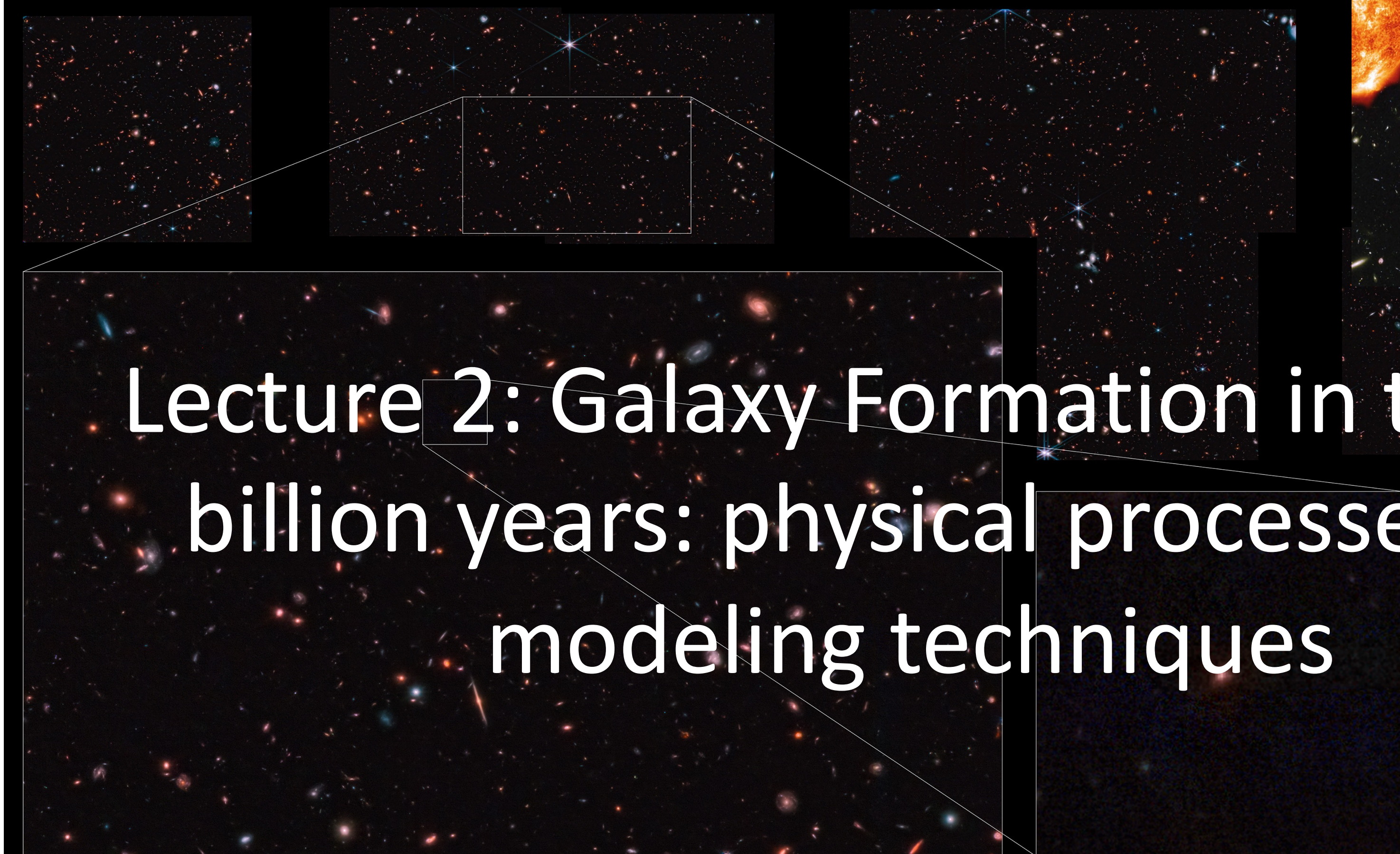
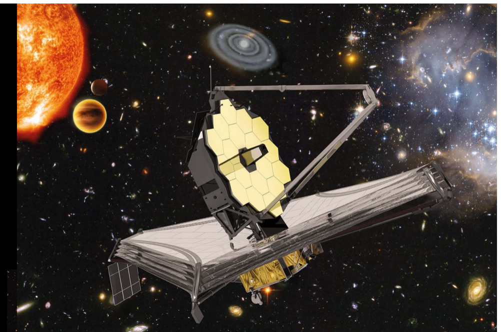
Lecture 2: Galaxy Formation in the first billion years: physical processes and modeling techniques





CEERS JWST/NIRCam F115W F150W F200W F277W F356W F410M F444W NASA/STScI/CEERS/TACC/S. Finkelstein/M. Bagley/Z. Levay

- *rachel somerville*

Center for Computational Astrophysics

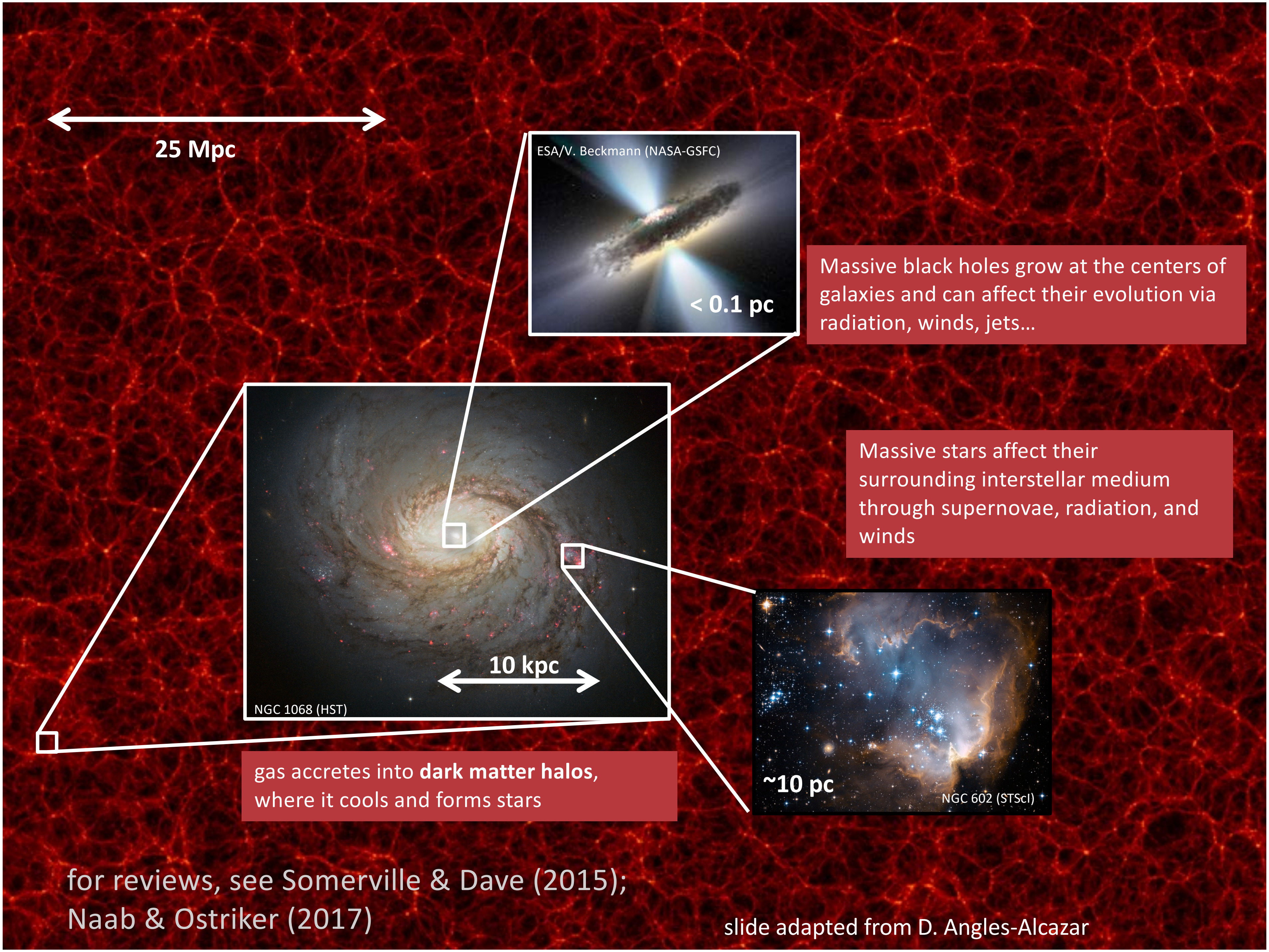
FLATIRON INSTITUTE

54th Saas-Fee Advanced Course

Galaxies and Black Holes in the First Billion Years as seen by the JWST

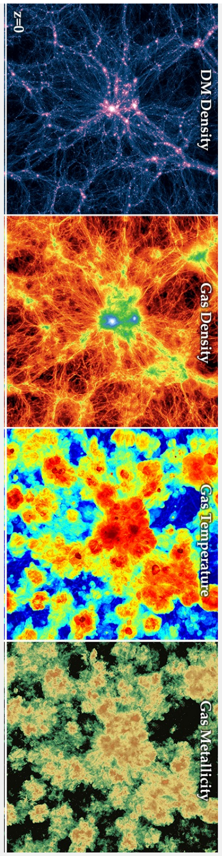
Jan 27-31, 2025

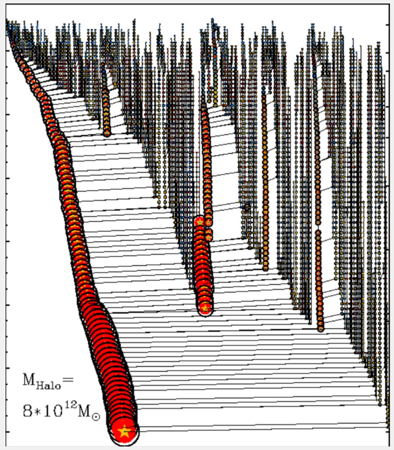
Swiss National Science Foundation EPFL scnat swiss academy of sciences UNIVERSITÉ DE GENÈVE SSAA


25 Mpc
ESA/V. Beckmann (NASA-GSFC)
< 0.1 pc
Massive black holes grow at the centers of galaxies and can affect their evolution via radiation, winds, jets…
Massive stars affect their surrounding interstellar medium through supernovae, radiation, and winds
10 kpc
NGC 1068 (HST)
~10 pc
NGC 602 (STScI)
gas accretes into **dark matter halos**, where it cools and forms stars
for reviews, see Somerville & Dave (2015); Naab & Ostriker (2017)
slide adapted from D. Angles-Alcazar

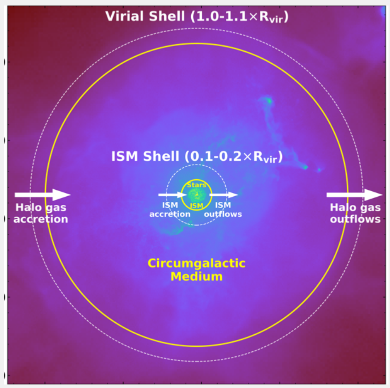
outline

- methods:
  - semi-analytic models
  - numerical hydrodynamic simulations
- physical processes
  - cooling
  - cosmic reionization & photoionization feedback
  - star formation, ISM, stellar feedback
  - chemical enrichment & dust
- status of theoretical models & simulations
  - successes, challenges, progress and outlook



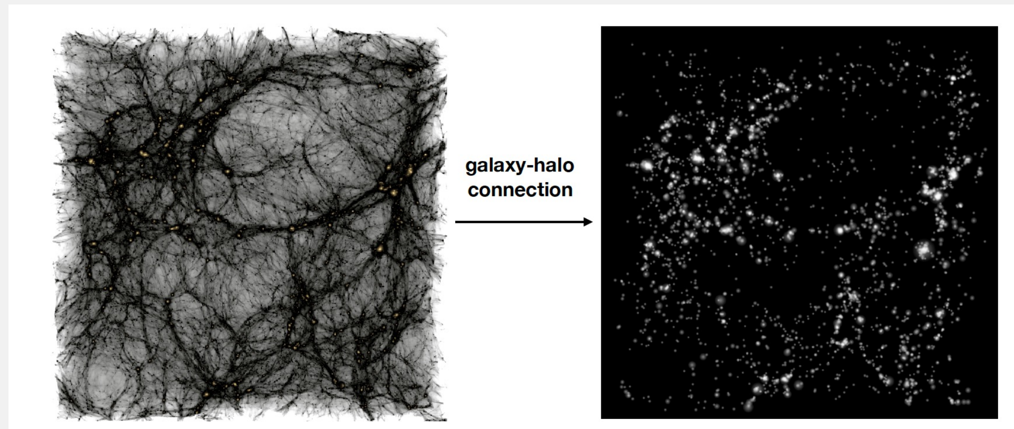


Pandya et al. 2020



Somerville & Davé 2015
Naab & Ostriker 2017
Crain & van de Voort 2023

Wechsler & Tinker 2018

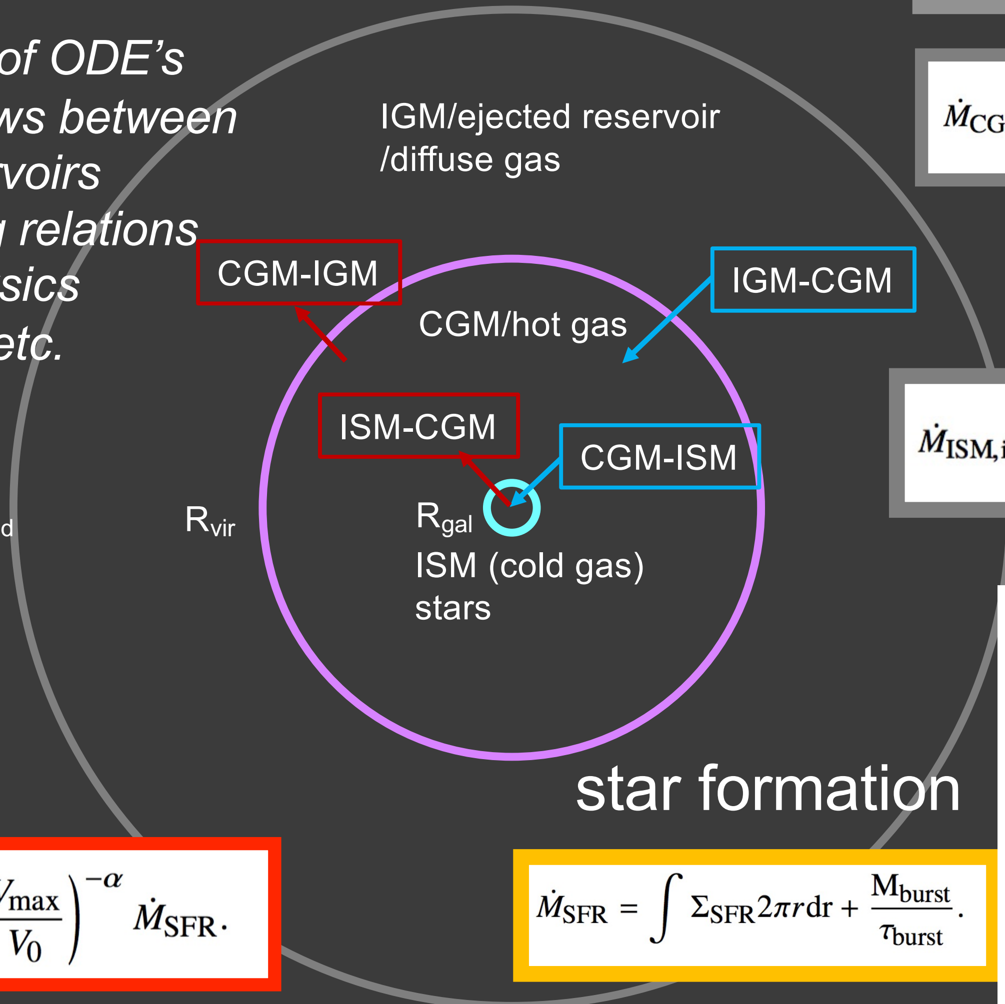


← physical models		empirical models →		
Hydrodynamical Simulations	**Semi-analytic Models**	**Empirical Forward Modeling**	**Subhalo Abundance Modeling**	**Halo Occupation Models**
solve PDEs for DM, stars, gas sub-grid models for SF, feedback, BH, etc	solve ODEs for gas flows between global reservoirs; recipes for SF, BH growth, feedback, etc	assume gas inflows track DM; empirical recipes for SF, etc	mapping from DM (sub)-halos to galaxy properties	model for n_{gal} as function of halo mass (or other halo properties)

semi-analytic models

Somerville & Davé (2015)

solve system of ODE's describing flows between different reservoirs
simple scaling relations represent physics of SF, winds, etc.



$$\dot{M}_{\rm CGM,in,pristine} = f_{\rm UV} f_b \dot{M}_{\rm vir}.$$

$$\dot{M}_{\rm CGM,in,recycled} = \chi_{\rm re-infall}\left(\frac{M_{\rm ejected}}{t_{\rm dyn}}\right).$$

inflows

$$\dot{M}_{\rm ISM,in} = \frac{1}{2} M_{\rm CGM} \frac{R_{\rm cool}}{R_{\rm vir}} \frac{1}{t_{\rm dyn}}$$

outflows

$$\dot{M}_{\rm ISM,out} = \epsilon_{\rm SN}\left(\frac{V_{\rm max}}{V_0}\right)^{-\alpha} \dot{M}_{\rm SFR}.$$

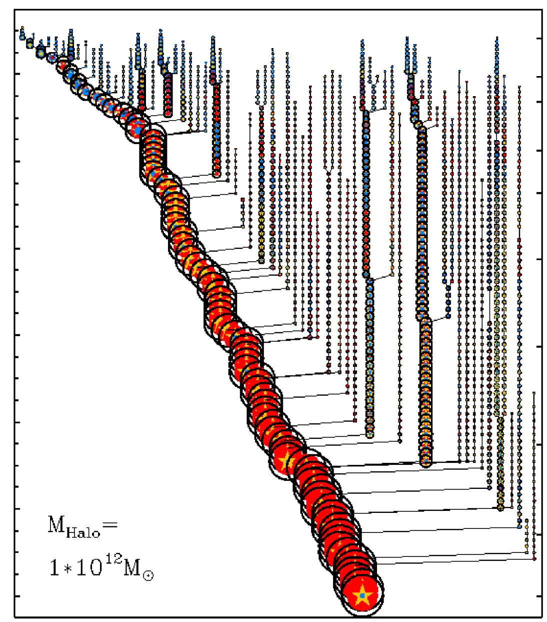
$$\dot{M}_{\rm CGM,out} = [1.0 + (V_{\rm vir}/V_{\rm eject})^{\beta}]^{-1} \times \dot{M}_{\rm ISM,out}.$$

star formation

$$\dot{M}_{\rm SFR} = \int \Sigma_{\rm SFR} 2\pi r {\rm d}r + \frac{{\rm M}_{\rm burst}}{\tau_{\rm burst}}.$$

Kennicutt-Schmidt

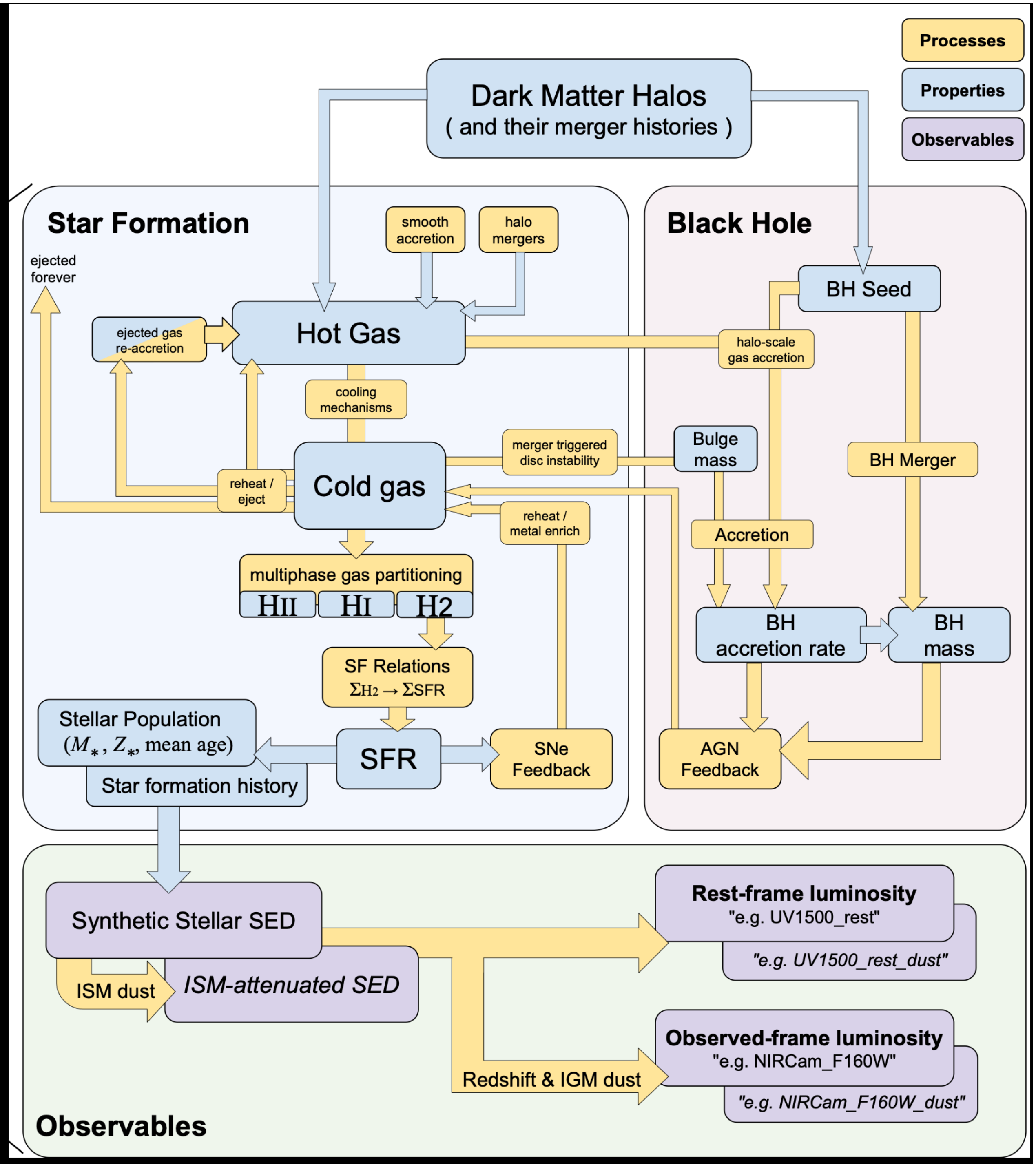
slide adapted from V. Pandya



L-galaxies, GAEA,
SAGE/DARK SAGE
GALFORM, GALACTICUS,
SHARK
CAT
Delphi, ASTRAEUS
MERAXES
Santa Cruz SAM

(again, an incomplete list,
in no particular order)

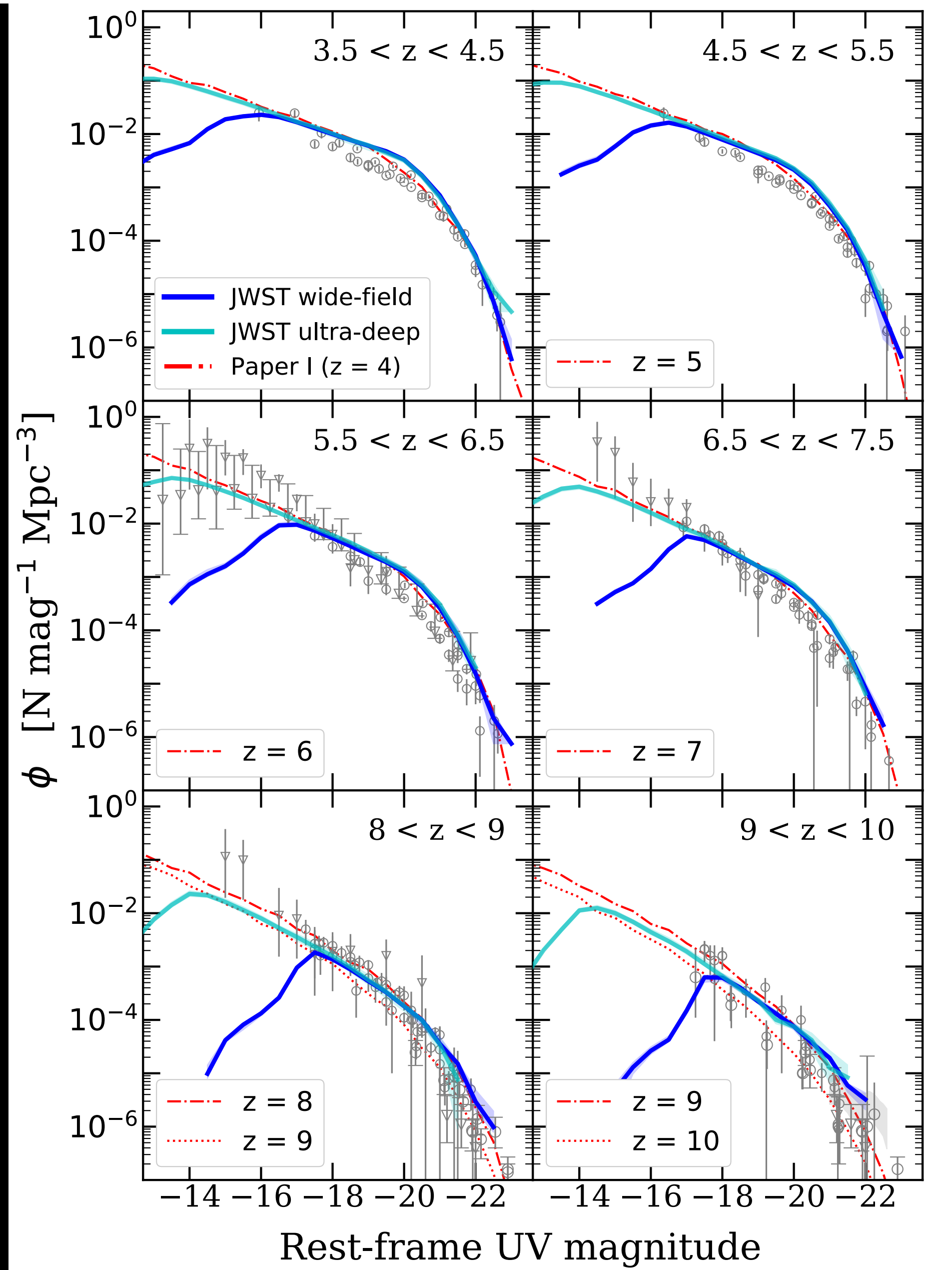
Yung et al. 2019



Semi-Analytic Forecasts for JWST

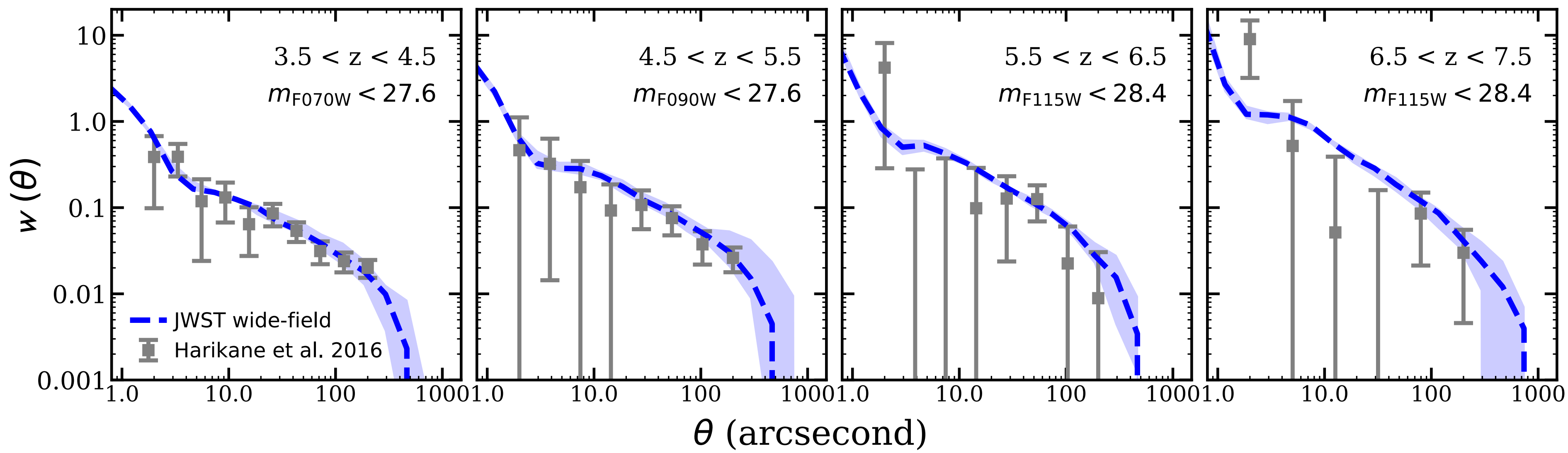
models calibrated on observations of nearby galaxies make predictions that are consistent with pre-JWST UV LFs out to z~10

