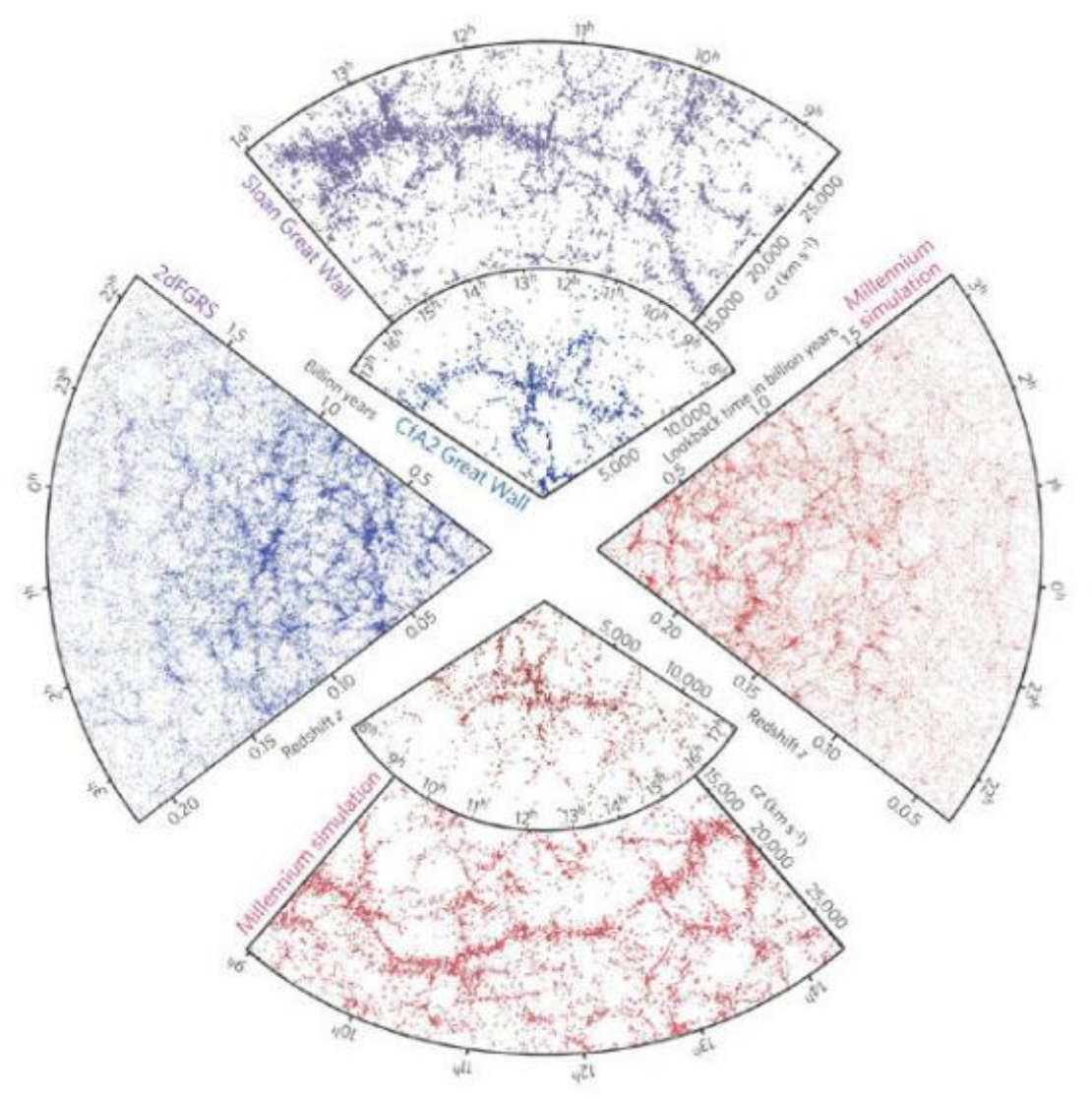
Quantum Gases, Fundamental Interactions, Cosmology

Pisa, October 2017

Large-scale Structure of the Universe

Volker Bromm
Department of Astronomy
University of Texas at Austin

Large-scale Structure (LSS)



- →Largest (and longest) physics experiment!

The Cosmic Web

Large Scale Structure:

Like Soap Bubbles

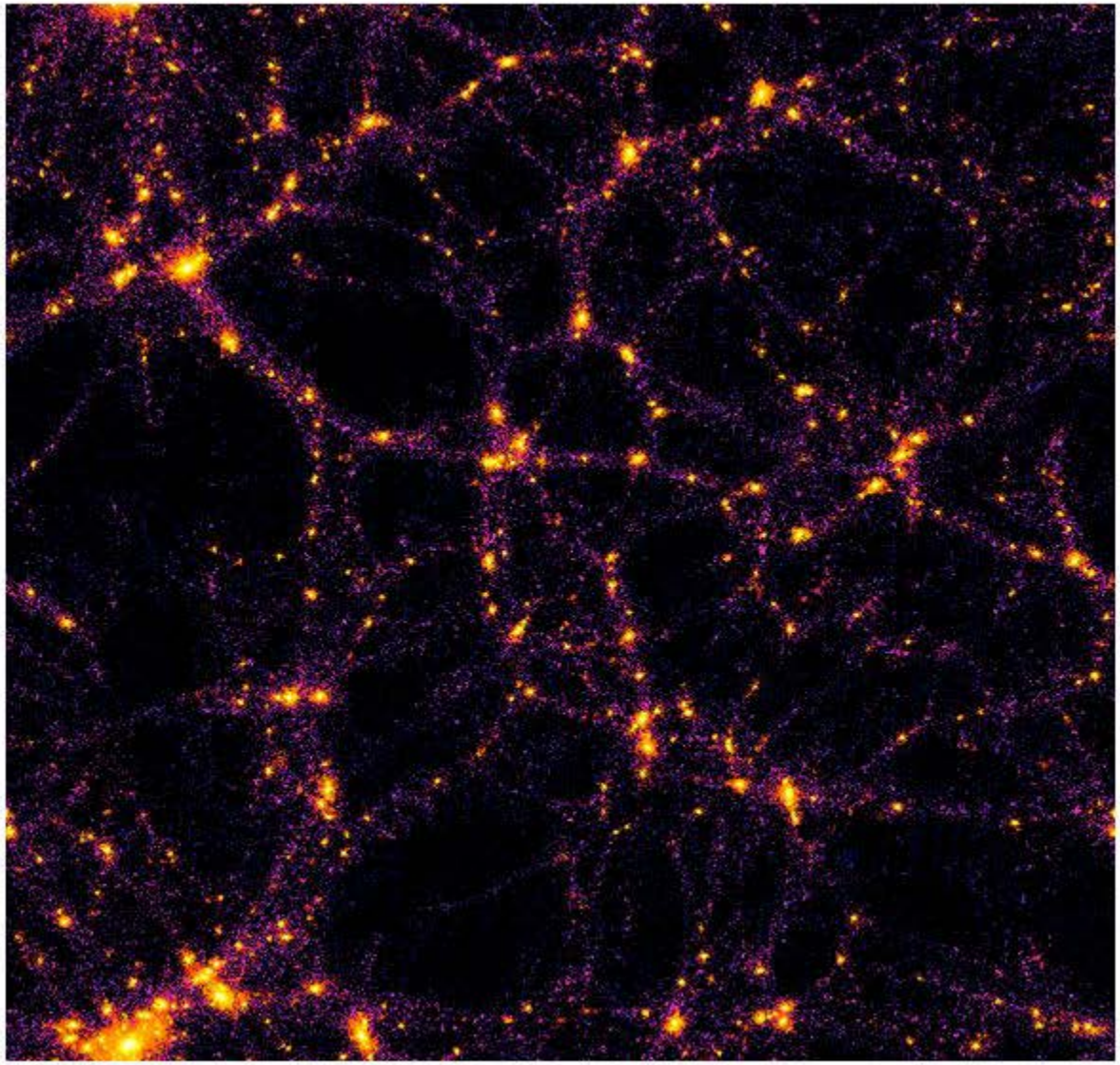
Empty **Voids**

~50Mpc.

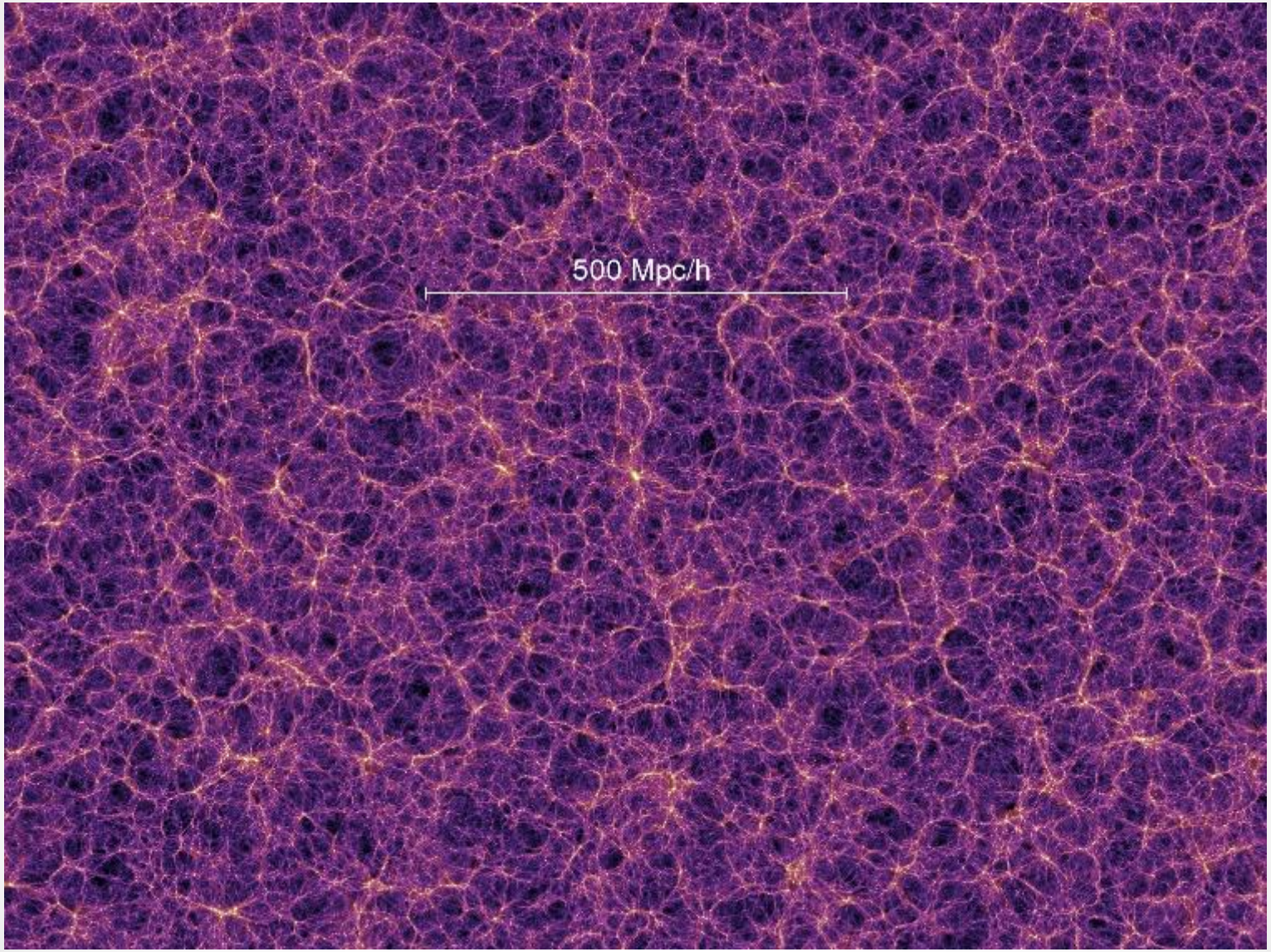
Galaxies are in
1. **Walls** between voids.

2. **Filaments** where walls intersect.

3. **Clusters** where filaments intersect.

