Title: Galaxy Evolution: Gas phases and Feedback

Speakers:

Series: Cosmology & Gravitation

Date: February 06, 2024 - 11:00 AM

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Abstract: Studying galaxy evolution is a human endeavour. Simulations would ideally include physical models based on relevance, but we are often limited by practical considerations like CPU time and code complexity. I will examine energy inputs to galaxies from radiation and stellar feedback, how they are modeled in simulations, and where they are expected to influence the state of the gas and the overall evolution of a galaxy. I will focus on superbubbles (clustered supernova and stellar wind feedback) and local radiation fields, looking at the differences in what these feedbacks can do in terms of where they act in the galaxy, how that impact changes over cosmic time and how the limitations of simulations have affected our view of them.

Zoom link

Galaxy Evolution: Gas phases and Feedback

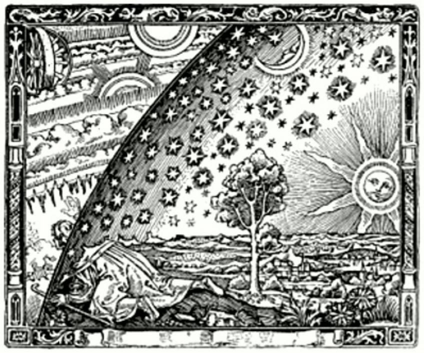
James Wadsley, Ben Keller, Samantha Benincasa, Padraic Odesse, Sijing Shen, Bernard Baumschlager, Jasper Grond, Hugh Couchman

McMaster University

Galaxy formation: Simulations

- Galaxies simulation movies are pretty to look at
- Lets look under the hood ….

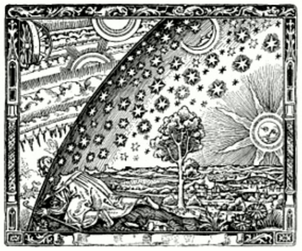
"Fire" Galaxy simulation, P. Hopkins
sub-grid models for everything



Galaxy Simulations: Under the hood…

Simulation Components:

- Dark Matter (Collisionless Boltzmann Equation via particles: N-body, e.g. Tree-code)
- Hydrodynamics (Euler's equations via Mesh or particles) (incl. radiative cooling/heating, *usually no radiative transfer*)
- Stars, Black Holes (N-body) form from gas (stochastic e.g. density > threshold, SFR ~ density $^{3/2}$)
- Feedback from stars, BH (many ways!)



Energy input to Galaxies

Drivers for turbulence, outflows, ISM structure

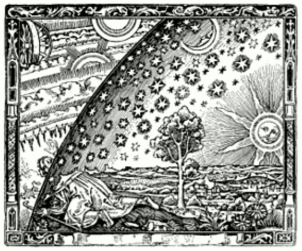
Sources:

Galactic: Accretion, Shear/MRI, Thermal Instab.

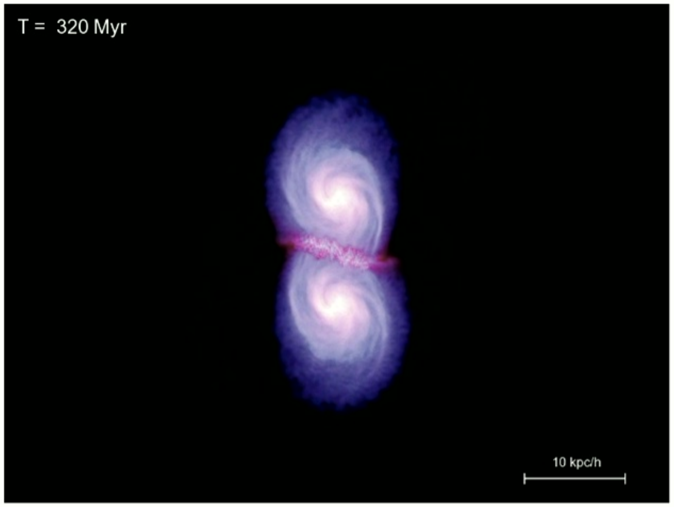
Stellar: Jets, Winds, Radiation (IR/rad. Pressure), FUV, EUV (blister HII regions), Supernovae

-- Also: X-rays, UVB, Cosmic Rays

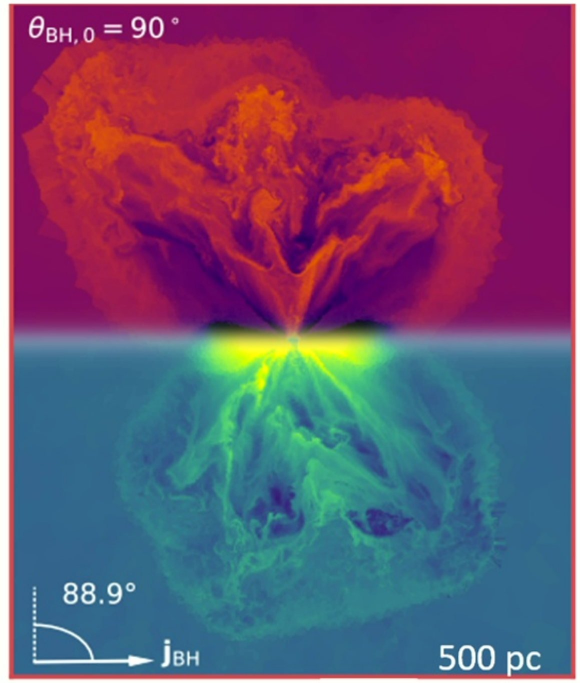
AGN: Jets/radiation



Galaxy Simulations:
Finite resolution vs. All-the-details → AGN



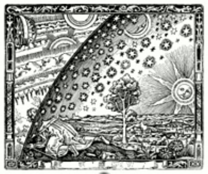
di Matteo+ 2005
AGN Feedback calibrated to quench galaxies by ejecting gas
Best resolution ~ 0.1-0.2 kpc
Entire Talbot+ 2022 accretion torus comparable to one resolution element

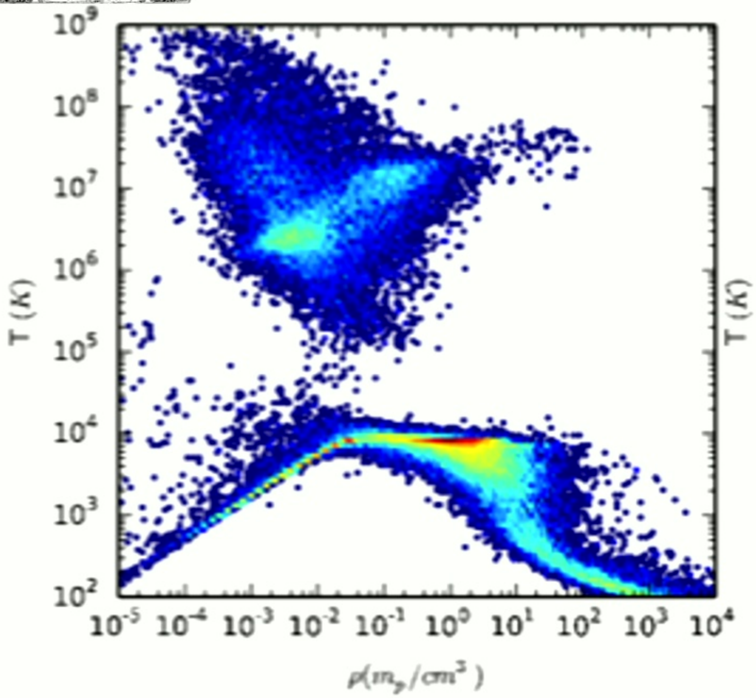


Talbot, Sijacki & Bourne 2022
Even sideways jet does not destroy disk
Resolution 250 M_{SUN}

Simulator view of gas around galaxies

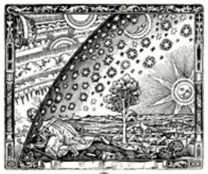
Temperature-Density Phase space





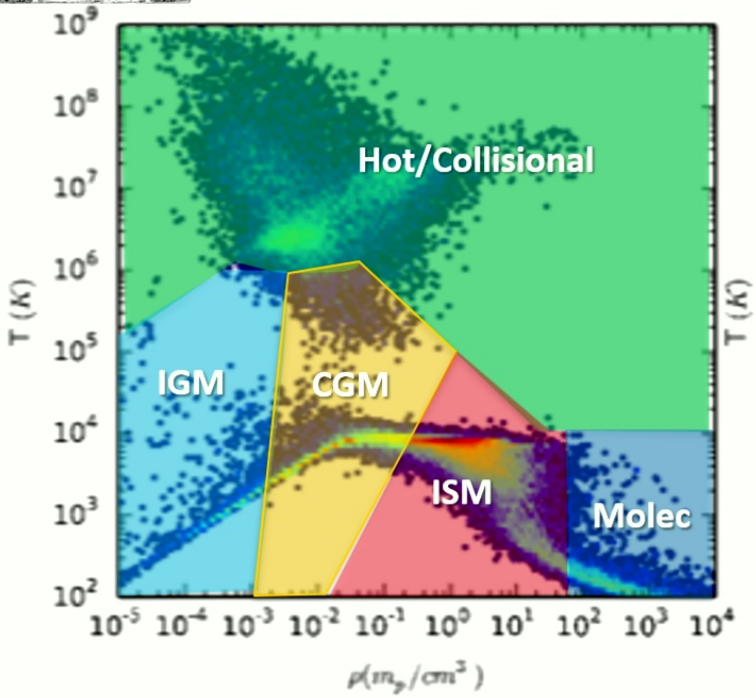
MUGS2 Galaxy simulation (Keller+ 2016)
Colour scale indicates mass at that density/temperature (log)
Physics: UV background, metal cooling & mixing, star formation, super bubble feedback (no AGN)

- Galaxy simulations can now resolve gas up to fairly high densities
- Simulated gas can be identified with observed gas phases.
- Models still reflect old low res ideas (e.g. for heating,cooling, star formation & feedback)



Simulator view of gas around galaxies

Temperature-Density Phase space



MUGS2 Galaxy simulation (Keller+ 2016)

Coloured zones: Somewhat arbitrary divisions (neglects location/overlaps)

Hot/Collisional:

- Halo, outflows, hot inflows (accretion) and remnants, HIM

IGM

- Lyman alpha forest, WHIM, cold inflows (accretion)

CGM

- Intermediate CGM gas, fountains, cooling gas, metal line absorbers

ISM

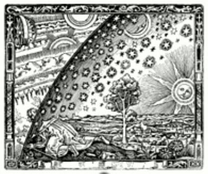
- Classic ISM: WIM, WNM, CNM

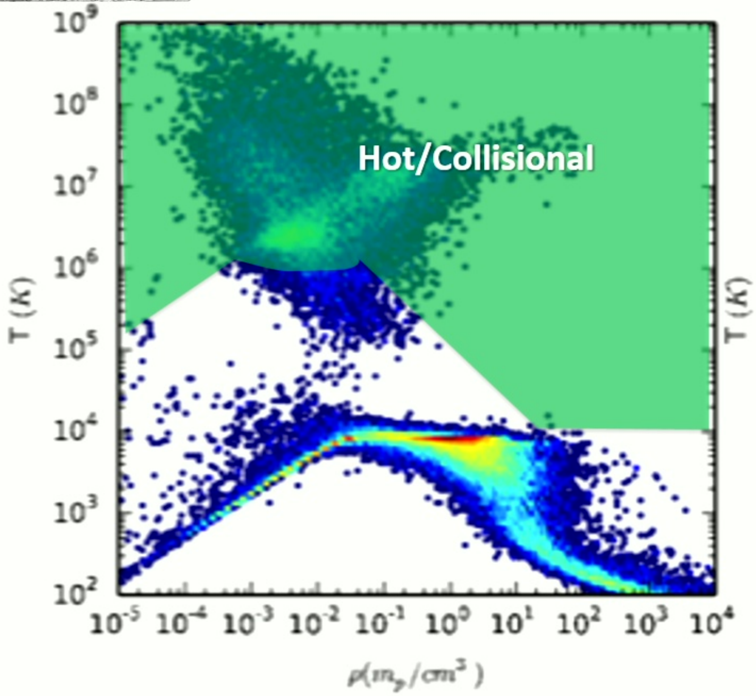
Molecular (Shielded)