number of galaxies



brighter galaxies→

L.Y.A. Yung, rss et al.
2019a, b; 2020a,b;2021;2022

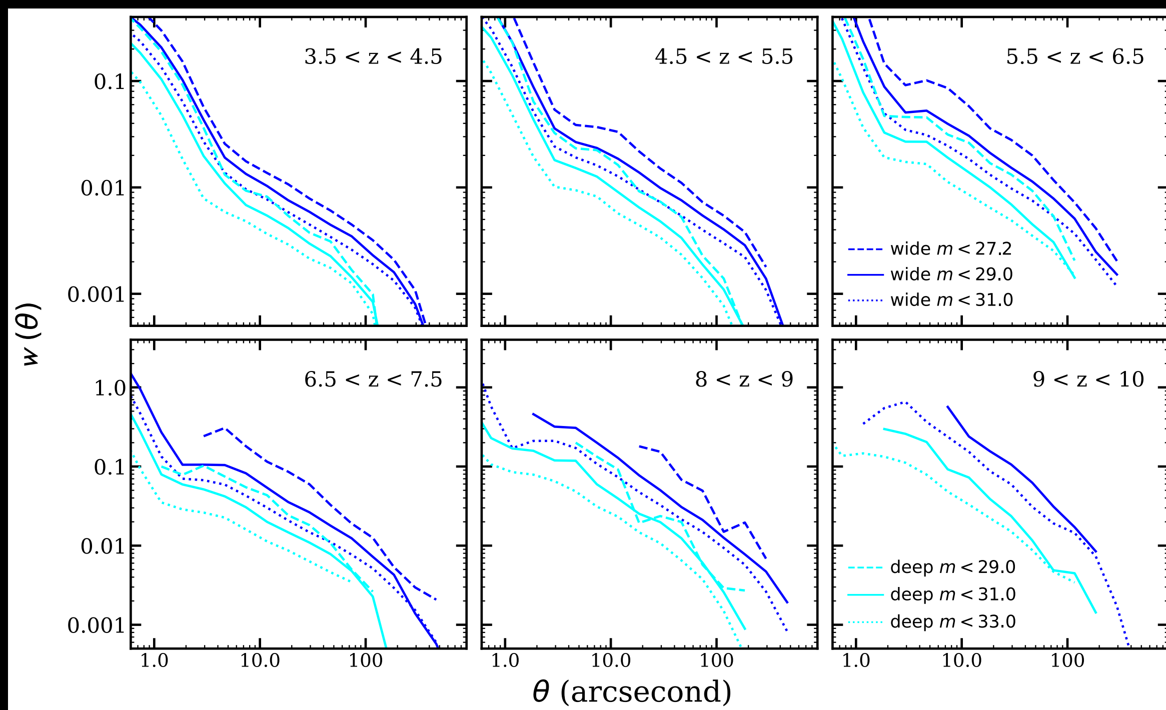


how galaxies clustered at early times: angular spatial correlation function

independent constraint on galaxy host halo masses

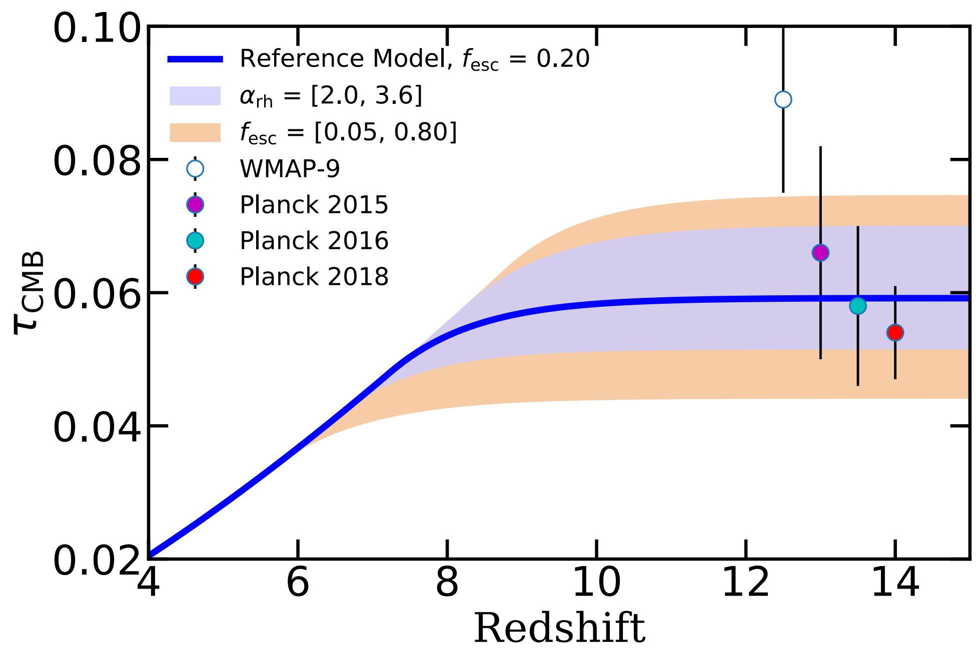
Yung, rss et al. 2022

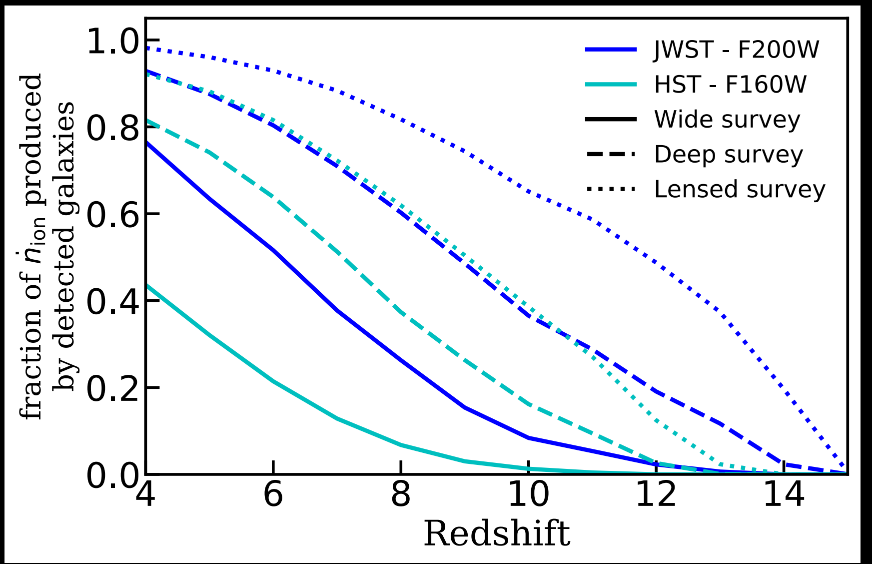
JWST forecast

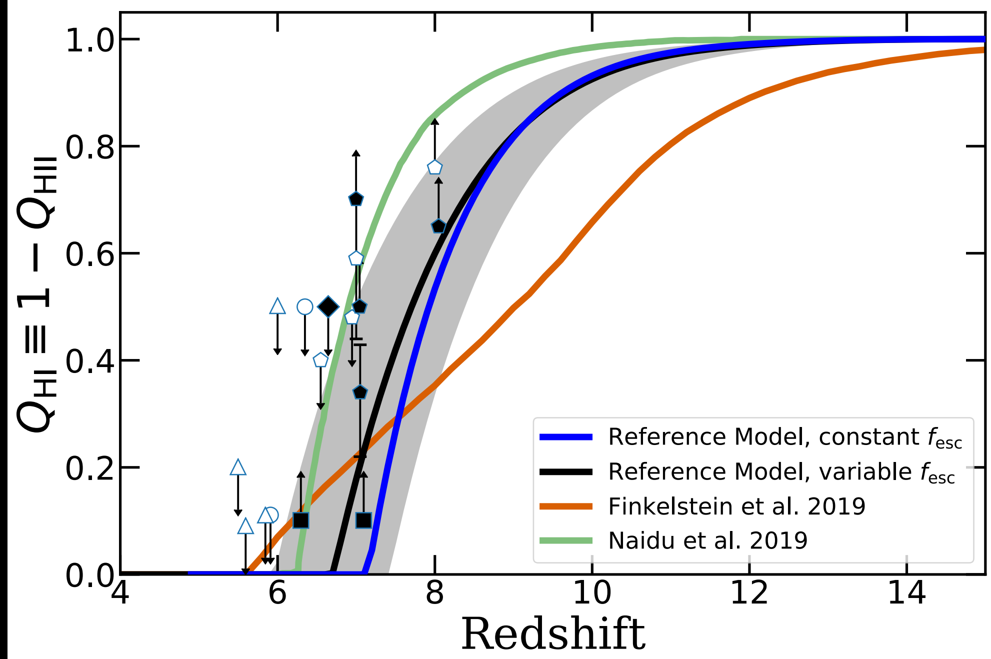


Cosmic Reionization

predictions of the fiducial Santa Cruz SAMs agree with observational constraints on when the Universe was reionized.







for impact of AGN on H and He reionization, see Yung et al. 2021

Yung, rss et al. 2020b

The Euler Equations

Changes at fixed position + Fluid motion along gradients = Changes experienced by fluid elem.

Density

$$\frac{\partial \rho}{\partial t} + \boldsymbol{u} \cdot \nabla \rho = \frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho \nabla \cdot \boldsymbol{u}$$

Velocity

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = \frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} = -\frac{\nabla P}{\rho} - \nabla \Phi$$

Energy

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{u} \cdot \nabla \varepsilon = \frac{\mathrm{D}\varepsilon}{\mathrm{D}t} = -\frac{P}{\rho} \nabla \cdot \boldsymbol{u} + \frac{\Gamma}{\rho} - \frac{\Lambda}{\rho}$$

Inflow of density into fluid element

Pressure gradient

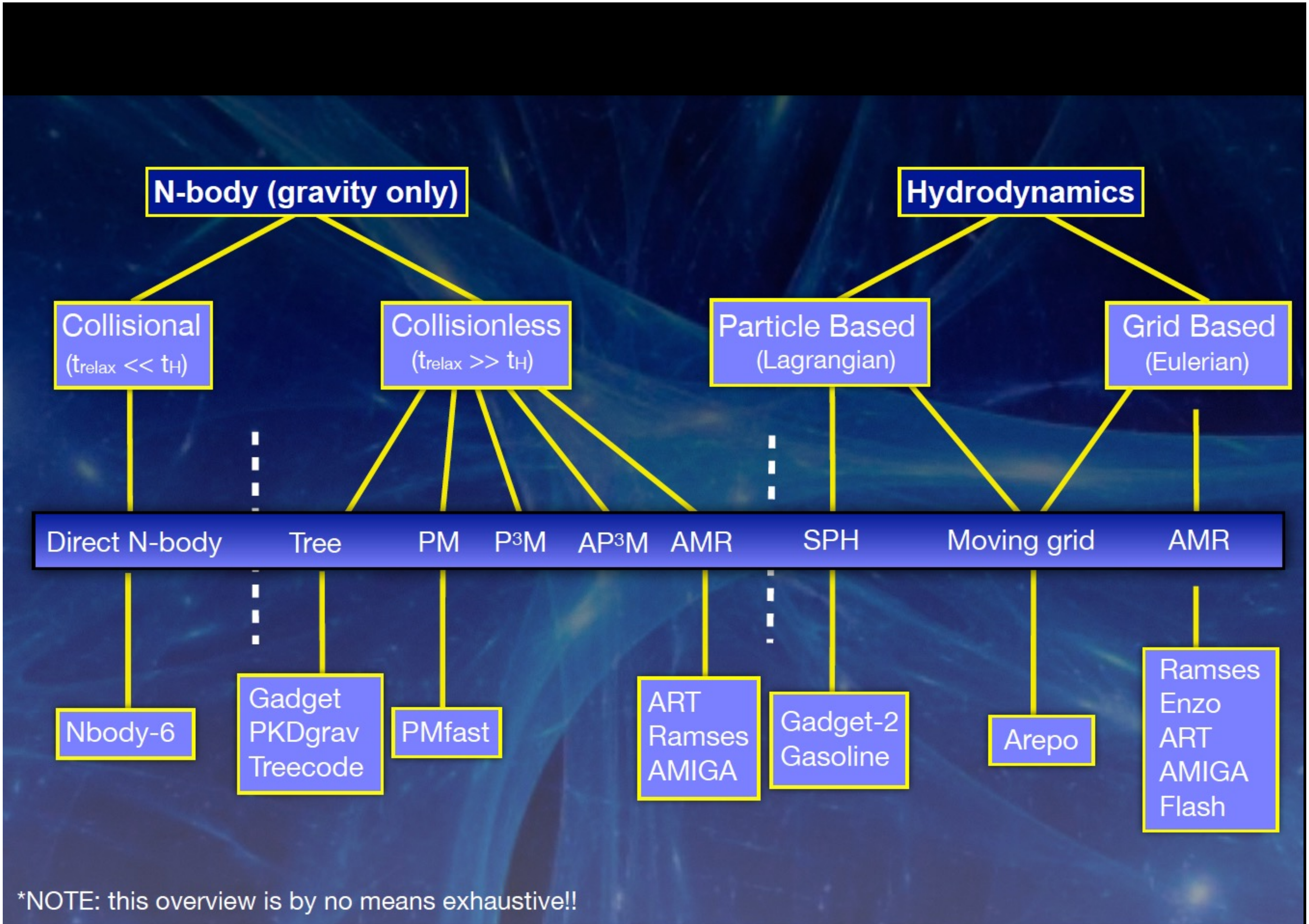
Gravitational force

PdV work

Heating

Cooling

B. Diemer



slide: F. van den Bosch

Table 1: Major galaxy formation simulation codes

code name	gravity treatment[a]	hydrodynamics treatment[b]	parallelization technique[c]	code availability[d]	primary reference
ART	PM/ML	AMR	data-based	public	Kravtsov (1997)[27]
RAMSES	PM/ML	AMR	data-based	public	Teyssier (2002)[38]
GADGET-2/3	TreePM	SPH	data-based	public	Springel (2005)[39]
Arepo	TreePM	MMFV	data-based	public	Springel (2010)[40]
Enzo	PM/MG	AMR	data-based	public	Bryan et al. (2014)[41]
ChaNGa[e]	Tree/FM	SPH	task-based	public	Menon et al. (2015)[42–44]
GIZMO[f]	TreePM	MLFM/MLFV	data-based	public	Hopkins et al. (2015)[45]
HACC	TreePM/P^3M	CRK-SPH	data-based	private	Habib et al. (2016)[46]
PKDGRAV3	Tree/FM	–	data-based	public	Potter et al. (2017)[47]
Gasoline2	Tree	SPH	task-based	public	Wadsley et al. (2017)[48]
SWIFT	TreePM/FM	SPH	task-based	public	Schaller et al. (2018)[49]

[a] PM: particle-mesh; TreePM: tree + PM, FM: fast multipole, P^3M: particle-particle-particle-mesh; ML: multilevel; MG: multigrid

[b] SPH: smoothed particle hydrodynamics, CRK-SPH: conservative reproducing kernel smoothed particle hydrodynamics , AMR: adaptive-mesh-refinement, MMFV: moving-mesh finite volume, MLFM/MLFV: mesh-free finite mass / finite volume

[c] data-based: data parallelism focuses on distributing data across different nodes, which operate on the data in parallel; task-based: task parallelism focuses on distributing tasks concurrently performed

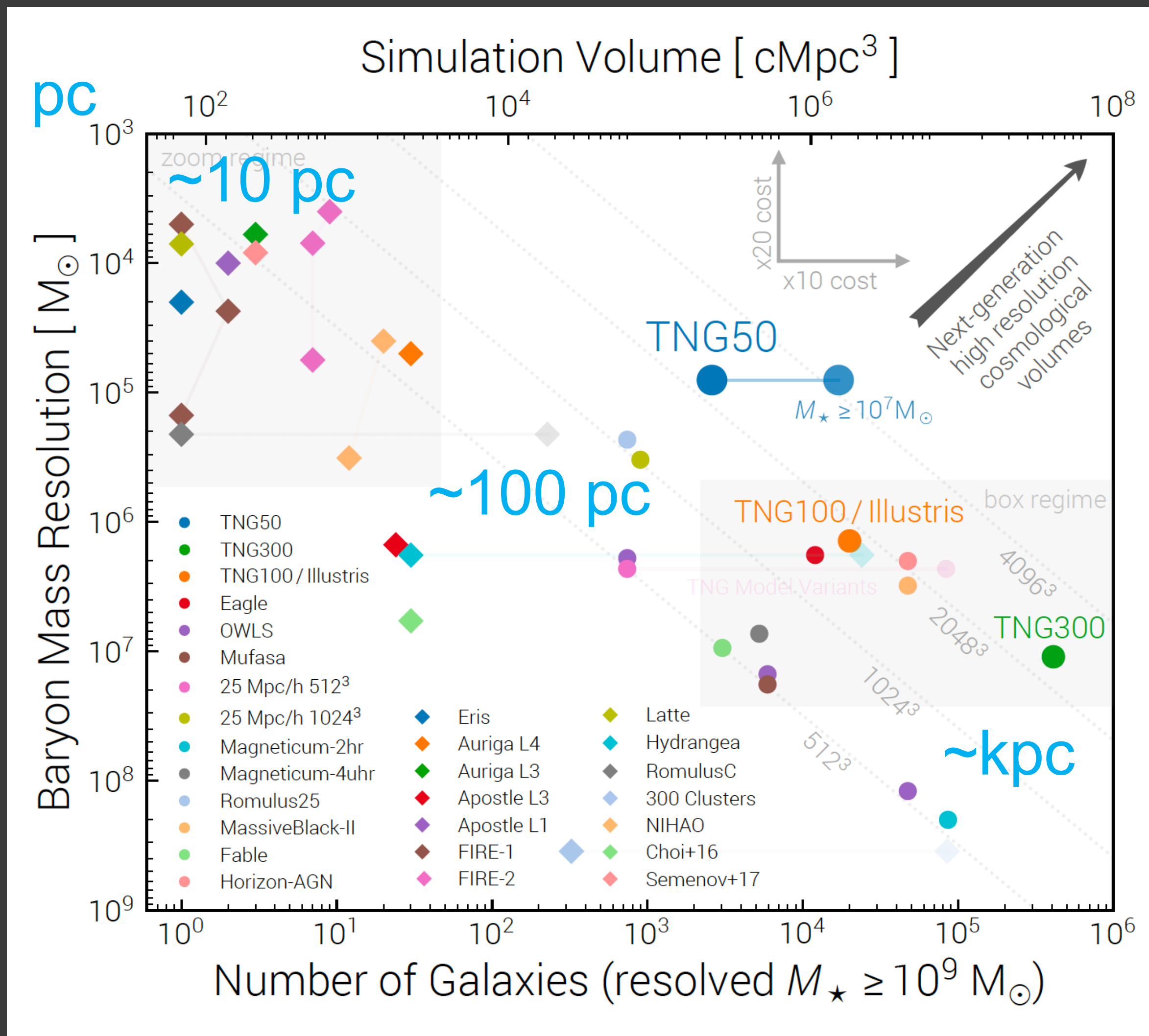
[d] private: private code; public: publicly available code (in some cases with limited functionality)

[e] gravity solver is based on PKDGRAV3

[f] based on the GADGET-3 code

Vogelsberger et al. 2020

“resolved”/ explicit physics → semi-resolved, mixed explicit+ sub-grid → sub-grid

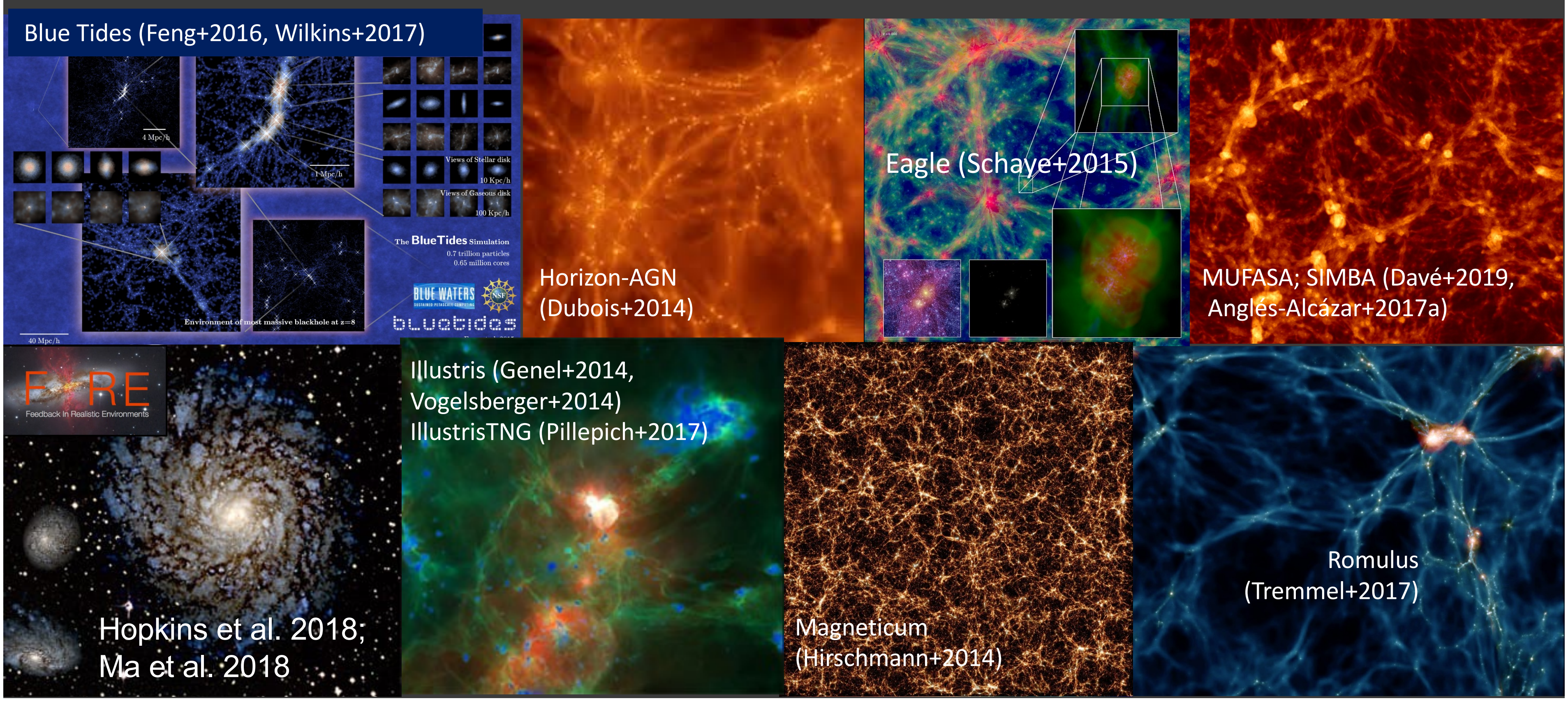


Nelson et al. 2019

an incomplete list of processes* that currently require sub-grid treatment in large-volume cosmological simulations

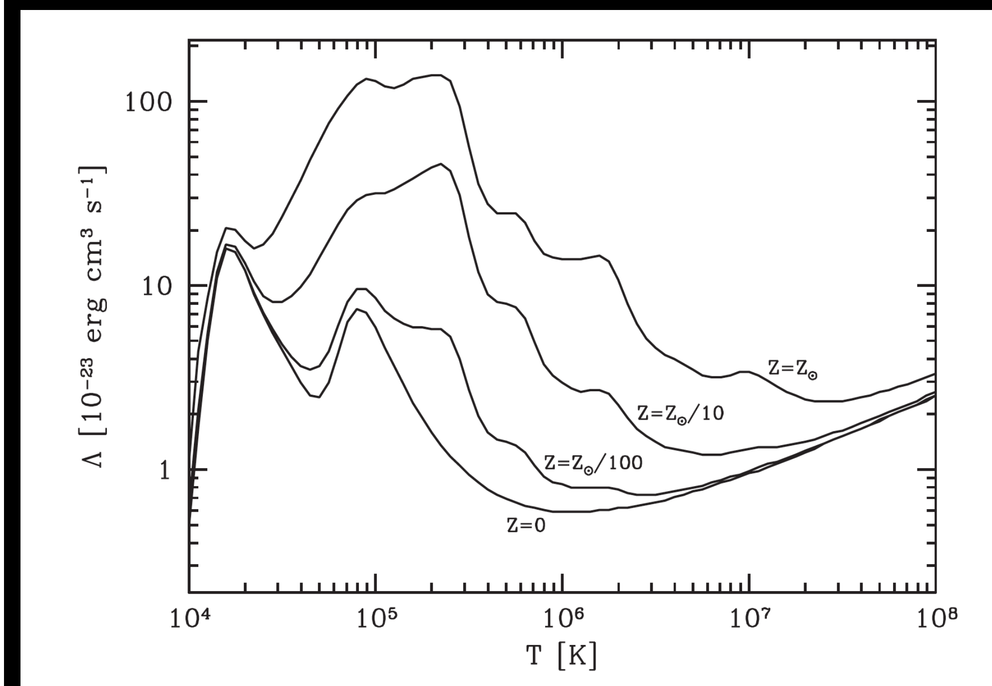
- the multiphase interstellar medium (ISM)
- star formation (conditions for its onset, and its efficiency)
- stellar feedback (stellar winds, radiation, SNae)
- chemical evolution and metal diffusion
- black hole seeding
- black hole accretion
- black hole feedback (kinetic, thermal, radiation)

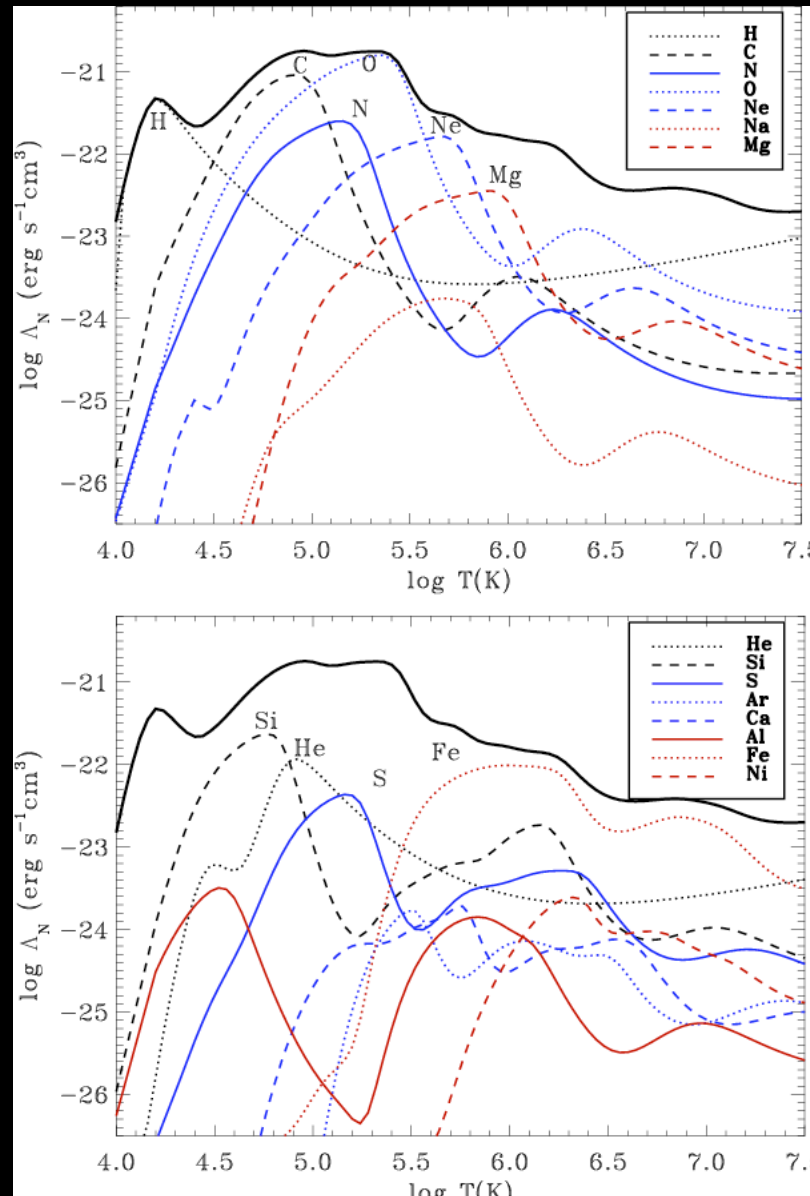
in addition to different hydro solvers, different groups have adopted different implementations of these sub-grid physics processes…



cooling function

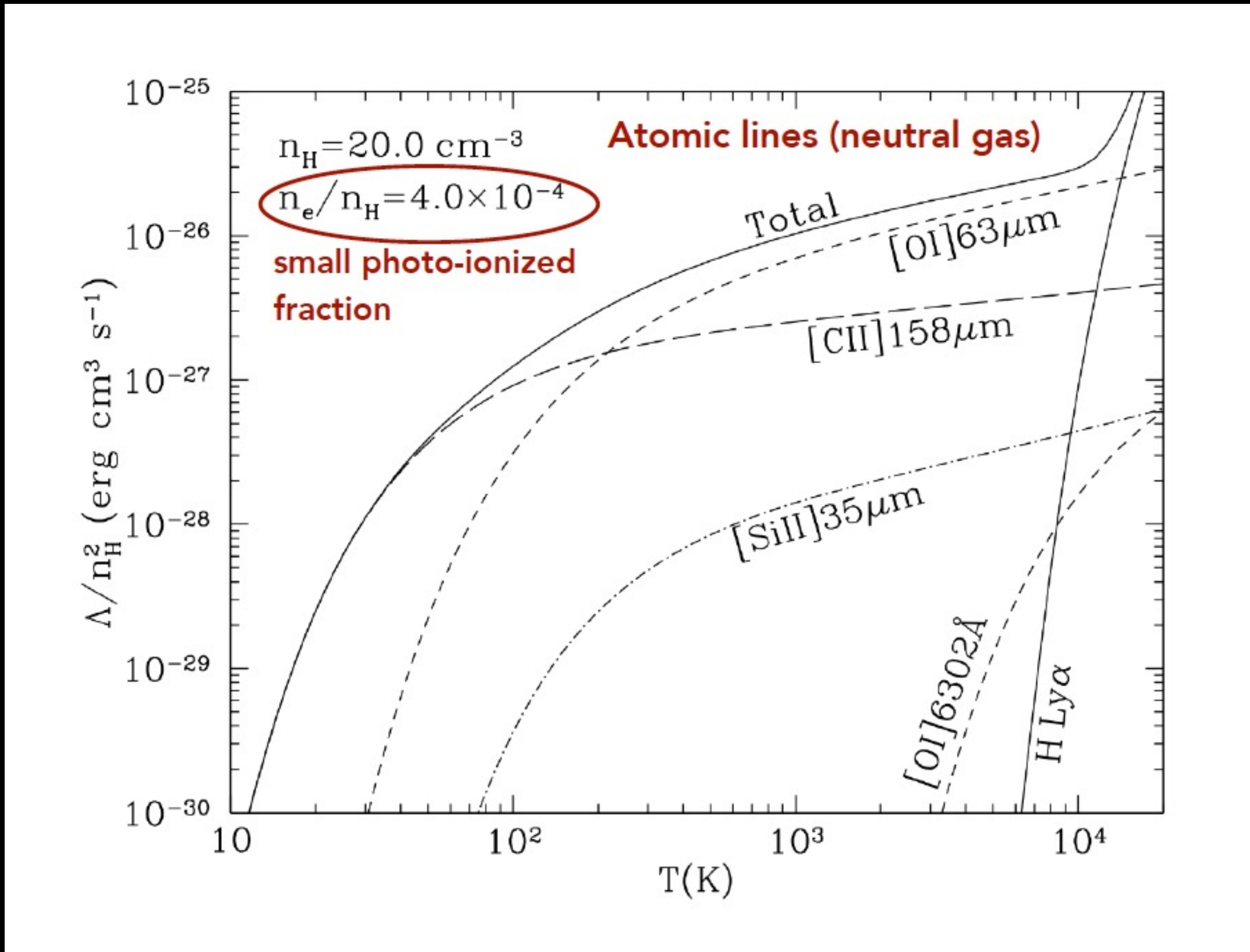
$$\Lambda(T) \equiv \frac{\mathscr{C}}{n_{\mathrm{H}}^2},$$