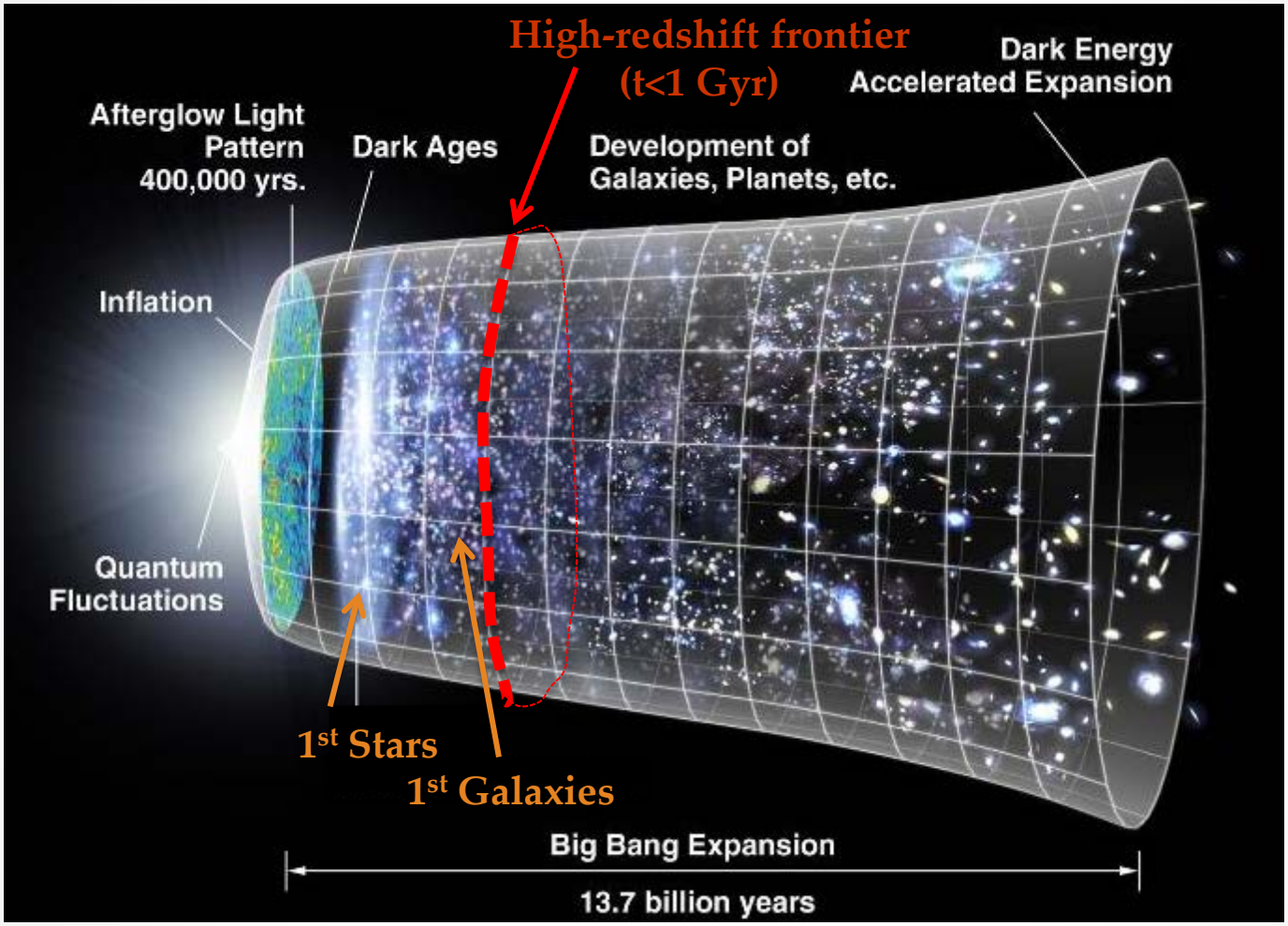


Smoothness on Largest Scales



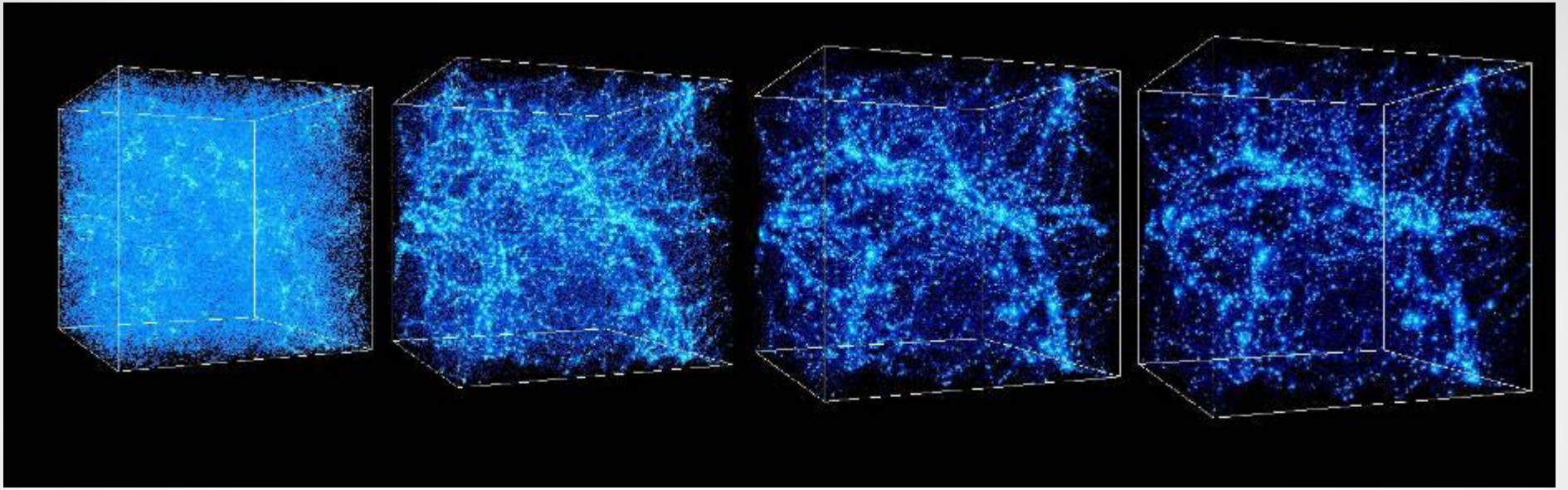
→**Universe is *not* a fractal** (not clusters of clusters ad infinitum)

Emergence of Cosmic Structure



- Cosmic history → From Simplicity to Complexity

Emergence of Cosmic Structure: Simulations

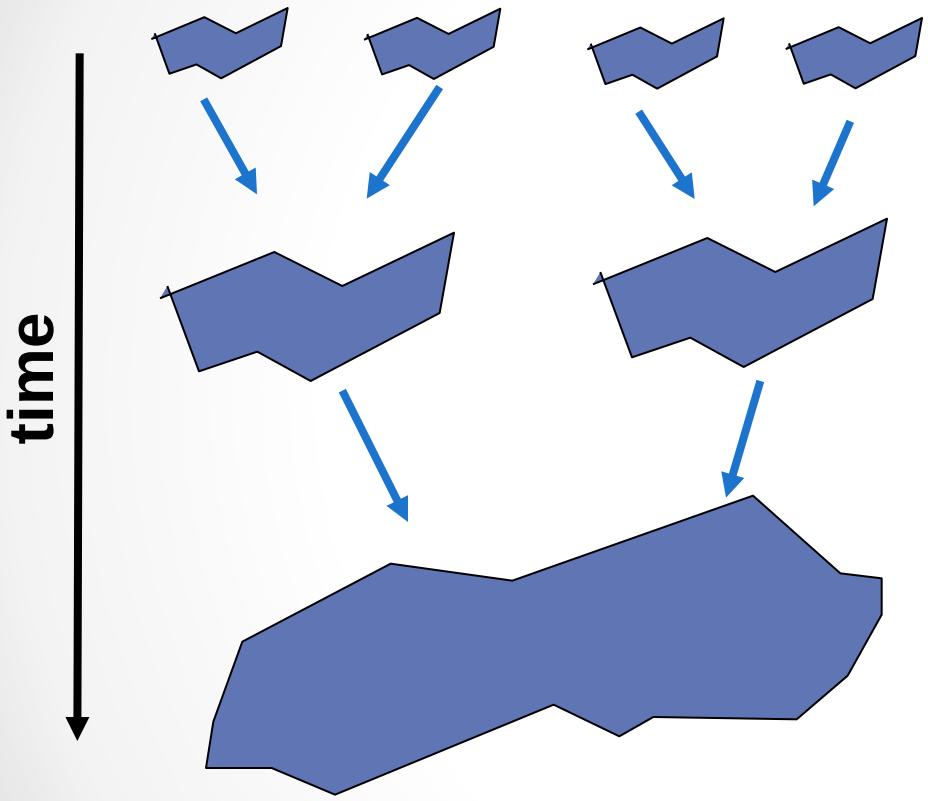


Cosmic time

- "Anti-thermodynamic" effect of gravity!

The Cold Dark Matter Model

- Galaxies form from the `bottom up' (hierarchical)



Small galaxies

Larger galaxies

Clusters of galaxies

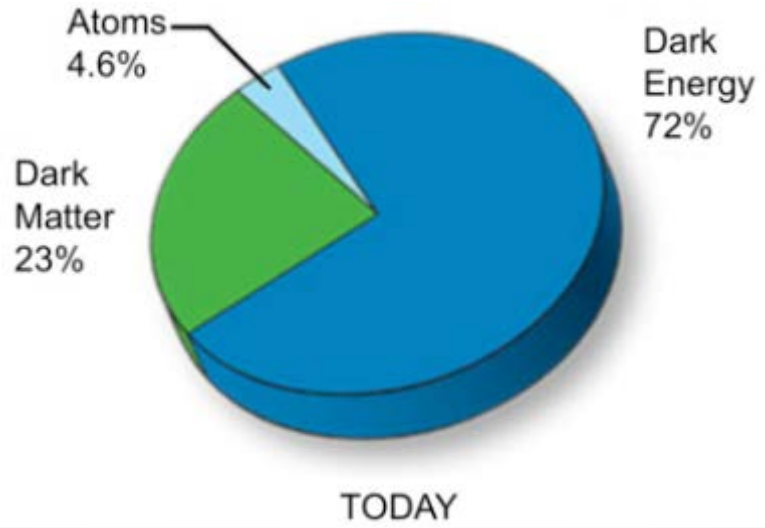
- larger structures form *after* smaller ones!

ΛCDM=Standard Model of Cosmology

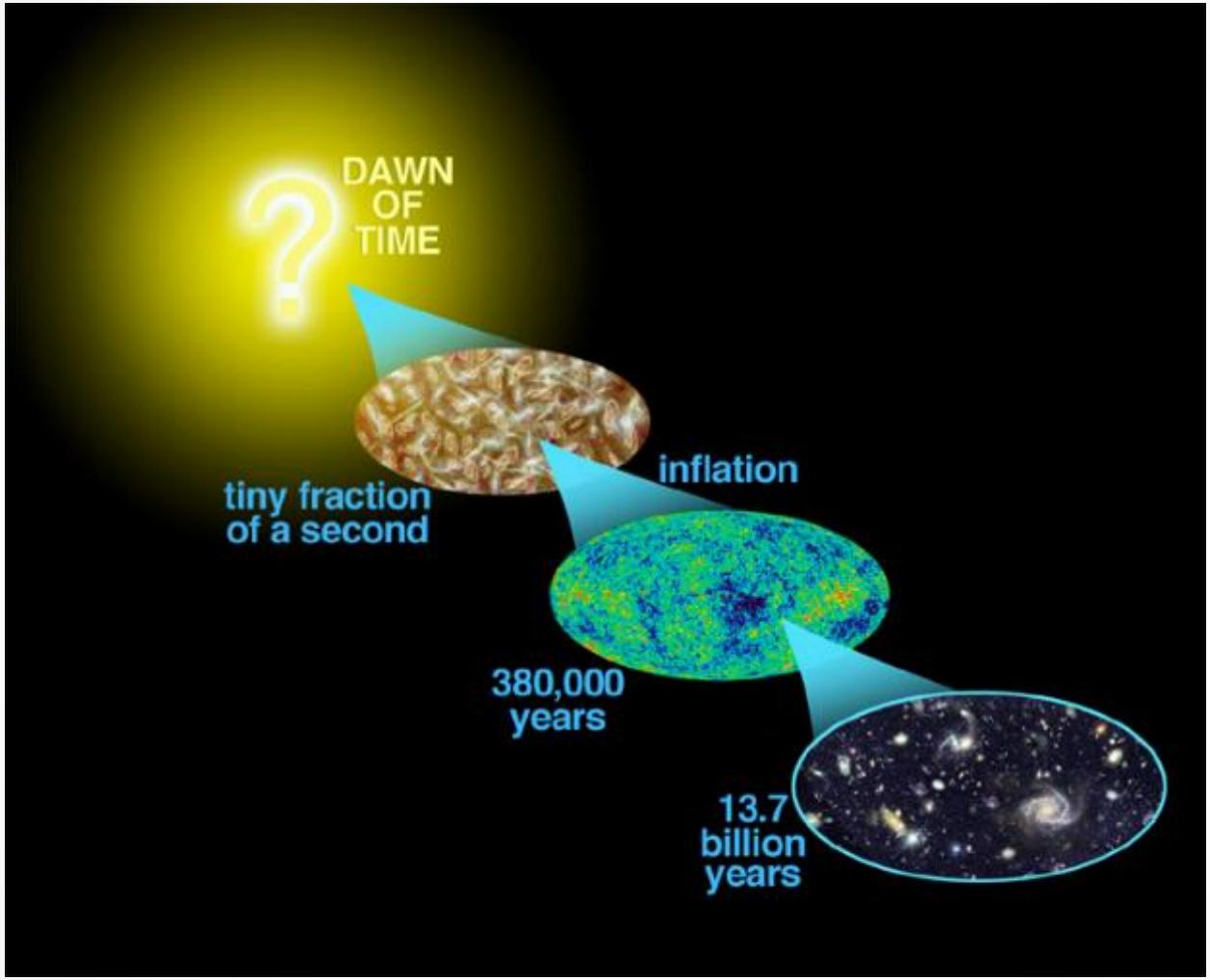
- **Dynamics: GR** **(with cosmological constant)**

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- **Matter-energy contents: - dark energy**
  - cold dark matter (CDM)
  - flat (Euclidean) geometry



CDM: Origin of Density Fluctuations



- Quantum fluctuations→ inflation
- → seeds for galaxy formation

CDM Fluctuations: Power spectrum

- **Dimensionless power spectrum:**
  - **function of scale: $k=2\pi/\lambda$**
  - **and time: $a=a(t)=1/(1+z)$ → scale factor**

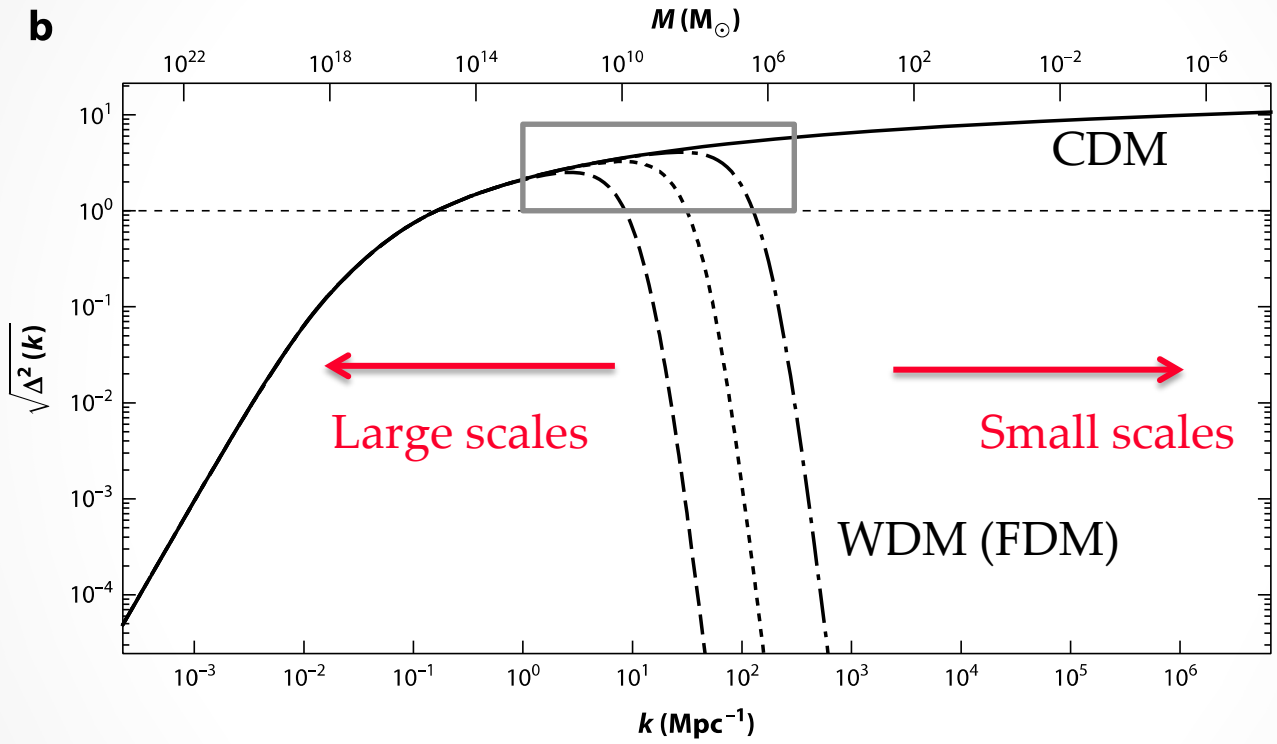
$$\Delta^2(k,a) = \frac{k^3}{2\pi^2} P(k)\, T^2(k)\, d^2(a)\,,$$

- **P(k): primordial power (out of inflation)**
  - **(nearly) scale invariant**
  - **adiabatic (metric), Gaussian (random phases)**

- **T(k): transfer function (processing until recombination)**
- **D(a): growth factor (D~a)**

CDM Fluctuations: Power spectrum

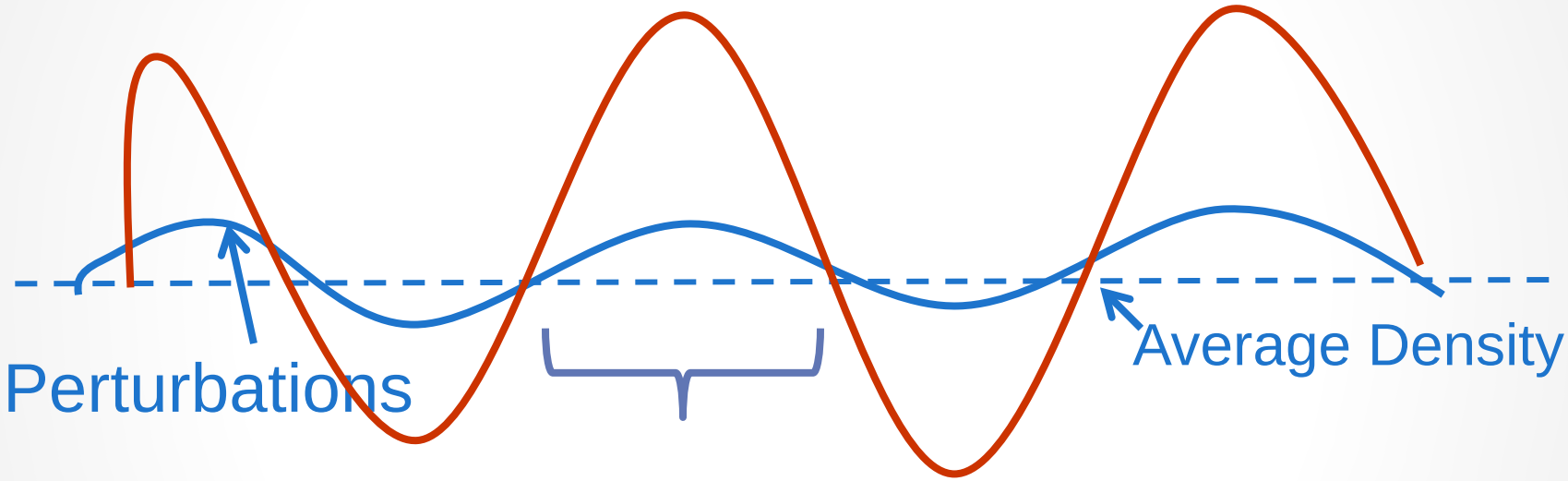
- **Average density contrast vs. scale:**



