The evolution of galaxy habitability

(fun with galaxy evolution models)

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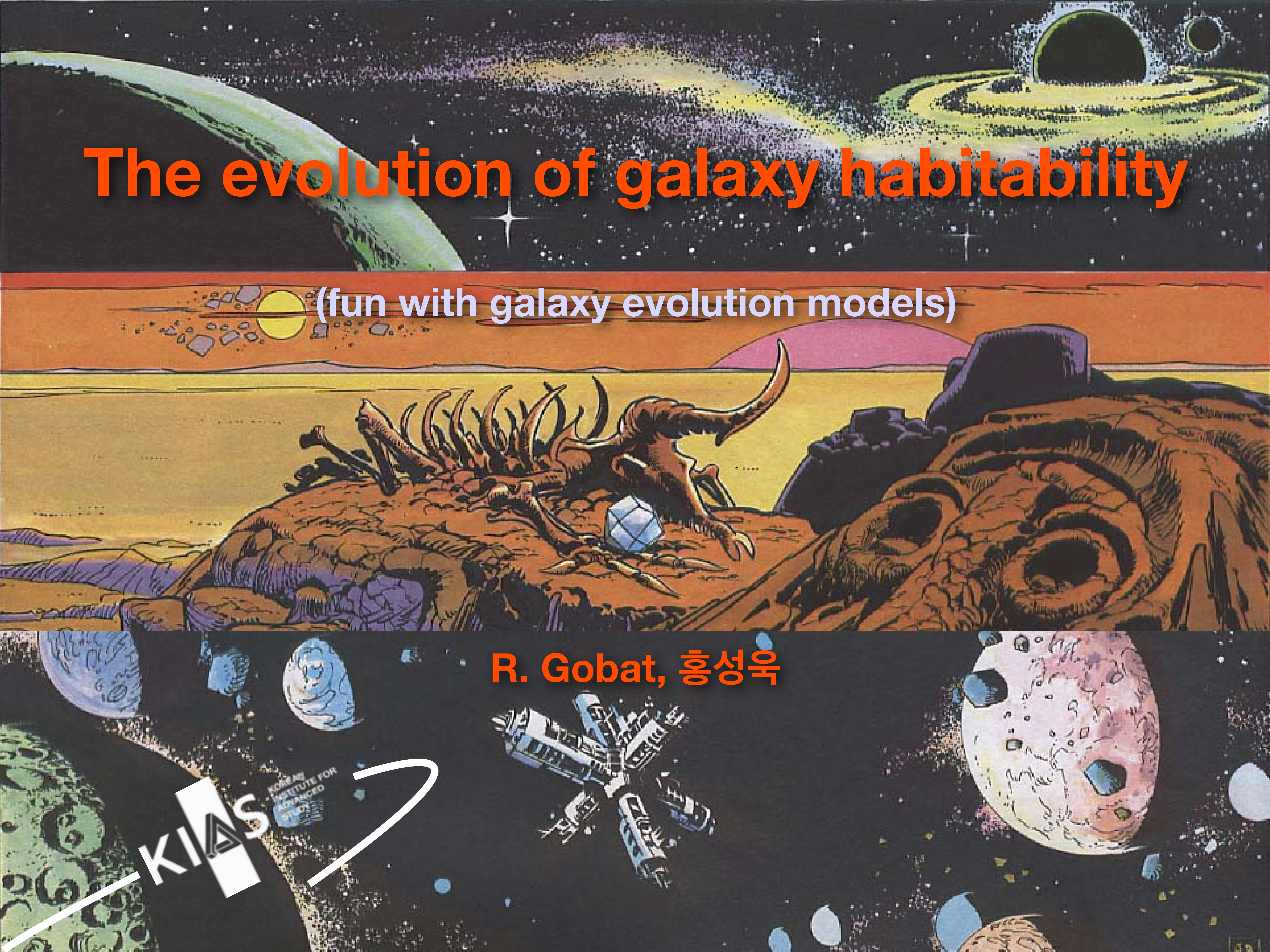
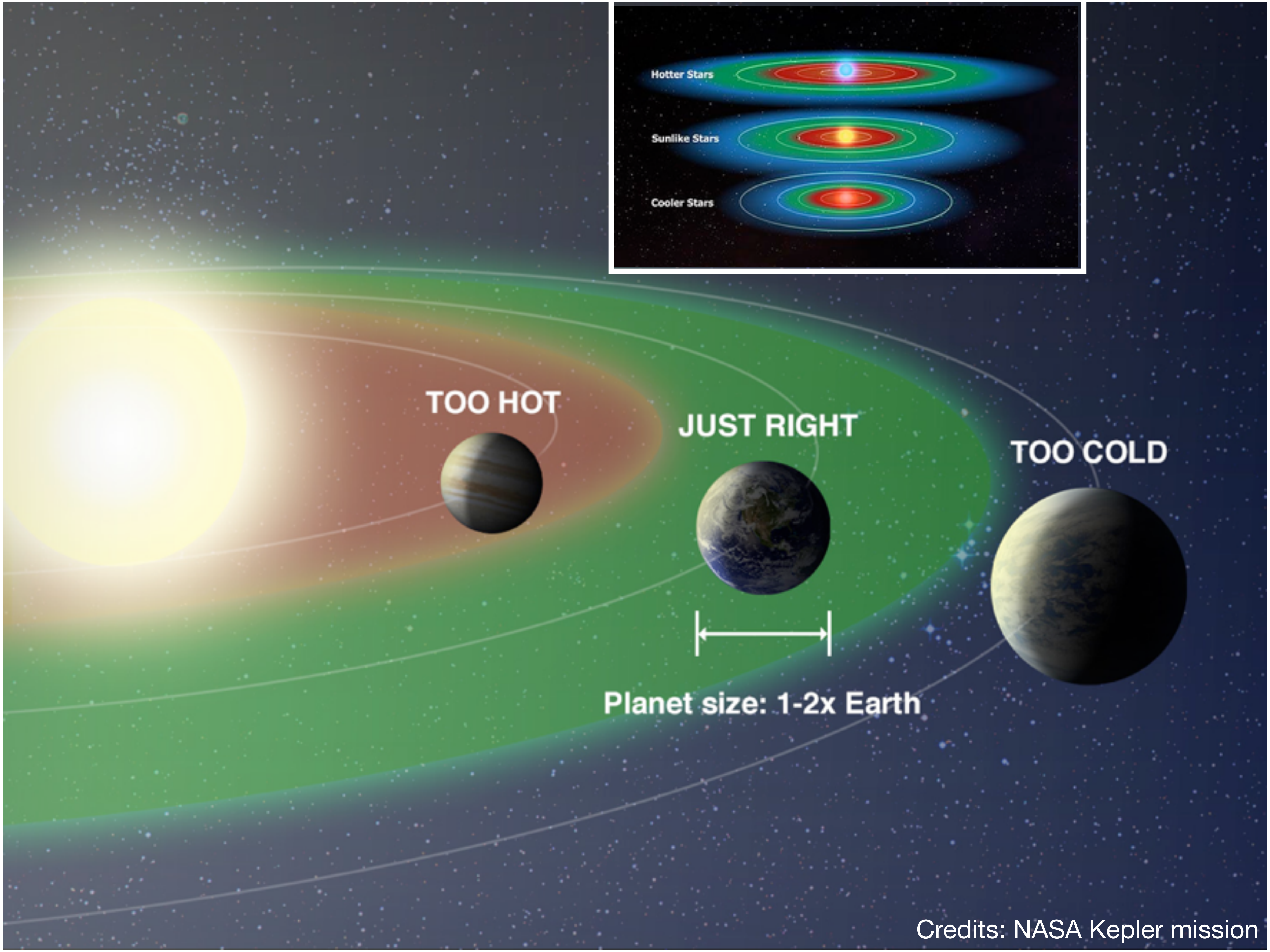
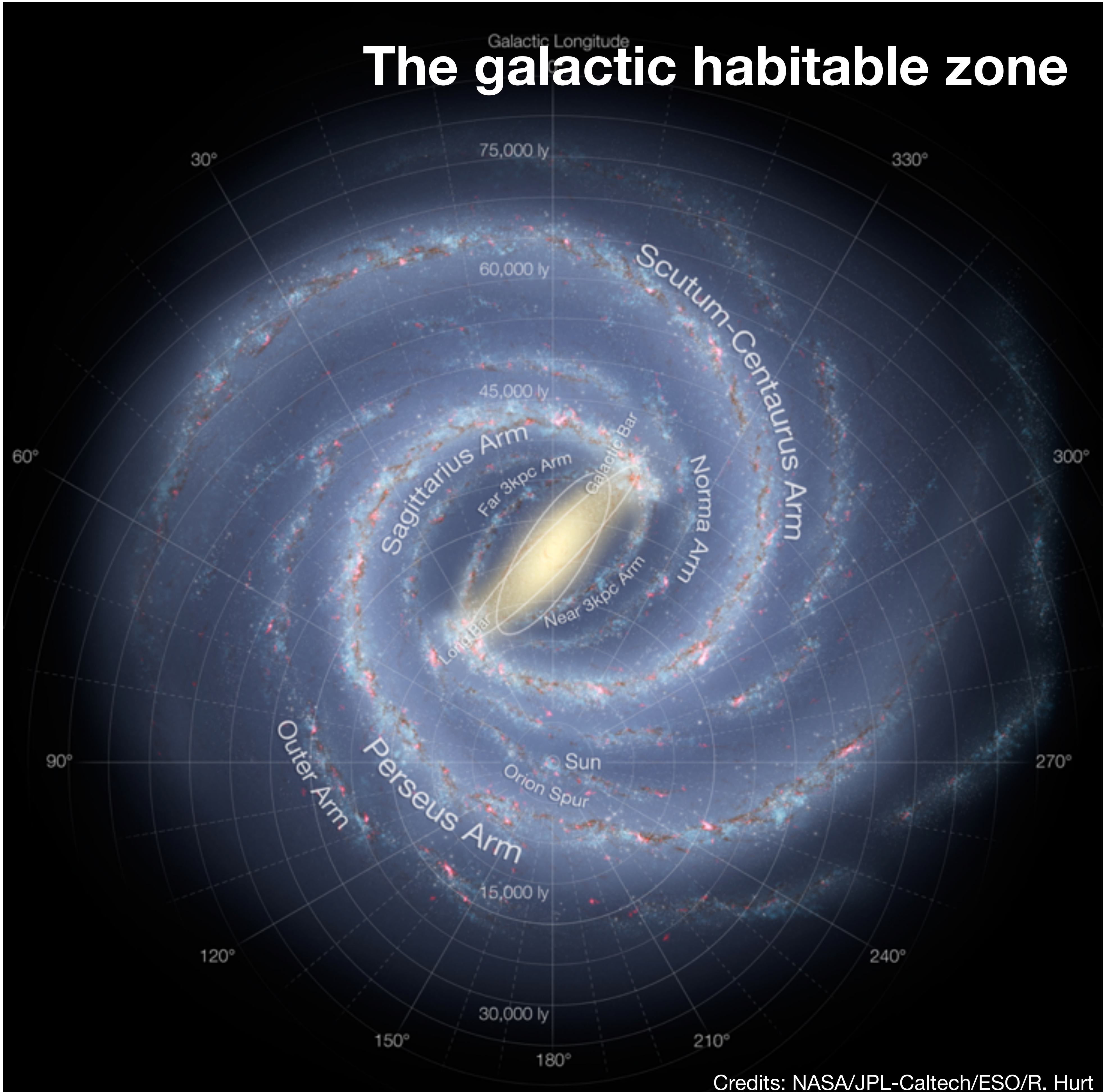


