# You Can’t Always Get What You Want: Making Sense of Observable Tracers of Gas and Star Formation

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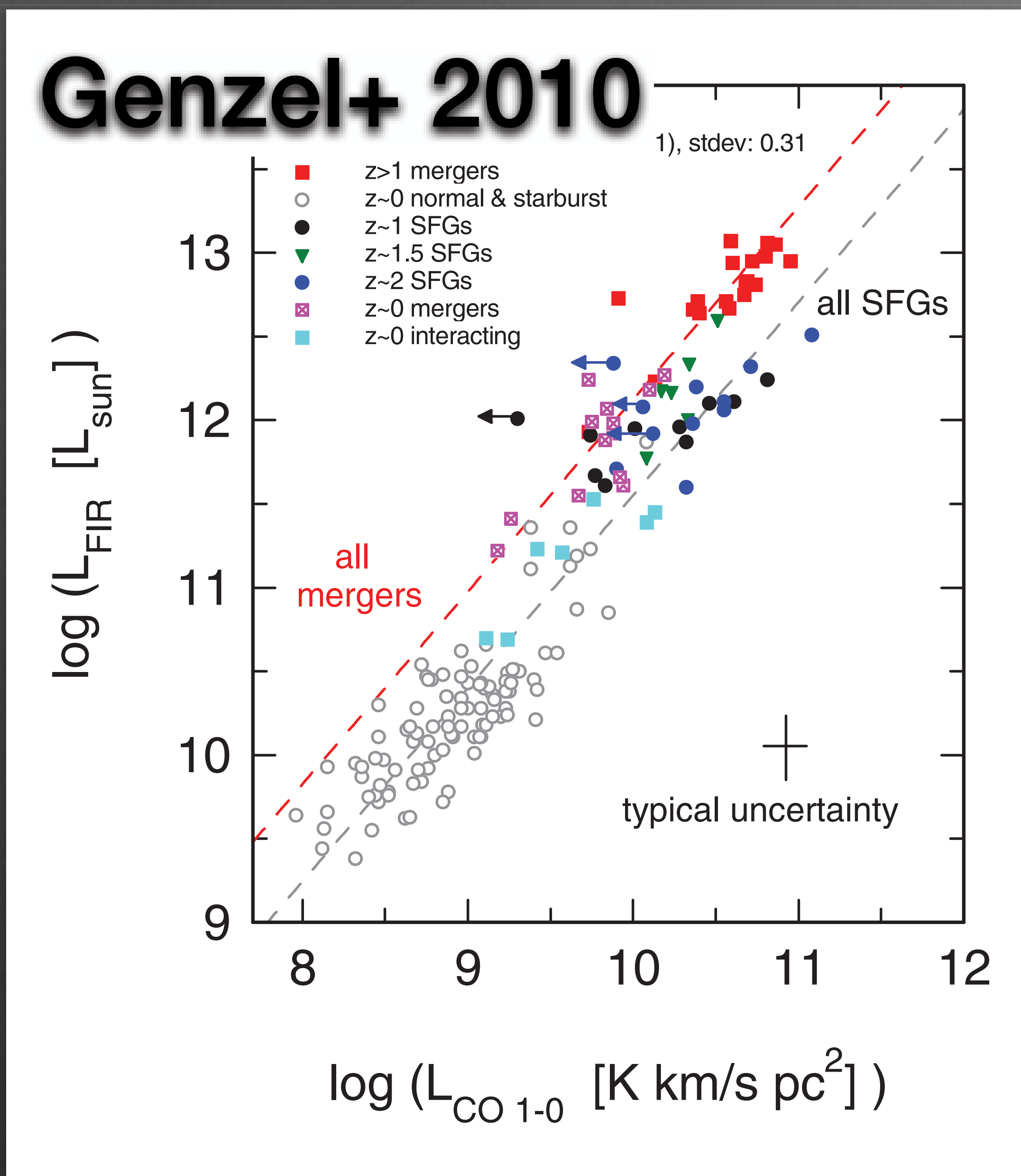
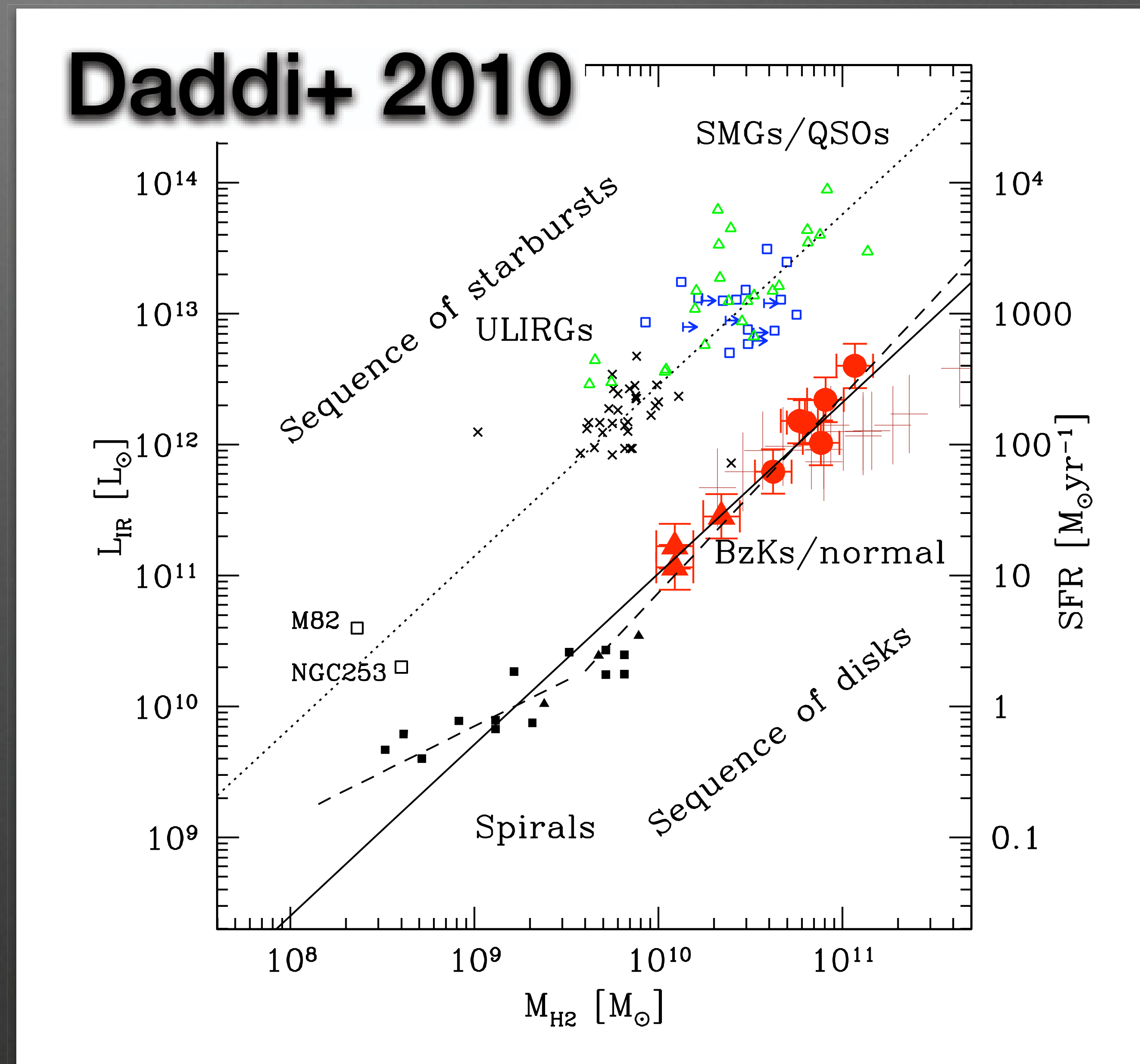
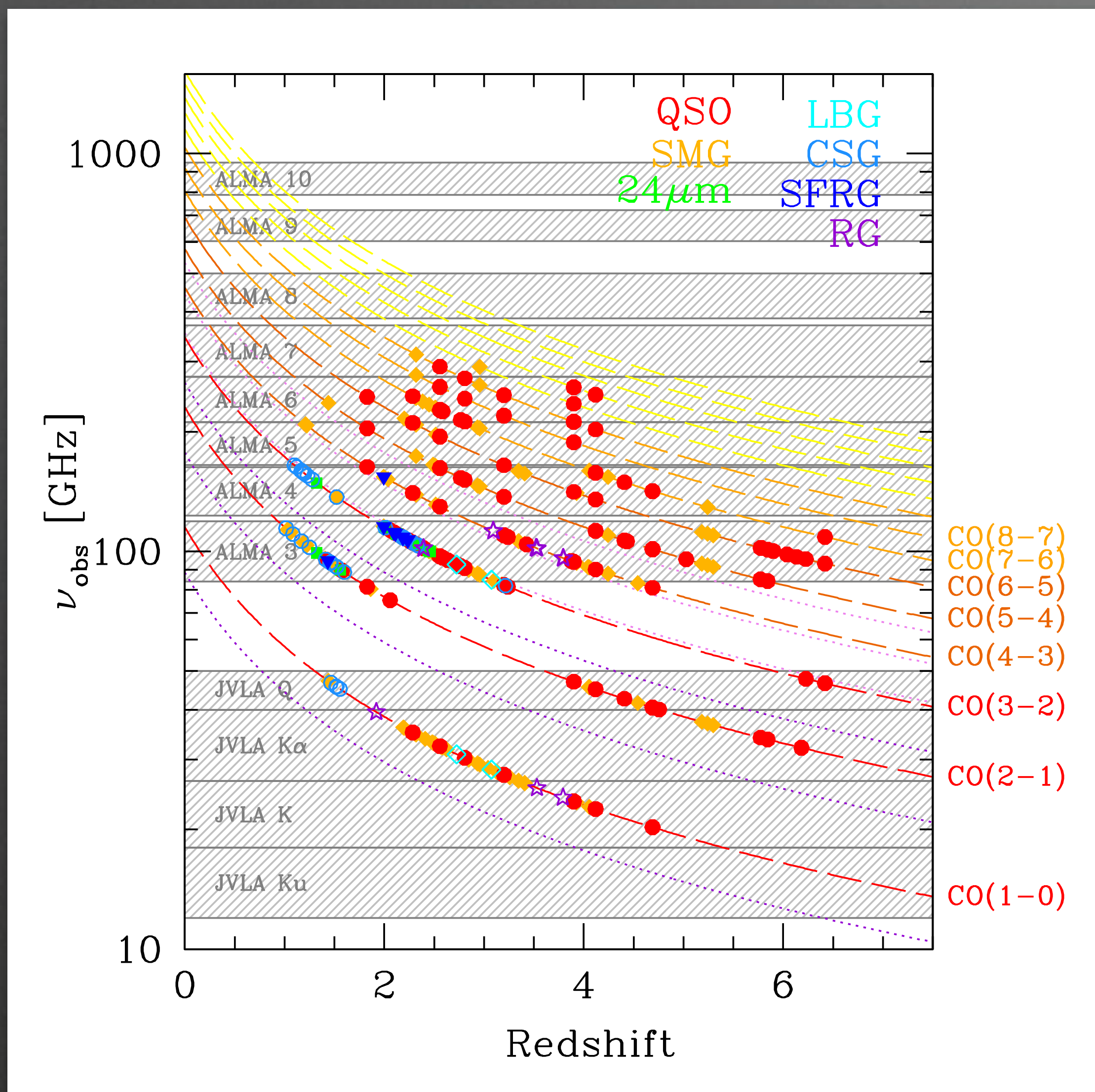
- Measure ionization proxy (e.g., $H\alpha$, OIII), or FUV or IR luminosity; infer SFR
- Plot what we can and pray

