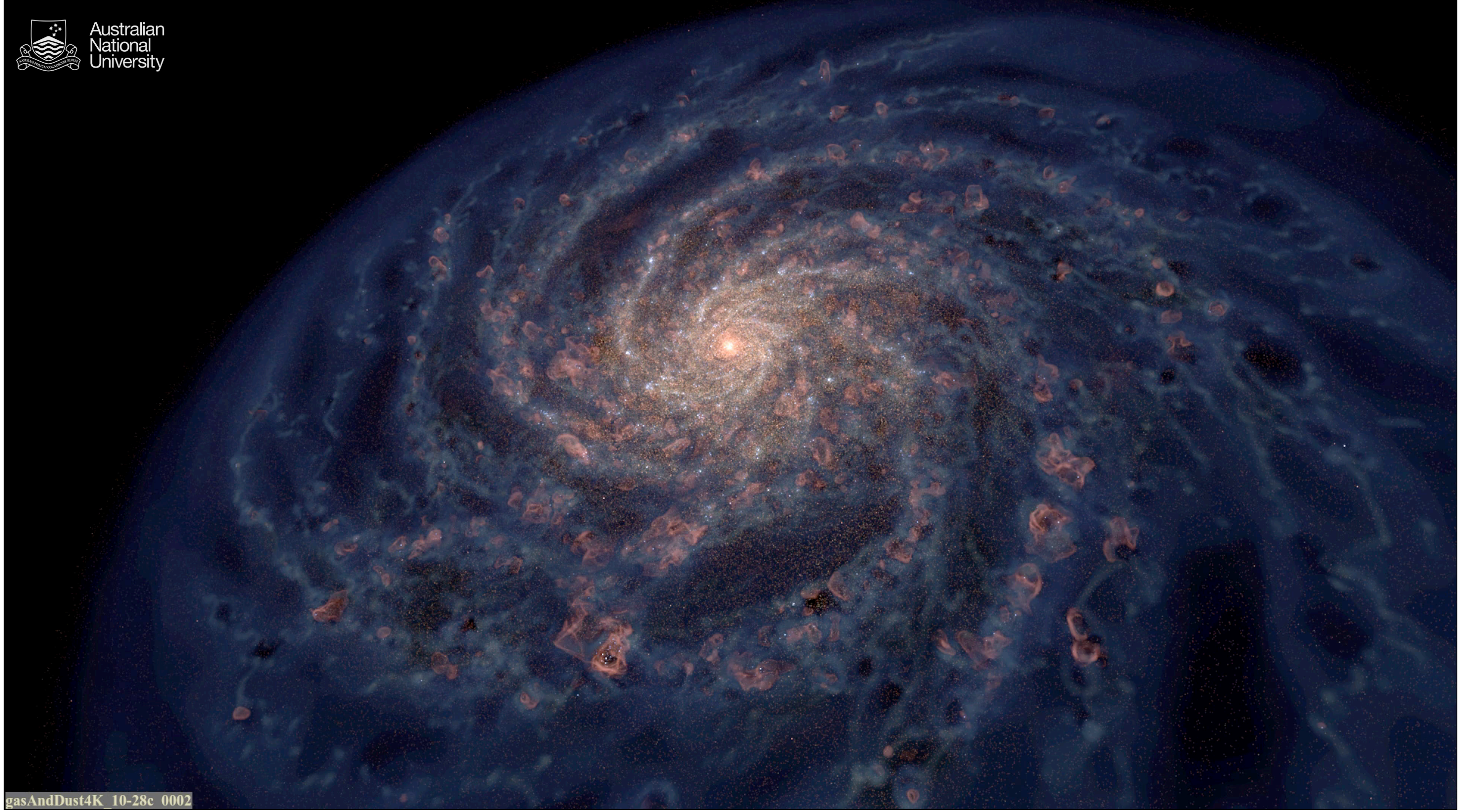


Star formation science with UVEX

Mark Krumholz
Australian National University

Overview — three problems in where UVEX can (hopefully) help

- The initial mass function in low-mass, low-metallicity galaxies
- Star formation “laws” in the dwarf galaxy regime
- The most quiescent dwarf galaxies

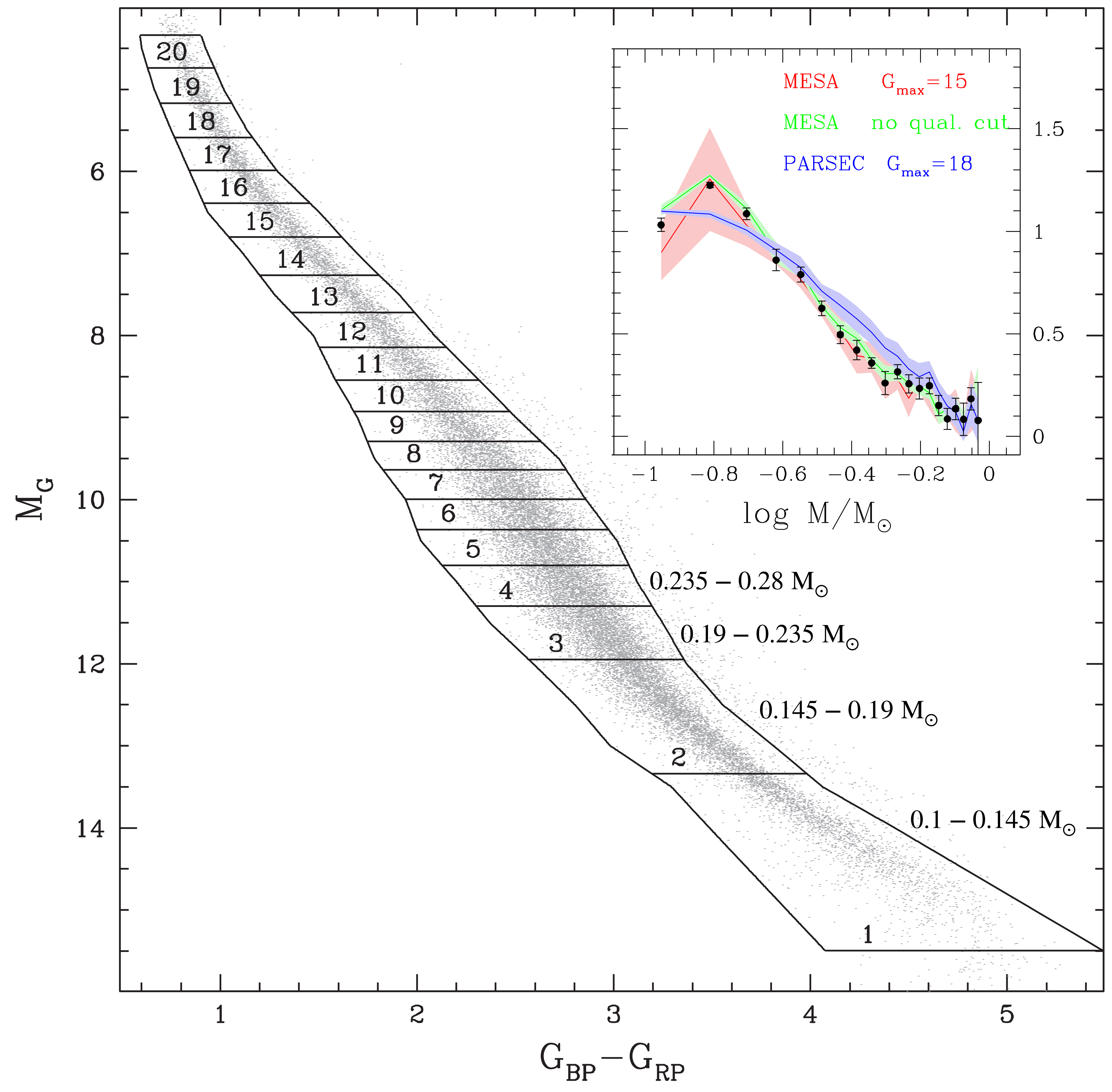
The initial mass function in low-mass, low-metallicity galaxies

