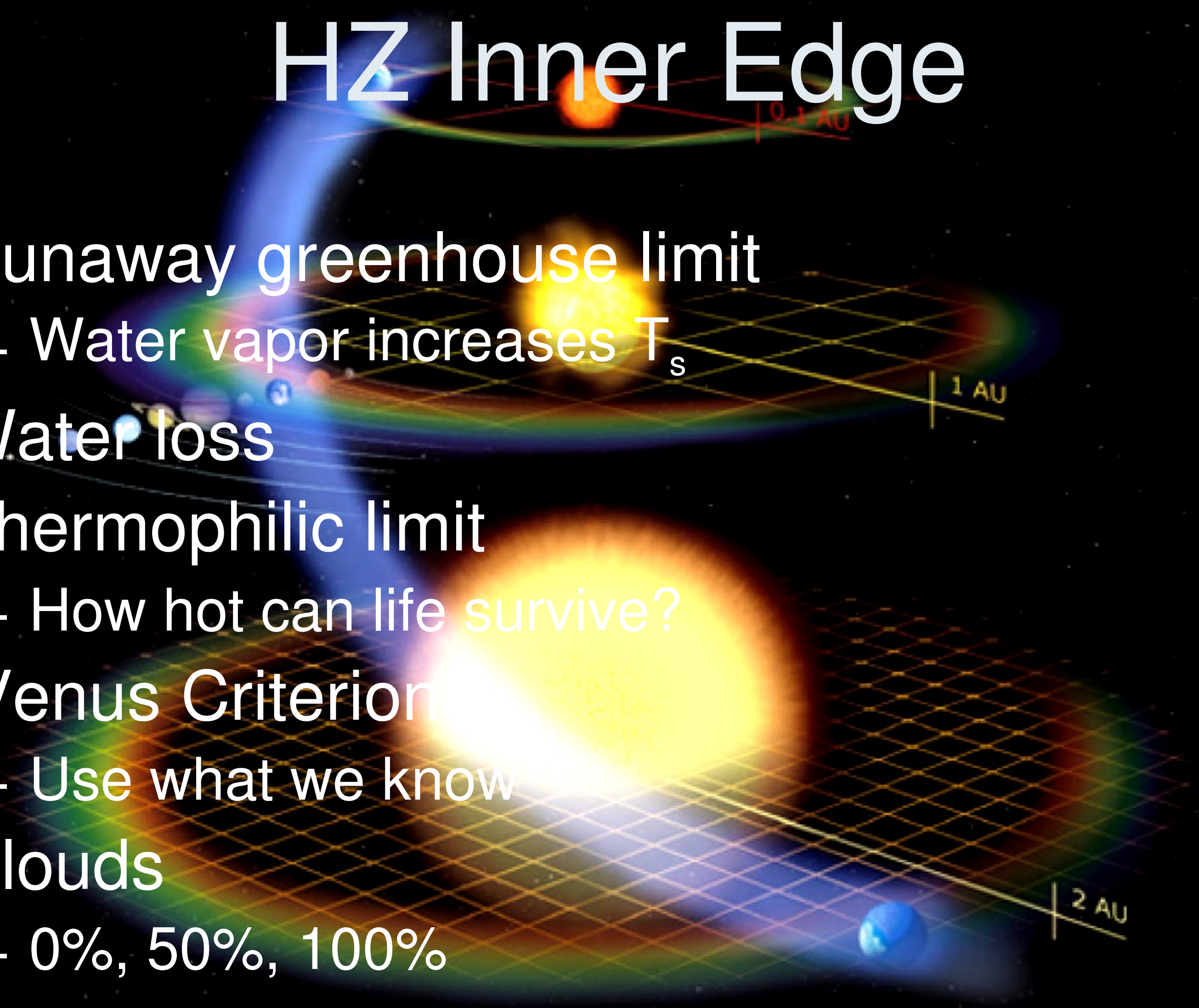
- Must have liquid water and CO_2 (or other greenhouse gas)
- Equilibrium Temperature:

$$T_{eq} = \left(\frac{S(1-A)}{f\sigma} \right)^{\frac{1}{4}}$$

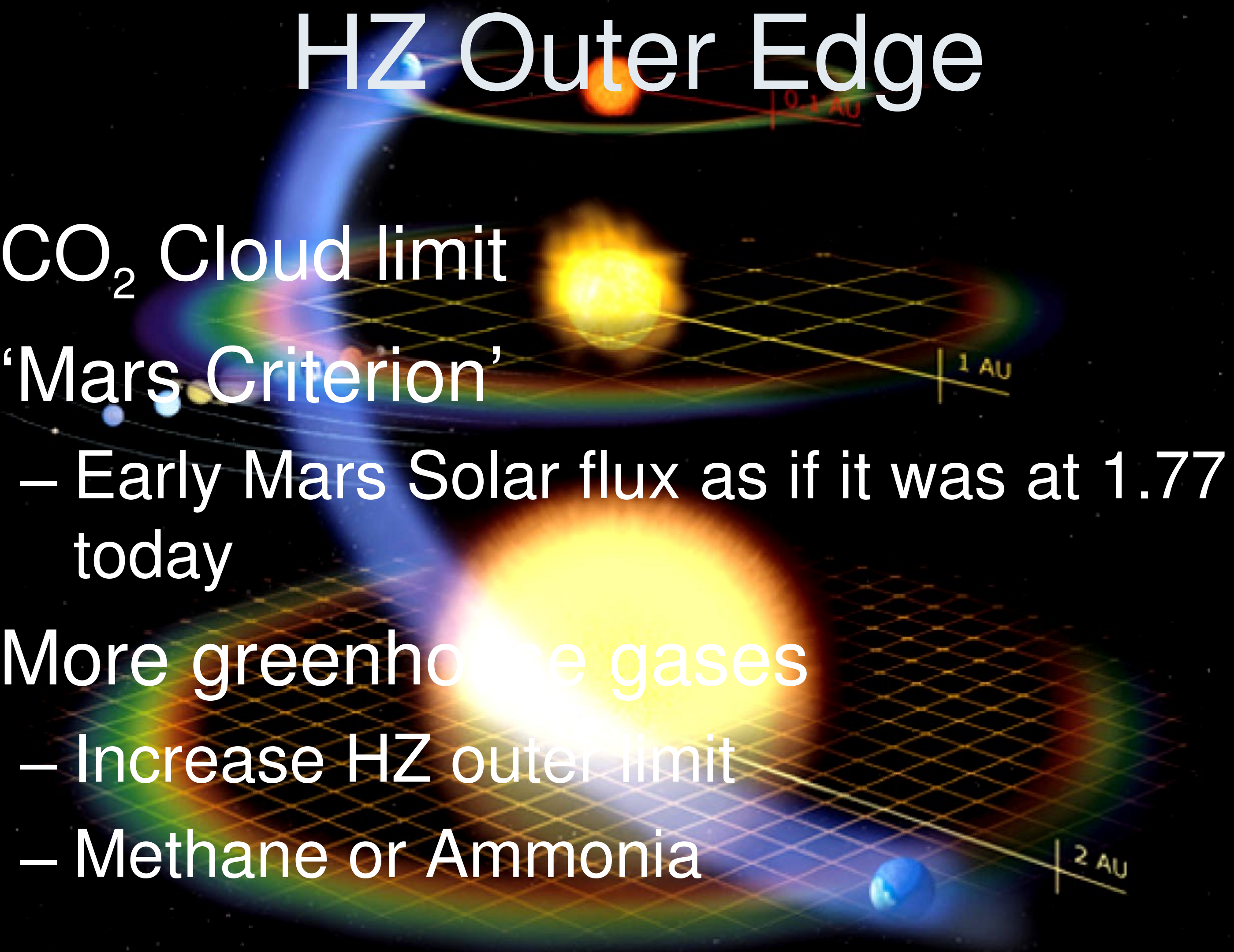
- Can't forget atmosphere! (T_{eq}=255 K for Earth, but T_{surf} = 288 K)
- Clouds with affect Albedo (and Temp)

