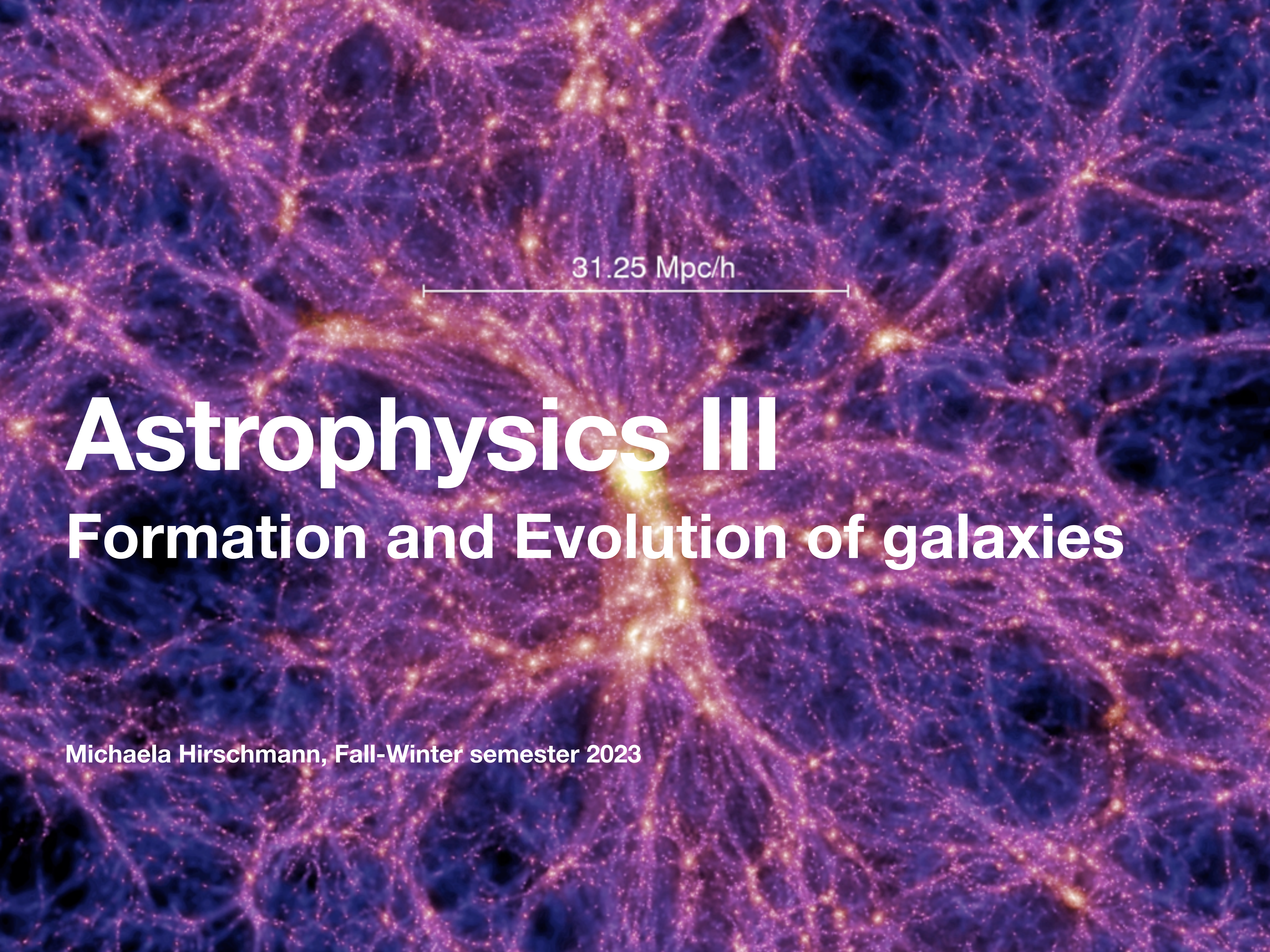


Astrophysics III

Formation and Evolution of galaxies

Michaela Hirschmann, Fall-Winter semester 2023

Lecture content and schedule

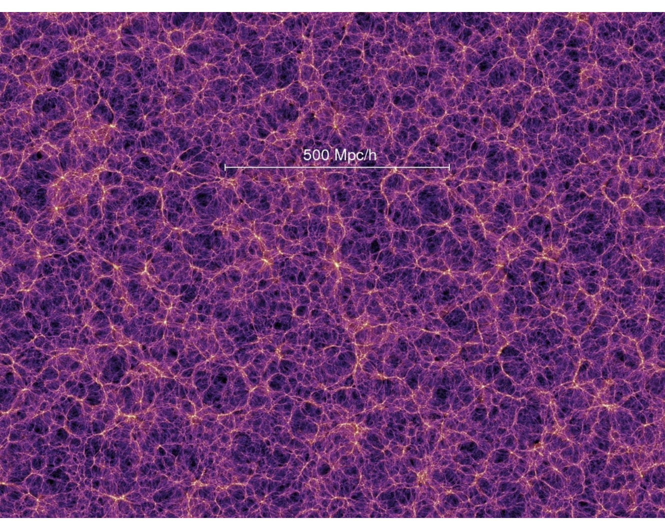
- *Chapter 1*: Introduction (galaxy definition, astronomical scales, observable quantities — repetition of Astro-I)
- *Chapter 2:* Brief review on stars
- *Chapter 3*: Radiation processes in galaxies and telescopes;
- *Chapter 4:* The Milky Way
- *Chapter 5*: The world of galaxies I
- *Chapter 6*: The world of galaxies II
- *Chapter 7:* Black holes and active galactic nuclei
- *Chapter 8:* Galaxies and their environment;
- *Chapter 9:* High-redshift galaxies
- *Chapter 10*:
    - Cosmology in a nutshell; Linear structure formation in the early Universe
- *Chapter 11*:
    - Dark matter and the large-scale structure
    - Cosmological N-body simulations of dark matter
- *Chapter 12*: Populating dark matter halos with baryons: Semi-empirical & semi-analytical models
- *Chapter 13:* Modelling the evolution of gas in galaxies: Hydrodynamics
- *Chapter 14*: Gas cooling/heating and star formation
- *Chapter 15*: Stellar feedback processes
- *Chapter 16*: Black hole growth & AGN feedback processes
- *Chapter 17*: Modern simulations & future prospects

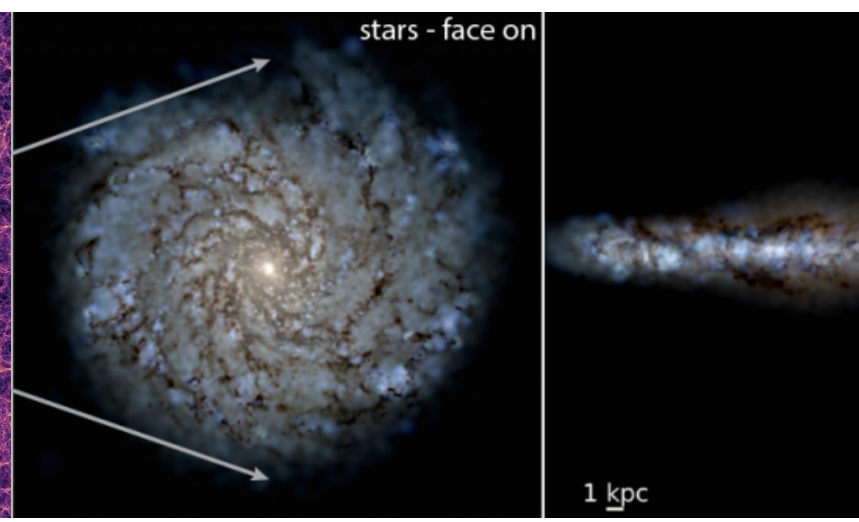
Part I:
Observational basics & facts of galaxies
first 7 lectures

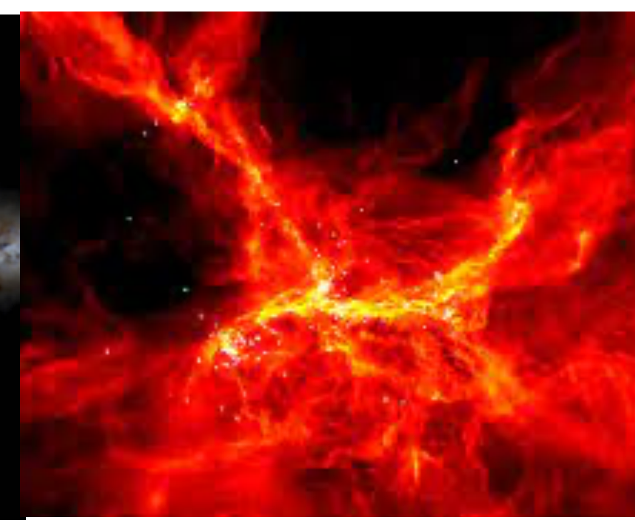
Part II:
Theory & models of
galaxy evolution processes
second 7 lectures

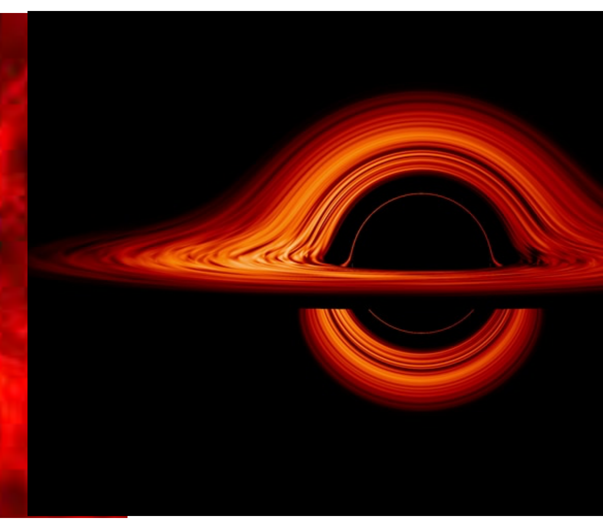
Dynamic range problem in cosmological sims.

- Up to now, simulations include gravity and hydrodynamics
- All other processes happen on scales we cannot resolve in the simulations
    - Dynamic range problem!









Cosmological scales
Mpc-Gpc

Galaxy scales
pc-kpc

Star formation
subpc-pc scales

BH accretion
below 10^{-4} pc

cosmological boxes Gpc to a few 100s pc	cosmo zooms 100s kpc to pc	Star formation simulations	Accretion disk simulations

Modelling gas-physical processes

- Up to now, simulations include gravity and hydrodynamics
- All other processes happen on scales we cannot resolve in the simulations
    - Dynamic range problem!
- Now we discuss effective models (sub-resolution models) to describe these small-scale physics:
    - (Radiative) gas cooling & heating — still coupled to hydro equations
    - Star formation
    - Chemical enrichment
    - Feedback from different evolutionary stages of massive stars
    - BH growth and AGN feedback
    - (Magnetic fields)
    - (Cosmic rays etc…)
- All processes (except for cooling) not very well understood, and thus mostly modelled in a phenomenological way

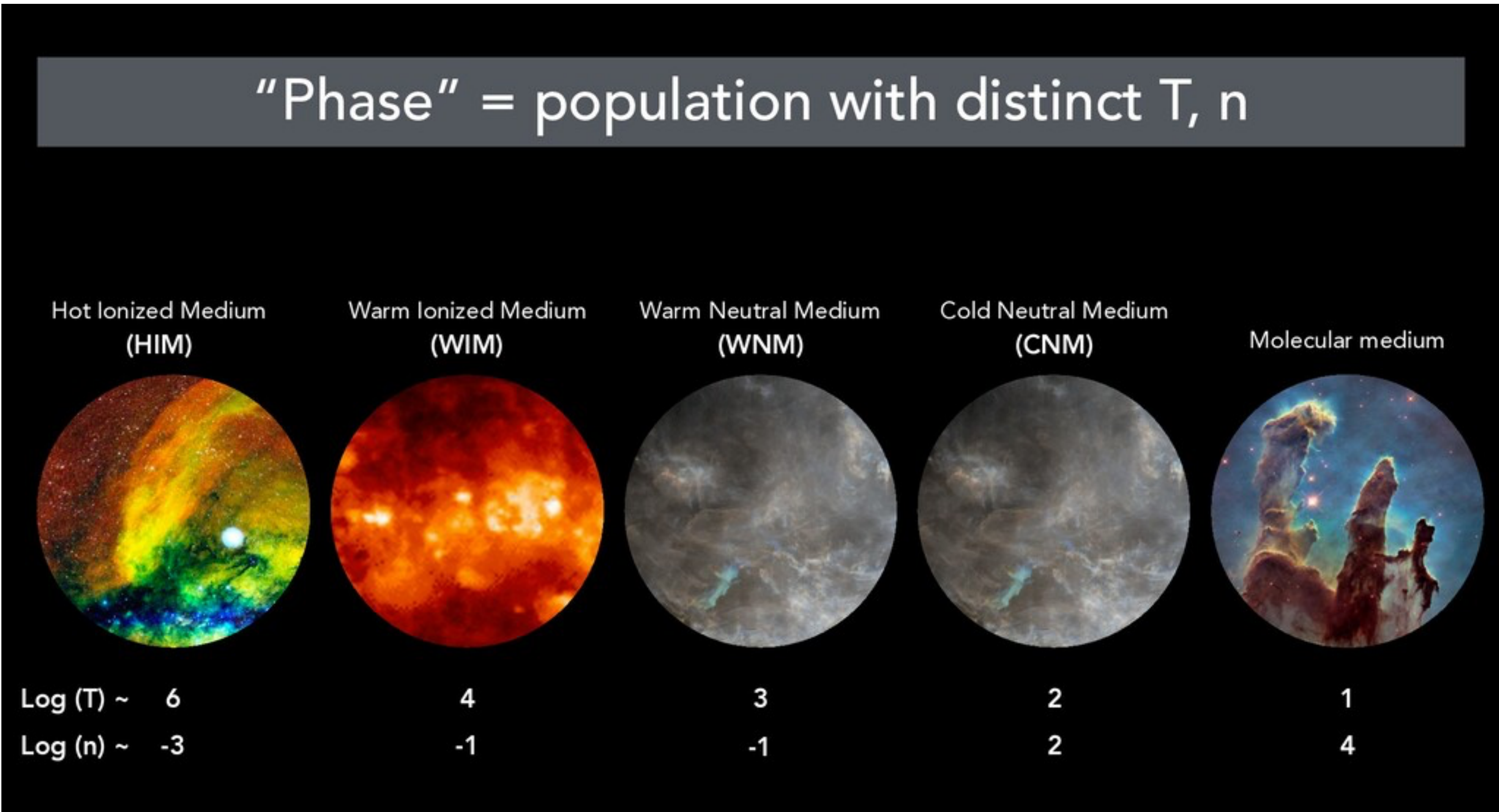
Outline of this lecture

- Gas cooling/heating
  - Cooling processes
  - Heating processes
  - Gas cooling in DM halos

- Star formation
  - Molecular clouds as sites for SF
  - Jeans instability
  - Phenomenological models
  - Different implementations of SF
  - Stellar populations
  - Chemical enrichment

Observed composition of the ISM

- Why should we care about gas cooling and heating?
- Responsible for complex composition of different gas phases in the interstellar medium



Gas cooling processes

- **Gas cooling means a decrease of the thermal energy (and T) of the gas (cell/particle)**
- Gas can cool via various radiative and collisional processes of atoms, ions and e^- (radiative: interaction with photon and/or absorption/emission of photon involved)
- Gas can cool via molecular cooling processes
- Gas can cool adiabatically (energy stays the same, but volume of gas is expanding, and thus, T is decreasing, e.g. phase in SN explosion) —> automatically captured in HD

Gas heating processes

- **Gas heating means an increase of the thermal energy (and T) of the gas (cell/particle)**
- Gas be heated via various radiative and collisional processes (radiative: interaction with and/or absorption/emission of photon involved), e.g., Photo-ionisation heating, Compton-heating
- Gas can be heated adiabatically due to compression (no heat exchange, "isolated process" e.g. gravitational collapse) —> automatically captured in HD
- Gas can be shock-heated, typically in rapid and violent events (not adiabatic e.g. SN explosion, gas infall onto a halo, mergers galaxies) —> automatically captured in HD

Radiative/collisional cooling & heating of gas

How can we model/calculate radiative cooling and heating processes?

