Evolution of Gas and Dust in the ISM of High-Redshift Galaxies

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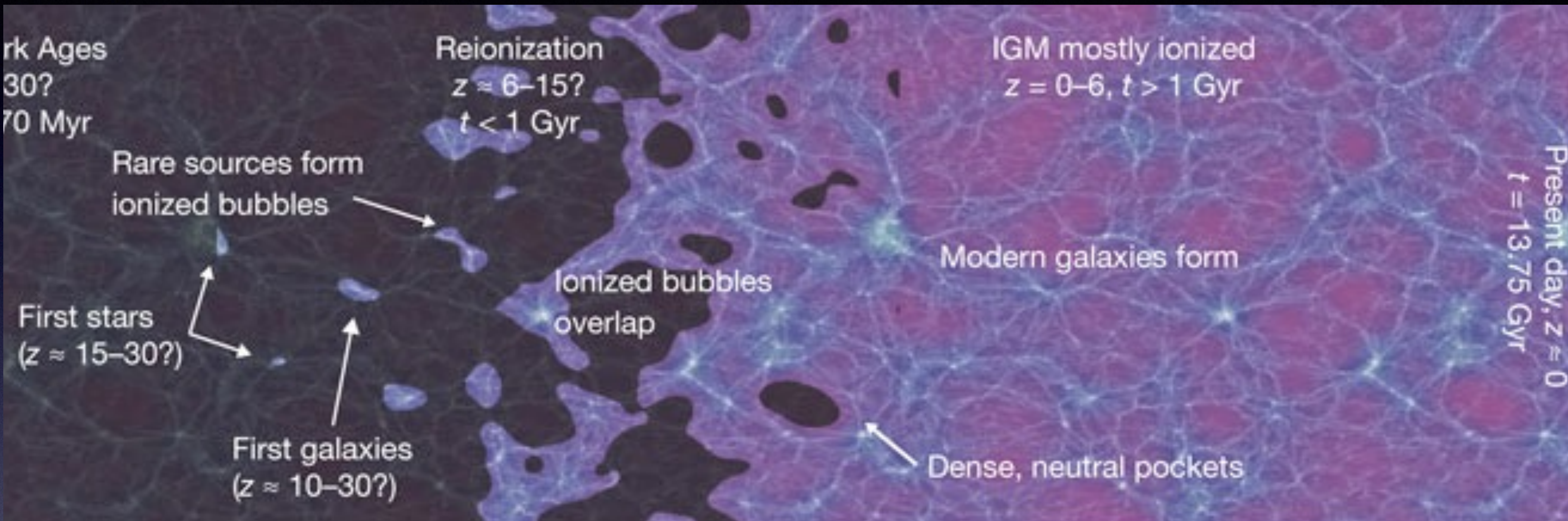
Universe Timeline

Robertson et al. (2010)



z=10-30 z=6-10 z=0

Universe Timeline

Robertson et al. (2010)

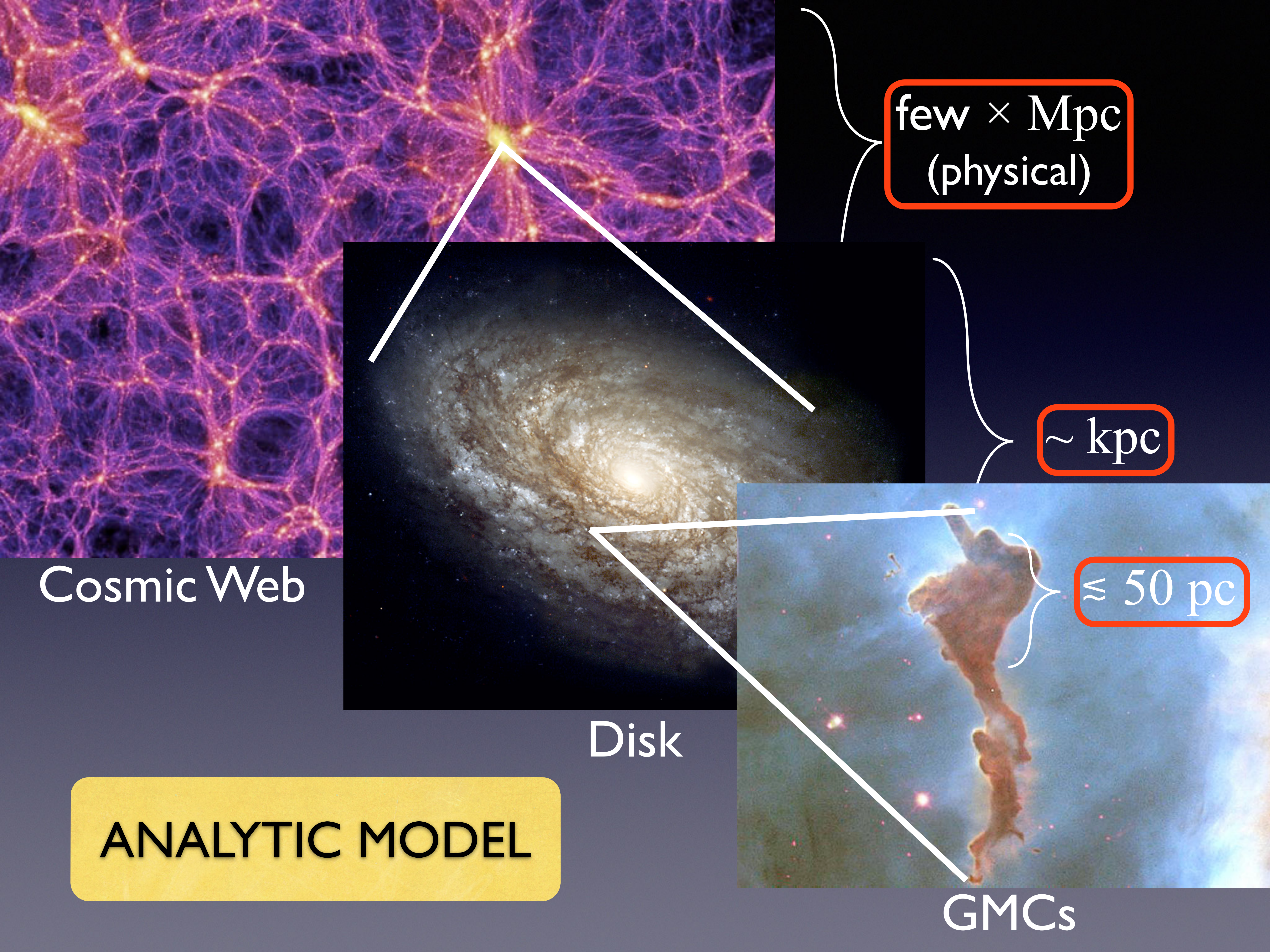
This Talk

z=10-30 z=6-10 z=0

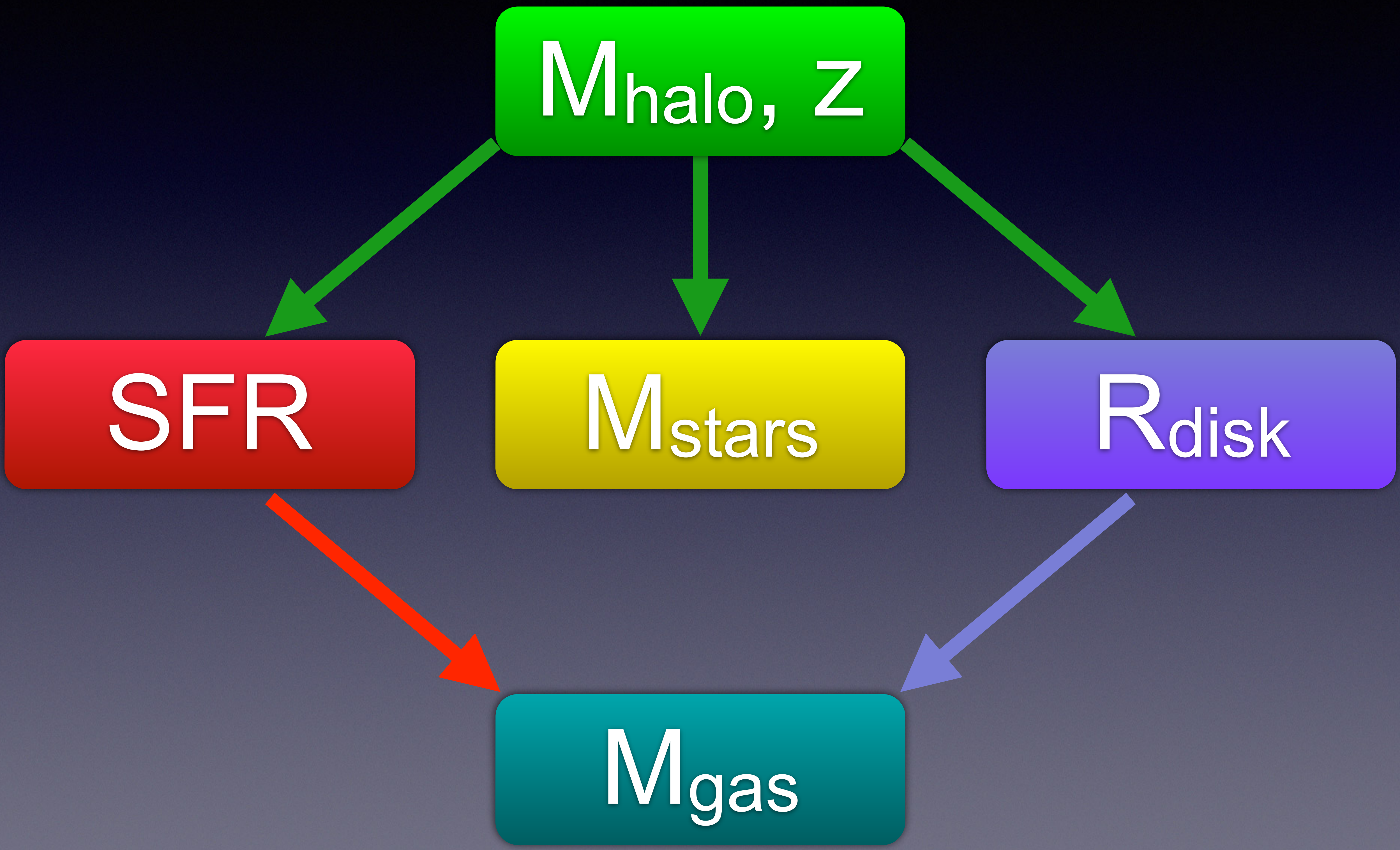
- Sources of Reionization
- Growth of SMBHs
- Extreme limits of galaxy formation

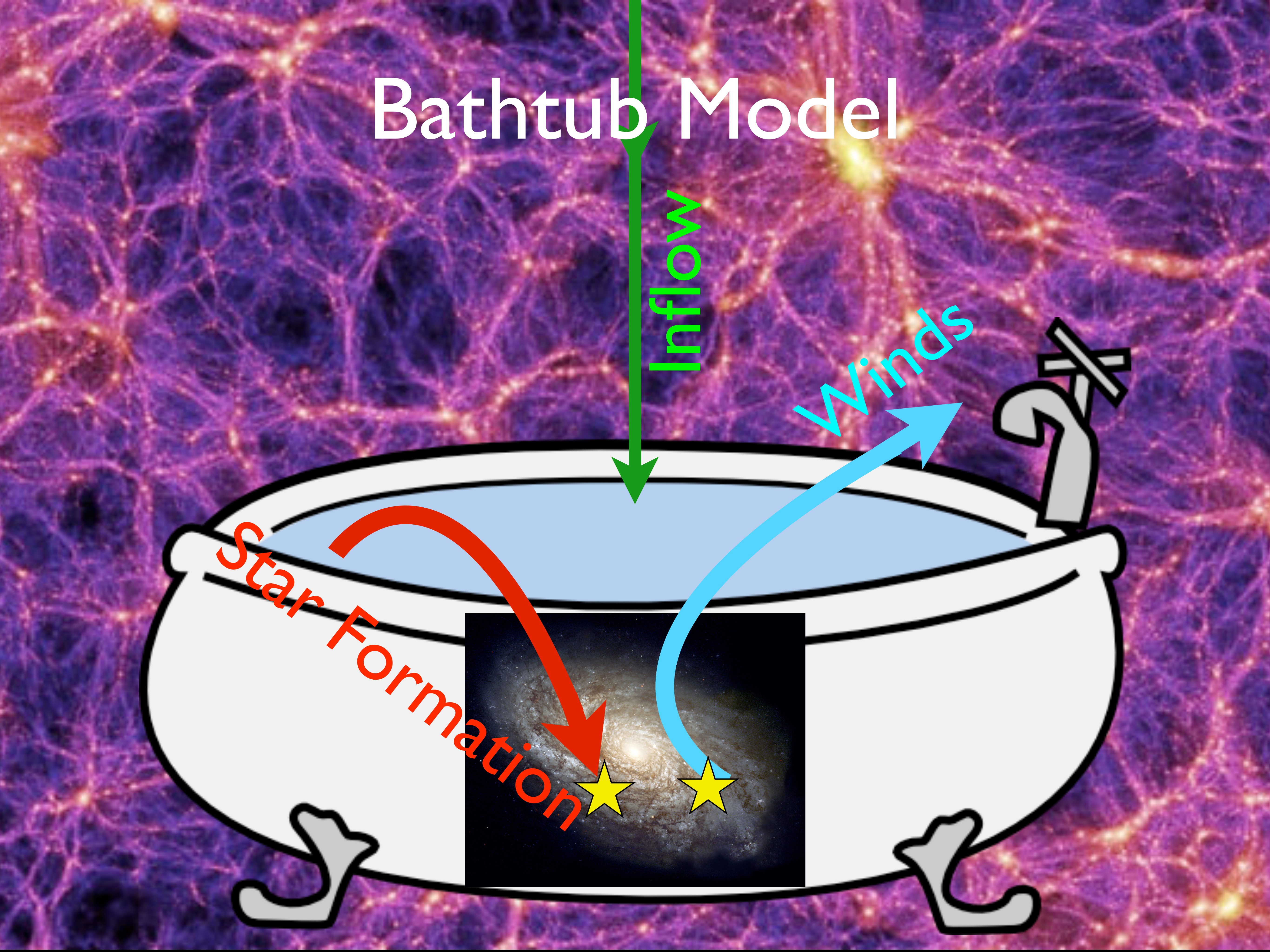
Strategy

- Develop simple analytic model of galaxies/ISM
- Understand empirical scalings of molecular/atomic/continuum emission
    - Gas: evolution of gas fraction
    - Dust/Metals: FIR, CO, CII
- Understand dust enrichment: depleted? too much?