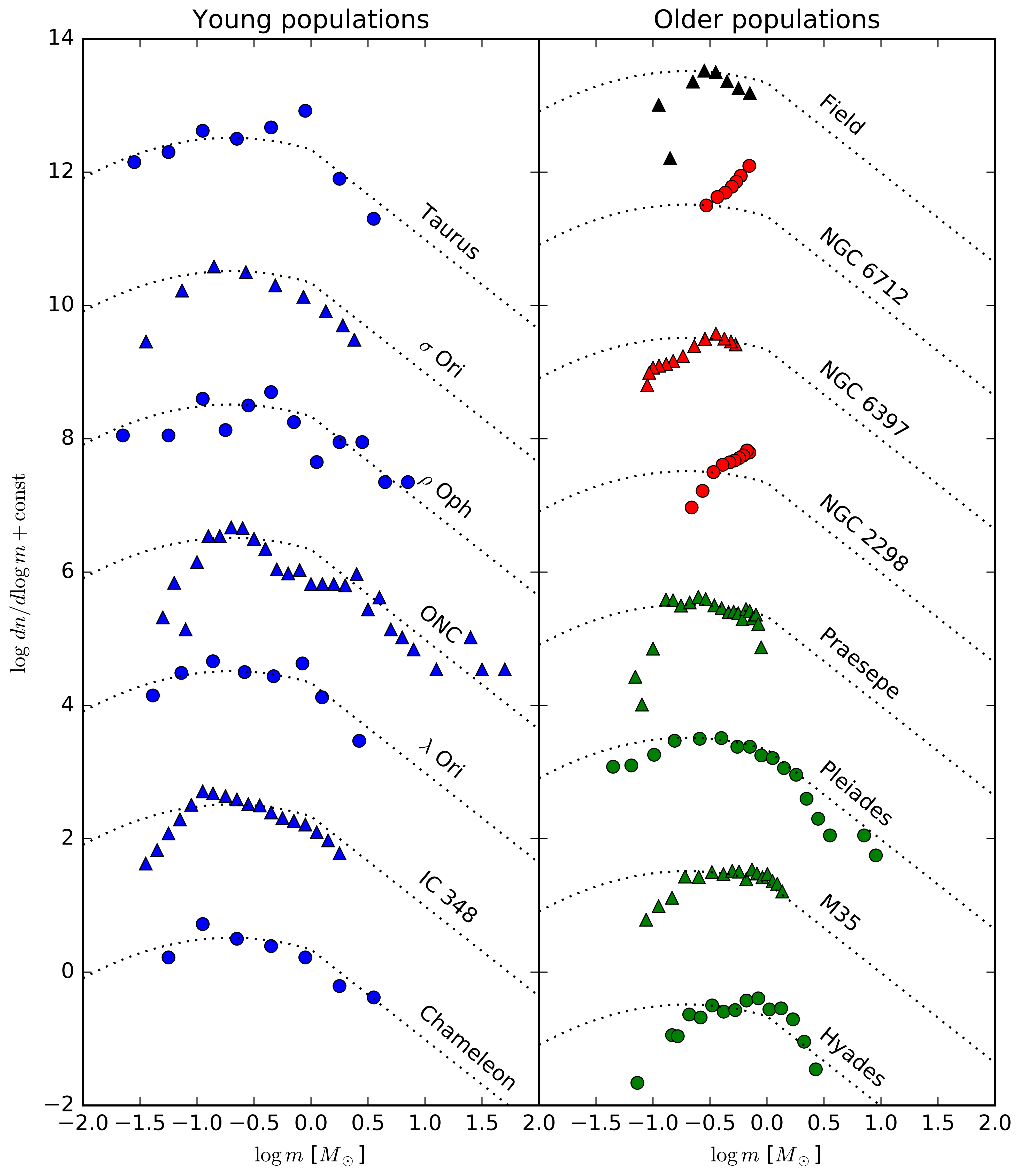
The picture on the right has nothing to do with the talk… it's just that UVEX Safety Australia is the top hit when you google "UVEX" in Australia

The IMF: a quick background

- The IMF is arguably the most important distribution in astrophysics:
  - It is a key assumption whenever we turn observations of unresolved stellar populations into physical properties (mass, SFR, etc.)
  - It determines the energy balance of the ISM
  - It determines all of post-BBN chemical evolution

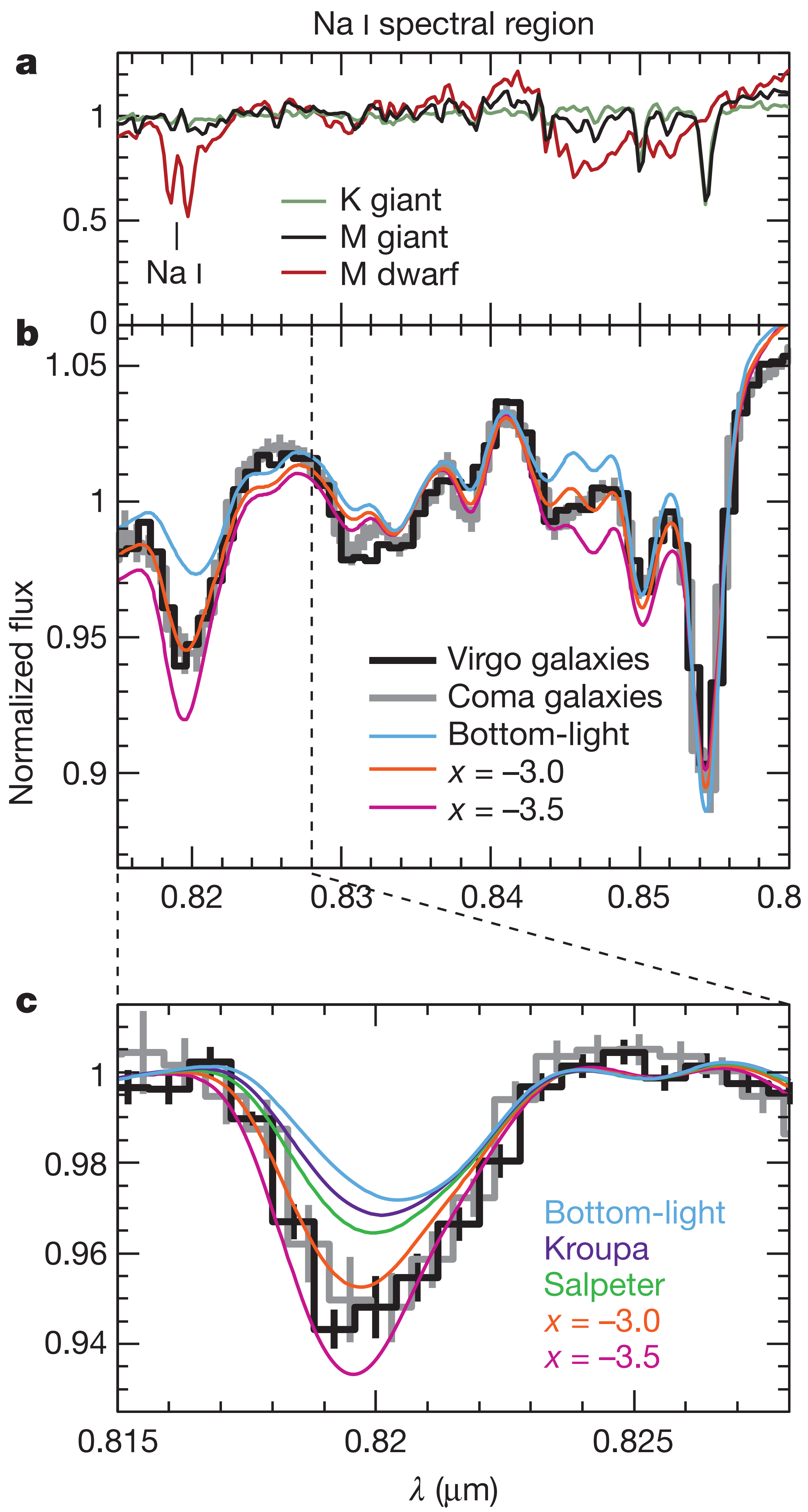
- Major unsolved questions:
  - By what amount (if at all) does the IMF vary with the larger galactic environment?
  - If it does vary, what are the most important factors driving its variation?

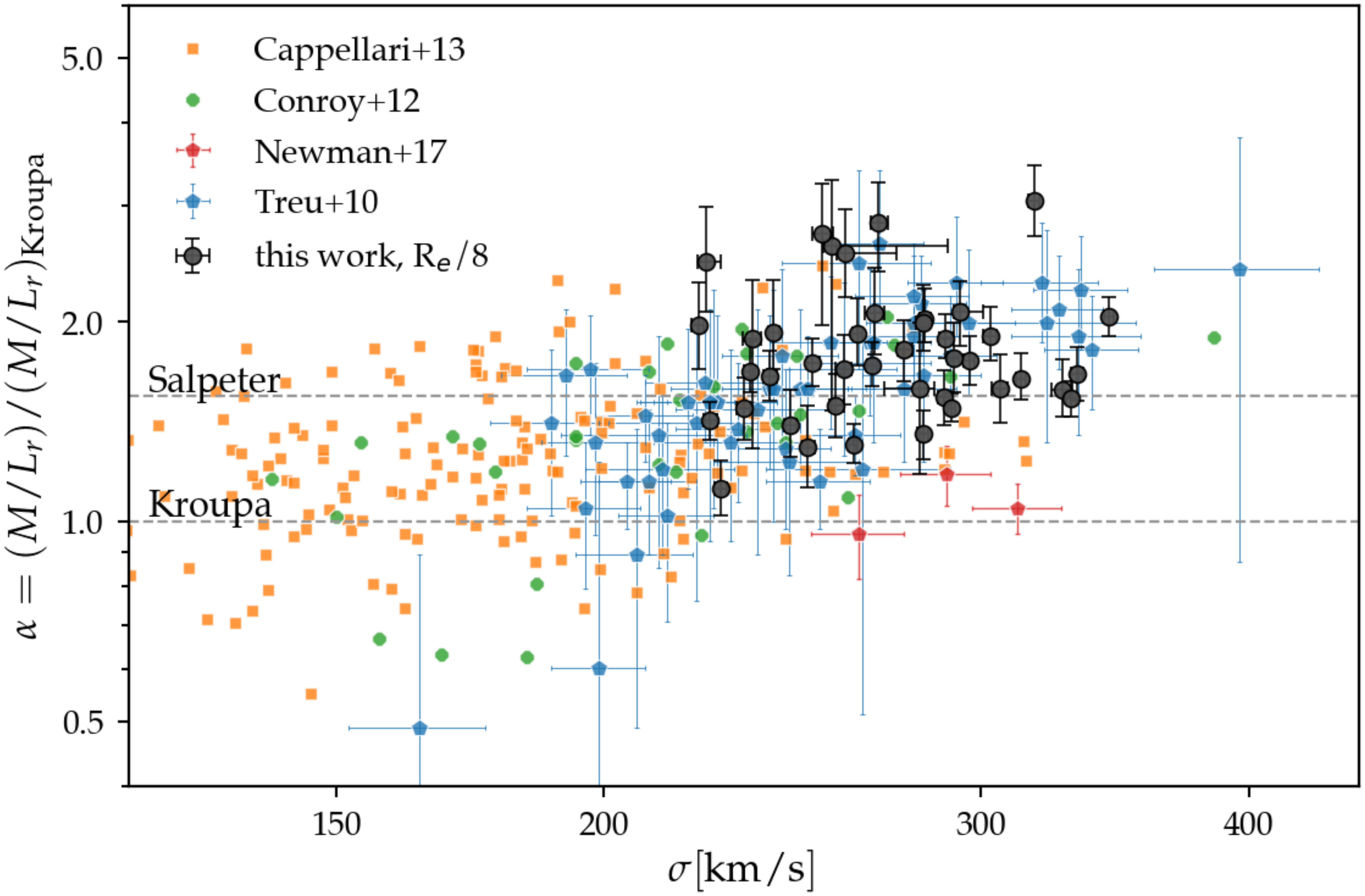




The Milky Way: limited to no evidence for variation

Left: Solar neighbourhood IMF (Sollima+ 2019)
Right: star cluster IMFs (Bastian, Covey, & Meyer 2010)





