Panel B/Chapter 3

How do galaxies form and evolve?

- **Science Questions**
- **Recommendations**
- **Input from the Community**

Science Questions

- **How did the Universe emerge from its dark ages?**
- **How did the structure of the cosmic web evolve?**
- **Where are most of the metals throughout cosmic time?**
- **How were galaxies assembled?**
- **How did the Milky Way form?**

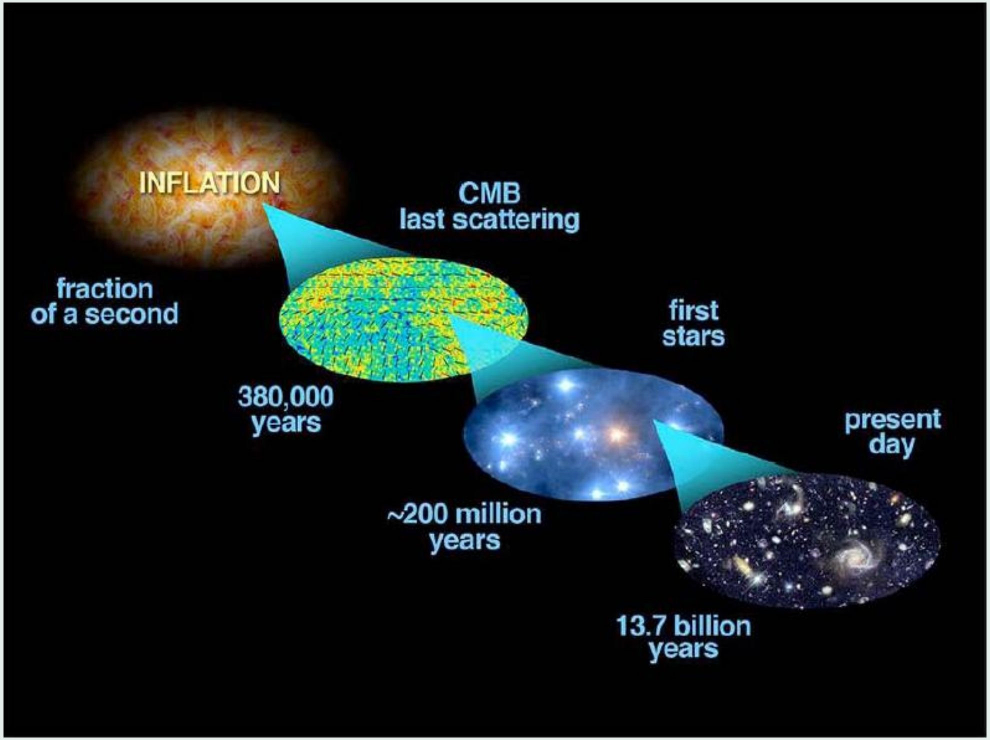
J. Bergeron, R. Kennicutt, X. Barcons, F. Bertoldi, A. Ferrara, M. Franx, A. Helmi, G. Kauffmann, I. Smail, M. Steinmetz

Panel B
ASTRONET

Dark ages

- Onset of re-ionization
  - $\mathbf{t(z{\sim}11?){=}0.41\ Gyr}$
- Galaxy of highest z
  - $\mathbf{t(z{=}7){=}0.75\ Gyr}$
- End of re-ionization
  - $\mathbf{t(z{\sim}6){=}0.91\ Gyr}$

$\Omega_\Lambda, \Omega_{\rm m}, h =$0.7, 0.3, 70



How did the Universe emerge from its dark ages?