HZ Inner Edge

- Runaway greenhouse limit
  - Water vapor increases T_s
- Water loss
- Thermophilic limit
  - How hot can life survive?
- ‘Venus Criterion’
  - Use what we know
- Clouds
  - 0%, 50%, 100%



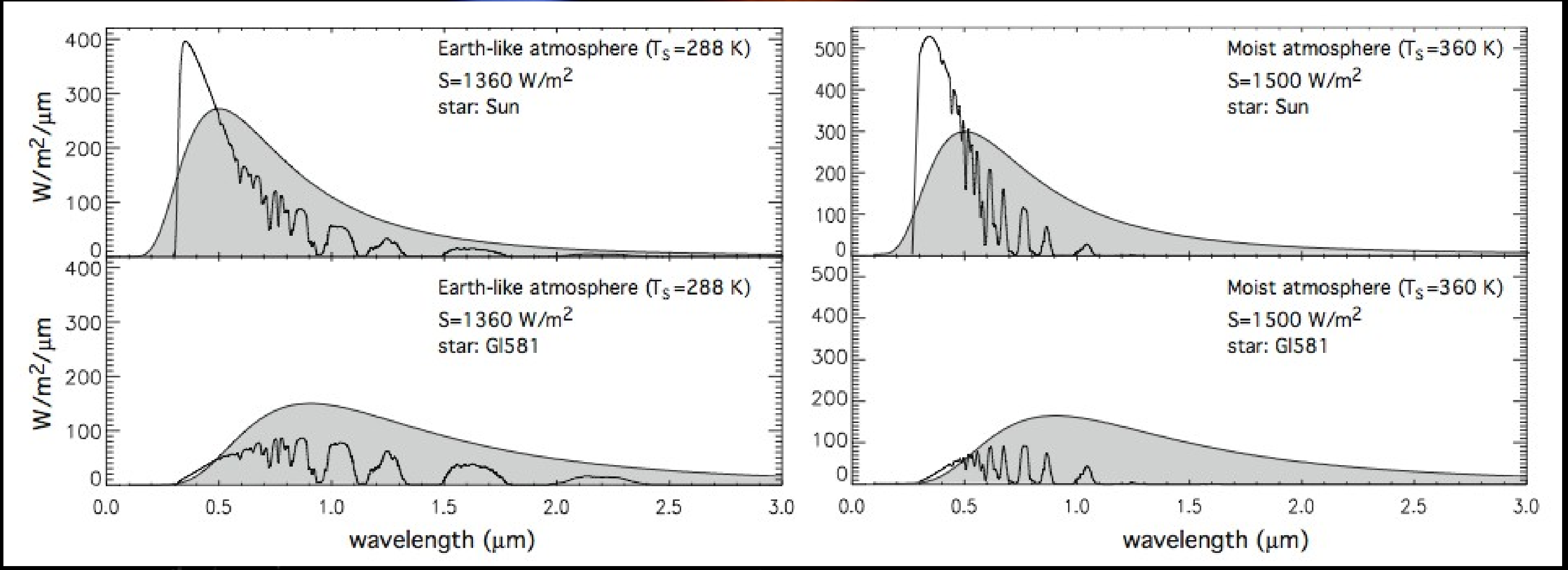
HZ Outer Edge



- CO_2 Cloud limit
- 'Mars Criterion'
  - Early Mars Solar flux as if it was at 1.77 AU today
- More greenhouse gases
  - Increase HZ outer limit
  - Methane or Ammonia