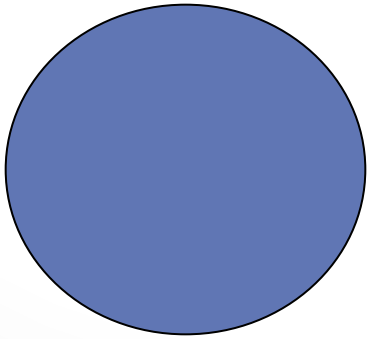
- **Note: Δ~1 → scale has gone non-linear**
  (collapsed, virialized)→ DM "halo" has formed

Collapse of Dark Matter Halos

Growth of small perturbations due to excess gravity



"Halo":

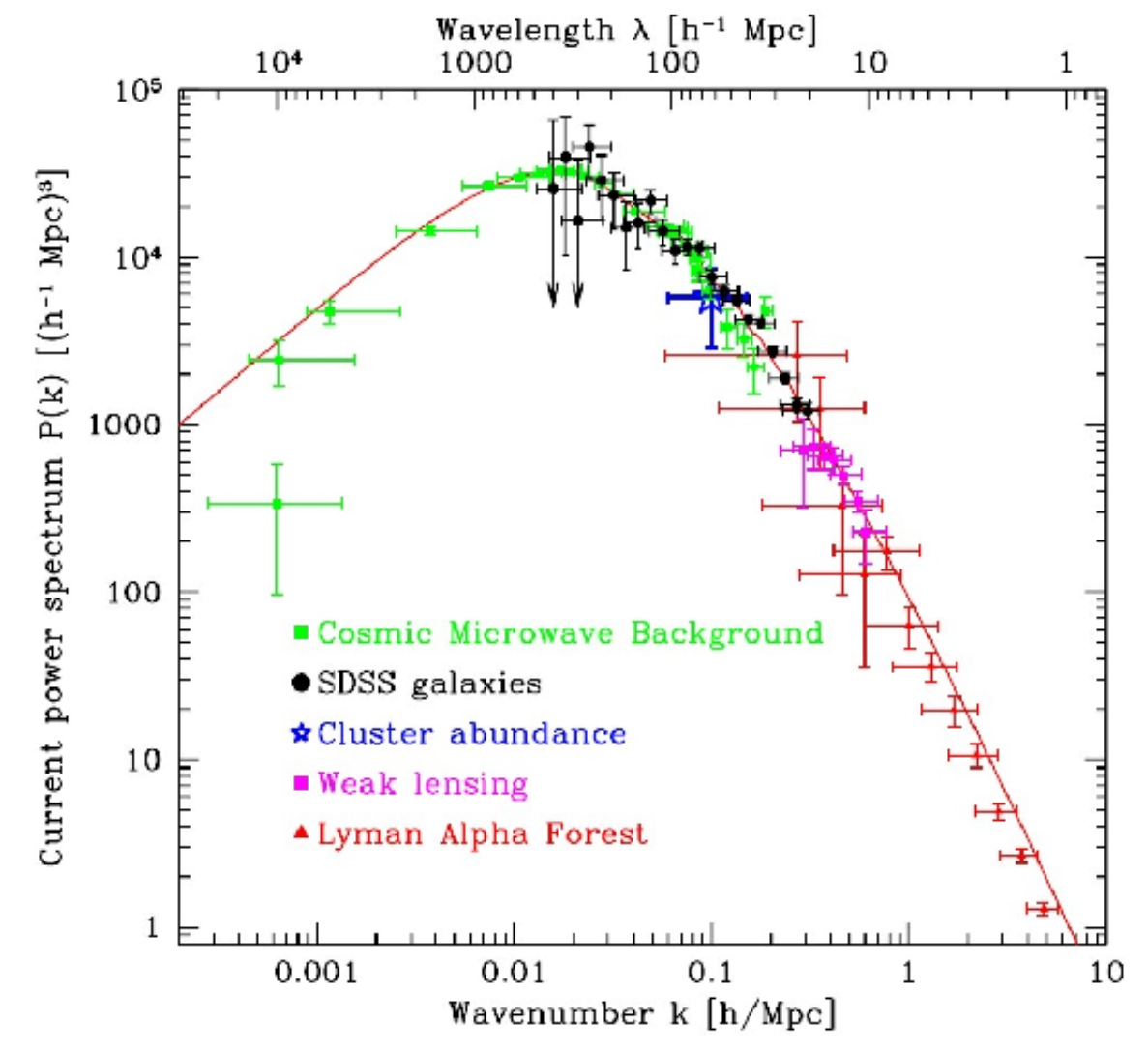


Equilibrium state:

Kinetic energy ~
potential energy

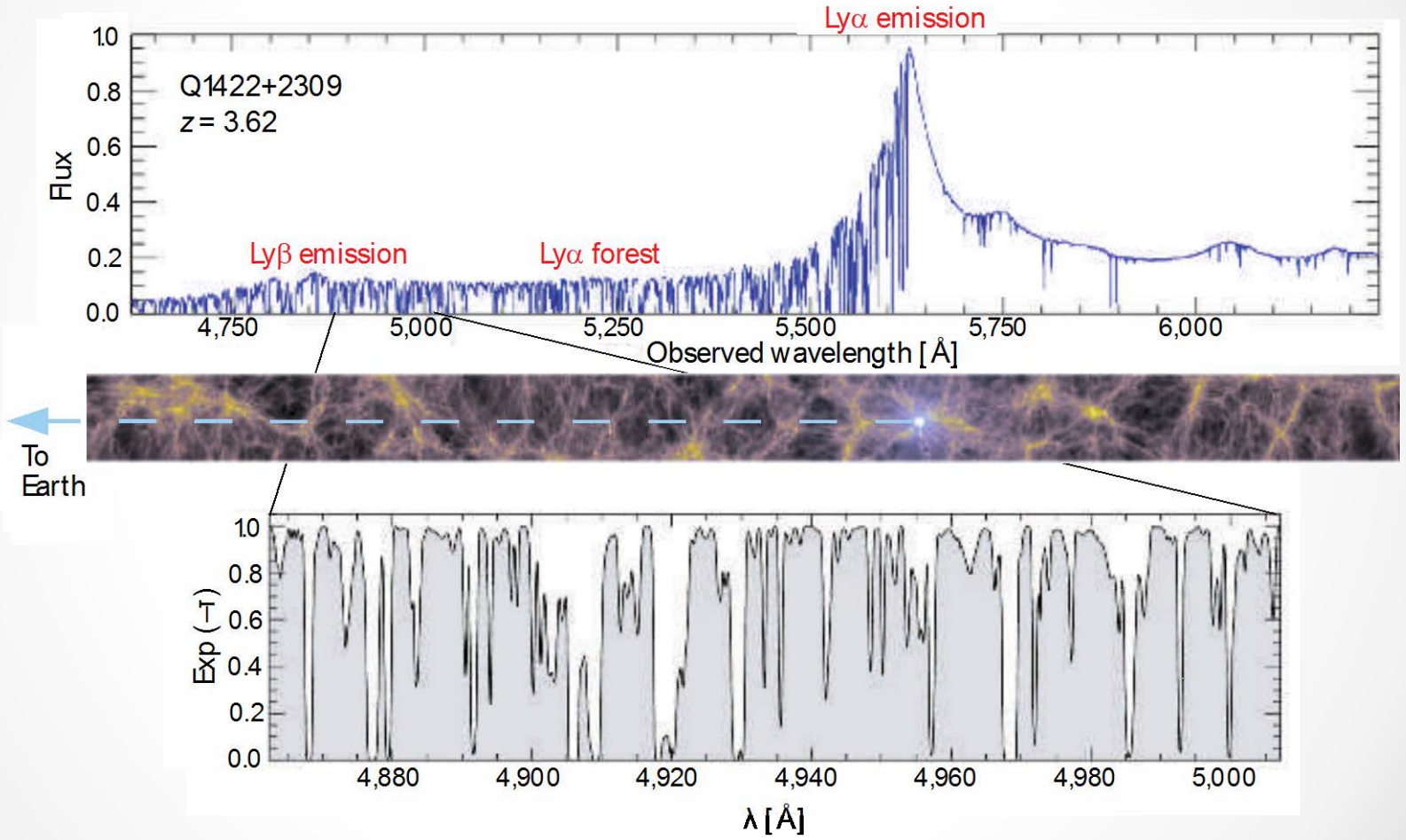
ΛCDM: Precision tests

- **Power spectrum**



ΛCDM: Precision tests

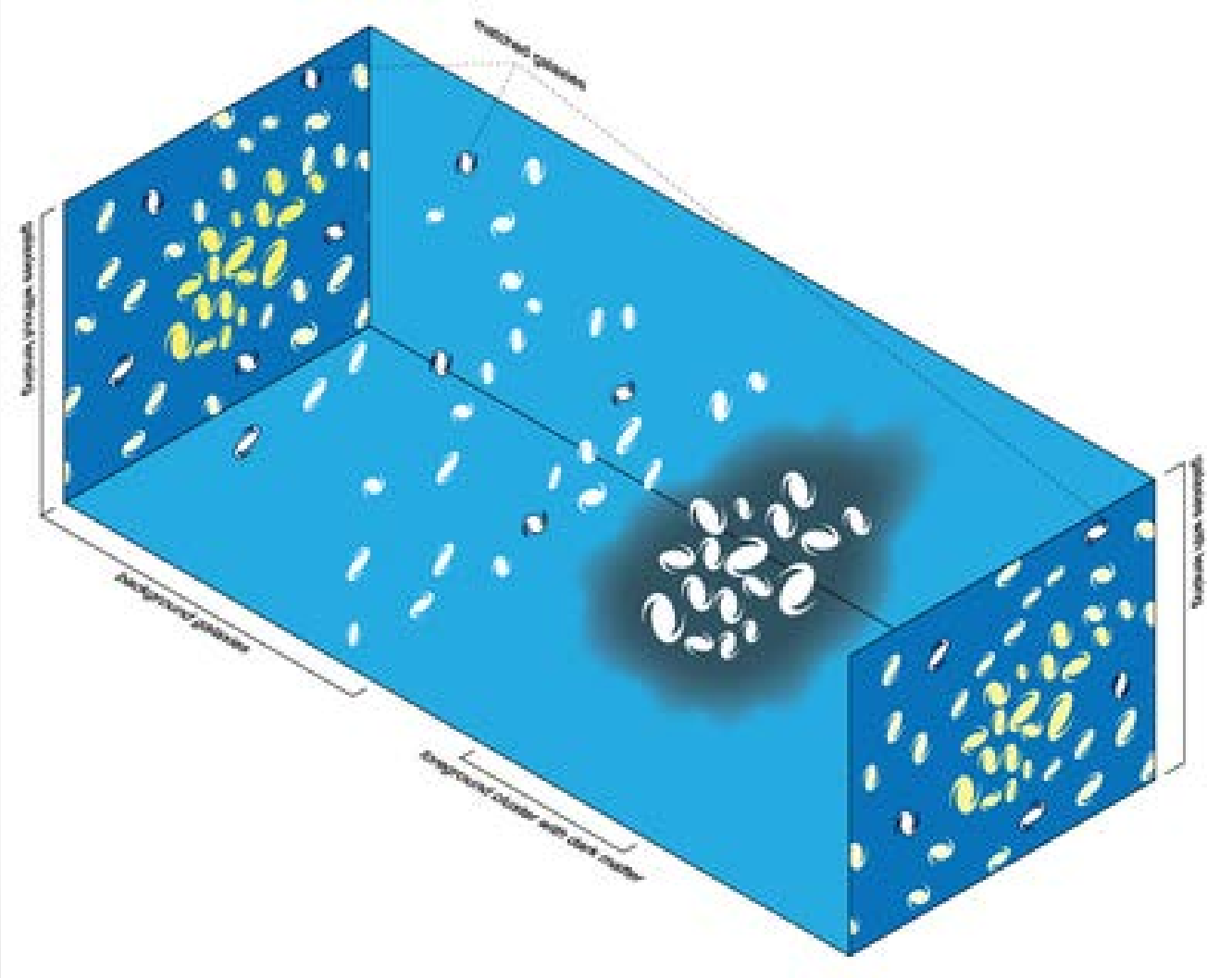
- **Lyman-alpha forest**



→ Powerful probe of cosmic web (mostly filaments)

ΛCDM: Precision tests

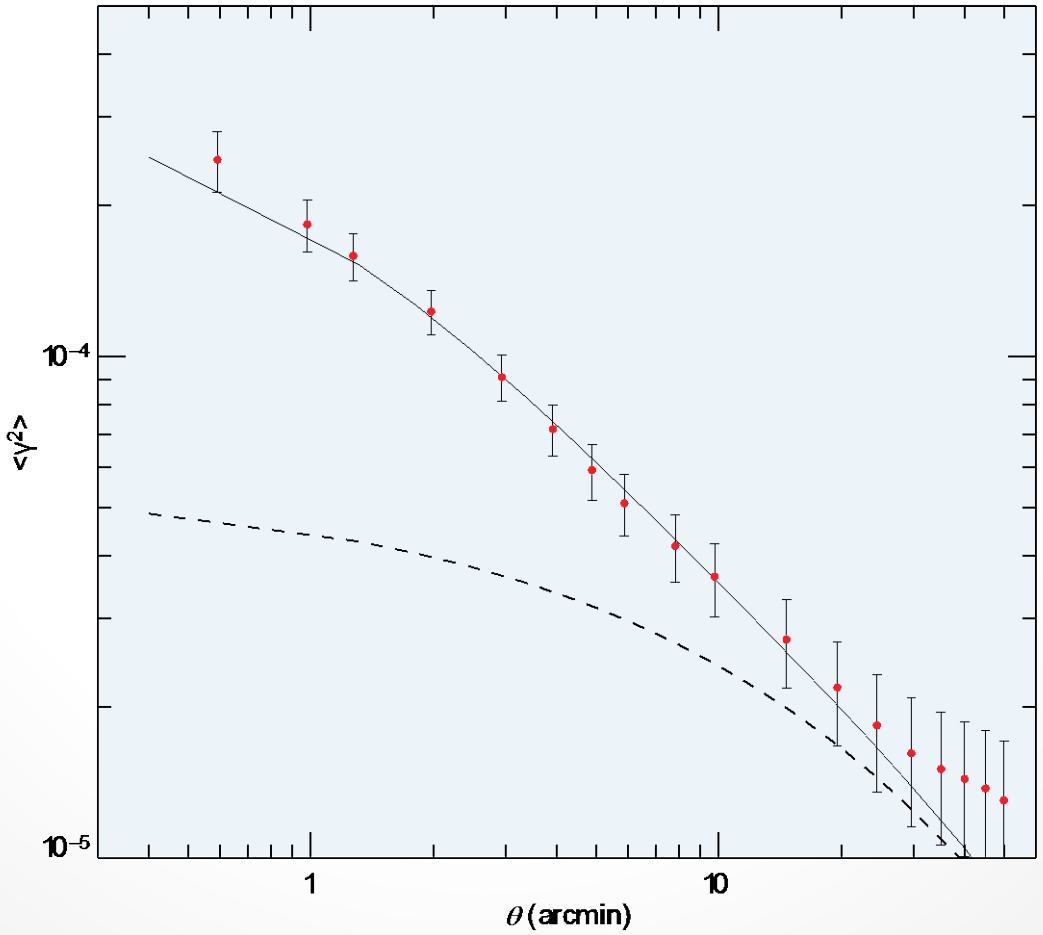
- **Weak gravitational lensing → galaxy images distorted (sheared)**



ΛCDM: Precision tests

- **Weak gravitational lensing**

Shear vs. scale



Incompleteness of ΛCDM

- **Nature of dark energy (DE)?**
  - Equation of state: w=f(z)

$$w = \frac{p_{de}}{\rho_{de}} \qquad \frac{1}{\rho_{de}} \frac{d\rho_{de}}{dt} = -3H(1+w)$$

  - For cosmological constant: w= -1 = const.