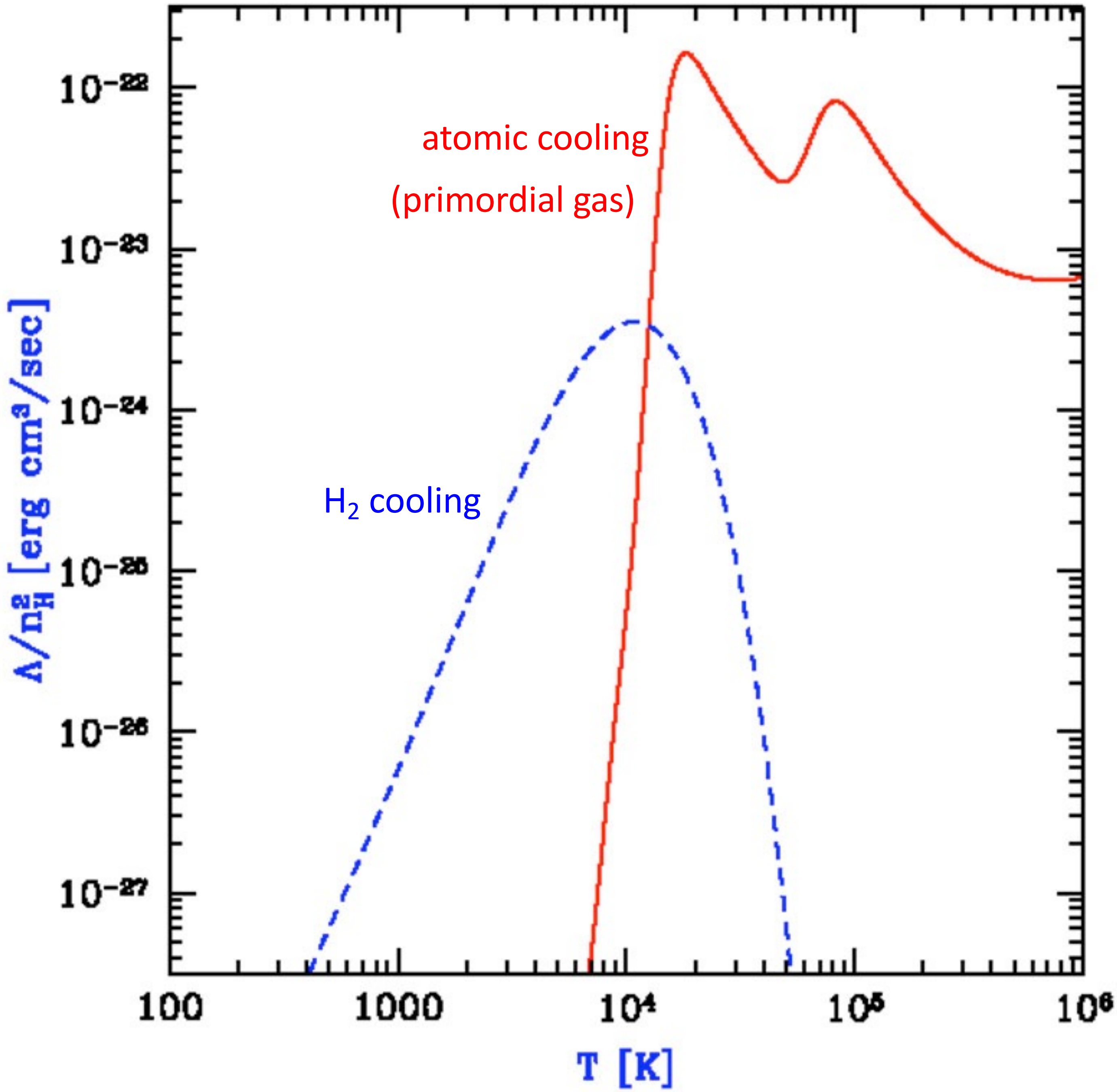


Sutherland & Dopita 1995

[independent of gas density for optically thin gas]



Draine Ch. 30.4, 34.1



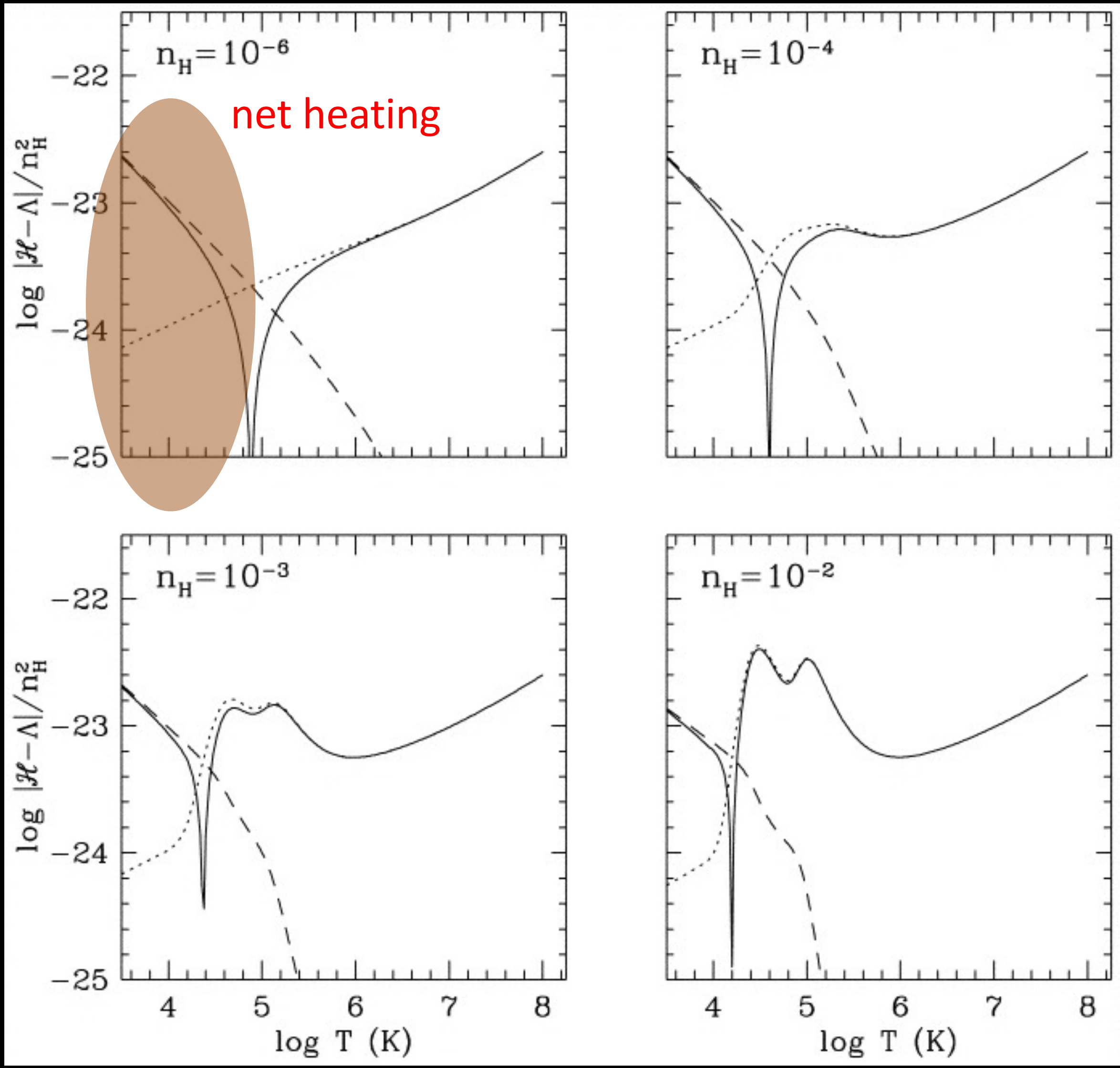
atomic cooling
(primordial gas)
H$_2$ cooling
Λ/n_H^2 [erg cm^3/sec]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
100
1000
10^4
10^5
10^6
T [K]

A. Loeb

photoionization

- changes population density of ions, thereby changing the cooling rate
- heats gas (any surplus energy is translated into heat)

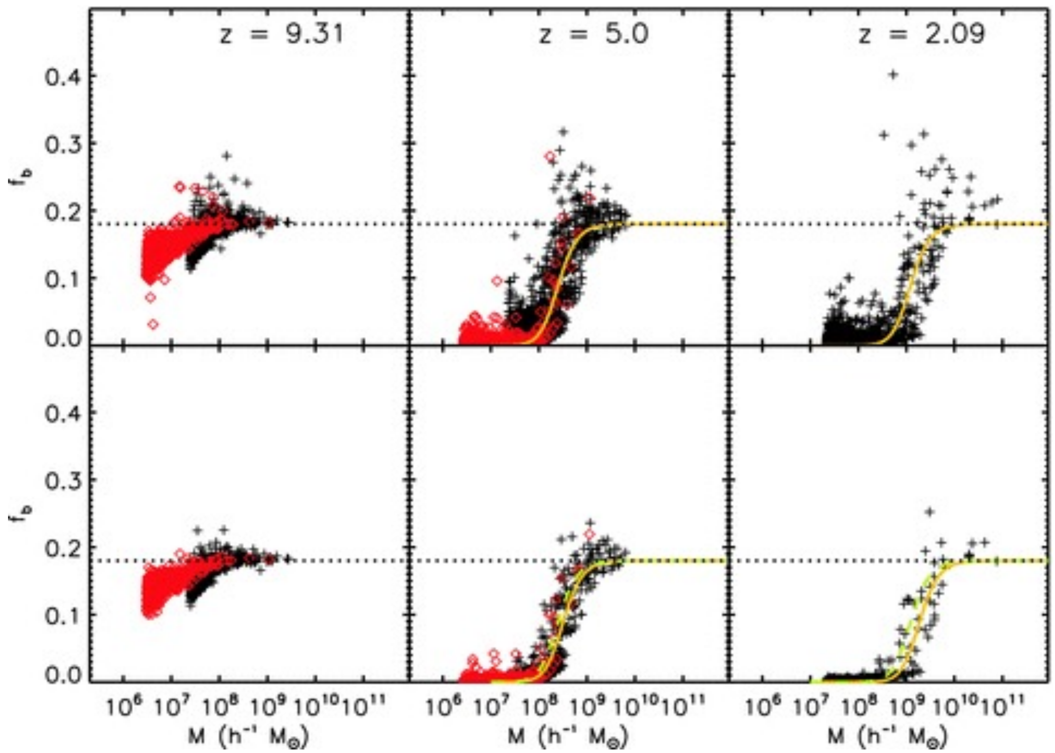
impact of a meta-galactic photoionizing radiation field on cooling/heating

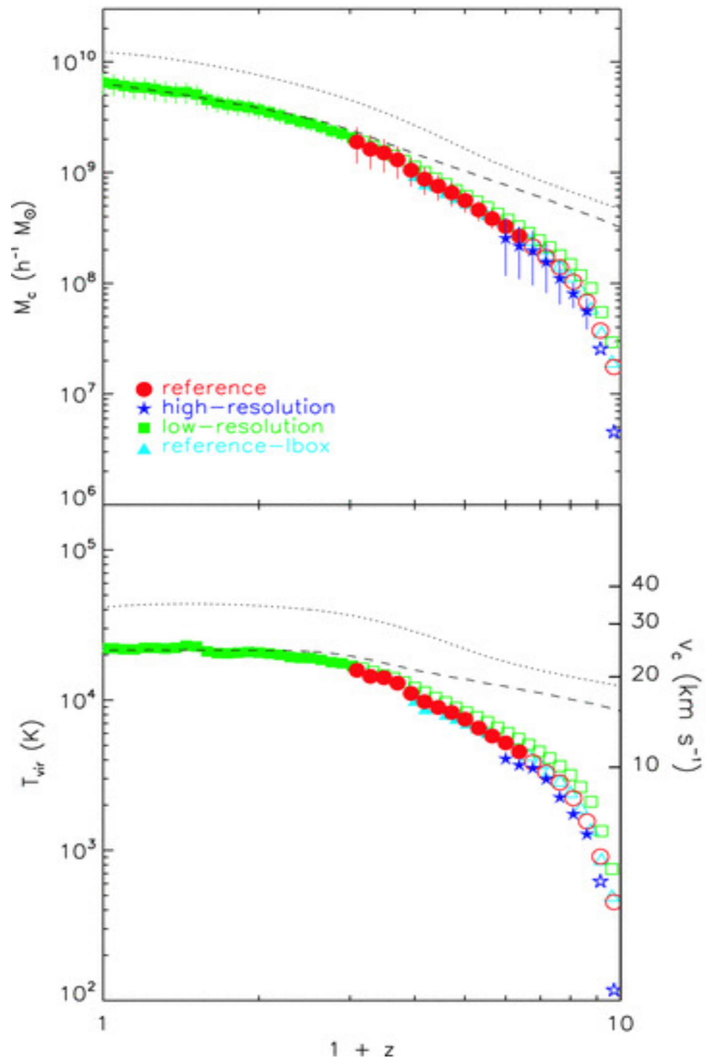


Weinberg et al. 1997

impact of cosmic reionization on gas accretion & cooling

Okamoto et al. 2008



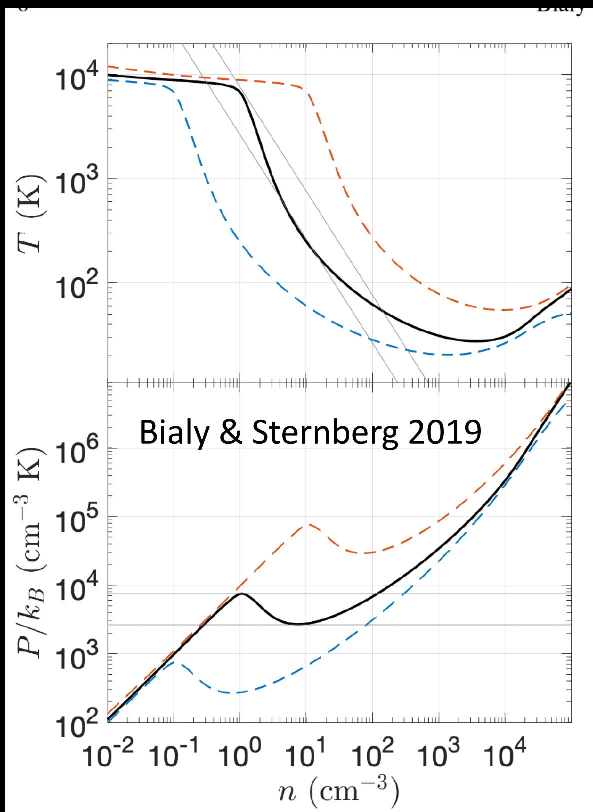


$$f_{\rm b}(M,z) = \langle f_{\rm b}\rangle \left\{1 + (2^{\alpha/3} - 1)\left[\frac{M}{M_{\rm c}(z)}\right]^{-\alpha}\right\}^{-3/\alpha}$$

the ISM, star formation,
and stellar feedback

Interstellar medium (ISM) comes in different phases with wildly different physical conditions:

from coolest to hottest:
cold neutral medium (CNM)
warm neutral medium (WNM)
warm ionized region (WIM)
hot ionized medium (HIM)



McKee & Ostriker 1977

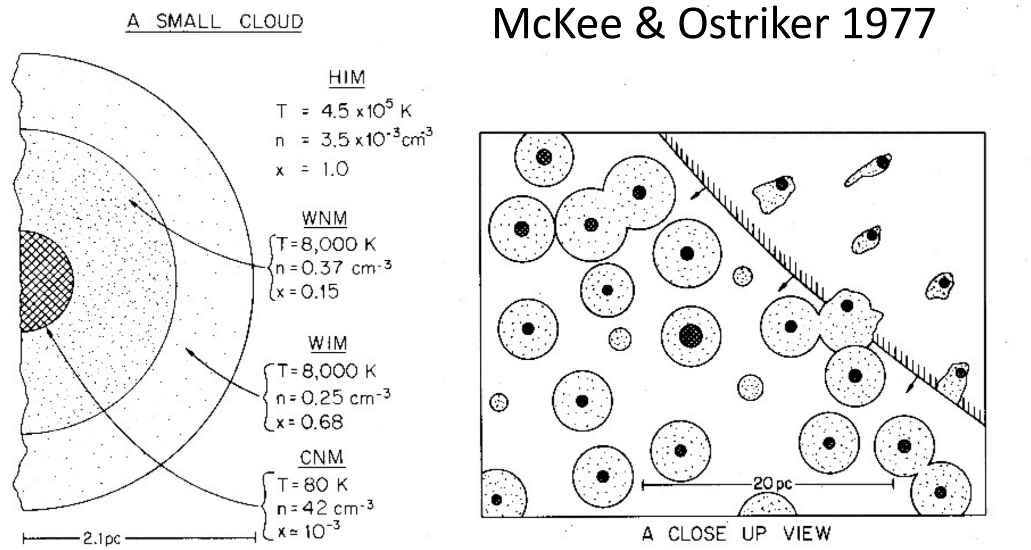
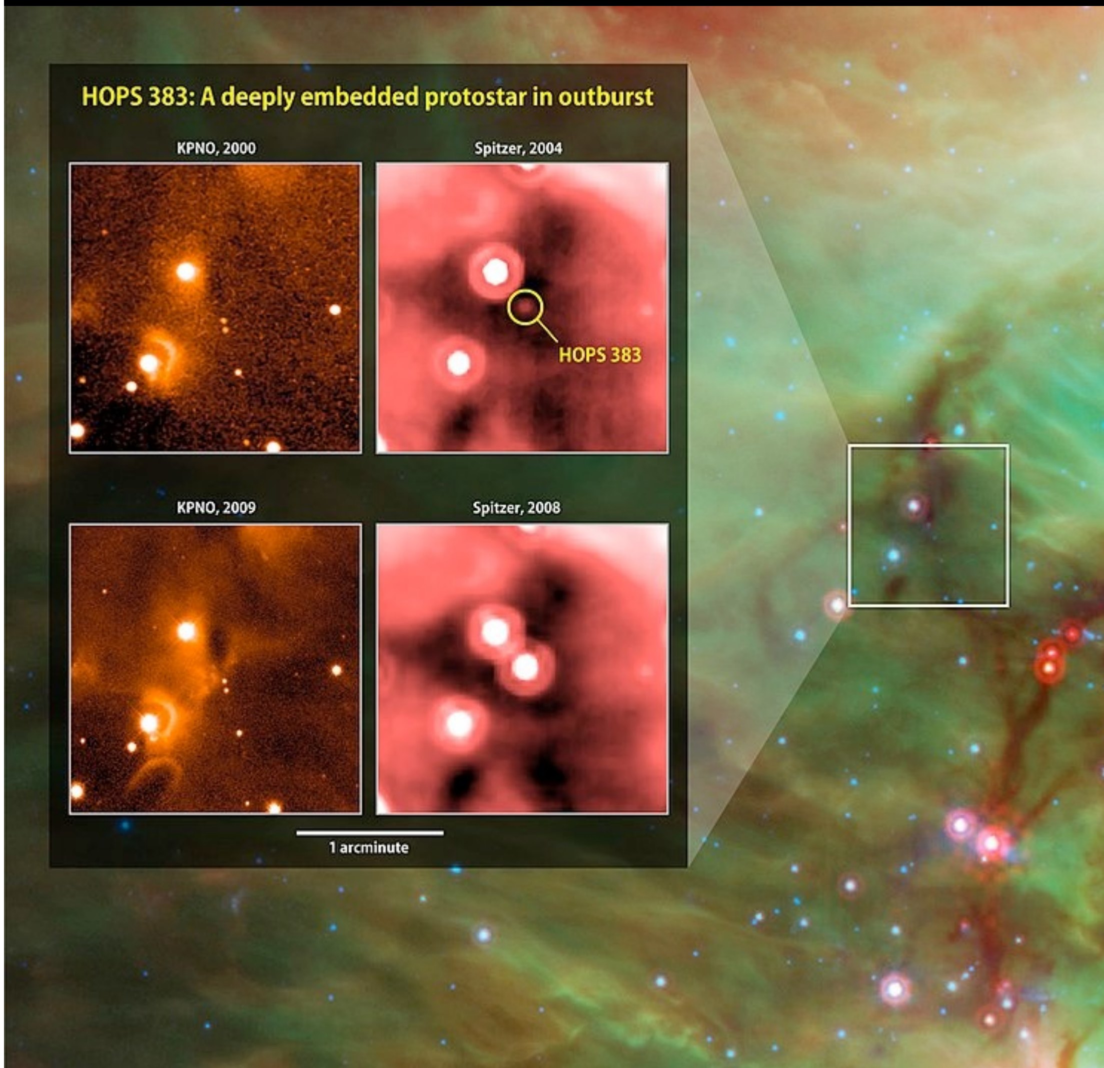


Fig. 1 Fig. 2

Fig. 1.— Cross section of a characteristic small cloud. The crosshatched region shows the cold core, which gives the usual optical absorption lines. Next is the warm neutral medium (WNM) with ionization produced by soft X-ray background. The outer layer (WIM) is gas largely ionized by stellar UV background. Typical values of hydrogen density n, temperature T, and ionization $x = n_e/n$ are shown for each component, except that a higher than average value of the soft X-ray flux has been assumed in order to produce a significant amount of WNM at this pressure.

Fig. 2.— Small-scale structure of the interstellar medium. A cross section of a representative region 30 pc × 40 pc in extent is shown, with the area of the features being approximately proportional to their filling factors. A supernova blast wave is expanding into the region from the upper right. The radius of the neutral cores of the clouds (represented by crosshatching) ranges from about 0.4 to 1 pc in this small region; all the clouds with cores have warm envelopes (*dotted regions*) of radius $a_w \sim 2.1$ pc. A few clouds are too small to have cores. The envelopes of clouds inside the SNR are compressed and distorted.

a star is born...



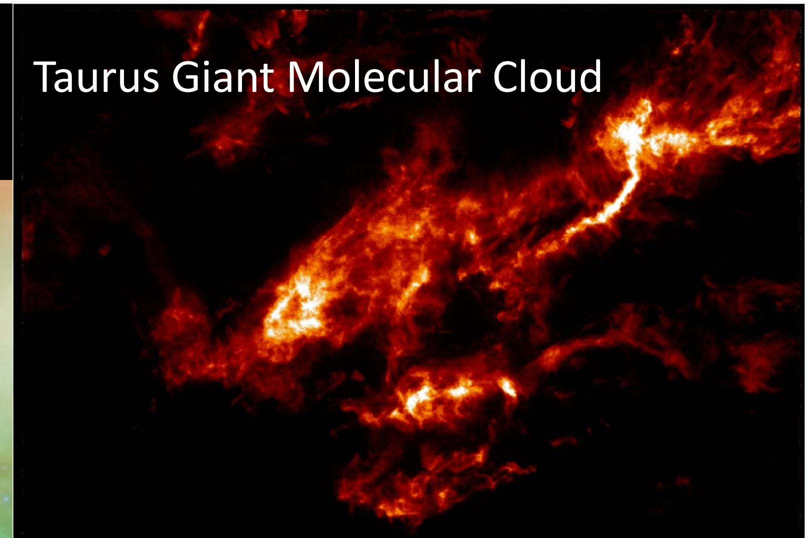
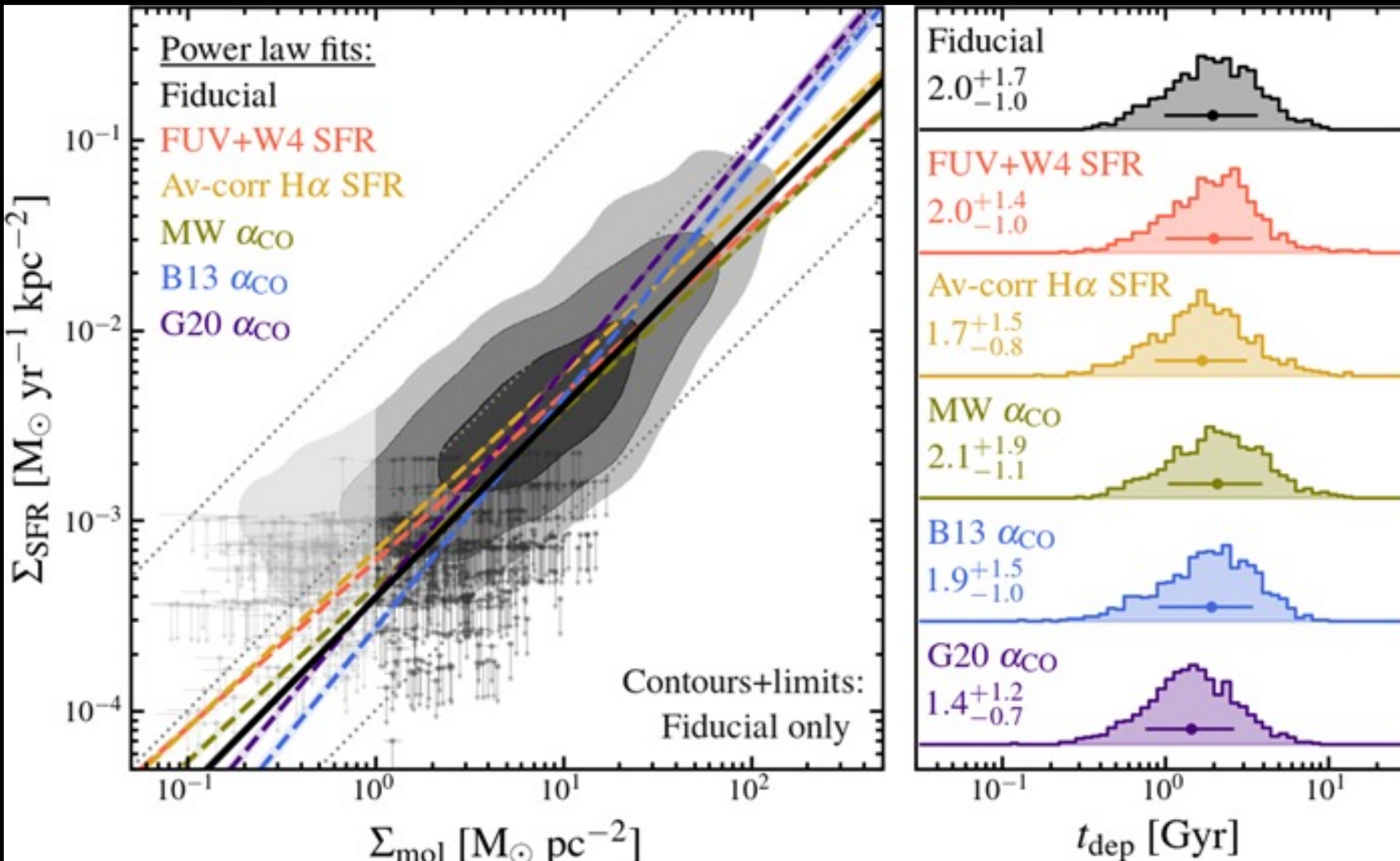


Figure 5.2 An image[2] of ^{13}CO $J = 1\text{-}0$ emission from the Taurus Molecular Cloud, a nearby star-forming region observed with the FCRAO 14 m

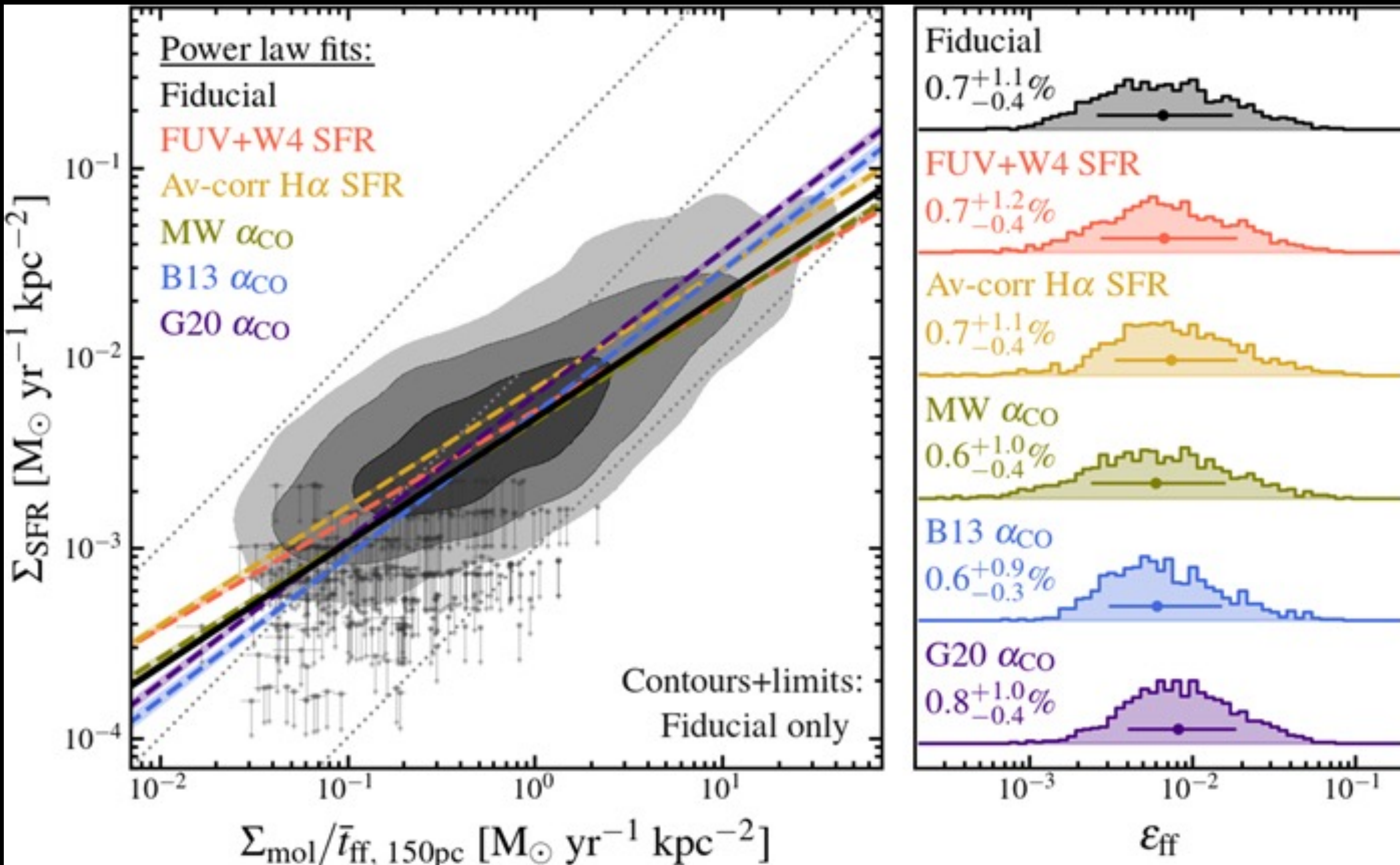
how efficiently can stars form in GMC?

