Galaxy, SMBH formation
(including Reionization)
「銀河・ブラックホール形成（再電離を含む）」

Ken NAGAMINE
(Osaka / K-IPMU / UNLV)

NAOJ Future Symposium
国立天文台将来シンポジウム：〜波長を超えて将来計画を考える〜

◆銀河・巨大ブラックホール形成（再電離を含む）

○ レビュア：

コミュニティ	プロジェクト
光赤天連	JASMINE
	TMT (MICHIを含む)
	HabEx
	GREX-PLUS
	LAPYUTA
	ELT特推
	（せいめい望遠鏡）
	ULTIMATE-Subaru
	ULTIMATE-START, TMT-AGE
	Roman
	(PRIMEx)
	LUVOIR
	CIBER-2/CIBER-MIR
	IPST/IPST Pathfinder
	Transformer
宇電懇	Square Kilometre Array Phase 1 (SKA1)
	南極テラヘルツ望遠鏡（ATT10）
	大型サブミリ波望遠鏡 (LST)
	ngVLA
	ALMA2
CRC	KAGRA
	B-DECIGO
	LISA
V懇	East Asian VLBI Network (EAVN) (+Japanese VLBI Netwo
高宇連	XRISM
	ATHENA
	FORCE
	HiZ-GUNDAM
	SuperDIOS

Task:

「サイエンス軸の発展において、何が大きな課題で、どんなアプローチが考えられるのか？」

What are the big scientific issues?

How can we approach them?

“Beyond the wavelengths”

US National Academies Decadal Survey 2020

Pathways to Discovery in Astronomy and Astrophysics for the 2020s

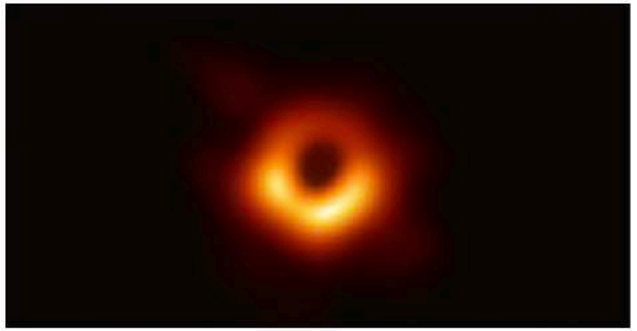
What are the key scientific challenges for astronomy and astrophysics in the next decade? *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, the National Academies' latest decadal survey, identifies the most compelling science goals and presents an ambitious program of ground- and space-based activities for future investment. The report recommends critical near-term actions to support the foundations of the profession as well as the technologies and tools needed to carry out the science.

Three Priority Science Themes

https://nap.edu/resource/26141/interactive/

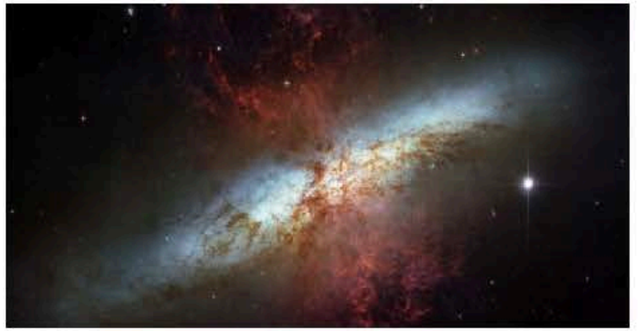
Worlds and Suns in Context

Priority Area: Pathways to Habitable Worlds



New Messengers and New Physics

Priority Area: New Windows on the Dynamic Universe

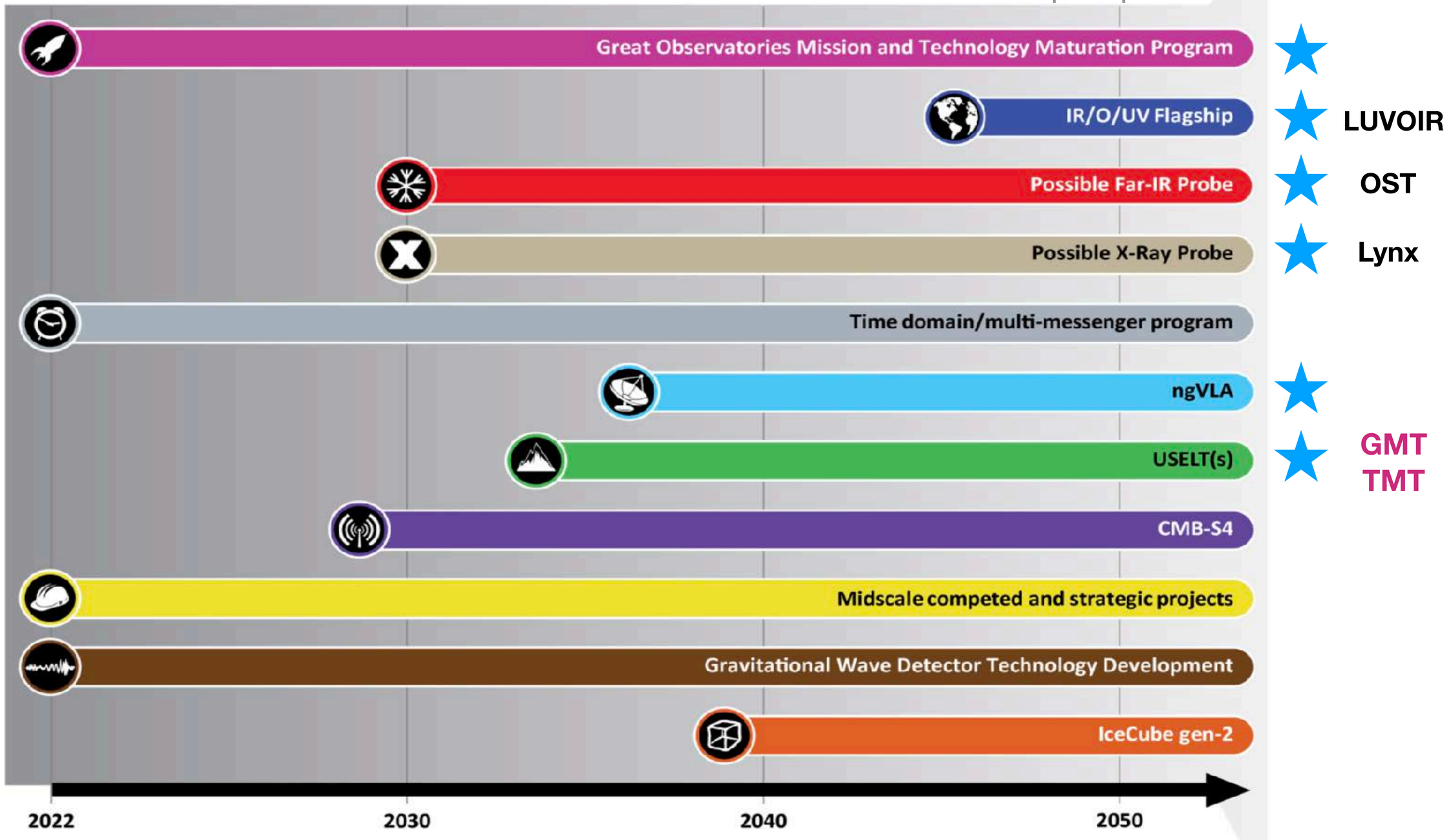


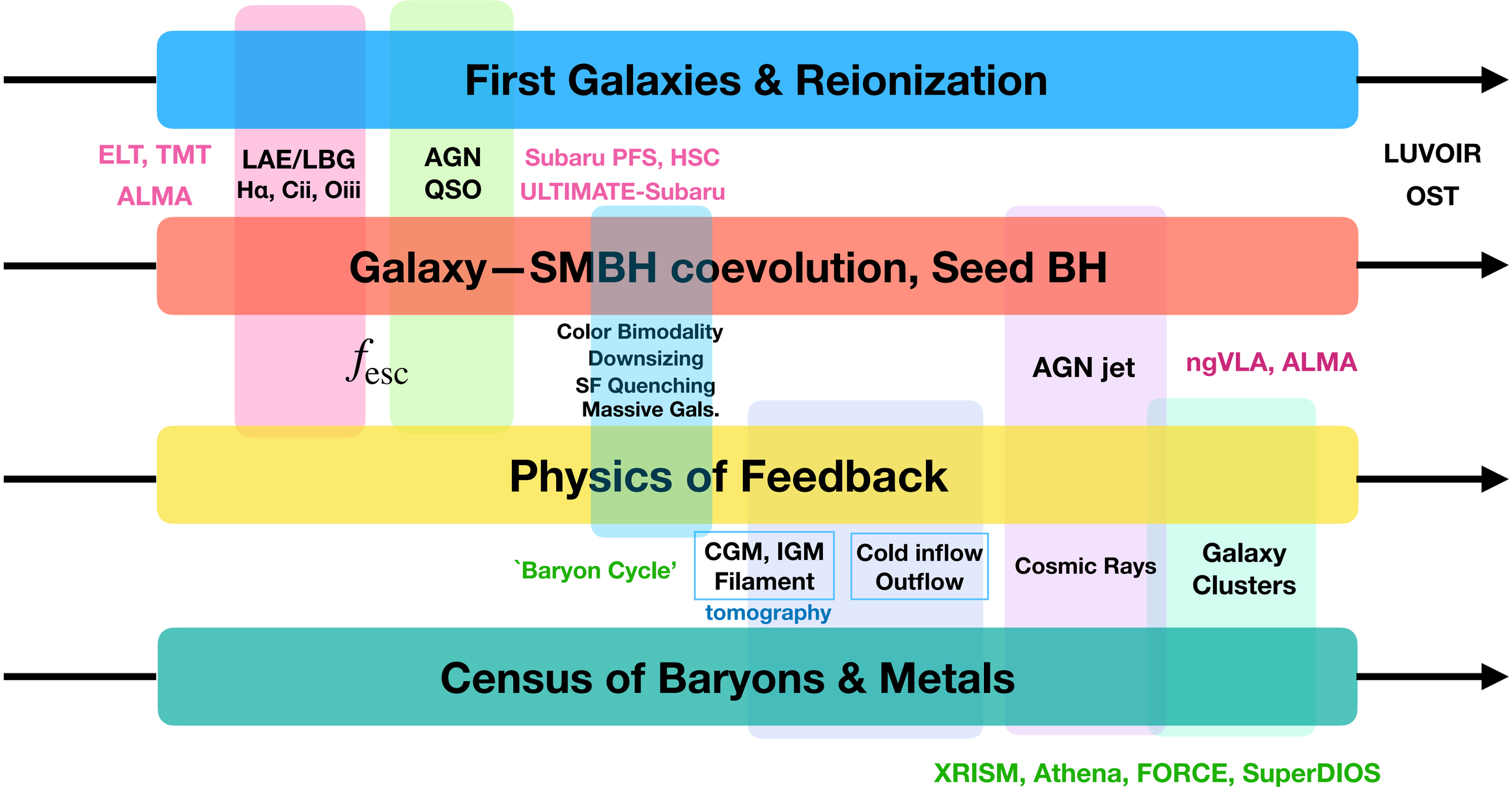
Cosmic Ecosystems

Priority Area: Unveiling the Drivers of Galaxy Growth

US Decadal Survey 2020 — timeline for medium & large programs

https://nap.edu/resource/26141/interactive/




First Galaxies & Reionization
ELT, TMT
ALMA
LAE/LBG
Hα, Cii, Oiii
AGN
QSO
Subaru PFS, HSC
ULTIMATE-Subaru
LUVOIR
OST
Galaxy—SMBH coevolution, Seed BH
$f_{\rm esc}$
Color Bimodality
Downsizing
SF Quenching
Massive Gals.
AGN jet
ngVLA, ALMA
Physics of Feedback
`Baryon Cycle'
CGM, IGM
Filament
tomography
Cold inflow
Outflow
Cosmic Rays
Galaxy
Clusters
Census of Baryons & Metals
XRISM, Athena, FORCE, SuperDIOS

When did the first galaxies & BH form?

When was $M-\sigma$ relation established?

How did galaxies acquire gas & eject metals?

First Galaxies & Reionization

When did the first galaxies & BH form?

Reionization Epoch

Big Bang

Later Univ.

1 Gyr

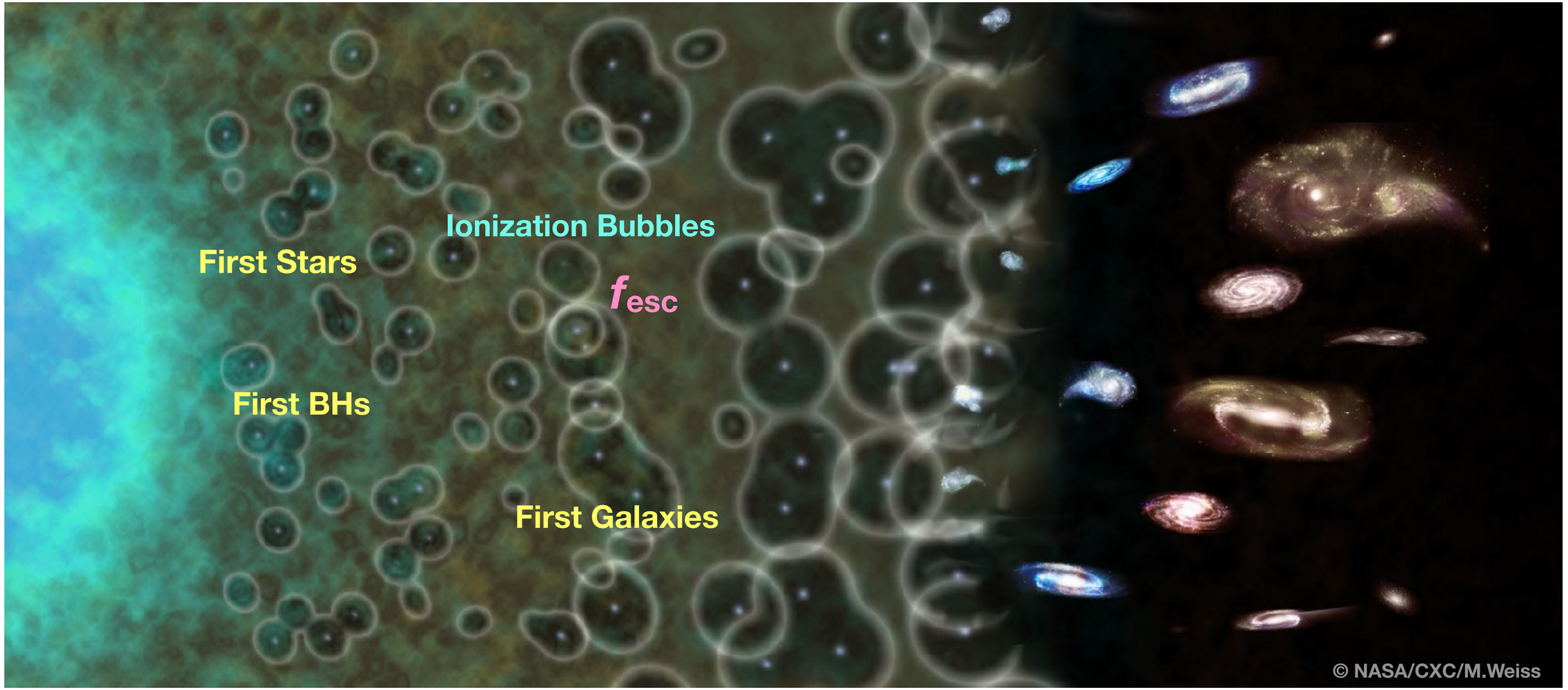
2 Gyr

z=20-30

z=15

z=6

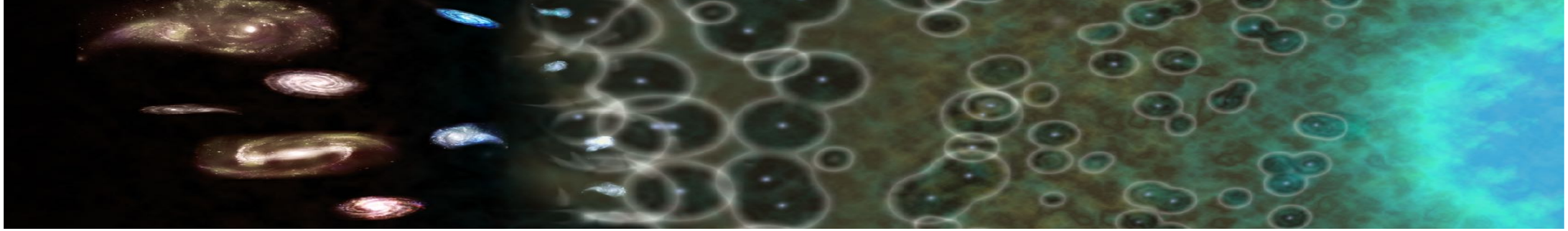
z=5



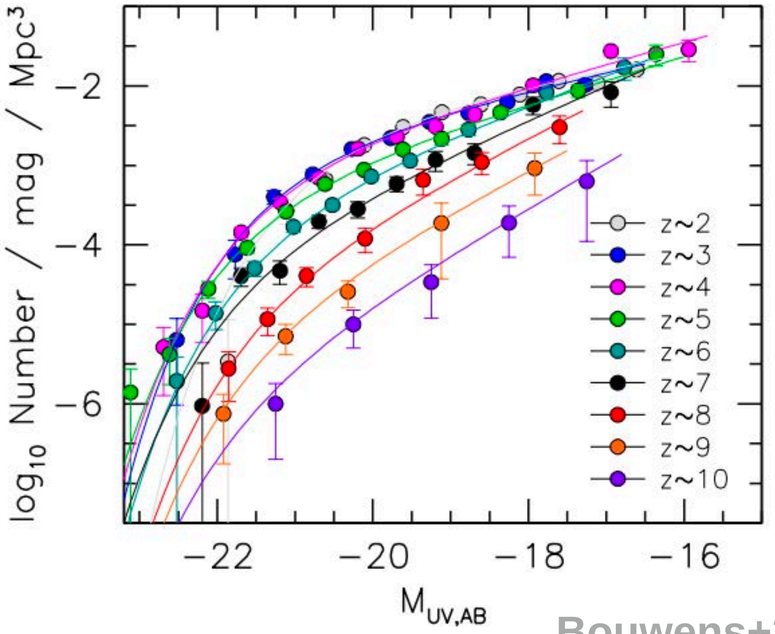
Percolation

End of Reionization

"non-uniform & anisotropic"

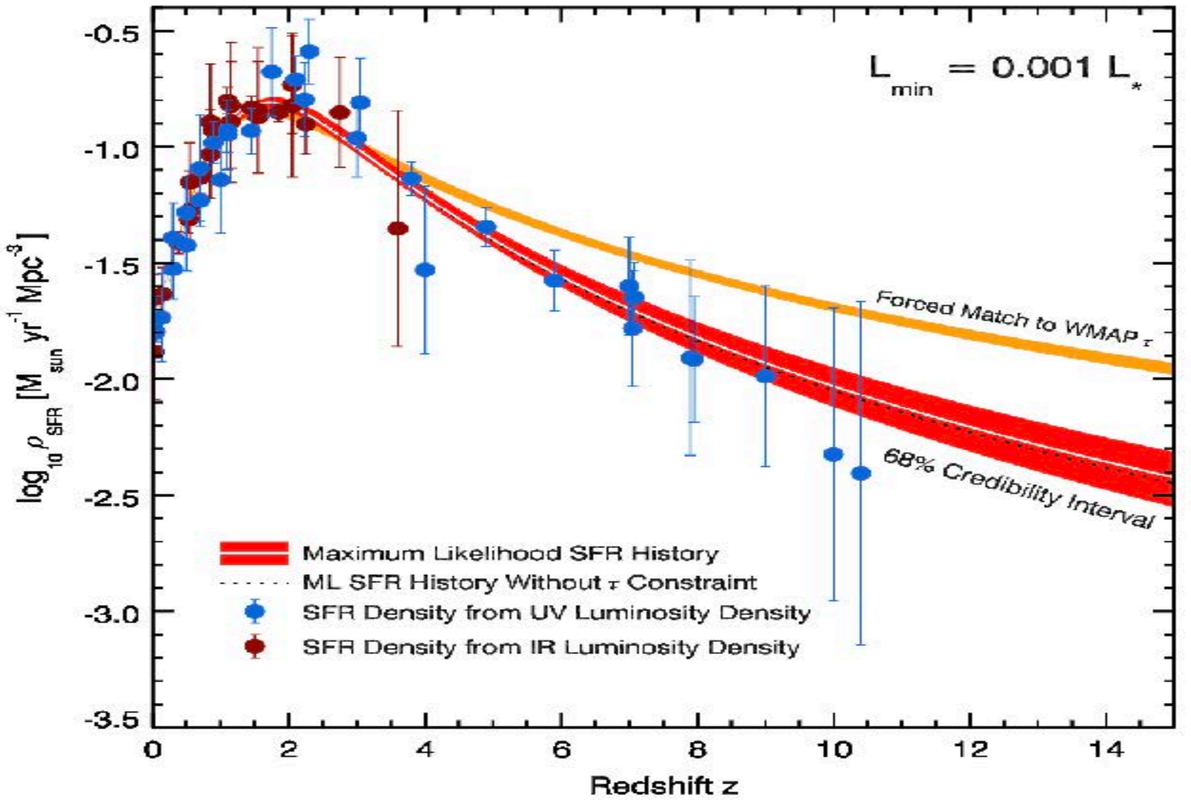


rest-frame UV LF



Bouwens+21

Subaru, HST,
ELT, TMT, GMT, …



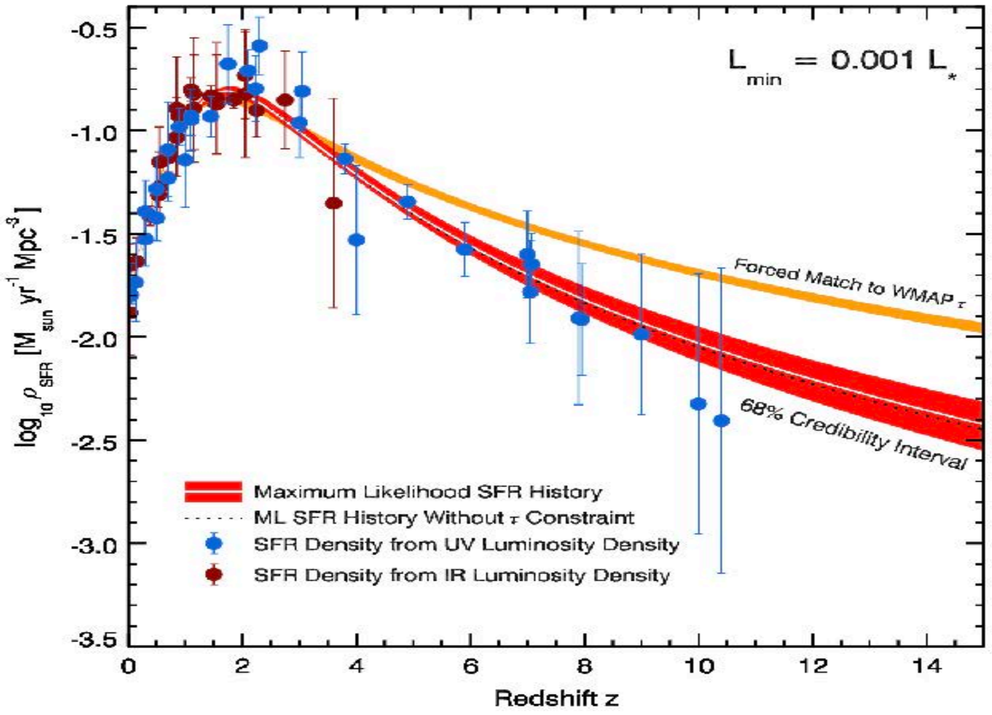
$$\rho_L \quad \rho_{\rm SFR}(z) = a_p \frac{(1+z)^{b_p}}{1+\left[(1+z)/c_p\right]^{d_p}},$$

