Star formation in the ISM is surprisingly inefficient

THE GAS CONSUMPTION TIMESCALE OF STAR FORMATION

depletion time:

$$t_{\mathrm{dep}} \equiv M_{\mathrm{gas}}/\dot{M}_*$$

gravitational free-fall time:

$$t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G\rho}}$$

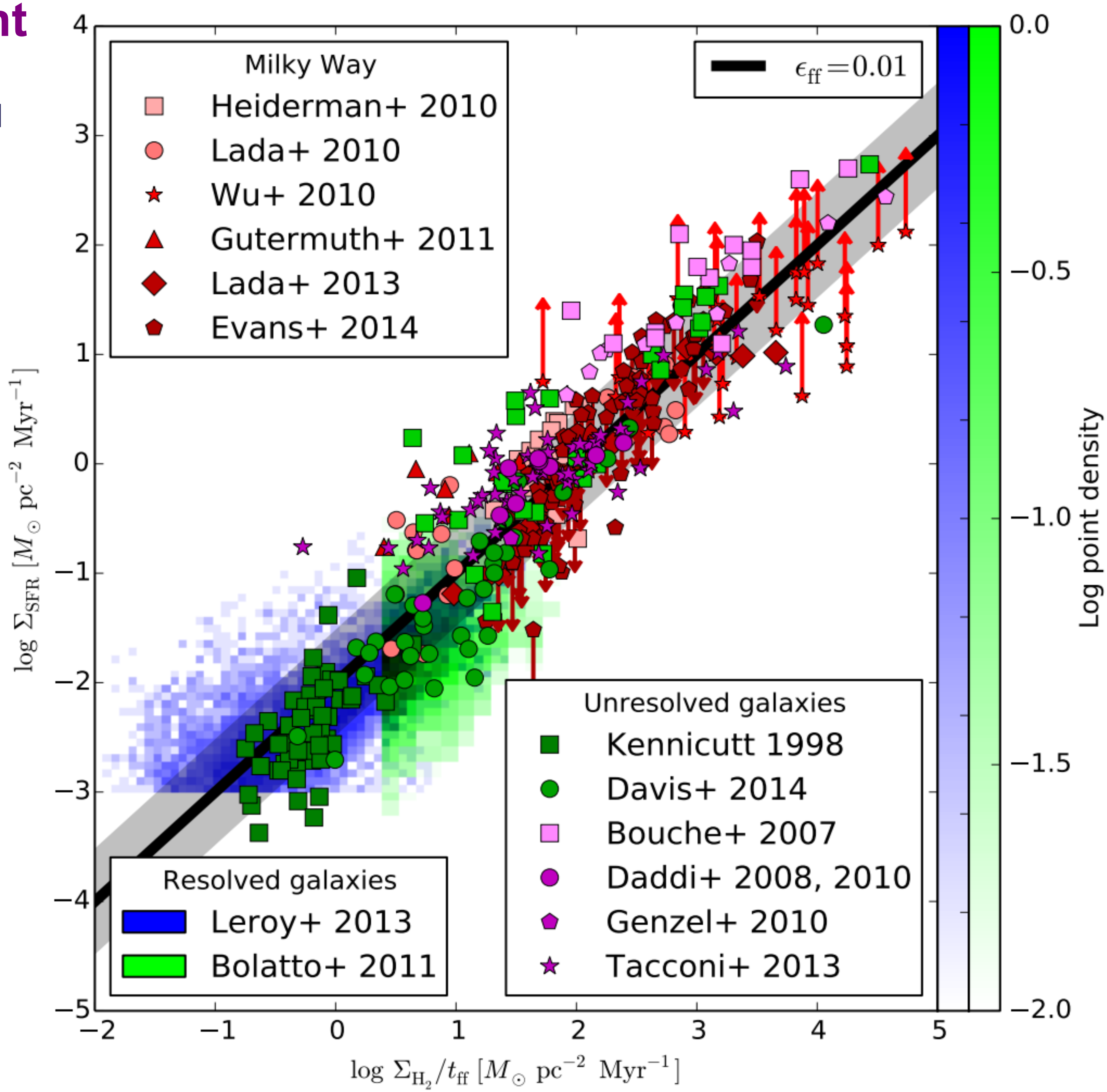
dimensionless "efficiency" of star formation:

$$\epsilon_{\mathrm{ff}} \equiv \frac{t_{\mathrm{ff}}}{t_{\mathrm{dep}}}$$

observed is:

$$\dot{\Sigma}_\star \simeq \epsilon_{\mathrm{ff}} \frac{\Sigma_{\mathrm{H_2}}}{t_{\mathrm{ff}}}$$

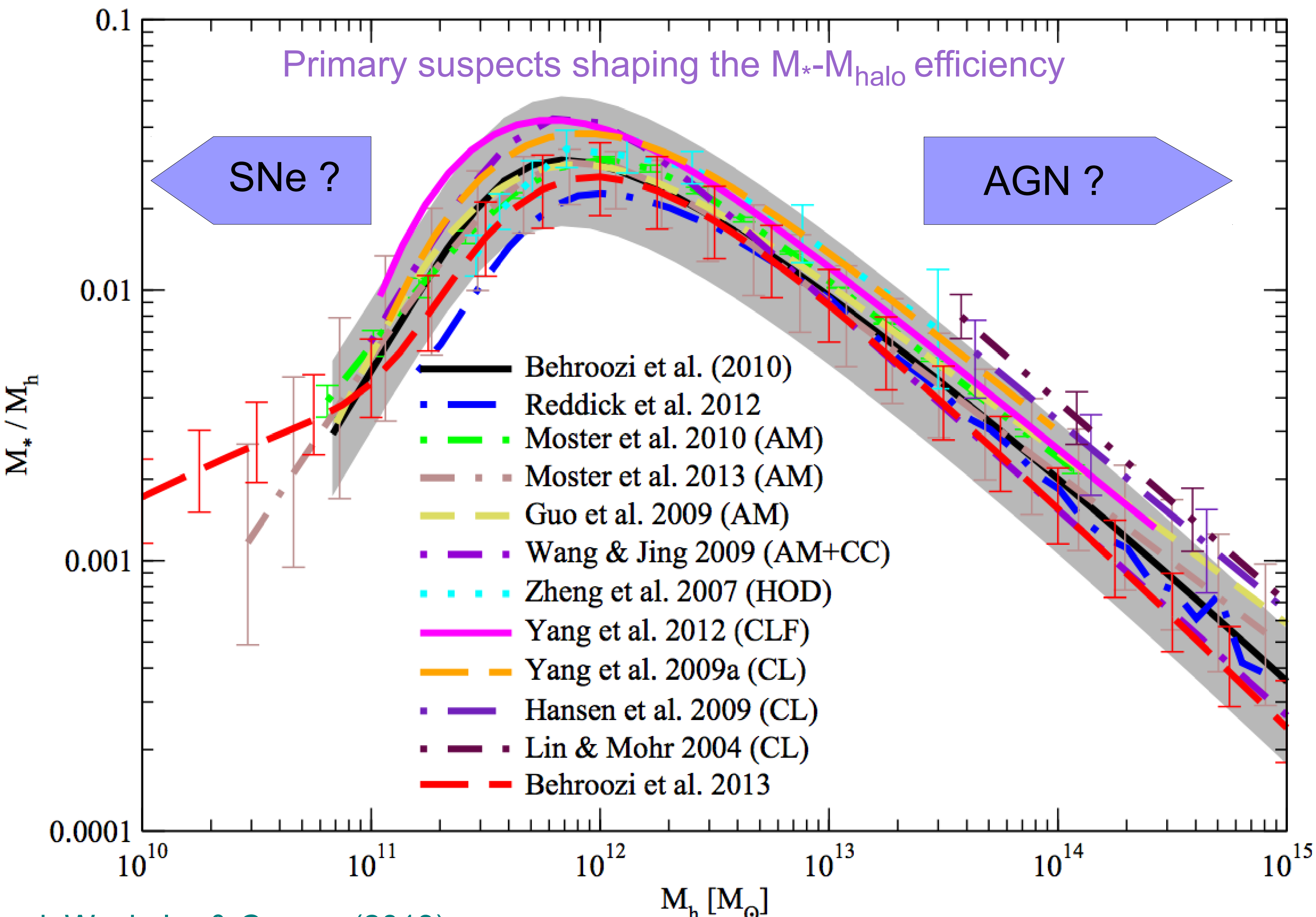
$$\epsilon_{\mathrm{ff}} \sim 0.01$$



Krumholz et al. (2014)