- Molecular clouds or bulk ISM (star bursts)

Temperature-Density Phase space

High Energy (SN, AGN, CR) impact

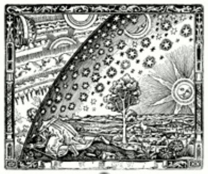




Hot/Collisional:

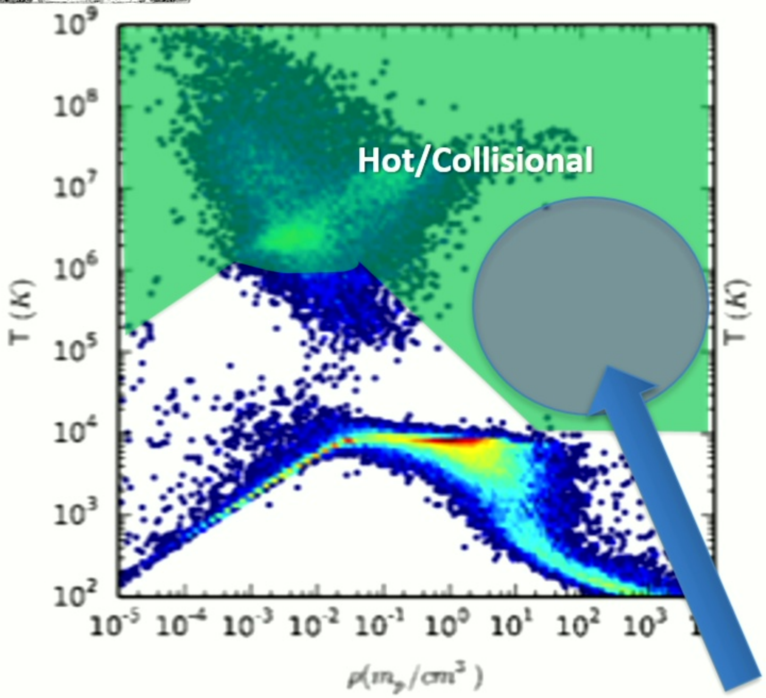
Halo, outflows, hot inflows (accretion) and remnants

(*1) Big contributors: Supernovae, Accretion (virial shock)



Temperature-Density Phase space

High Energy (SN, AGN, CR) impact



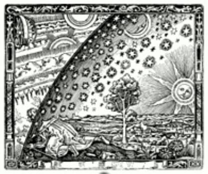
Hot/Collisional:

Halo, outflows, hot inflows (accretion) and remnants

(*1) Big contributors: Supernovae, Accretion (virial shock)

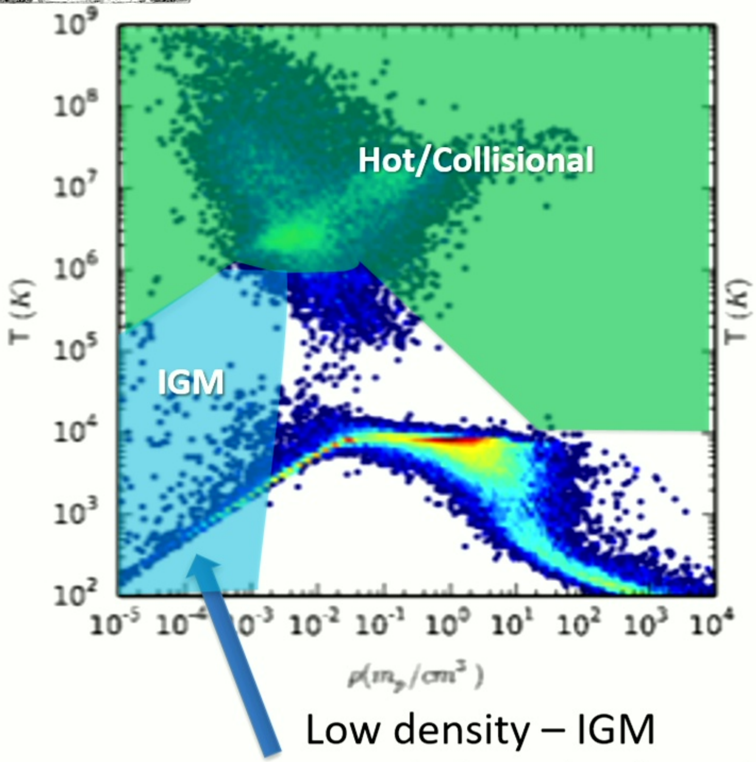
Essentially empty region > 1 H/cc

Some transients but
expected for careful high energy feedback

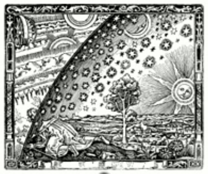


Temperature-Density Phase space

High Energy + Cosmic UV Bg.

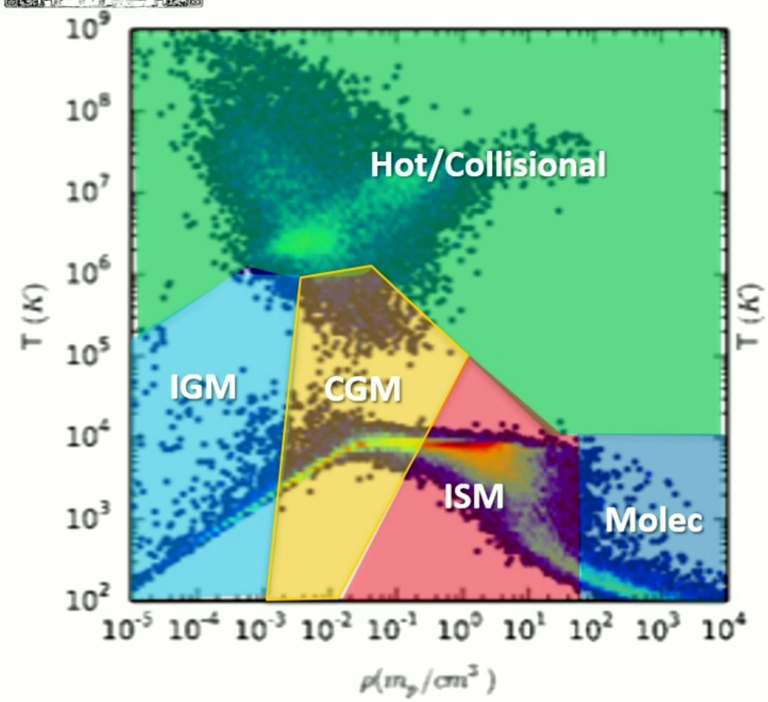


Low density – IGM
Haardt & Madau (2012) Background
Only place uniform radiation is reasonable



Temperature-Density Phase space

Radiation impacts



Hot/Collisional:
- Accretion/SN/AGN/CR

IGM
- UV/X-ray Background

CGM
- UV/X-ray Background +Galaxy

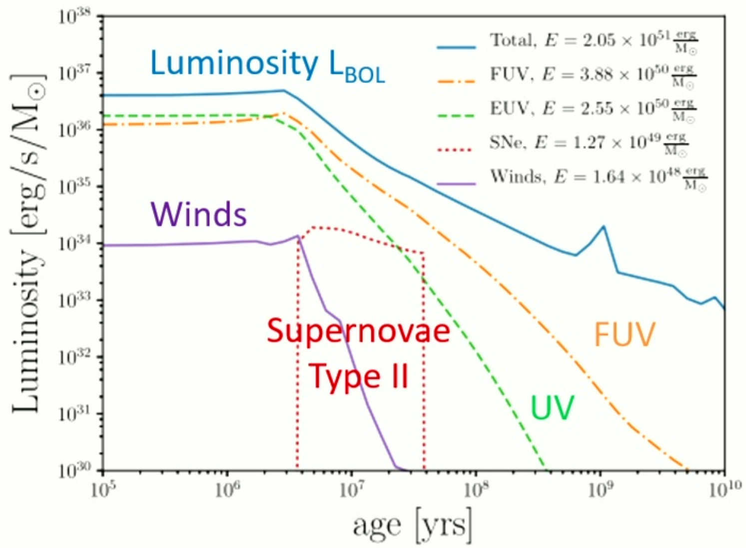
ISM
- FUV (State: EUV, X-ray)

Molecular (Shielded)
- X-ray/CR (State: EUV,LW)

(*2) Need Radiative Transfer to get a lot of observable gas right, especially ionization states

Stellar Feedback Budget

Starburst '99 Energy per Solar Mass



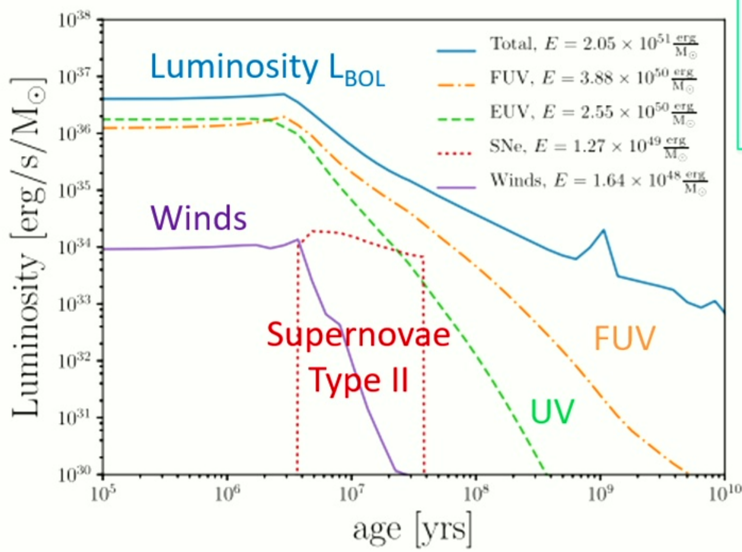
Grond + 2019

- Stellar Winds
  ~ 4 Myr
- Supernovae Type II
  ~ 4-40 Myr
- L_{BOL} → Radiation Pressure:
  While $\tau_{IR} >> 1$
- UV, Jets, etc..
  Cloud disruption
  $v_{ESC} < 10$ km/s
  small scales

Walch+ 2014, Dale+ 2012

Stellar Feedback Budget

Starburst '99 Energy per Solar Mass



Grond + 2019, Starburst '99 instantaneous

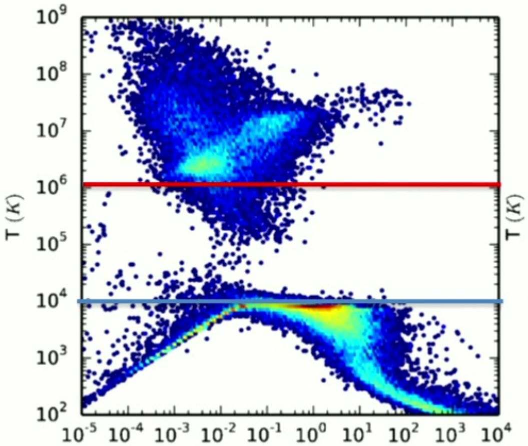
- Stellar Winds , ~ 4 Myr
- Supernovae Type II ~ 4-40 Myr