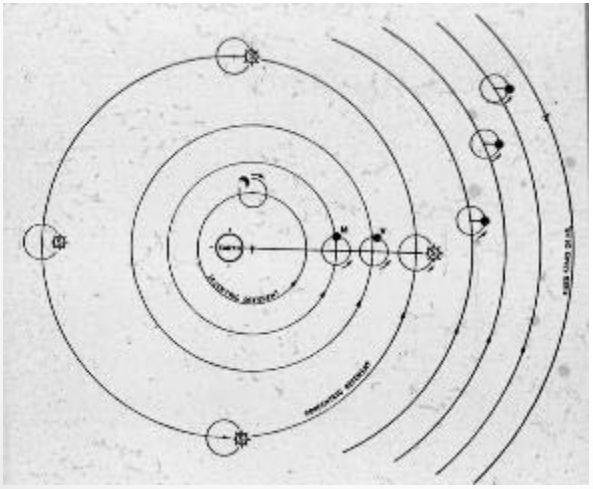
- **Nature of CDM?**
  - Supersymmetric WIMP?
  - QCD axion?
  - Fuzzy DM (FDM)?
  - …

A warning from History

- **Q: How to take down a (wrong) standard model?**

→ (In-)Famous example:
Ptolemy's model of the universe

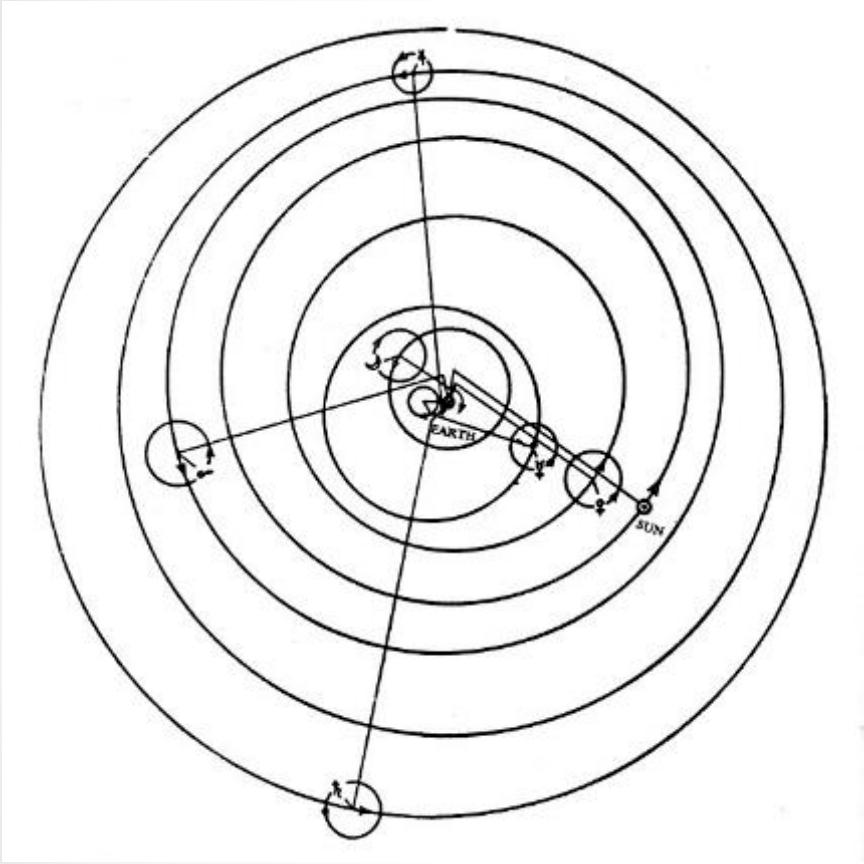
- **Not taken down by high-precision data!**
- **But: "out-of-the box" thinking (e.g., Galileo's inertia)**



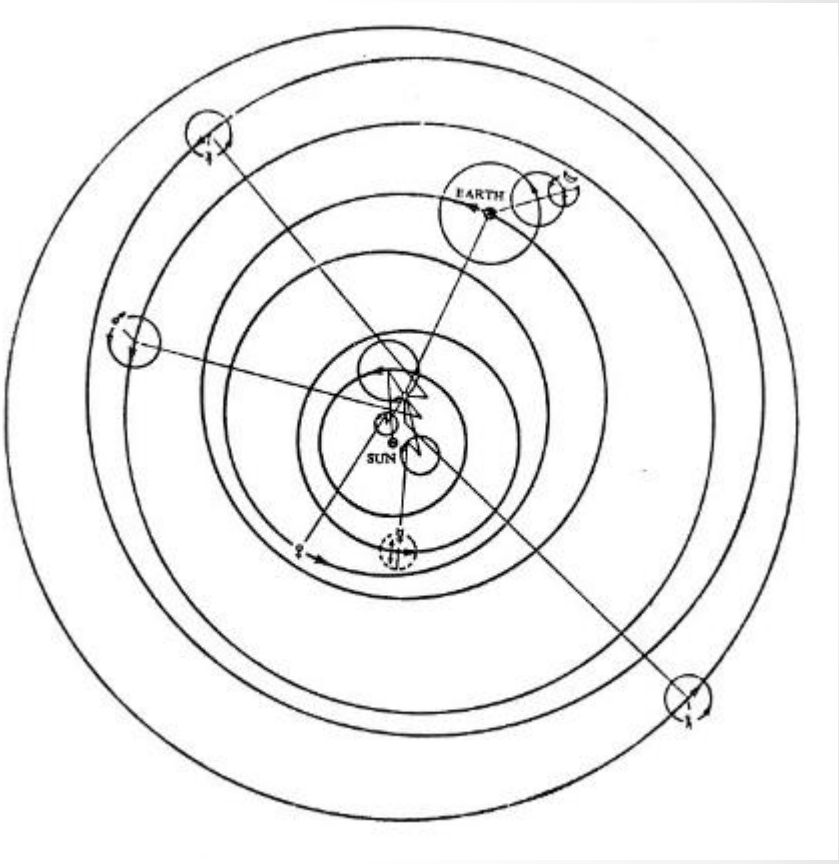
- Add more epicycles as demanded by more precise data

A warning from History

Ptolemy



Copernicus



- Copernicus as messy as Ptolemy, not more accurate, but conceptually better (more “natural”)

Incompleteness of ΛCDM

- **Nature of dark energy (DE)?**
  - Equation of state: w=f(z)

$$w = \frac{p_{de}}{\rho_{de}} \qquad \frac{1}{\rho_{de}} \frac{d\rho_{de}}{dt} = -3H(1+w)$$

  - For cosmological constant: w= -1 = const.

Expansion rate of the universe:

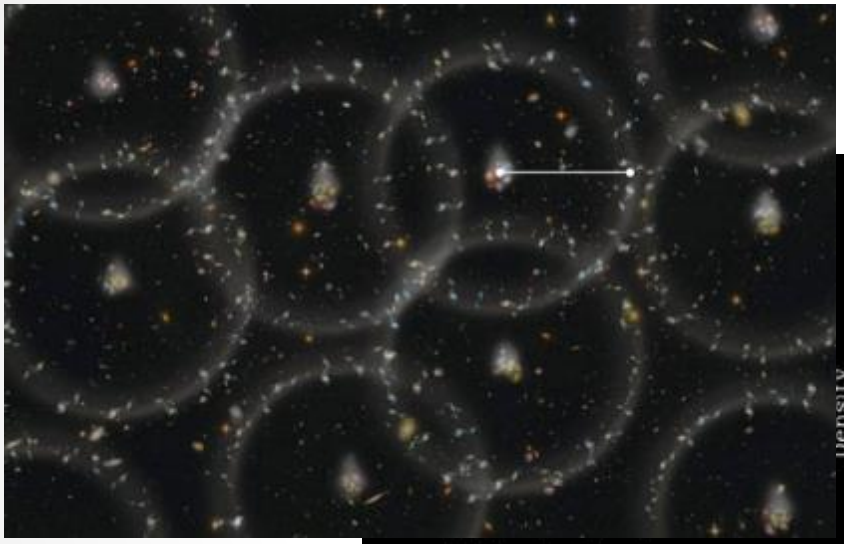
$$H^2(z) = H^2_0 \left[\Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)}\right]$$

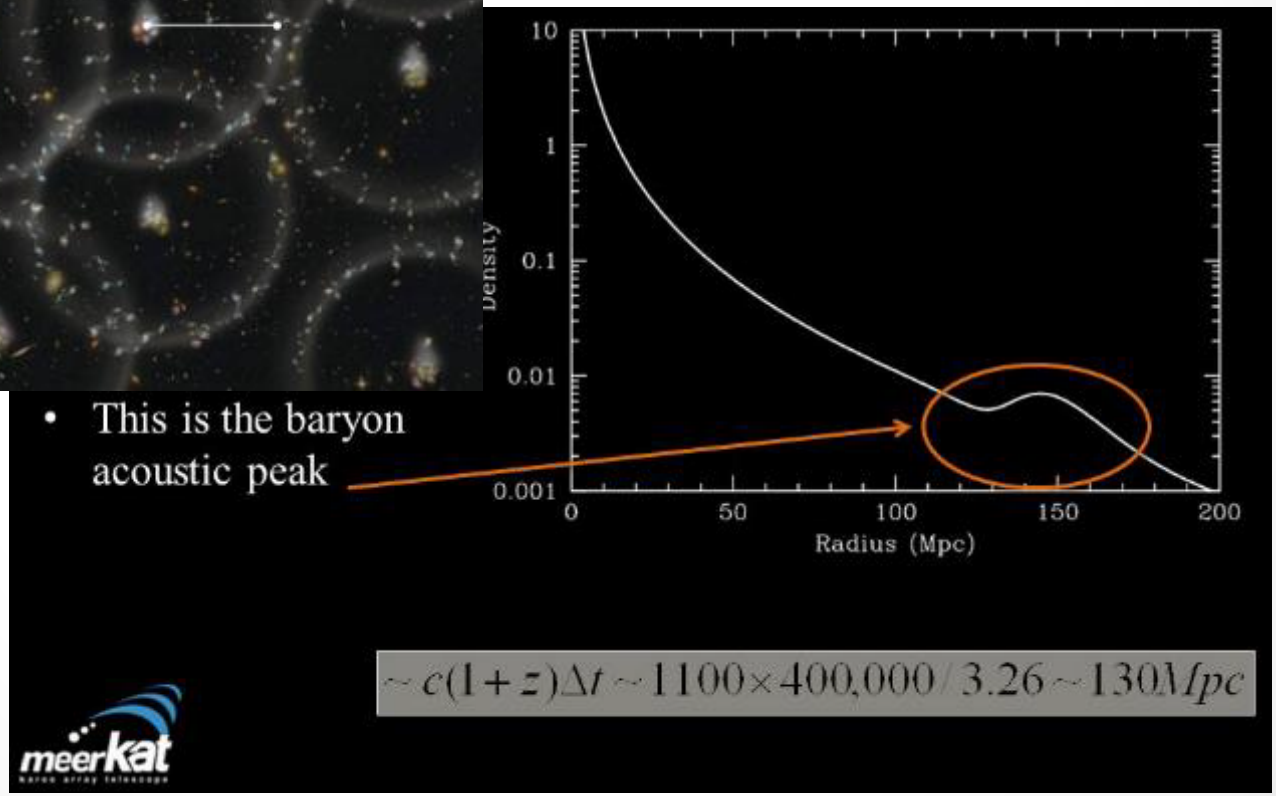
dark matter — dark energy

→ Similar effect on growth of LSS (growth factor)