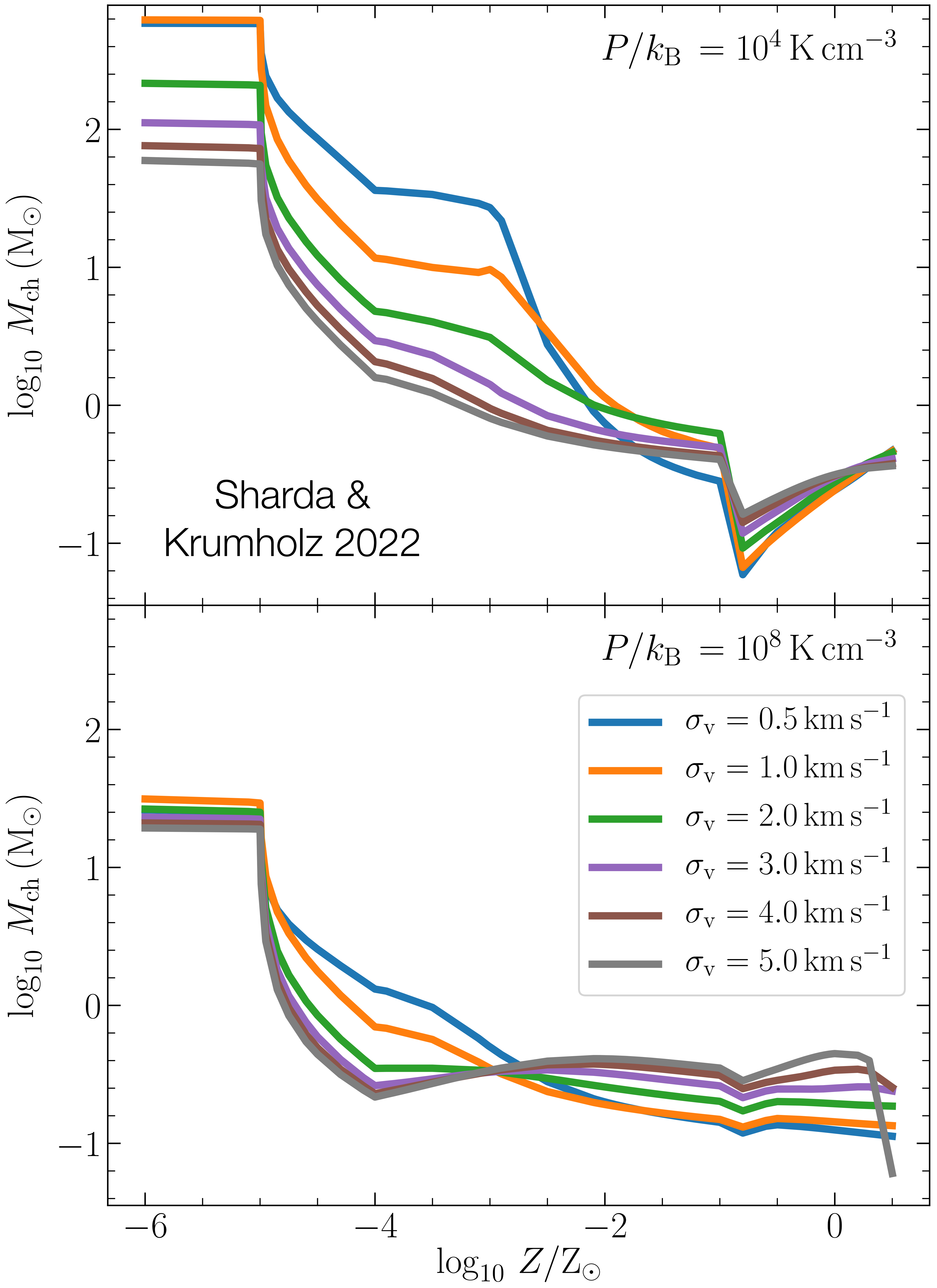
Evidence for variation in old, metal-rich stellar populations

Left: van Dokkum & Conroy (2010)
Right: Gu+ (2022)

What about dwarf galaxy stellar populations?

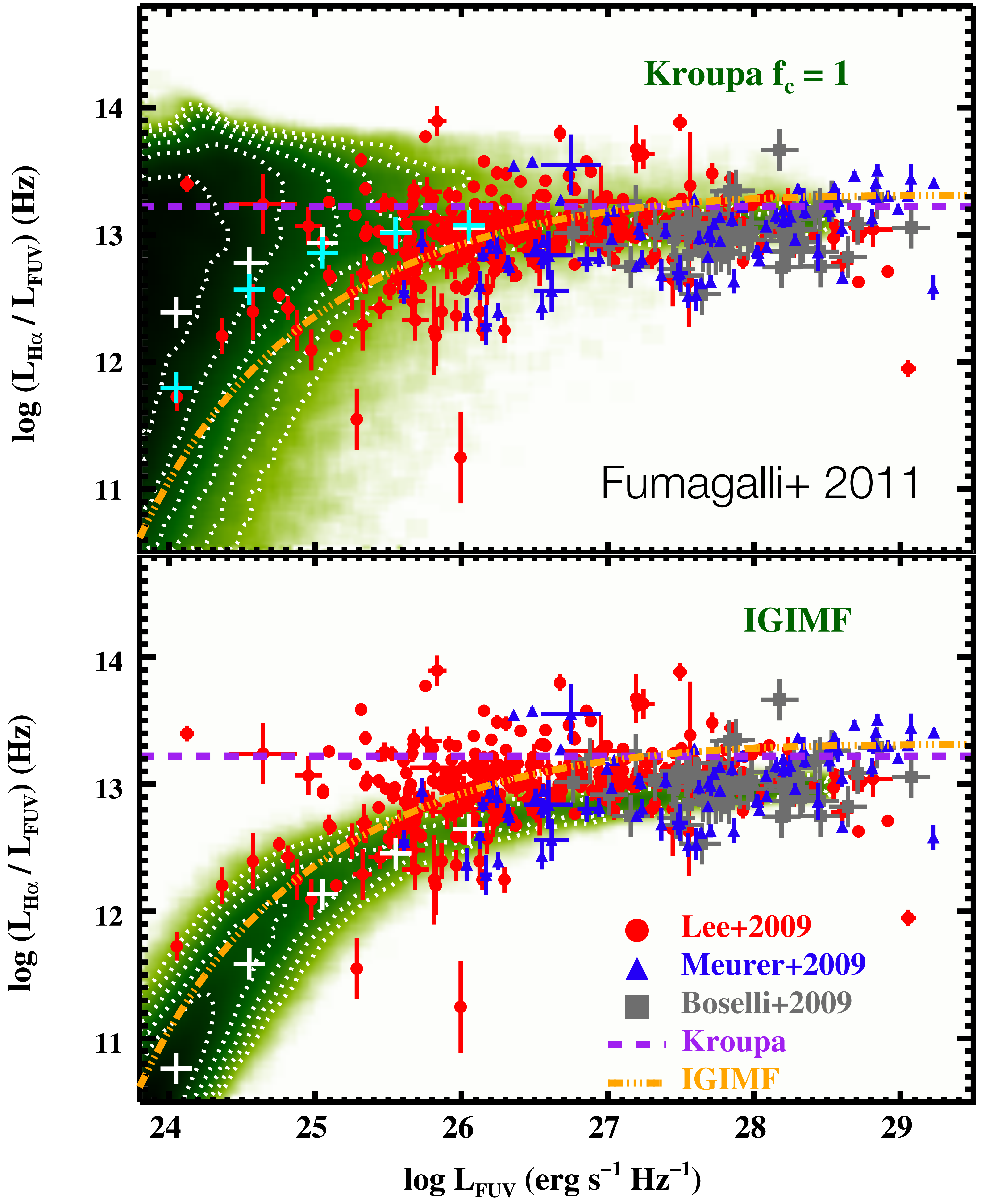
- Theoretical models predict that the IMF should change in dwarfs — but different models predict different variations!
  - Low Z → weaker cooling → higher mass stars (e.g., Sharda+ 2022, Bate 2023)
  - Low pressure → less fragmentation → higher mass stars (e.g., Tanvir+ 2022)
  - Low SFR → less mass available in each "clump" → deficit of massive stars (e.g., Weidner, Kroupa, & Bonnell 2010)
  - Different effects cancel, same as usual IMF (e.g., Guszejnov+ 2022)

- Can we detect any of this in observations?