- Start from energy equation in the set of hydro equations

$$\frac{\partial \rho e_{\rm tot}}{\partial t} + \nabla \cdot ((\rho e_{\rm tot} + P)\mathbf{u}) = 0 \qquad e_{\rm tot} = e + \frac{u^2}{2}$$

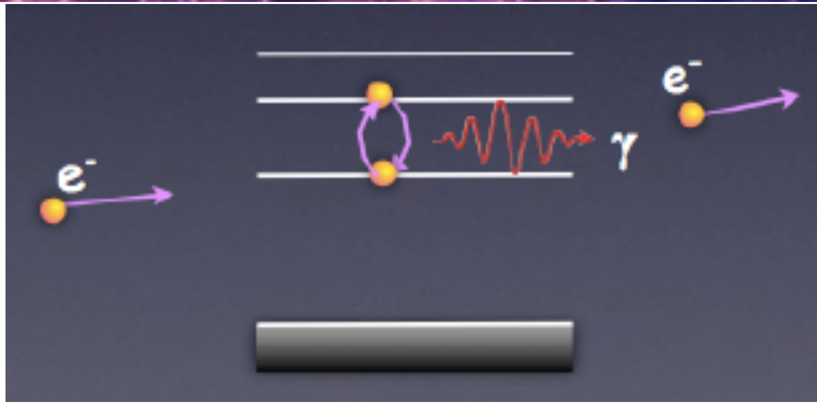
- We can add a gravitational potential, cooling and heating as a source

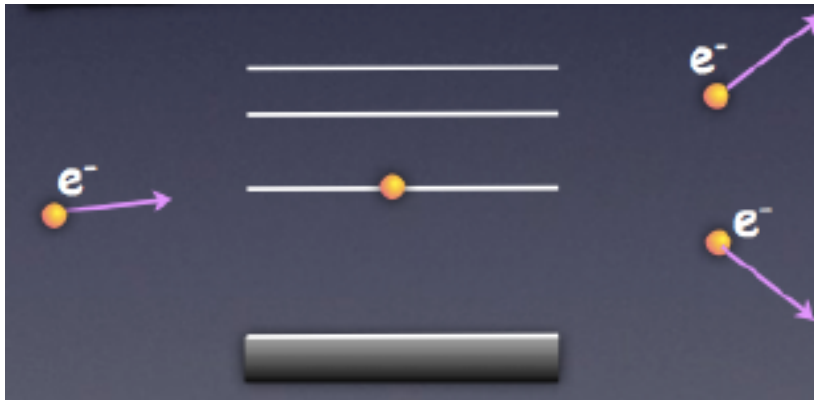
$$\frac{\partial \rho e_{\rm tot}}{\partial t} + \nabla \cdot ((\rho e_{\rm tot} + P)\mathbf{u}) = \rho \mathbf{u} \cdot \nabla \Phi + (\mathcal{H} - \mathcal{C})$$

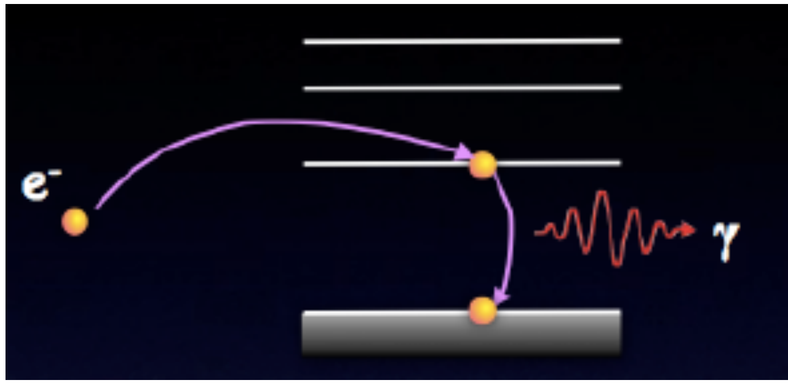
- $\mathcal{H}$: Heating rate per unit volume [erg/s/cm³]
- $\mathcal{C}$: Cooling rate per unit volume [erg/s/cm³]
- Simplest case: only primordial cooling considering only H and He
- Additional cooling via "metals", all elements heavier than H and He
- Gas can be heated by a background of high-energy UV photons produced by massive stars and AGN, and other energy sources in a galaxy (AGN and stellar feedback etc…)

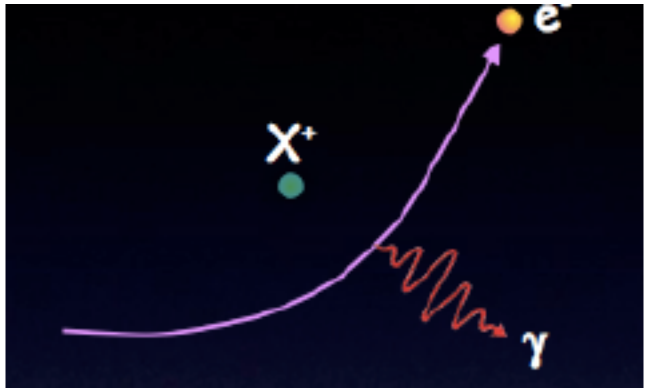
Cooling via collisional/radiative processes

- Radiative processes involve the interactions of photons with atoms, ions and electrons (collisional are w/o photons)
- Radiative/collisional processes can be classified into several broad categories:
  - Bound-bound process: e^- makes a transition from one level to another via collision with e^- (collisional excitation or de-excitation) or via an interaction with a photon (photon excitation, spontaneous or stimulated decay)
  - Bound-free process: e^- is removed from a bound orbit via collision with a e^- (collisional ionisation) or when it absorbs a photon (photoionization), the reverse process is recombination, by which a e^- recombines with an ion
  - Free-free process: unbound e^- are accelerated or decelerated in an ionised plasma, absorbing or emitting a photon (free-free absorption, Bremsstrahlung)
  - Compton scattering: photons (e.g. from CMB) are scattered by free e^- in the hot gas;
    - if photon energy high —> e^- gain energy (Compton process)
    - if kinetic e^- energy is higher —> energy transferred from e^- to photon (inverse Compton process)



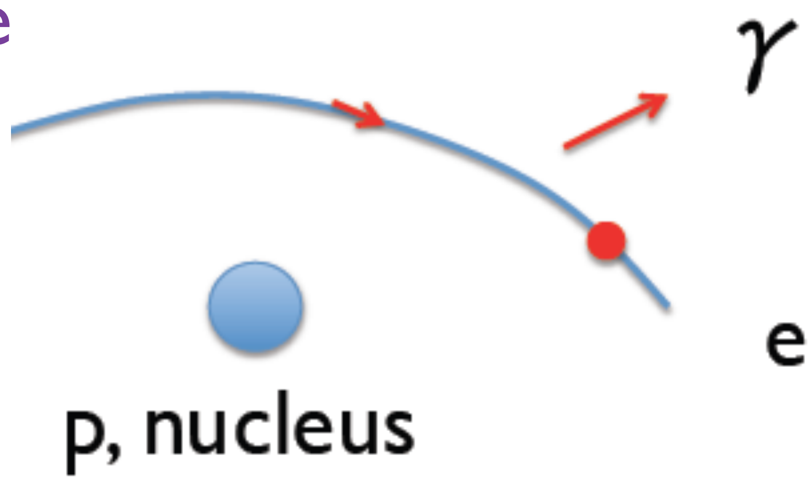






Cooling via Bremsstrahlung

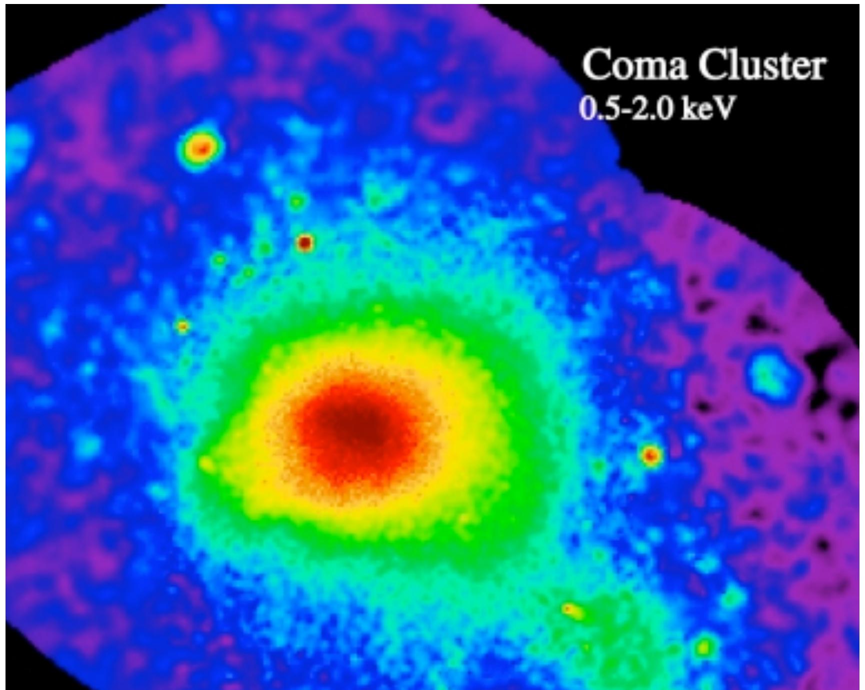
- In general: primary cooling processes for structure formation are two-body radiative processes in which gas loses energy through radiation as a result of two-body interactions



- At T above 10^6 K, primordial gas is almost entirely ionised, i.e. cooling happens only via deceleration of electrons as they encounter atomic nuclei, (which is fairly inefficient)
- For an optically thin gas, the volume cooling rate (for H) is related to the bremsstrahlung emissivity through

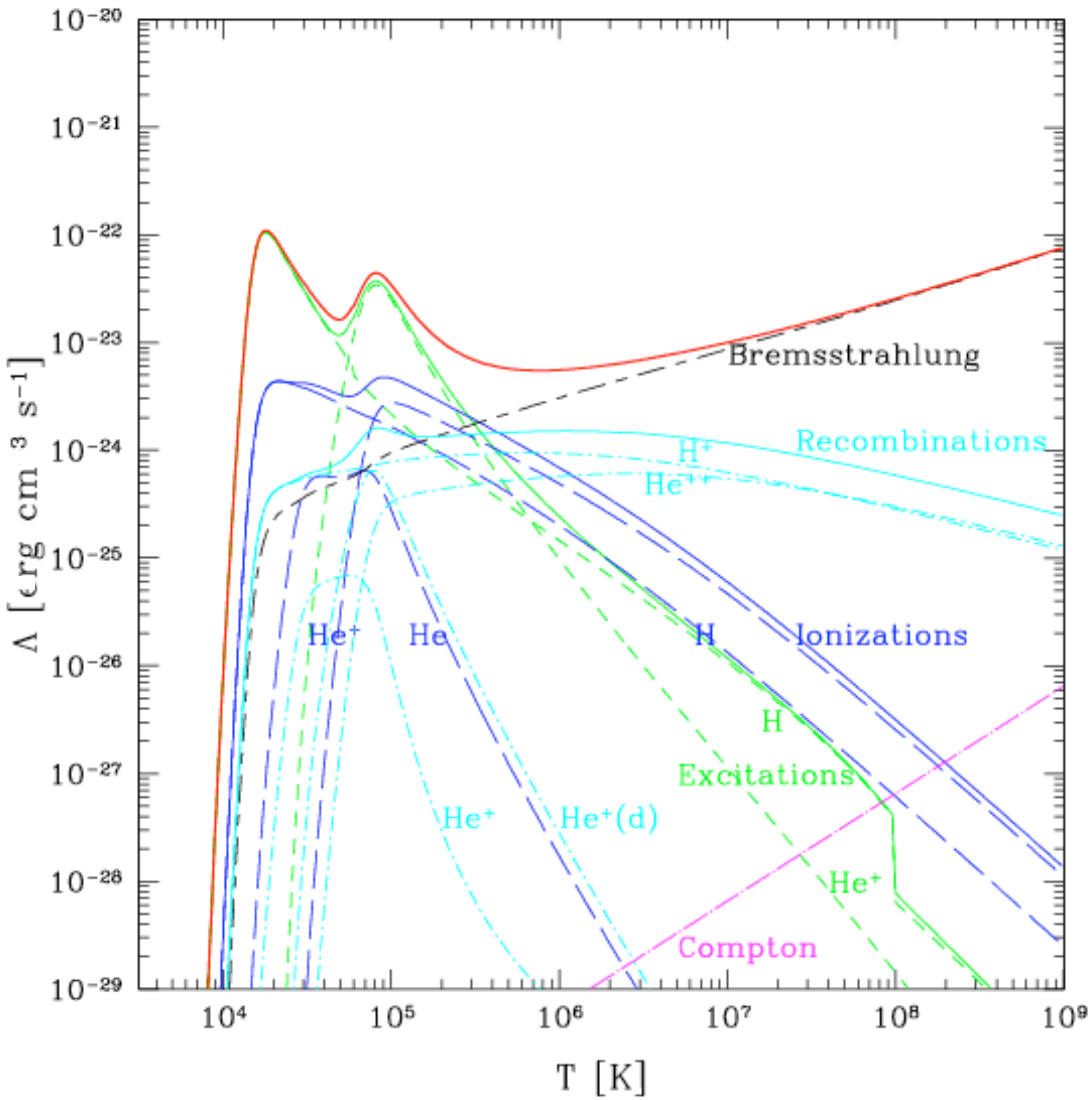
$$\mathcal{C}_{\rm Brems} = \int \epsilon(\nu) \approx 1.4 \times 10^{-23} (T/10^8 K)^{1/2} (n_e/cm^{-3})^2 erg/s/cm^3$$

- Hotter gas cools more efficiently
- Denser gas cools more efficiently
- Photons are highly energetic, radiation emitted (and observed) in the X-ray



Atomic cooling of primordial gas

- At lower temperatures, several other processes are important for cooling (in the absence of any radiation field):



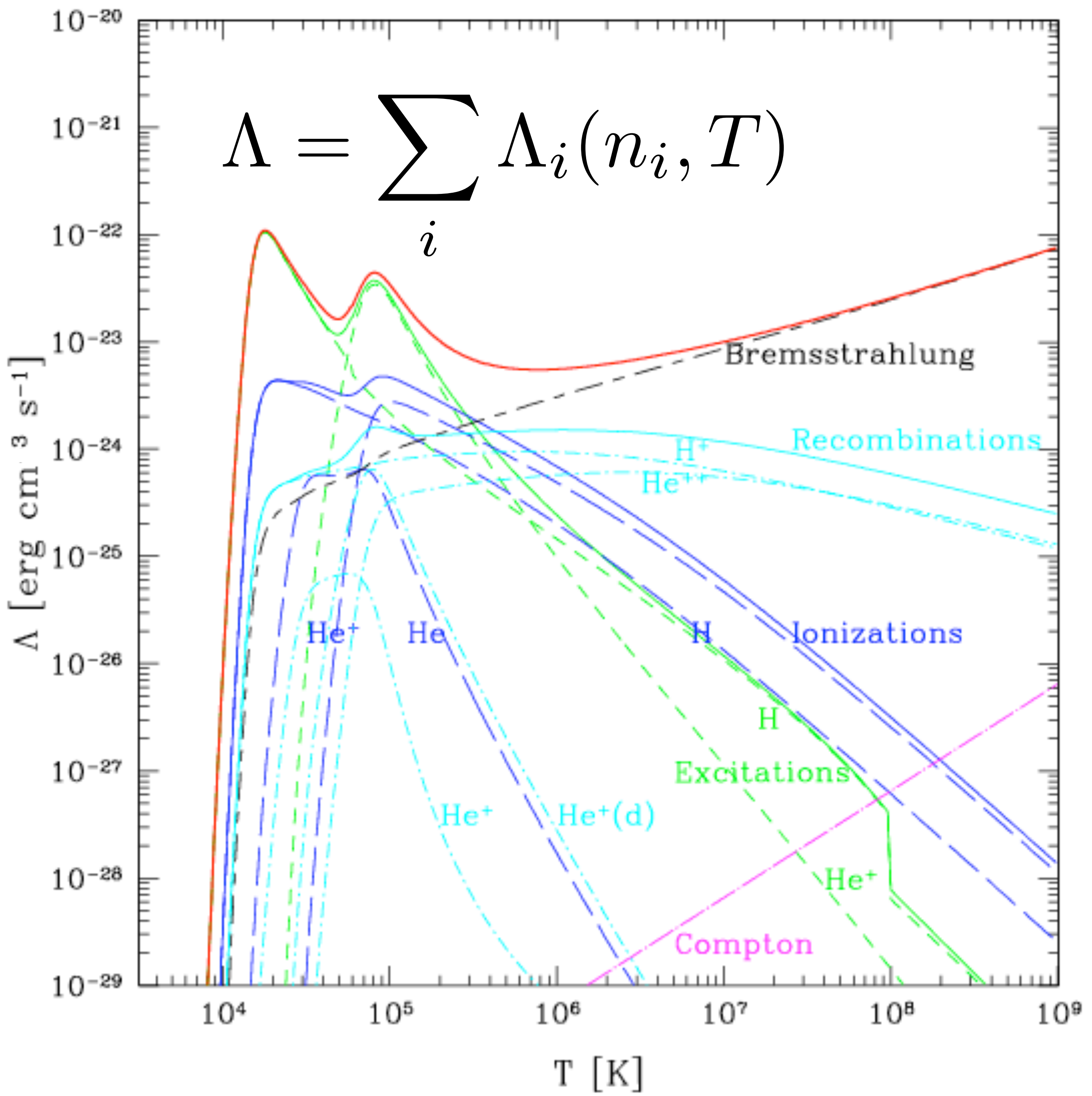
- Ionisation
- Excitation
- Recombination
- Cooling rate is strongly T dependent (even in ionisation equ.)

