EPCC-CCS workshop 2019 @ CCS, 12/3-4, 2019

Simulations of galaxy formation with radiative transfer and its application for near-infrared bio-imaging

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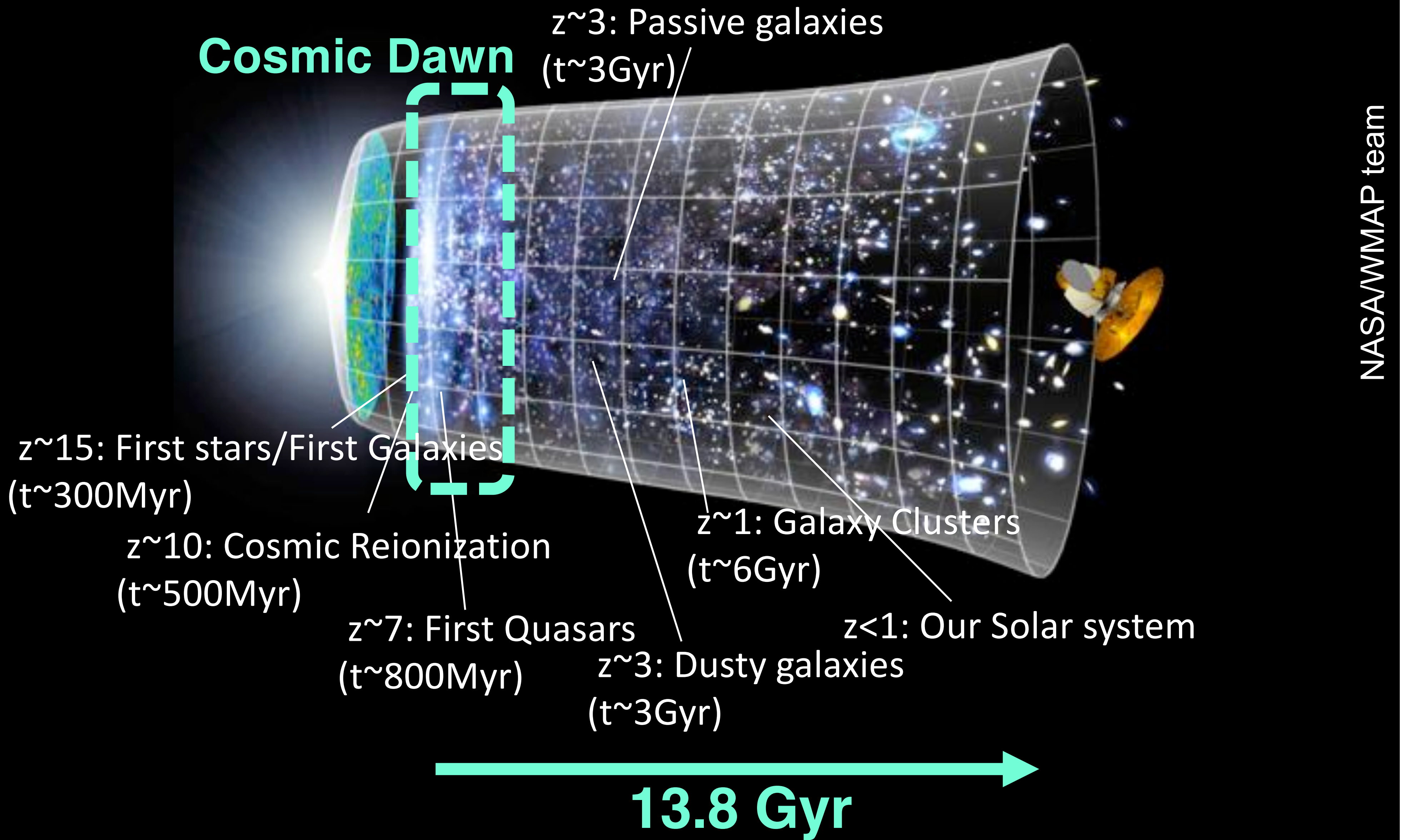
(CCS, University of Tsukuba)

History of our Universe



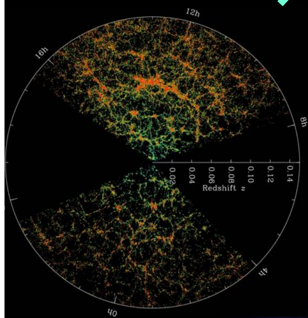
Theoretical astrophysics group

Large-scale structure

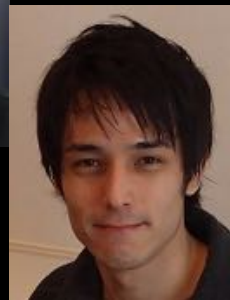
Inter-galactic medium

Large scale
~10^{20} km

7 faculty
8 pos-docs
23 students



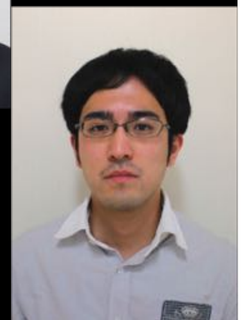
Galaxy



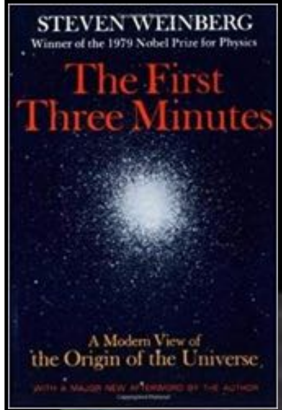
Black hole

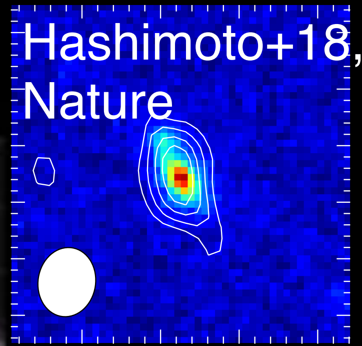
Small scale
~0.1μm

Planet/Dust



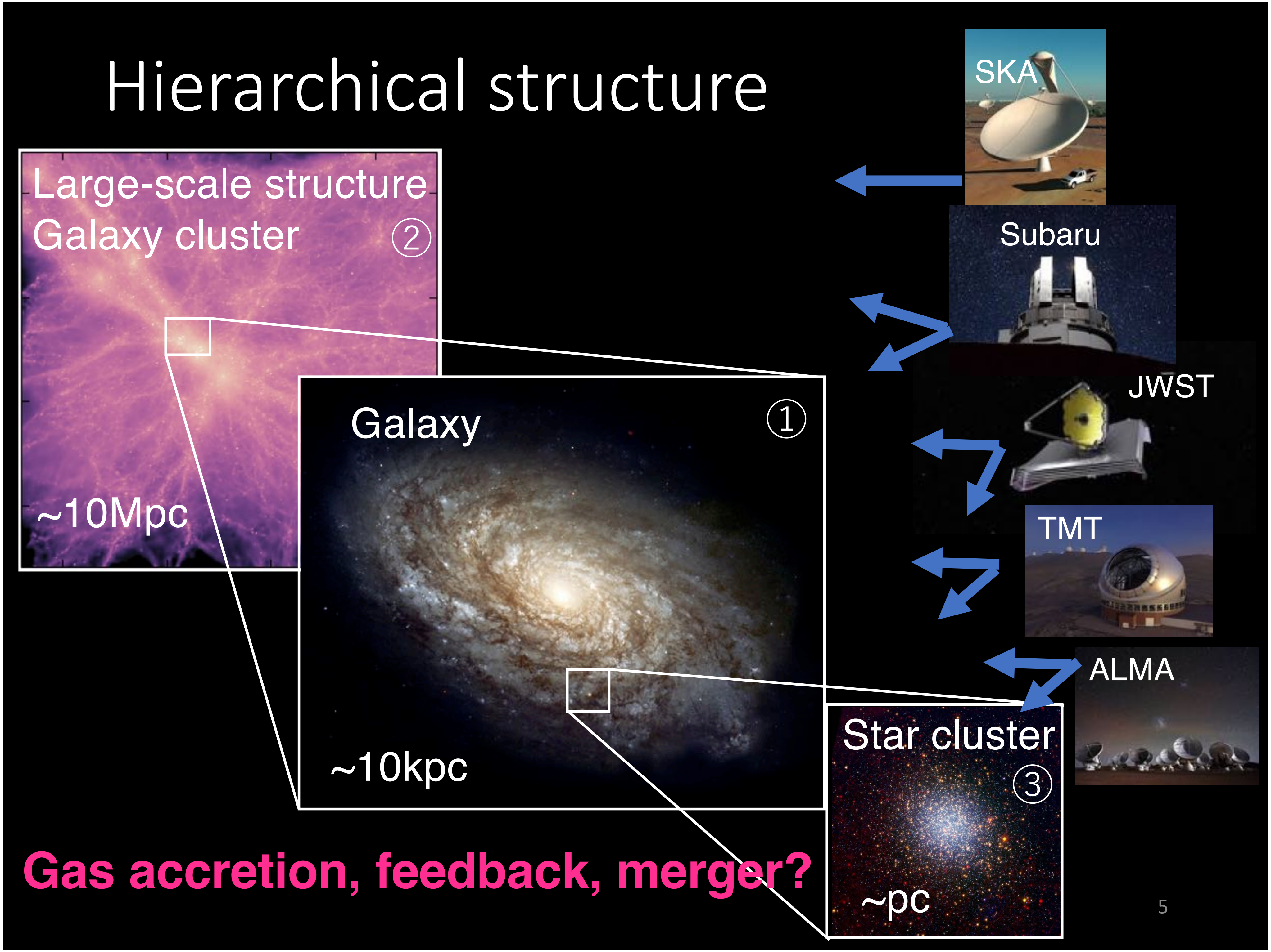
First billion years





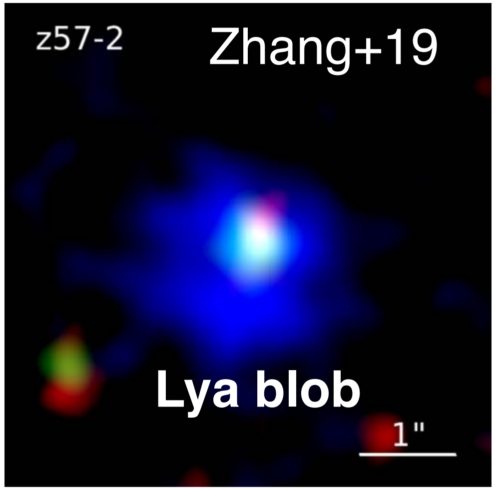
How first galaxies form and evolve?
What star formation history?
How radiation properties change with the galaxy evolution?
How massive BHs form?
How reionization proceeds?

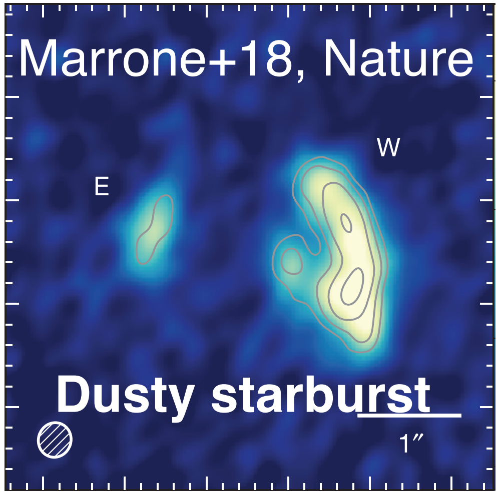
~2020s-2030s


Hierarchical structure
SKA
Subaru
JWST
TMT
ALMA
Large-scale structure
Galaxy cluster ②
~10Mpc
Galaxy ①
~10kpc
Star cluster ③
~pc
Gas accretion, feedback, merger?