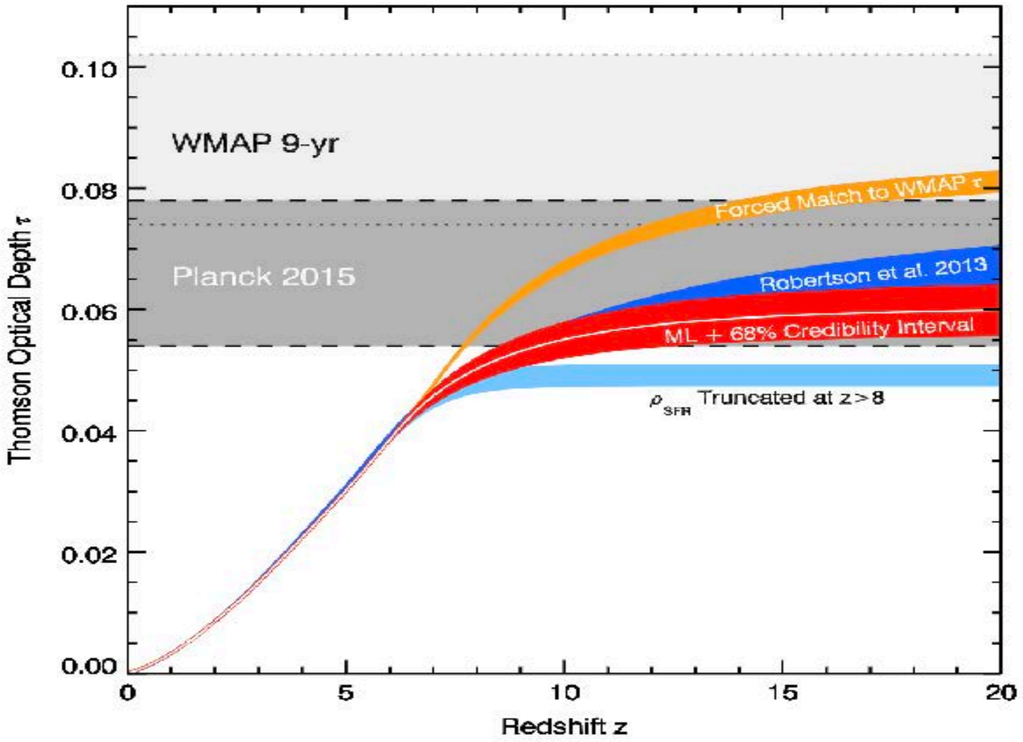
$$\dot{n}_{\rm ion} = f_{\rm esc}\,\xi_{\rm ion}\,\rho_{\rm SFR},$$

Robertson+15

$$\dot{Q}_{\mathrm{H_{II}}} = \frac{\dot{n}_{\mathrm{ion}}}{\langle n_{\mathrm{H}} \rangle} - \frac{Q_{\mathrm{H_{II}}}}{t_{\mathrm{rec}}},$$

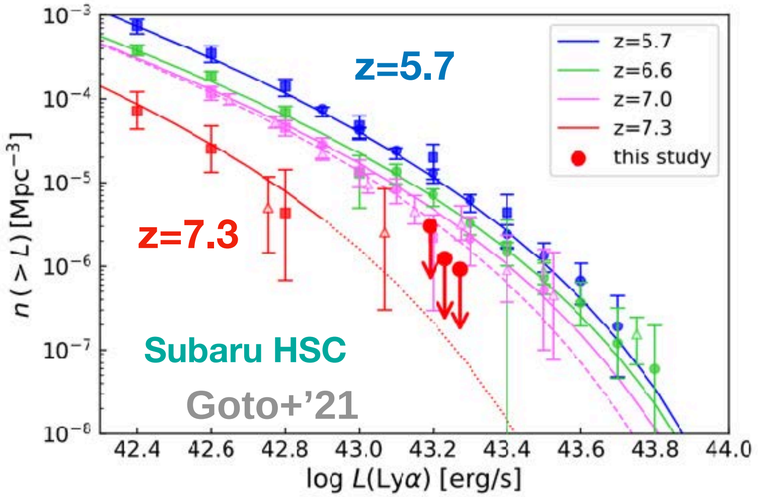
$$\tau(z) = c\,\langle n_{\mathrm{H}} \rangle\,\sigma_{\mathrm{T}} \int_0^z f_{\mathrm{e}}\,Q_{\mathrm{H_{II}}}(z')H^{-1}(z')(1+z')^2 dz',$$





Robertson+15

When did the “first galaxies” form?



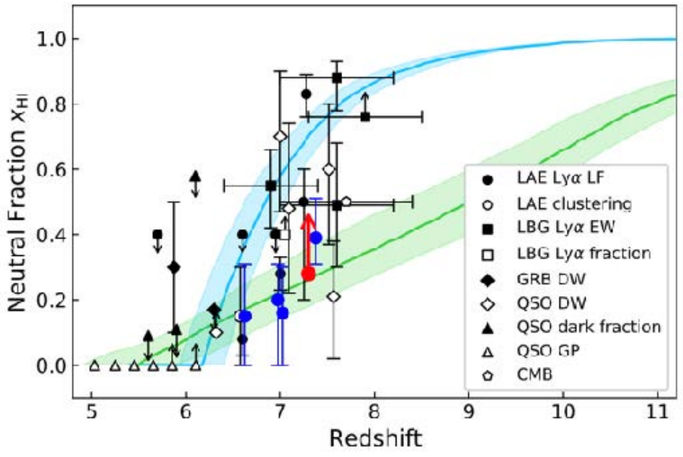
cf. Konno+14,18; Itoh+18; Hu+19

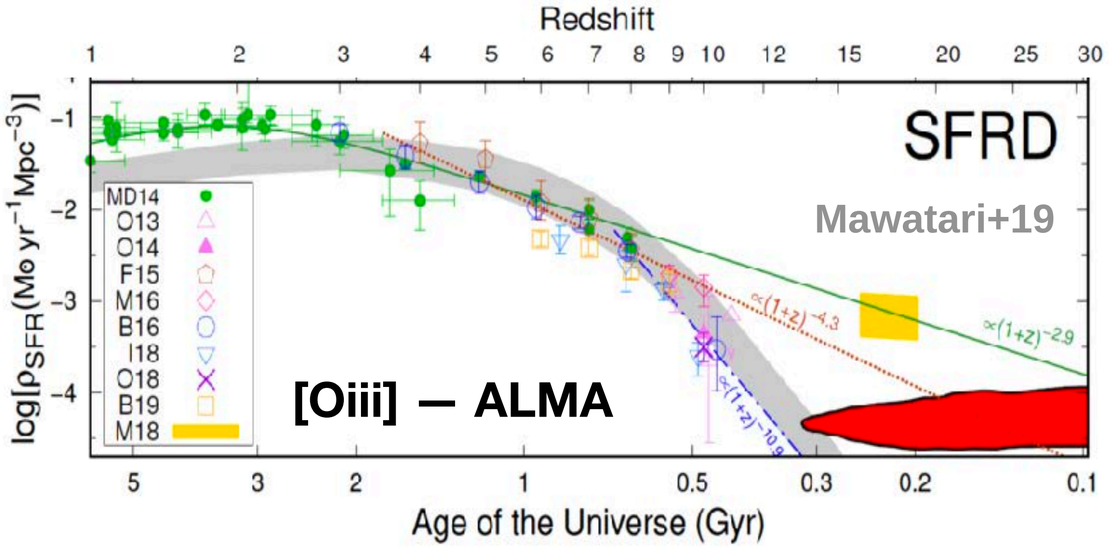
$$T_{\mathrm{Ly}\alpha}^{\mathrm{IGM}}(7.3)/T_{\mathrm{Ly}\alpha}^{\mathrm{IGM}}(5.7) < 0.77,$$

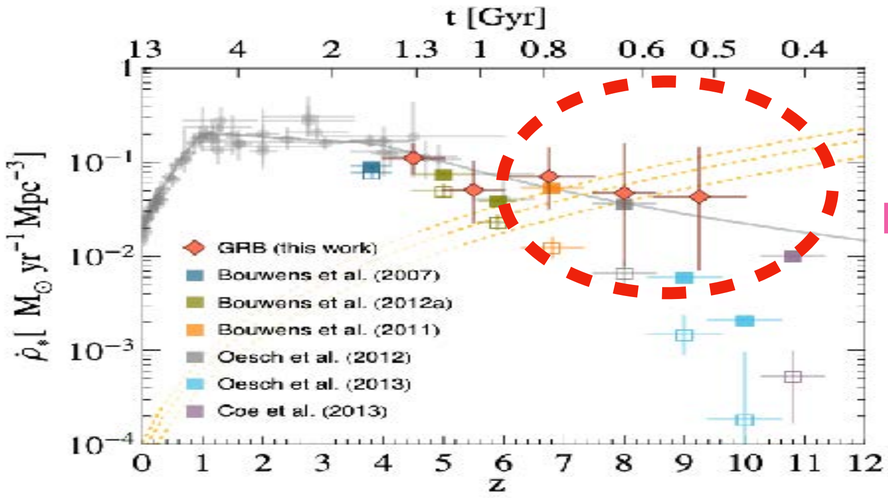
$$x_{\mathrm{HI}}(7.3) > 0.28.$$

Lya emitter — NB survey

Subaru, ELT, GMT, TMT



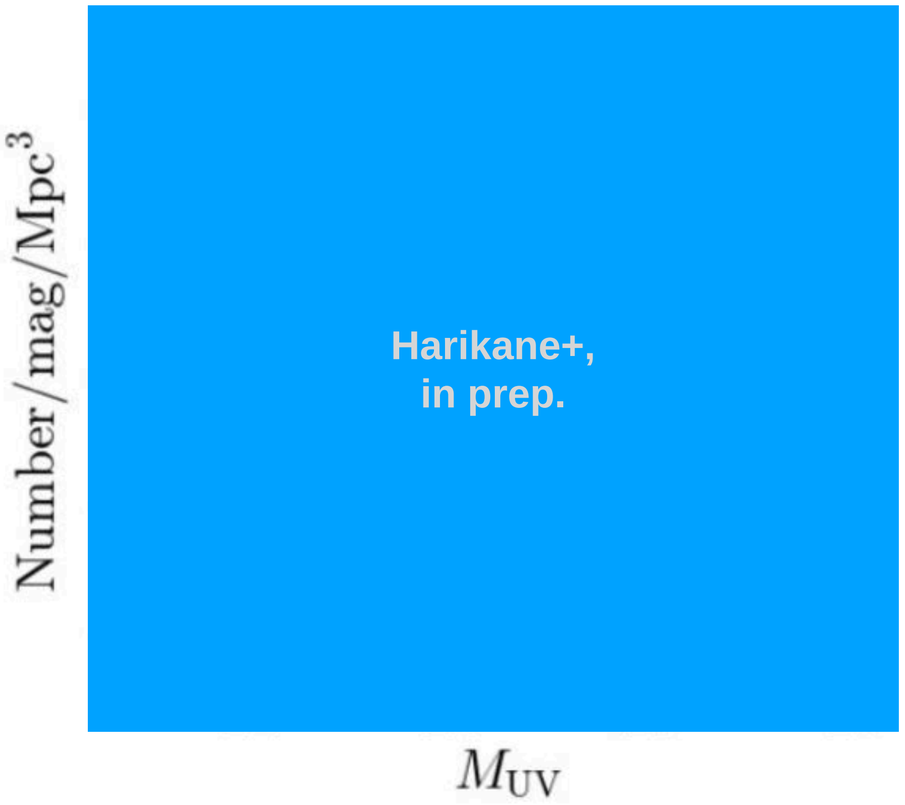


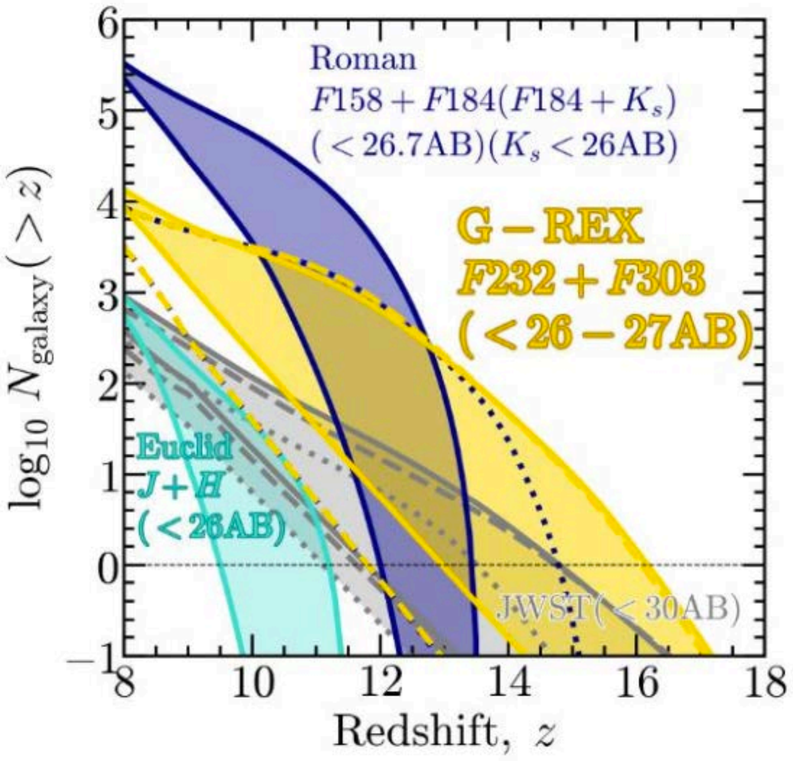


GRBs — Hi-z GUMDAM

Kistler+09,13

When did the “first galaxies” form?



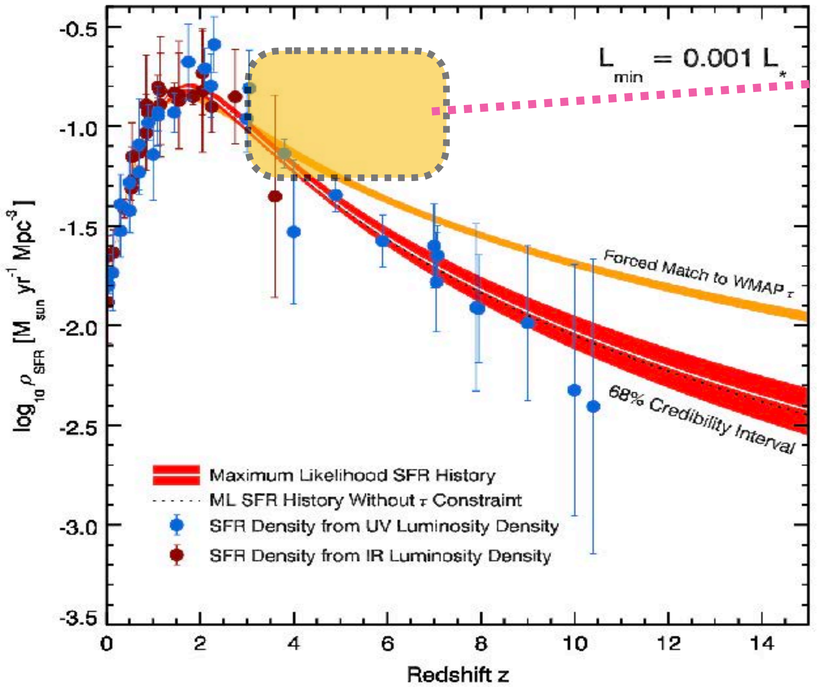


GREX-PLUS提案書

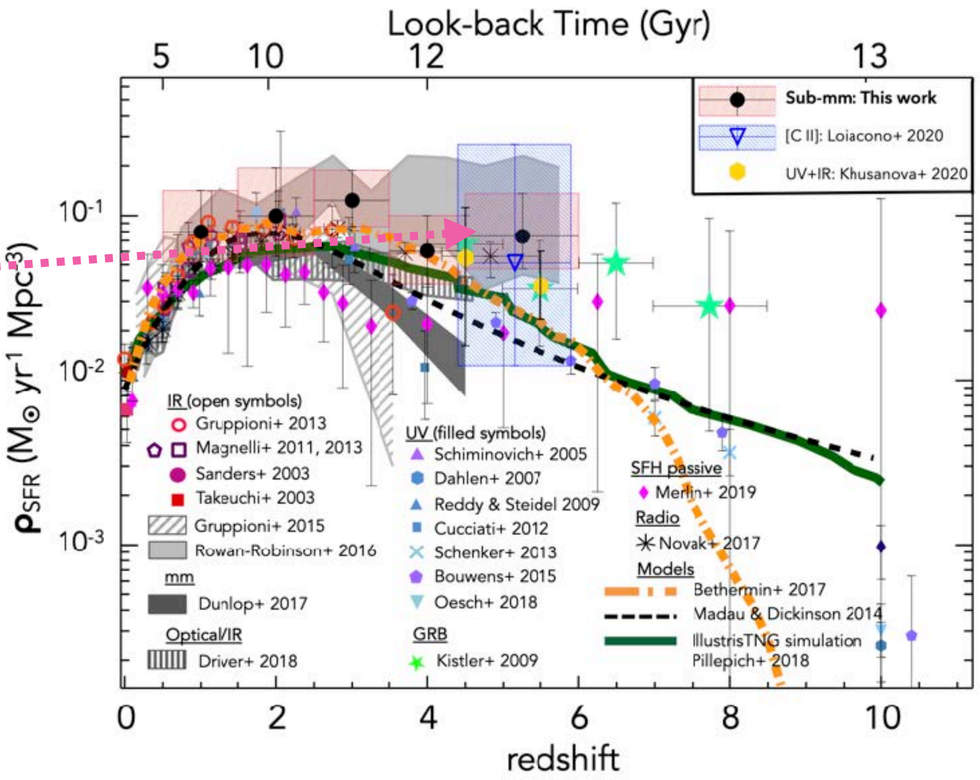
Inoue+’21

Near-IR, Submm — ALMA, JWST, ULTIMATE-Subaru, ELT, GMT, TMT, GREX-PLUS, …

Obscured Star Formation

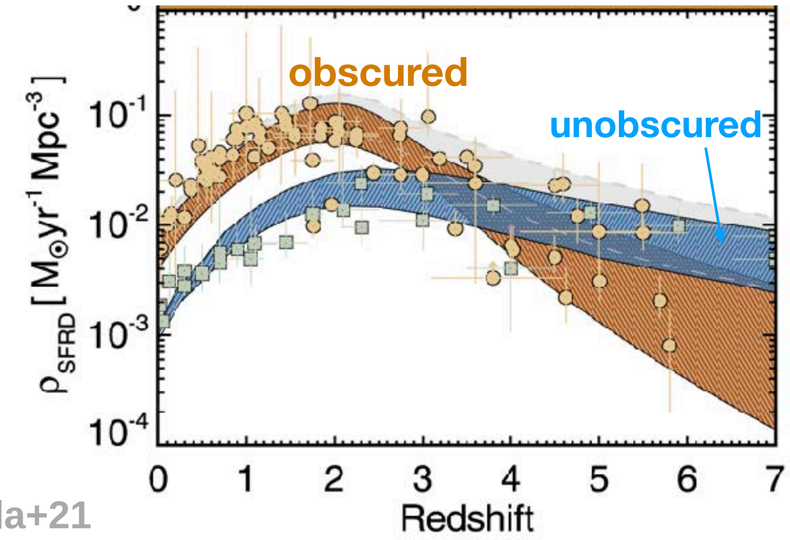


Robertson+15

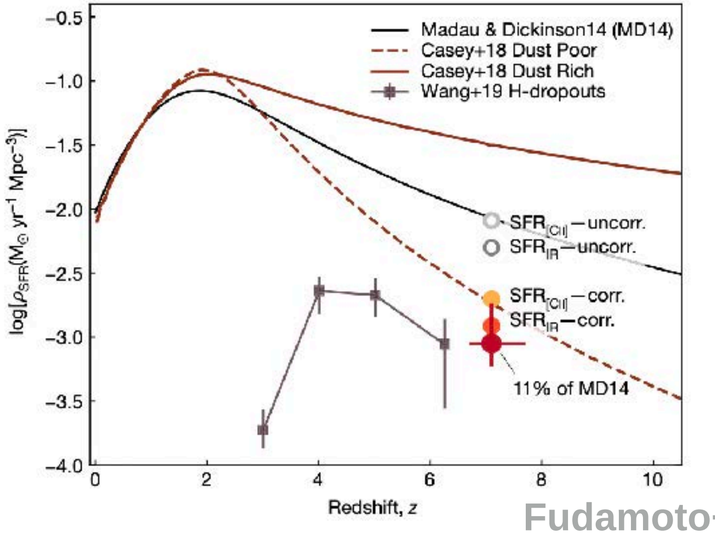


Gruppioni+20

Herschel, SCUBA
ALMA, OST



Zavala+21

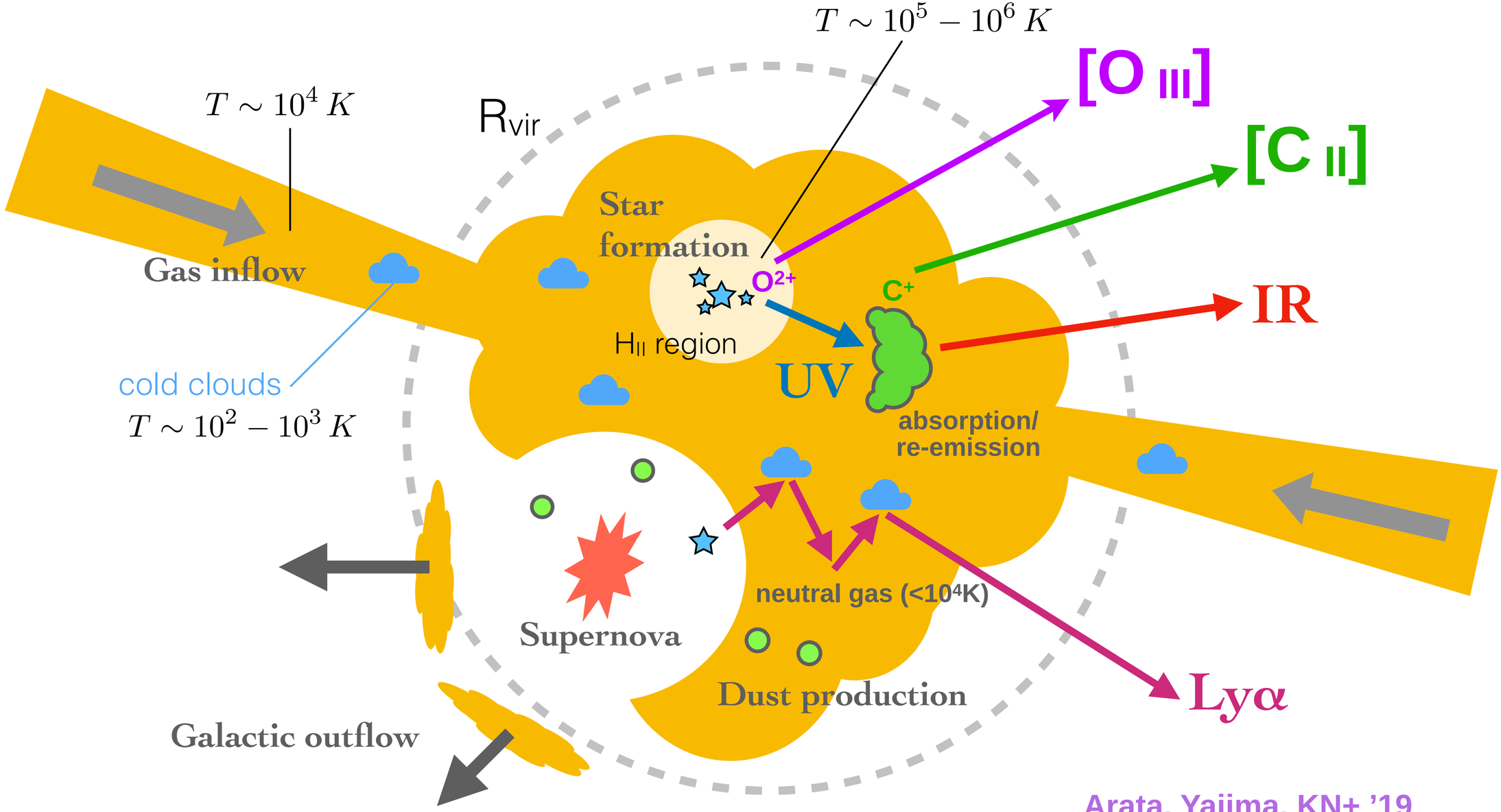


Fudamoto+21

Physical Processes in High-z Galaxies

— multiphase ISM/CGM

resol.: 120pc (JWST), 60pc (GMT), 30pc (ELT)