- free-fall time of GMC

$$\tau_{\rm ff} = \left(\frac{3\pi}{32G\overline{\rho}}\right)^{1/2} \simeq 3.6\times10^{6}\,{\rm yr}\left(\frac{n_{\rm H_2}}{100\,{\rm cm^{-3}}}\right)^{-1/2}$$



Sun et al. 2023



Sun et al. 2023

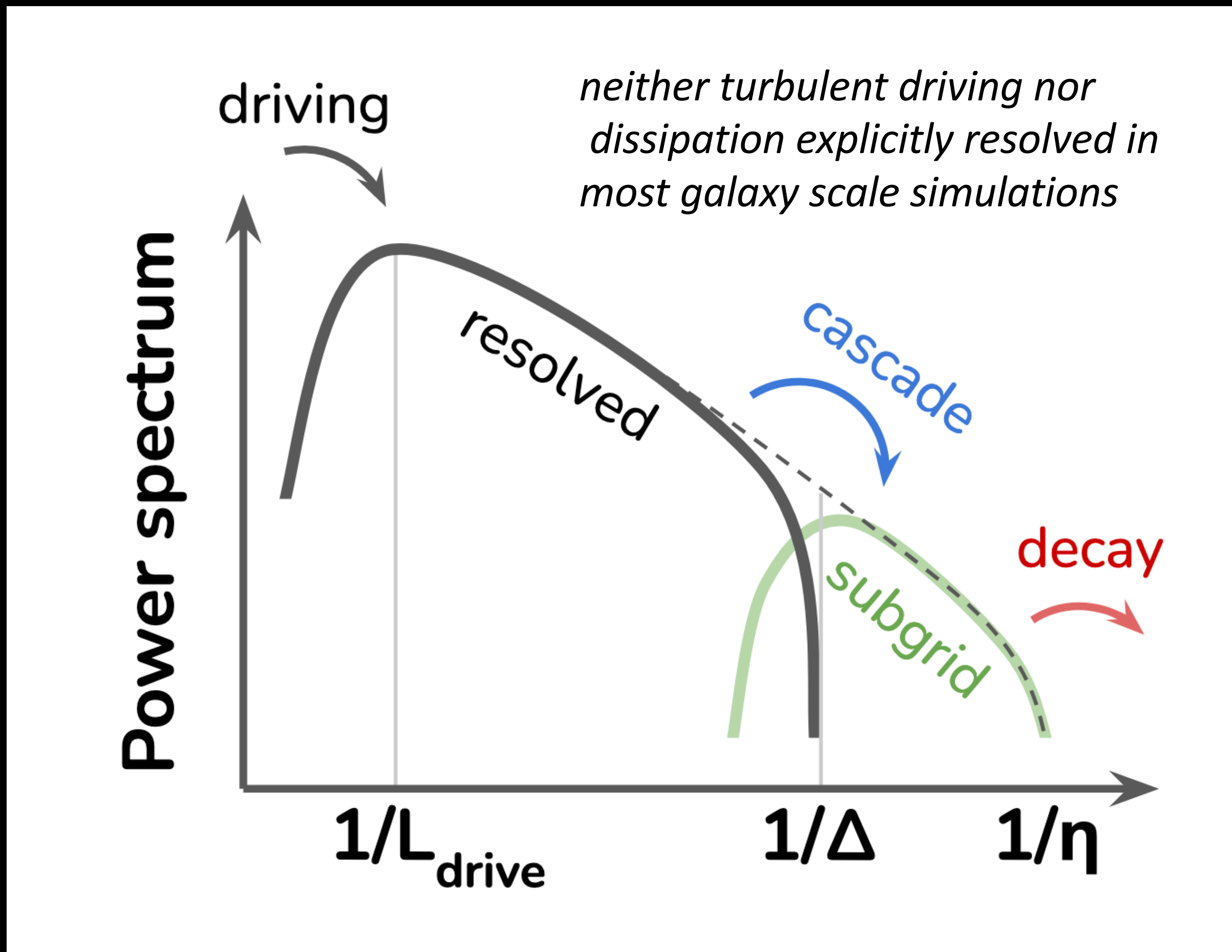
why are molecular clouds orders of magnitude more massive than the Bonner-Ebert mass?

why are star formation efficiencies per ff time so low (~1-2%) from scales of GMC to ~100pc?

magnetic fields vs. turbulence

- magnetic field support was the favored mechanism in the 1980s-90s but…
- improved observational constraints on magnetic field strength shows most GMCs magnetically supercritical
- observed linewidths of GMC (~10 km/s) much larger than expected from thermal broadening (0.2 km/s) – indication of turbulence
- direct evidence for supersonic turbulence over a broad range of scales

Turbulence driven by: cosmological accretion & mergers, viscous transport through disks, stellar feedback & supernovae explosions (see e.g. Forbes et al. 2023)



Semenov 2024

stellar feedback

Protostellar Outflows

Stellar Winds

Radiation

ionization & heating

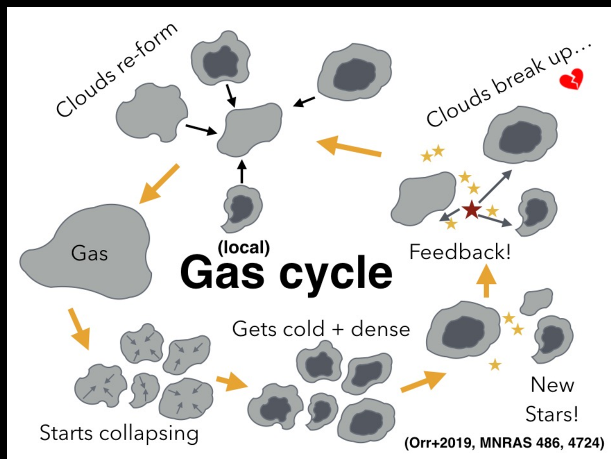
Supernovae

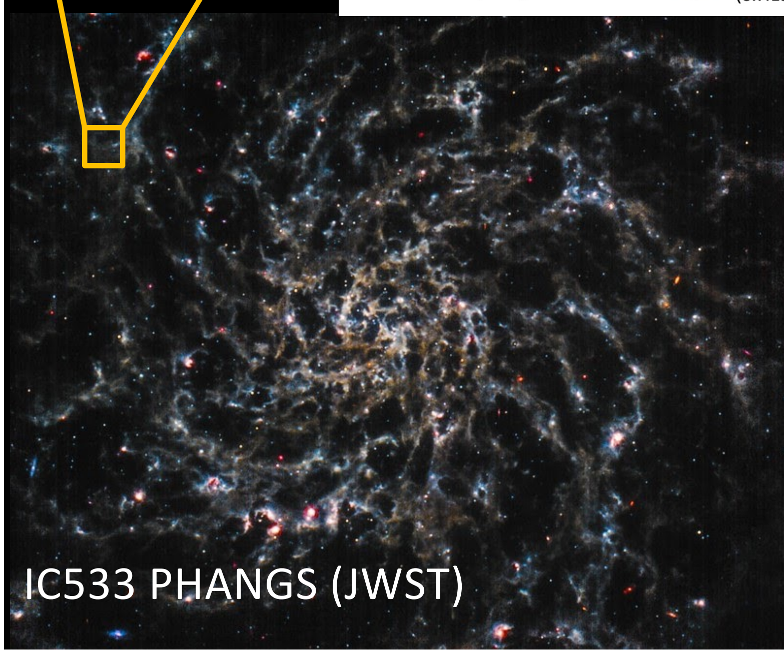
slide credit: Mike Grudić

what physics determines the star formation efficiency in galaxies on different scales?

cloud scale

Carina Nebula, HST





IC533 PHANGS (JWST)

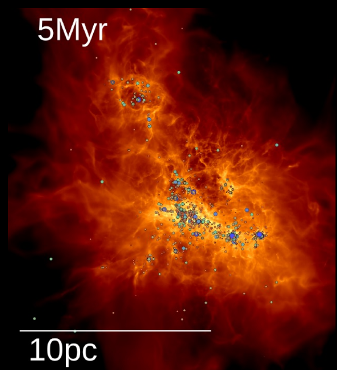
galaxy scale

Crab Nebula, HST

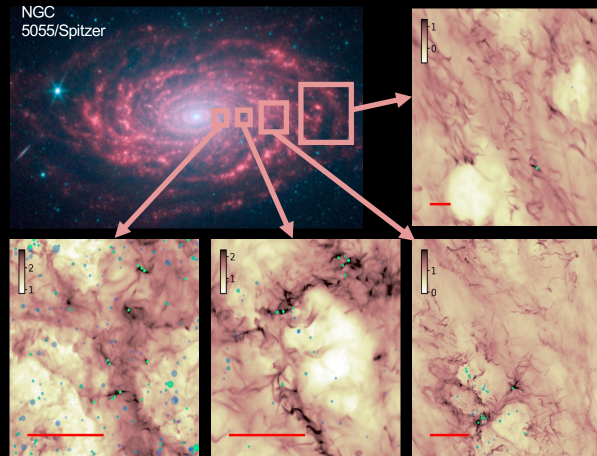
galactic winds eject mass from ISM & inject energy into CGM

(ejective/preventative feedback)

NASA, ESA and the Hubble Heritage Team (STScI/AURA)

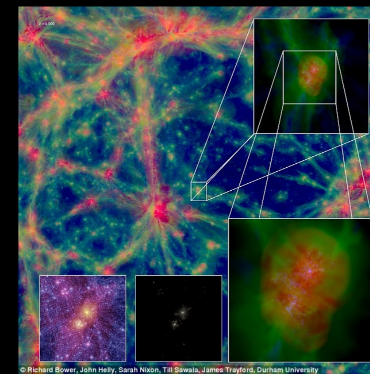


Guszejnov+22



Kim et al. 2020

Hopkins+12



Schaye+15

individual GMC or star cluster (STARFORGE)

ISM patch (TIGRESS, SILCC)

whole galaxy at single star resolution (GRIFFIN, Aeos)

zooms: semi-resolved multiphase ISM (FIRE, SMUGGLE, SPHYNX, SERRA)

cosmological volumes: effective EOS, pop. averaged FB (TNG, SIMBA, EAGLE, etc)

sub-pc
sub M_{sun}

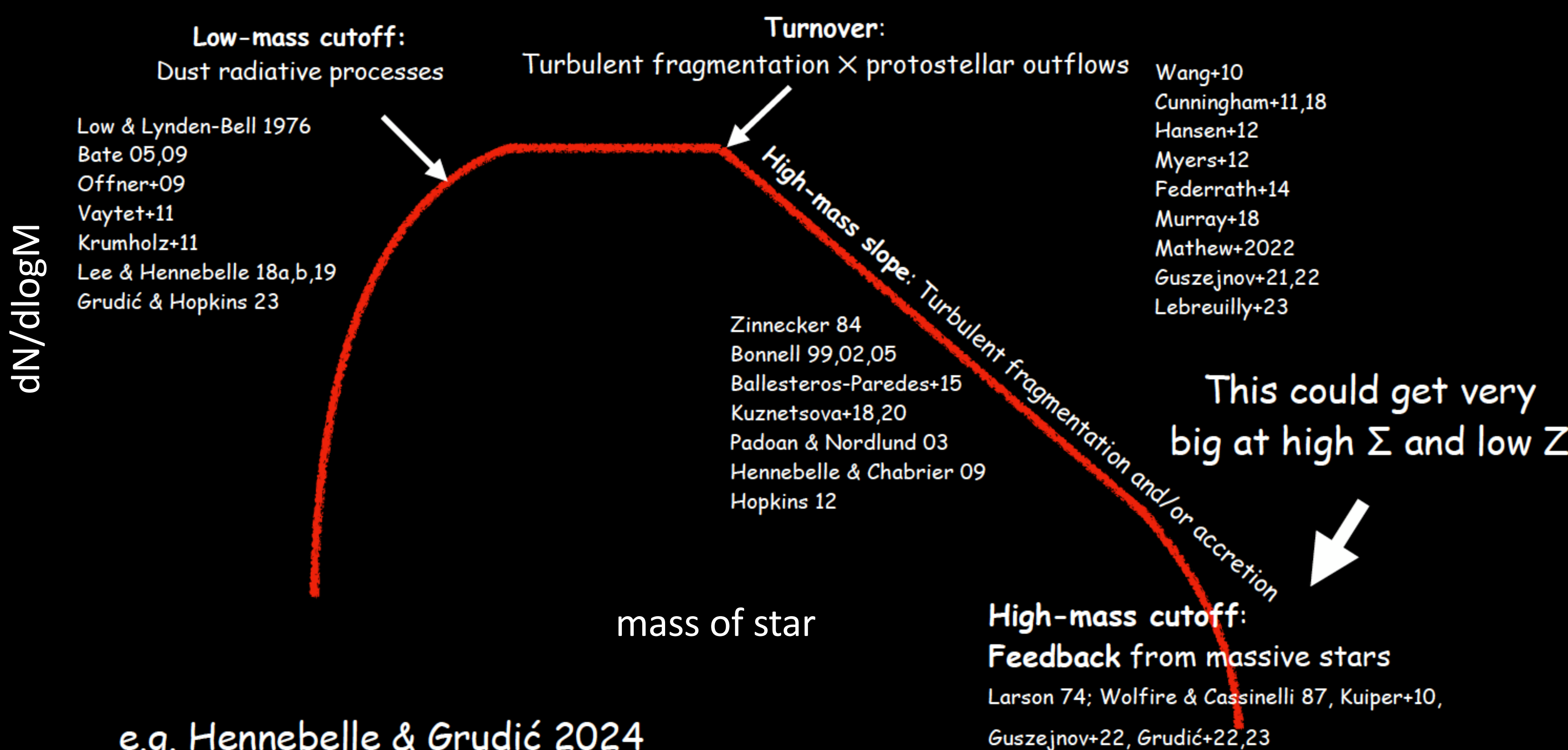
1-10 pc
1-4 M_{sun}

10's of pc
10^3-10^4 M_{sun}

100's of pc
10^4—10^6 M_{sun}

again, very much NOT a complete list!

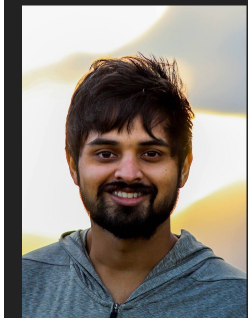
What physics shapes the (Pop II/I) stellar initial mass function?*



e.g. Hennebelle & Grudić 2024 review

*I will talk about Pop III in the last lecture…

slide credit: M. Grudić

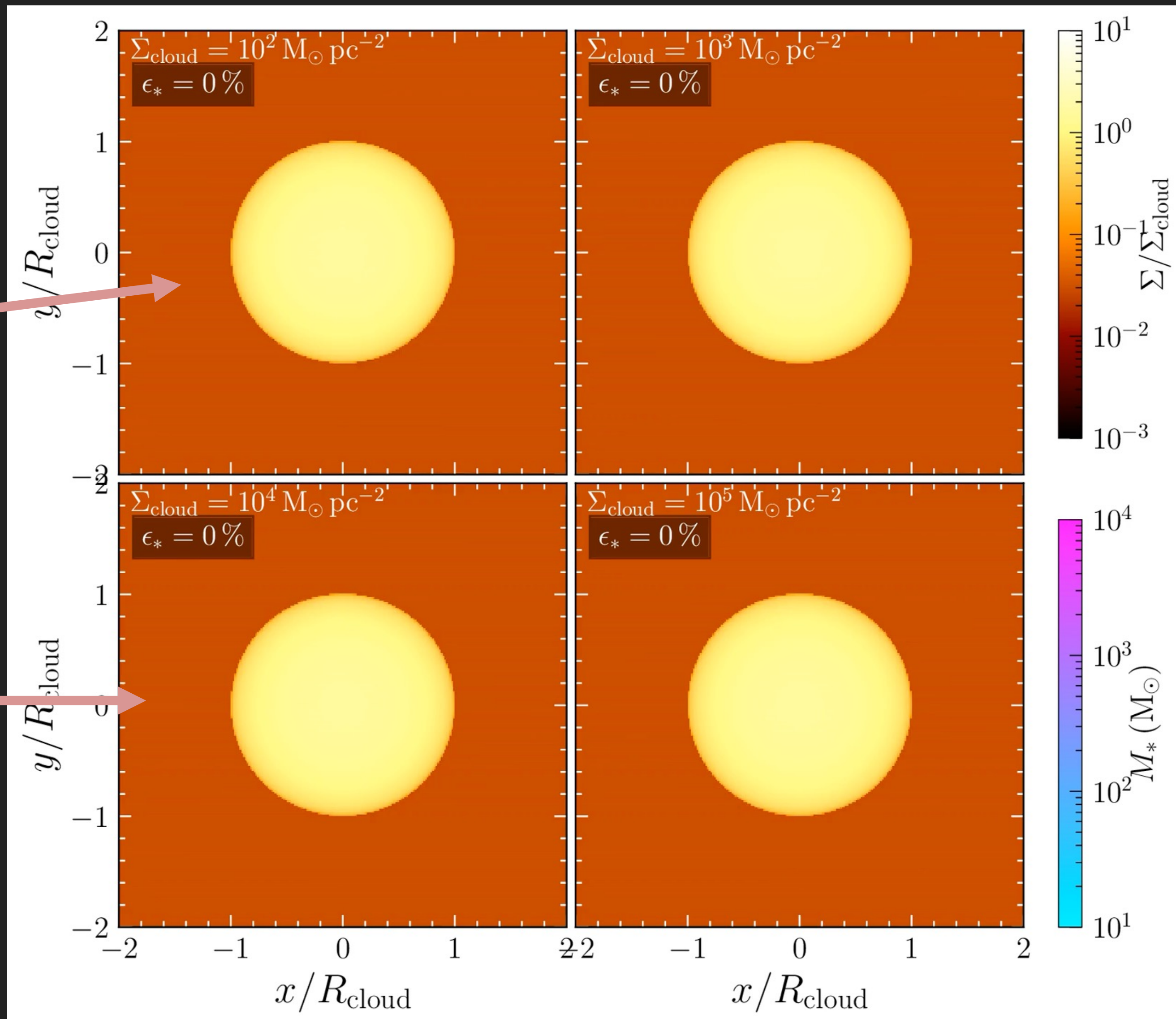


Shyam Menon

simulations of individual star cluster mass

local Universe

high-z Universe

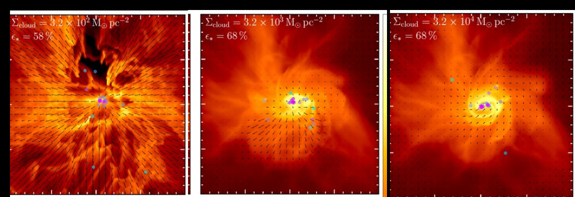


Menon et al. 2024

cloud scale SF efficiency increases with surface density

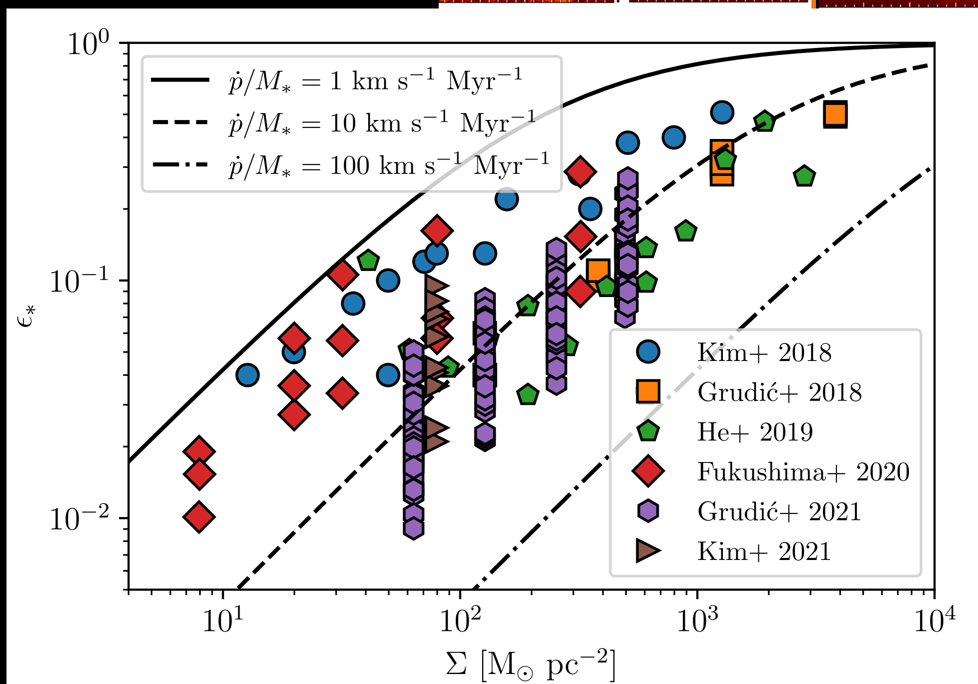
observed super star clusters:
$\Sigma \sim 10^4$-10^5 M_{sun} pc^{-2}
SFE ~ 70% (e.g. Emig+'20)

Menon+23, 24



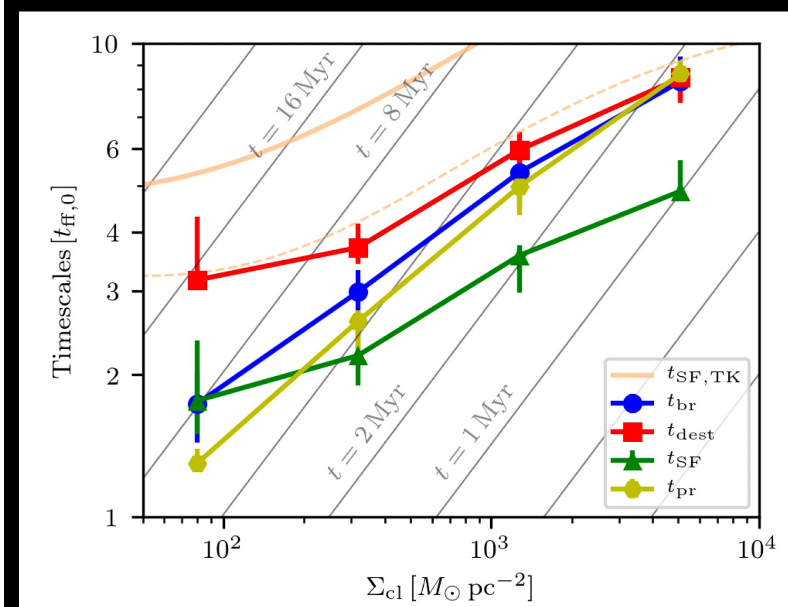
Chevance et al. 2022

fraction of gas turned into stars

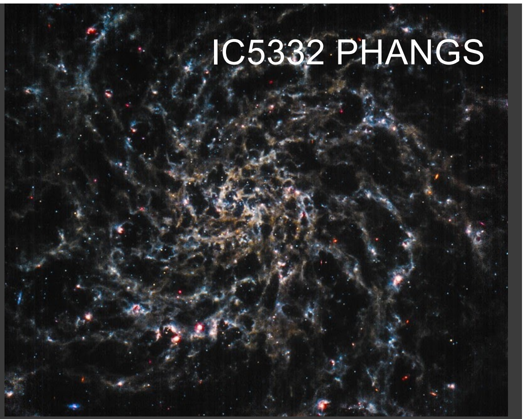


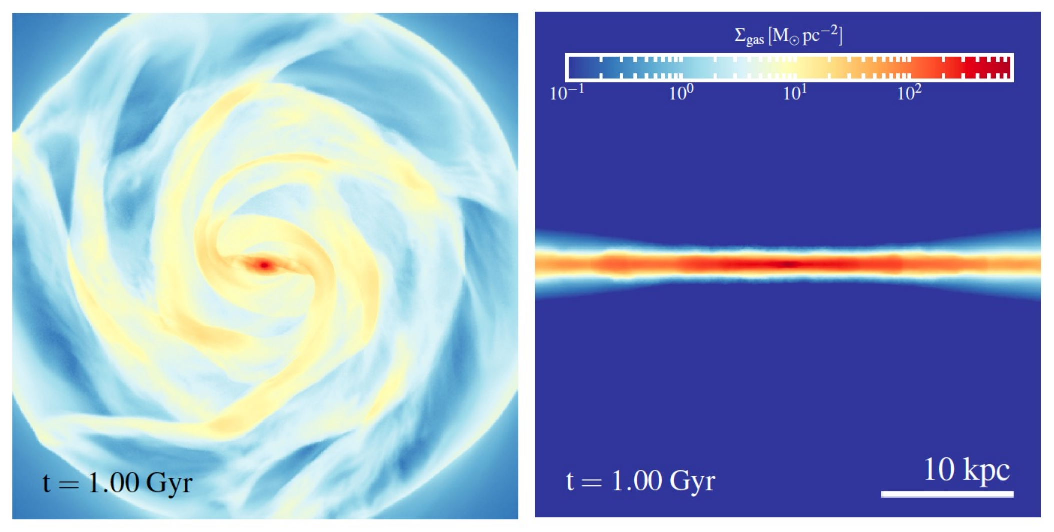
cloud scale surface density

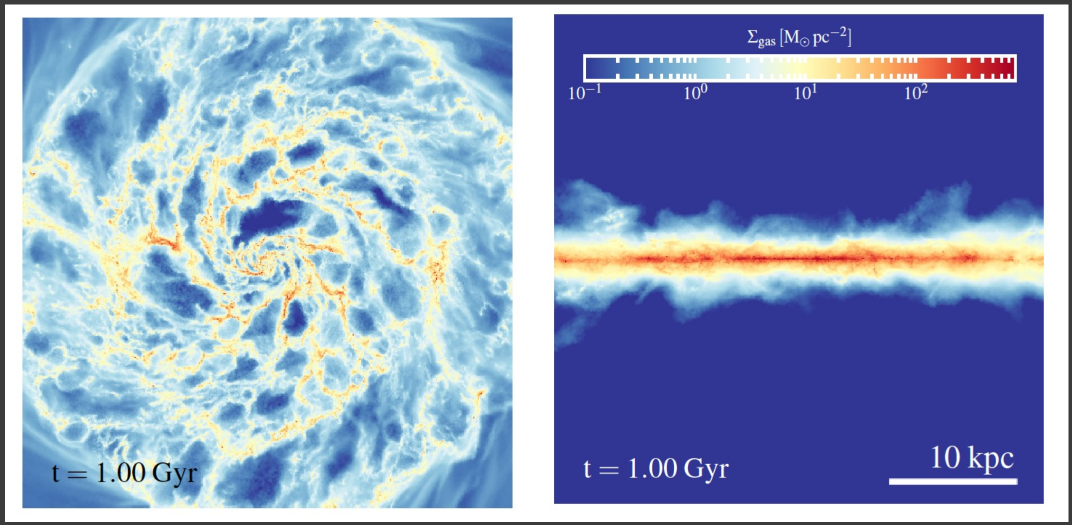
denser clouds survive longer
(in units of ff time)
before they are dispersed



Lancaster et al. 2021

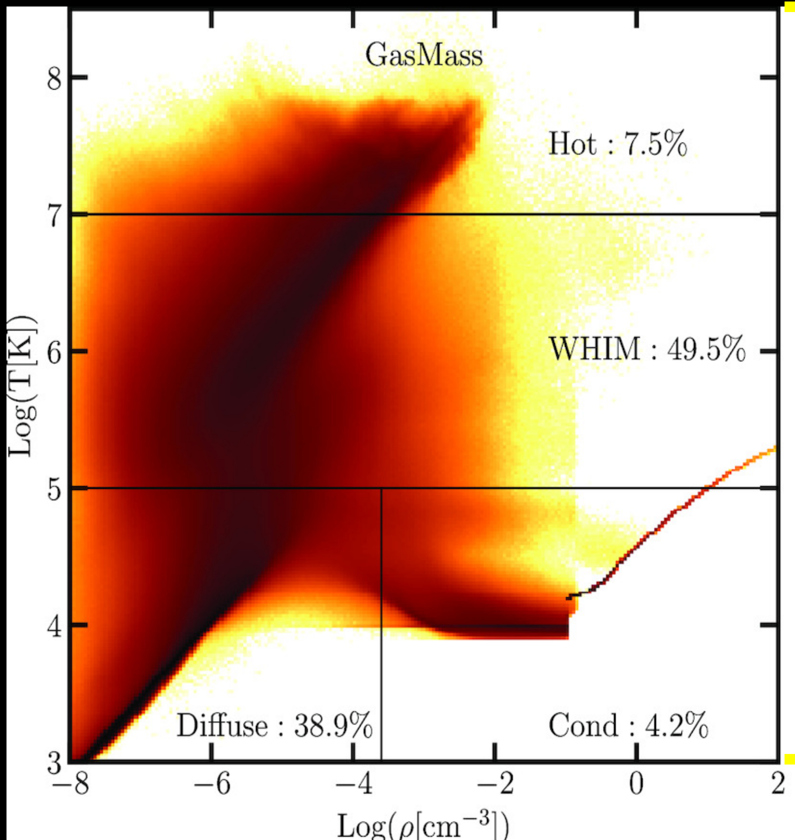






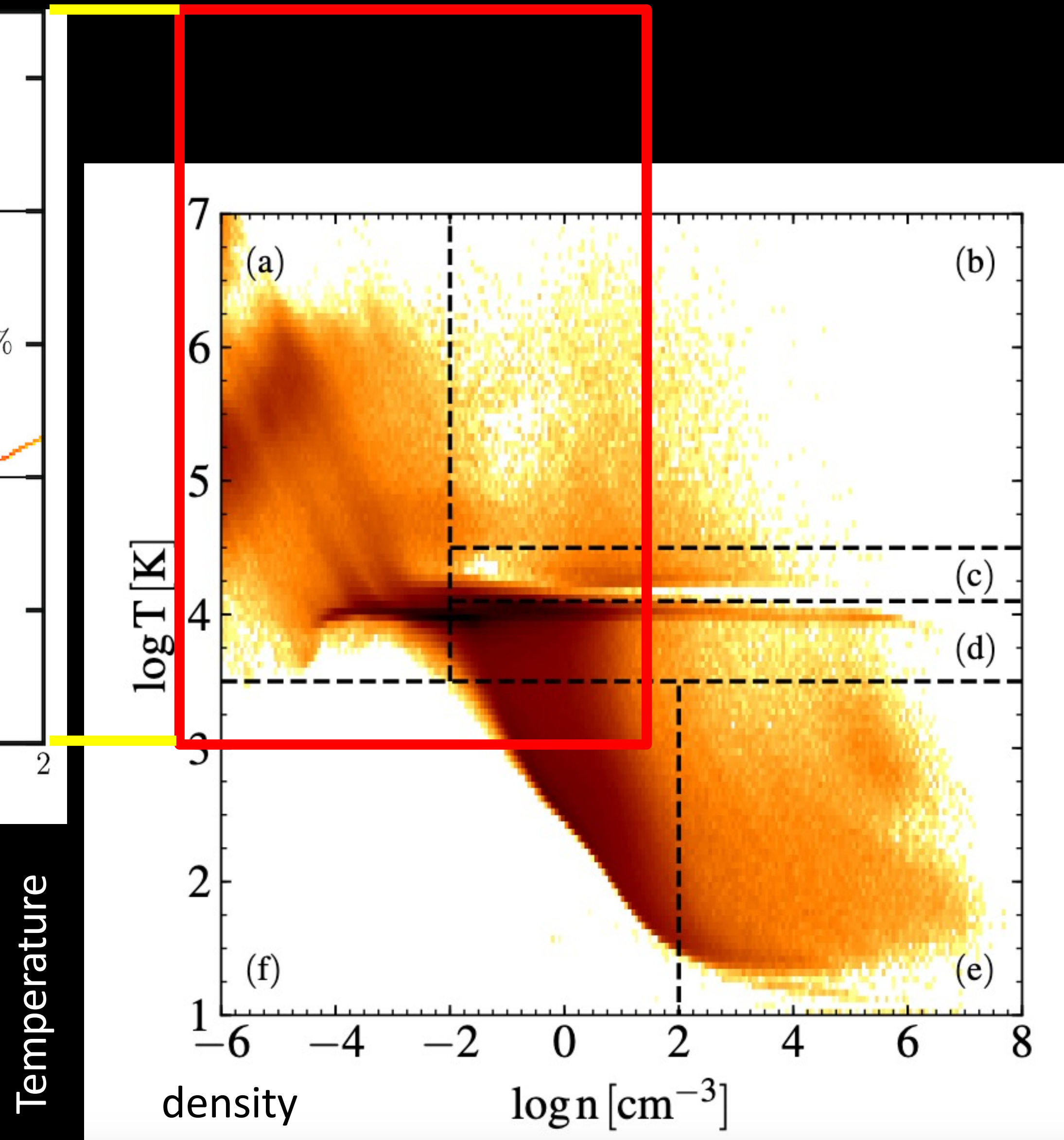
most large volume cosmo sims adopt an ‘effective equation of state’;
artificially pressurizes and ‘smooths’ ISM –
many consequences