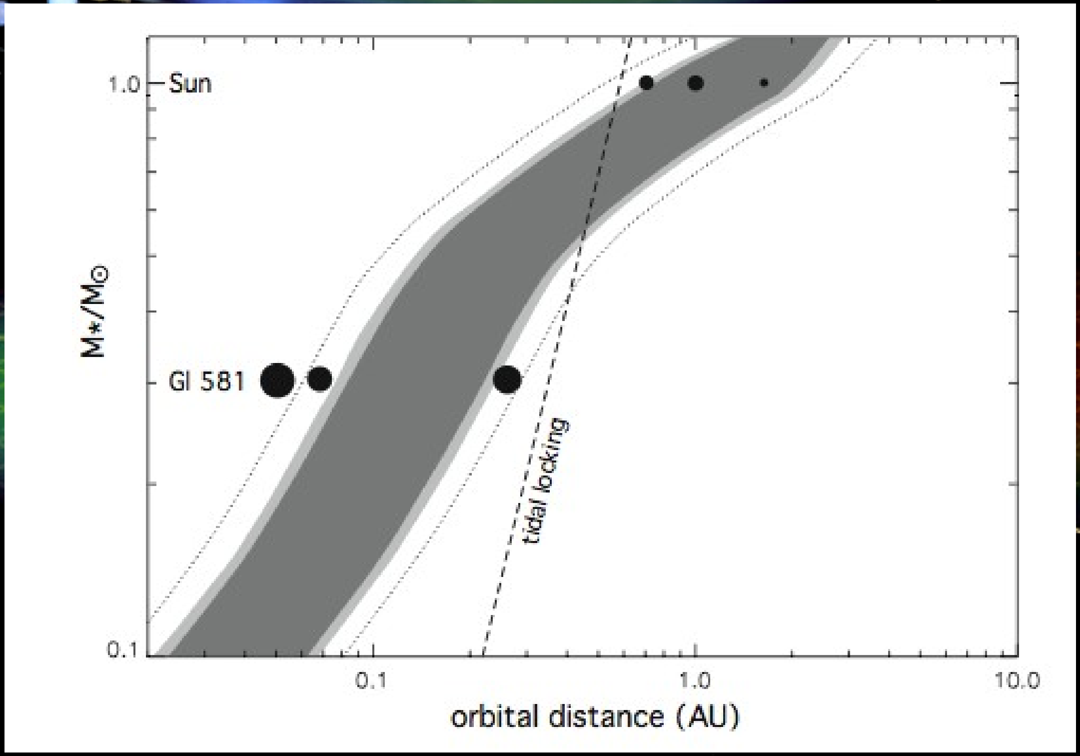
HZ for M stars

- Stellar radiation matters!
  - Can not just account for flux difference, need to use T_{eff} for star.



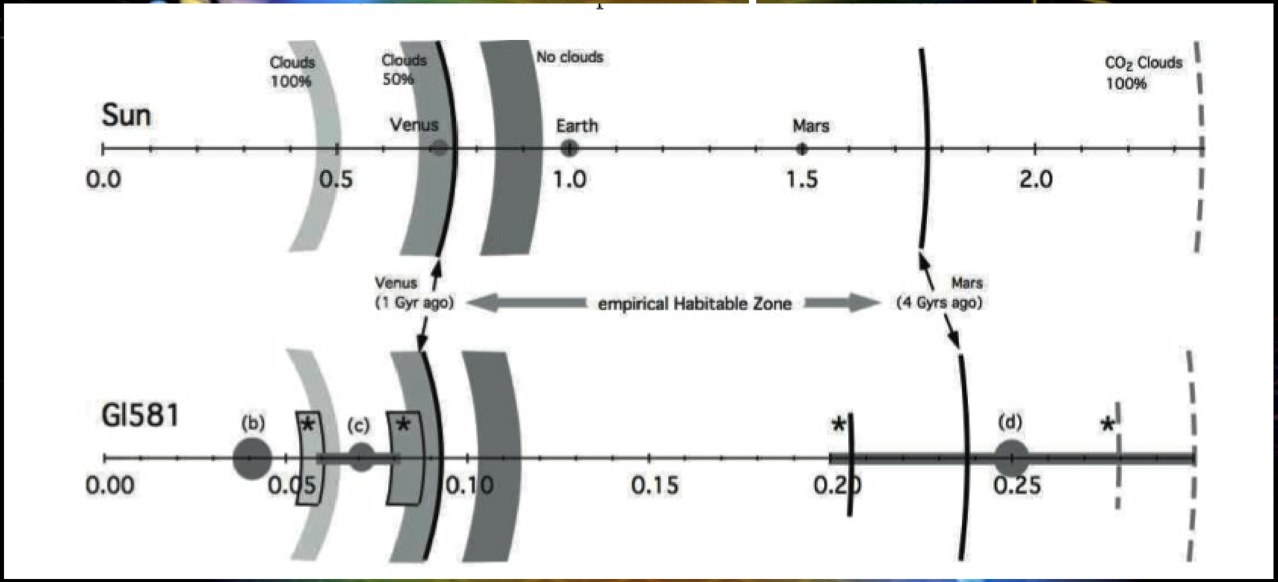
CHZ

- Continuously habitable zone - habitable longer than a given time (5 Gyr below)



Gliese 581(c & d)