Large scale,
1.Superbubbles

- L_{BOL} → Radiation Pressure: While $\tau_{IR} >> 1$
- UV, Jets, etc.. Cloud disruption $v_{ESC} < 10$ km/s small scales

Walch+ 2014, Dale+ 2012

Large / Small Scale



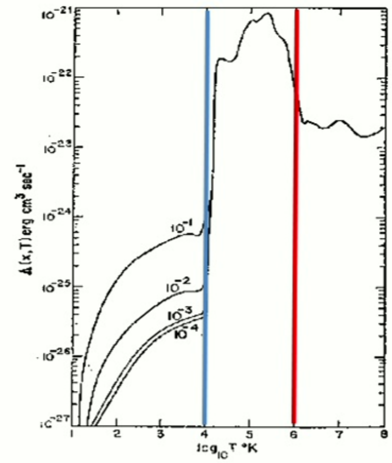
Density (atoms/cc)

Galaxy phase diagram
(Simulated Milky Way)

10^6 K

10^4 K

Cooling Curves
Dalgarno & McCray



T > 10^6 K – "Hot" accessible by Supernovae (Cosmic Rays, AGN)

Long cooling, times, c_sound > v_escape: outflow

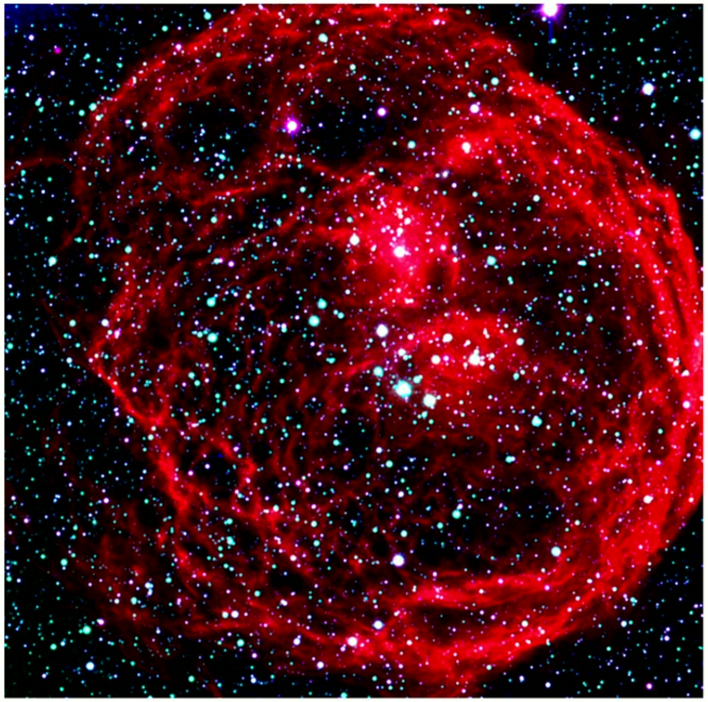
T ~ 10^4 – 10^6 K

Rapid cooling

T < 10^4 K – "Cold/Kinetic" Accessible by Jets, Radiation Pres., UV

Turbulence, Star forming gas, 2-phase instability

1. **Superbubble Feedback**: Star clusters



N70 Superbubble LMC Image: ESO
D 100 pc Age: 5 Myr v ~ 70 km/s
Driver: OB assoc. 1000+ stars

- Massive star formation highly correlated in time and space
- Typical star cluster ~ 10,000 M_{SUN} in ~10 pc age spread < 1 Myr

$\Rightarrow$ Stellar Feedback highly correlated

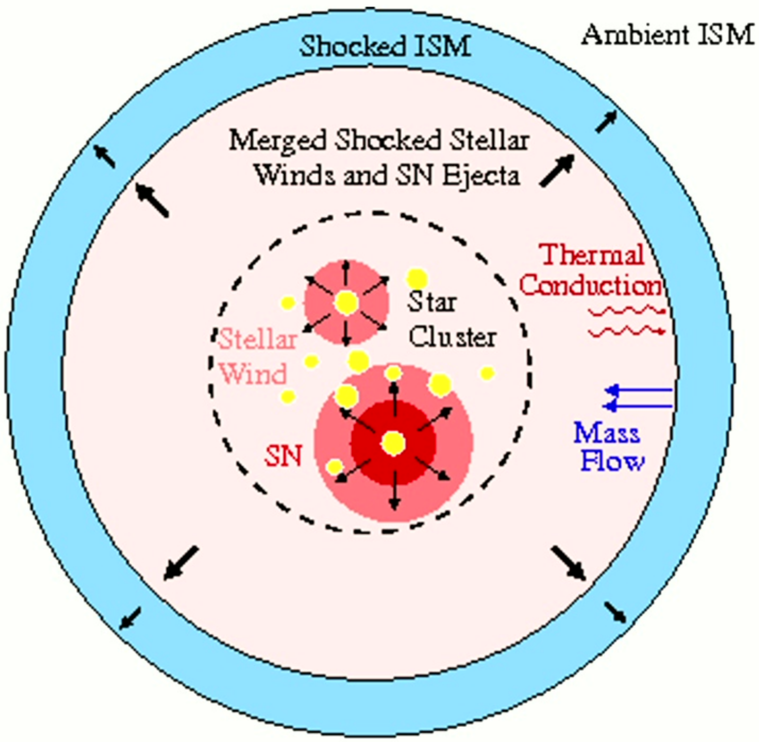
$\Rightarrow$ Natural unit of feedback is a Superbubble combining feedback of 100+ massive stars

$\Rightarrow$ How *real* galaxies make hot gas

Super bubble features

Classic model:

- Stellar winds + supernovae shock and thermalize in bubble
- Steady input Mechanical Luminosity $L=10^{34}$ erg/s/Msun
- In practice: some intermittency due to SN (see e.g. Krause+ 14)



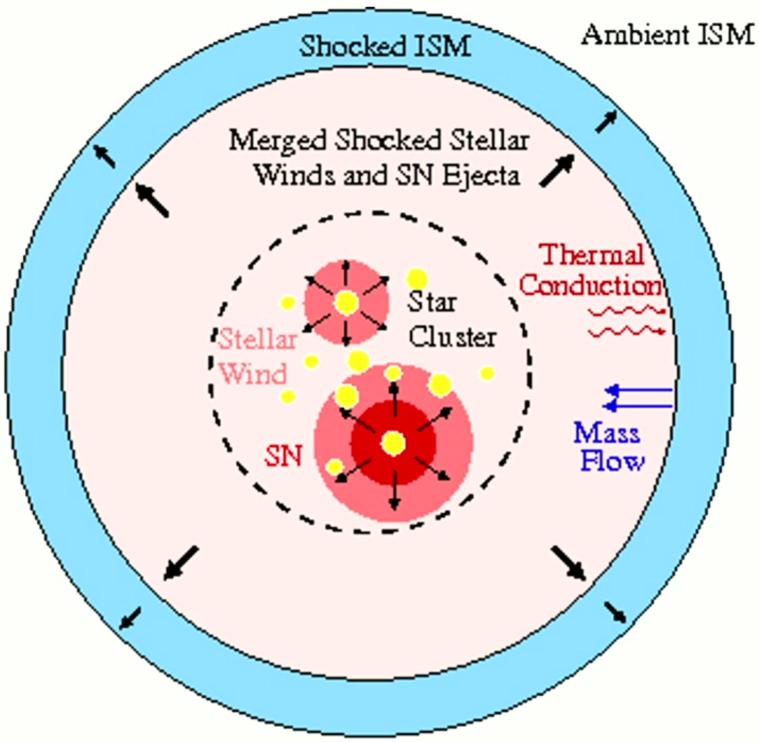
MacLow & McCray 1988, Weaver et al 1977, Silich et al 1996, Orr+ 2022

Super bubble features

Limiting factor:

Radiative Cooling of bubble determined by bubble temperature ~ Eth/Mb and density Mb/R^3

Hot bubble mass (Mb) set by **thermal conduction** rate into bubble -- self regulating (conduction ~ $T^{7/2}$)



MacLow & McCray 1988, Weaver et al 1977, Silich et al 1996

Modeling Superbubbles in Galaxies

Key required physics (not in most codes):

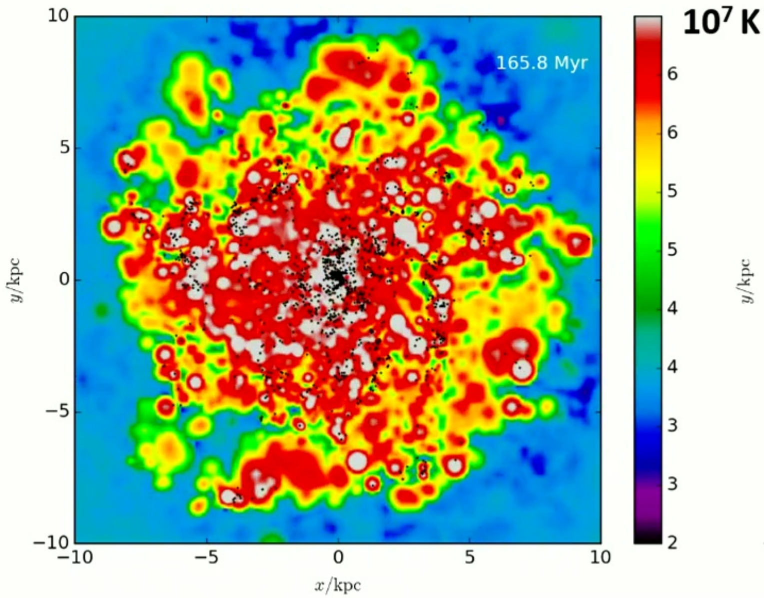
- Conduction (Spitzer 1962)
  Without conduction bubble mass, temp arbitrary
  (even at high res – incorrect limit is ejecta mass)
- Evaporation resulting from conduction – hard to resolve directly (subgrid model)
- Low resolution, early bubble stages $m_{bubble} < m_{gas\ particle}$ subgrid 2-phase model to avoid overcooling via low density hot phase

Keller, Wadsley, Benincasa & Couchman
2014 MNRAS 442 3013

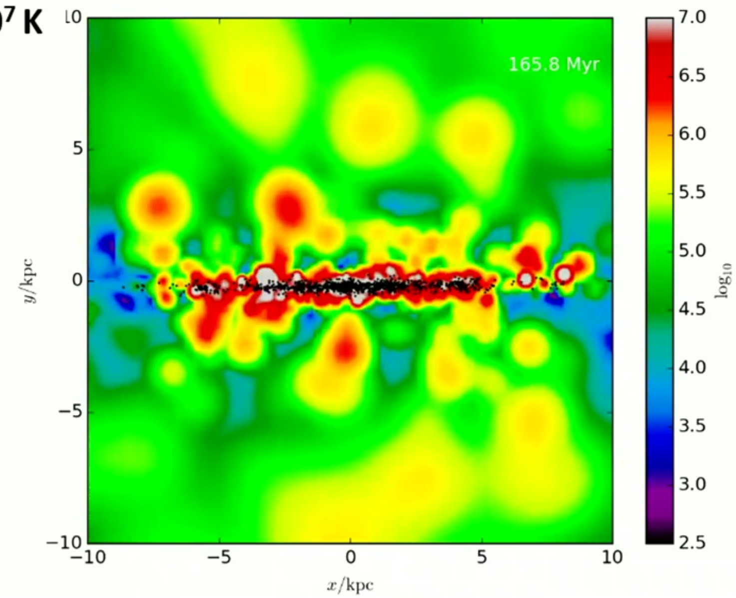
Disk Galaxy Tests

Similar to Dalla Vecchia & Schaye (2012) --

Milky Way analogue ($M_{gas} \sim 10^9\ M_{sun}$ $N_{gas} = 10^5$)

