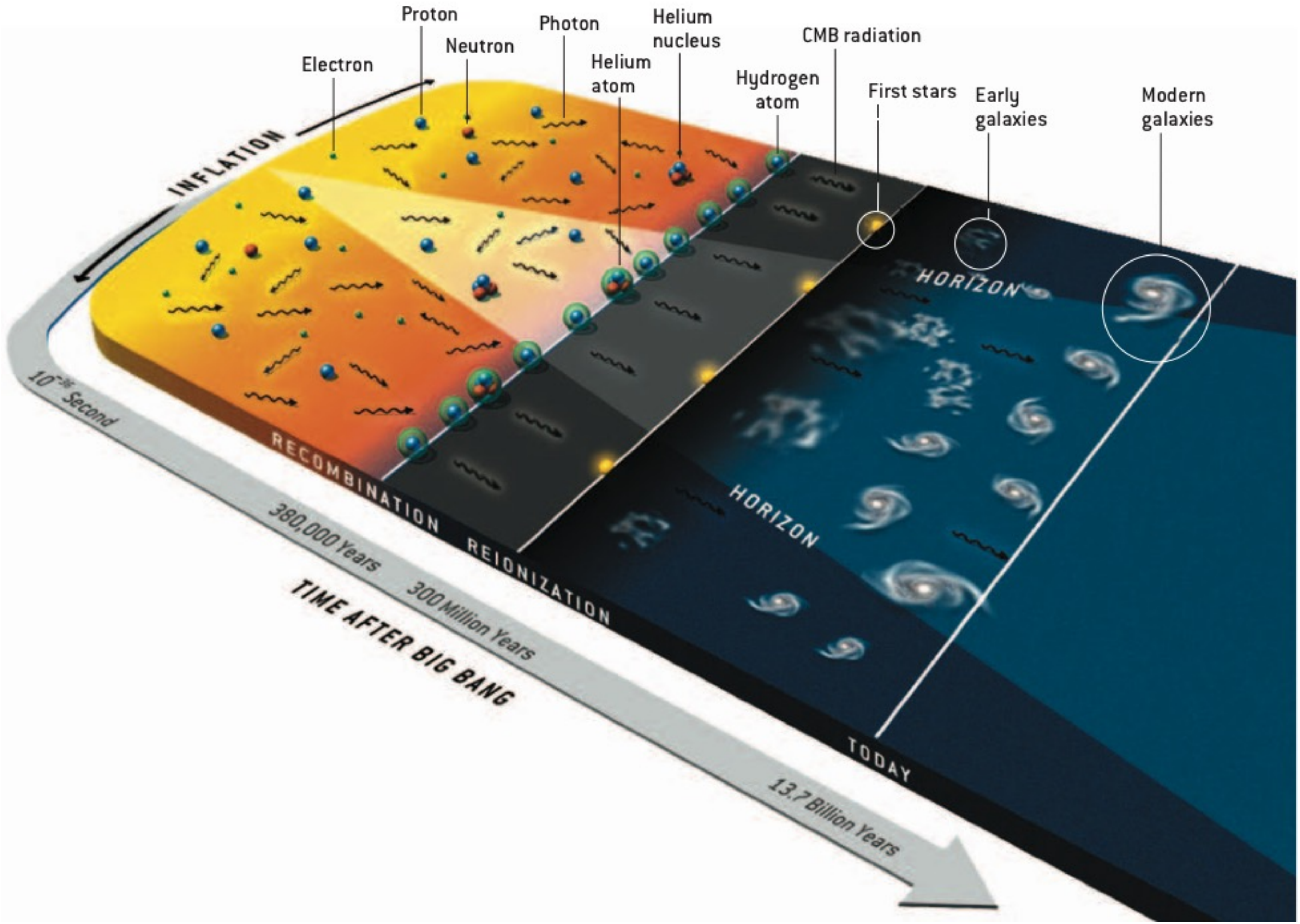
Alexander Knebe (*Universidad Autonoma de Madrid*)

"We've discovered a massive dust and gas cloud which is either the beginning of a new star, or just an awful lot of dust and gas."

Cosmic Dawn: The First Stars & Galaxies



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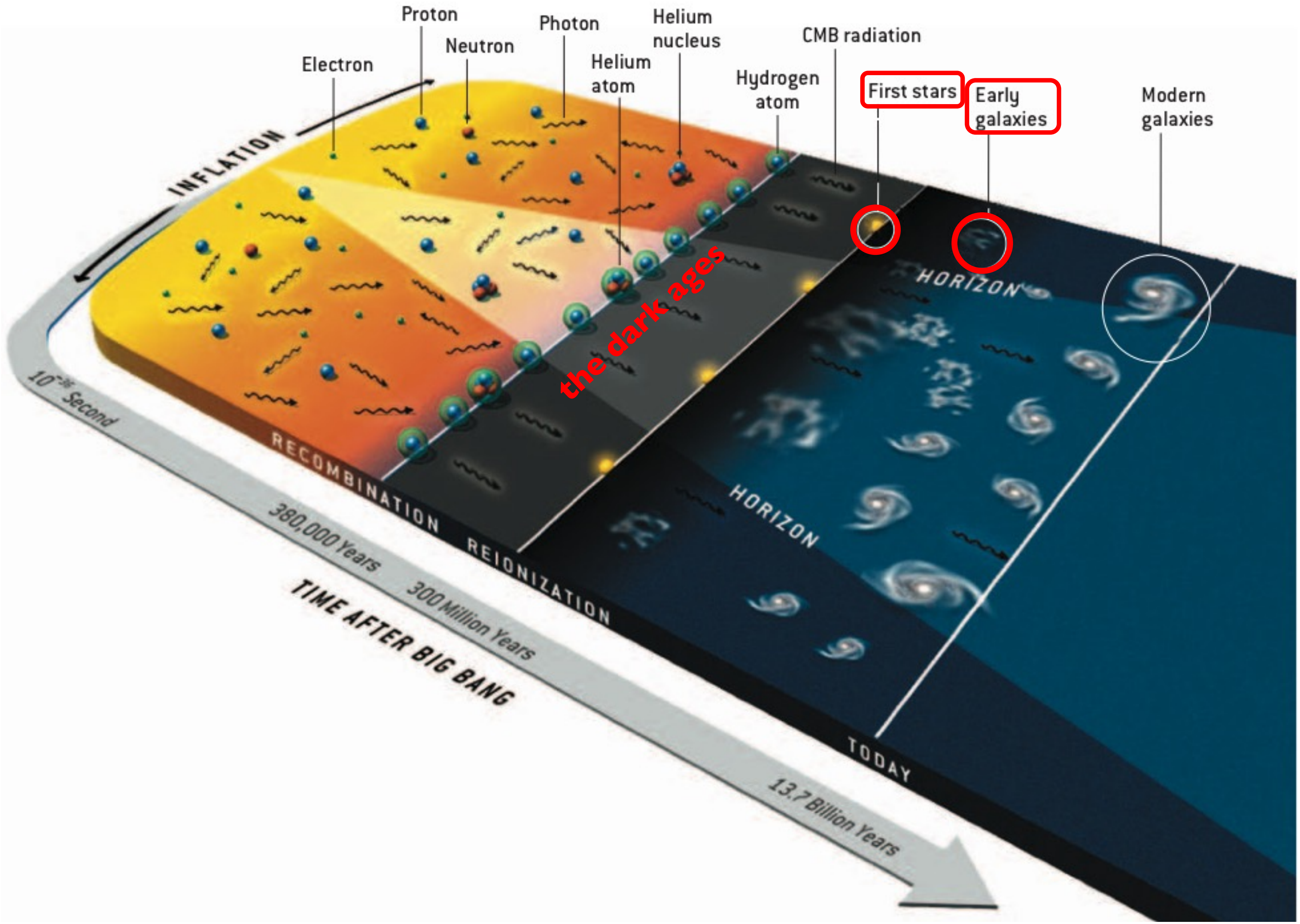

- the dark ages of the Universe
- the first stars
- the first galaxies
- implications for subsequent structure formation

- **the dark ages of the Universe**
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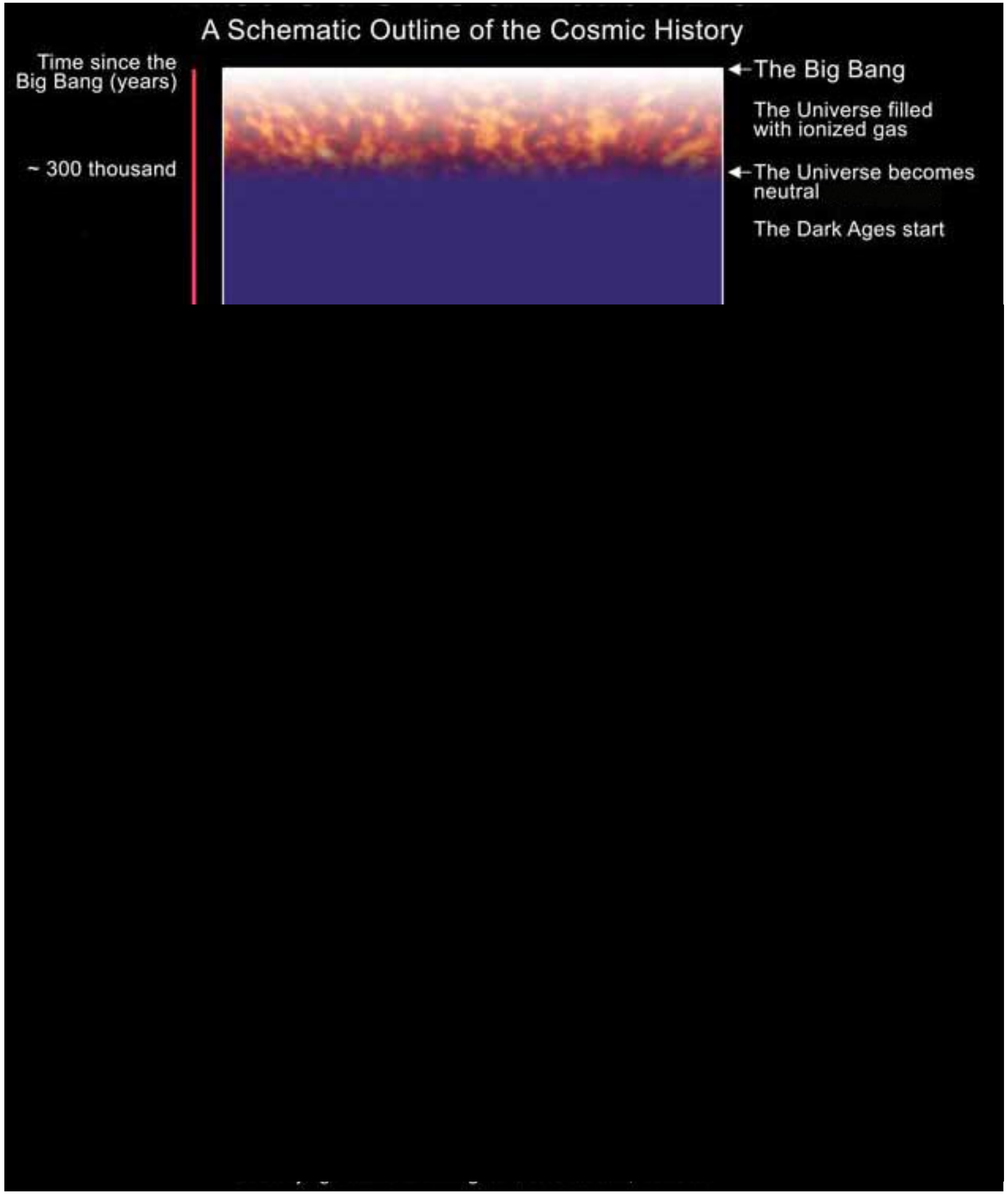
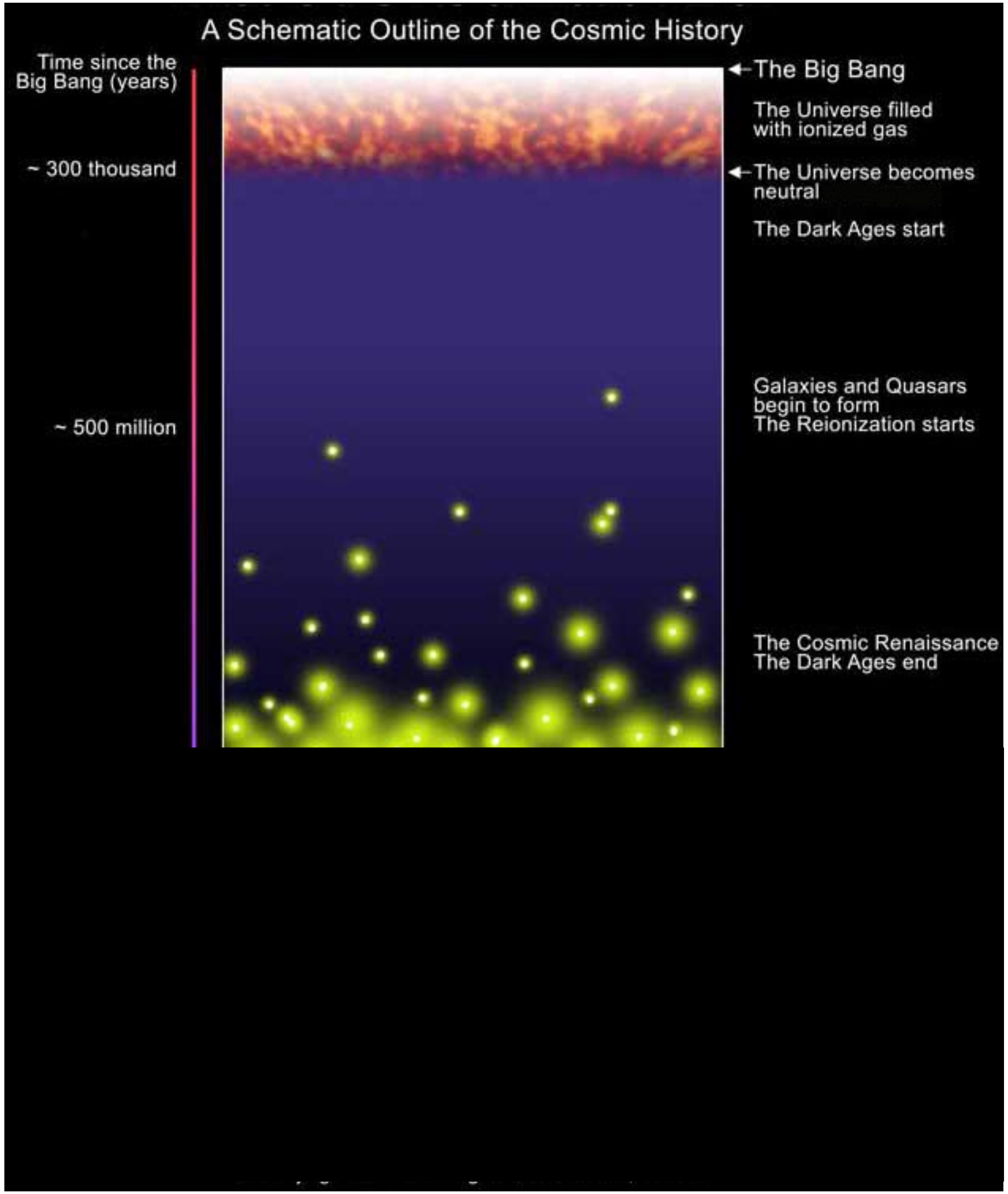

A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral
The Dark Ages start


A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
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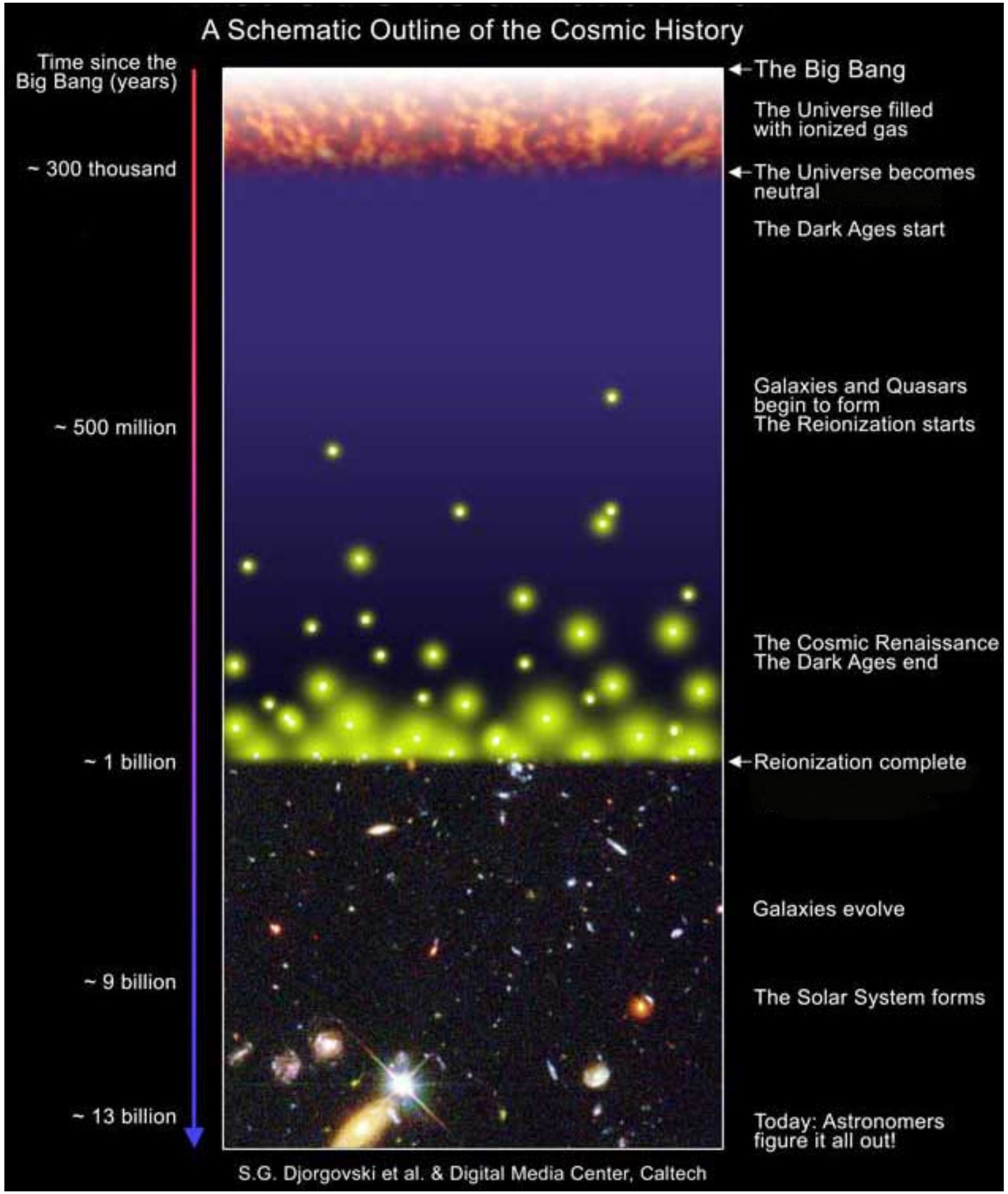
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end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Time since the Big Bang (years)
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~ 500 million
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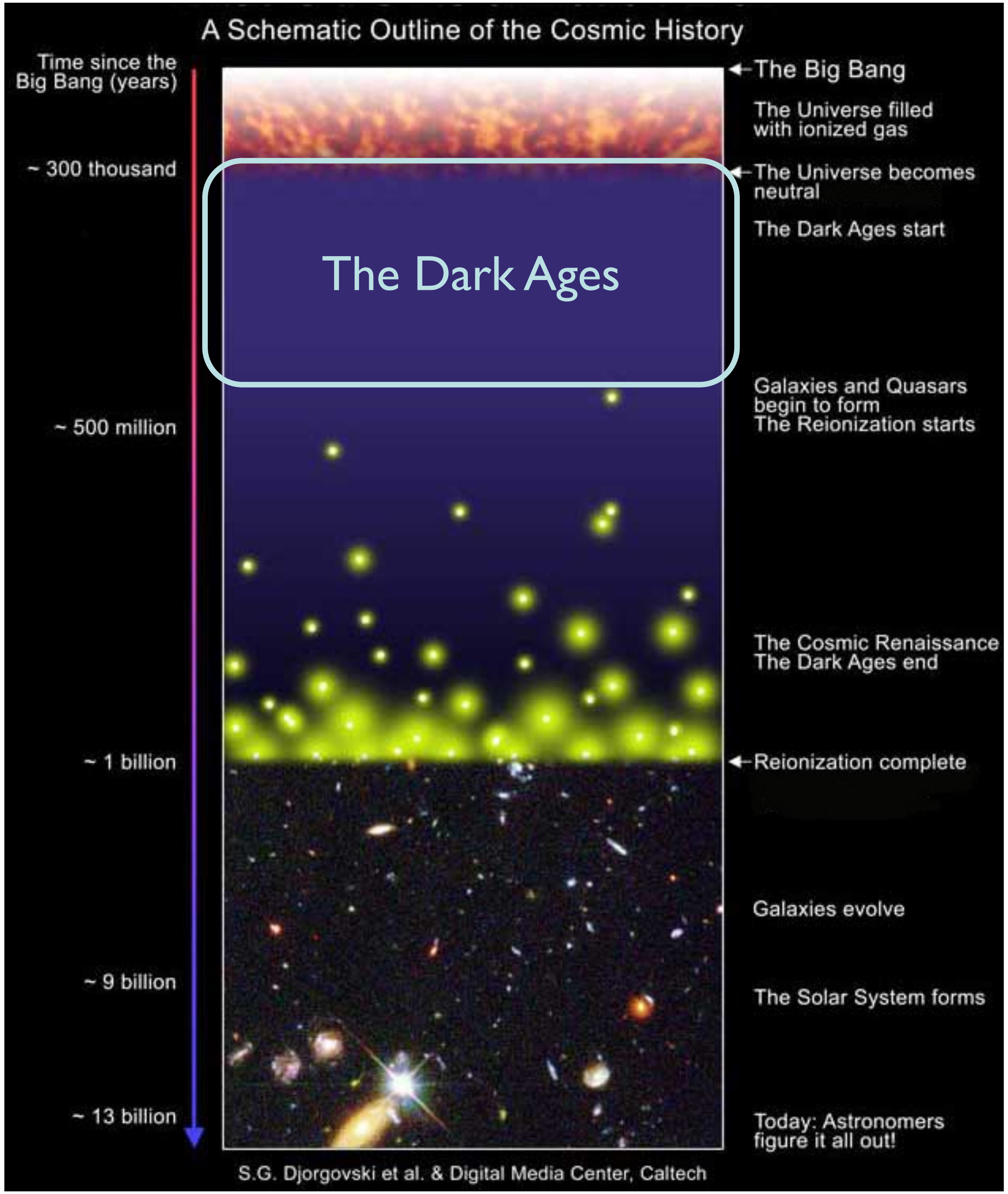
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech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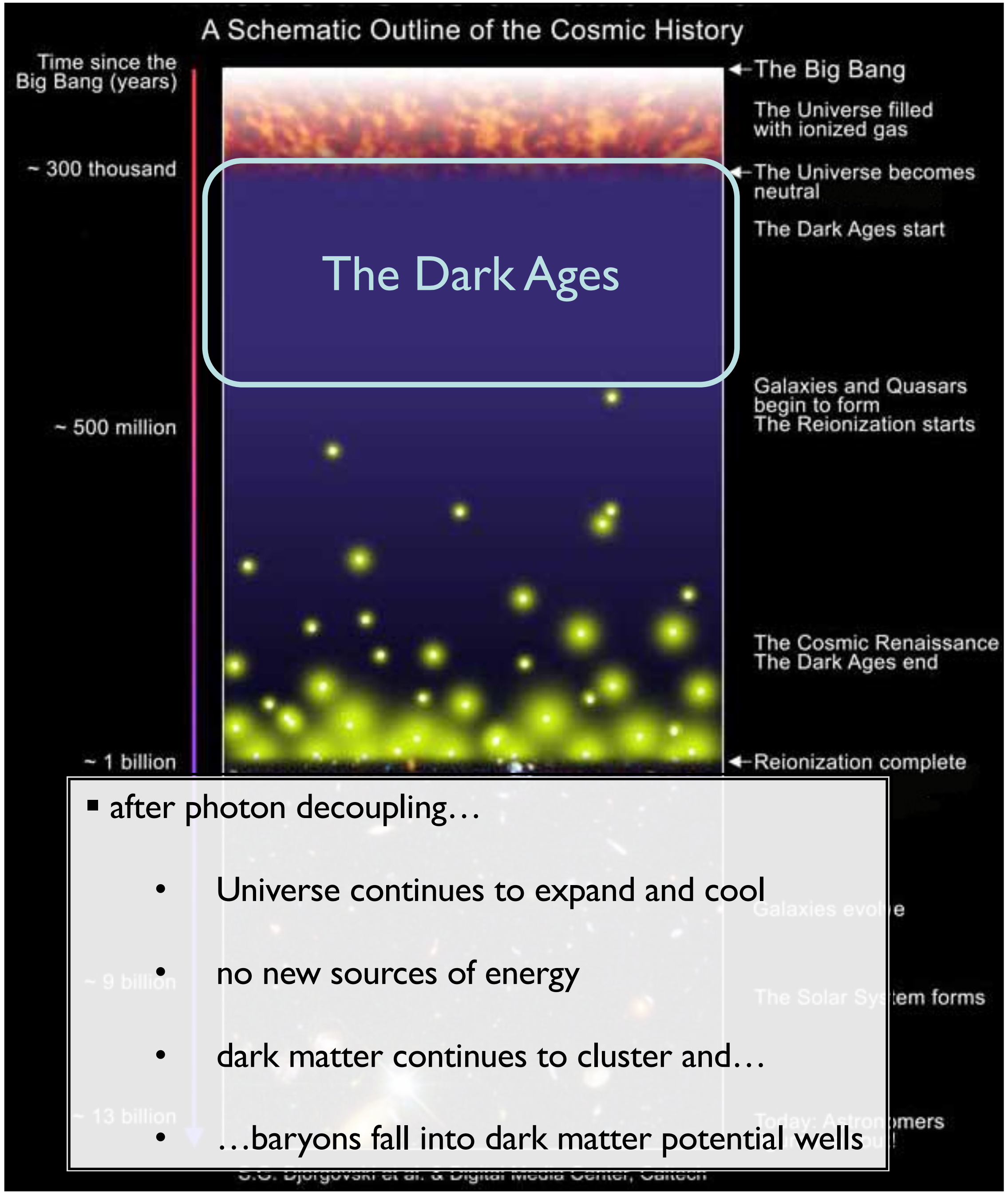
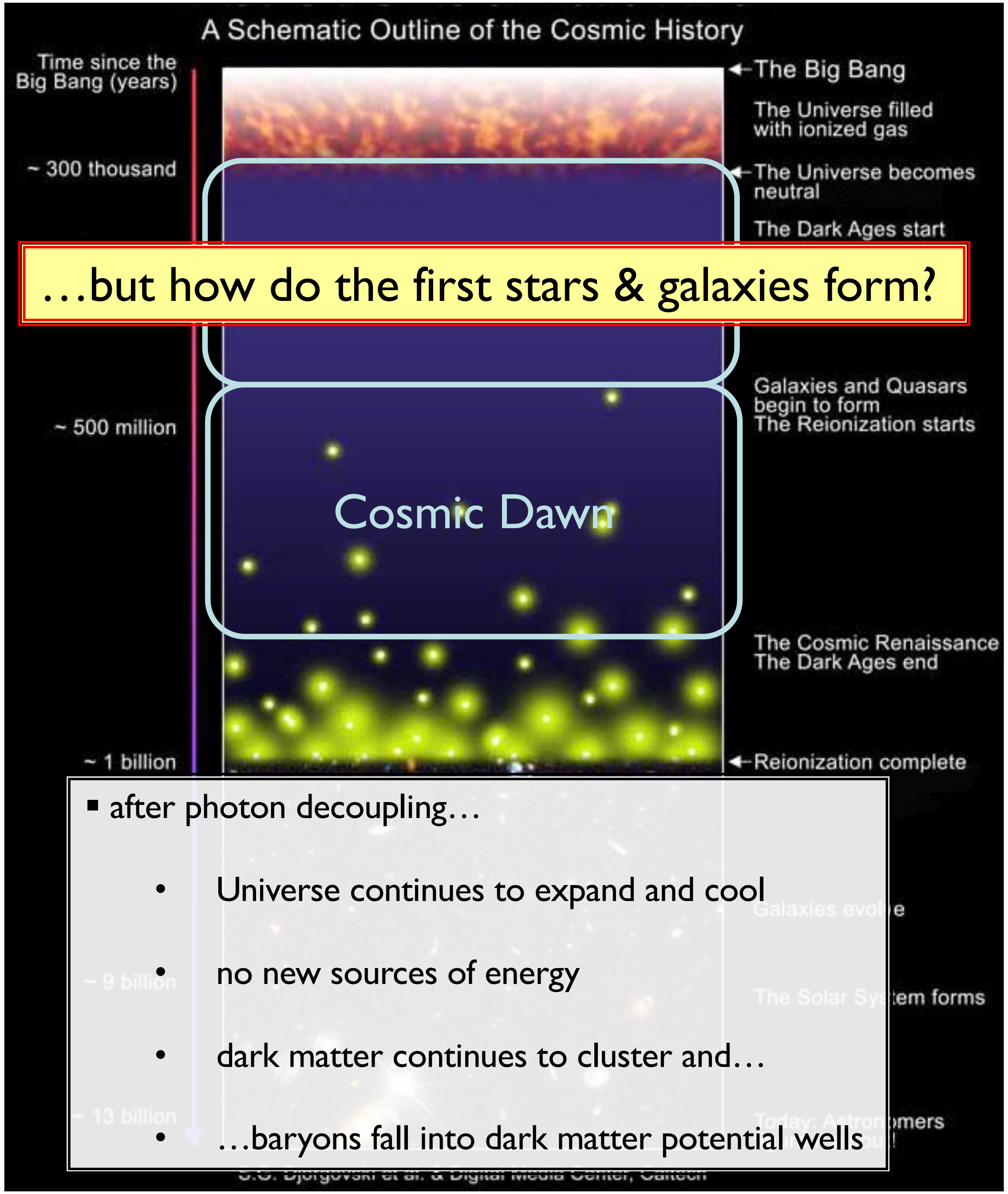