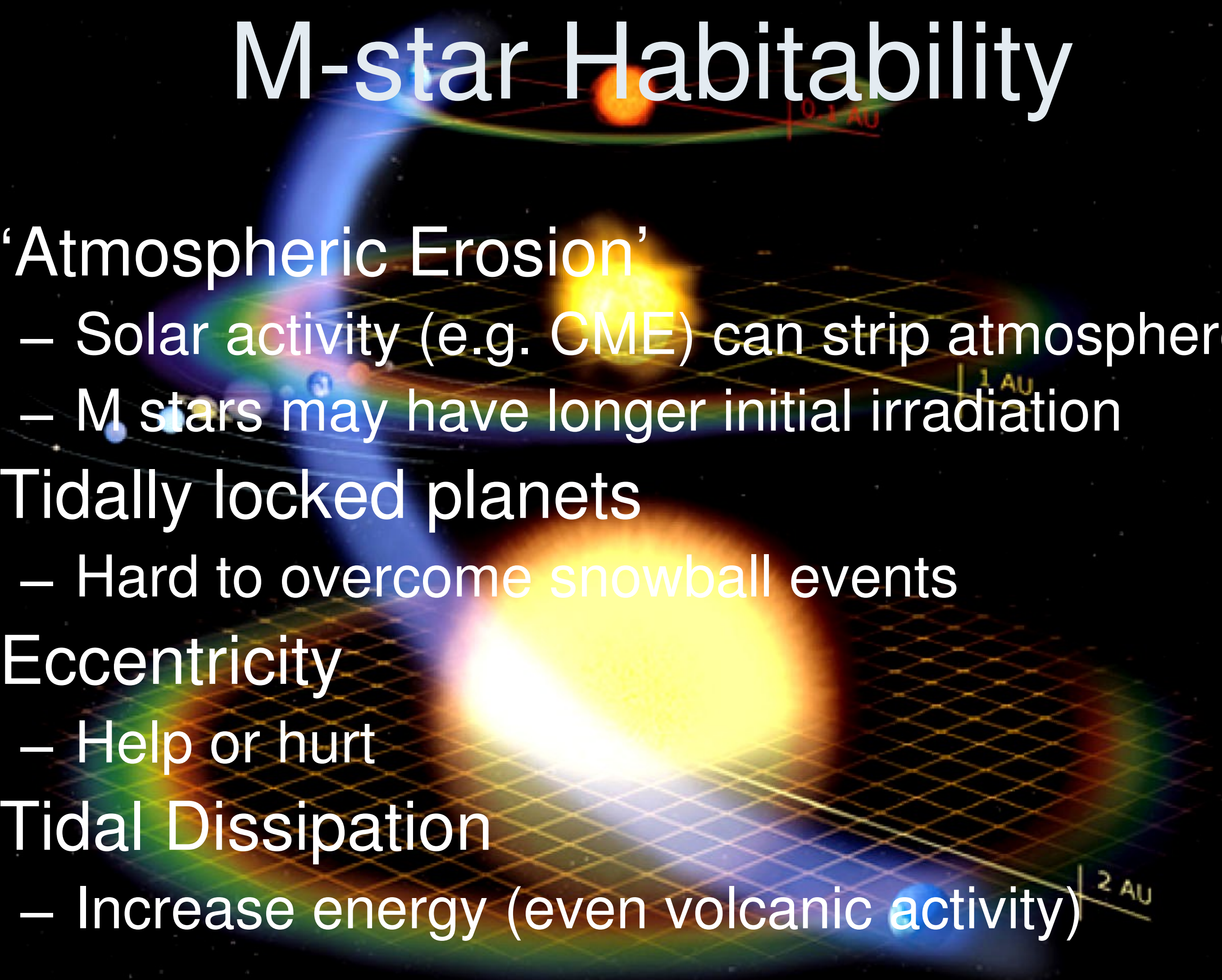
- Gliese 581 is a M star - 0.013 L砿 and 3200 K effective temperature



Gliese 581(c & d)

- 581c : M_{min}=5$M_{\oplus}$ 1.3 times Venus flux
  - – Cloud cover not enough, but could have started very wet
- 581d : M_{min}=8$M_{\oplus}$ 0.5 times Mars flux
  - – However CO_2 rich atm. absorb more energy from M stars.
  - – However M_{min} may imply M>10$M_{\oplus}$

M-star Habitability



- ‘Atmospheric Erosion’
  - Solar activity (e.g. CME) can strip atmospheres
  - M stars may have longer initial irradiation
- Tidally locked planets
  - Hard to overcome snowball events
- Eccentricity
  - Help or hurt
- Tidal Dissipation
  - Increase energy (even volcanic activity)

Forming Terrestrial Planets Around M Stars

- Raymond, Scalo and Meadows 2007
- Find the stellar mass, below which habitable size planets cannot form
- They put a $0.3M_{\oplus}$ lower limit for habitable planet.
  - To have significant tectonics for Gyrs
  - Need this to release CO_2 (which can overcome ‘Snowball’ episodes)

Disk Properties

$$\Sigma(r) = \Sigma_1 f Z \left(\frac{r}{1\ \mathrm{AU}}\right)^{-\alpha} \left(\frac{M_\star}{M_\odot}\right)^{h},$$

- Surface density of disk
  - h is the density scaling factor
    - Use 1 (but vary 1/2 to 2)
  - f is the disk scaling factor
    - f=1 for Min. Mass Solar Nebula (very variable)
  - α is the steepness of the density profile
    - Use 1 (but vary 1/2-3/2 later)
  - Z is metallicity (use 1 but can vary)