- The cooling rate of a cosmic gas is represented by a cooling function defined as

$$\Lambda(T) = \mathcal{C}/n_H^2$$

Atomic cooling of primordial gas

- Primordial gas composed of 75% H and 25% He —> total n_H and n_{He} are known
  - Ion number densities derived from ionisation equilibrium
- Implementation: Cooling function used for gas in simulations: Sum up over cooling rates from different processes
- We can then calculate the change in energy for a gas particle: $$\frac{\partial e_{i,tot}}{\partial t} = -\frac{\mathcal{C}_i}{\rho_i}$$ $$\mathcal{C}_i = n_H^2 \Lambda$$
- T < 5e5K: Dominating process is collisional excitation
- For primordial gas composition, cooling does not go below 1e4 K

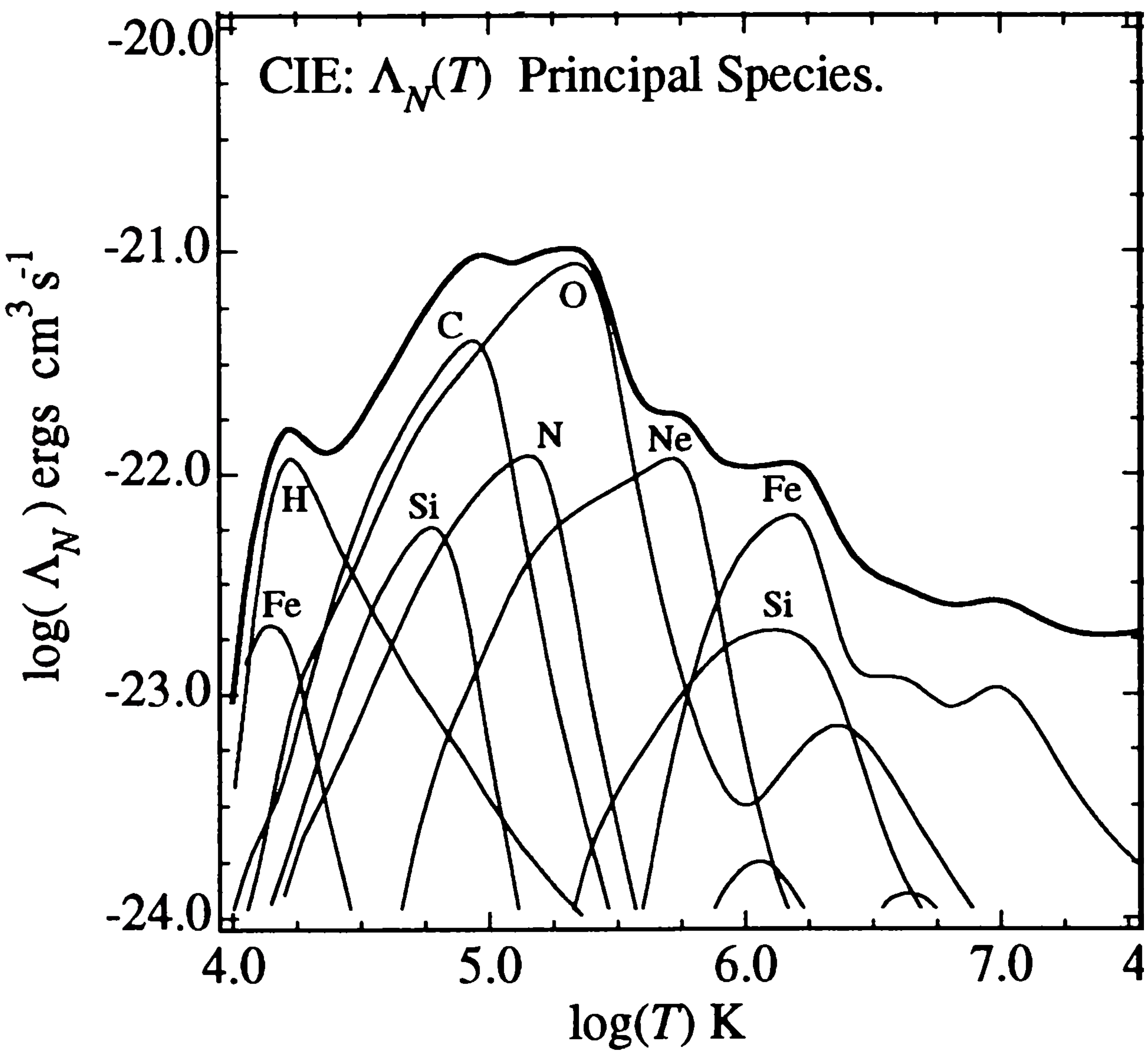


Metal-line cooling

- In reality: Gas is enriched by heavier elements (nuclear fusion)
- Cooling function is computed on an element-by-element basis

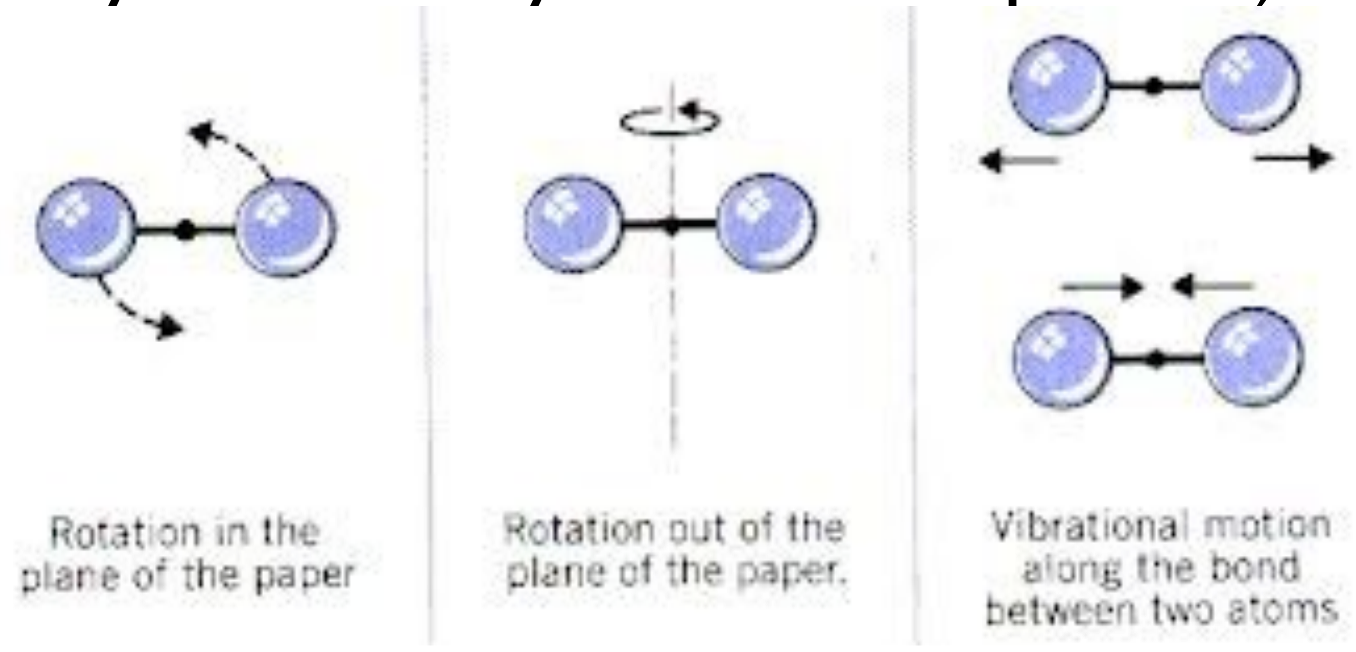
$$\Lambda = \Lambda_{\mathrm{H,He}} + \sum_{j>He} \Lambda_j$$

- Typically, 11 elements are traced in modern simulations
- Cooling via Bremsstrahlung mainly dominating above 3e7K
- Metals represent the main cooling channels for T < 1e7K, mostly via collisional excitation of O, C, Ne, Fe, Si, Mg
- Limited cooling below 1e3K, but going down to 1e2K



Molecular cooling

- At $T<1e4K$, e^- start to recombine, and $T<1e2$ K, most e^- recombined
  ➡Metal-line/atomic cooling drops continuously. Cooling still possible, but at reduced rate
- If molecules are present (H_2, CO) in the gas, collisional (de)excitation of their rotational/vibrational levels can also contribute to gas cooling at low T (not necessarily followed by emission of photon)



- Molecular clouds are birth places of stars, e.g. molecular cooling seems to be crucial for star formation
- But so far, molecular cooling hardly explicitly followed in fully cosmological simulations

Gas cooling in DM halos

General thoughts and analytic estimates

- Gravitational collapse of a perturbation produces a virialized object with an average density of roughly 200 x critical density (dark matter halos)
- For a given virial mass, we can calculate a characteristic radius R, velocity dispersion σ=GM/R, and virial temperature $T \sim GMm_p/(kR)$
- A plausible assumption: gas that participates in this collapse is heated to this virial temperature by shocks forming a gaseous halo, and one can then calculate a cooling time from the temperature and H density.

$$t_{\rm cool} = \frac{\rho e}{\mathcal{C}} = \frac{3nk_BT}{2n_H^2\Lambda(T)}$$

Cooling time and efficiency

- Cooling time regulates the cooling efficiency:
  - If/where cooling inefficient, the shocked gas will remain hot forming a hot gaseous halo in a hydrostatic equilibrium

$$\nabla P_g(\vec{r}) = -\rho_g(\vec{r})\nabla\Phi(\vec{r}) \qquad 1D: \ \frac{dP_g}{dr} = -G\frac{\rho_g M(r)}{r^2}$$

  - If/where cooling efficient, gas is cooling from a hot halo, looses its pressure support and falls onto the centre (shocked energy quickly dissipated)

How can we distinguish these two regimes?

Efficiency of cooling

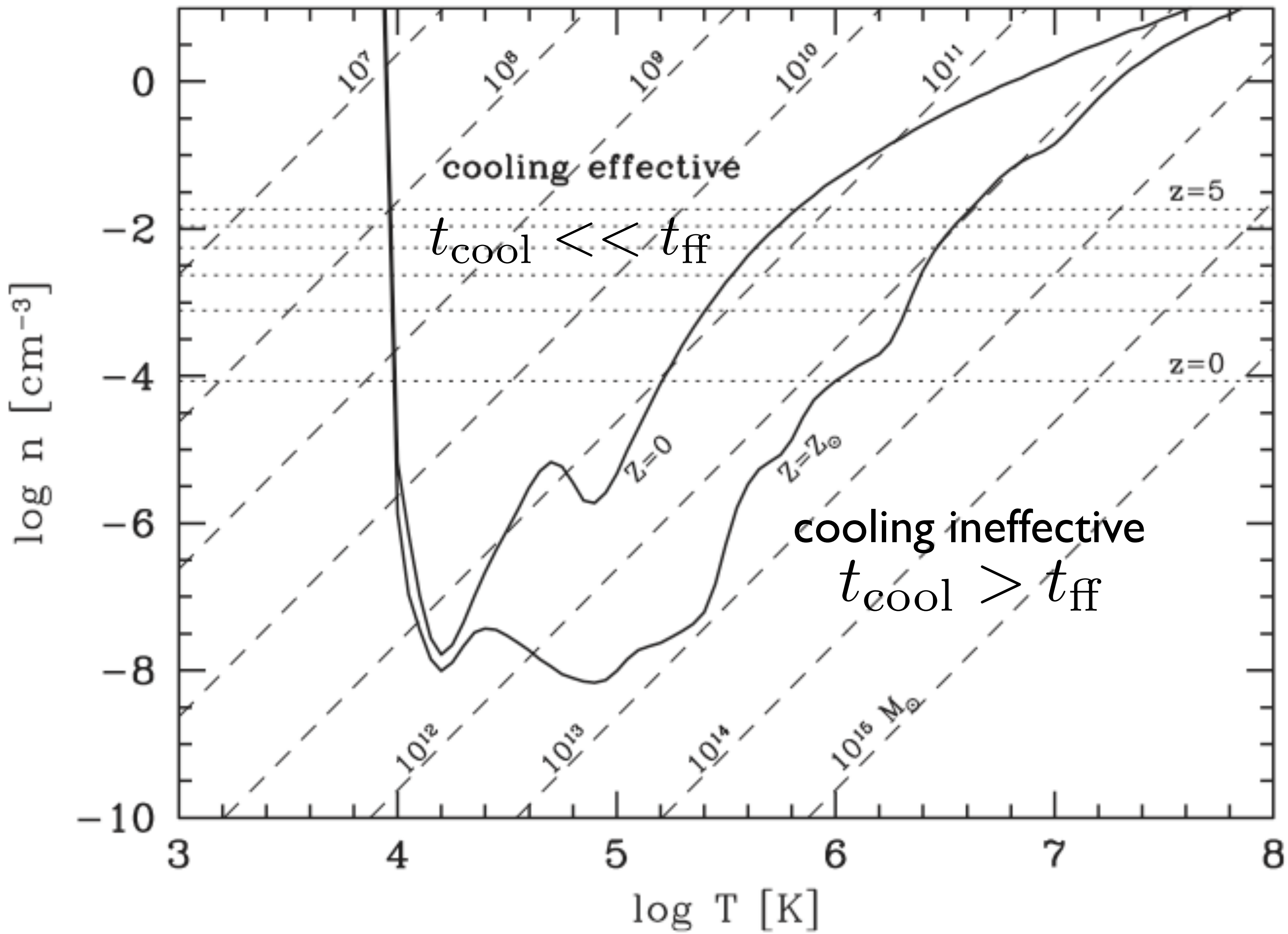
To quantify the efficiency of cooling, calculate cooling time and compare to free-fall time (collapse under own gravity)

- Consider a uniform spherical gas cloud in virial equilibrium
- The free-fall time scales as