- after photon decoupling…
  - Universe continues to expand and cool
  - no new sources of energy
  - dark matter continues to cluster and…
  - …baryons fall into dark matter potential wells



…but how do the first stars & galaxies form?

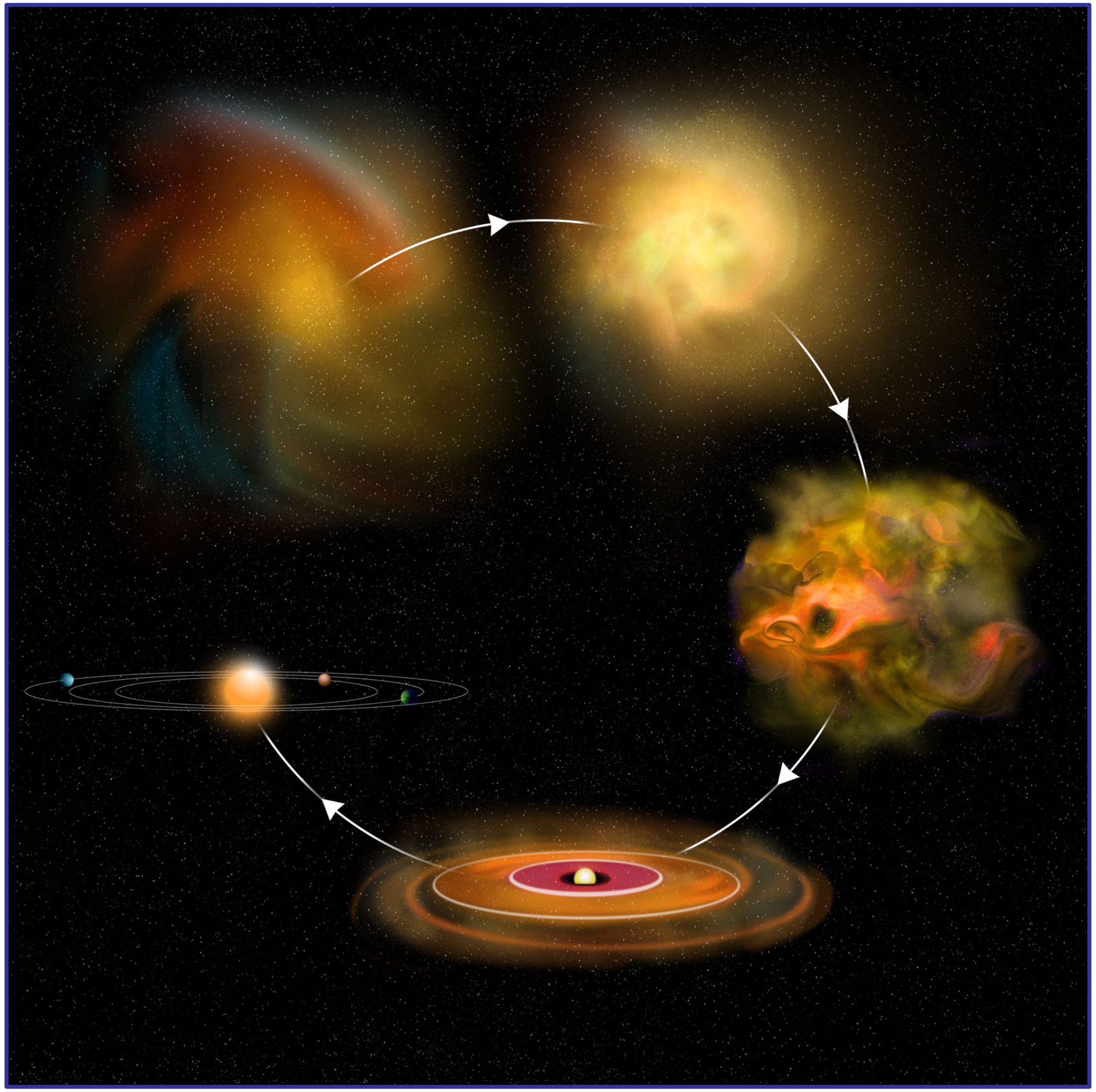
- after photon decoupling…
  - Universe continues to expand and cool
  - no new sources of energy
  - dark matter continues to cluster and…
  - …baryons fall into dark matter potential wells

- the dark ages of the Universe
- **the first stars**
- the first galaxies
- implications for subsequent structure formation

- first stars – summary

  - star formation requires coolant for collapse
  - only available coolant for first stars = H_2
  - sufficient conditions are given for $z < 100$
  - numerical models suggest that first stars are very massive $M \in [10, 500] M_\odot$
  - massive stars die hard & fast:
    - supernovae of $M \in [8, 100] M_\odot$ will pollute IGM with metals, and
    - those metals facilitate subsequent star formation

- star formation in general



- star formation in general
  - virial theorem
  - energies of homogeneous sphere
  - Jeans Mass
  - isothermal gravitational collapse
  - cooling

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- <u>star formation in general</u>

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  - isothermal gravitational collapse
  - **cooling!**

- <u>star formation in general</u>

  - virial theorem

$$G = \sum_i \vec{p}_i \cdot \vec{r}_i \quad *$$

**Note*: moment of inertia => $I = \sum_i m_i |\vec{r}_i|^2 \quad \Rightarrow \quad \frac{1}{2}\frac{dI}{dt} = \frac{1}{2}\frac{d}{dt}\sum_i m_i |\vec{r}_i|^2 = \frac{1}{2}\sum_i m_i \frac{d|\vec{r}_i|^2}{dt} = \sum_i m_i \frac{d\vec{r}_i}{dt}\cdot\vec{r}_i = \sum_i \vec{p}_i \cdot \vec{r}_i = G$

star formation in general

- virial theorem

$$G = \sum_i \vec{p}_i \cdot \vec{r}_i \qquad \Rightarrow \qquad \frac{d}{dt} G = \sum_i \dot{\vec{p}}_i \cdot \vec{r}_i + \sum_i \vec{p}_i \cdot \dot{\vec{r}}_i$$

$$= \sum_i \vec{F}_i \cdot \vec{r}_i + \sum_i \vec{p}_i \cdot \dot{\vec{r}}_i$$

$$= \sum_i \vec{F}_i \cdot \vec{r}_i + 2 \sum_i E_{kin,i}$$

$$= \sum_i \vec{F}_i \cdot \vec{r}_i + 2 E_{kin}$$

- <u>star formation in general</u>

  - virial theorem

$$\frac{dG}{dt} = \sum_i \vec{F}_i \cdot \vec{r}_i + 2E_{kin}$$

- star formation in general

  - virial theorem

$$\frac{dG}{dt} = \sum_i \vec{F}_i \cdot \vec{r}_i + 2E_{kin}$$

$$\downarrow$$

$$\sum_i \vec{F}_i \cdot \vec{r}_i \quad = \quad \sum_i \left(\nabla E_{pot}\right) \cdot \vec{r}_i \quad = \quad nE_{pot}$$

$$\vec{F} = -\nabla E_{pot} \qquad E_{pot} \equiv Cr^n \quad \Rightarrow \quad \nabla E_{pot} = n\frac{E_{pot}}{r} \Rightarrow F \cdot r = nE_{pot}$$

- star formation in general

  - virial theorem

$$\frac{dG}{dt} = nE_{pot} + 2E_{kin}$$

- star formation in general

  - virial theorem

$$\frac{dG}{dt} = nE_{pot} + 2E_{kin}$$

$$\left\langle \frac{dG}{dt} \right\rangle_\tau = \frac{1}{\tau}\int_0^\tau \frac{dG}{dt}\,dt = \frac{1}{\tau}\left[G(\tau) - G(0)\right]$$

▪ star formation in general

• virial theorem

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bound system!
(coordinates and velocities have upper and lower limits…)

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bound system!
(coordinates and velocities have upper and lower limits…)

$$\Rightarrow \quad 0 = \left\langle \frac{dG}{dt} \right\rangle_\tau = 2\left\langle E_{kin} \right\rangle_\tau + n\left\langle E_{pot} \right\rangle_\tau \qquad ; \; E_{pot} \propto r^n$$

- star formation in general

  - virial theorem (n = -1 for gravity)

$$0 = 2\langle E_{kin} \rangle_\tau - \langle E_{pot} \rangle_\tau \quad , \quad E_{pot} = Cr^{-1}$$

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→ can be used to derive the Jeans mass for a homogenous sphere…

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  - virial theorem (n = -1 for gravity)

$$0 = 2\langle E_{kin}\rangle_\tau - \langle E_{pot}\rangle_\tau \quad , \quad E_{pot} = Cr^{-1}$$

  - gravitational potential of homogeneous sphere (i.e., ρ = const.)

$$M(r) = \rho \frac{4\pi}{3} r^3$$

$$dM(r) = \rho 4\pi r^2 dr$$

$$dE_{pot} = -G \frac{M(r)dM(r)}{r}$$

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$$dE_{pot} = -G\frac{M(r)dM(r)}{r} \quad \Rightarrow \quad E_{pot} = -4\pi G\rho \int_0^R \frac{M(r)}{r} r^2\, dr$$

$$= -4\pi G\rho^2 \int_o^R \frac{\frac{4\pi}{3}r^3}{r} r^2 dr$$

$$= -\frac{16\pi^2}{3} G\rho^2 \int_o^R r^4 dr$$

$$= -\frac{16\pi^2}{15} G\rho^2 R^5$$

$$= -\frac{16\pi^2}{15} G \frac{M^2}{(\frac{4\pi}{3}R^3)^2} R^5$$

$$= -\frac{3}{5} G \frac{M^2}{R}$$

▪ star formation in general

- virial theorem ($n = -1$ for gravity)

$$0 = 2\left\langle E_{kin} \right\rangle_\tau - \left\langle E_{pot} \right\rangle_\tau$$

- gravitational potential of homogeneous sphere (i.e., $\rho = \text{const.}$)

$$E_{pot} = -\frac{3}{5} G \frac{M^2}{R} \qquad R = \sqrt[3]{\frac{M}{\frac{4\pi}{3}\rho}}$$

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- kinetic energy of homogeneous (gas) sphere

$$E_{kin} = \frac{3}{2} N k_B T = \frac{3}{2} \frac{M}{\mu_H m_H} k_B T$$

▪ star formation in general

- virial theorem (n = -1 for gravity)

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- kinetic energy of homogeneous (gas) sphere

$$E_{kin} = \frac{3}{2}Nk_BT = \frac{3}{2}\frac{M}{\mu_H m_H}k_BT$$

$$M_J = \sqrt{\frac{3(5k_B)^3}{4\pi(G\mu_H m_H)^3}}\sqrt{T^3}\frac{1}{\sqrt{\rho}}$$

star formation in general

- virial theorem (n = -1 for gravity)

$$0 = 2\langle E_{kin} \rangle_\tau - \langle E_{pot} \rangle_\tau$$

- Jeans mass

$$M_J = 5.46 \left(\frac{k_B}{G\mu_H m_H} \right)^{3/2} \left(\frac{T^3}{\rho} \right)^{1/2}$$

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relation between T and ρ determines fate of collapse...

- star formation in general
  - nature of gravitational collapse

    = adiabatic?

- <u>star formation in general</u>

  • nature of gravitational collapse

  = adiabatic?

$$PV^{\gamma} = const. \quad \Rightarrow \quad T \propto \rho^{\gamma-1} \quad \Rightarrow \quad T \propto \rho^{2/3}$$

$P = \frac{\rho}{\mu_H m_H} k_B T$ $\gamma = 5/3$ (monatomic gas)

- <u>star formation in general</u>

  - nature of gravitational collapse

    = adiabatic?

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$P = \frac{\rho}{\mu_H m_H} k_B T$ $\quad\quad$ $\gamma = 5/3$ (monatomic gas)

$$\boxed{M_J = 5.46 \left(\frac{k_B}{G \mu_H m_H} \right)^{3/2} \left(\frac{T^3}{\rho} \right)^{1/2} \propto \sqrt{\rho}}$$

$M > M_J$ => collapse starts => ρ ↗ => M_J ↗ => collapse **stops!**

- star formation in general

  - nature of gravitational collapse

    = isothermal?

- star formation in general

  - nature of gravitational collapse

    = isothermal!

$$T = const.$$

$$\Downarrow$$

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- <u>star formation in general</u>

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$$M_J = 5.46\left(\frac{k_B}{G\mu_H m_H}\right)^{3/2}\left(\frac{T^3}{\rho}\right)^{1/2} \propto \frac{1}{\sqrt{\rho}}$$

$$\Downarrow$$

$M > M_J$ => collapse starts => ρ ↗ => M_J ↘ => "runaway" collapse!

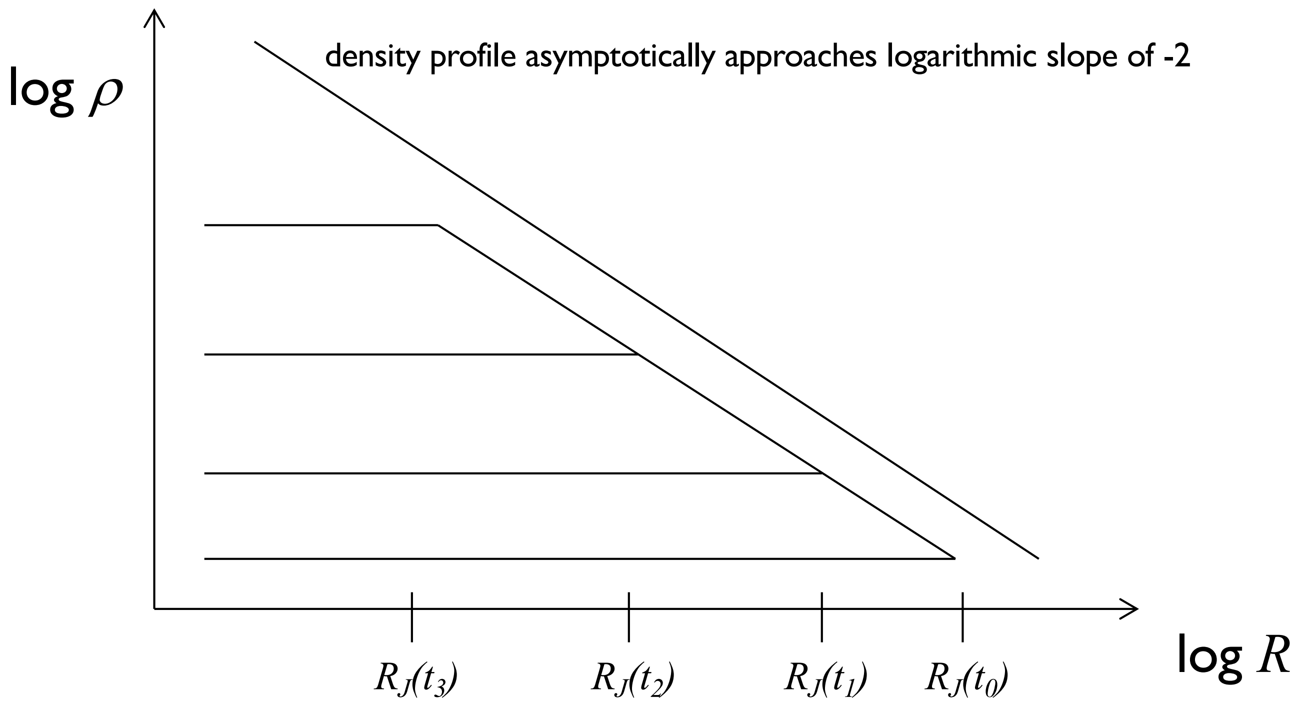
collapse converges to ***isothermal sphere***…

- <u>star formation in general</u>

  - nature of gravitational collapse

    = isothermal sphere

$$\rho \propto \frac{M_J}{R_J^3} \propto \frac{1/\sqrt{\rho}}{R_J^3} \quad \Rightarrow \quad \rho^{3/2} \propto \frac{1}{R_J^3} \quad \Rightarrow \quad \rho \propto \frac{1}{R_J^2} \quad \Rightarrow \quad \log\rho \propto -2\log R$$



- <u>star formation in general</u>

  • nature of gravitational collapse

  = isothermal collapse ***requires cooling***:

  dust grains/metals can absorb and re-emit energy…
  …but there are no such things at cosmic dawn!?*

* see BBNS lecture

- star formation in general

  • nature of gravitational collapse

  = isothermal collapse ***requires cooling***:

  dust grains/metals can absorb and re-emit energy…
  …but there are no such things at cosmic dawn!?*

this is where and why the first star formation differs from today's:
in the primeval Universe was no dust/metal acting as coolant!

* see BBNS lecture

- first star formation
  - cooling

    the dominant coolant is (molecular) hydrogen H_2 !

- first star formation

  - cooling

    the dominant coolant is (molecular) hydrogen H_2 !