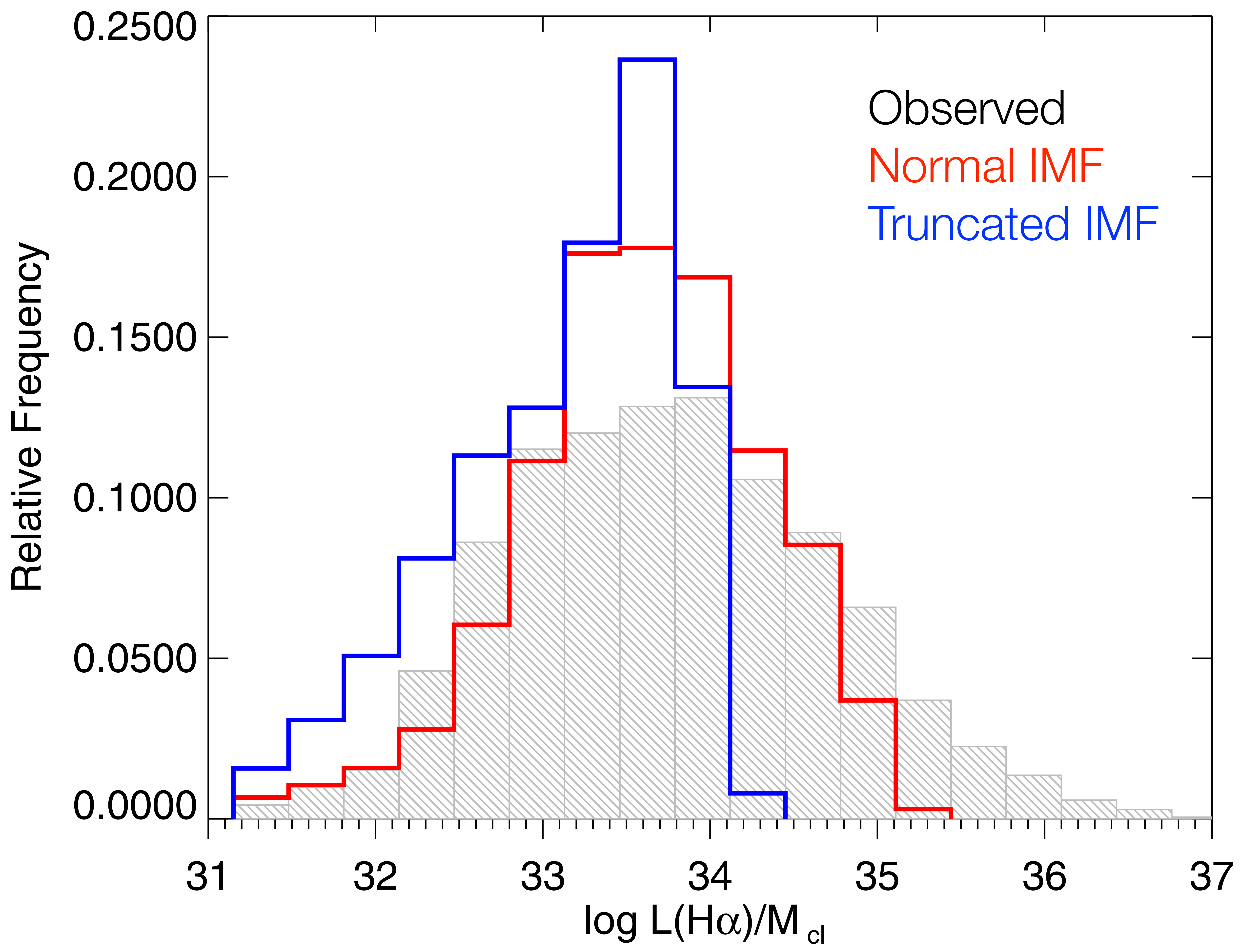
IMF studies in dwarfs from integrated light

- Difficult to use resolved stellar populations: even with HST sensitivity, statistics available beyond the Magellanic Clouds too poor (El-Badry+ 2017)
- But can (in principle) constrain upper part of IMF from integrated light
  - Luminosity ratios in two bands constrain IMF for continuous star-formation
  - Luminosity ratios in three bands constrain IMF and age simultaneously in a simple stellar population
- Problem for whole galaxy data: degenerate with stochasticity, SF history (Fumagalli+ 2011, Weisz+ 2012, Eldridge 2012)



IMF studies in SSPs

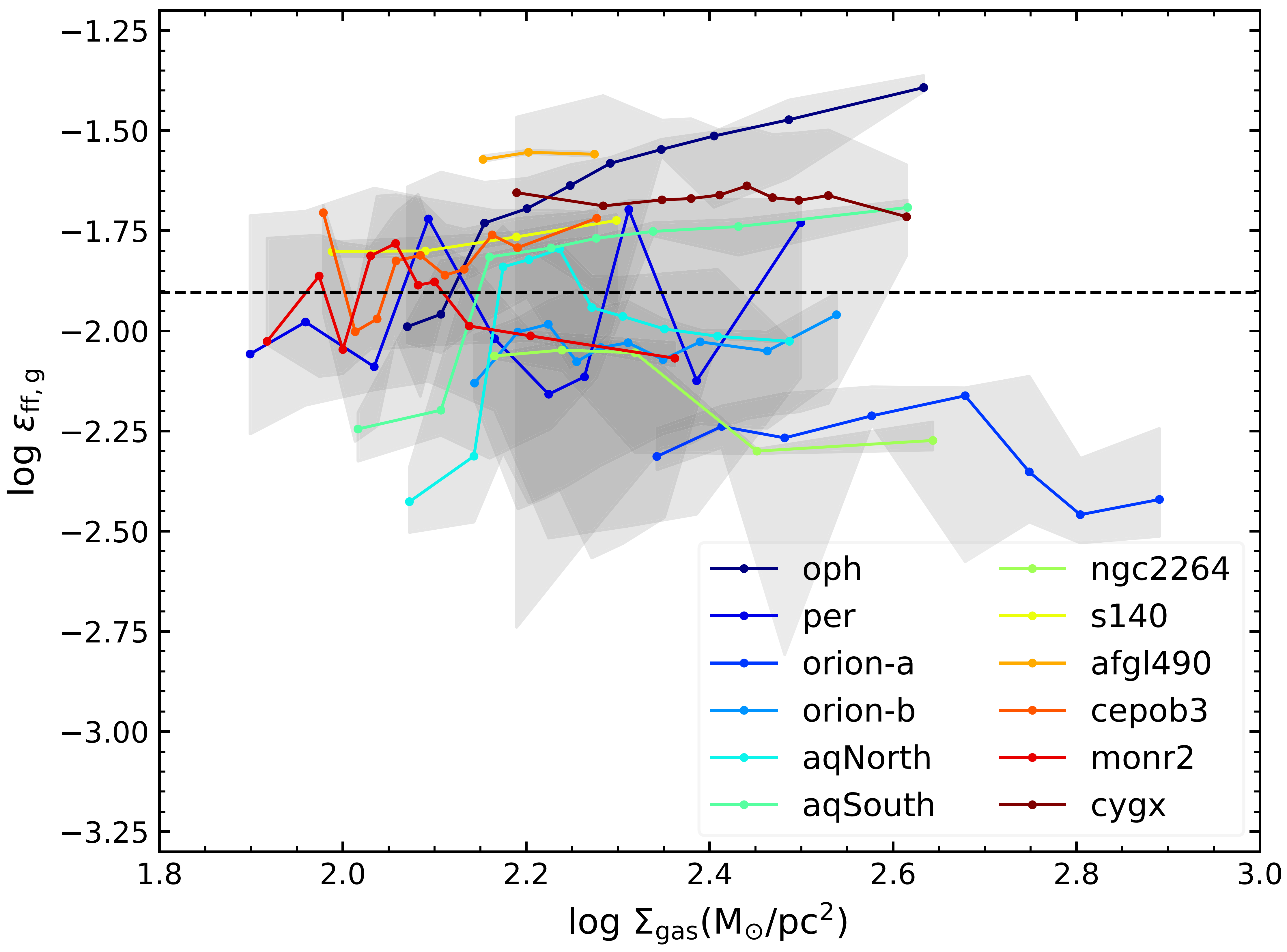
- Can avoid SF history degeneracy using SSPs — analogous to IMF studies in young clusters with resolved stars
- Basic observable: ratio of luminosity in bluer bands (ionising, FUV — tracing upper IMF) to luminosity / colours in redder bands (tracing lower mass stellar population)
- Need good statistics to beat stochasticity
- Studies to date find no evidence for IMF variation in dwarfs, but limited by uncertain ages and masses in red bands
- Can't do this with GALEX due to insufficient resolution — UVEX would help a lot