few × Mpc
(physical)
~ kpc
≲ 50 pc
Cosmic Web
Disk
GMCs
ANALYTIC MODEL

Gas

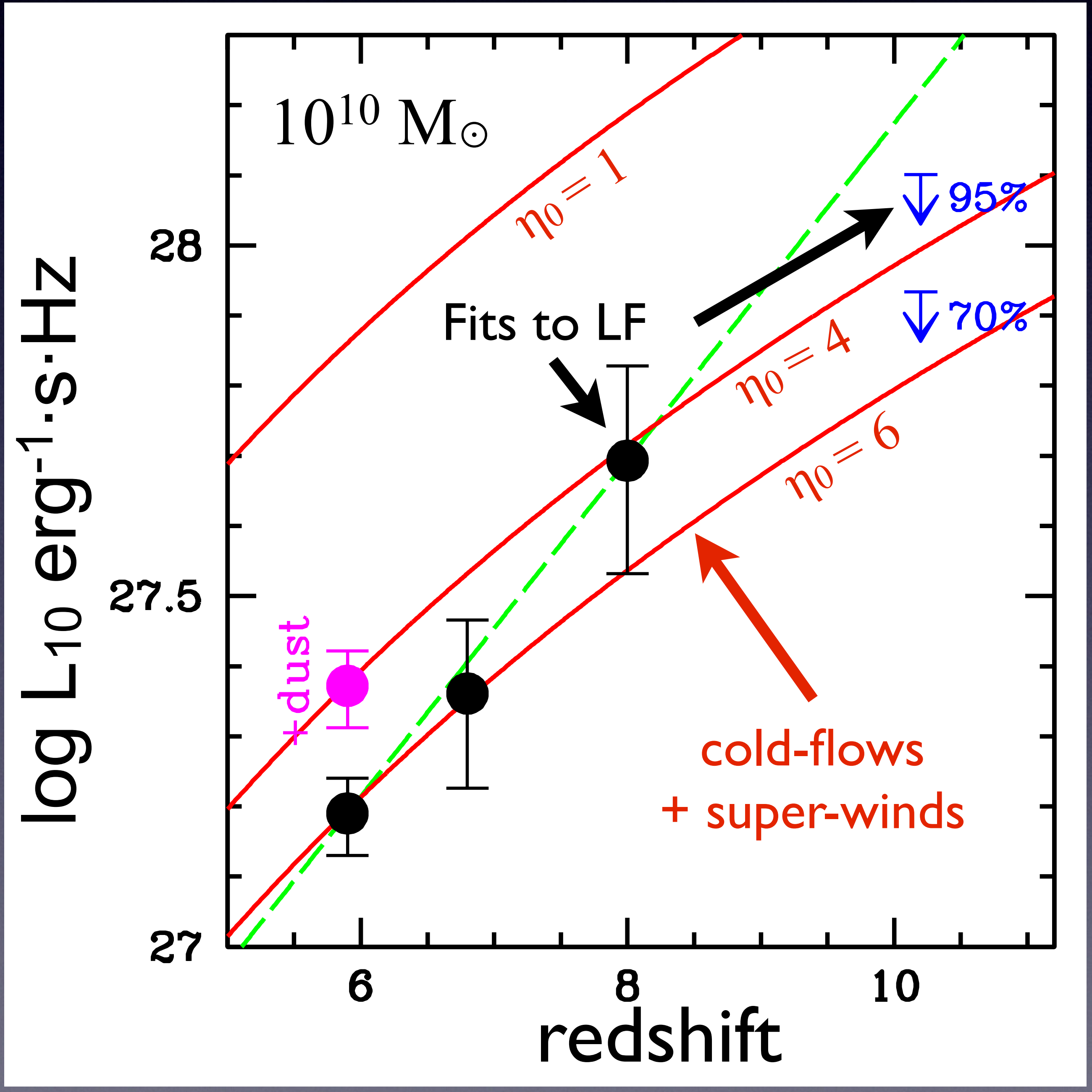




Bathtub Model
Inflow
Winds
Star Formation

Calibrate Feedback from LF

$$\dot{M}_{\rm acc} = \dot{M}_{\rm SFR}\,(1+\eta_{\rm wind})$$

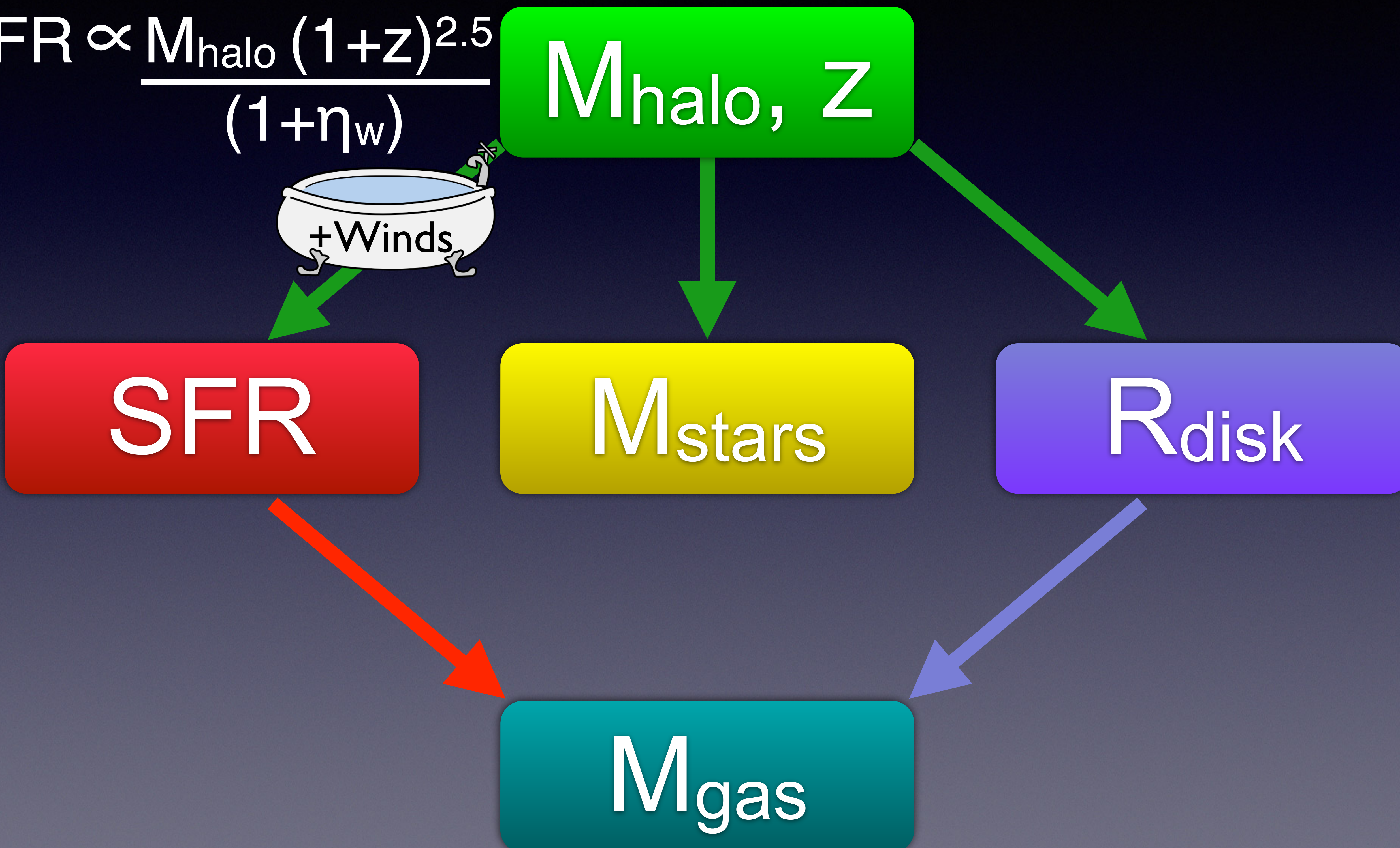


Muñoz (2012)

$$\eta_{\rm wind} = \eta_0 \, \frac{100\,{\rm km/s}}{\sigma}$$

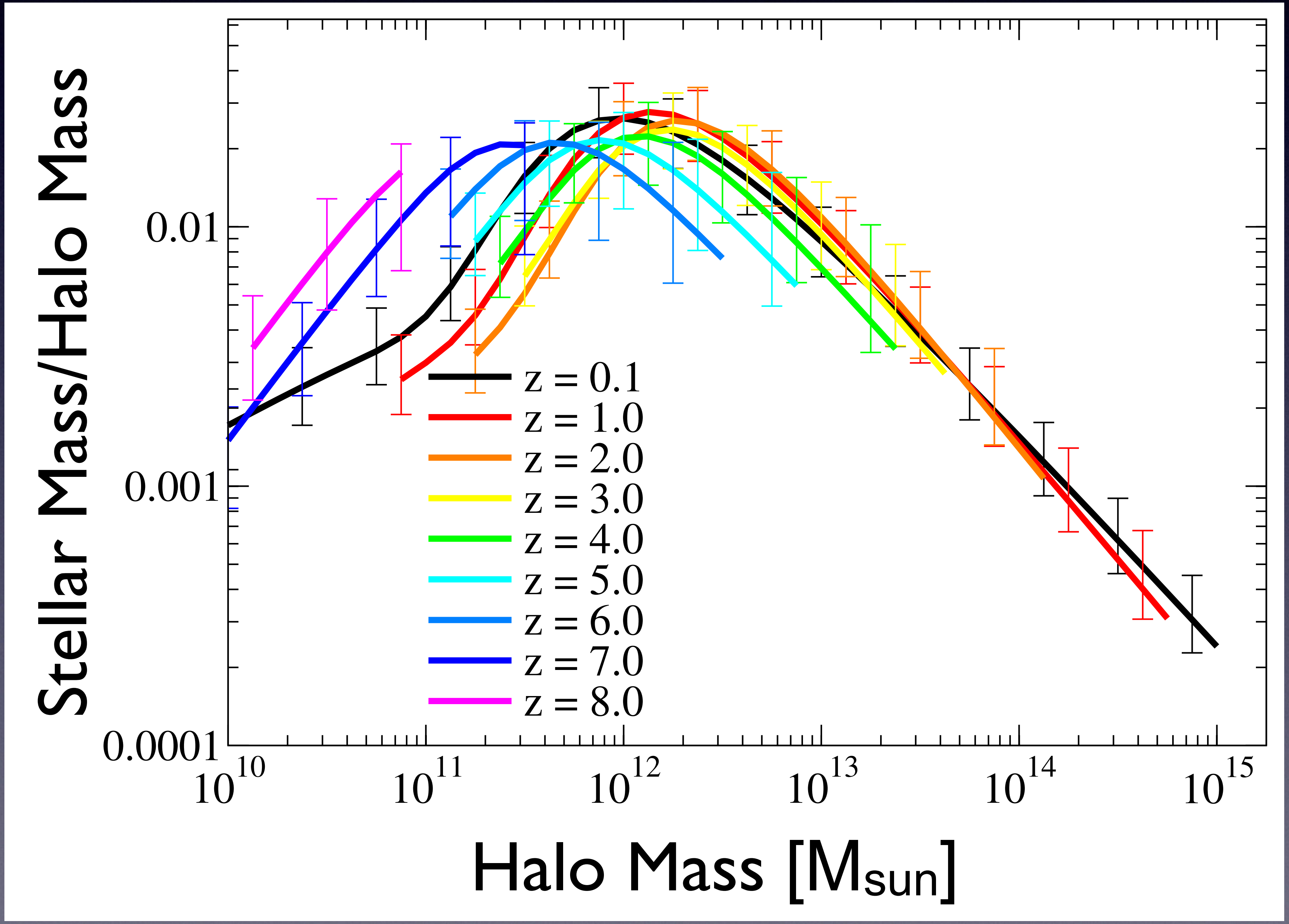
- Model describes LF evol.
- Mass-loading consistent with sims
(e.g. Oppenheimer+08)

$$SFR \propto \frac{M_{halo}\,(1+z)^{2.5}}{(1+\eta_w)}$$

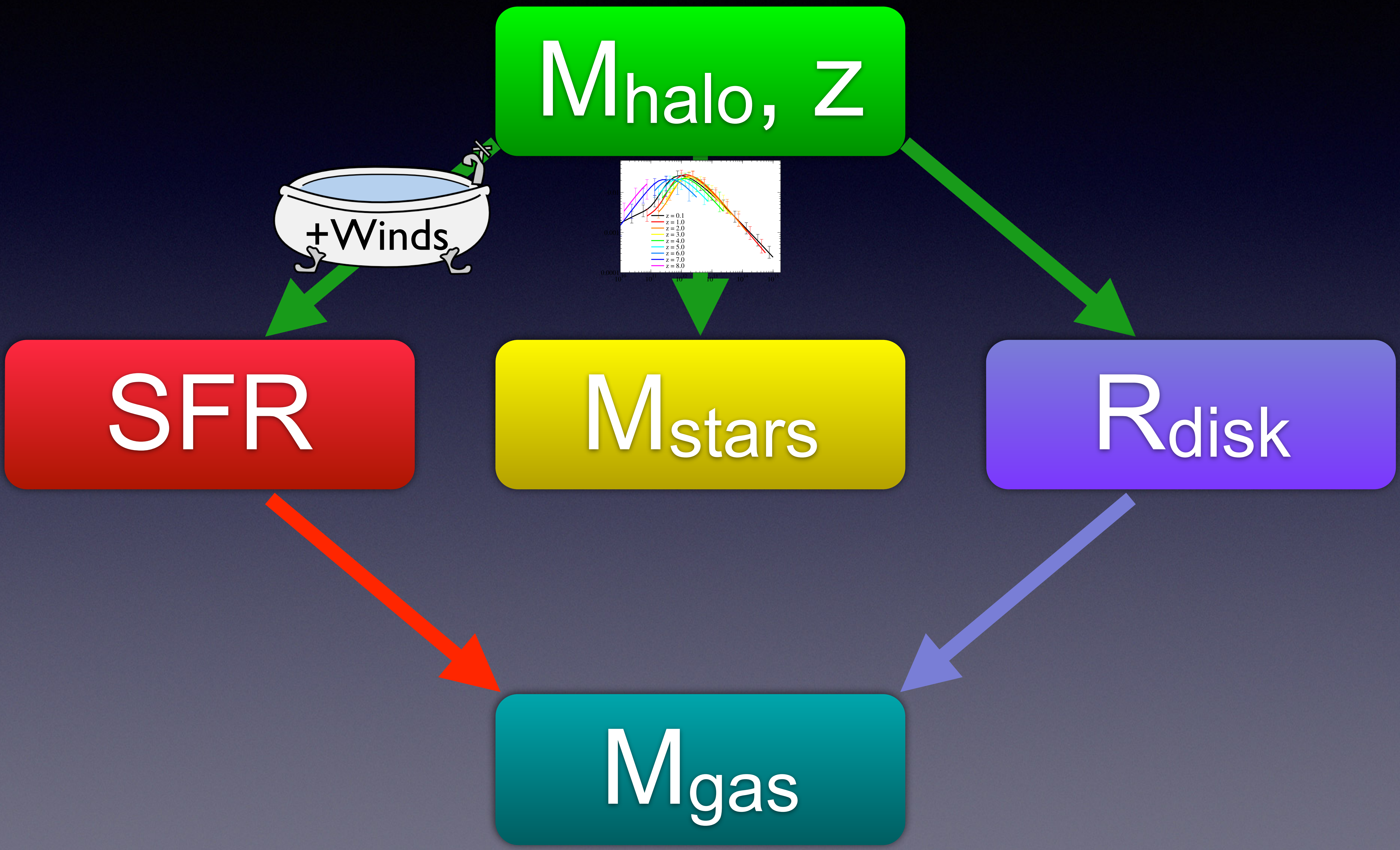


Stellar to Halo Mass

From abundance matching

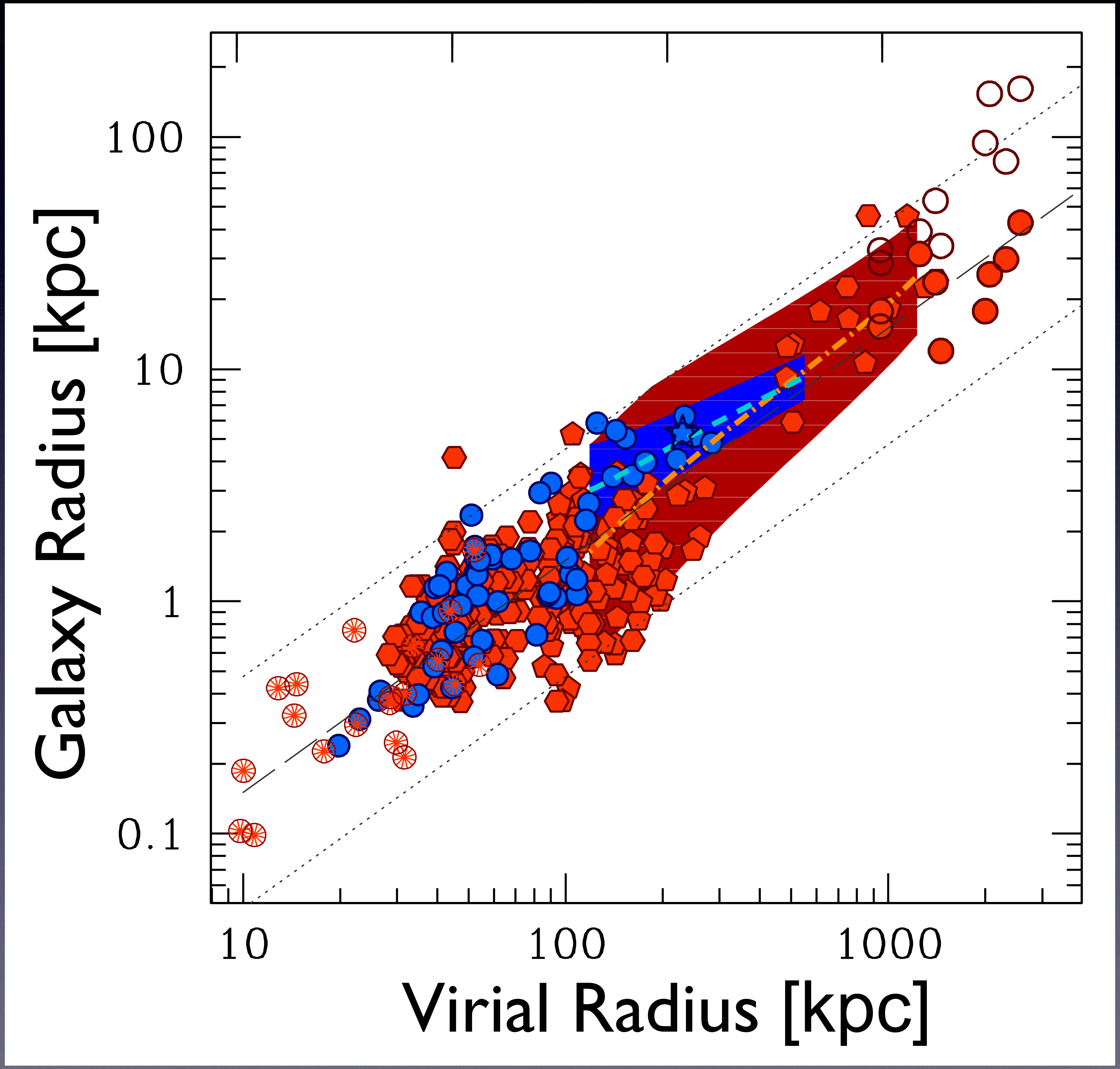


Behroozi et al. (2013)