- **Growth of matter density fluctuations : H I mapping**
  - Probing the Dark Ages $z \gg z_{\rm reion}$ $T_s = T_k < T_{\rm CMB}$
    $\longrightarrow$ absorption signature at $\nu < 30$ MHz $(z \sim 50)$
    $\longrightarrow$ erased/modified by annihilating/decaying DM radiation

- **First stars**
  - transition from top-heavy IMF to a 'Salpeter' IMF?
    $\longrightarrow$ critical metallicity : $Z \sim 10^{-4}\ Z_{\odot}$?
  - connection to metal-poor halo stars
  - GRBs and pair-instability pop III SNe : detection of transient sources
  - formation of intermediate mass BHs
  - early metal pollution of the IGM : observation of bright background targets
  - improving current models : environment, self-propagation, rotation, convection ...

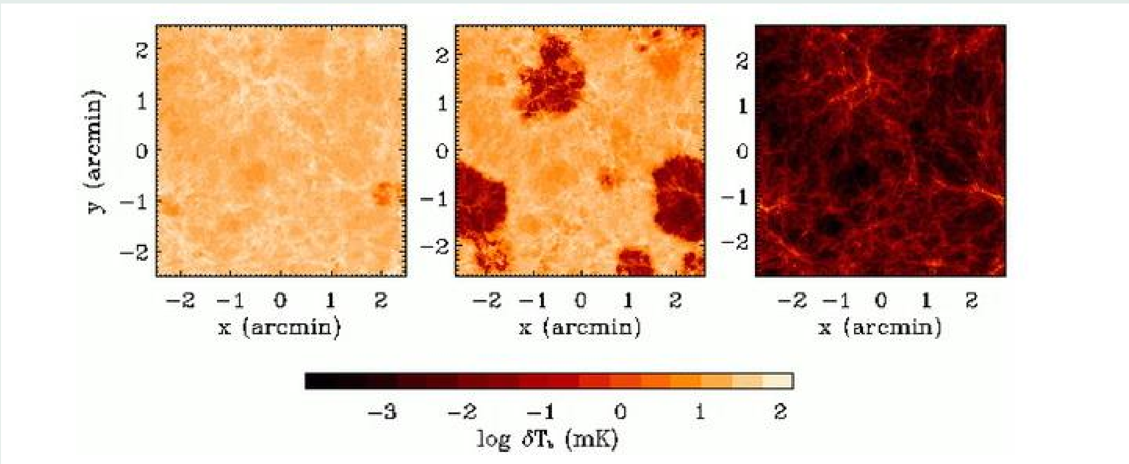
- **Cosmic re-ionization**
  - Onset of re-ionization ? CMB polarisation
  - dominant sources for re-ionization : stars, AGNs, decaying supersymmetric particules?
  - How long did it take?
  - patchy re-ionization (arcmin scales) : maps of H I 21 cm brigthness fluctuations
CMB secondary anisotropies
  - first seed of galaxies
  - simulations : large volume
feedback processes (radiative, chemical, mechanical, magnetic)
predictions (nb cts, LF, SN & GRB burst rates)

- **First Black-holes and their evolution**
  - SDSS $z \sim 6$ QSOs (very rare objects) : $M_{\rm BH} \gtrsim 10^6 M_\odot$ at $z \sim 10$
  - BH growth : accretion, merging, tidal capture of stars
  - strong X-ray emitters, production of gravitational waves
  - close environment : metal-rich and dusty?

H I 21 cm brightness fluctuations

- Maps of 21 cm brightness temperature (5×5 arcmin^2) at $z = 12.1$, 9.2 and 7.6 (left to right) with a width $10h^{-1}$ comoving Mpc and depth $\Delta\nu = 0.1$ MHz
  assuming a late, single epoch of reionization and $T_S \gg T_{CMB}$
  HII regions have negative brightness temperatures relative to ⟨H I signal⟩

