Milestones and Challenges in galaxy formation

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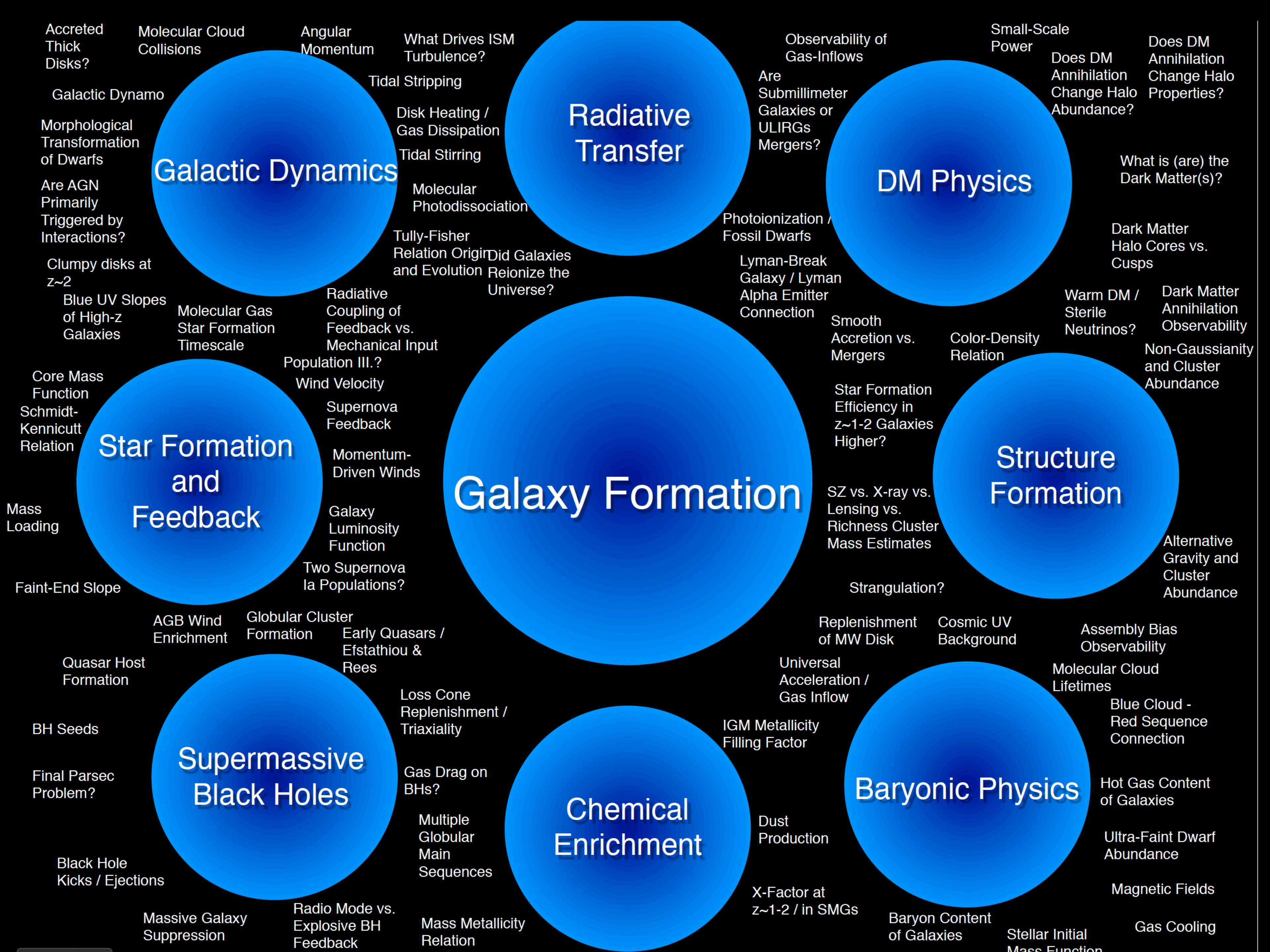
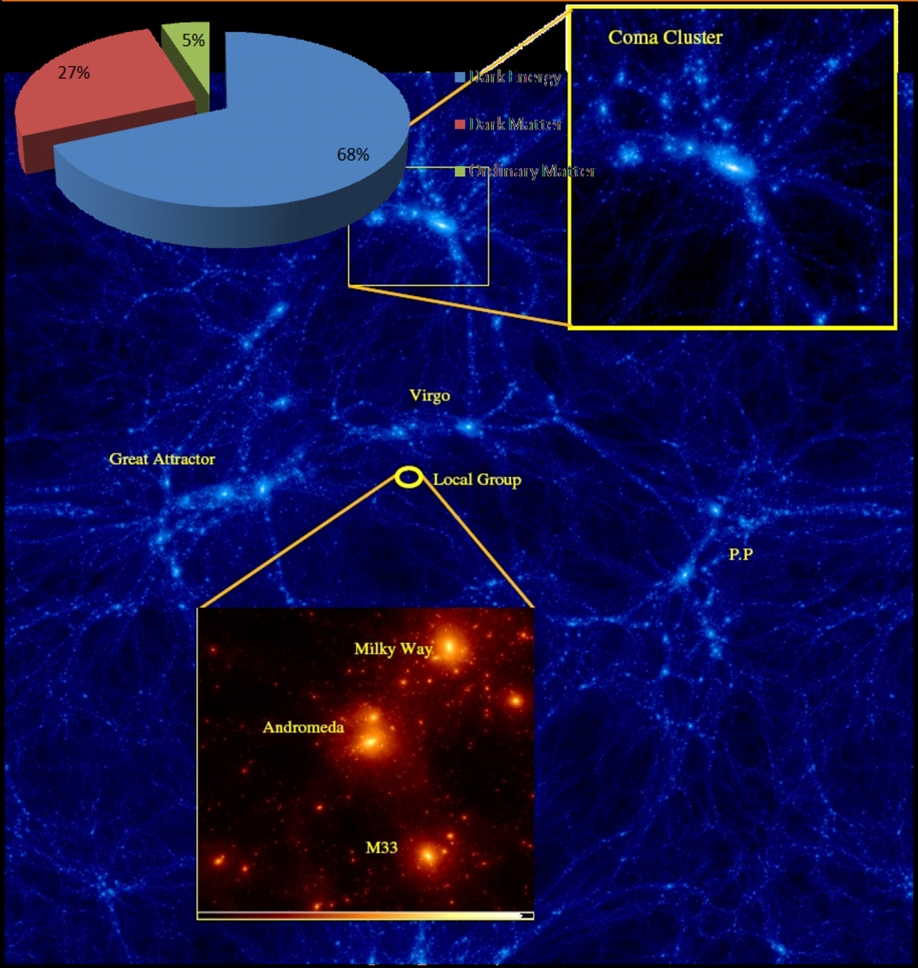


Galaxy Formation
Galactic Dynamics
Radiative Transfer
DM Physics
Star Formation and Feedback
Structure Formation
Supermassive Black Holes
Chemical Enrichment
Baryonic Physics
Accreted Thick Disks?
Molecular Cloud Collisions
Angular Momentum
What Drives ISM Turbulence?
Tidal Stripping
Galactic Dynamo
Disk Heating / Gas Dissipation
Morphological Transformation of Dwarfs
Tidal Stirring
Are AGN Primarily Triggered by Interactions?
Molecular Photodissociation
Tully-Fisher Relation Origin and Evolution
Did Galaxies Reionize the Universe?
Clumpy disks at z~2
Blue UV Slopes of High-z Galaxies
Molecular Gas Star Formation Timescale
Radiative Coupling of Feedback vs. Mechanical Input
Population III.?
Wind Velocity
Observability of Gas-Inflows
Are Submillimeter Galaxies or ULIRGs Mergers?
Small-Scale Power
Does DM Annihilation Change Halo Abundance?
Does DM Annihilation Change Halo Properties?
What is (are) the Dark Matter(s)?
Photoionization / Fossil Dwarfs
Lyman-Break Galaxy / Lyman Alpha Emitter Connection
Dark Matter Halo Cores vs. Cusps
Smooth Accretion vs. Mergers
Color-Density Relation
Warm DM / Sterile Neutrinos?
Dark Matter Annihilation Observability
Non-Gaussianity and Cluster Abundance
Core Mass Function
Schmidt-Kennicutt Relation
Supernova Feedback
Momentum-Driven Winds
Mass Loading
Galaxy Luminosity Function
Two Supernova Ia Populations?
Faint-End Slope
Star Formation Efficiency in z~1-2 Galaxies Higher?
SZ vs. X-ray vs. Lensing vs. Richness Cluster Mass Estimates
Alternative Gravity and Cluster Abundance
Strangulation?
AGB Wind Enrichment
Globular Cluster Formation
Early Quasars / Efstathiou & Rees
Quasar Host Formation
Replenishment of MW Disk
Cosmic UV Background
Assembly Bias Observability
Universal Acceleration / Gas Inflow
Molecular Cloud Lifetimes
Blue Cloud - Red Sequence Connection
Loss Cone Replenishment / Triaxiality
BH Seeds
IGM Metallicity Filling Factor
Final Parsec Problem?
Gas Drag on BHs?
Hot Gas Content of Galaxies
Multiple Globular Main Sequences
Dust Production
Ultra-Faint Dwarf Abundance
Black Hole Kicks / Ejections
X-Factor at z~1-2 / in SMGs
Magnetic Fields
Massive Galaxy Suppression
Radio Mode vs. Explosive BH Feedback
Mass Metallicity Relation
Baryon Content of Galaxies
Stellar Initial Mass Function
Gas Cooling