The circumstellar habitable zone

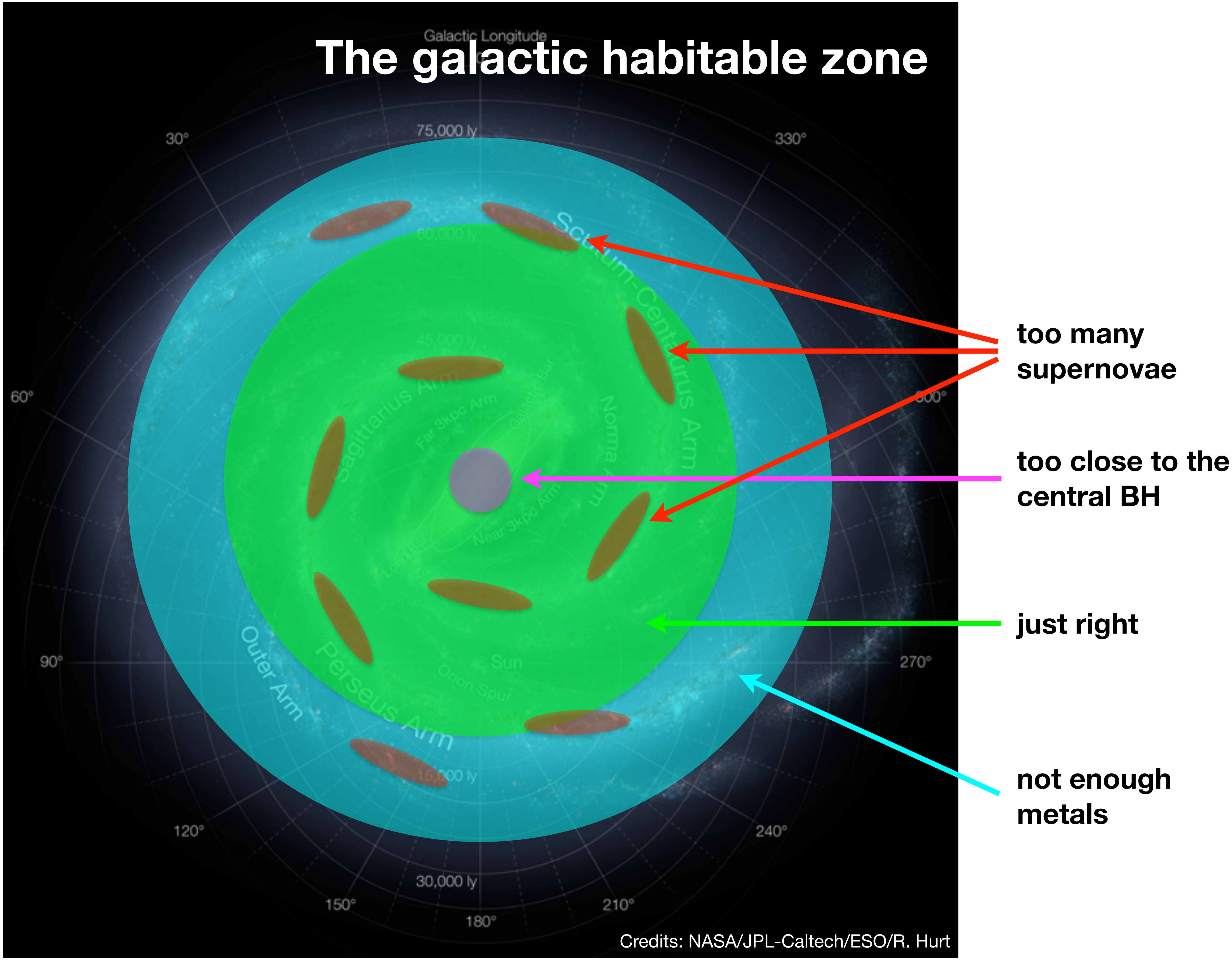


The galactic habitable zone

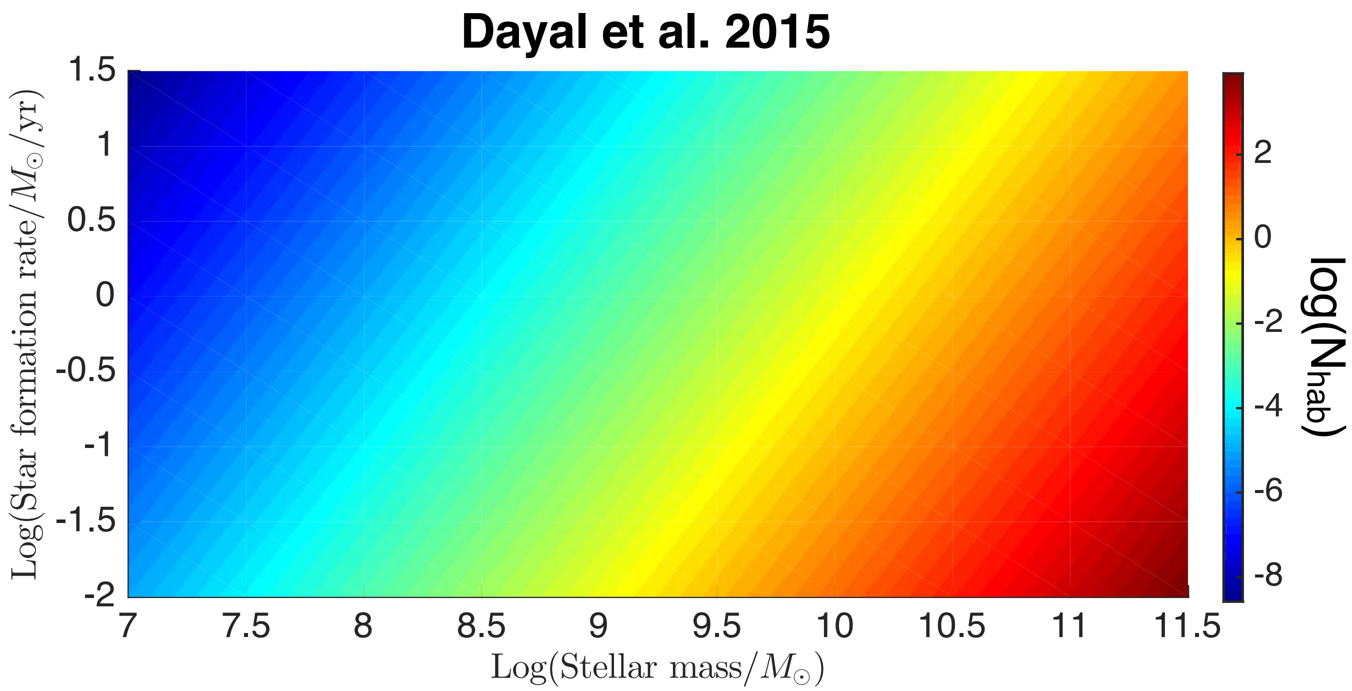


Credits: NASA/JPL-Caltech/ESO/R. Hurt

The galactic habitable zone

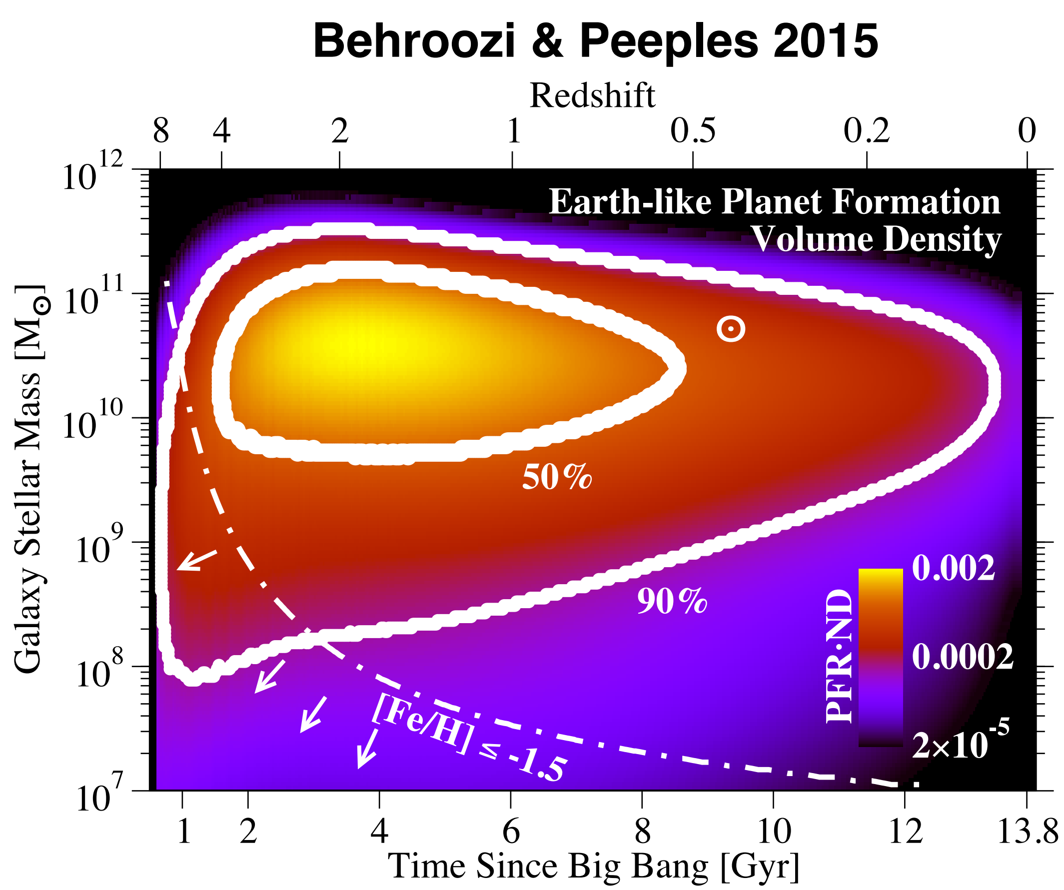


Extension to galaxy populations



N_{hab} increases with mass and decreases with SFR
(more stars, higher Z/Z⊙, less SN)

$$N_t \propto \frac{0.739 M_* Z_g^\alpha M_*/\rho}{(\psi/53.17)\times(4/3)\pi(Q\,\mathrm{pc})^3(28.6\,\mathrm{Myrs})}$$