  → information on the the sources responsible for reionization



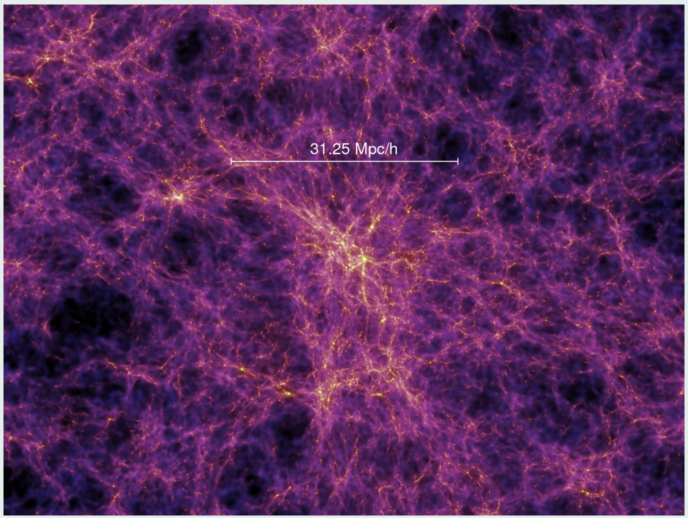
How did the structure of the cosmic web evolve?

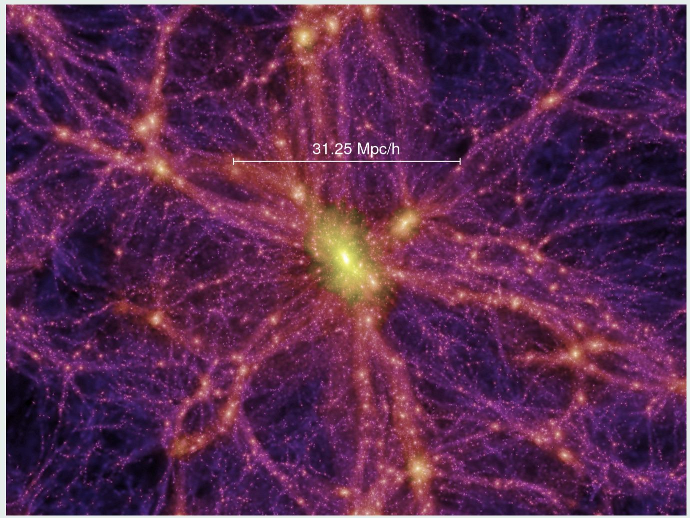
- **Clusters and groups of galaxies**
  - cluster DM mass function?
    $\longrightarrow$ cosmic shear - very deep large area surveys
  - ICM/dominant baryonic component : X-ray emission - all sky survey
    $\longrightarrow$ metallicity at high z? at $z \lesssim 1$: Z $\sim$1/3 $Z_\odot$
    $\longrightarrow$ kinematics
  - galaxy populations : deep, large area (all sky) optical, near-IR multi-colour surveys
  - magnetic field : diffuse synchroton emission
    radio spectropolarimetry (Faraday rotation of radio sources)
  - rare high z massive clusters : spectral distortion of CMB by hot electrons (SZ effect)
    coupled to optical/near-IR & X-ray surveys
    $\longrightarrow$ constraints on Ω_m, Ω_Λ & DE equation of state vs cosmic time
  - simulations vs observations

Millennium simulations

Largest simulations (10^{10} DM particules) carried out to date, used to construct complex semi-analytical models of galaxy and structure formation.

Image of a galaxy cluster at $z = 5.7$ (left) and $z = 0$ (right)





- **Cluster progenitors**
  - environment of high z, rare luminous objects : QSOs
radio and starburst galaxies
  - detection of hot ICM gas : SZ effect
diffuse X-ray emission
  - high z galaxy overdensities

- **Lower density environments**
  - topology of the DM density field & kinematics of the IGM
$\longrightarrow$ 3D mapping of Ly-α absorbers at $z \sim 3$
  - magnetised IGM : Faraday RMs of large samples of distant sources
$\longrightarrow$ seed field for galaxies and clusters?
  - intergalactic shocks : low ν synchrotron emission (large angular-scale fluctuations)
$\longrightarrow$ could trace the low z warm-hot IGM

Where are the metals throughout cosmic time?