Abundance matching gives the expected halo mass – stellar mass relation in ΛCDM

MODULATION OF GLOBAL STAR FORMATION EFFICIENCY AS A FUNCTION OF HALO MASS



Behroozi, Wechsler & Conroy (2013)

Small scale star formation theories aim to explain why

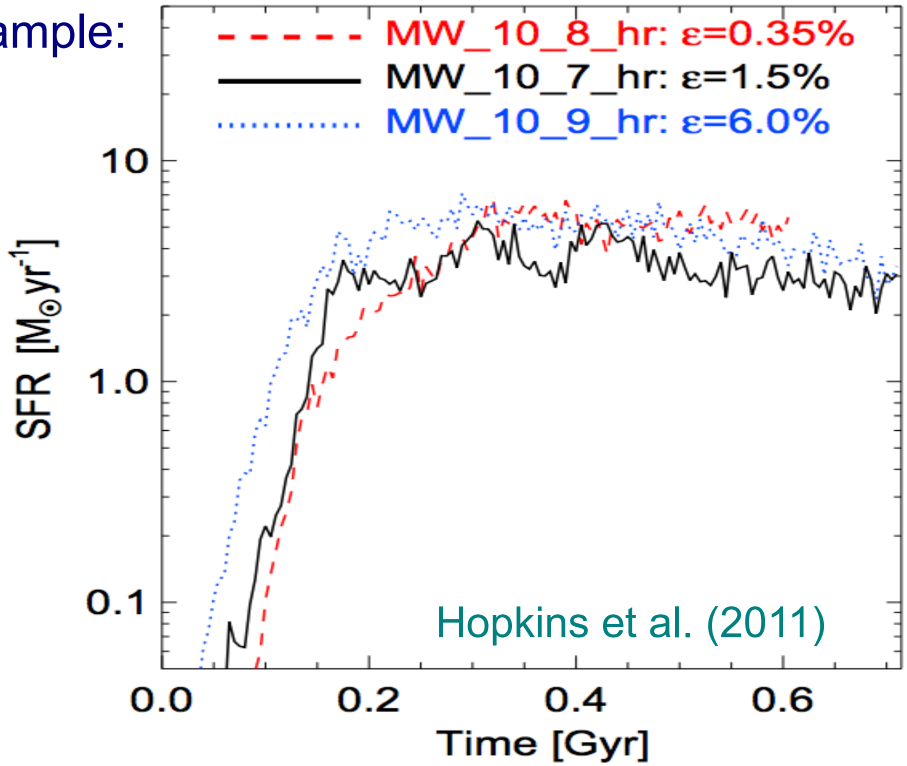
$$\epsilon_{ff} \sim 0.01$$

Galaxy formation theories need to (additionally) explain why

$$\frac{M_\star}{M_{\rm halo}} \ll \frac{\Omega_b}{\Omega_{\rm tot}}$$

This disconnect is often exploited by galaxy formation studies – they can yield the same result for widely different assumptions about ε_{ff} on the scale of molecular clouds.

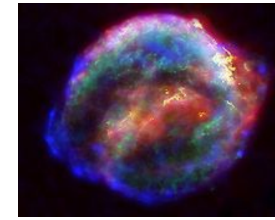
Example:



Roadblock I: Star formation theories do not explain why galaxy stellar masses are much smaller than integrated cosmological gas accretion rates.

But what physics is responsible for feedback in the first place?

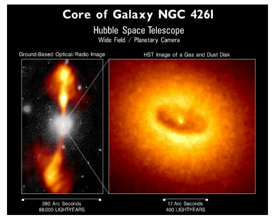
- Supernova explosions (energy & momentum input)



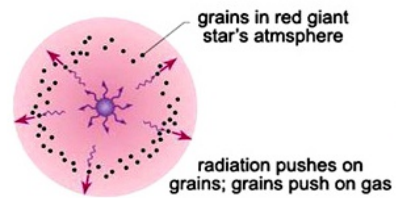
Kepler's Supernova

Bubble Nebula

- Stellar winds

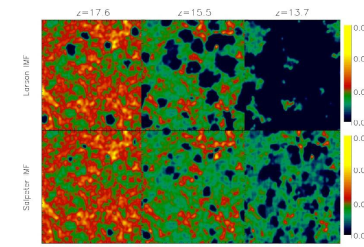


- AGN activity



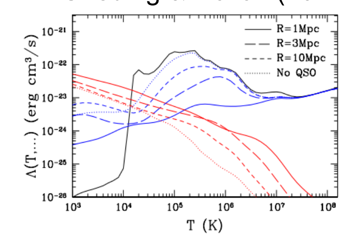
- Radiation pressure on dust

Ciardi al. (2003)



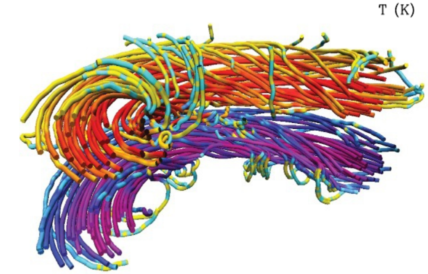
- Photoionizing UV background and Reionization

Gneding & Hollon (2012)

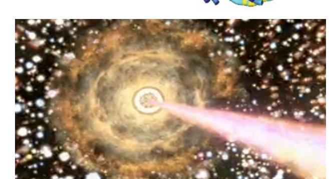


- Modification of cooling through local UV/X-ray flux
- Photoelectric heating

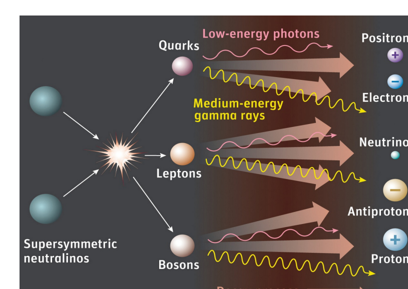
- Cosmic ray pressure



- Magnetic pressure and MHD turbulence



- TeV-blazar heating of low density gas

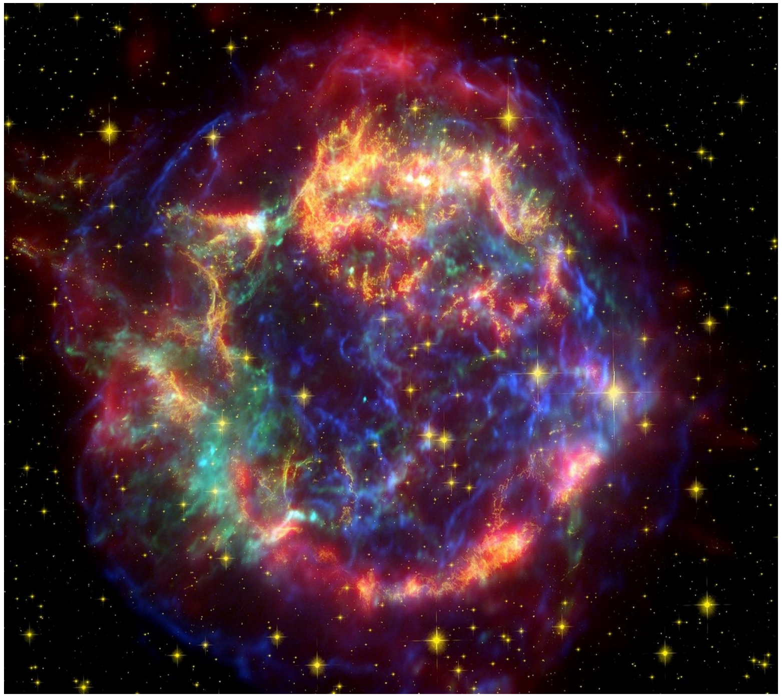


- Exotic physics (decaying dark matter particles, etc.)