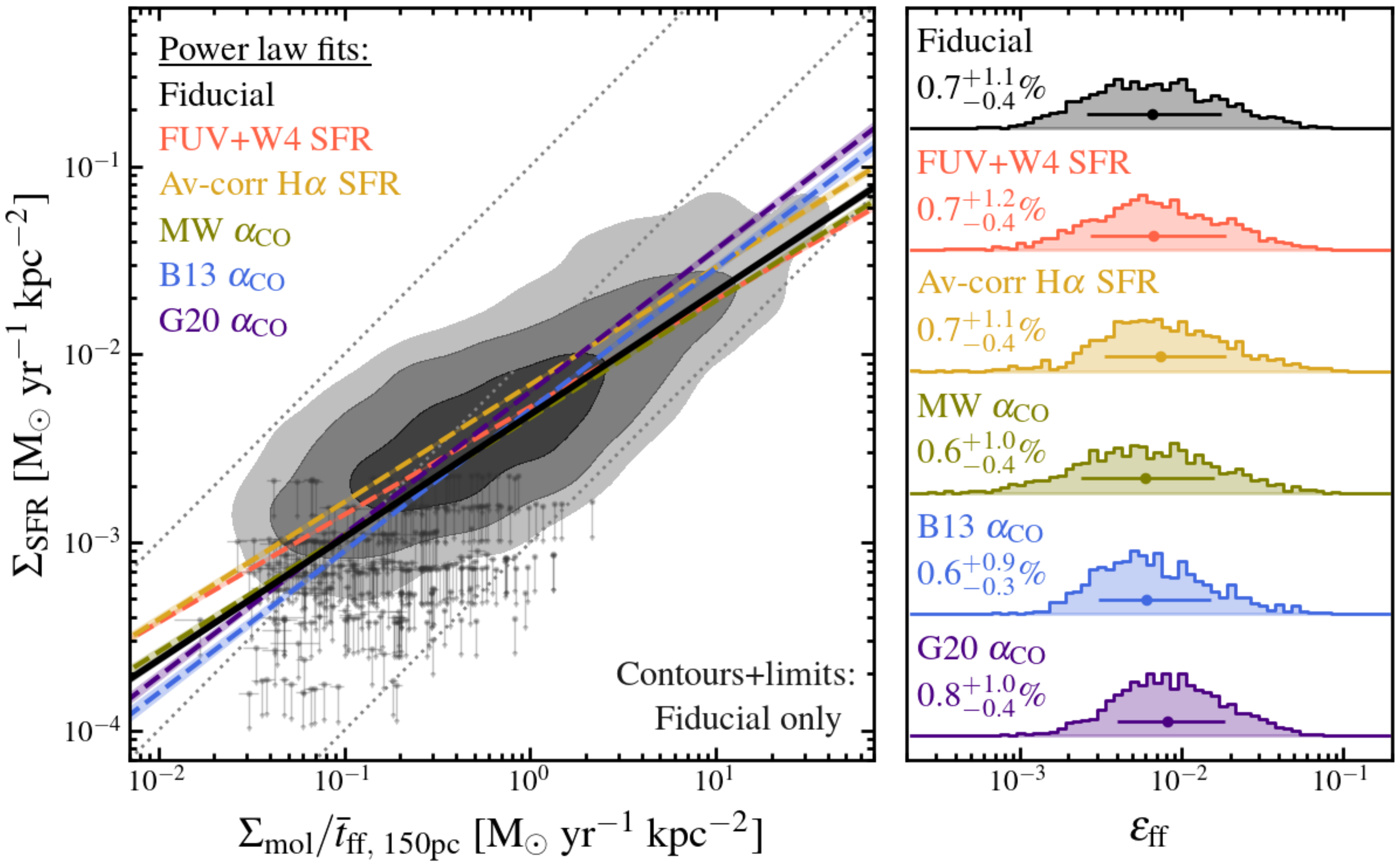


Andrews+ 2013

Star formation “laws” in the dwarf galaxy regime

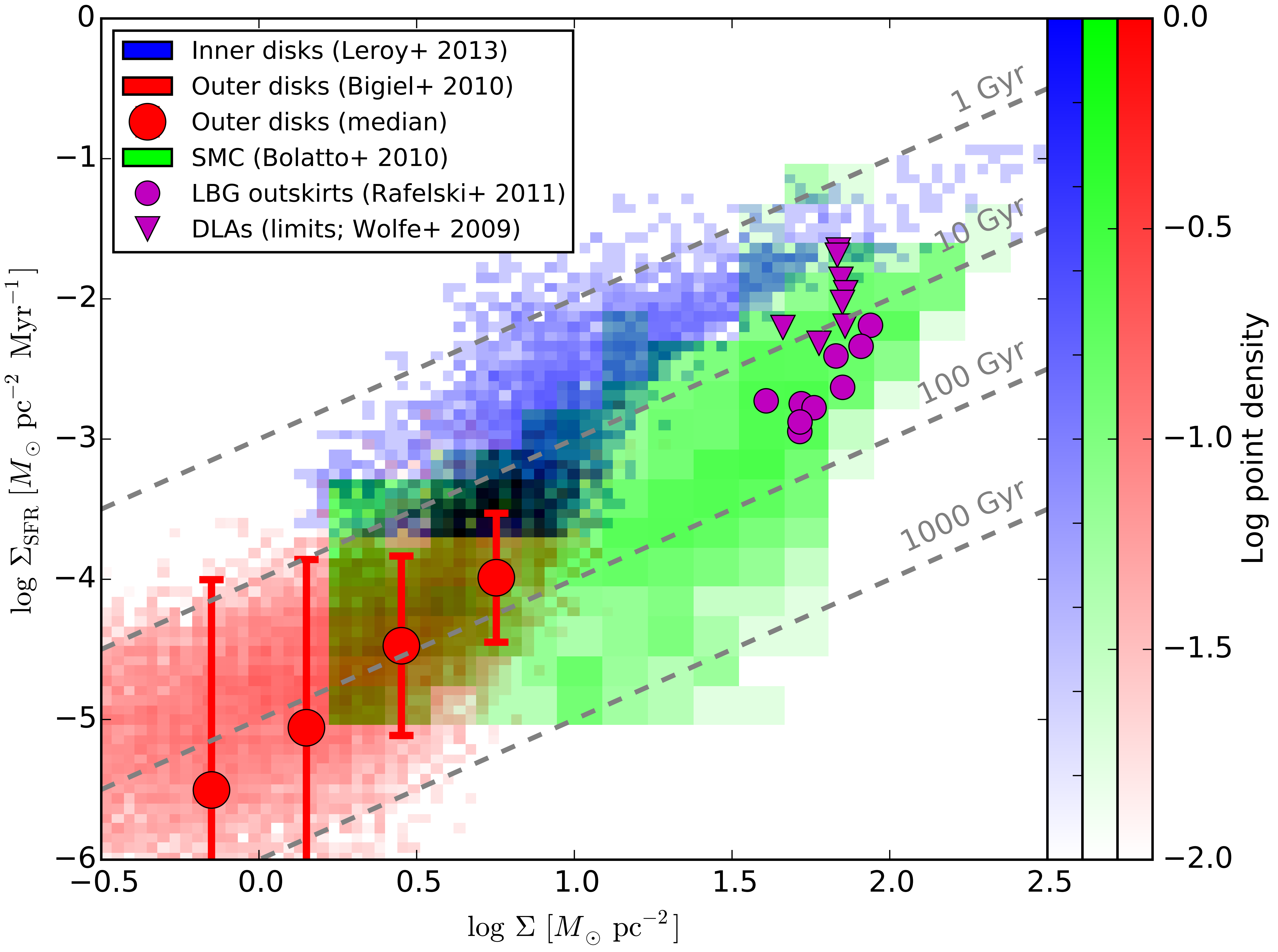
I’m just going to keep showing pictures of industrial safety equipment from UVEX here…