# Why CO to $H_2$ is a Problem

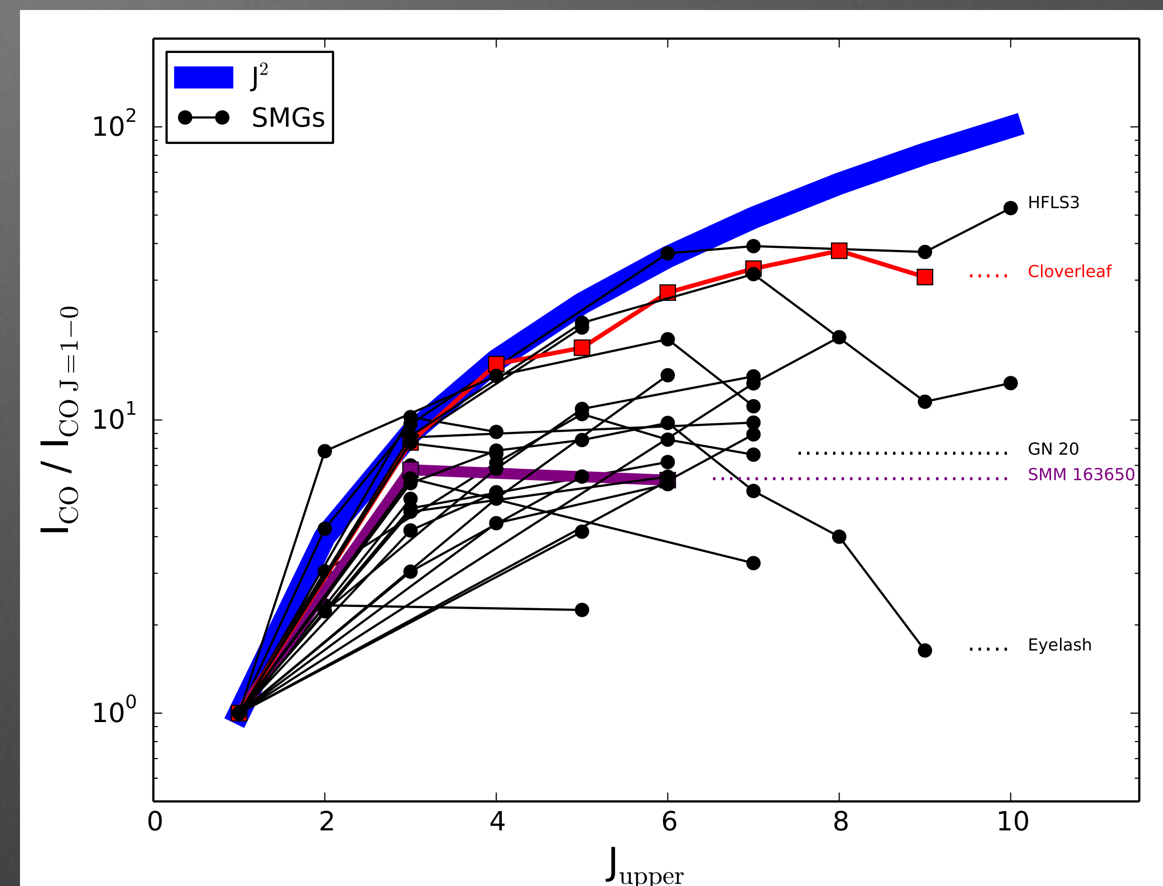


# Why is High-J CO a Problem

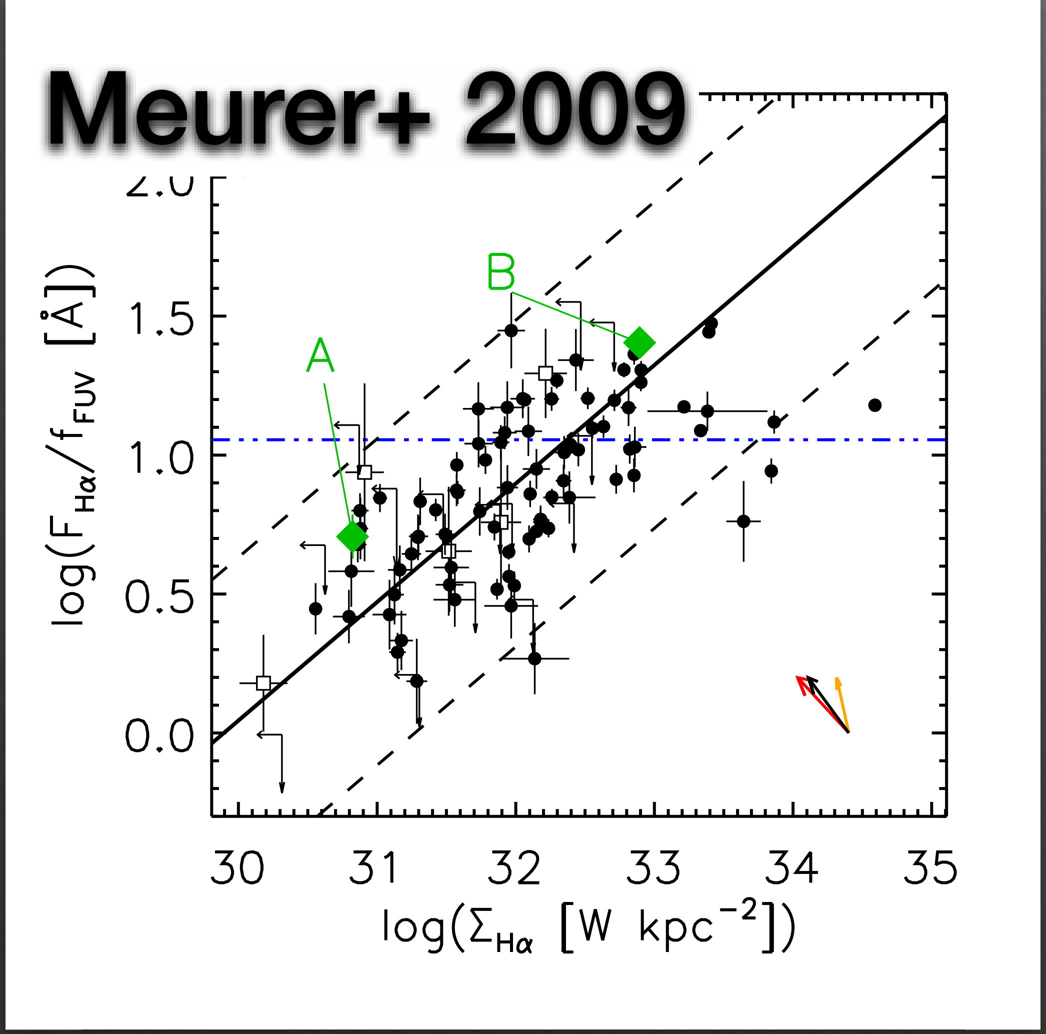


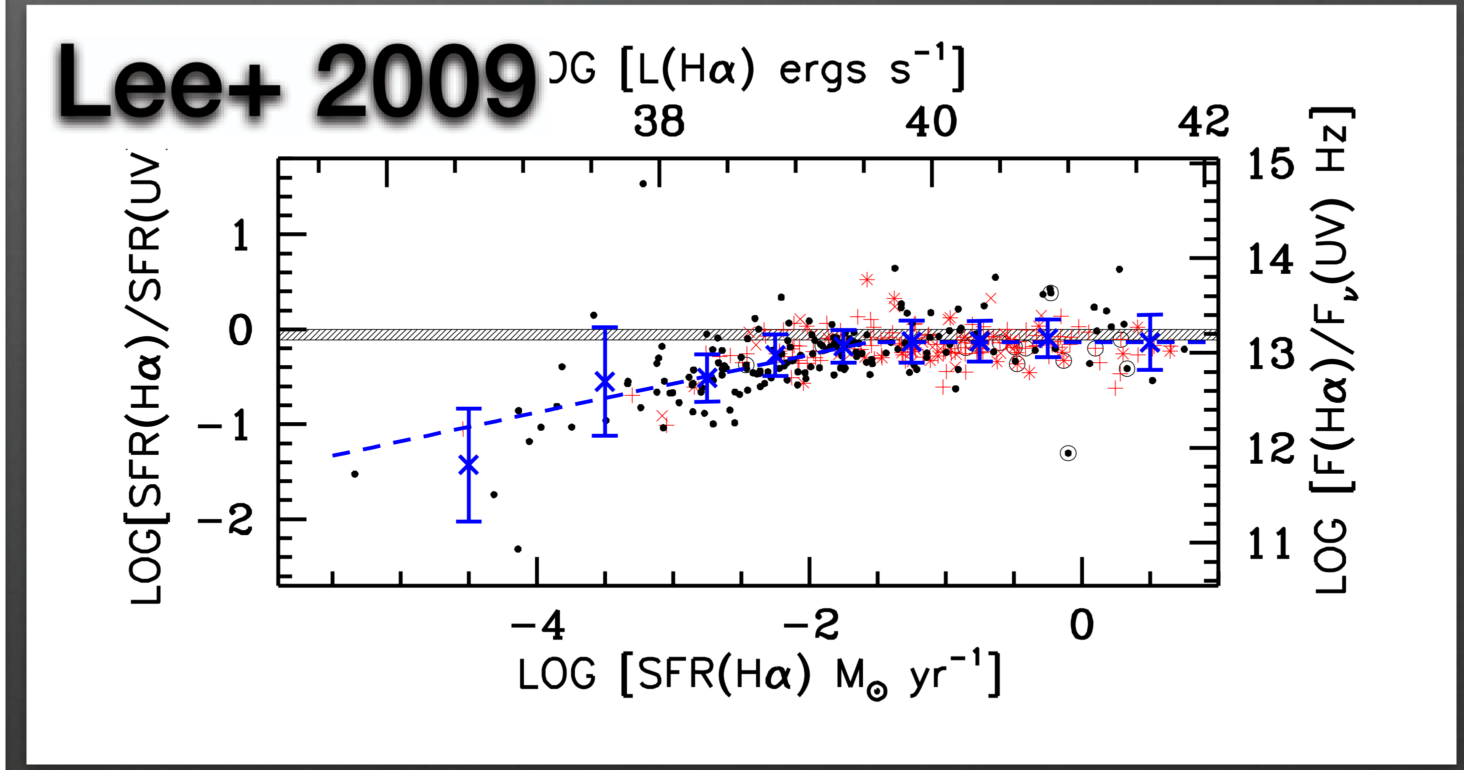

All CO detections at z > 1(circa 2013, Carilli & Walter 2013)




All z > 1 SMGs for which CO J=1-0 has been measured (circa 2014, Narayanan & Krumholz 2014)

# Why Ionization-Based SFRs are a Problem



# CO Emission: 30 sec Tutorial

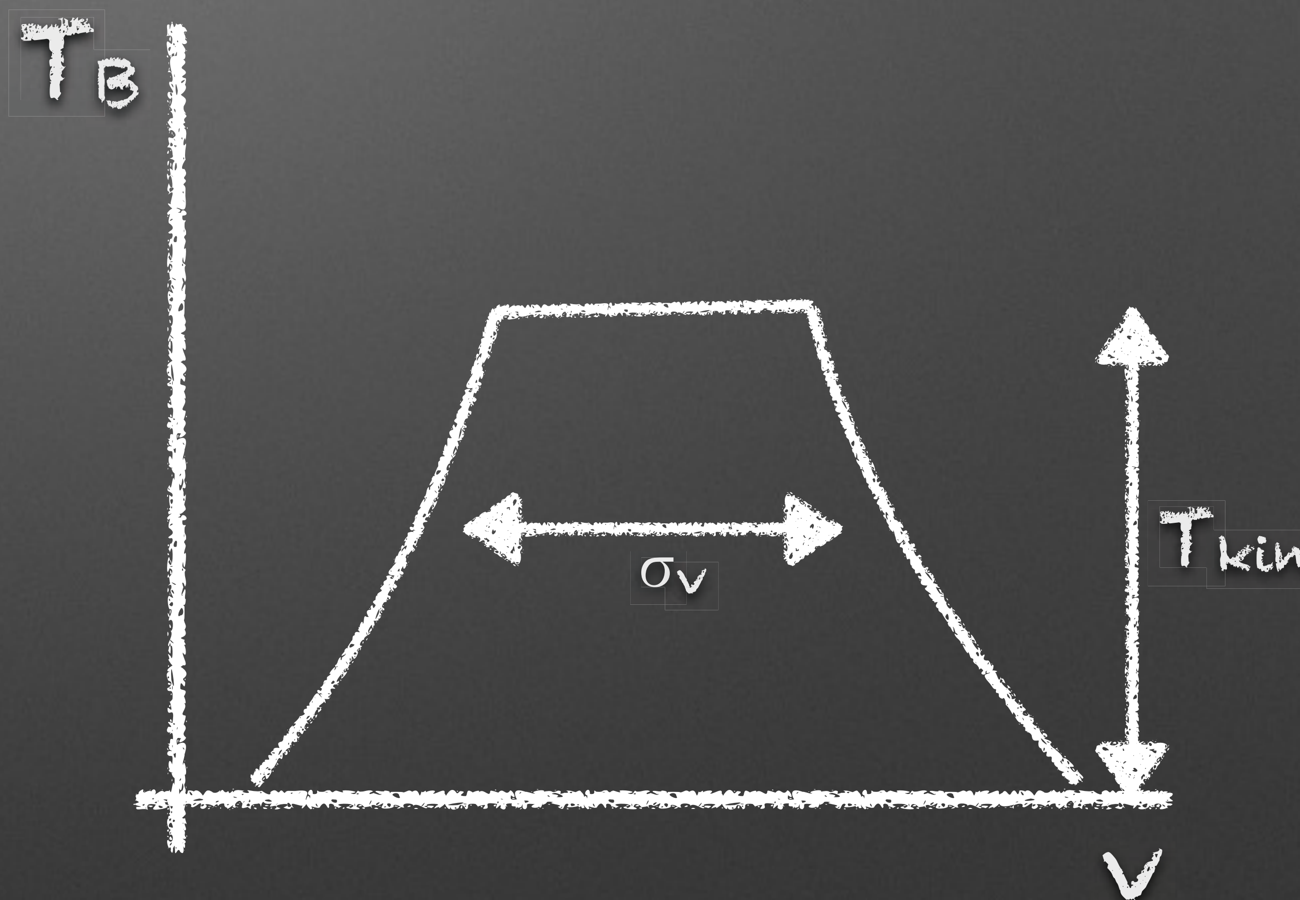
- Low-J CO almost always optically thick ⇒

  $W_{CO} \approx T_{kin}\, \sigma$

- Related to CO mass via virial thm: $\sigma \sim (\alpha_{vir} GM/R)^{1/2} \sim N_H\, (\alpha G/n_H)^{1/2}$

- Thus $W_{CO} \sim N_H\, X_{CO}$ with $X_{CO} \sim (\alpha_{vir} G/n_H)^{1/2}\, T_{kin}$