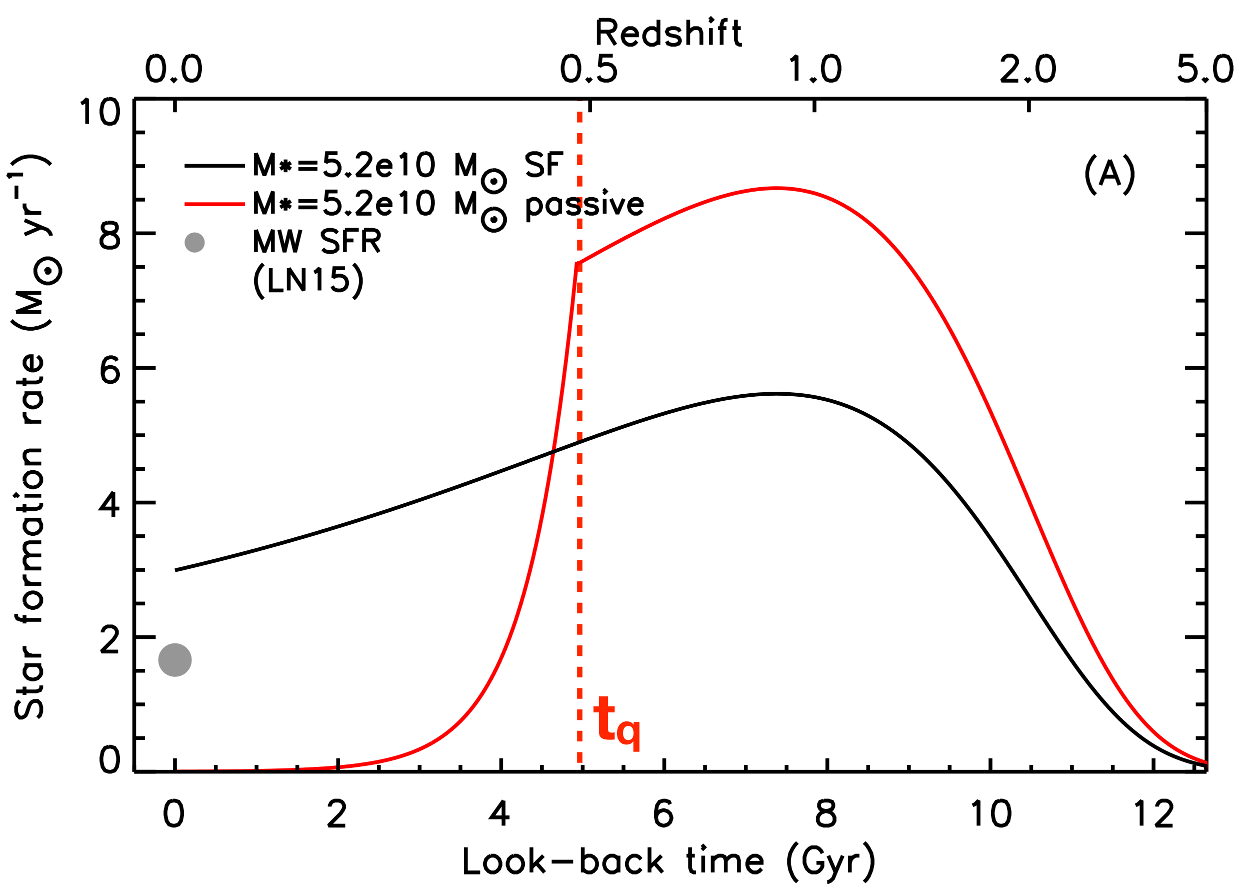


The comoving density of terrestrial planets only goes up with time

$$\mathrm{PFR}(M_*,t) = n\frac{(Z(M_*,t)/Z_\odot)^\alpha}{\langle m_*\rangle}\mathrm{SFR}(M_*,t)$$

Ingredients: star formation histories and GMF

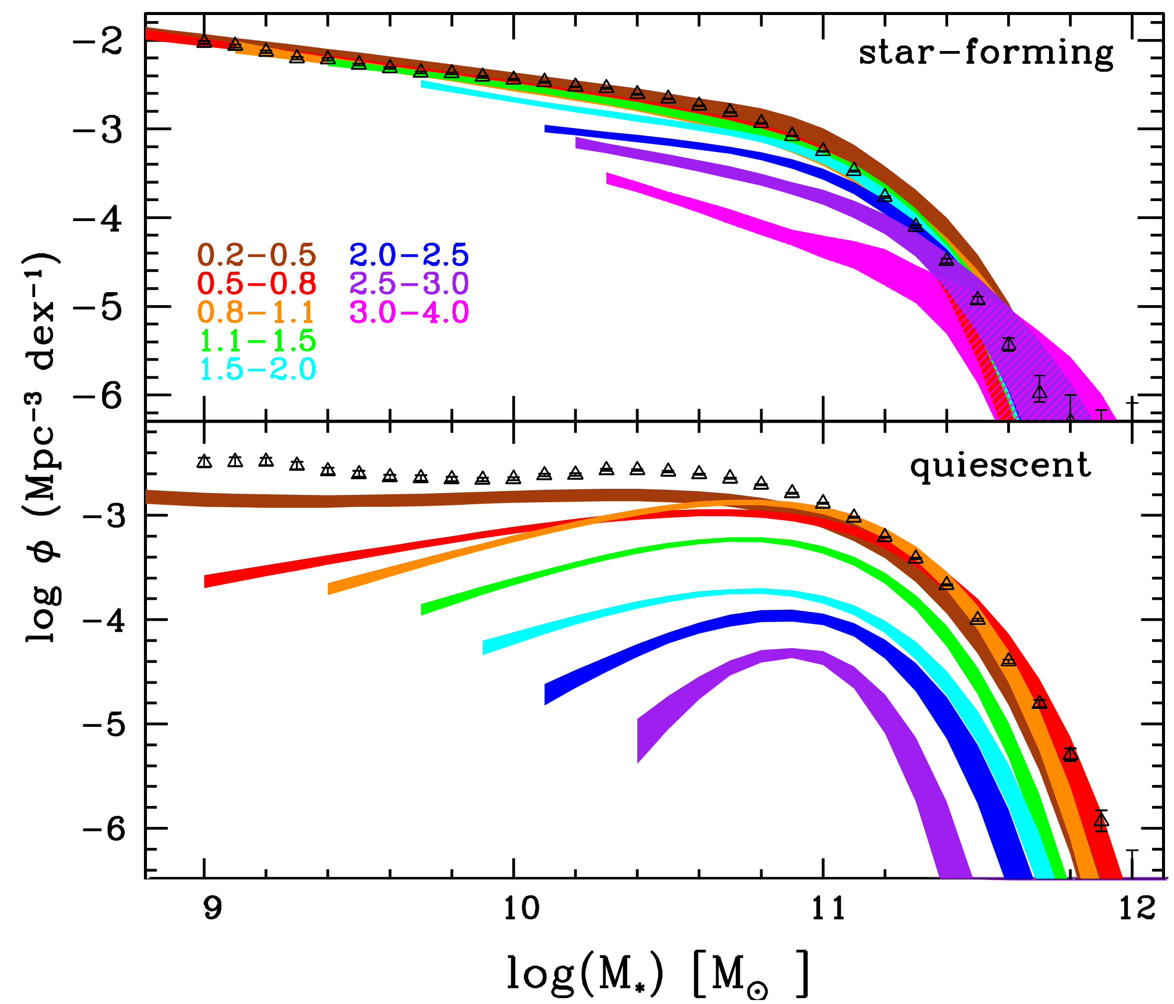
Main sequence SFH



$$\Psi(z) = \mathrm{sSFR}_{\mathrm{MS},0} M_*(z) \left(\frac{M_*(z)}{10^{11}\mathrm{M}_\odot} \right)^{\alpha_{\mathrm{MS}}-1} (1+\min(z, z_{\mathrm{MS}}))^{\gamma_{\mathrm{MS}}}$$

Observed galaxy mass functions

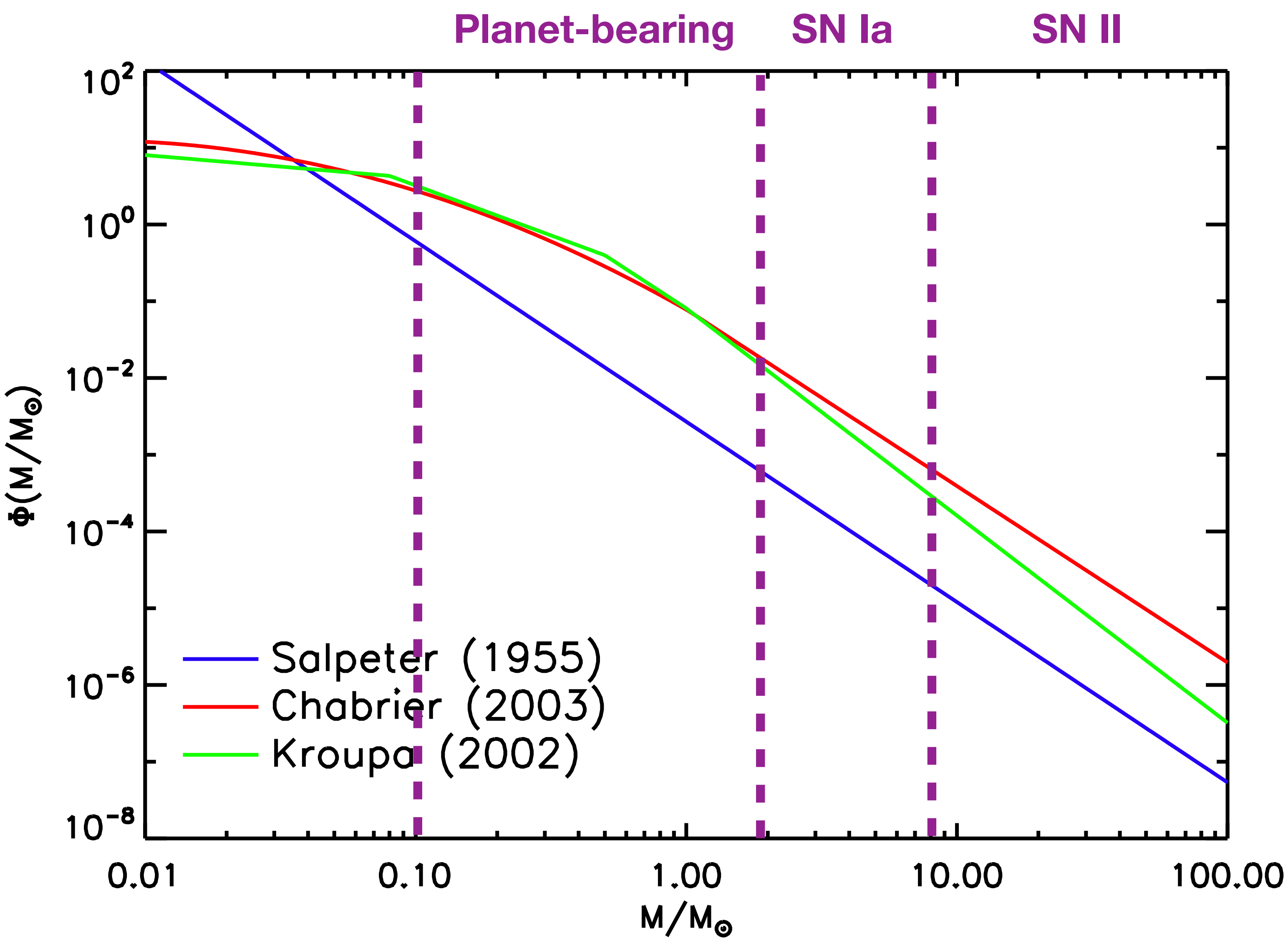
Ilbert+ 2013



$$x(M_*, z_j) = \frac{\sum_{i=j}^{z_i \le z_{\max}} w_{i,j} x(M_*, z_i)}{\sum_i w_{i,j}}$$