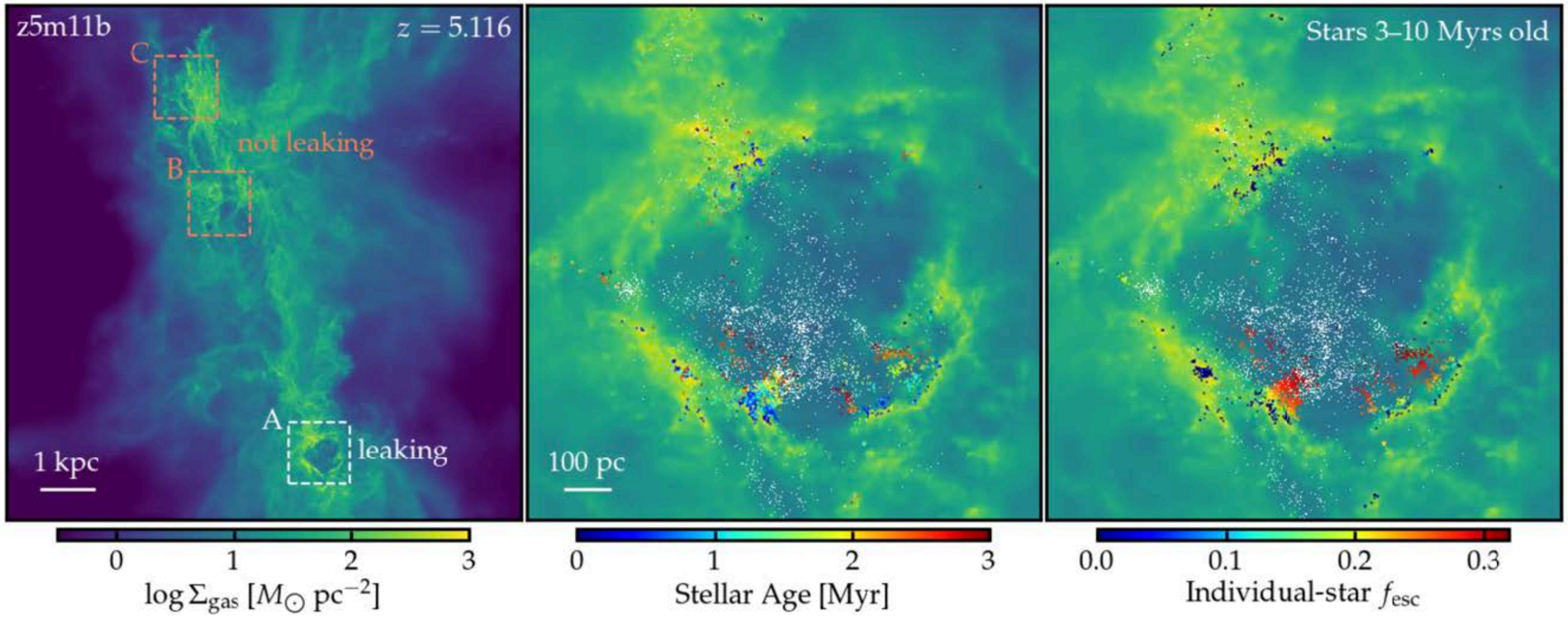


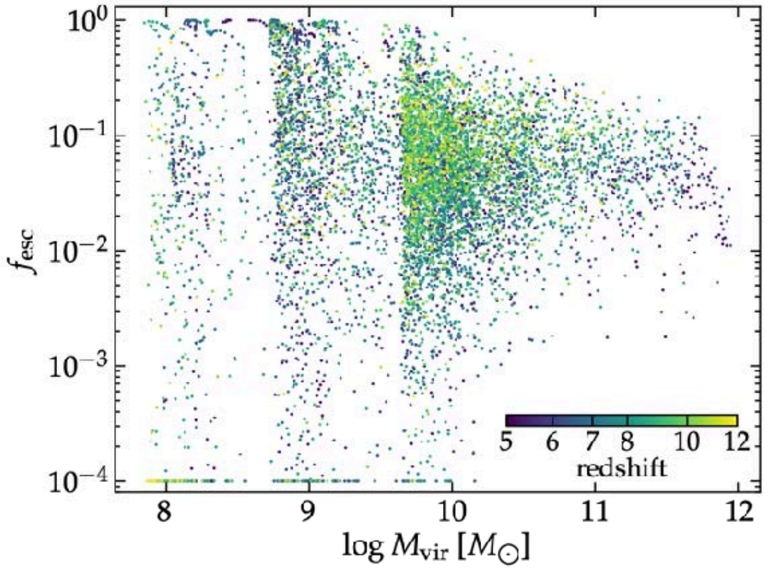
Arata, Yajima, KN+ '19

“f_{esc}”

GIZMO SPH
FIRE-2 sim

Ma+20





$M_{vir} = 3.7 \times 10^{10} M_\odot$ ($M_* = 1.5 \times 10^8 M_\odot$)

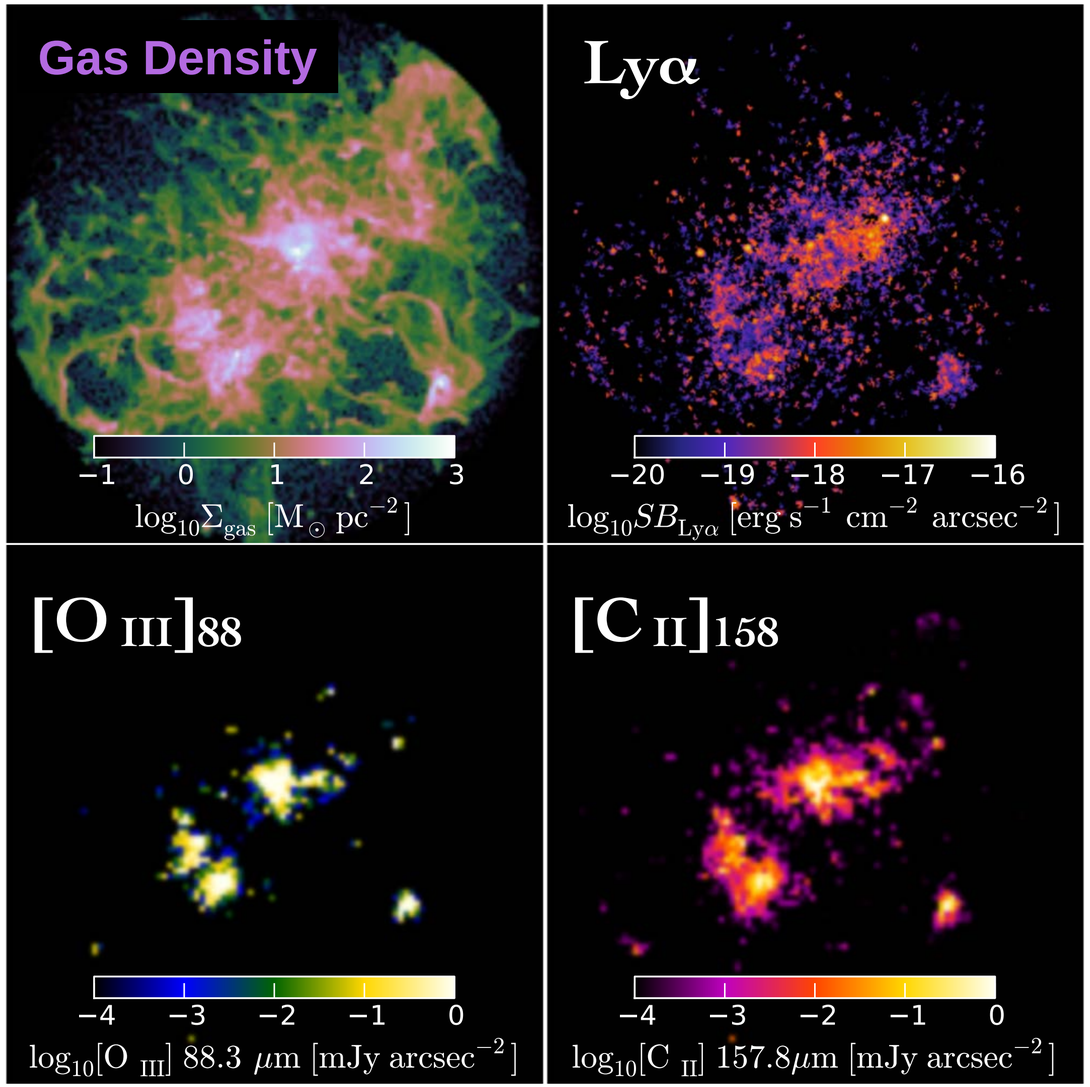
SPH mass resolution: 100, 900, 1000 $M_\odot$

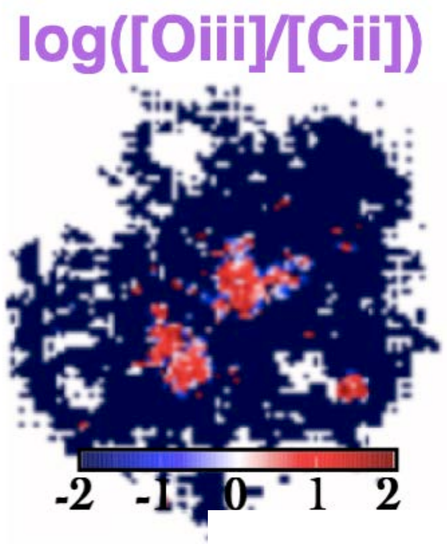
spatial resolution: ~ pc

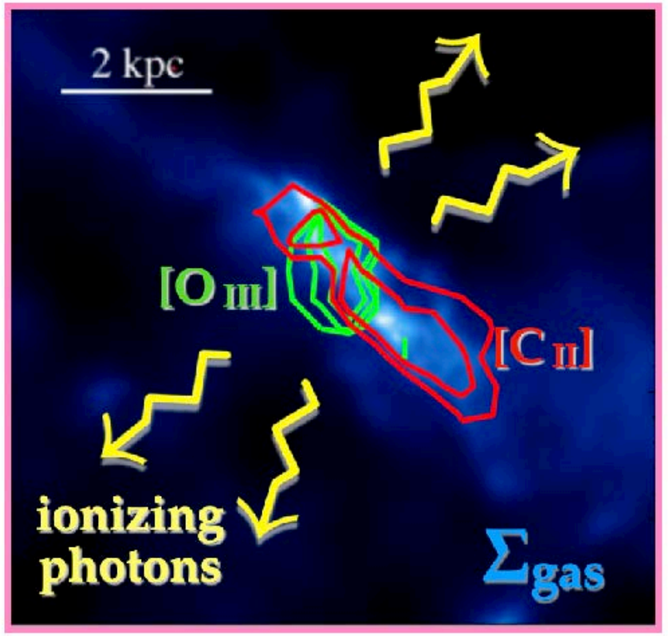
kpc-scale superbubble

$f_{esc} \sim 0.2$ **but with large spatial / temporal variations**

Intensity Maps of [Oiii], [Cii]







- Ionizing photons escape perpendicular to filament.
  - **Velocity offset of [O III] and [C II] can reveal ionizing structure.**

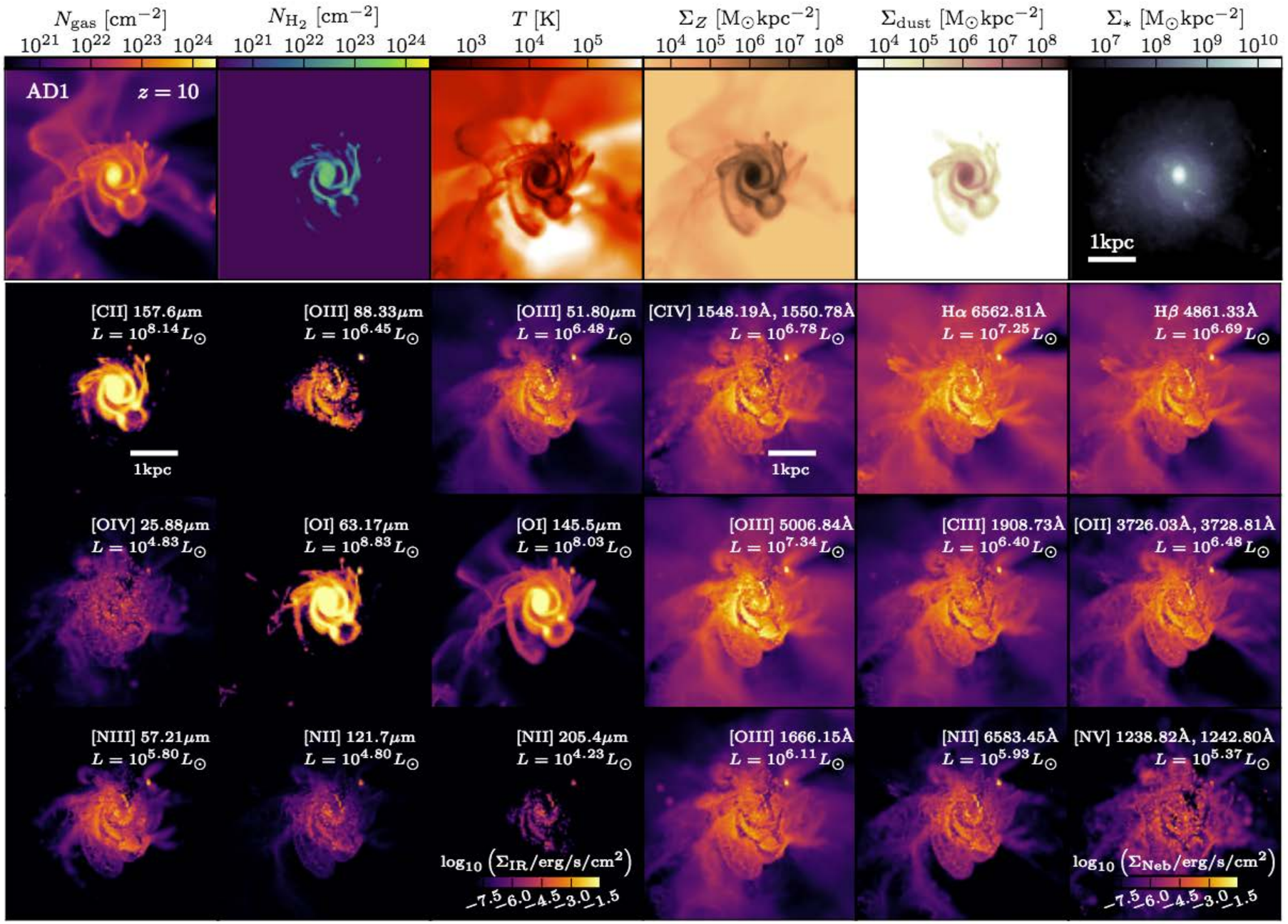
Arata, Yajima, KN+ ‘20+

cf. Vallini+15; Pallottini+14,15,17,19; Moriwaki+18; Katz+19; …

RAMSES-RT SPHINX simulation

Katz+19, 21

- enrichment by low-Z CCSN
- top-heavy IMF w. reduced [C/O]
- [O I] could be useful too.



cf. Vallini+15; Pallottini+14,15,17,19; Moriwaki+18; Arata+20 …

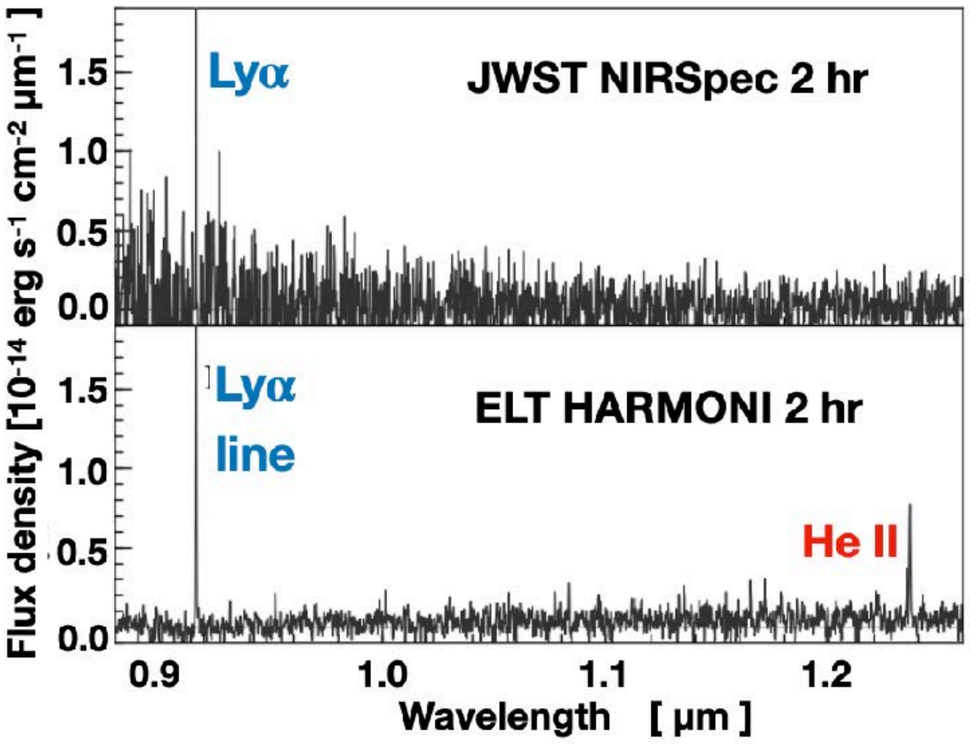
Example: time-line for ELT/TMT

Science of ELT特推 (PI: KN)

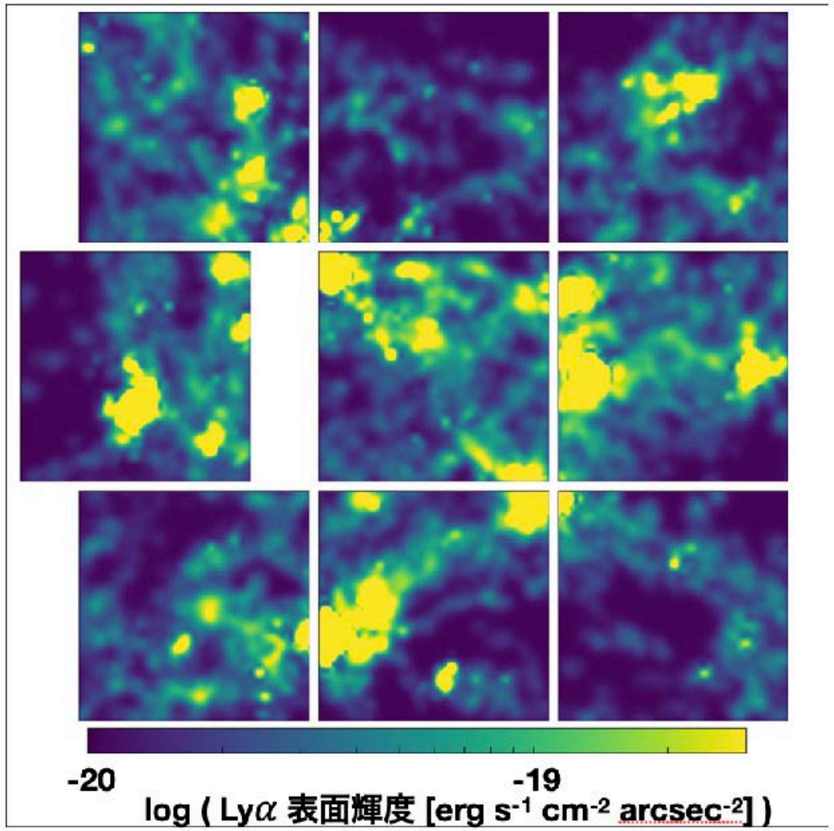
* First Galaxies and Reionization
* Co-evolution of SMBH & Galaxies
* Massive Galaxies