Roadblock II: The precise momentum input of supernova is not accurately understood

SOME UNCERTAINTIES

Supernova remnant Cassiopeia A



- If supernovae go through a successful Sedov-Taylor phase, their momentum may be boosted by factors 5-10 or more.

- Radiative cooling losses in a supernova are uncertain – perhaps only 10% of the energy may be efficiently thermalized and drive an energy-driven wind (Thornton et al. 1998)

- The radiation may be trapped by dust, such that through multi-scatterings the radiation pressure may be boosted significantly.

$$\dot{p}_{\rm rad} \sim \tau_{\rm IR} L/c$$

$$\tau_{\rm IR} = 10 - 100\ ?$$

- Lack of stability of feedback driven shells may limit the amount of momentum input (Krumholz & Thompson 2013)

Radiation pressure on dusty shells has been suggested as a means to efficiently expell gas from star forming regions and galaxies

PHOTONS AS LARGE-SCALE GAS MOVERS

Murray, Quataert & Thompson (2005)
Murray, Menard & Thompson (2011)

$$\frac{d}{dt}(M_{\rm sh} v) = -\frac{G M M_{\rm sh}}{r^2} + \left(1 + \tau_{\rm IR} - e^{-\tau_{\rm UV}}\right)\frac{L}{c}$$

The Eddington luminosity is defined as the L for which the radiation pressure just balances gravity.

Optically thick case to UV and IR:

$$L_{\rm Edd} = \frac{G\, c\, M(r) M_{\rm sh}(r)}{r^2}$$

(Note: dynamics of a fixed mass shell radially unstable.)

Isothermal sphere halo model:

$$M(<r) = \frac{2\sigma^2 r}{G} \qquad M_{\rm sh} = f_g\, M$$

$$L_{\rm Edd} = \frac{4 f_g c}{G}\sigma^4$$

Faber-Jackson relation ?

Optically thin case:

$$1 - \mathrm{e}^{-\tau} \simeq \tau = \kappa\rho\Delta l = \kappa\frac{M_{\rm sh}}{4\pi r^2}$$

$$L_{\rm Edd} = \frac{4\pi c\, G M}{\kappa}$$

(Note: For a thin shell of constant mass, the acceleration becomes independent of its mass.)

If there are optically thin conditions around the BH for electron scattering and it shines with Eddington ratio Γ :

$$L_{\rm BH} = \frac{4\pi c\, G M_{\rm BH}}{\Gamma \kappa_{\rm el}}$$

Identifying this with the optically thick Eddington luminosity above gives:

$$M_{\rm BH} = \frac{f_g \Gamma c}{\pi G^2 \kappa_{\rm el}}\sigma^4$$

M-σ relation ?

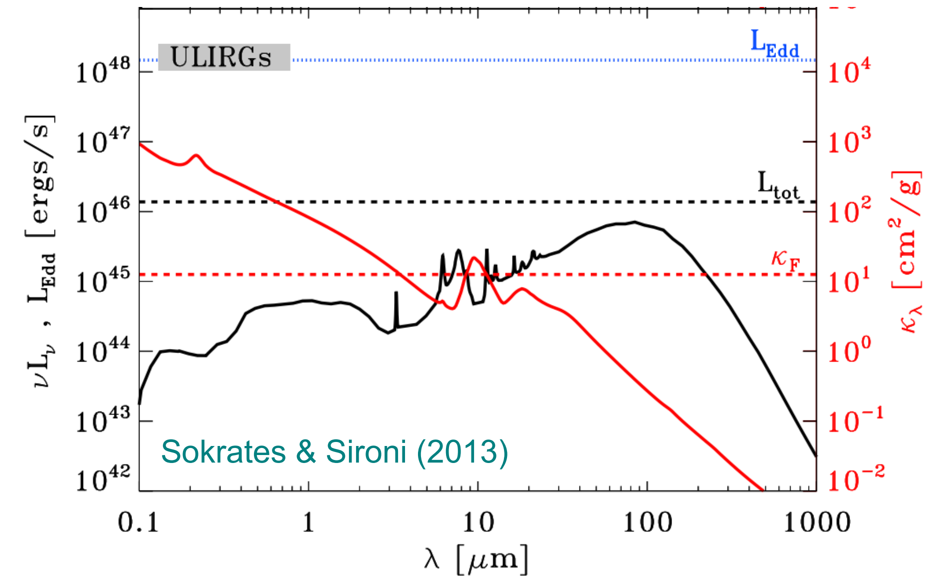
There are multiple caveates to the simple radiation pressure idea

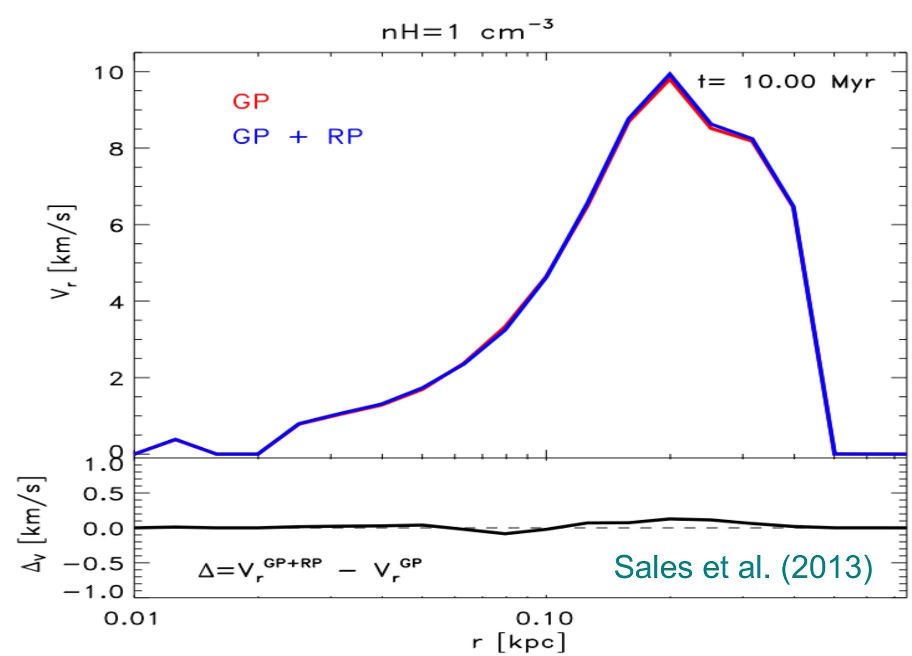
OBSTACLES FOR EFFICIENT RADIATION PRESSURE FEEDBACK

- galaxies radiate well below their Eddington rate (Sokrates & Sironi 2013)
- timescale for RP effects quite long – thermal pressure from photoionization acts earlier (Sales et al. 2013)
- radial instability of shells allows radiation to escape (Krumholz & Thompson, 2012)
- analytic models neglect swept up CGM gas – this can easily stop the shell
- In RHD simulations of star formation regulation, RP does not reach the required p_*/m_*, falling short by more than a factor of 10 (Skinner & Ostriker 2015, Rosdahl, Schaye, Teyssie, & Agertz 2015)
- Observationally, thermal pressure from photoionization greatly dominates over radiation pressure in HII regions (Lopez, Krumholz, et al. 2014)

$$L_{\rm Edd} = \frac{4\pi\, G\, M_{\rm enc}\, c}{\kappa_F} \qquad \kappa_F \equiv \frac{\int d\nu\, \kappa_\nu\, L_\nu}{\int d\nu\, L_\nu}$$

$$\kappa_{\rm UV} \neq \kappa_F$$





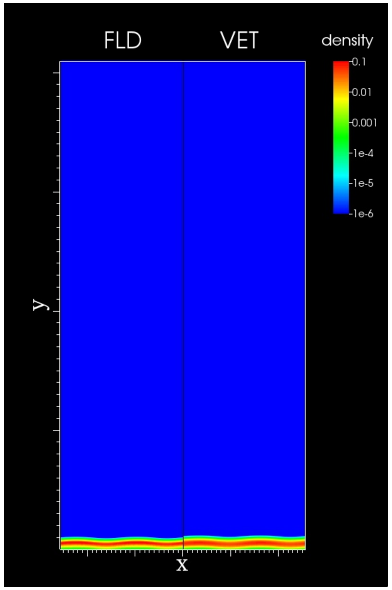
Roadblock III:
We really need to do radiation-magnetohydrodynamics.