$$w_{i,j} = \frac{\Phi(M_*, z_i) - \Phi(M_*, z_{i-j})}{\Phi(M_*, z_j)}$$

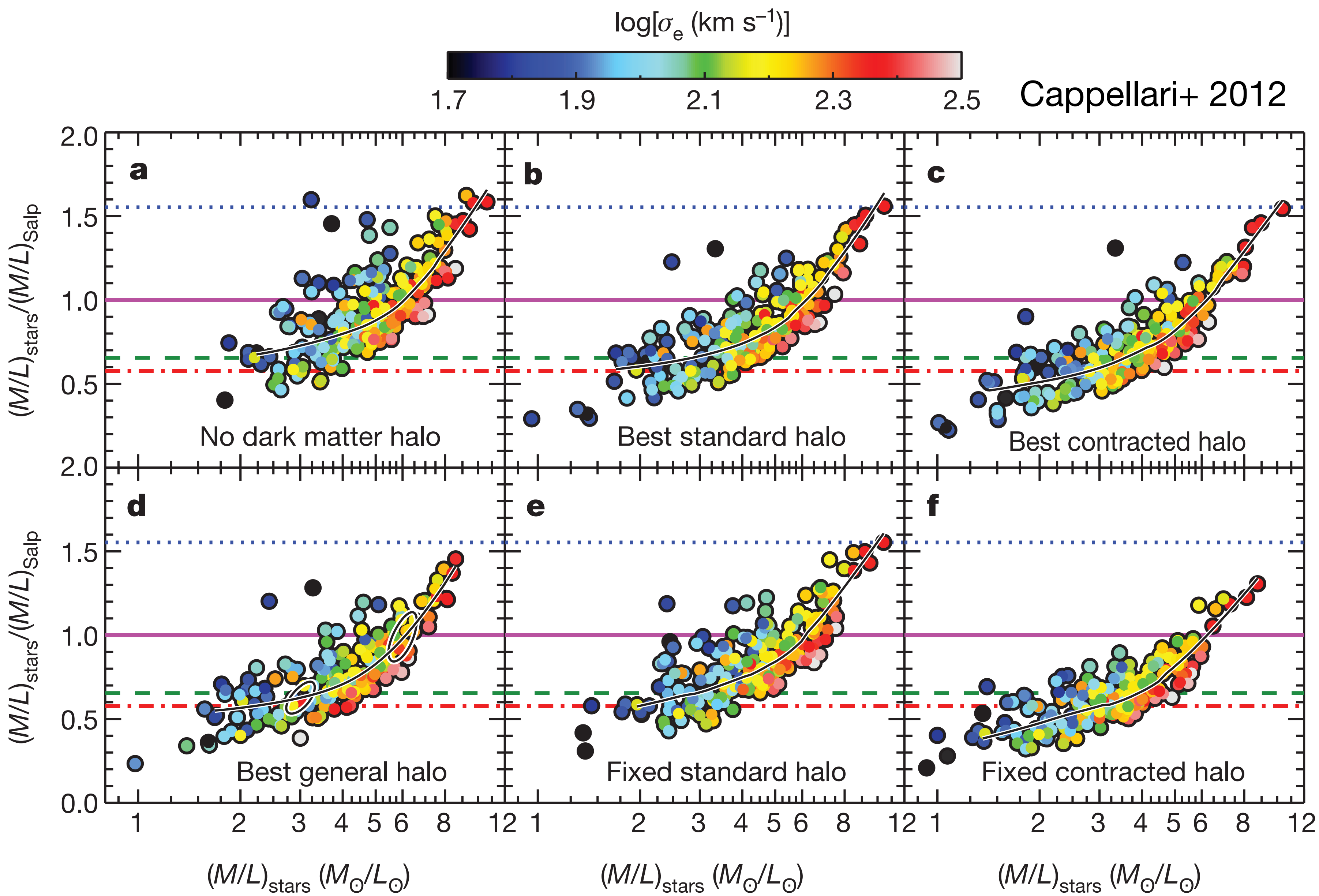
Ingredients: the stellar initial mass function (IMF)



⇒ M/L, SFR, SN rates, metallicity, etc

Ingredients: the stellar initial mass function (IMF)

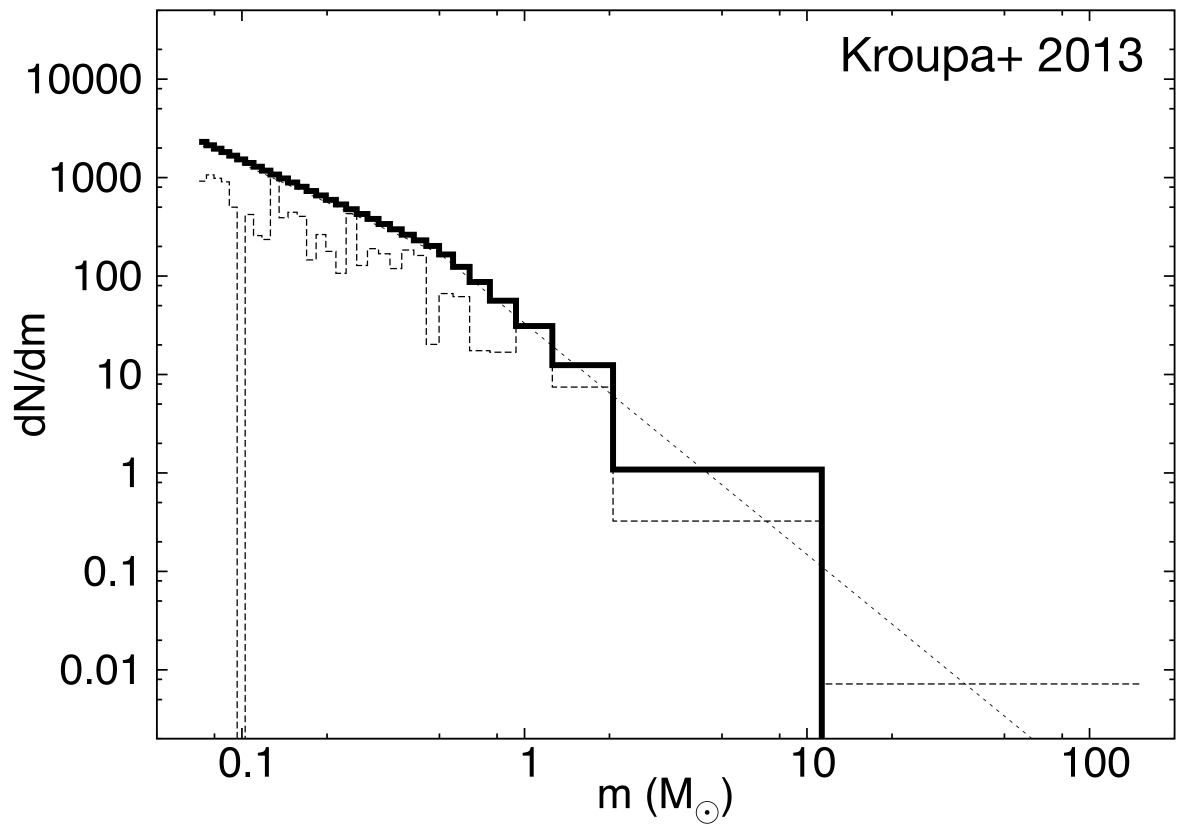
But there is evidence that the IMF varies



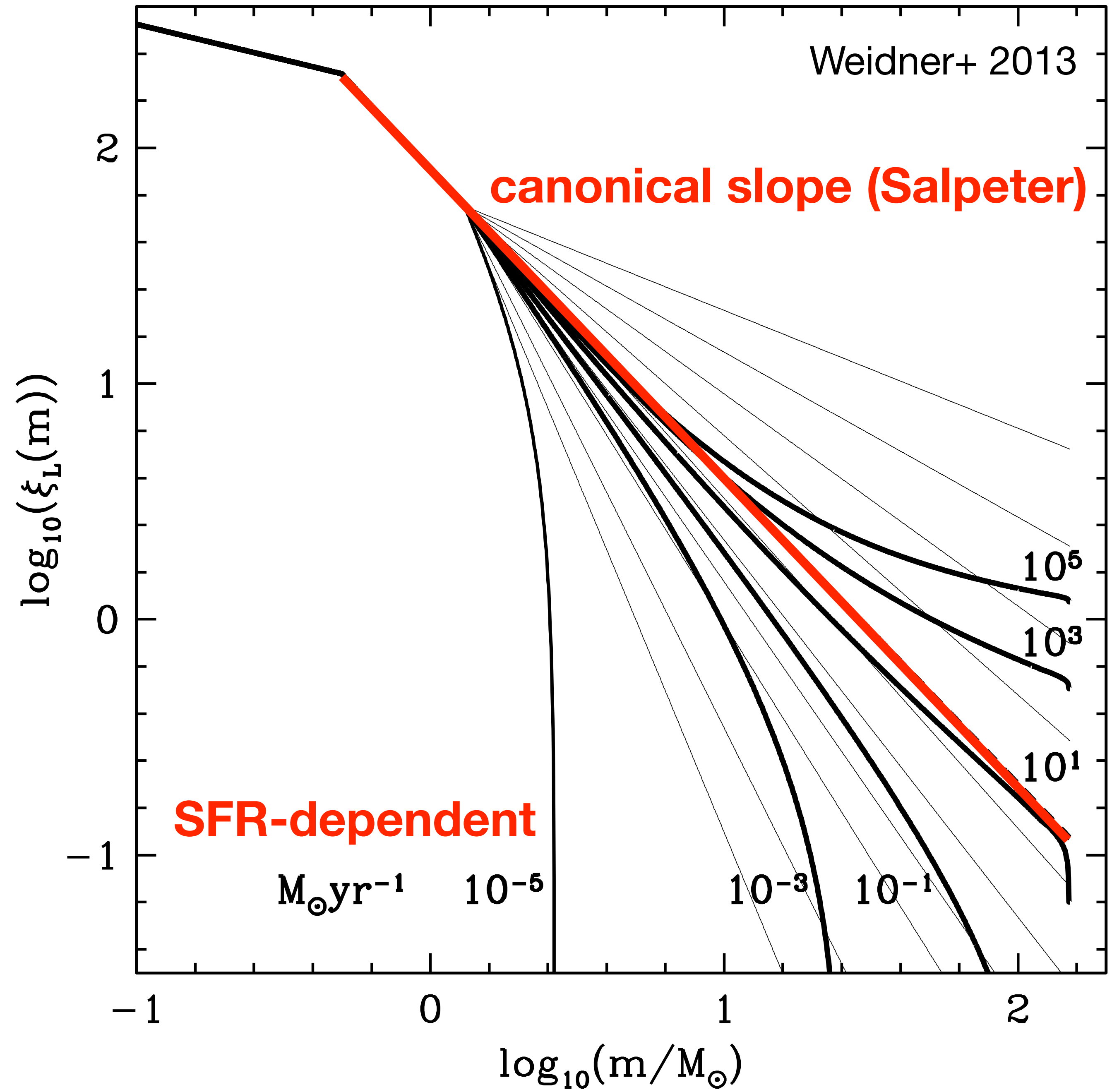
Cappellari+ 2012

Ingredients: integrated galactic IMF (IGIMF)