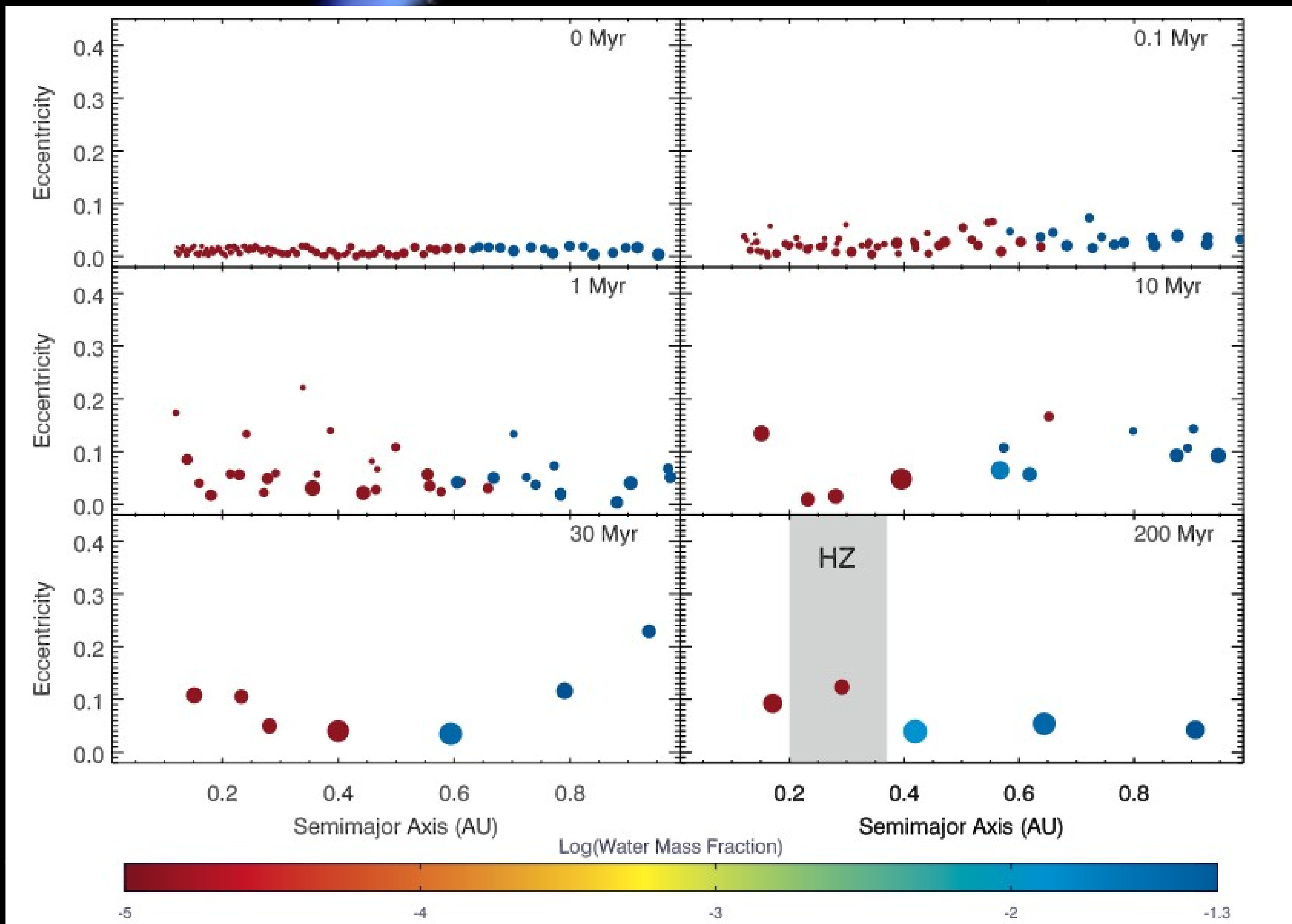
Simulation/Model

- Used Mercury Orbital Integrator
- Vary mass of star from 0.2 to 1 $M_{\odot}$
- Start with embryos:

Initial Conditions for Simulations

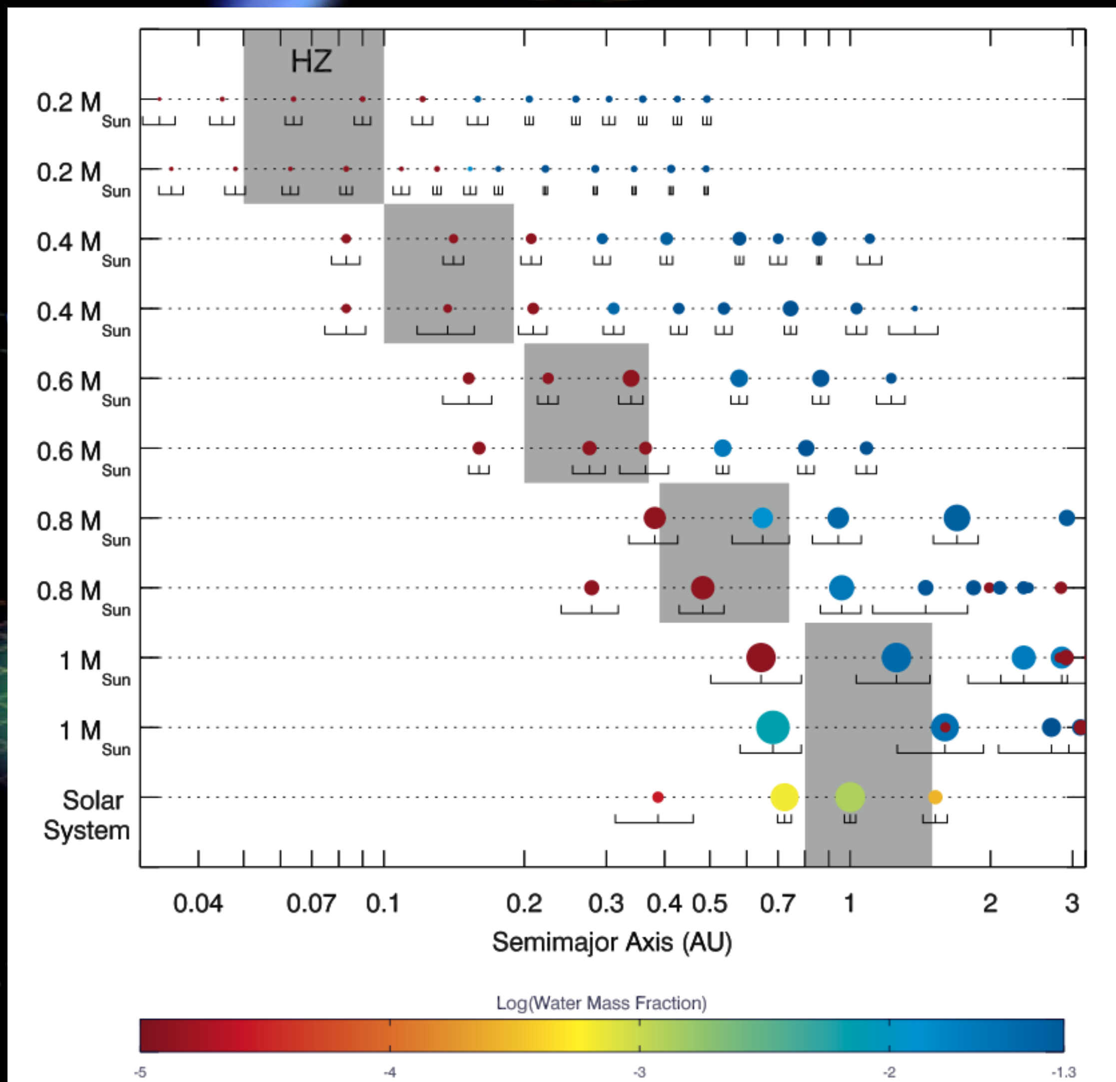
$M_{\star}$ (1)	Range (AU) (2)	Mass ($M_{\oplus}$) (3)	N (4)	Time Step (days) (5)	HZ (AU) (6)	Water Line (AU) (7)
1.0.........	0.5–4	4.95	75	6	0.8–1.5	2.5
0.8.........	0.25–2	1.98	75	2.5	0.39–0.74	1.23
0.6.........	0.12–1	0.75	100	1.0	0.20–0.37	0.61
0.4.........	0.06–1	0.53	130	0.4	0.10–0.19	0.32
0.2.........	0.03–0.5	0.13	190	0.2	0.05–0.1	0.16