- Constant $X_{CO}$ only if $(\alpha_{vir}/n_H)^{1/2}\, T_{kin} \sim$ constant



# Steps Toward a Theoretical Model of CO Emission

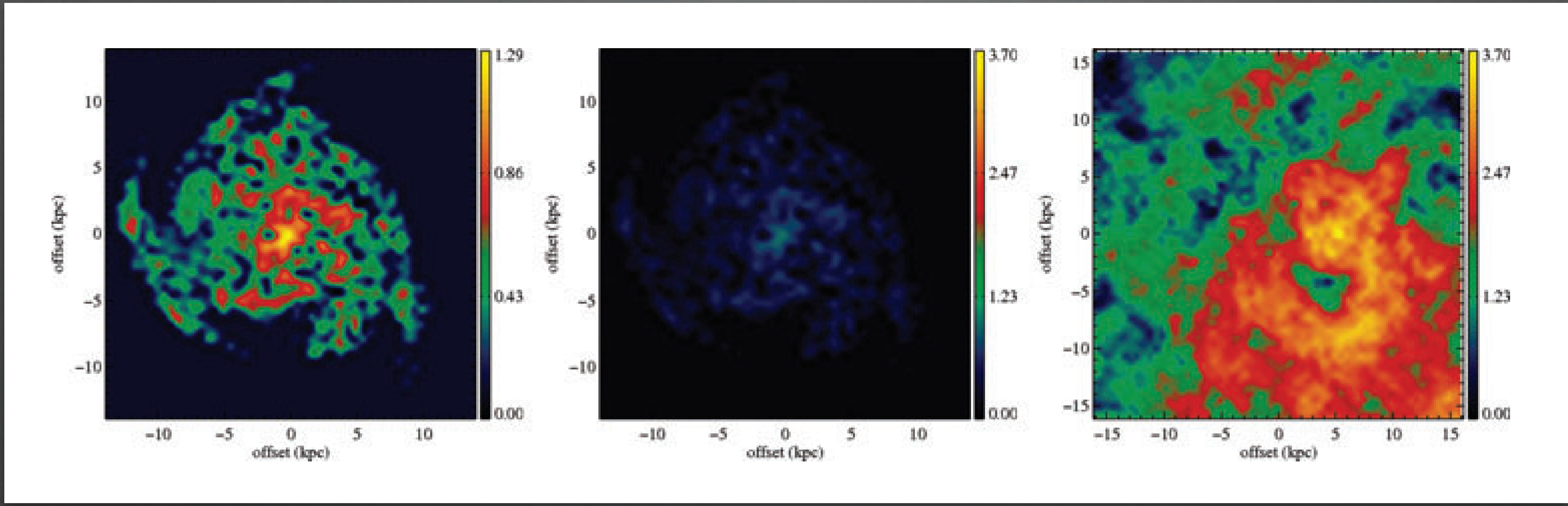
1. Need distribution of gas and star formation: GADGET simulations of isolated, merging galaxies (Narayanan+ 2011)

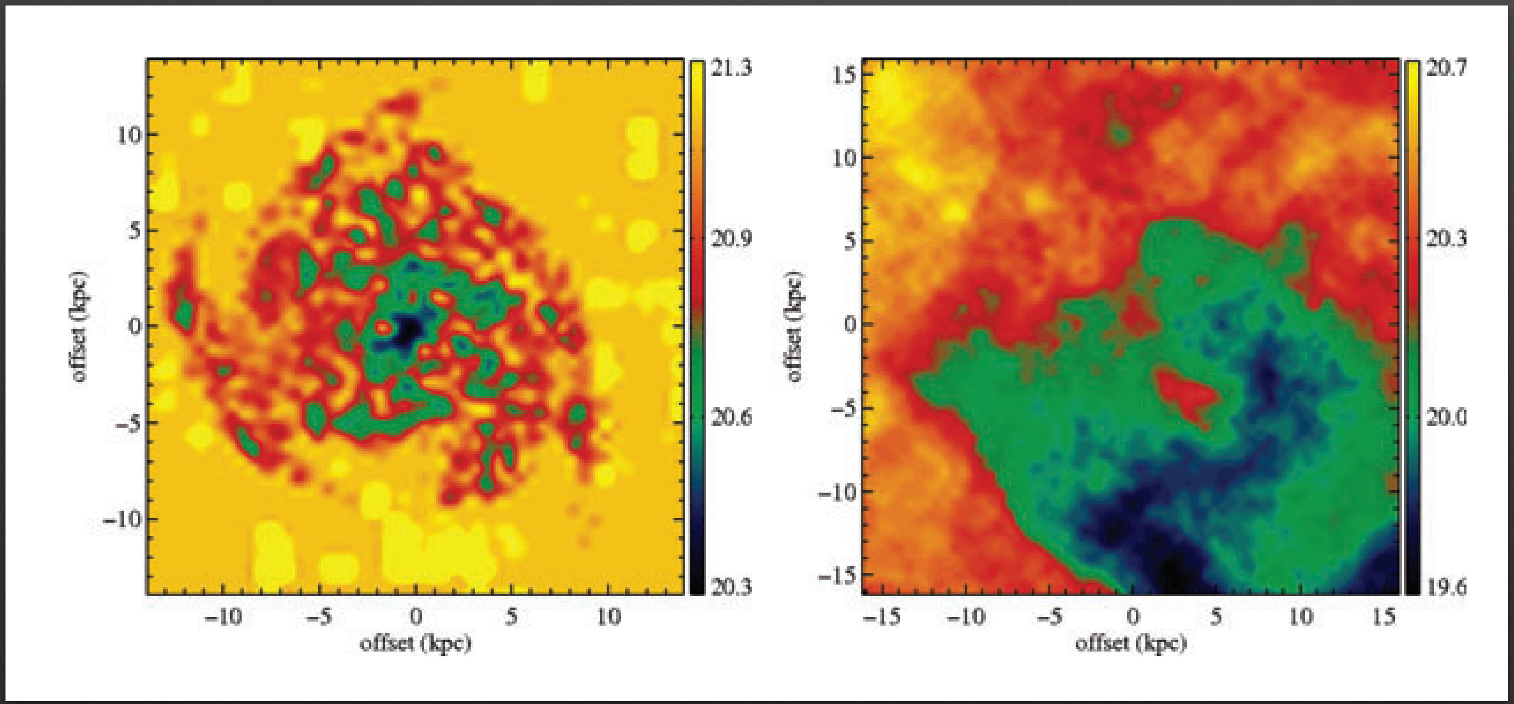
2. Self-consistently compute dust temperature: post-process with SUNRISE (Jonsson 2006, Jonsson+ 2010)

3. Compute gas chemical state ($H_2$, CO abundance) w/ equilibrium chemical models (Krumholz+ 2008, 2009; Wolfire+ 2010)

4. Solve for gas temperature, CO excitation ladder, CO emissivity with DESPOTIC (Krumholz 2014)

# Example: Disk and Merger



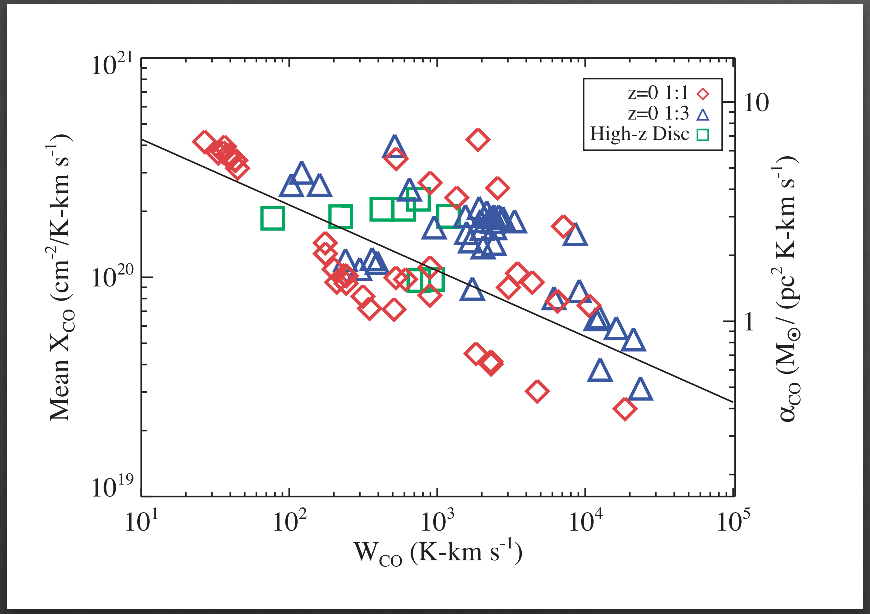




Nayanan+ 2011:

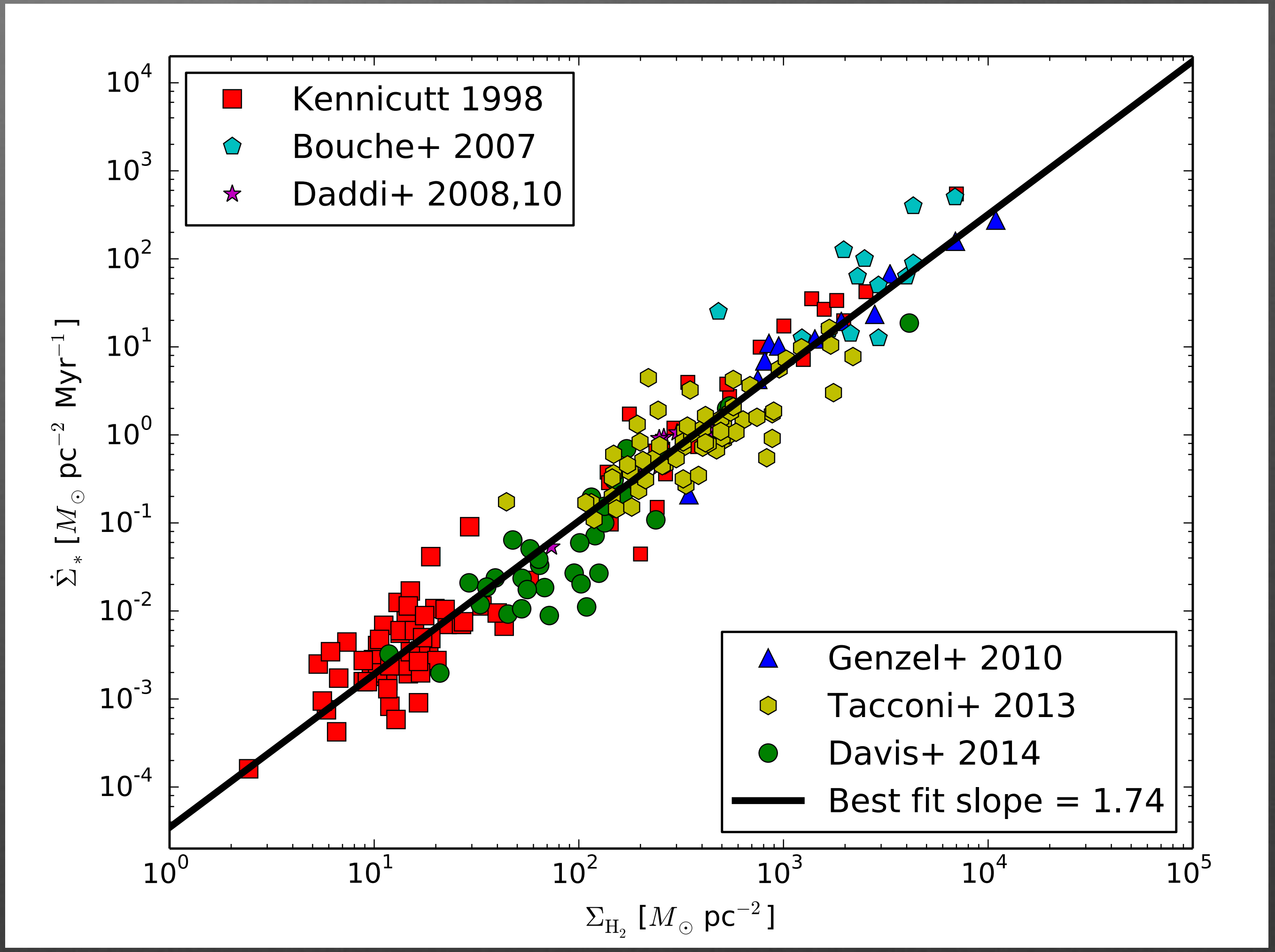
- Top: $W_{CO}$ vs. position in disk and merger simulations
- Bottom: $X_{CO}$ vs. position in the same simulations

# Application to Observations

- From simulation library, best correlation of $X_{CO}$ with another observable is with $W_{CO}$




- Fitting formula: $X_{CO}/10^{20} \approx \min[4, 6.75 \times \langle W_{CO} \rangle^{-0.32}]$ (Narayanan+ 2011, 2012)

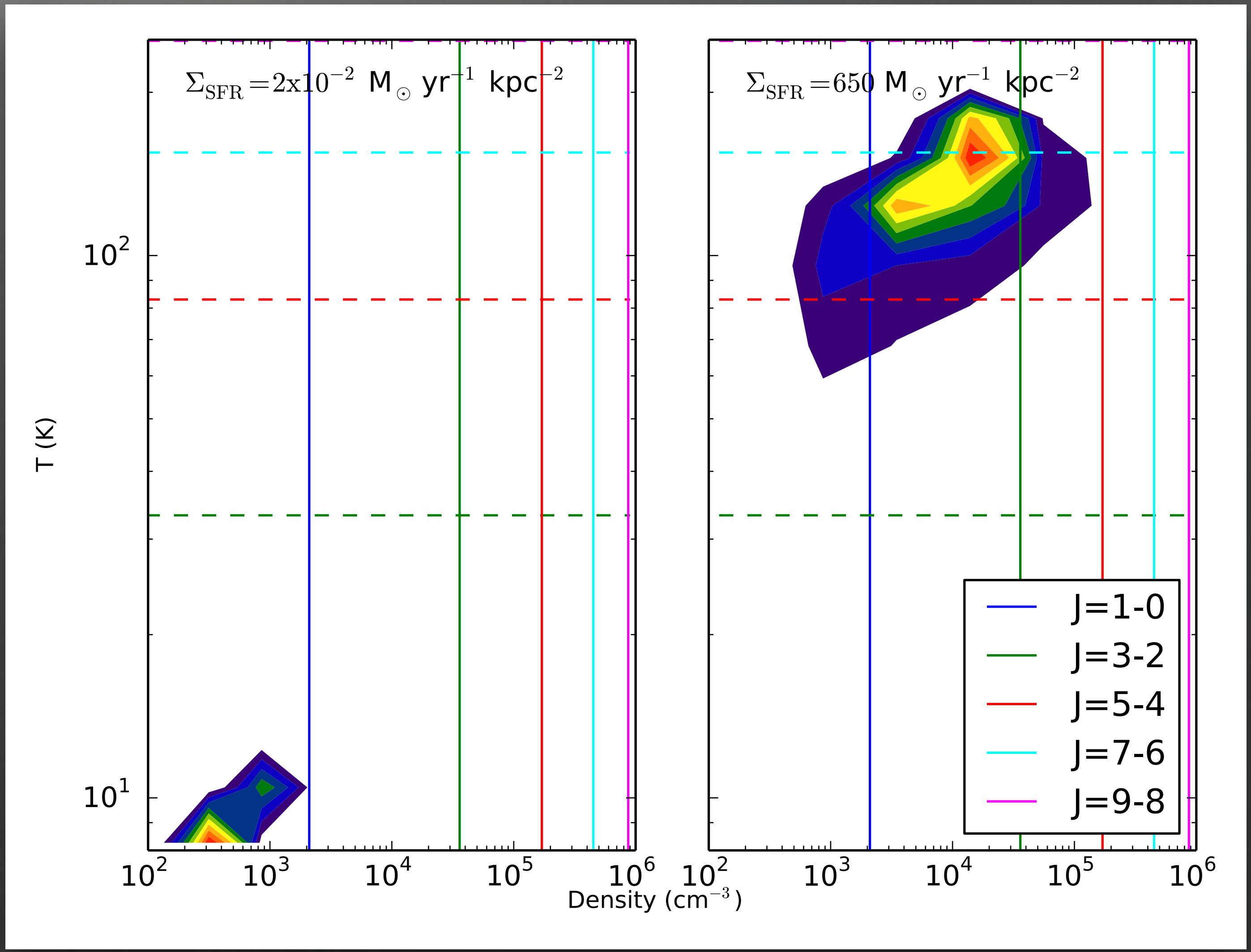



Updated KS plot with Narayanan+ 2012 fitting formula for $X_{CO}$ (Thompson & Krumholz 2014)