Example: Science of ELT特推

He II line from a first galaxy



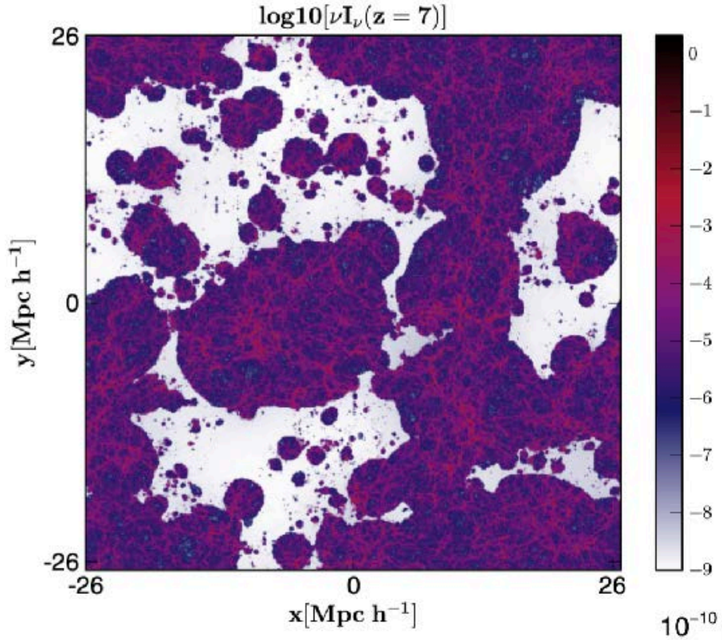
Lya filament at z~6



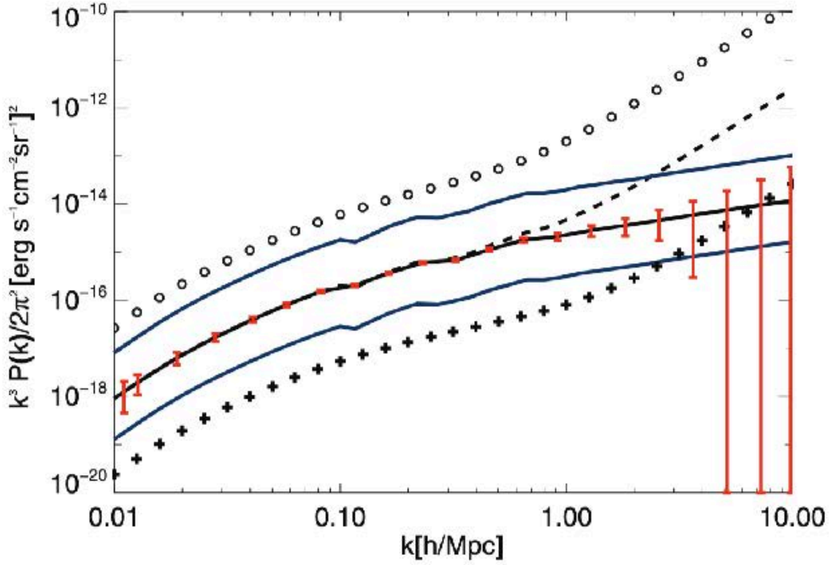
NB survey

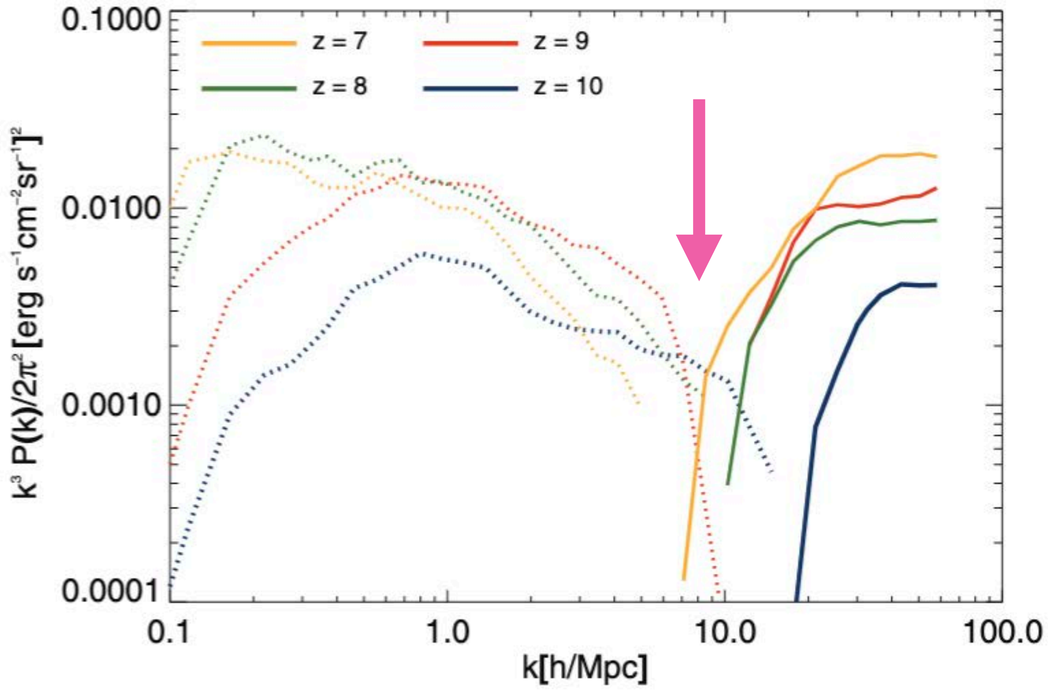
Witness formation of
the `first large-scale structure'

Intensity Mapping: Lyα , [Cii], …



Lya clustering power spectrum





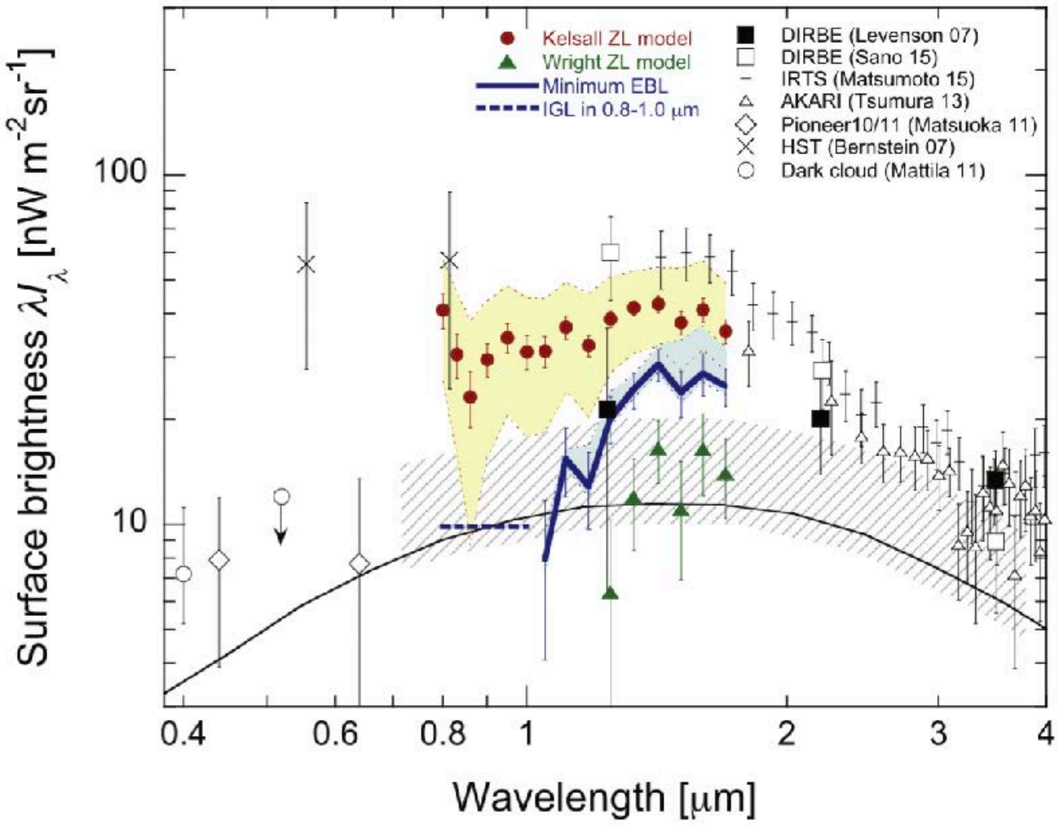
21cm — Lya cross-power

SKA, Subaru, ELT, GMT, TMT, …

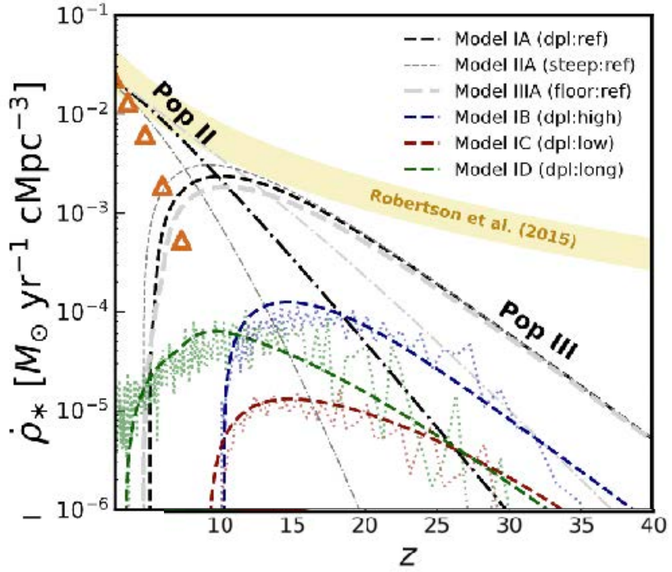
Silva+13

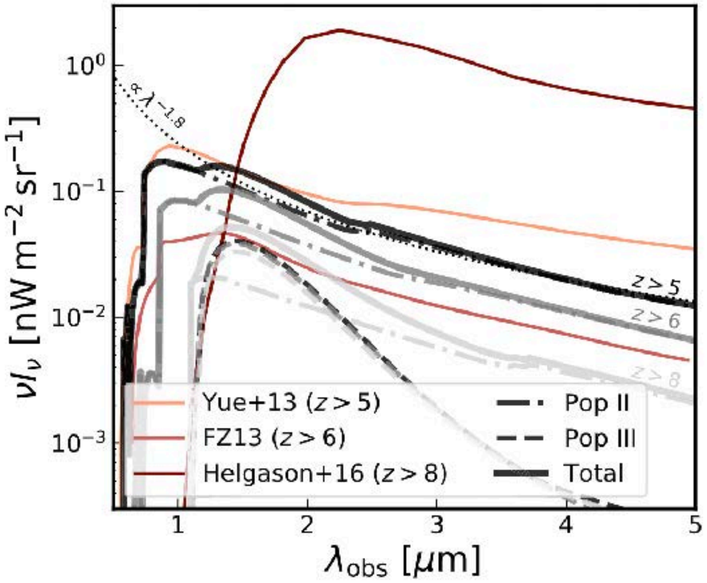
cf. Yue & Ferrara ‘21

Near-IR background radiation



Matsuura+17





Sun+'21

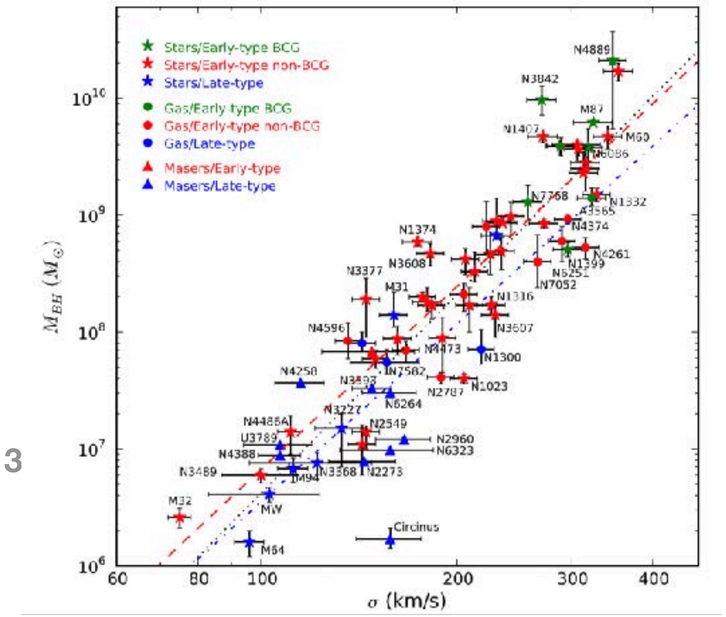
CIBER-2, IPST, SPHEREx, CDIM

cf. HESS+'13: γ—CMB interaction

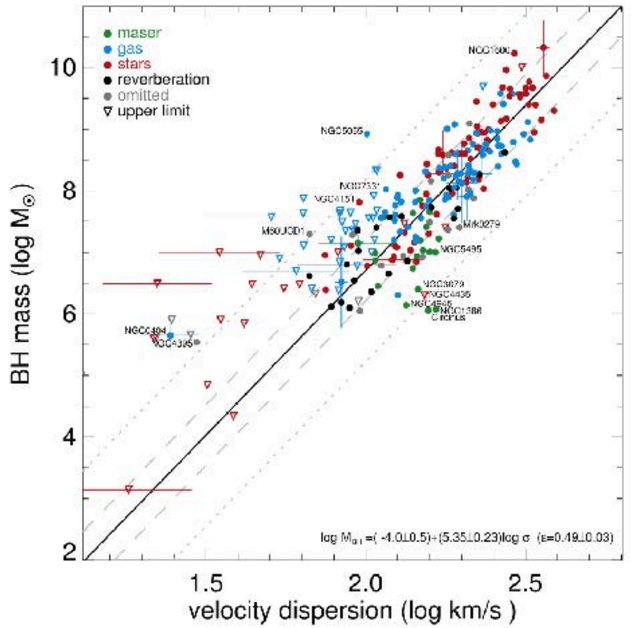
cf. Yue+'13; Helgason+'16

Galaxy-SMBH co-evolution & Seed Black Holes

When was $M-\sigma$ relation established?

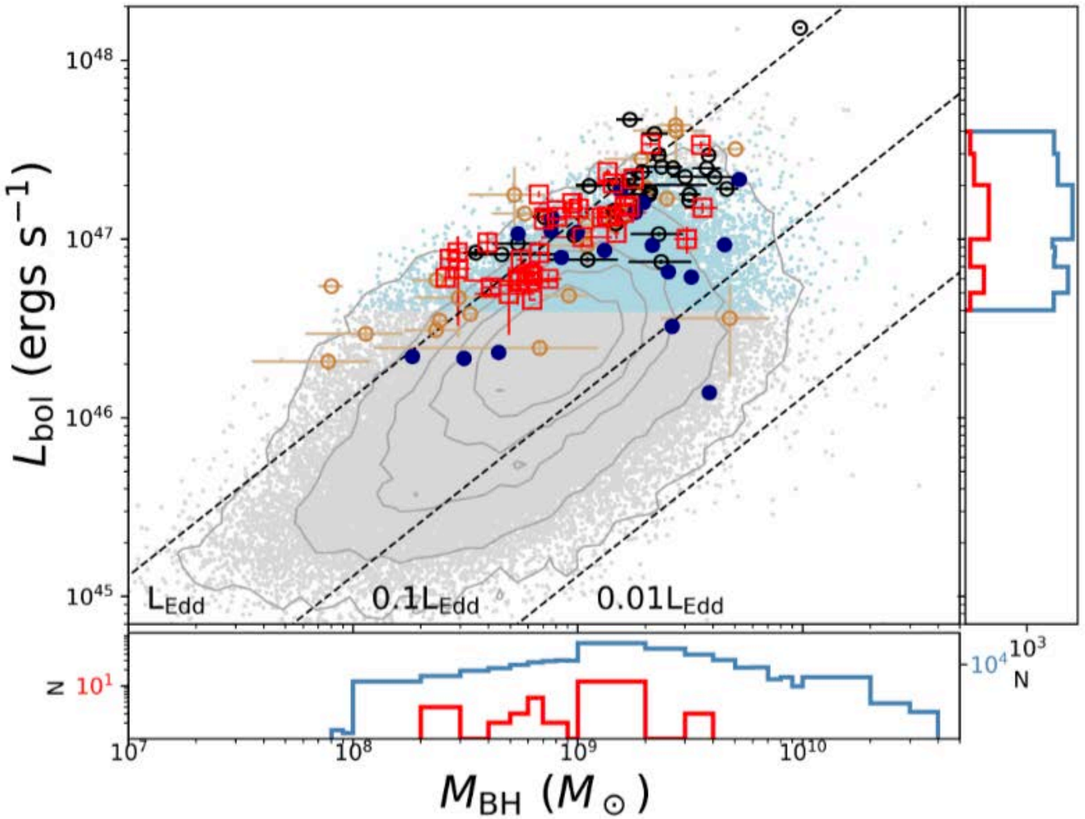


McConnell & Ma ‘13

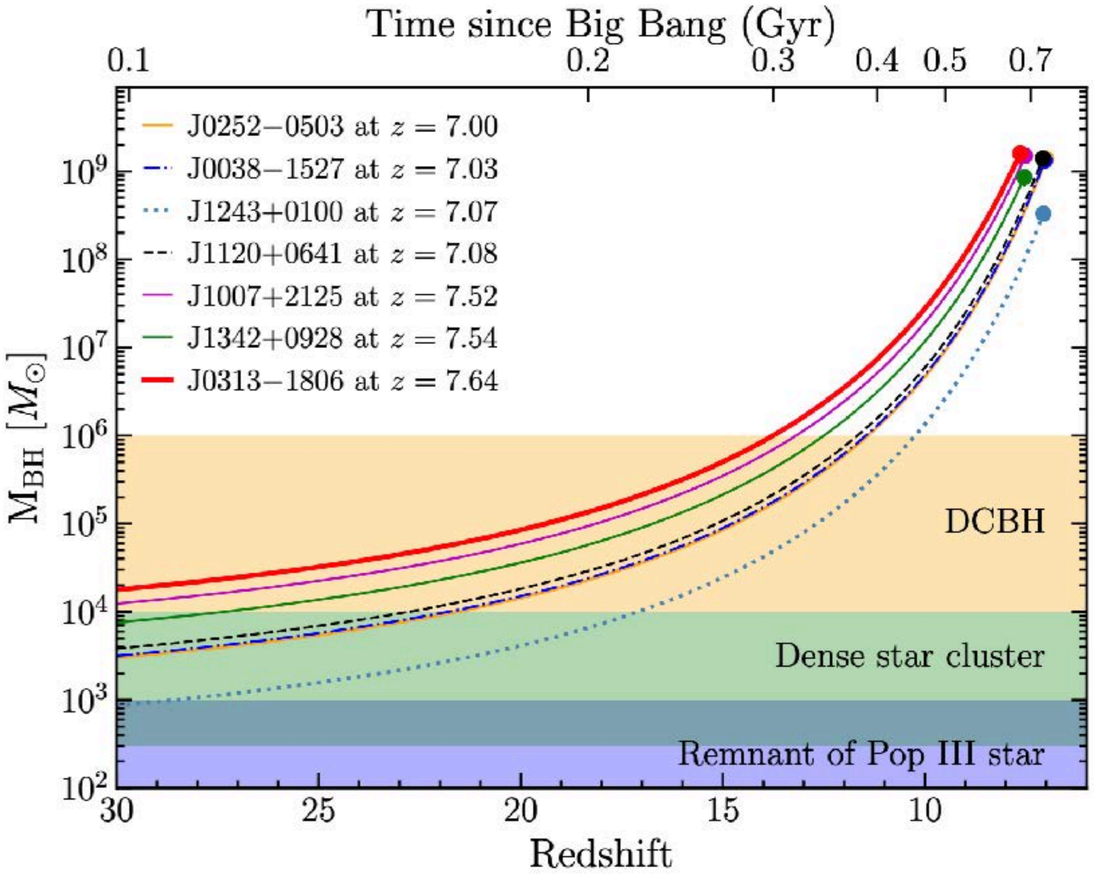


van den Bosch ‘16

cf. Ferrarese & Meritt ’00; Haring & Rix ’04; Kormendy & Ho ’13; McConnell & Ma ’13；Marconi & Hunt ’13; van den Bosch 16



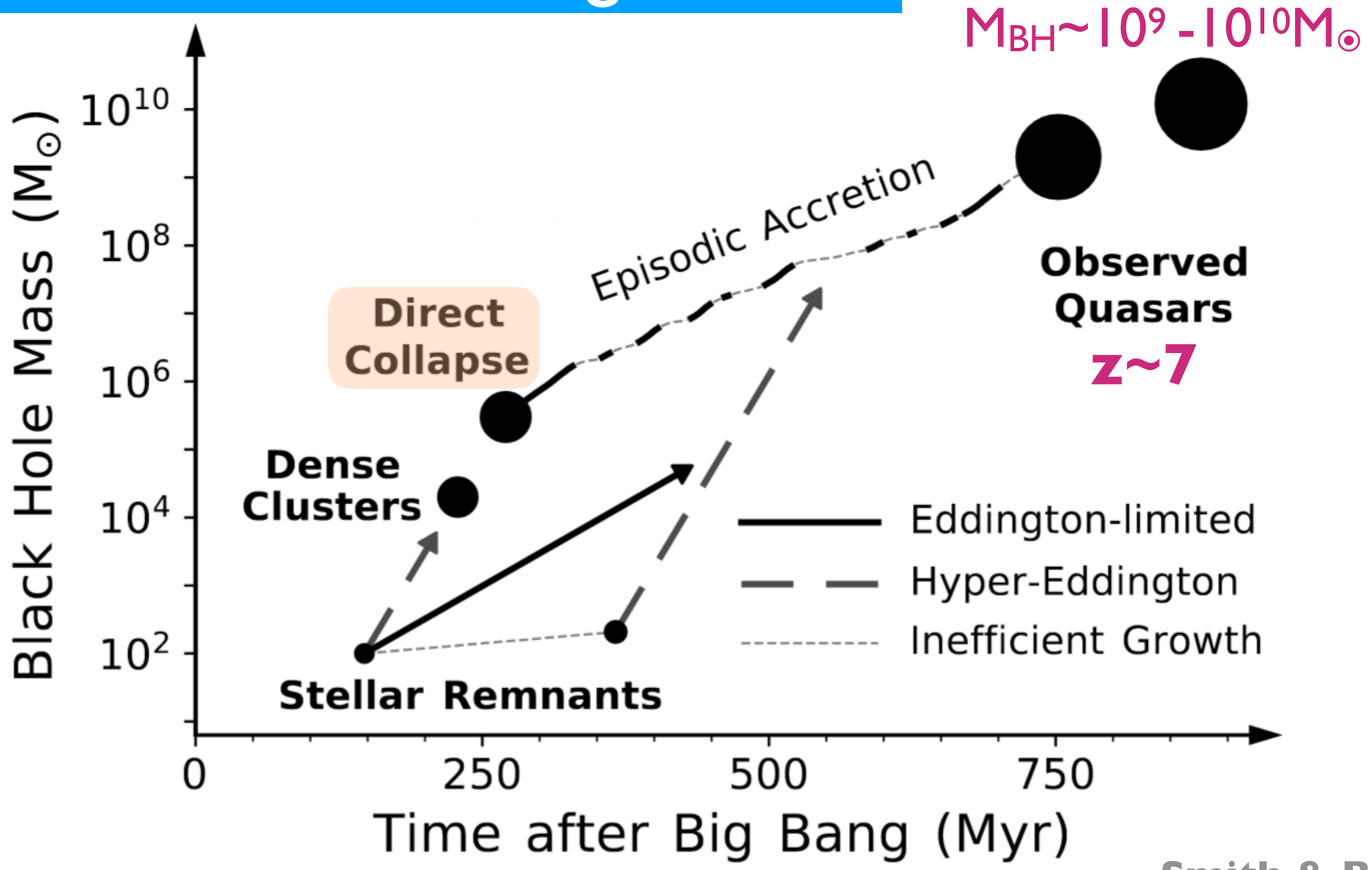
Yang+21



Even with Eddington accretion & duty cycle=1, only the "direct collapse" scenario works!

Wang+21

How did the seed BH grow?