0.6 M砿



0 Myr
0.1 Myr
1 Myr
10 Myr
30 Myr
200 Myr
HZ
Eccentricity
0.0
0.1
0.2
0.3
0.4
0.2
0.4
0.6
0.8
Semimajor Axis (AU)
Log(Water Mass Fraction)
-5
-4
-3
-2
-1.3

0.2 to 1 $M_{\odot}$

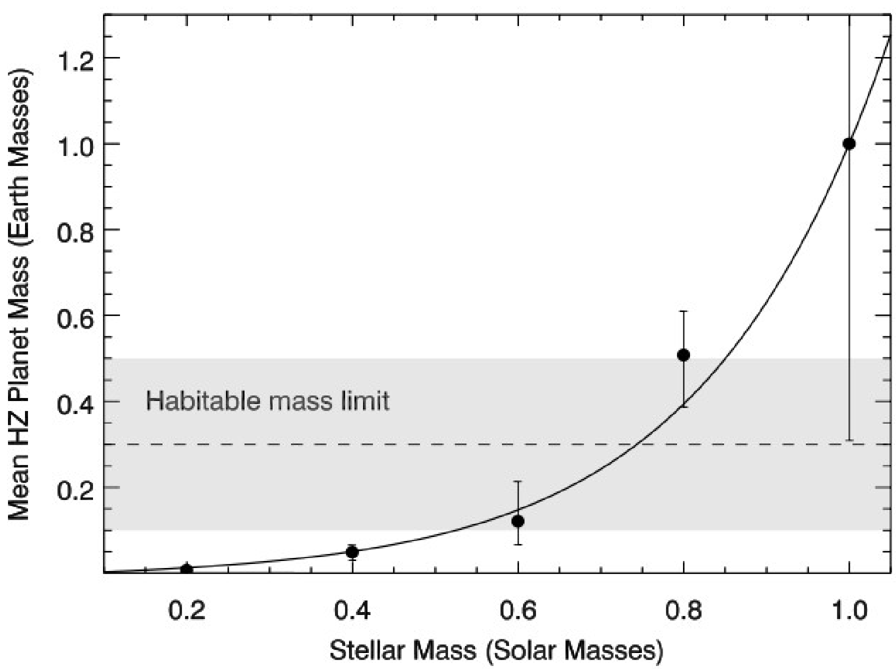


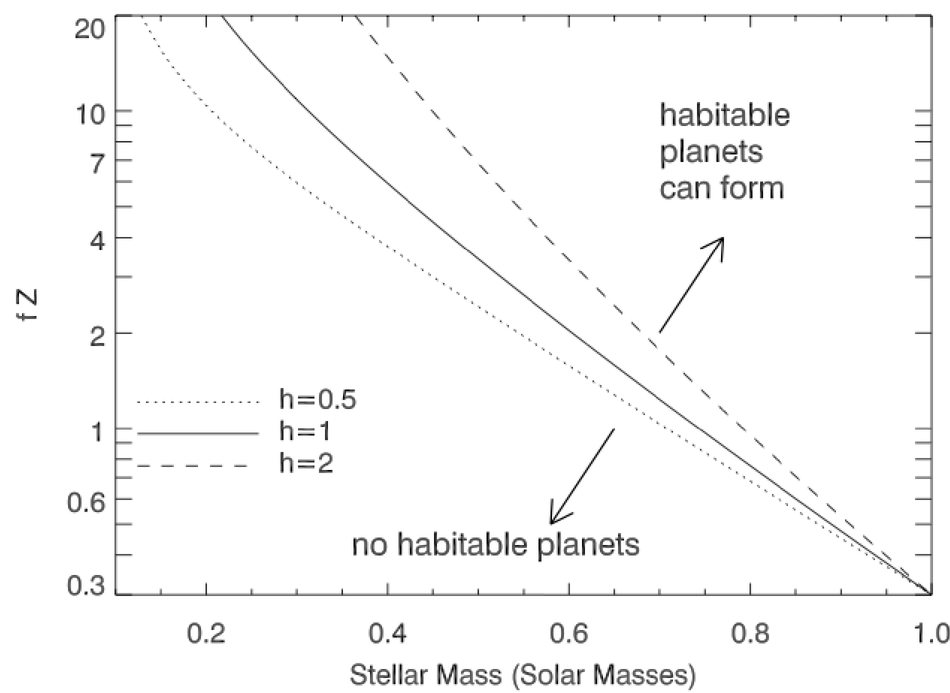
HZ
0.2 M Sun
0.2 M Sun
0.4 M Sun
0.4 M Sun
0.6 M Sun
0.6 M Sun
0.8 M Sun
0.8 M Sun
1 M Sun
1 M Sun
Solar System
0.04 0.07 0.1 0.2 0.3 0.4 0.5 0.7 1 2 3
Semimajor Axis (AU)
Log(Water Mass Fraction)
-5 -4 -3 -2 -1.3

Results

$$M_{\rm pl} \propto \frac{\Sigma_1 f Z M_\star^h}{2-\alpha}\left(r_{\rm HZ,out}^{2-\alpha} - r_{\rm HZ,in}^{2-\alpha}\right),$$

– Model calibrated so if fZ=1, a 1 $M_\oplus$ planet forms in HZ (around solar star)