# Extension to High-J Lines

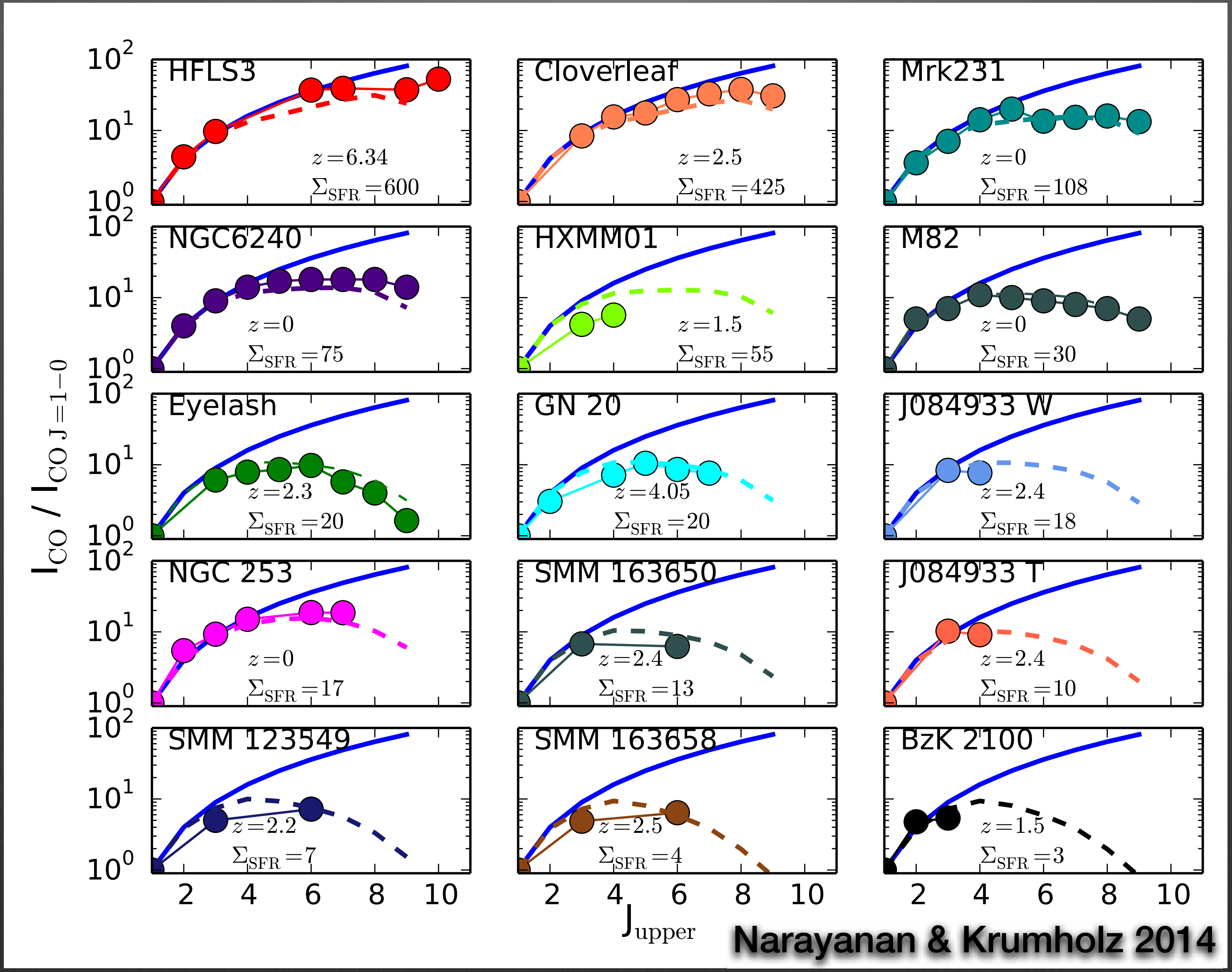
Need to worry about:

1. Gas temperatures: must be warm enough to excite the line
2. Gas density: must be dense enough to thermalize high J states
3. Column density: must be opaque enough for line to saturate




ρ-T PDFs with CO level temperatures, critical densities overlaid in a quiescent disk (left) and a merger (right) (Narayanan & Krumholz 2014)

# Comparison to Observed CO SLEDs




Narayanan & Krumholz 2014

# High $n_{crit}$, Low T lines

- SFR is a fixed mass fraction per free-fall time, so for density n, SFR $\propto L_{IR} \propto n^{3/2}$
- Line luminosity depends on mass above $n_{crit}$
- Low $n_{crit}$ (e.g. CO 1-0) lines give $L_{line} \propto n^1$
- High $n_{crit}$ (e.g. HCN 1-0) lines give $L_{line} \propto n^p$, $p > 1$
- $\Longrightarrow L_{IR} \propto L_{line}^q$, $q \sim 3/2$ for low $n_{crit}$, $q < 3/2$ for high $n_{crit}$

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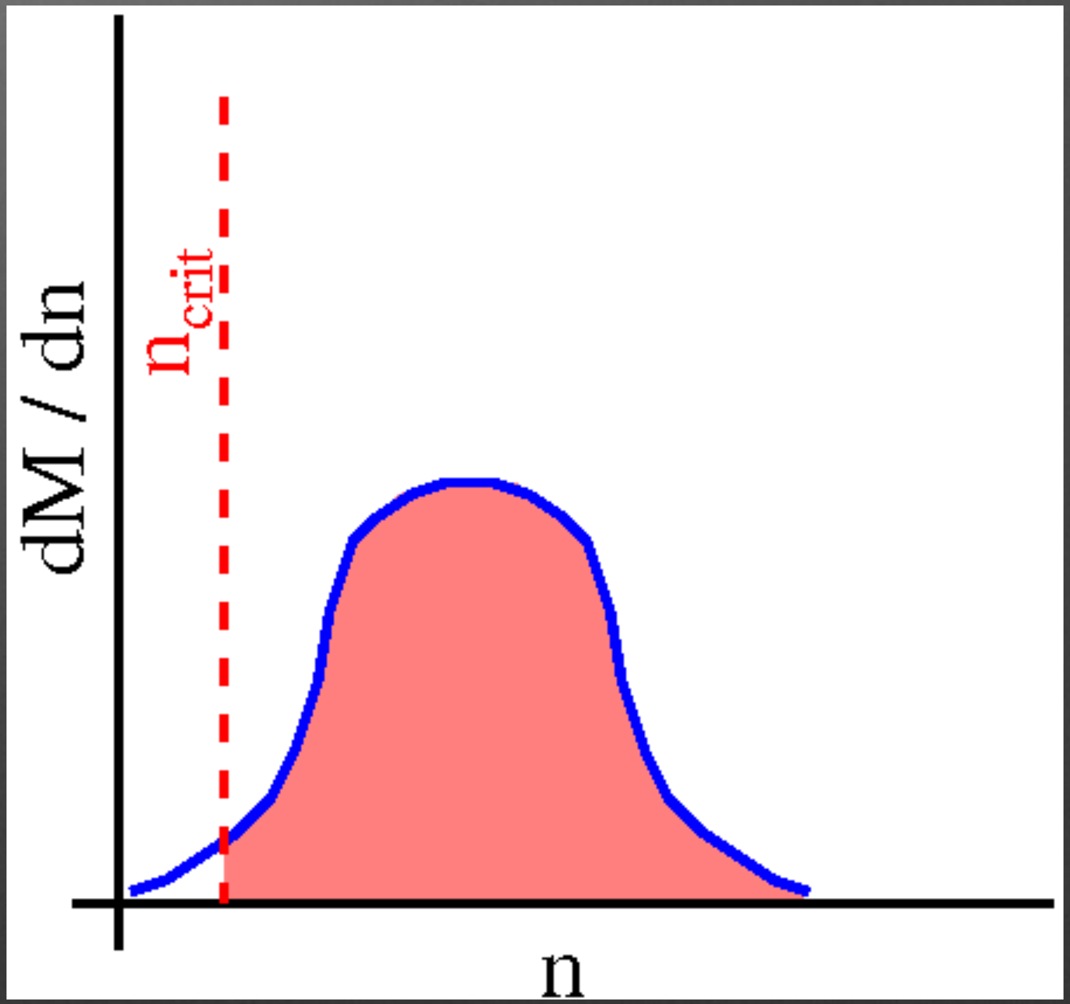

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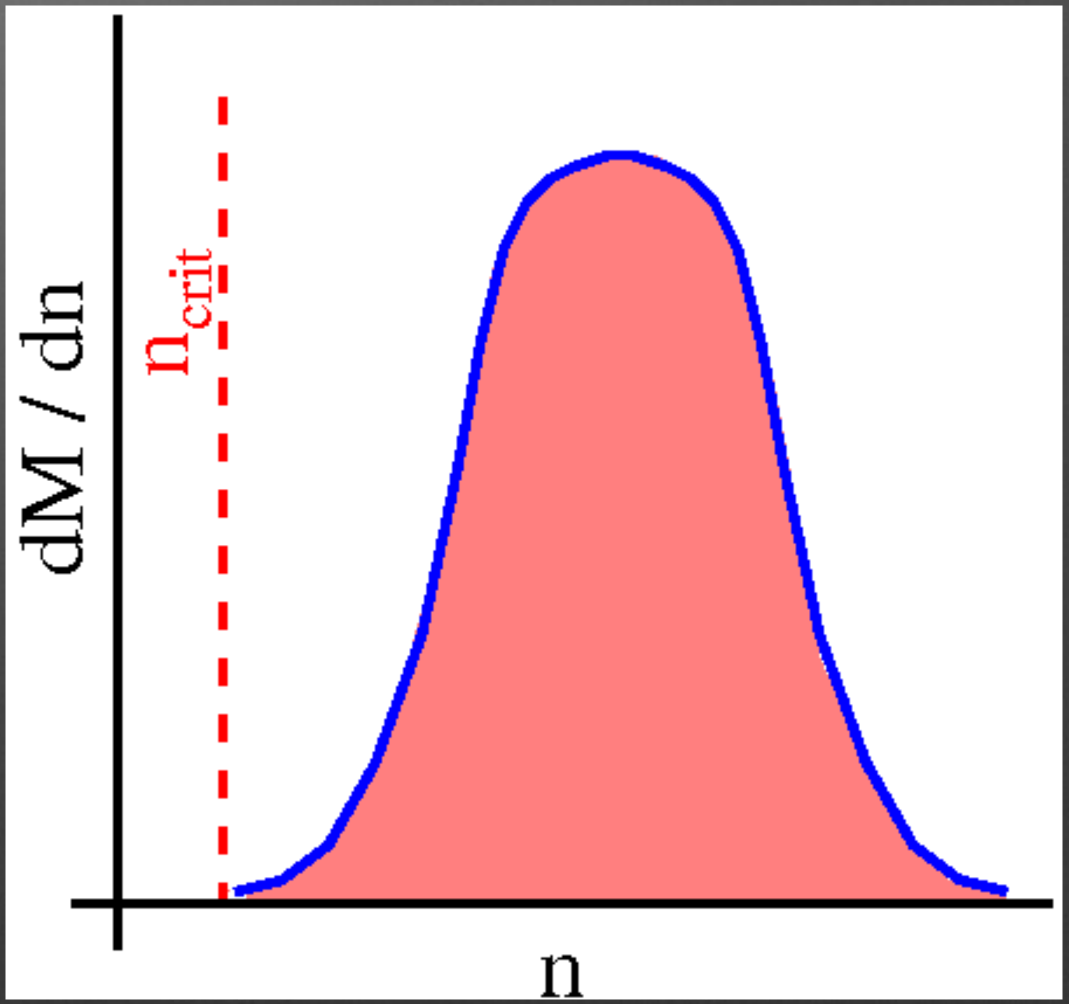