Aside from computational cost, there are lingering accuracy issues in different RHD approximations.

Example: Calculations done with two different radiation-hydrodynamic schemes for impacting a well-coupled gas-dust atmosphere

flux-limited diffusion (FLD): Using this, Krumholz & Thompson (2012) found radiation pressure to be ineffective in driving an outflow due to the onset of Rayleigh-Taylor instabilities that let the radiation eventually escape.

variable Eddington tensor (VET): Based on this, Davis et al. (2014) find a qualitatively different outcome. While RT instabilities do develop, continuous net acceleration of gas nevertheless develops and leads to blow out.

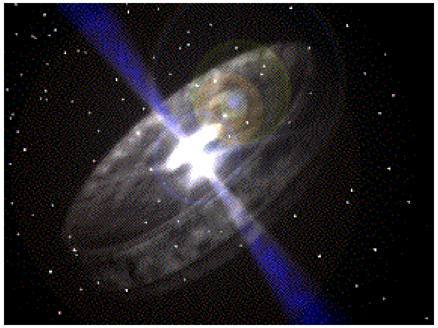


Davis et al. (2014)

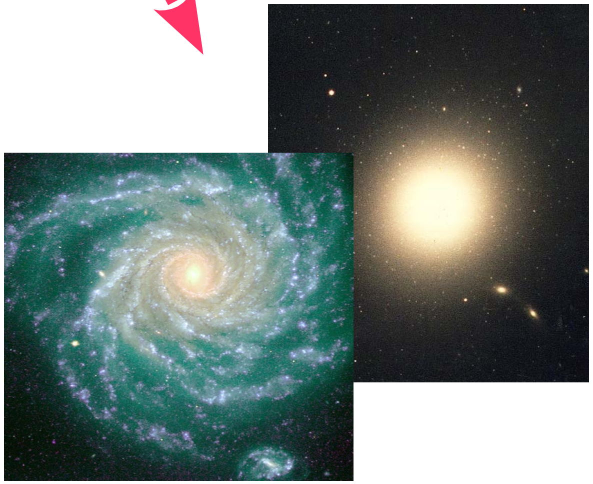
Roadblock IV: Understanding the BH-galaxy connection

How does AGN energy couple to halo gas?

quasars



What's the connection?



galaxies

Galaxy formation and accretion on supermassive black holes appear to be closely related

BLACK HOLES MAY PLAY AN IMPORTANT ROLE IN GALAXY FORMATION

Observational evidence suggests a link between BH growth and galaxy formation:

- M_B-σ relation
- Similarity between cosmic SFR history and quasar evolution
- Local BH density matches integrated quasar light
- Downsizing observed for BH growth, just like for galaxies

Theoretical models often assume that BH growth is self-regulated by **strong** feedback:

- Removal of gas around the hole once a crtitical M_B is reached

Silk & Rees (1998), Wyithe & Loeb (2003)

Quasars release plenty of energy

$$L_Q \sim 10^{12}\, L_\odot \qquad t_Q \sim 10^7 - 10^8\,\mathrm{yr} \qquad E_Q \sim 10^{60} - 10^{61}\,\mathrm{erg}$$

a billion supernovae !

Total available feedback energy from BHs is comparable to that of supernovae

$$\rho_{\mathrm{BH}} \simeq 0.001\,\rho_\star$$

$$E_{\mathrm{BH}}/V \simeq 0.1\,\rho_{\mathrm{BH}}\,c^2$$

$$E_{\mathrm{SN}}/V \simeq \frac{10^{51}\,\mathrm{erg}}{100\,\mathrm{M}_\odot}\,\rho_\star$$

$$\frac{E_{\mathrm{BH}}}{E_{\mathrm{SN}}} \simeq 1.8$$

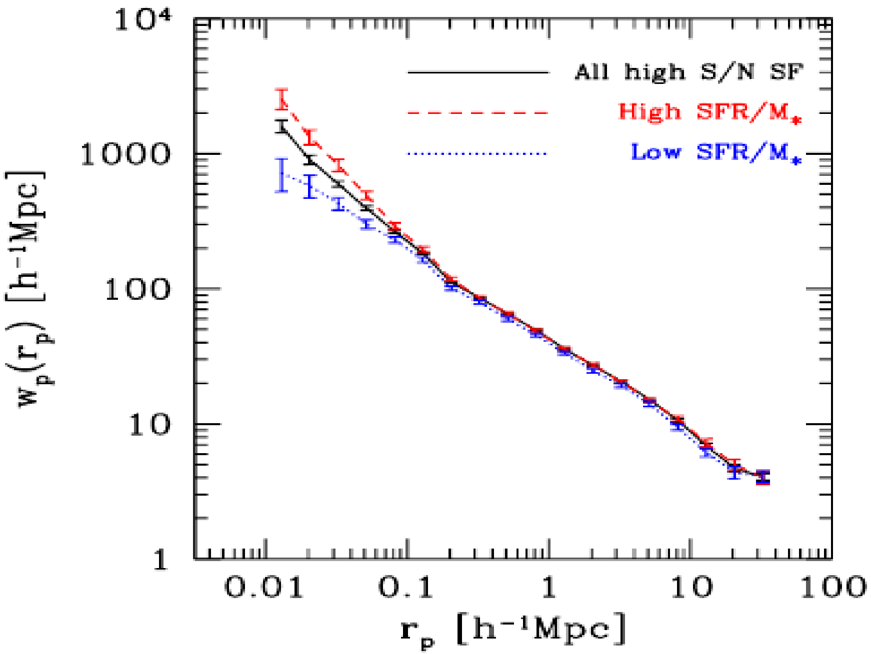
The idea of a self-regulated growth of black holes is not universally accepted

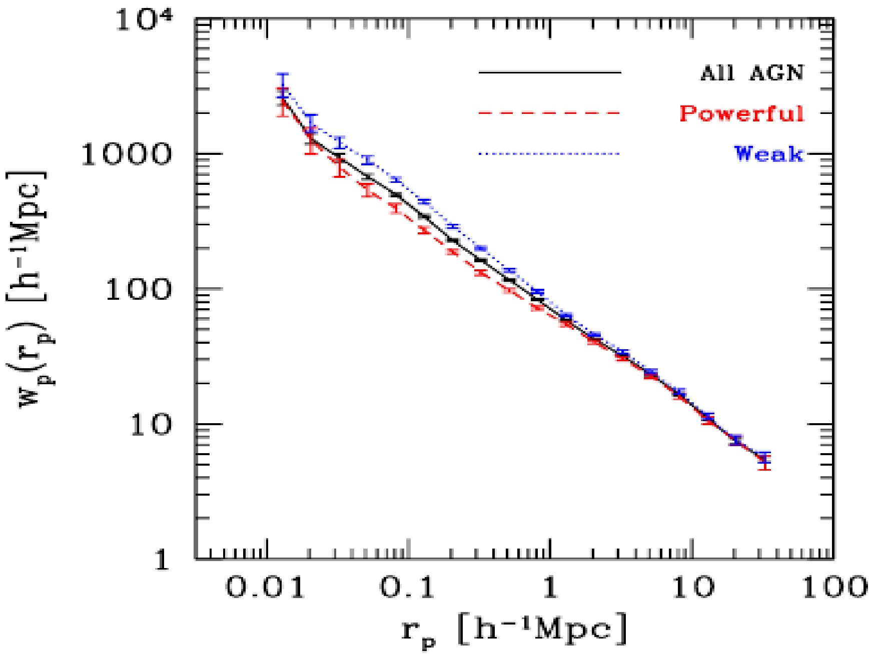
ALTERNATIVE EXPLANATIONS OF BLACK HOLE – GALAXY CORRELATIONS

Jahnke & Maccio (2011): Hierarchical merging may create black hole - galaxy scaling relations

Angles-Alcazar et al. (2013, 2016): Self-regulation not required if Bondi doesn't apply and instead torque-limited accretion detemines BH growth. Common gas supply can then lead to co-evolution of black-holes and galaxies

Li, Kauffmann, Heckman et al. (2008): Find that close pairs of galaxies have enhanced SFR, but no evidence for increased AGN activity.