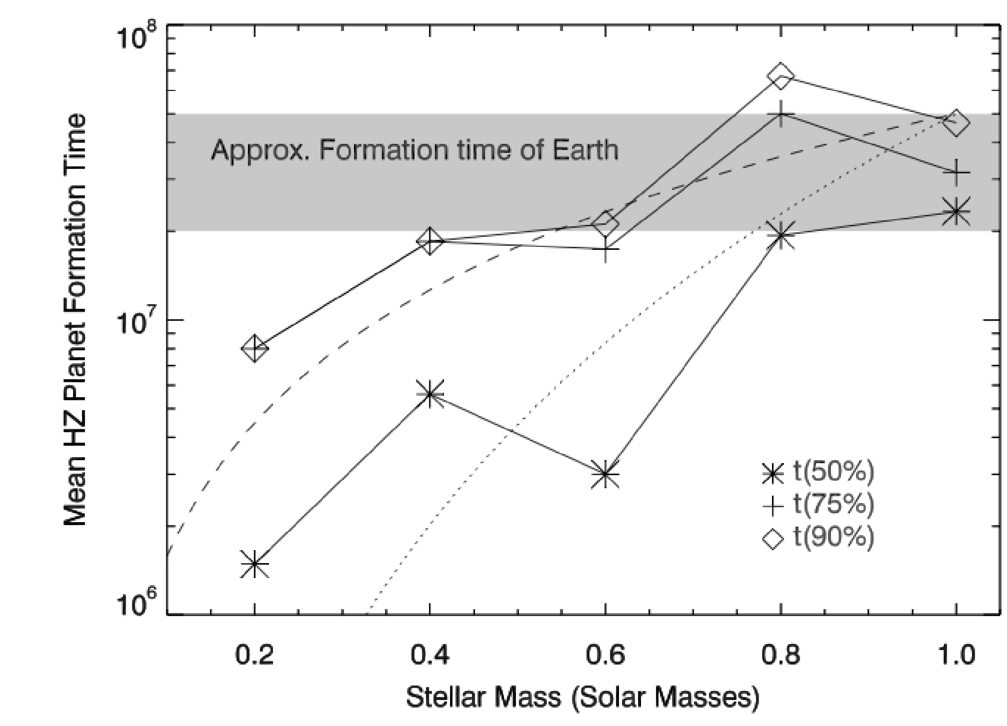
Minimum Stellar Mass

- This constrains a minimum stellar mass to produce large enough HZ planets
  - Remember no migration (or giant planets)
- To get a 0.3 $M_{\oplus}$ planet:
  - For fZ< 0.3 need 1 $M_{\odot}$
  - For fZ = 1 need 0.74 $M_{\odot}$
  - For fZ = 5 need 0.43 $M_{\odot}$

Timescales

- Time scales:
- $t_G \alpha (\Sigma_{HZ} v_{HZ})^{-1}$

  $\alpha M_*^{3/2}$



Water

- Of the 19 HZ planets around $M<0.6\ M_{砿}$
  - 1 had significant water
- Of the 10 HZ planets around 0.8 and 1 $M_{砿}$
  - 4 had significant water
- Insufficient dynamical stirring
  - Need more massive embryos to increase eccentricities

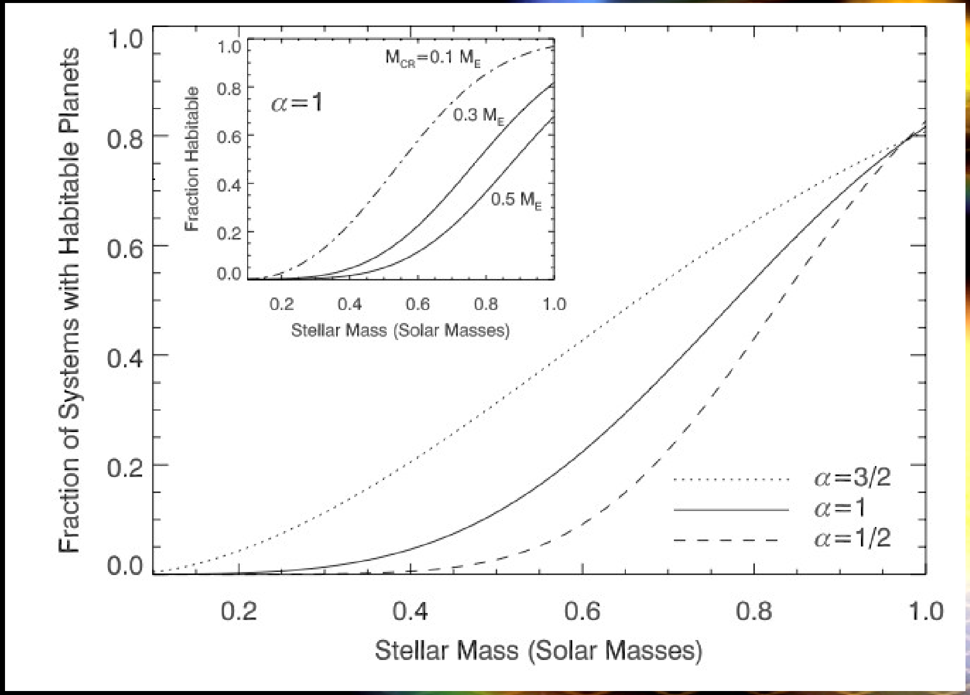
Improvements

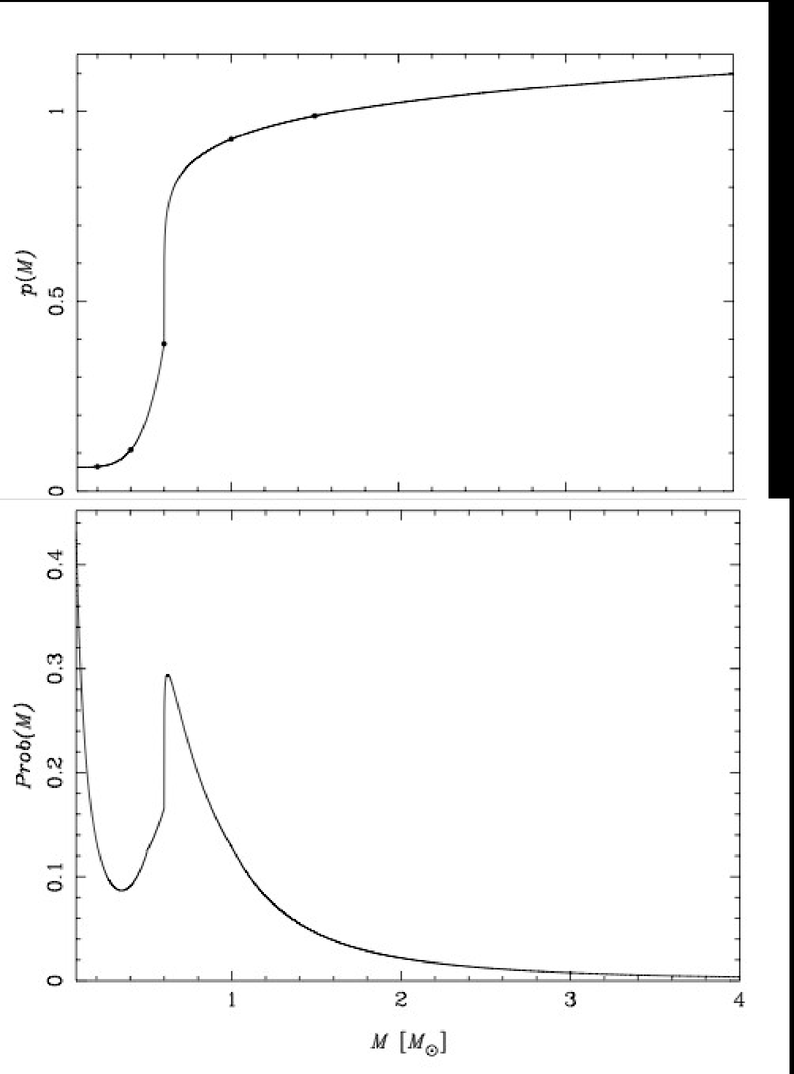
- Giant planets
  - Help stir up eccentricities
    - More massive, less numerous
- Ran a 0.6 $\mathrm{M}_{\text{砿}}$ model with a Jupiter and Neptune sized planet:
  - Increased mean HZ mass from 0.10 to 0.11 $\mathrm{M}_{\oplus}$
  - However 2/11 HZ planets were wet