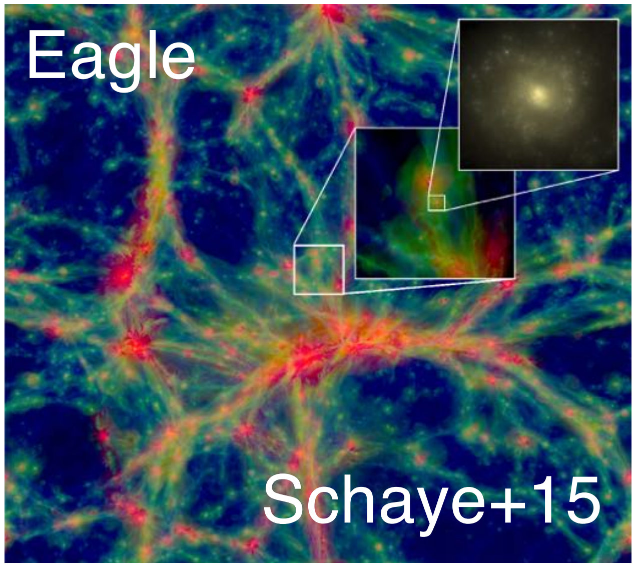
Diversity in observed galaxies

Various radiative properties of high-redshift galaxies





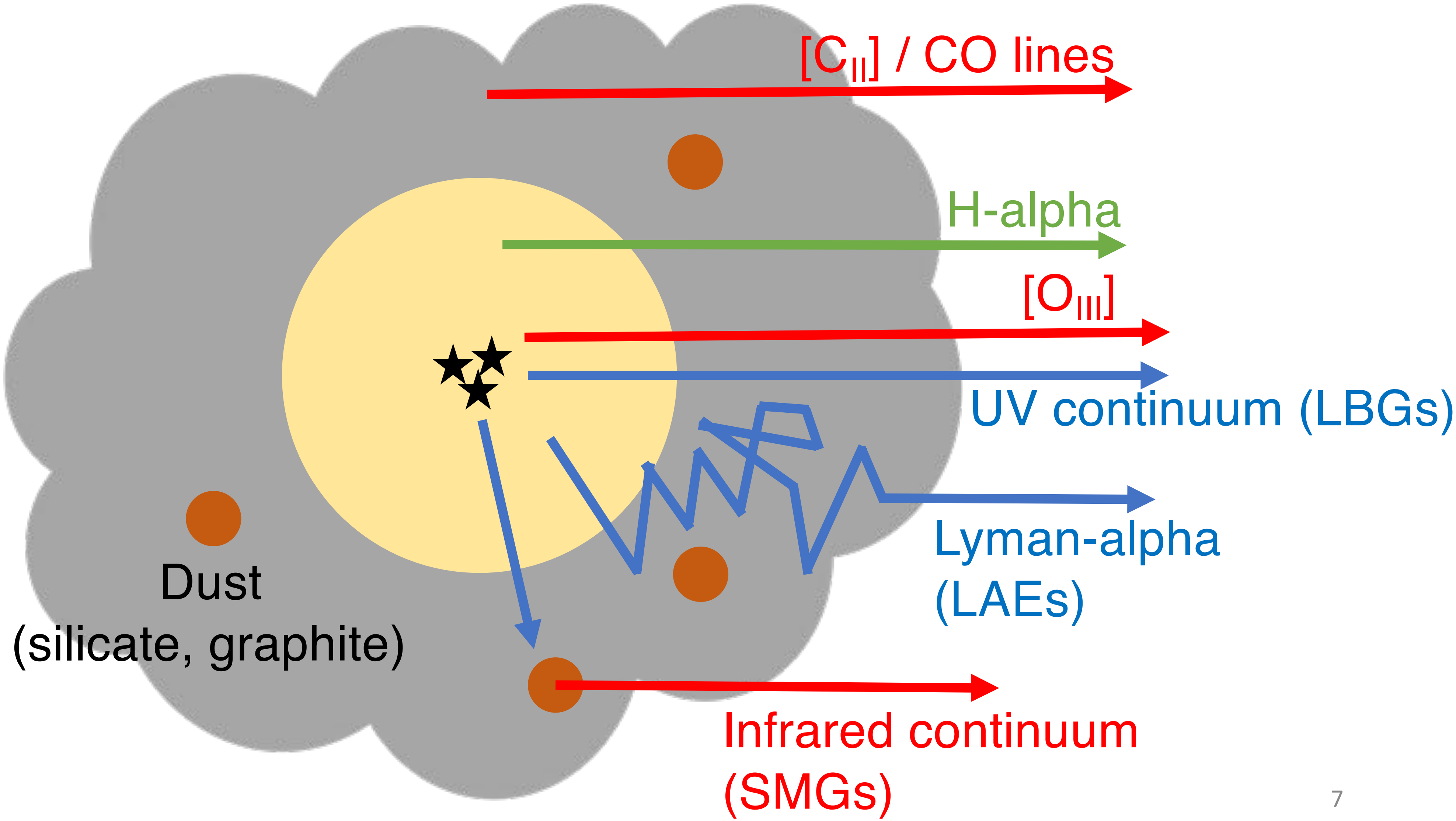
Numerical simulations



- ✓ Sub-grid models
- ✓ Feedback
- ✓ Statistics
- △ High-resolution

?

Radiative processes



Simulations

Cosmological hydrodynamics simulations
Gadget-3 (Springel+05; Johnson+13)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

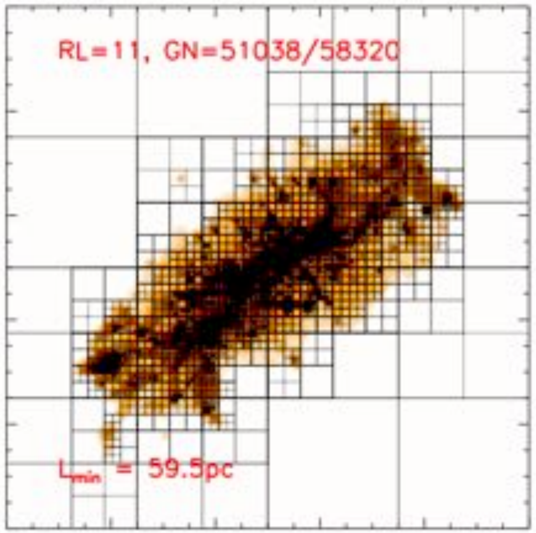
$$\rho \left[\frac{\partial v}{\partial t} + (v \cdot \nabla) v \right] = -\nabla p + F_{\rm rad} + F_{\rm grav}$$

$$\rho \left[\frac{\partial e}{\partial t} + (v \cdot \nabla) e \right] = -p \nabla v + \Gamma - \Lambda$$

Dark matter
Star formation
Feedback
Chemistry

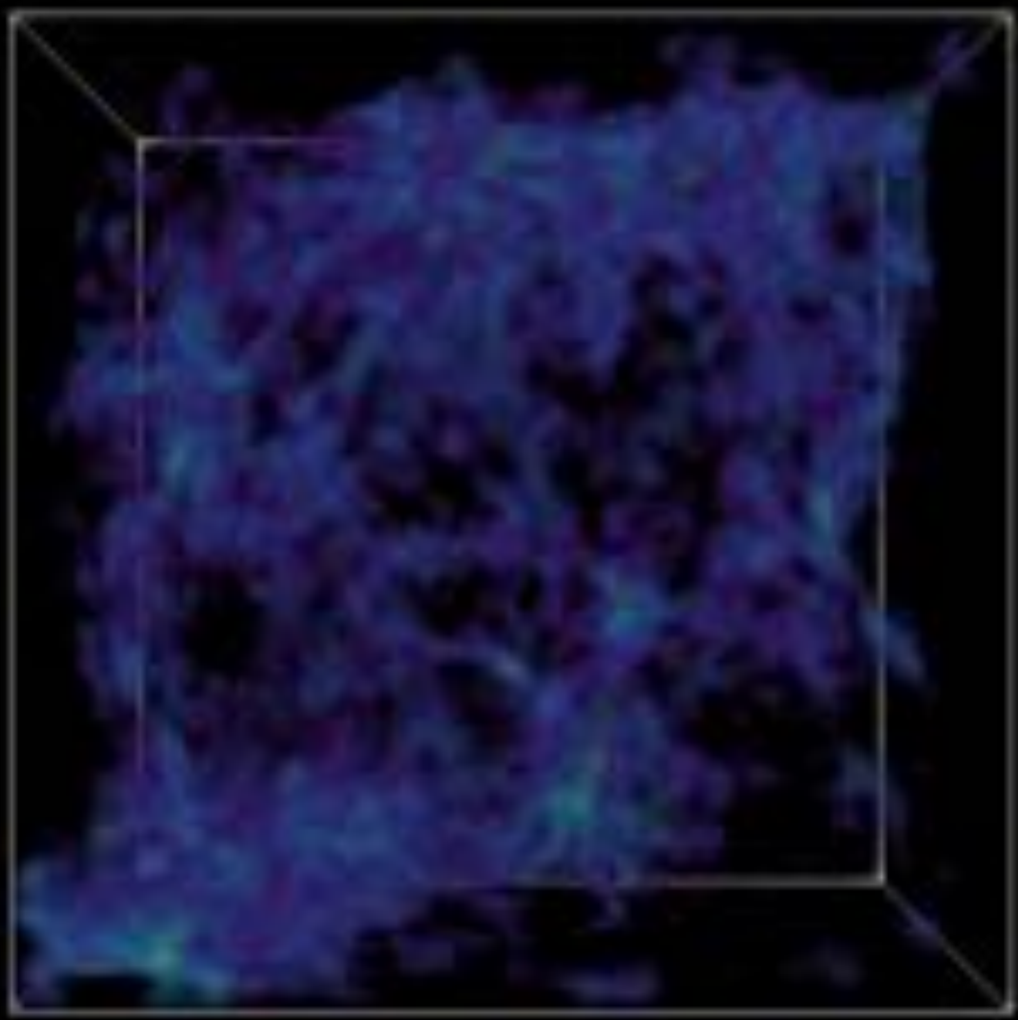
Multi-wavelength radiative transfer
ART^2 (Li+08; Yajima+12)

$$\frac{\partial I}{c \partial t} + n \cdot \nabla I = -\alpha I + \epsilon + \oint \phi(\Omega', \Omega) I d\Omega'$$



Formation of first galaxy

(**Yajima** et al. 2017, ApJ, 846, 30)



250 kpc/h (comoving)