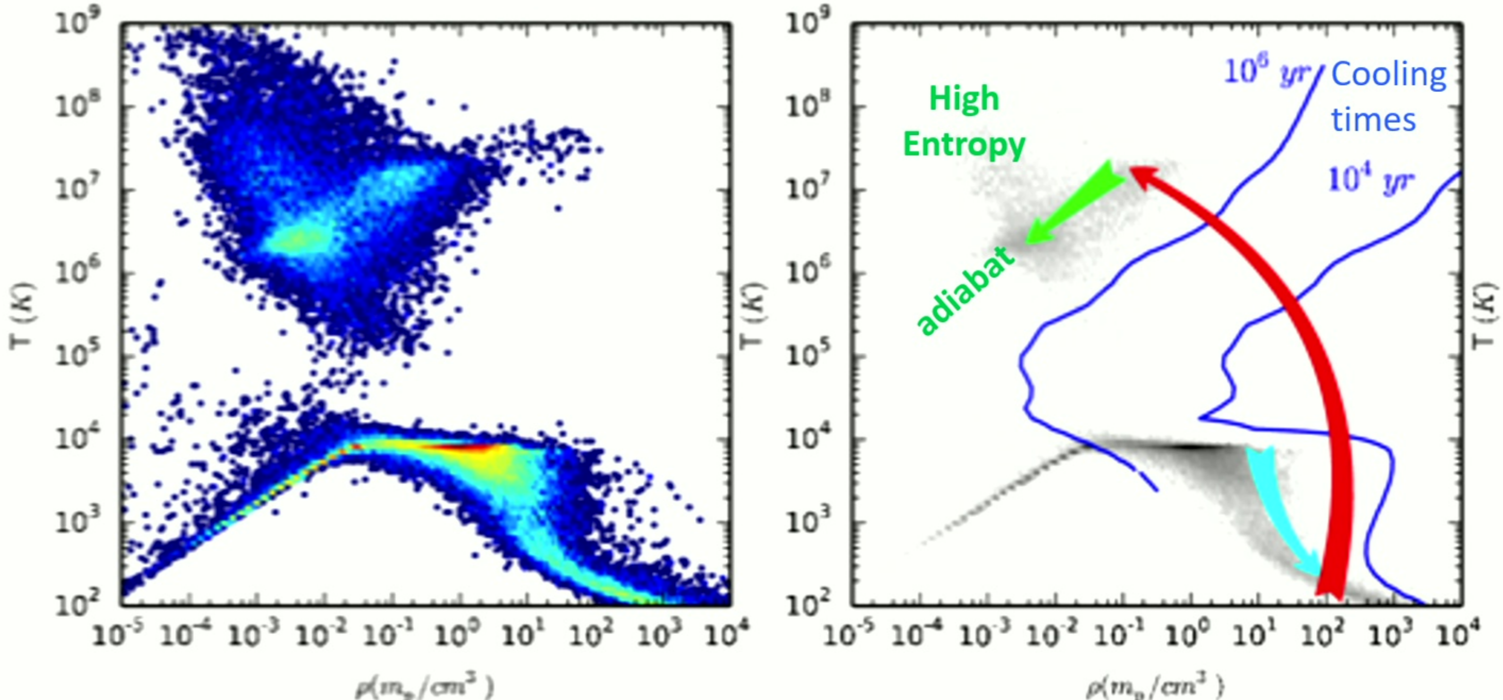


Temperature: Face on



Temperature: Edge on

Temperature-Density Phase space



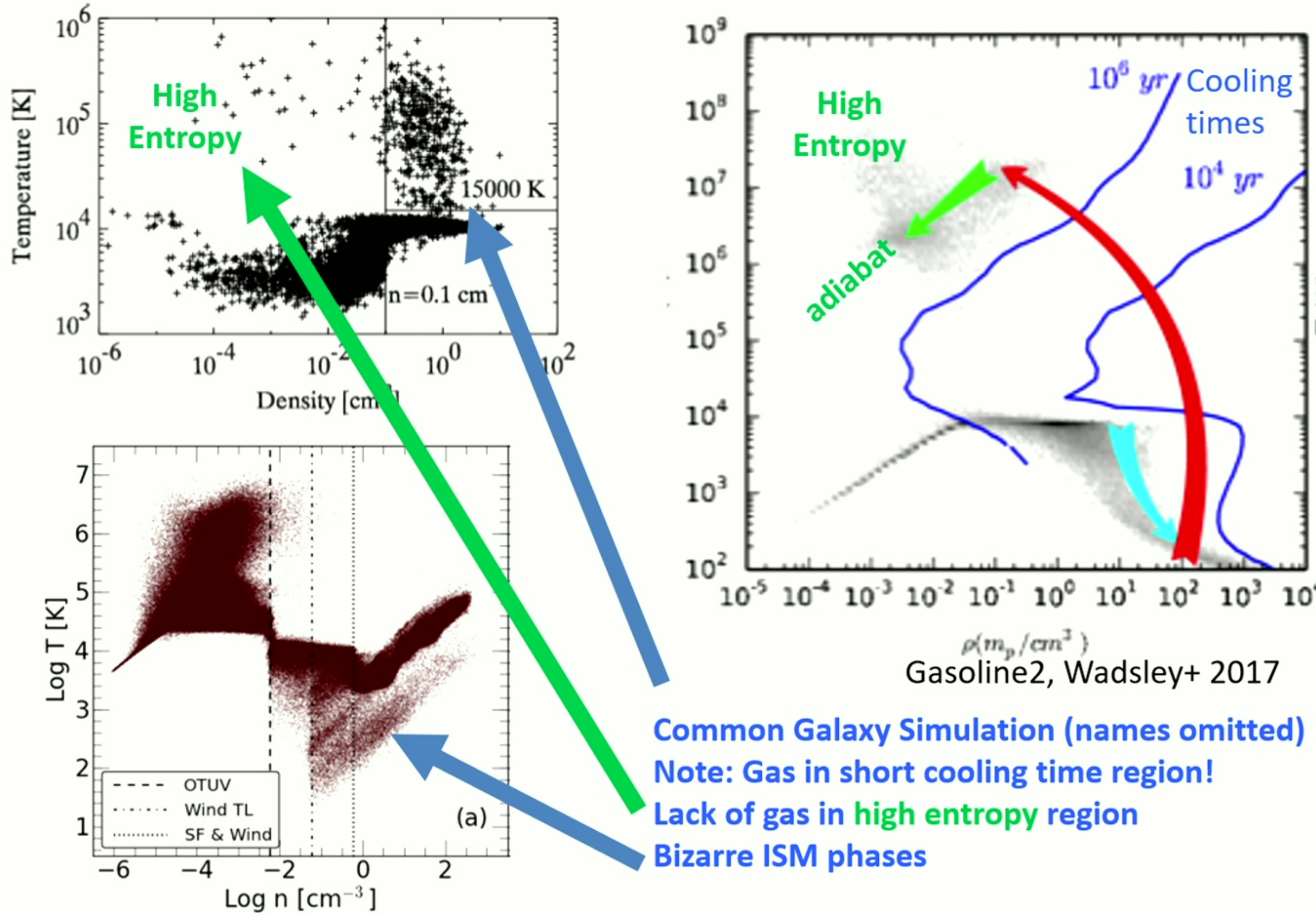
Gasoline2, Wadsley+ 2017

No gas in short cooling time region

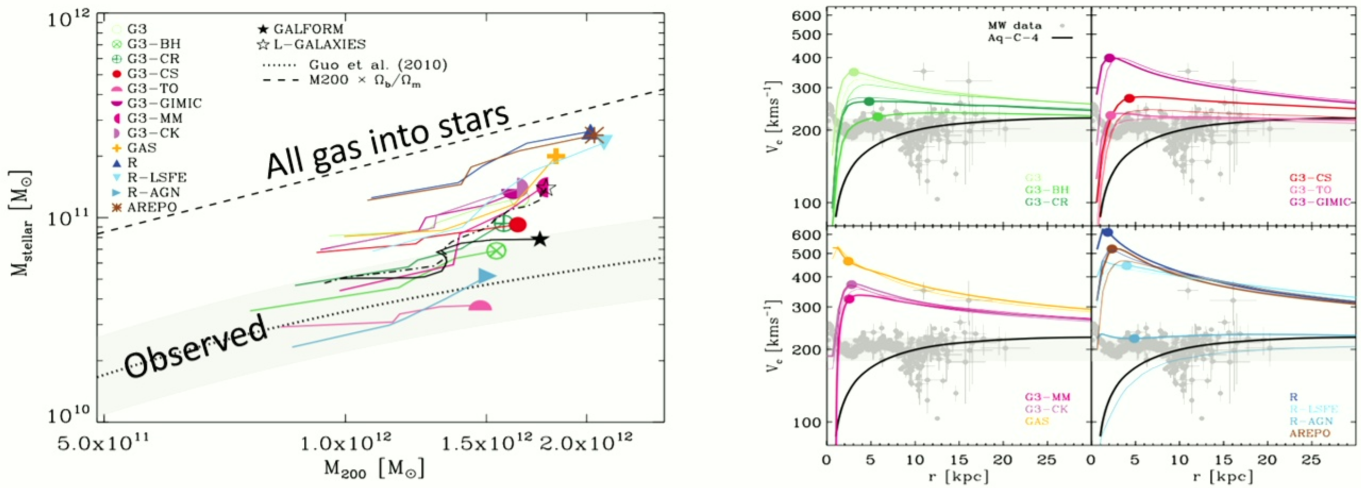
Particles split into cold dense + hot rarefied phases:
allows correct high entropies

Rapidly become hot, single phase – evolve adiabatically

Temperature-Density Phase space



What happens when simulators don't know the right answer in advance?



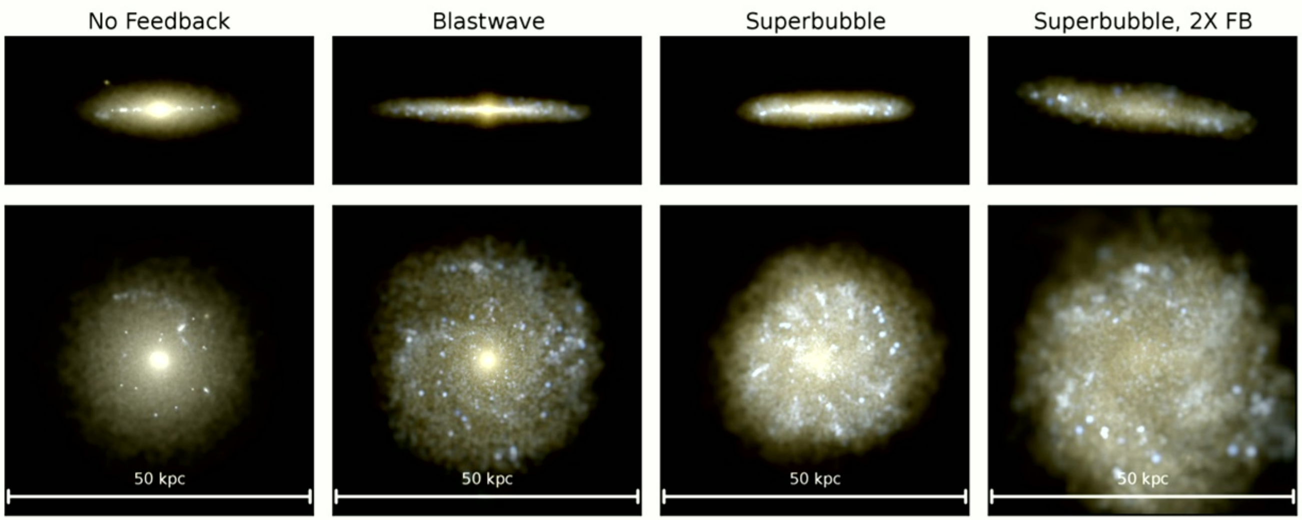
Aquila comparison (Scannapieco+ 2012)

- Compared feedback models & simulation codes on same cosmological initial conditions
- Most produced too many stars, too large bulge/disk ratios
- None had both reasonable stellar mass fraction and small bulge.