Discussion

- How do you explain Gl581 with this data
  - 1) Large disk (fZ 30-50)
    - Formed in situ from larger disk
  - 2) Migration
    - Formed in dense outter disk

Probability of HZ planets

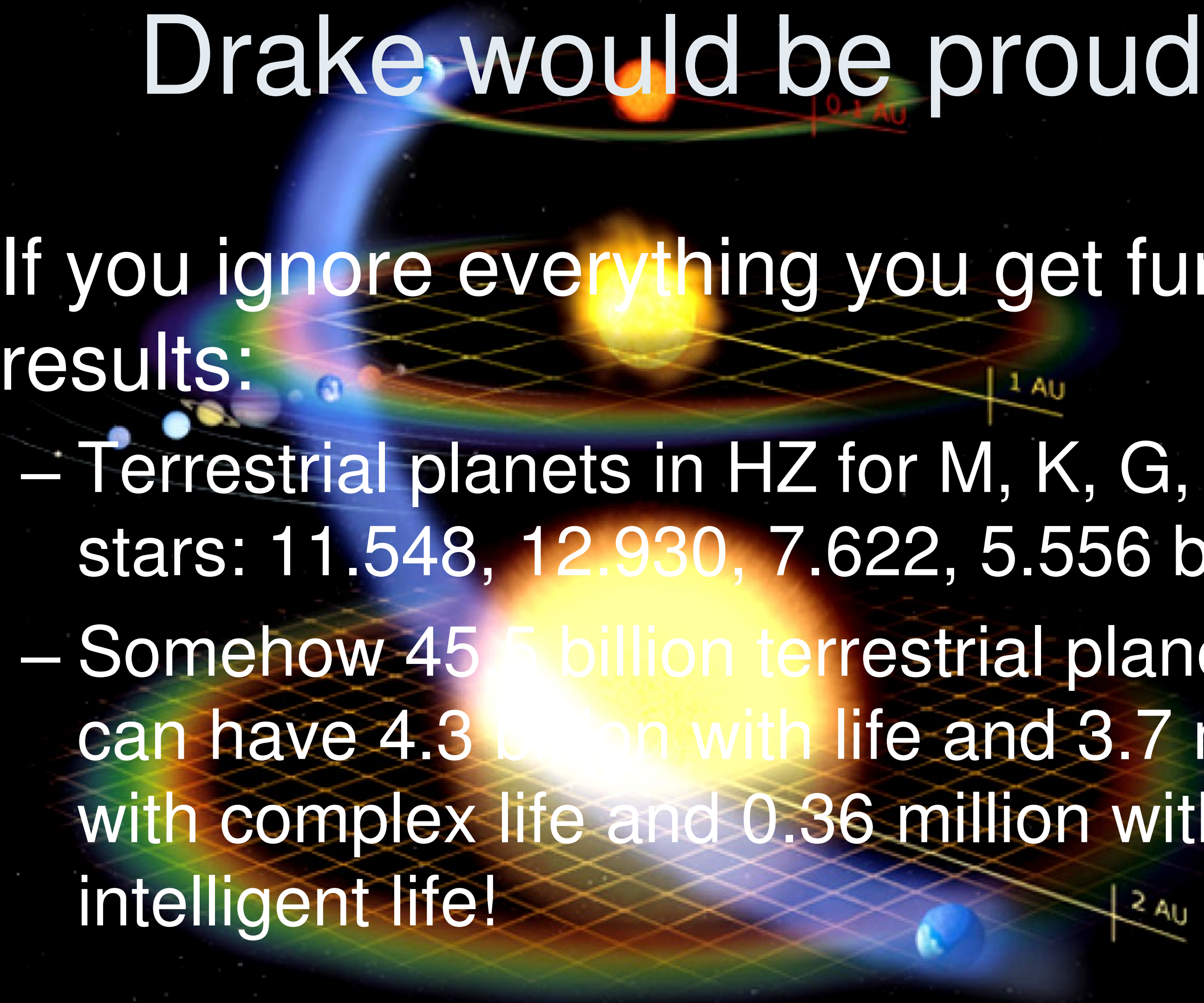




Raymond, Scalo & Meadows (2007)-above

Guo et al. 2009 - right

Drake would be proud



- If you ignore everything you get fun results:
  - Terrestrial planets in HZ for M, K, G, F stars: 11.548, 12.930, 7.622, 5.556 billion!
  - Somehow 45.5 billion terrestrial planets can have 4.3 billion with life and 3.7 million with complex life and 0.36 million with intelligent life!

Conclusions

- M stars may not prove best for habitable planets:
  - 1)Terrestrial planets ‘may’ be too small, unless migration is very prevalent
  - Long irradiative period:
    - M stars may have longer periods of initial activity to strip atmospheres
  - Tidal locking + Eccentricity can snowball
  - Many caveats - mostly hurtful to habitability