Mhalo, z
+Winds
SFR
Mstars
Rdisk
Mgas

Galaxy Radius

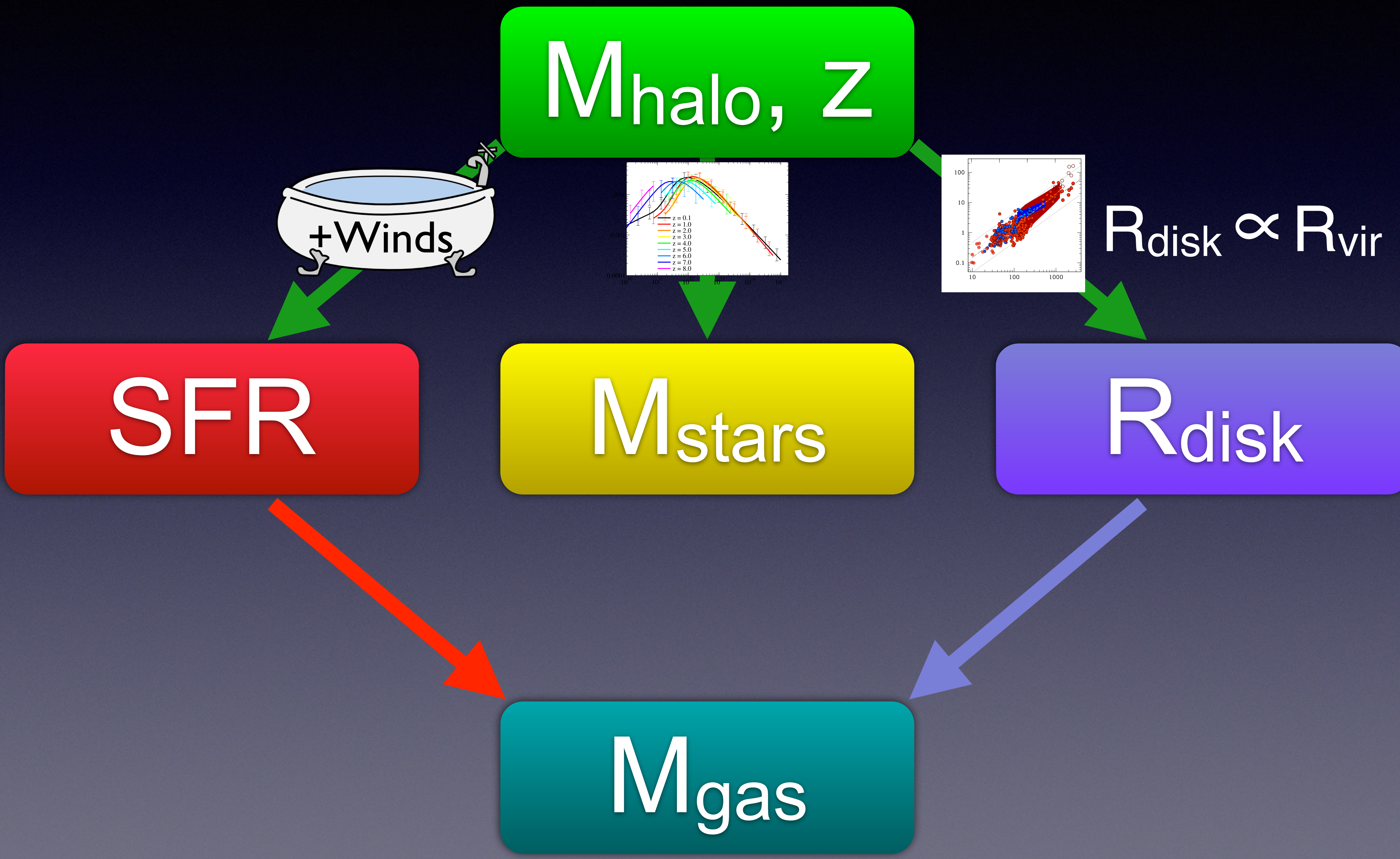


Kravtsov et al. (2014)

Angular momentum
+
Feedback

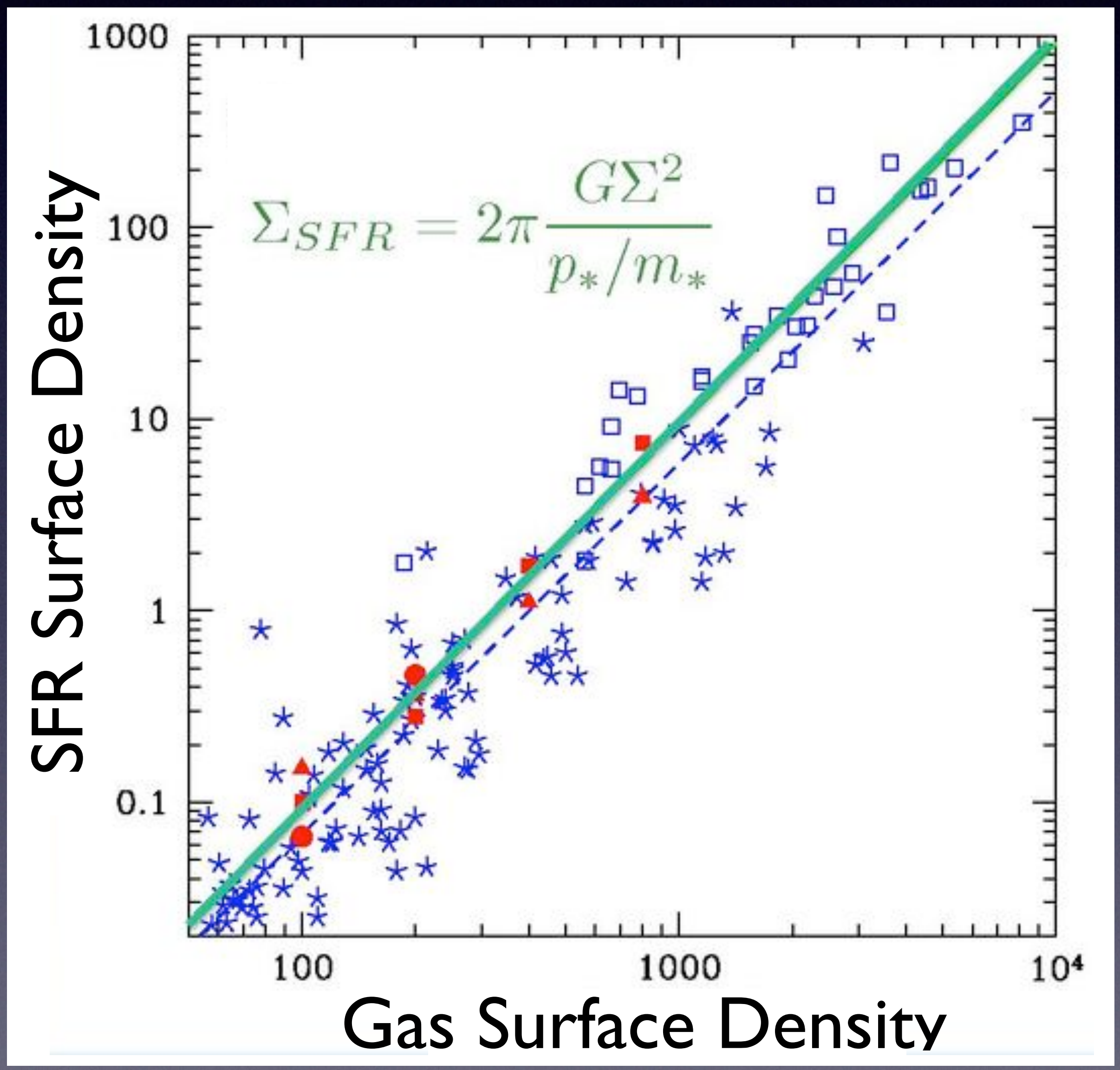
$R_{disk} \propto R_{vir}$

$\propto M_{halo}^{1/3} (1+z)^{-1}$

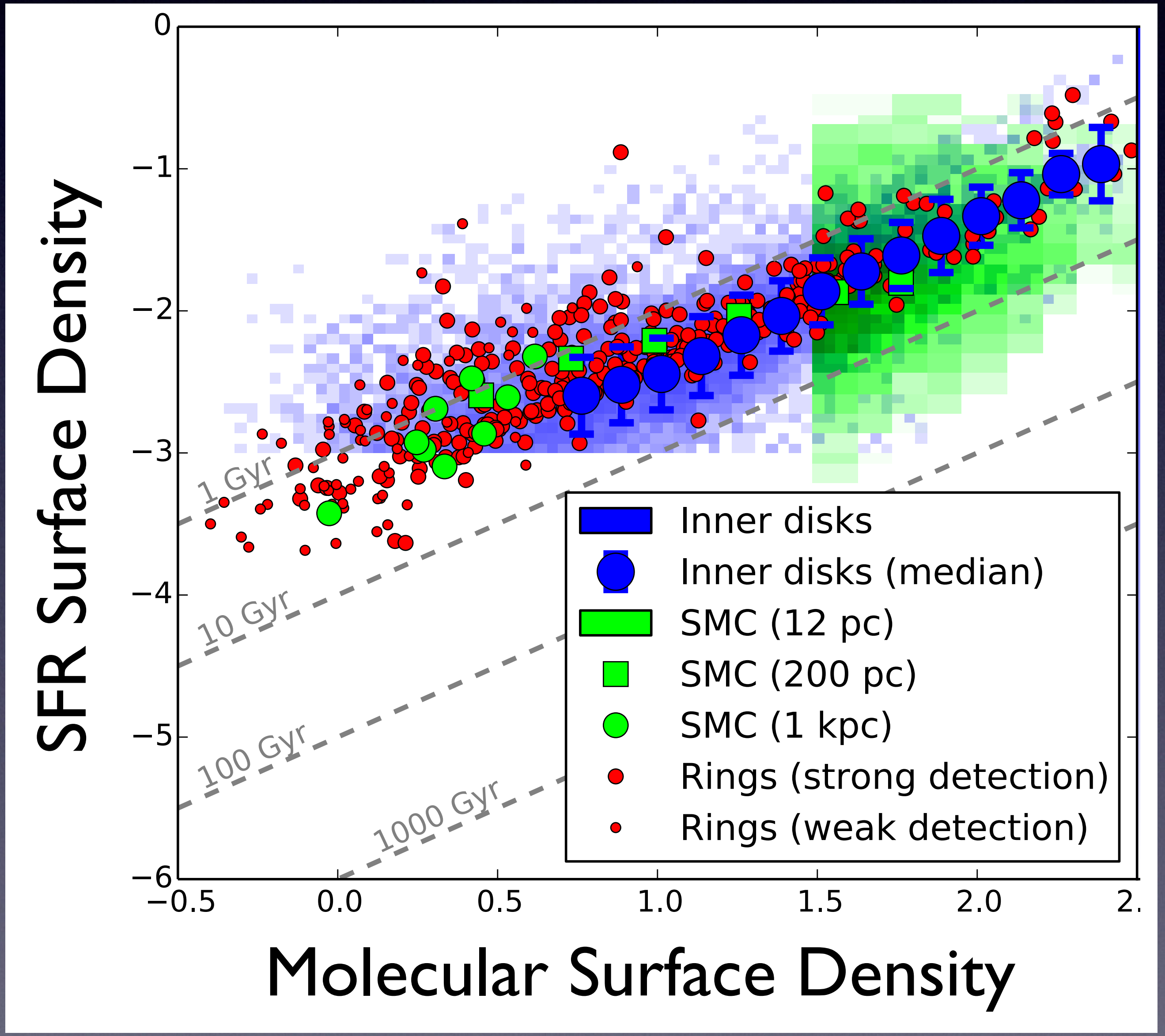


M_{halo}, Z
+Winds
$R_{disk} \propto R_{vir}$
SFR
M_{stars}
R_{disk}
M_{gas}

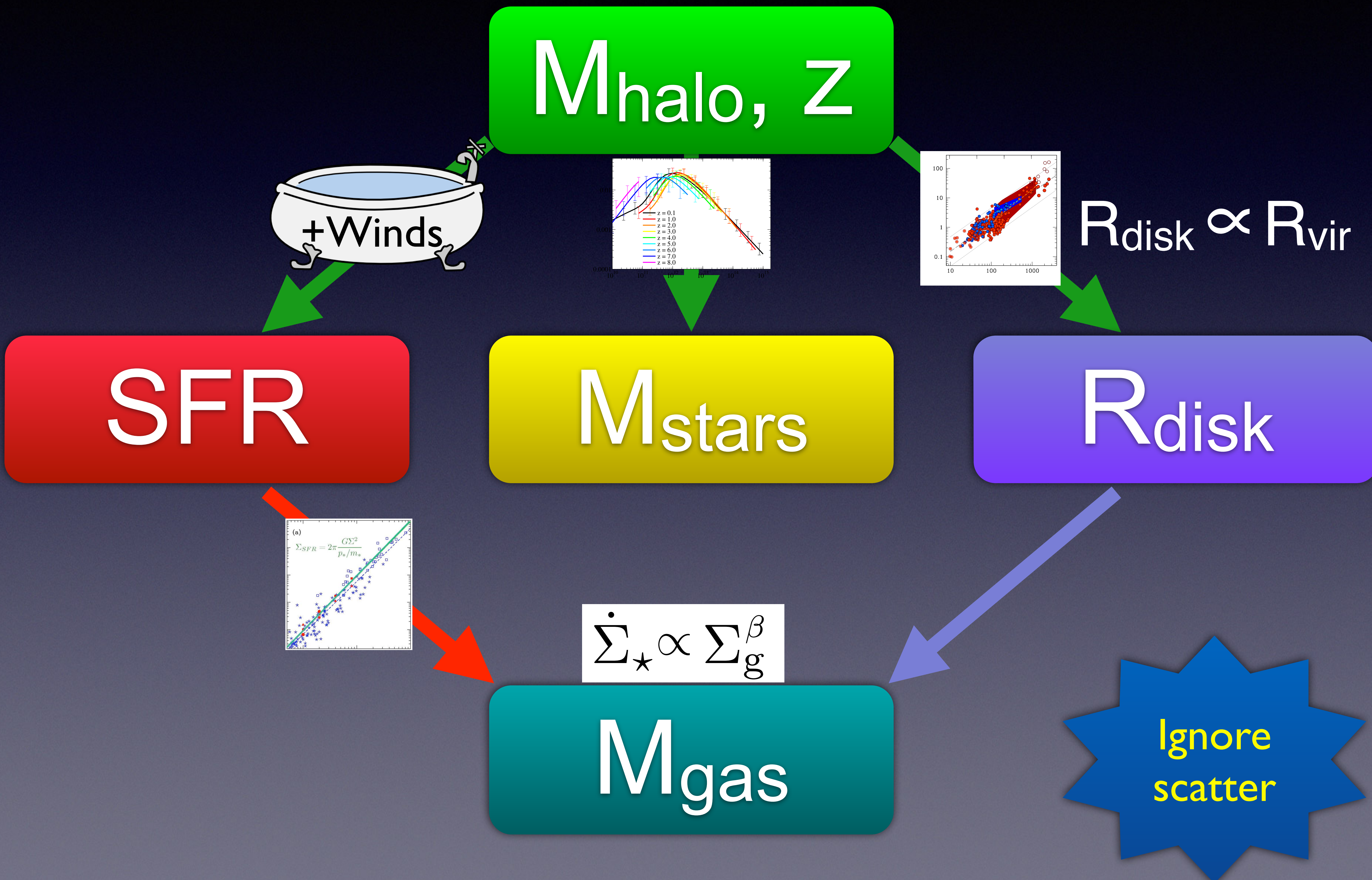
K-S Relation



Ostriker & Shetty (2011)