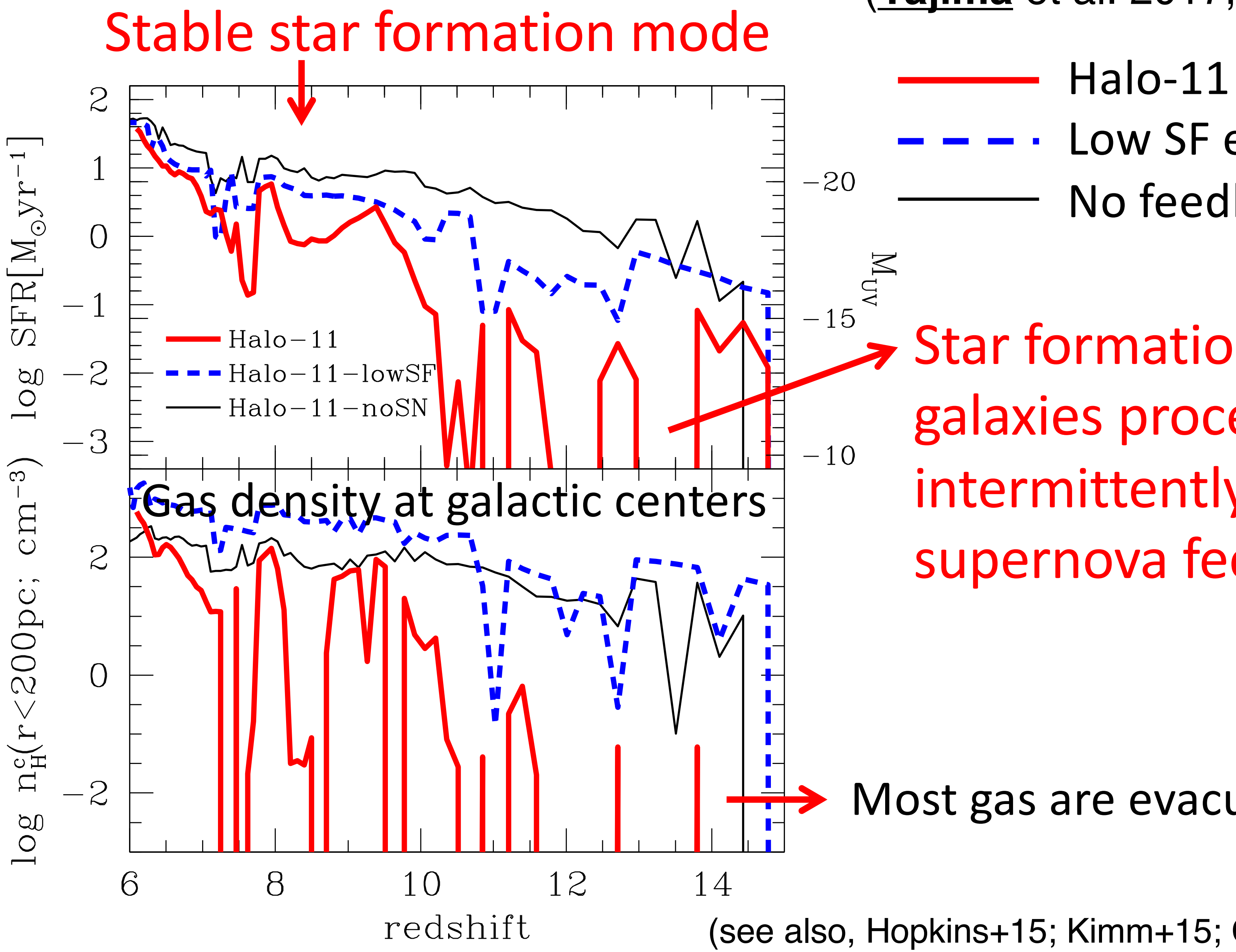
Zoom-in simulation
L_{box}=20Mpc
L_{zoom}~1Mpc
$M_{halo}=10^{11}M_{sun}$

Blue
(gas density)

Yellow
(Metal-enriched gas)

Star formation history

(**Yajima** et al. 2017, ApJ, 846, 30)

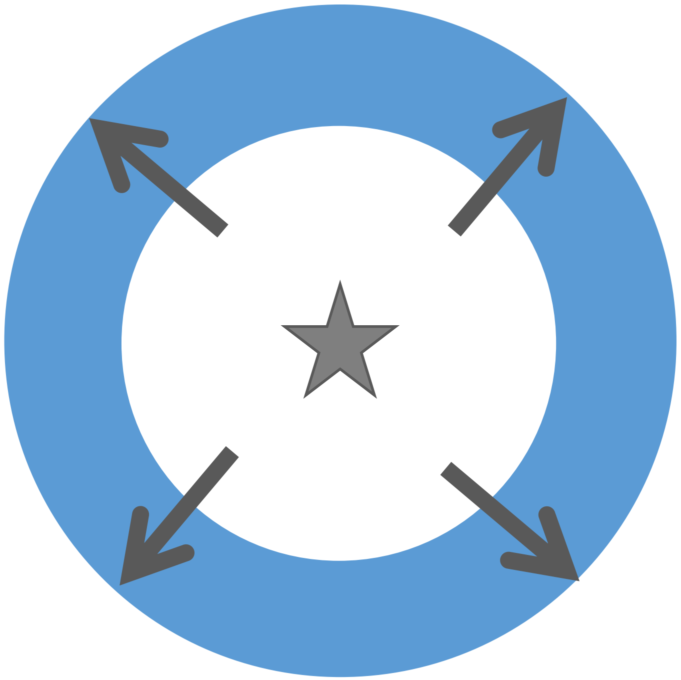


Star formation in first galaxies proceeds intermittently due to the supernova feedback

Most gas are evacuated

(see also, Hopkins+15; Kimm+15; Ceverino+18)

Critical halo mass based on a spherical shell model



$V_{outflow} > V_{esc}$?

$$M_{gas}V_{outflow} = \sqrt{2\eta_{SN}^{0}E_{SN}M_{cool}}$$

$$\eta_{SN} = \eta_{SN}^{0}\frac{M_{cool}}{M_{gas}}$$

M_{cool}: Gas mass in cooling radius

M_{gas}: Total gas mass

$$V_{esc} = \sqrt{\frac{2GM_{h}}{R_{vir}}}$$

↓

$$M_{h,crit} = 0.8 \times 10^{10}\ M_{\odot}\left(\frac{\epsilon_{SF}}{0.1}\right)^{3/2}\left(\frac{\eta_{SN}}{0.5}\right)^{3/2}\left(\frac{1+z}{7}\right)^{-3/2}$$

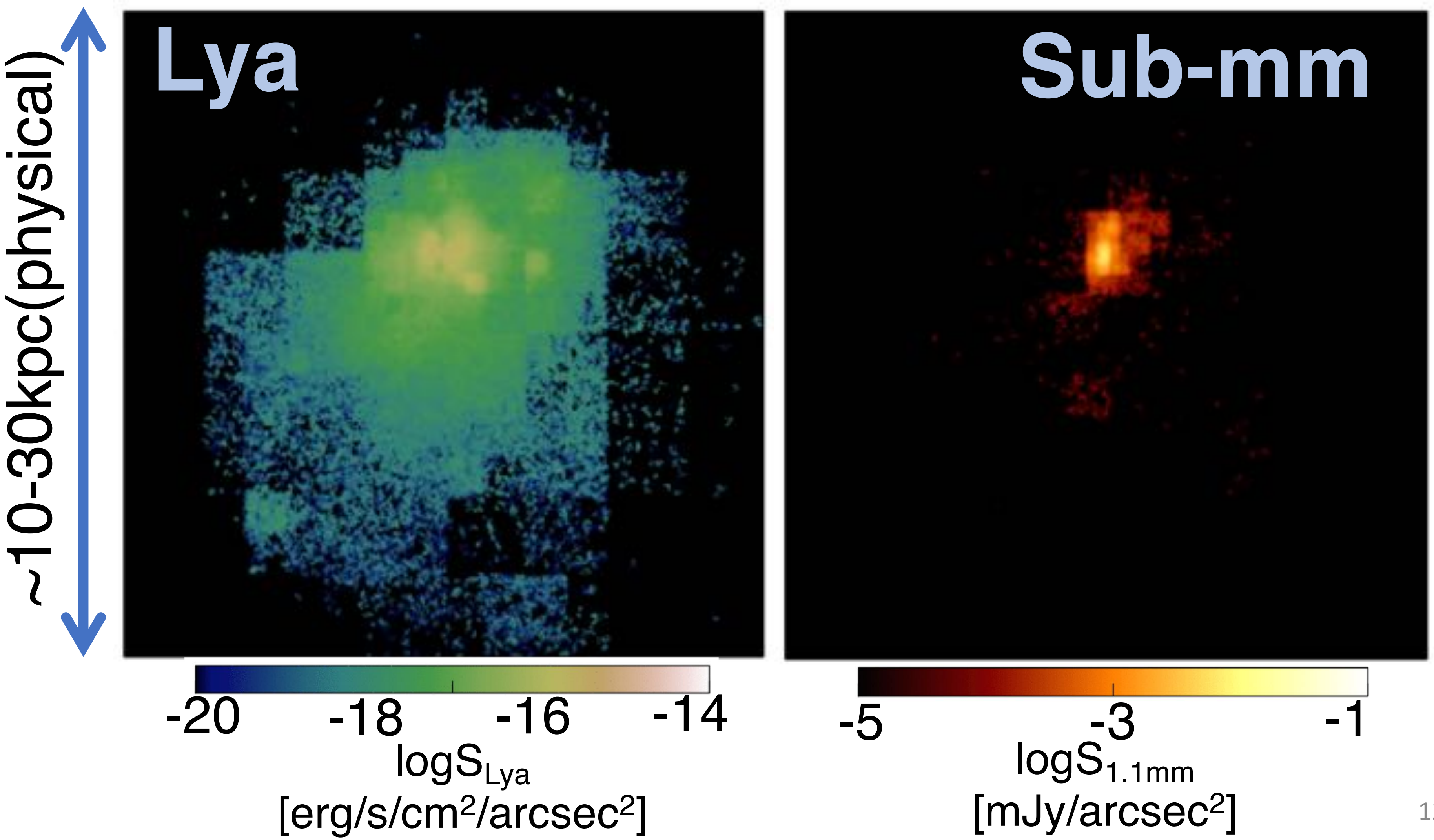
ϵ_{SF}: Star formation efficiency

η_{SN}: Energy conversion rate

Radiative transfer calculations

Surface brightness (z=10➔6)