Marinacci et al. 2019

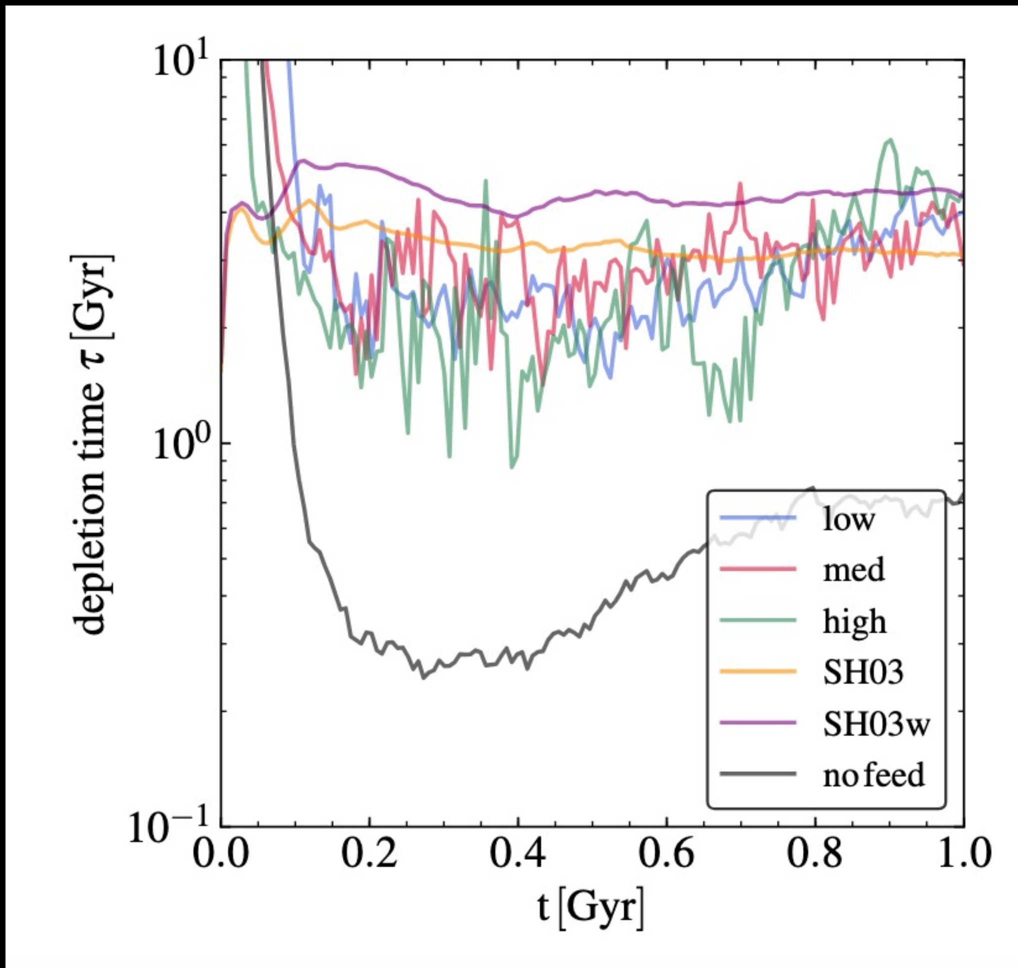


Torrey et al. 2019

TNG (effective EoS)



Marinacci et al. 2019 – SMUGGLE (no eEoS)



the lack of resolution AND eEOS result in smoother, less bursty SF

conditions for star formation

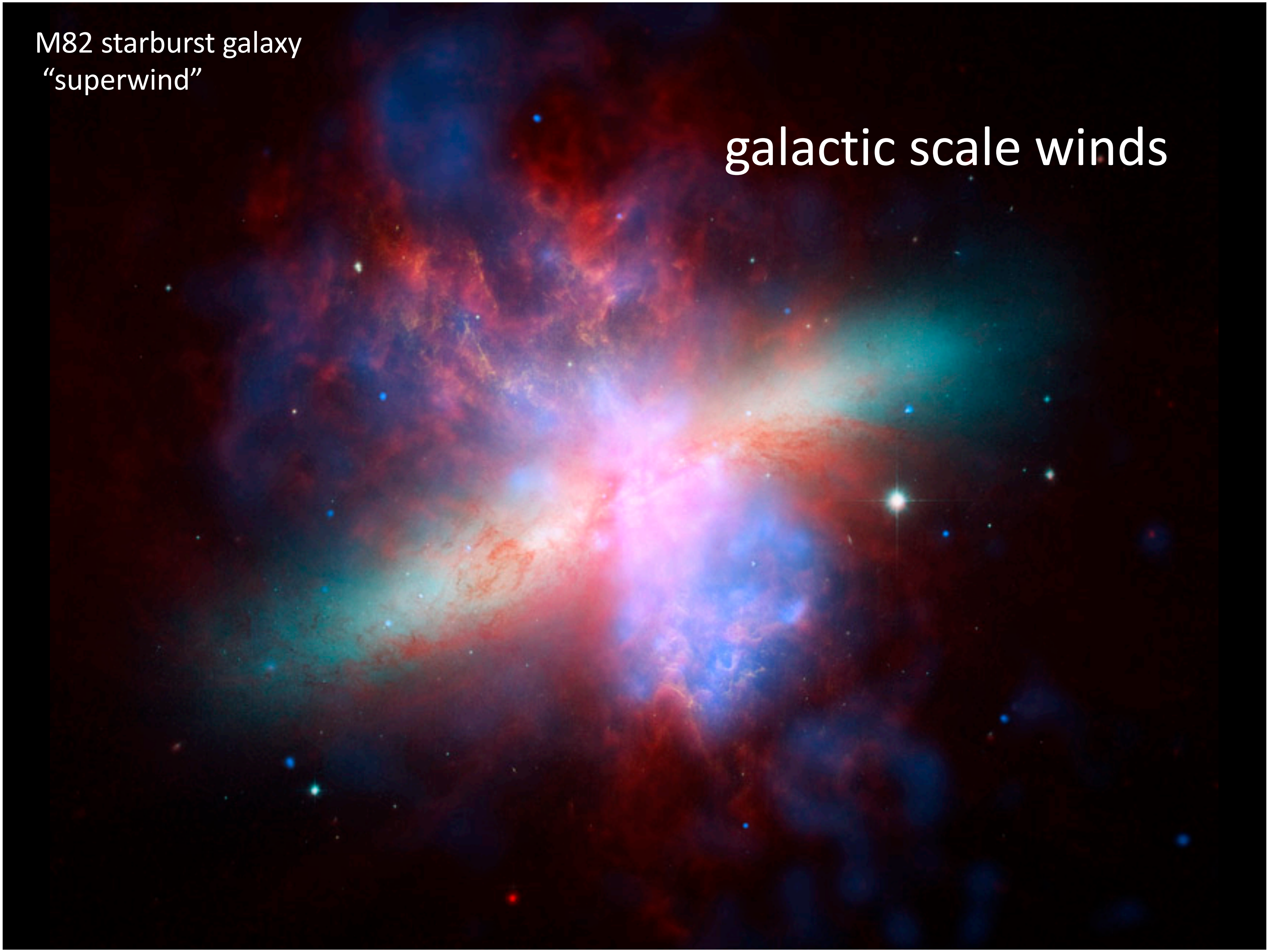
- density threshold
- temperature threshold
- molecular gas (SFR based on ρ_{H2})
- self-gravitating (virial parameter <1)
- Jeans unstable ($m_J<m_{cell}$)
- convergent flow

typically used in 'lower res' sims

used in 'higher res' sims

+ an assumed value of ε_{ff} (or a model for it) on the smallest resolved scale

ε_{ff} = star formation efficiency per ff time


M82 starburst galaxy
“superwind”
galactic scale winds

“mass loading factor” of galactic winds

$$\eta_{\mathrm{M}} = \frac{\dot{M}_{\mathrm{wind}}}{\mathrm{SFR}}$$

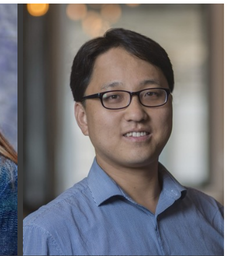
“energy loading factor” of galactic winds

$$\eta_{\mathrm{E}} = \frac{\dot{E}_{\mathrm{wind}}}{e_{\mathrm{SN}}\mathrm{SFR}}$$

$\Longrightarrow \dfrac{\eta_{\mathrm{E}}}{\eta_{\mathrm{M}}}$ **is the specific energy of the wind**

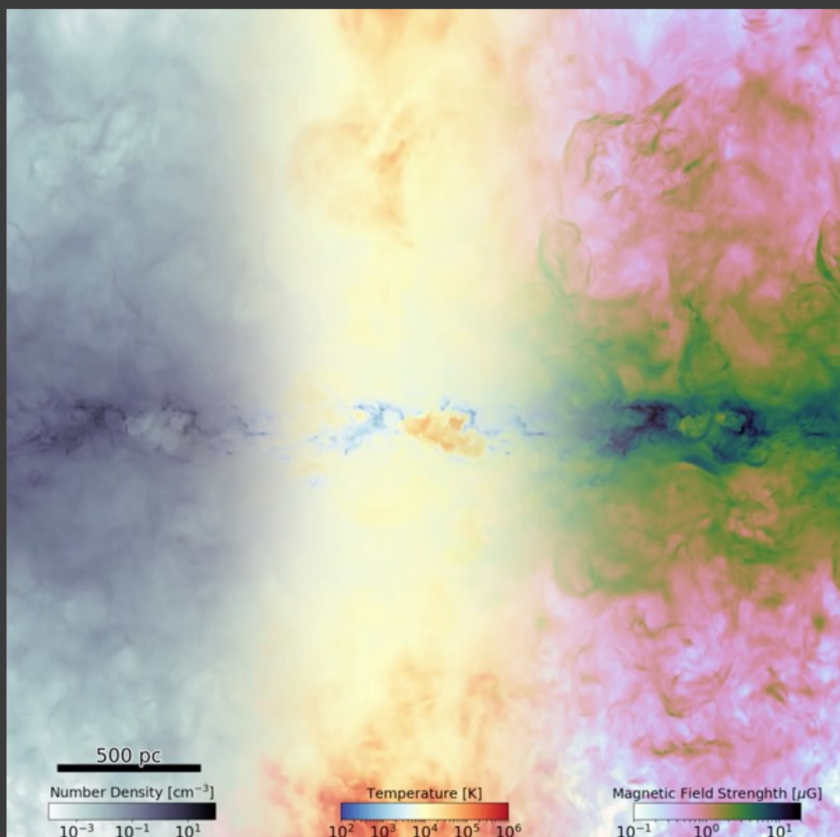
TIGRESS

Kim & Ostriker 2017,
ApJ, 846, 133



Eve Ostriker

Chang-goo Kim



Three-phase ISM in Galaxies Resolving Evolution with Star formation and Supernova feedback

- MHD + Self-Gravity in a local shearing box with ATHENA code; vertically stratified with outflow BCs
- external gravity (old stars + dark matter)
- sink particles (= star clusters)
- population synthesis for FUV radiation and SN rates
- optically thin cooling (10K<T<10^9K)
- photoelectric heating
- multiphase, warm/cold ISM (T<10^4K); hot ISM (T>10^6K) created by SN shocks (resolved Sedov phase)
- SN in clusters + OB runaways

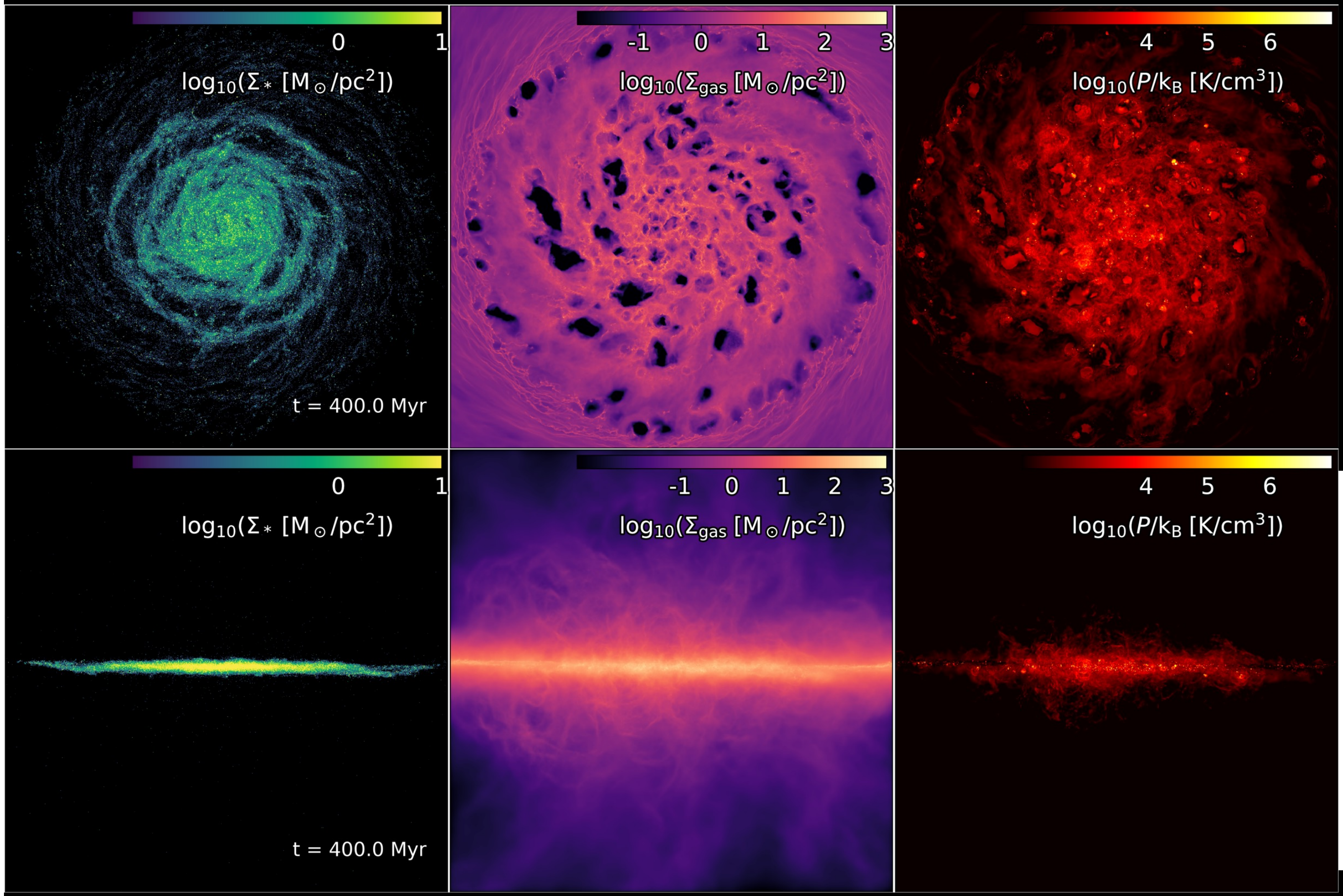
SMAUG

a new generation of whole-galaxy "resolved feedback" simulations

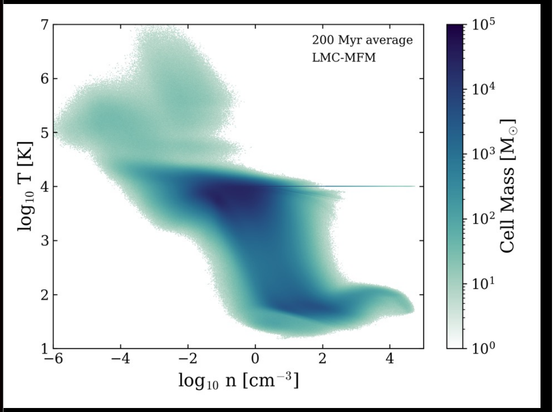
Ulrich Steinwandel

similar to the Large Magellanic cloud (LMC)

stellar mass 2E09 M_{sun}; halo mass 10^{11} $M_{sun;}$ total gas mass ~10^8 $M_{sun;}$ 4 M_{sun}, 1 pc resolution



multiphase gas and supernovae blastwaves are fully resolved



Steinwandel et al. 2022a, b; 2024; see also Hu et al. 2016,2017,2019; 2022;

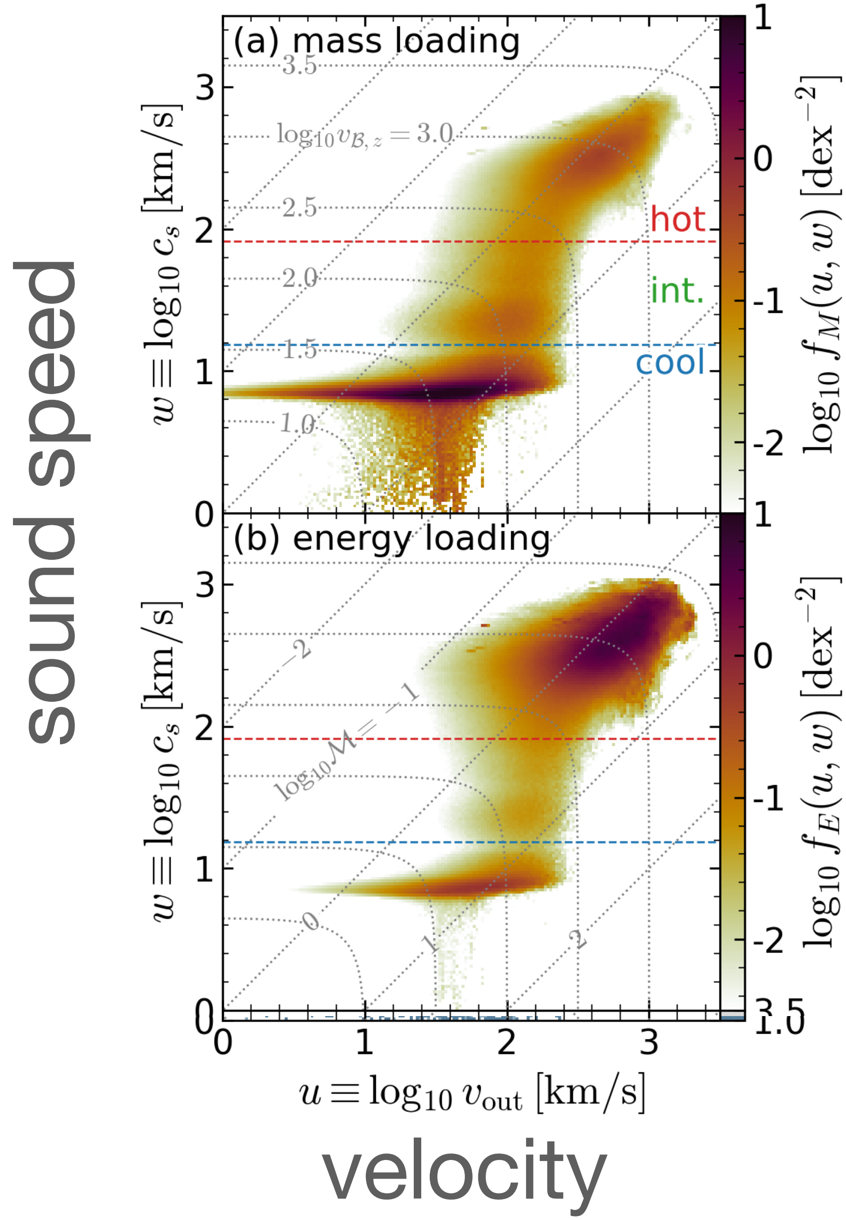
How are galactic winds launched?

emergent winds are *multiphase*, with a broad distribution of velocities

Mass loading dominated by cold/warm slow moving material

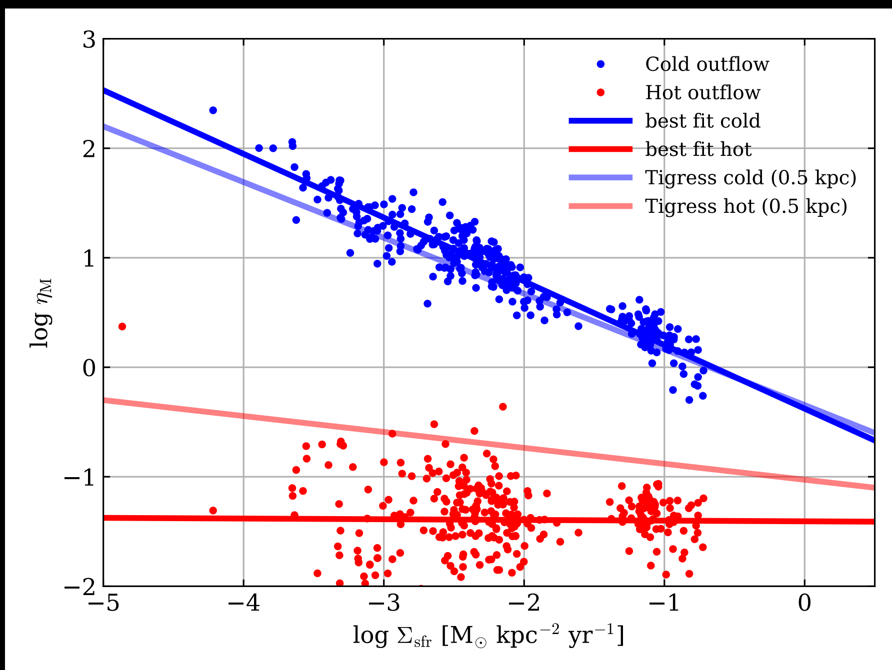
Energy loading dominated by hot, fast, metal enriched outflow

TIGRESS: Kim & Ostriker 2017
Kim, Ostriker & SMAUG 2020a,b



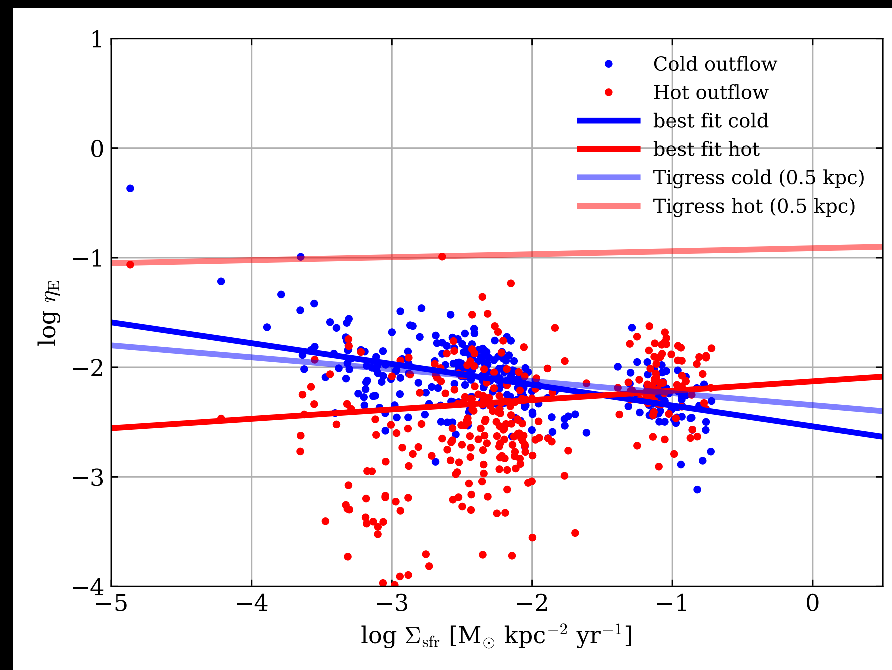
mass and energy loading as a function of ”semi-local” conditions—
pretty good agreement between “tall box” simulations with MW conditions and LMC-like galaxy scale simulation

mass loading



SFR surface density

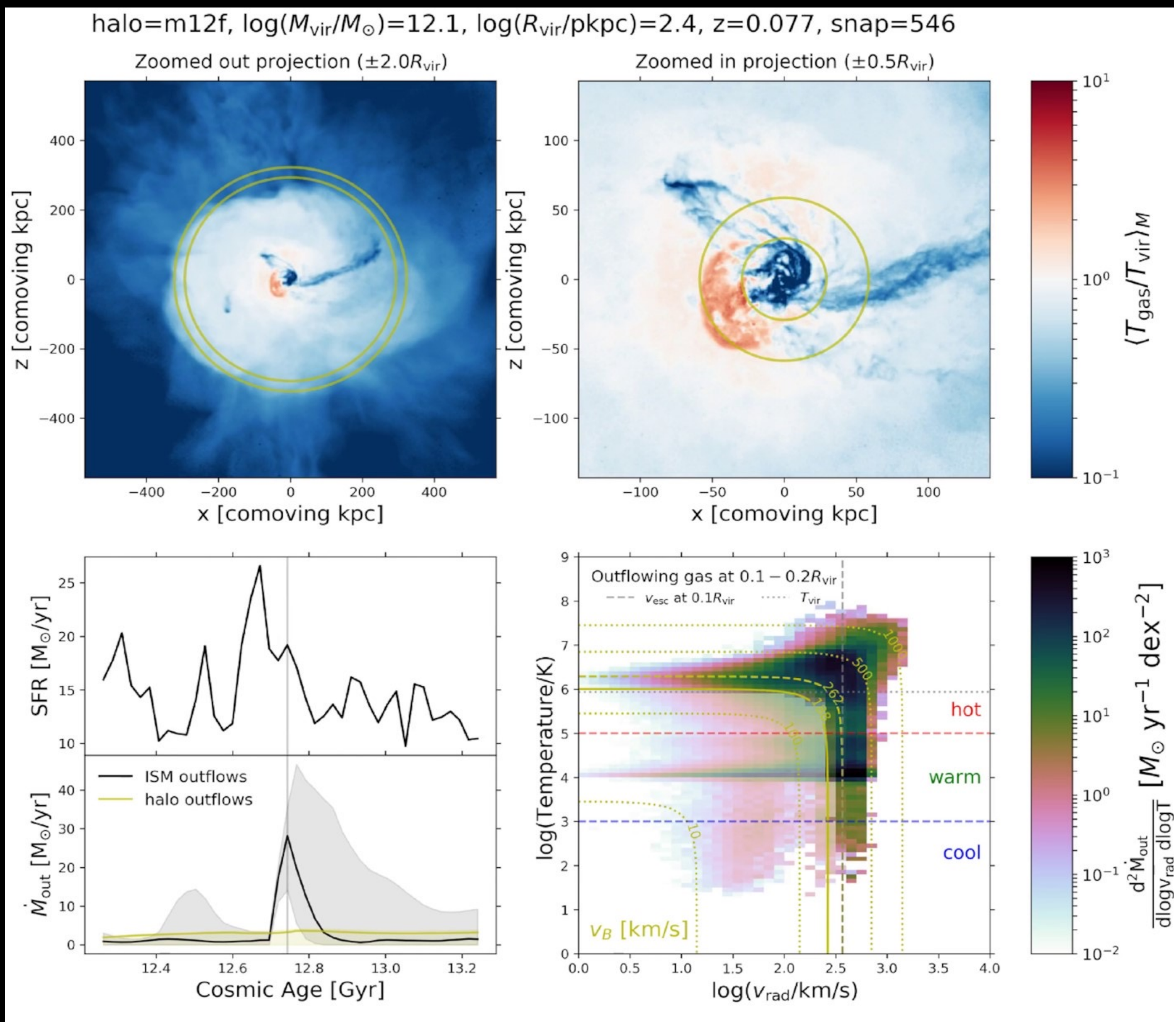
energy loading



SFR surface density

Steinwandel et al. 2024

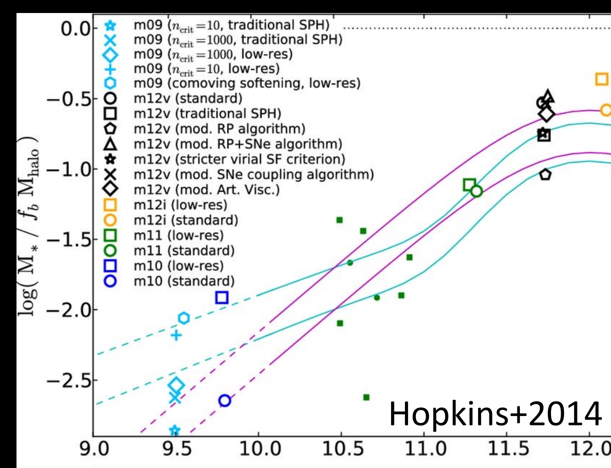
simulations with ‘partially resolved’ feedback (e.g. FIRE, SMUGGLE)