DE: Measuring the equation of state

→ **Baryon Acoustic Oscillations (BAO)**



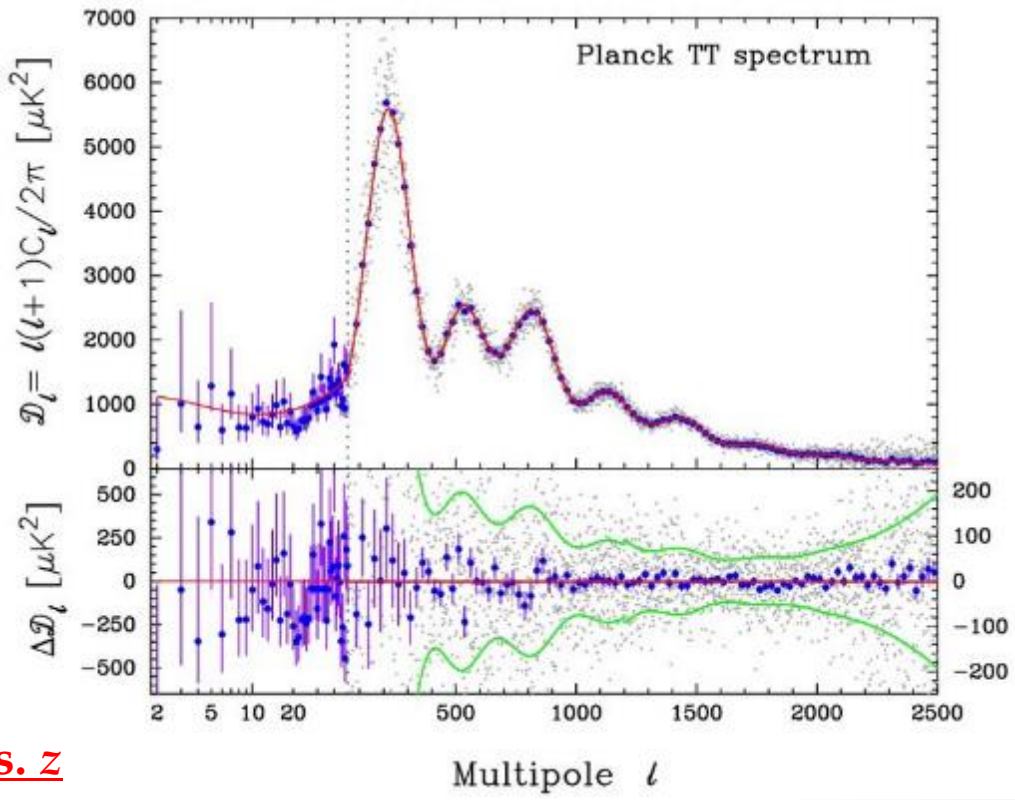


- Cosmic sound horizon → a standard ruler

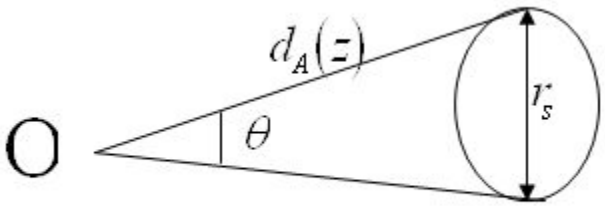
DE: Measuring the equation of state

→ **Baryon Acoustic Oscillations (BAO)**

- Seen in CMB



Angular diameter distance vs. *z*



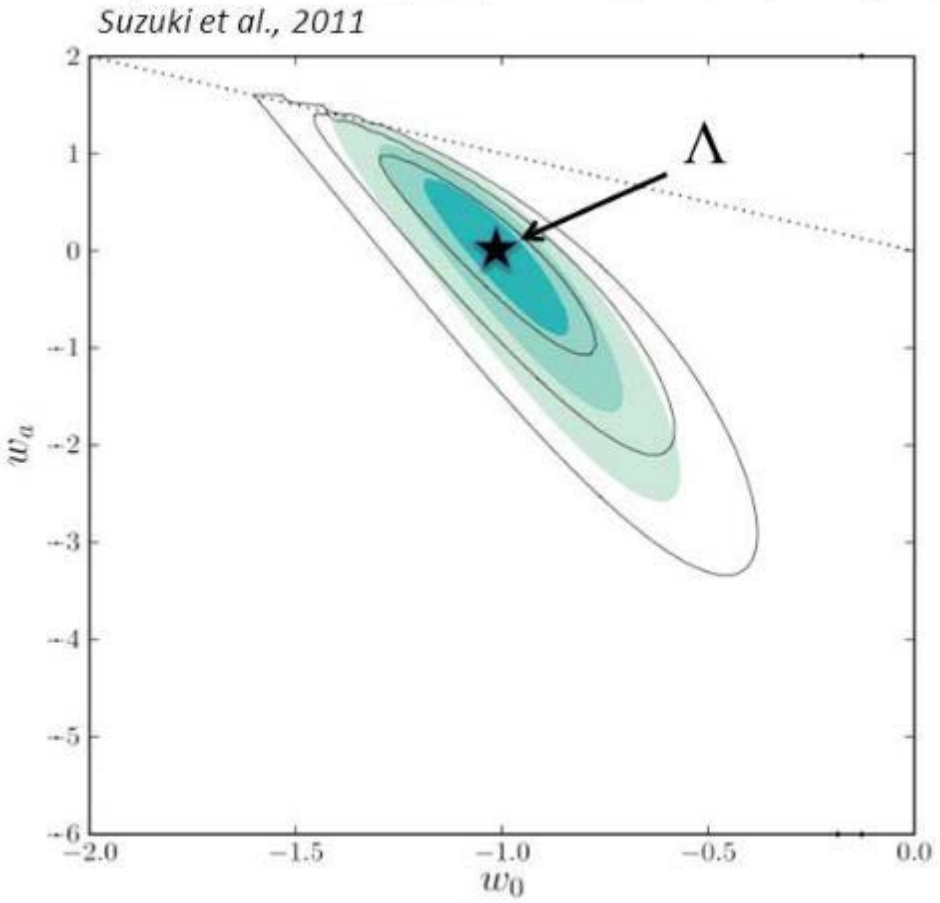
$$d_A(z) = \frac{r_s}{\theta}$$

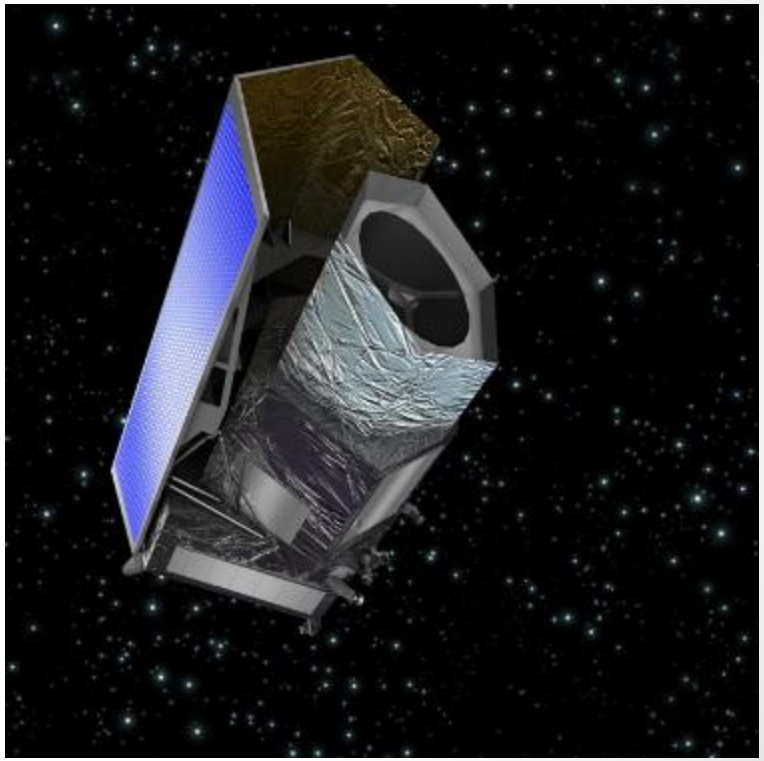
$$d_A(z)_{th} = \frac{c}{(1+z)} \int_0^z \frac{dz'}{H(z')}$$

DE: Measuring the equation of state

Redshift dependent w:

$w(a)=w_0+(1-a) \times w_a$





EUCLID (also: WFIRST)

Incompleteness of ΛCDM

- **Nature of DM?**
  - Supersymmetric WIMP?
  - QCD axion?
  - Fuzzy DM (FDM)?
  - Warm dark matter (WDM)→ sterile neutrinos?
  - …

- **Strategy: Explore small-scale frontier**
  - Locally: dwarf galaxies in Local Group
    → a.k.a. "near-field cosmology"
  - High redshift (where small structures dominate)

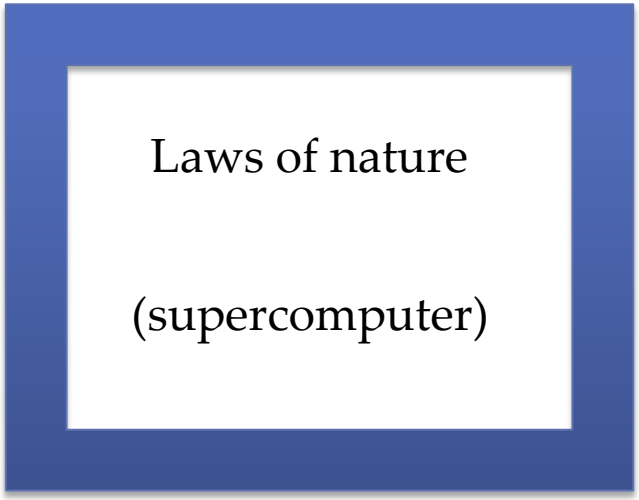
Structure Formation from Cosmological ICs

→ Properties of First Stars, Galaxies, Black Holes

- *ab initio* structure formation (or: the *Laplace Demon* at work)

Input:

Ω_B, Ω_Λ, Ω_m,
σ_8, n_s, H_0,
chemical abundances,
DM particle physics



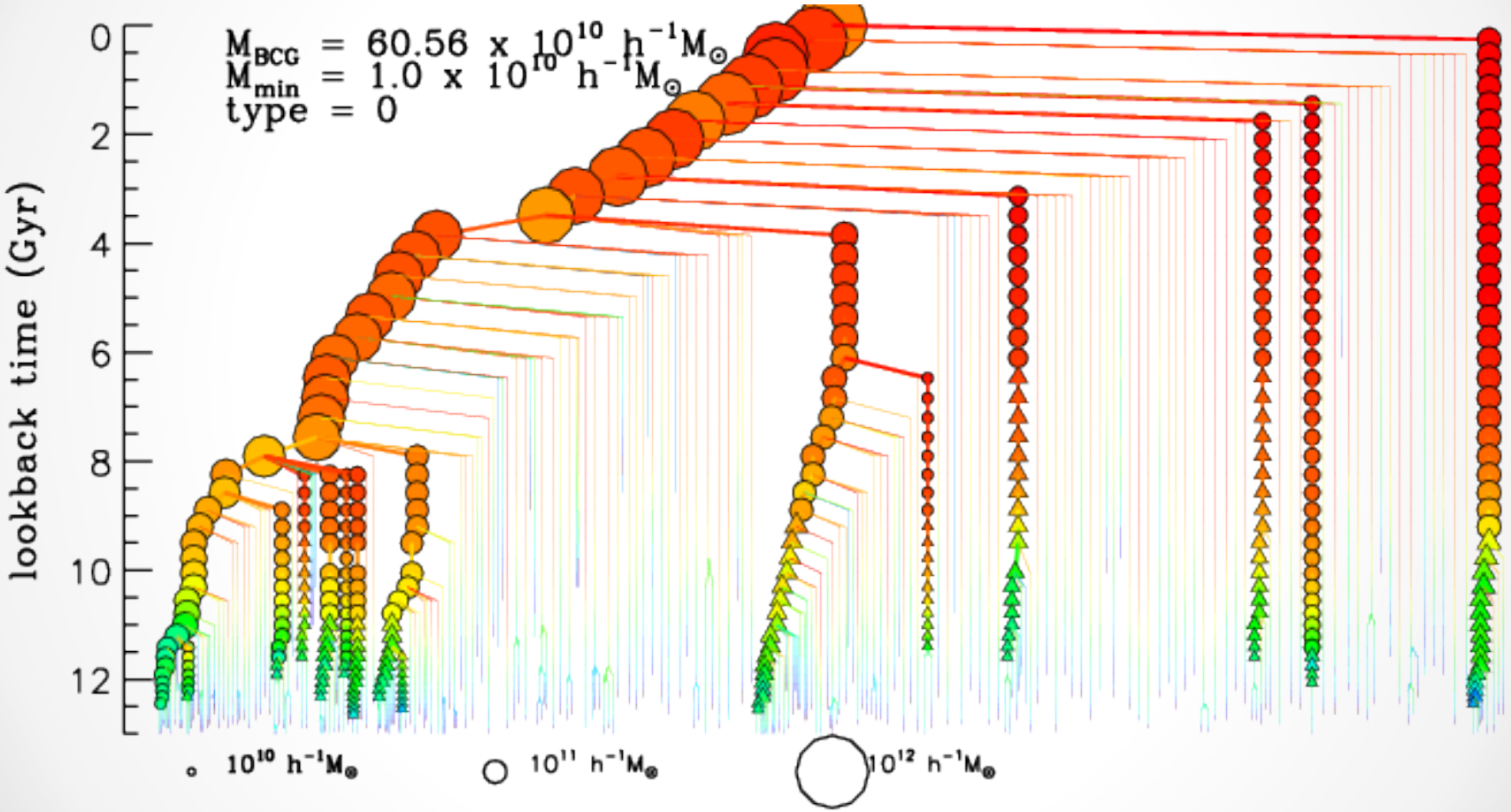
Output:

Stellar systems,
galaxies, explosions

→ **Non-linear amplifier!**

Small-scale Frontier: Local probes

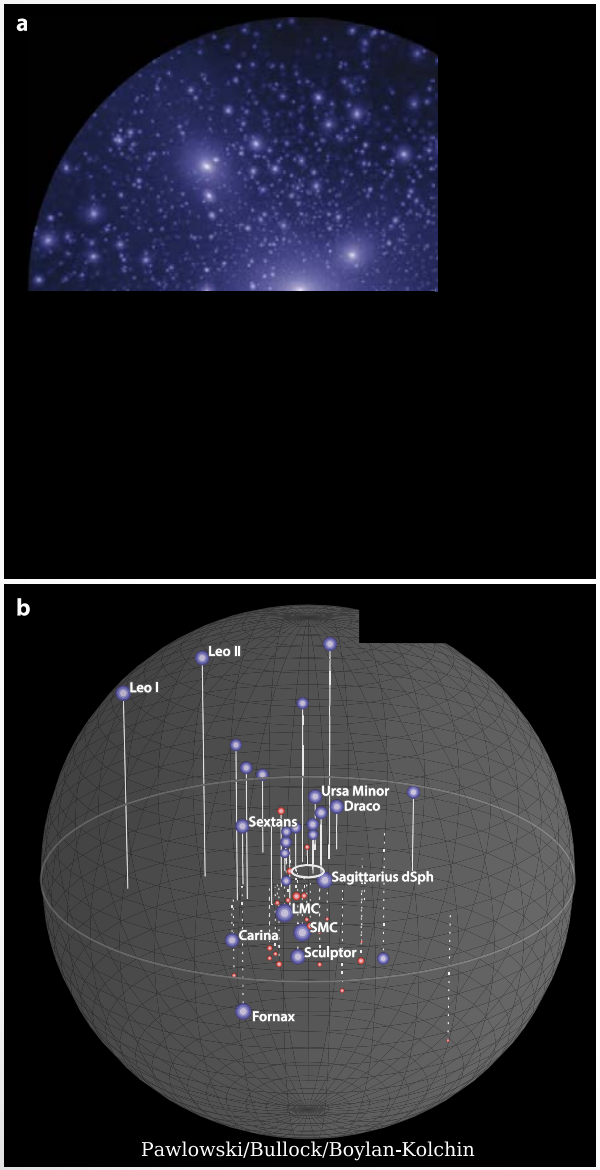
- **(Hierarchical) Assembly history of Milky Way system:**



- **Some small systems may survive until present (z=0)**

Small-scale Frontier: Local probes

- **Missing satellites problem (in Milky Way system)**



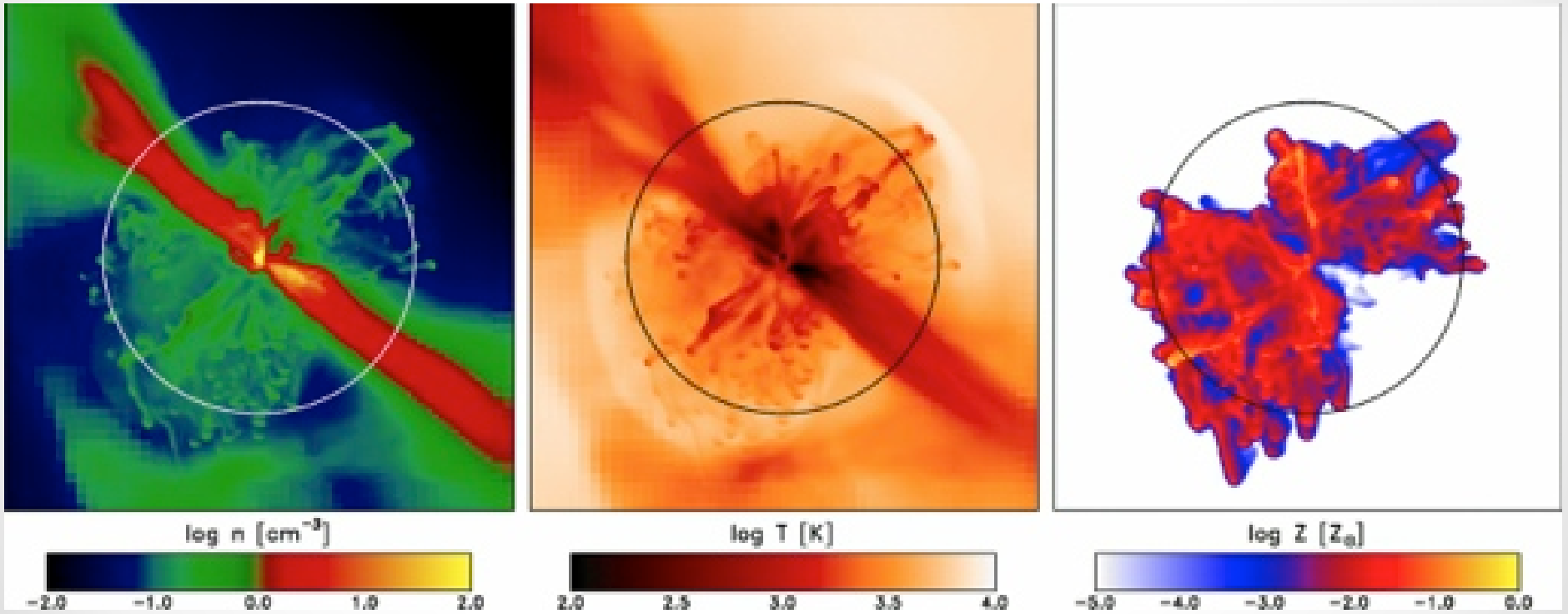
- **ΛCDM prediction:**
  - **DM-only simulation**
  - **1,000s of subhalos (with mass > 10^7 $M_\odot$**