IMF of a single star cluster



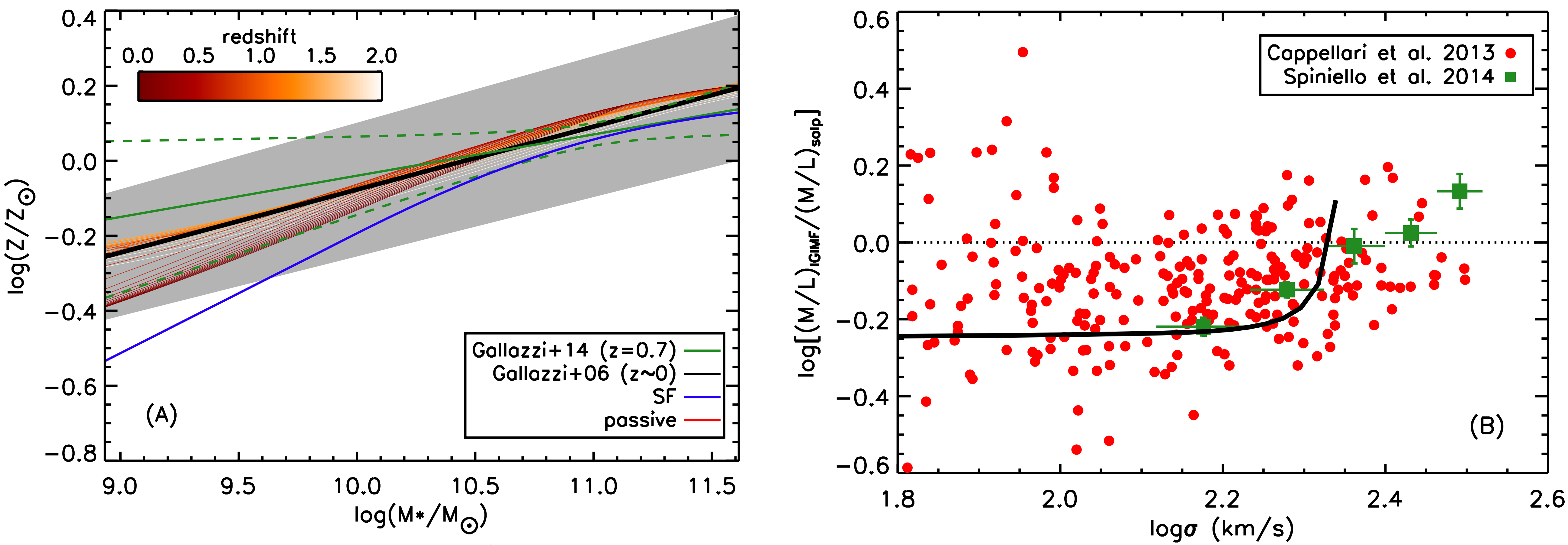
IMF of a whole galaxy



$$\xi_{\rm ecl}(M_{\rm ecl}) \propto M_{\rm ecl}^{-\beta}$$ (star cluster MF)

$$\xi_{\rm IGIMF}(m,t) = \int_{M_{\rm ecl,min}}^{M_{\rm ecl,max}(\mathrm{SFR}(t))} \xi(m \le m_{\rm max}(M_{\rm ecl}))\xi_{ecl}(M_{\rm ecl})\mathrm{d}M_{\rm ecl}$$

Ingredients: quenching and metal enrichment



$$M_g(t > t_g) = M_g(t_q) - \int_{t_q}^{t} \Psi(t')dt$$ **gas mass**

$$\Psi(t > t_g) = \varepsilon(t - \Delta t) M_g(t - \Delta t)$$ **SFR**

$$Z_g(t > t_g) = Z_g(t_g) - y \ln\left(\frac{M_g(t)}{M_g(t_q)}\right)$$ **gas metallicity**

$$\log \varepsilon(t) = (1-\beta_2)\log\Psi(t) - \alpha_2$$ **SFE**

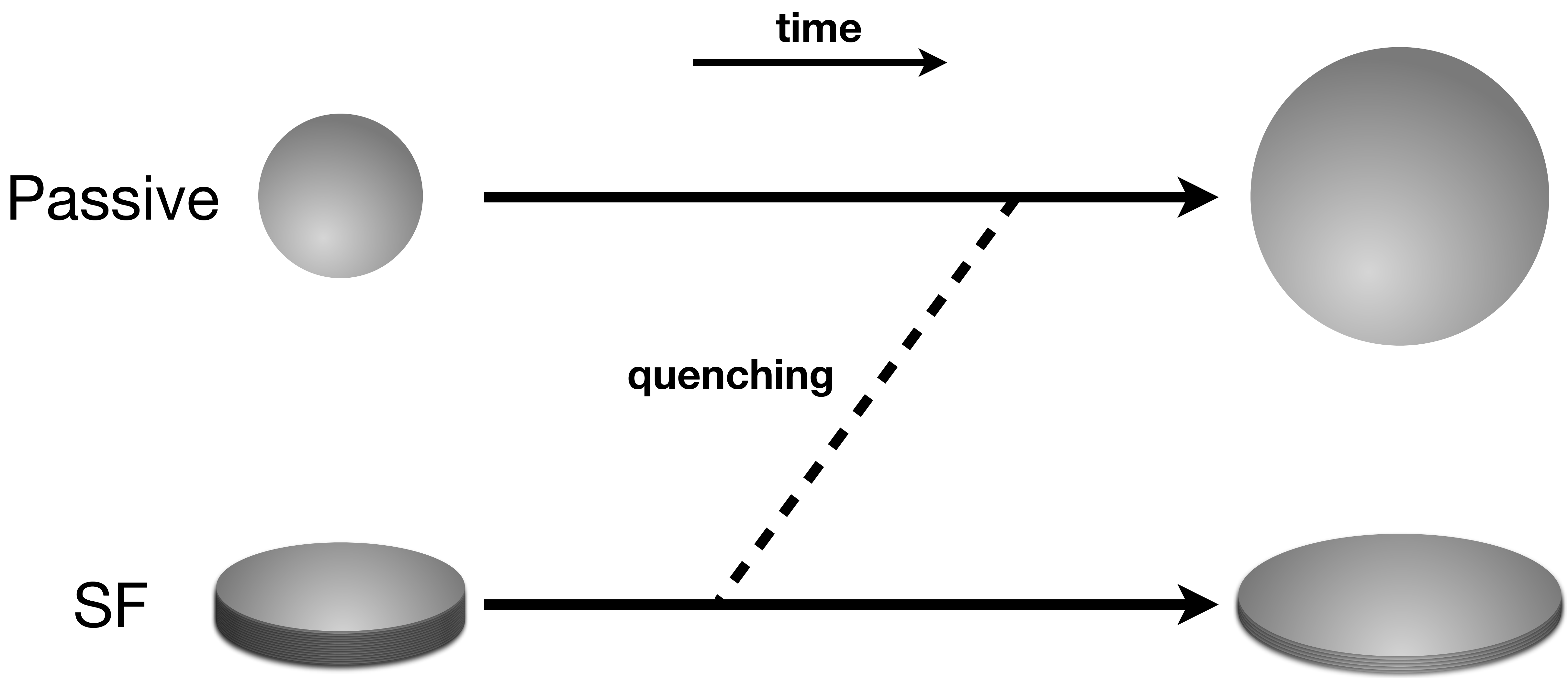
$$\log M_g(t_q) = \alpha_2 + \beta_2 \log\Psi(t_q)$$

} **2-SFM framework**

Closed box + IGIMF recovers observed mass-to-light ratios

Ingredients: morphological evolution

(e.g., van der Wel+ 2014)



transition to thin disk after peak SF (Lehnert+ 2014)

Ingredients: supernovae

$$\mathrm{SNR}_{\mathrm{II}}(t) = \Psi(t)\int_{8}^{m_{\max}} m\phi(m,t)\,\mathrm{d}m$$ **SNII rate**

$$\mathrm{SNR}_{\mathrm{Ia}}(t) = \eta_{\mathrm{WD}}\int_{m_{\min}}^{8} m\int_{\tau_{\mathrm{Ia}}+t_{\mathrm{MS}}(8)}^{t} \Psi(t')\phi(m,t')\,\mathrm{d}t'\,\mathrm{d}m$$ **SNIa rate**

$$V_{irr}(t) = \mathrm{H}(t_{\mathrm{rec}} - t)\begin{cases} \mathrm{SNR}_{\mathrm{Ia}}(t)\dfrac{r_{\mathrm{Ia}}^{3}}{r_e^{3}(t)} & \mathbf{P} \\[2ex] \dfrac{4}{3h_{\mathrm{d}}(t)r_e^{3}(t)}\left(\mathrm{SNR}_{\mathrm{II}}(t)r_{\mathrm{II}}^{3} + \mathrm{SNR}_{\mathrm{Ia}}(t)r_{\mathrm{Ia}}^{3}\right) & \mathbf{SF} \end{cases}$$

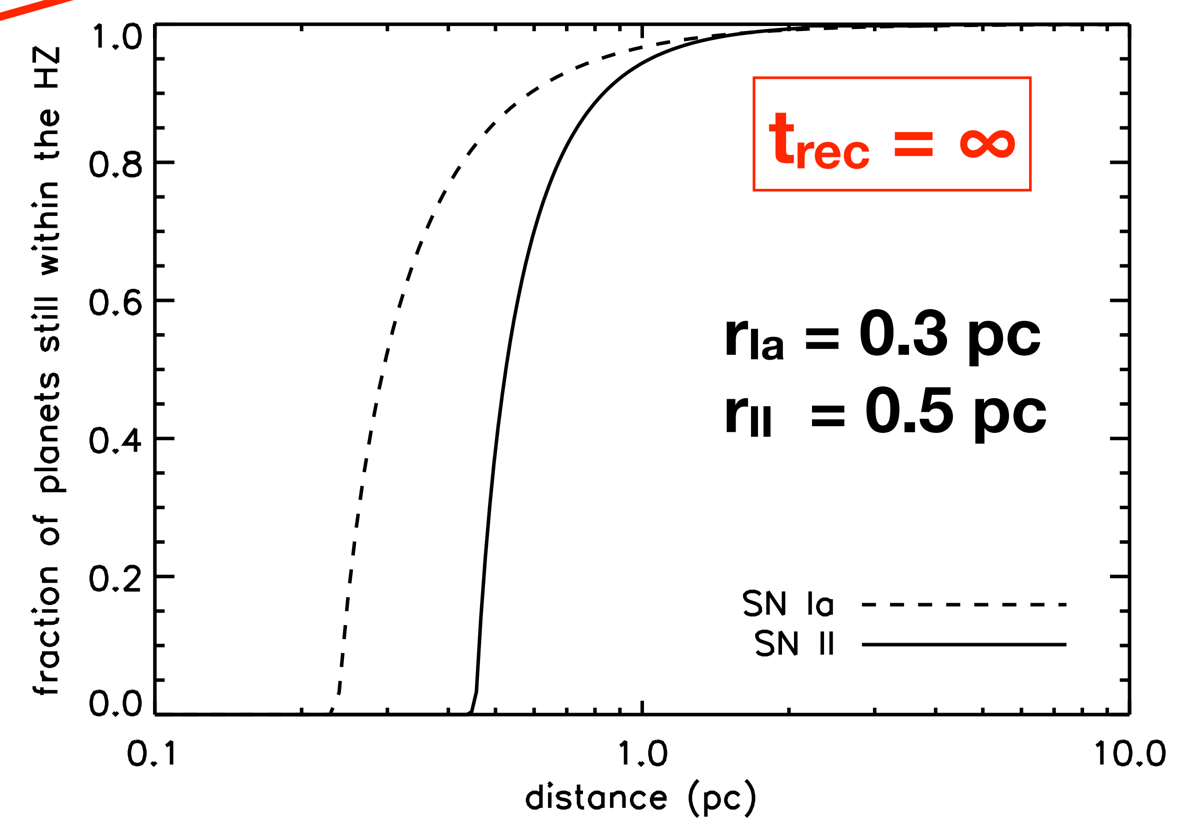
Irradiated volume

recovery time

disk scale height

effective radius

lethal radii



Ingredients: planetary distribution function

$$f_{\mathrm{Terrestrial}}(Z) = \begin{cases} 0.4\times(Z/Z_\odot)^\alpha & \textbf{case 1} \\ 0.4-0.03\times(Z/Z_\odot)^\alpha & \textbf{case 2} \end{cases}$$

+ Cutoff at $0.1\times Z_\odot$ (e.g., Johnson & Li 15)

+ Habitable zone (Kopparapu+13)

+ main sequence stars with ≥1 Gyr (late heavy bombardment, etc.)