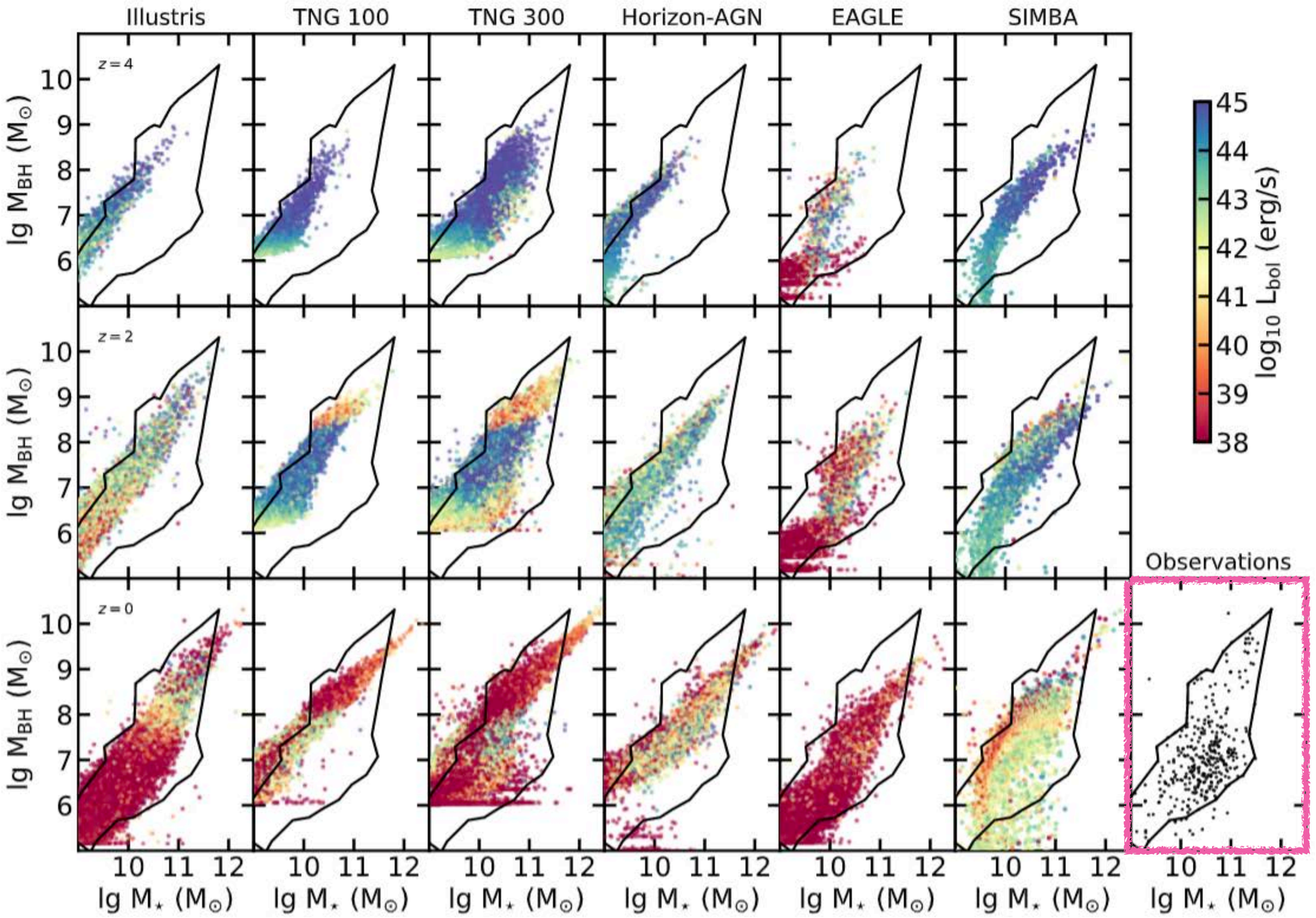
Smith & Bromm '19

When & how was M_{BH}—M_* relation established?

z=4

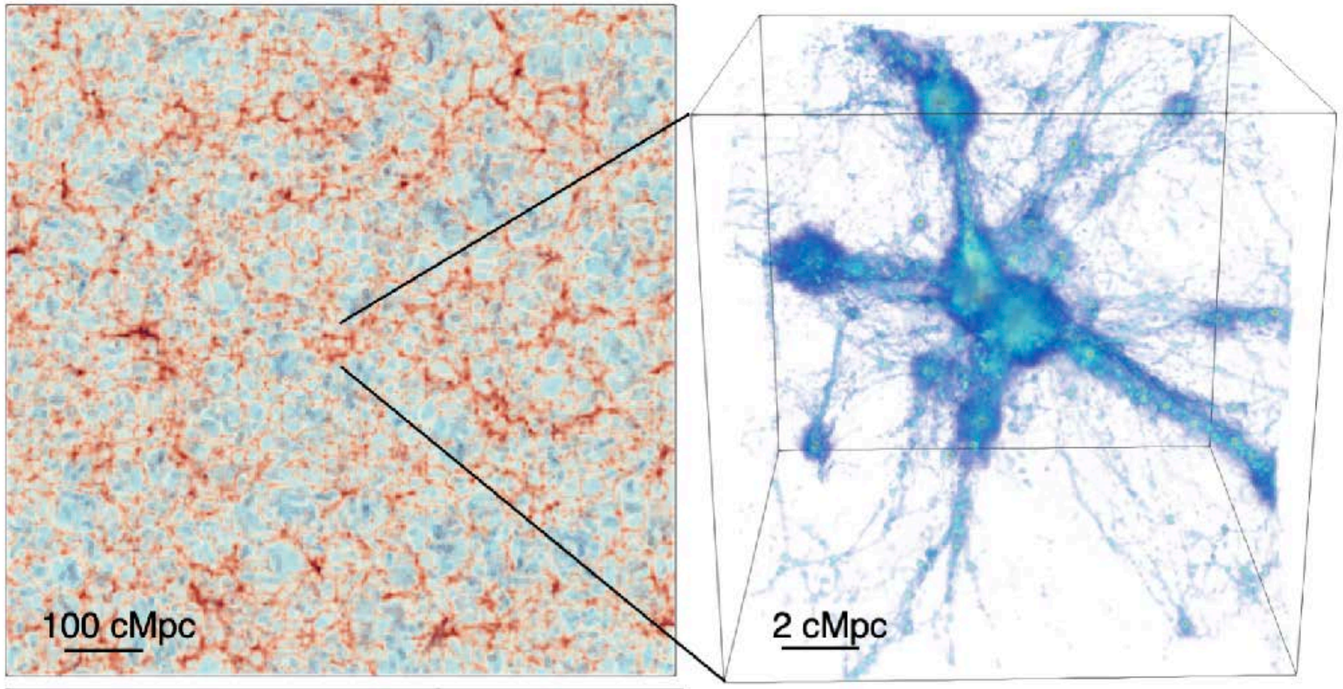
z=2

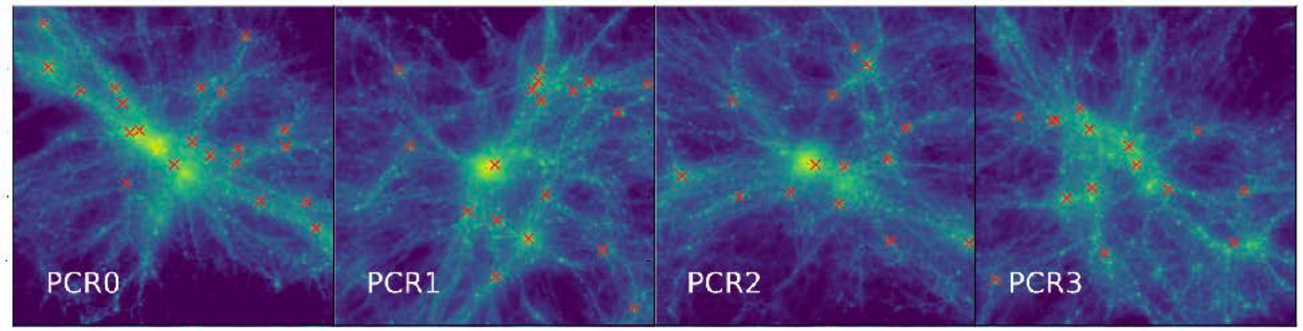
z=0



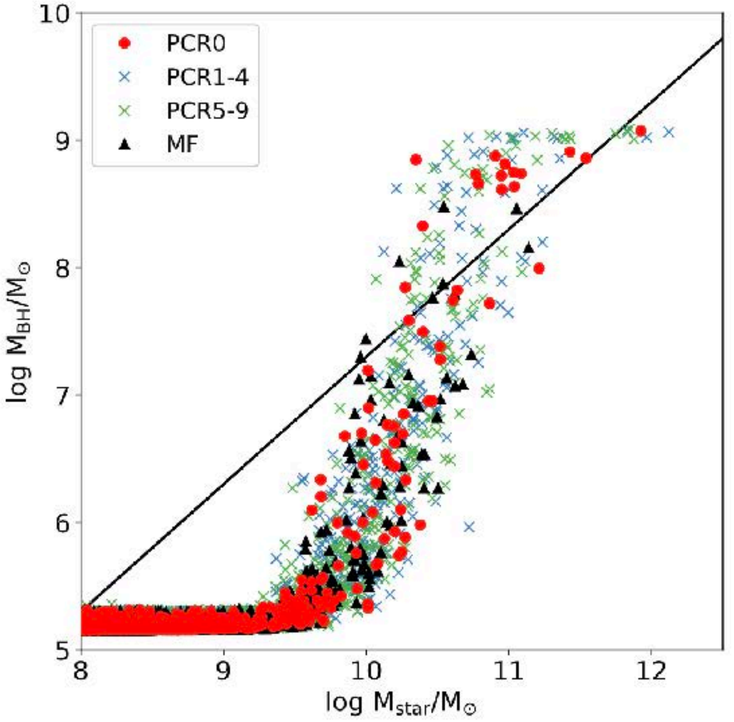
Habouzit+21

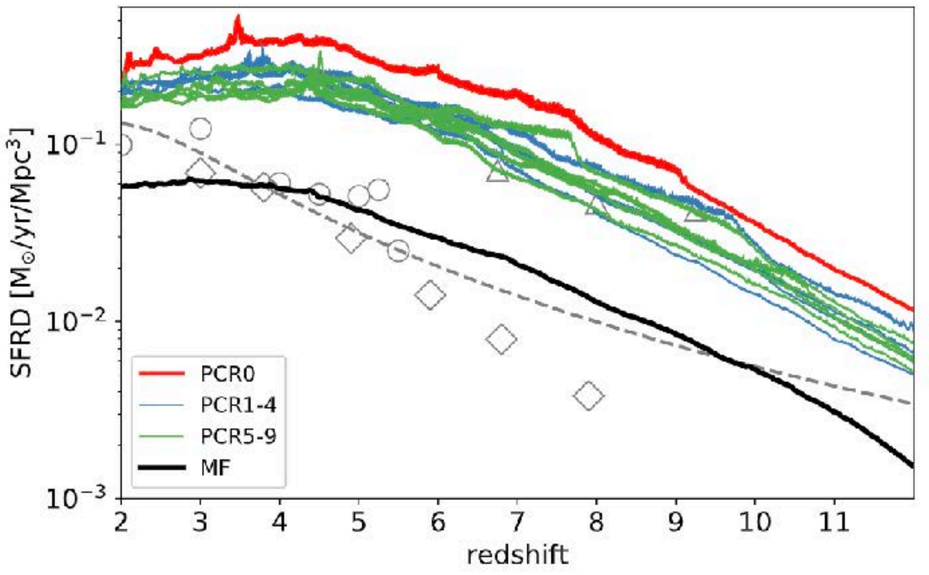
FOREVER22 project





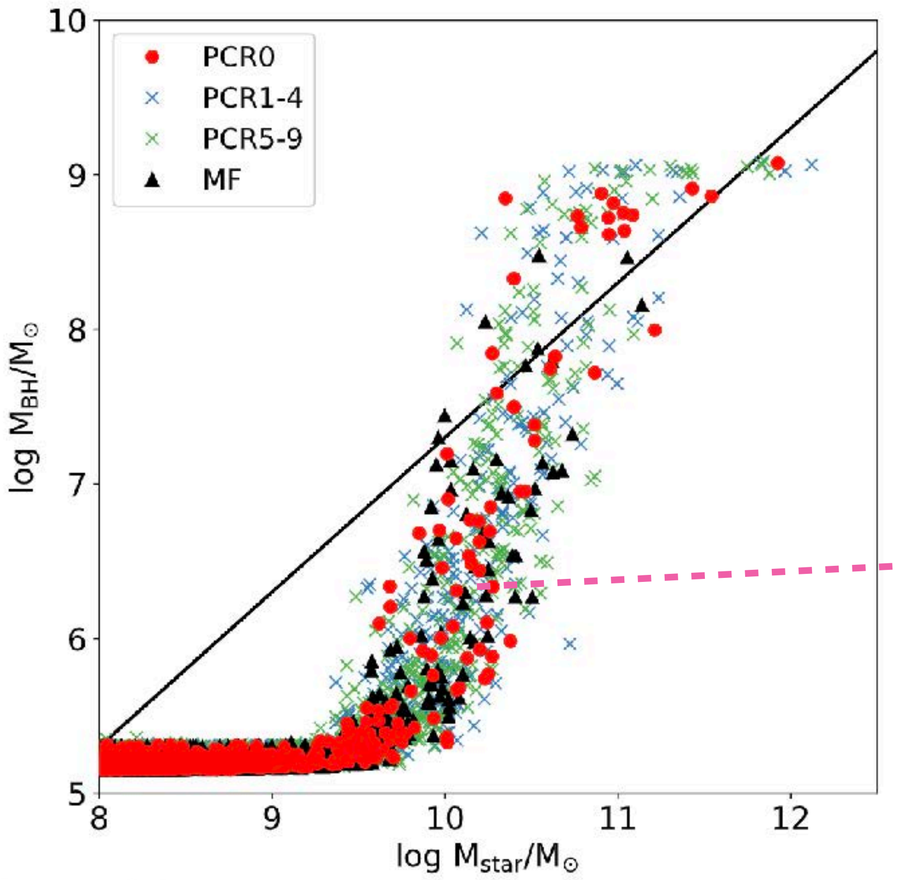
z=3 10 cMpc PCR regions



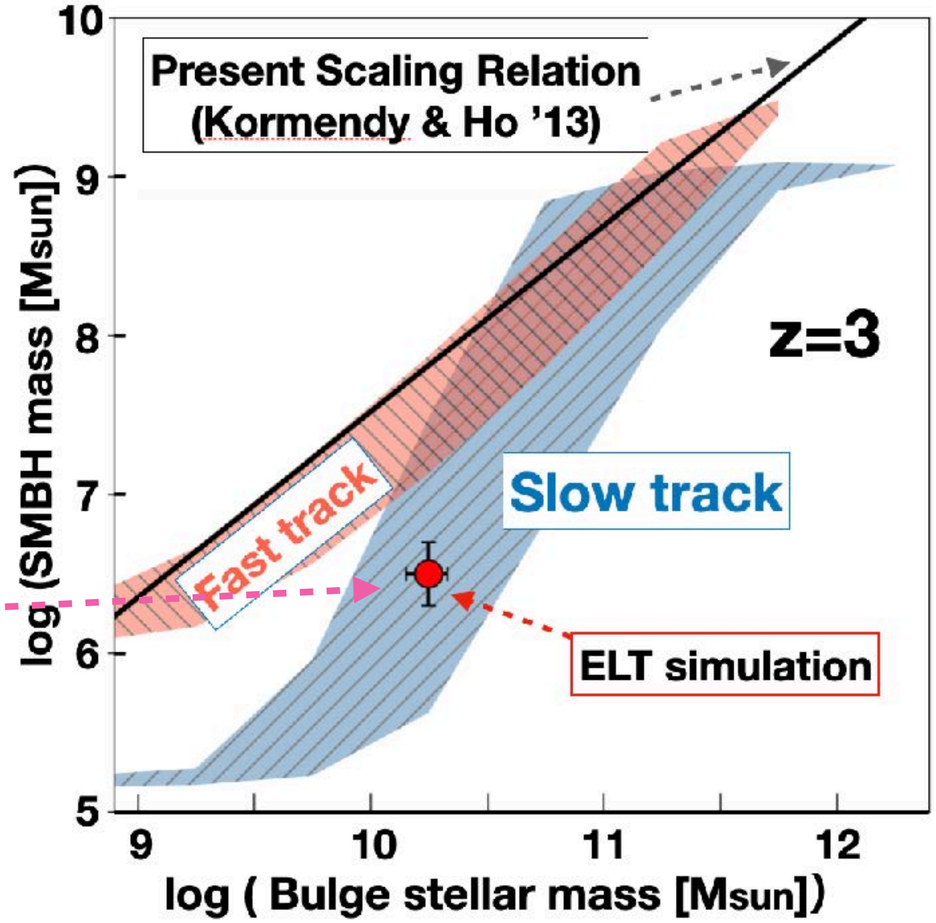


Yajima+21

Early evolution: fast or slow?