- **Observations (~mid 2017):**
  - **large-scale surveys (SDSS)**
  - **50 dwarf galaxy satellites**

Tricky caveat: Supernova (SN) Feedback:

(Ritter, Safranek-Shrader, Gnat, Milosavljevic, Bromm 2012, ApJ, 761, 56)

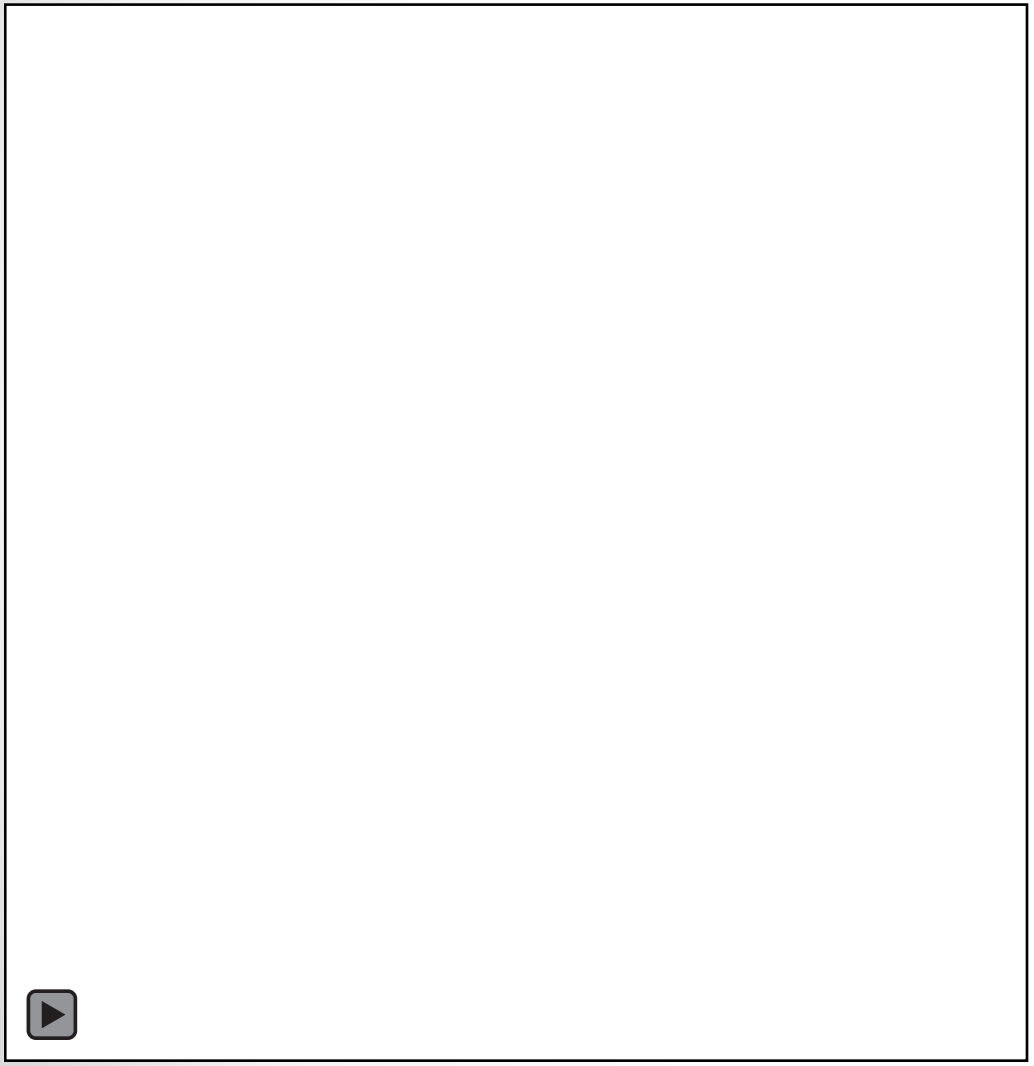
- FLASH/AMR, cosmological ICs
- Less-extreme mass (40 $M_\odot$) → core-collapse SN



- Situation ~ 8.5 Myr after explosion

Galaxy Formation with Stellar Feedback

(Jeon, Bromm, Pawlik & Milosavljevic 2015, MNRAS, 452, 1152)



- SPH/TRAPHIC, cosmological ICs
- galaxy collapses at z~10

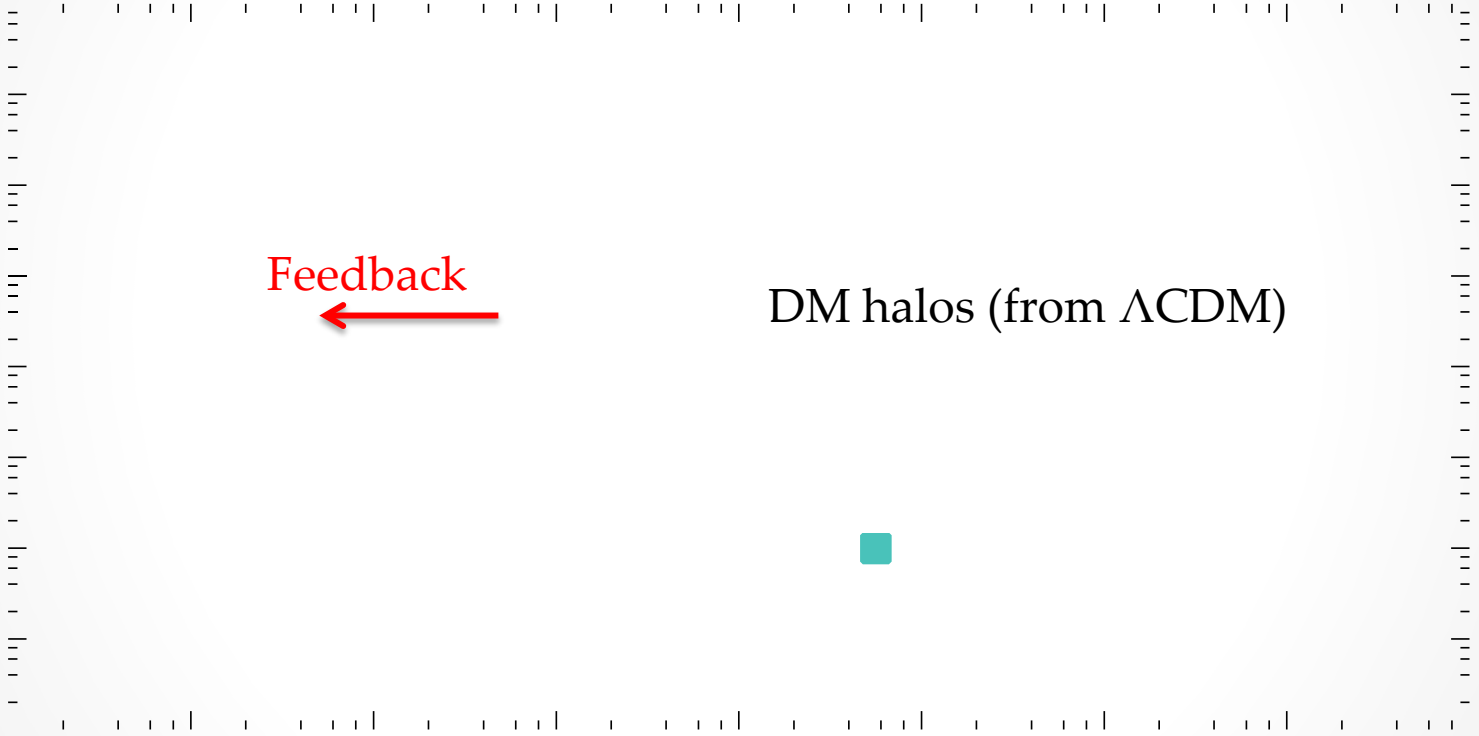
- Self-consistent feedback

→ One-star-at-a-time

Tricky caveat: Supernova (SN) Feedback:

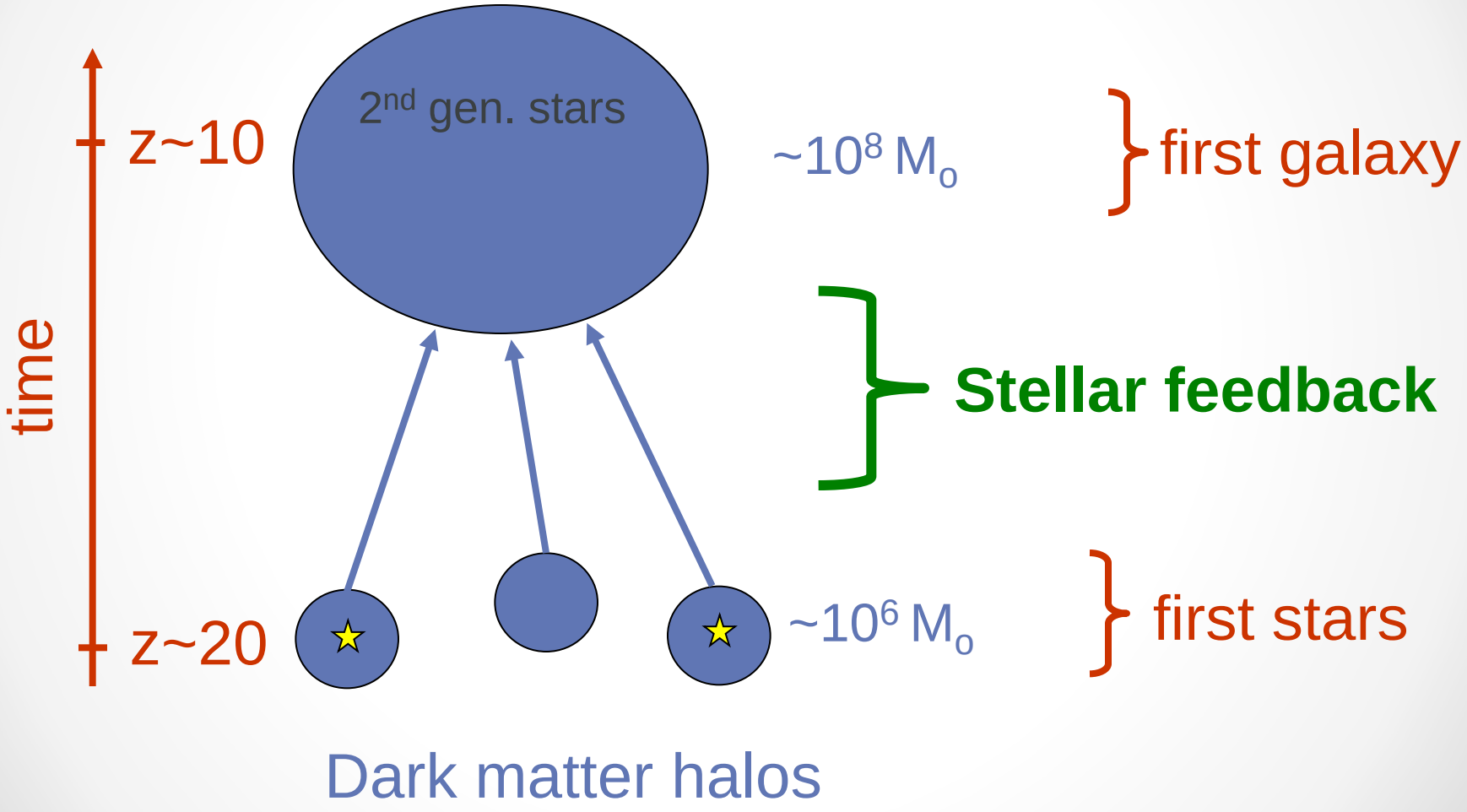
(Ritter, Safranek-Shrader, Gnat, Milosavljevic, Bromm 2012, ApJ, 761, 56)

Number of Sources vs. Mass

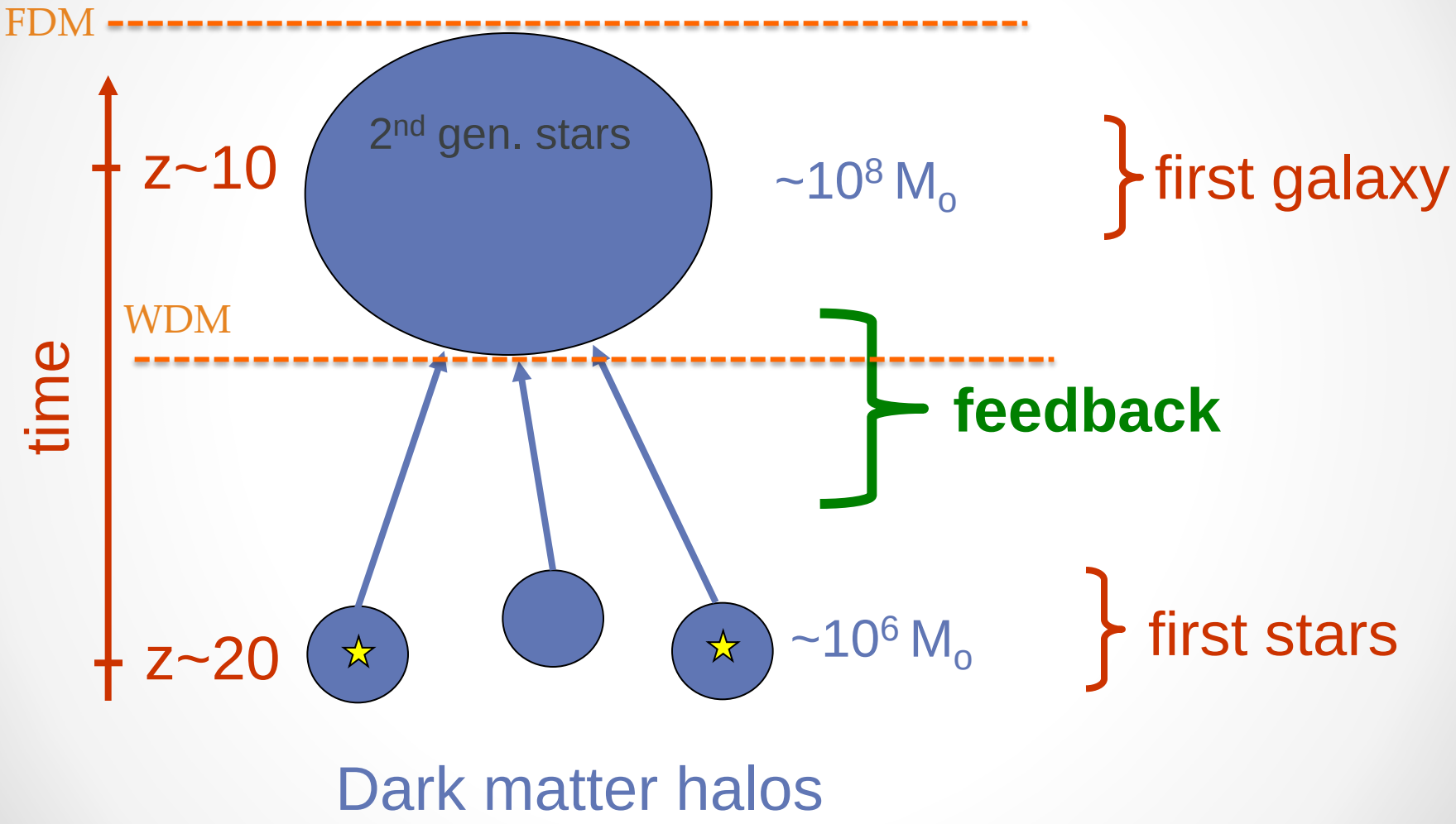


- Stellar (baryonic) feedback modifies DM-only picture!