  - cooling by H_2 via rotational/vibrational channels:

    - rotational/vibrational excitation through collision

    - de-excitation via…
      - radiation (→ cooling) or
      - collision

- <u>first star formation</u>

  - cooling by H_2 requires H_2 in the first place…

    ∴ formation of H_2

    - $H + e^- \rightarrow H^- + \gamma$
    - $H + H^- \rightarrow H_2 + e^-$

    - $H + p \rightarrow H_2^+ + \gamma$
    - $H + H_2^+ \rightarrow H_2 + H^+$

    - $H + H + H \rightarrow H_2 + H$
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- <u>first star formation</u>

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<u>we require*:</u>

- presence of free e and p (for the first four reactions)

*remnants of the epoch of recombination plus ionized H by energy of initial collapse

▪ first star formation

- cooling by H_2 requires H_2 in the first place…

$\therefore$ formation of H_2

we require*:

- $H + e^- \rightarrow H^- + \gamma$
- $H + H^- \rightarrow H_2 + e^-$
- $H + p \rightarrow H_2^+ + \gamma$
- $H + H_2^+ \rightarrow H_2 + H^+$

} • presence of free e and p

- $H + H + H \rightarrow H_2 + H$
- $H + H + H_2 \rightarrow H_2 + H_2$

} • high densities $n_H > 10^8 cm^{-3}$

*remnants of the epoch of recombination plus ionized H by energy of initial collapse

- first star formation

  - cooling by H_2 requires H_2 in the first place…

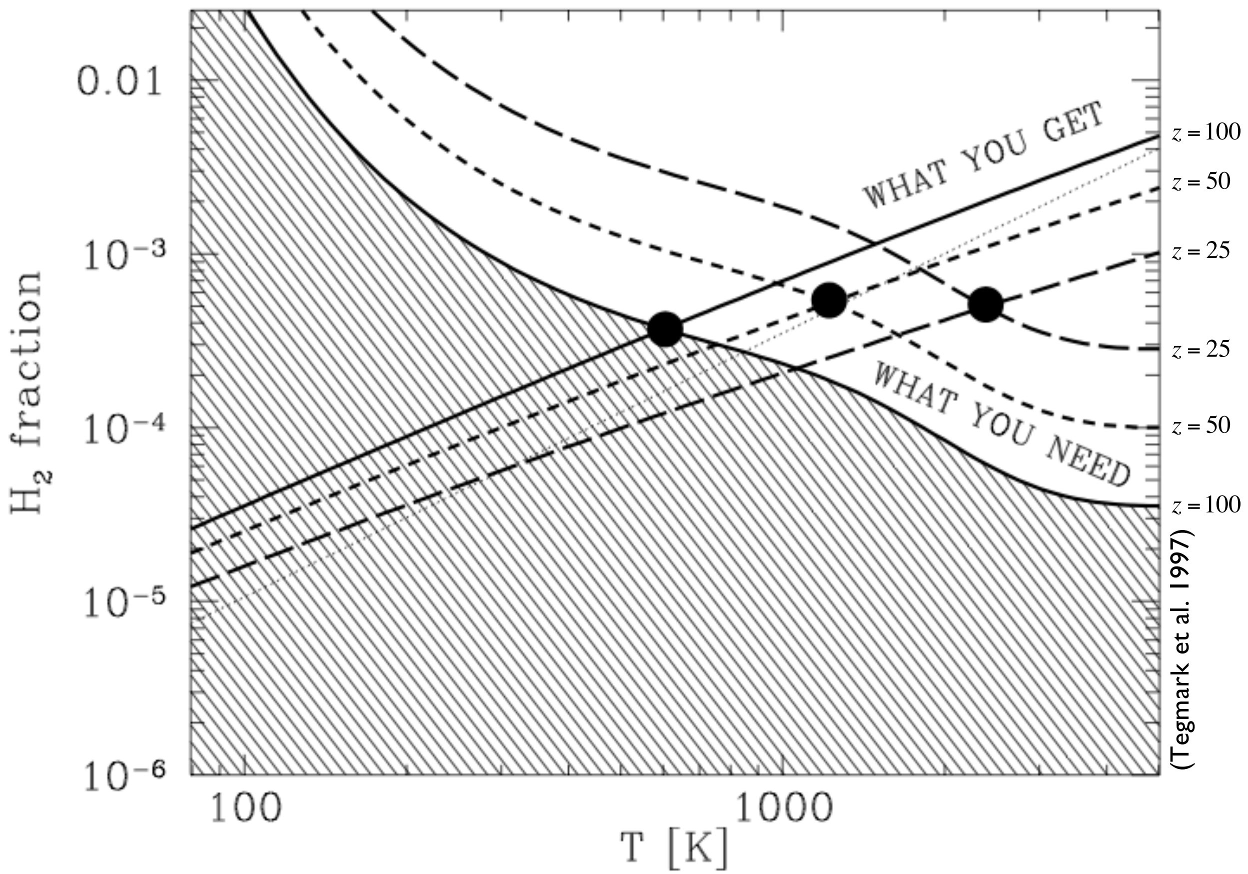
    $\therefore$ formation of H_2 requires:
    - presence of free e and p
    - high densities $n_H > 10^8 cm^{-3}$

    $\therefore$ H_2 fraction χ_{H2} must exceed $\sim 5x\ 10^{-3}$ for cooling to be effective

▪ <u>first star formation</u>

• cooling by H_2: *formation of H_2*

H_2 fraction



(Tegmark et al. 1997)

H_2 fraction produced in Hubble time

$$t_{Hubble} \propto H^{-1}(z)$$

H_2 fraction able to cool in Hubble time

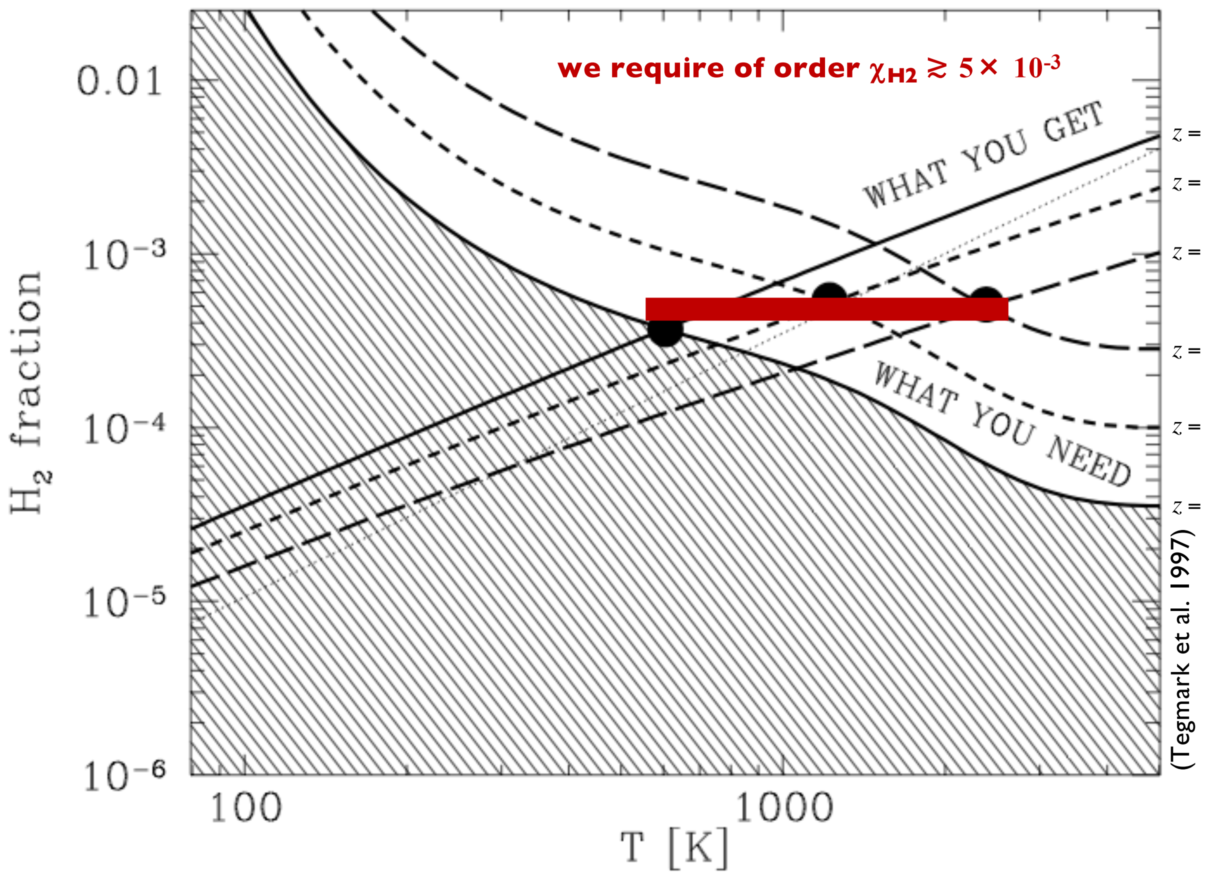
$$t_{cool} = \frac{3kT}{2n\Lambda(T)}$$

($\Lambda(T)$: cooling function)

- <u>first star formation</u>

  - cooling by H_2: *formation of H_2*

H_2 fraction



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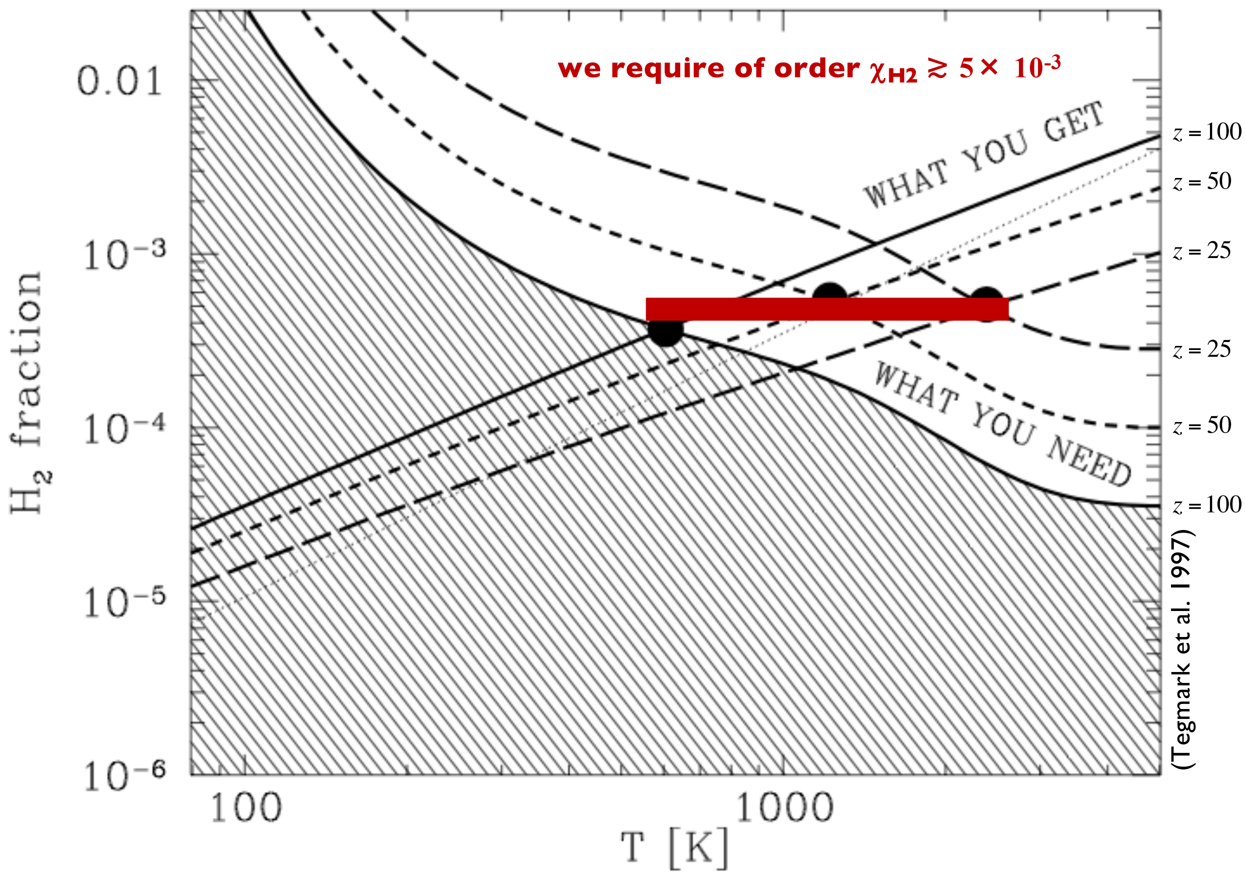

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?

- <u>first star formation</u>

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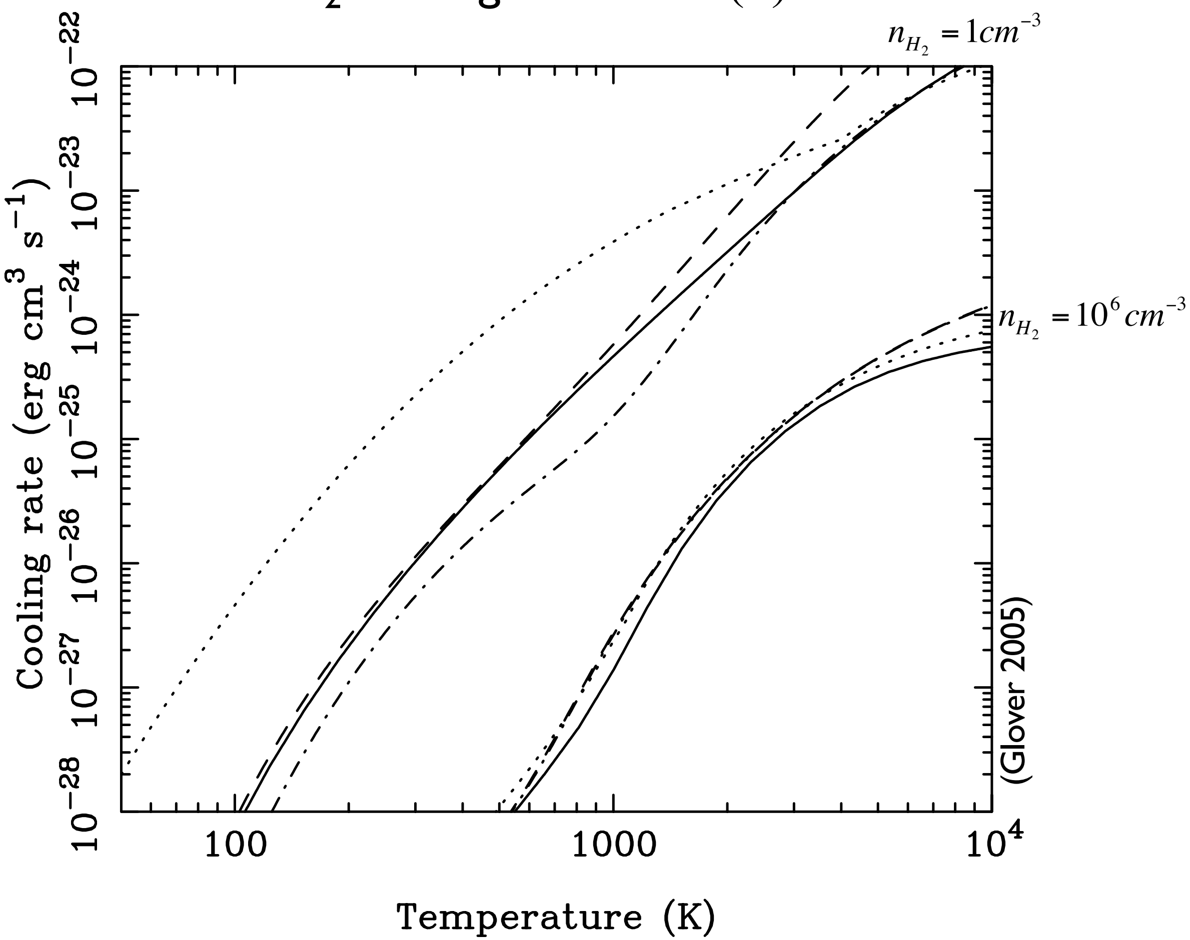
H_2 cooling function $\Lambda(T)$



cooling efficiency increases with temperature!

- <u>first star formation</u>
  - cooling by H_2
    - adiabatic collapse due to lack of sufficient H_2
    - increasing density leads to more H_2
    - increasing temperature leads to more efficient cooling
    - collapse becomes isothermal…

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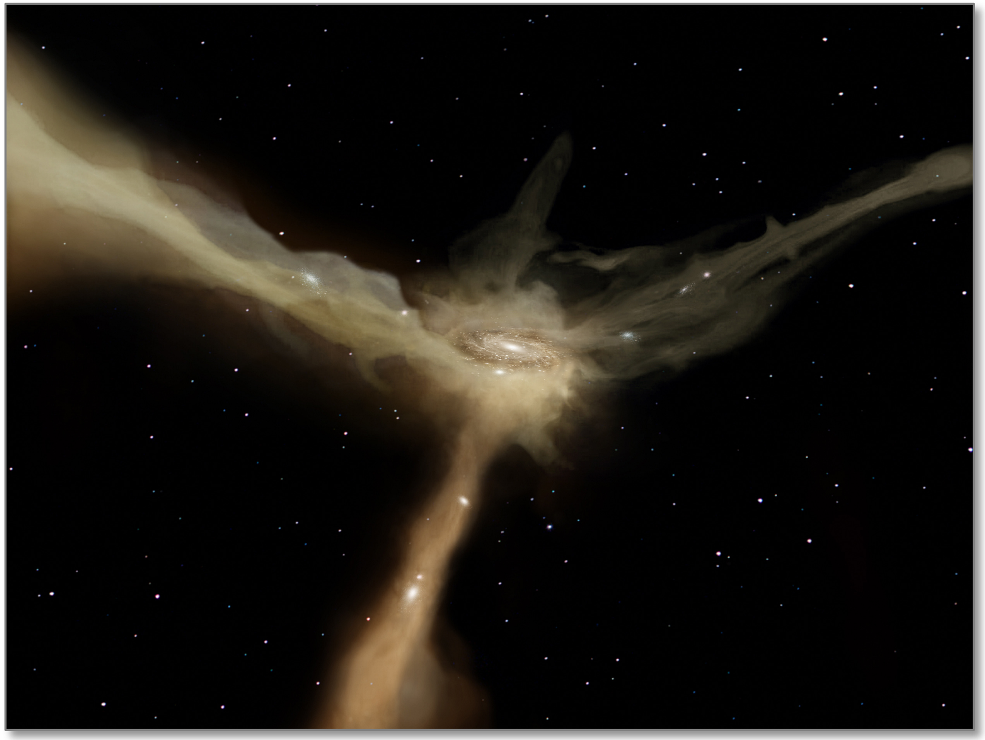
…how massive are those first stars?

- <u>first star formation</u>

  - masses of first stars

    - mass growth of proto-stellar gas cloud: $M_*(t) = M_{pr} + \int_0^t \dot{M}(\tau)\,d\tau$



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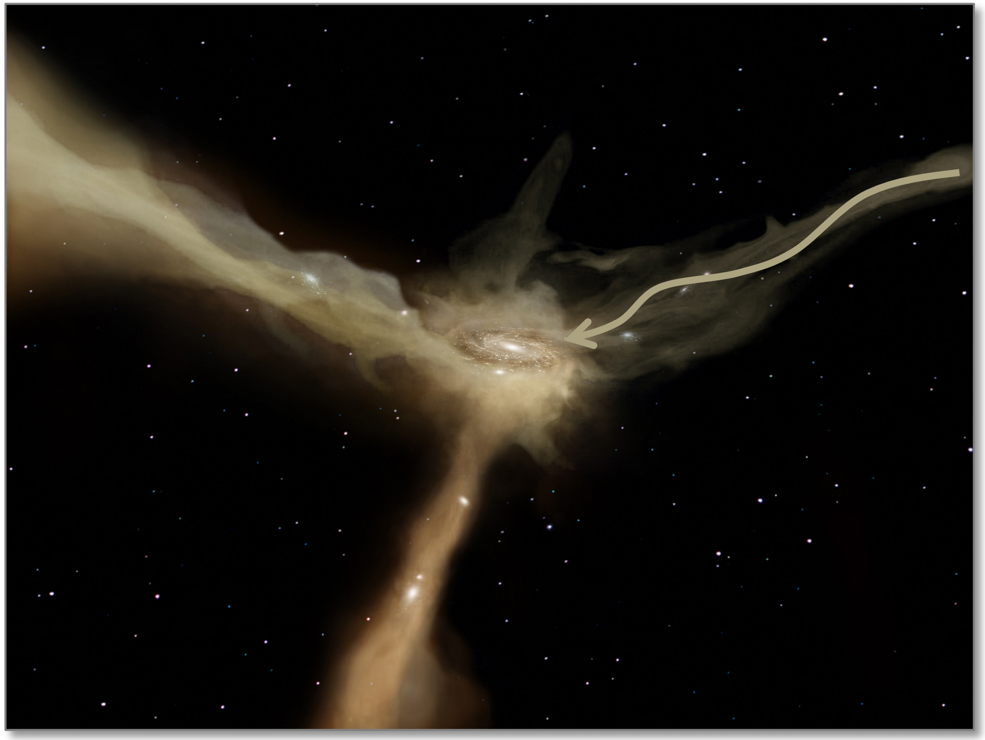
$\dot{M} = \mathrm{d}M/\mathrm{d}t$



- <u>first star formation</u>

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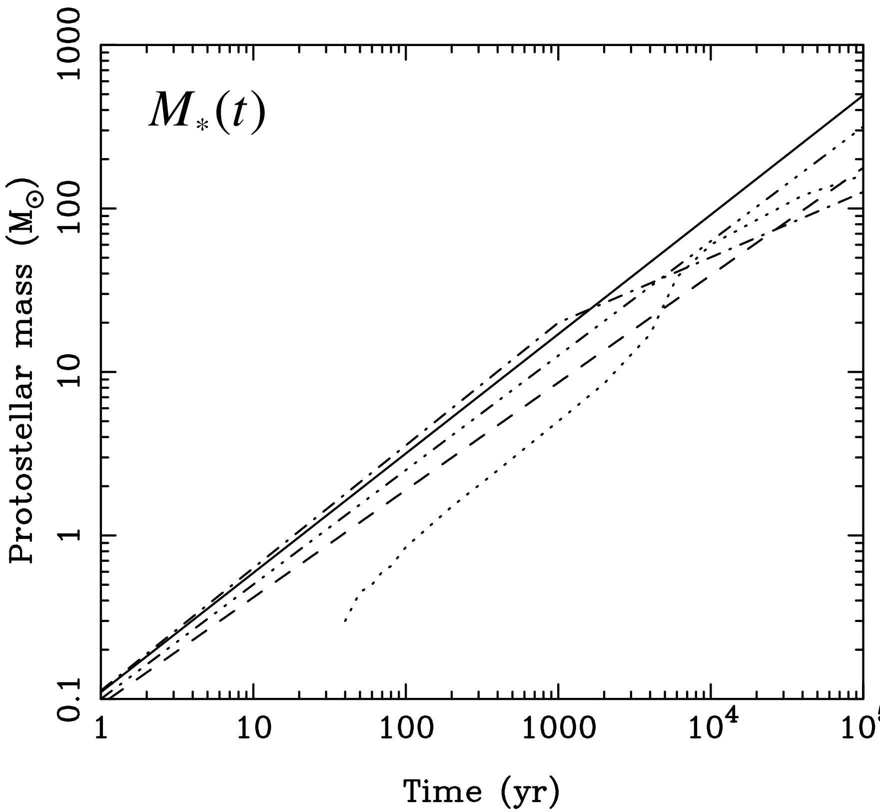
    - numerical models for mass accretion rate $\dot{M}=\mathrm{d}M/\mathrm{d}t$ lead to…



(Glover 2005)

- <u>first star formation</u>
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    - mass growth of proto-stellar gas cloud: $M_*(t) = M_{pr} + \int_0^t \dot{M}(\tau)d\tau$
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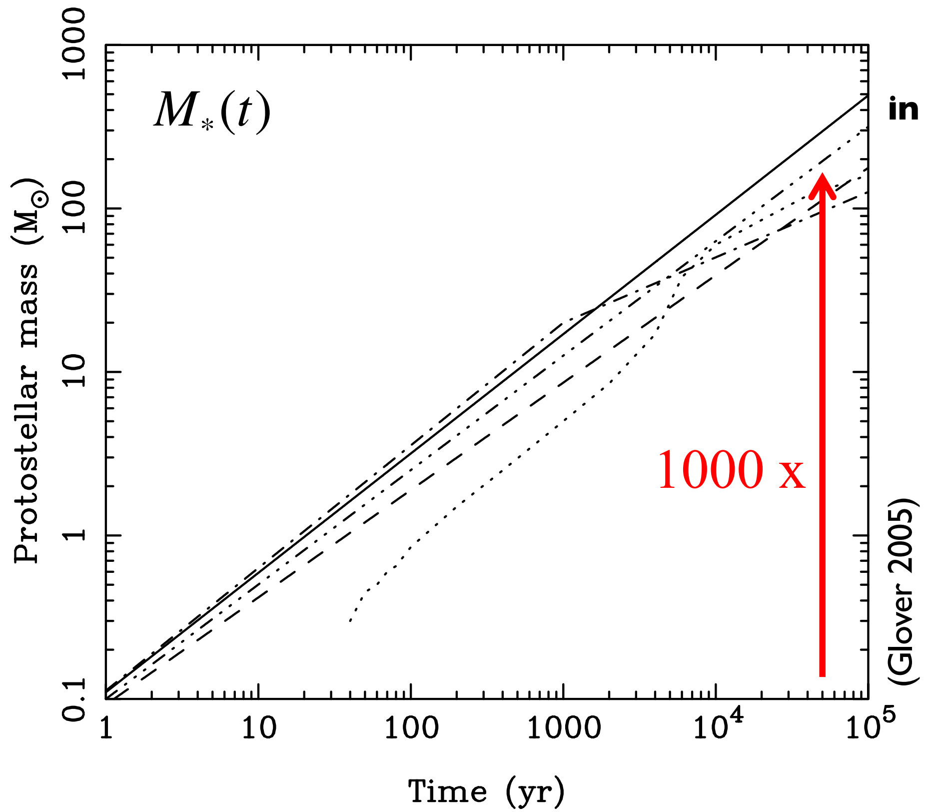
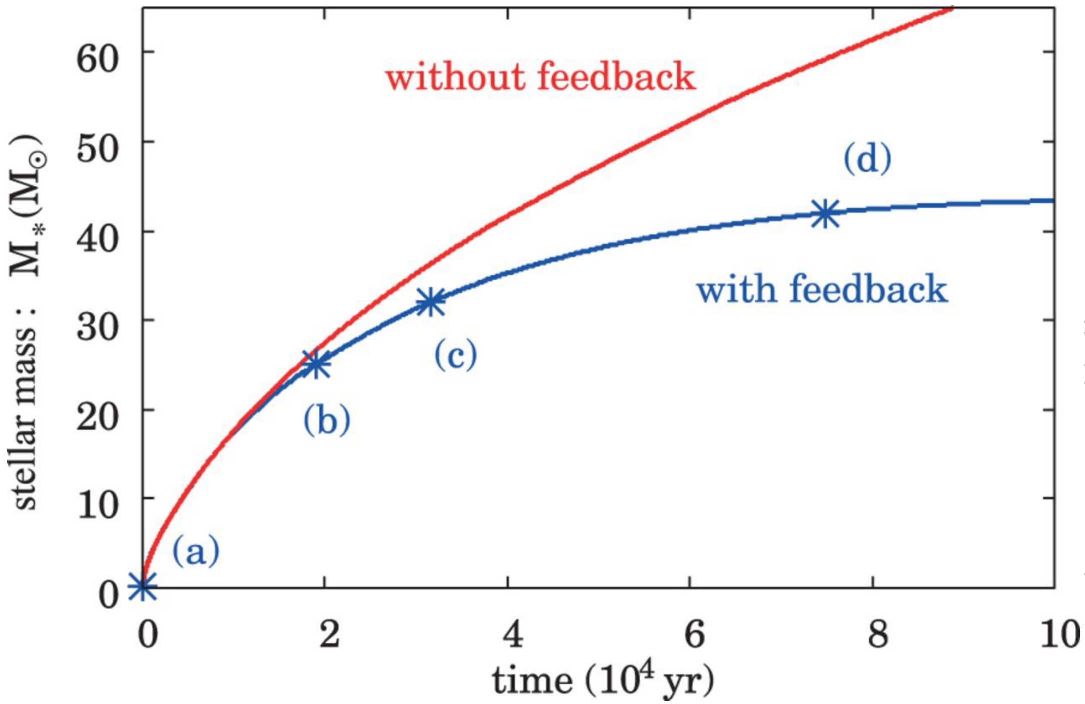


in very short times the proto-star becomes extremely massive!