+ Orbital period distribution $T^{-\beta}$, $\beta = 0.74$ (e.g.; Cumming+08, Bonavita+12)

+ stellar evolution prescription (Hurley, Pols & Tout 2000)

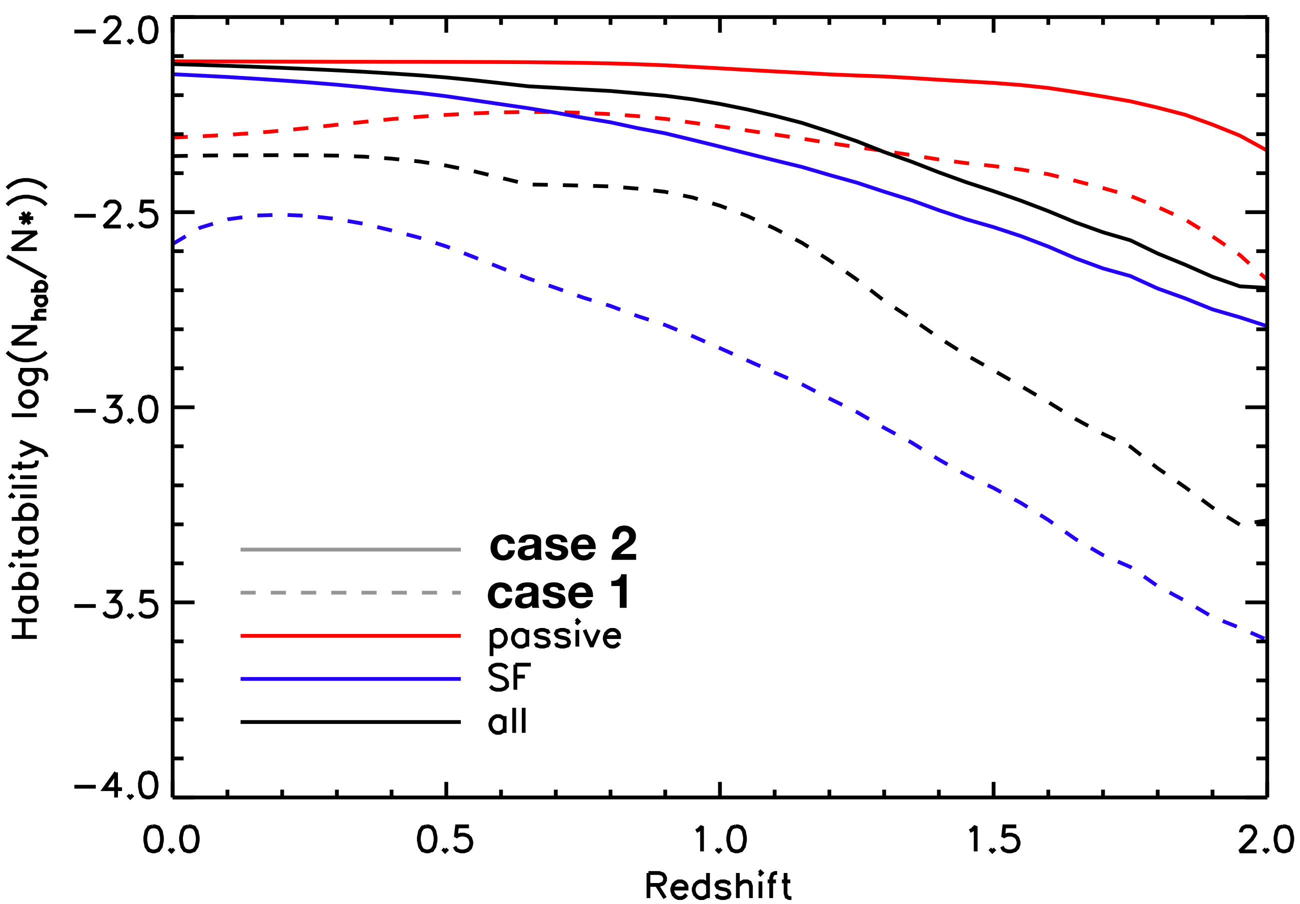
edges of the HZ

$$w_{\mathrm{h}}(m,Z,t) \propto f_{\mathrm{T}}(Z)\,\mathrm{H}(1.5-m)\int_{r_{h,i}(m,Z,t)}^{r_{h,o}(m,Z,t)} P(r,m)^{\beta_{\mathrm{P}}}\frac{\mathrm{d}P}{\mathrm{d}r}\,\mathrm{d}r$$

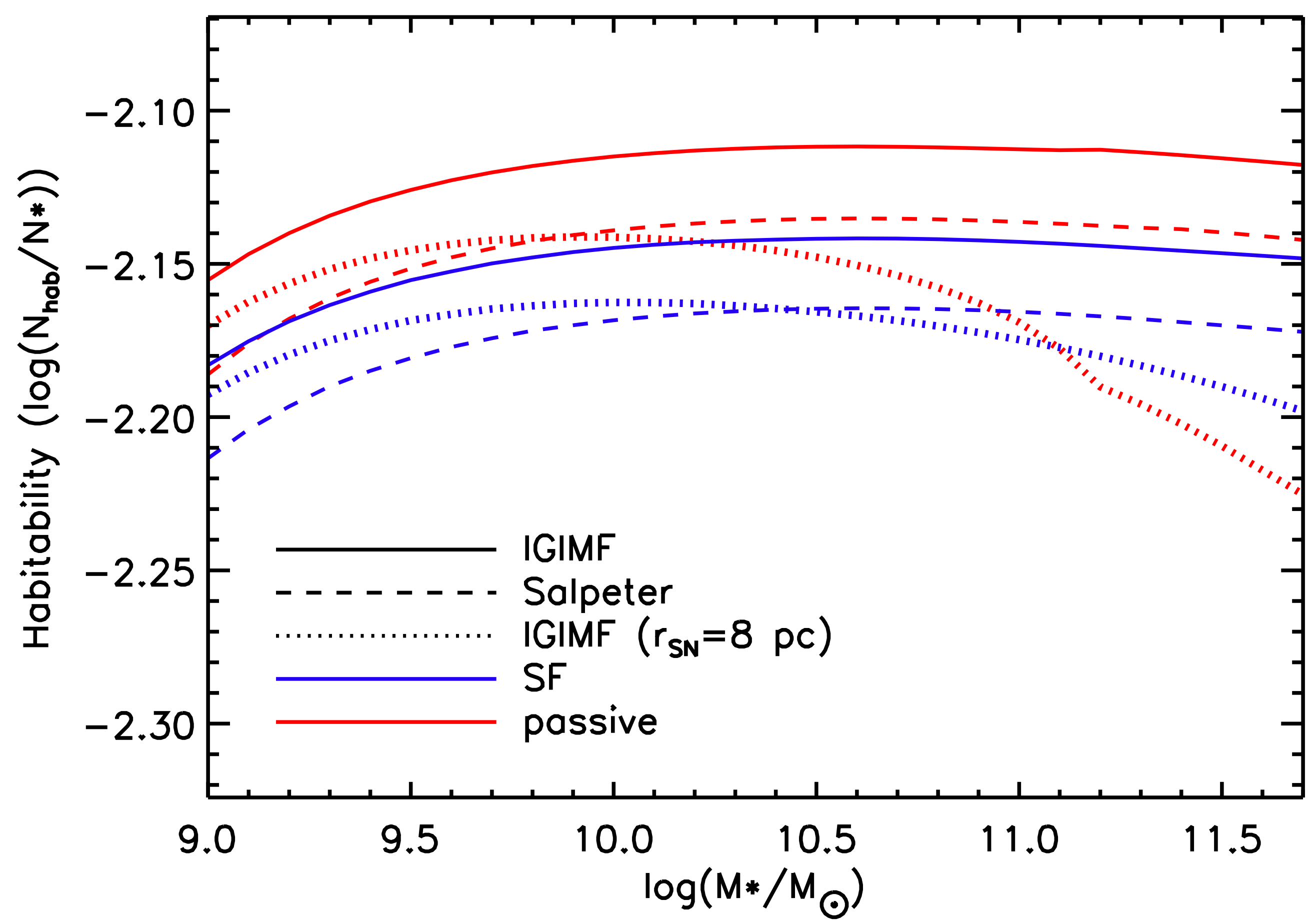
Galaxy habitability

$$h = \frac{\int_0^{t_z - t_{\min}} (1 - V_{irr}(t))\Psi(t) \int_{m_{\min}}^{1.5} m\phi(m,t)\mathrm{H}(t_{\mathrm{MS}}(m) - t) w_{\mathrm{h}}\, \mathrm{d}m\, \mathrm{d}t}{\int_0^{t_z} \Psi(t) \int_{m_{\min}}^{m_{\max}} m\phi(m,t)\mathrm{H}\left(t_{\mathrm{MS}}(m) - t\right) \mathrm{d}m\, \mathrm{d}t}$$