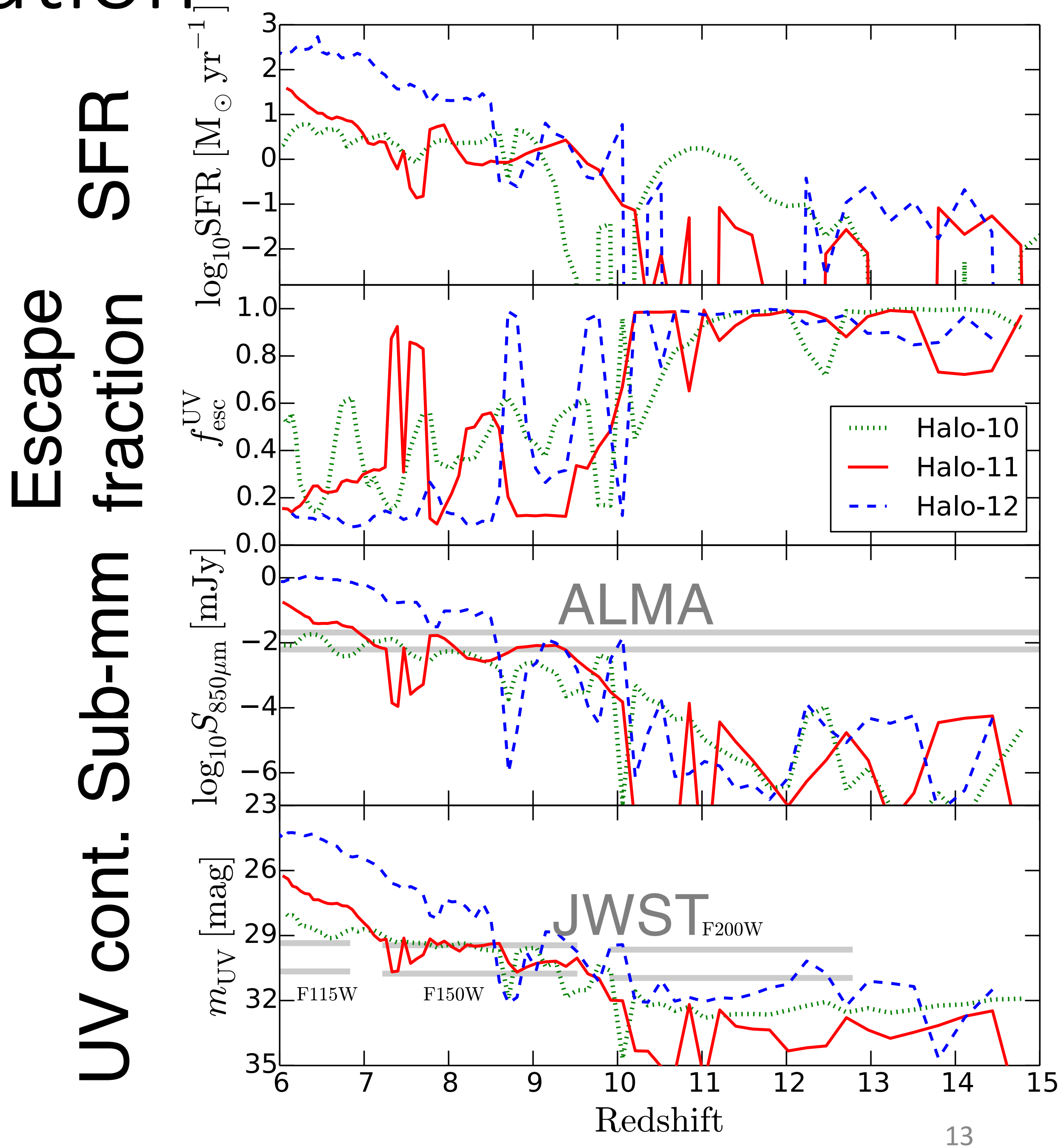
Halo-11



Redshift evolution of flux

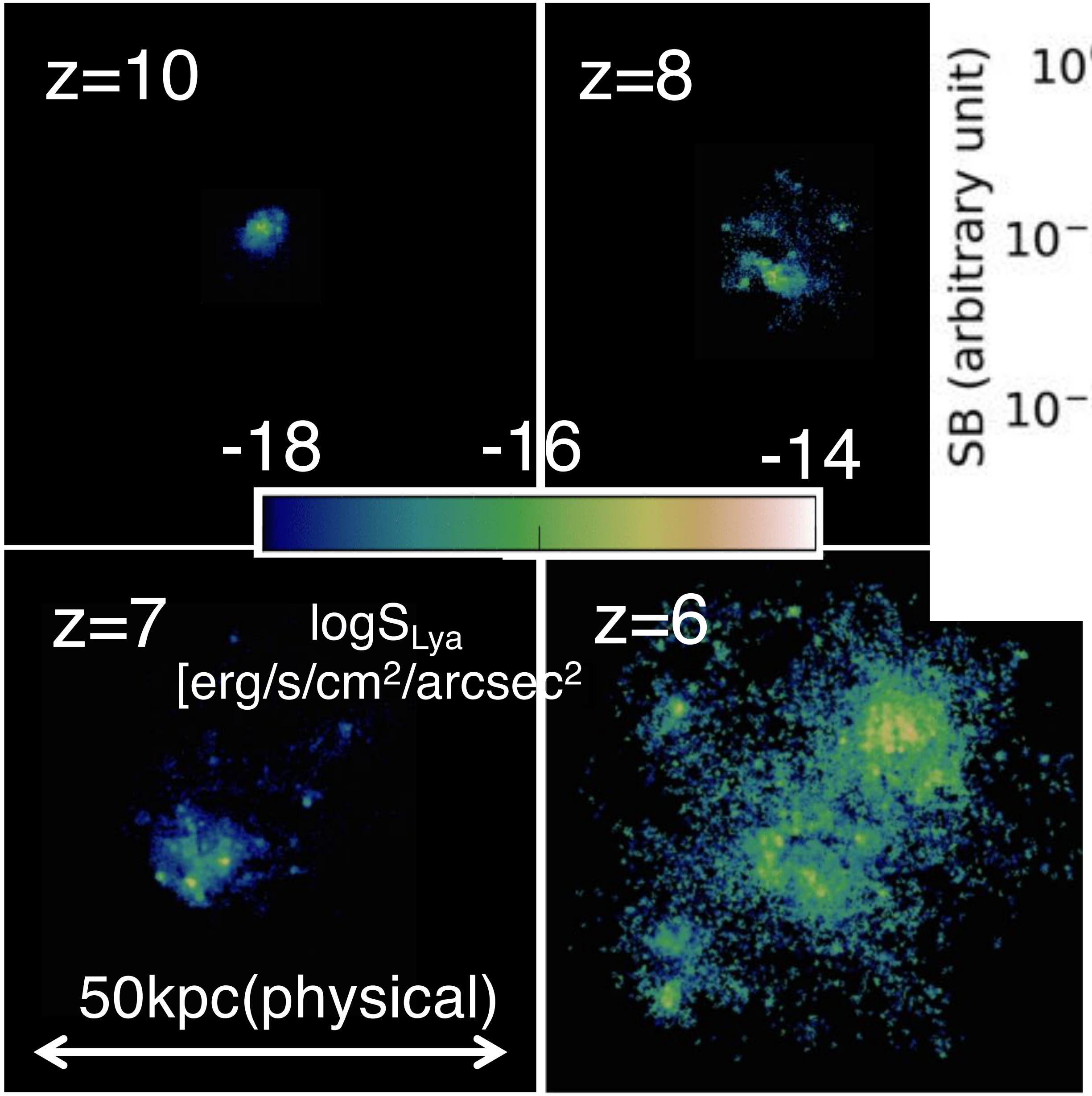
Time scale of the fluctuation

$$t \sim \frac{\lambda R_{\rm vir}}{V_{\rm c}}$$
$$\lesssim 10\ {\rm Myr}$$

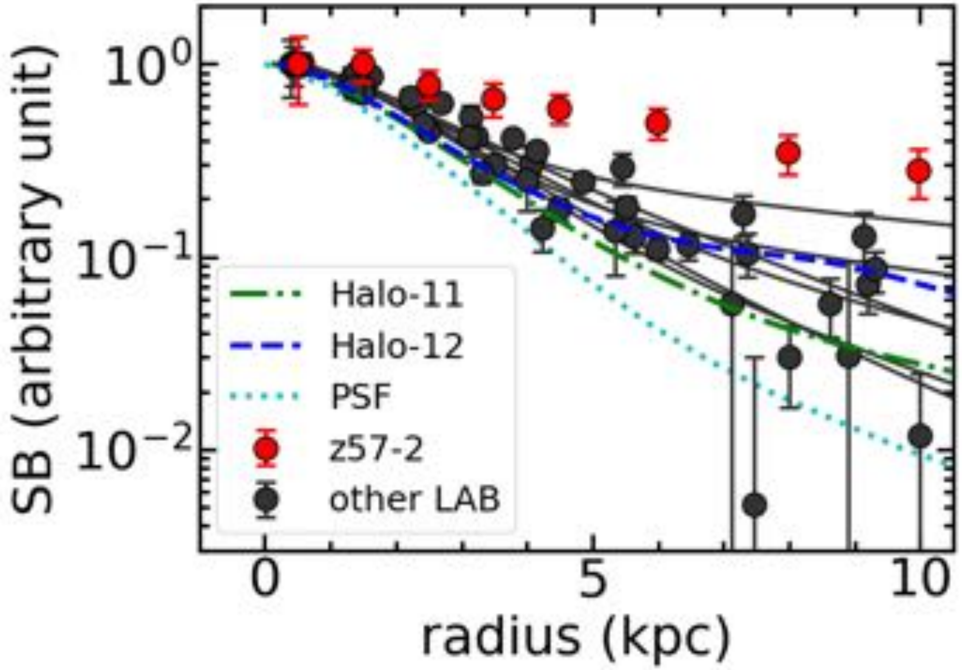


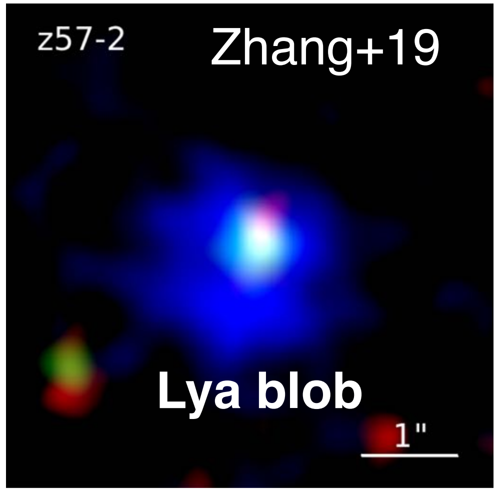
Arata, **Yajima**, et al. (2019)

Lya surface brightness



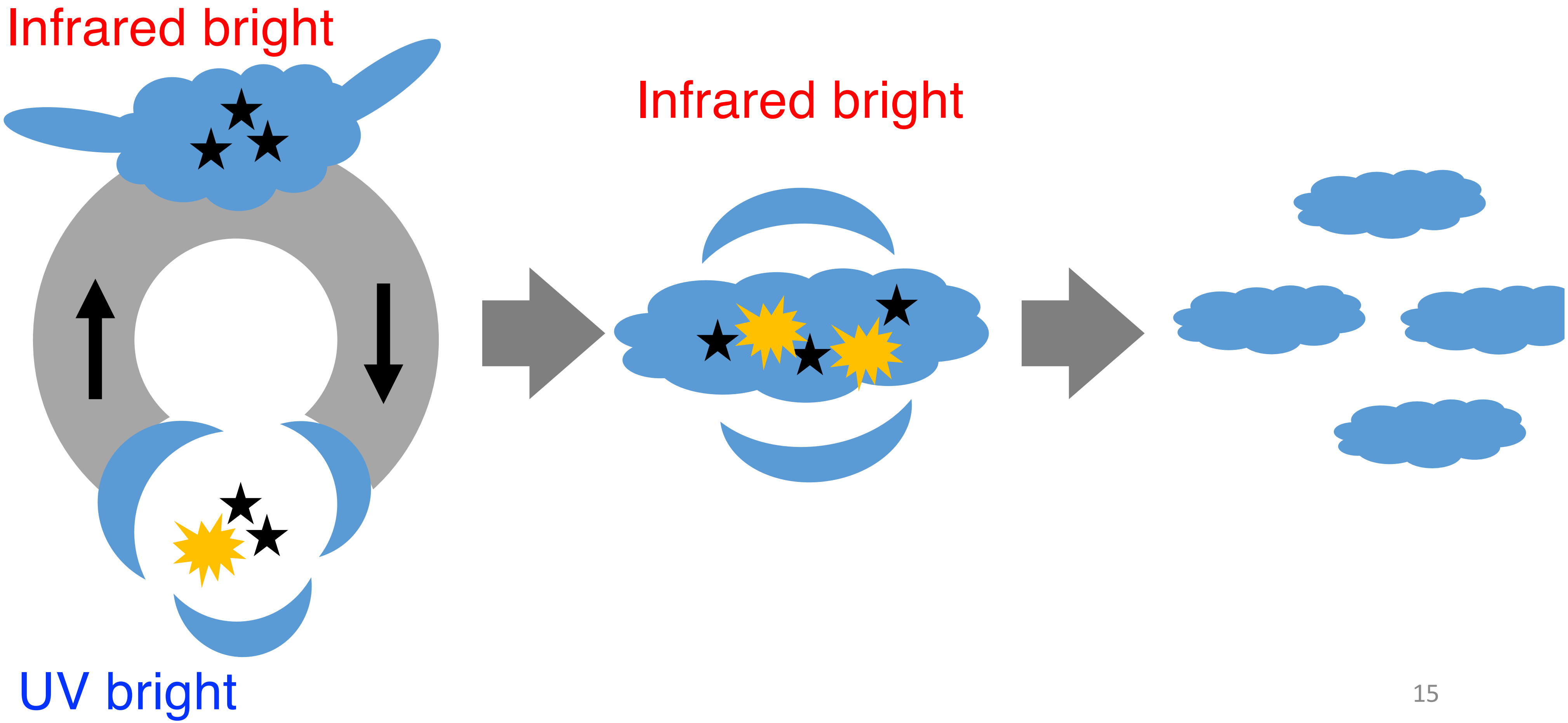
Zhang,, **Yajima**, et al. (2019)