- first star formation

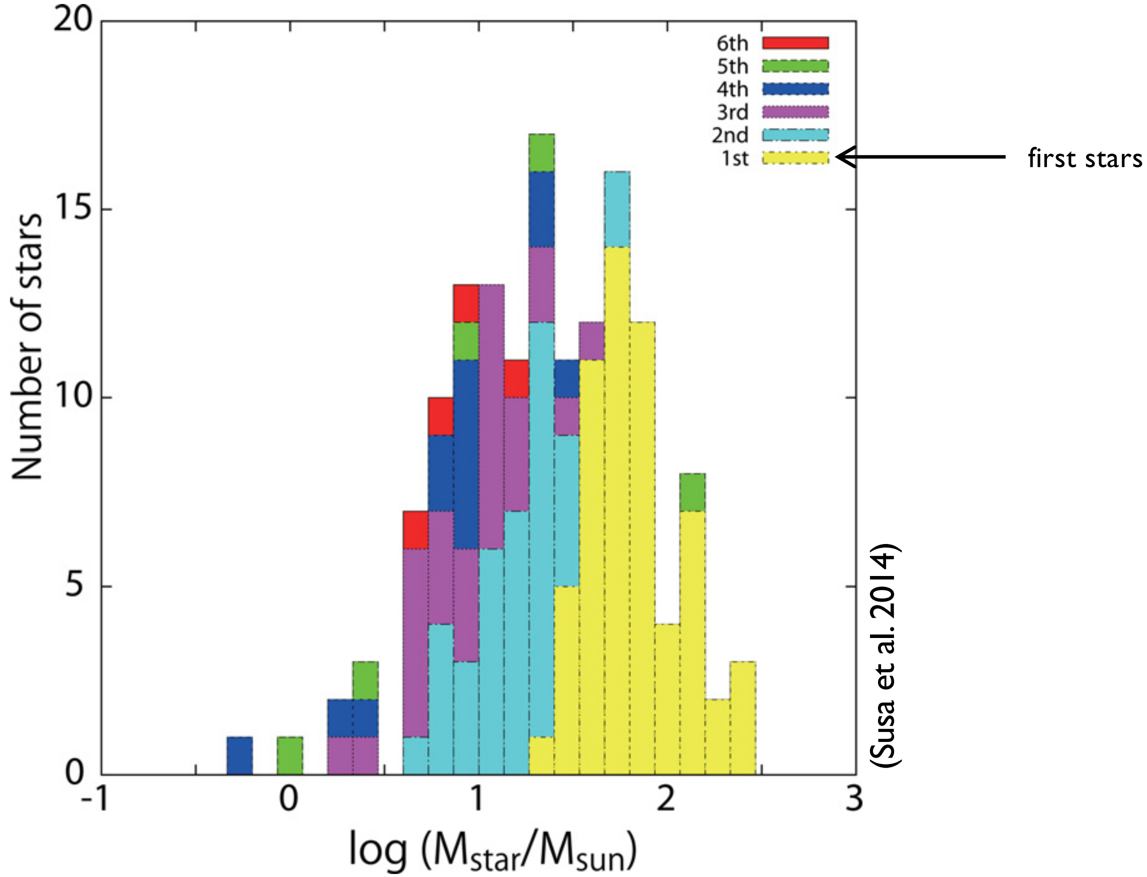
  - masses of first stars

    - mass growth of proto-stellar gas cloud: $M_*(t) = M_{pr} + \int_0^t \dot{M}(\tau)\,d\tau$
    - numerical models for mass accretion rate $\dot{M}=\mathrm{d}M/\mathrm{d}t$ lead to…
    - feedback can substantially reduce accretion rates and hence M_*:



(Yoshida et al. 2012)

- first star formation
    - primeval Initial Mass Function
        - first stars have mass $M \in [10, 500] M_\odot$
        - determined via simulations:



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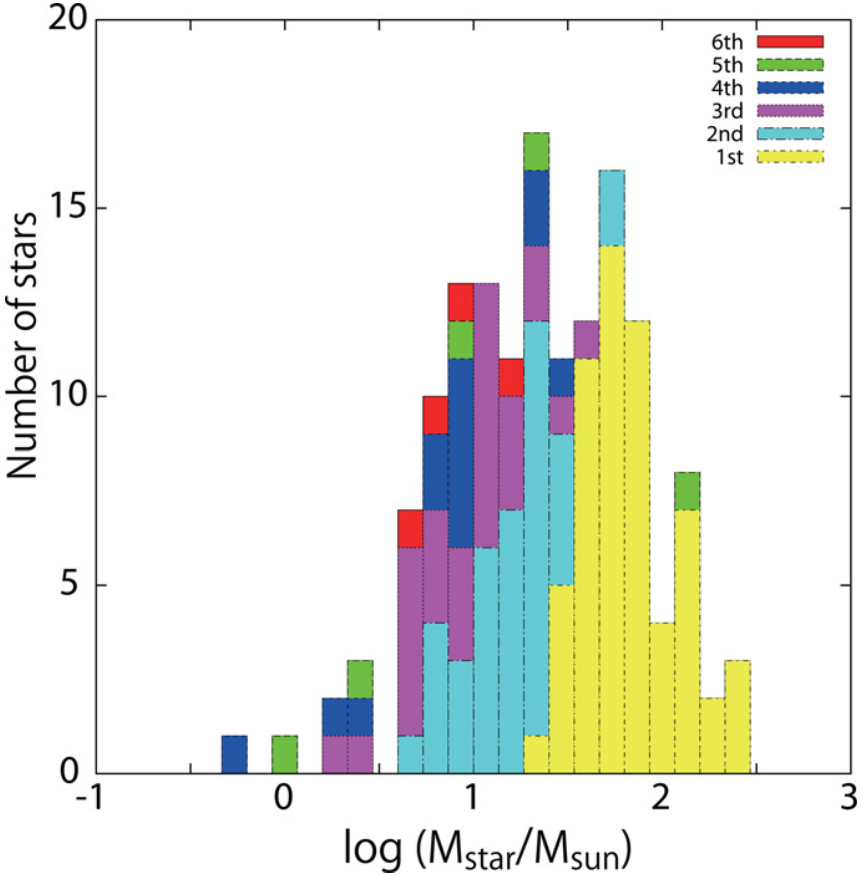
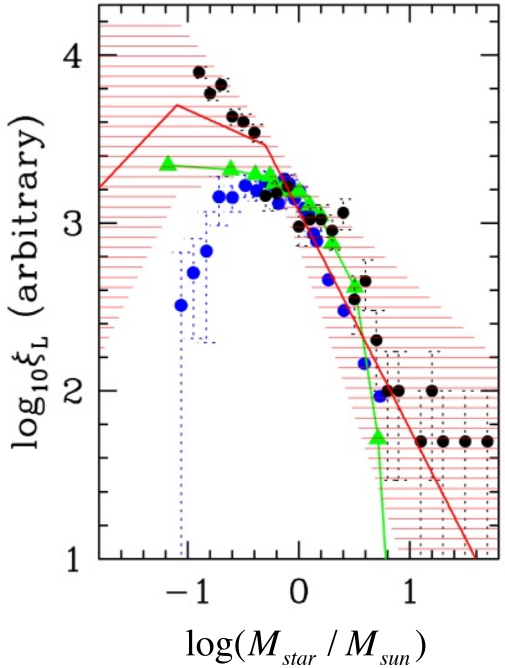


(Susa et al. 2014)

substantially different from current IMF:



(Kroupa 2002)

- on the life and death of high-mass stars

  - mass-luminosity relation for main sequence stars

$$L \propto \frac{dE}{dt}$$

- <u>on the life and death of high-mass stars</u>

  - mass-luminosity relation for main sequence stars*

$$L \propto \frac{dE}{dt} \propto M^{3.5}$$

---

*approximate derivation:

perfect black-body radiator: $L = 4\pi R^2 \sigma T^4$

hydrostatic equilibrium: $\frac{dP}{dr} = -\frac{GM\rho}{r^2} \quad \Rightarrow \quad \langle P \rangle = -\frac{1}{3}\frac{E_{pot}}{V} \quad \Rightarrow \quad \langle P \rangle V = -\frac{1}{3}E_{pot} = \frac{1}{5}\frac{GM^2}{R} = NkT = \frac{M}{m_H}kT = \frac{M}{m_H}k\frac{L^{1/4}}{4\pi R^{1/2}}$

$$M^{3.33} \propto L \quad \Leftarrow \quad M^4 \propto L\, M^{2/3} \quad \overset{R \propto M^{1/3}}{\Leftarrow} \quad M^4 \propto L\, R^2 \quad \Leftarrow \quad M \propto L^{1/4} R^{1/2} \quad \Leftarrow \quad \frac{M^2}{R} \propto M \frac{L^{1/4}}{R^{1/2}}$$

- <u>on the life and death of high-mass stars</u>

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high-mass stars die hard § & fast*

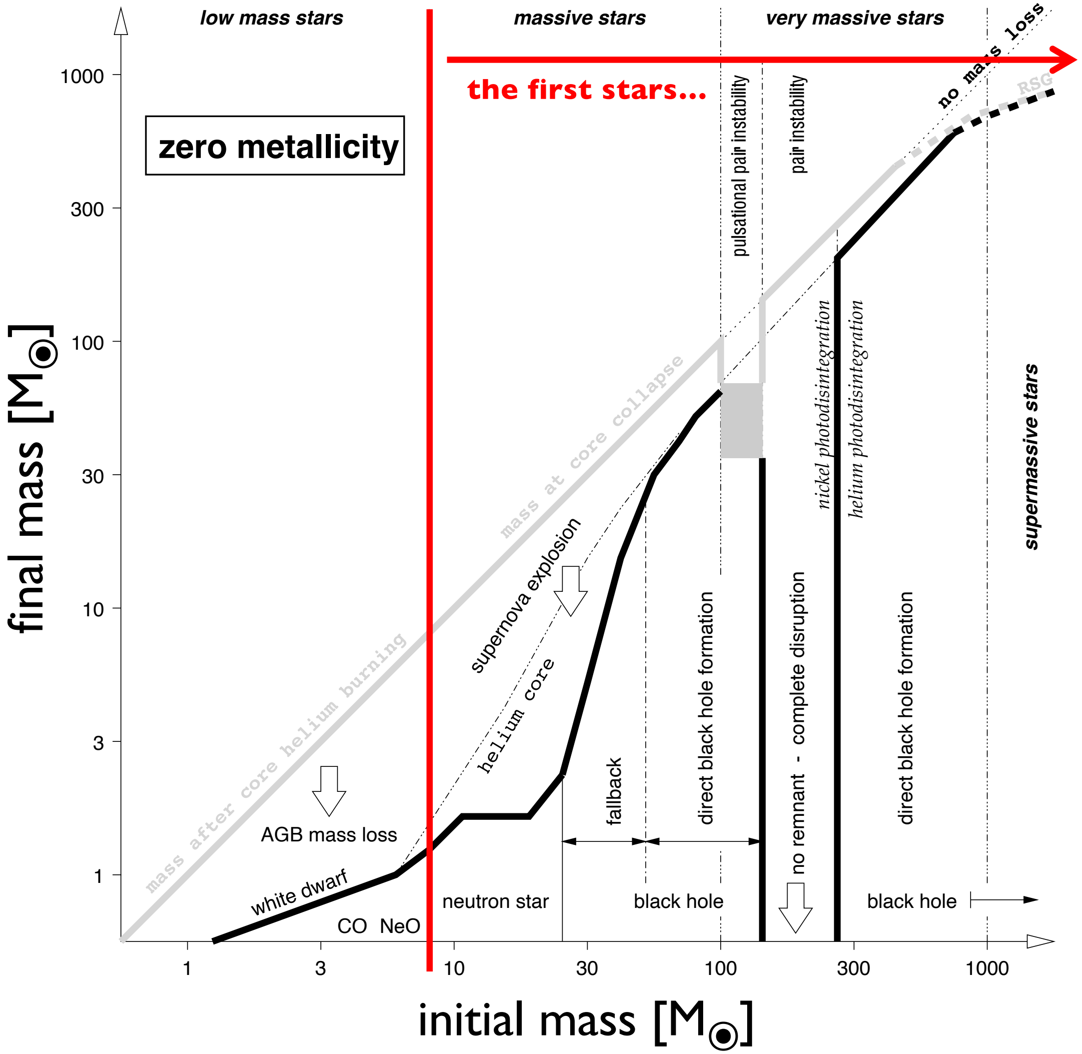
§ spectecular end-stages

*after a few Myrs only!

- on the life and death of high-mass stars
  - metal-free high-mass stars either…
    - form a black hole or…
    - completely disrupt ('pair instability supernova')

- <u>on the life and death of high-mass stars</u>

  - initial mass vs. final mass in general



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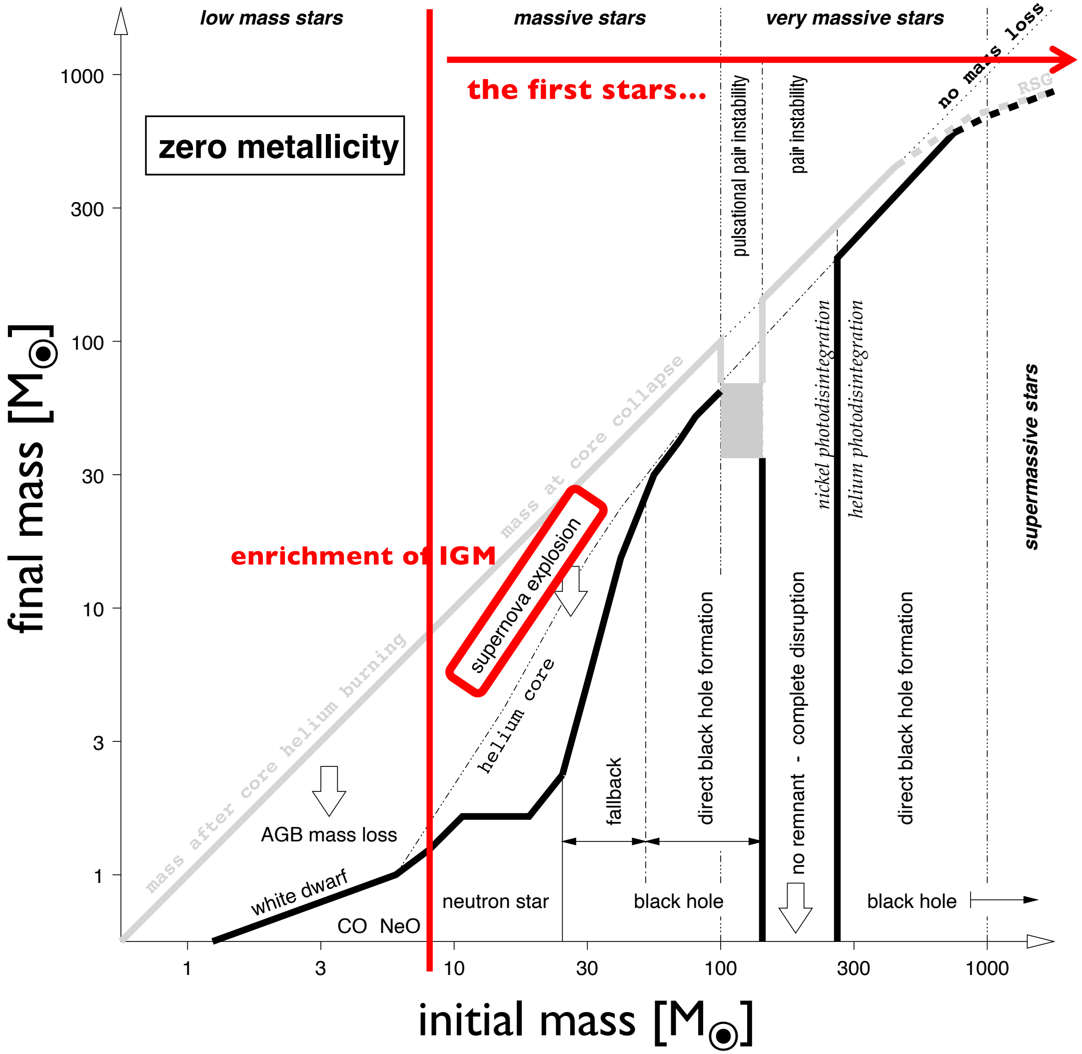

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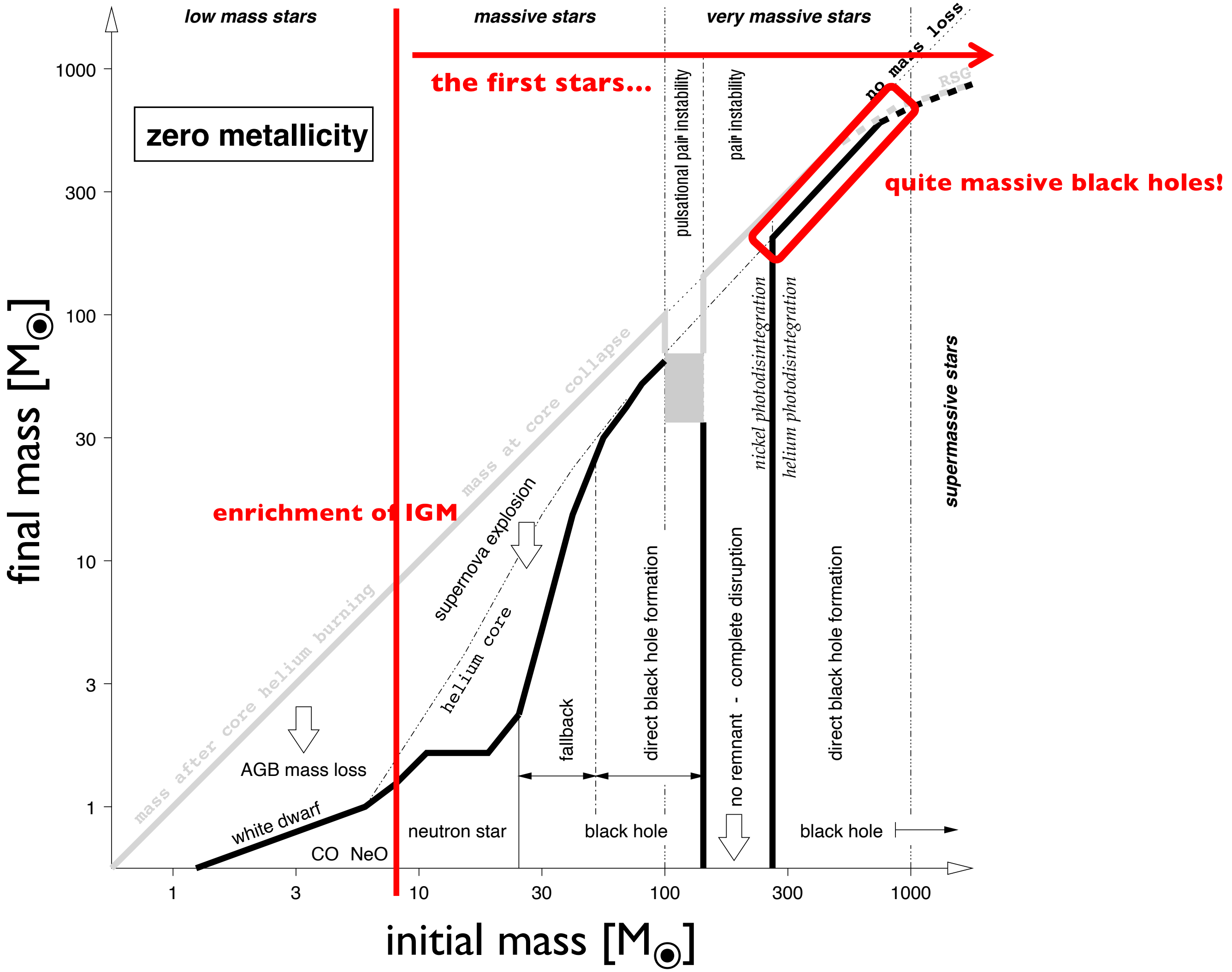

- first stars – summary

  - star formation requires coolant for collapse
  - only available coolant for first stars = H_2
  - sufficient conditions are given for $z < 100$
  - numerical models suggest that first stars are very massive $M \in [10, 500] M_\odot$
  - massive stars die hard & fast:
    - supernovae of $M \in [8, 100] M_\odot$ will pollute IGM with metals, and
    - those metals facilitate subsequent star formation

- first stars – open questions

  - do the first stars also form in binaries?
  - how did Pop III star formation come to an end?
  - what is the influence of magnetic fields?
  - how exactly works turbulence/fragmentation?
  - what about dark matter?

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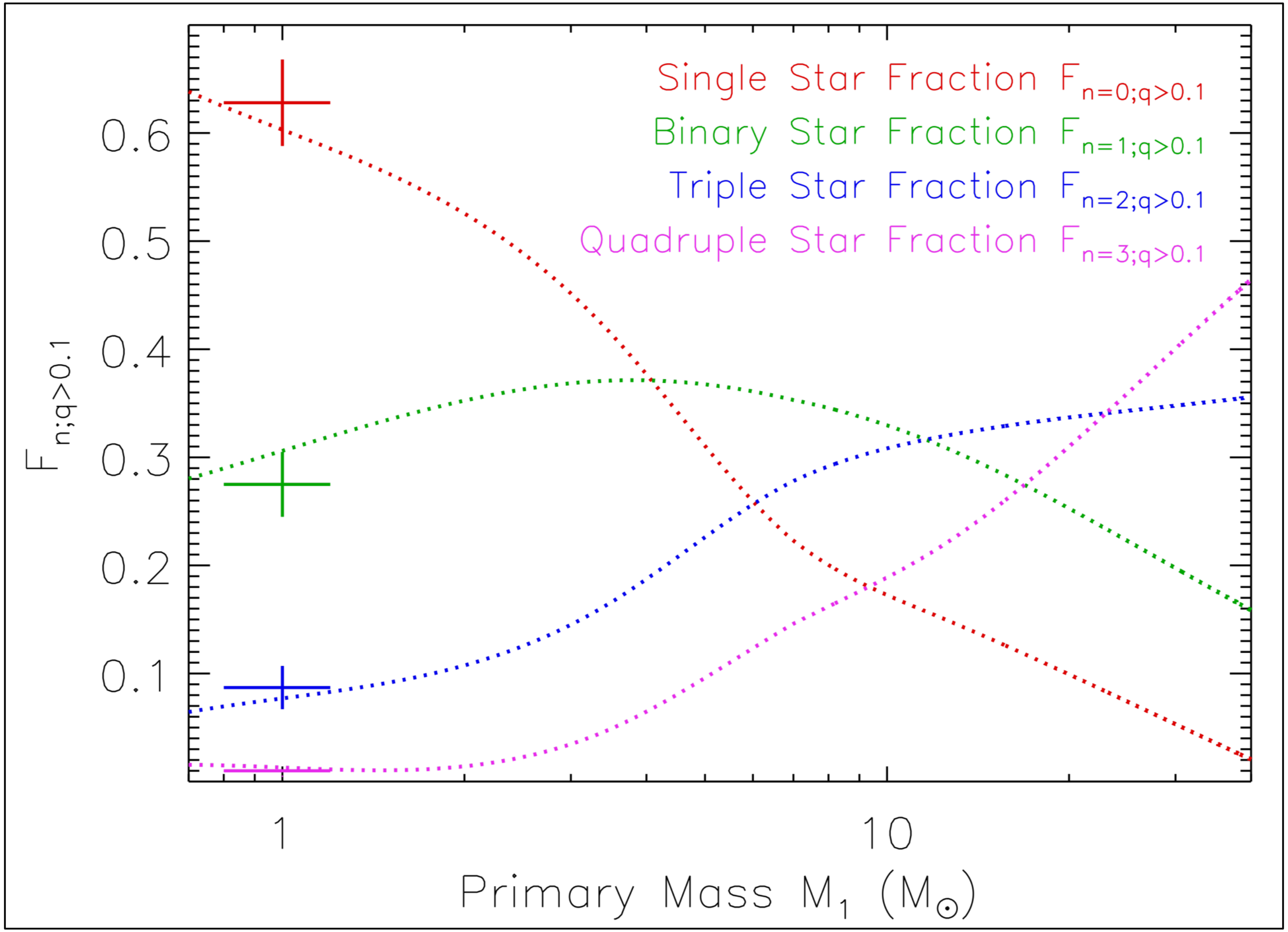

Moe et al. (2017)