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

- The cooling time scales as

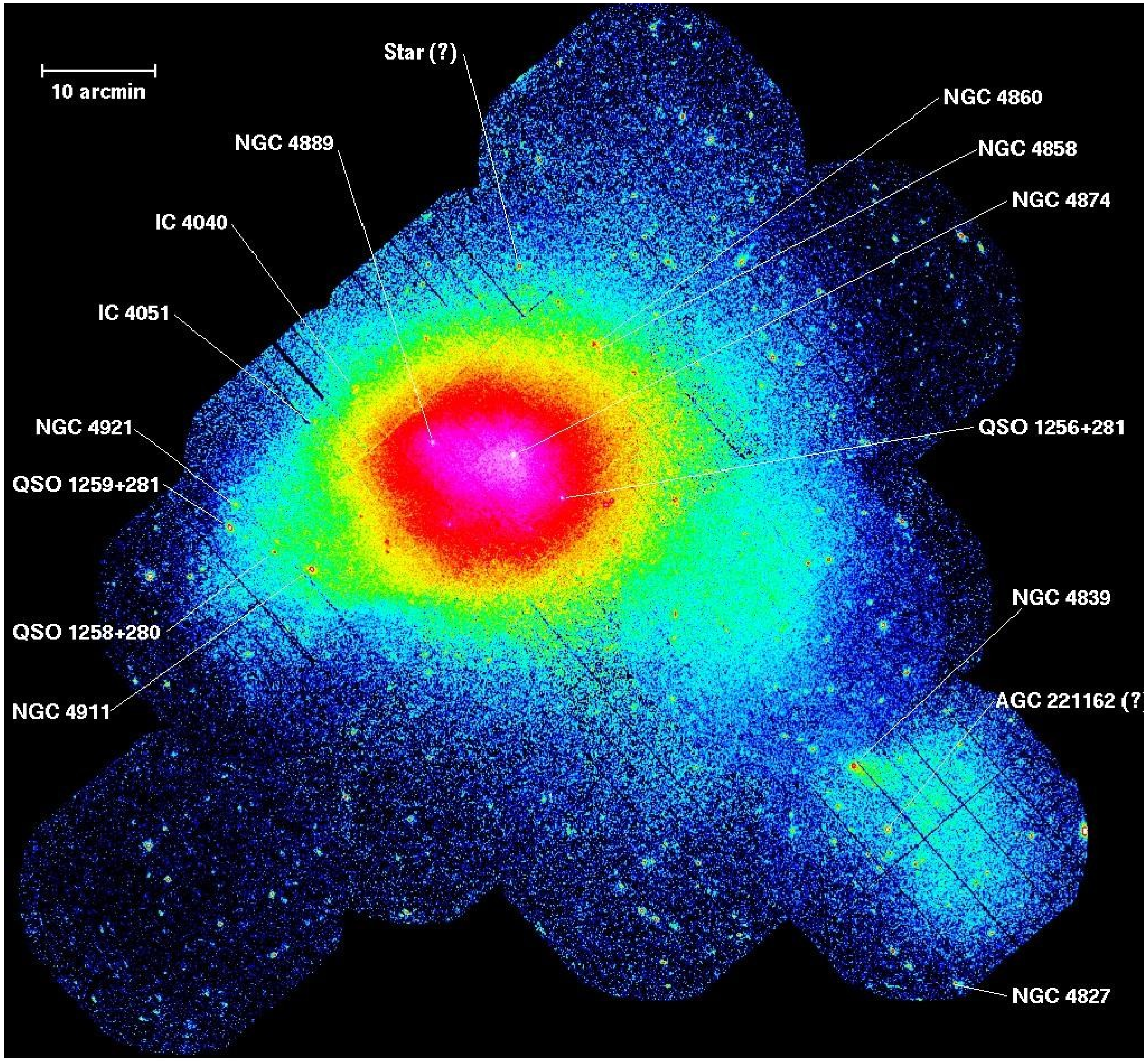
$$t_{\rm cool} = \frac{\rho e}{\mathcal{C}} = \frac{3nk_BT}{2n_H^2\Lambda(T)}$$



- Figure shows the locus of $t_{\rm cool}=t_{\rm ff}$ for $f_{\rm gas}=0.15$

Hydrostatic hot gas in clusters

Clusters exhibit a large amount of hot gas which is (partly) a consequence of the inefficient cooling…



Coma Cluster of galaxies

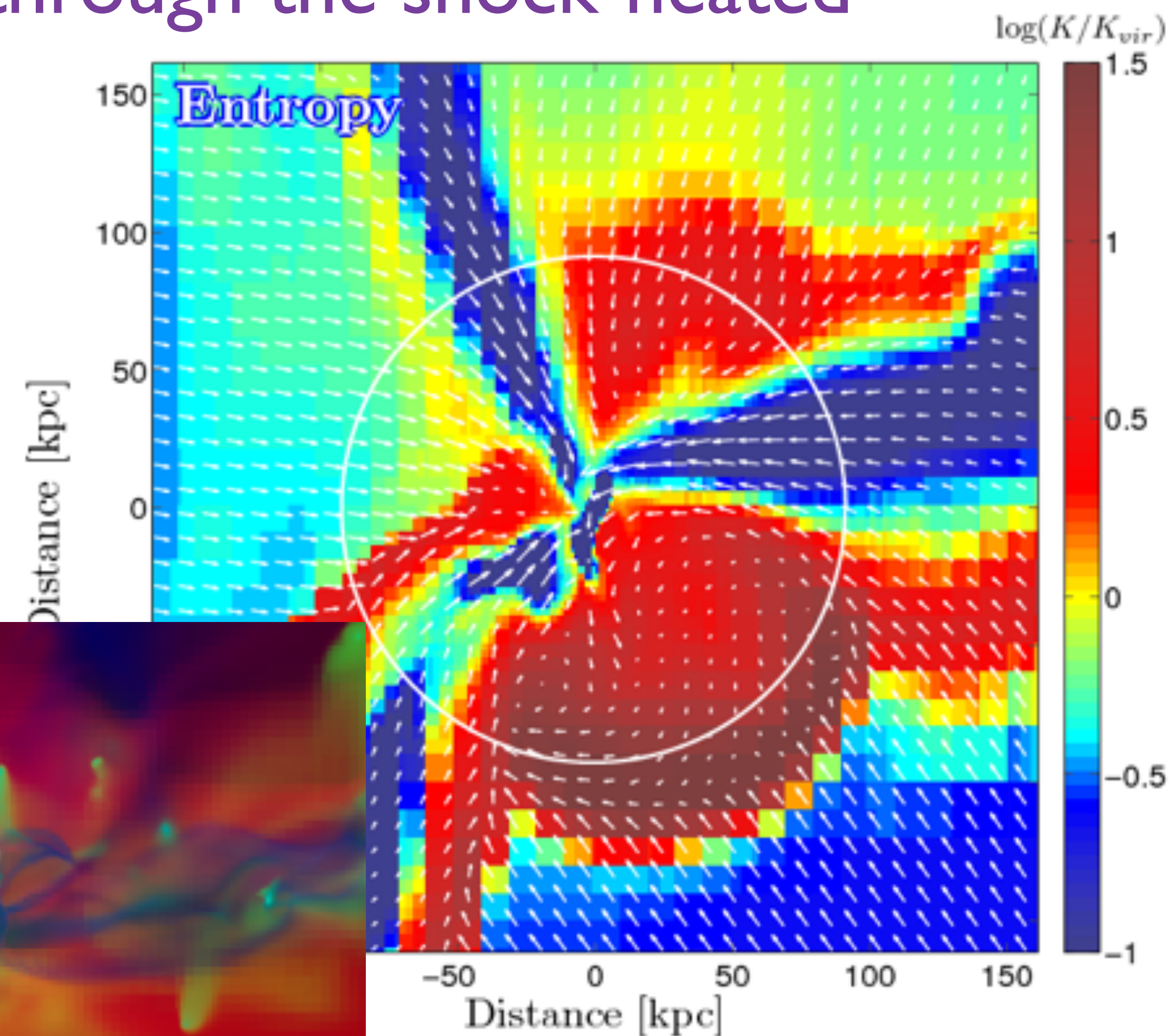
Image courtesy of U. Briel, MPE Garching, Germany

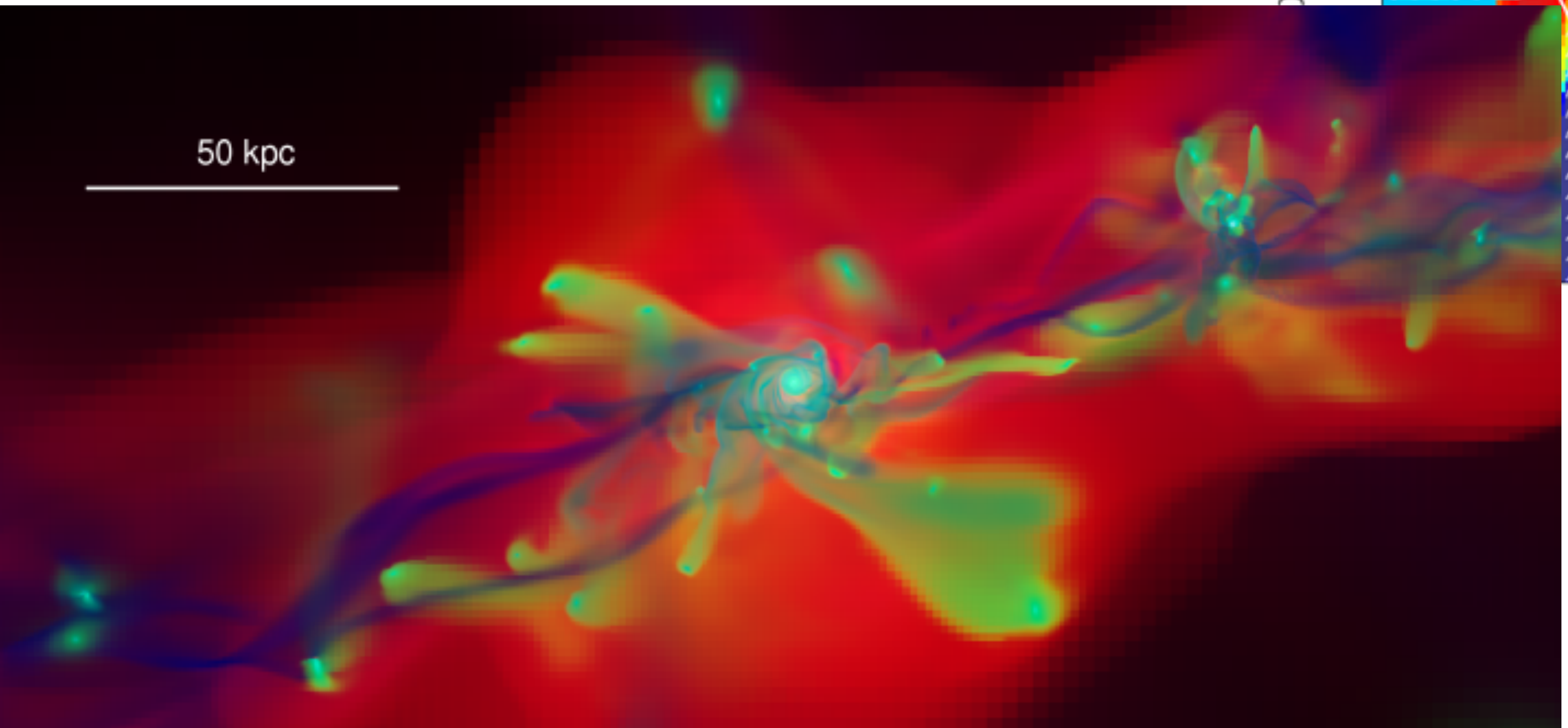
European Space Agency

Cold streams

Hydrodynamic simulations find that gas is often not accreted smoothly, but in cold streams

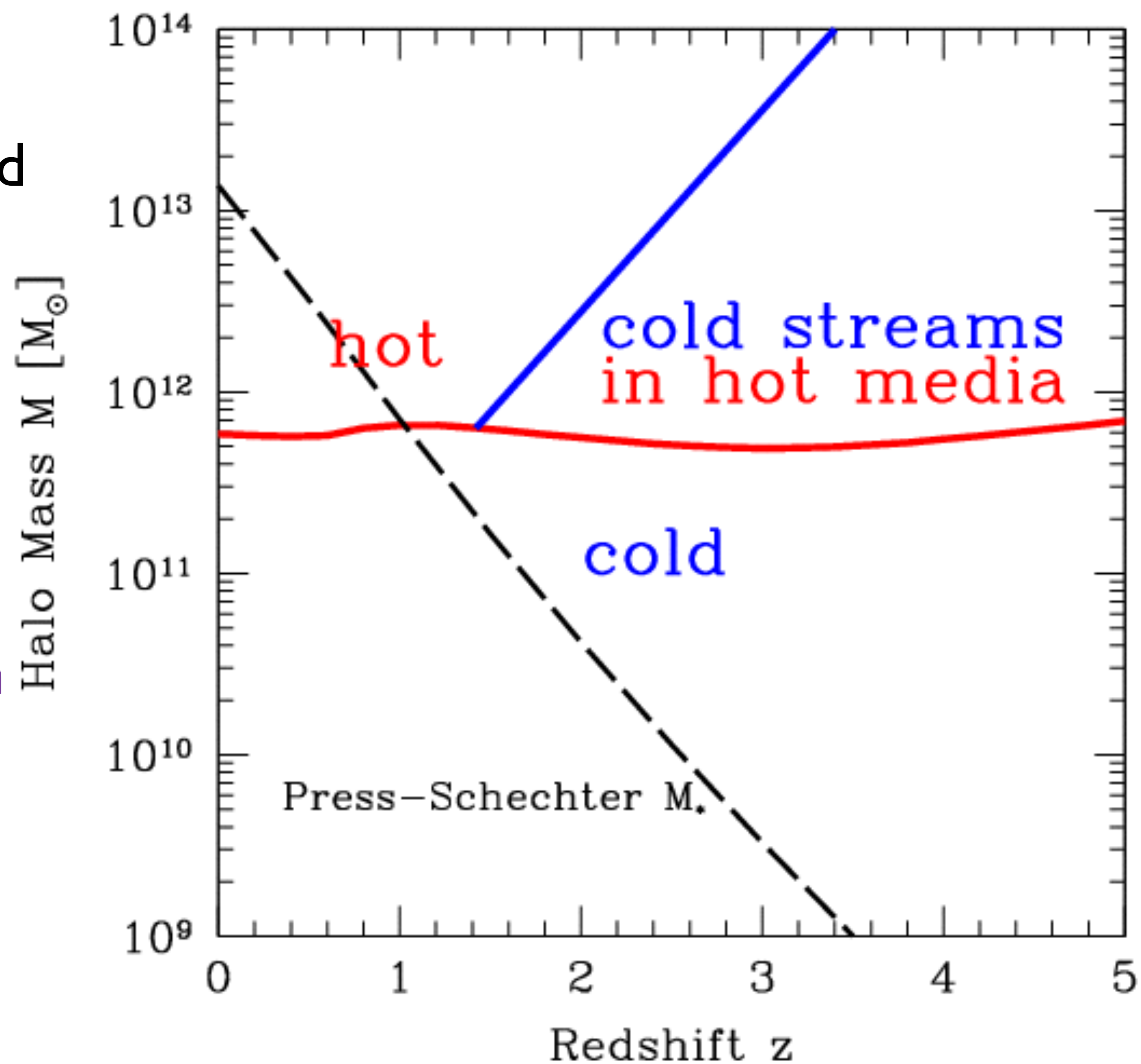
- Streams can penetrate effectively through the shock-heated media of DM halos
- Unlike major mergers, these flows can keep disks intact although rather thick and disturbed, and can e.g. fuel SF or central BH





When and where does gas cool?