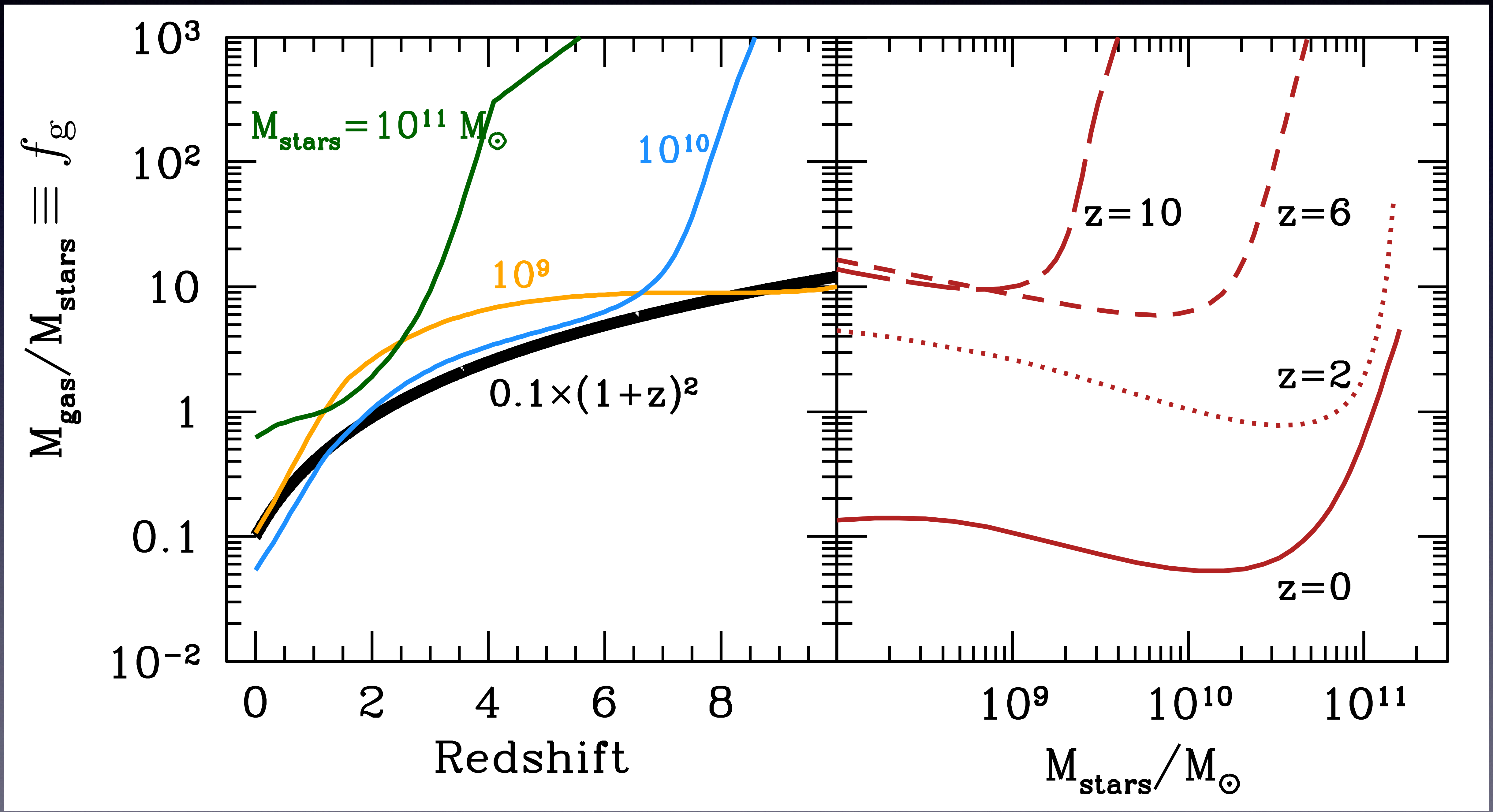


Krumholz (2014)



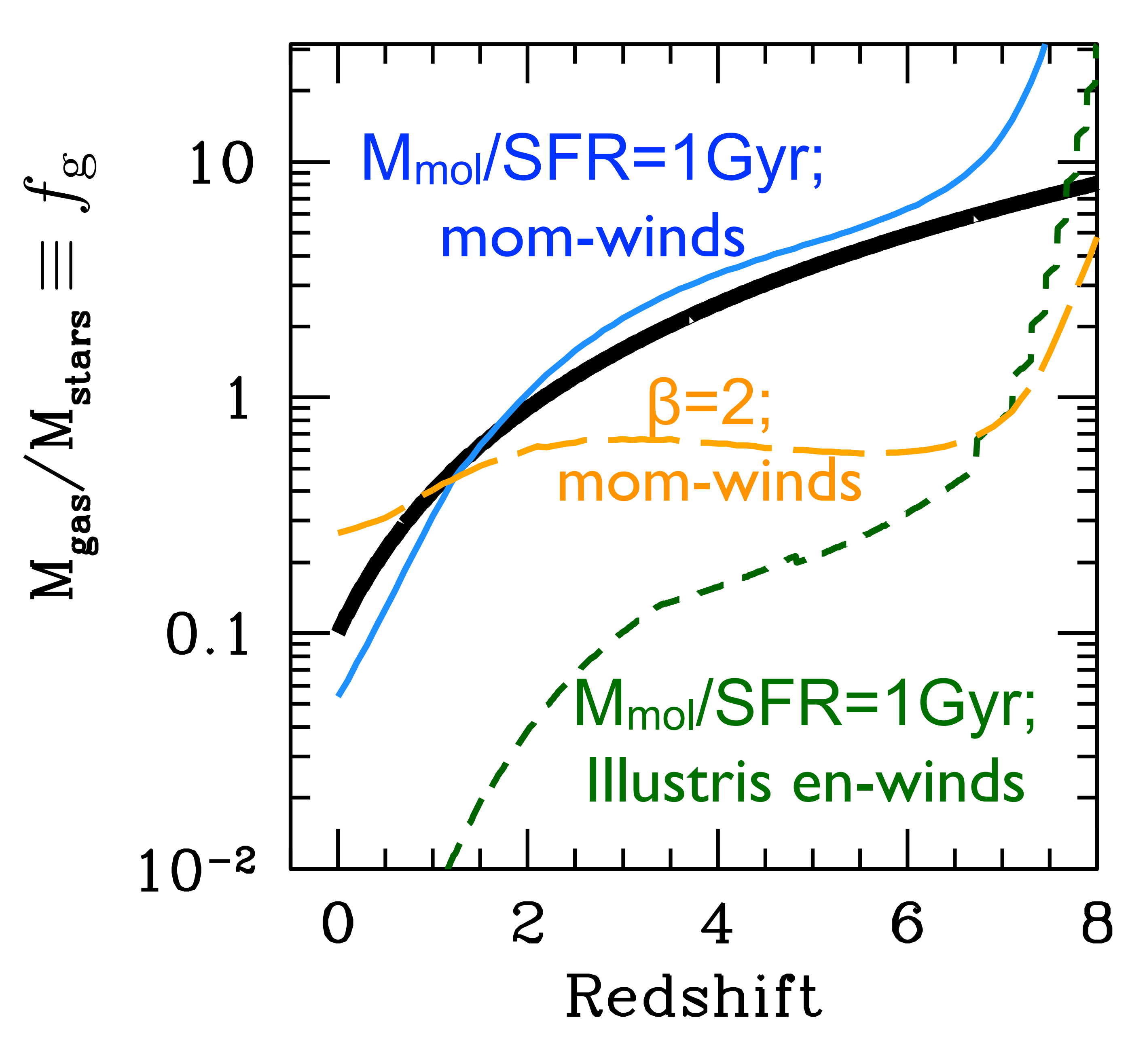
Mhalo, Z
+Winds
Rdisk ∝ Rvir
SFR
Mstars
Rdisk
$\dot{\Sigma}_\star \propto \Sigma_g^\beta$
Mgas
Ignore scatter

Gas Fraction



Muñoz & Oh (in prep.)

Gas Fraction



Muñoz & Oh (in prep.)

$$\mathrm{SFR} \propto \frac{\mathrm{M_{halo}}\,(1+z)^{2.5}}{\sigma^{-\alpha}}$$

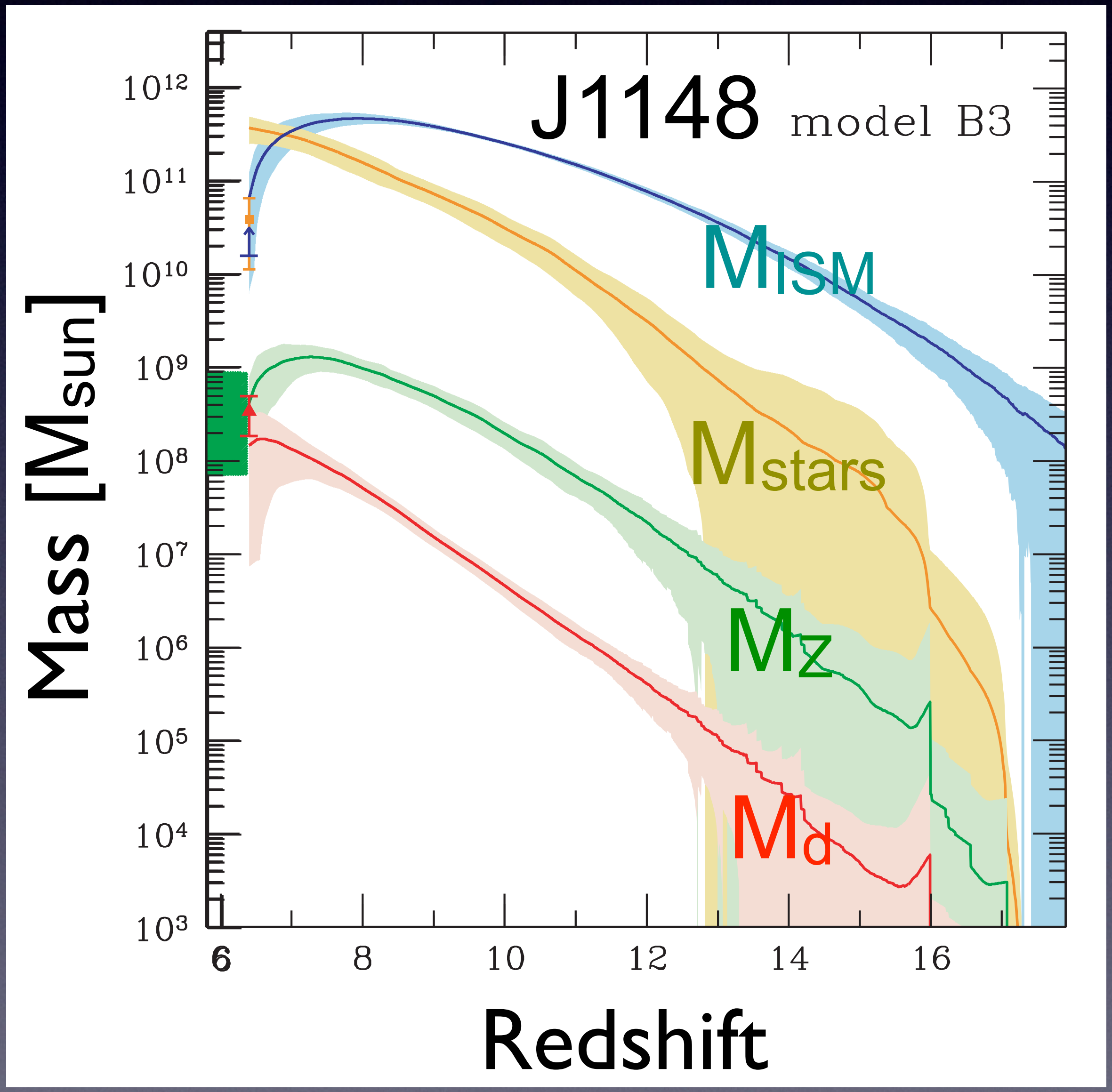
$$\dot{\Sigma}_\star \propto \Sigma_g^\beta$$

$$f_g \propto \mathrm{M_{halo}}^{\nu_m}\,(1+z)^{\nu_z}$$

Gas Fraction Scalings

α	β	ν_m	ν_z
0	1	0	2.5
1	1	1/3	3
2	1	2/3	3.5
0	2	-1/6	0.25
1	2	0	0.5
2	2	1/6	0.75

Gas→Dust

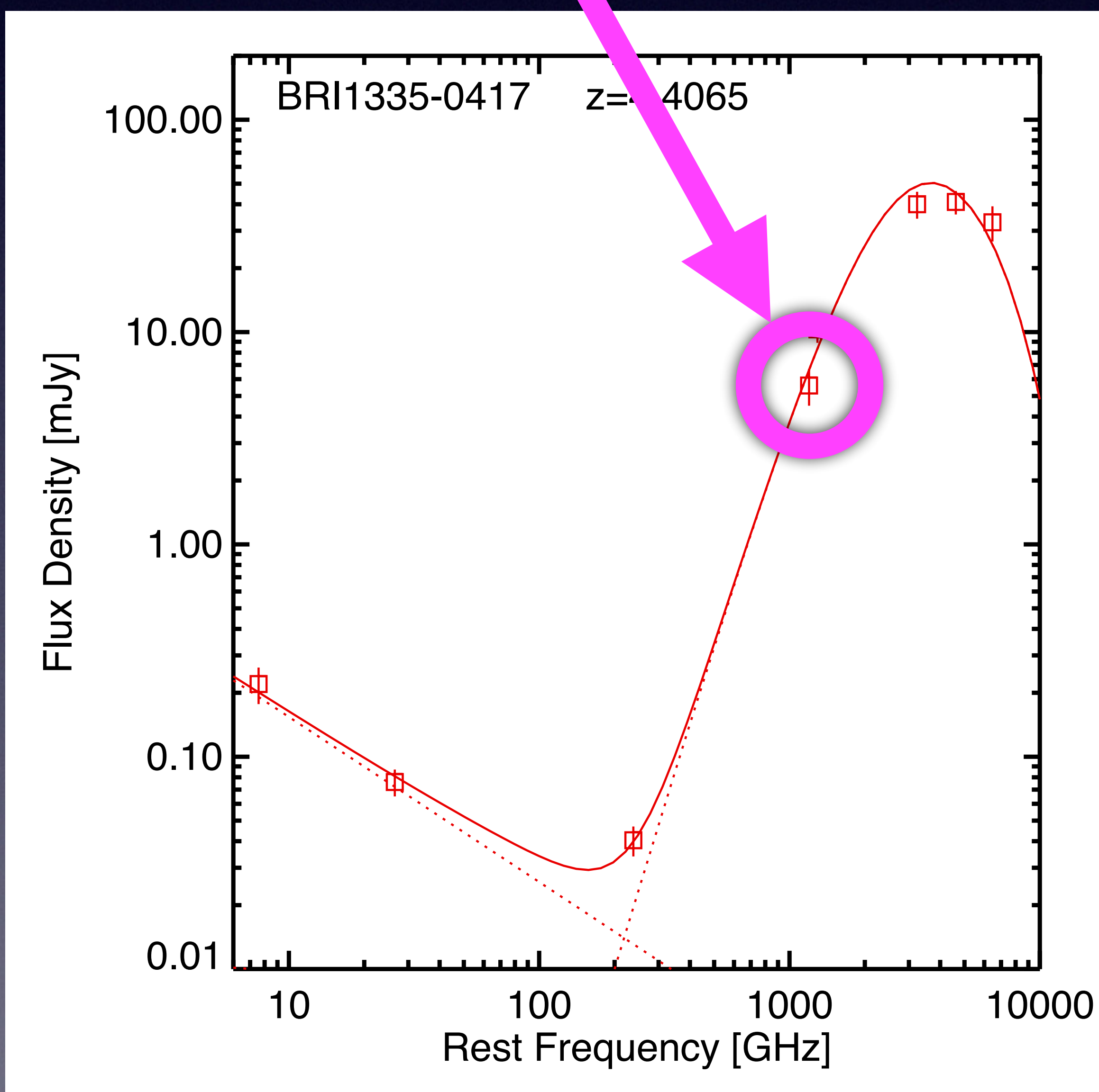


Valiante et al. (2011)

- Can't produce dust mass observed at high-z
- Dust budget crisis (Rowlands et al. 2014)
- SN dust at high-z?