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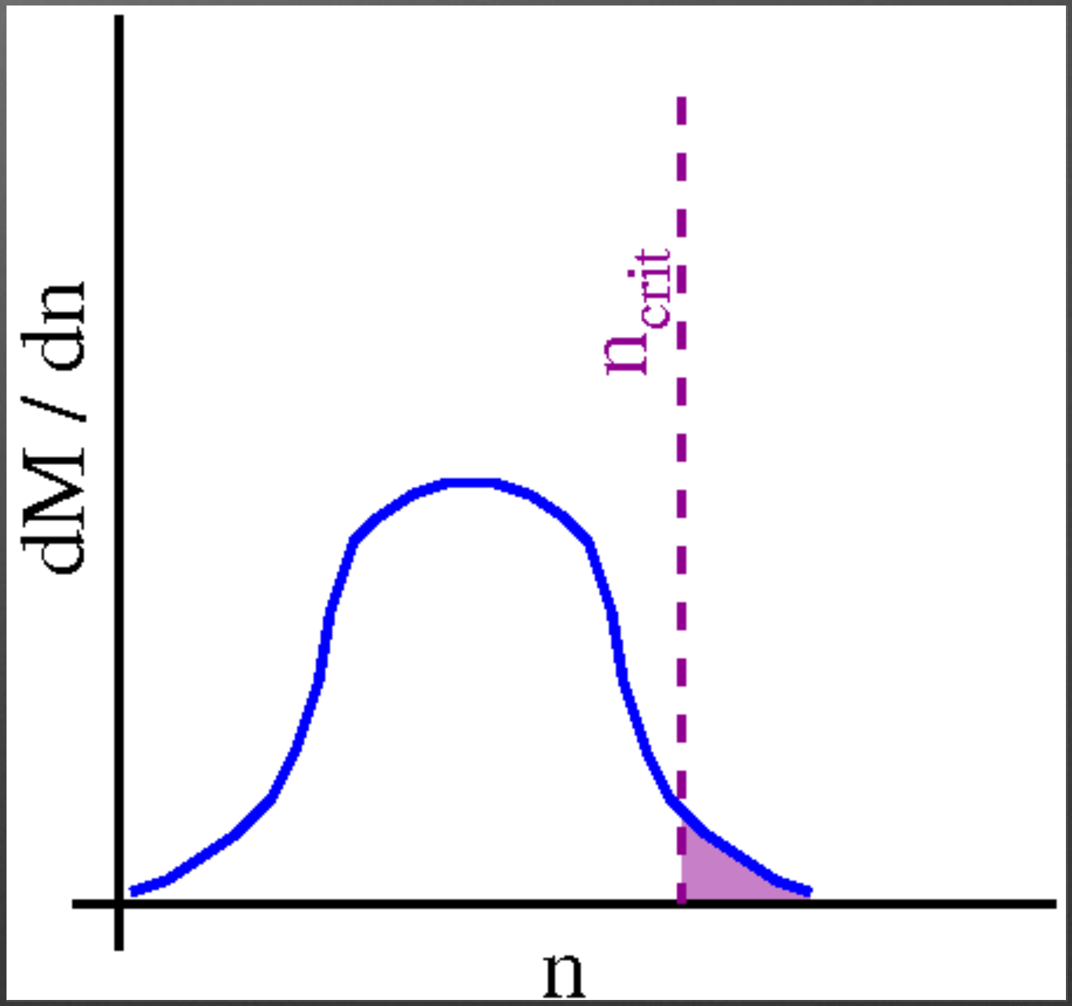

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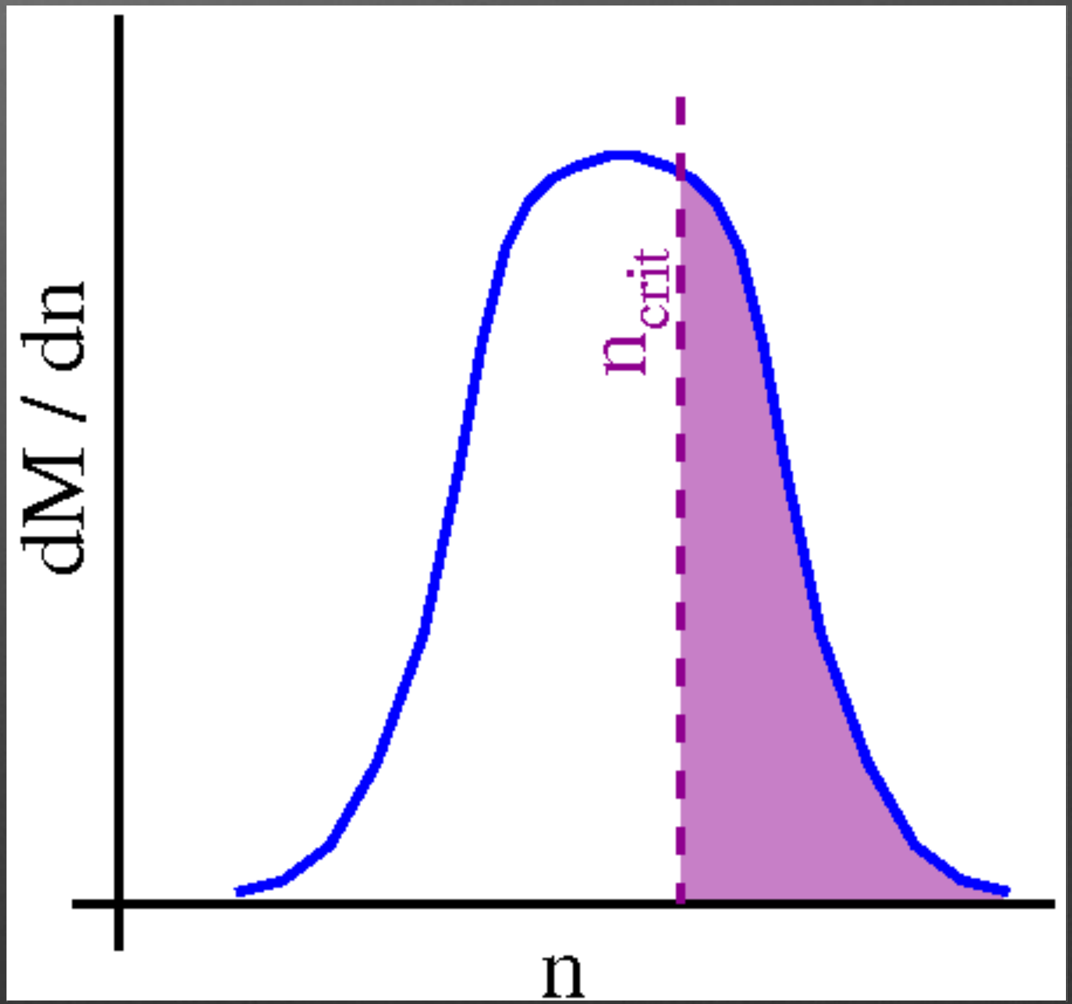
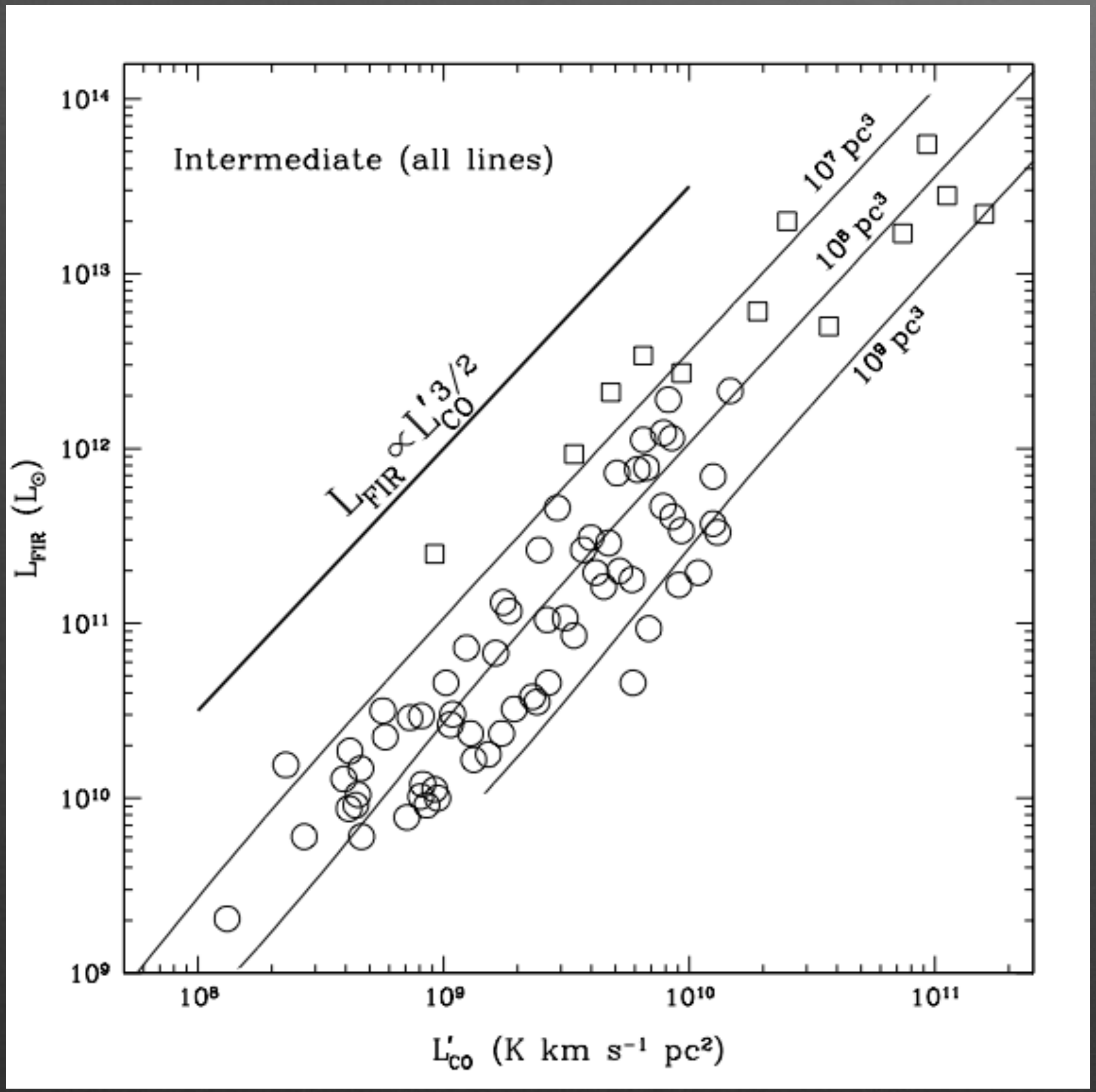
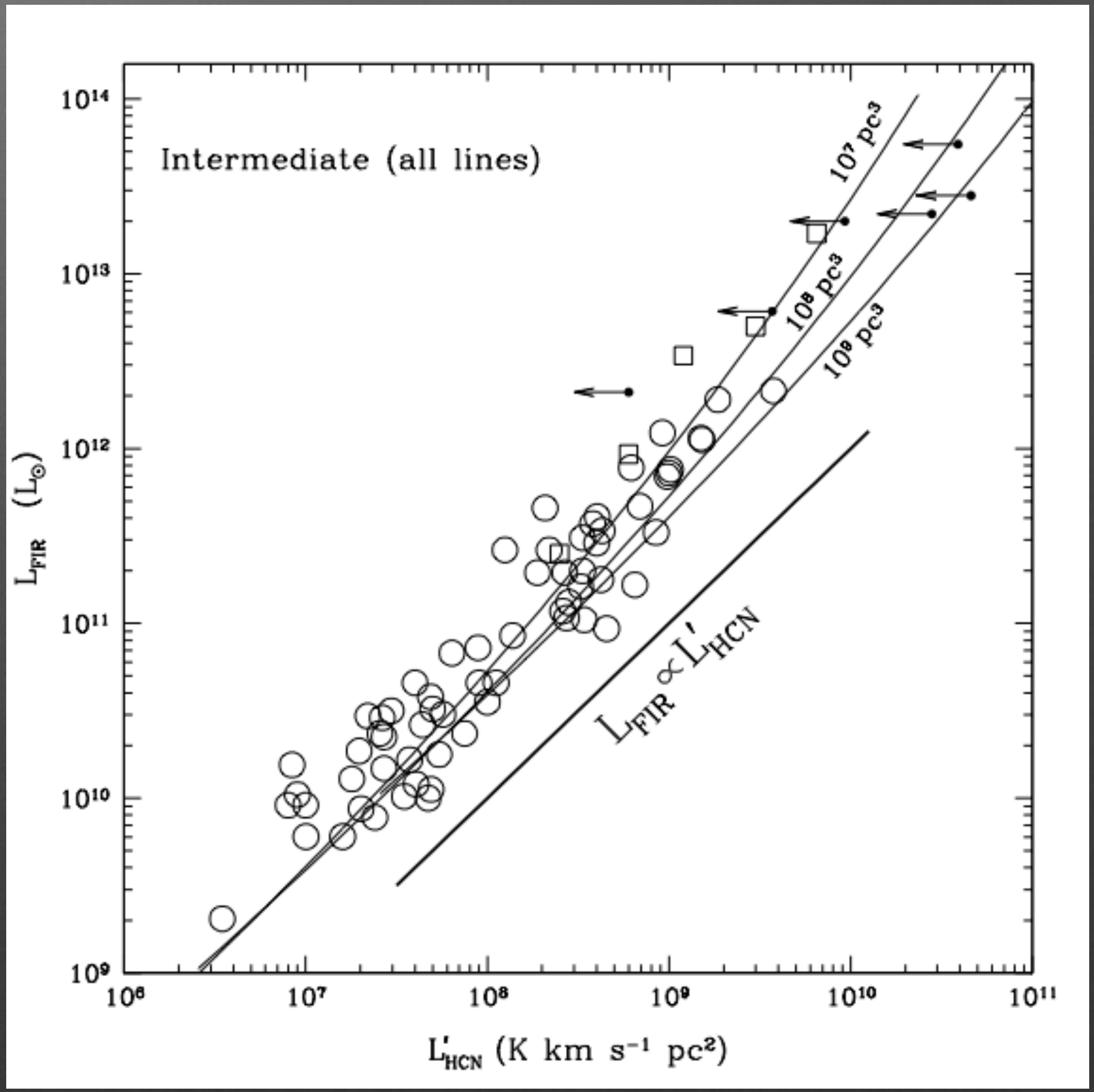


# Observations of High $n_{crit}$ Lines




Krumholz & Thompson 2007

# Line Emission: Next Steps

- Embed the Narayanan et al. numerical results within an analytic model for the full ρ-T PDF

- Use that plus a grid of DESPOTIC models to predict full line spectrum of galaxies as a function of gas surface density, SFR, chemical abundance