Overview of galaxy formation

100 yrs ago we didn't even know for sure there were other galaxies apart from our own. Since then:



- **LCDM** gives a very good representation of the large scale structure of the Universe
- Hydrodynamical simulations of structure formation at Kpc resolution can reproduce the fundamental properties and scaling relations of observed galaxies
- Baryonic physics processes modeled in hydrodynamical simulations:

- Gas inflowing and cooling
- Star formation
- Feedback (mechanical, thermal, kinetic, radiation pressure) from SNae, massive stars, AGNs

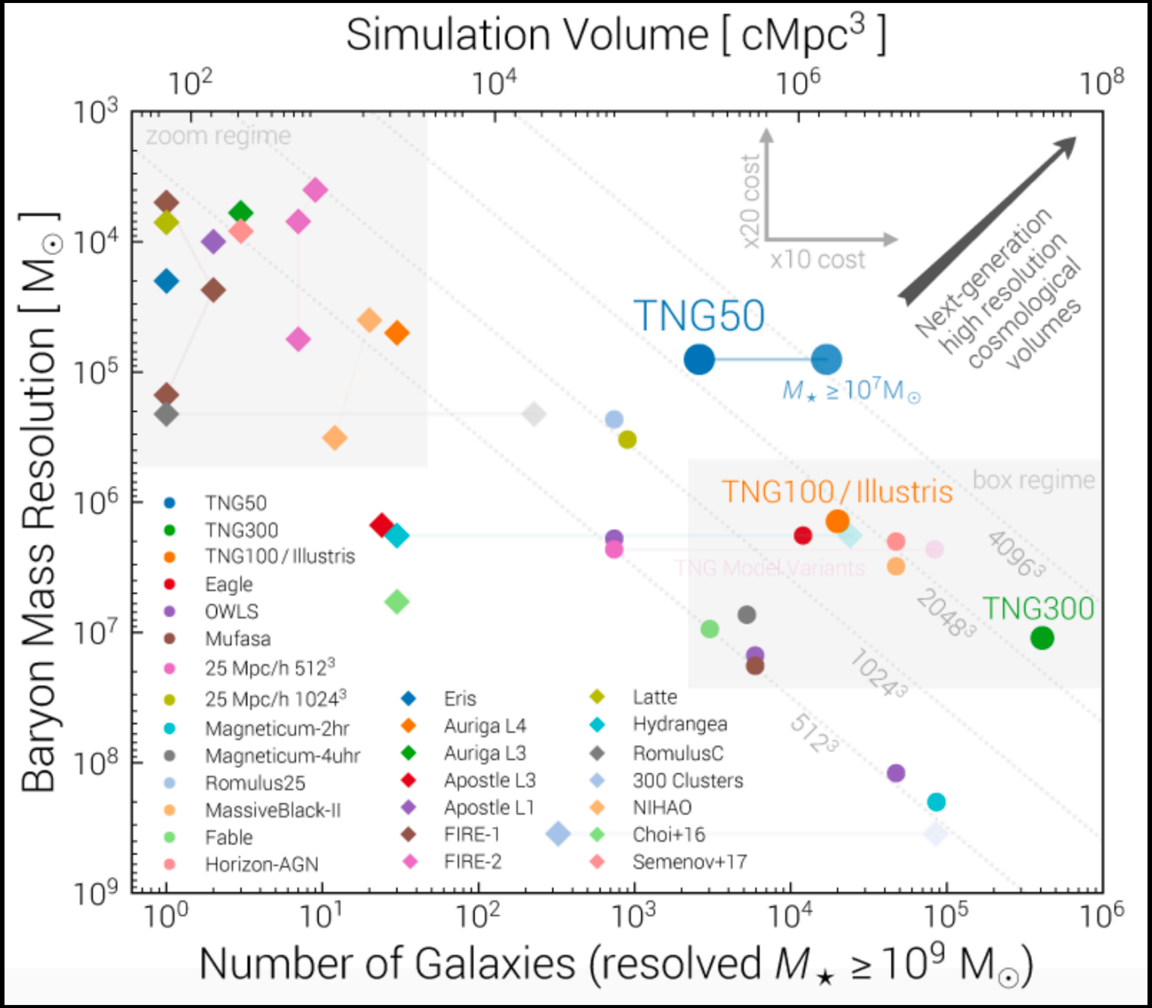
Credit: CLUES collaboration

Advances in Computer Technology

Zoom-in sims => high resolution but low number of simulated galaxies

Box-region => large number of simulated galaxies but low resolution

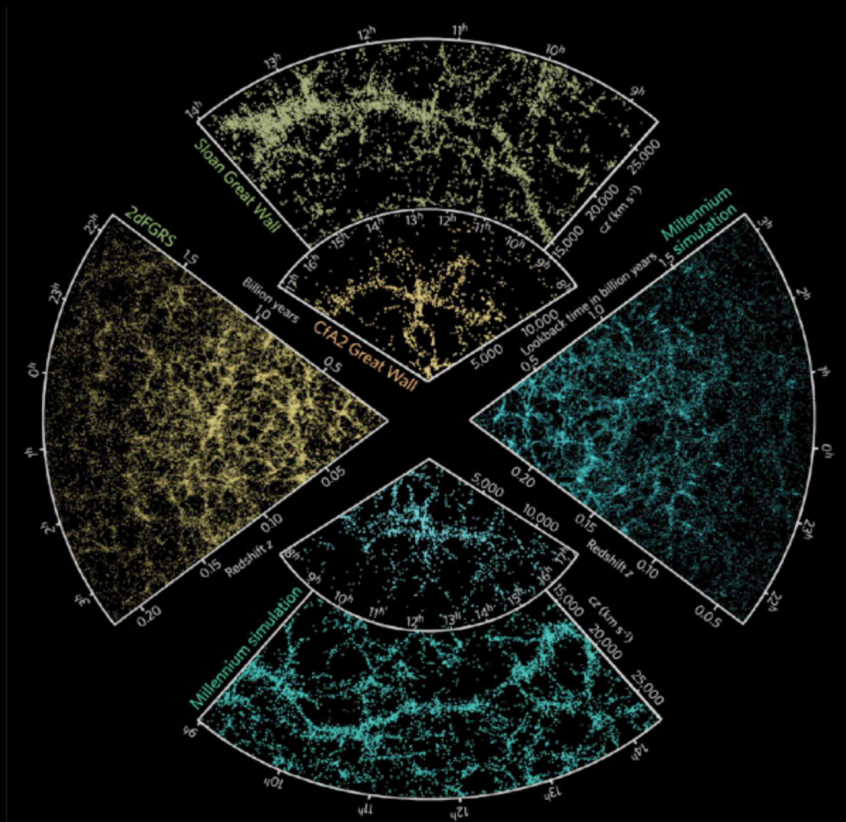
Future => simulate cosmological volumes with high resolution, to resolve individual galaxies