FIR

Take advantage of observations in the optically thin limit



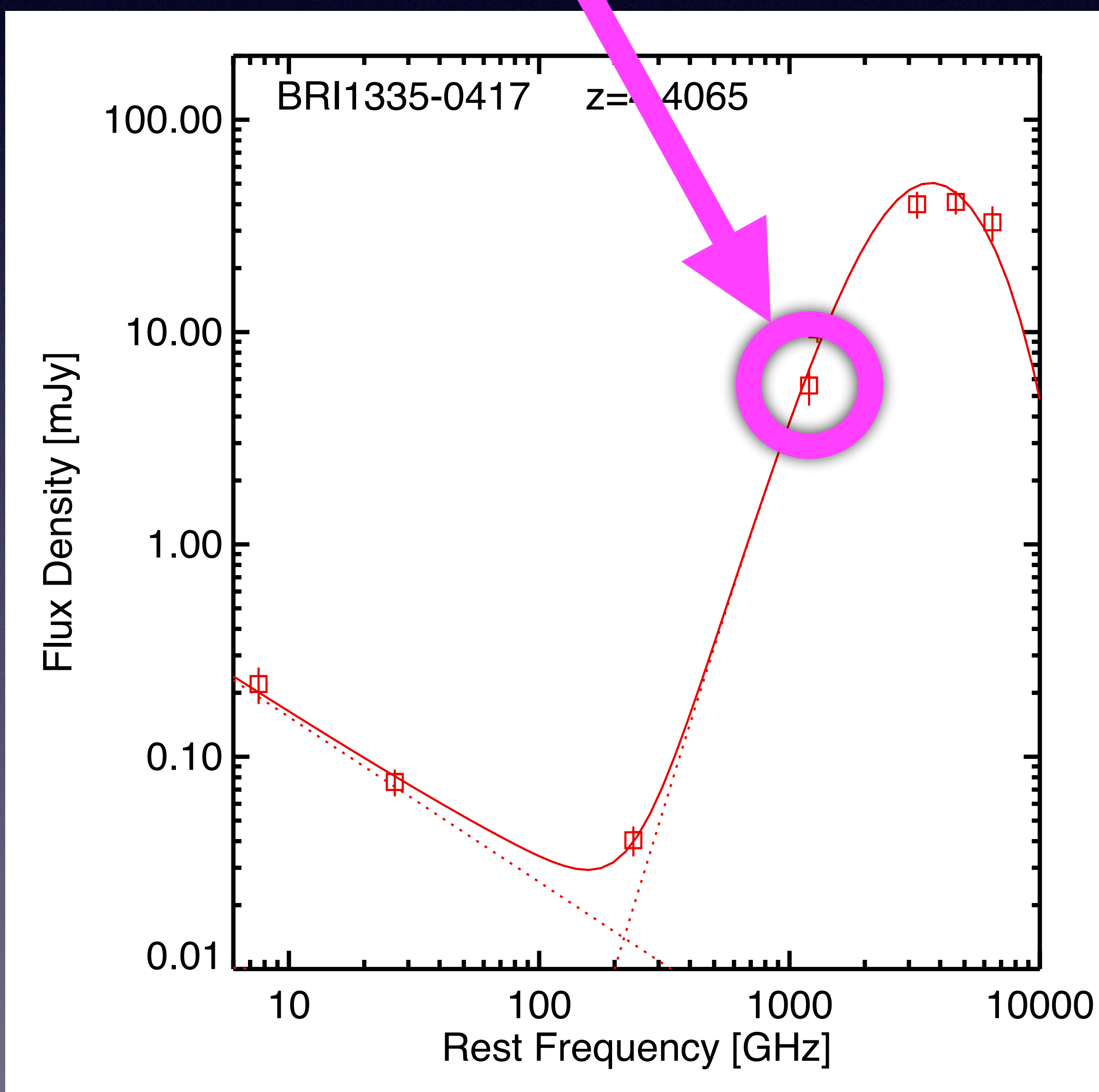
Wagg et al. (2014)

$$T_{\rm SF} = \left(\frac{\epsilon\, \dot{\Sigma}_\star\, c^2}{2\, \sigma_{\rm SB}} \right)^{1/4}$$

$$F_{\nu_{\rm obs}} = \frac{(1+z)\,\kappa\, B_{\nu_{\rm em}}(T)\, M_{\rm g}}{D_{\rm L}^2}$$

FIR

Take advantage of observations in the optically thin limit



Wagg et al. (2014)

$$T_{\rm SF} = \left(\frac{\epsilon \, \dot{\Sigma}_\star \, c^2}{2 \, \sigma_{\rm SB}} \right)^{1/4}$$

$$F_{\nu_{\rm obs}} = \frac{(1+z) \, \kappa \, B_{\nu_{\rm em}}(T) \, M_{\rm g}}{D_{\rm L}^2}$$

$$\kappa \approx 0.07 \, {\rm cm}^2 \, {\rm g}^{-1} \, Z'_{\rm d} \left(\frac{\lambda_{\rm em}}{230 \, \mu{\rm m}} \right)^{-2}$$

Sample at High-z

- 17 QSOs & SMGs from literature
- both FIR (100-400 μm rest) and CII
- z>4.3
- SFR=100s-1000s M_{sun}/yr (lot of variation)
- M_{gas}~10^{10}-10^{11} M_{sun} (lot of variation)
- R_{disk}~1-10 kpc (extent of CII)

  → Σ_{gas}~100s-1000s M_{sun}/pc^{-2}

- Plus a few LAEs w/ upper limits

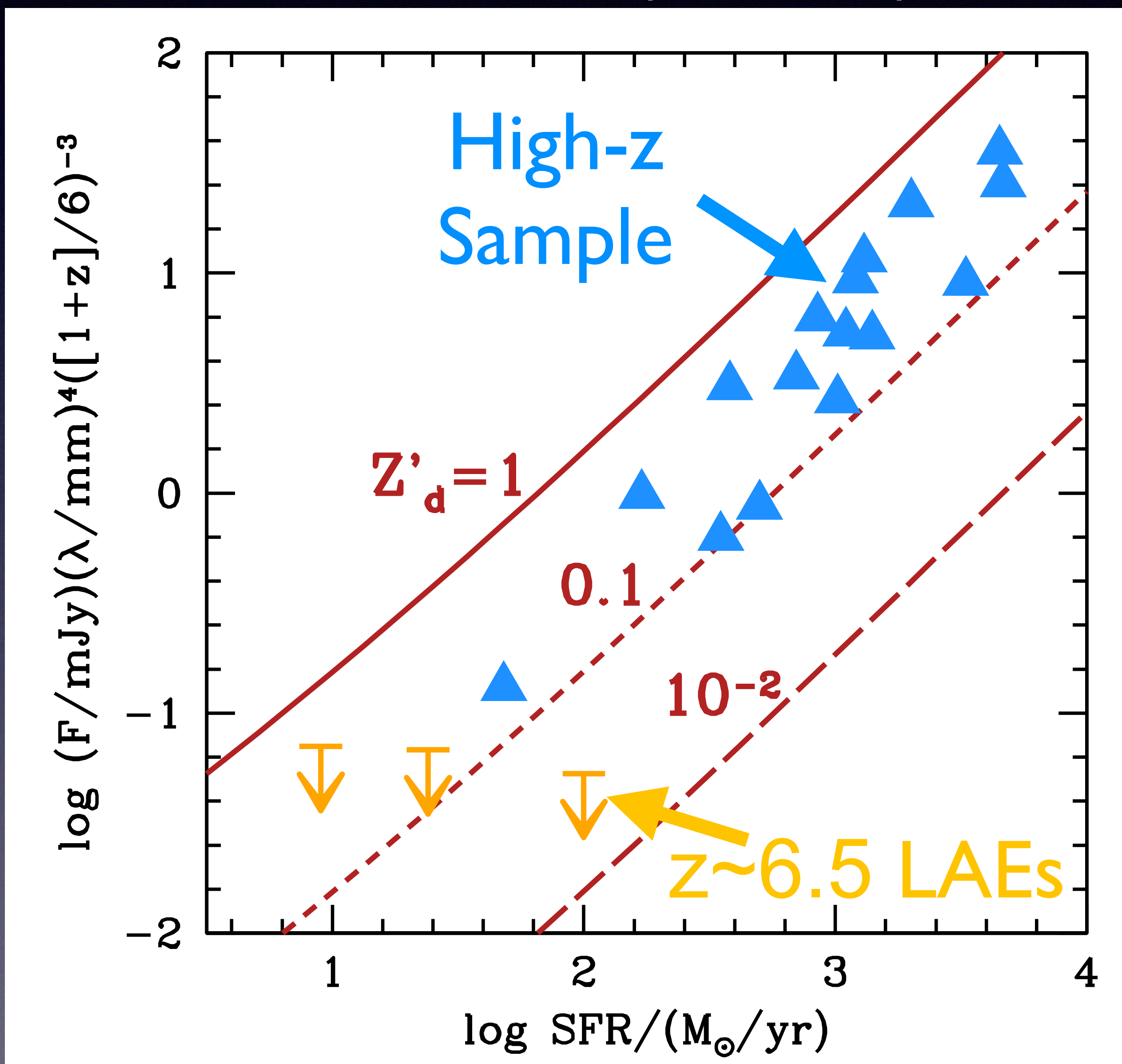
FIR

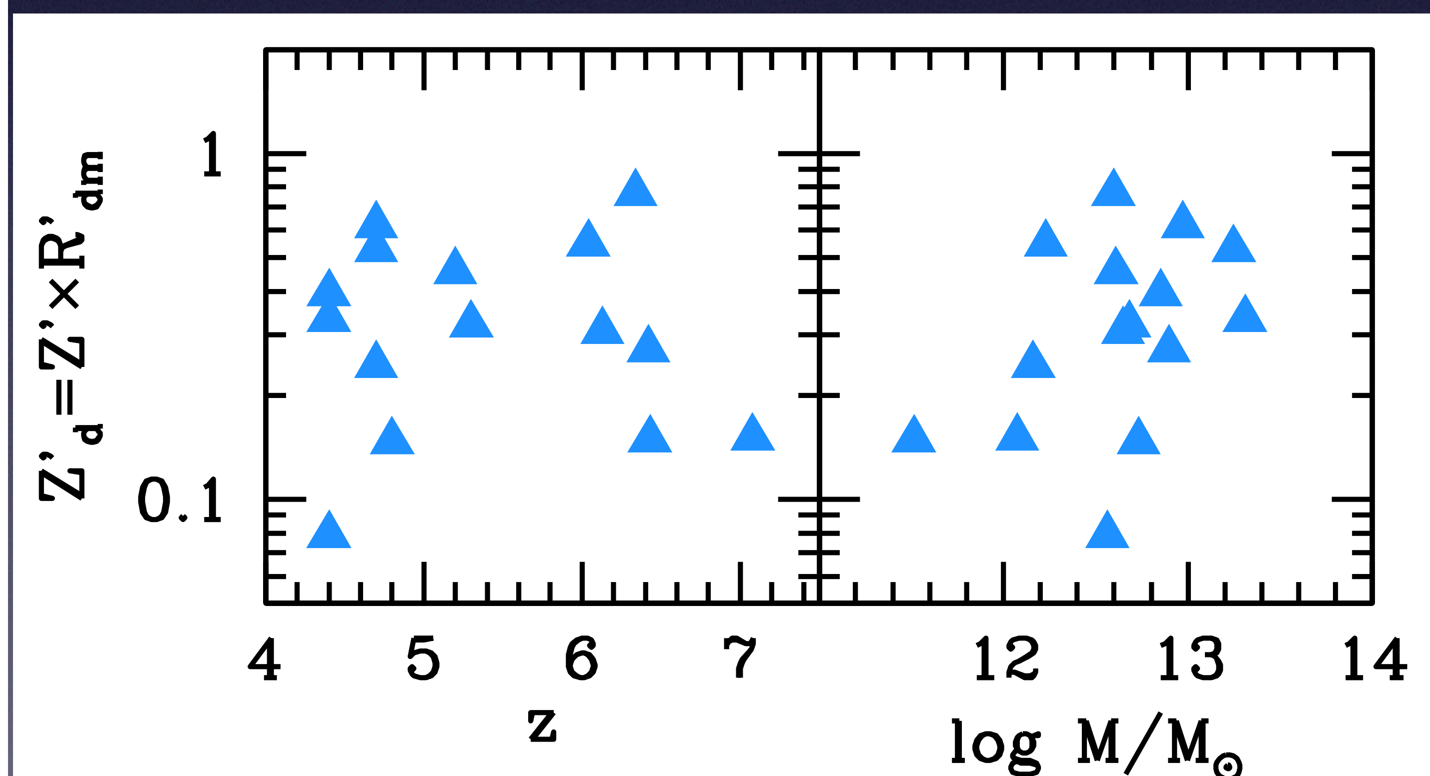
$$F_{\nu_{\rm obs}} = \frac{(1+z)\,\kappa\,B_{\nu_{\rm em}}(T)\,M_{\rm g}}{D_{\rm L}^2}$$

dust-to-gas ratio =

Z'$_d$/150

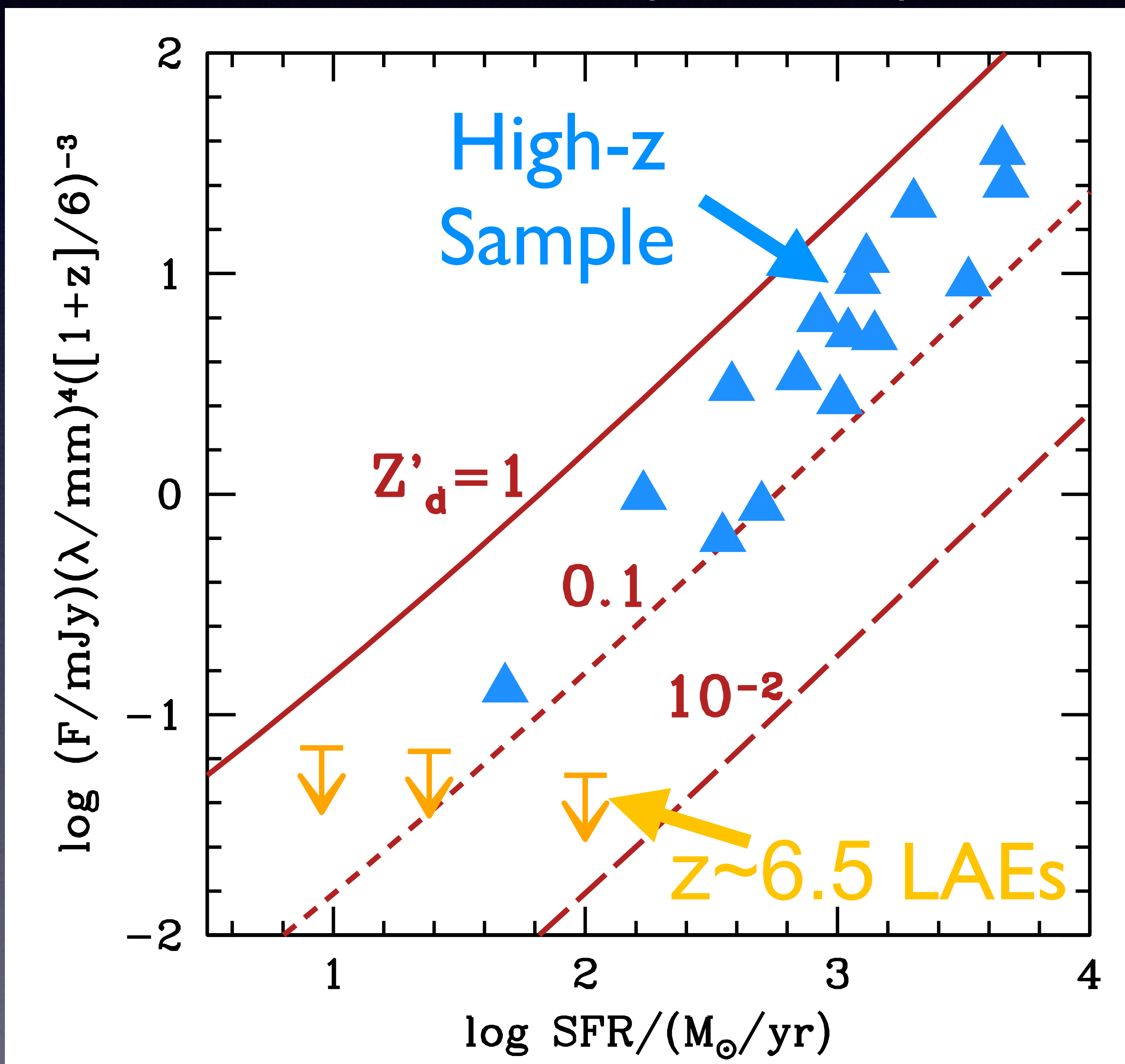
Muñoz & Oh (in prep.)