Rapid change of radiative properties

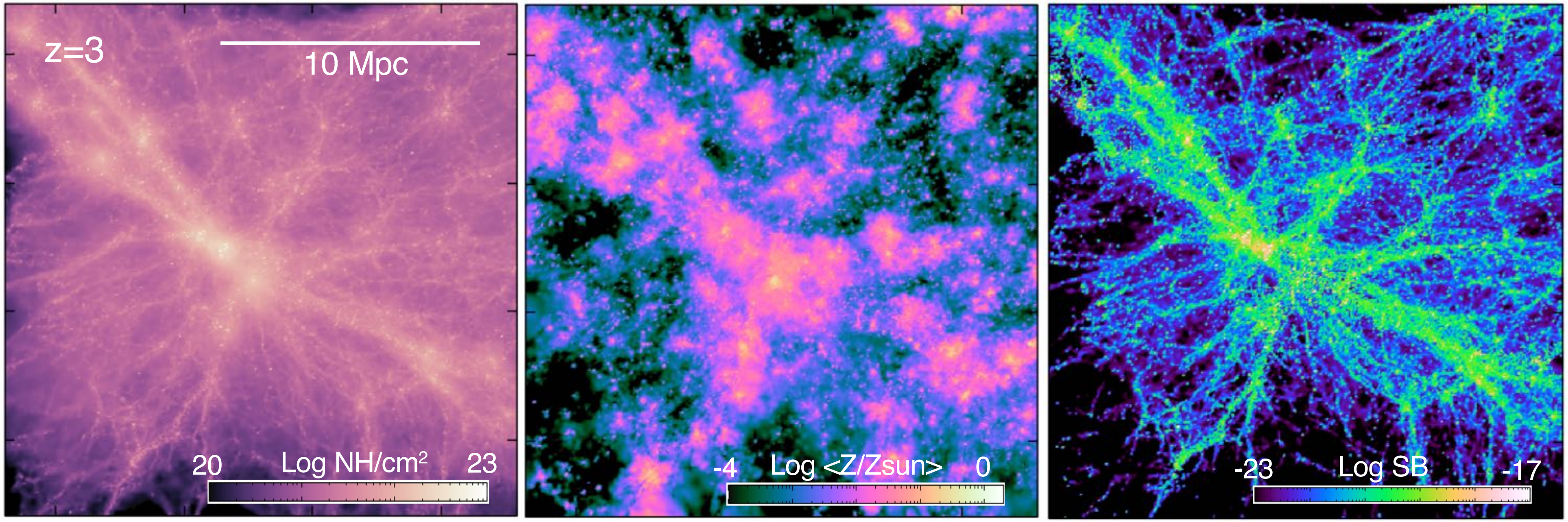
Low-mass galaxies ($M_{halo} < 10^{11}$ M_{sun}) | Massive galaxies ($M_{halo} \sim 10^{11\text{-}12}$ M_{sun}) | Clustering ($M_{halo} \sim 10^{13}$ M_{sun})



Lya intensity map

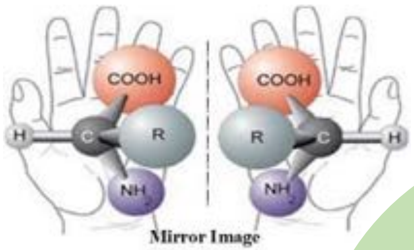
We consider Lya cooling radiation under UVB
(Stellar and AGN radiation are not included)

Gas Metal Lya



Metal enriched along filaments
Filaments are bright at Lya line

Interdisciplinary science



Astrophysics

Prof. Umemura
Dr. Yajima
Dr. Abe
Dr. Takamizu
Mr. Tazaki
+
Prof. Hoshi (MD)

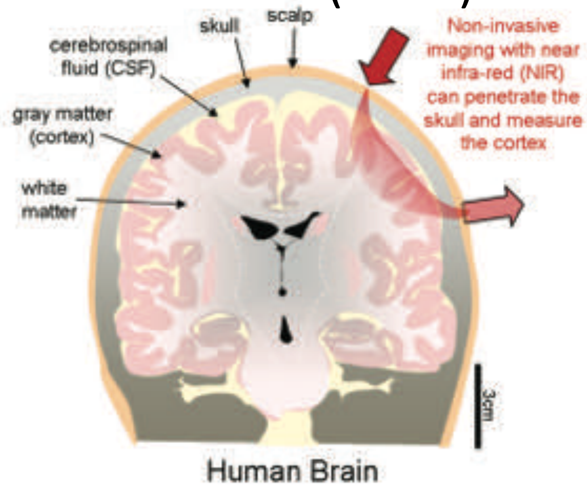
Astrobiology

Medical bioimaging

High-performance computing (FPGA/GPU)

Optical/NIR bio-imaging

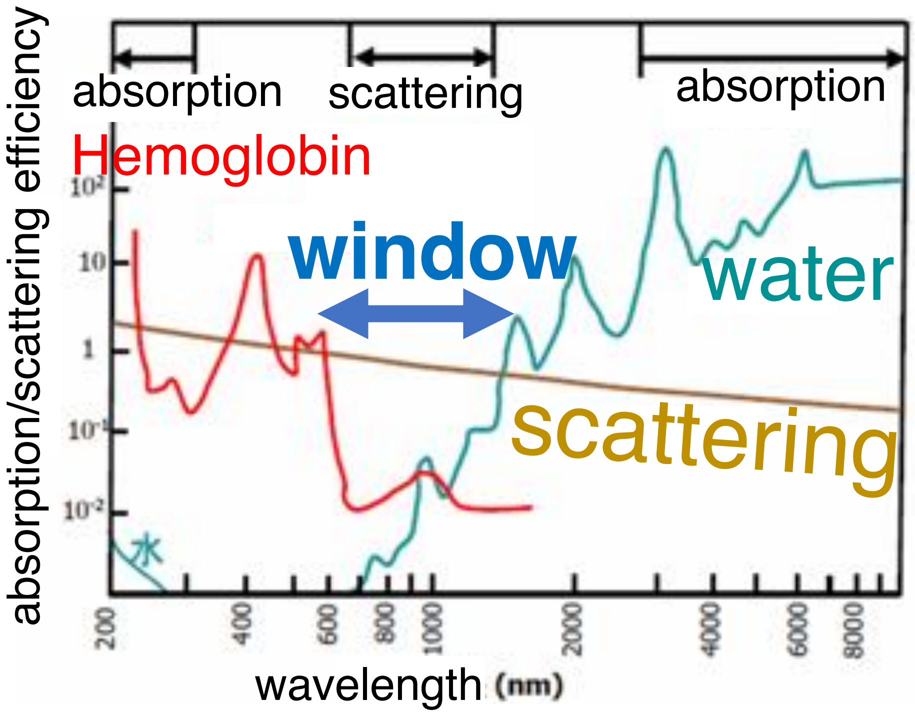
Hillman (2007)



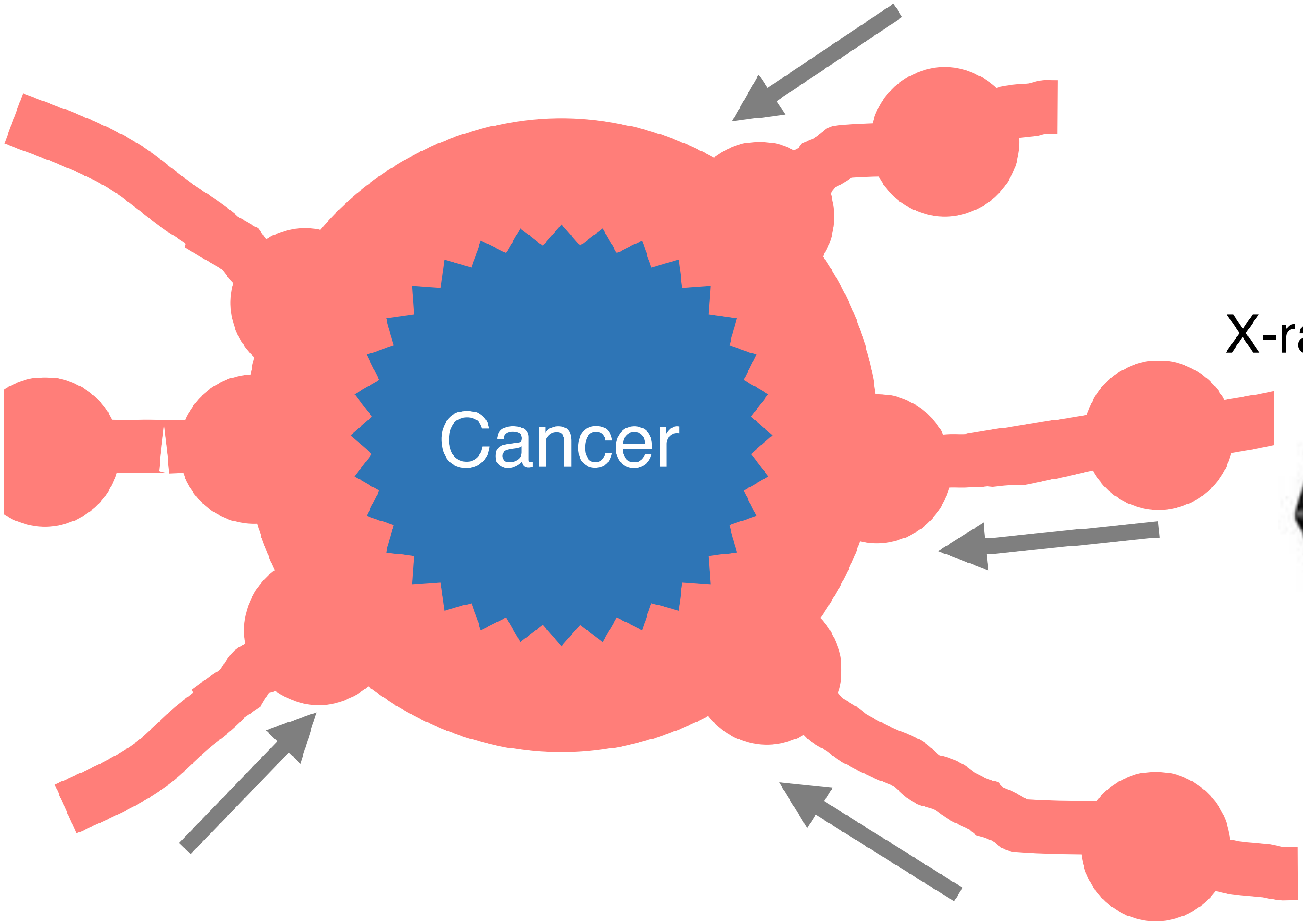
Medical diagnosis using near-infrared light which is returned from a human body via scattering processes

This diagnostic method requires radiative transfer simulations

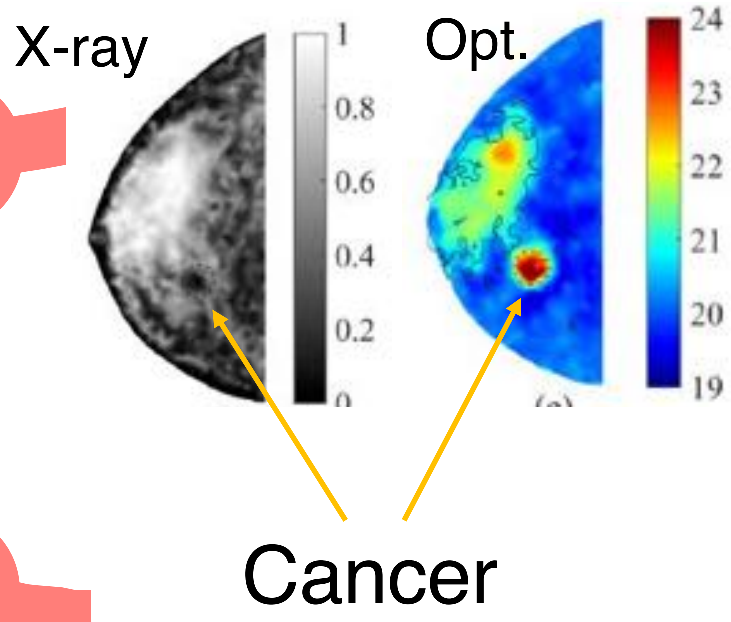
No radiative exposure,
Non-invasive,
No contrast medium required,
No side effect,
Low-cost, high-time resolution
So, OK for new-born babies and infants