Credit: TNG collaboration

Successes and tensions

Large scale structure

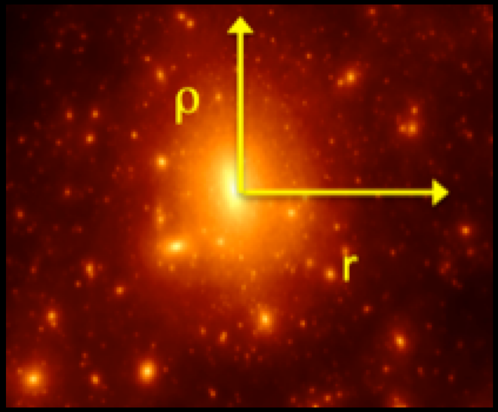


credit: Springel V. et al. 2005, Nature

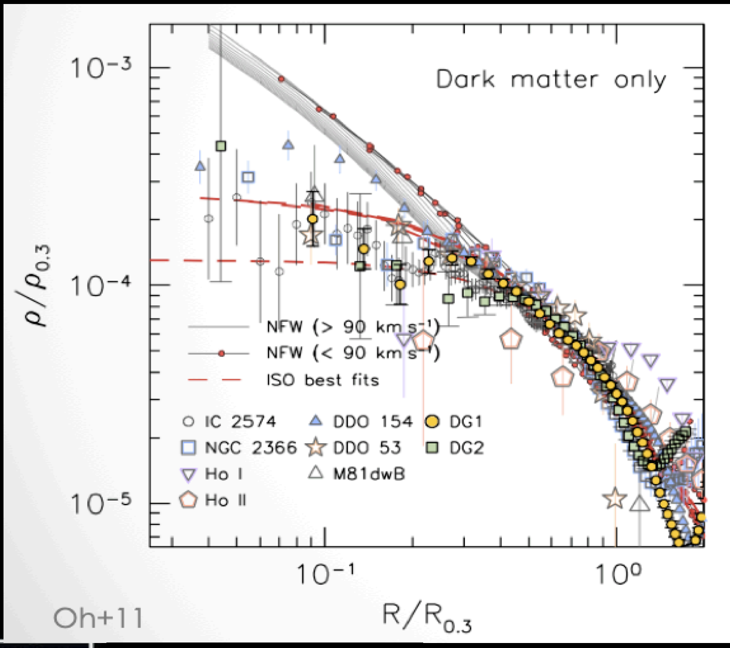
Small scales

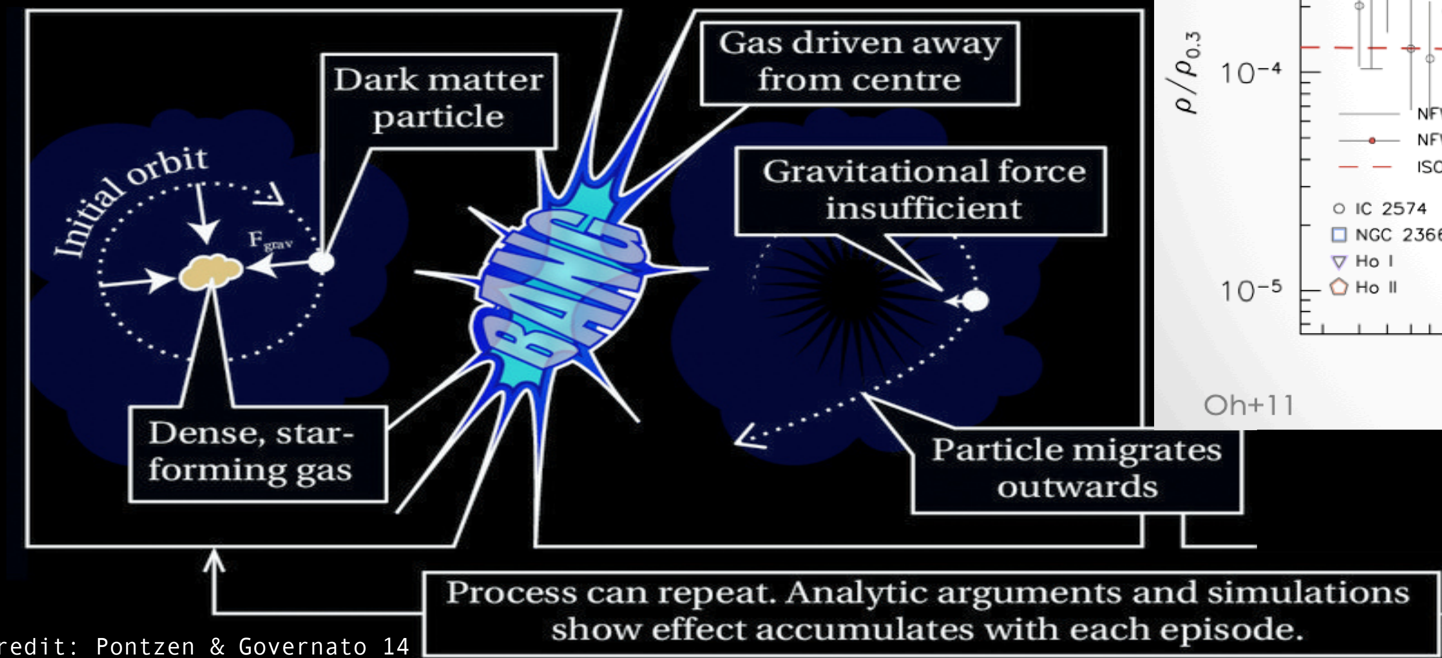
- Cusp-core discrepancy ➔ Diversity of RC in galaxies
- Planes of satellites
- … Missing satellite problem
- Number and radial distribution of satellites
- Mass discrepancy acceleration relation
- Velocity function of galaxies
- Large size of Ultra-Diffuse galaxies
- Kinematic of satellite galaxies (TBTF problem)...

Cusp-core discrepancy: the impact of baryonic physics



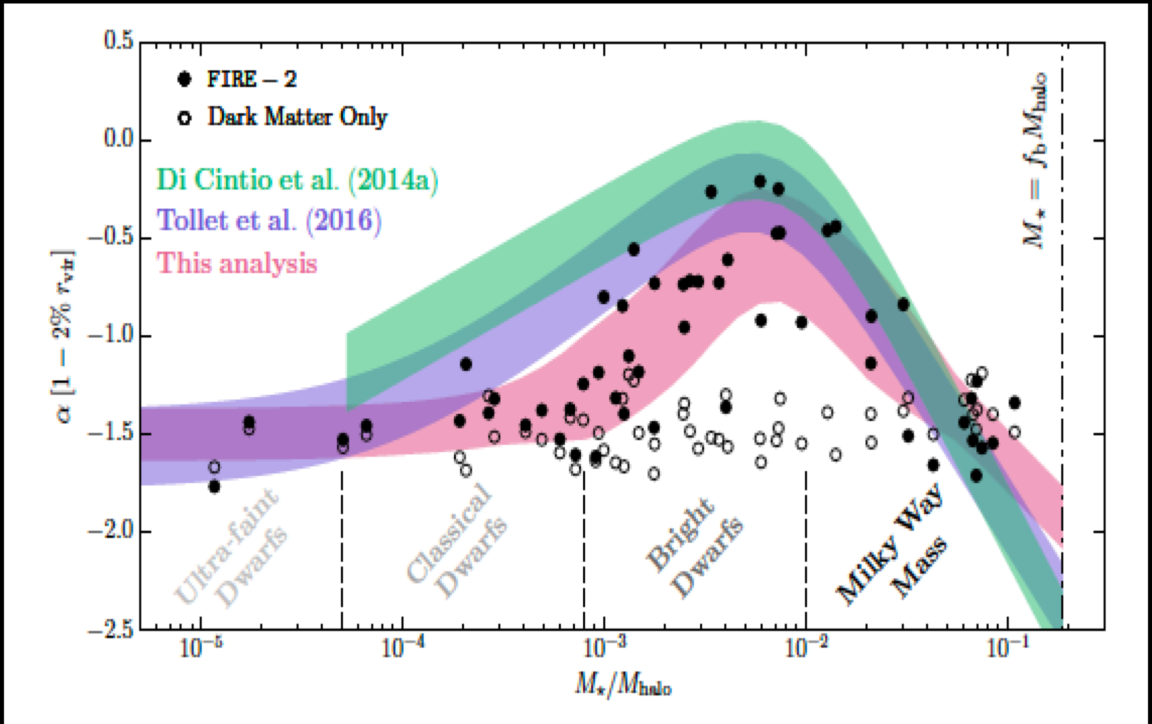
Adiabatic approximation does not work in reality
Core formation mechanism -> outflows driven by SNae feedback
Core created during starburst events that launch powerful gas outflows