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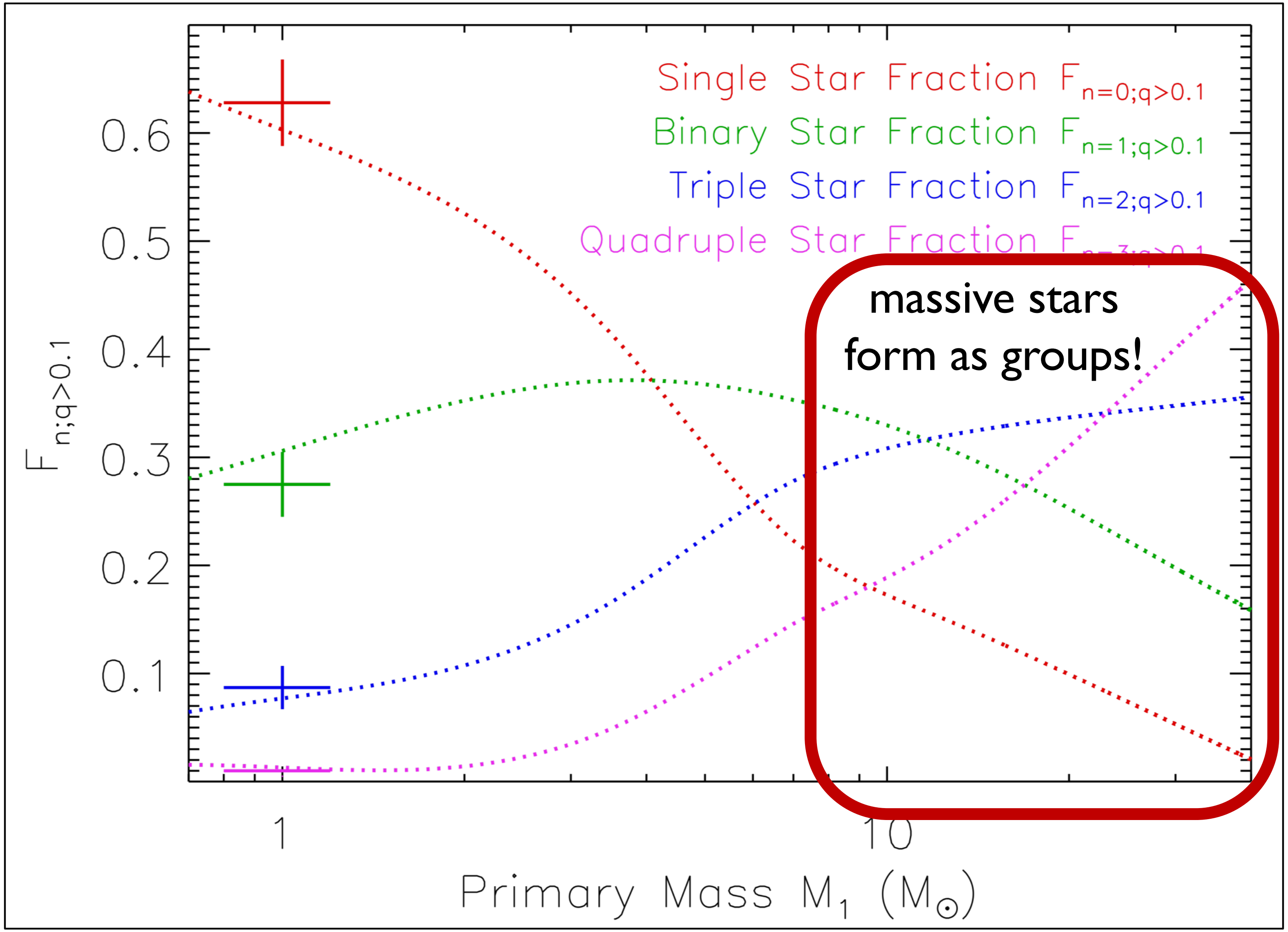

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- <u>first stars – open questions</u>
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- the dark ages of the Universe
- the first stars
- **the first galaxies**
- implications for subsequent structure formation

- <u>the first bound objects</u>

  - protogalaxies[1] are forming **within** dark matter halos

    $\rightarrow$ baryons fall into dark matter potential wells

[1]protogalaxy = gravitationally bound gas cloud

- the first bound objects

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biased galaxy formation scenario (White & Rees 1974)

- <u>the first bound objects – summary</u>

  - characterize DM peaks by their “height” ν

$$\nu = \frac{\delta_c}{D(a)\sigma_0(M)}, \quad \sigma_0^2(M) = \frac{1}{2\pi^2}\int_0^\infty P_0(k)\hat{W}_M^2(k)k^2 dk, \quad \ddot{D} + 2H\dot{D} - \frac{3}{2}\Omega_m H^2 D = 0$$

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  - number density of dark matter halos (according to Press-Schechter formalism)

$$\frac{dn}{dM}dM = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M}\,\frac{\delta_c}{\sigma_M}\left|\frac{d\ln\sigma_M}{d\ln M}\right|\exp\left(\frac{-\delta_c^2}{2\sigma_M^2}\right)\frac{dM}{M}$$

$$\sigma_M^2 = \frac{1}{2\pi^2}\int_0^{+\infty} P(k)\hat{W}^2(kR)k^2\,dk$$

$$\hat{W}(x) = \frac{3}{x^3}\left(\sin(x) - x\cos(x)\right)$$

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combine and introduce

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!?!?!?!?!

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  - **dark matter halo mass > Jeans mass:** $M_J \propto \left(\frac{T^3}{\rho}\right)^{1/2}$

(cf. "star formation" slides)

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?

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$$E_{kin} = \frac{3}{2} N k_B T = \frac{1}{2} m \sigma_v^2$$

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scaling with redshift?

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⇒ formation becomes easier and easier...

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<u>**Note:**</u>

This Jeans mass refers to the mass of a dark matter halo, but determines whether its baryonic component is able to collapse or will be prevented from it.

- the first bound objects

  - **dark matter halo mass > Jeans mass:** $M_J \propto \left(\frac{\sigma_v^6}{\rho}\right)^{1/2}$

    evolution of $M_{v\sigma}(a)$?

$$\left.\begin{aligned}\sigma_v &\propto a^{-1}\\ \rho &\propto a^{-3}\end{aligned}\right\} \quad \boxed{M_J \propto a^{-3/2}} \quad \longrightarrow \quad a \nearrow \;\Rightarrow\; M_J \searrow$$

⇒ formation becomes easier and easier...

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  - "**3-σ** dark matter halos"

$$\nu = \frac{\delta_c}{D(z)\sigma_0(M_{3\sigma})} = \mathbf{3}$$

$D(z)$ = linear growth factor (cf. LSS lecture)

$$\sigma_0^2(M) = \frac{1}{2\pi^2}\int_0^\infty P_0(k)\hat{W}_M^2(k)k^2dk$$

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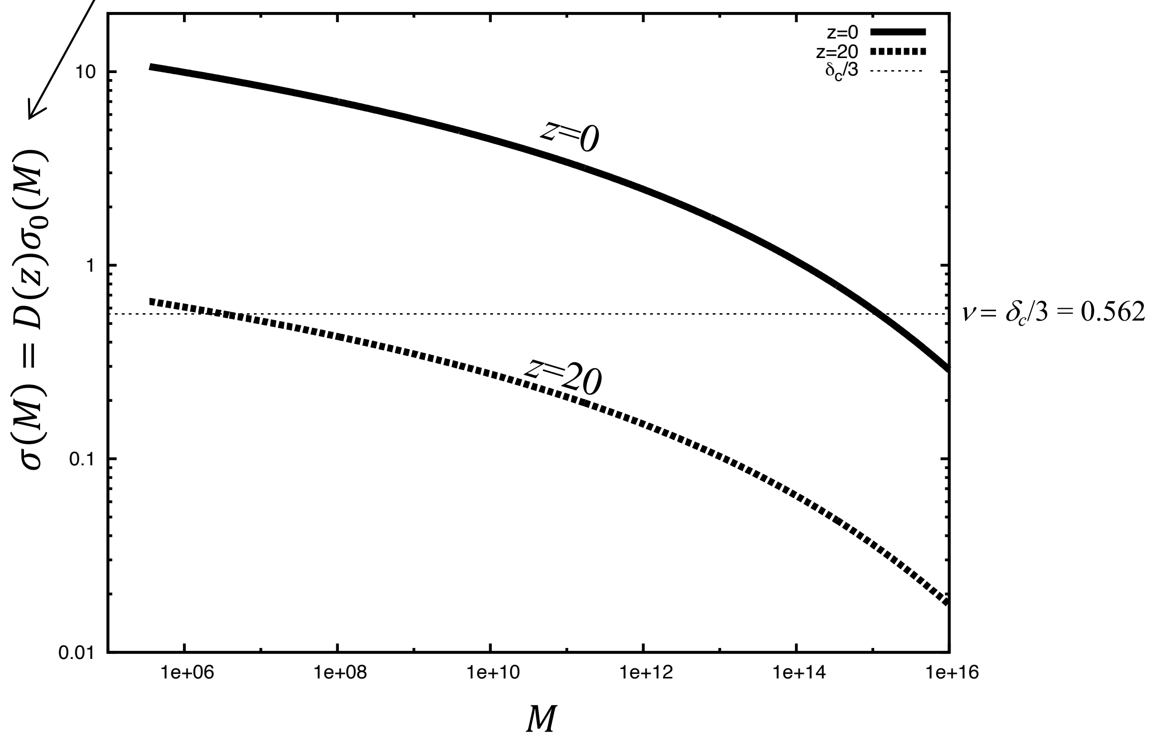
ΛCDM model



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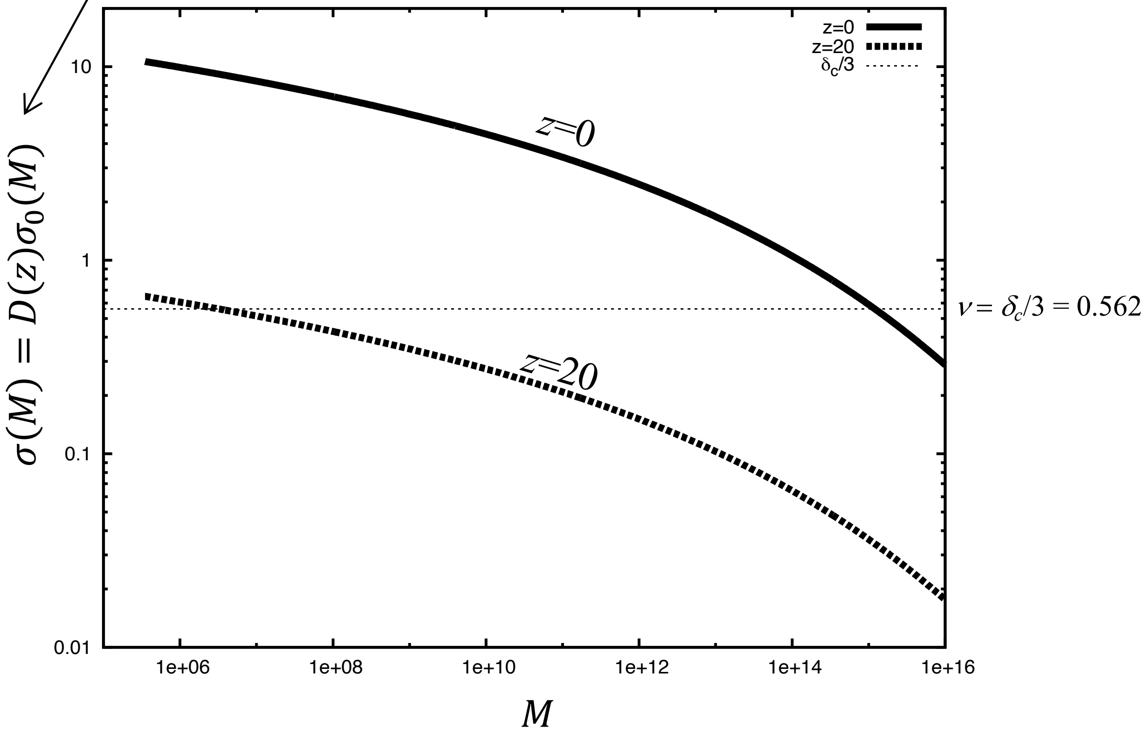

▪ the first bound objects

• "**3-σ** dark matter halos"

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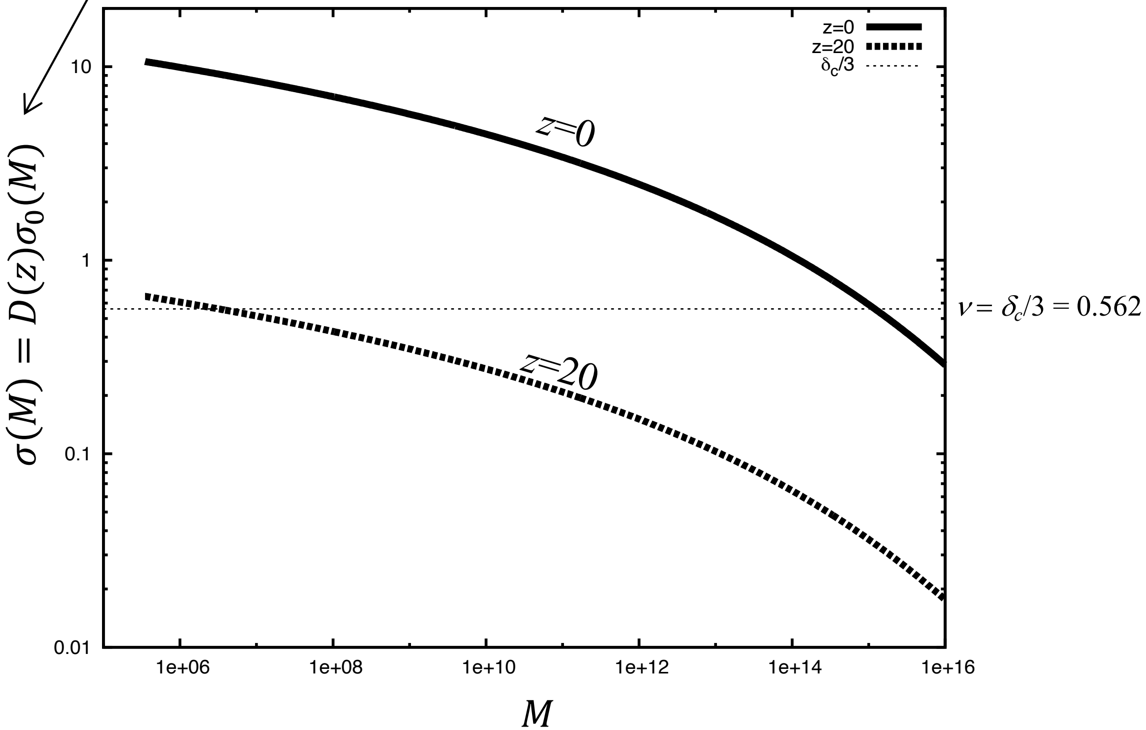

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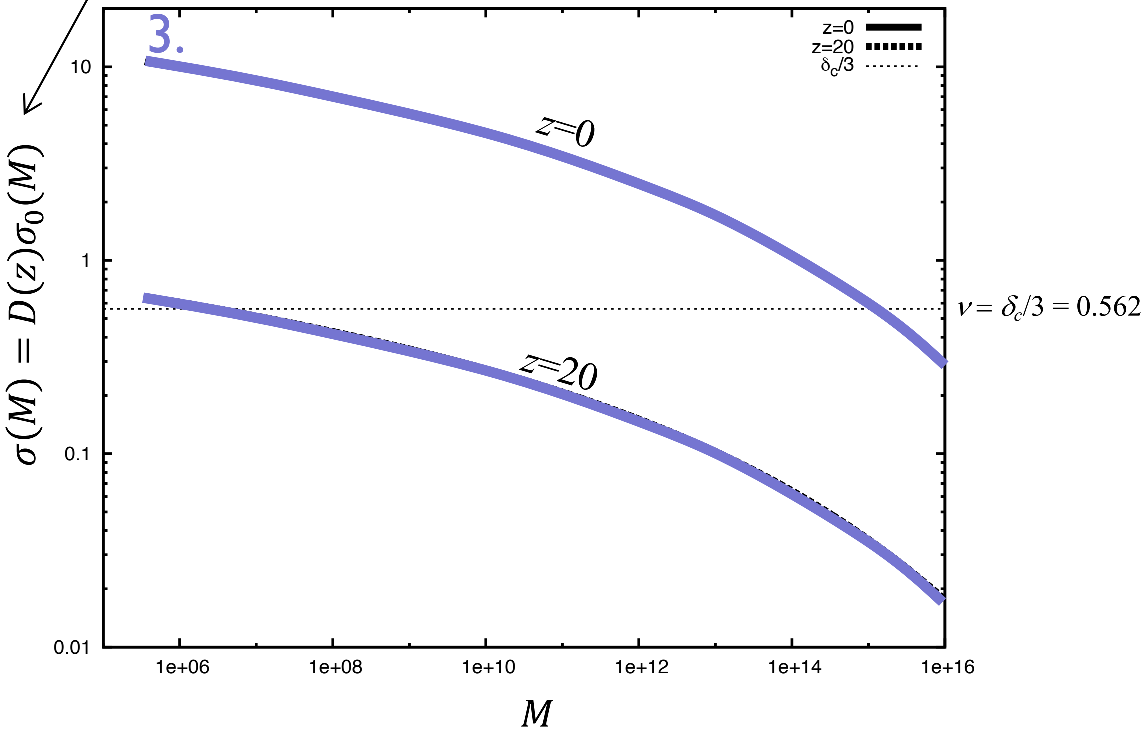

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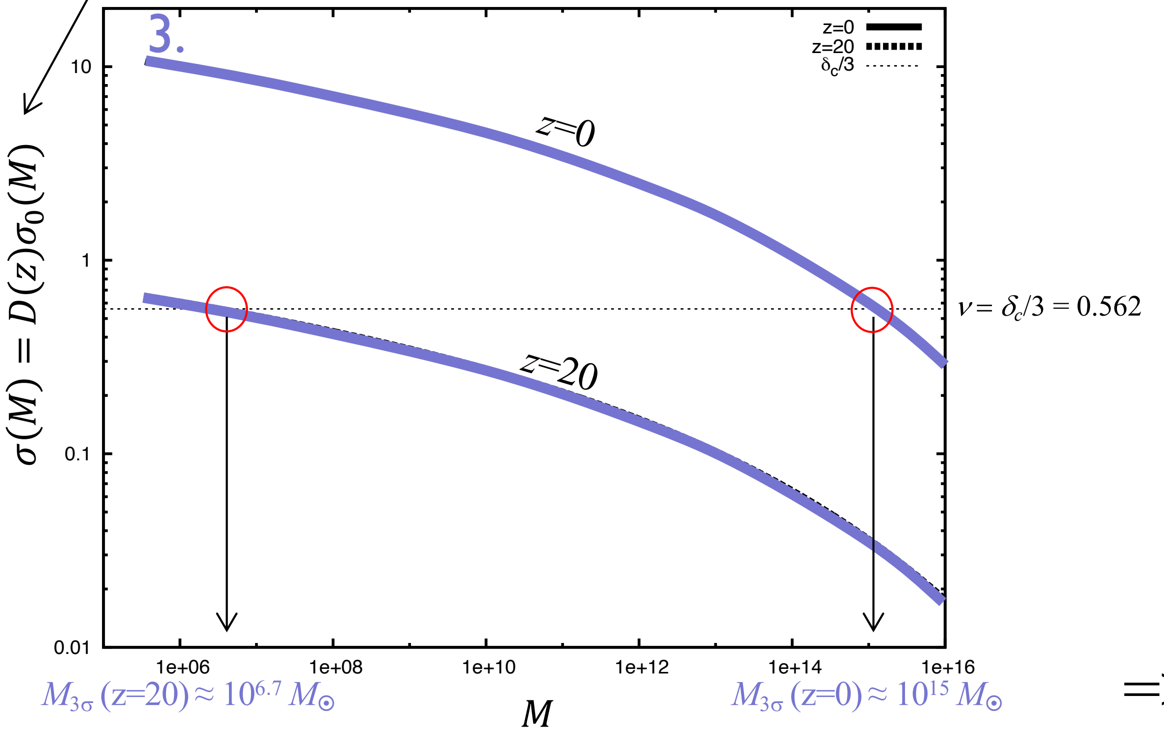

4. $M_{3\sigma}(z=20) \approx 10^{6.7}\, M_\odot$ $M_{3\sigma}(z=0) \approx 10^{15}\, M_\odot$ => $M_{3\sigma}(z)$

- <u>the first bound objects</u>
  - "**3-σ dark matter halos**"

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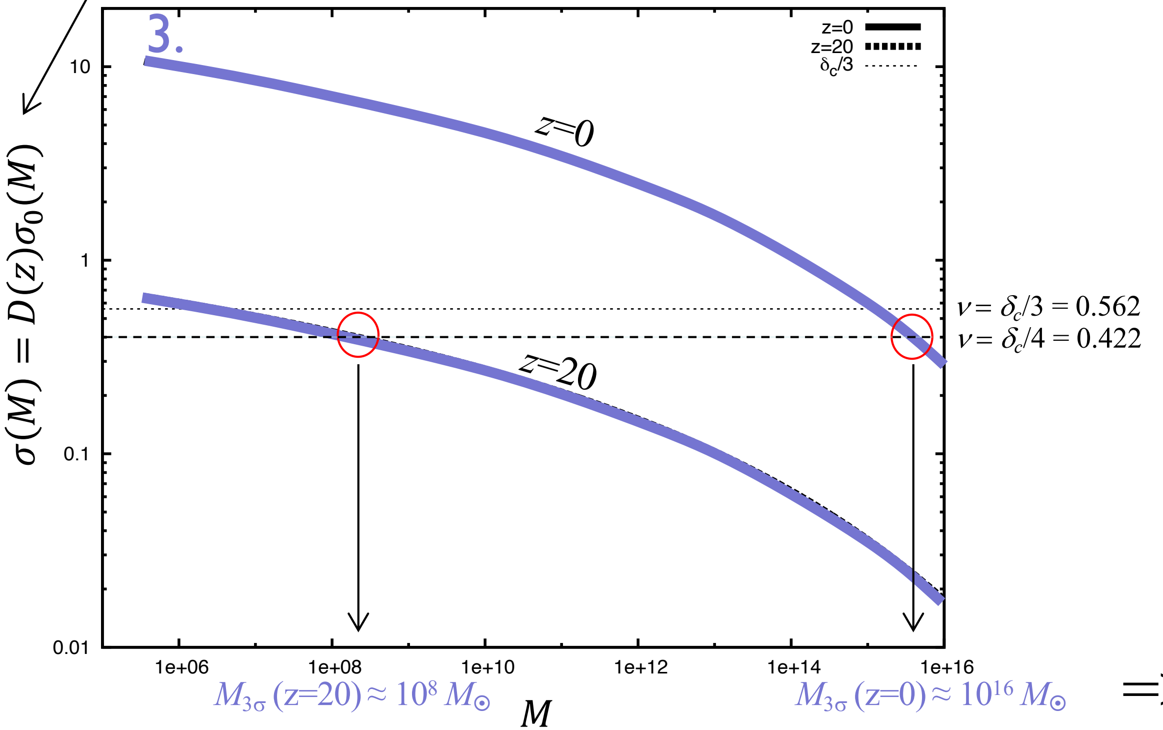
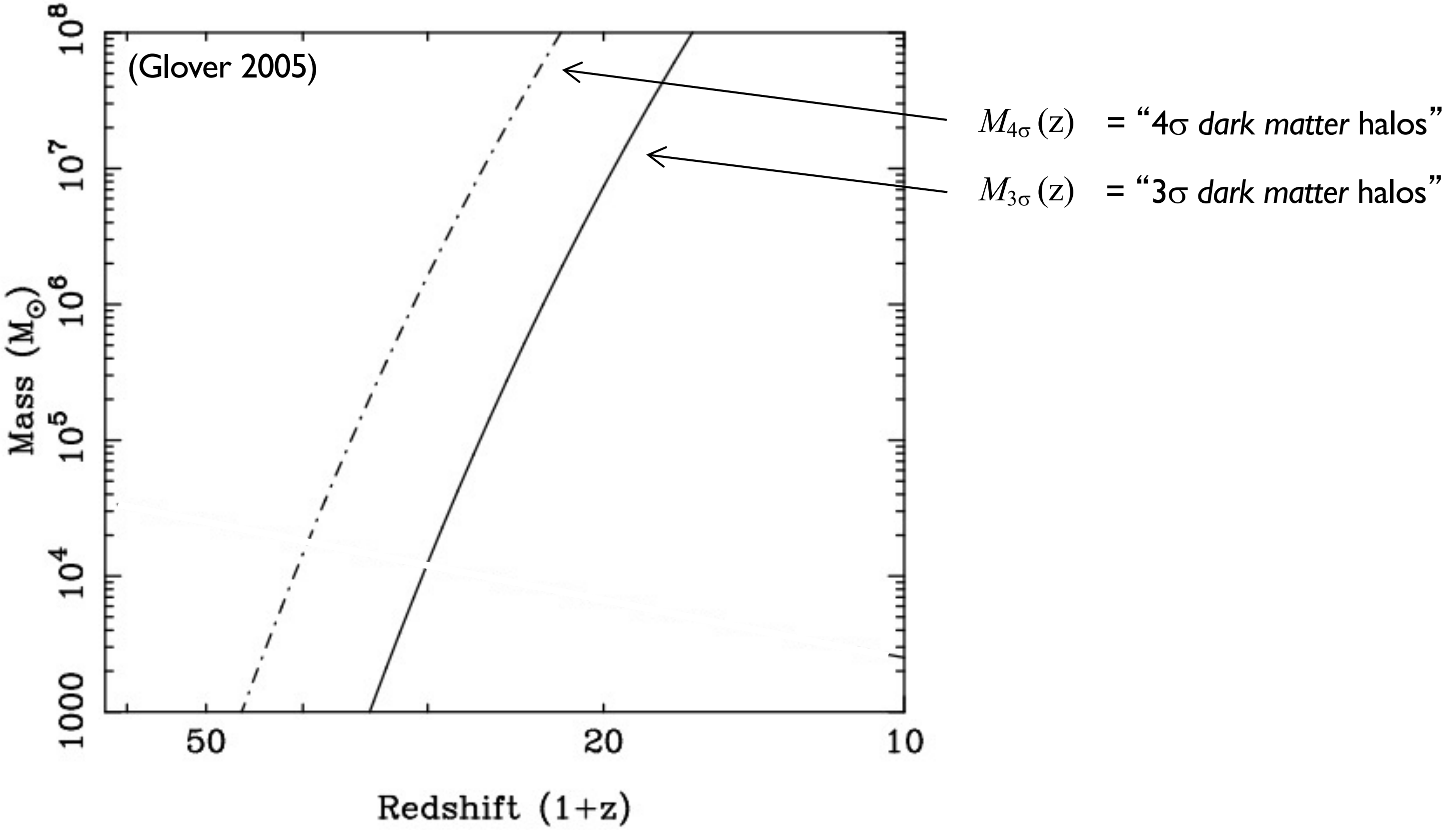