Missing feature: Baryon expulsion!

Cosmological Galaxy Simulations

- 4 test cases:
  - No Feedback
  - Blastwave (old Feedback)
  - Superbubble Feedback
    $E=10^{51}$erg/SN
  - Superbubble Feedback E x 2
- Initial Conditions
  - 8 x $10^{11}M_{sun}$ halo
  - Cosmological zoom-in
  - Last major merger at z=2.9



G1536, Keller, Wadsley+ 2014

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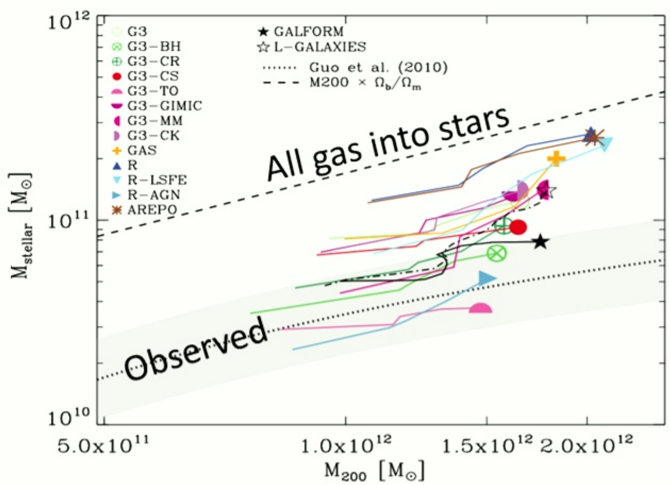

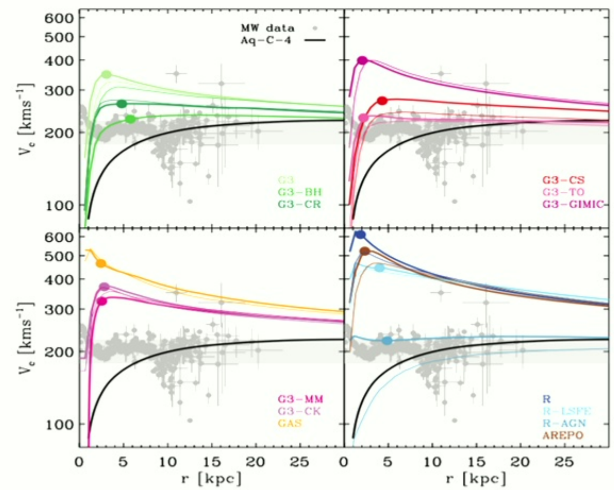

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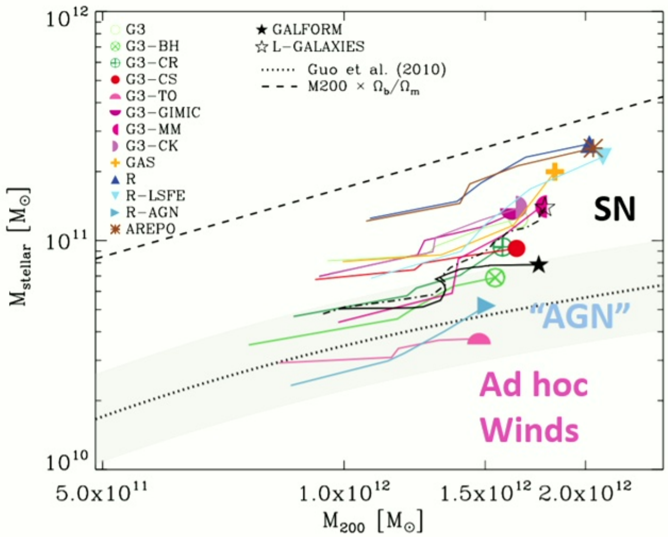
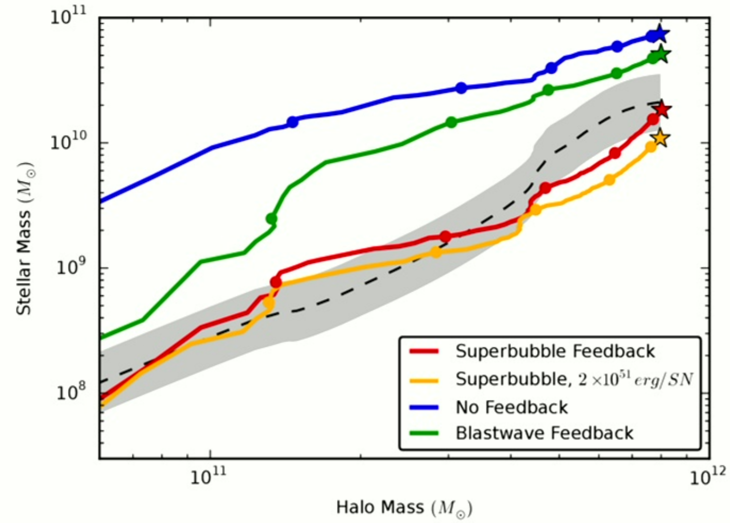
Stellar Mass Fraction





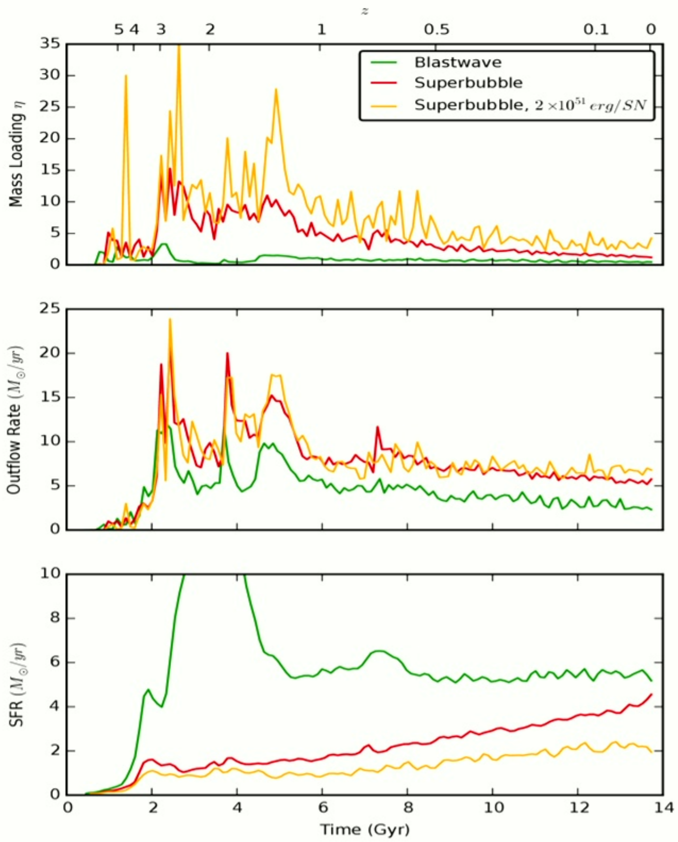
Current Big Box Galaxy Simulations Trends: Extra feedbacks, Multipliers > 100% on SN Energy

vs

Superbubble: Comfortably match low end of M_*/M_{halo} with 100% SN Energy.
→ Room to lower efficiency

Abundance Matched Stellar Mass History: Behroozi+ 2013

High Redshift Outflows Are Key

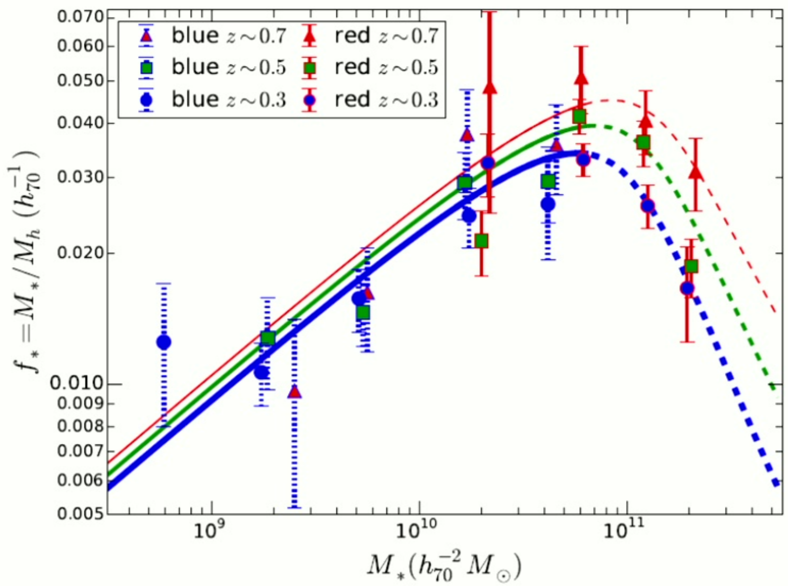


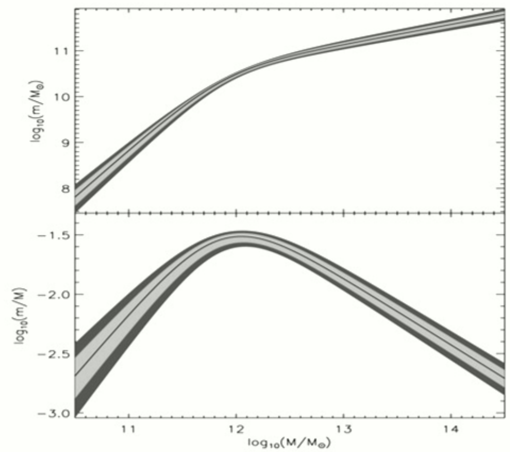
Preferentially remove low angular momentum gas from young galaxy

Some escapes, remaining hot gas has long residence time in halo

Gas available late to continue star formation at current epoch

Can Supernovae do it all?