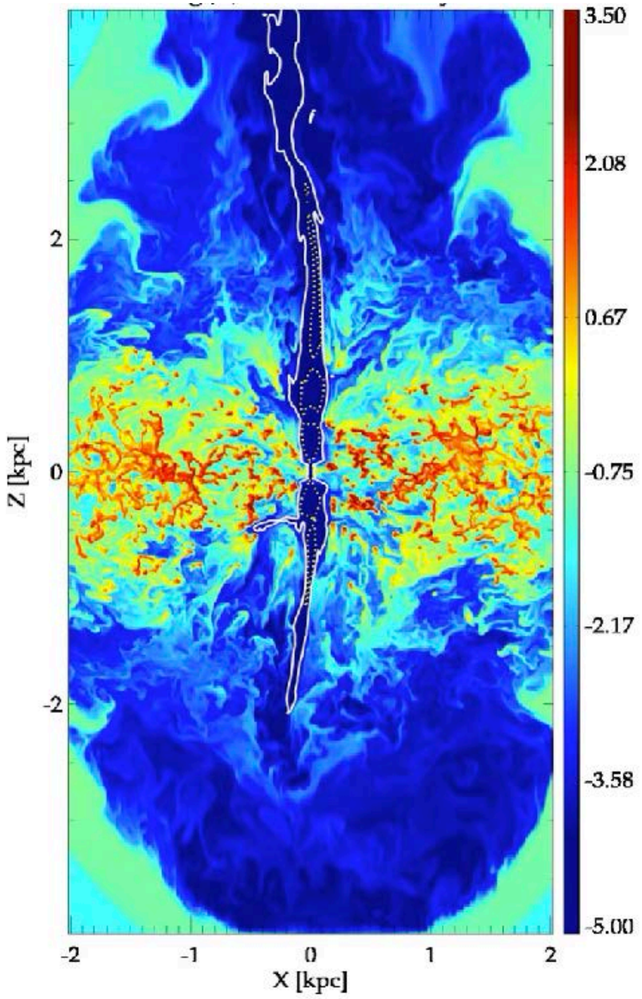


Yajima+21



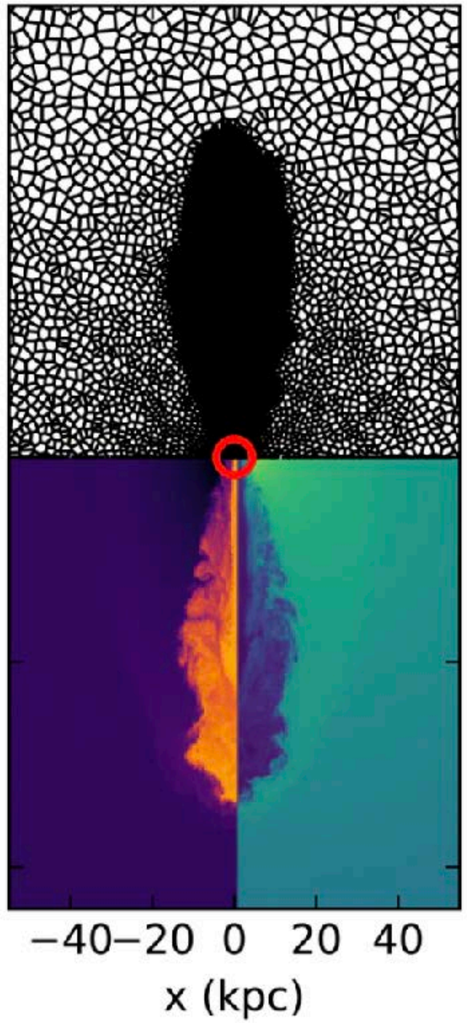
ELT特推申請 '21

AGN jet feedback



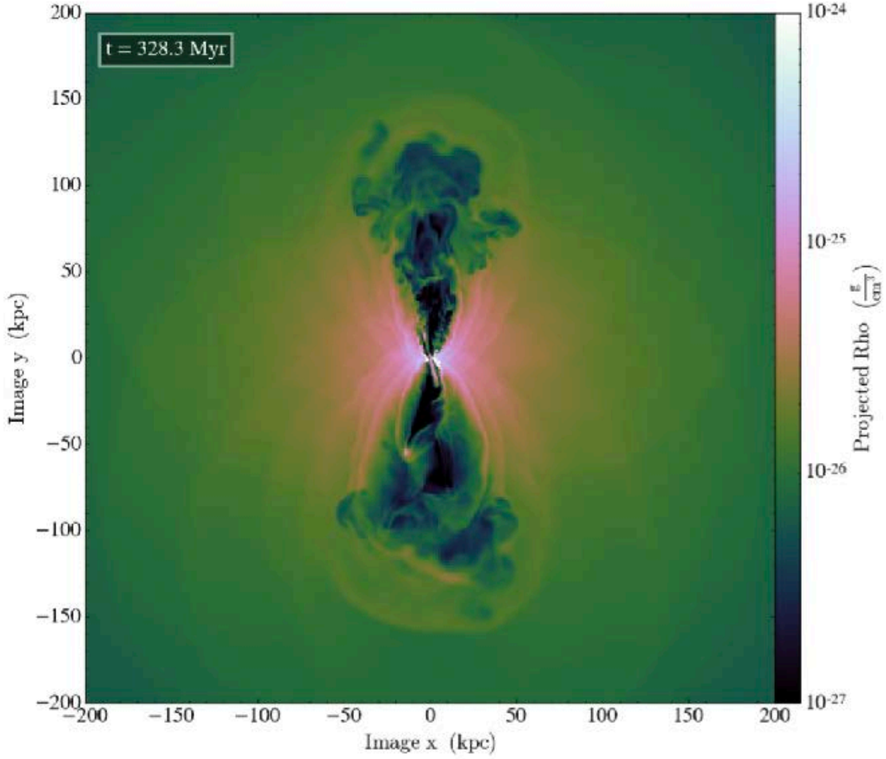
Mukherjee, Wagner+18

Jet-ISM interaction



Bourne & Sijacki ’17

AREPO



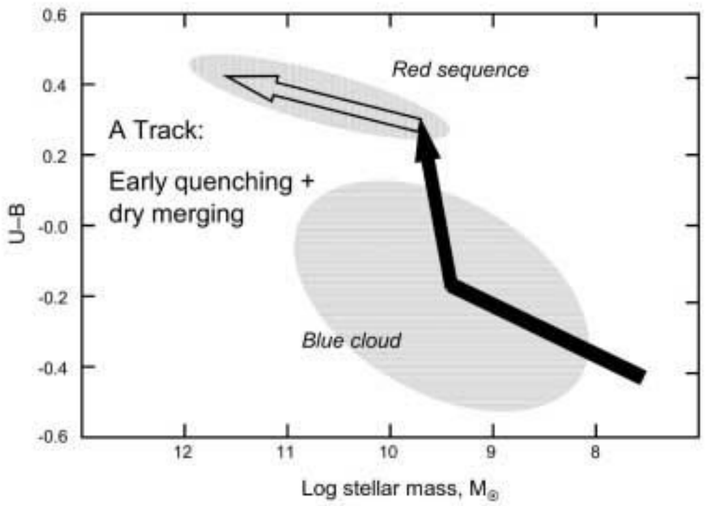
Martizzi+19 **~200 pc**

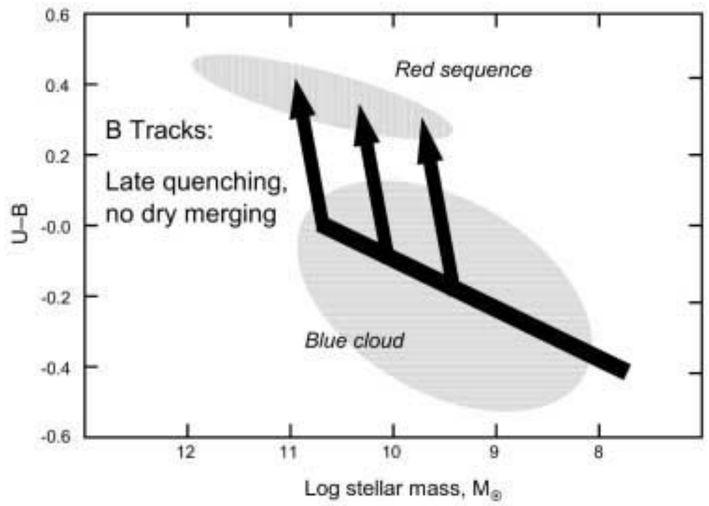
Athena

X-ray: FORCE, XRISM, Athena

Radio: ngVLA

Evolution from Blue to Red Sequence



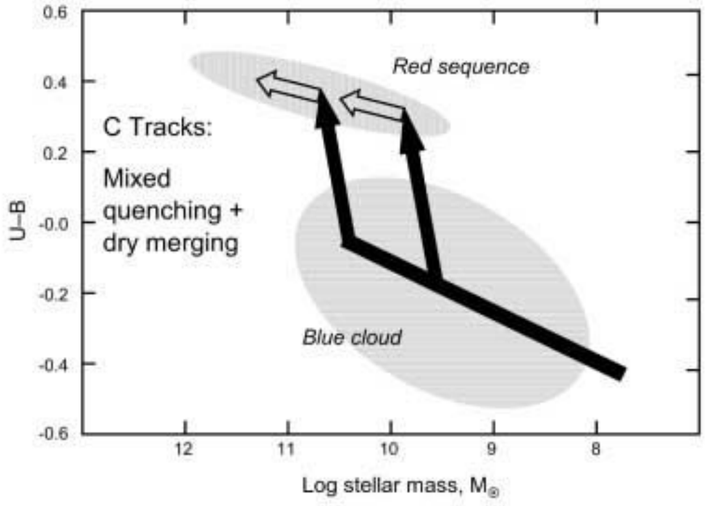


Faber+'07

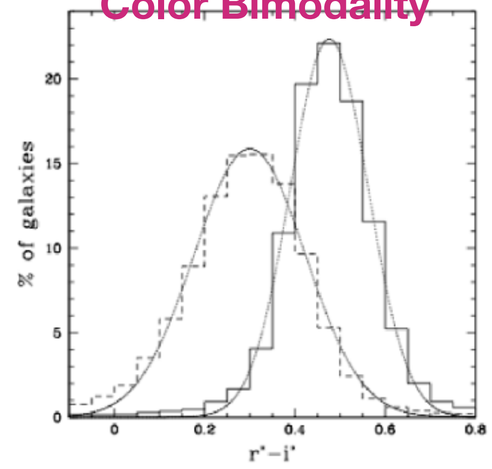
Chen+'20

$M_*, R_e, \Sigma_1, M_{\rm BH}$

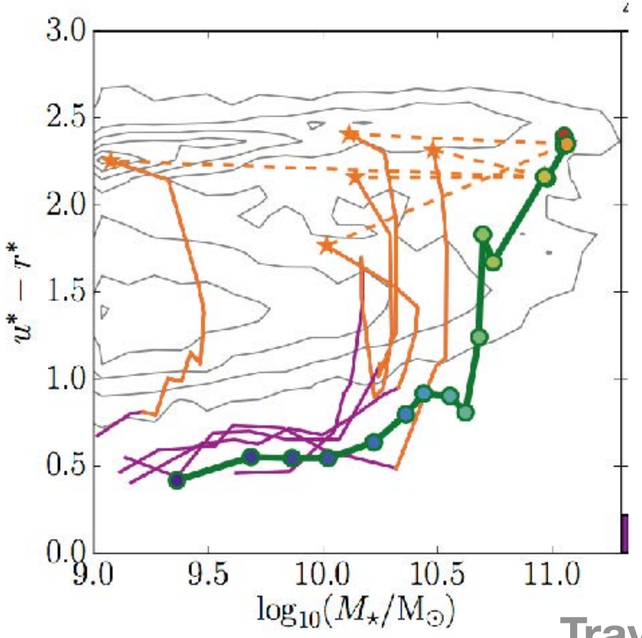
Σ_1: projected M_{star} density @R<1kpc



Color Bimodality



Strateva+'01



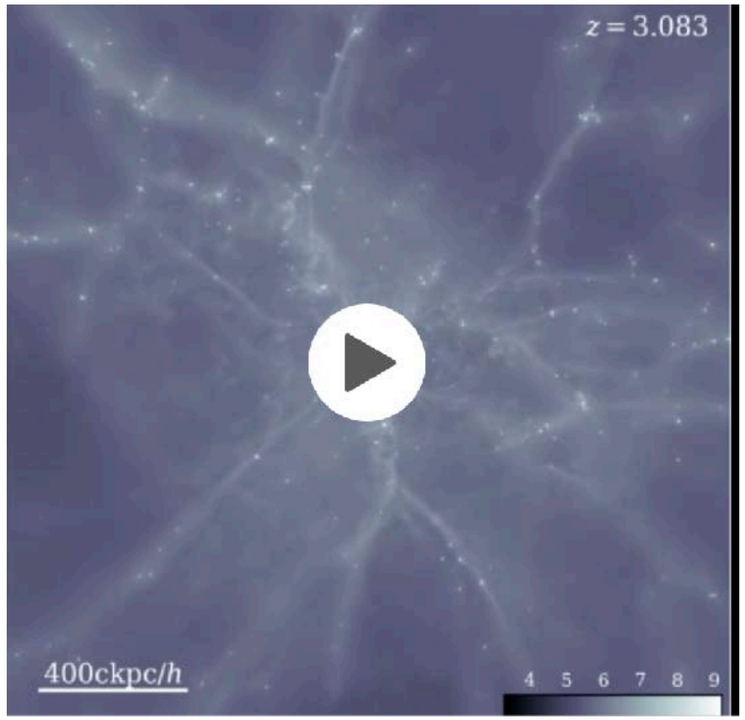
Trayford+'17

How did galaxies acquire gas & eject metals?

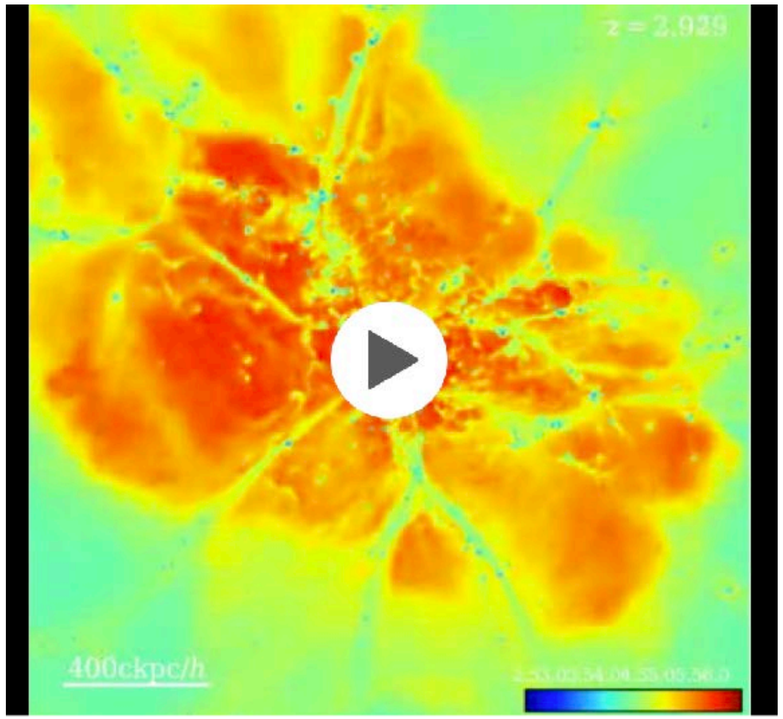
— cold flow, multiphase outflow

Movies: zoom-in sim

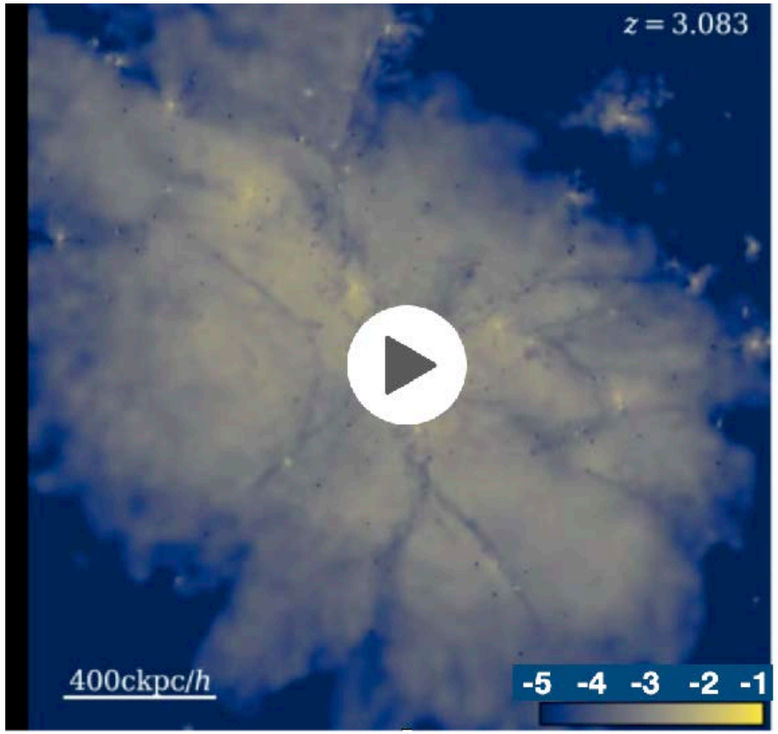
Gas Density



log(Temperature)



log(Metallicity)

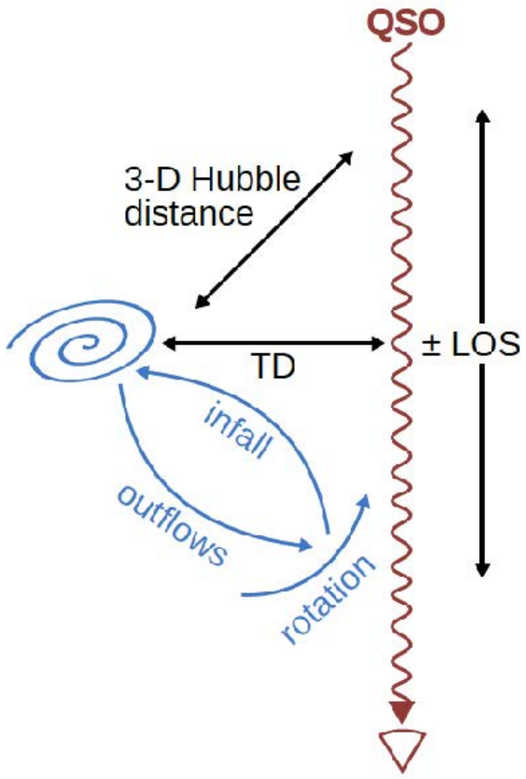


AGORA L12 GADGET3-Osaka sim. Shimizu, KN+19

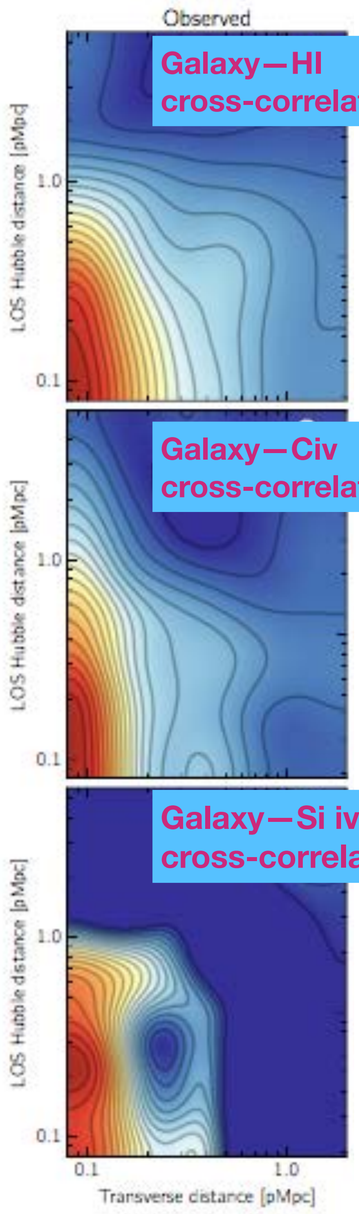
cf. Roca-Fabrega+21 https://sites.google.com/site/santacruzcomparisonproject/

2D Velocity Structure

KBSS: log(τ) in color

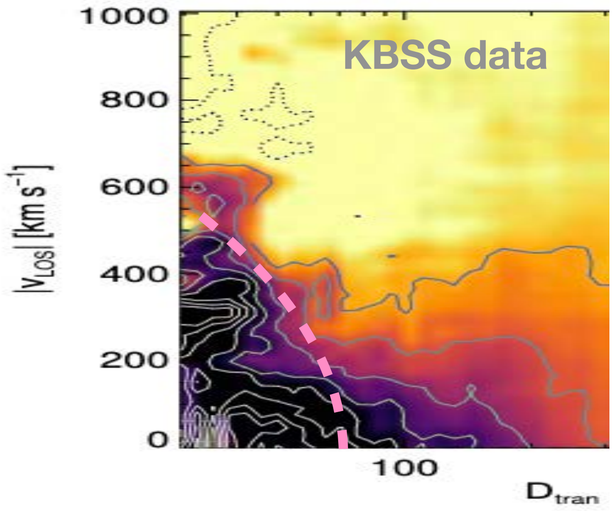


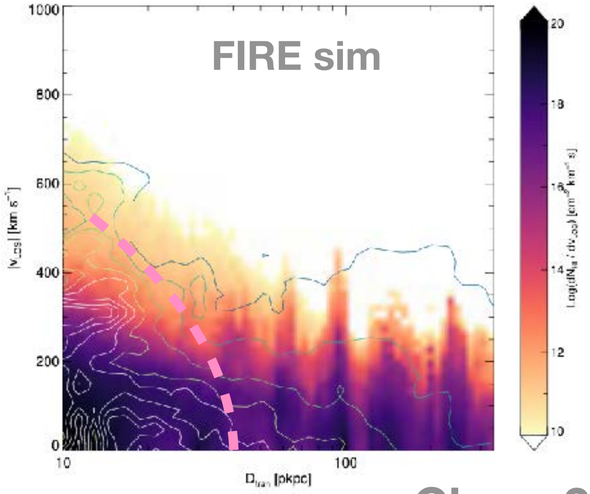
Turner+17



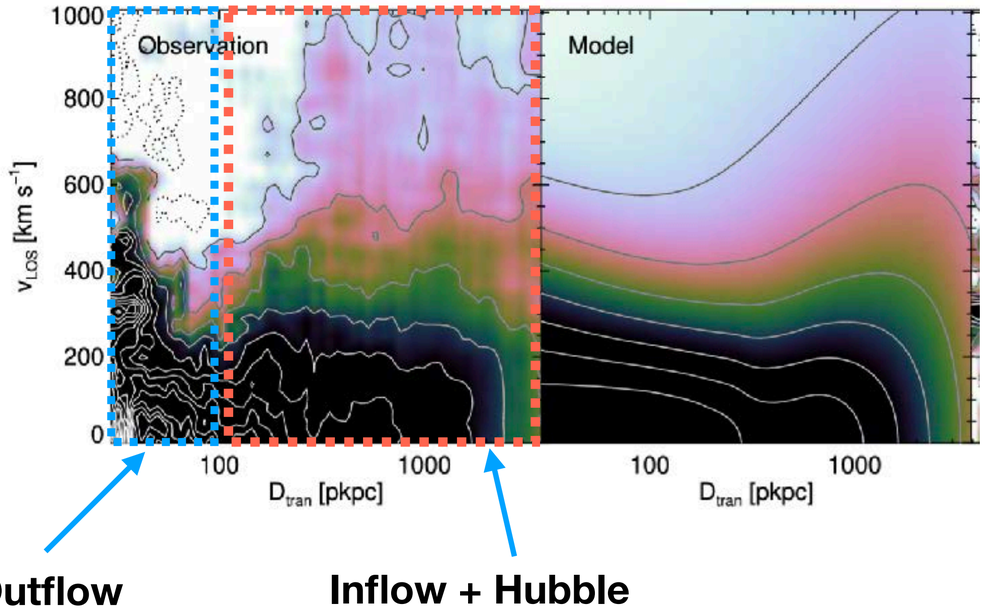
Finger-of-God like elongation

Halo mass can be constrained too.





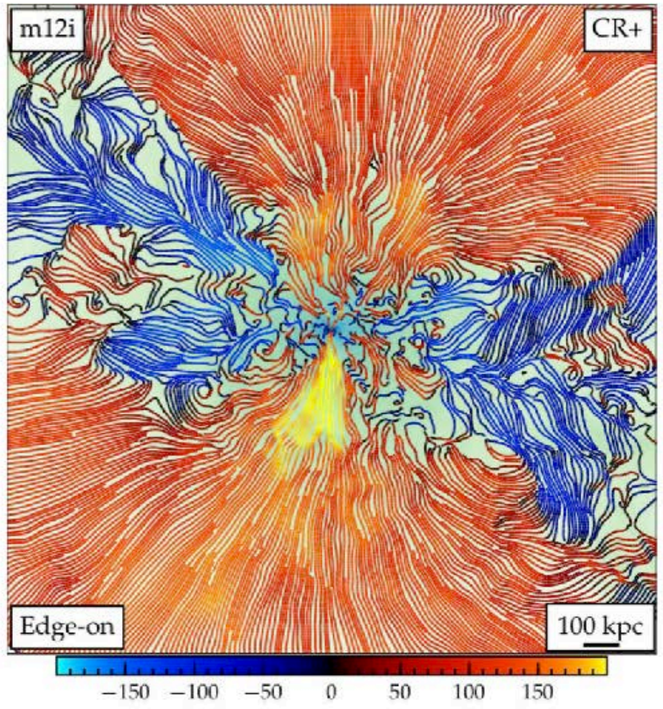
Chen+20



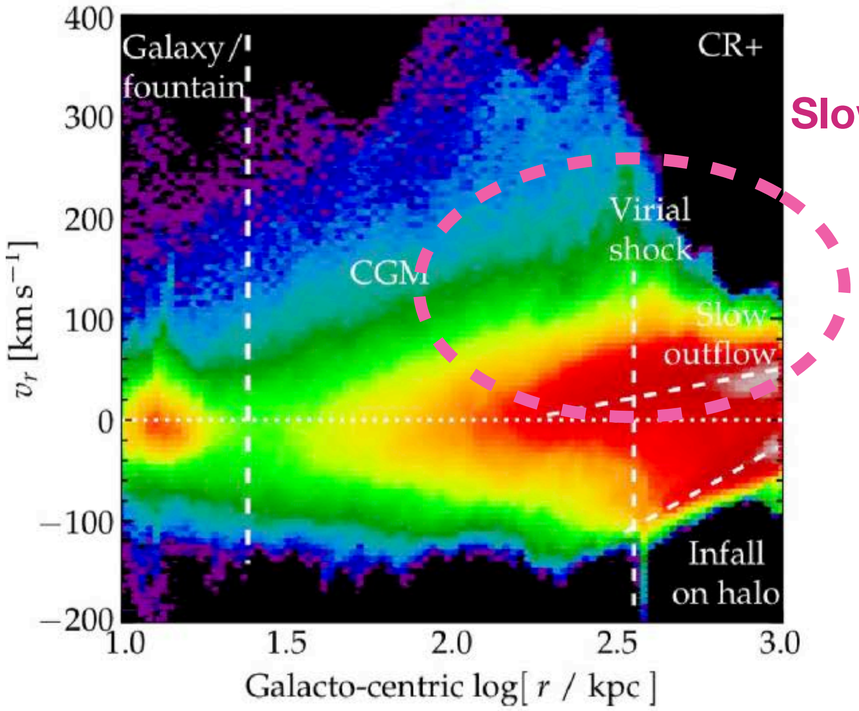
Outflow

Inflow + Hubble

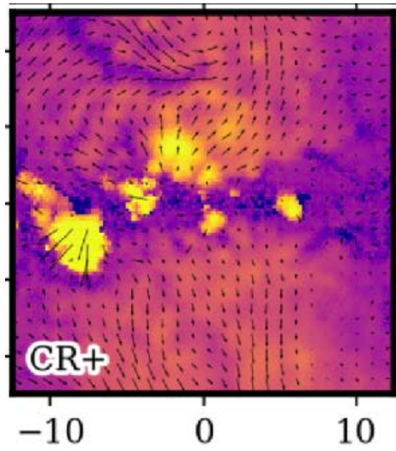
Cosmic Ray feedback

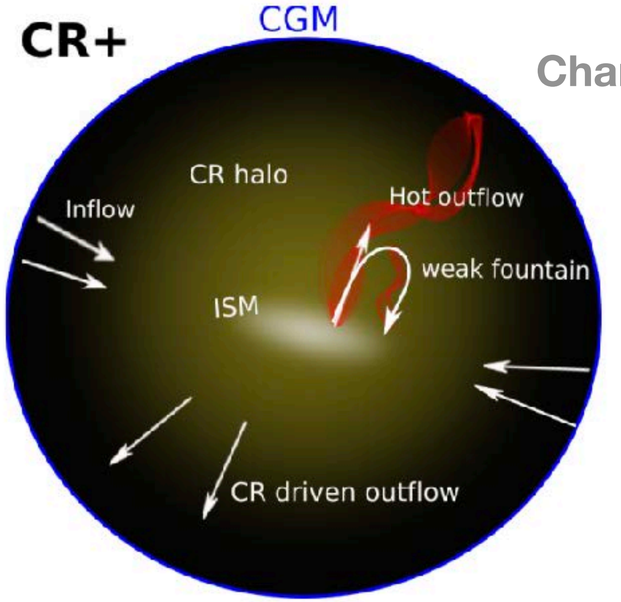


Hopkins+21



Slow outflow accelerated in-situ by CR





Chan+21

An old problem, but with renewed interest.

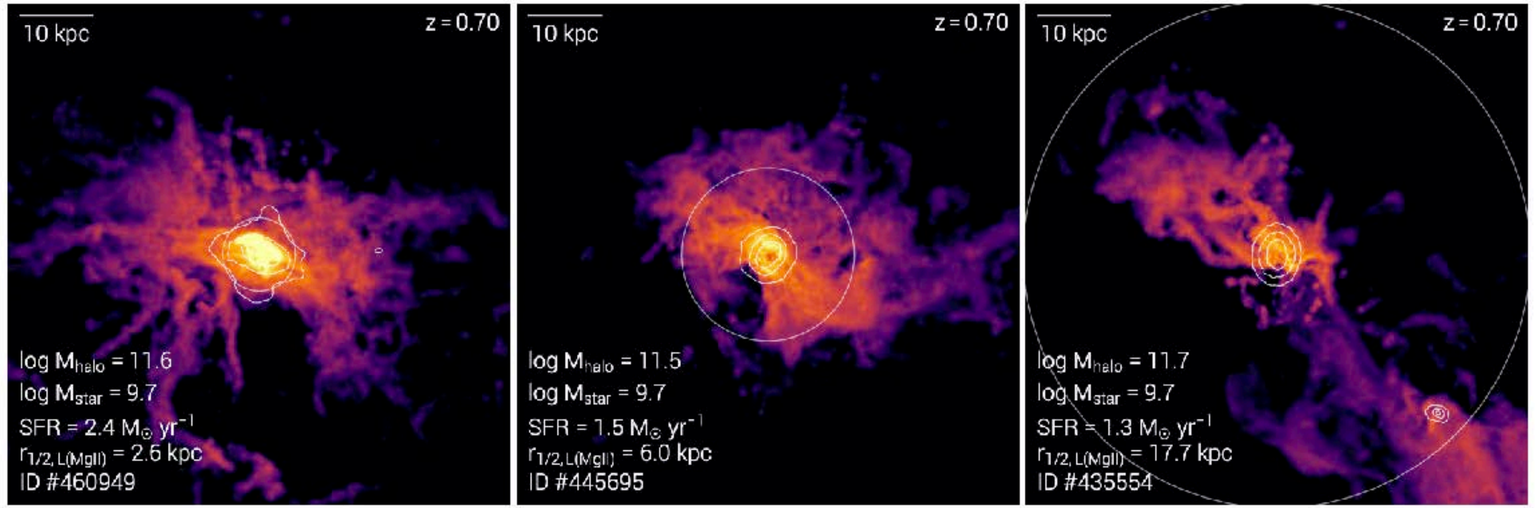
Analytic: Ipavich ’75; Boulares & Cox 90; Breitschwerdt+91; Everett+08; Socrates+08; Mao & Ostriker’18; ….