Evolution with redshift



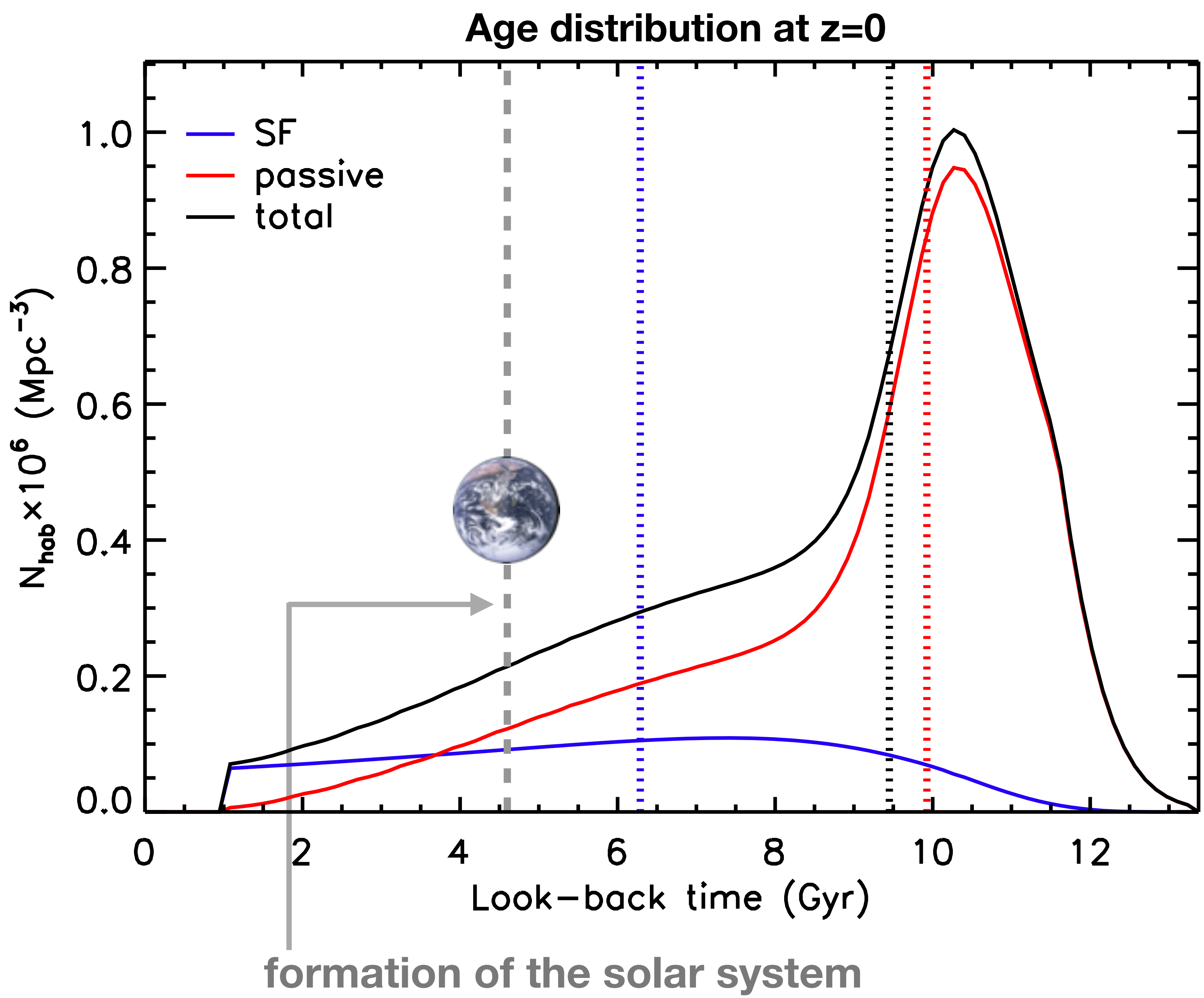
As a function of mass at z=0



- total: plateau since z~1
- SF: leveling off at z~0.5

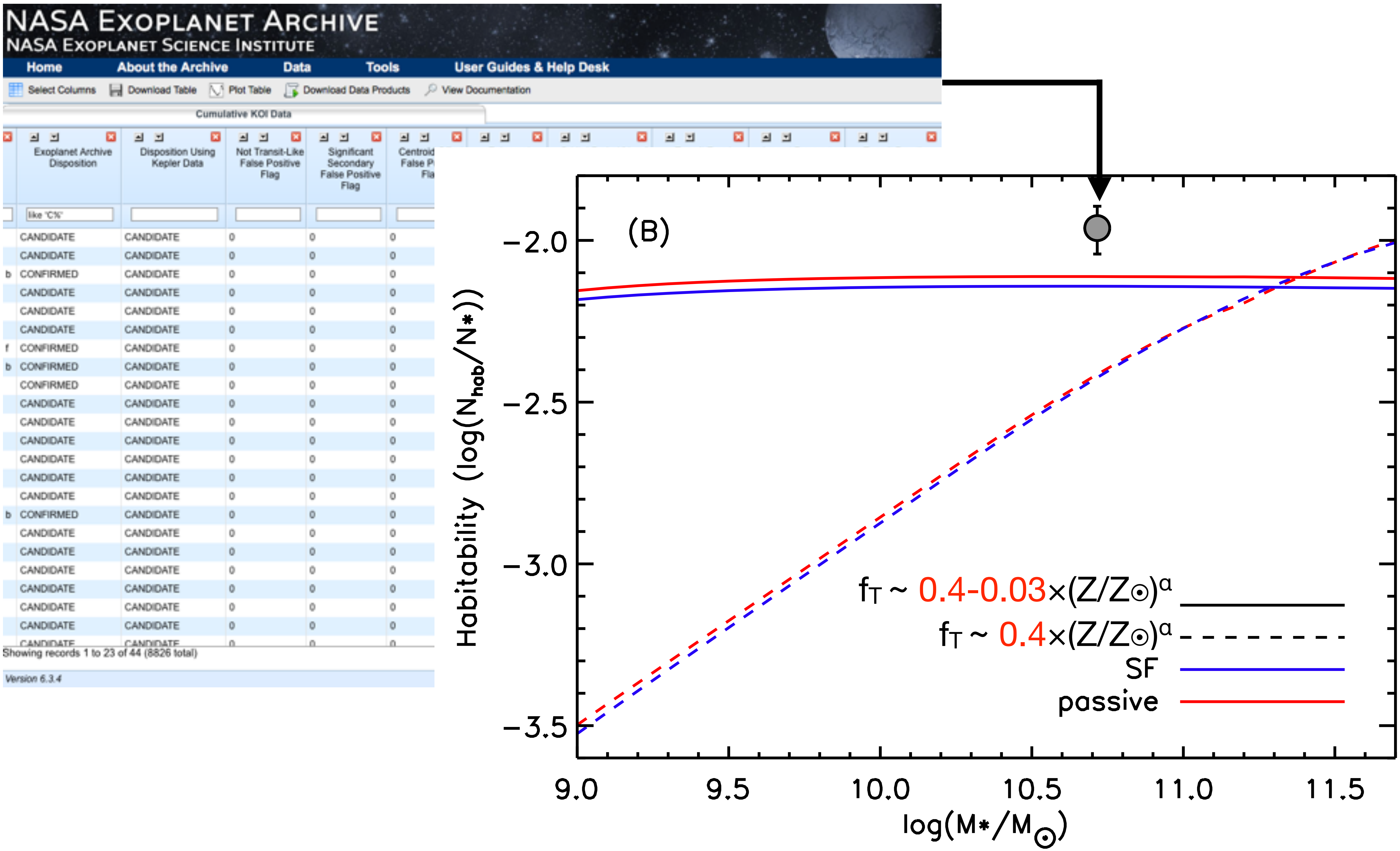
- maximum at ~$4{\times}10^{10}$ M⊙
- effect of SN negligible

Ages of habitable planets



Comparison with observations

http://exoplanetarchive.ipac.caltech.edu



	Exoplanet Archive Disposition	Disposition Using Kepler Data	Not Transit-Like False Positive Flag	Significant Secondary False Positive Flag	Centroid False P... Fla...
	like 'C%'				
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
b	CONFIRMED	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
f	CONFIRMED	CANDIDATE	0	0	0
b	CONFIRMED	CANDIDATE	0	0	0
	CONFIRMED	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
b	CONFIRMED	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
	CANDIDATE	CANDIDATE	0	0	0
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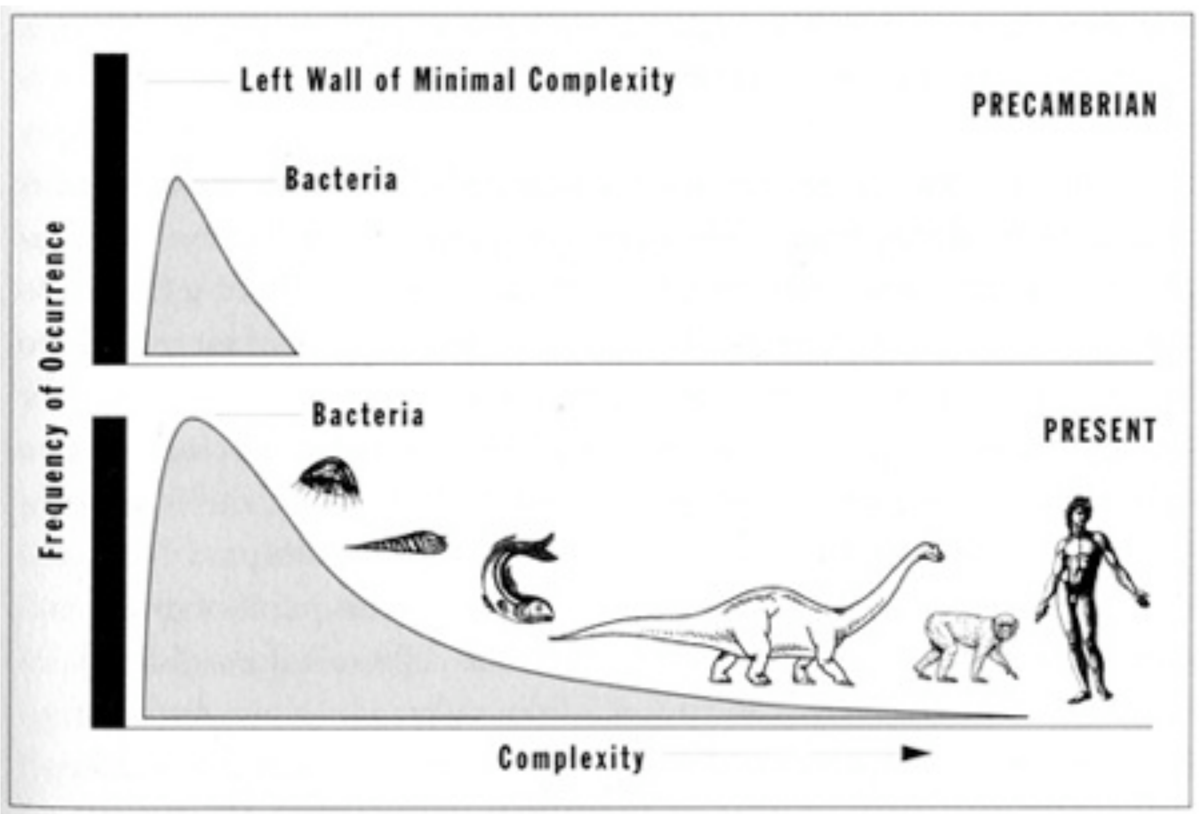
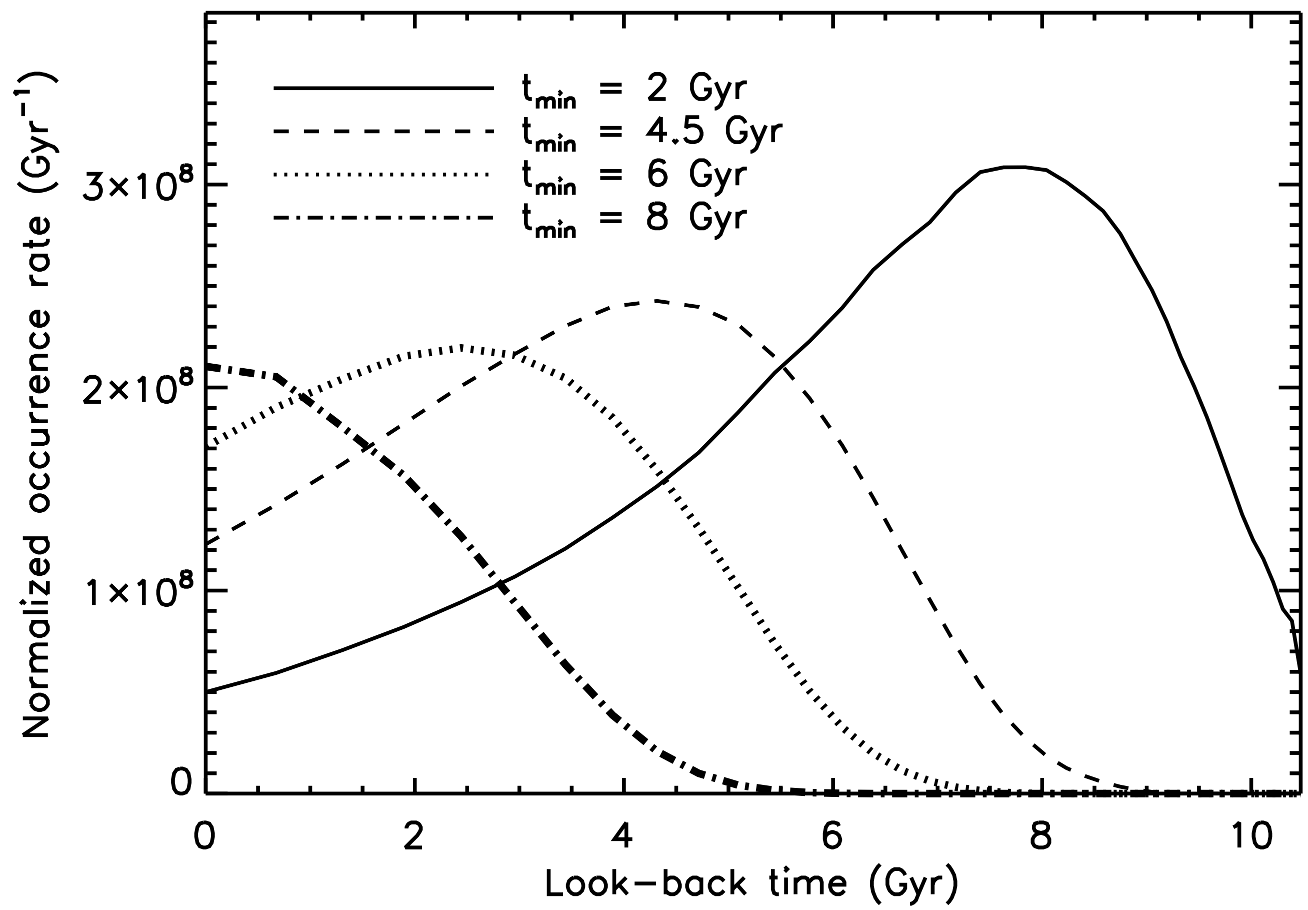
	CANDIDATE	CANDIDATE	0	0	0