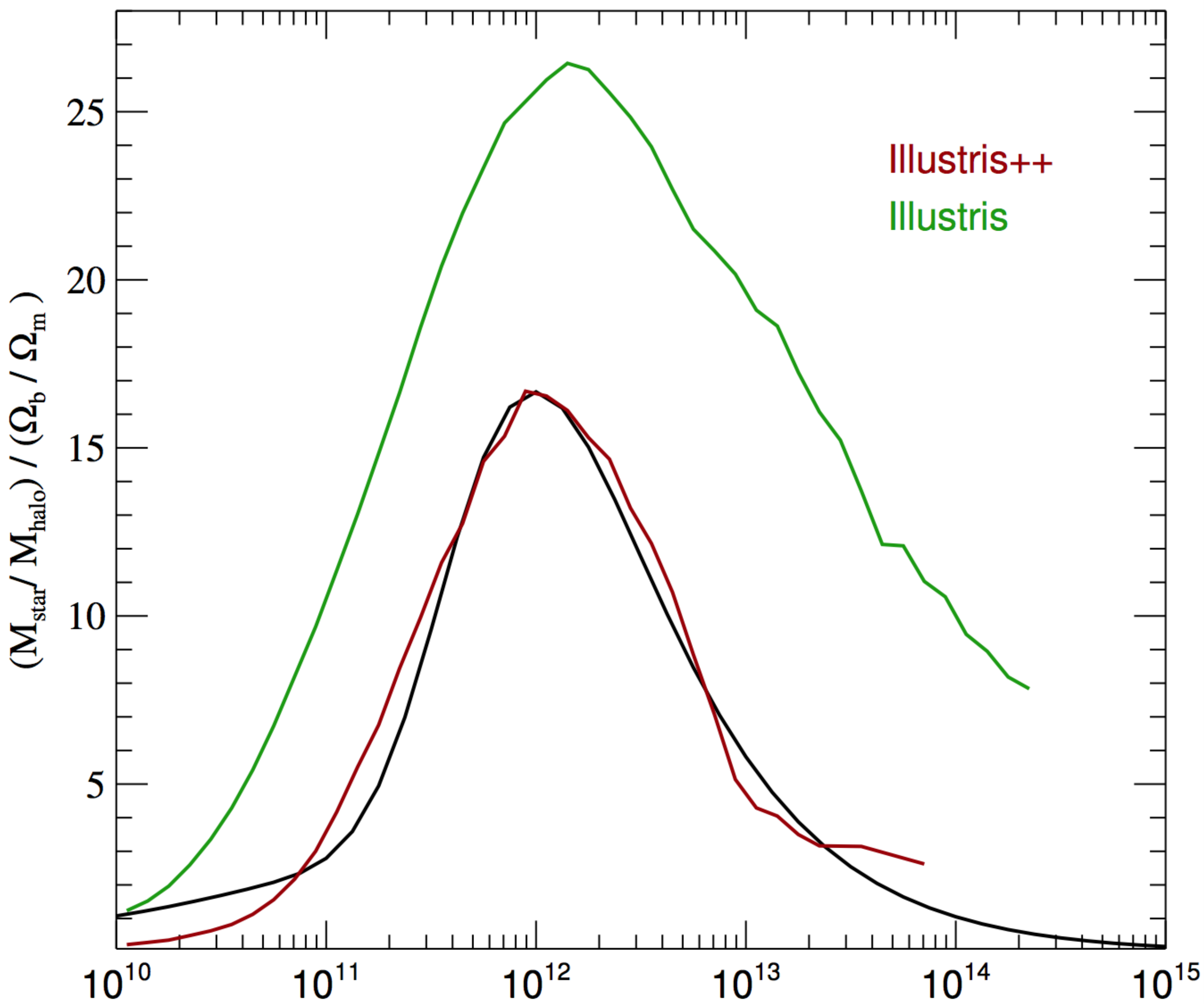


But: Hennawi et al. (2006), Serber et al. (2006): Find some evidence for enhanced small scale-clustering of optical quasars.

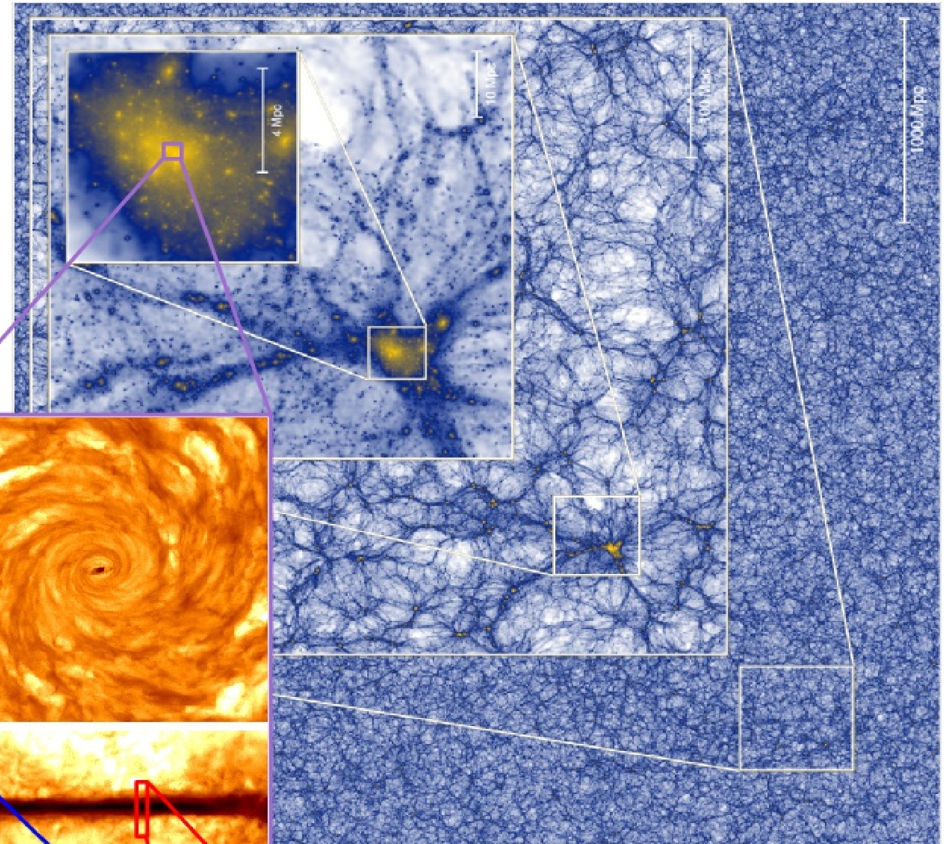
Quenching needs to happen effectively in ΛCDM to reproduce the bright end of the galaxy luminosity function

IMPACT OF THE ILLUSTRIS++ AGN MODEL

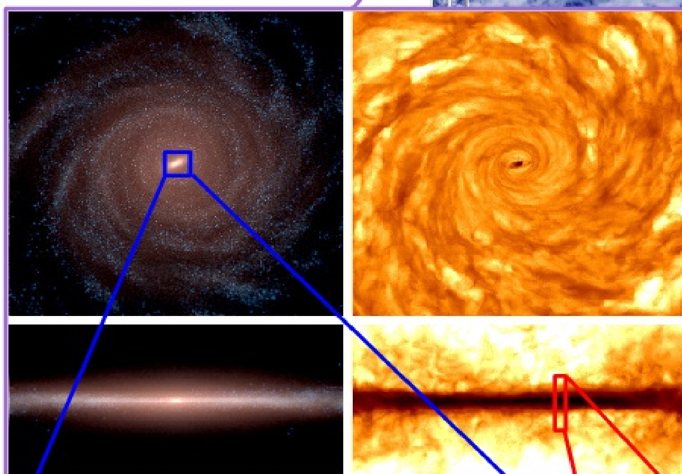
We need **sudden** quenching setting in at around M_{halo}~10^{12}