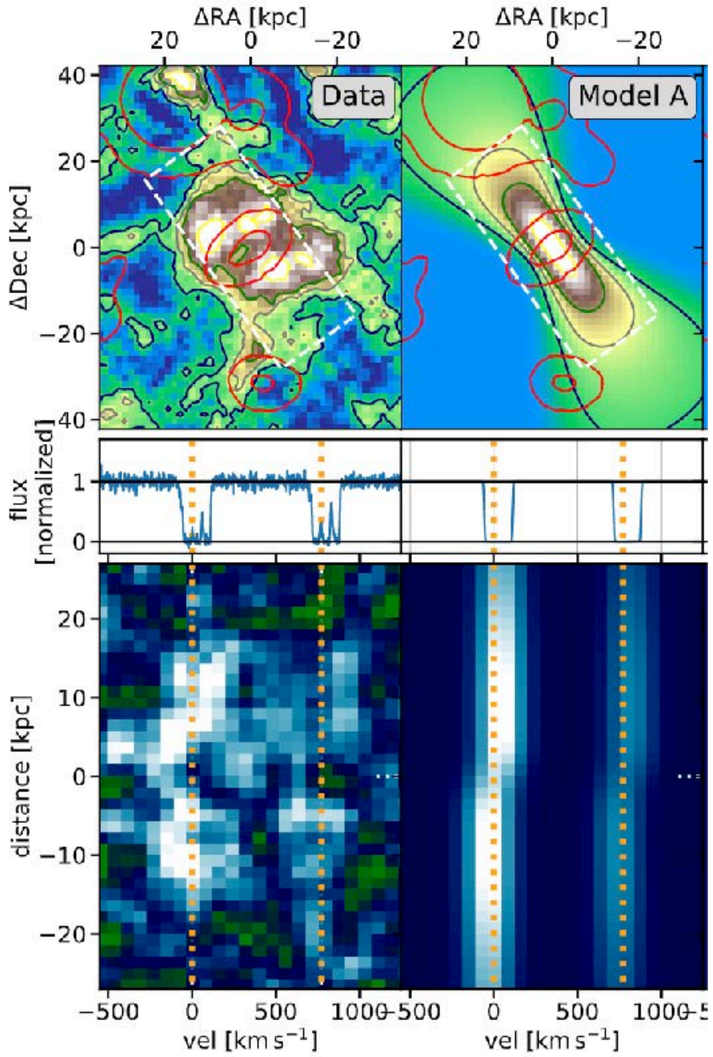
Simulation: Booth+13; Pakmor+16; Ruszkowski+17; Wiener+17; Chan+19; Hopkins+20; Ji+20; Su+20; Hopkins+21; ….

X, γ-ray community: XRISM, Athena, FORCE, GRAMS, SuperDIOS

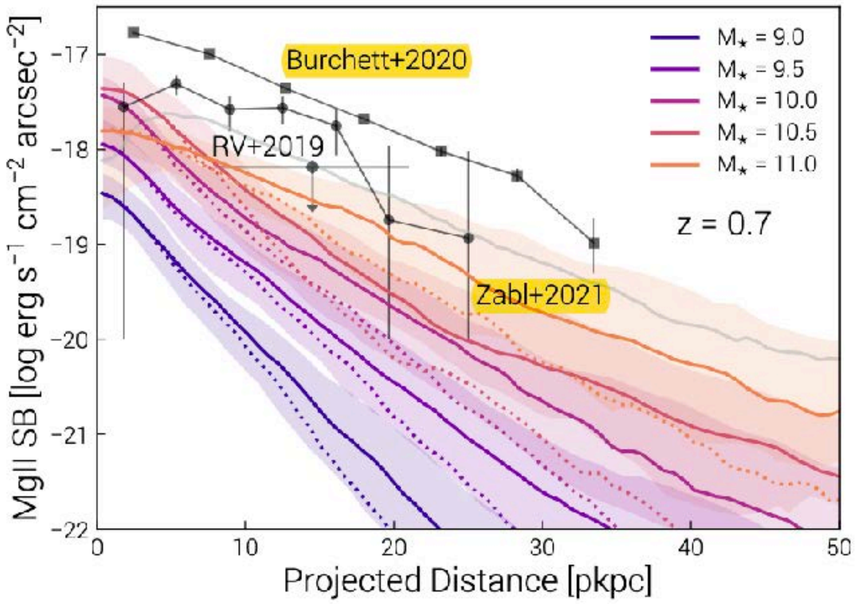
Mg II emission

TNG50 sim (AREPO) Nelson+21



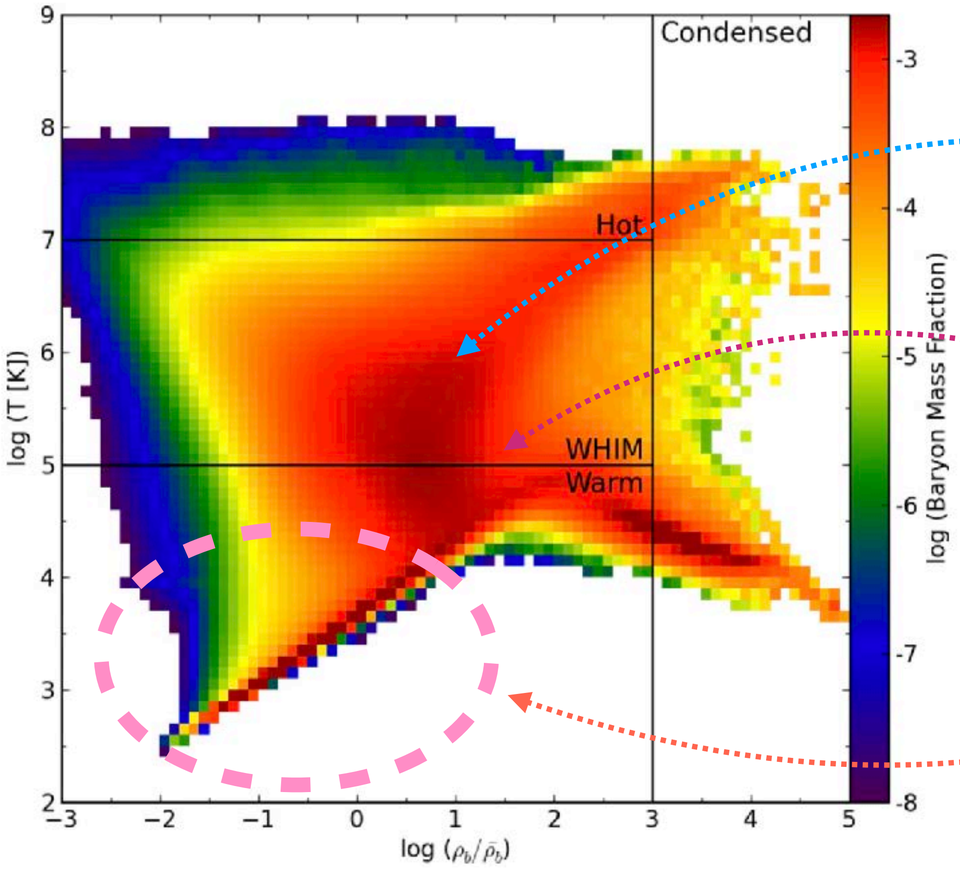


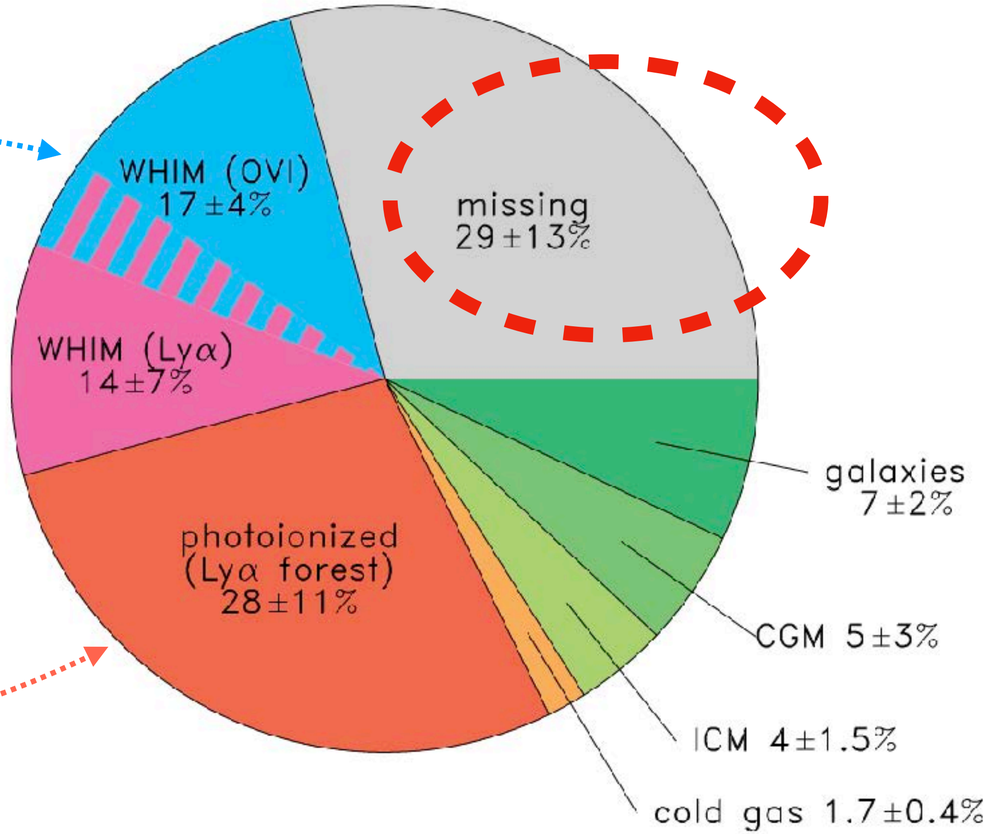
MEGAFLOW (Zabl+21)



cf. MAGG (Dutta+20) **c.f. SWIMS IFU** **cf. also Mg II absorption (Schroetter+21)**

Missing Baryon Problem



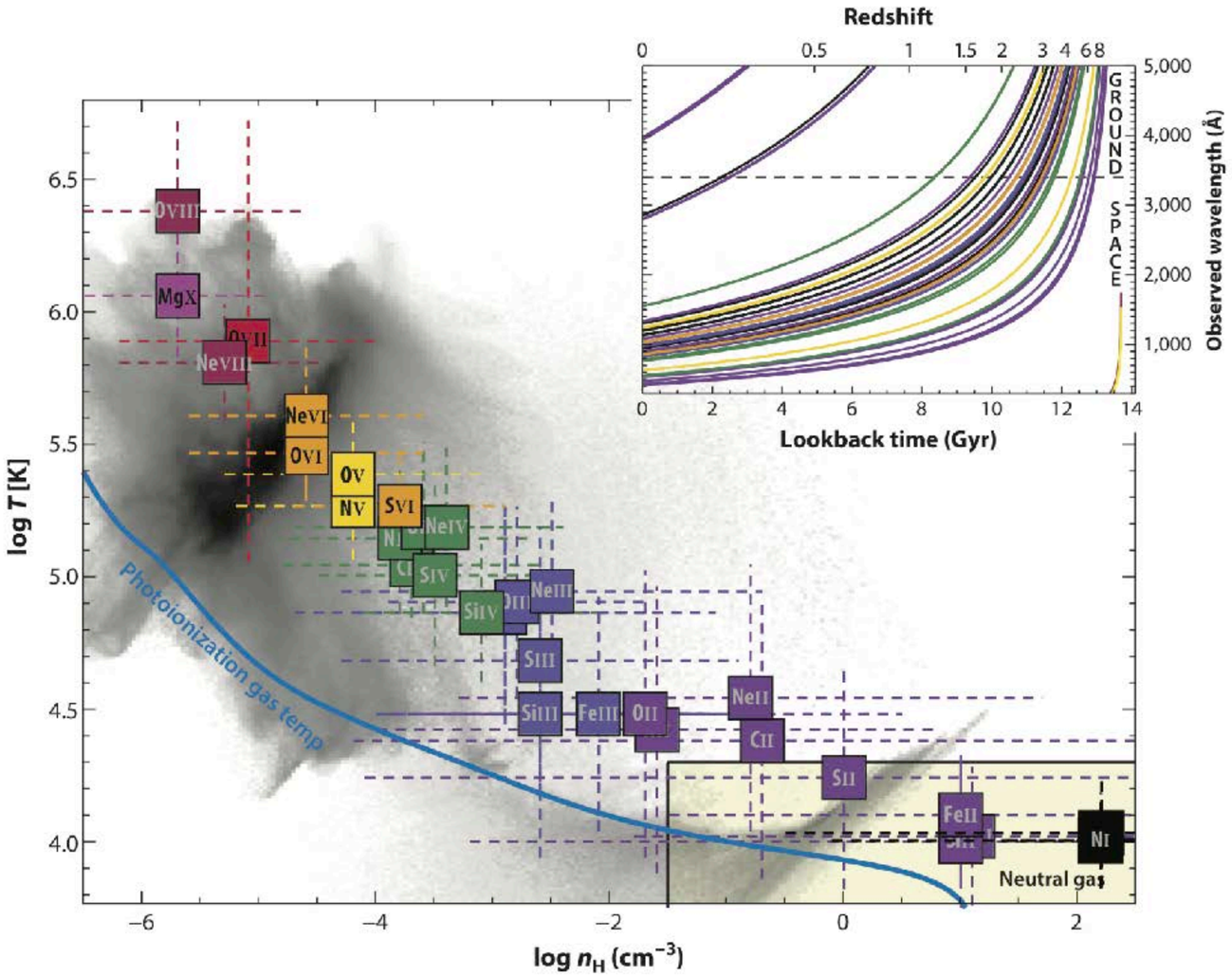


Shull+'12

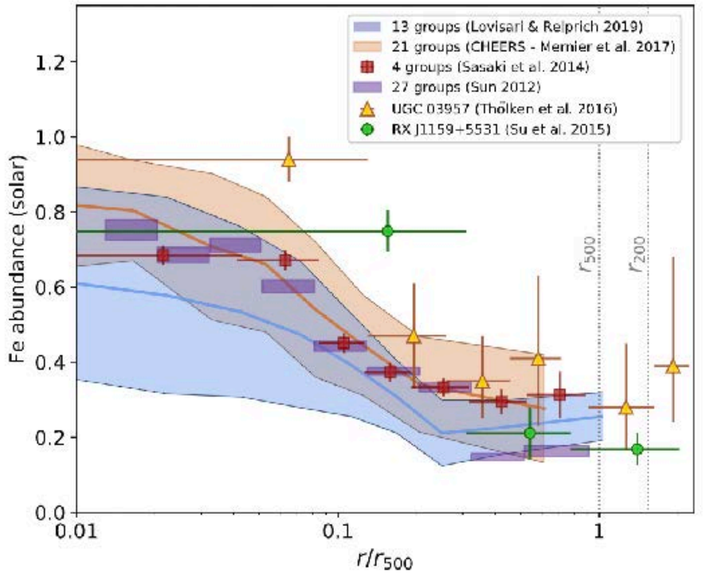
cf. Nicastro+17

X, γ-ray community: XRISM, Athena, FORCE, GRAMS, SuperDIOS

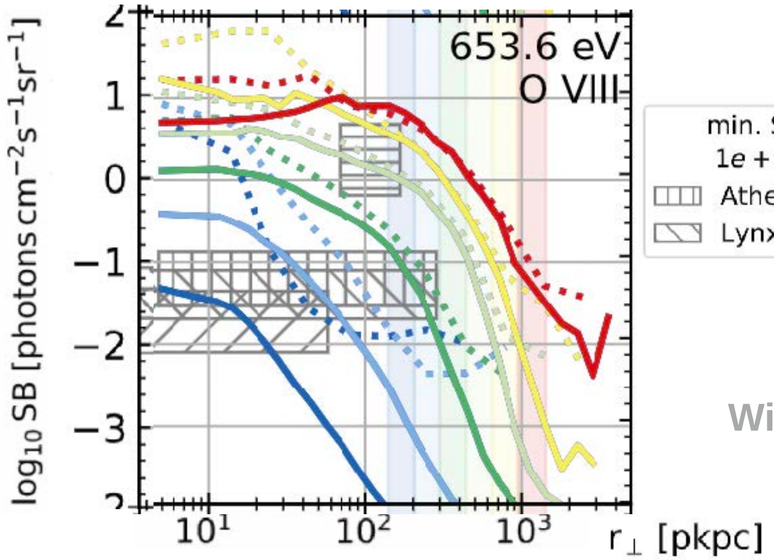
Metal lines as probes of ISM/CGM/ICM/IGM



Tumlinson+'17, ARAA



Gastaldello+21

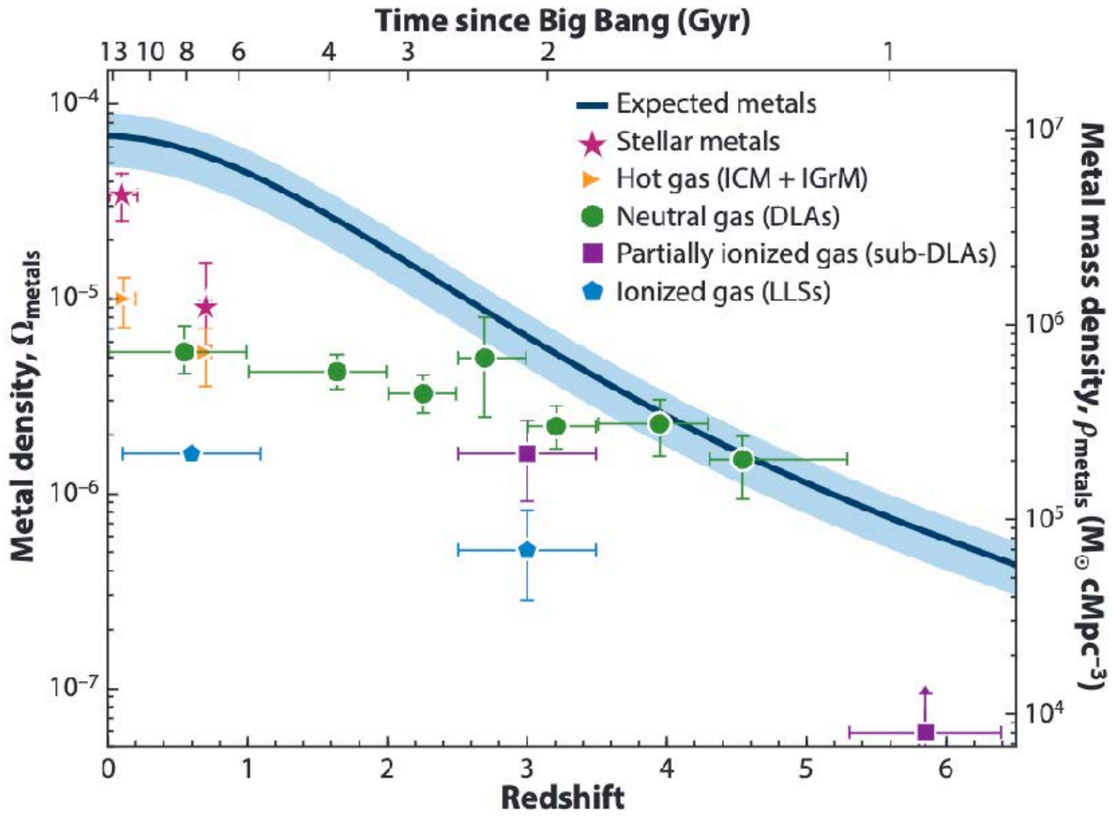


Wijers+21

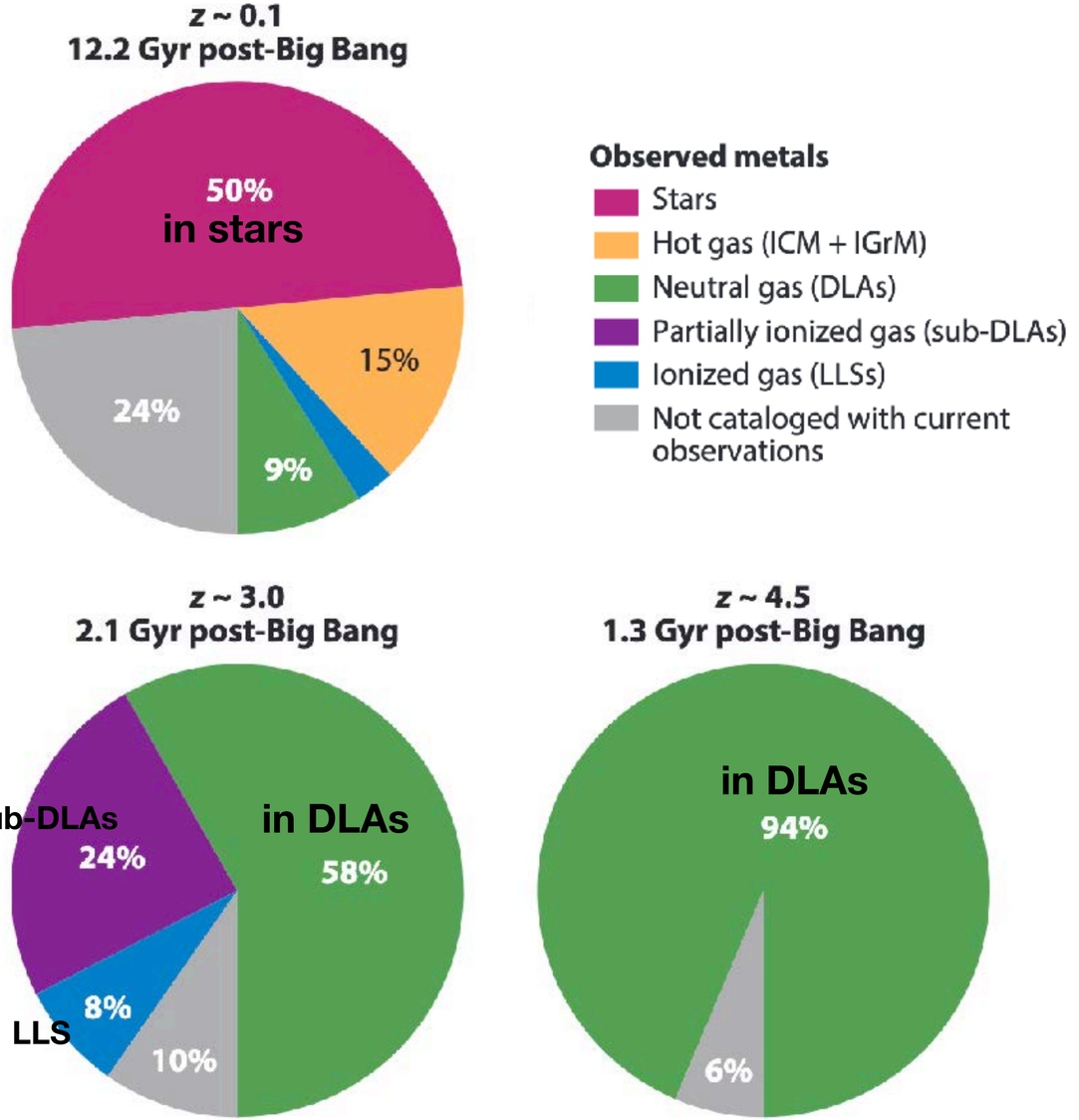
X, γ-ray : XRISM, Athena, FORCE, GRAMS, Lynx, SuperDIOS

Census of Cosmic Metals

$$\rho_\star(z) = (1-R)\int_0^{t(z)} \mathrm{SFR}\left|\frac{\mathrm{d}z}{\mathrm{d}t}\right| \mathrm{d}t. \qquad \rho_{\mathrm{metals}}(z) = y\rho_\star(z),$$



$$\Omega_{\mathrm{metals}} = \Omega_{\mathrm{gas}}\,\langle Z_{\mathrm{gas}}\rangle,$$



Most of the metals at 2.5<z<4 are in absorbers (DLAs, LLS).