- **Metal enrichment on large scales**
  - stellar winds and SN explosions
  - enrichment of the IGM : powerful galactic outflows?

- **Re-ionization epoch**
  - highly inhomogeneous pollution of the IGM by heavy elements
  - at the end of re-ionization : $\langle \mathrm{Z} \rangle \sim \mathbf{10^{-4}}\ \mathrm{Z}_{\odot}$
  - IGM mostly in the form of neutral & singly ionized species
  - H II bubbles (around stars & IMBHs) mainly traced by C IV

  - Inventory of metals and abundances : H I (21 cm) + metal (near-IR) absorptions

    $\longrightarrow$ search for extremely rare, luminous background targets

    including transient sources

    $\longrightarrow$ evolution of L and M of the re-ionization sources

Simulated 21 cm absorption spectrum

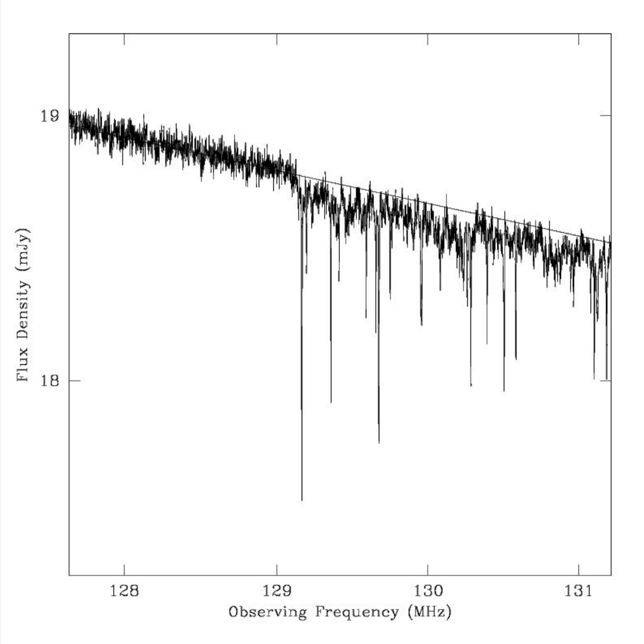
- **intervening H I absorption**

  Highly luminous z=10 source

  flux : S(120 MHz)=20 mJy

  spectral resolution : $\Delta\nu = 1$ kHz

  – very few sources
    expected at $z > 8$ & S $>$ 10 mJy :
    $\mathbf{10^{-2}}$ deg^{-2} (M$_{\mathbf{BH}} > \mathbf{10^7}$ M$_\odot$)
    GRB radio afterglows : too faint
    possibly hypernovae : flux up to 1 mJy?



- **$z \sim 3$: peak activity of galaxy and QSO formation**
  - over 95% of the baryons are in the IGM
  - only ∼50% of the produced metals are detected
  - missing metals : around SF sites or in the IGM (numerical simulations)

    ⟶ strength of galactic superwinds?

⟶ absorber-galaxy connection : 3D mapping (optical) of Ly-α & metal-rich absorbers
⟶ metallicity level in IGM underdense regions
⟶ census of metals in various types of galaxies

- **The local universe**
  - ∼90% of the baryons are still in the IGM - only half of them are detected
  - simulations : missing baryons should be in a warm-hot phase of IGM (WHIM)
  - not enough baryons detected in the warm-phase ($10^5 < T < 10^6$ K)

⟶ X-ray searches of the WHIM signatures (absorption/emission)
⟶ ∼20% of the metals could be in the WHIM

How were galaxies assembled?