Ages of habitable planets



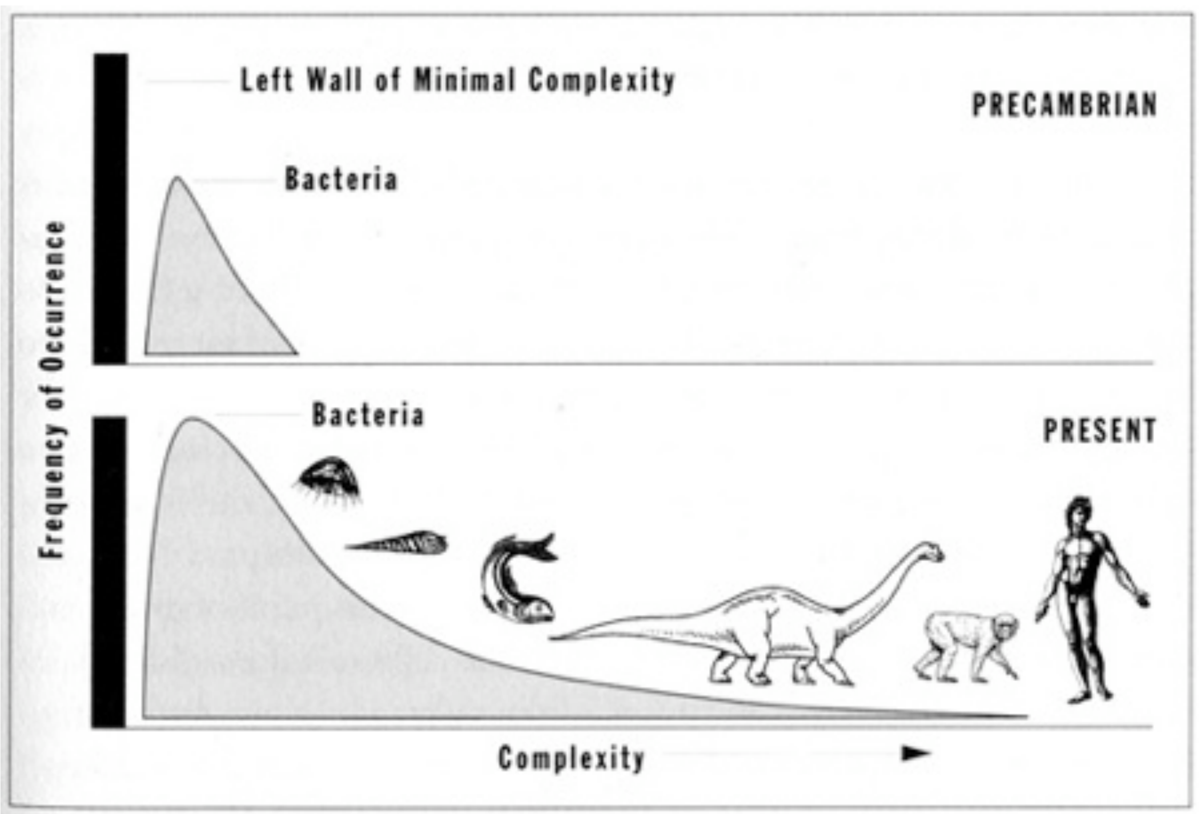
Gould 1997

Occurence rate of Earth-analogues

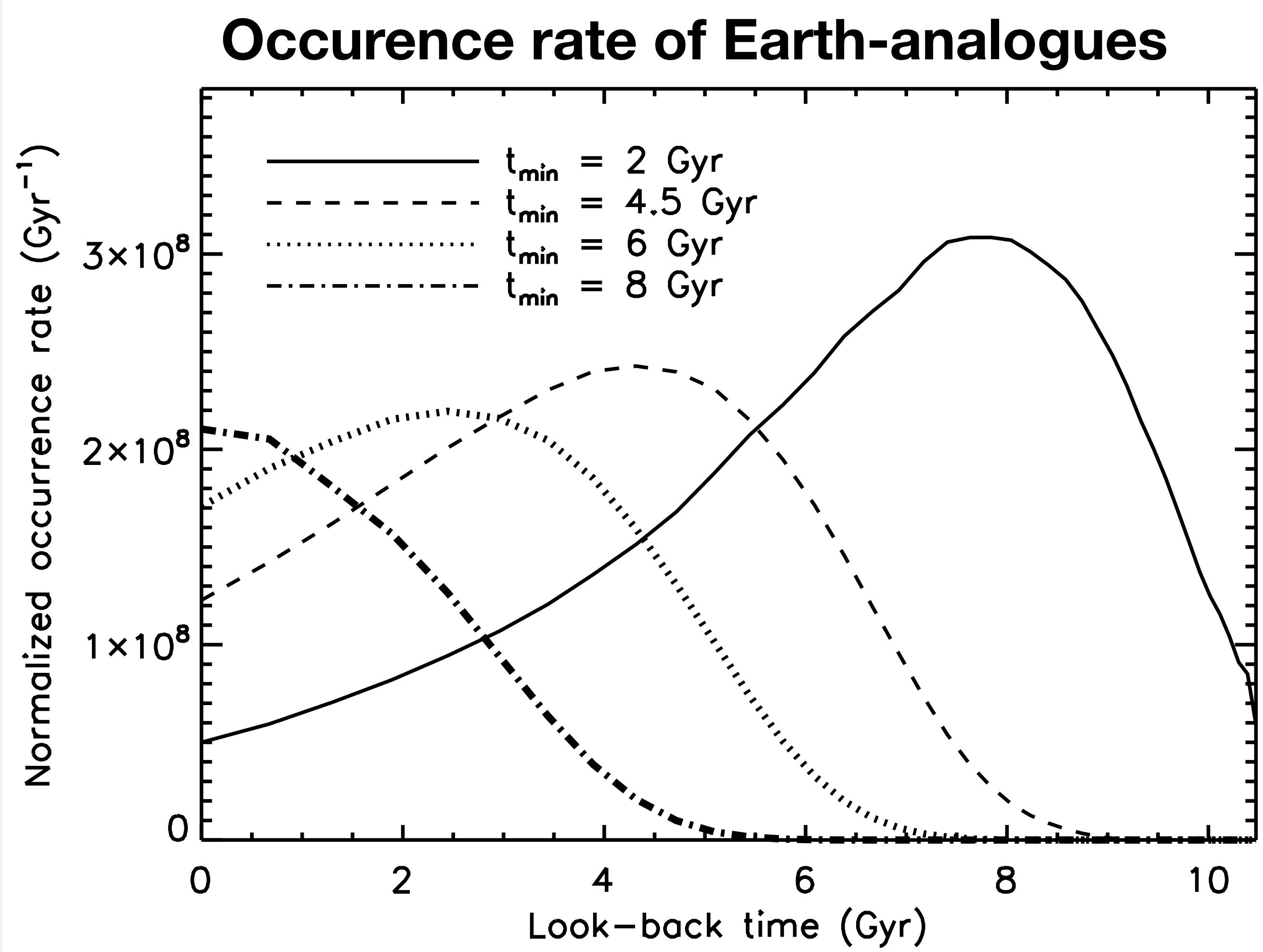


- variable delay time t_{min}
- habitable for $t > t_{min}$
- include {r_{SN}=8 pc, t_{rec} = 50 Myr}

Ages of habitable planets



Gould 1997



"Civilizations"

- variable delay time t_{min}
- habitable for $t > t_{min}$
- include {r_{SN}=8 pc, t_{rec} = 50 Myr}

Some numbers

(Gobat & Hong, A&A, 592, 96)

- 0.65-0.8% of stars can be expected to have a terrestrial planet in their HZ $\Rightarrow$ ~2×10^{9} in the Milky Way

- most habitable planets orbit K & M stars **(caveat)**

- median age of stars hosting habitable planets: 6 Gyr in disks
  9.5 Gyr in ETGs

- civilizations in the observable universe: $N_{MW}\times10^{9-0.22(\Delta t/\mathrm{Gyr})}$
  $\sim10^{8}$ if we are representative

- if we are unique in the MW: $P_{us} < 7\times10^{-10}$
  or
  $\Delta t > 8$ Gyr


Thank you for your attention
and remember to check the planning office regularly.