Cancer gathers blood

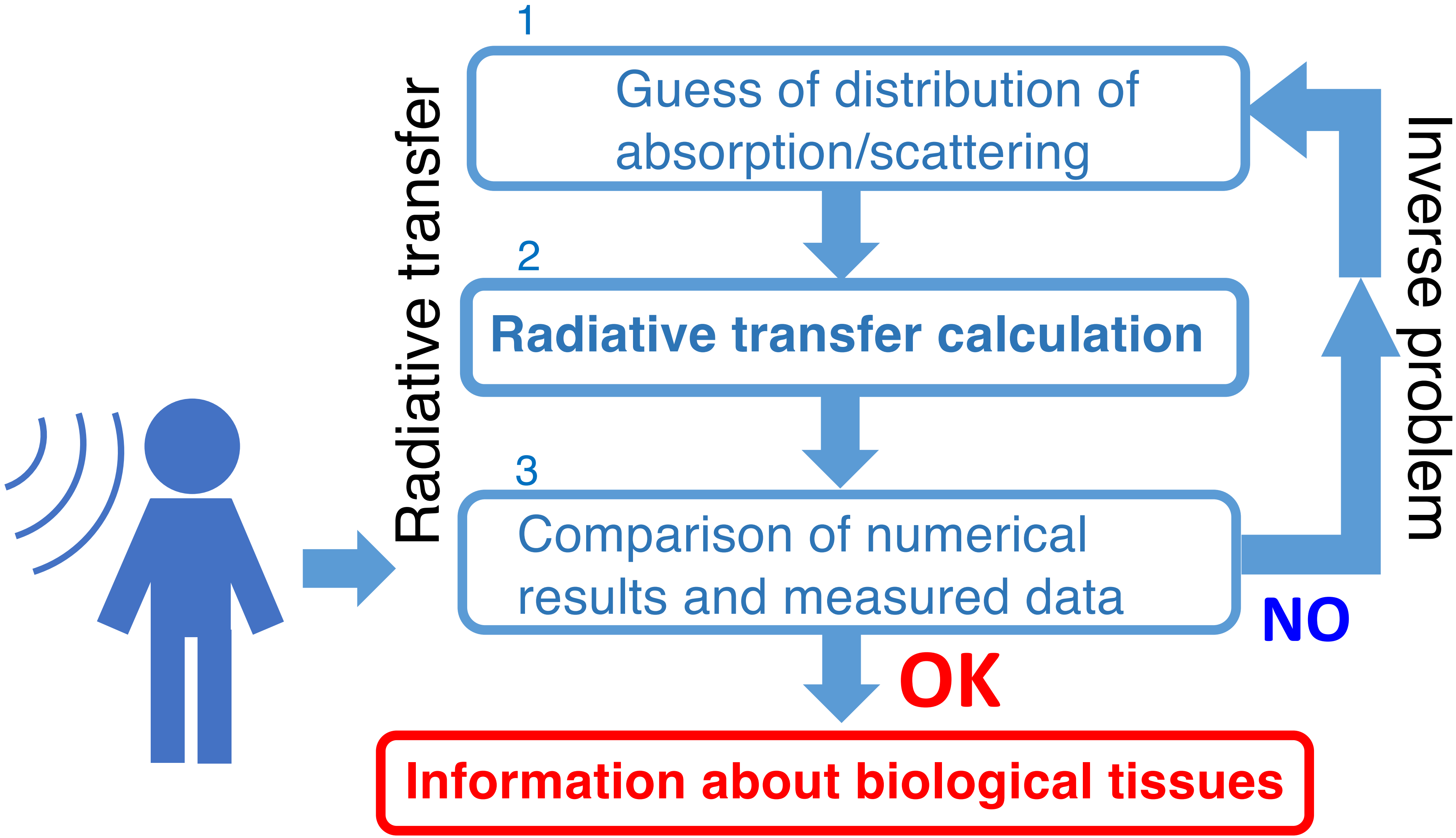


Breast cancer



Increase of absorption efficiency

Diffuse Optical Tomography (DOT)

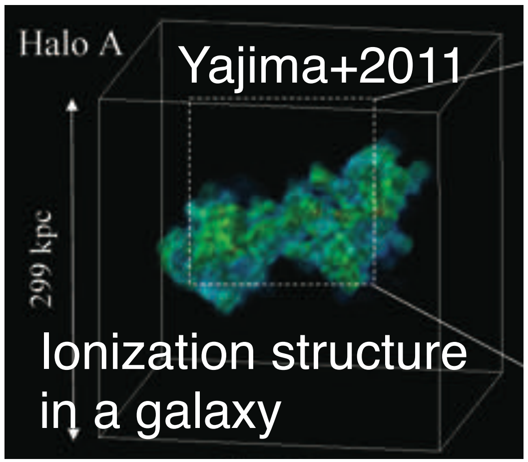


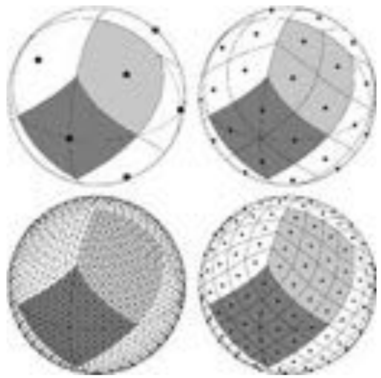
Numerical simulations of radiative transfer in a human body

<u>Basic equation</u>

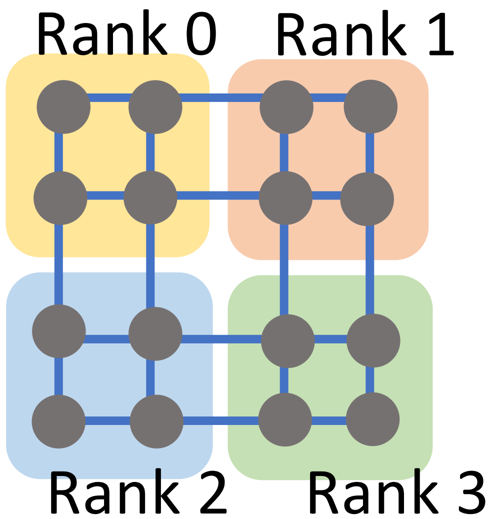
$$\frac{\partial I}{c\partial t} + n \cdot \nabla I = -\alpha I + \oint \phi(\Omega', \Omega) I d\Omega'$$

* Scheme: ART method (Yajima+2009)
* Angle grids made by HEALPix
* Parallelization: domain decomposition





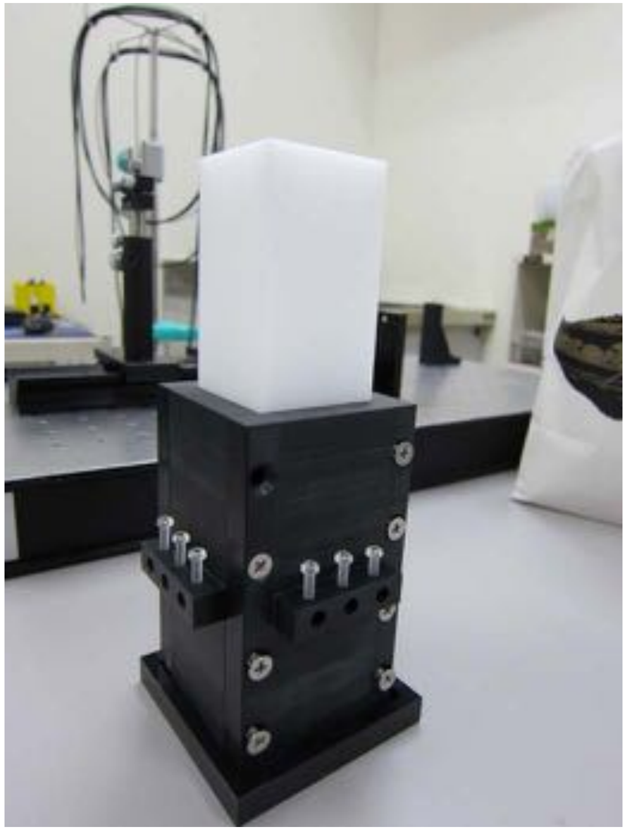
HEALPix (Gorski et al. 2005)