- **Simulations - remaining challenges :**
  include all major 'gastrophysical' processes and feedback mechanisms

- **Gas cooling, accretion and star formation**
  - amount of cold gas content in galaxies at $z > 0.1$
    $\longrightarrow$ H I masses and cold gas accretion
    SFR vs N(H I) : validity of Kennicutt-Schmidt law at high z?
    $\longrightarrow$ molecular census - observations in the sub-mm to cm range
    importance of feedback processes : kinematics of H I/molecular/ionized gas
  - SFRs : multi-λ diagnostics
    $\longrightarrow$ dust extinction - mid- and far-IR observations
    $\longrightarrow$ radio continuum
    thermal : $L_{\rm UV}$ - synchrotron : $L_{\rm synchrotron}$ vs $L_{\rm far-IR}$
  - magnetic field structure
    $\longrightarrow$ Faraday RMs - magnetic field amplification

- **High z galaxies : internal physics and dynamical evolution**
  - are they in equilibrium state? importance of merging?
    $\longrightarrow$ kinematics : stellar masses (total, bulge), signature of galactic winds-feedbacks
  - spatial distribution of stars, metals and dust
    $\longrightarrow$ IFU spectroscopy at high spatial resolution

- **Star formation & metal enrichment vs galaxy assembly**
  - colour-magnitude diagrams
    $\longrightarrow$ goal : reaching the Virgo cluster ('normal Ellipticals')
    depth and highest spatial resolution
  - kinematics and chemical abundances
    $\longrightarrow$ **assembly of the Hubble sequence**

- **Key physical processes**
  - disantangle evolutionary effects due to age, mass, morphology, environment
    $\longrightarrow$ spectroscopy of very large samples (10^4-10^5) of galaxies up to $z \sim$2-3

Massive, young galaxy at $z = 2.2$

- The Spider galaxy
  and its many satelitte galaxies
  - $\mathbf{t(z{=}2.2){=}2.9\ Gyr}$

How did our galaxy form?

- **Assembly and chemical history : stellar census of our Galaxy**
  - are there zero-metallicity stars?
  - what is the typical mass of the 'first' stars?
  - when did the transition to the present-day IMF take place?

  $\longrightarrow$ stellar LF, IMF

  survey of positions, distances and motions of several 10^9 stars

- **Nature and distribution of DM**
  - total mass and density profile of our Galaxy
  - mass and shape of the DM halo : tidal streams
  - Galactic satellites : total mass and DM density profile

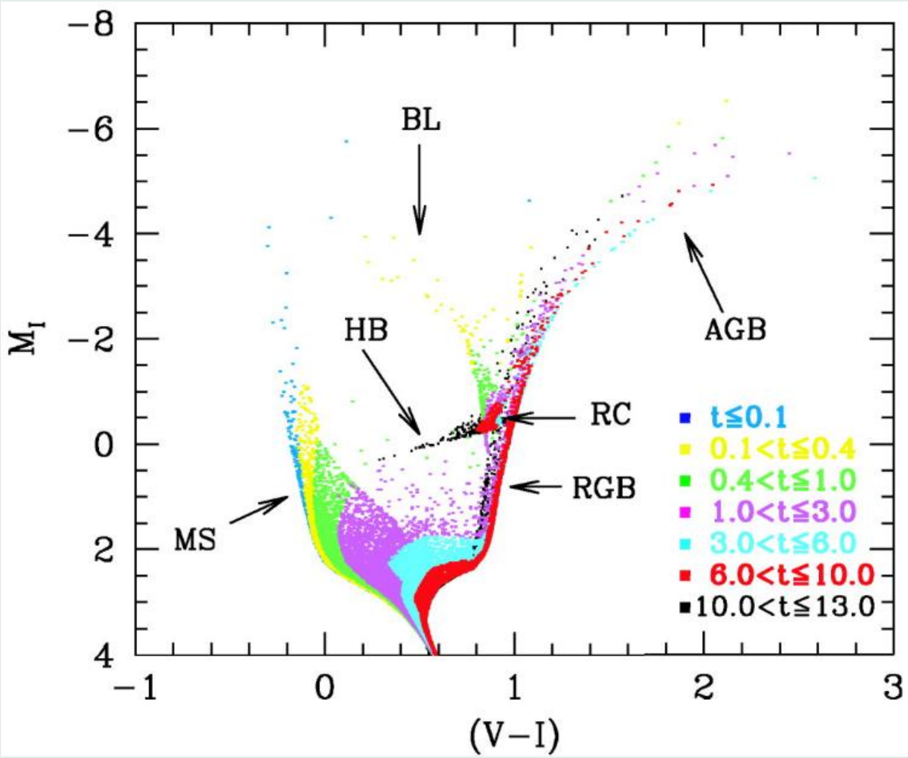
  $\longrightarrow$ radial velocities and chemical abundances of faint stars