Roadblock V: Bridging the spatial dynamic range

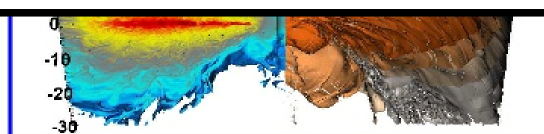


Angulo et al. (2012)

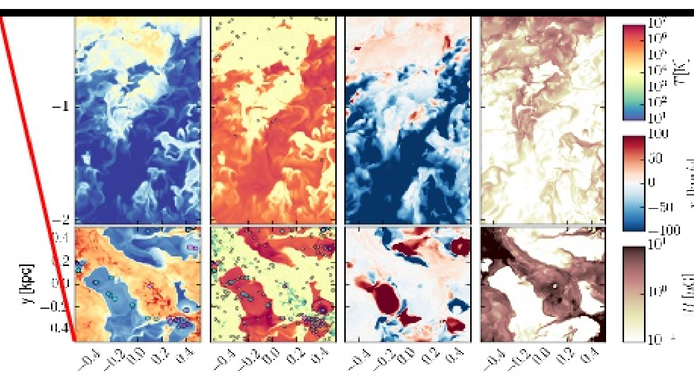


Grand et al. (2016)

1. Need more capable zooms
2. Need systematic approaches to combine calculations on different scales



Jiang, Stone & Davis (2014)

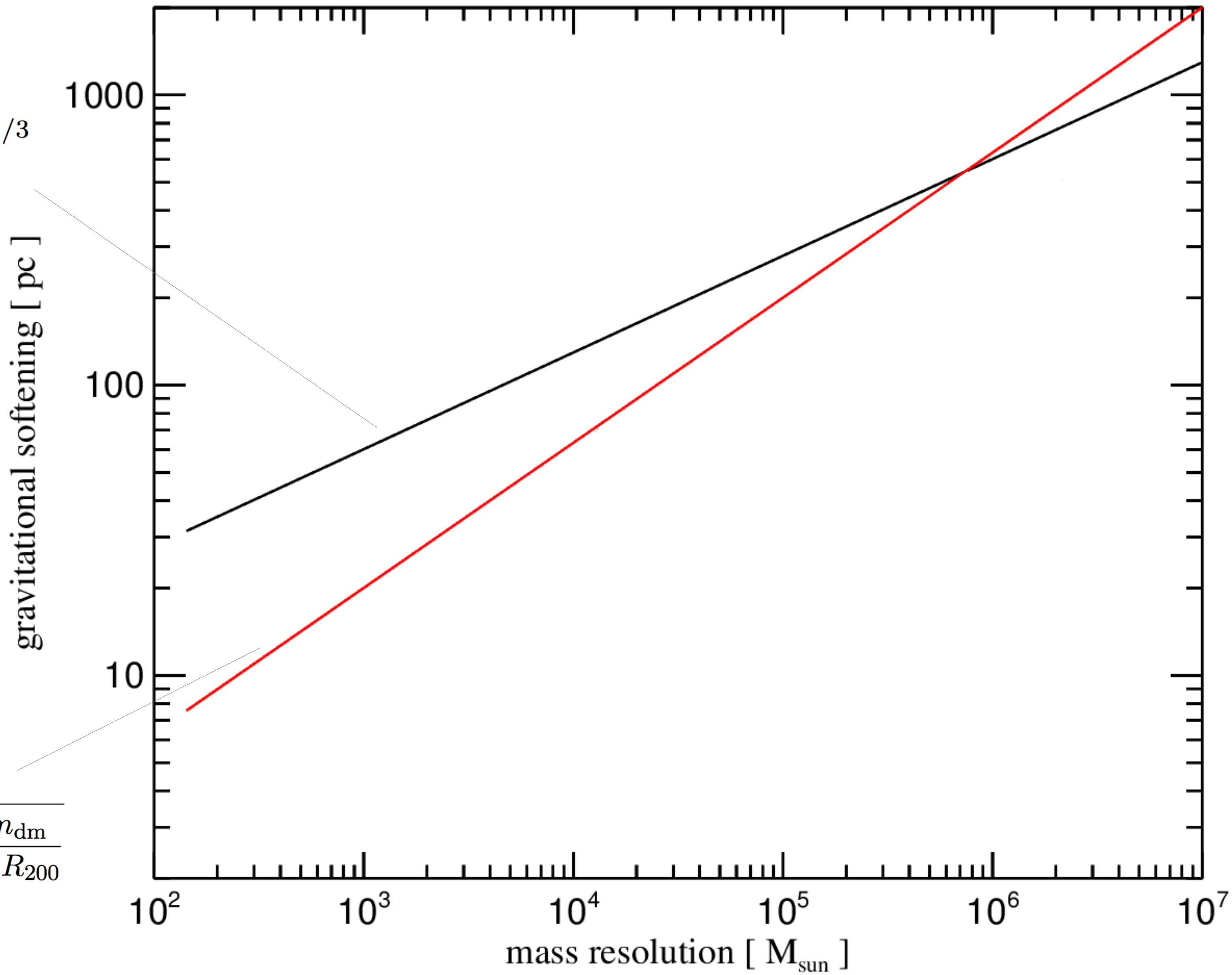


Kim & Ostriker (2016)

Gravitational softening lengths cannot be chosen independently of the mass resolution in collisionless dynamics

THE RACE TO THE BOTTOM

$$\epsilon = \frac{1}{50}\left(\frac{m_{\rm dm}}{\rho_{\rm dm}}\right)^{1/3}$$



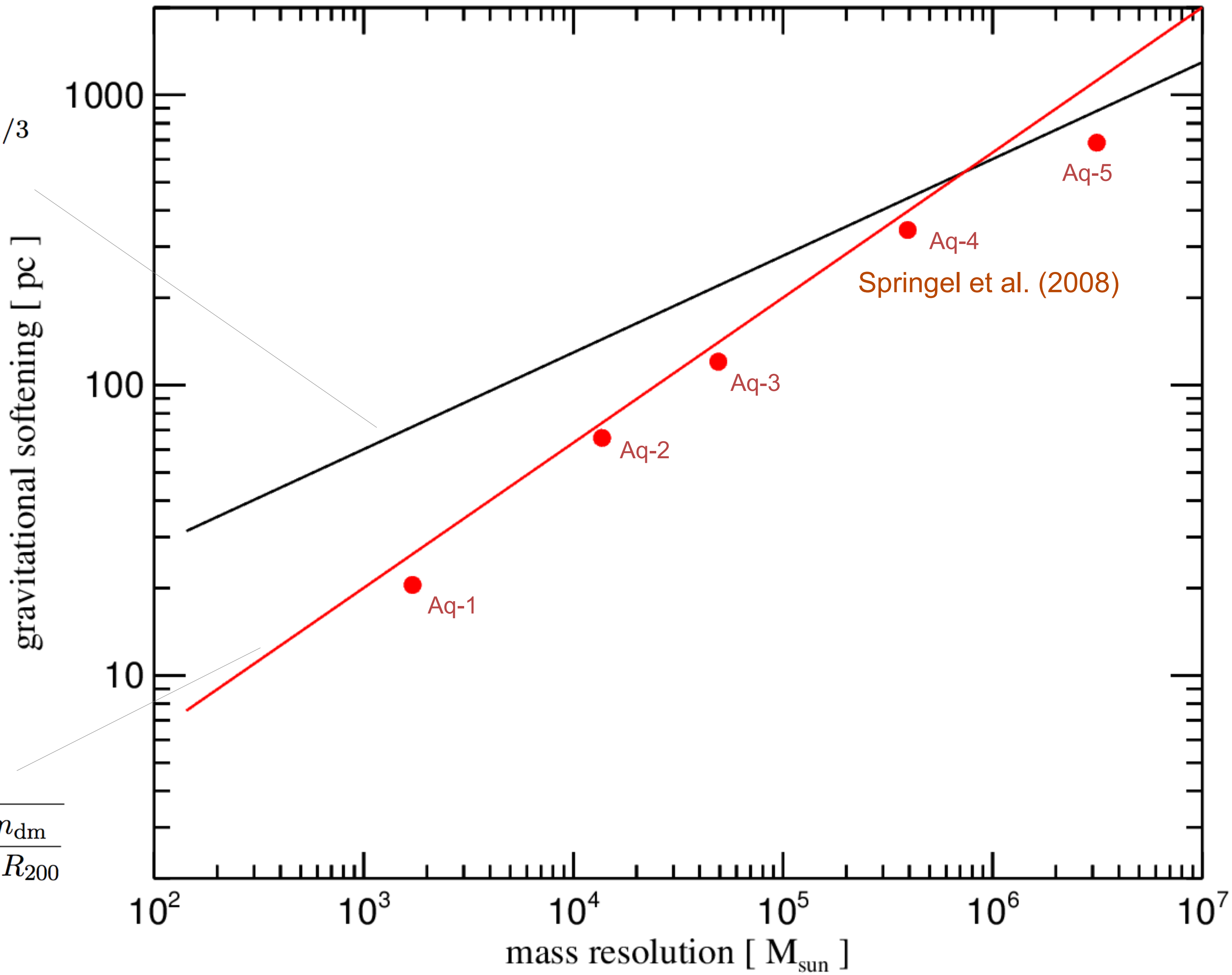
Power et al. (2003)