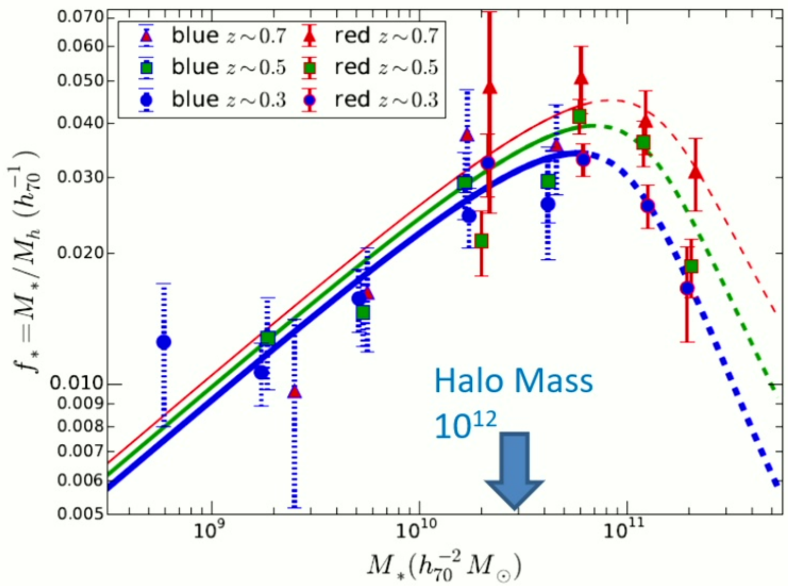




Hudson+ 2015 CFHT Lens
Direct measurement of stellar mass vs. Galaxy Halo Mass (using gravitational lenses and stacking – Direct Dark Matter observation!)

Dramatic fall-off
In stellar/total mass ratio
For larger galaxies

Can Supernovae do it all?



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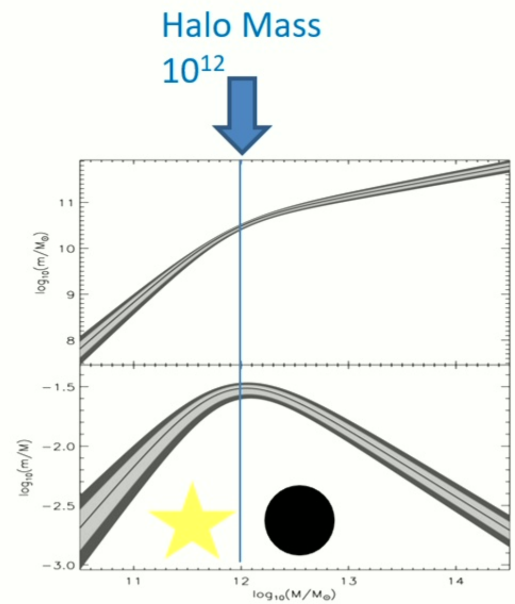
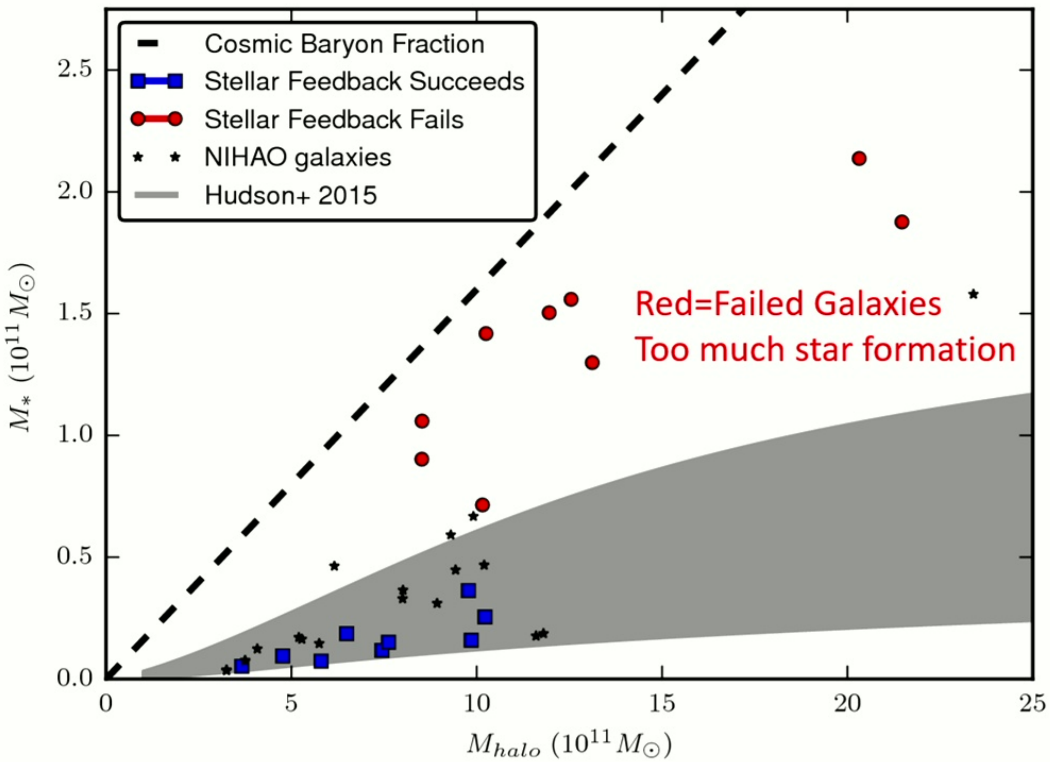


Stars vs. AGN (Black holes)?

Dramatic fall-off
In stellar/total mass ratio
For larger galaxies

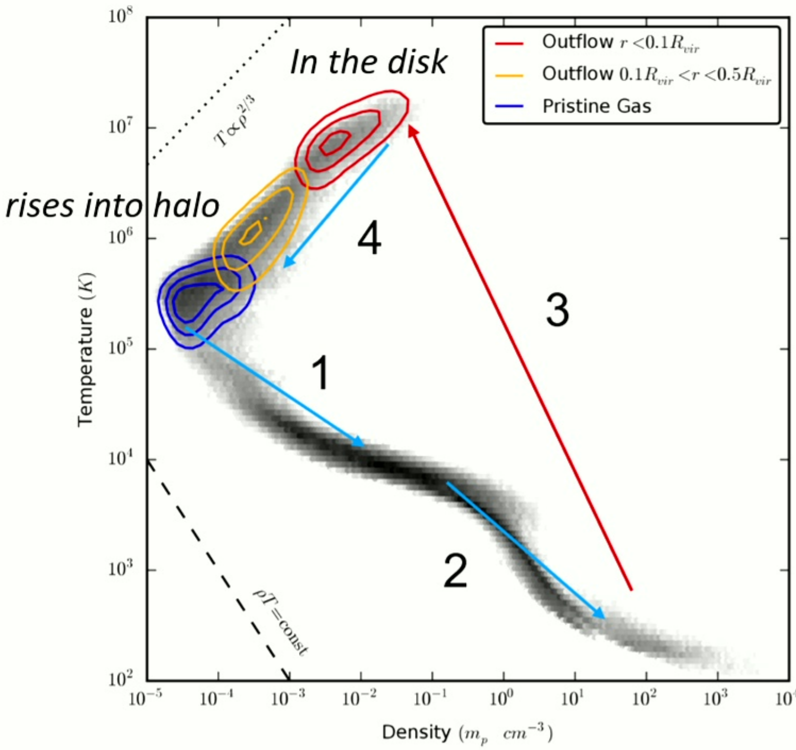
Can Supernovae do it all? No!



MUGS2 galaxies, Keller & Wadsley 2016

Other Implications from Superbubbles?

Winds from Superbubbles are qualitatively different: hot and slow

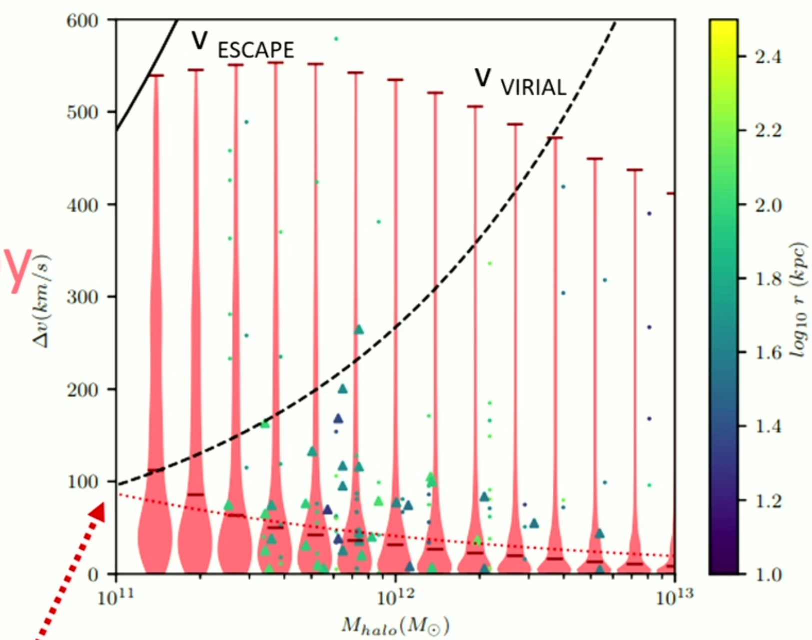


1. Virialized halo gas cools to form disk ISM
2. Disk ISM cools, forming stars
3. SNII heat gas to form superbubbles *in the disk*
4. **High entropy** Superbubbles rise buoyantly out of disk, cooling adiabatically & mixing with pristine gas

Winds from Superbubbles

Keller, Kruijssen & Wadsley 2020

- Comparison to COS halos (CGM OVI absorption systems)
- Predictions for entropy driven winds
- Data points from Tumlinson+ 2013 (points) and Werk+ 2016 (triangles)



Fit to Werk+ 2016 subset

2. Radiation: Bands/Sources

Radiation Bands

FUV
~ 6 eV-13.6 eV Photoelectric heating
Opacity: Dust ~ 300 cm^2/g (Z/Z_{solar})
11.2 eV- Lyman-Werner Dissociate H_2
Extra Opacity: H_2
Complicated: see Gnedin & Draine 2014

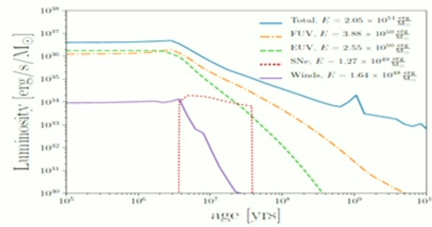
EUV/X-Ray
13.6 eV Ionize HI
Opacity: HI ~ 5,000,000 cm^2/g (HI/H)

15.2 eV Ionize H_2
24.6 eV Ionize He

> 6 eV Ionize Metals, e.g. 11.2 eV Carbon
In principle detailed spectrum needed!

Radiation Sources

Stars: LW, FUV, EUV, X-ray
Young Stars (e.g. Starburst 99)



Evolved Binaries: X-ray

Coronal Gas: Recombinations = scattering,
X-ray emission
Note: All gas is a source!

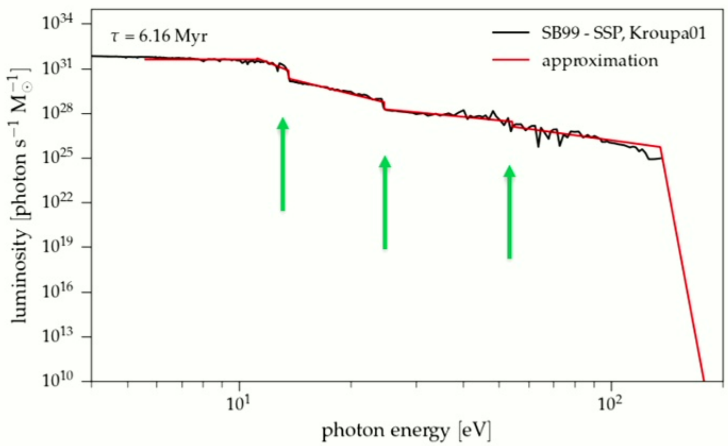
Backgrounds (distant stars, AGN)
e.g. Haardt & Madau (2012)

AGN: All

10 Narrow Band Approximation

10 Narrow Bands ~ 0.1 eV
(opacity constant in band)

0 FUV:	8.4 eV
1 LWL:	11.2 eV
2 LWH:	13.6 eV -
3 HIL:	13.6 eV +
4 HIH:	24.6 eV-
5 HeIL:	24.6 eV+
6 HeIH:	54.4 eV-
7 HeIIL:	54.4 eV+
8 HeIIH:	136eV
9 136_500H:	500 eV



Piece-wise power-law approximation for full spectrum.