- Below 10^{12} $M_\odot$ gas cools rapidly (free-fall time) and energy from shock-heating is dissipated rapidly
- Above 10^{12} $M_\odot$ gas is shock-heated to virial temperature and cools slowly, but still too much w/o any other energy source
- But at high z, cold streams can penetrate this hot medium even in massive halos
- Gas cooling particularly efficient in low mass halos (which predominantly form at high z) —> a large fraction of gas in the Universe can cool at high z
- Simplified picture, in reality a combination of processes occurs

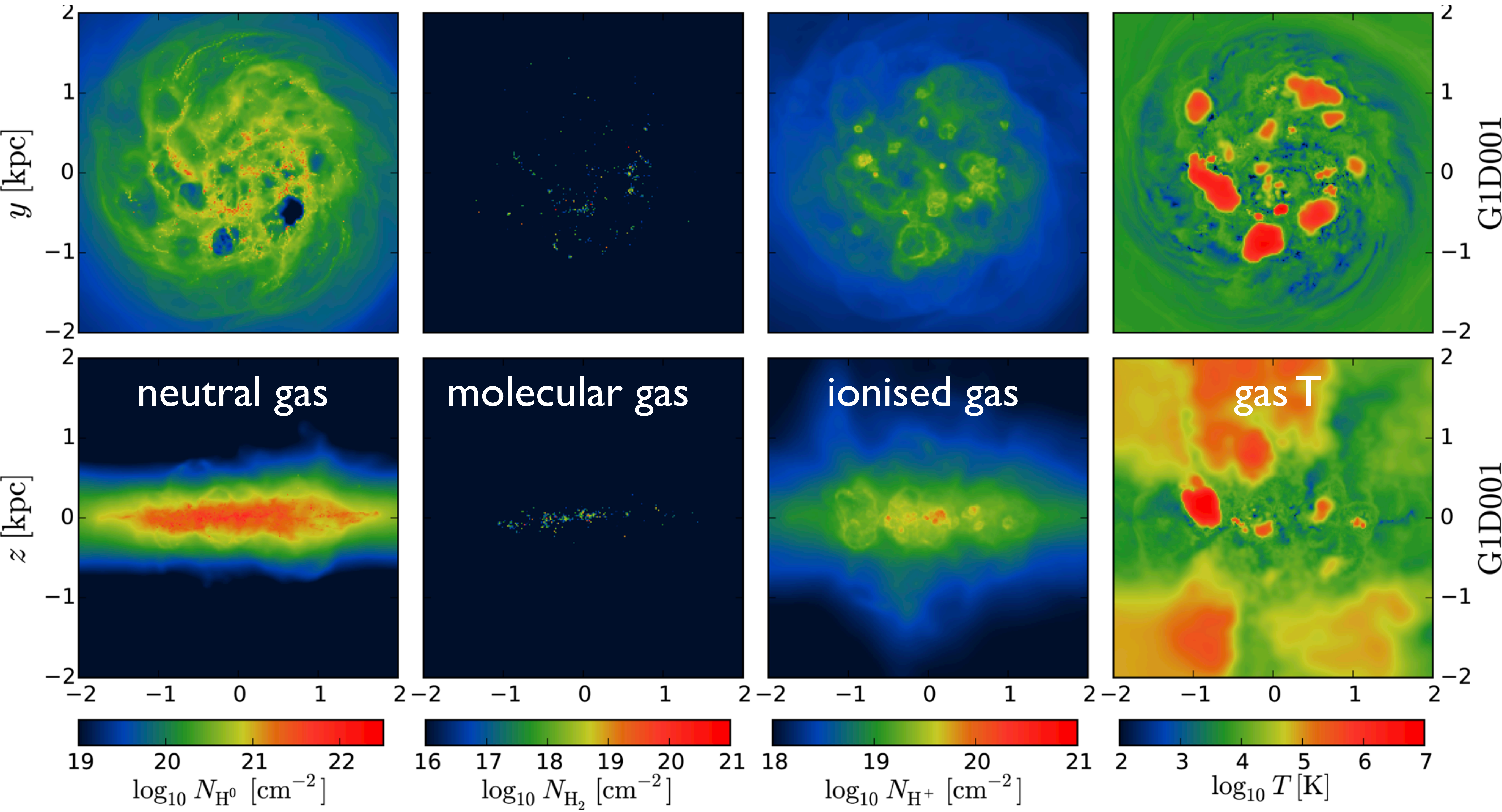


Caveat: If nothing prevents the cooled gas from forming stars $\Omega_{*,0} \sim \Omega_{bar,0}$:

Not observed

The complex interstellar medium

Multi-phase ISM in a simulated dwarf galaxy: inhomogeneous & complex structure!



Note: not only gas cooling, but also other processes (SF and stellar fb)

Cold gas dominates mass budget, warm/hot gas volume-filling

Summary — Gas cooling

- Modelling gas cooling and heating of the gas of a galaxy is important to obtain realistic multi-phase ISM.

- Gas can cool via
  (i) collisional/radiative processes of atoms, ions, electrons and molecules.
  (ii) adiabatic expansion

- Gas can be heated via
  (i) radiative processes
  (ii) shock-heating
  (iii) adiabatic heating

- Metals dominate the cooling between 1e3 and 1e7 K, molecules below 1e3 K, above 1e7 K Bremsstrahlung dominates

- Effective gas cooling in low-mass halos, cooling flows in massive halos at high z, hydrostatic hot halo in massive halos at low z

Outline of this lecture

- Gas cooling/heating
  - Cooling processes
  - Heating processes
  - Gas cooling in DM halos

- Star formation
  - Molecular clouds as sites for SF
  - Jeans instability
  - Phenomenological models
  - Different implementations of SF
  - Stellar populations
  - Chemical enrichment

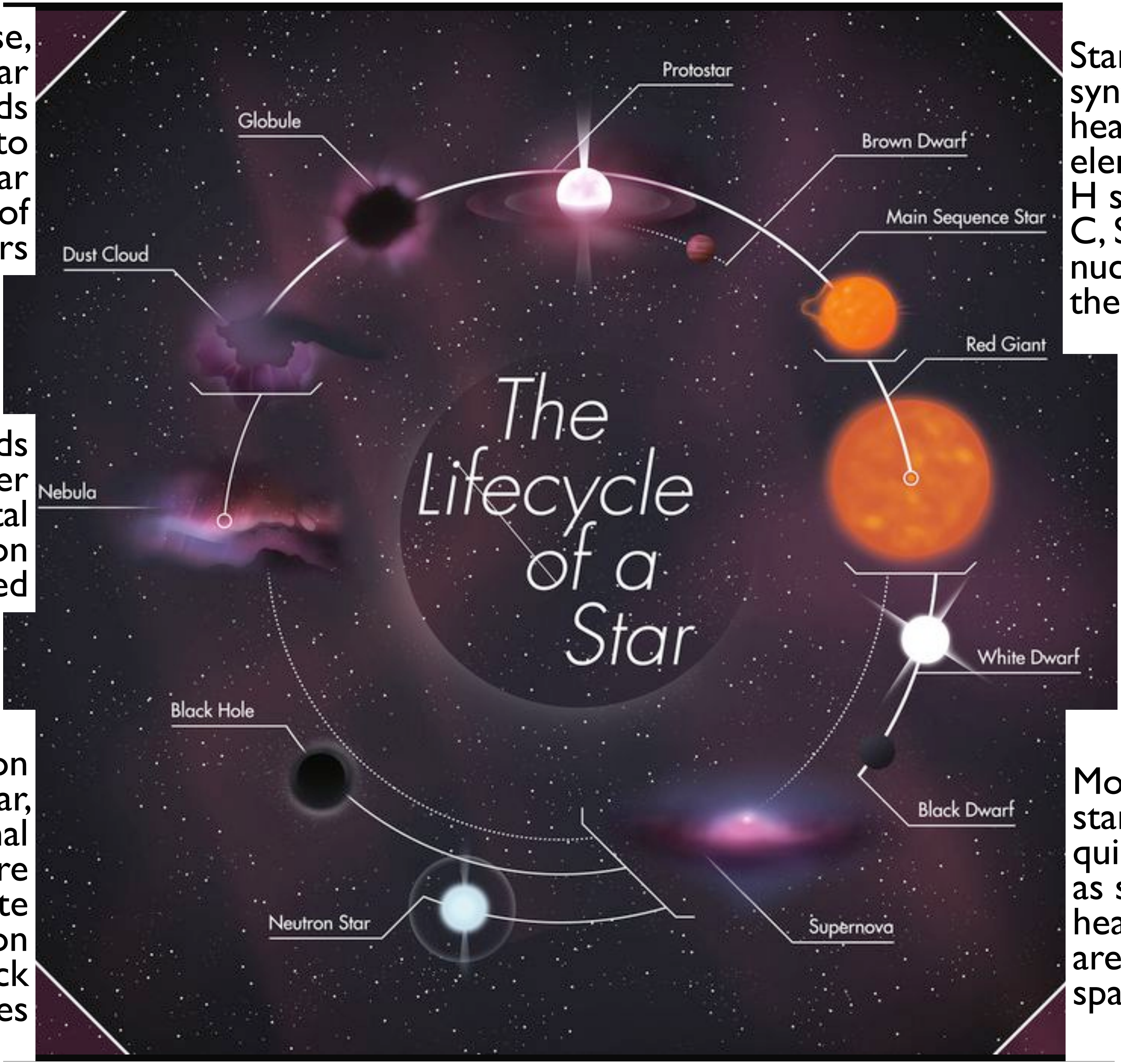
Star formation in a nutshell

Let's start with understanding what happens on small scales…

Dense, molecular clouds collapse to form stellar clusters of stars

New clouds with heavier metal composition are formed

Depending on mass of the star, different final stages are reached: white dwarfs, neutron stars or black holes



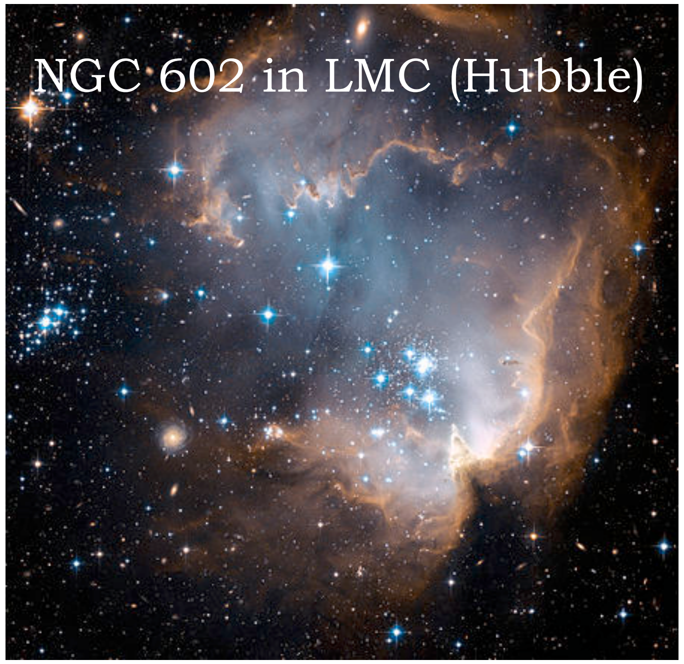
Stars synthesize heavier elements than H such as He, C, Si, Fe via nucleosyn-thesis

Most massive stars evolve quickly and die as supernovae – heavier elements are injected into space

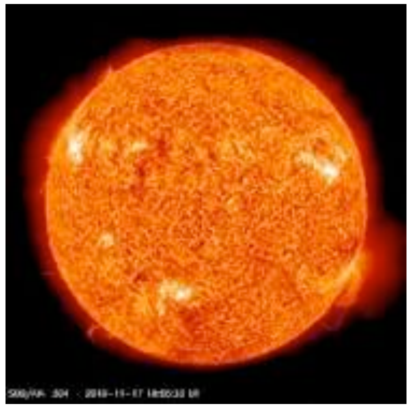
From molecular clouds to stars

Decrease spatial scale, increase in density

Density of a molecular cloud: few 100 particles/cm^3 ~ 1e-22 g/ccm
Size: ~ few 10s of pc



Size of a young cluster: ~1pc



Density of the sun: 1.4 g/cm^3
Size of the sun: $1.4*10^{10}$ cm ~ 1e-9 pc

•Contracting force: *GRAVITY*

•Opposing forces: several processes can work against gravity:
GAS PRESSURE
TURBULENCE
MAGNETIC FIELDS
RADIATIVE FEEDBACK

All that happens on scales which cannot be resolved in cosmological simulations of galaxy formation

Gravitational instability I

When does a cloud become gravitationally unstable so that it may collapse?

- **Collapse: gravitational force must overcome the gas pressure**
- James Jeans was the first to define a general criterion for stability (1902, 1929)
- Treat gas as an ideal gas at constant T
- Assume an infinite, static medium with an initial uniform ρ_0 and a uniformly isothermal (=const T) sound speed v_S
- Purely thermally/pressure supported
- Consider hydrodynamic equations and do linear perturbation analysis to see, if there exist unstable wave modes
- Temporal evolution of a small perturbation ρ_1 ($\ll\rho_0$), which induces the velocity field v_1 (v_0=0), pressure P_1 and the gravity field Φ_1

$$\rho = \rho_0 + \rho_1(r,t),\ \ P = P_0 + P_1(r,t) = v_s^2\rho,\ \ \Phi = \Phi_1(r,t),\ \ \vec{v} = \vec{v}_1(r,t)$$

Gravitational instability II

When does a cloud become gravitationally unstable so that it may collapse?

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} = -\frac{1}{\rho}\vec{\nabla} P - \vec{\nabla}\Phi$$ Euler

$$\frac{\partial \rho}{\partial t} + \vec{v} \cdot \vec{\nabla}\rho + \rho\vec{\nabla} \cdot \vec{v} = 0$$ Continuity

$$\nabla^2\Phi = 4\pi G\rho$$ Poisson

$$\rho = \rho_0 + \rho_1(r,t),\ \ P = P_0 + P_1(r,t) = v_s^2\rho,\ \ \Phi = \Phi_1(r,t),\ \ \vec{v} = \vec{v}_1(r,t)$$

- Resulting equations with linear perturbation:

$$\frac{\partial \vec{v}_1}{\partial t} = -\vec{\nabla}\left(\Phi_1 + v_S^2\frac{\rho_1}{\rho_0}\right)$$ Euler

$$\frac{\partial \rho_1}{\partial t} + \rho_0\vec{\nabla} \cdot \vec{v}_1 = 0$$ Continuity

$$\nabla^2\Phi_1 = 4\pi G\rho_1$$ Poisson

Gravitational instability III

When does a cloud become gravitationally unstable so that it may collapse?

- Start from Continuity equation and take the derivative to t:

$$\frac{\partial^2 \rho_1}{\partial t^2} + \rho_0 \vec{\nabla} \cdot \frac{\partial \vec{v}_1}{\partial t} = 0 \qquad \frac{\partial \vec{v}_1}{\partial t} = -\vec{\nabla}\left(\Phi_1 + v_s^2 \frac{\rho_1}{\rho_0}\right)$$

- Insert Euler into Continuity equation:

$$\nabla^2 \Phi_1 = 4\pi G \rho_1$$

$$\frac{\partial^2 \rho_1}{\partial t^2} = \rho_0 \vec{\nabla} \cdot \left[\vec{\nabla}\left(\Phi_1 + v_s^2 \frac{\rho_1}{\rho_0}\right)\right]$$

- With the Poisson equation, we obtain (similar to "growth equation"):

$$\frac{\partial^2 \rho_1}{\partial t^2} = 4\pi G \rho_0 \rho_1 + v_s^2 \nabla^2 \rho_1 \qquad \text{(I)}$$

- To solve the above equation, we can try a plane wave:

$$\rho_1 = \exp\left[i\left(\frac{2\pi x}{\lambda} - \omega t\right)\right]$$

Jeans length and mass

- Inserting ρ_1 into eq. (I), we obtain the DISPERSION RELATION:

$$\omega^2 = v_s^2 \left(\frac{2\pi}{\lambda}\right)^2 - 4\pi G \rho_0$$

- Instability, when $\omega^2 < 0$, i.e. for large λ

Jeans length and mass

- Inserting ρ_1 into eq. (I), we obtain the DISPERSION RELATION:

$$\omega^2 = v_s^2 \left(\frac{2\pi}{\lambda}\right)^2 - 4\pi G\rho_0$$

- Instability, when $\omega^2 < 0$, i.e. for large λ

JEANS LENGTH: Critical wavelength, at which the wave grows exponentially, corresponds to a critical length scale, at which a gas cloud collapses under self-gravity:

$$\lambda_J = \sqrt{\frac{\pi}{G\rho_0}} v_s$$

JEANS MASS: equivalent critical mass, associated with the Jeans length such that:

$$M_J = \frac{4\pi}{3}\rho_0 \left(\frac{\lambda_J}{2}\right)^3 = \frac{\pi}{6}\rho_0 v_s^3 \left(\frac{\pi}{G\rho_0}\right)^{3/2} \propto \frac{v_s^3}{\sqrt{\rho_0}} \propto \sqrt{\frac{T^3}{\rho_0}}$$

Minimum mass above which gas becomes unstable

Jeans length and mass

JEANS MASS: equivalent critical mass, associated with the Jeans length such that:

$$M_J = \frac{4\pi}{3}\rho_0 \left(\frac{\lambda_J}{2}\right)^3 = \frac{\pi}{6}\rho_0 v_s^3 \left(\frac{\pi}{G\rho_0}\right)^{3/2} \propto \frac{v_s^3}{\sqrt{\rho_0}} \propto \sqrt{\frac{T^3}{\rho_0}}$$

For a GMC of "ideal" gas with T = 20K & $\rho_0 = 10^3$ molecules/cm^3

$$\rightarrow \; M_J \sim 10 M_\odot$$

This would imply that giant molecular clouds ($M \sim 10^4\, M_\odot$) are highly Jeans unstable, yet they do not form stars at high rate with high efficiency

WHY?