FIR

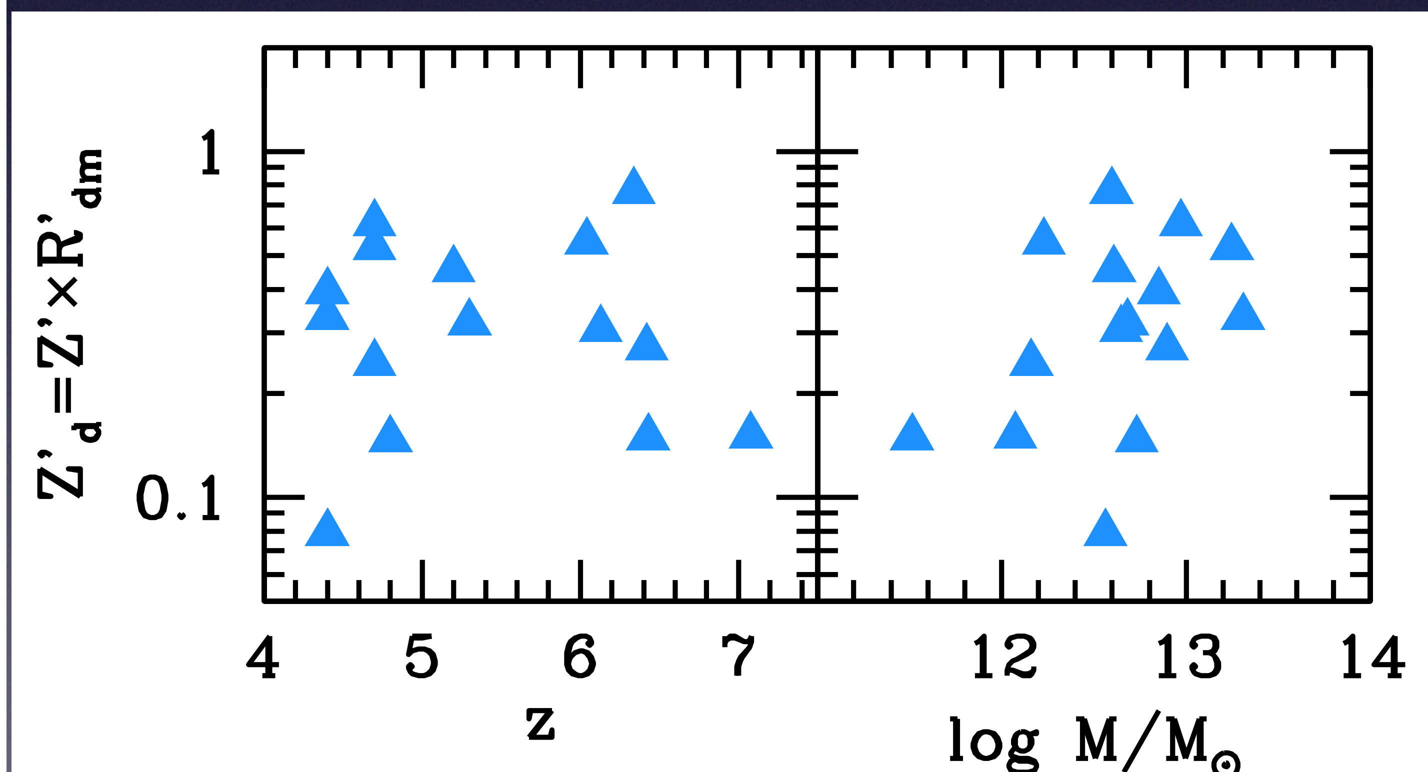
Muñoz & Oh (in prep.)



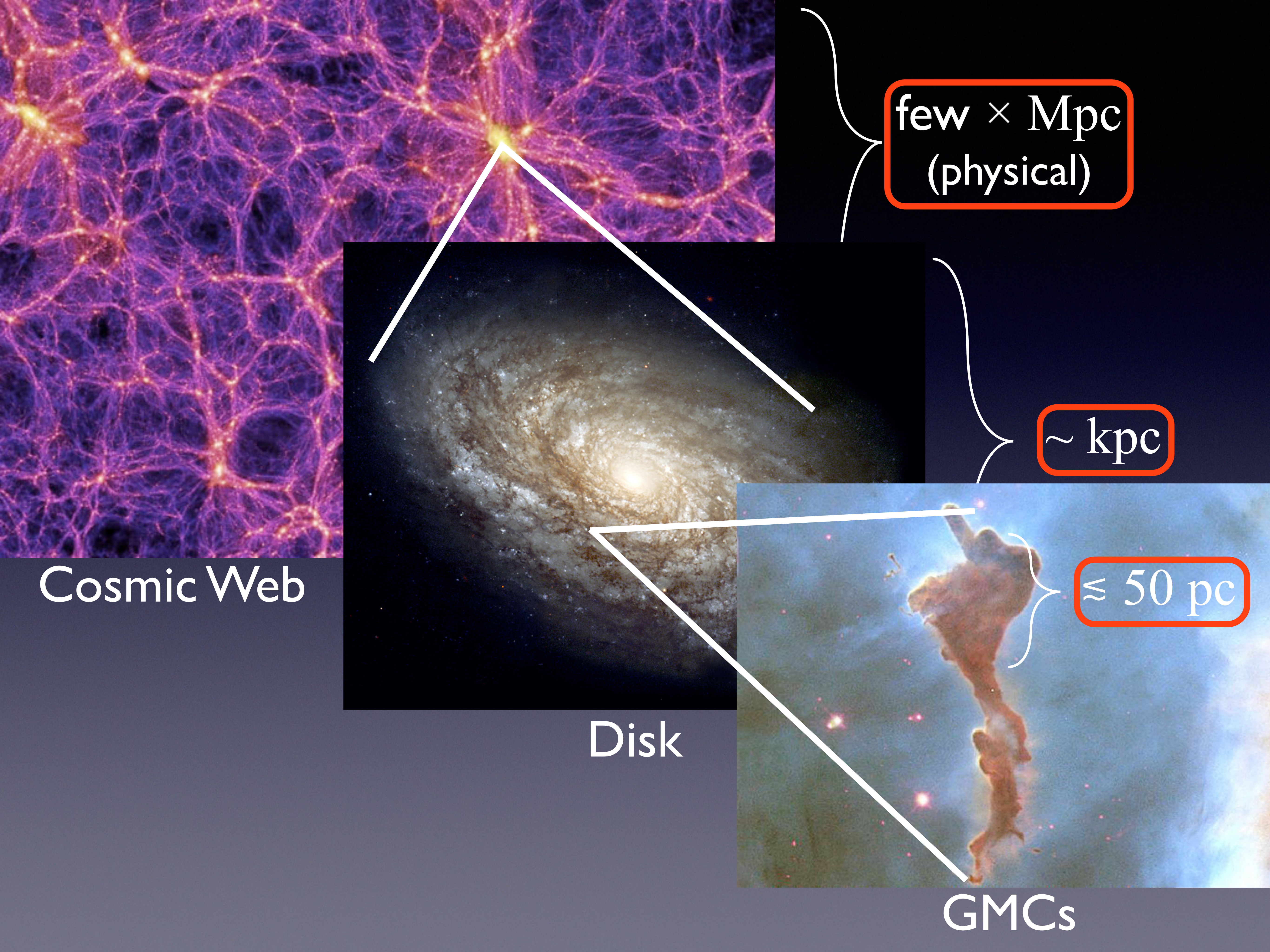
$$F_{\nu_{\rm obs}} = \frac{(1+z)\,\kappa\,B_{\nu_{\rm em}}(T)\,M_{\rm g}}{D_{\rm L}^2}$$

dust-to-gas ratio =

Z'd/150

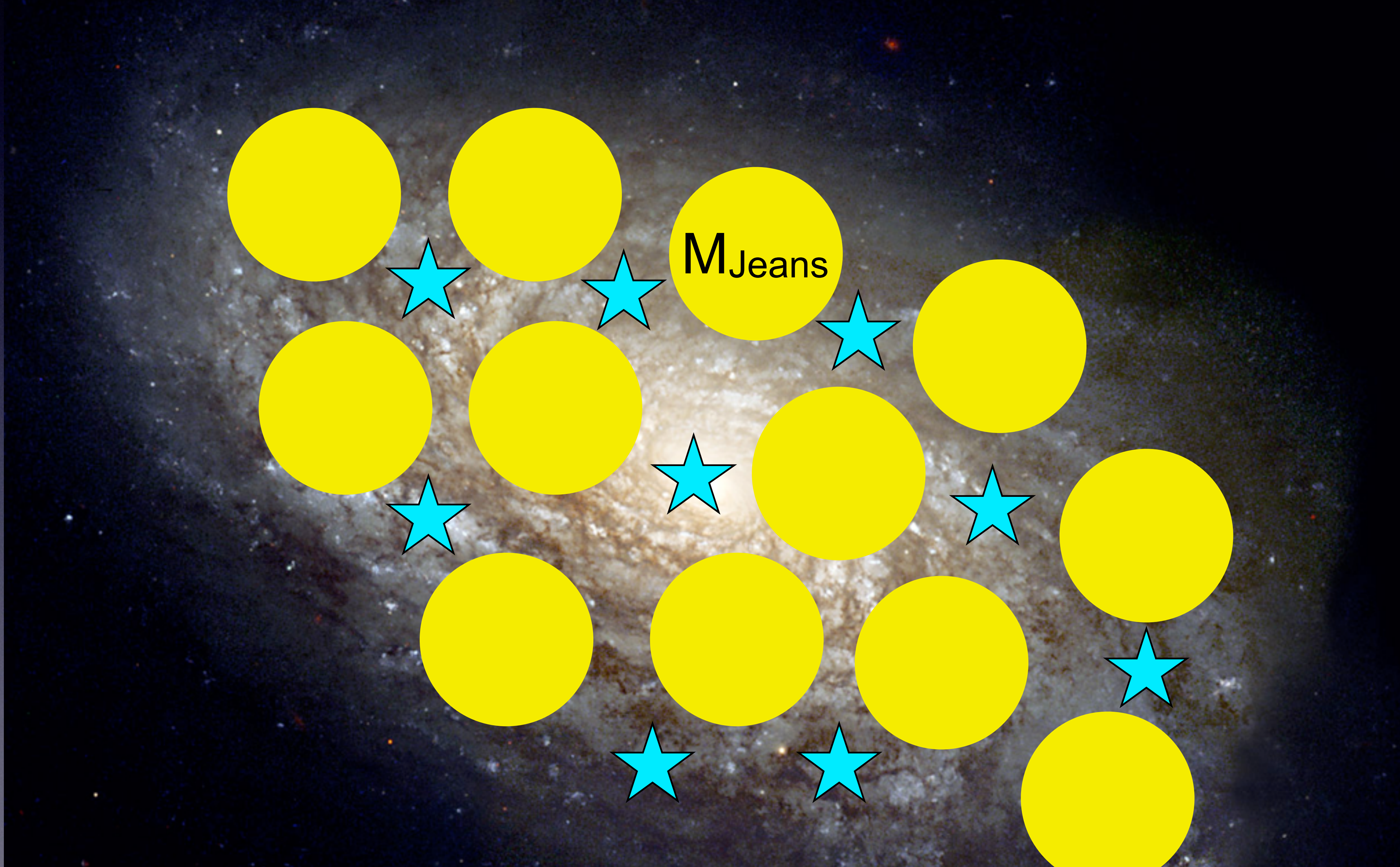


How does this dust affect CO/CII?


few × Mpc
(physical)
~ kpc
≲ 50 pc
Cosmic Web
Disk
GMCs

Molecular Clouds

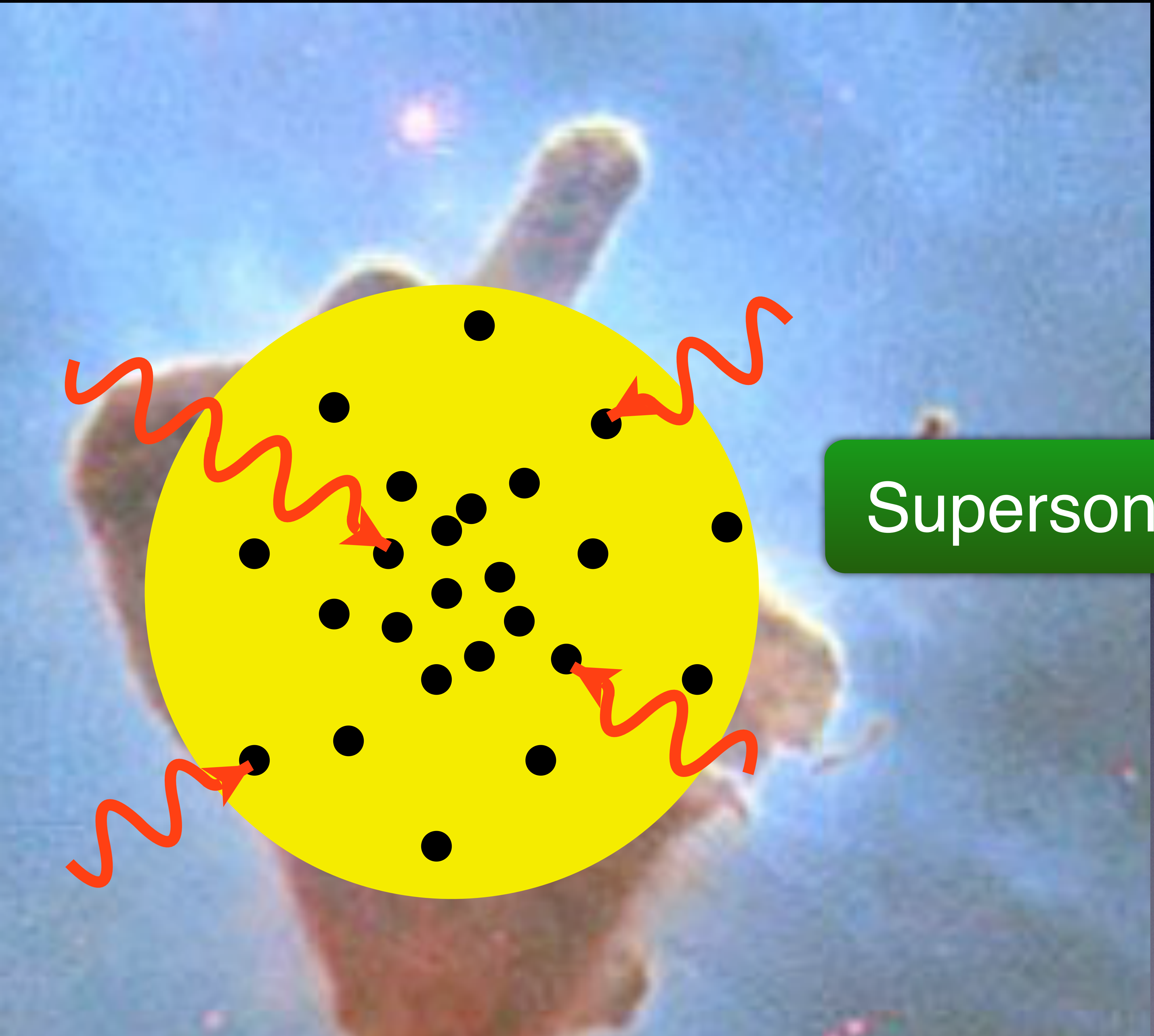
$\Sigma_{cloud} = \max(\Sigma_g, 85\ M_{sun}\ pc^{-2})$