The (relatively) simple molecular Kennicutt-Schmidt relation

Left: Hu+ 2022
Right: Sun+ 2023



The horribly complicated total gas Kennicutt-Schmidt relation

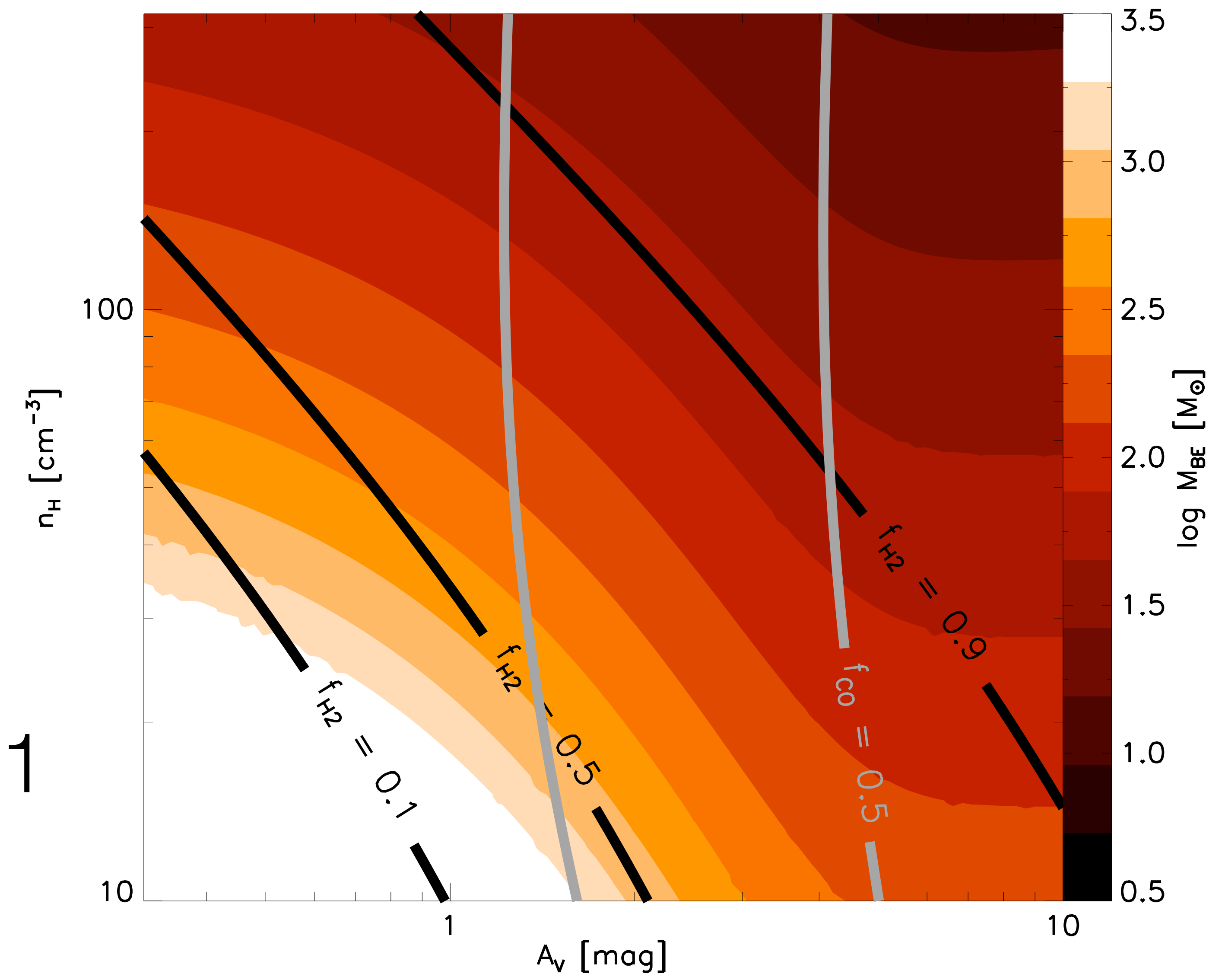
Krumholz 2014 compilation

Phenomenological summary

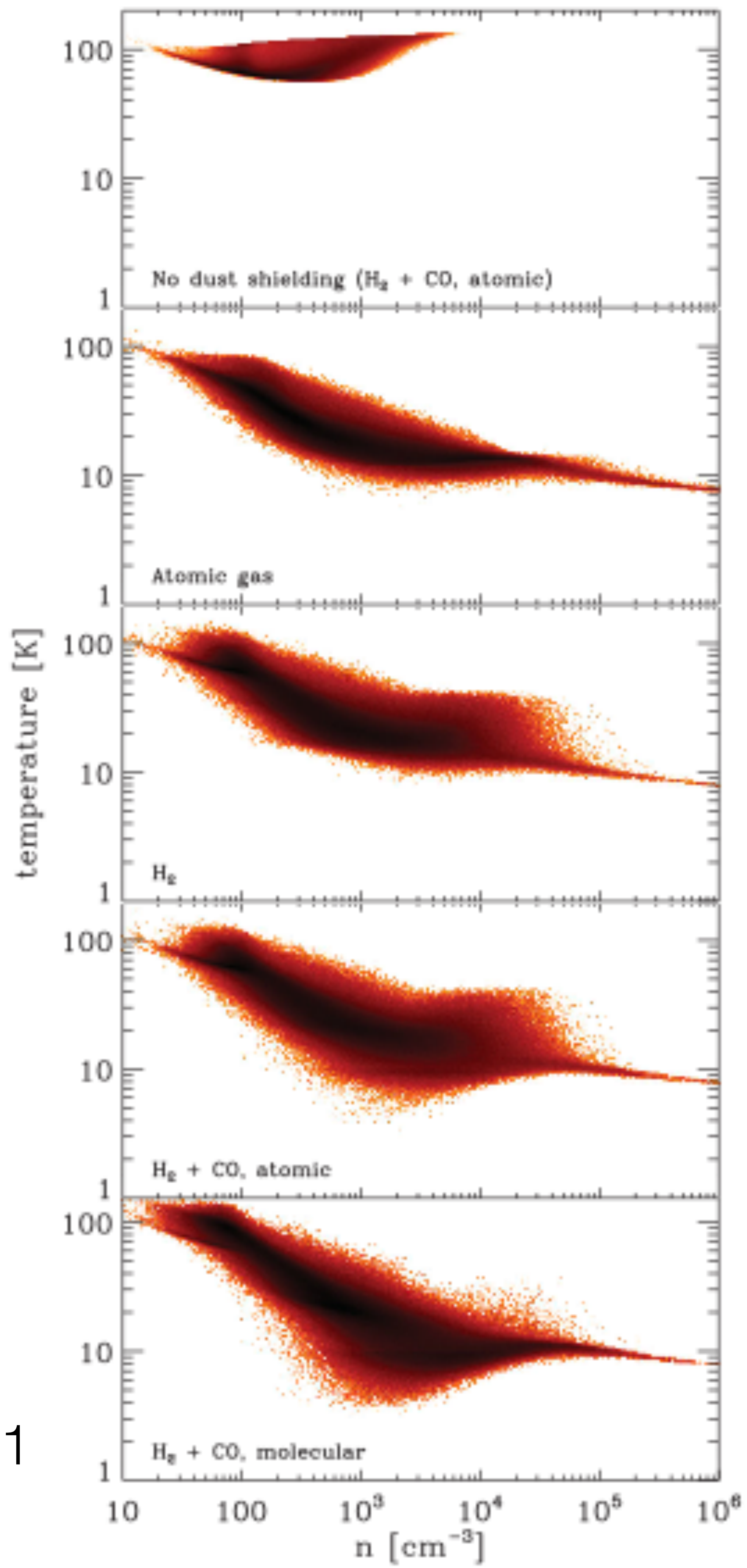
- Molecular gas forms stars at ~1% / t_{ff}; this yields a tight molecular KS relation
- The total gas KS relation is similarly tight at high Σ, where gas is mostly H_2, but:
  - There is a sharp transition to longer depletion time and lower H_2 fraction once Σ drops below some value
  - The value of Σ at which this transition occurs is not the same in all galaxies
  - In the low-Σ regime, there is huge scatter in SFR at fixed Σ — other parameters clearly matter more than they do at high Σ
- Questions: (1) what causes the transition in regimes? (2) what parameters control the SF rate in the low-Σ regime?

Model 1: metallicity and thermodynamics

- Gas temperature controlled by photo-electric and cosmic ray heating: $\Gamma = \Gamma_{\rm PE} + \Gamma_{\rm CR}$; for unshielded ISM, $\Gamma_{\rm PE} \approx 20 \times \Gamma_{\rm CR}$
- Gas cold enough to collapse in shielded regions where $\Gamma_{\rm PE} \approx 0$
- Chemical phase correlates with shielding: H_2 forms only in places where FUV photons are blocked by extinction → explains tight molecular KS relation