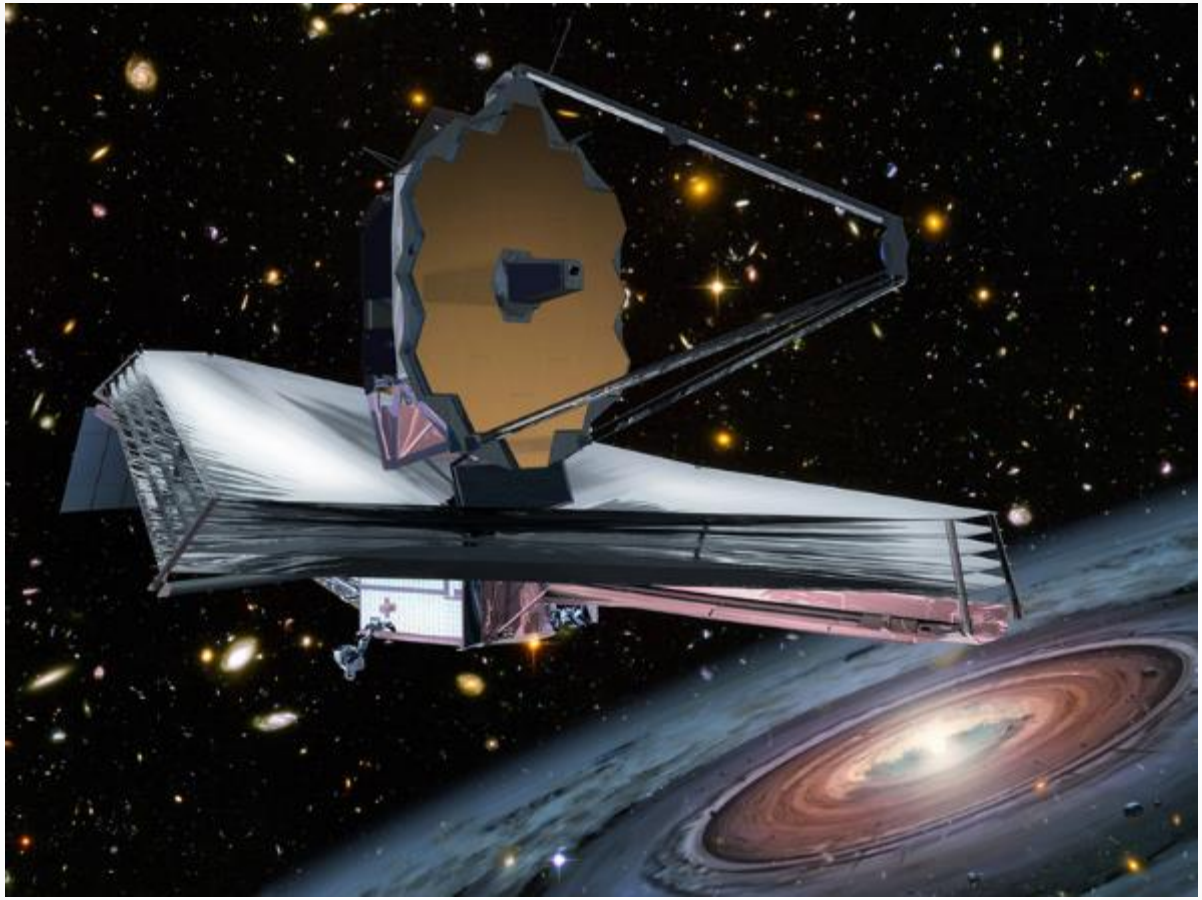
Small-scale Frontier: High redshifts



Sensitivity to Small-scale Nature of DM



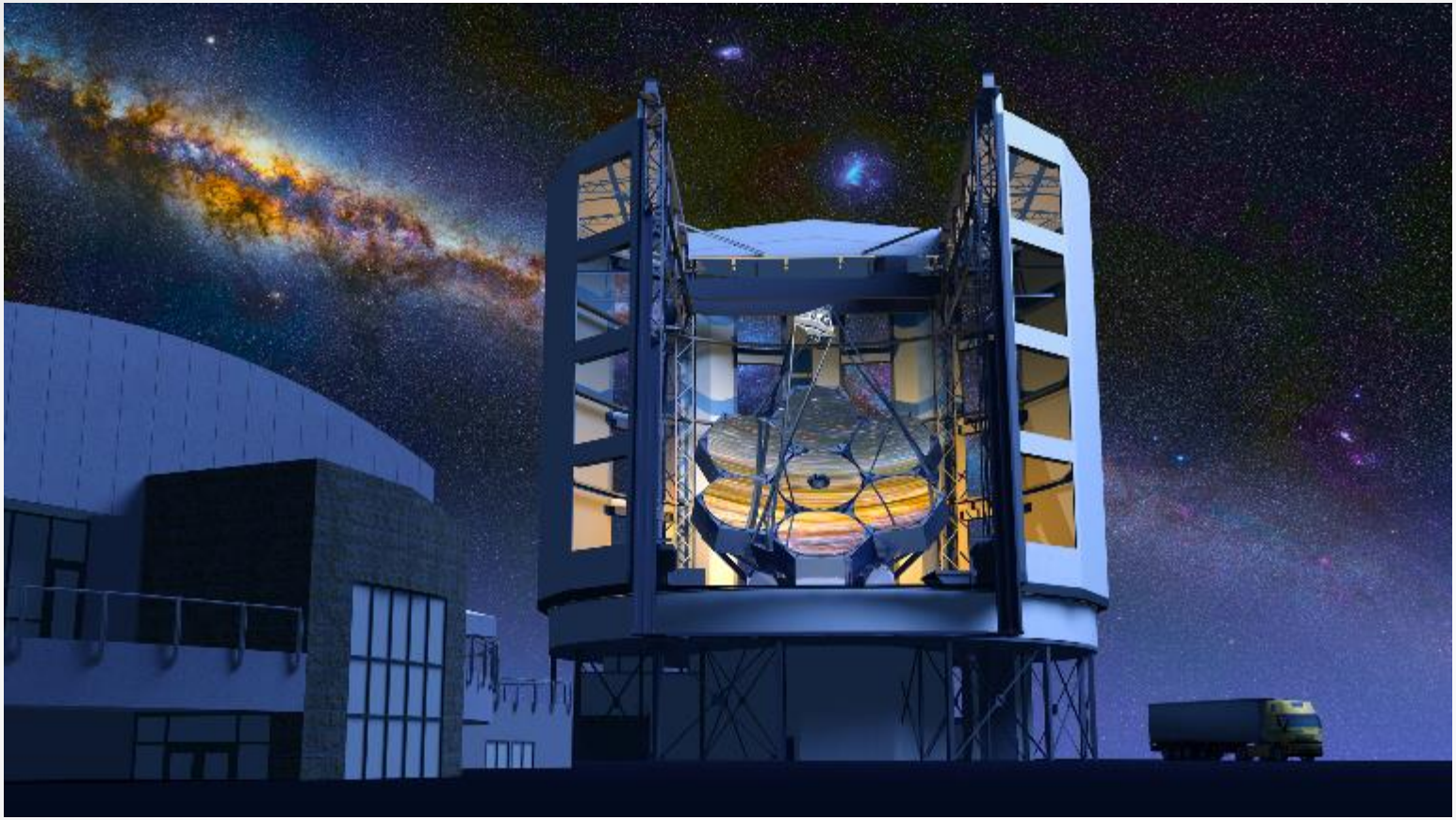
Next-generation Telescopes I



James Webb Space Telescope (JWST)

- To be launched ~2019 (successor to Hubble Telescope)

Next-generation Telescopes II

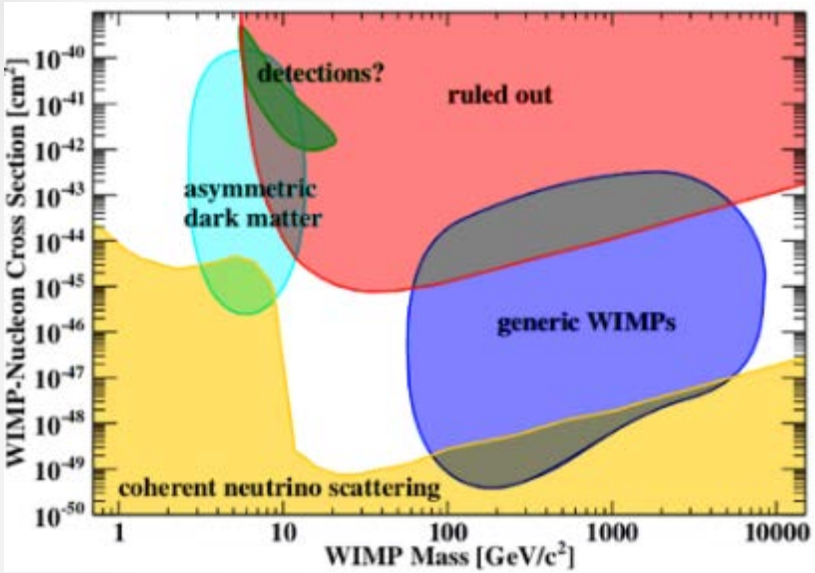


Giant Magellan Telescope (GMT)

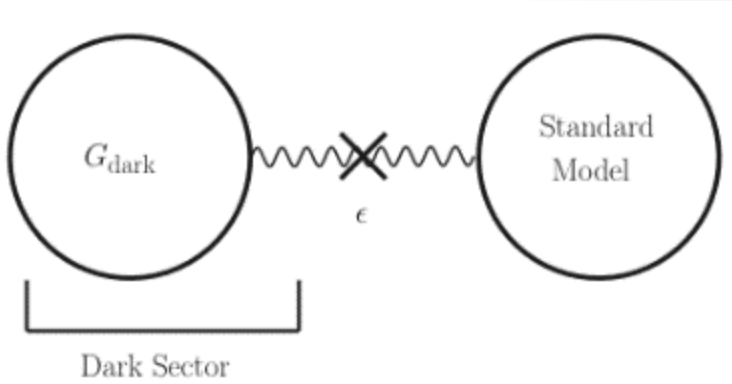
- Giant (30-40m) telescopes on the ground
  (also: E-ELT, TMT)

Sensitivity to Small-scale Nature of DM

→ **Direct WIMP searches have been unsuccessful so far!**



→ A completely Dark Sector?



→ Alternatives to cold dark matter (ΛCDM):

- Warm Dark Matter (WDM)
- "Fuzzy" Dark Matter (FDM); ultra-light particle with QM (de Broglie) wavelength of ~ 1 kpc!

First Stars in Ultra-light ("Fuzzy") Dark Matter

(Hirano, Sullivan & Bromm 2017, MNRAS, in press; arXiv:1706.00435)

Star Formation Site

FDM

CDM

Non-linear collapse

- Collapse along 3 axes, rate described by eigenvalues (λ):

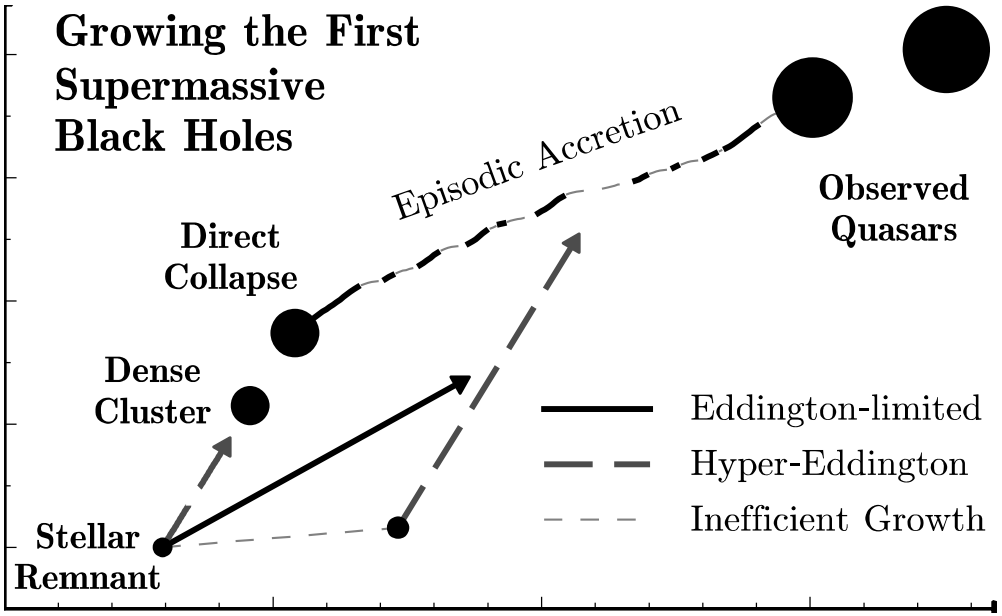
$$\rho(\boldsymbol{r}, t) = \frac{\bar{\rho}(t)}{\det\left[\delta_{ij} + b(t)(\partial p_j/\partial q_i)\right]}$$

$$= \frac{\bar{\rho}(t)}{[1 - b(t)\lambda_1(\boldsymbol{q})][1 - b(t)\lambda_2(\boldsymbol{q})][1 - b(t)\lambda_3(\boldsymbol{q})]},$$

- From halos (CDM) to filaments (FDM)

Pathways to Early SMBH Formation

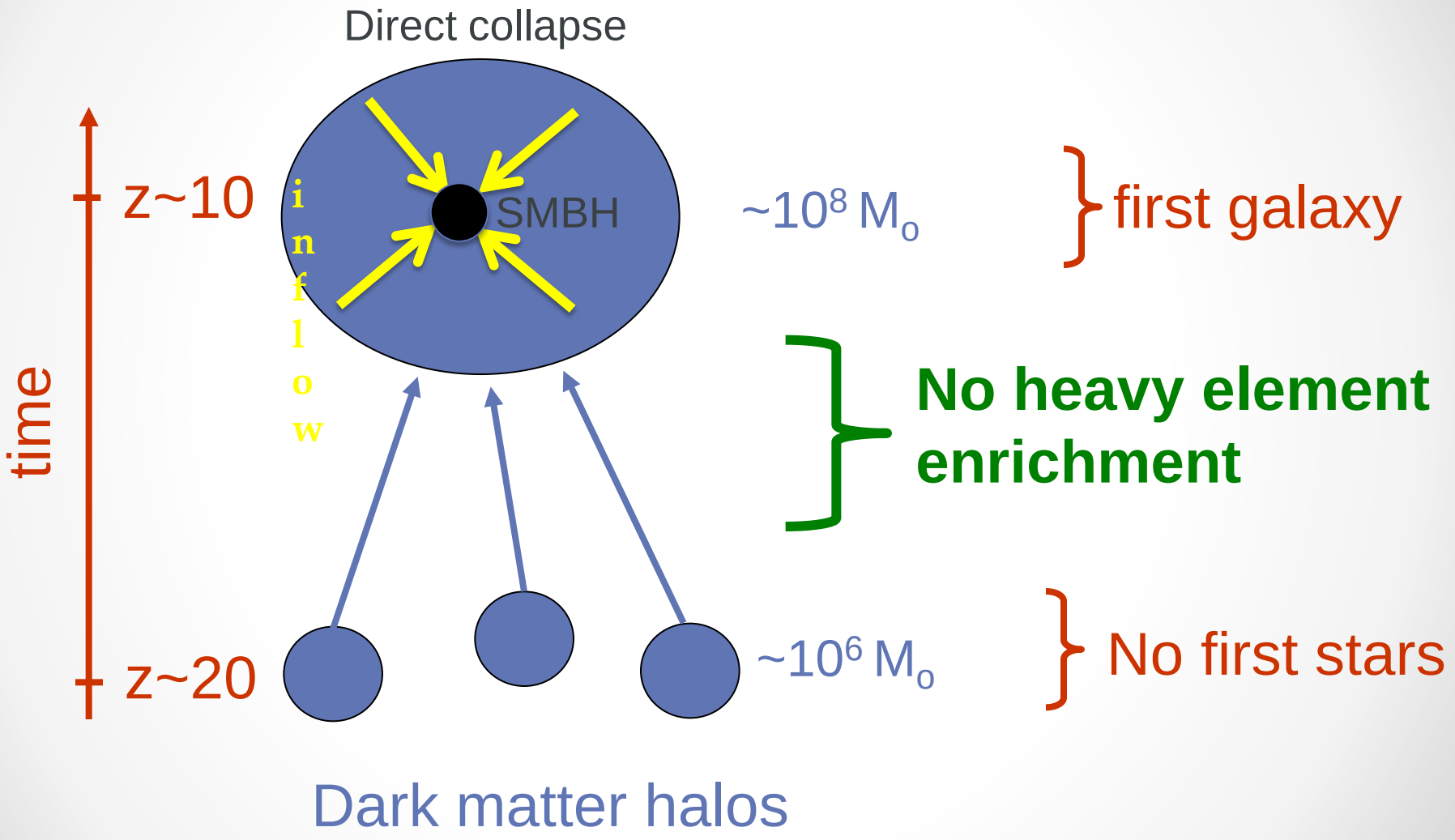
BH Mass vs. Cosmic Time



(Smith, Bromm & Loeb 2017, A&G, in press; arXiv:1703.03083)