Jeans approximation and low SF efficiency

Giant molecular clouds ($M \sim 10^4 M_\odot$) do not form stars at high rate with high efficiency because of oversimplified assumptions in Jeans approximation:

•No extended, uniform and static clouds observed

•Because Jeans mass drops with increasing density, a collapsing cloud will fragment further and further rather than collapse into one object

•Only gas pressure support against gravity considered, but other means of support such as

— Indications for (supersonic) turbulence

— Additional magnetic field pressure

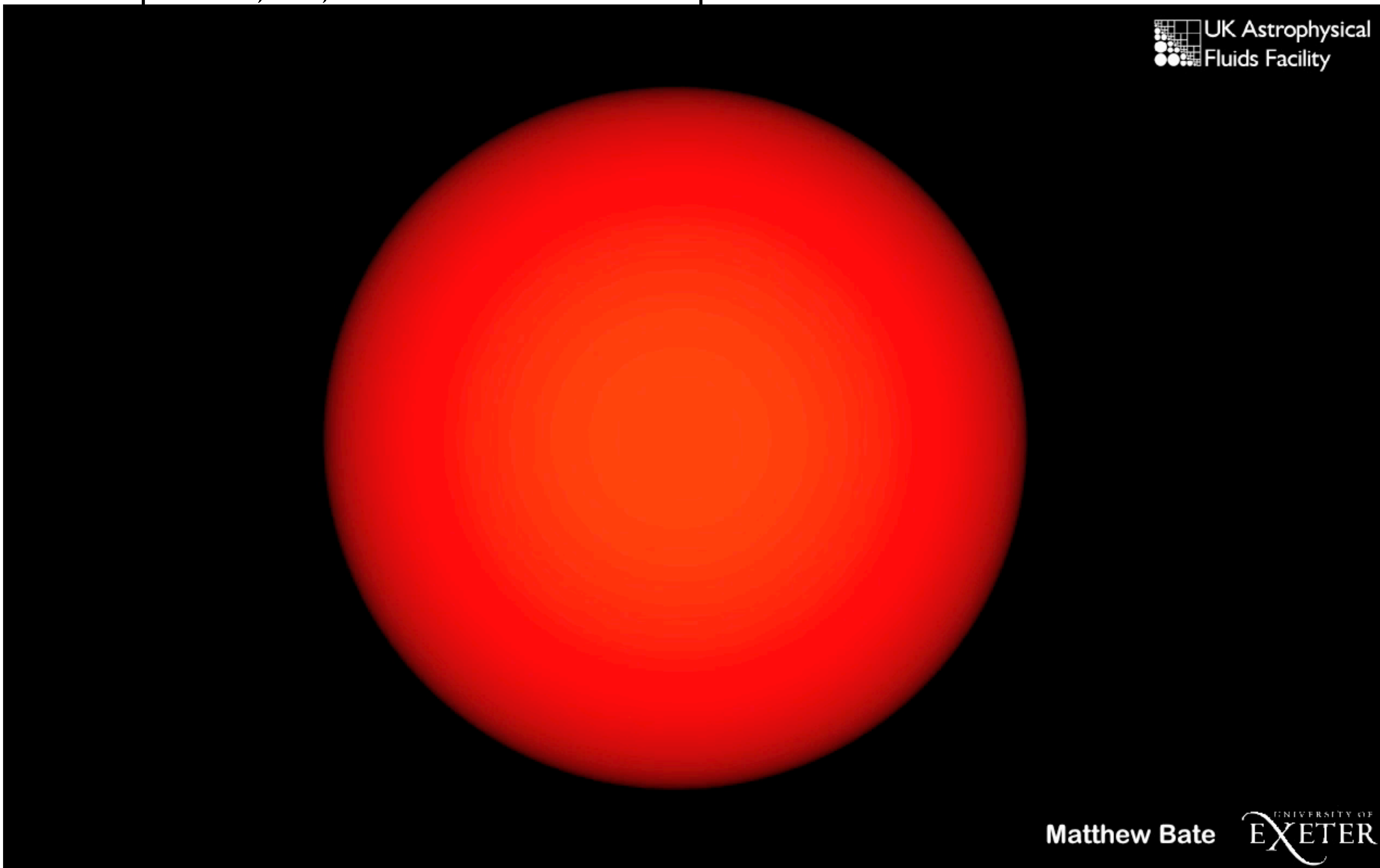
— radiative feedback from young stars

Understanding why the overall SF efficiency of GMCs (revealed by observations) is so low, is one of the most important questions for our understanding of star formation.

How stars may form…

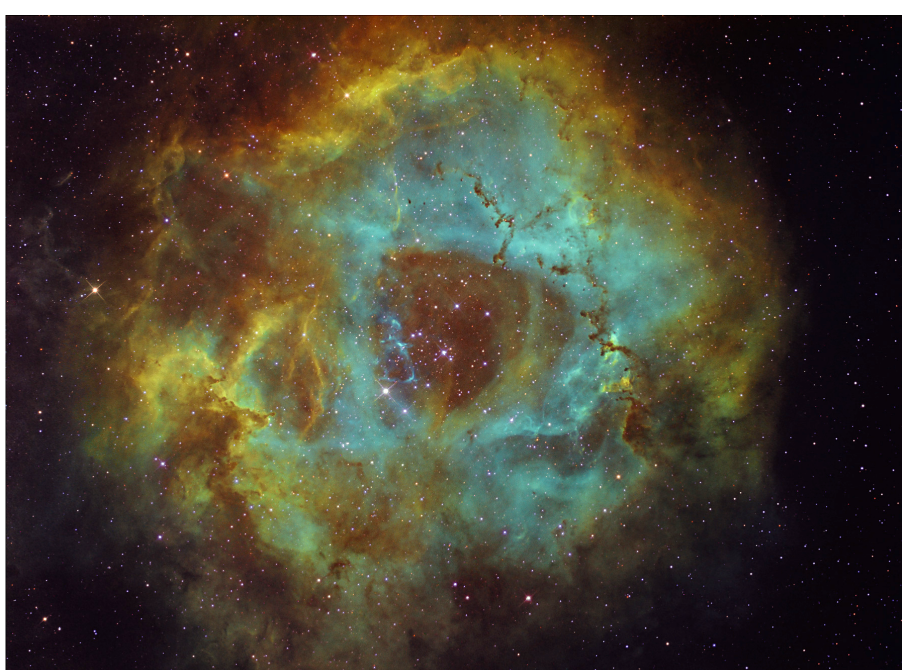
... from a collapsing gas cloud of 500 $M_\odot$ & 0.8 pc diameter at initial T of10K (M_{Jeans}~1$M_\odot$):

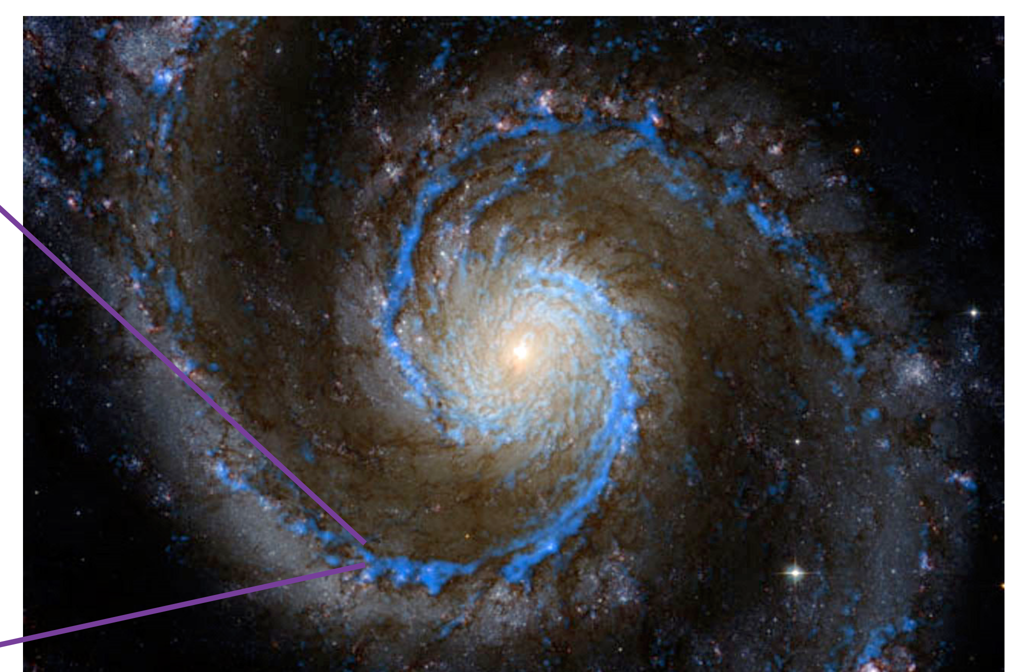
- numerically solving gravity & hydrodynamical equations
- starting with a supersonic velocity field, ran for two free-fall times ~2.5e5yrs
- 35 Mill. particles, 100,000 CPU hours ran on 16 processors



What drives star formation in a galaxy?

- The total star formation in a galaxy is related to a superposition of GMC formation and of the SF efficiency in GMCs
- The SF efficiency in GMC is regulated by magnetic fields, super-sonic turbulence and self-regulation (via feedback from OB stars mainly)
- What triggers GMC formation? — Two plausible scenarios:
  - Cooling and molecule formation in gas that triggers gravitational collapse
  - Cooling and molecule formation is a consequence of a gravitationally unstable or turbulent gas (e.g density waves in spiral arms or galaxy interactions and mergers)





How to model star formation in a hydro sim?

How can we model such a complex star formation process on galaxies scales in a cosmological context?

- Relevant scales cannot be resolved in cosmological simulations (>100pc vs subpc scales!)
  - We need an effective "sub-resolution" model for SF
  - Full theory/description is still missing, so we cannot (yet) derive a SF law self-consistently from small-scale sims
  - Derive phenomenological models from observations similar to SAMs — How was it done there?
  - Improvement compared to SAMs: follow the spatial resolution of SF due to the modelling underlying gas flows (detecting regions with high density)

Empirical SF laws

- Observations of disk galaxies show a relation between gas and SFR surface density, mostly happening in the spiral structure

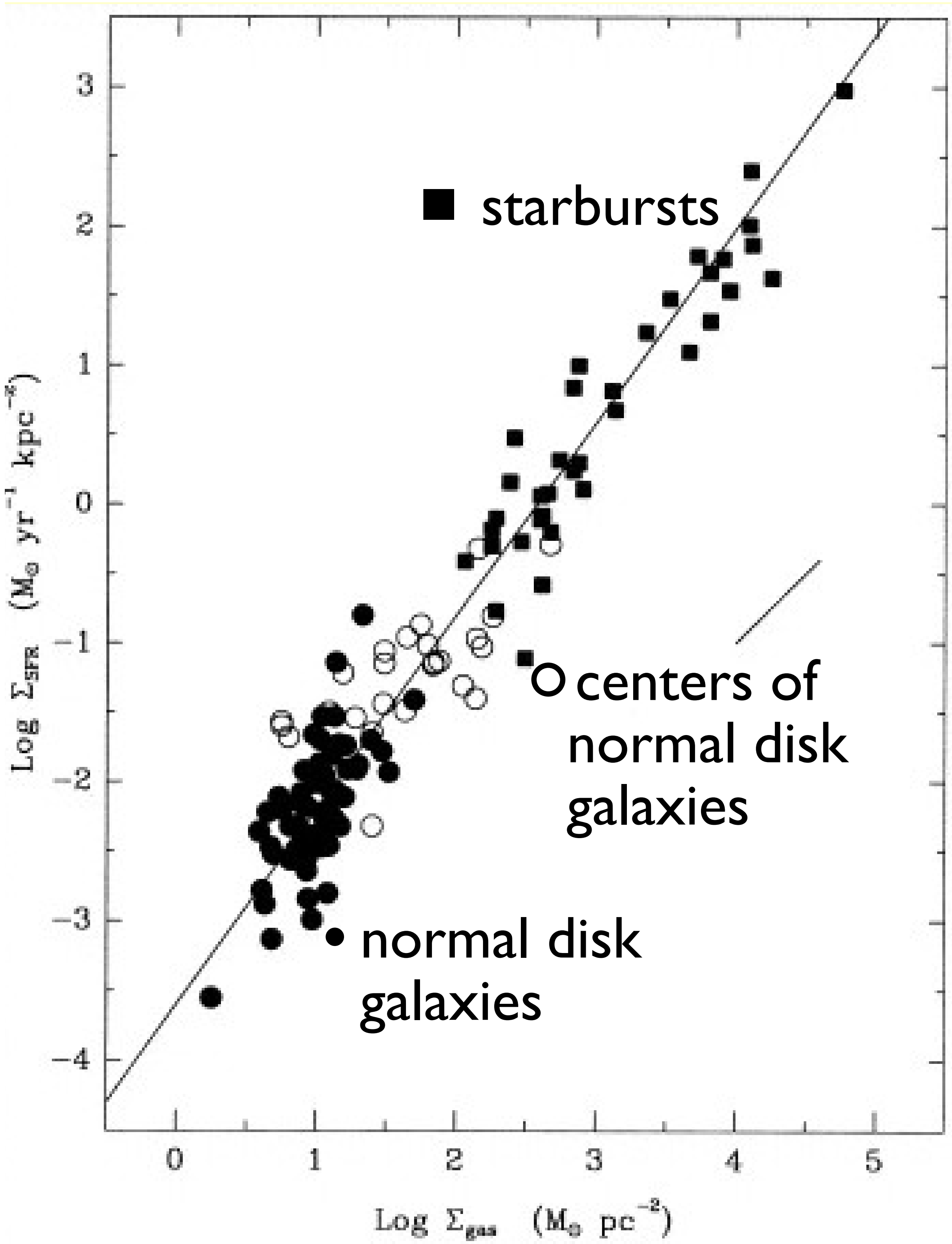
- Schmidt relation

$$\frac{d\Sigma_*}{dt} = \Sigma_{\rm SFR} = A_{\rm SF} \cdot \Sigma_{\rm gas}^{N_{\rm SF}}$$

with N_{SF} ~ 1.4

- Often interpreted as indicating that the SFR is controlled by self-gravity of the gas

$$\frac{d\rho_*}{dt} = \epsilon \frac{\rho_g}{t_{\rm sf}}$$



SF efficiency and time-scale

- Parameters of SF law ε and t_{sf} are tuned to observed Schmidt relation $$\frac{d\rho_*}{dt} = \epsilon \frac{\rho_g}{t_{\rm sf}}$$
- How to choose the SF time-scale?
  - When we have a gravitational collapse, assume that all gas is turned into stars on a free-fall time-scale

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}} \rightarrow \dot{\rho}_* \propto \frac{\rho_g}{t_{\rm ff}} \propto \frac{\rho_g}{\rho_g^{-1/2}} \propto \rho_g^{3/2}$$