Pandya et al. 2021

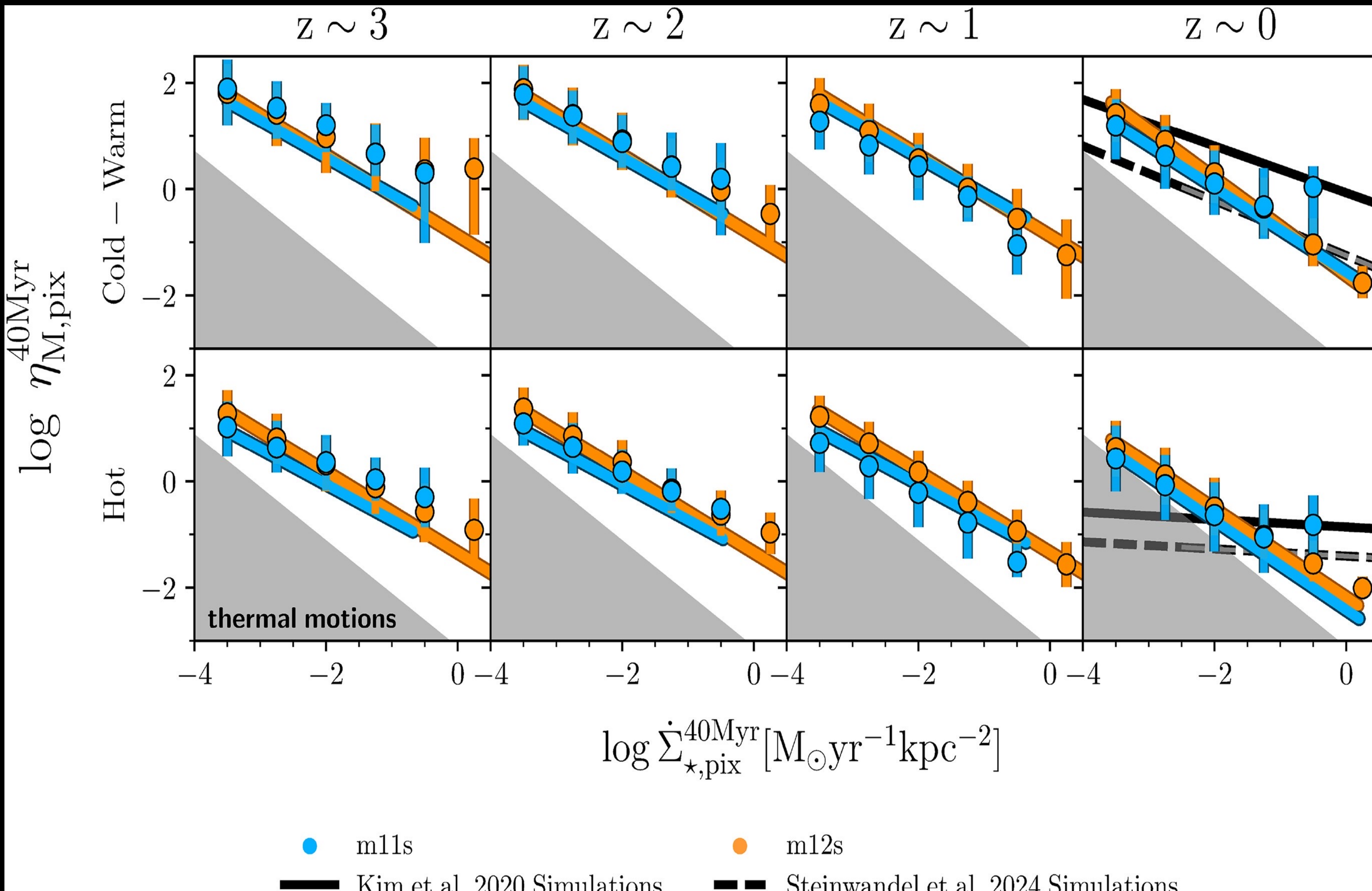
where Sedov phase of SN blastwave unresolved, momentum & energy deposited according to STARBURST99 SSP models

FIRE zooms reproduce observed stellar mass vs. halo mass rln



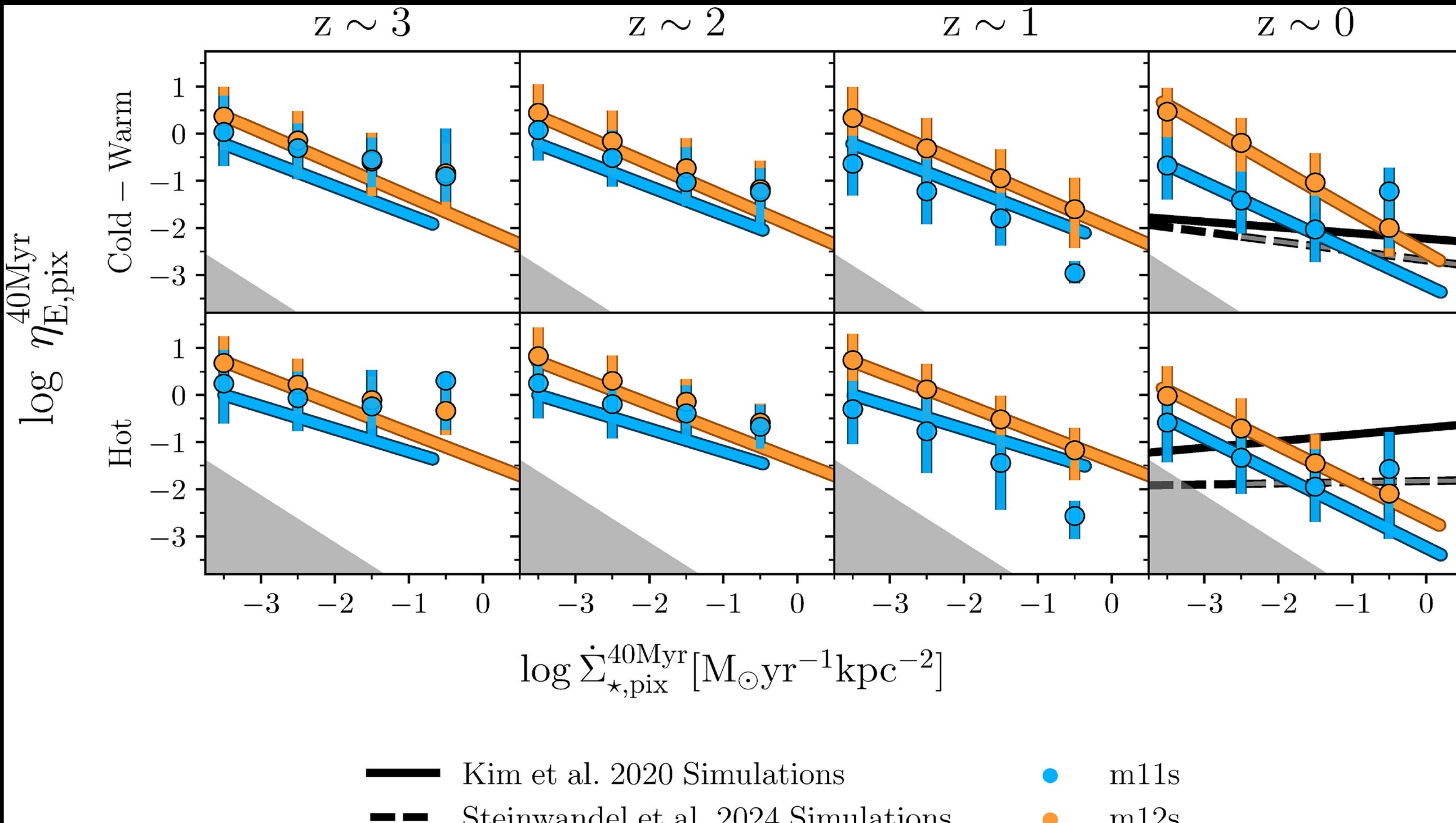
log halo mass

mass loading vs SFR density: FIRE vs. 'resolved feedback' simulations



Porter et al. 2024

energy loading vs SFR density: FIRE vs. 'resolved feedback' simulations



Porter et al. 2024

two main approaches for sub-grid modeling of galactic winds in [large volume] cosmological hydro sims

kinetic

- dialed in function for mass loading and velocity of wind particles
- wind particles are 'launched' by imparting kinetic energy 'kicks'
- hydro is turned off until wind particle gets out of ISM

IllustrisTNG/MillenniumTNG/THESAN/SIMBA

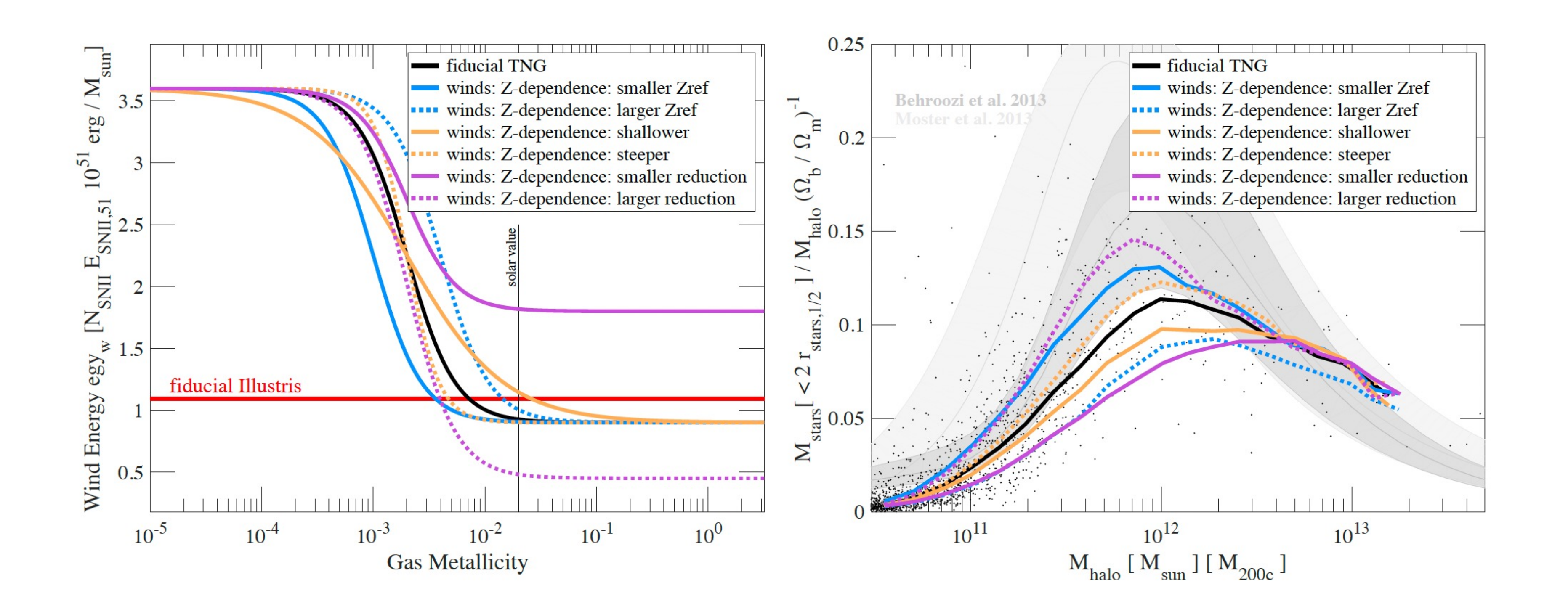
thermal

- thermal energy deposited into neighbors of star forming gas
- energy is 'stored up' until a critical temperature difference is achieved ($\Delta T \sim 10^{7.5}$ K)
- dialed in function: fraction of the total amount of energy from core collapse supernovae per unit stellar mass that is injected on average (can exceed unity)

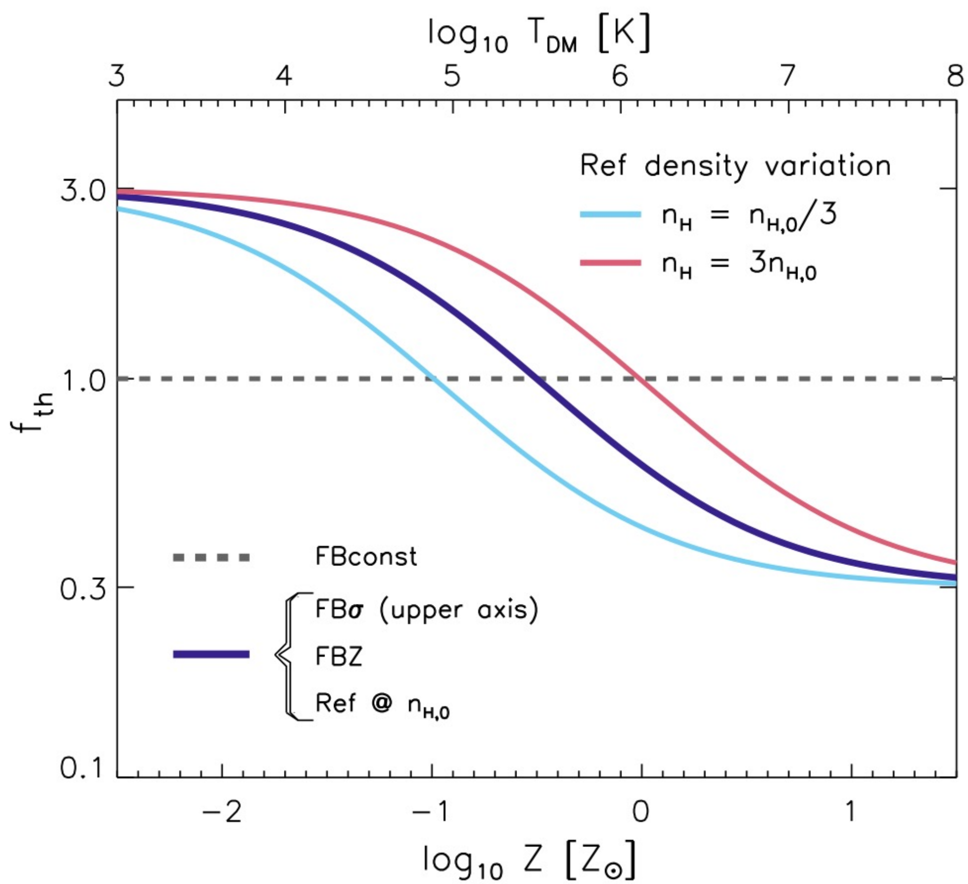
EAGLE/FLARES, Romulus

example: IllustrisTNG

wind energy has been adjusted to reproduce the low star formation efficiencies seen in the local universe



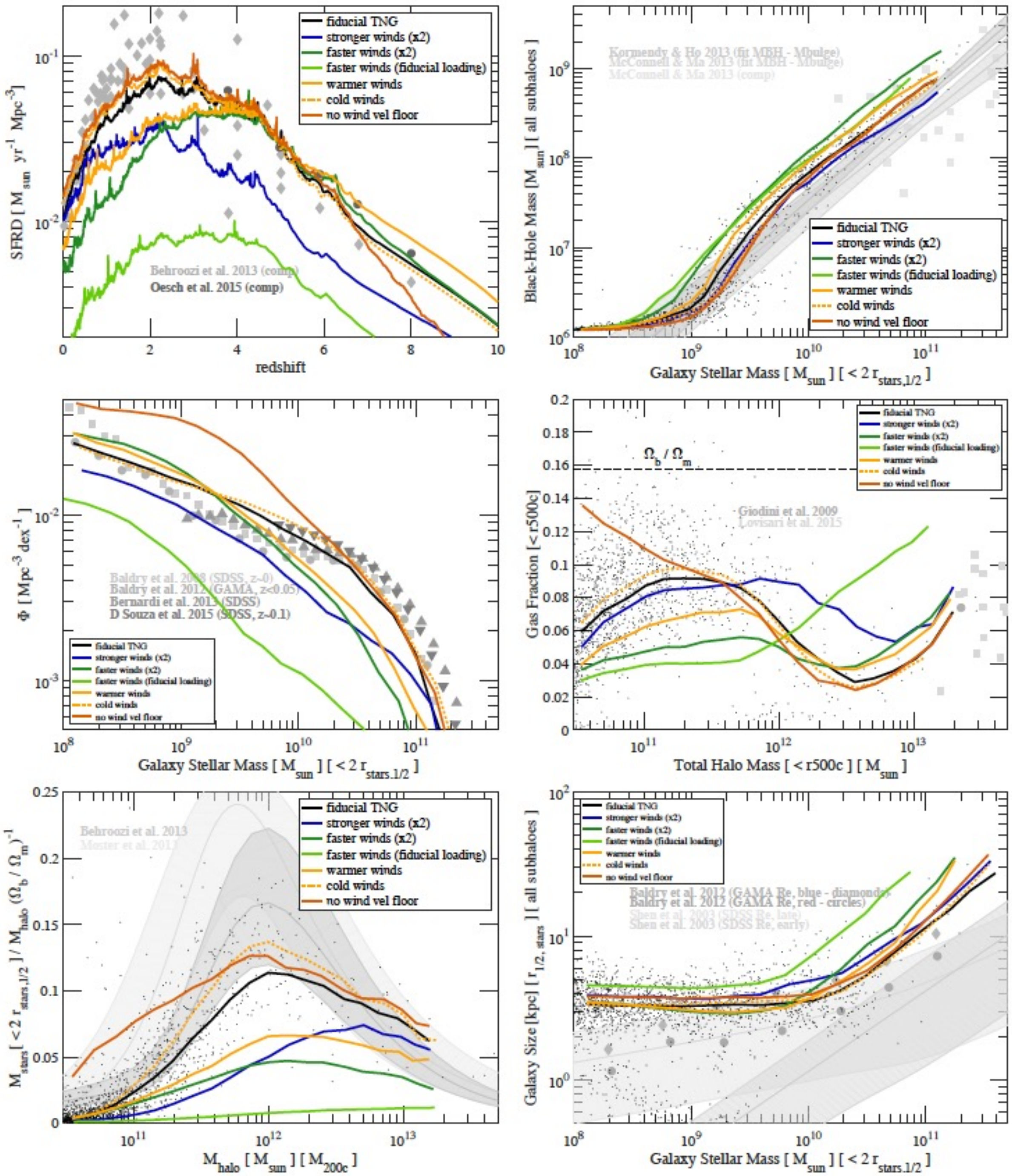
EAGLE/FLARES: feedback is more efficient at low metallicity **and** at high density



$$f_{\rm th} = f_{\rm th,min} + \frac{f_{\rm th,max} - f_{\rm th,min}}{1 + \left(\frac{Z}{0.1\mathrm{Z}_\odot}\right)^{n_Z} \left(\frac{n_{\rm H,birth}}{n_{\rm H,0}}\right)^{-n_n}},$$

$n_n \sim 1$

Schaye et al. 2015; Crain et al. 2015



parameters are tuned to achieve a “best” match (by eye) to a set of calibration observations

other calibrated parameters:
- -stellar wind mass loading and velocity
- -wind metal loading
- -SF timescale (efficiency)
- -BH accretion efficiency
- -parameters controlling mode & effect of BH FB

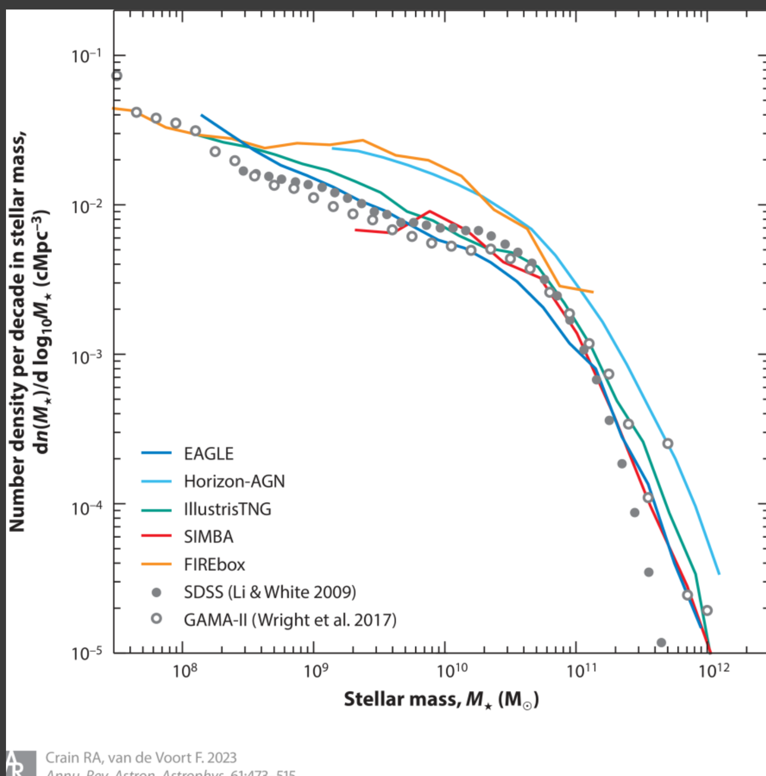
IllustrisTNG
Pillepich et al. 2018

take-away points

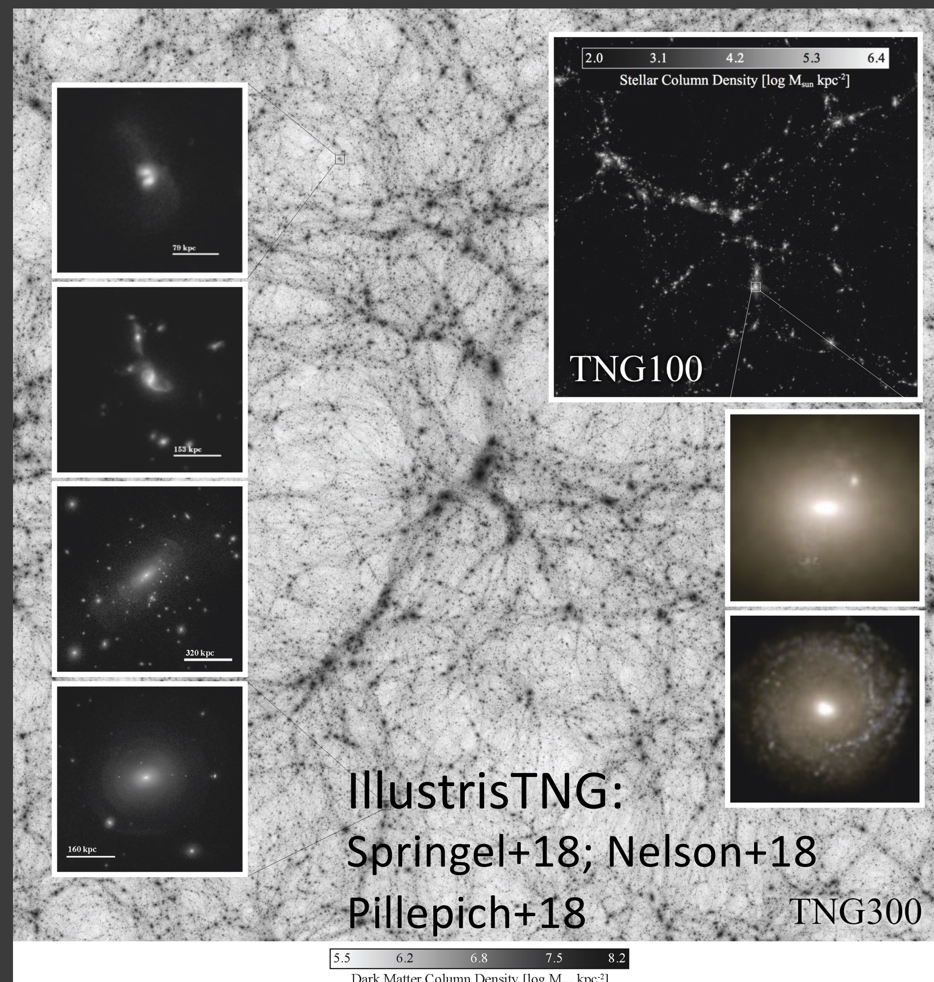
- after the Universe is reionized, the meta-galactic ionizing background suppresses cooling in halos with $M_h<10^8$-10^9 M_{sun}
- the low star formation efficiency on GMC scales is primarily due to supersonic turbulence and feedback from massive stars
- in galactic winds in simulations with ‘resolved feedback’, the cold phase carries most of the mass, while the hot phase carries most of the energy
- lack of agreement between wind mass & energy outflow rates/loadings in simulations with resolved/partially resolved/fully subgrid prescriptions
- ‘large volume’ cosmological simulations must adopt sub-grid recipes for many key physical processes, including star formation & stellar feedback. parameters are calibrated to match primarily local stellar properties of galaxies.

non-trivial success: current cosmological (magneto-)hydrodynamic simulations qualitatively reproduce many key observables (*shown by many groups*; see e.g. reviews by Somerville & Dave 2015 Naab & Ostriker 2017; Vogelsberger 2020; Crain & van de Voort 2023

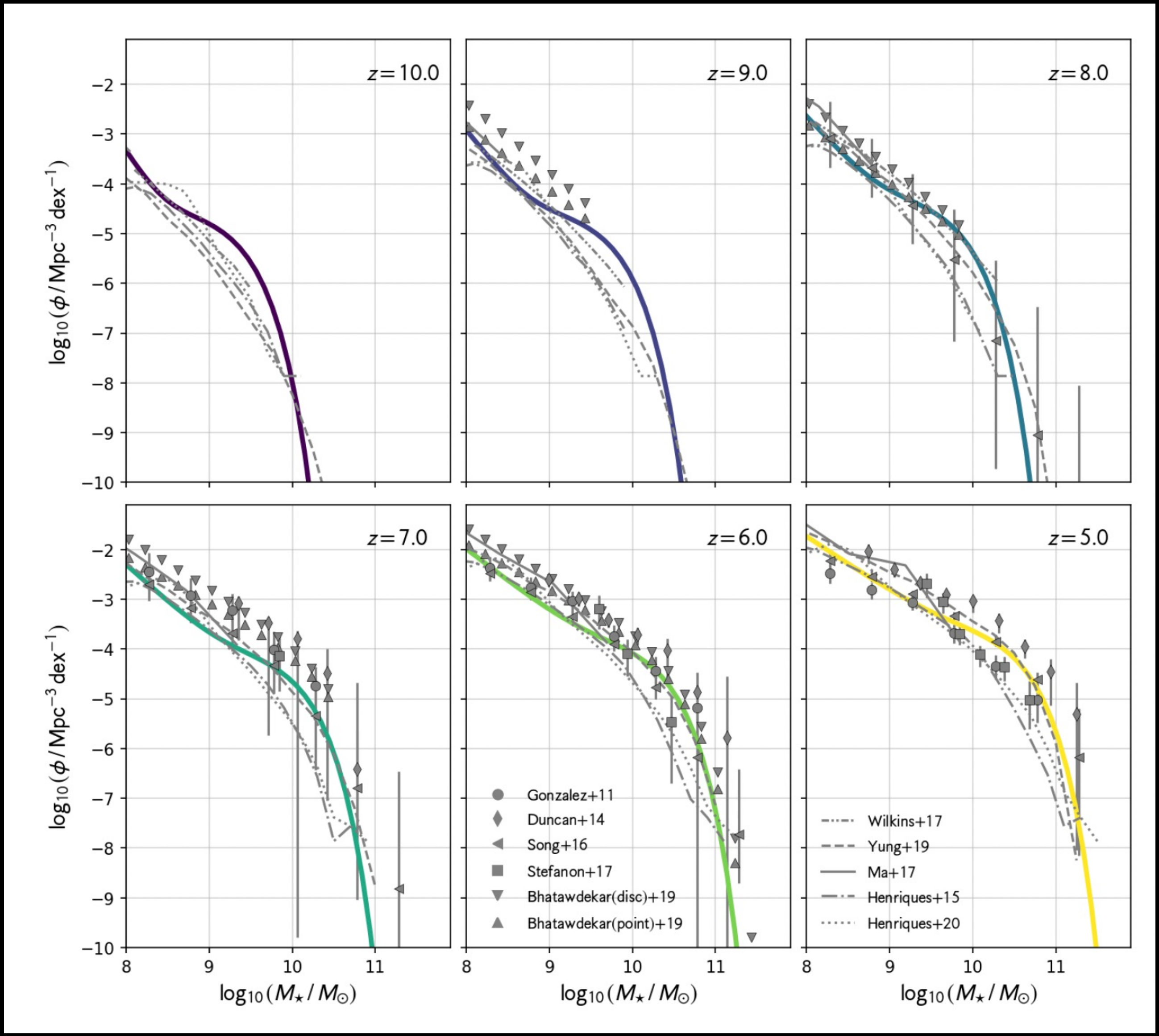
stellar mass function



Crain & van de Voort 2023



stellar mass function to z~10



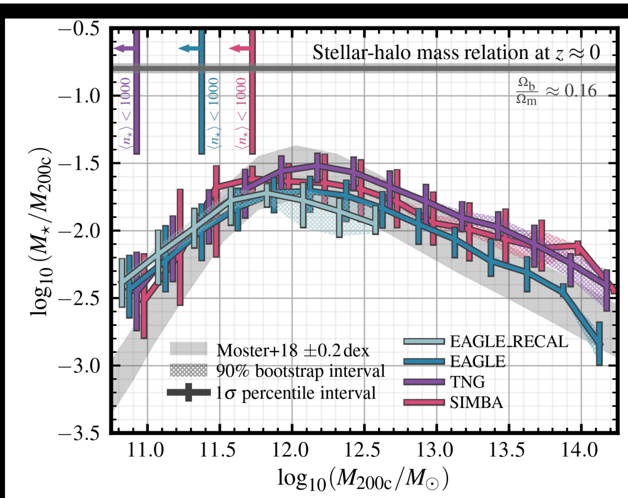
different models/ simulations consistent at factor of few level