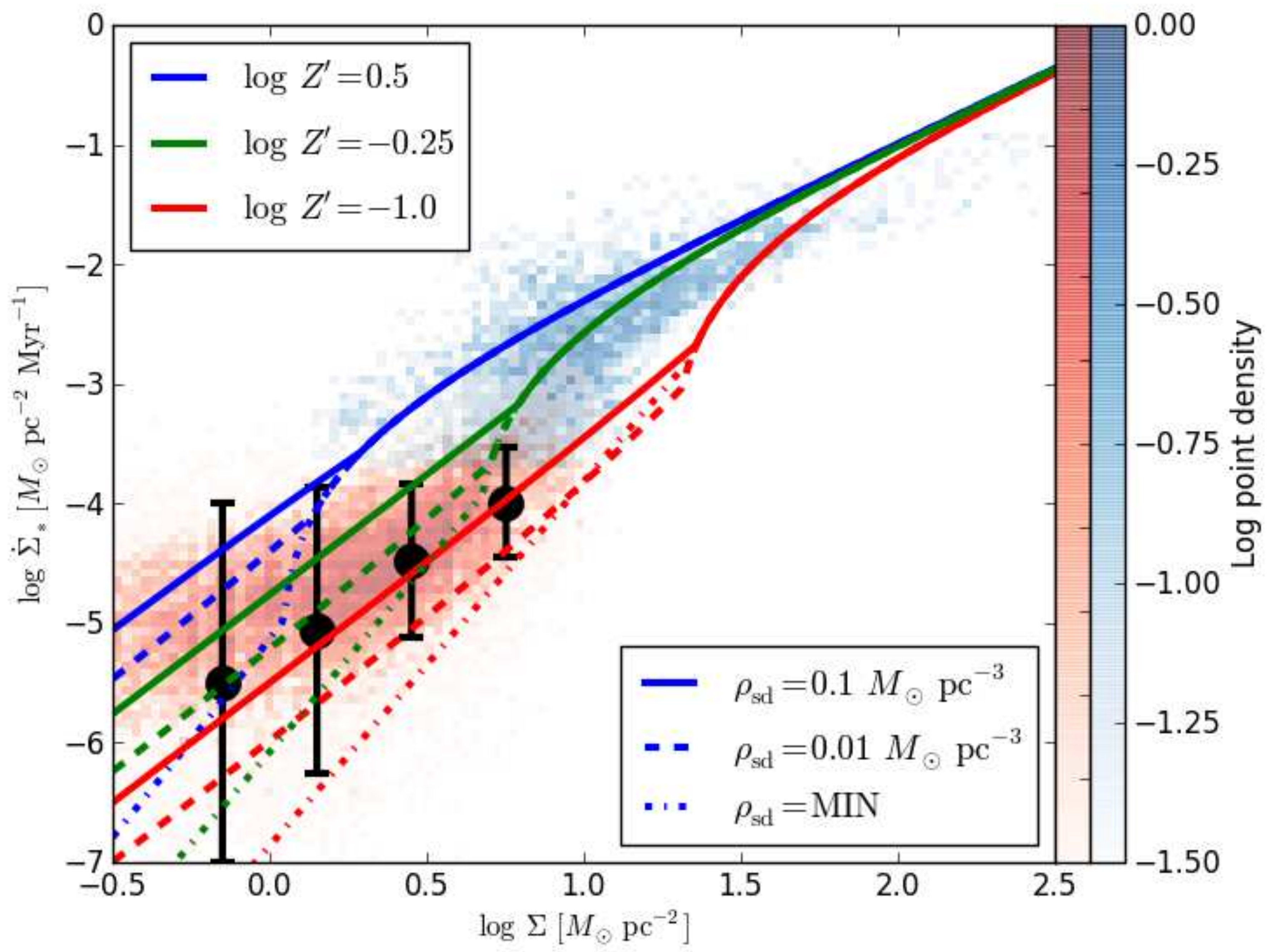
Krumholz+ 2011



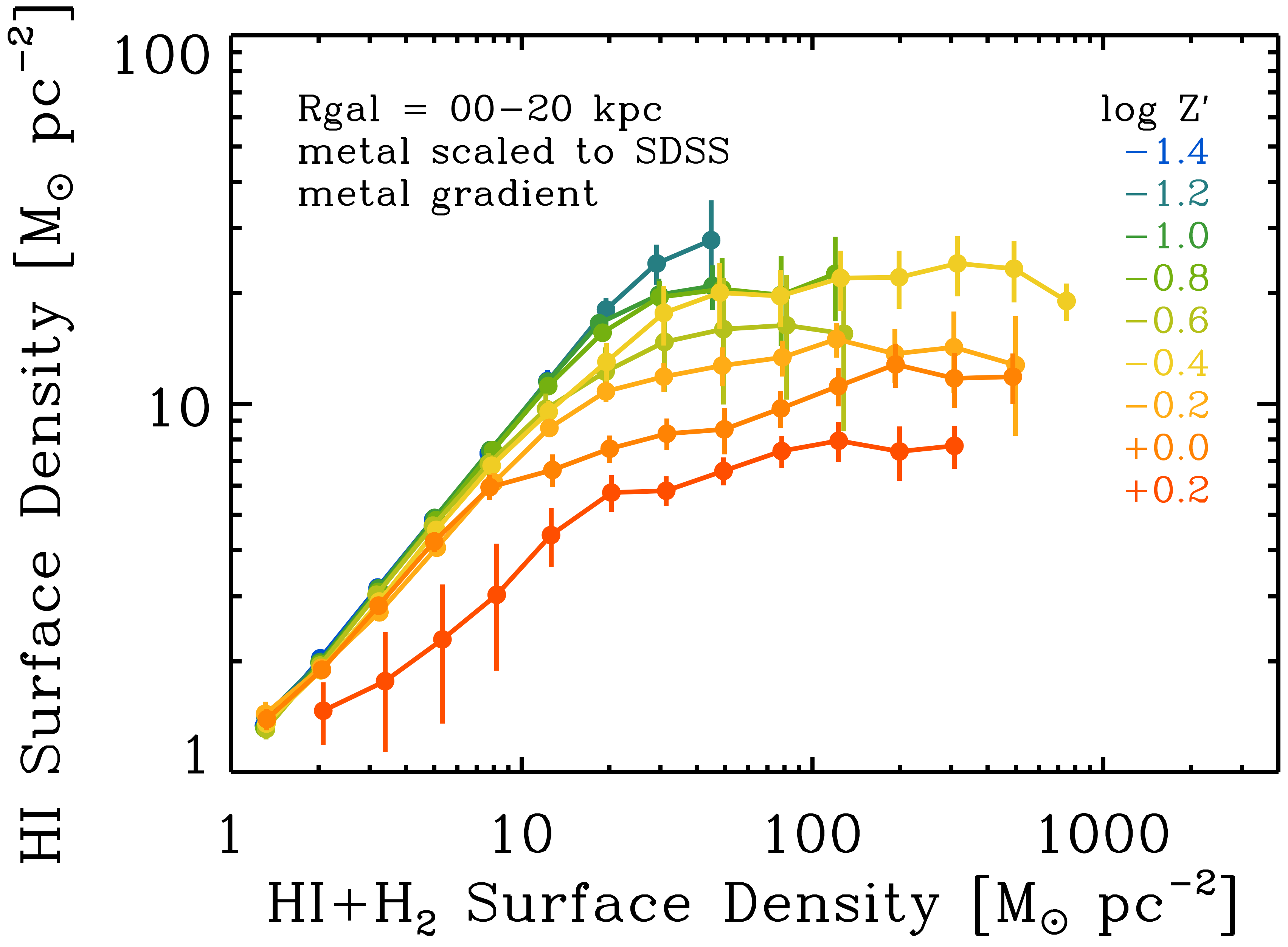
Glover & Clark 2011

Explaining the total gas KS relation

- If shielding is key physics, this naturally explains sharp transition in KS relation with Σ — transition corresponds to where mean optical depth ~ 1
- This also explains why the transition varies from galaxy to galaxy, and why there is a large scatter: different galaxies have different dust to gas ratios
- Strong prediction of these models that is confirmed by observations: transition from HI to H_2-dominated ISM at a metallicity-dependent surface density $\Sigma_{\rm trans} \approx 10(Z/Z_\odot)^{-1}\ {\rm M_\odot\ pc^{-2}}$



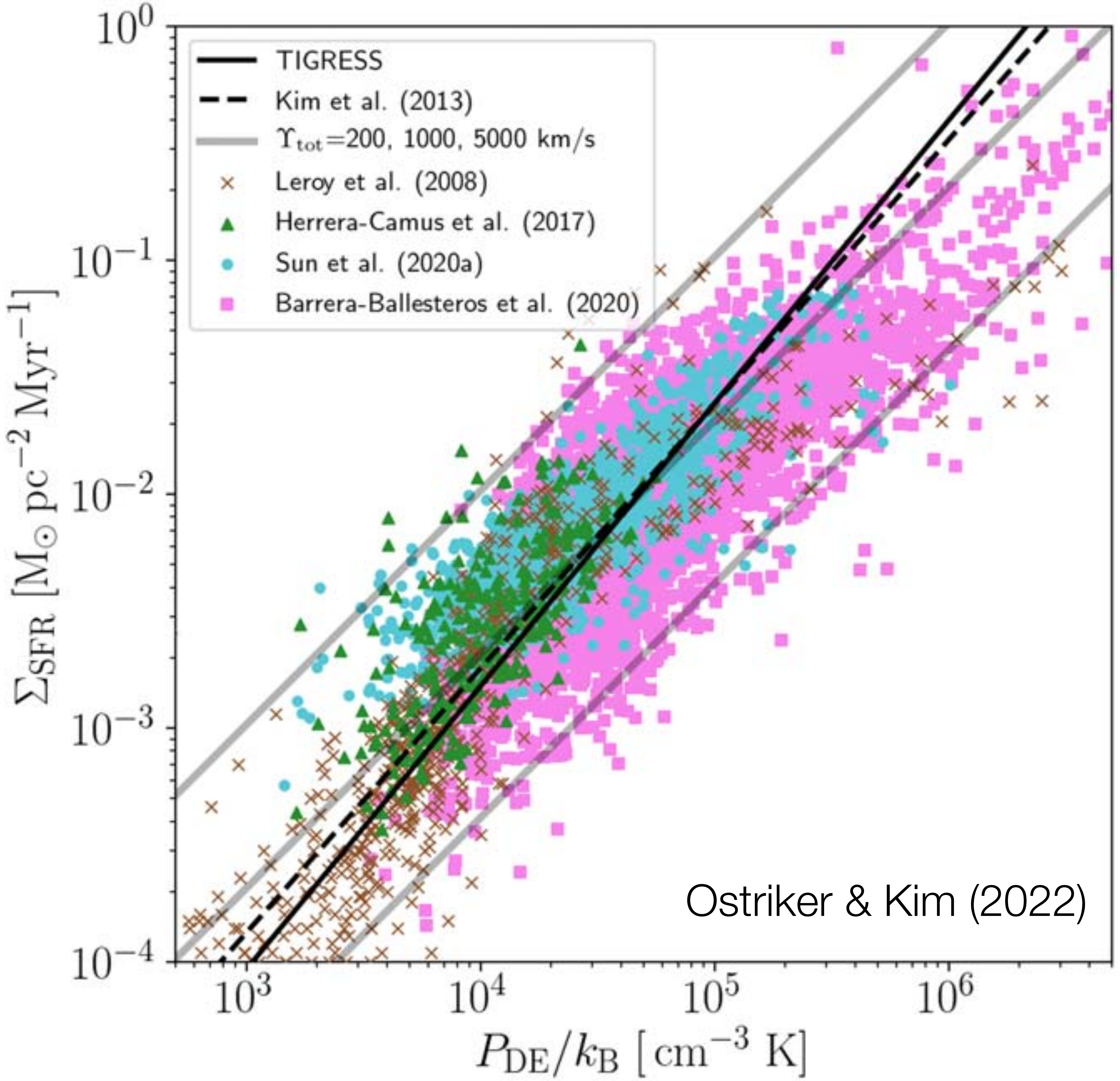
Krumholz 2013



Schruba+ 2018

Model 2: stellar gravity and pressure

- Basic hypothesis: SF drives turbulence in ISM, and SFR equilibrates to value such that turbulent ram pressure ≈ weight of ISM
- Predicts that SFR scales with gas pressure rather than surface density; non-linearity explained as variation in feedback efficiency with gas density
- In inner spirals, strength of stellar gravity roughly constant → close to linear KS relationship
- In outer spirals and dwarfs, large scale heights → weak stellar gravity, low-Σ regime; scatter is from range of stellar scale heights and surface densities



How can UVEX help?

- Difficult to disentangle models now because data in dwarf regime are limited and stellar gravity and metallicity are correlated —
  - Do spirals have higher Σ_{SFR} than dwarfs at fixed Σ_{gas} because they are more metal rich, or because they have stronger stellar gravity?