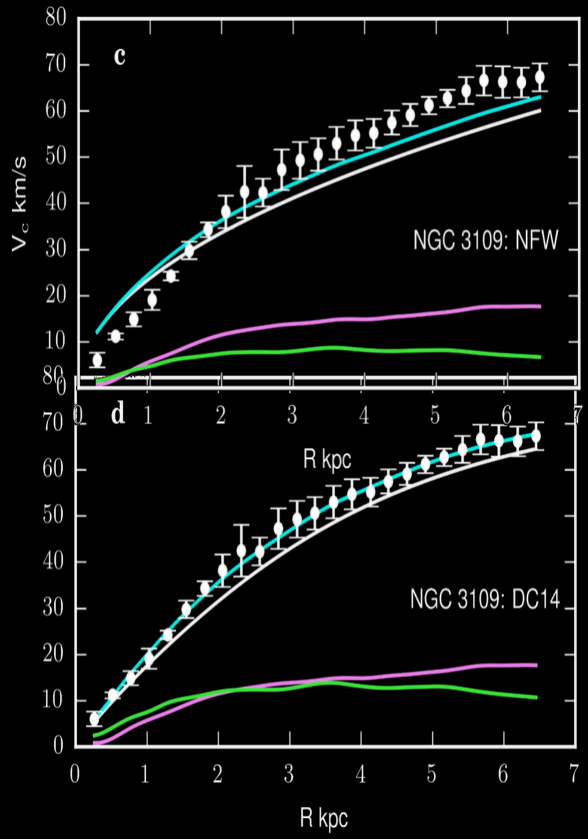




Credit: Pontzen & Governato 14

Sweet spot of core formation

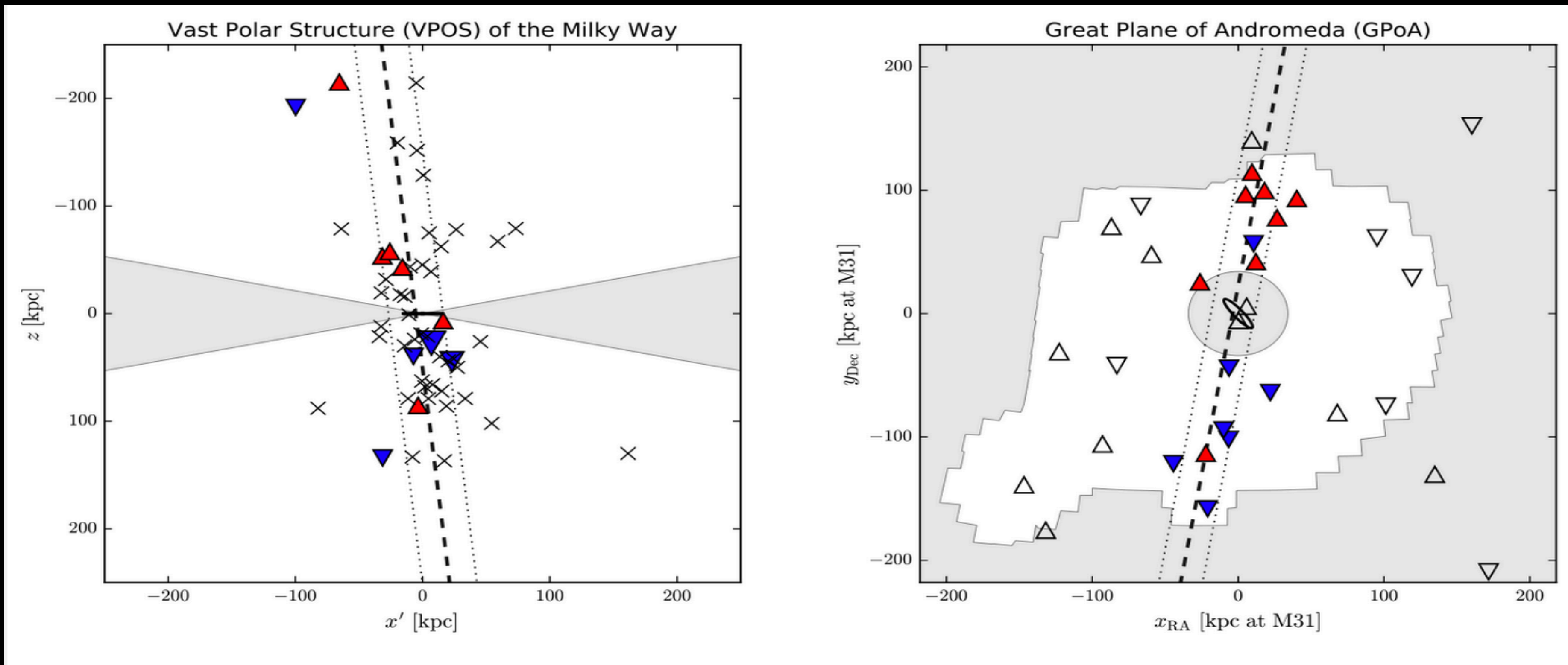




Credit: Lazar+20, Katz+17,Tollet+16, Chan+15, Di Cintio + 14a.b

Dark matter profiles determined by two opposite effects: energy from SNae vs
gravitational potential of underlying DM halo
(see Penarrubia+12, Di Cintio+14a,b , Katz+17..)

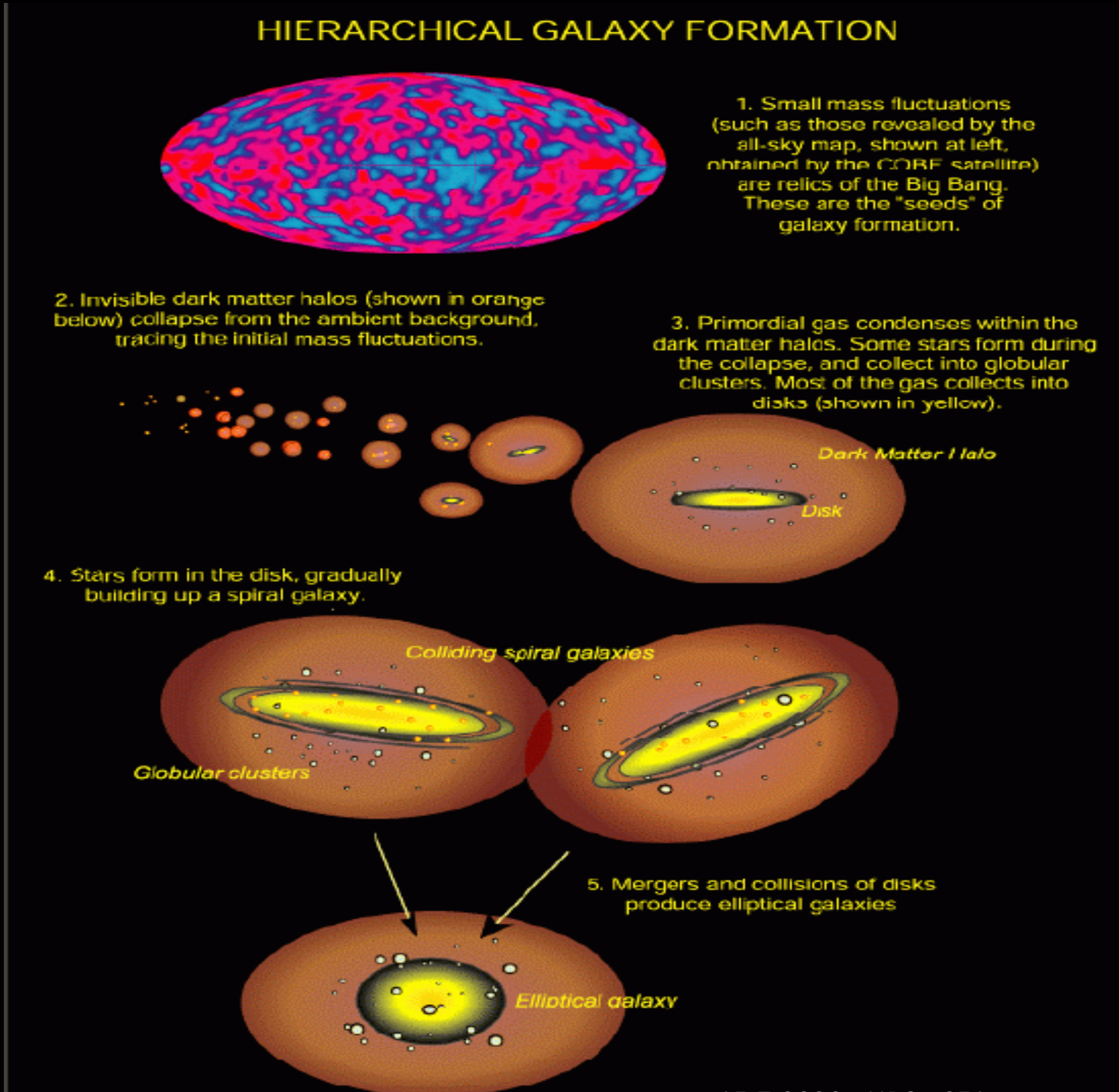
Planes of satellites



Credit: Pawlowski +18,19, Muller+17,Ibata+13,14

Planes of satellite galaxies are extremely unlikely in simulations, showing up in 0.1% (Millennium-II) to 0.5% (ELVIS) of simulated galaxies. Not solved with baryonic physics nor with special host halo properties!