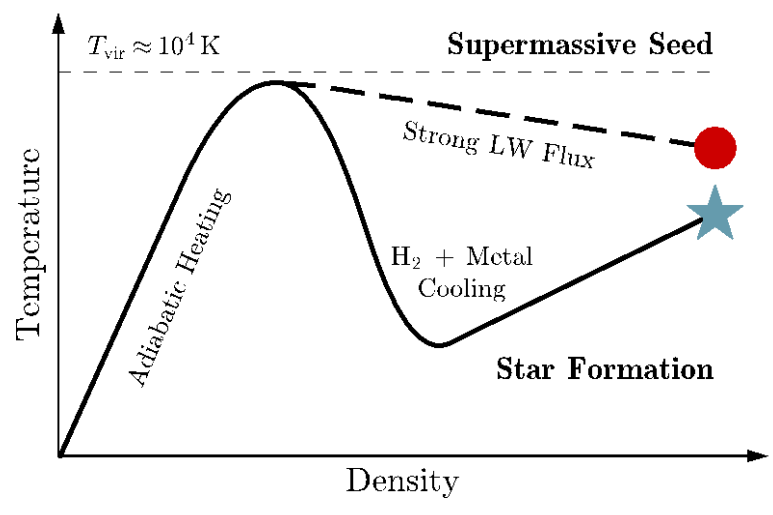
- A “head-start” scenario: Direct collapse black holes (DCBHs)

Pathways to Early SMBH Formation



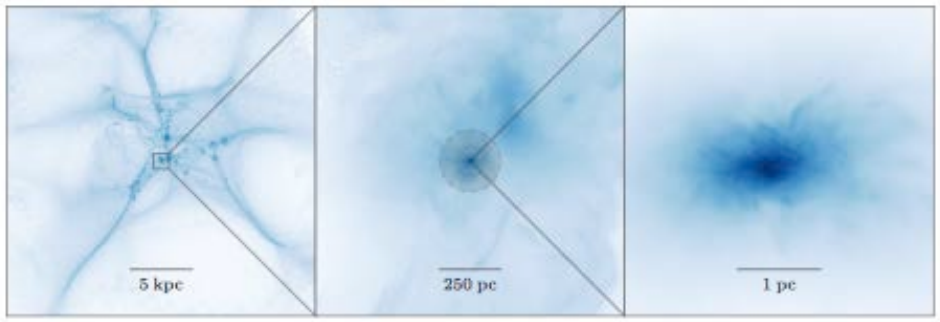
Direct-Collapse Black Holes

T vs. Density



(Smith et al. 2017; arXiv:1703.03083)

(Near-)Isothermal collapse



(Becerra et al. 2017; arXiv:1702.03941)

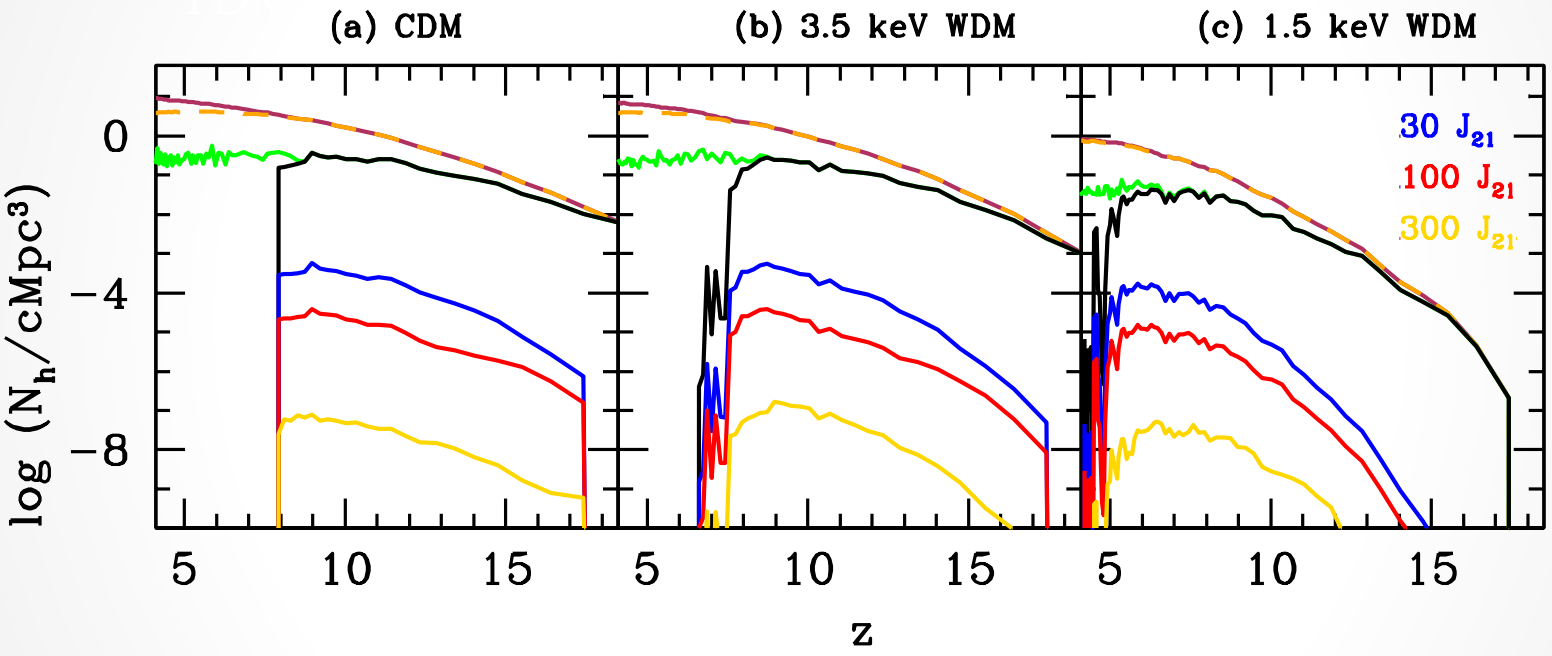
- Virial temperature: $kT_{vir}(r) = \gamma \frac{G\mu m_p M(r)}{3r}$,
- Lyman-Werner (LW) flux: hν<13.6eV

- DCBH formation: Strong LW flux suppresses SF during collapse of metal-free gas into atomic cooling halo (M_{vir}~10^8 $M_\odot$)

Testing WDM with DCBH Sources

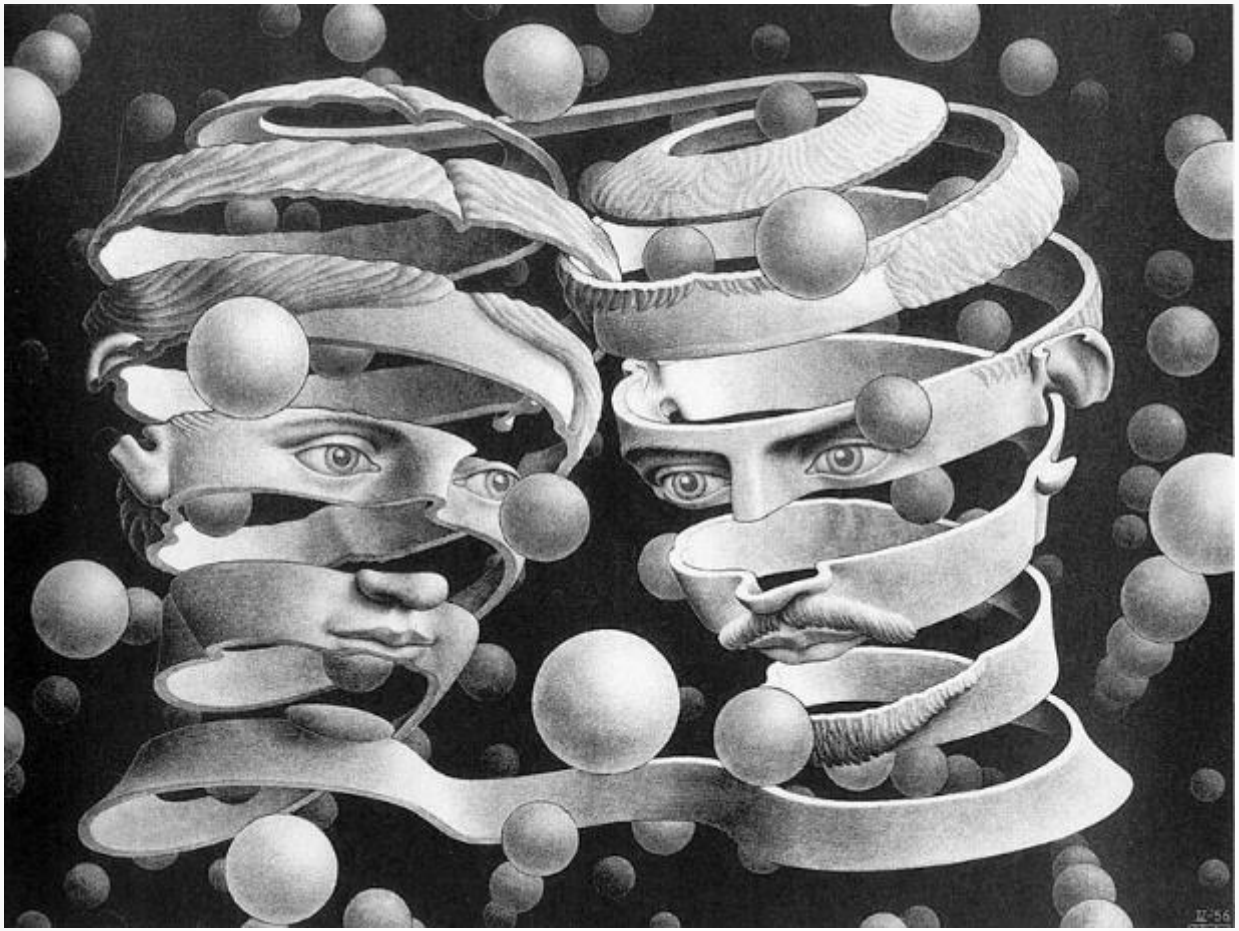
(Dayal, Roy Choudhury, Pacucci & Bromm 2017, MNRAS, 472, 4414)

of DCBH Sources vs. Redshift (z)



- For WDM models, DCBH formation continues longer, to lower redshifts → Doable test for the JWST

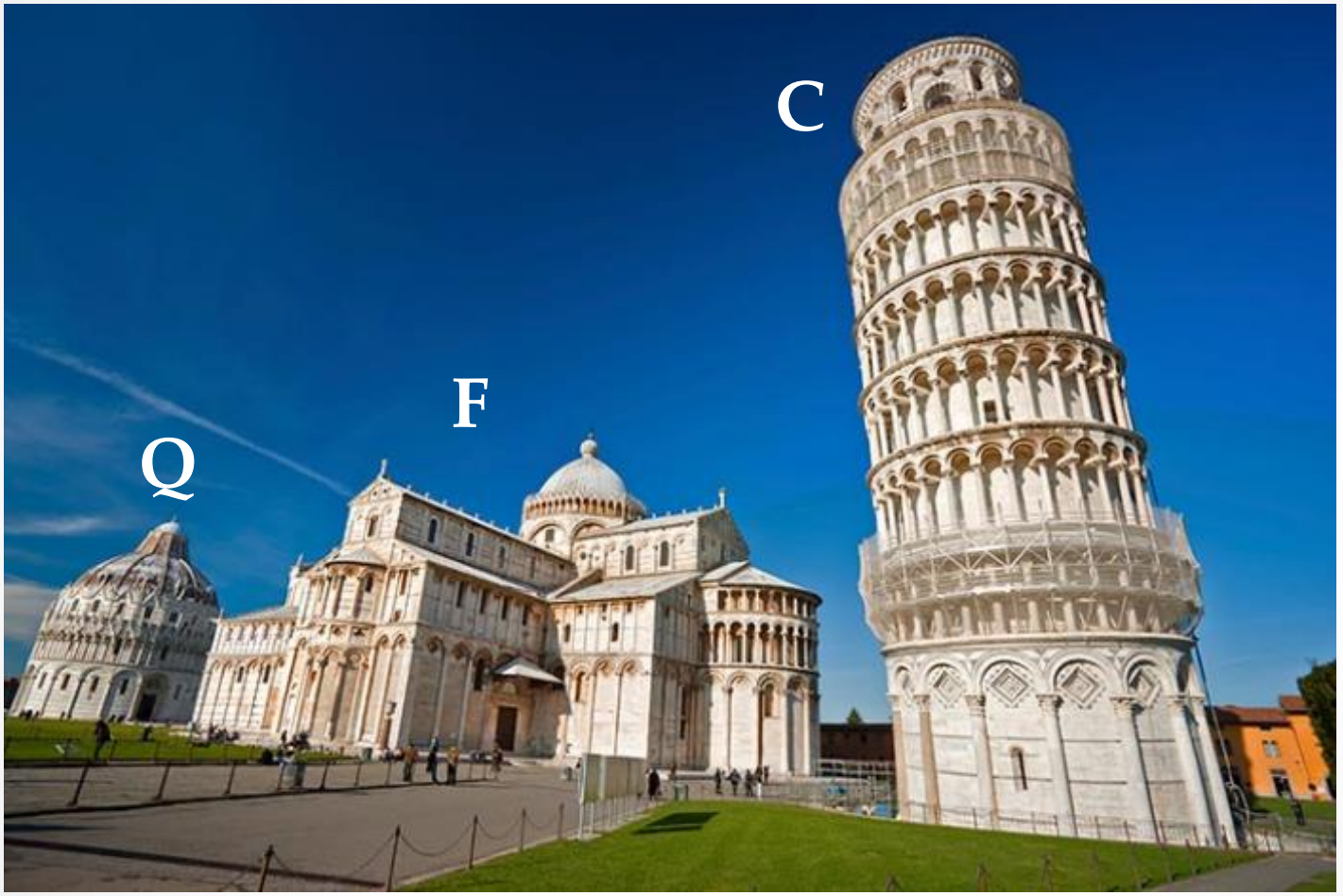
Union of micro- and macrocosm



(Escher, Bond of Union)

- Towards humanity's deepest questions!

Union of micro- and macrocosm



- A new tradition? → “Pisa Symposium on QFC”

(recall: Texas Symposium on Relativistic Astrophysics)

Some Big Questions:

- What is the optimal synergy between QF and C?
- What if dark energy a true cosmological constant (*w=-1*)?
- How could we test ultra-light scalar DM (FDM)?
- What kind of theory do we need in the age of precision measurements?
- What measurements do we need in the age of SM theory?

Perspectives:

- LSS: a powerful probe of fundamental physics
- Timing of LSS growth: handle on dark energy
- Small-scale frontier: handle on dark matter
- Driven by technology: supercomputers and next-generation telescopes