$$\epsilon = \frac{4R_{200}}{\sqrt{N_{200}}} = \sqrt{\frac{4G\,m_{\rm dm}}{25H_0^2 R_{200}}}$$

Gravitational softening lengths cannot be chosen independently of the mass resolution in collisionless dynamics

THE RACE TO THE BOTTOM

$$\epsilon = \frac{1}{50}\left(\frac{m_{\rm dm}}{\rho_{\rm dm}}\right)^{1/3}$$



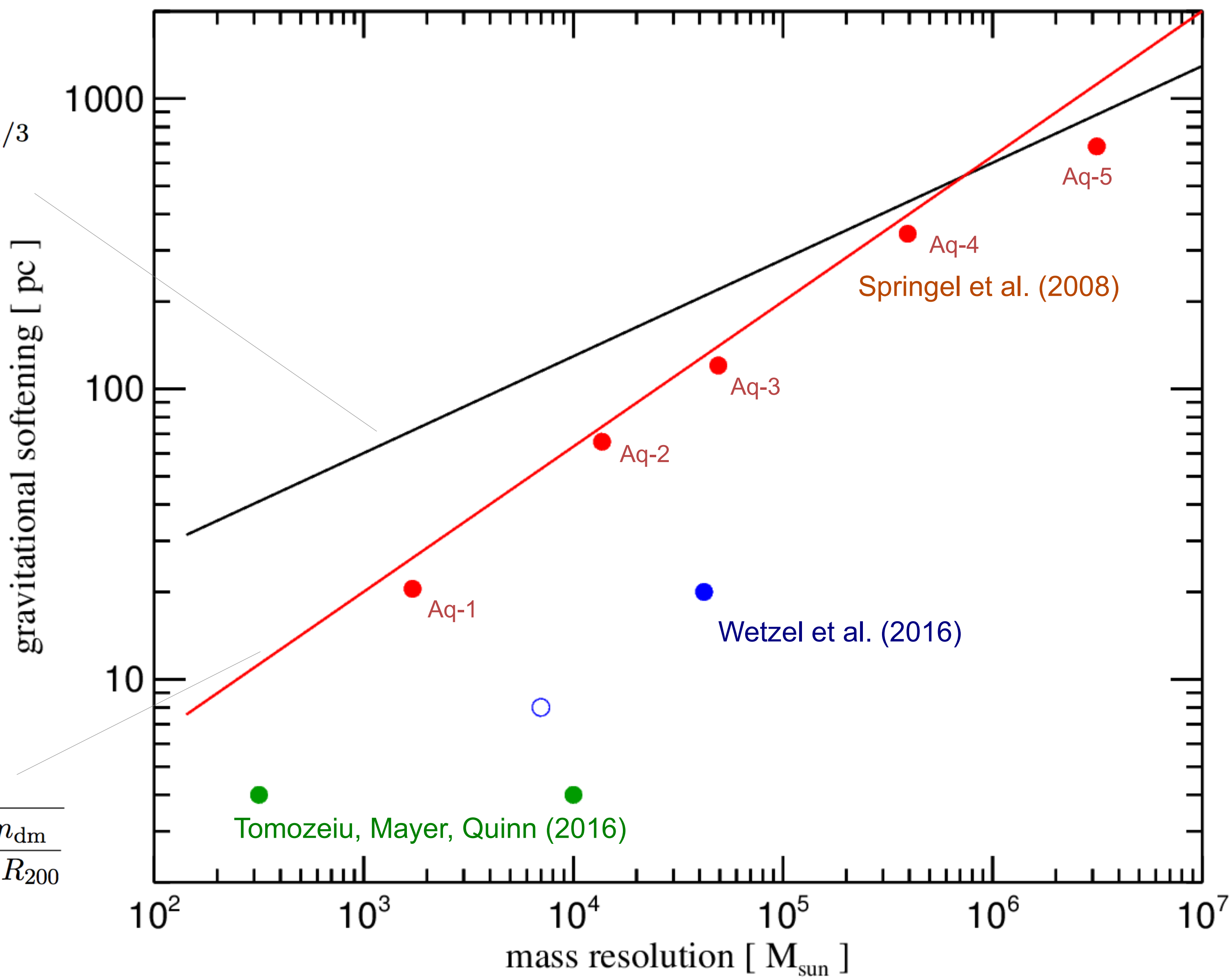
Power et al. (2003)

$$\epsilon = \frac{4R_{200}}{\sqrt{N_{200}}} = \sqrt{\frac{4G\,m_{\rm dm}}{25H_0^2 R_{200}}}$$

Gravitational softening lengths cannot be chosen independently of the mass resolution in collisionless dynamics

THE RACE TO THE BOTTOM

$$\epsilon = \frac{1}{50}\left(\frac{m_{\rm dm}}{\rho_{\rm dm}}\right)^{1/3}$$



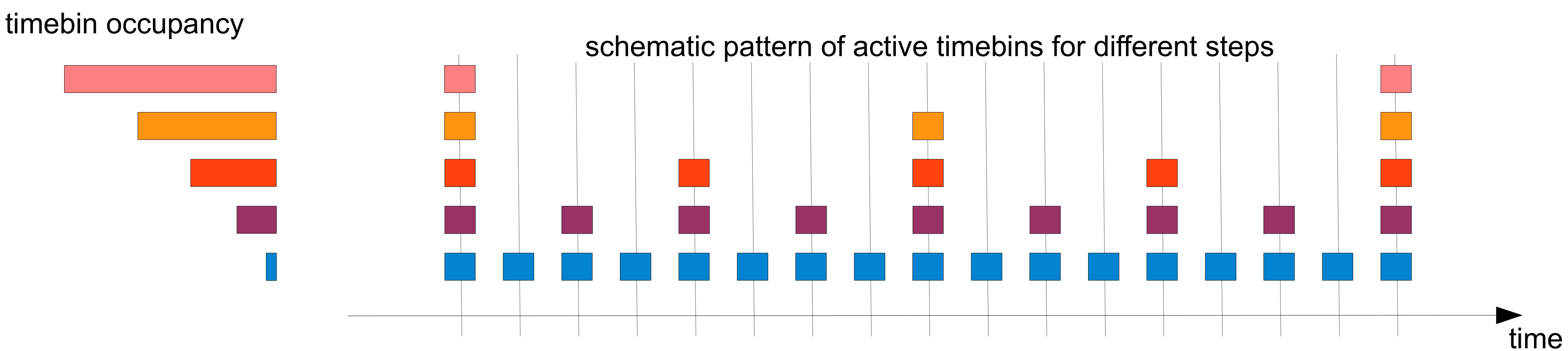
Power et al. (2003)

$$\epsilon = \frac{4R_{200}}{\sqrt{N_{200}}} = \sqrt{\frac{4G\,m_{\rm dm}}{25 H_0^2 R_{200}}}$$

Roadblock VI: Bridging the temporal dynamic range

Spatial adaptivity and huge variations of density and temperature create a **wide range of timestep sizes**

$$\Delta t = C_{\rm CFL}\,\frac{h}{c_s + |\tilde{\mathbf{v}}|} = C_{\rm CFL}\,\frac{m_g^{1/3}\,\rho^{-1/3}}{c_s + |\tilde{\mathbf{v}}|} \qquad \Delta t = \eta\sqrt{\frac{3\pi}{32G\rho}} \propto \rho^{-1/2}$$



Causes all sorts of problems and performance issues....