FLARES; FIRE SC-SAM; L-galaxies

[not shown] simulations that are not calibrated at low redshift tend to produce higher stellar masses/luminosities

Lovell et al. 2020; see also Yung et al. 2019

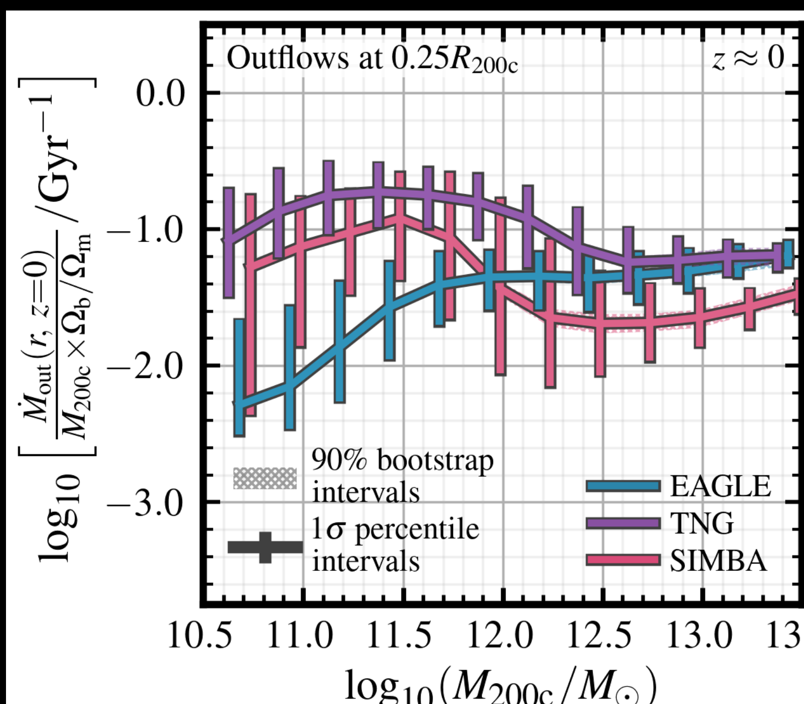
video from CAMELS project; F. Villaescusa-Navarro



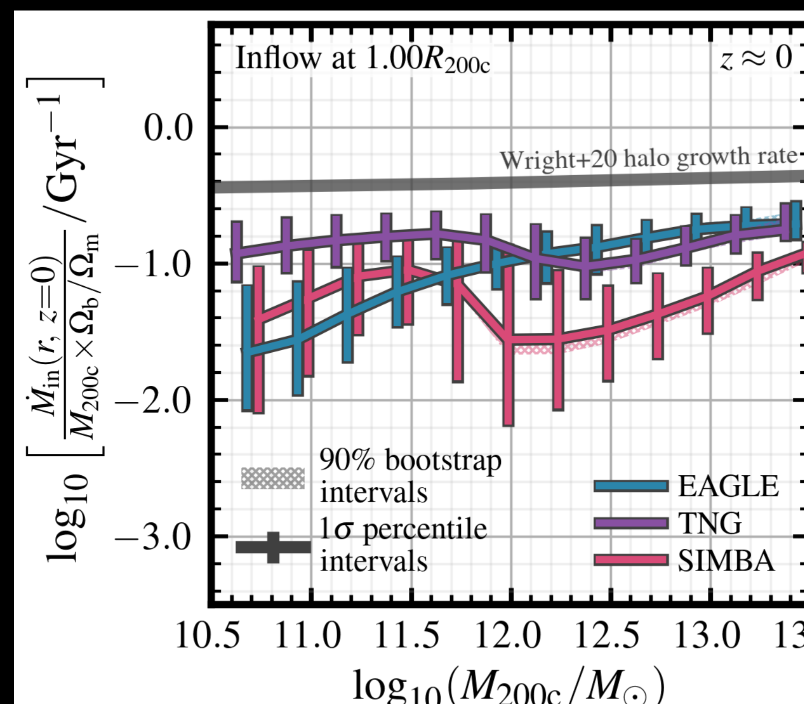
the predicted baryon cycle in cosmological simulations with different sub-grid FB implementations is very different

Ruby Wright

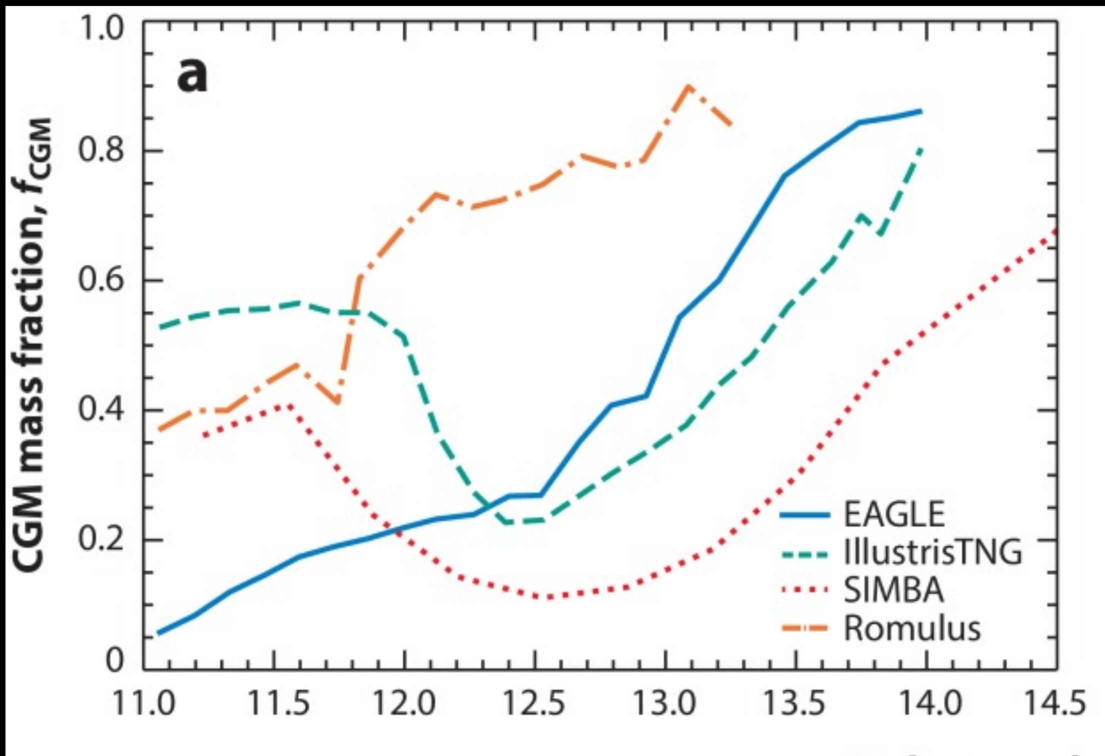
outflows at galaxy scale



inflows at halo scale



Wright, rss et al. 2024; see also Nelson+19, Mitchell+20, Pandya+21 circumgalactic medium mass fraction



log halo mass

huge dispersion in predicted CGM properties, and sims struggle to reproduce observational probes of CGM (e.g. SZ)
ditto for Lyman-α forest (Tilman et al. 2024a,b)

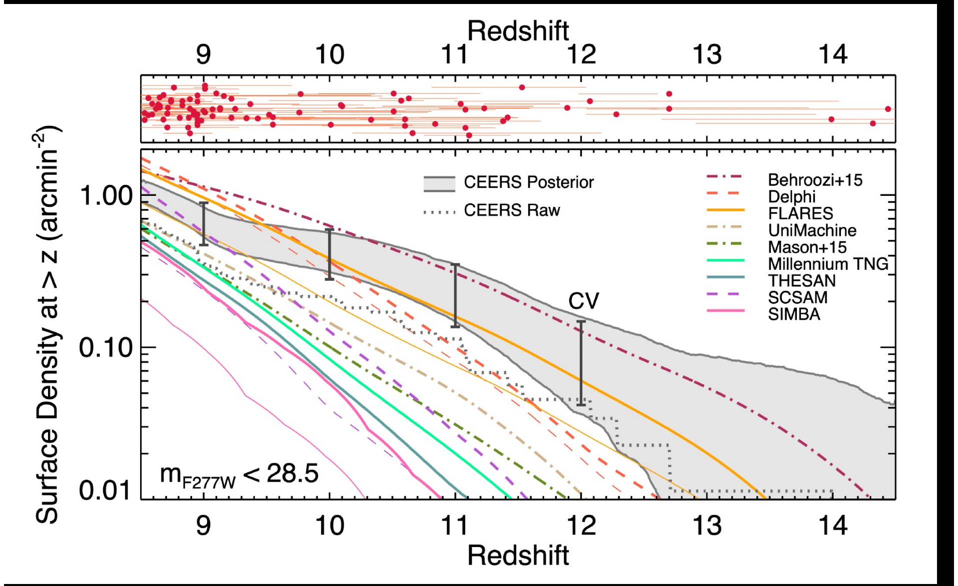
Crain & van de Voort 2023; see also Wright et al. 2024

for comparison of cold ISM gas content in sims, see Davé et al. 2020

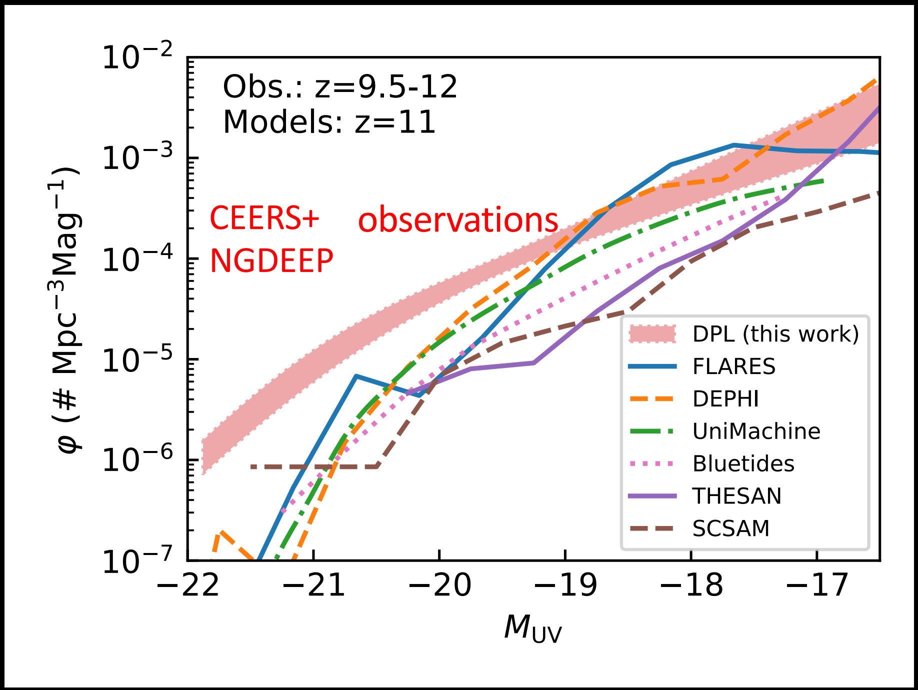
how predictive are the current generation of cosmological simulations?

all physics-based pre-launch models and simulations predict a *much steeper decline* in the number density of UV luminous galaxies at z>~9-10

model underpredictions particularly severe at *bright end*



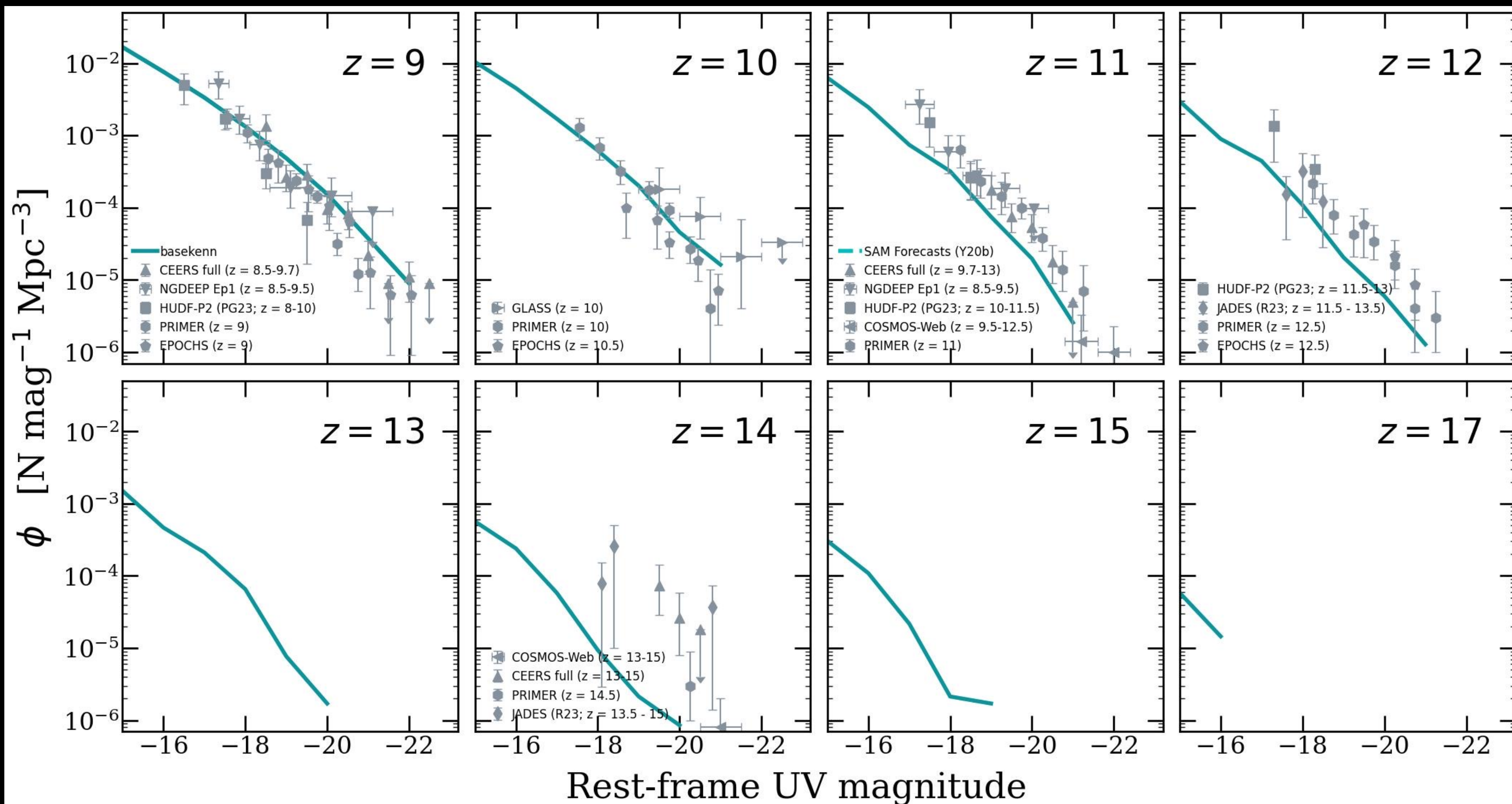
Finkelstein et al. 2023 (CEERS full sample)



Leung et al. 2023; see also Adams et al. 2023; Harikane et al. 2022 + many others!

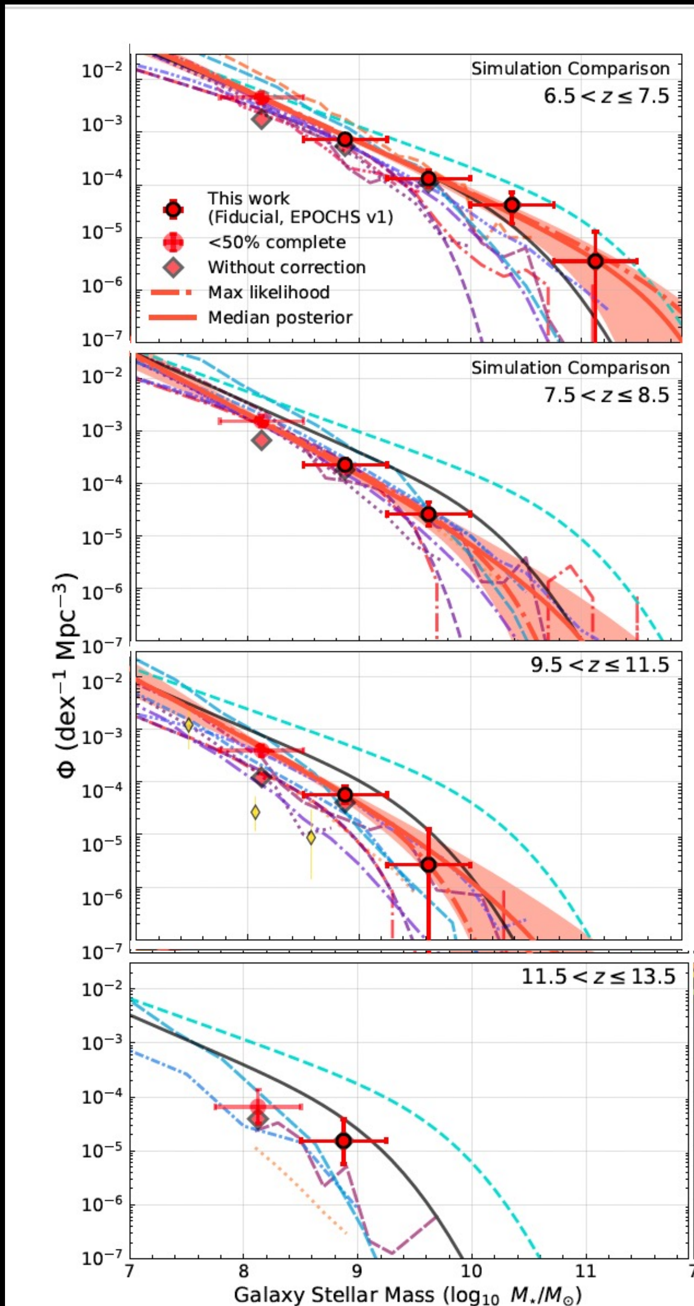
NO DUST

predictions from pre-launch `Santa Cruz' SAMs implemented in new high-z optimized GUREFT N-body simulation suite



Yung et al. 2023; + in prep

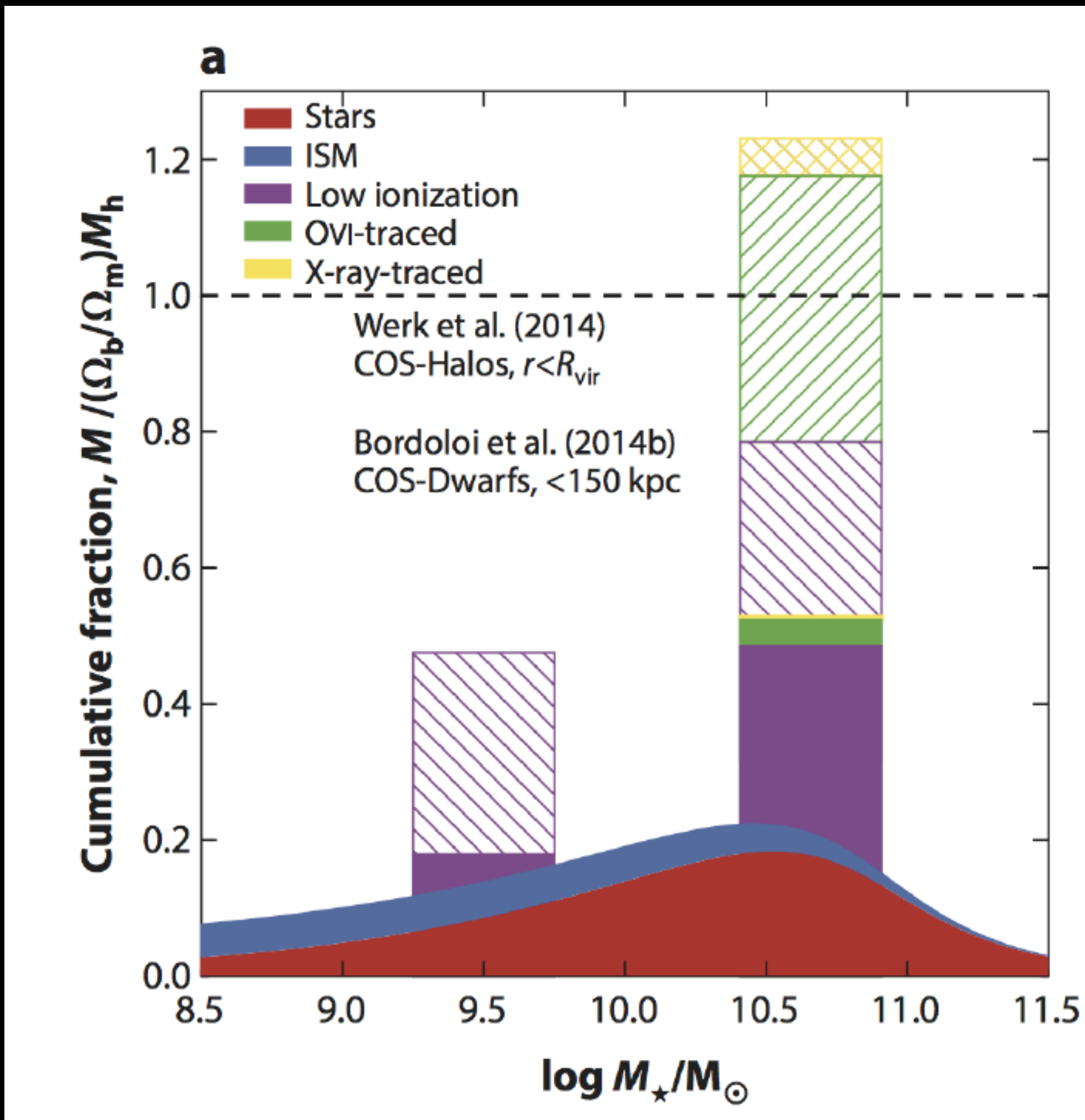
[bright end limited by volume of our biggest N-body box…]



hint that some/most physics-based models are under-producing stellar masses of most massive galaxies at z>6, but uncertainties are v. large

Harvey et al. 2024
see also Weibel+24

chemical enrichment



as many metals (or more) outside of galaxies as inside them!

how did they get there?

potentially very strong constraint on feedback modeling!

Peeples et al. 2014

chemical enrichment in hydrodynamic simulations

- add tags to track element abundances in gas cells/particles and star particles based on SNII, SNIa, AGB rates
- create metals according to yield tables (but highly uncertain; see Weinberg+24)
- metal flow cycle (subject to all the same issues just discussed)
- are winds metal enhanced or metal depleted?
- metals strongly impact cooling, stellar physics

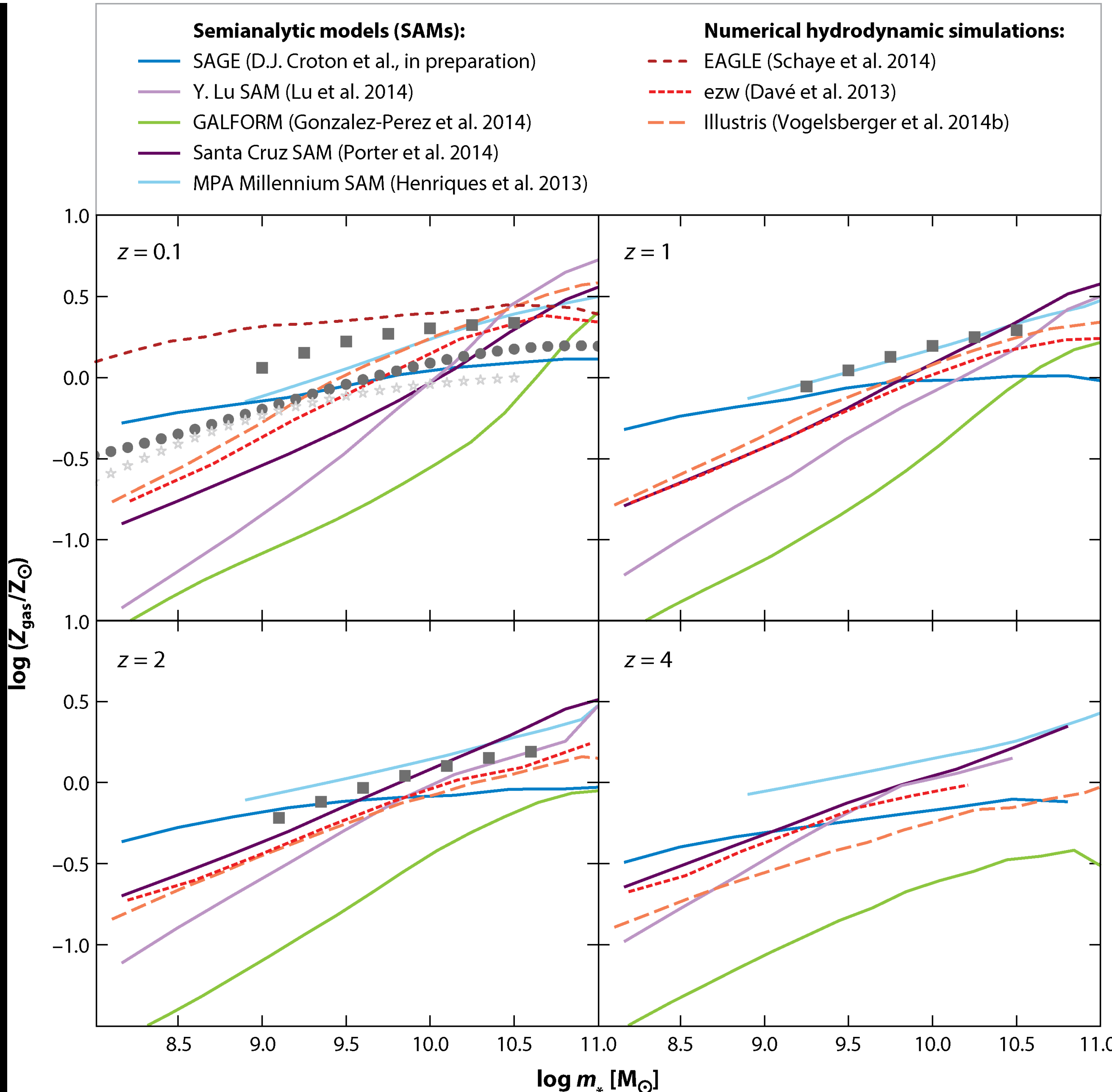
see reviews by Maiolino & Manucci (2019)
Kobayashi et al. 2020

stellar yields

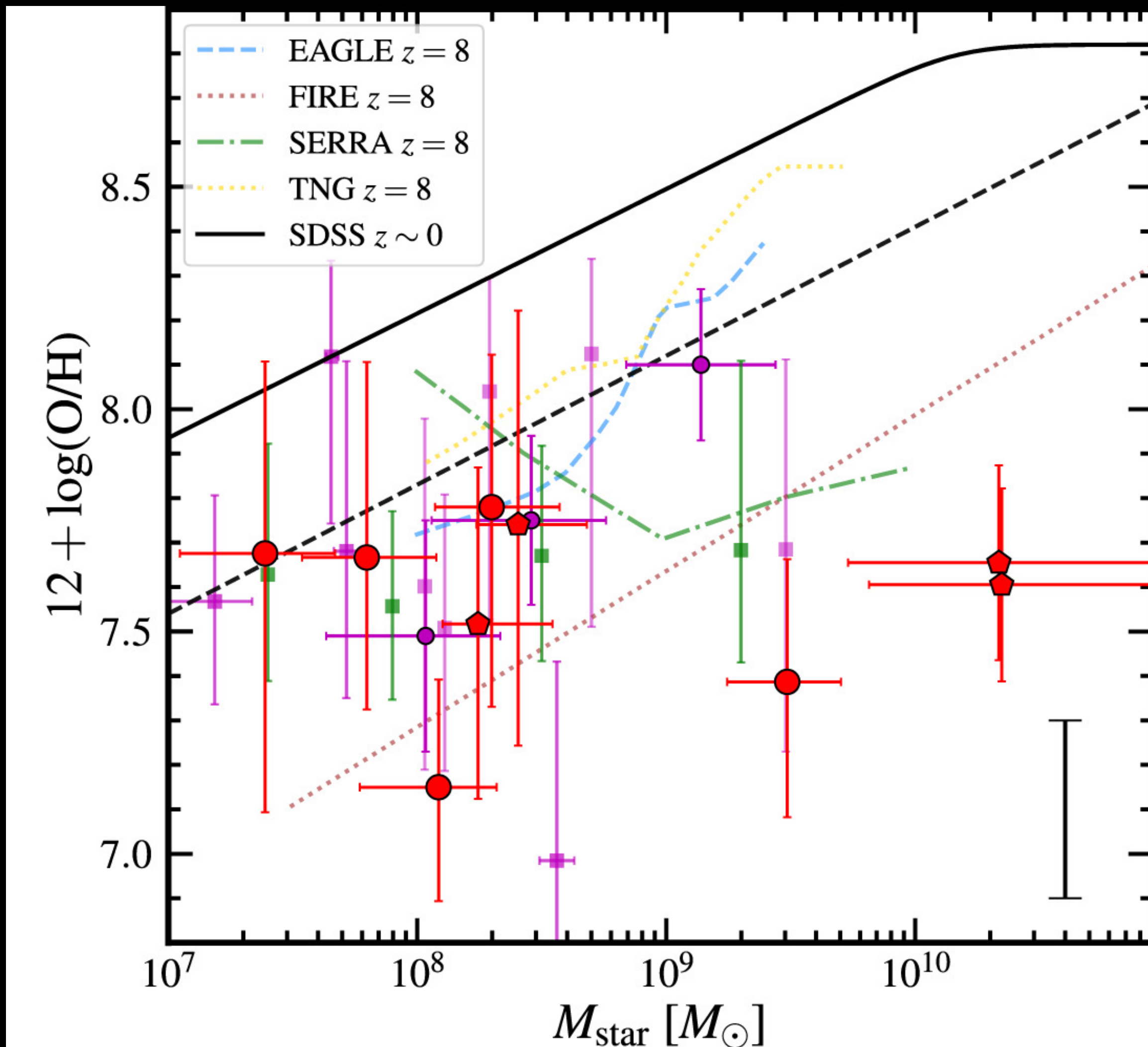
Table 8.1 Stellar yields

Initial mass ($\mathcal{M}_{\rm ini}$) ($\mathcal{M}_\odot$)	Ejection phase	Species	$y_i \mathcal{M}_{\rm ini}$ ($10^{-3}\,\mathcal{M}_\odot$)
11–40[a]	SN II	^{16}O	53–5720
		^{20}Ne	31–1240
		^{28}Si	17–345
		^{12}C	24–259
		^{24}Mg	≤ 235
		^{32}S	≤ 159
		^{56}Fe	11–26
		^{40}Ca	≤ 10
7–8	AGB	^{14}N	68–88
		^{13}C	~ 1
4–6[b]	AGB	^{14}N	3–52
		^{12}C	< 19
2.5–4	AGB	^{12}C	4–20
		^{14}N	0.5–7
$\lesssim 1.4$[c]	SN Ia	^{56}Fe	610
		^{28}Si	160
		^{54}Fe	140
		^{24}Mg	90
		^{32}S	80
		^{58}Ni	60

Cimatti, Fraternali & Nipoti (textbook)

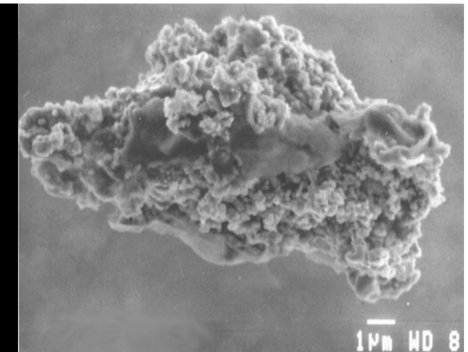


Somerville RS, Davé R. 2015.
Annu. Rev. Astron. Astrophys. 53:51–113



Fujimoto et al. 2023

dust in the ISM of galaxies



- created in ejecta of supernovae, AGB stars, and via grain accretion in the ISM; destroyed by SN shocks, sputtering, etc.; grain size distribution modified by shattering/coagulation (see Draine 2002 review)
- primarily graphite, silicate, polycyclic aromatic hydrocarbons (PAH)
- dust plays a critical role in the thermodynamics and chemistry of the ISM, as well as impacting the observed spectral energy distributions of galaxies
- in general, galaxy scale/cosmological simulations do not include *'live'* dust physics (but see Jones et al. 2024)

take-away points

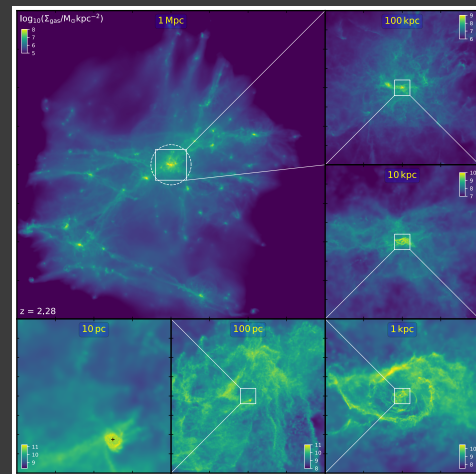
- current generation of ‘large volume’ cosmological simulations make strongly divergent predictions for uncalibrated quantities such as CGM mass, and achieve a fixed outcome in terms of m_*/M_h via very different paths (baryon cycles are very different)
- different simulations & SAMs agree pretty well with each other and with stellar-based galaxy properties (LFs, SMF) out to z~10
- different simulations make very divergent predictions for stellar & gas phase metallicities at all redshifts
- all pre-launch physics-based simulations appear to significantly underpredict the UV-luminous galaxy population at z>10 discovered by JWST

future directions
in galaxy formation modeling*

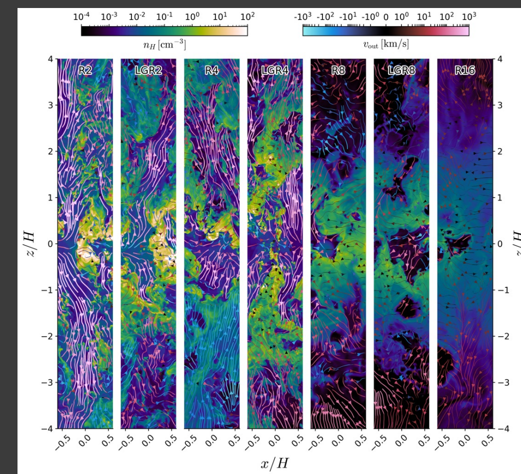
*warning! extra super biased towards work by my group & my collaborators!