Note: jumps at 3 ionization edges ↑

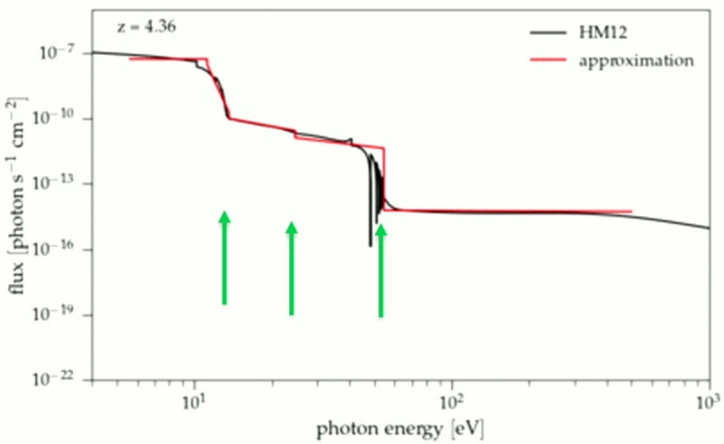
Spectrum discontinuous with different values left/right of ionization edges

Narrow bands allow precise opacities

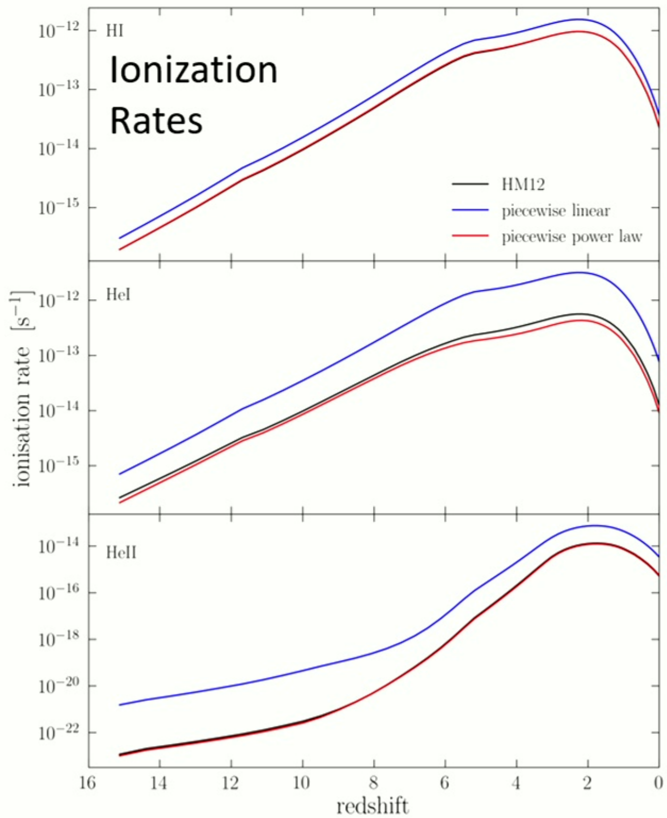
Baumschlager, Shen & Wadsley (2024)

10 Narrow Band Approximation

Cosmic Background (z)



Fit to Haard & Madau (2012) for background radiation (small errors entire range)
Note 1: Large jumps at ionization edges ↑
Note 2: slopes vary a lot with redshift
c.f. Piecewise constant/linear poor fit
errors ~ 2 dex



Baumschlager, Shen & Wadsley (2024)

Radiative Transfer: **TREVR 2 Algorithm**

Target: Fast Ray Trace for Cosmology Simulations/ Galaxy Formation

Typical Galaxy Simulation approach:
Spatially uniform Ionization rates, $\Gamma(t)$

Goal: For similar cost to hydro+gravity:
Approximate Local $\Gamma(x,y,z,t)$

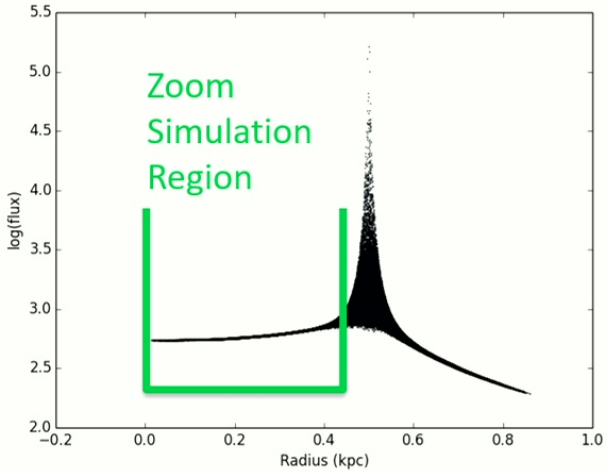
Reverse Ray Trace: Tree approach $O(N_{ACTIVE} \log_2 N)$
Only trace radiation to elements that need it (cf. Tree Gravity)
No speed of light timestep
Con: Cannot do explicit photon counting
Trevr2 code: Wadsley, Baumschlager & Shen (2024)

see also URCHIN (Altay & Theuns 2013), C^2-ray (Mellema+ 2006), Kannan+ 2014, Lahén+ 2020, TreeRay (Wünsch+ 2021), **TREVR1 (Grond+ 2019)**

Cosmic (e.g. UV) Backgrounds

Instead of periodic replicas of box sources, use background flux at fixed distance (cf. Altay & Theuns 2013)

Zoom-in simulations: simpler, surround active region with shell of fixed surface flux (e.g. particle sources)



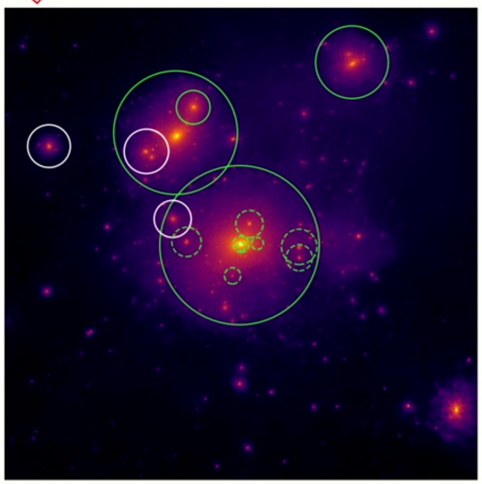
Shell approximation:
Uniform radiation field in inner shell
Field cuspy at shell radius (no gas there for zoom runs)

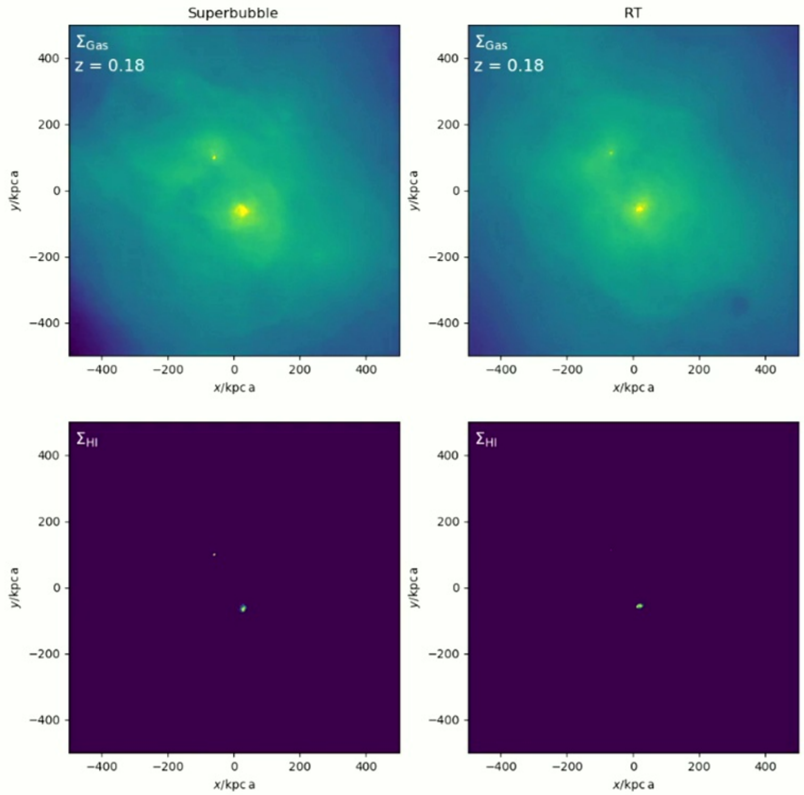
TREVR1: Grond, Woods, Wadsley & Couchman (2019)

TREVR2 Application

PRELIMINARY

CGM around zoom galaxies with UV





"7 Dwarfs" simulations (Shen+ 2014)

Mass resolution ~ $3x10^3$ M_{sun}

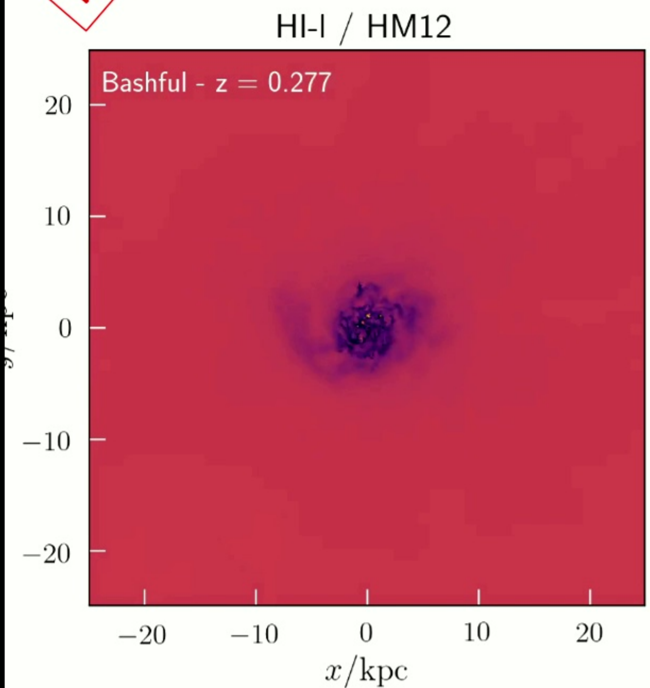
Update: Metal cooling, superbubble (Mina+ 2021) ....