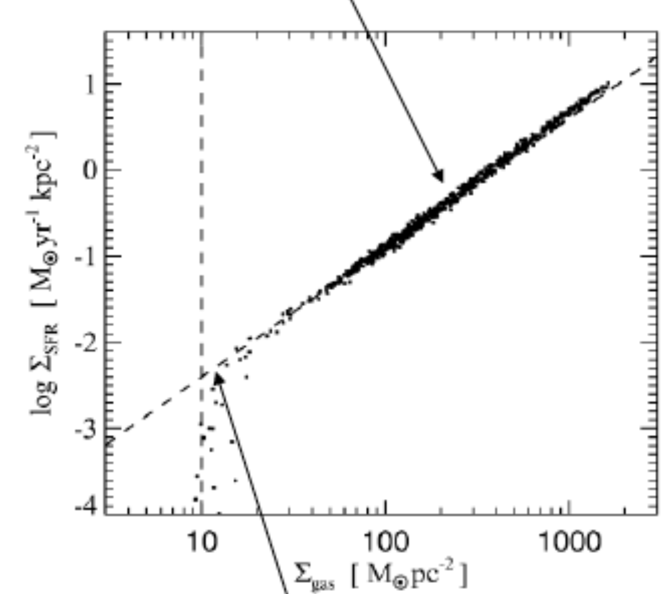
  - However, to form stars gas must be able to cool t_{SF} = max(t_{ff}, t_{cool}), leads to somewhat lower slope in good agreement with observations
  - Very similar to observed Schmidt-Kennicutt relation with the slope 1.4

- SF efficiency ε is set according to the normalisation of the observed Schmidt-relation (ratio of free-fall time-scale to gas consumption time-scale)

How to form star particles

- Implementation of SF: Once we adopt a SF model, we need to turn gas particles into stars
  - Stochastically, a gas particle (meeting the conditions to be SF) is turned into a star with a given probability
- For global Schmidt law, SFR of the gas is $\dot{m}_* = \epsilon m_g / t_{\rm SF}$
- For each timestep, compute probability p for turning a gas particle into a star particle (such that the total formed stellar mass is not overestimated)
- Draw random number between 0 and 1, if r < p then gas particle is converted into a star particle
- New star particle will have the same position, velocity, mass (1e3-1e8Msun) and metallicity as the gas particle/cell
- Subsequently, they are followed as collisionless particles interacting only via gravitation along with DM particles using N-body techniques

SF rate as a function of gas surface density in a controlled simulation of a gas disk

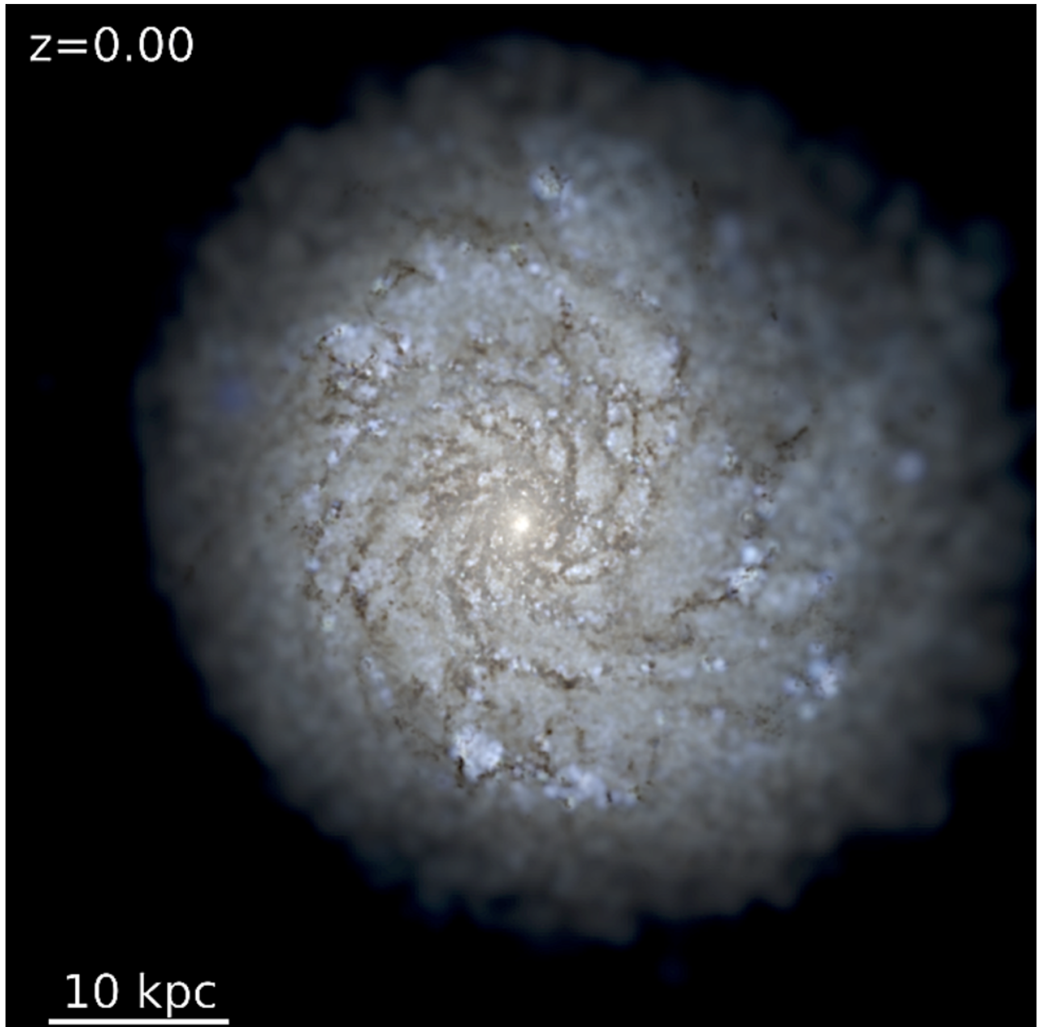


observed law (Kennicutt 1998)

Springel & I

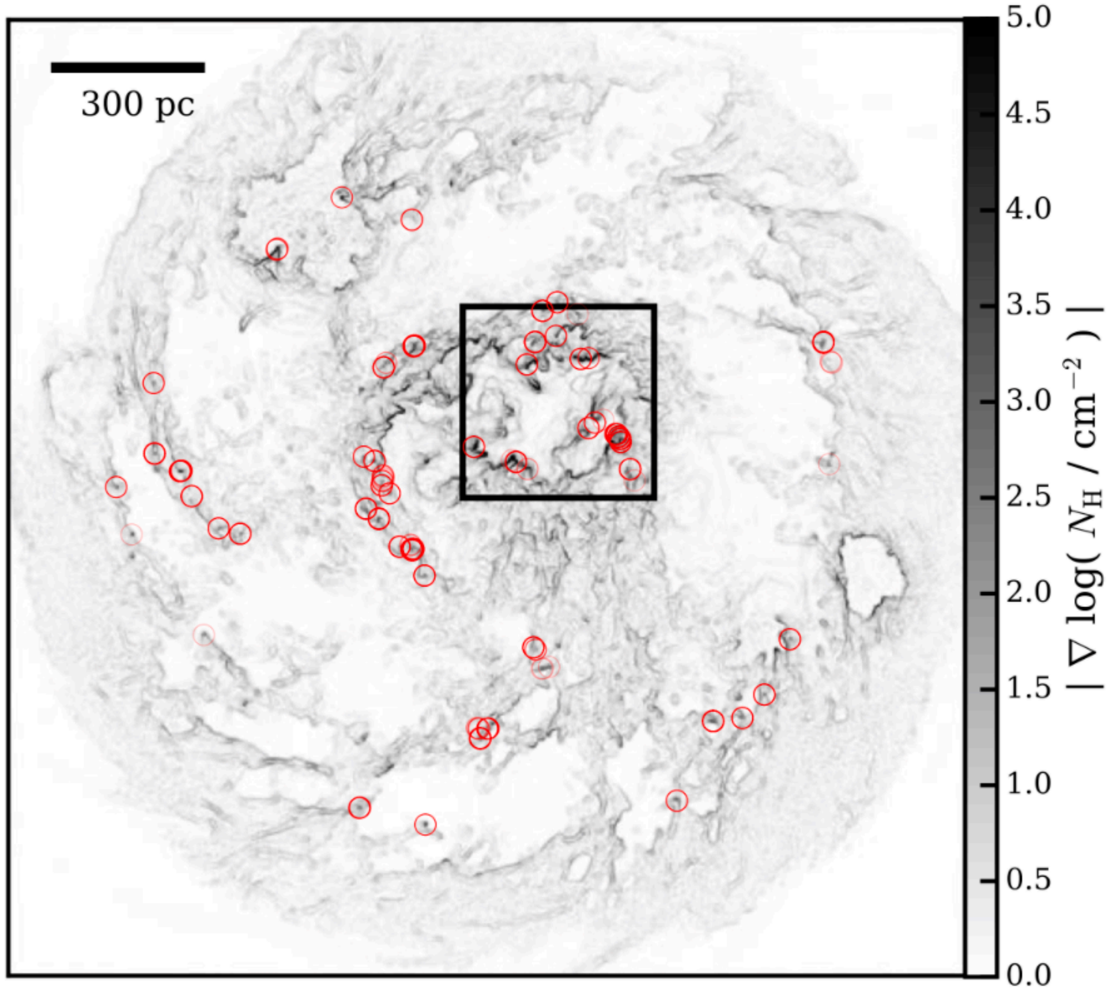
SF from "resolved" GMCs

- Performing cosmological zoom-in simulations allows now to go to very high resolution thanks to increasing computational power
- "FIRE" simulations (Hopkings+14): high enough spatial resolution of ~10pc, to start to resolve GMCs and their Jeans mass/length
- High SF threshold
- Identify locally self-gravitating regions as sites of star formation
- Calculate the molecular fraction (based on the gas pressure)
- Turn that gas fraction into stars over a free-fall time-scale
- In these simulations, since the structure of the ISM is better resolved, SF efficiency not set by hand (not tuned to observations) but regulated be feedback (next lecture)

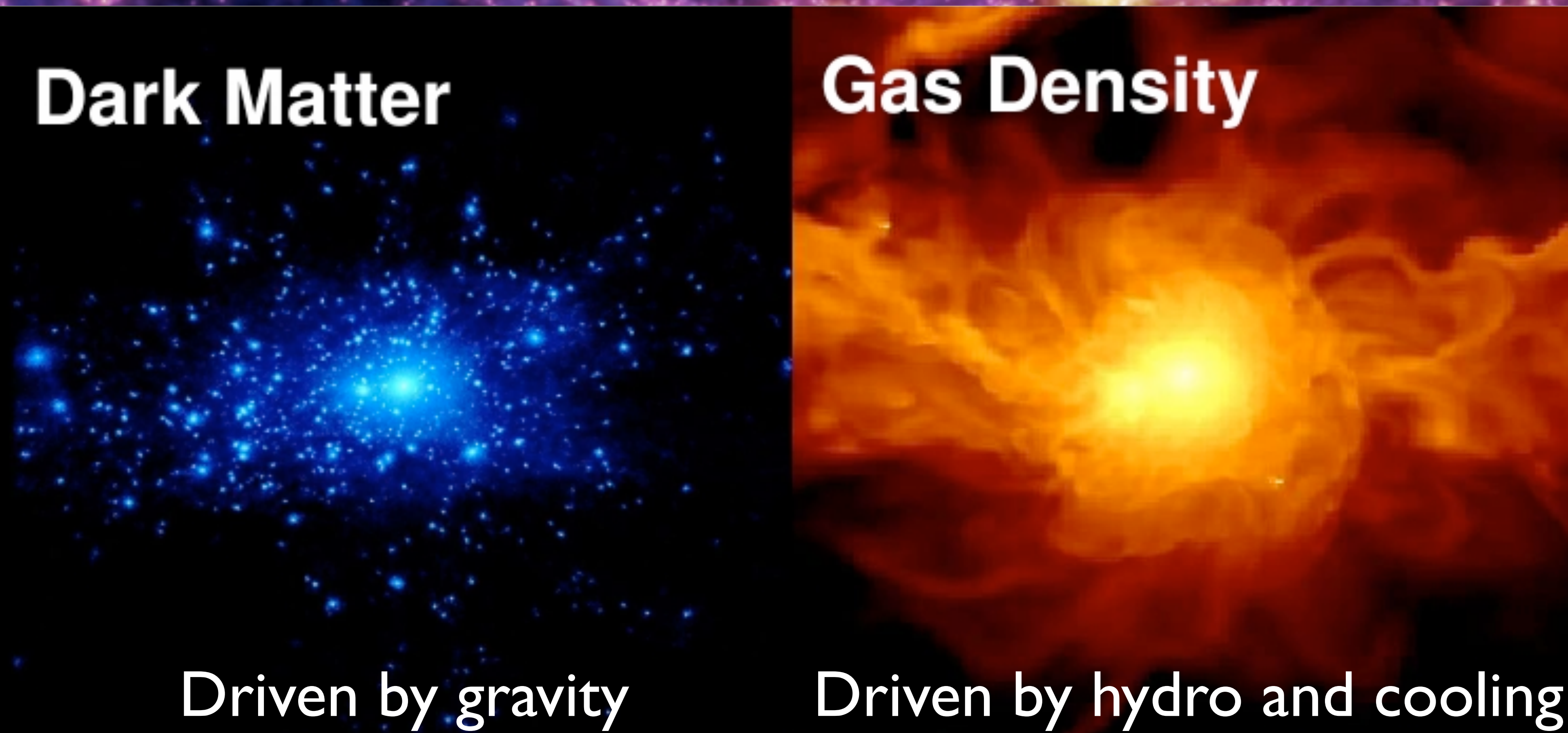


Resolving individual massive stars

- LYRA simulations of Gutcke et al. 2022: Cosmological zoom-in simulations of dwarfs at high redshifts: resolve molecular clouds so that one can follow **formation of individual massive stars (4 M_{sun}) via sampling the IMF and tracking their lifetimes and death pathways individually.**
- Major achievement: first simulation with individual stars within a full cosmological context
- Only for low-mass dwarfs, but high accuracy.



Stars are what we observe!