4. $M_{3\sigma}$ (z=20) ≈ $10^8\, M_\odot$ $M_{3\sigma}$ (z=0) ≈ $10^{16}\, M_\odot$ => $M_{3\sigma}(z)$

- <u>the first bound objects</u>

  - compare dark matter $M_{\nu\sigma}(a)$ to its Jeans mass $M_J(a)$



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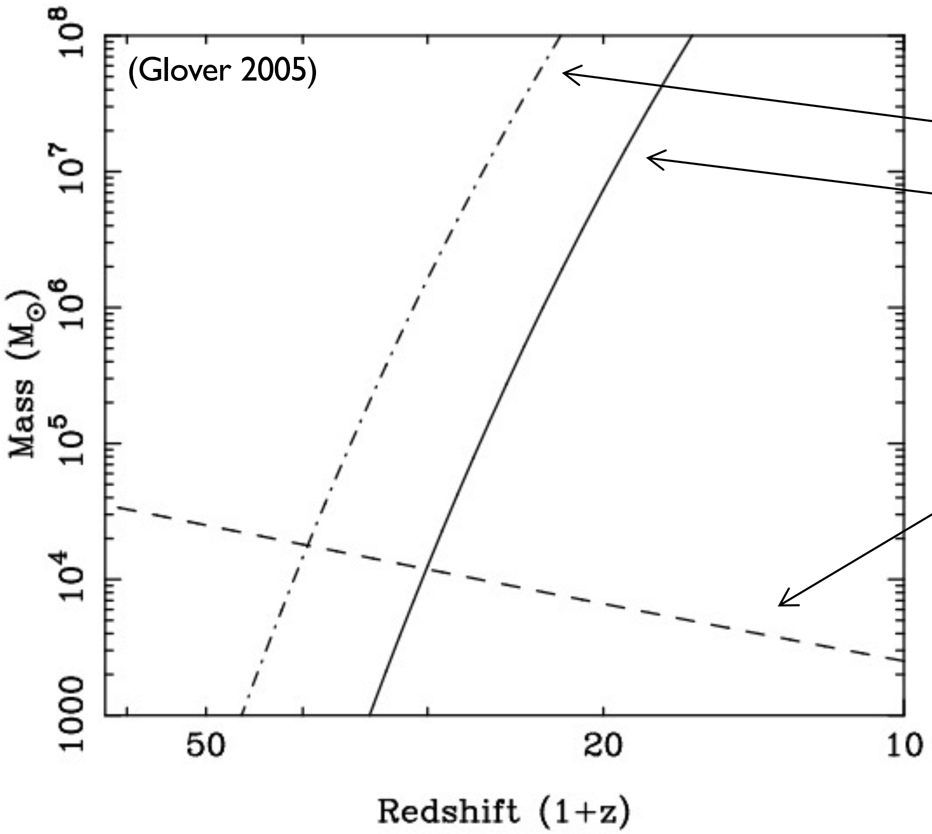

$M_{4\sigma}$ (z) = "4σ *dark matter* halos"

$M_{3\sigma}$ (z) = "3σ *dark matter* halos"

Jeans Mass (Glover 2005):

$$M_J = 4.9 \times 10^4 \left(\Omega_{m,0} h^2\right)^{-1/2} \left(\frac{1+z}{150}\right)^{3/2} M_\otimes$$

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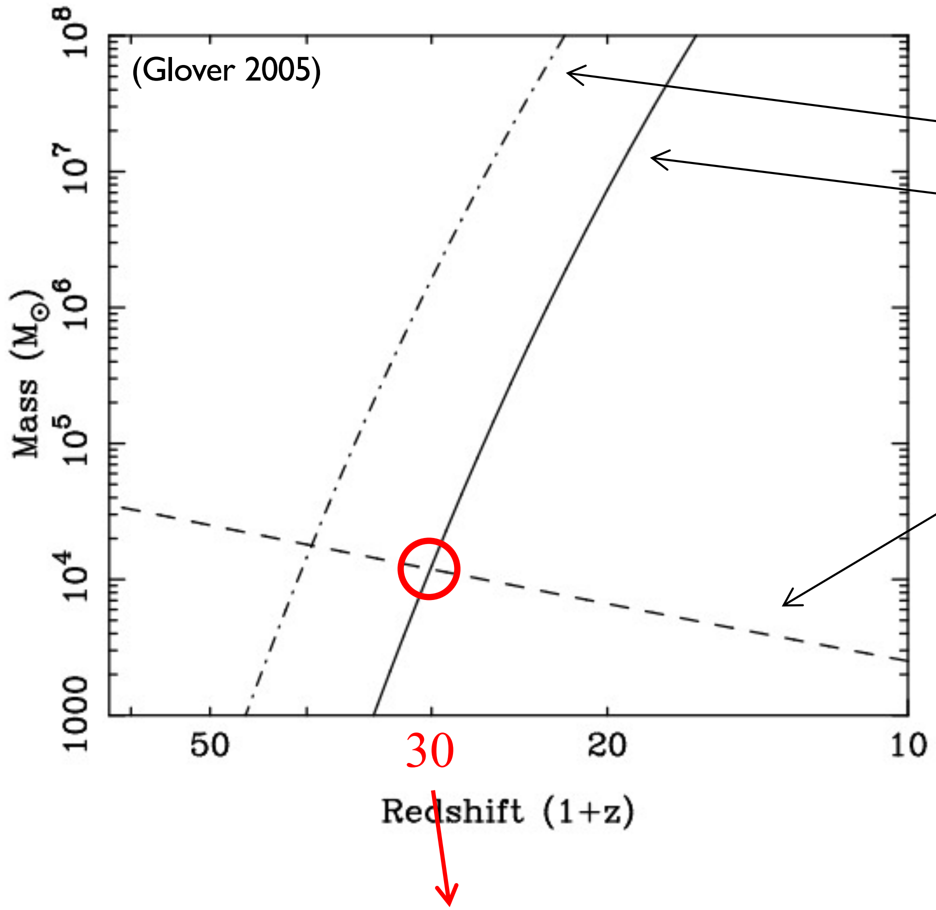

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$M_{3\sigma}(\mathrm{z})$ = "3σ *dark matter* halos"

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formation of first proto-galaxies at $z \approx 30$

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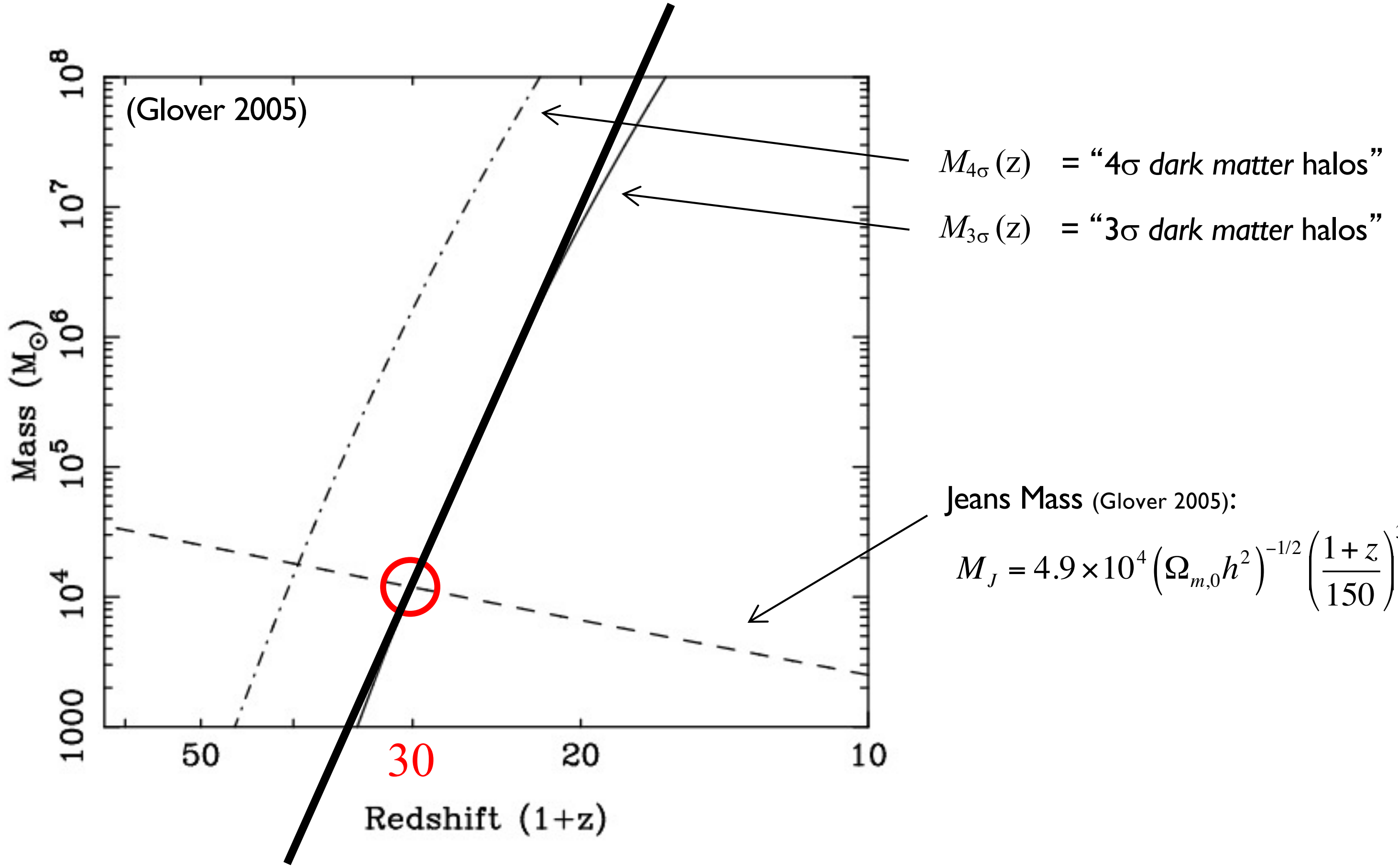


$$M_J = 4.9\times10^4\left(\Omega_{m,0}h^2\right)^{-1/2}\left(\frac{1+z}{150}\right)^{3/2} M_{\otimes}$$

no strong redshift dependence due to steep $M_\sigma(z)$

- the first bound objects

  - spherical top-hat collapse: $1+\delta_{TH}(t_{vir}) = 18\pi^2 \approx 178$ (cf. LSS lecture)

- <u>the first bound objects</u>

  - spherical top-hat collapse: $1+\delta_{TH}(t_{vir}) = 18\pi^2 \boxed{\approx 178}$ (cf. LSS lecture)

assumption of virial theorem in derivation!

…but how do dark matter haloes reach it?

- <u>the first bound objects</u>

  - spherical top-hat collapse: $1+\delta_{TH}(t_{vir}) = 18\pi^2 \approx 178$ (cf. LSS lecture)

  - relaxation & virialisation:
    - *relaxation*: process by which system acquires equilibrium*
    - *virialisation*: finally reaching virial equilibrium $2T = -U$

*re-distribute gravitational collapse energy into random motion

- <u>the first bound objects</u>

  - spherical top-hat collapse: $1+\delta_{TH}(t_{vir}) = 18\pi^2 \approx 178$ (cf. LSS lecture)

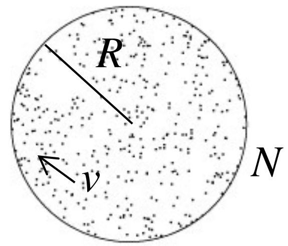
  - relaxation towards virial equilibrium:
    - *two-body relaxation:* two-body interactions
    - *violent relaxation:* change in energy due to change in overall potential
    - *phase-mixing:* spreading of phase-space due to different frequencies of orbits
    - *chaotic mixing:* spreading of phase-space due to chaotic nature of orbits
    - *Landau damping:* damping and decay of perturbations

▪ the first bound objects

- spherical top-hat collapse: $1+\delta_{TH}(t_{vir}) = 18\pi^2 \approx 178$ (cf. LSS lecture)

- relaxation towards virial equilibrium:
  - *two-body relaxation:* two-body interactions

$$t_{relax} \approx \frac{N}{10 \ln N} t_{cross} \quad , \quad t_{cross} \approx \frac{R}{v}$$



$$t_{relax} >> t_{Hubble}$$

(for all cosmological objects of interest to us…)

- <u>the first bound objects</u>

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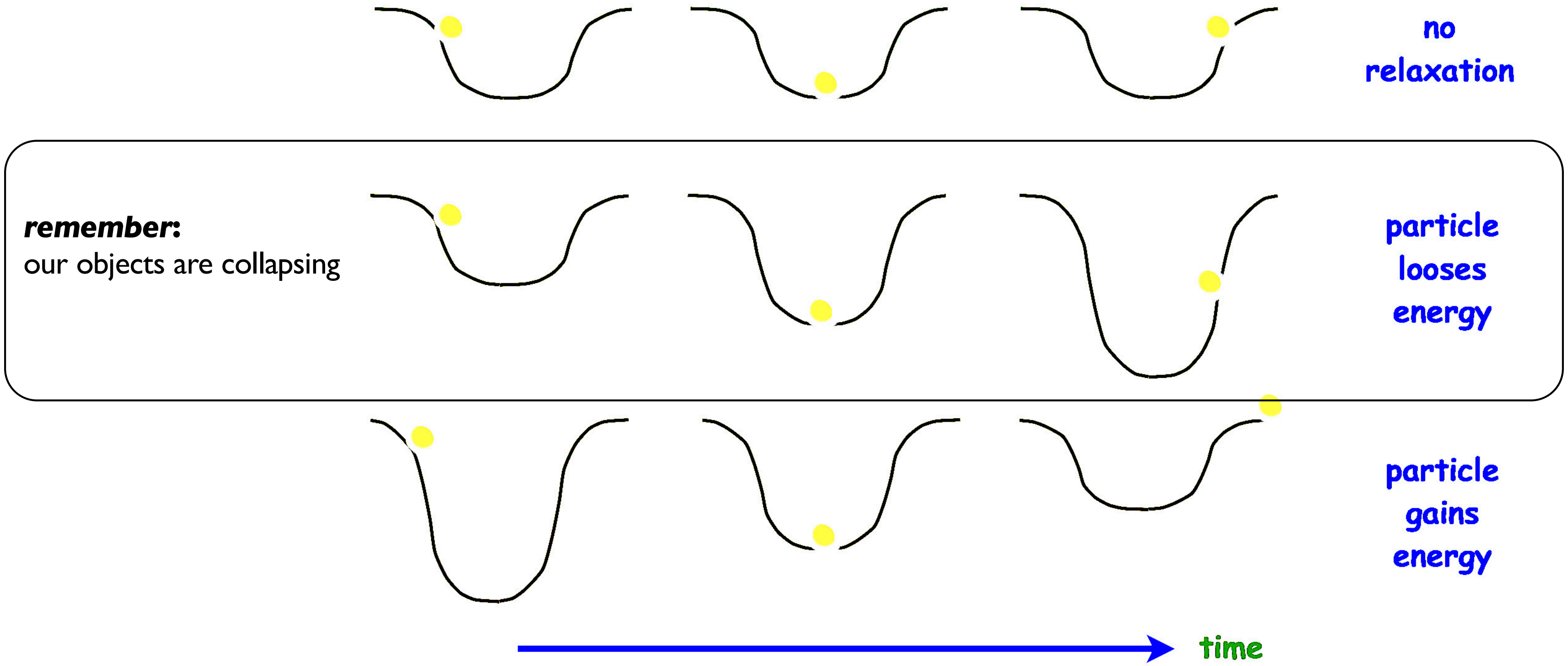

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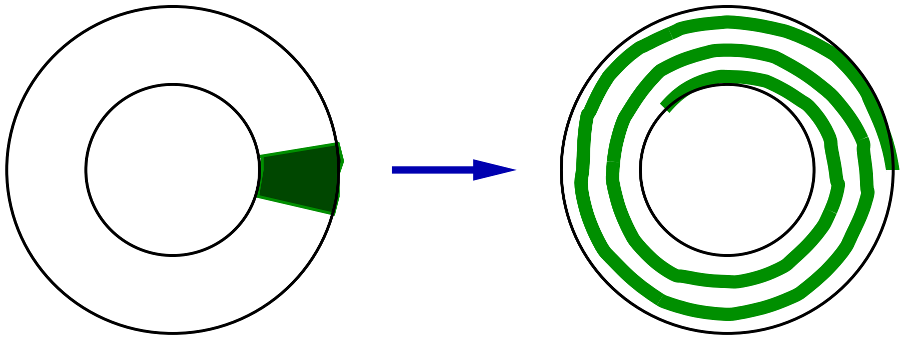

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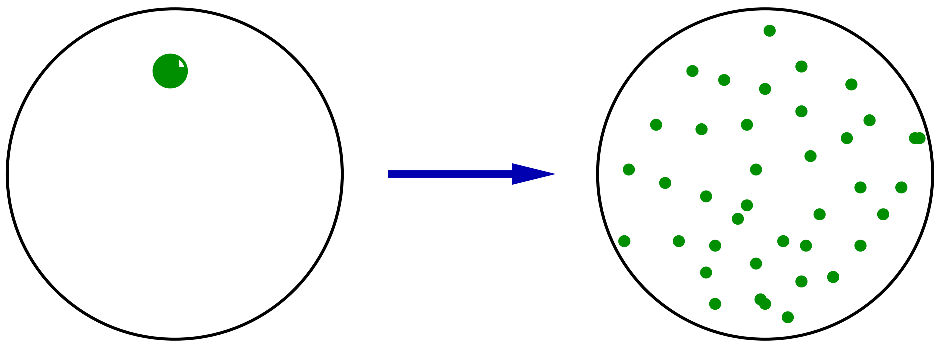
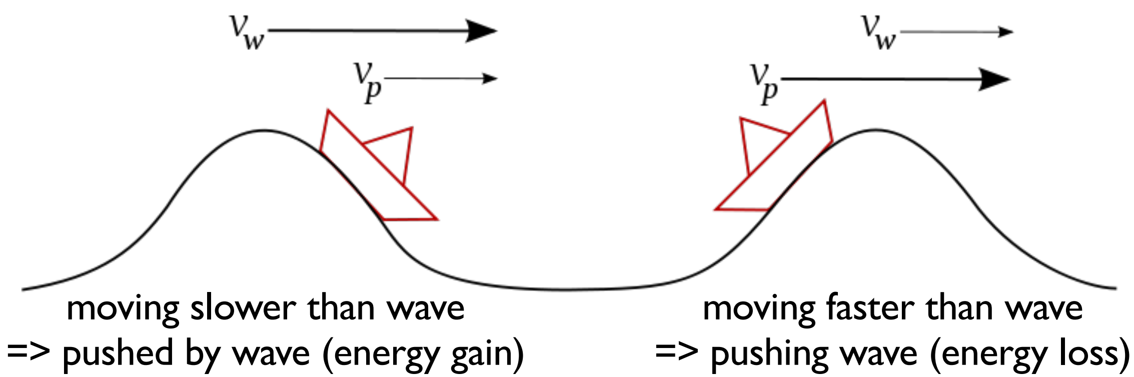


- <u>the first bound objects</u>

  - spherical top-hat collapse: $1+\delta_{TH}(t_{vir}) = 18\pi^2 \approx 178$ (cf. LSS lecture)

  - relaxation towards virial equilibrium:
    - *Landau damping:* damping and decay of perturbations…

      …due to interaction of particles with (density) waves



- the first bound objects – summary

  - characterize DM peaks by their "height" ν

$$\nu = \frac{\delta_c}{D(a)\sigma_0(M)}, \quad \sigma_0^2(M) = \frac{1}{2\pi^2}\int_0^\infty P_0(k)\hat{W}_M^2(k)k^2 dk, \quad \ddot{D} + 2H\dot{D} - \frac{3}{2}\Omega_m H^2 D = 0$$

  - compare dark matter $M_{\nu\sigma}(a)$ to its Jeans mass $M_J(a)$

  - it is possible to form 3-σ dark matter haloes already at $z \approx 30$

  - dark matter haloes virialize due to relaxation processes

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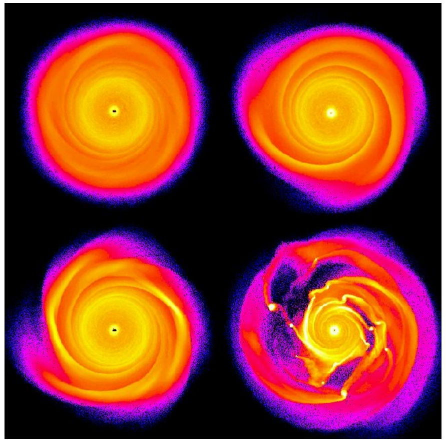
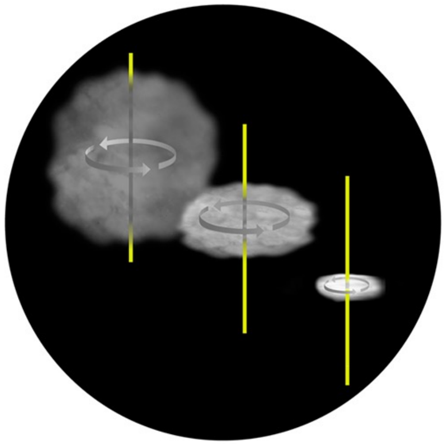
...and what about the proto-galaxies now?