Prospects for the future



Credit: astronomy.nmsu.edu

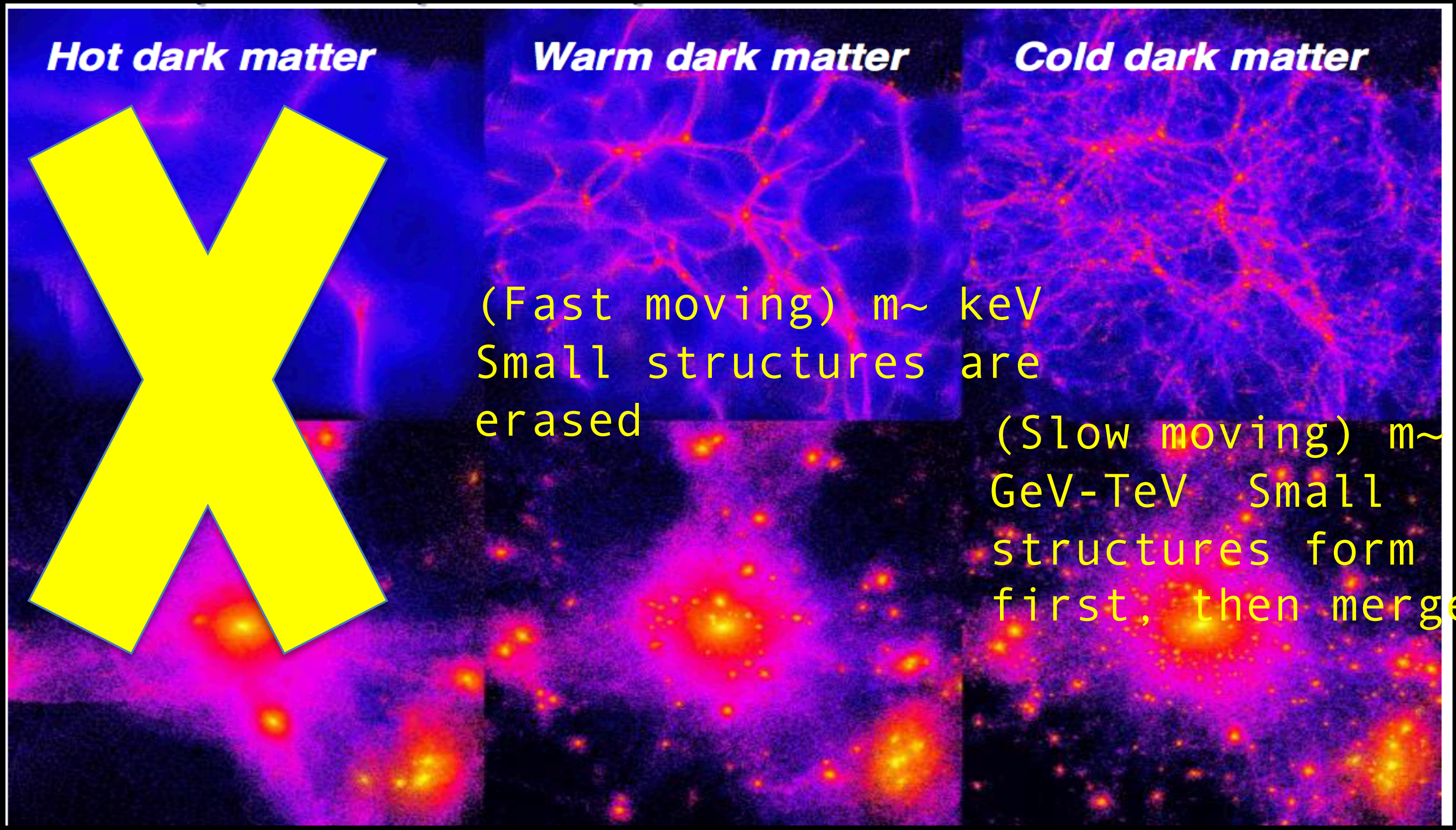
How can we test LCDM using galaxy formation?

Several dark subhalos should exist, and they can be found via gravitational lensing

They are too small for hosting a galaxy, but should exist in large numbers!

The nature of DM: structure formation depends on DM type

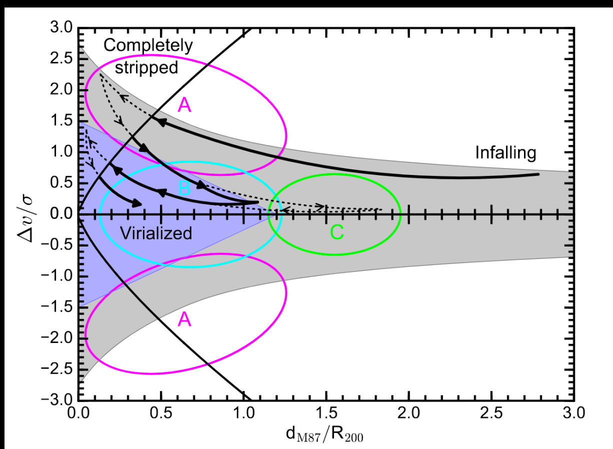
LCDM is the standard cosmological model of structure formation , based o
Cold dark matter particles, which have ten to a hundred times the mas
of a proton

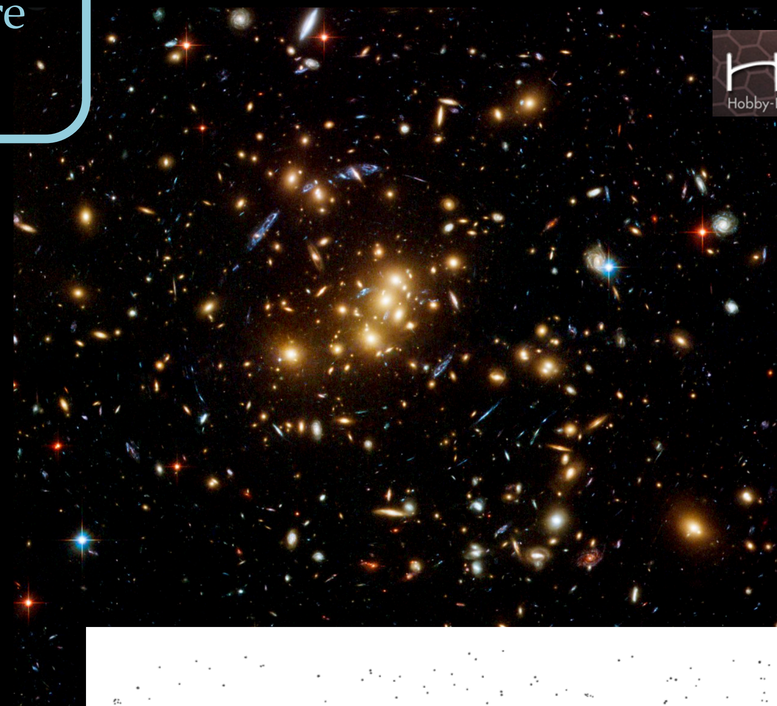


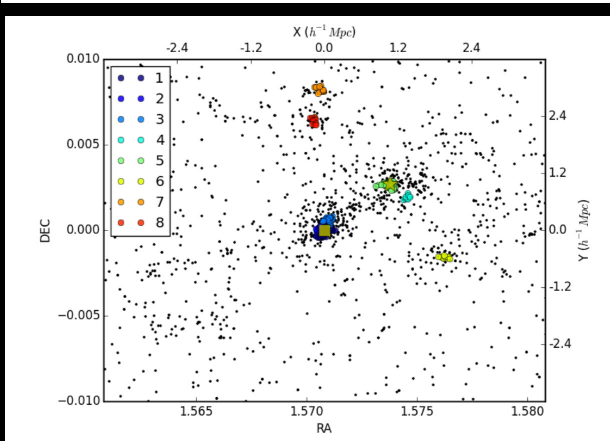
Credit: Ben Moore

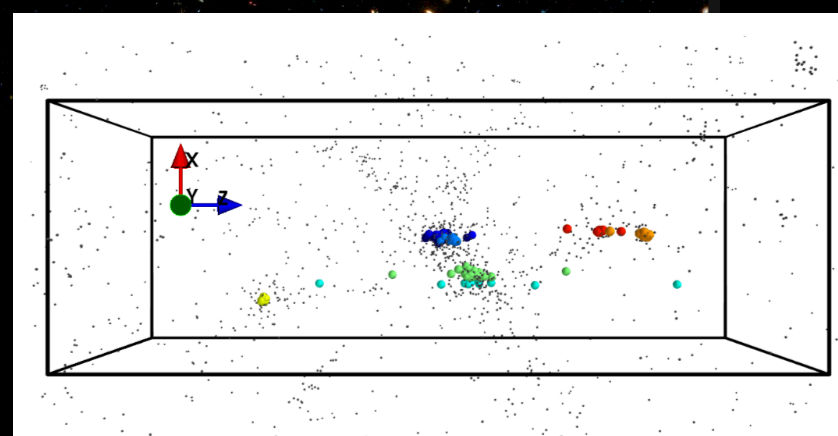
Redshifts in cluster galaxies

- Mass profiles of clusters
- Identification of substructure
- Mass Accretion Rates