- Compare to growing library of Herschel and ALMA observations

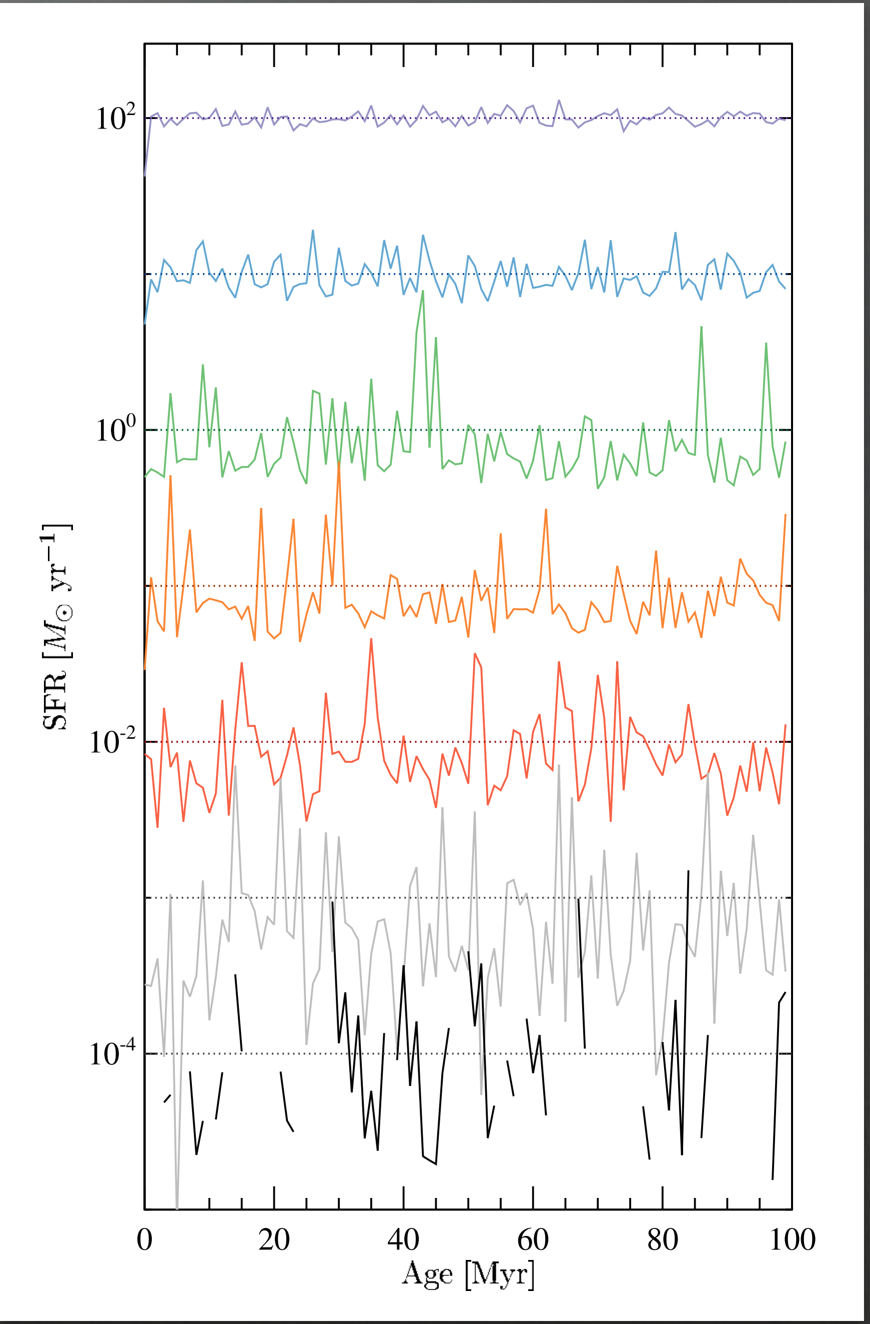
# Ionization-Based SFR Tracers

- Many SFR tracers sensitive to ionizing radiation from massive, short-lived stars

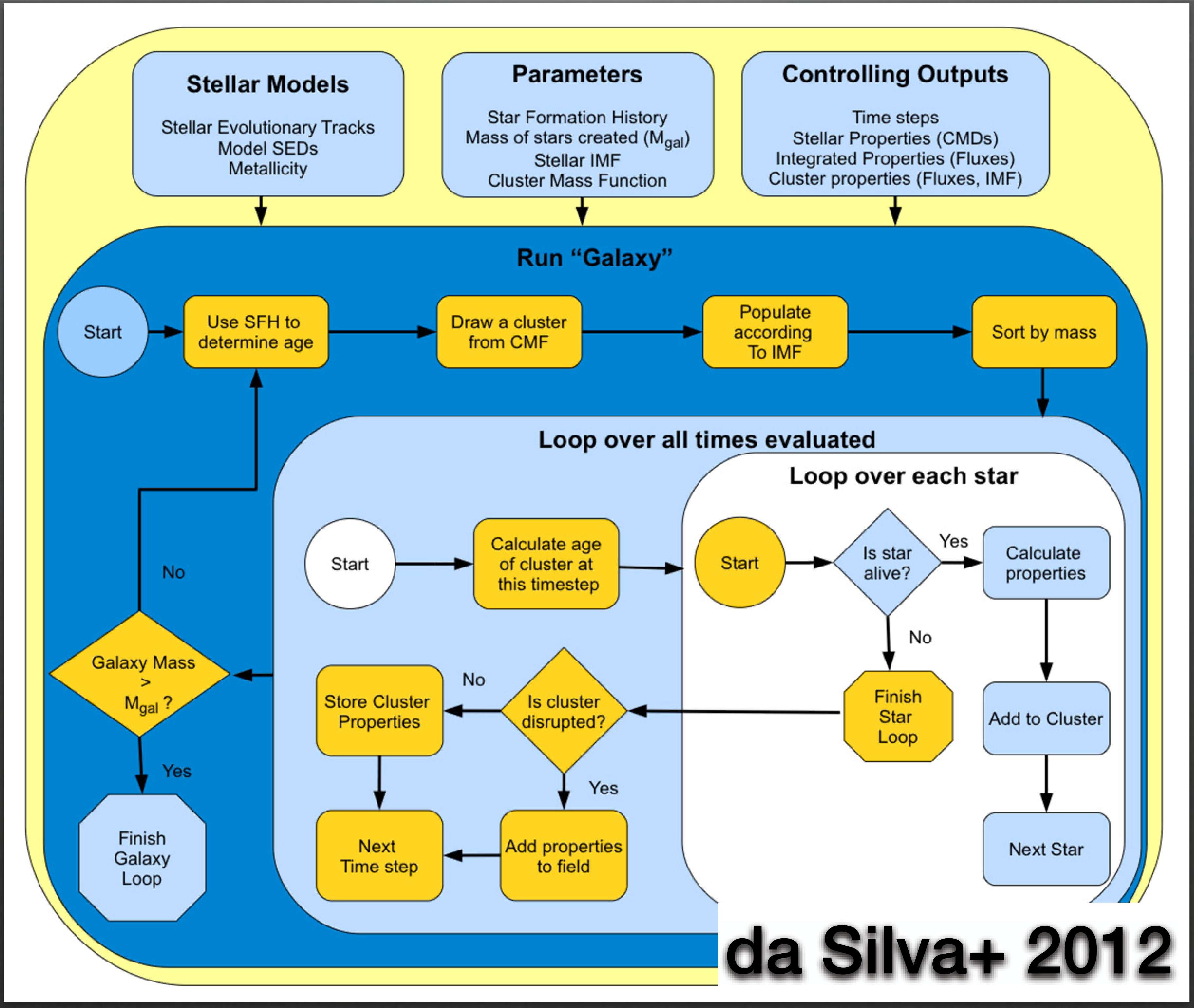
- Problem: massive stars have short lifetimes, and from in temporally-correlated clusters

- Result: lots of variation in total ionizing luminosity even at fixed mean SFR

- Amount of fluctuation depends on choice of tracer

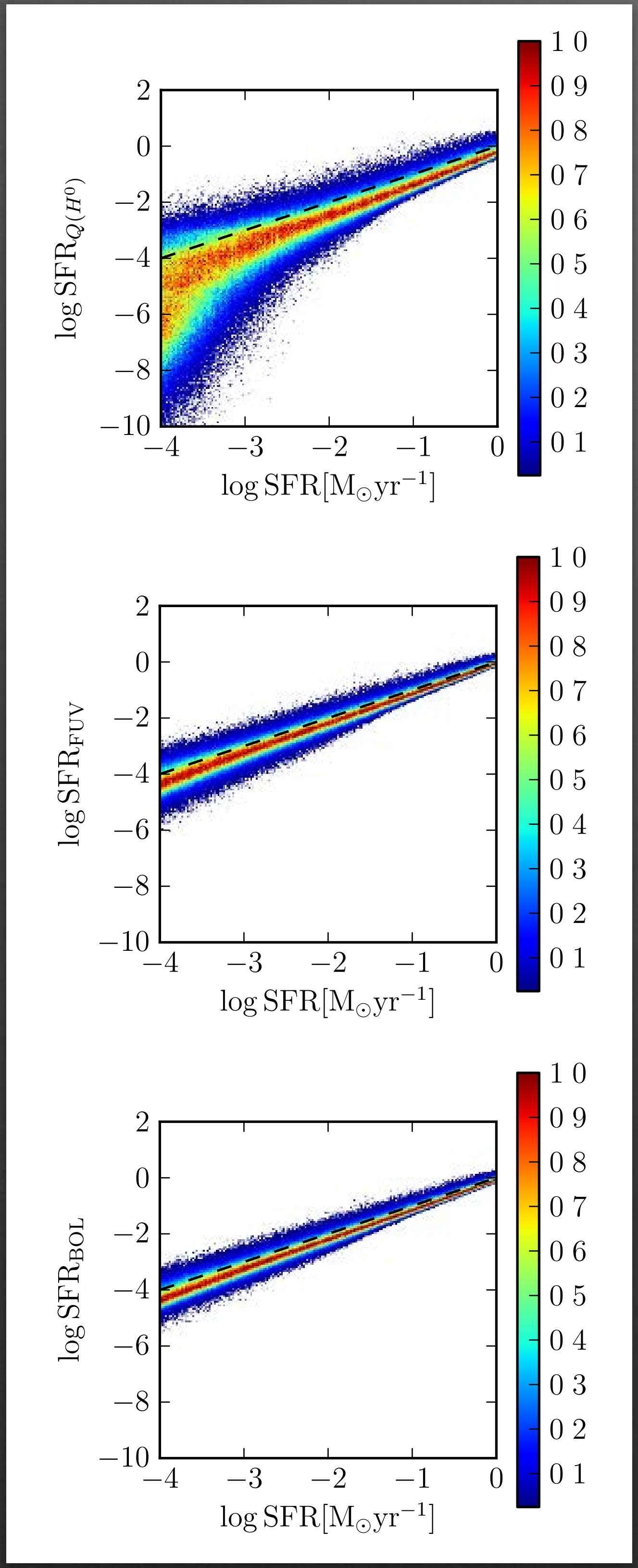


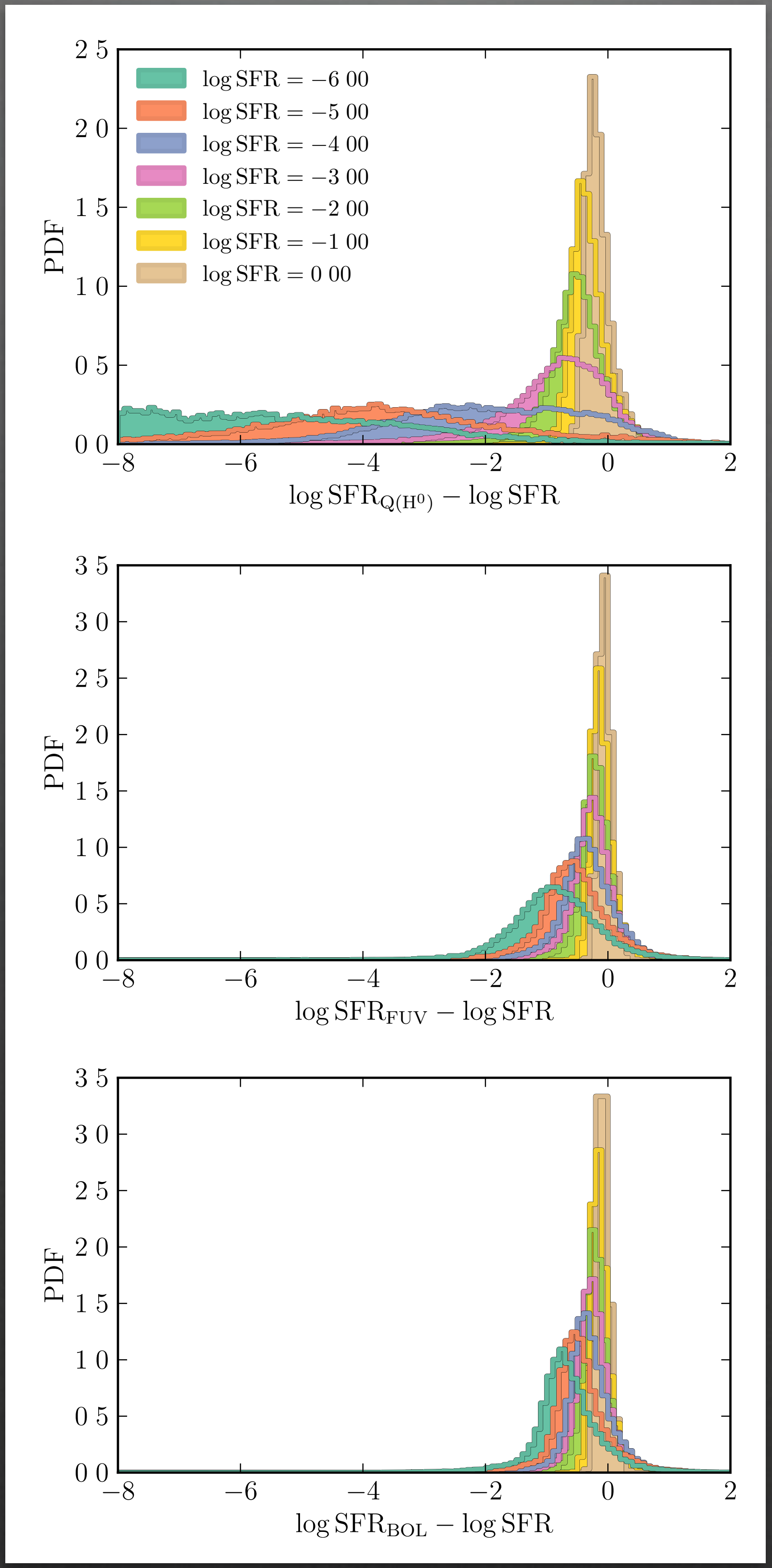
# The Solution: SLUG!