Assume equilibrium $H_2 \rightarrow f_{mol} \sim 1$

Photo-dissociative regions

Photo-dissociative regions



Supersonically turbulent

Photo-dissociative regions

$$\ln\left(\frac{f_{\rm CO}}{f_{\rm H_2}}\right) = \frac{-4.0}{A_V}\left[0.53 - 0.045\ln\left(\frac{G_0'}{n_{\rm c}\,{\rm cm}^3}\right) - 0.097\ln(Z')\right]$$

Wolfire et al. (2010)

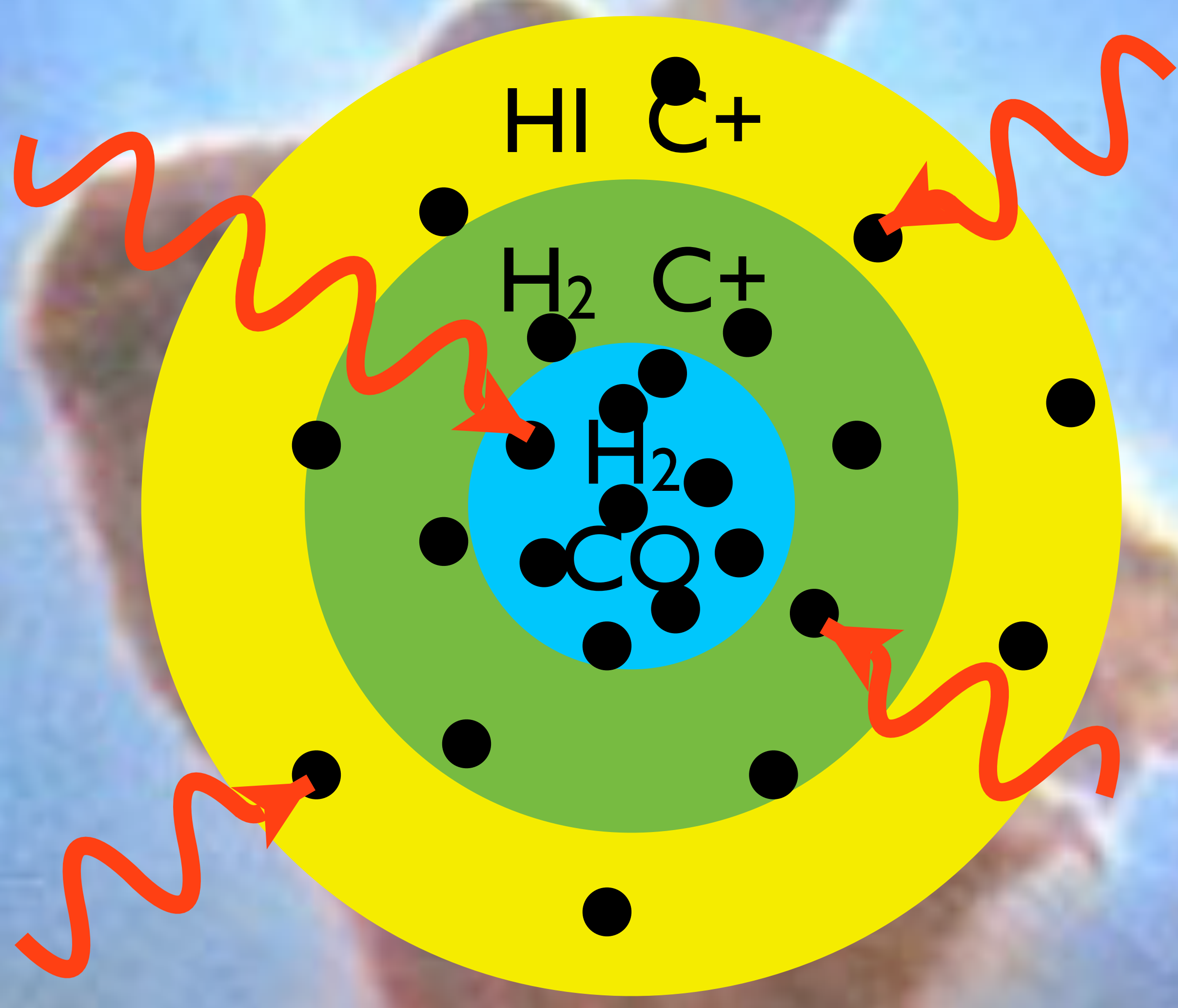


Photo-dissociative regions

$$\ln\left(\frac{f_{\rm CO}}{f_{\rm H_2}}\right) = \frac{-4.0}{A_V}\left[0.53 - 0.045\ln\left(\frac{G'_0}{n_{\rm c}\,{\rm cm}^3}\right) - 0.097\ln(Z')\right]$$

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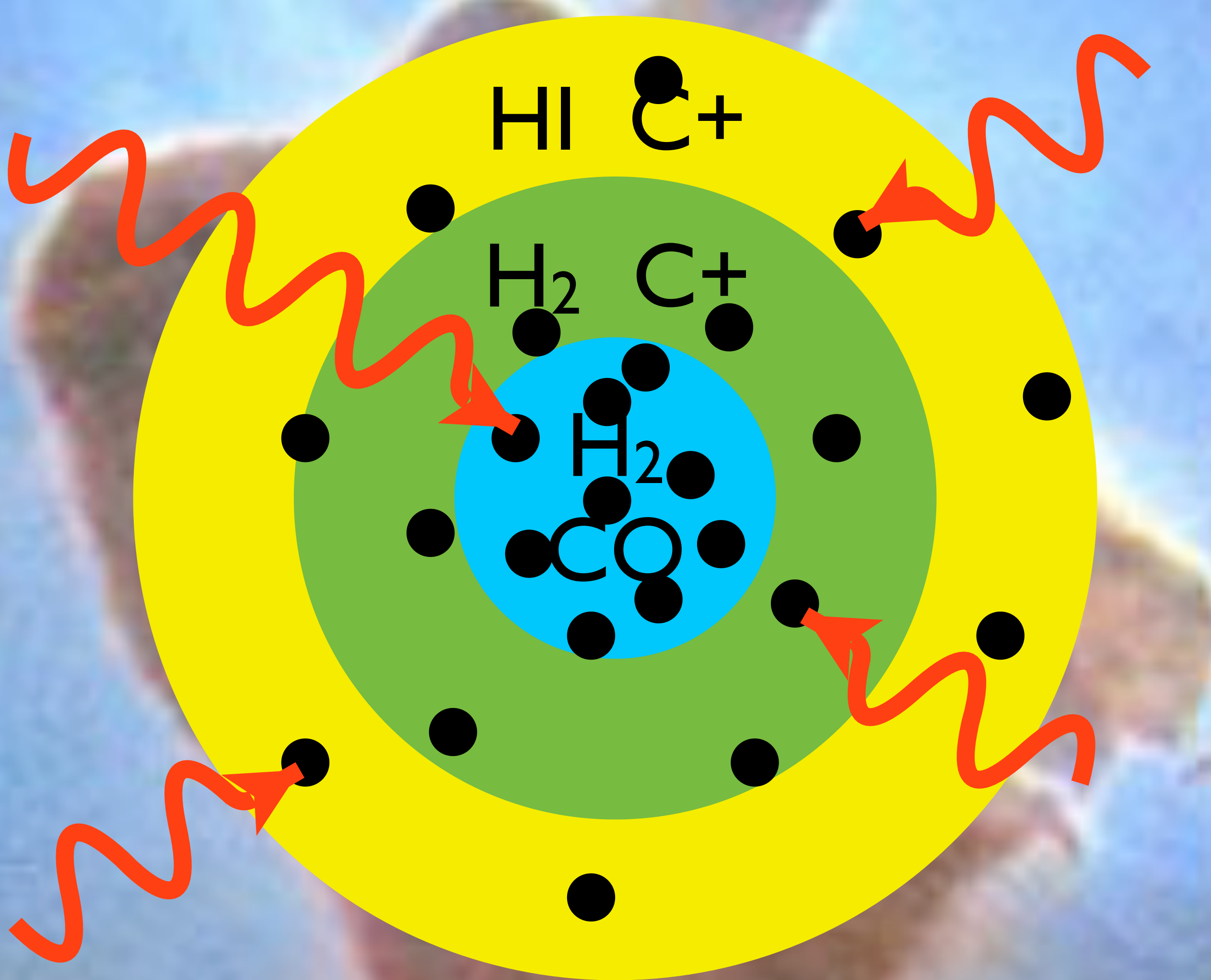

$$\ln(f_{\rm CO}/f_{\rm mol}) \approx -2.12/A_V$$

$$\propto 1/(Z_d\,\Sigma_{\rm gas})$$

Photo-dissociative regions

$$\ln\left(\frac{f_{\rm CO}}{f_{\rm H_2}}\right) = \frac{-4.0}{A_V}\left[0.53 - 0.045\ln\left(\frac{G_0'}{n_{\rm c}\,{\rm cm}^3}\right) - 0.097\ln(Z')\right]$$

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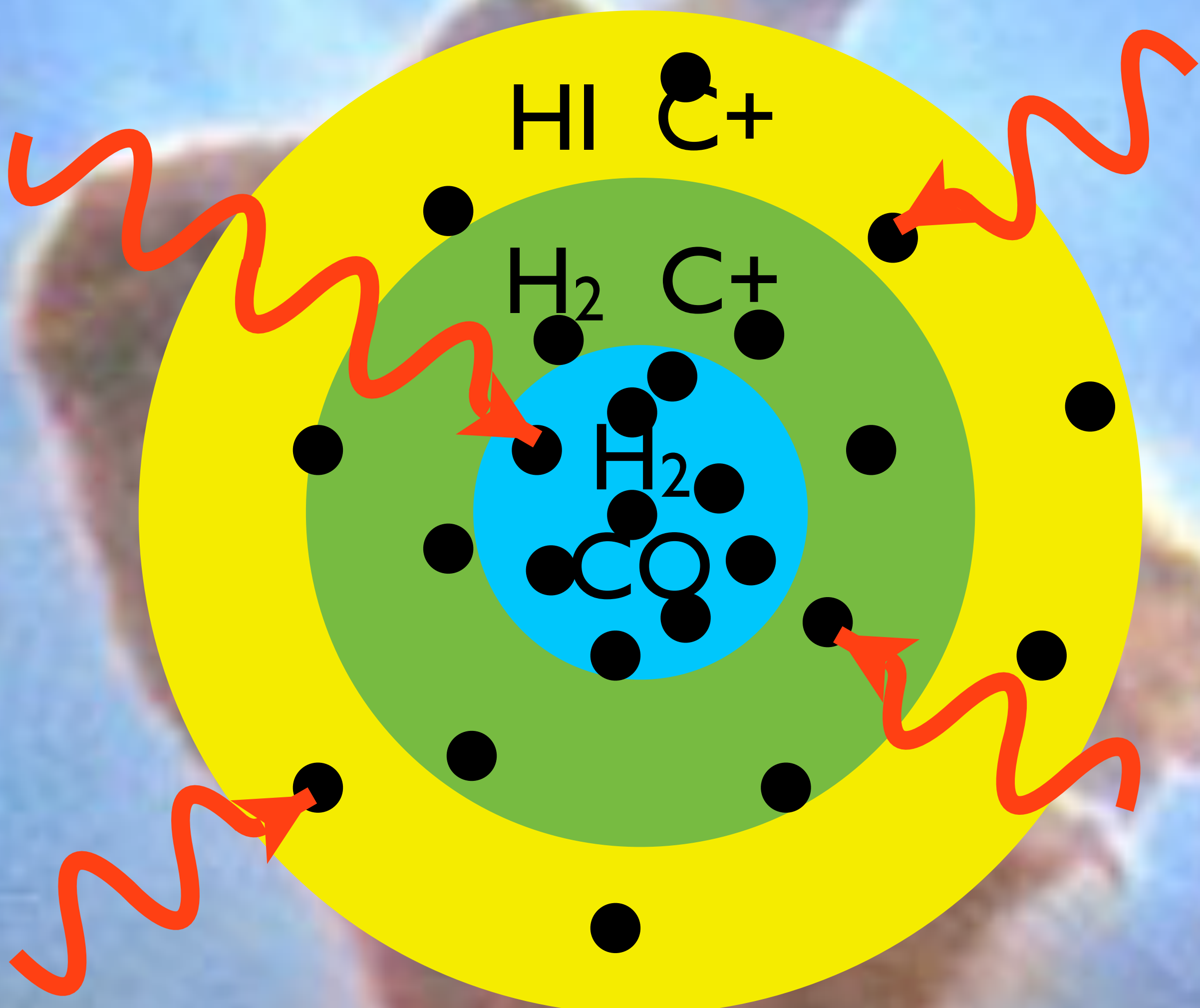
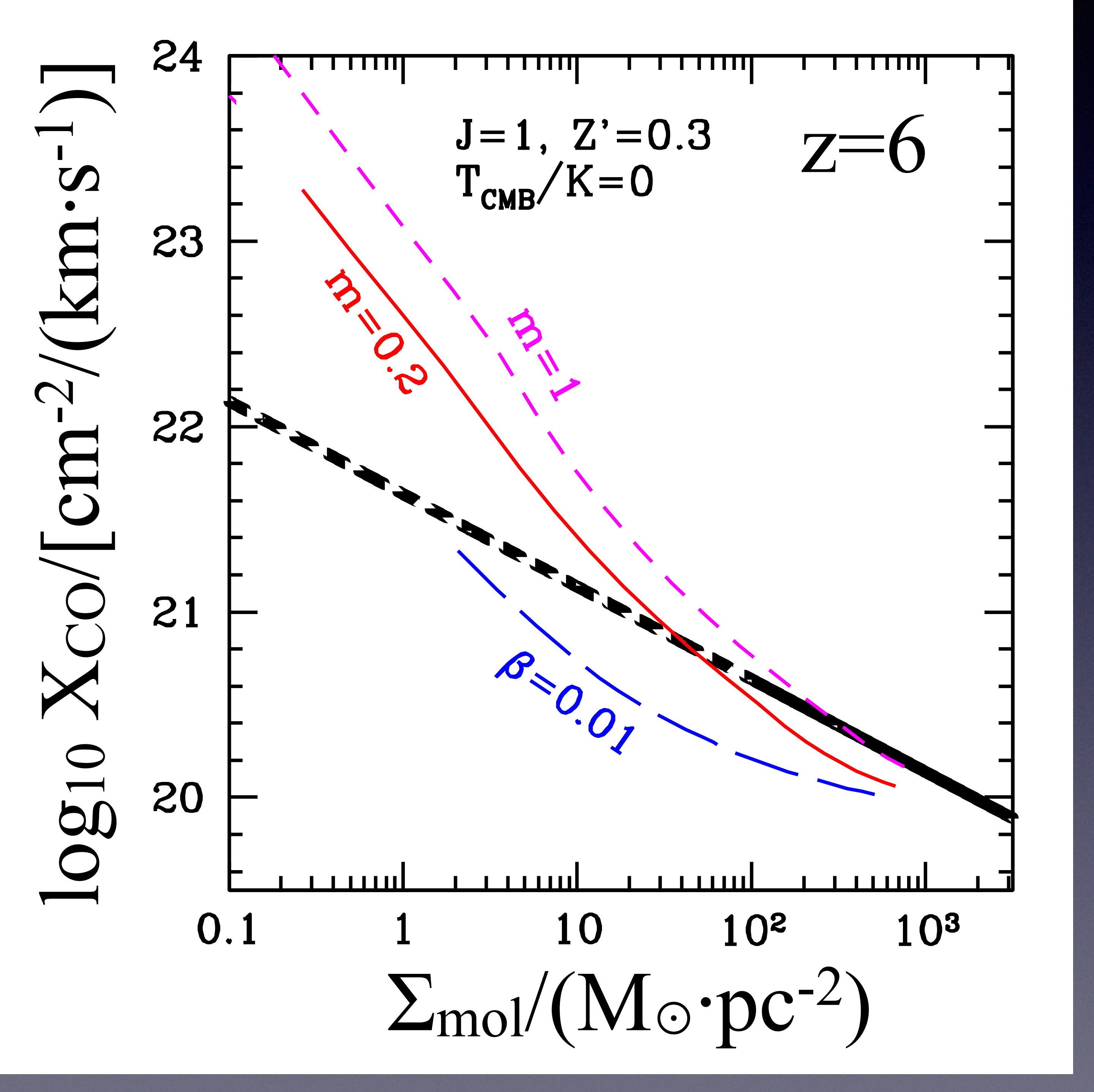


$$\ln(f_{CO}/f_{mol}) \approx -2.12/A_V$$
$$\propto 1/(Z_d\,\Sigma_{gas})$$

Compute emission:
Escape probability code
Krumholz & Thompson (2007)