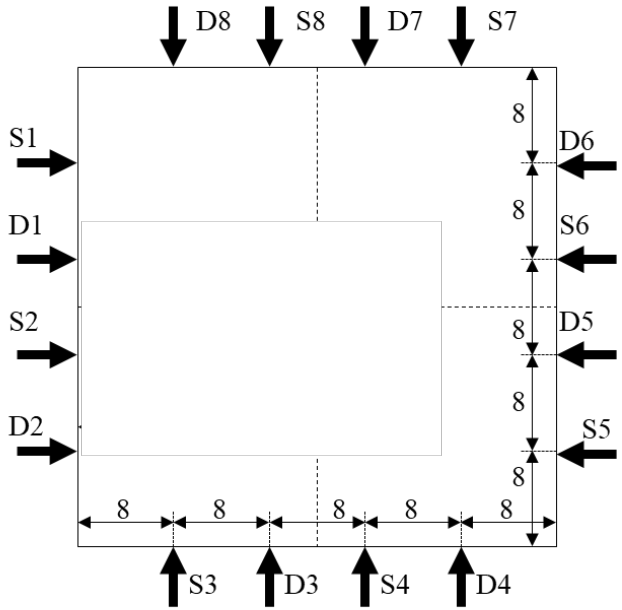


Test calculation

Pulse injection test for polyurethane modeling biological tissues

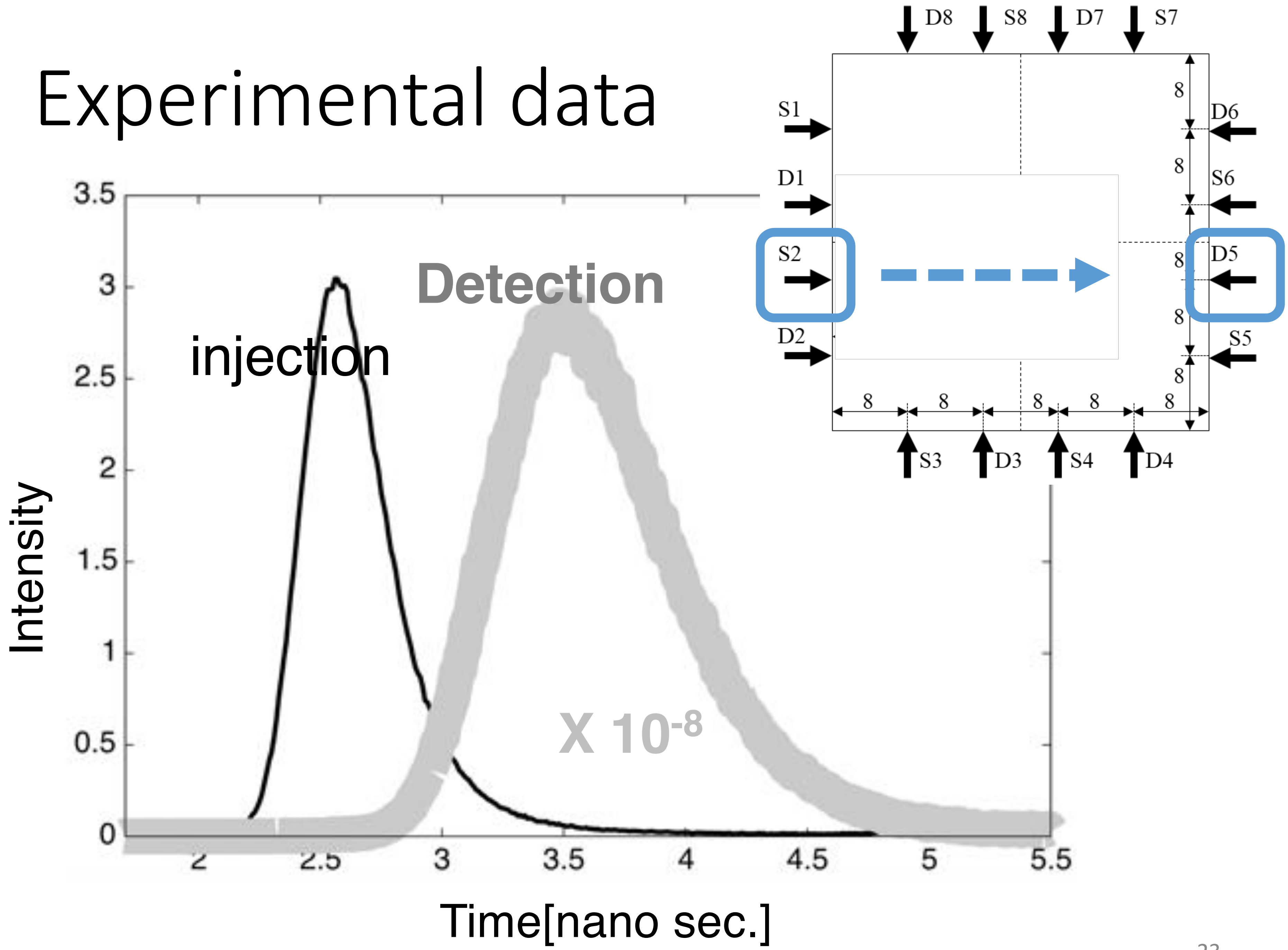
From Prof. Hoshi



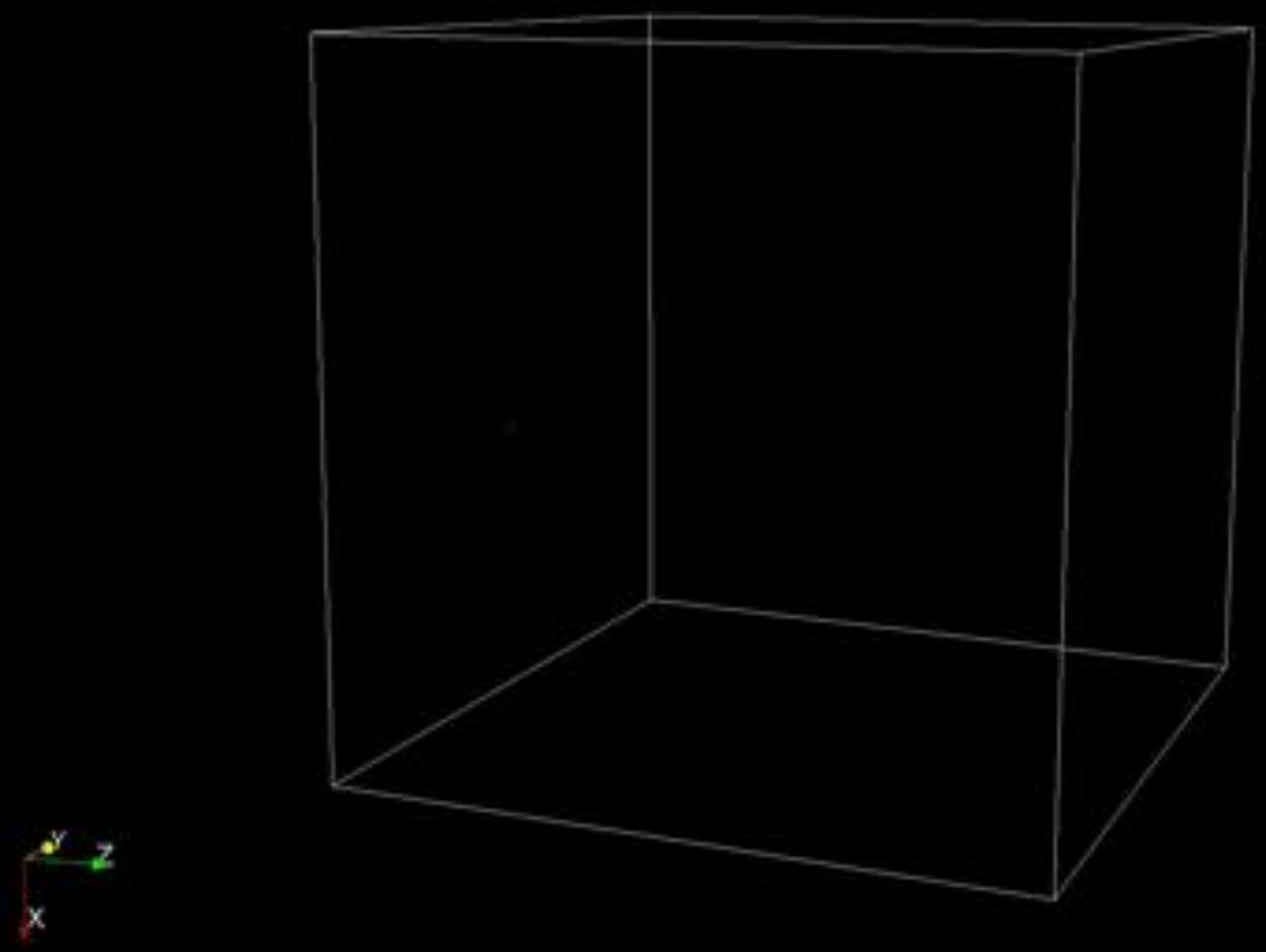


S, 照射；D, 受光、最短SD間隔, 8 mm
計測平面：ファントム底面から、35 mm, 45 mm, 55 mm

Experimental data

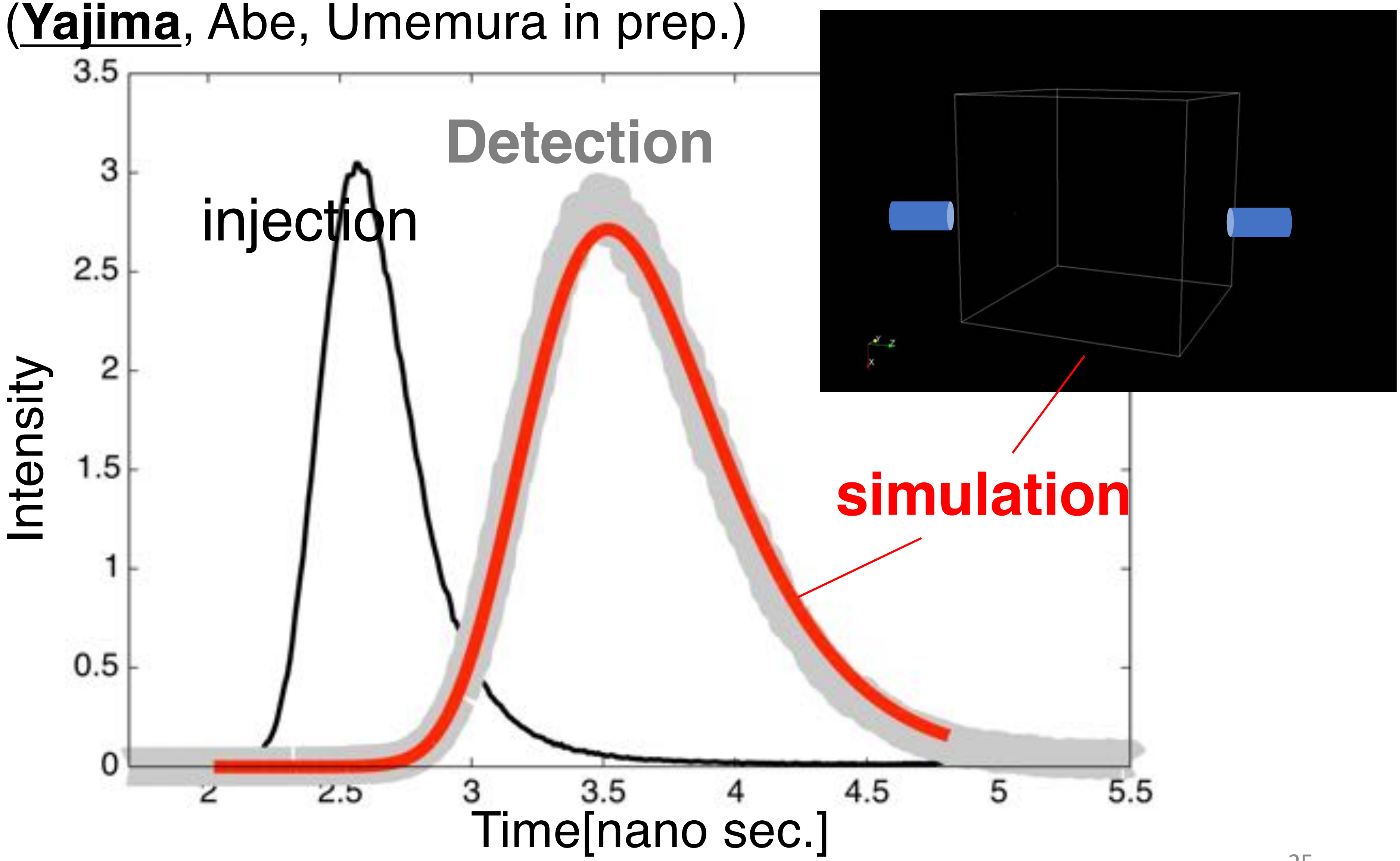


Simulation results



Simulation results

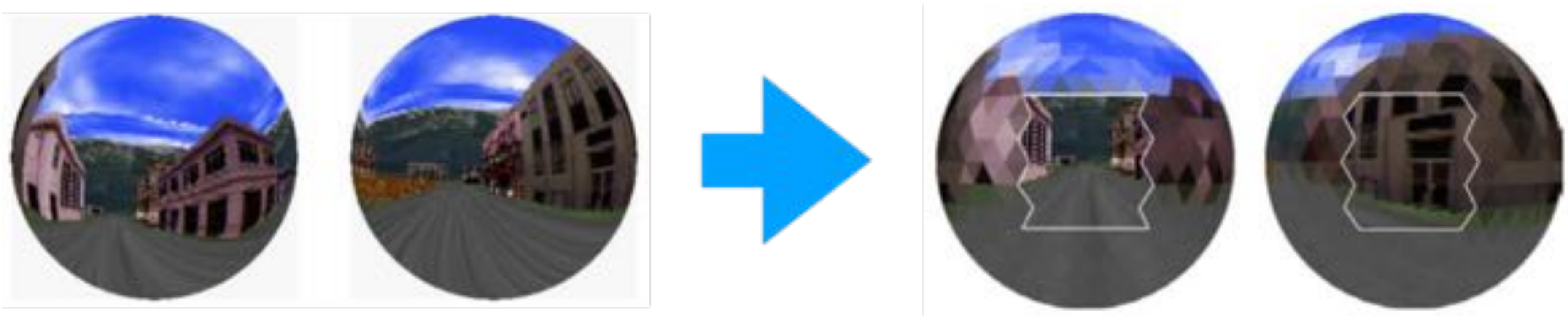
(**Yajima**, Abe, Umemura in prep.)