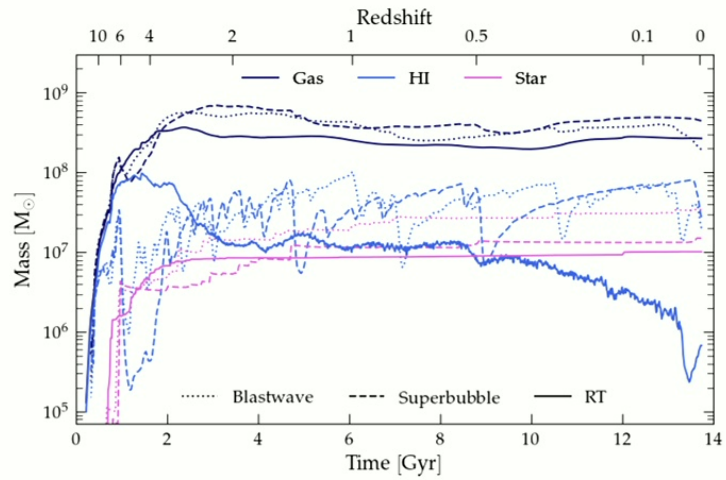
Now: radiative transfer, including background and stellar (Baumschlager, Shen & Wadsley, in prep)

TREVR2 Application

PRELIMINARY

CGM around zoom galaxies with UV





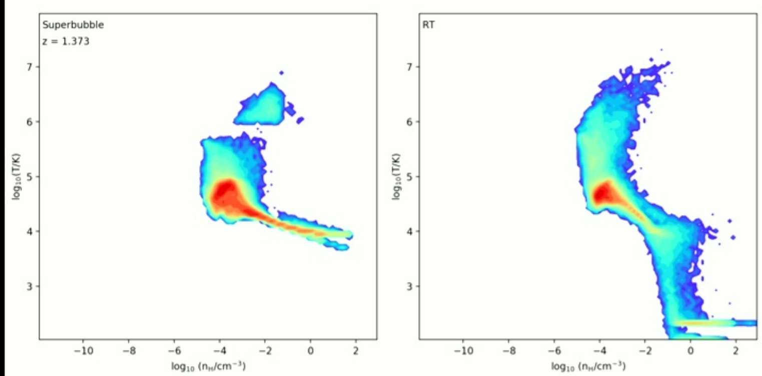
Star formation history much smoother with RT, radiative feedback regulates SF without bursty outflows

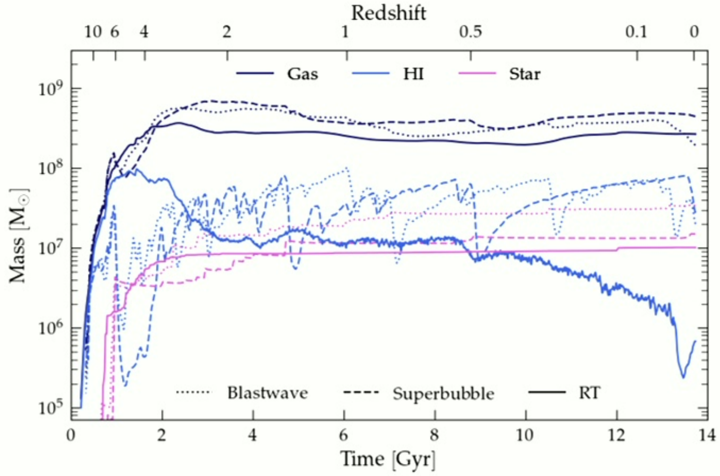
Radiative flux ratio vs. background at 13.6 eV. Note bursty – high escape events Bashful (most massive dwarf)
(Baumschlager, Shen & Wadsley, in prep)

TREVR2 Application

CGM around zoom galaxies with UV

PRELIMINARY



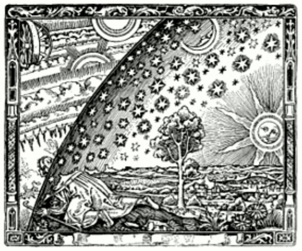


Phase diagram.
Superbubble only cools and has burstly of SF (left)
Superbubble + RT stable, steady SF
Bashful (most massive dwarf)
(Baumschlager, Shen & Wadsley, in prep)

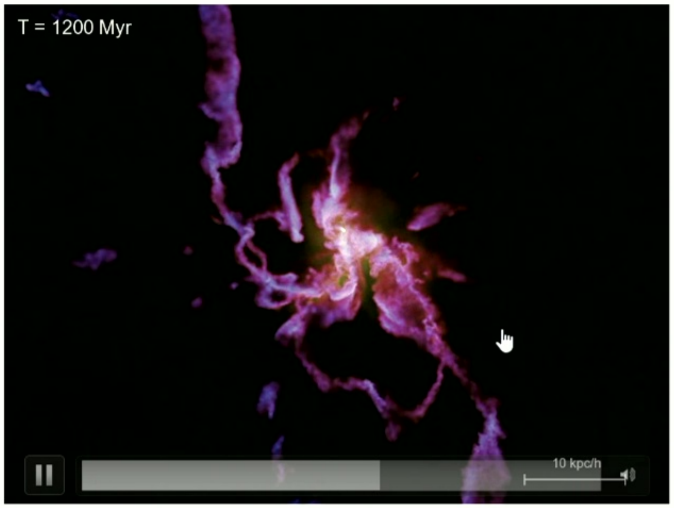
Star formation history much smoother with RT, radiative feedback regulates SF without bursty outflows

2. Summary:
Radiative Transfer for galaxies

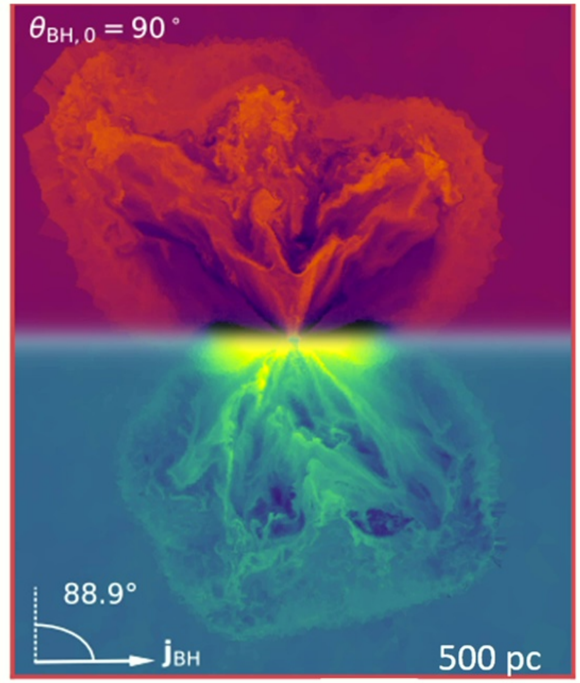
- TREVR2 $O(N_{ACTIVE} \log_2 N)$ reverse ray tracing. Important due to gas & stars both sources
  - Wadsley, Baumschlager & Shen
- ISM/CGM states need a detailed spectrum: Piecewise power-laws: a new approach, resolves opacity, hardening, source combination issues.
  - Baumschlager, Shen & Wadsley
- **Goal – develop single-set of physically motivated models that work for both cosmological & ISM (isolated) galaxies… in progress**



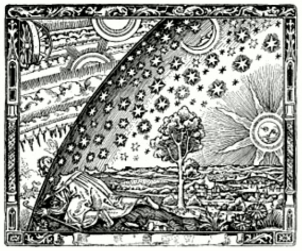
Galaxy Simulations:
Finite resolution vs. All-the-details → AGN



di Matteo+ 2005
AGN Feedback calibrated to quench galaxies by ejecting gas
Best resolution ~ 0.1-0.2 kpc
Entire Talbot+ 2022 accretion torus comparable to one resolution element



Talbot, Sijacki & Bourne 2022
Even sideways jet does not destroy disk
Resolution 250 M_{SUN}



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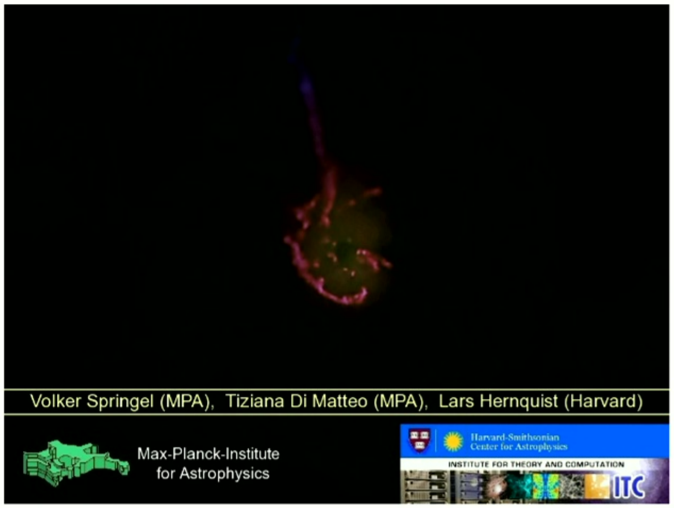

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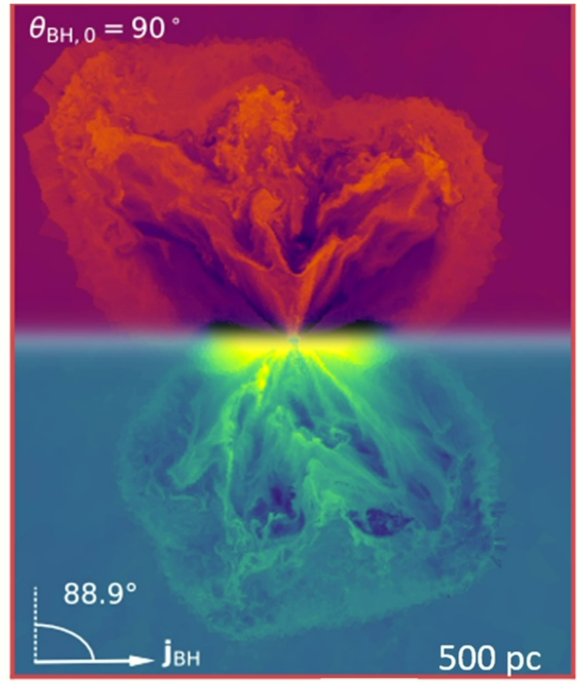

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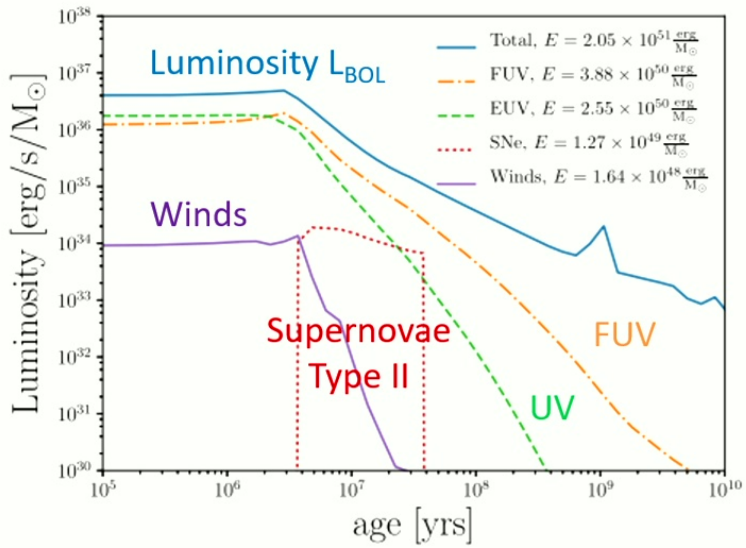
Stellar Feedback Budget

Starburst ‘99 Energy per Solar Mass



Grond + 2019

- Stellar Winds
  ~ 4 Myr
- Supernovae Type II
  ~ 4-40 Myr
- L_{BOL} → Radiation Pressure:
  While τ_{IR} >> 1
- UV, Jets, etc..
  Cloud disruption
  v_{ESC} < 10 km/s
  small scales

Walch+ 2014, Dale+ 2012