- proto-galaxies

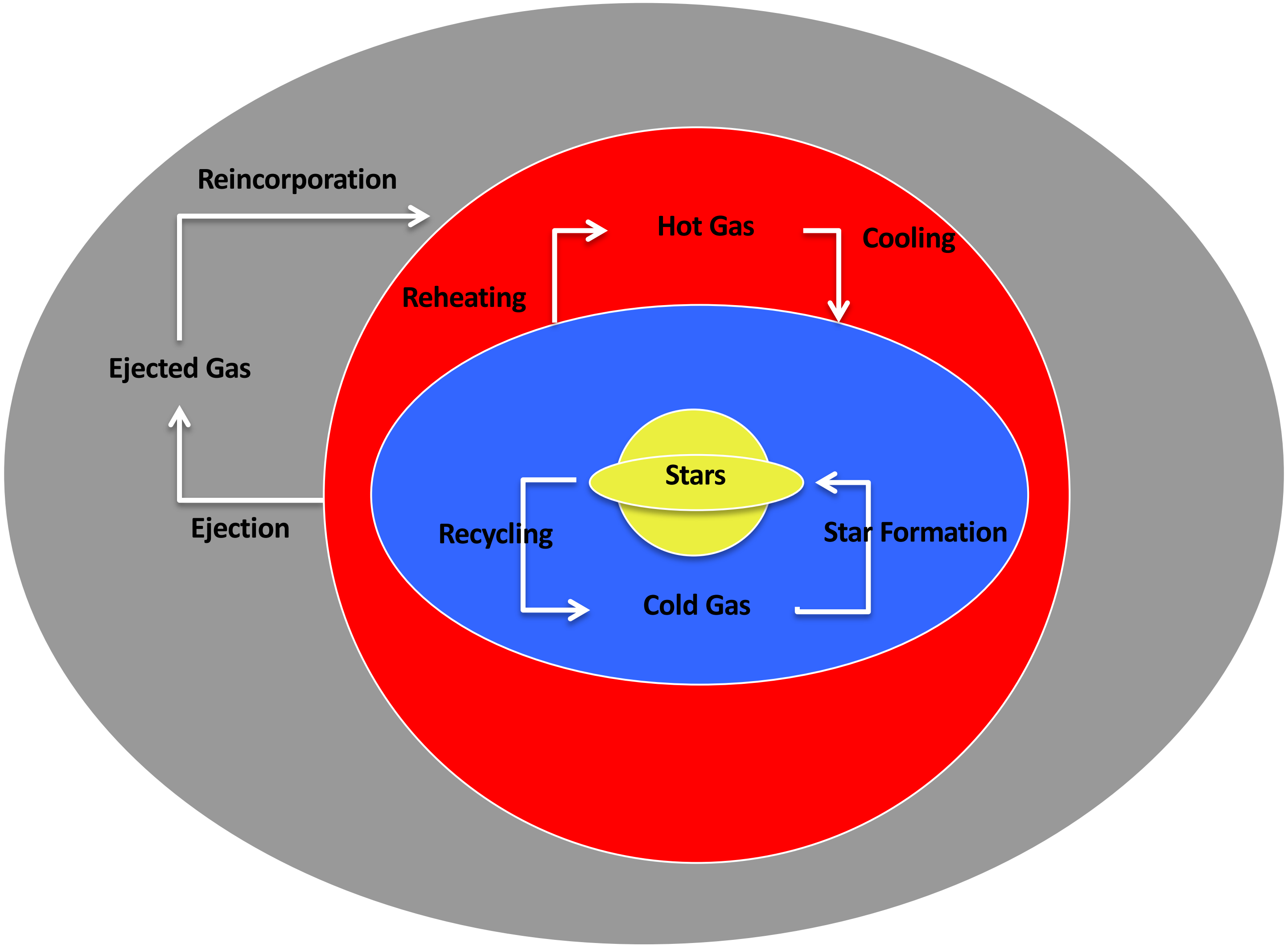
  - presence of DM halo appears inevitable, but
  - potential well of DM halo needs to be sufficiently deep to retain gas heated to high temperatures ($>10^4$K) by first stars
  - cooling of gas cloud required
  - collapse to disk-like structure because of angular momentum* conservation
  - fragmentation via turbulence





*tidal torque theory: anisotropic collapse of δ

- <u>proto-galaxies</u>
  - complexity of galaxy formation in general:



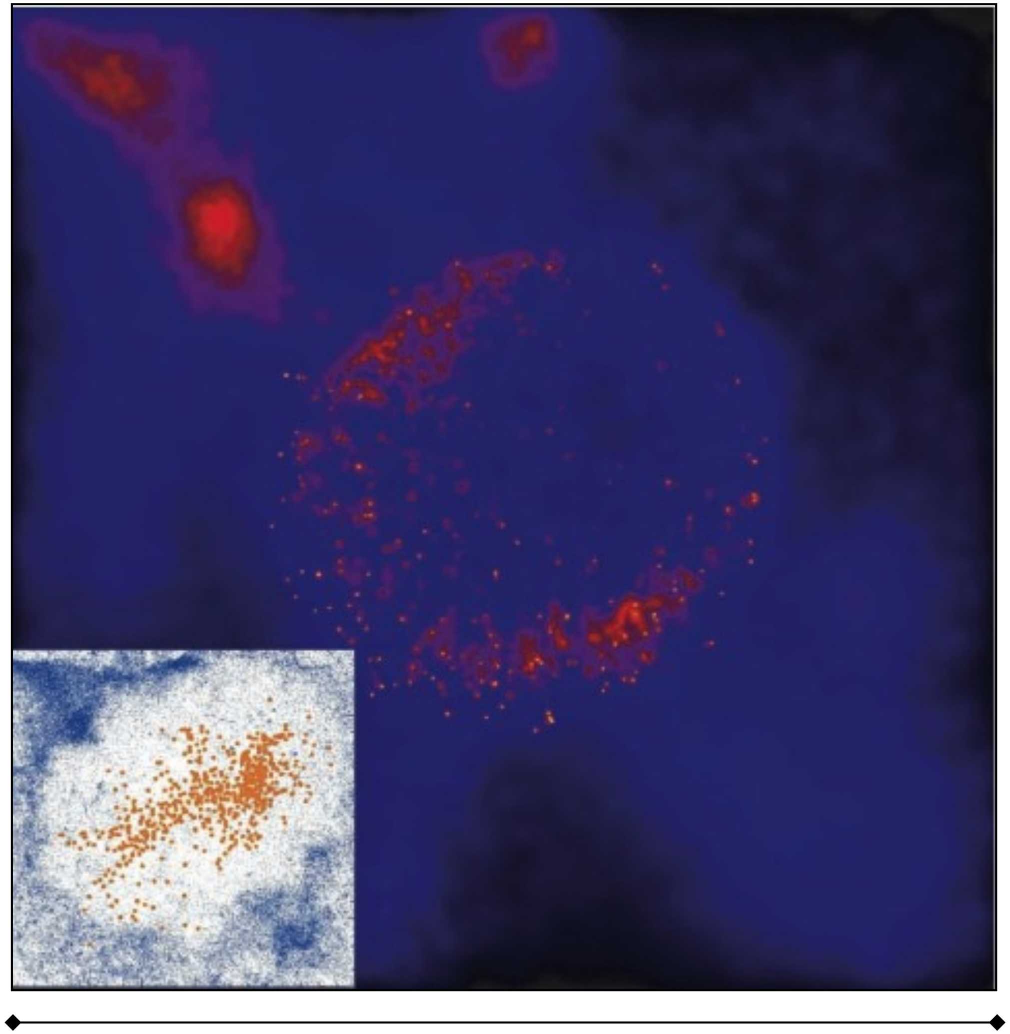
- the dark ages of the Universe
- the first stars
- the first galaxies
- **implications for subsequent structure formation**

- proto-galaxies
  - enrichment of the Universe with heavy elements
  - re-ionisation of the Universe

$\rightarrow$ first objects affect everything that comes afterwards

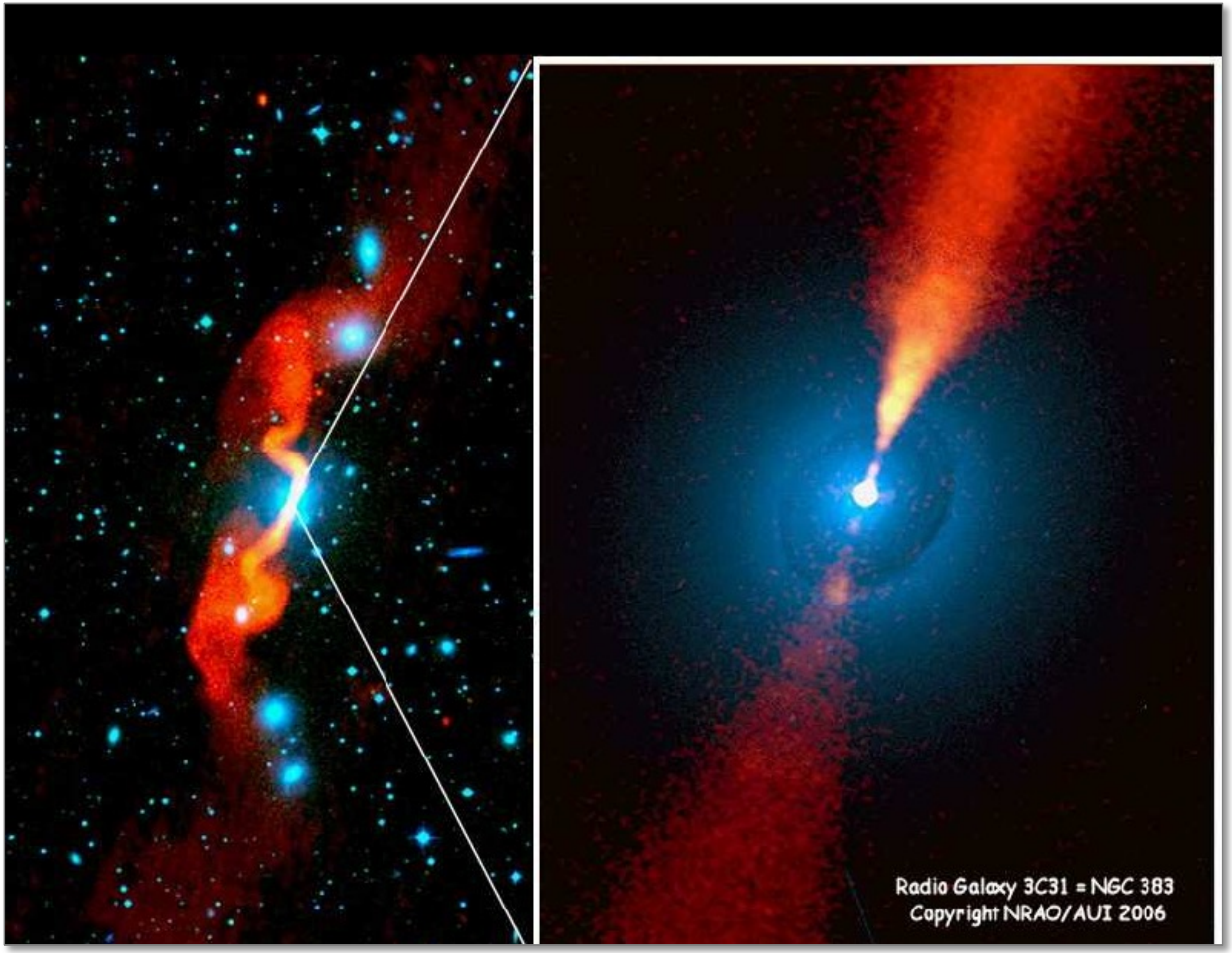
▪ the first supernova explosion

- explosion after ca. 10^6 years
- $E_{SN} = 10^{53}$ ergs
- color-coded gas density after 1 Myr
  - red dots = stellar ejecta
  - blue dots = HII regions
- inset panel:
  - metal distribution after 3Myrs

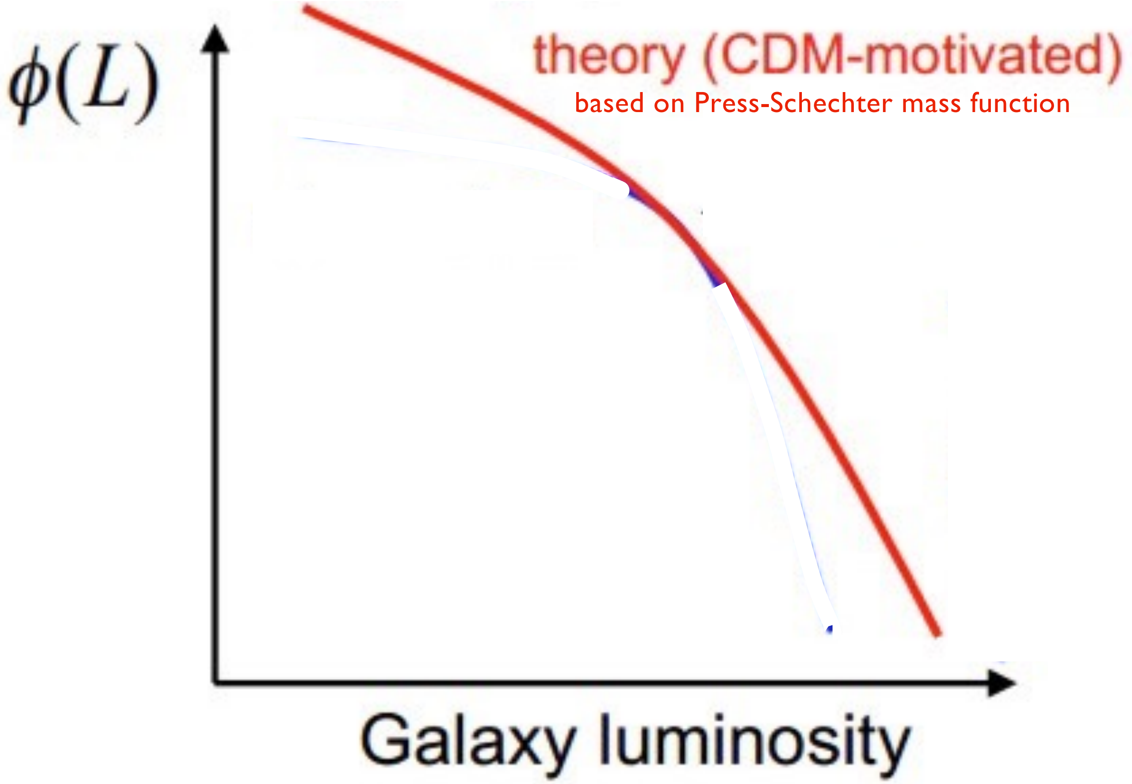


(Bromm et al. 2003)

- <u>Active Galactic Nuclei</u>



- <u>shaping the luminosity function of galaxies</u>



(Silk et al., 2013)

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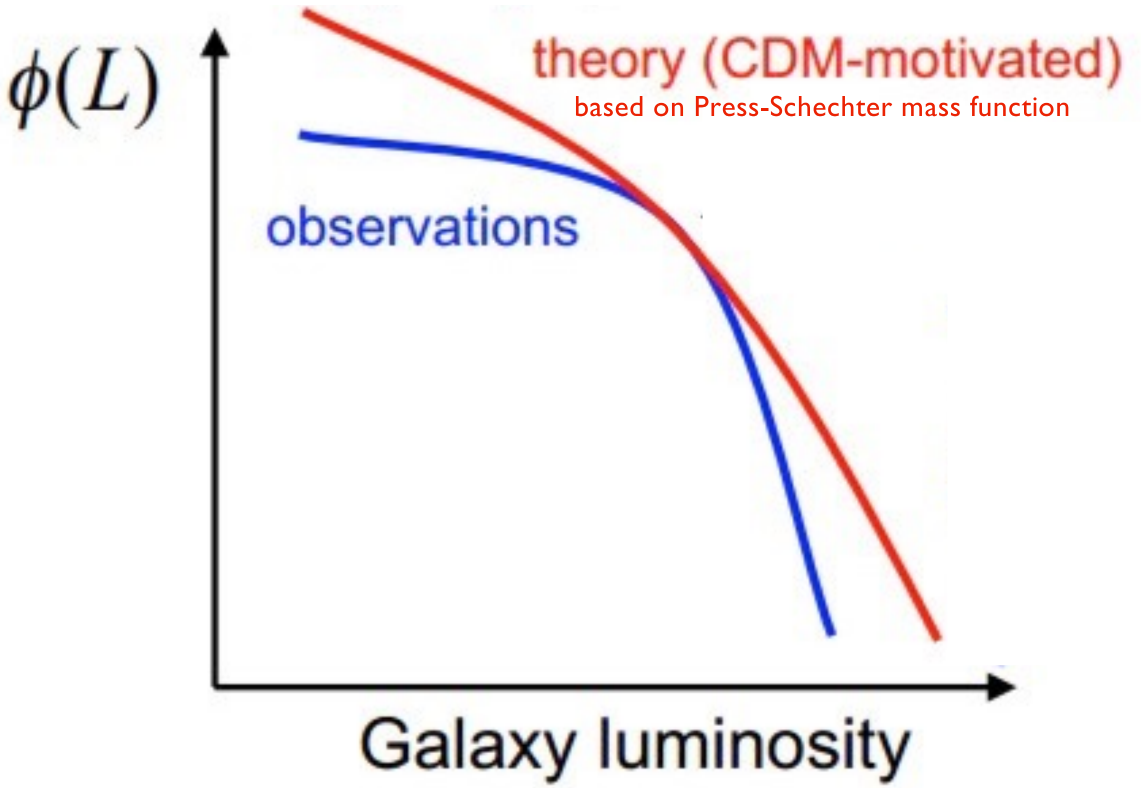

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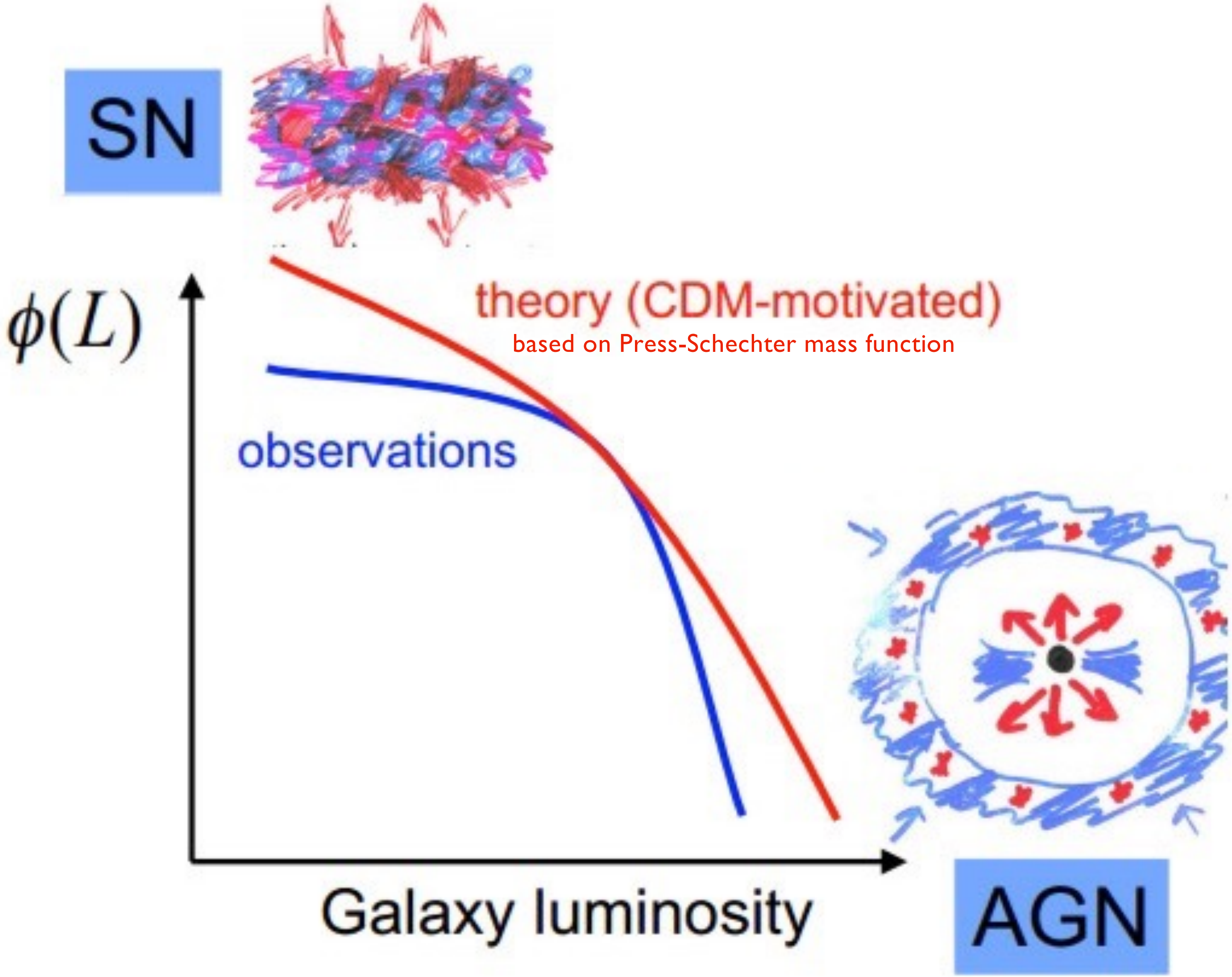
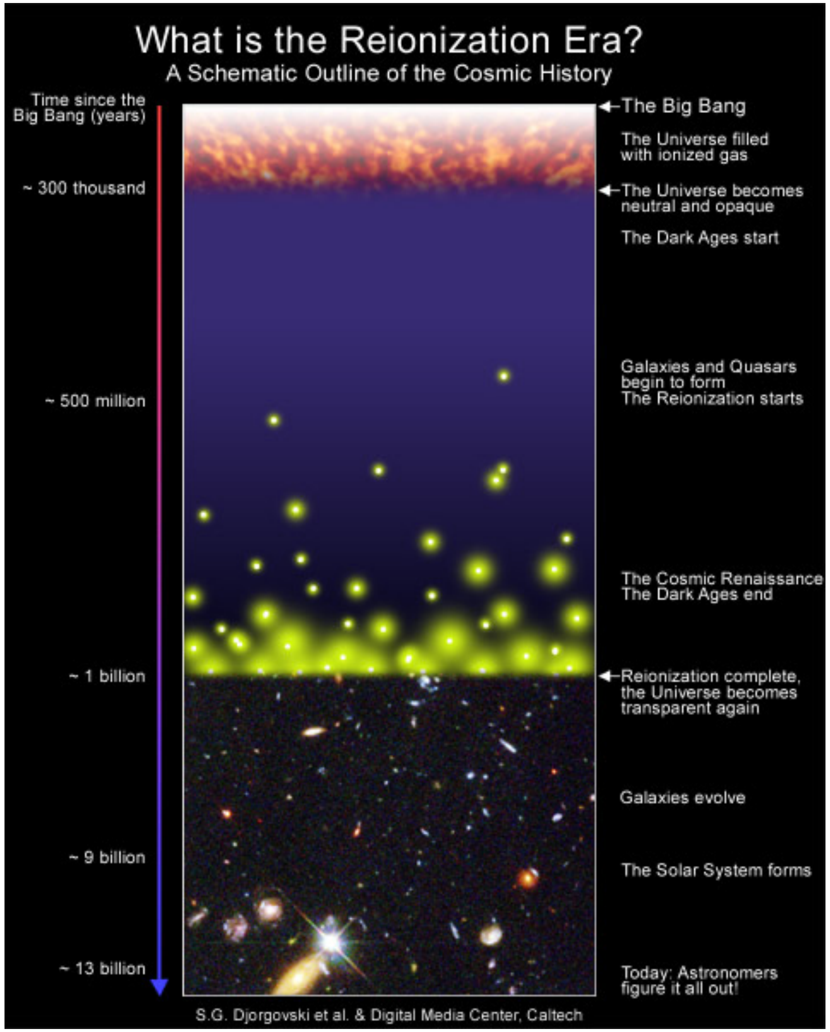


(Silk et al., 2013)

- reionising the Universe

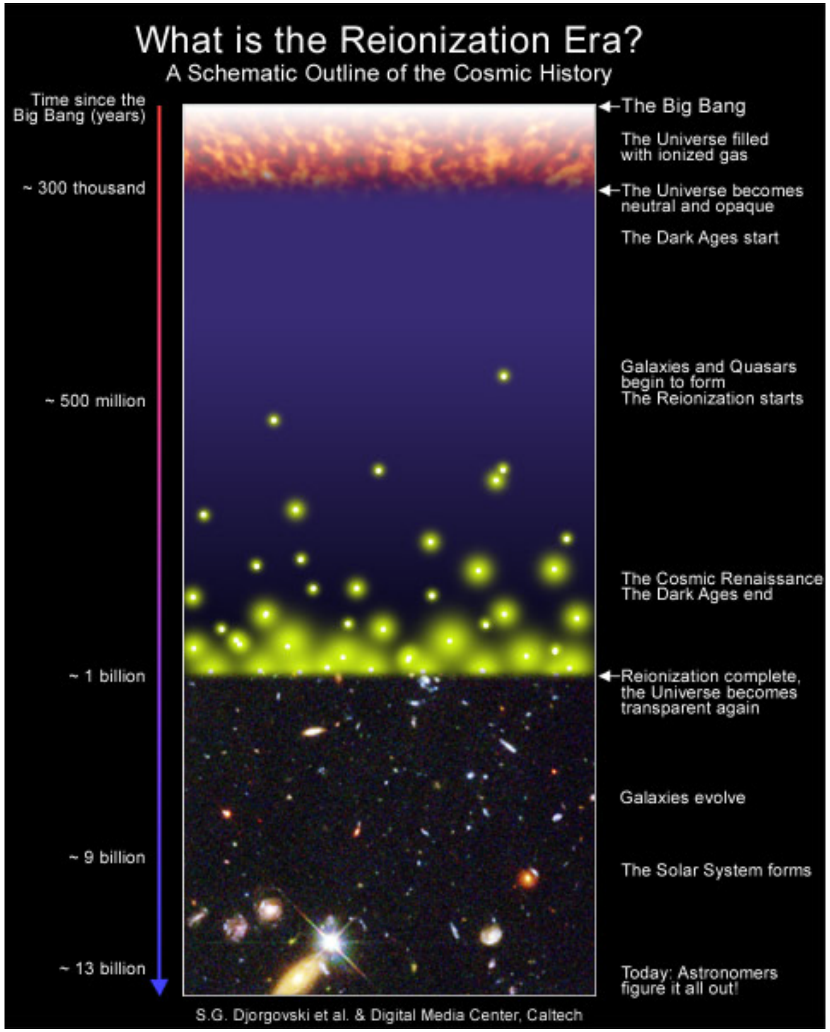


▪ reionising the Universe

• energy released by first objects ionizes neutral hydrogen

• detected via…

…Gunn-Peterson trough in QSO spectra:
neutral hydrogen along line-of-sight absorbs photons



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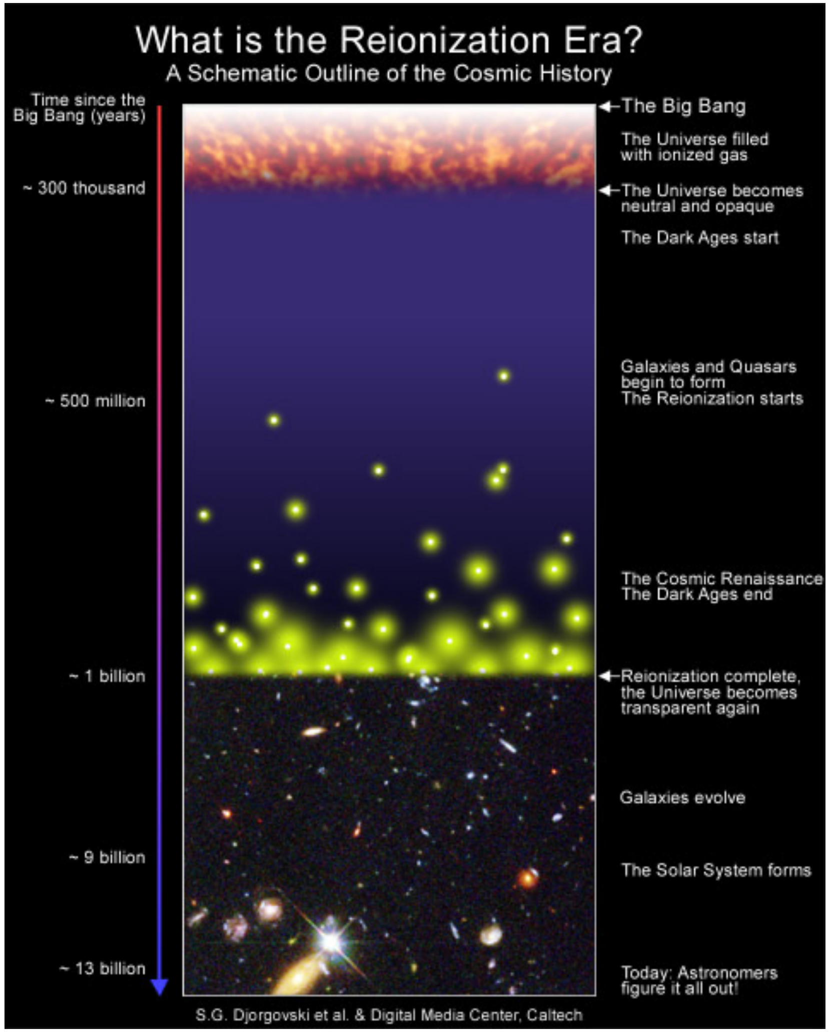