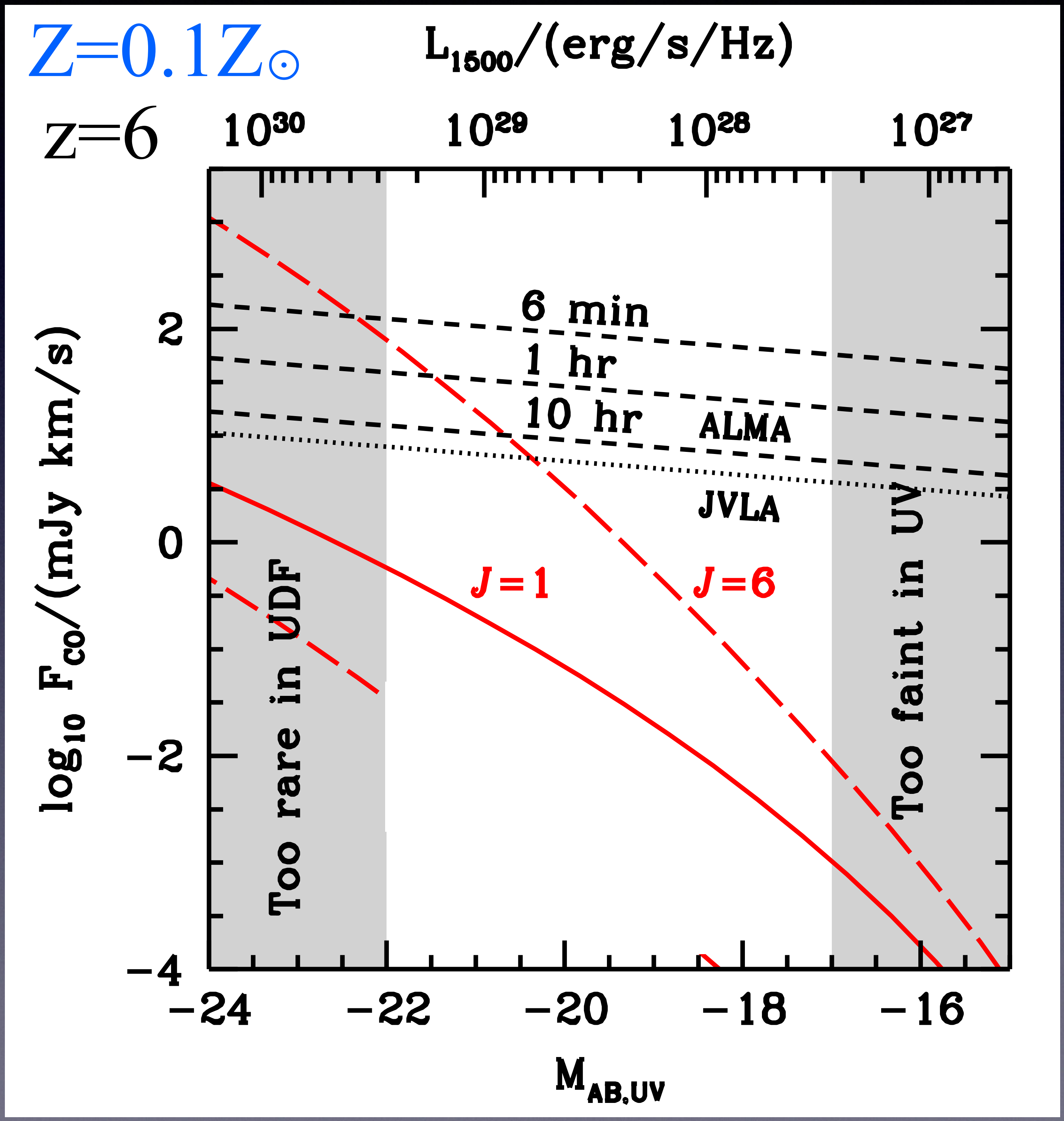
Consistency with Lower-z CO



Muñoz & Furlanetto (2013)

Following up LBGs in CO

Muñoz & Furlanetto (2013)



- low-Z kills you twice
- CMB subtraction

- CO(1–0): unobservable
- CO(6–5): depends on metallicity/ density peaks

CII

$L_{[CII]} \propto (1\text{-}f_{CO})\ Z'\ M_{gas}$

Assume: optically thin

CII

$$L_{[CII]} \propto (1-f_{CO})\, Z'\, M_{gas}$$

$$\ln\,(f_{CO}/f_{mol}) \propto A_V^{-1}$$

$$A_V \propto \Sigma_{gas}\, Z'\, R'_{dm}$$

CII

$$L_{[CII]} \propto (1-f_{CO})\, Z'\, M_{gas}$$

$$\ln (f_{CO}/f_{mol}) \propto A_V^{-1}$$

$$A_V \propto \Sigma_{gas}\, Z'\, R'_{dm}$$

if $f_{mol} \approx 1$ and $A_V \gg 1$, then:

$$1-f_{CO} \propto A_V^{-1} \propto R_{disk}^2/(M_{gas}\, Z'\, R'_{dm})$$

CII

$L_{[CII]} \propto (1-f_{CO})\, Z'\, M_{gas}$

$L_{[CII]} \propto R_{disk}^2/R'_{dm}$

$\ln (f_{CO}/f_{mol}) \propto A_V^{-1}$

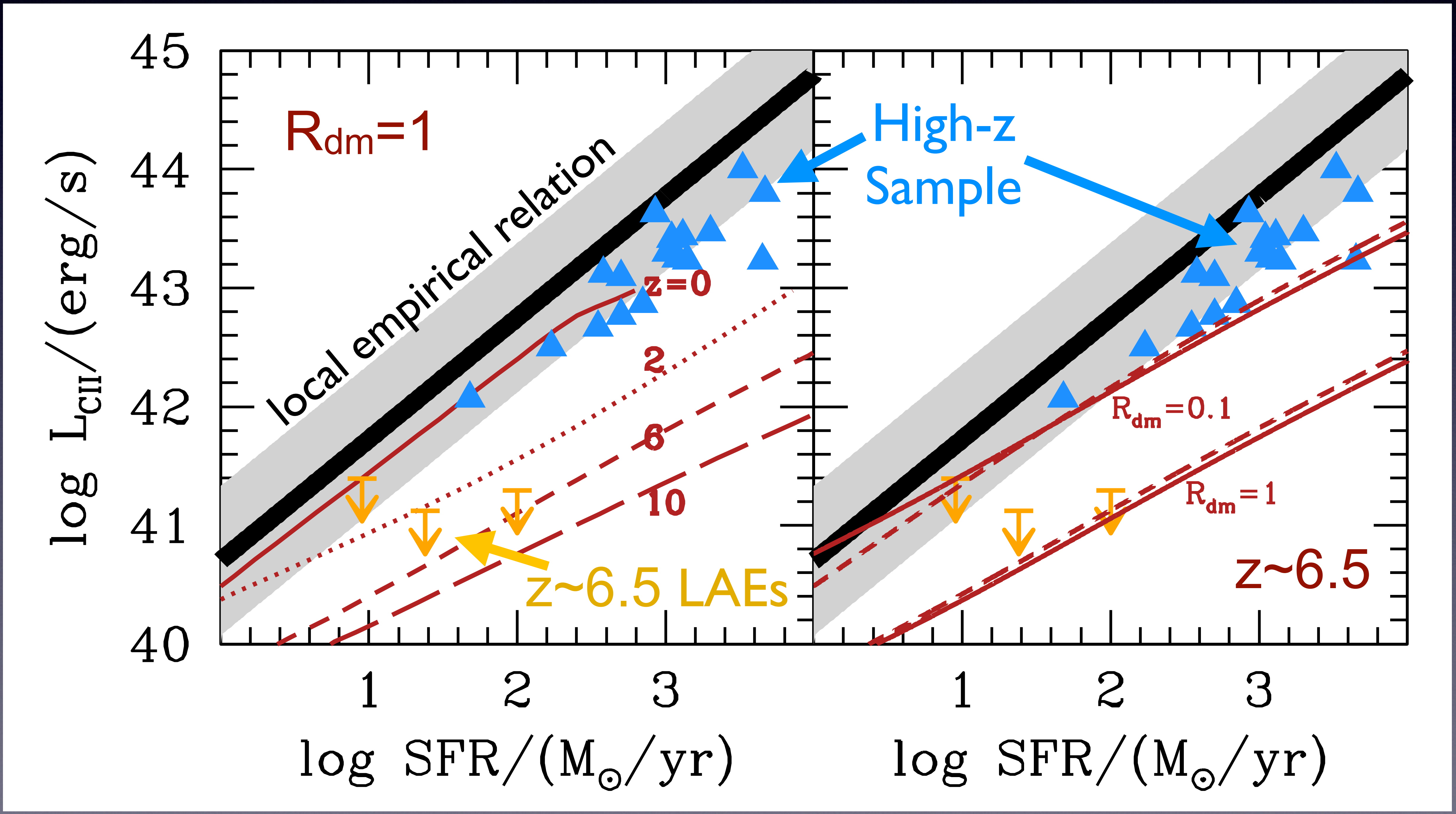
$A_V \propto \Sigma_{gas}\, Z'\, R'_{dm}$

if $f_{mol} \approx 1$ and $A_V \gg 1$, then:

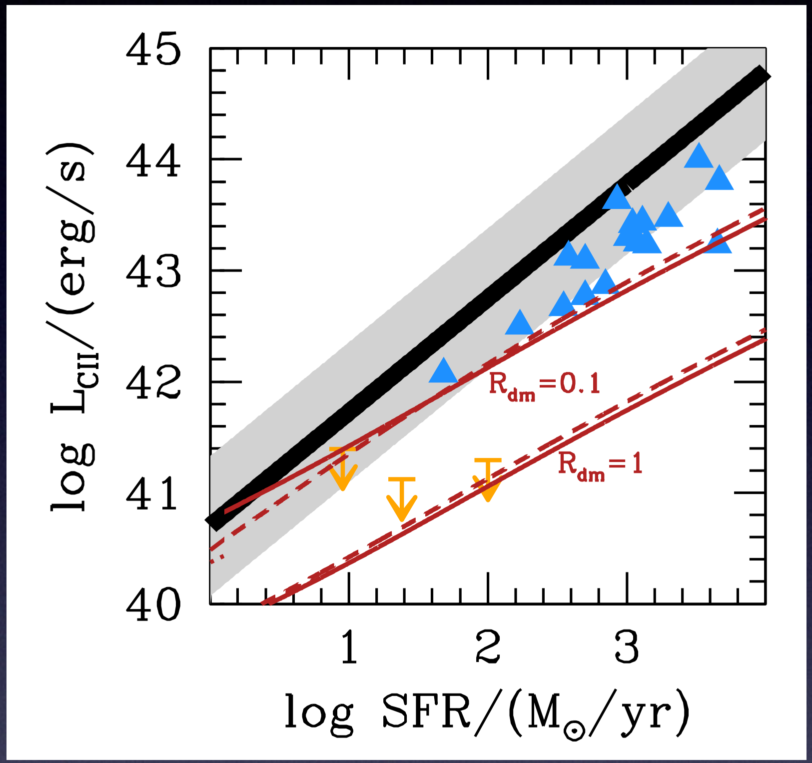
$1-f_{CO} \propto A_V^{-1} \propto R_{disk}^2/(M_{gas}\, Z'\, R'_{dm})$

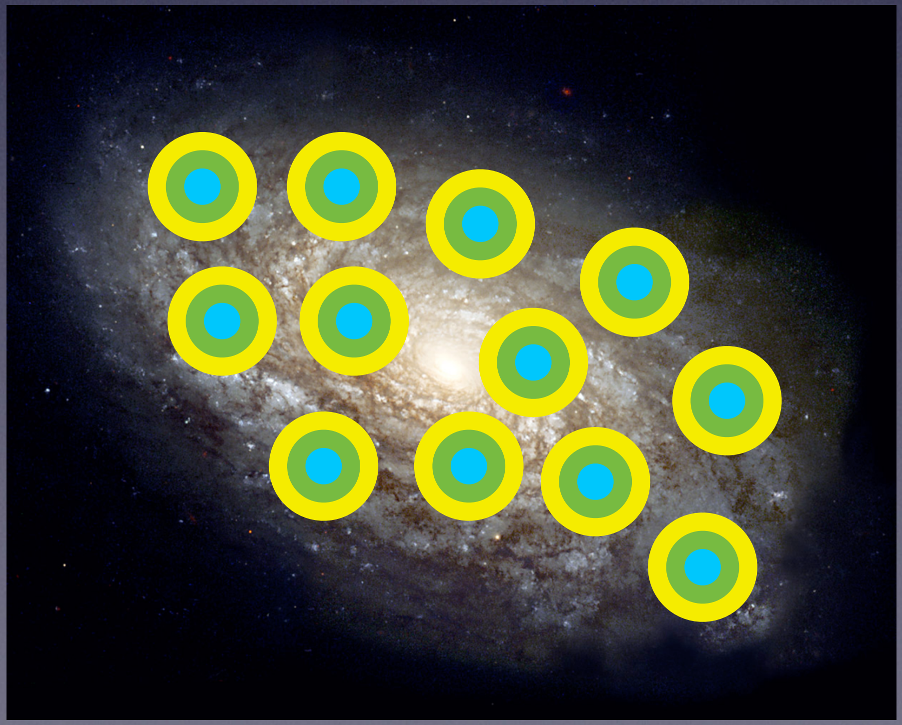
CII

$$L_{[CII]} \propto R_{disk}^2 / R'_{dm}$$



Possible Interpretations





- Dust is depleted at a given metallicity by > factor of 10
- Radius relation is wrong or biased
- Dust/dissociation is anisotropic
- Hot component
- Standard PDR model doesn't apply in limit of extreme extinction

Summary

- Analytic model of high-z ISM
- Describes how gas fractions relate to feedback
- Unlikely to observe z~6 LBGs in CO
- FIR+[CII] sets Z<0.3 for undetected LAEs
- [CII] in QSOs/SMGs requires more dissociation than can be explained with galaxy+PDR model
    - new picture?
- Probe feedback and dust enrichment at high-z