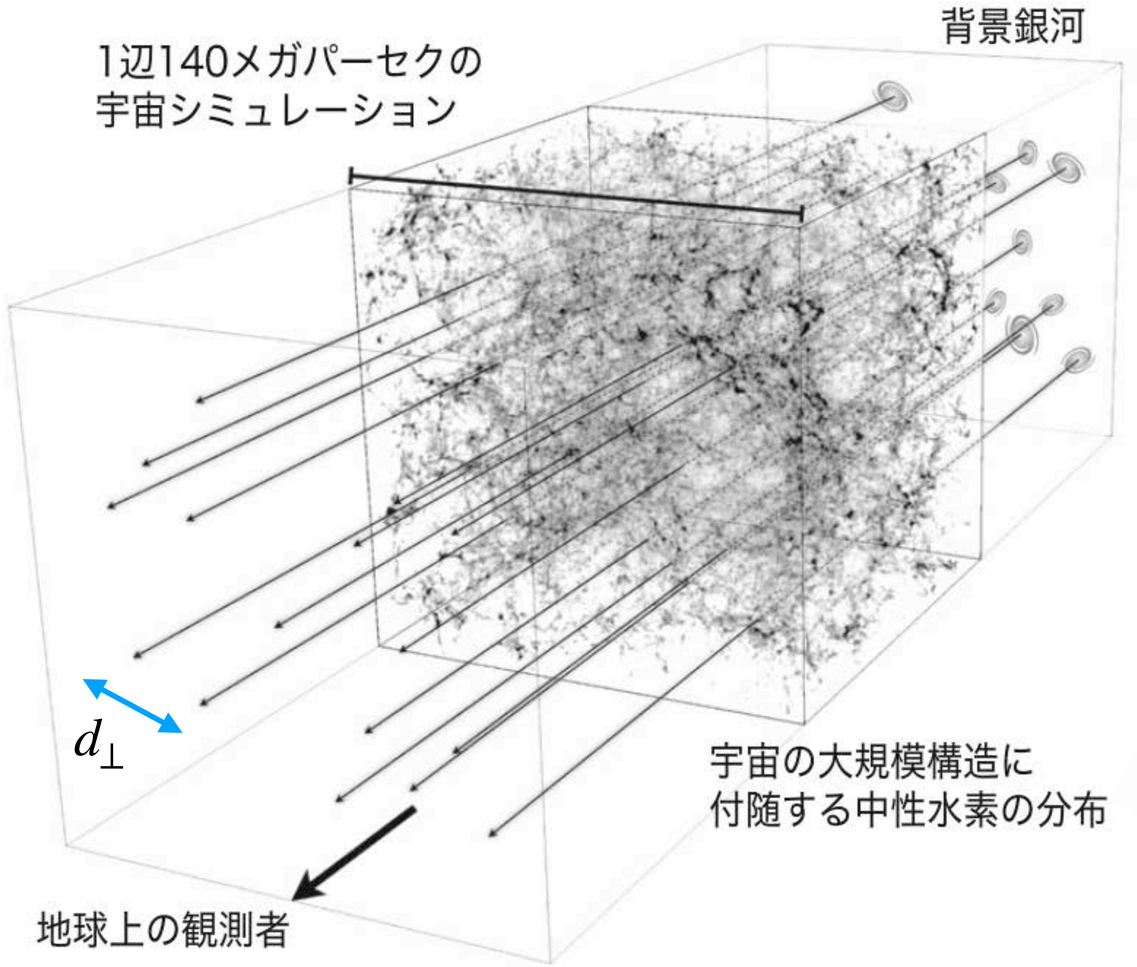
Peroux & Howk '00, ARAA

IGM tomography

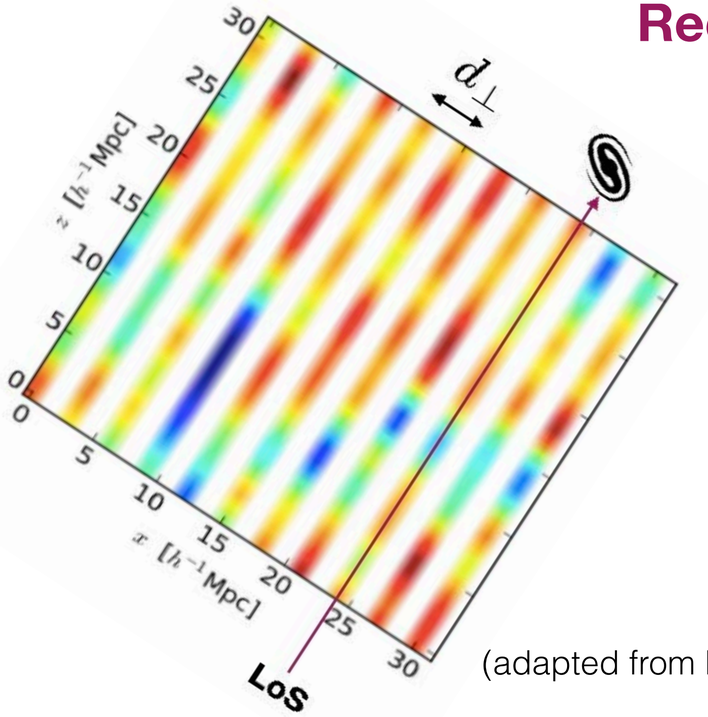
Numerous background star-forming galaxies

Many Lyα forest skewers

Reconstruct baryon density field



TMT JP Science Book 2020



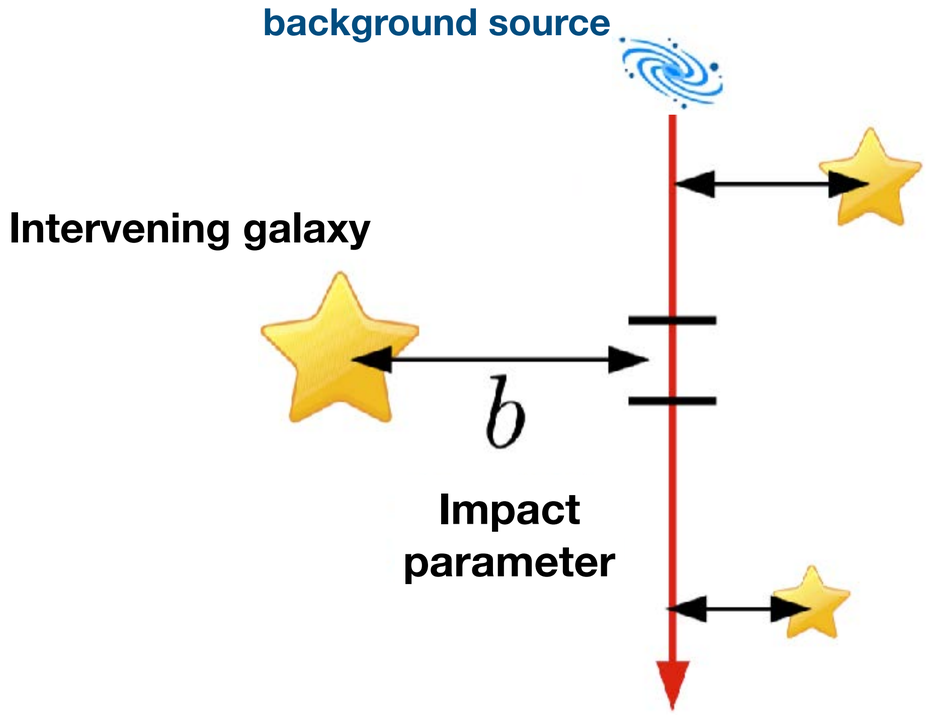
(adapted from M. White)

Probing CGM: Lyα forest mean flux contrast

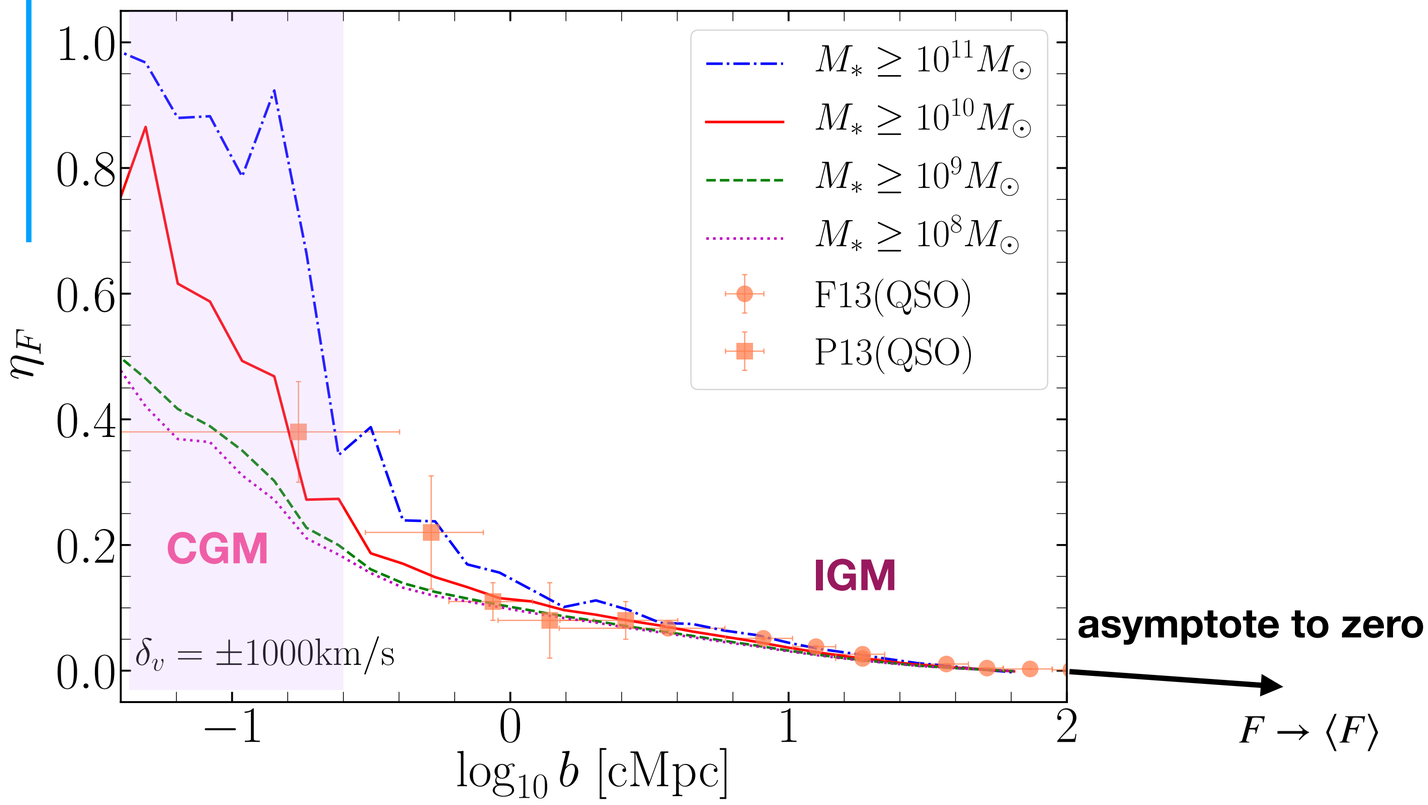
Flux Contrast

$$\eta_F \equiv -\delta_F = 1 - \frac{F}{\langle F \rangle}$$

$$F = e^{-\tau}$$



Stronger HI absorption



Impact Parameter from galaxies

KN+'21

- Understand gas density profiles
- Relation to dark matter halo

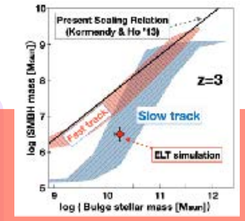
First Galaxies & Reionization

ELT, GMT, TMT
ALMA

LAE/LBG
Hα, Cii, Oiii

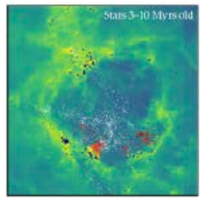
AGN
QSO

Subaru PFS, HSC
ULTIMATE-Subaru



LUVOIR
OST

Galaxy—SMBH coevolution, Seed BH

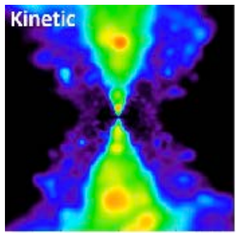


$f_{\rm esc}$

Color Bimodality
Downsizing
SF Quenching
Massive Gals.

AGN jet

ngVLA, ALHA



Physics of Feedback

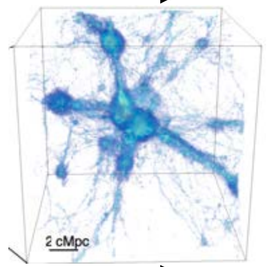
`Baryon Cycle'

CGM, IGM
Filament
tomography

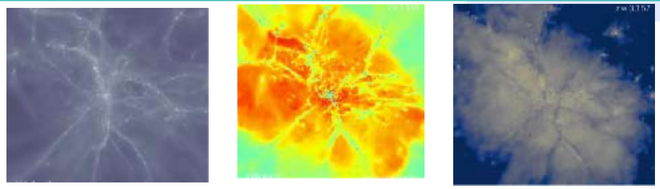
Cold inflow
Outflow

Cosmic Rays

Galaxy
Clusters

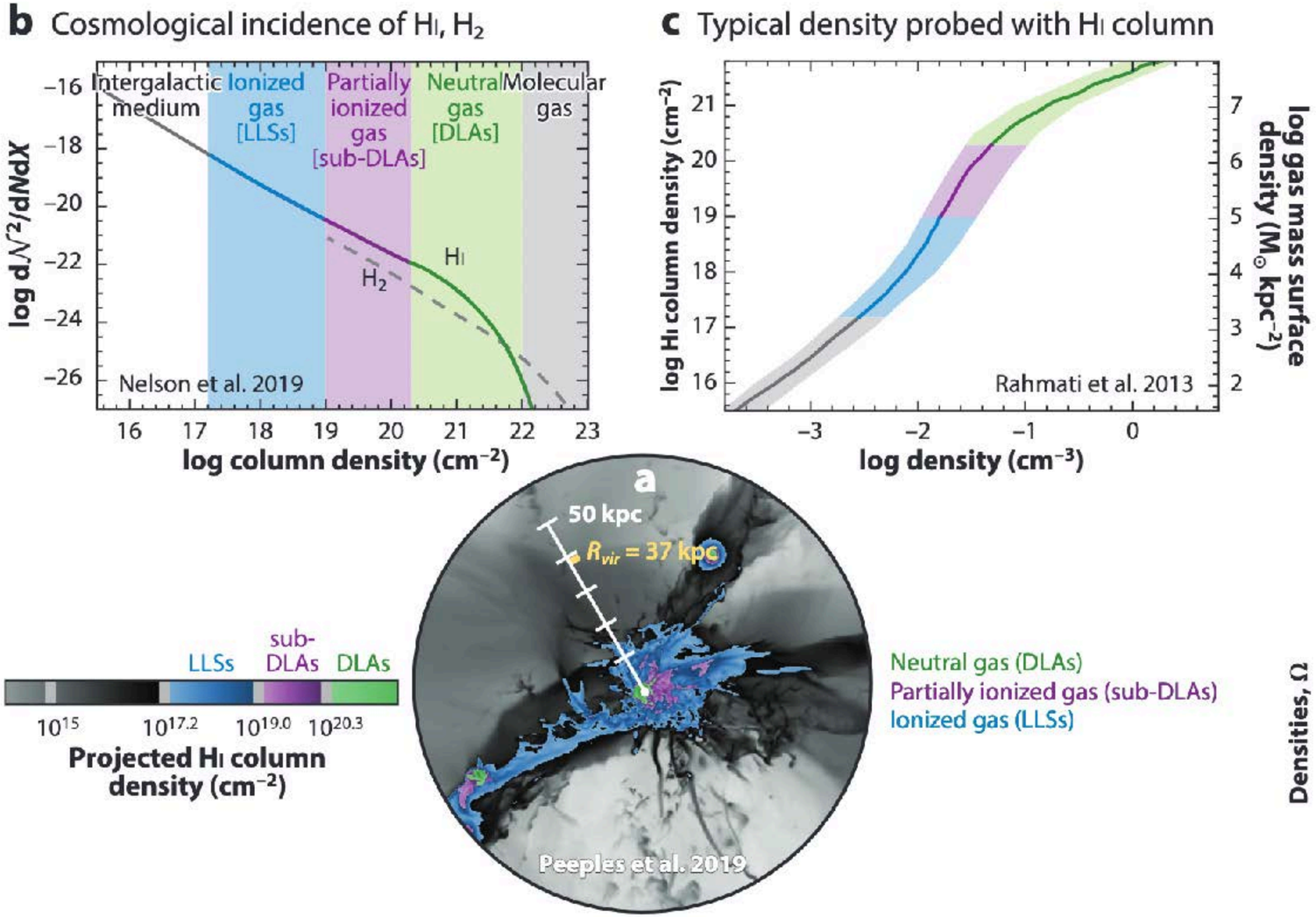


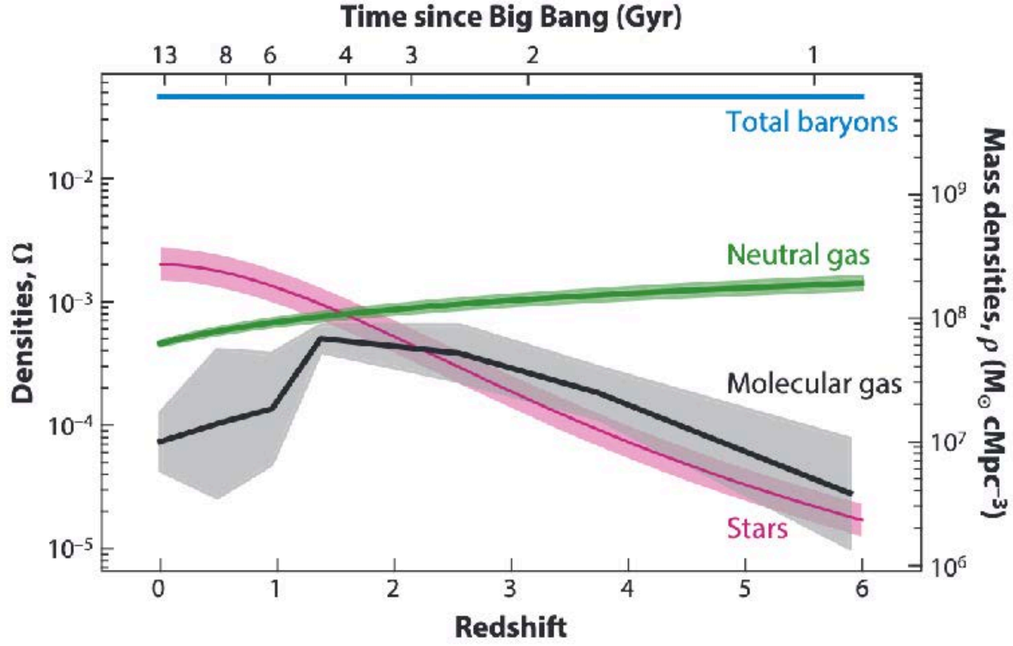
Census of Baryons & Metals



XRISM, Athena, FORCE, SuperDIOS

Supplement





Peroux & Howk '00, ARAA

Example: Science of ELT特推 – massive galaxies

1. 星形成活動の遷移

銀河を空間分解して、中心からの距離の関数として
H Balmer線を用いて、星の年齢を1億年の精度で測定する。

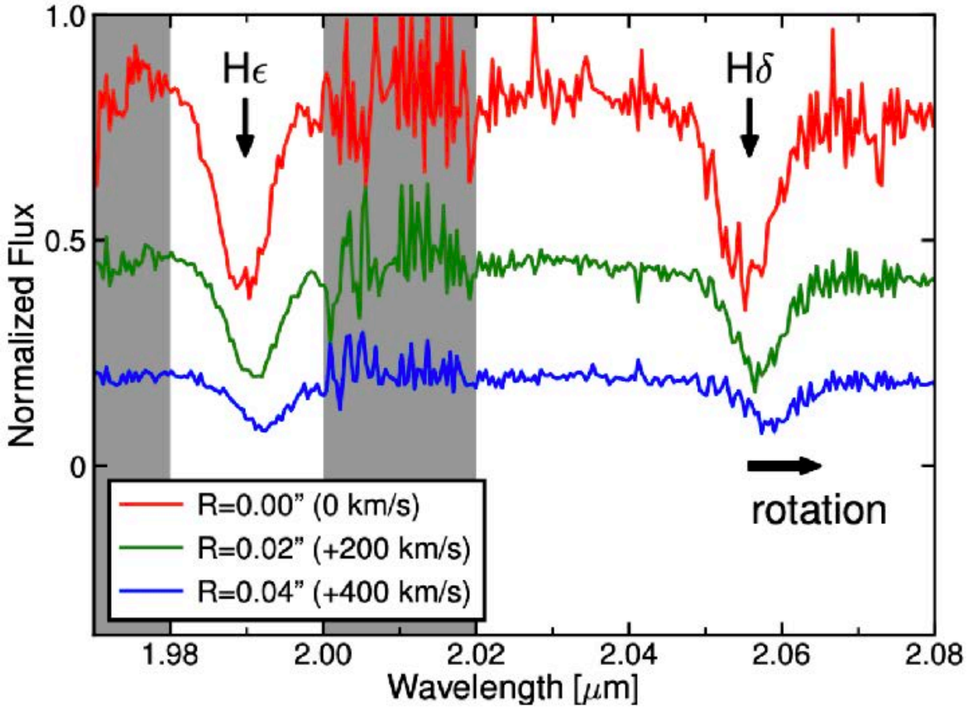
中心から外縁にかけて、星形成が止まったタイムスケール

2. 形態の遷移

バルジの獲得時期は？　(related to M-σ relation)

3. 運動の遷移

回転からランダム運動への遷移時期は？



Tadaki+, ELT特推申請書

Decadal Survey 2020 — Galaxy Panel

★ Most compelling science questions

Question D-Q1. How did the intergalactic medium and the first sources of radiation evolve from cosmic dawn through the epoch of reionization?

Question D-Q2. How do gas, metals, and dust flow into, through, and out of galaxies?

Question D-Q3. How do supermassive black holes form and how is their growth coupled to the evolution of their host galaxies?

Question D-Q4. How do the histories of galaxies and their dark matter halos shape their observable properties?

Discovery Area: Mapping the circumgalactic medium and the intergalactic medium in emission