Spherical wavelet

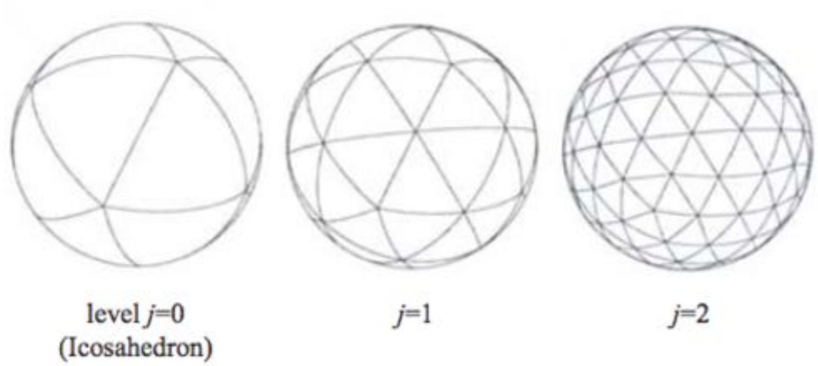
Usual radiative transfer simulations take huge memory

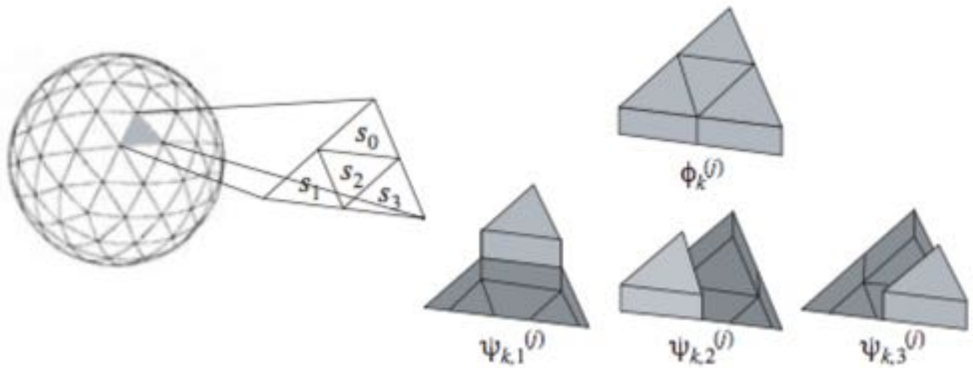
place (x,y,z), direction (theta, phi), time(~10) => ~ 1TB



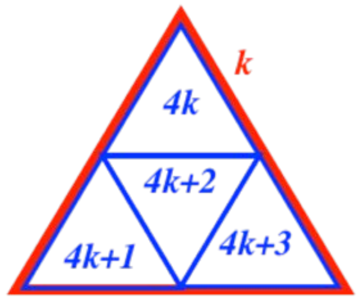
<u>**By using spherical wavelet method, we reduce memory and accelerate the simulations**</u>

Formulation





$$S_k^{(J)}(\vec{n}) = \lambda_k^{(0)}\varphi_k^{(0)}(\vec{n}) + \sum_{j=0}^{J-1}\sum_{m=1}^{3}\gamma_{k,m}^{(j)}\psi_{k,m}^{(j)}(\vec{n})$$



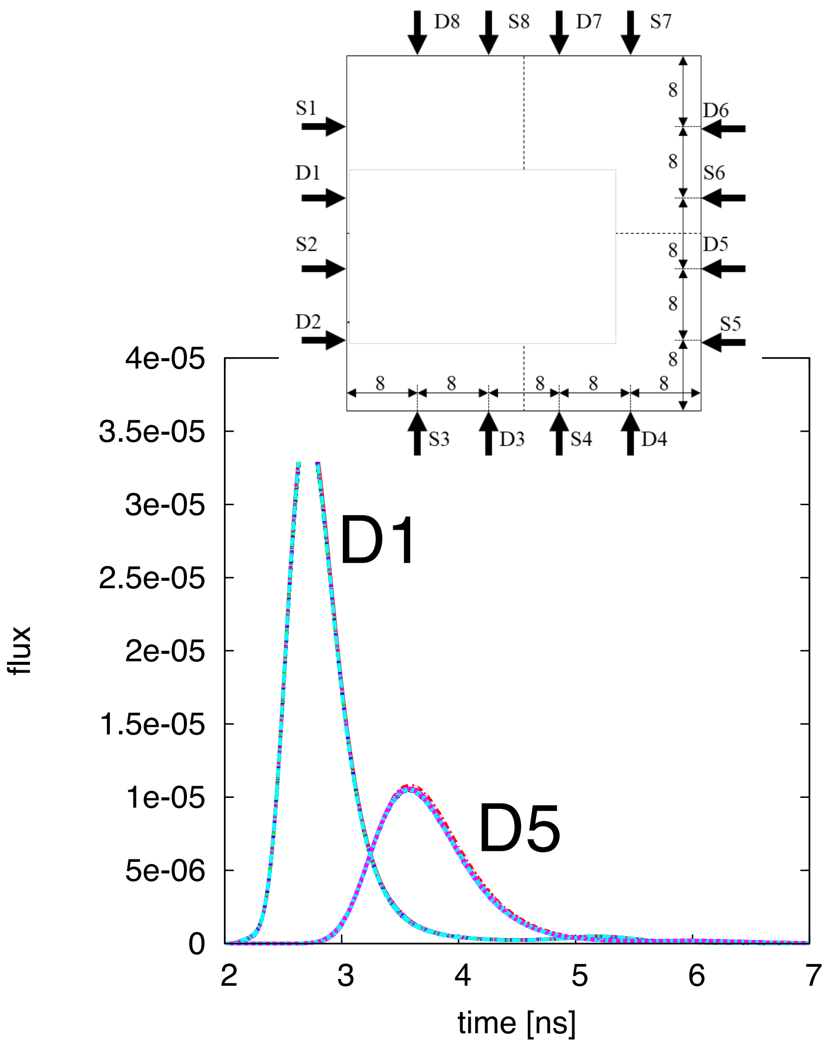
where

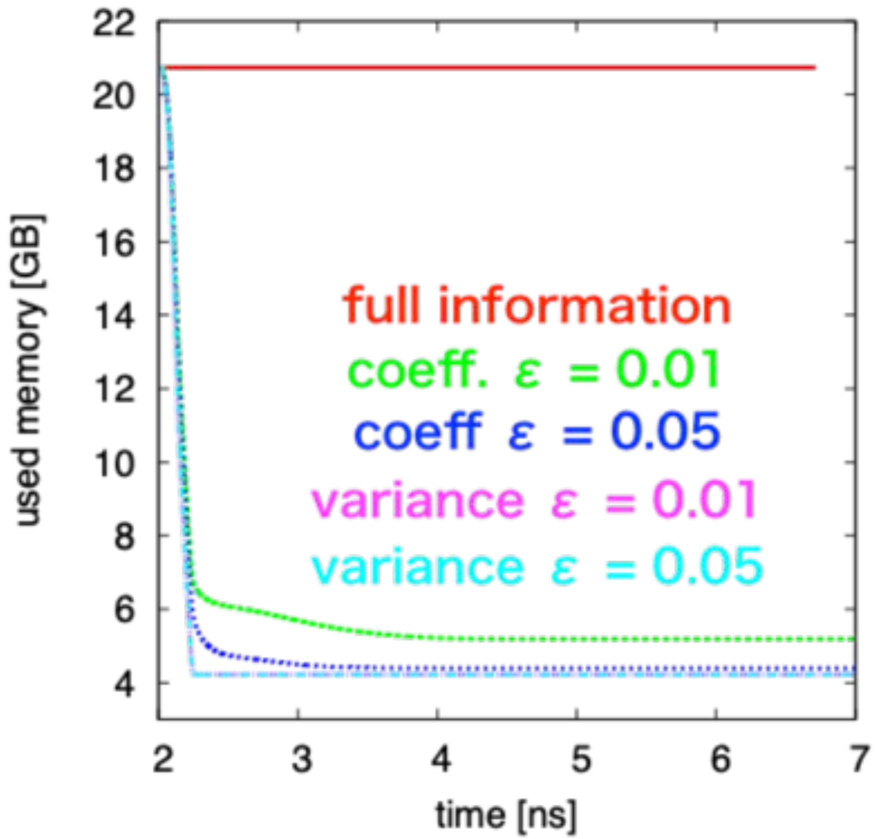
$$\lambda_k^{(j)}(\vec{n}) = \int d\Omega' I^{(j+1)}(\vec{n}') \int d\Omega \phi^{(j+1)}(\vec{n},\vec{n}')\varphi_k^{(j+1)}(\vec{n}) \equiv \int d\Omega' I^{(j+1)}(\vec{n}') w_{\lambda,k}^{(j)}(\vec{n}',\vec{n})$$

$$\gamma_{k,m}^{(j)}(\vec{n}) = \int d\Omega' I^{(j+1)}(\vec{n}') \int d\Omega \phi^{(j+1)}(\vec{n},\vec{n}')\gamma_{k,m}^{(j+1)}(\vec{n}) \equiv \int d\Omega' I^{(j+1)}(\vec{n}') w_{\gamma,k,m}^{(j)}(\vec{n}',\vec{n})$$

Reduced memory

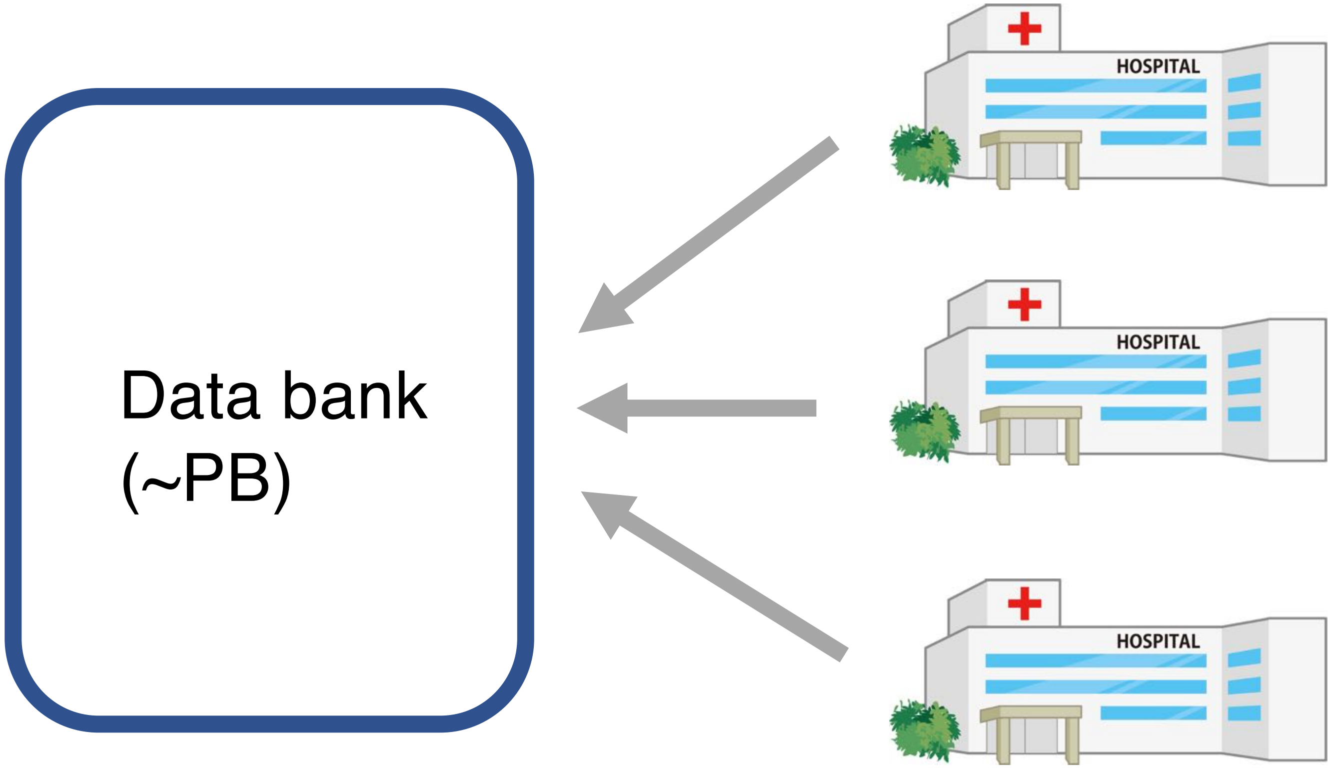
(Abe, Yajima, Umemura in prep.)





Future plan

Acceleration of radiative transfer simulations with FPGA/GPU on Cygnus
Simulations of huge parameter space



Summary

- We study galaxy formation and radiative properties by combining cosmological hydrodynamics simulations and radiative transfer calculations
- We find the galaxy evolve with supernova feedback and the radiative properties rapidly change that reproduce the observed diversity of distant galaxies
- We develop a new radiative transfer code to model near-infrared bio-imaging, and show the simulation matches the experimental data nicely