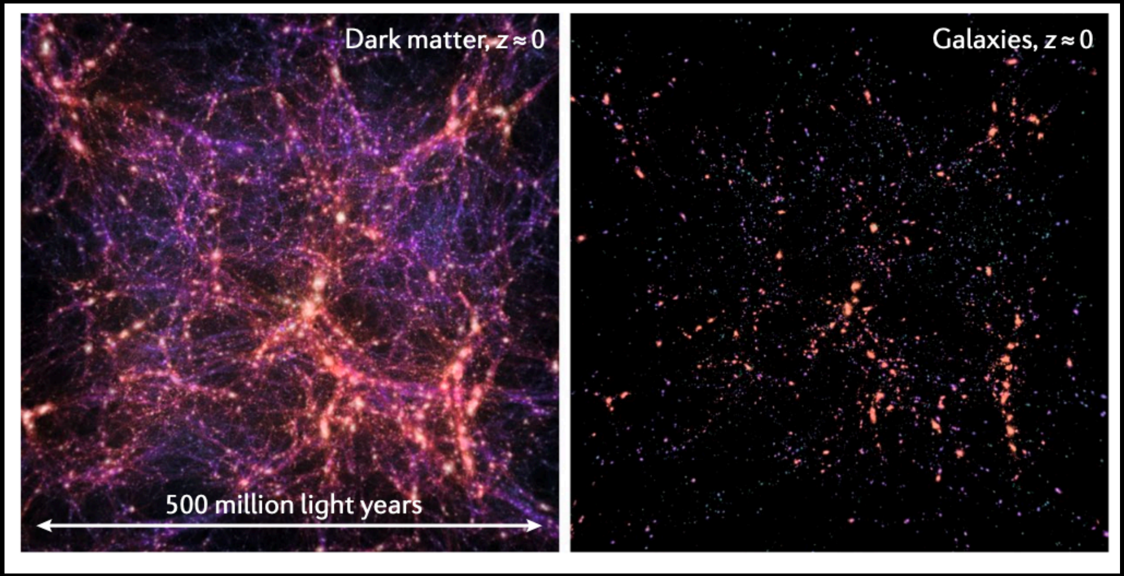








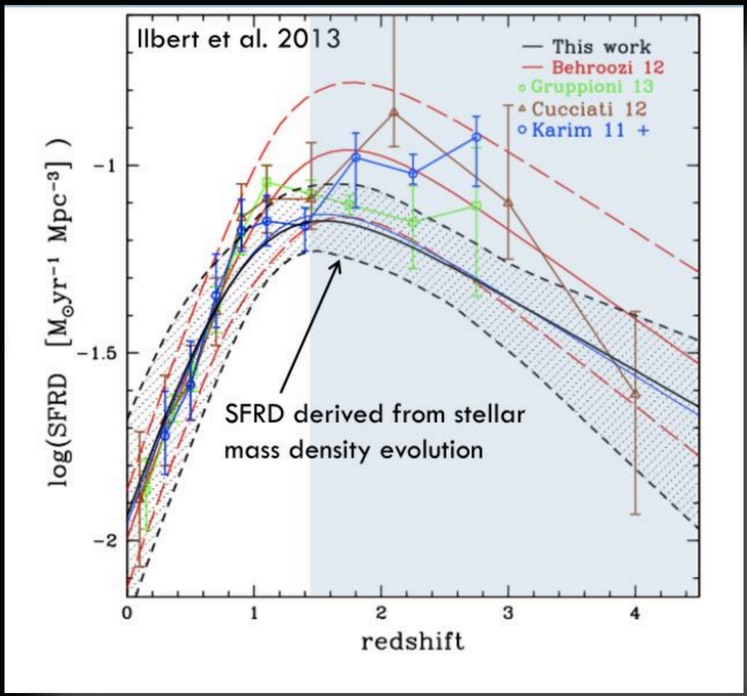
The connnection between halos and galaxies



How galaxies acrete their gas?

When, where and how galaxies formed their stars?

Cosmic star formation history: steady rise from EoR, peak at 3.5 Gyr after the Big-Bang (z~2) and exponential drop at z<1



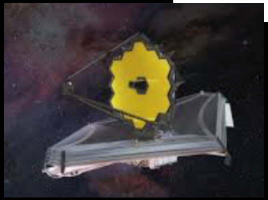
Key questions:

- Is there a characteristic cosmic epoch of the formation of stars in galaxies?
- How is the stellar mass density evolution with redshift?
- How does the CSFH compares with the history of mass acretion into the black hole?
- How does SF vary with galaxy properties and environment?
- Do galaxies reionize the Universe at a z> 6?

extinction, IMF (change with redshift?)

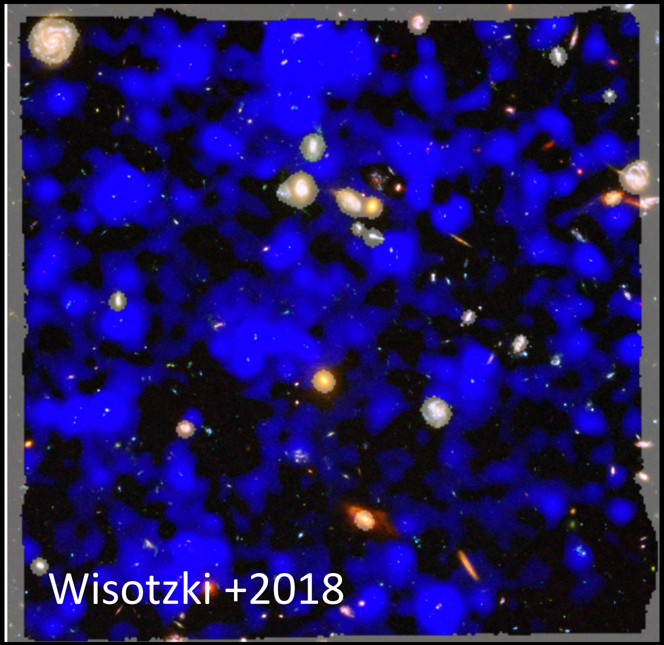
SKA: can provide a measure of the CSFH free from extinction
JWST: evolution of the stellar mass density with redshift

SKA SQUARE KILOMETRE ARRAY



Gas acretion

Lyα emission with MUSE 3 < z < 6



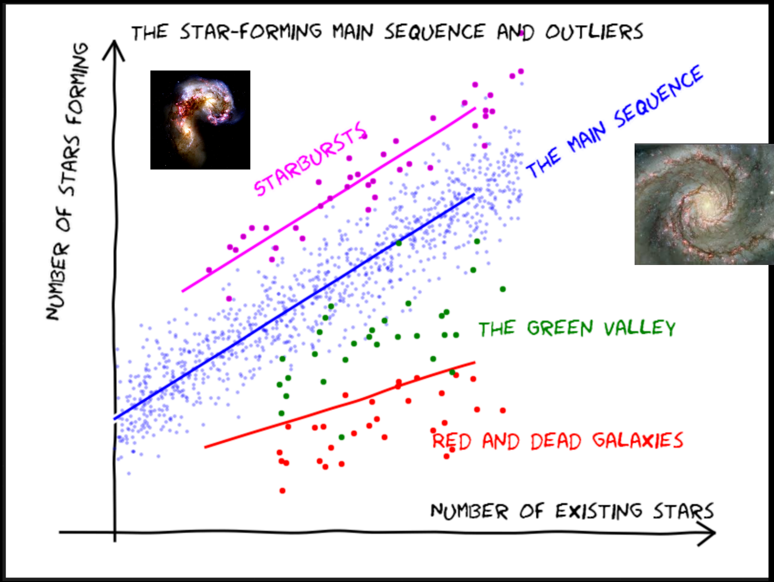
2 < z < 3

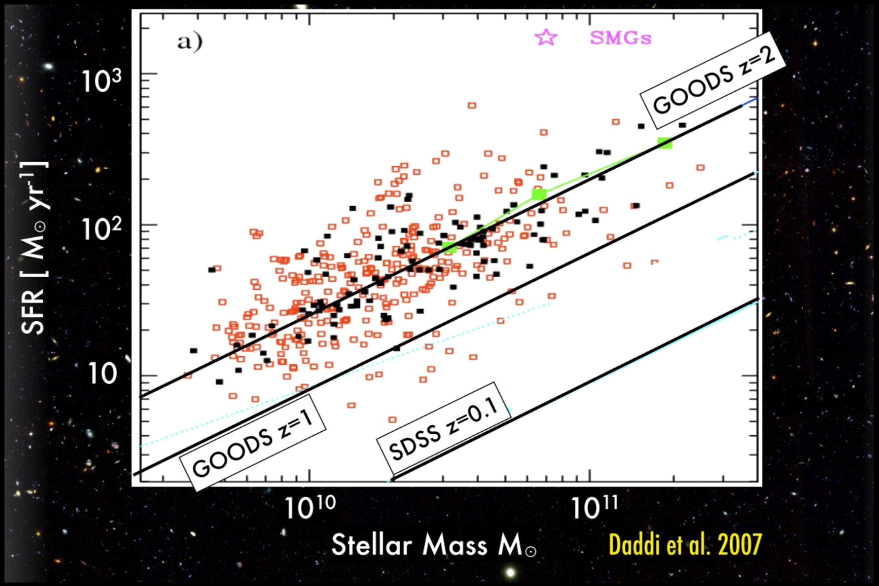
1.6 < z < 3

Key questions:
- How do galaxies exchange baryons with the Intergalactic Medium?
- How do the CGM properties evolve when reaching the peak of galaxy star-formation?
- What is the spatial extent and how is the CGM gas around galaxies distributed, spatially and kinematically?