  multi-object spectroscopic surveys

  next generation dynamical models

Synthetic Colour-Magnitude Diagram

- constant SFR
- metallicity $Z/Z_\odot$ linear $\nearrow$ from 0.0001 to 0.02 in Δt bin in Gyr



Recommendations

General

- **Large collecting-area facilities (space- and ground-based)**
  - major contribution to most science questions
    λ range from low-ν radio to gamma-ray
- **Key role of theoretical work**
  - enhanced numerical simulations of structure and galaxy formation
    large cosmic volumes, detailed physical processes & feedback mechanisms
  - models of first star and IMBH formation
  - dynamical model of our Galaxy

Recommendations

Requirements for principal facilities/1

- There is no priority order in the list given below

- **An ELT with adaptive optics**
  - high-resolution imagers and spectrometers ($R \sim 5 \times 10^4$)
  - highly multiplexed near-IR spectrographs

    evolution of the large-scale structures over cosmic time
    internal physics of high z galaxies
    stellar populations in the local supercluster
    complement to revolutionary information that will come from JWST and Gaia

Recommendations

Requirements for principal facilities/2

- **An extremely large collecting area telescope in the cm radio domain**
  - wide dynamical and spectral ranges , such as the proposed SKA

    cosmic reionization
    formation of galaxies, stars & black holes
    formation and amplification of magnetic fields
    build on submm-cm work opened up by ALMA and LOFAR (coming decade)

- **A large-aperture X-ray space mission**
  - moderate-resolution spectroscopic capability ($R \sim 1000$)

    galaxy-IGM connection at high z
    missing baryons at low z
    BH evolution
    galaxy assembly

Recommendations

Requirements for principal facilities/3

- **A cooled 4-8 m class infrared space telescope**
  dust-obscured galaxy formation
  star formation
  BH formation and growth back to the reionization epoch
- **A 4-8 m class UV-optimized space telescope**
  - high-resolution imaging and spectroscopy
    evolution of intergalactic baryons
    exchange of matter & metals between galaxies & the IGM over cosmic time

Recommendations

Requirements for secondary facilities

- **A wide-field optical/infrared telescope**
  constrain DM and DE
- **A next-generation gamma-ray mission**
  such as the Advanced Compton Telescope (ACT) space mission concept
- **A space-based gravitational wave mission**
  such as the Laser Interferometer Space Antenna (LISA)

- **Longer term : A far-infrared space interferometer**
  dust-obscured and shock-heated regions
  groundbreaking observations of H_2 molecules at high z
  ideal complement to ALMA

Input from the community

- **R. Beck (oral presentation during the discussion sessions)**
  - importance of magnetic fields

    added in panel B presentation (and the Science Vision report)

    Milky Way section still to be updated
  - Effelsberg 100m will be added together with the GBT (cosmic web sub-section)

- **T. Krichbaum**
  - highest angular resolution (BLBI technique) for compact HII regions, pulsars, BHs and SNe

    combining cm-VLBI with SKA, mm-VLBI with ALMA will be added in the report

- **D. Baade**
  - spectropolarimetry

    will be added in the report, in particular for obscured AGNs and SNe