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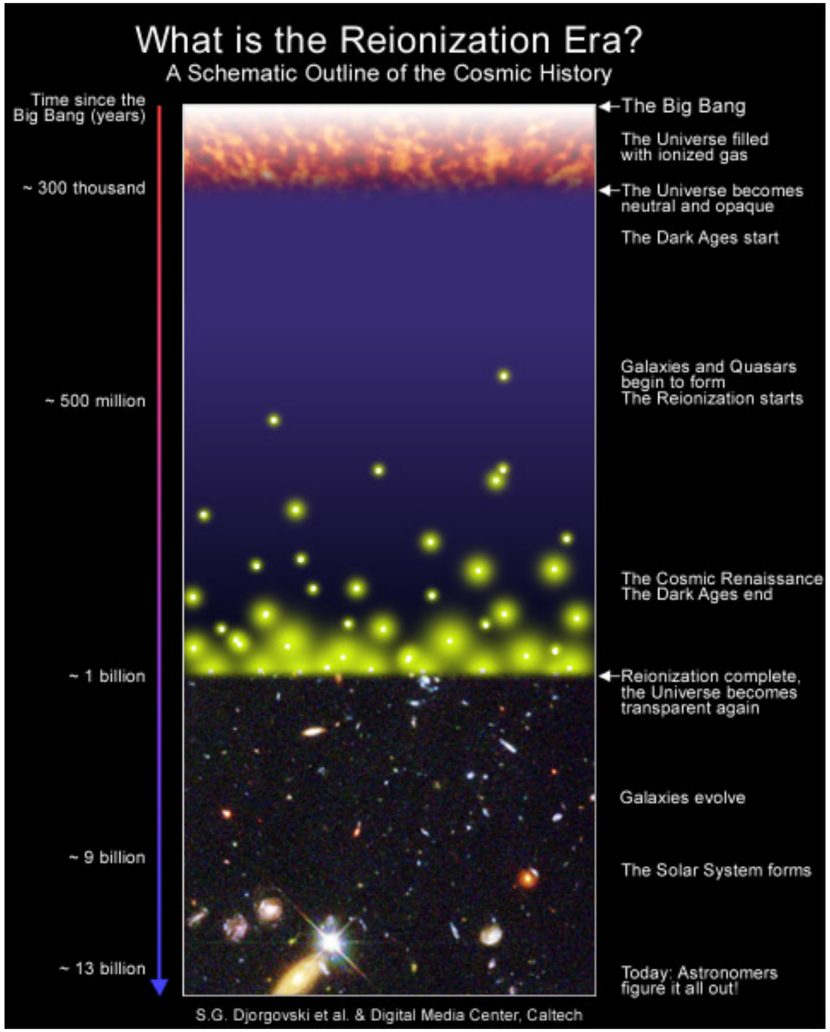
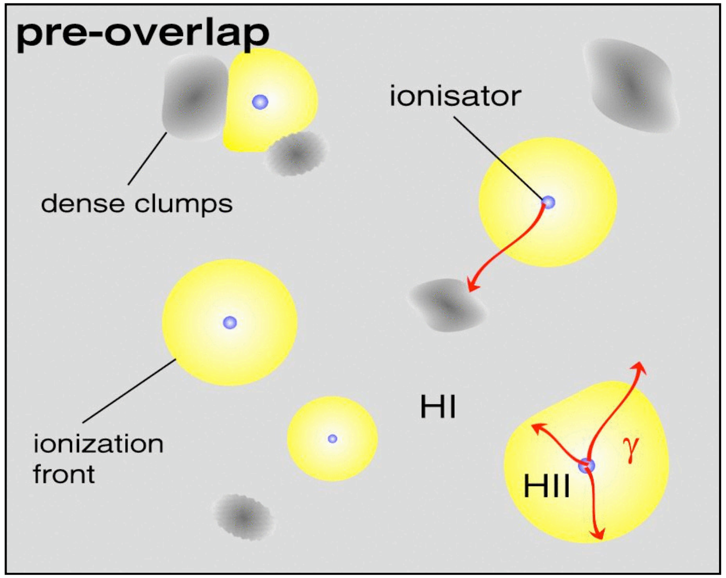
…Thomson scattering of CMB photons:
erasing of small scale anisotropies, polarization of CMB,
Planck 2013: reionisation started at z=11



- <u>reionising the Universe - inhomogenous process</u>



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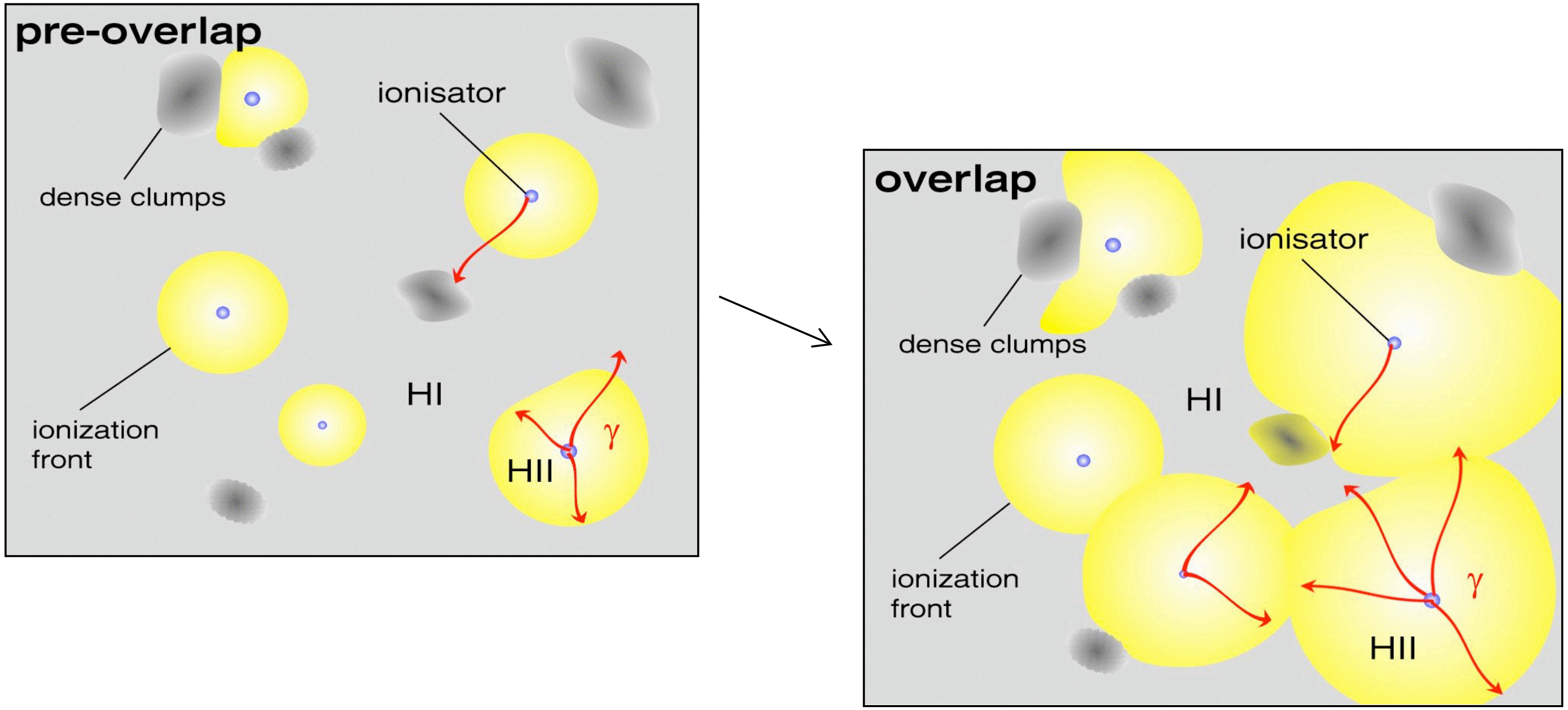

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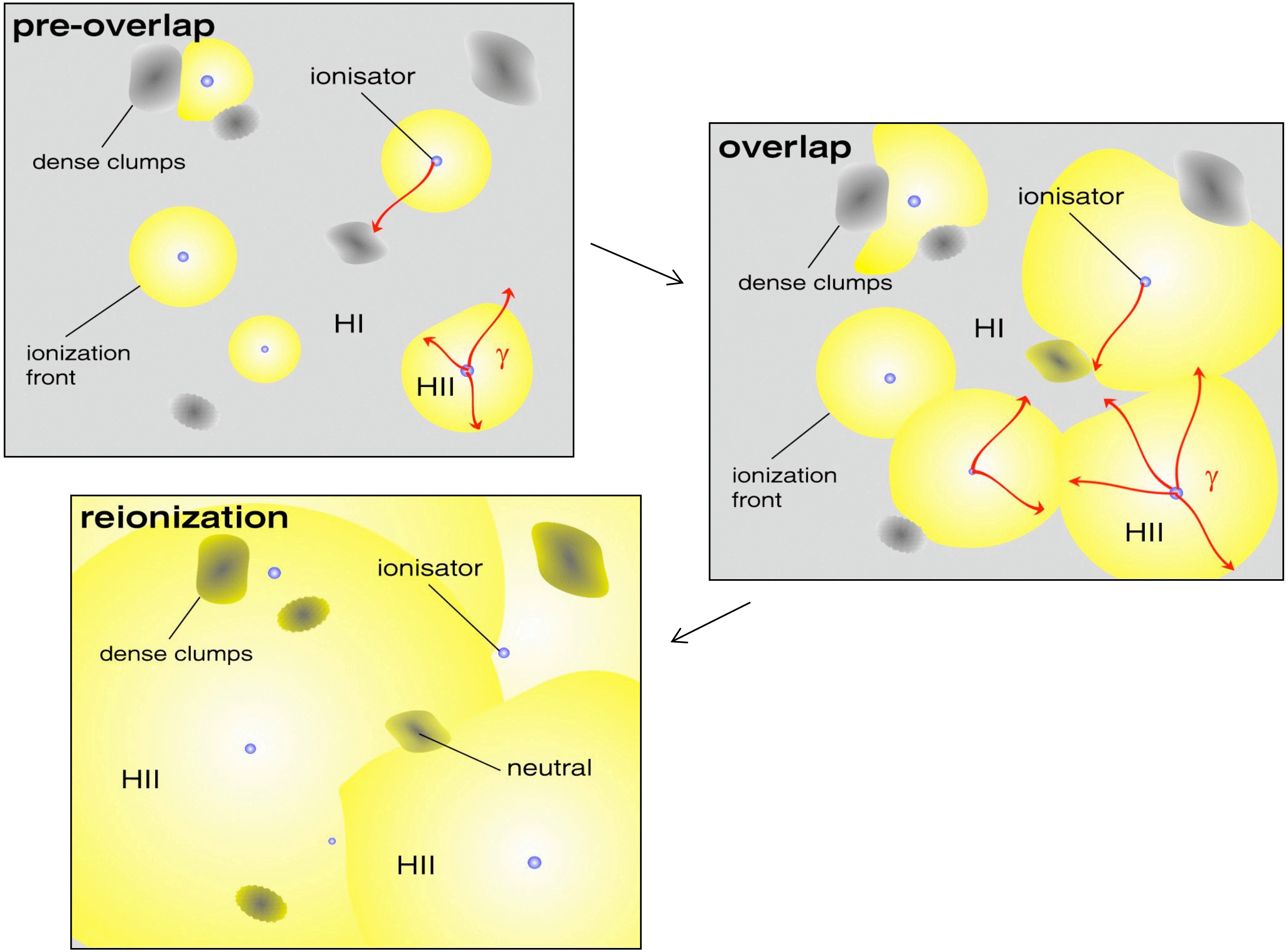
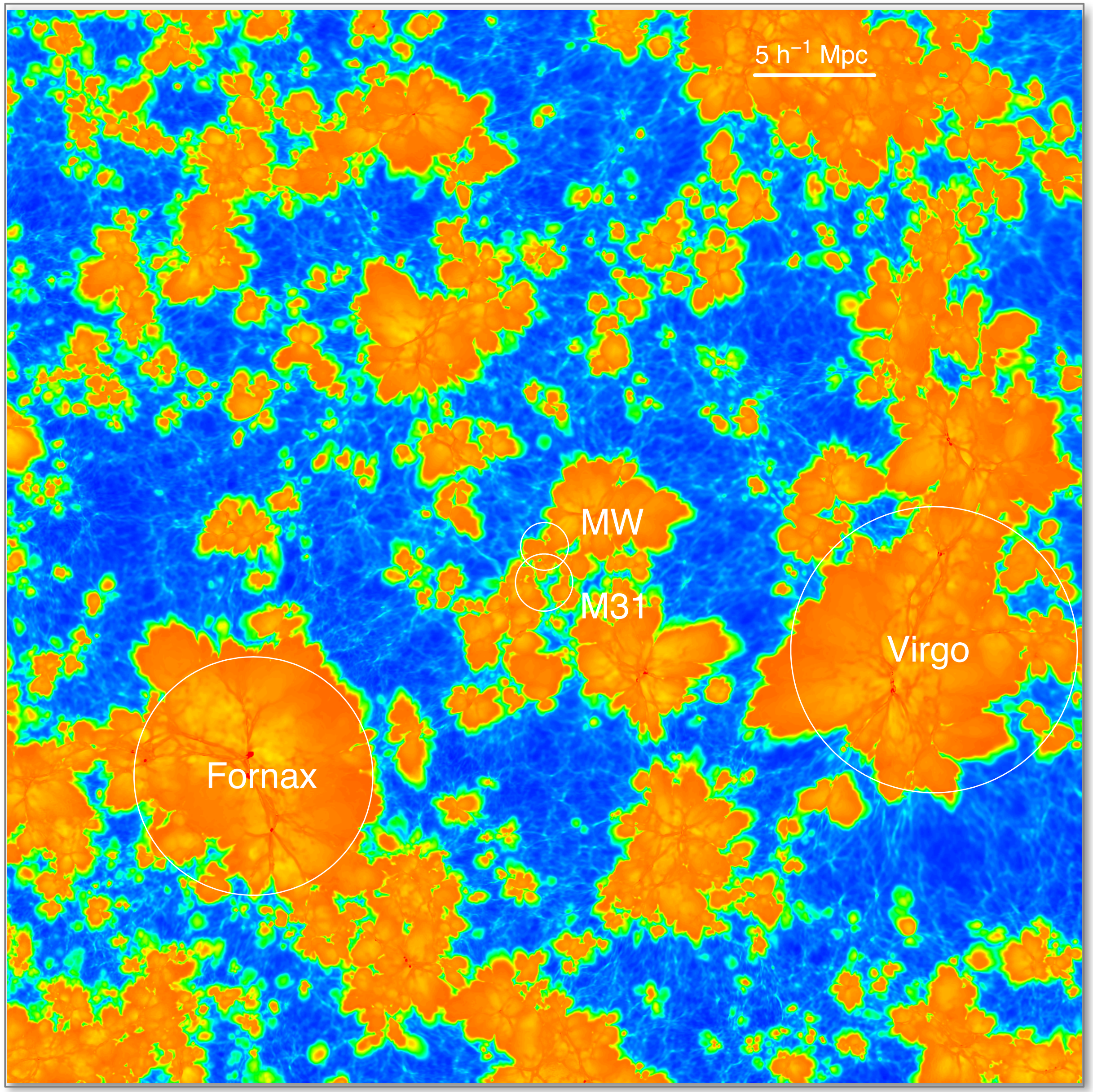


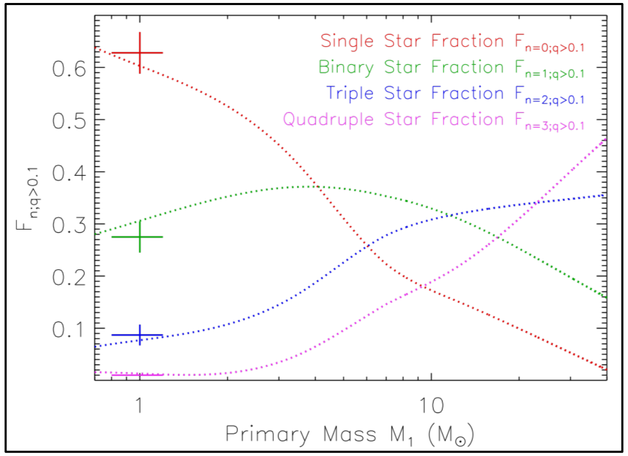
- reionising the Universe - Cosmic Dawn simulation (Ocvirk et al. 2016)



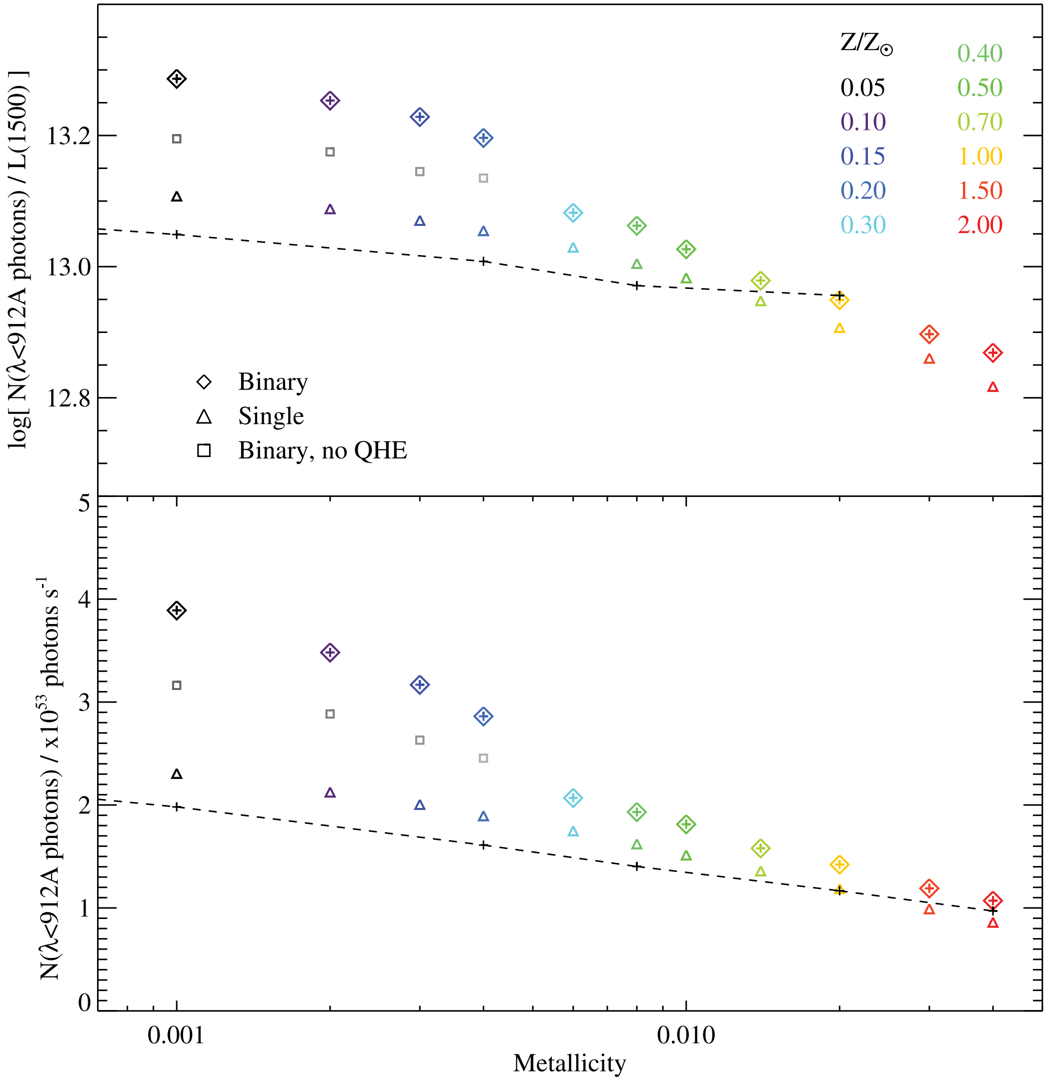
- reionising the Universe – first stars? first galaxies?

strength of ionizong photons

effect of binary systems on ionizing photon flux

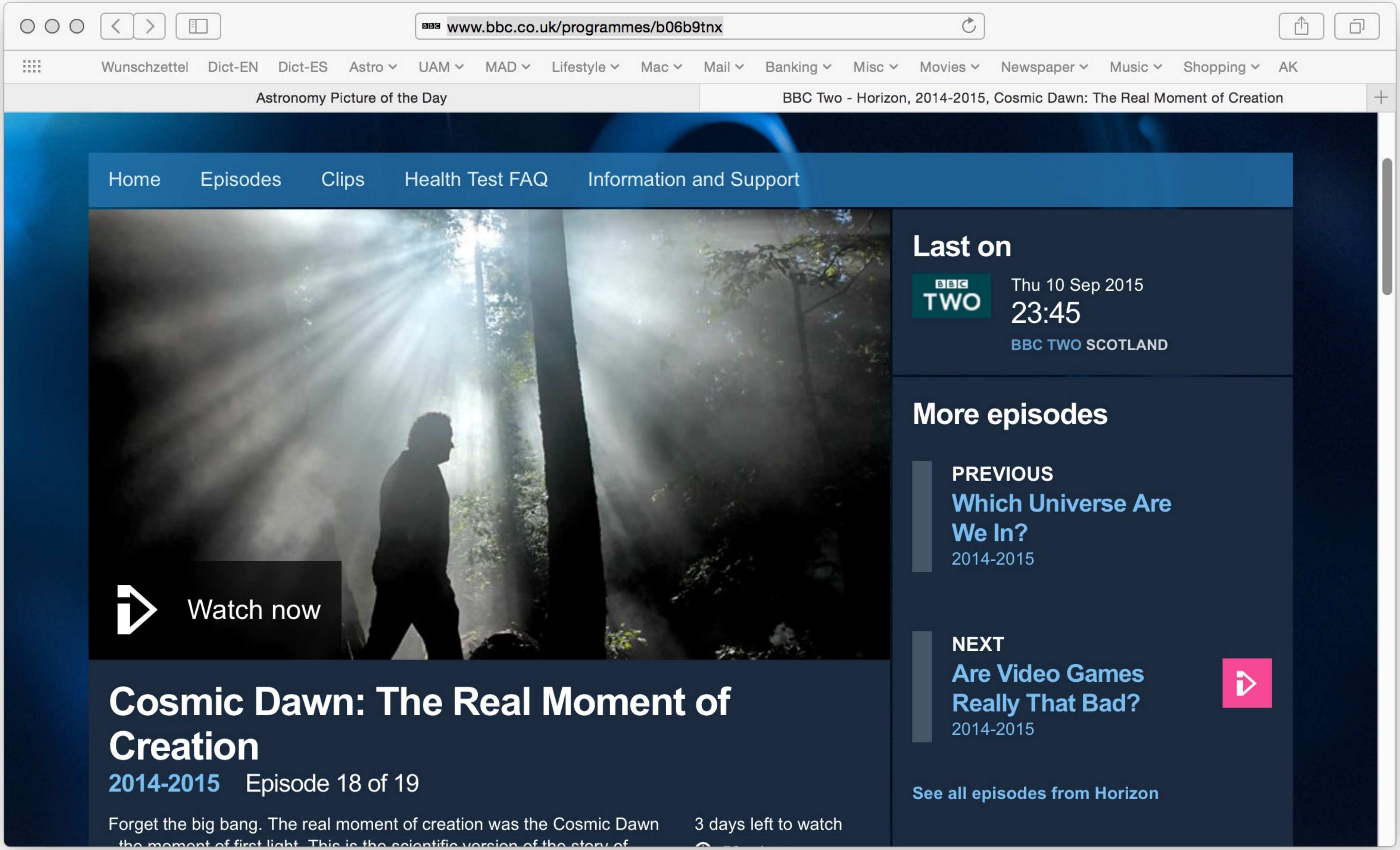


Moe et al. (2017)



Stanway et al. (2016)

- Cosmic Dawn: The Real Moment of Creation



http://www.bbc.co.uk/programmes/b06b9tnx