da Silva+ 2012

# Stochastic SFR Indicators




From observations:
p(log L | data)

SLUG gives us:
p(log L | log SFR)

Prior gives us:
p(log SFR)

We want:
p(log SFR | data)

da Silva+ 2014

# Bayesian SFRs

From prior From SLUG

- p(log SFR, log L) = p(log SFR) x p(log L | log SFR)
- … but p(log SFR, log L) = p(log L) x p(log SFR | log L)

From integrating What we want

- So p(log SFR | data) =

From observation

∫ [p(log SFR, log L) / p(log L)] p(log L | data) d log L

From SLUG + prior

# Bayesian SFRs

SLUG

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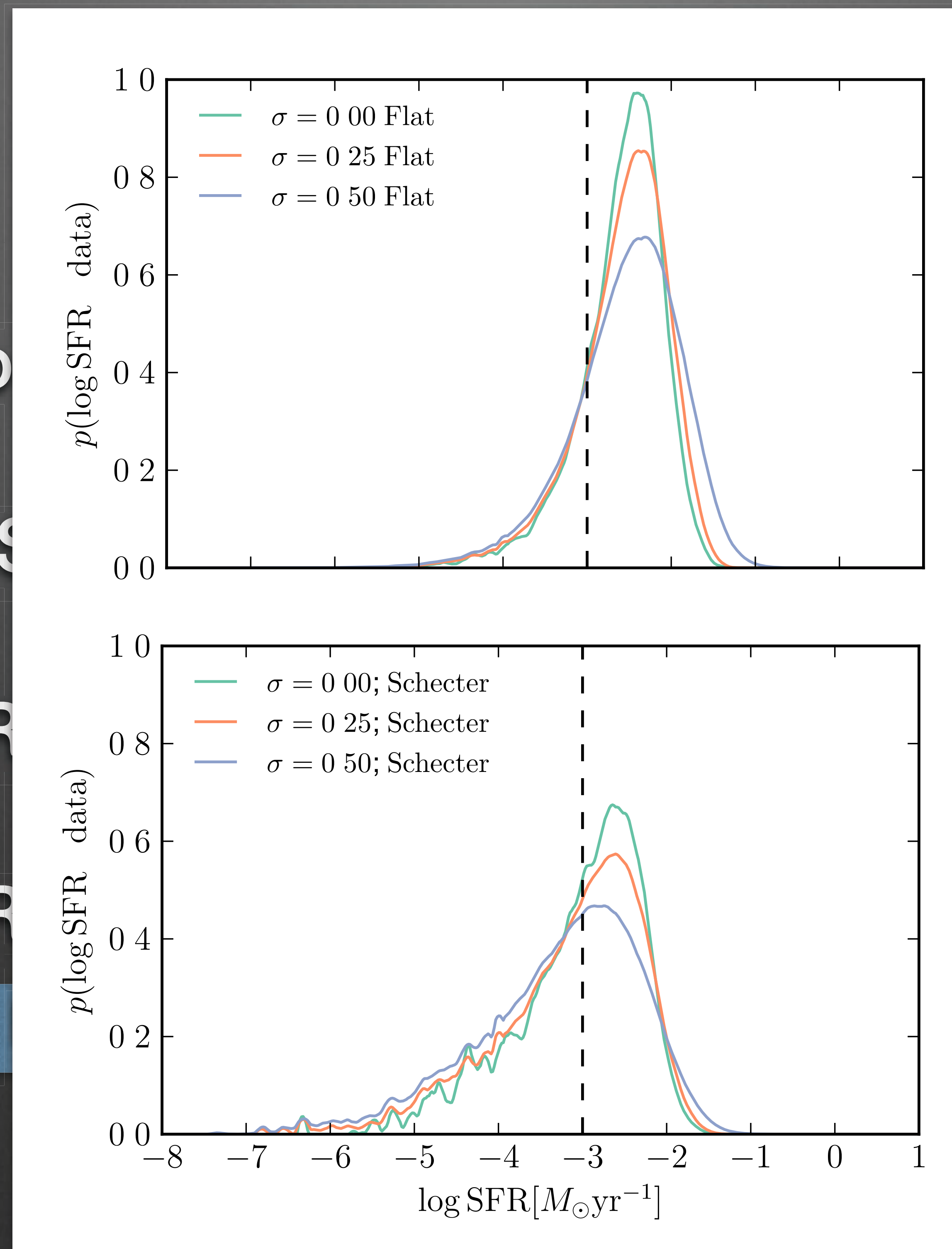
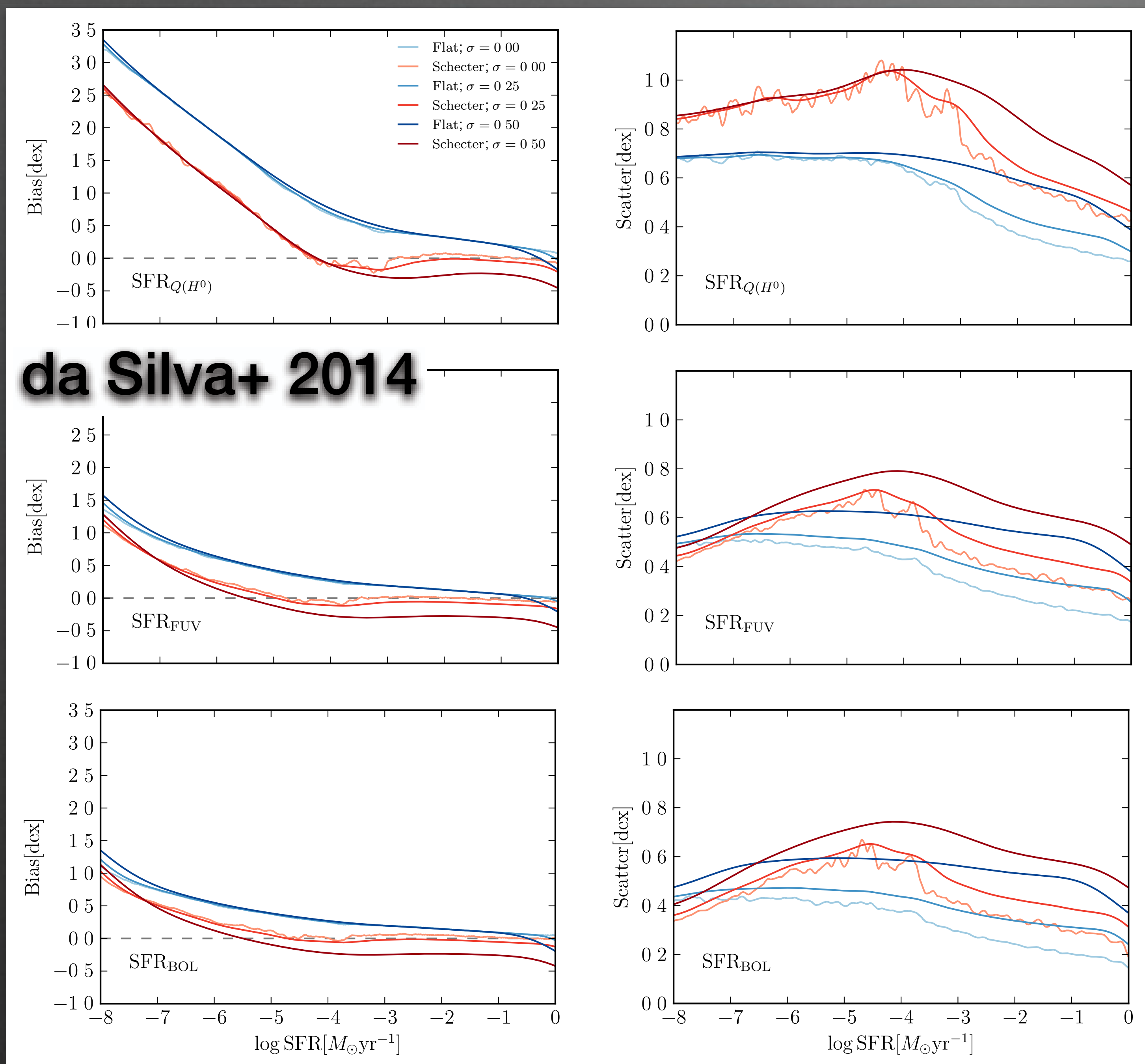
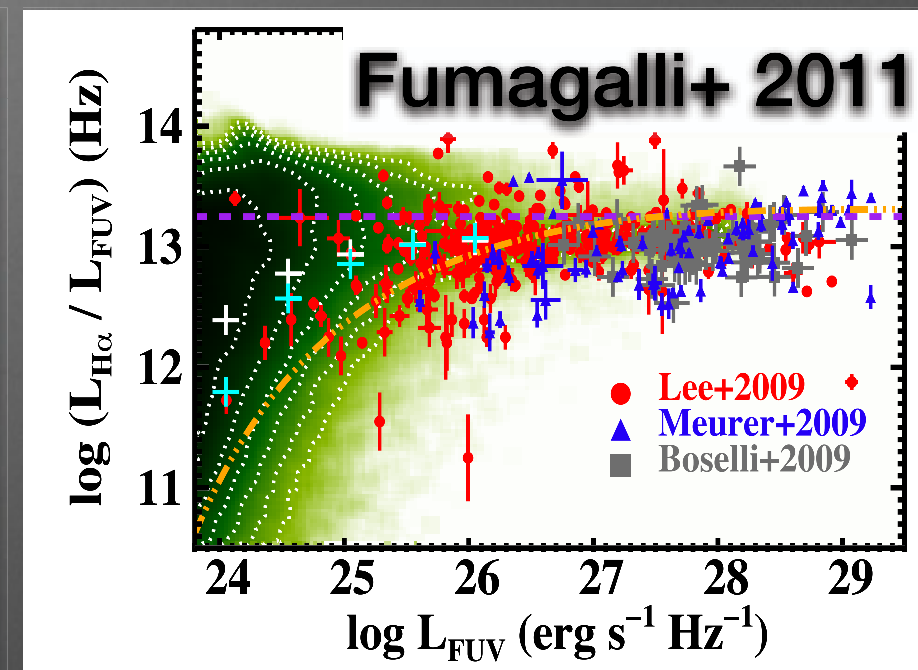
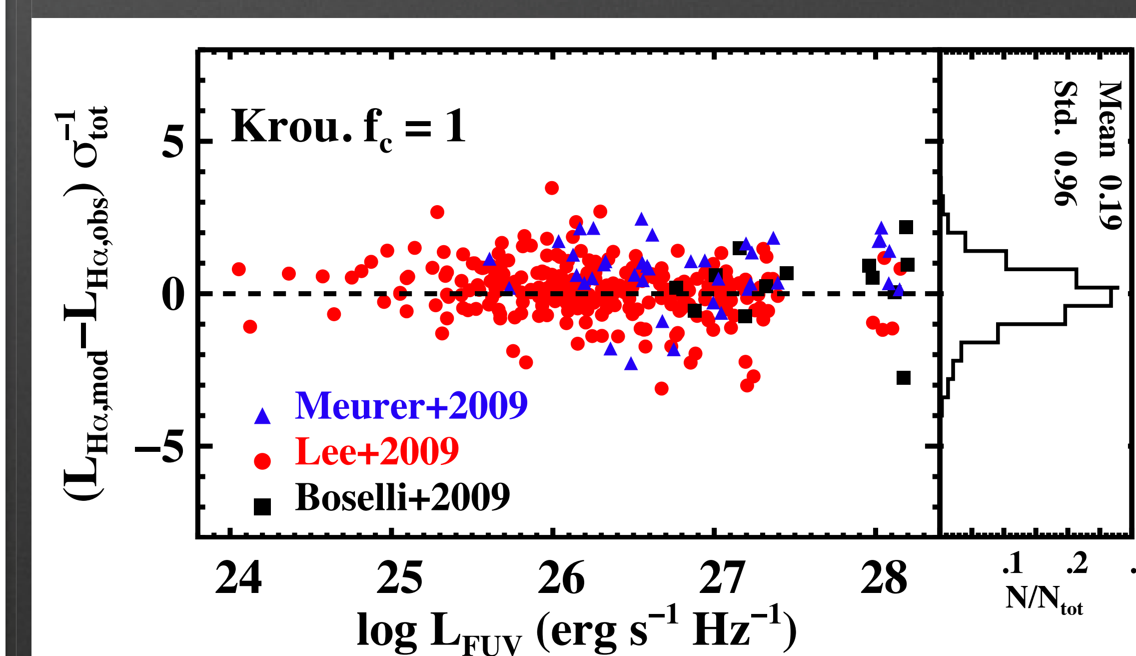