Makes people sometimes resort to tricks, e.g.:

> *"When the outflowing winds dominate the material in a single cell as sometimes happens in our simulations, this high temperature can slow down the simulation substantially and cause other numerical problems associated with a high density contrast. To ameliorate this issue we cap the wind specific energy at $10^{8.5}$ K."*

Nature (2016)

Execution times of different levels of the timestep hierarchy in Illustris

```
Sync-Point 912913, Time: 0.999995, Redshift: 4.62727e-06, Systemstep: 2.31361e-06, Dloga: 2.31363e-06
Occupied timebins: non-cells     cells       dt                     cumulative A D    avg-time  cpu-frac
    bin=16      4866563102  4542638866    0.000592288851      11907084302   *      319.98     16.0%
    bin=15      1029558638   496930277    0.000296144425       2497882334          162.70      8.1%
    bin=14       456190725   185824857    0.000148072213        971393419          128.60     12.9%
    bin=13       216201669    42568324    0.000074036106        329377837           65.53     13.1%
    bin=12        64651120     2745964    0.000037018053         70607844           28.49     11.4%
    bin=11         3004109      186565    0.000018509027          3210760           10.45      8.4%
    bin=10              99       18602    0.000009254513            20086            2.91      4.7%
 X  bin= 9              23        1236    0.000004627257             1385 <          2.75      8.8%
 X  bin= 8               4         122    0.000002313628              126            2.62     16.8%
               ------------------------
Total active:           27        1358    Sum:       1385
```

Problem:
The short timesteps take way too long and end up dominating the CPU budget.

Advancing the system over the time-interval corresponding to the largest timestep takes:

$$319.98 + 162.70 + 2 * 128.60 + 4 * 65.53 + 8 * 28.49 + 16 * 10.45 + 32 * 2.91 + 64 * 2.75 + 128 * 2.62 = 2001.60$$

If however the more thinly occupied timesteps would consume time proportional to the number of active particles, we would expect in the most optimistic case:

$$319.98 + 67.13 + 2 * 26.10 + 4 * 8.85 + 8 * 1.90 + 16 * 0.086 + 32 * 0.00054 + 64 * 3.72\text{e-}05 + 128 * 3.39\text{e-}06 = 491.3$$

This is in principle a factor of 4 in speed up.

A hierarchical Hamiltonian split has been implemented in AREPO to achieve a clean separation of timescales

AVOIDING OVERHEADS IN THE TAIL OF THE TIMESTEP DISTRIBUTION

Recall second-order symplectic integration:

$$H = H_1 + H_2$$

$$E(H, \Delta t) \simeq E\left(H_1, \frac{\Delta t}{2}\right) \circ E(H_2, \Delta t) \circ E\left(H_1, \frac{\Delta t}{2}\right)$$

For a Hamiltonian system P of particles, define a split into a slow system S (Δt), and a fast system F (Δt/2)

$$H = H_{\rm kin} + H_{\rm pot} \qquad \mathrm{P} = \mathrm{S} + \mathrm{F}$$

We can now write the system as:

$$H = H_{\rm kin}^{\rm S} + H_{\rm pot}^{\rm S} + H_{\rm kin}^{\rm F} + H_{\rm pot}^{\rm F} + H_{\rm pot}^{\rm FS}$$

$$H = H^{\rm S} + H^{\rm F} + H_{\rm pot}^{\rm FS}$$

A hierarchical Hamiltonian split has been implemented in AREPO to achieve a clean separation of timescales

AVOIDING OVERHEADS IN THE TAIL OF THE TIMESTEP DISTRIBUTION

$$H = H^{\mathrm{S}} + H^{\mathrm{F}} + H^{\mathrm{FS}}_{\mathrm{pot}}$$

We can now define a time-integration operator as:

$$E(H, \Delta t) \simeq E\left(H^{\mathrm{FS}}_{\mathrm{pot}}, \frac{\Delta t}{2}\right) \circ E\left(H^{\mathrm{F}}, \frac{\Delta t}{2}\right) \circ E(H^{\mathrm{S}}, \Delta t) \circ E\left(H^{\mathrm{F}}, \frac{\Delta t}{2}\right) \circ E\left(H^{\mathrm{FS}}_{\mathrm{pot}}, \frac{\Delta t}{2}\right)$$

Expressed as kick and drift operators, this becomes:

$$E(H, \Delta t) \simeq K^{\mathrm{F}}_{\mathrm{S}}\left(\frac{\Delta t}{2}\right) K^{\mathrm{S}}_{\mathrm{F}}\left(\frac{\Delta t}{2}\right) K^{\mathrm{F}}_{\mathrm{F}}\left(\frac{\Delta t}{4}\right) D_{\mathrm{F}}\left(\frac{\Delta t}{2}\right) K^{\mathrm{F}}_{\mathrm{F}}\left(\frac{\Delta t}{4}\right) K^{\mathrm{S}}_{\mathrm{S}}\left(\frac{\Delta t}{2}\right) D_{\mathrm{S}}\left(\Delta t\right) K^{\mathrm{S}}_{\mathrm{S}}\left(\frac{\Delta t}{2}\right) \cdots$$

commutes with D_F and can be moved

This can be simplified into:

$$E(H, \Delta t) \simeq K^{\mathrm{P}}_{\mathrm{P}}\left(\frac{\Delta t}{2}\right) K^{\mathrm{F}}_{\mathrm{F}}\left(-\frac{\Delta t}{4}\right) D_{\mathrm{F}}\left(\frac{\Delta t}{2}\right) K^{\mathrm{F}}_{\mathrm{F}}\left(\frac{\Delta t}{4}\right) D_{\mathrm{S}}\left(\Delta t\right) \cdots$$

- Can be applied hierarchically
- Momentum conserving despite individual timesteps

Execution times of different levels of the timestep hierarchy in Illustris++

```
Sync-Point 5034495, Time: 0.235176, Redshift: 3.25213, Systemstep: 1.70035e-08, Dloga: 7.23009e-08
Occupied timebins: gravity      hydro          dt                cumul-grav   cumul-sph A D    avg-time  cpu-frac
    bin=46     11812708589  5771513667      0.000296144425      11879513795   5794868748          183.75     20.5%
    bin=45        38994455    14513112      0.000148072213         66805206     23355081           43.02      4.8%
    bin=44        18003771     6143342      0.000074036106         27810751      8841969           30.57      6.8%
    bin=43         8016377     2070979      0.000037018053          9806980      2698627           15.08      6.7%
    bin=42         1661929      499560      0.000018509027          1790603       627648            6.41      5.7%
    bin=41           97086       96711      0.000009254513           128674       128088            2.30      4.1%
    bin=40           21885       21756      0.000004627257            31588        31377            1.54      5.5%
    bin=39            7264        7197      0.000002313628             9703         9621            0.84      6.0%
    bin=38            1917        1903      0.000001156814             2439         2424            0.32      4.6%
    bin=37             443         442      0.000000578407              522          521            0.20      5.6%
 X  bin=36              65          65      0.000000289204               79           79 <          0.11      6.2%
 X  bin=35              12          12      0.000000144602               14           14            0.08      8.9%
 X  bin=34               2           2      0.000000072301                2            2            0.06     14.4%
               ------------------------
Total active:           79          79
```

We can now do more than ~10 million steps – and in fact we have to.

Summary points

- Processes regulating star formation and galaxy accretion may be different
- Radiation pressure? (on life support)
- Galaxy formation at the bright end requires black hole feedback
- Need radiation magnetohydrodynamics with accurate self-gravity
- Dynamic range in time scales is arguably the most serious challenge for parallel codes
- Accuracy of the treatment of gravity for dark matter and stars deserves more attention