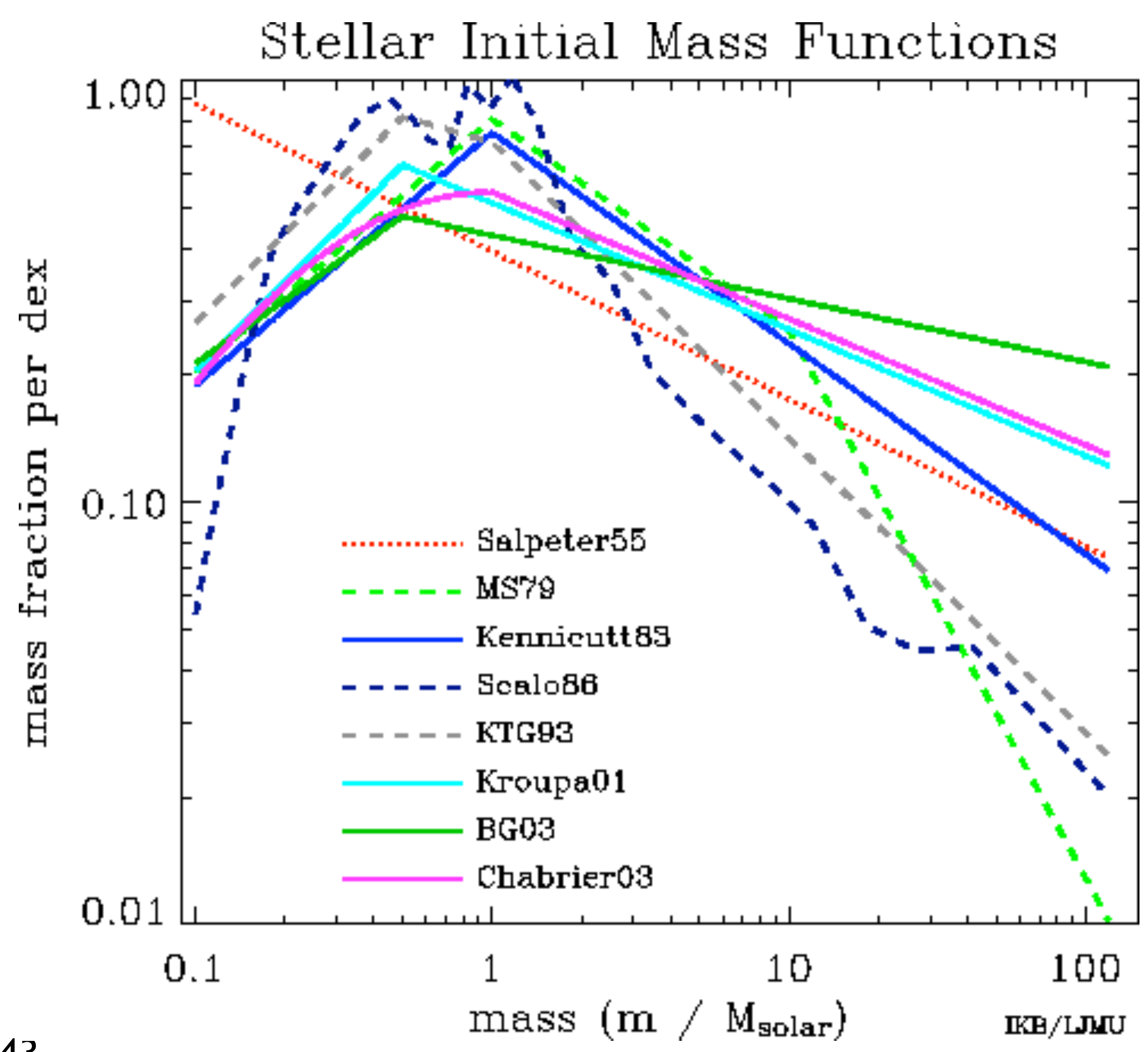
Simulation of
a galaxy cluster

8 Mpc

- Stars are in fact that what we observe!
- Less substructure than in DM halo
- Now we can study morphologies, stellar kinematics, stellar population properties, stellar sizes

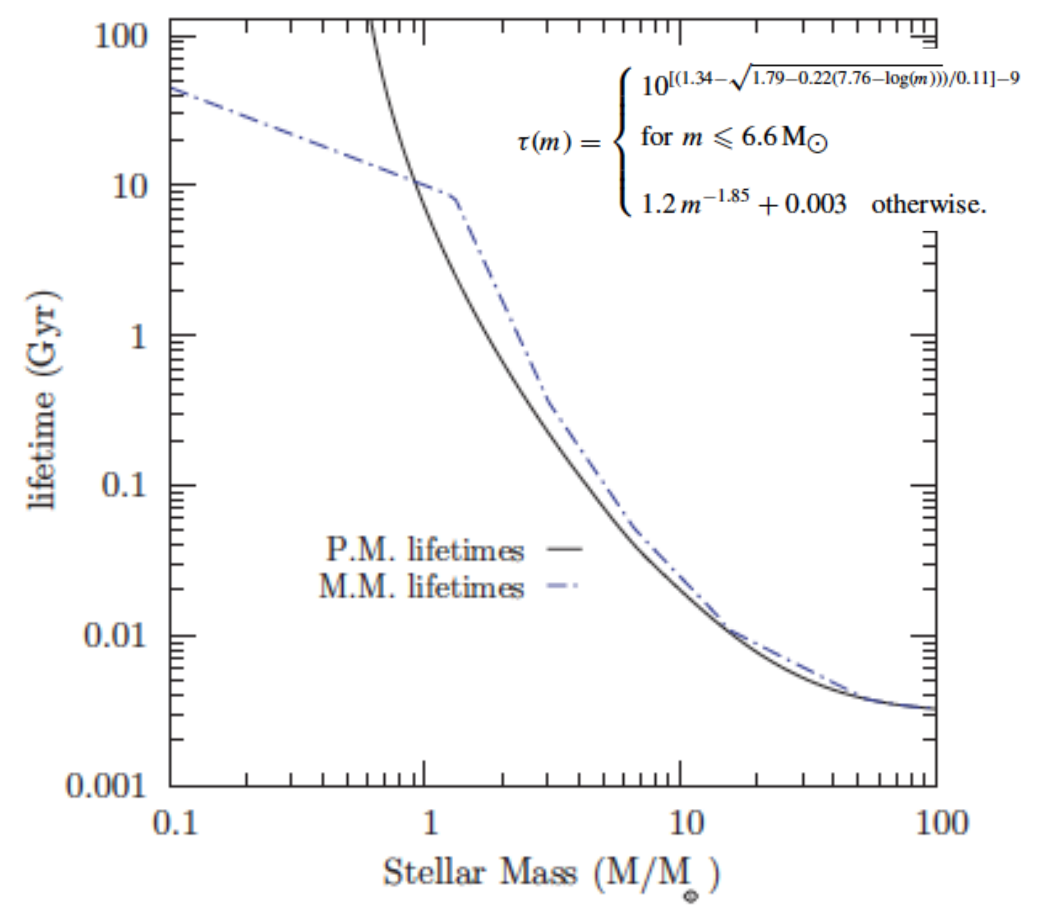
Star particles as stellar populations

- One star particle in most simulations ranges from ~10^3-10^8 $M_\odot$
- One star particle is considered as a simple stellar population with a mass distribution given by the initial mass function (IMF)
- A star particle/simple stellar population is further characterised by its age t_{age} (=time since birth, i.e. conversion into a star particle) and by its metallicity Z



Modelling chemical enrichment

- We can compute at any time for every star particle (=SSP) how many stars are dying as SNII and SNIa or under-go an AGB phase, given
  - Initial mass function
  - Life time distribution of stars of a given mass
  - Metal yields for SNIa&II/AGB (tabulated from theor. calculations)
  - Rate of exploding SNII and SNIa per time step (typically 10% & 2%)
  - Delay time distribution for SNIa, first stars explode after ~50Myr
- Low-intermediate mass stars 0.8-8$M_\odot$: AGB stars and SNIa (~2% of binaries)
- Massive stars > 8$M_\odot$: SNII (10%)
- The corresponding metals are returned to the ISM in 10s of Myr time steps
- Mass of a star particle is reduced by overall stellar mass loss at each time step
- Chemical elements are distributed to the gaseous neighbours of the star particles within the kernel



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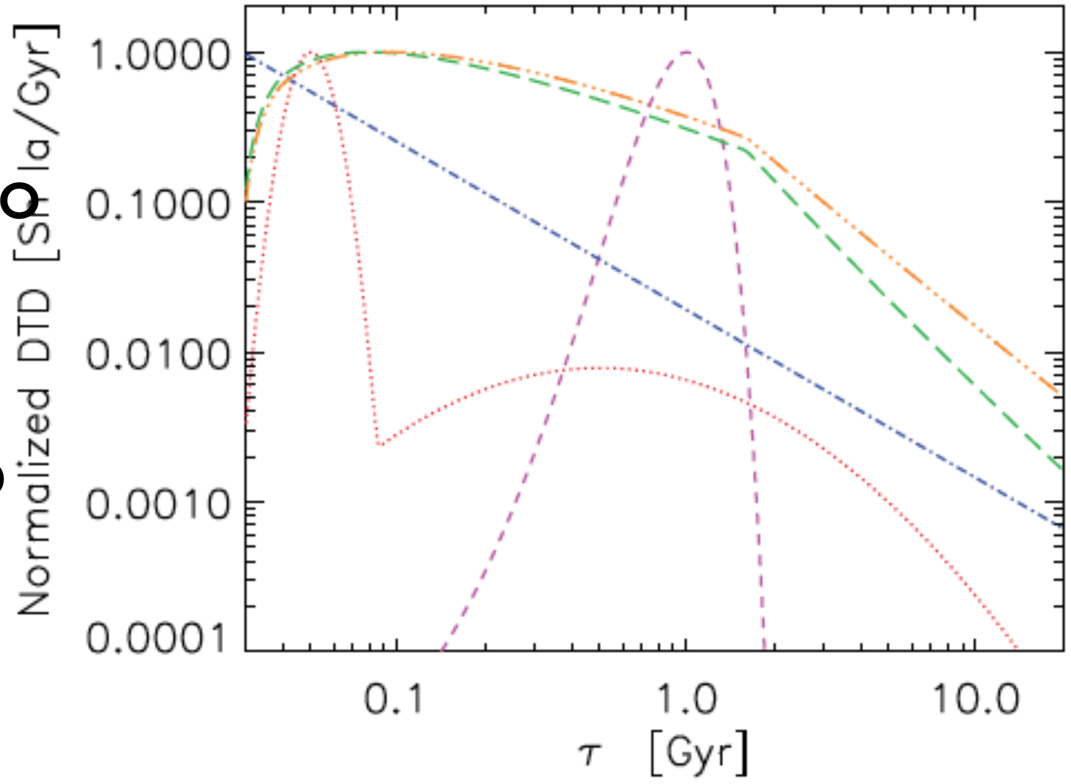

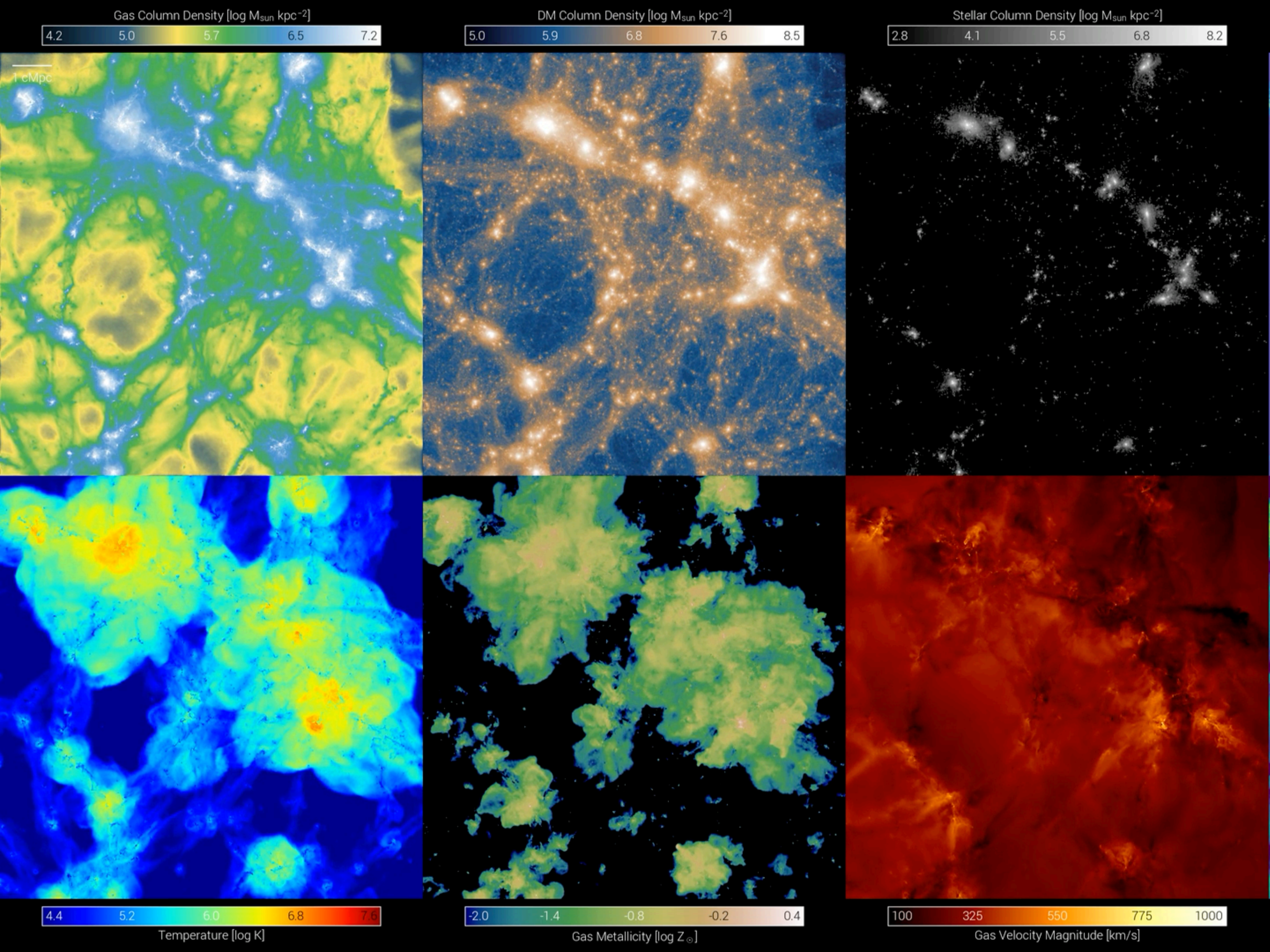

Gas Column Density [log Msun kpc-2]
4.2 5.0 5.7 6.5 7.2
DM Column Density [log Msun kpc-2]
5.0 5.9 6.8 7.6 8.5
Stellar Column Density [log Msun kpc-2]
2.8 4.1 5.5 6.8 8.2
1 cMpc
4.4 5.2 6.0 6.8 7.6
Temperature [log K]
-2.0 -1.4 -0.8 -0.2 0.4
Gas Metallicity [log Z☉]
100 325 550 775 1000
Gas Velocity Magnitude [km/s]

Summary — star formation

- Simulating a stellar component (via star particles) in a simulation is crucial as it is the main luminous matter observed.
- Stars from gravitational collapse of cold, dense molecular clouds (Jeans instabilities). GMCs are not forming stars at a high rate.
- Due to dynamic range problem, cosmological simulations have to adopt empirical sub-resolution models to model SF (typically following the SK law with some stochastic approach).
- A star particle is representing a simple stellar population of stars of a given Z, age and with a mass distr. following the IMF.
- Chemical enrichment is followed via modelling the life-time of stars in SSPs (AGB phases, type-1 and type-2 SN) to enrich the gas with metals.

Only cooling and star formation?

With only cooling, star formation and metal enrichment we encounter:

- Over-cooling problem (discussed for SAMs), too many stars in low mass and massive galaxies/halos (compared to abundance matching)
- Anti-hierarchical problem (discussed for SAMs):
  - Massive galaxies have too high star formation rates at late times, are too young
  - Low mass galaxies have too old stellar populations, form too early
- Missing satellite problem: Halos contain too many satellite galaxies compared to observations, e.g. our MW galaxies
- Angular momentum problem: no disk-like spiral galaxies
- Size problem: All galaxies are way too compact, too small size, too dense
- Cooling flow problem in clusters: Hardly any cooling flows are observed

HYDRO SIMULATIONS CONFIRM THE URGENT NEED FOR FEEDBACK (Chapter 15+16)

Up next…

- *Chapter 1*: Introduction (galaxy definition, astronomical scales, observable quantities — repetition of Astro-I)
- *Chapter 2:* Brief review on stars
- *Chapter 3*: Radiation processes in galaxies and telescopes;
- *Chapter 4:* The Milky Way
- *Chapter 5*: The world of galaxies I
- *Chapter 6*: The world of galaxies II
- *Chapter 7:* Black holes and active galactic nuclei
- *Chapter 8:* Galaxies and their environment;
- *Chapter 9:* High-redshift galaxies
- *Chapter 10*:
    - Cosmology in a nutshell; Linear structure formation in the early Universe
- *Chapter 11*:
    - Dark matter and the large-scale structure
    - Cosmological N-body simulations of dark matter
- *Chapter 12*: Populating dark matter halos with baryons: Semi-empirical & semi-analytical models
- *Chapter 13:* Modelling the evolution of gas in galaxies: Hydrodynamics
- *Chapter 14*: Gas cooling/heating and star formation
- *Chapter 15*: Stellar feedback processes
- *Chapter 16*: Black hole growth & AGN feedback processes
- *Chapter 17*: Modern simulations & future prospects

Part I: Observational basics & facts of galaxies
first 7 lectures

Part II: Theory & models of galaxy evolution processes
second 7 lectures