- Breaking the degeneracy requires a large dwarf galaxy sample covering a range of metallicity and stellar properties, in order to tease apart separate dependences on the two parameters

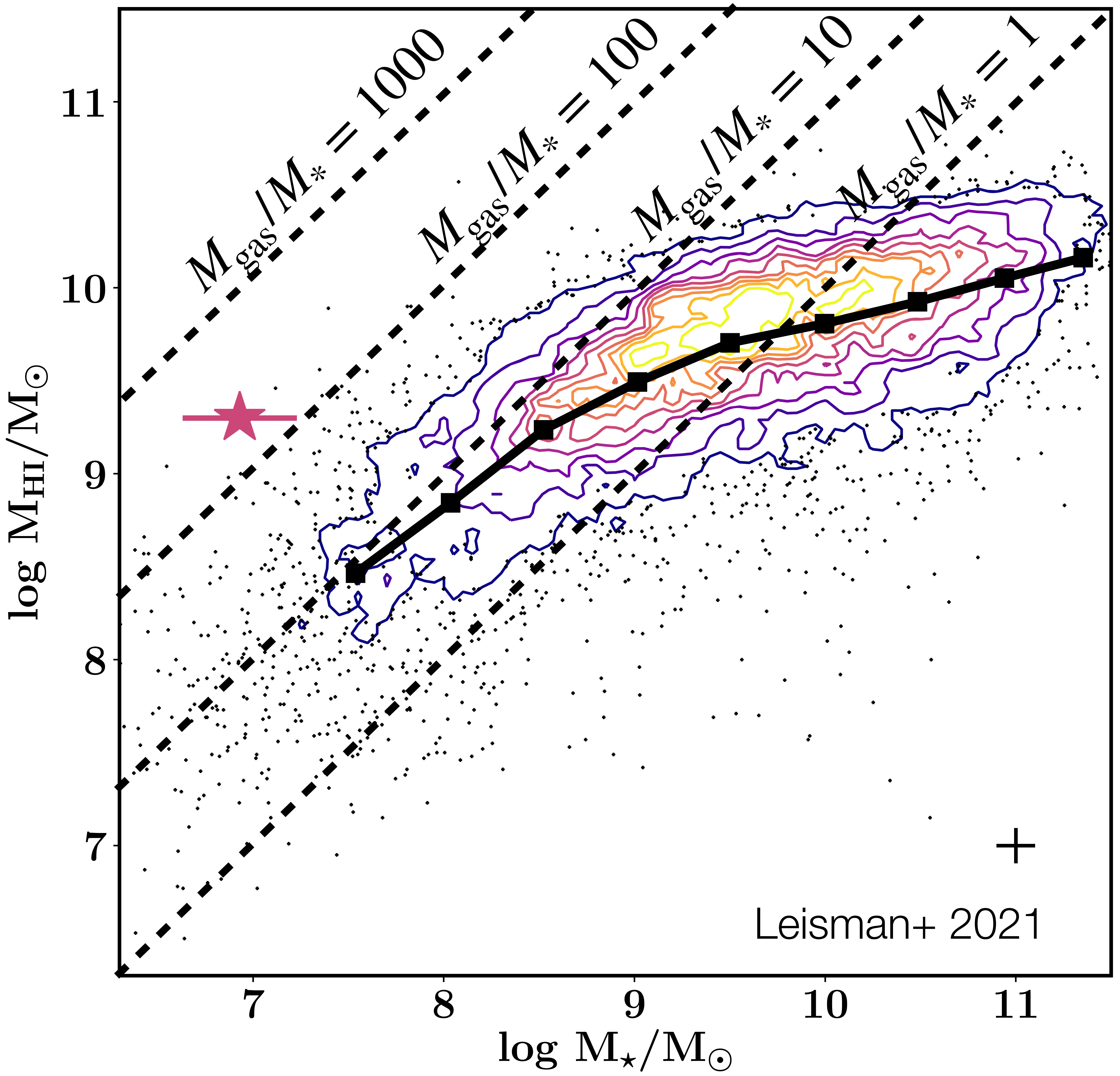
- At present this has been done for the HI - H_2 transition using a sample of BCDs (Fumagalli+ 2010), but it is difficult to measure meaningful SFRs for these — need a bigger but less extreme sample

The most quiescent dwarf galaxies

Apparently they make boots too…

Ultra-gas-dominated galaxies

- Blind HI surveys have turned up a population of *extremely* gas-dominated galaxies — most extreme examples have $M_{gas} / M_{star} > 100$
- Likely a heterogenous class — some are baryon-dominated and likely tidal in origin, some appear to be dark matter dominated (e.g. FAST J0139+4328, Xu+ 2023)
- Implied depletion times are very long
  - For non-tidal galaxies, age ~10 Gyr and $M_{gas} / M_{star} > 100 \rightarrow t_{dep} \gtrsim 1000$ Gyr!
  - For tidal galaxies, distances imply ages > 1 Gyr, so $M_{gas} / M_{star} > 100$ requires $t_{dep} \gtrsim 100$ Gyr!

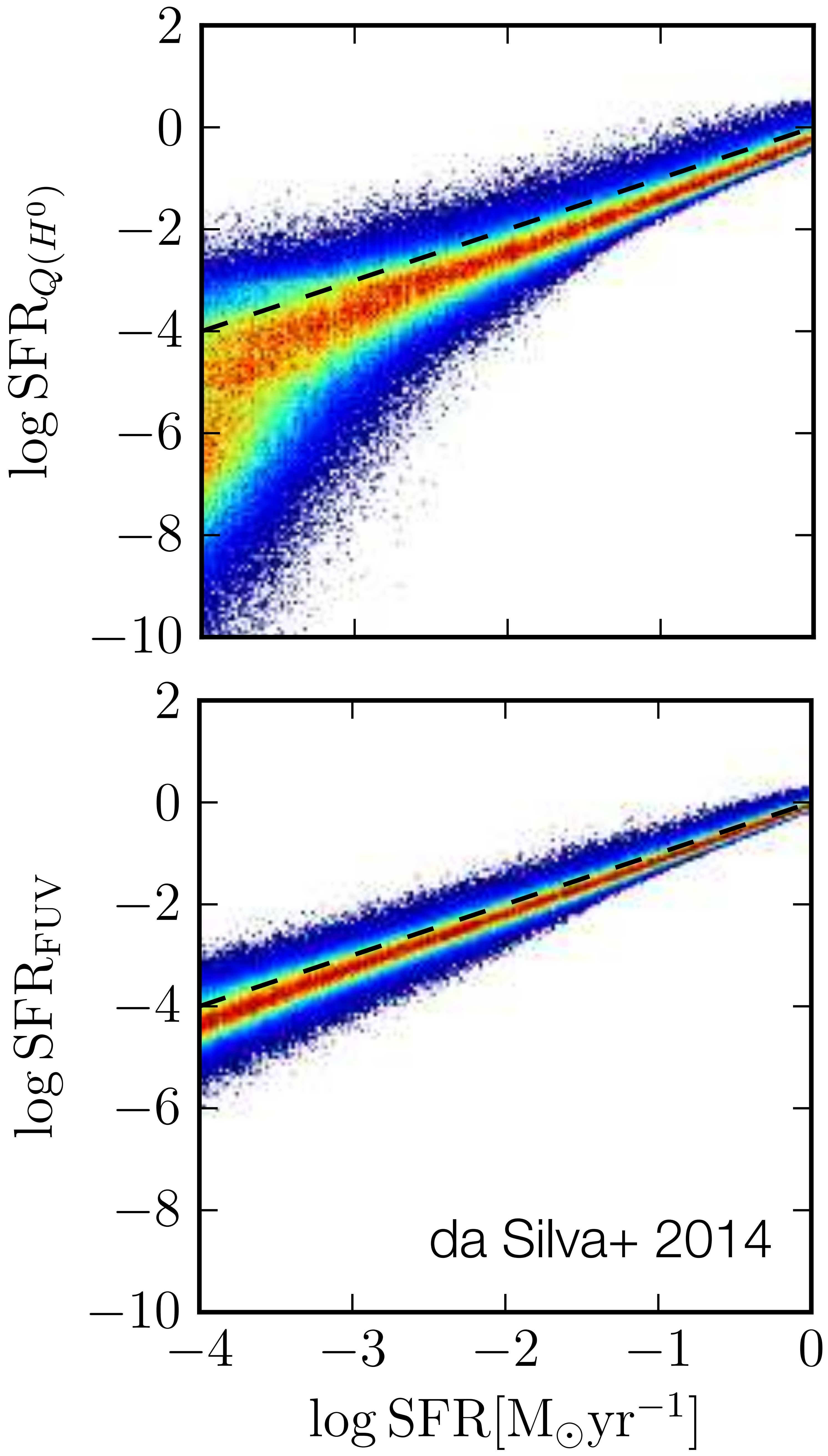


Star formation in ultra-gas-dominated galaxies (UGDGs?)

- What is inhibiting star formation and keeping depletion times long?
- Peak surface densities ≈ 5 $M_\odot$ pc^{-2} — lowish, but only a factor of ~few lower than Solar neighborhood, not optically thin to ionising radiation, and high enough gas should be able to cool and become unstable
- Hard to explain w/SNe or O stars — implied depletion time means SN rate or massive star formation rate / area is ≲ 1% of Solar neighborhood value
- Seems like an ideal system in which to test models for how SF is regulated

Why UVEX? SFRs and burstiness in UGDGs

- SFRs in these systems (≲ 10^{-3} M⊙ yr^{-1}) are essentially unmeasurable from recombination lines due to stochasticity
- FUV does much better due to longer lifetimes of stars that produce it, ~30 Myr rather than ~3 Myr
- Conversely, statistical distribution of recombination to FUV luminosities constrains degree of burstiness in SF history — bursty history → big scatter
- Knowing true SFRs and degree of burstiness very useful for constraining star formation models



Final thoughts

There is also a *completely separate* German company called UVEX Equestrian that makes horse riding gear…

Why the UV is powerful for studying star formation

- UV is powerful because it represents a compromise between ionizing and optical:
  - Ionizing sensitive to the most massive stars, so very sharp mass / age discrimination, but also very stochastic
  - Optical bands sensitive to a much broader range of stellar masses, so much less stochastic but also much less sharp discrimination
- In low SFR systems, stochasticity becomes a real liability for ionization-based tracers, so FUV is a good choice
- These systems are also the places where our SF models have been tested the least