Which galaxies dominate the SFRD in the Universe?

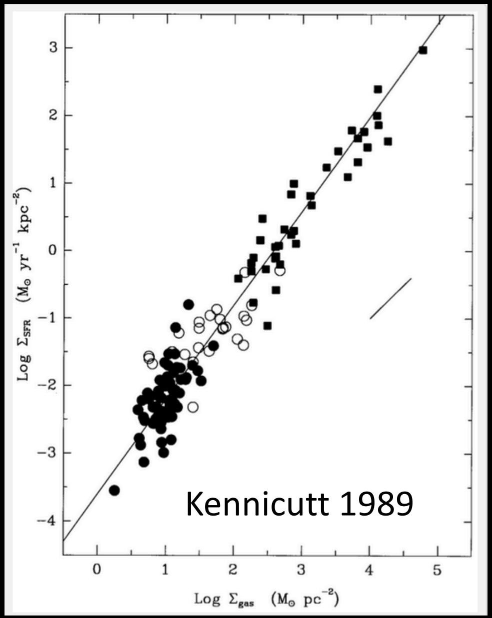
- From z≈2 to the present day, most stars formed in galaxies in the SFR-M (means that the evolution of the cosmic SFH is primarily determined by a balance between gas accretion and feedback processes?)

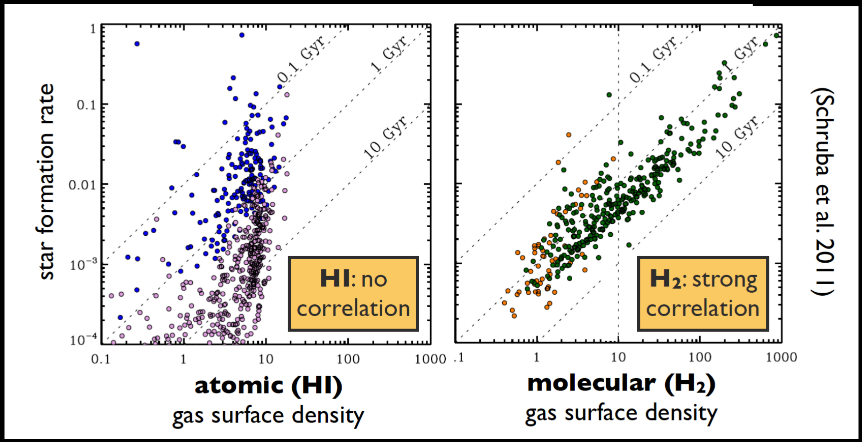


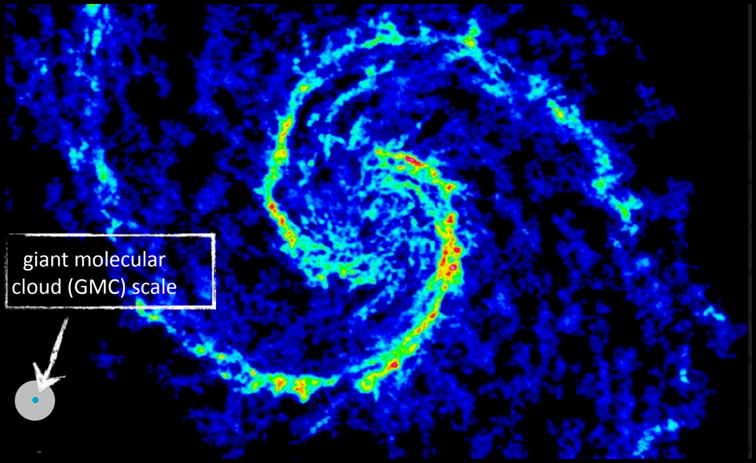


at z=2
COSMOS Hersche FIR data mainly detect starbursts
GOODS-s Herschel reaches the main sequence at intermediate stellar masses
UV-based SFRs are statistically robust for MS galaxies (however extinction)

Understading SF regulation





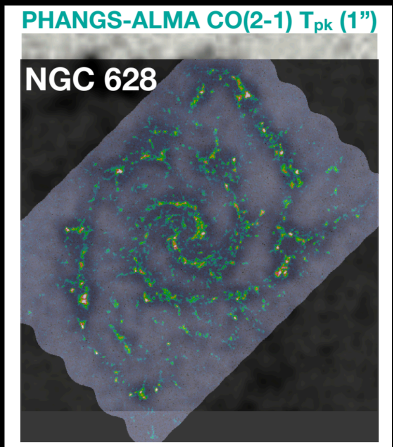


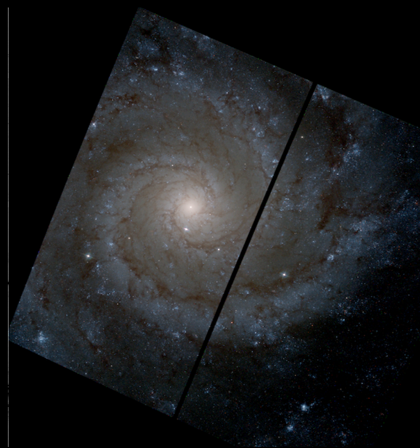
The processes that regulate SF occur at the scale of molecular clouds

PI: E. Schneider

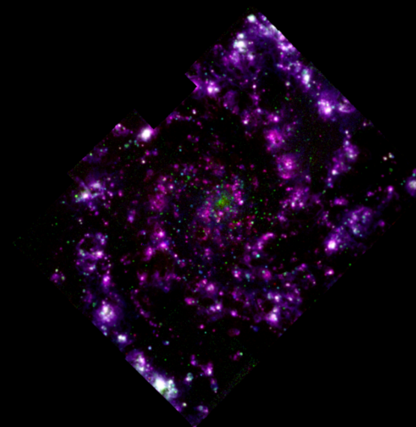
PHANGS

Physics at High Angular Resolution in Nearby GalavieS





HST (NUV+optical)



MUSE

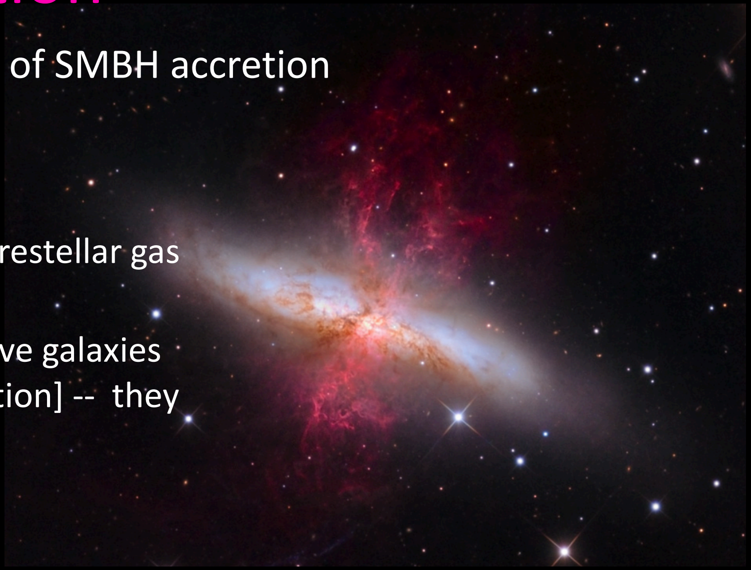
theoretical efforts also

Role of magnetic fields
Role of cosmic rays

- How do the properties and population of molecular clouds depend on host galaxy, dynamical environment, and galaxy disk structure?
- Star Formation: How does the ability of gas to form stars depend on the cloud-scale structure and dynamics of the molecular gas?
- Timescales: What are the statistical timescales implied by cross-correlation of molecular gas, young stellar populations, and dynamical features in the galaxy?
- Self-Regulation: How does the self-regulation of star formation in galaxy disks emerge from the violent cloud-scale processes of star formation and feedback?