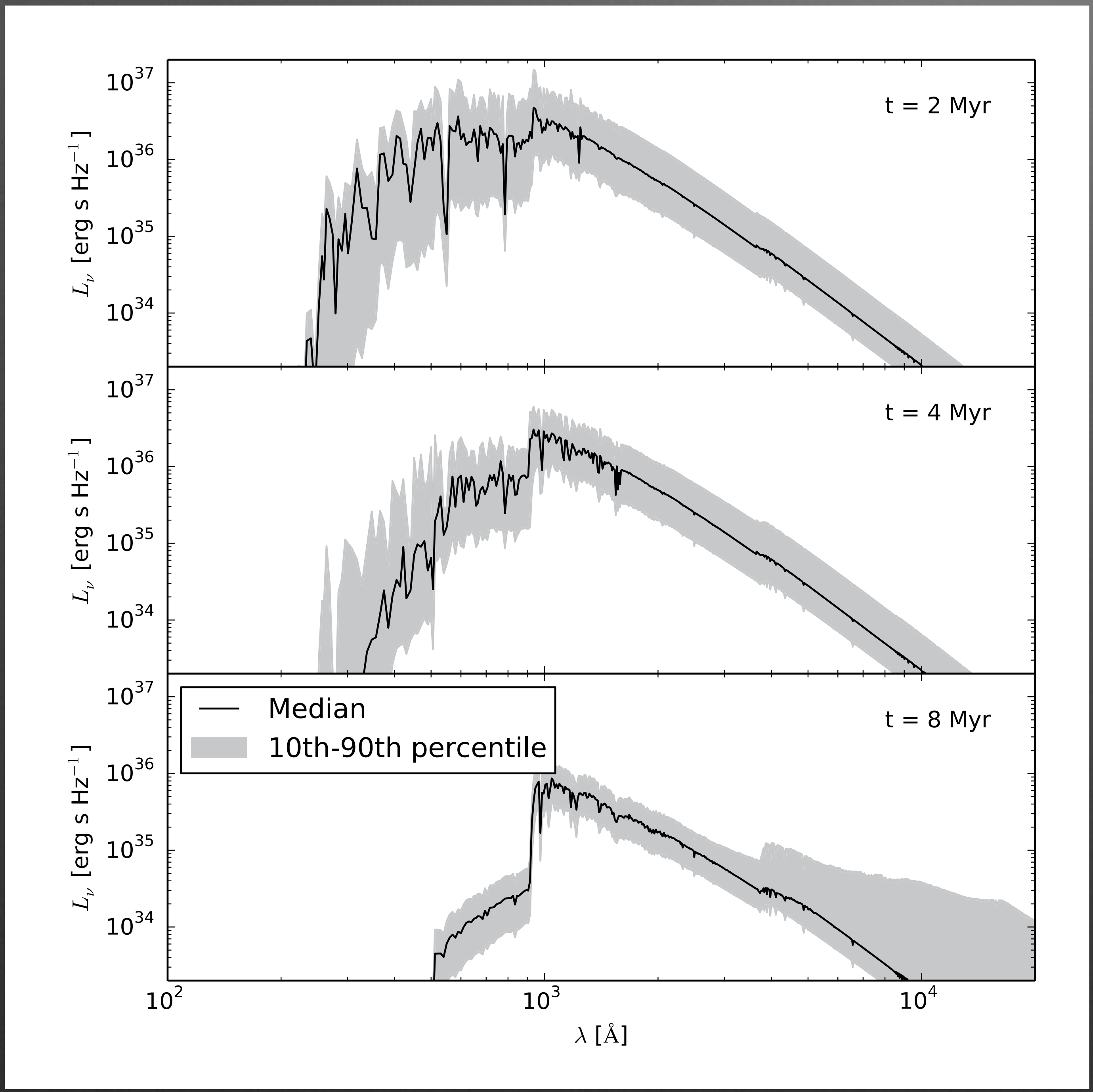
# So How Bad Is It?



# In Progress I: Stochasticity in Other Indicators




SLUG spectra, 1000 M$_\odot$ cluster

- Generate stochastic spectra w/SLUG
- Pipe through CLOUDY to get nebular emission
- Result: stochastic nebular lines (senior thesis, Teddy Rendahl)

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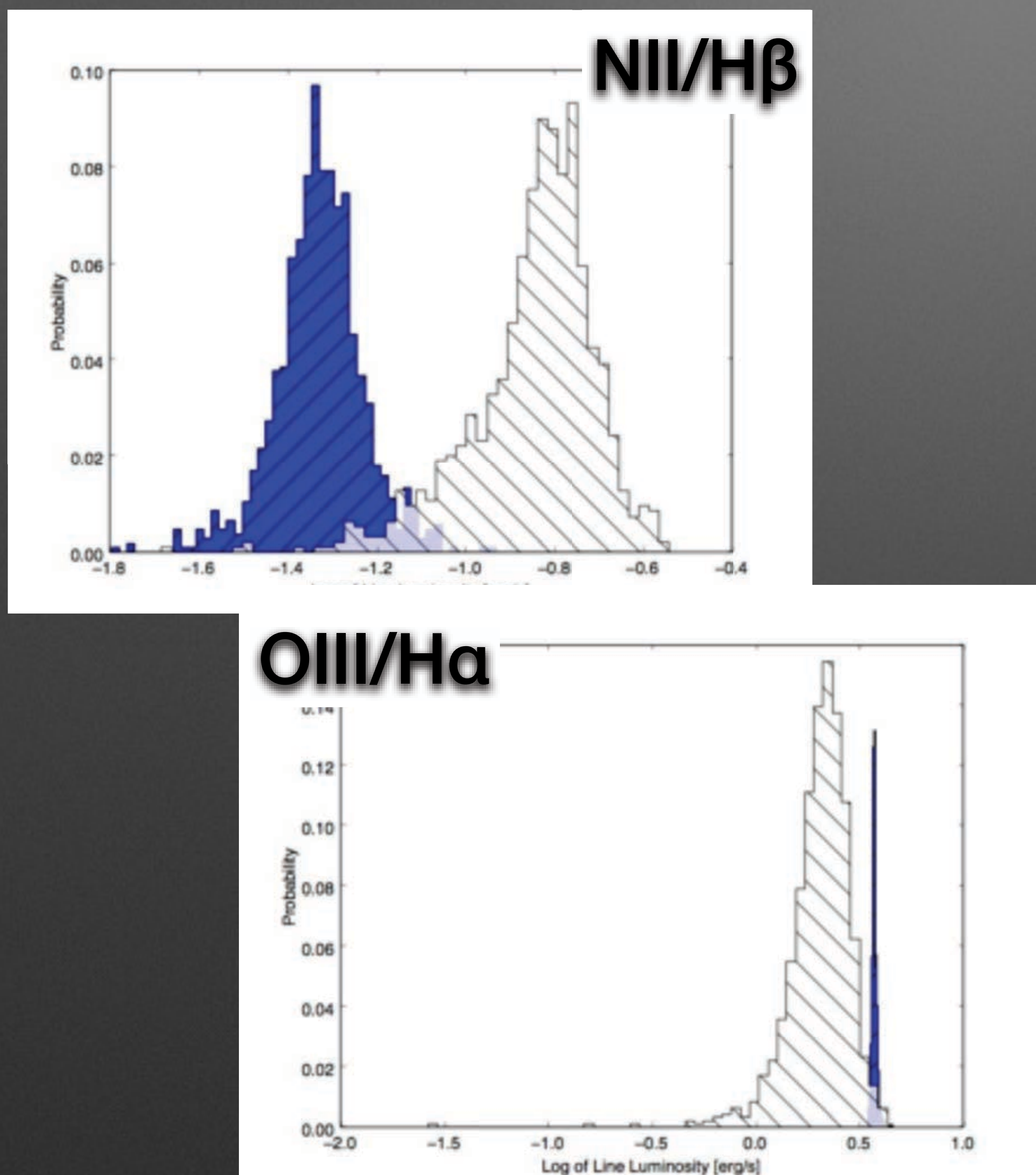


Stochastic line ratio distributions

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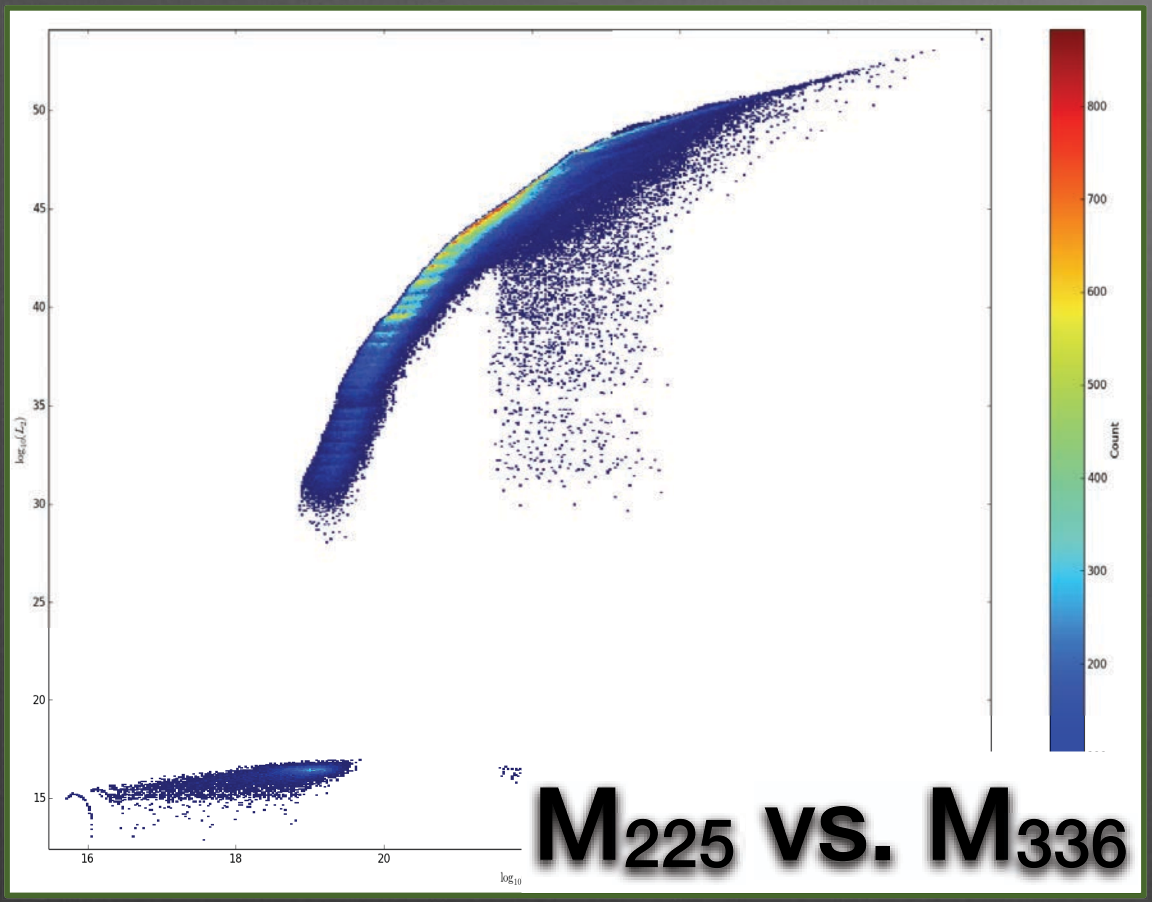
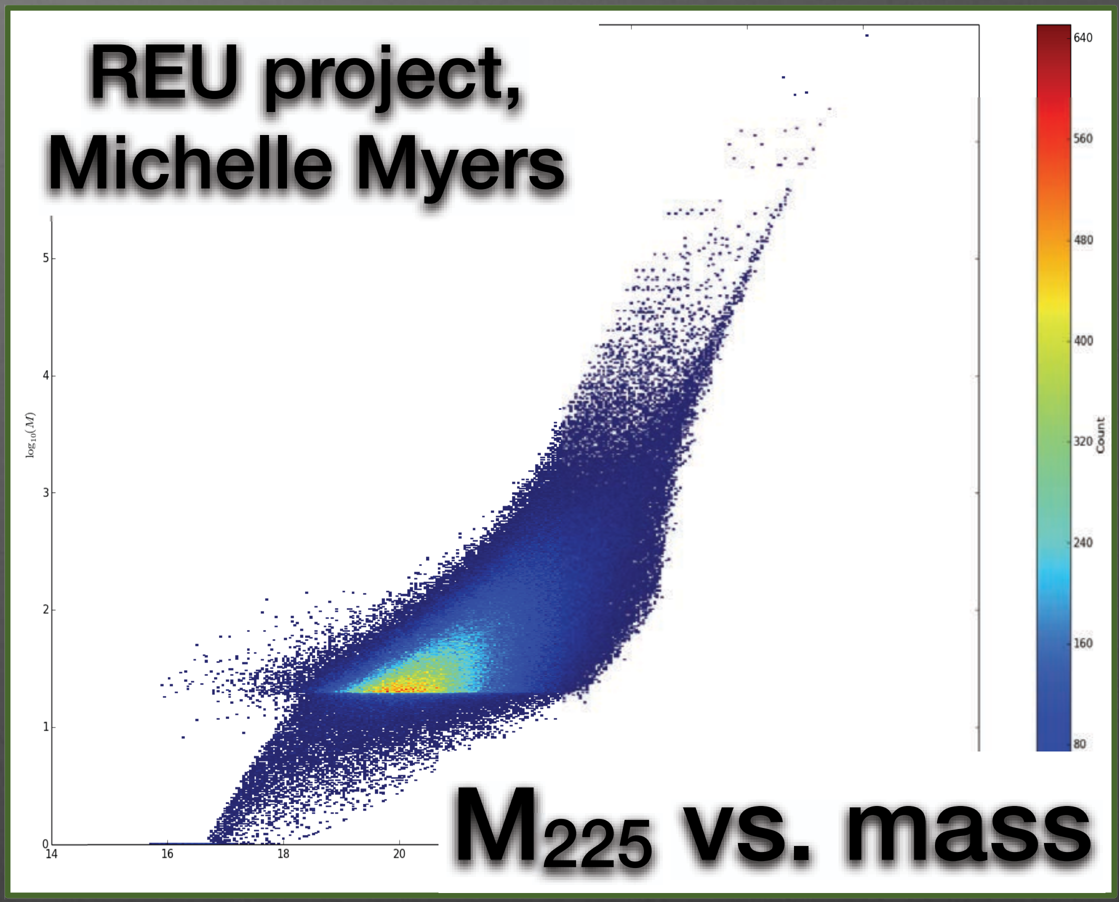
- Result: stochastic nebular lines (senior thesis, Teddy Rendahl)

# In Progress II: Bayesian Star Cluster Properties




- Extend technique for SFRs to > 2 dimensions
- Produce PDFs of star cluster mass, age vs. photometry in multiple filters
- Apply to LEGUS cluster catalog