Simulating Multiscale Astrophysics to Understand Galaxies (SMAUG)

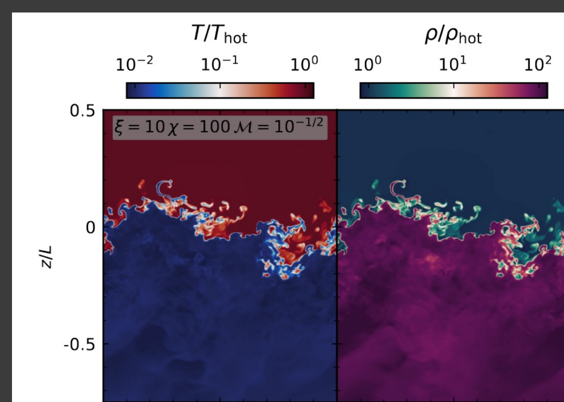
- use a ‘ladder’ of multiscale simulations to explore how physical processes work and interact across different scales
- use numerical simulations as laboratories to develop analytic scaling relations that can form the basis for sub-grid models
- any remaining parameters in sub-grid recipes are calibrated to higher resolution/more physically explicit simulations, not directly to observations



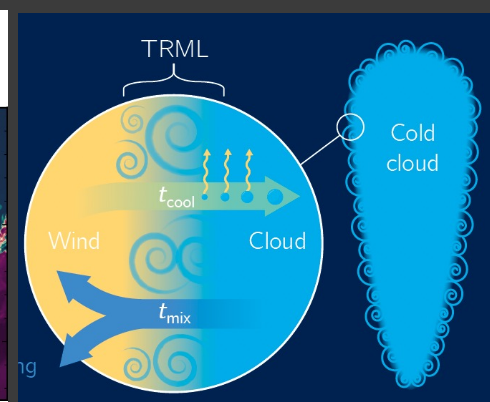
Angles-Alcazar+SMAUG 2020



Kim+SMAUG 2020a,b



Fielding et al. 2020

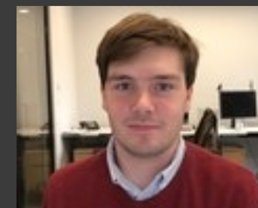


Fielding & Bryan 2022

www.simonsfoundation.org/flatiron/center-for-computational-astrophysics/galaxy-formation/smaug/

Project Arkenstone

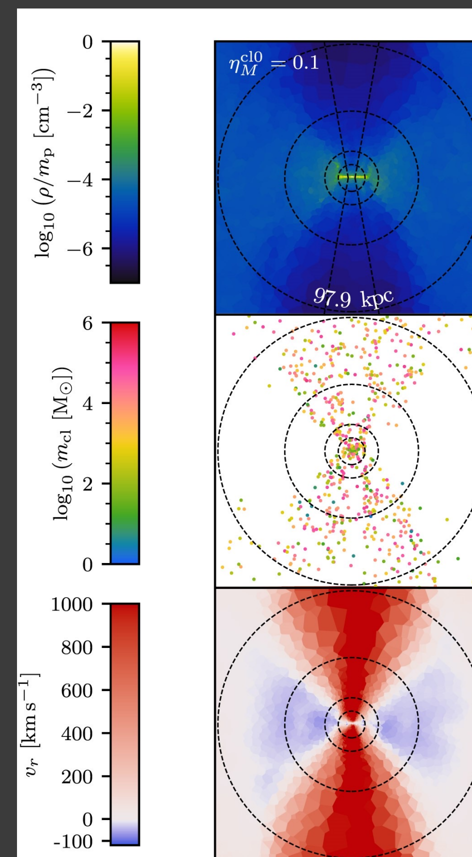
a new sub-grid model for multi-phase galactic winds



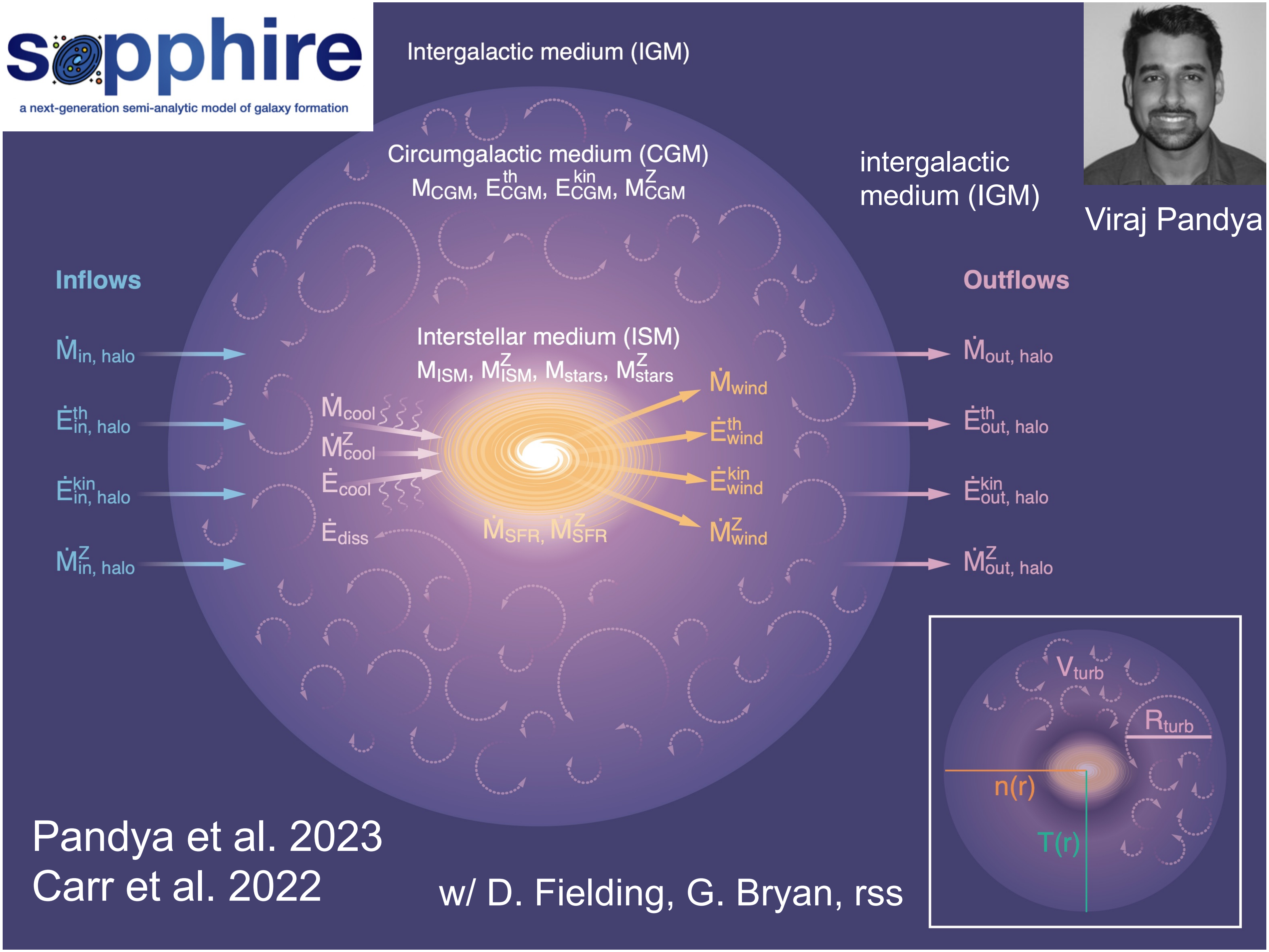
Matthew Smith

Drummond Fielding

- Winds are launched with hot and cool components with separate mass and energy loadings, inspired by the results from high-resolution simulations
- The hot, fast phase of the wind is injected and evolved with a new ‘displacement recoupling’ and refinement scheme that properly treats high-specific energy and low-density flows.
- The cool phase is modelled using ‘cloud particles’ to represent clouds embedded in the hot flow. These particles exchange mass, energy, momentum, and metals bidirectionally with the ambient hot wind.



Smith et al. 2024a,b; Bennett et al. 2024


sapphire
a next-generation semi-analytic model of galaxy formation
Intergalactic medium (IGM)
Viraj Pandya
Circumgalactic medium (CGM)
M_{CGM}, E^{th}_{CGM}, E^{kin}_{CGM}, M^{Z}_{CGM}
intergalactic medium (IGM)
Inflows
$\dot{M}_{in,\ halo}$
$\dot{E}^{th}_{in,\ halo}$
$\dot{E}^{kin}_{in,\ halo}$
$\dot{M}^{Z}_{in,\ halo}$
Interstellar medium (ISM)
M_{ISM}, M^{Z}_{ISM}, M_{stars}, M^{Z}_{stars}
$\dot{M}_{cool}$
$\dot{M}^{Z}_{cool}$
$\dot{E}_{cool}$
$\dot{E}_{diss}$
$\dot{M}_{SFR}$, $\dot{M}^{Z}_{SFR}$
$\dot{M}_{wind}$
$\dot{E}^{th}_{wind}$
$\dot{E}^{kin}_{wind}$
$\dot{M}^{Z}_{wind}$
Outflows
$\dot{M}_{out,\ halo}$
$\dot{E}^{th}_{out,\ halo}$
$\dot{E}^{kin}_{out,\ halo}$
$\dot{M}^{Z}_{out,\ halo}$
V_{turb}
R_{turb}
n(r)
T(r)
Pandya et al. 2023
Carr et al. 2022
w/ D. Fielding, G. Bryan, rss

A new model for CGM—galaxy co-evolution

(building on classical semi-analytic models of galaxy formation)

8 coupled ODEs governing time evolution of 8 CGM+galaxy state variables:

new

CGM thermal energy

$$\dot{E}^{\rm th}_{\rm CGM} = \dot{E}^{\rm th}_{\rm in,halo} - \dot{E}_{\rm cool} + \dot{E}_{\rm diss} + \dot{E}^{\rm th}_{\rm wind} - \dot{E}^{\rm th}_{\rm out,halo}$$

CGM turbulent kinetic energy

$$\dot{E}^{\rm kin}_{\rm CGM} = \dot{E}^{\rm kin}_{\rm in,halo} - \dot{E}_{\rm diss} + \dot{E}^{\rm kin}_{\rm wind} - \dot{E}^{\rm kin}_{\rm out,halo}$$

CGM mass

$$\dot{M}_{\rm CGM} = \dot{M}_{\rm in,halo} - \dot{M}_{\rm cool} + \dot{M}_{\rm wind} - \dot{M}_{\rm out,halo}$$

ISM mass

$$\dot{M}_{\rm ISM} = \dot{M}_{\rm cool} - (1 - f_{\rm rec})\dot{M}_{\rm SFR} - \dot{M}_{\rm wind}$$

Stellar mass

$$\dot{M}_{\rm star} = (1 - f_{\rm rec})\dot{M}_{\rm SFR}$$

CGM metal mass

$$\dot{M}^{\rm Z}_{\rm CGM} = \dot{M}^{\rm Z}_{\rm in,halo} - \dot{M}^{\rm Z}_{\rm cool} + \dot{M}^{\rm Z}_{\rm wind} - \dot{M}^{\rm Z}_{\rm out,halo}$$

ISM metal mass

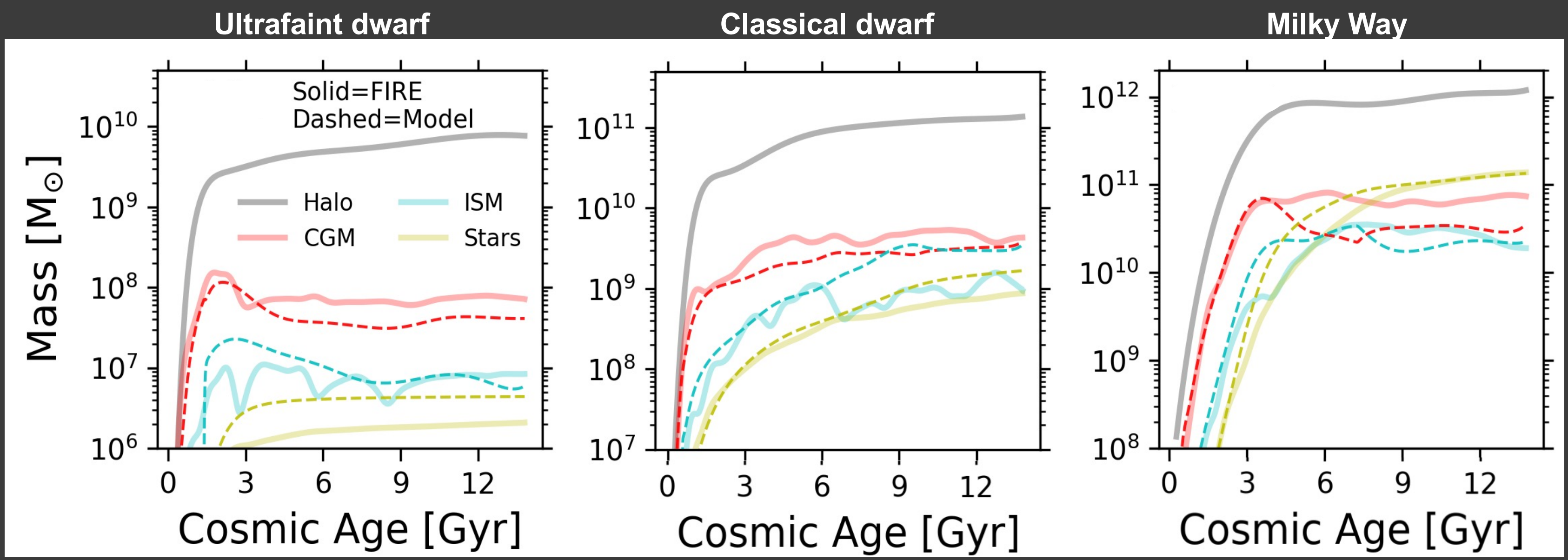
$$\dot{M}^{\rm Z}_{\rm ISM} = \dot{M}^{\rm Z}_{\rm cool} + \dot{M}^{\rm Z}_{\rm yield} - (1 - f_{\rm rec})\dot{M}^{\rm Z}_{\rm SFR} - \dot{M}^{\rm Z}_{\rm wind}$$

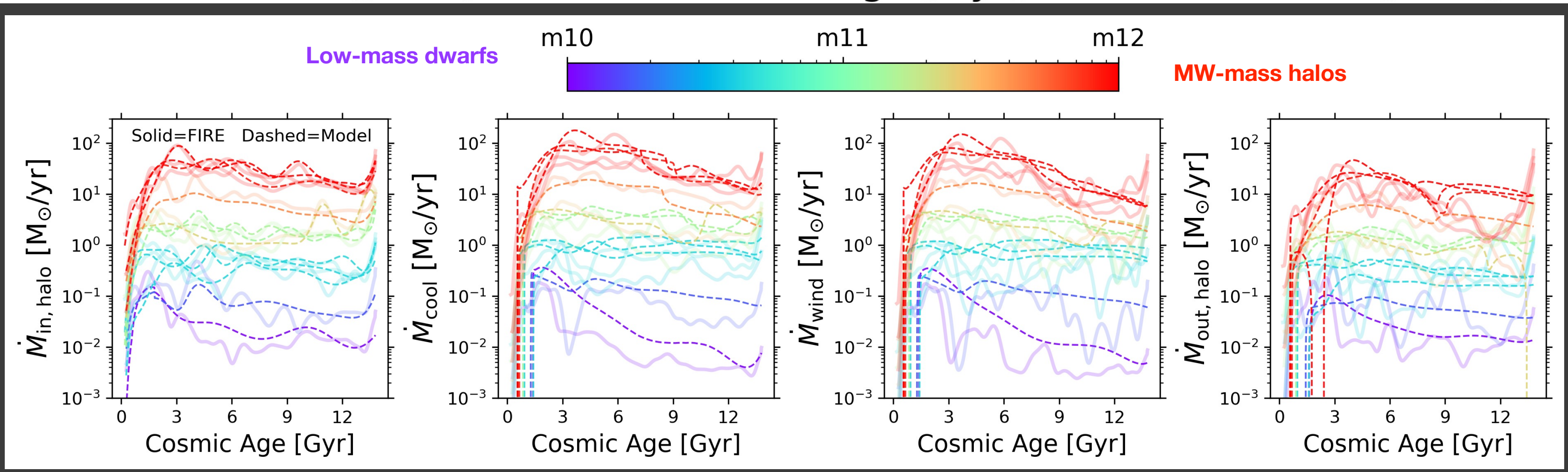
Stellar metal mass

$$\dot{M}^{\rm Z}_{\rm star} = (1 - f_{\rm rec})\dot{M}^{\rm Z}_{\rm SFR}$$

Pandya+ (in prep.)

reproduces FIRE-2 bulk properties (stellar mass, ISM mass, CGM mass, energy, metallicity) and mass, metal, & energy inflow and outflow rates over cosmic time and halo mass [NO BH/AGN]





Pandya+23

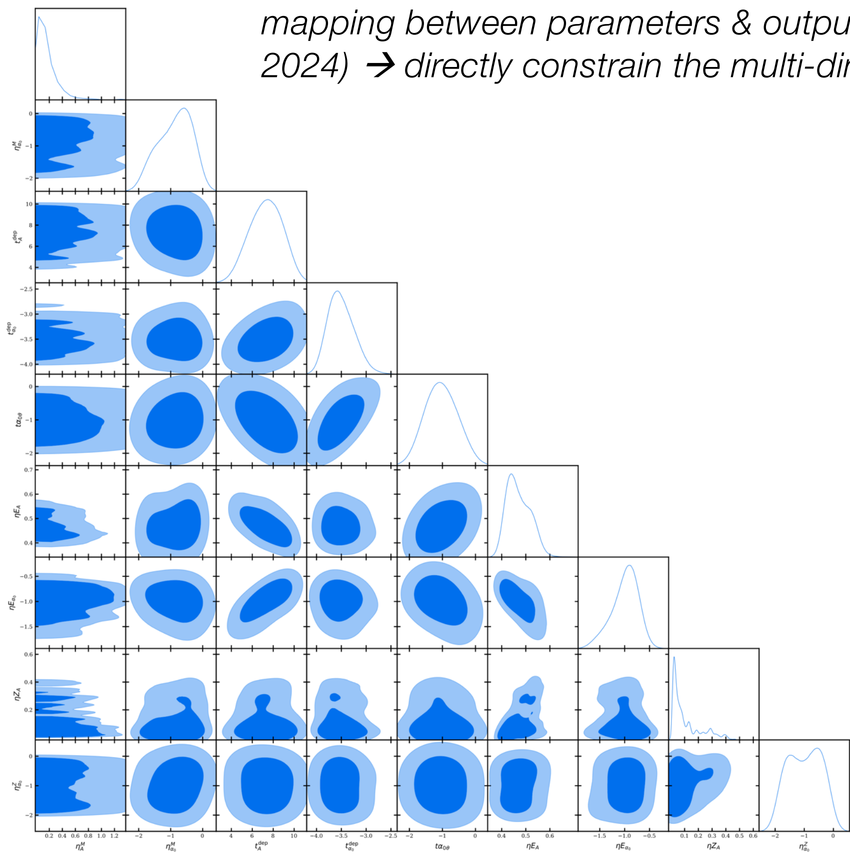
Viraj Pandya

modeling galaxies as complex dynamical systems

with automatic differentiation and parallelization

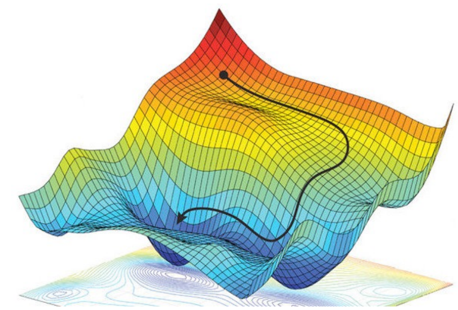
Implicit Likelihood Inference

train a neural network to learn the mapping between parameters & outputs (e.g. Ho et al. 2024) → directly constrain the multi-dimensional posterior



astrophysics parameters

hamiltonian monte carlo



use gradients to speed up parameter space exploration

with the Learning the Universe Simons Collaboration

sapphire

modeling galaxies as complex dynamical systems

with automatic differentiation and parallelization

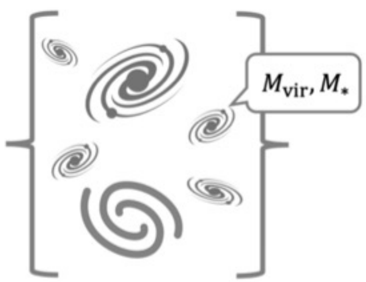
Lucas Makinen

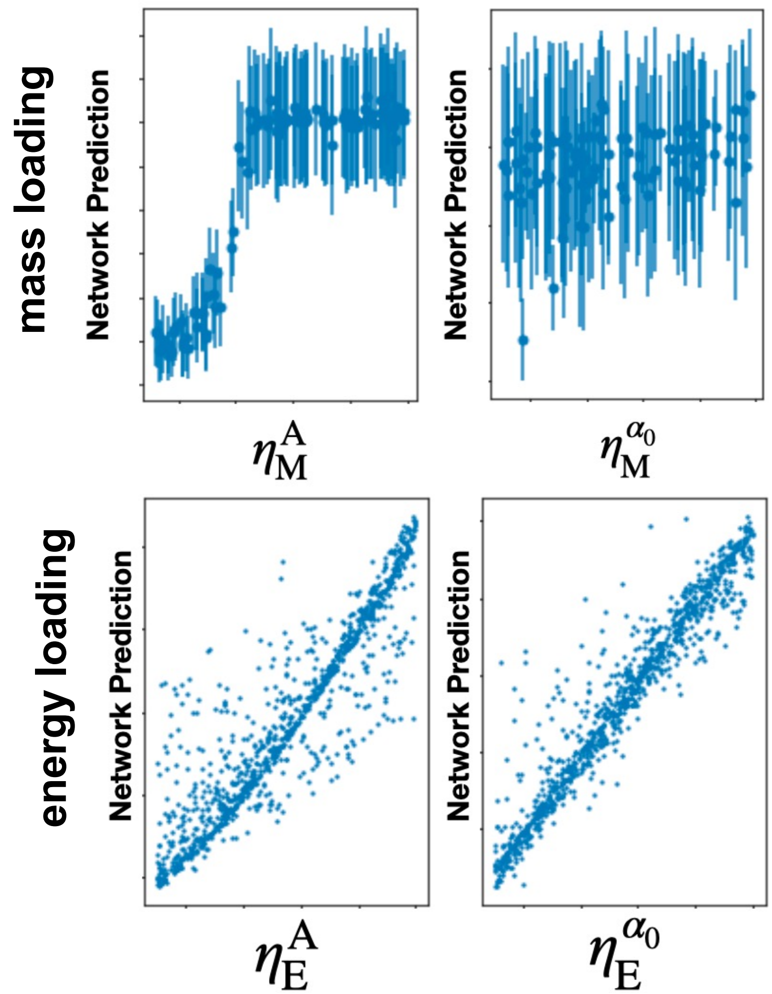
Implicit Likelihood Inference

training a neural network to learn the mapping between parameters & outputs

using Fishnet

constraints: stellar mass-halo-mass relation





NN cannot learn $\eta_{\rm M}$ from SMHM relation alone

But it *can* learn $\eta_{\rm E}$

Makinen, Pandya+ (in prep.)

sapphire

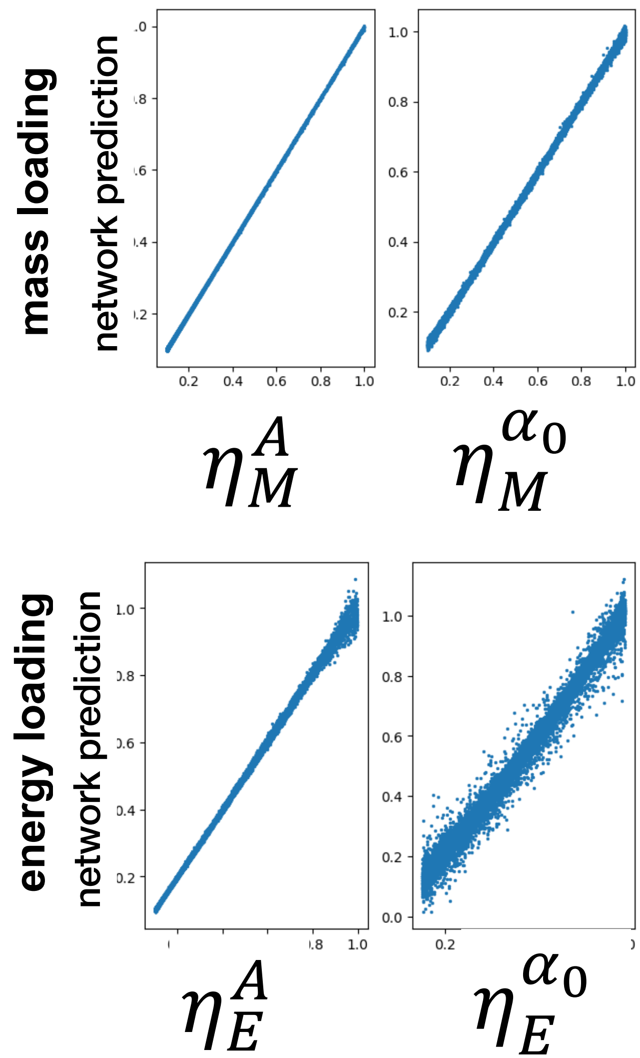
modeling galaxies as complex dynamical systems

with automatic differentiation and parallelization

Lucas Makinen

Implicit Likelihood Inference

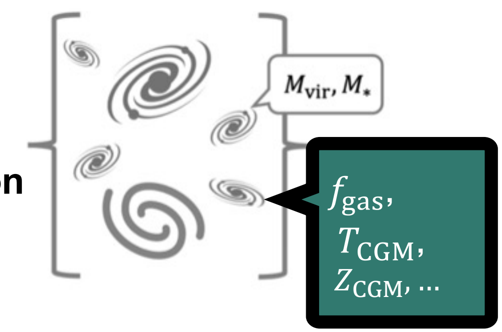
training a neural network to learn the mapping between parameters & outputs



adding gas constraints allows NN to learn the mass loading parameters

constraints: stellar mass-halo-mass relation

+ gas properties



Makinen, Pandya+ (in prep.)

takeaways

- the next generation of large volume cosmological simulations can benefit from more robust sub-grid recipes derived from higher resolution simulations
- high-res simulations can be informed by larger volume simulations
- a new generation of semi-analytic models may be able to ‘emulate’ numerical simulations and can be coupled with simulation based inference to efficiently explore parameter space, reveal degeneracies, and map high-dimensional posteriors