Importance of AGN in galaxy evolution

At least 25% of massive galaxies at $1.5 < z < 3$ show indication of SMBH accretion



Two types of AGNs:

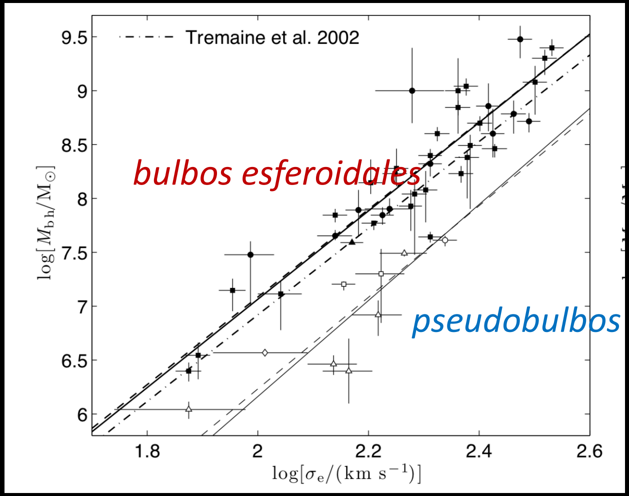
quasar mode [acretion at the Eddington limit] (able to remove interestellar gas from the galaxy)

radio mode [heat the gas preventing cooling flows] (found in massive galaxies in the center of the clusters and fundamental to explain mass function] -- they don't seem to fit in the unified model (Hardcastle 2007)

Key questions:

Are radio and quasar mode accretion/spin mechanisms or physically

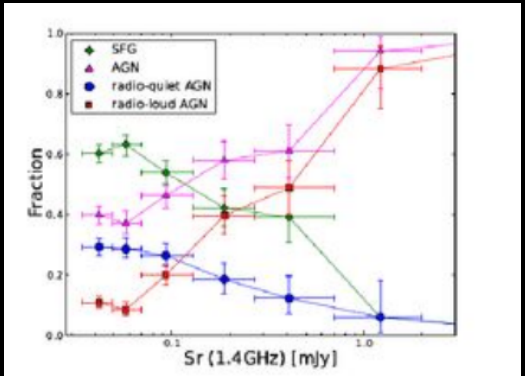
1. what is the impact of the energy released during the qso phase? (Di Matteo+2005)
   - generate large ouflows quenching SF?
   - Just modify the gas dynamics in the galactic nucleus? (Debuhr +2010)
2. Only spheroidal bulges follow a M_{BH}-σ relation or also pseudobulges?
3. Does the BH accretion history follow the cosmic SFH?
4. What is the impact of the so called radio-



Prospects for the Future

Will detect faint and radio loud AGN* → cosmic evolution of radio AGN activity to the cosmic dawn (z & 6), covering all environmental densities

(see HR4 by S. García-Burillo & A. Alsonso)



Adapted from Bonzini+2013

* down to a 1 GHz radio luminosity of about $2\ 10^{23}$ W/Hz at z = 6

Multi-frequency studies of the future

SKA (thermal and non-thermal components)

- Large area with µJy sensitivty → (combined with other bands) potential to obtain the SF free of extinction up to very high redshifts
- Cosmic magnetism

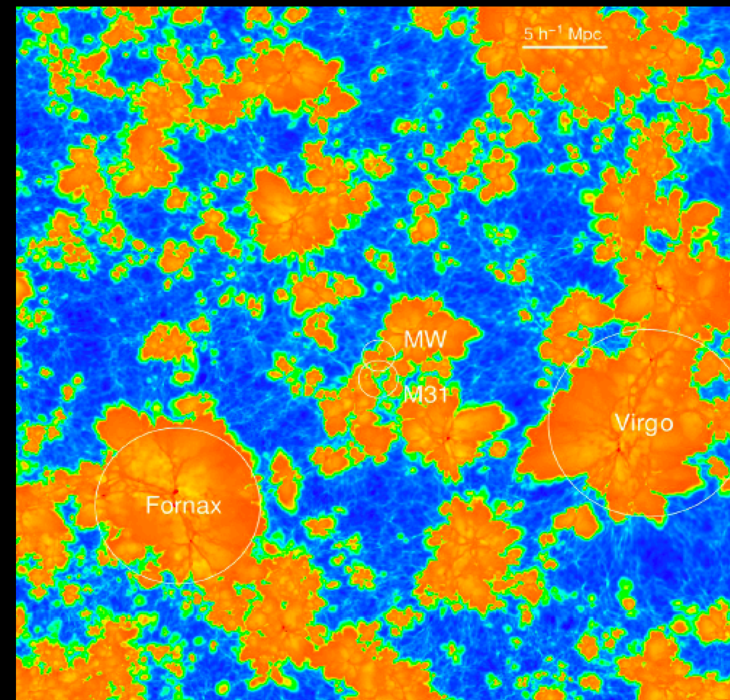
JWST: evolution of the mass density with redshift (not only SF galaxies) -- first objects

nearby galaxies: SKA will be able to resolve individual HII, SSCs,SNR, and PNe
→ extintion free SF / high-mass end of the IMF (complementary to ALMA)
HST+MUSE+ALMA+SKA+.... advances expected..

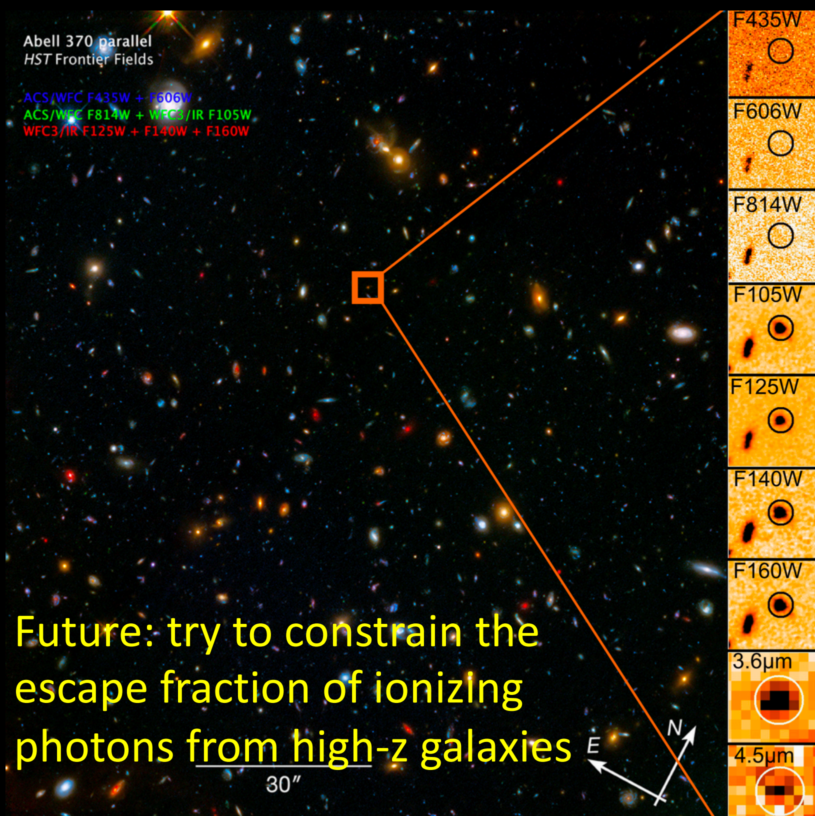
AGNs: SKA will provide a complete census of the evolution of AGN with redshifts
ALMA/SKA direct imaging of galaxy tory, outflows (S. Burillo & A. Alonso's talk)

How did reionization occur?

Computation: First Radiation-Hydrodynamics Simulation of Reionization in the Local Universe -> Reionization proceeds in patches around galaxies, it is not uniform



Ocvirk+15



Future: try to constrain the escape fraction of ionizing photons from high-z galaxies

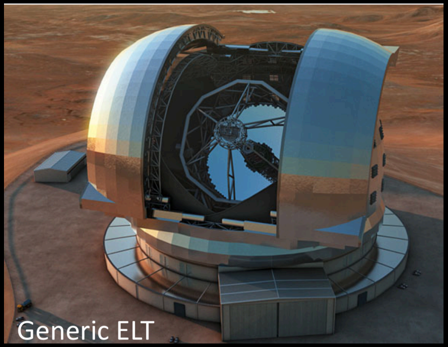
Observations: Discovery of $z=6.8$ galaxy with large escape fractions, entirely responsible for its local ionised bubble-> scenario with few bright galaxies are causing reionization, rather than lots of smaller ones

Meyer+20 sub to MNRAS

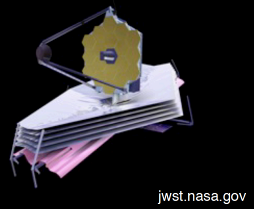
Conclusions

The modern theory of cosmological galaxy formation is a synthesis of many physical ideas involving an array of operative physics

A transformative decade ahead of us

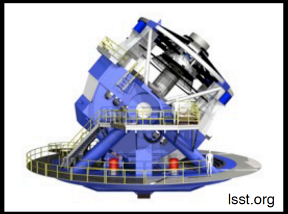


20-40m Ground-Based Telescopes



6m Space-Borne IR Telescopes

Large-Scale Radio Arrays



8m Telescope All-Sky Synoptic Surveys