MBH Binary Population Synthesis: NANOGrav's `holodeck` framework

Luke Zoltan Kelley

NANOGrav Astrophysics Working Group Chair
Lindheimer & Cottrell Postdoctoral Fellow
CIERA | Northwestern University

LZKelley@northwestern.edu
LZK www.lzkelley.com

NANOGrav
Physics Frontiers Center

Calculating the GW Background

$$h_c^2(f) = \int_0^\infty dz \, \frac{d^2 N}{dz \, d\ln f_r} \, h_s^2(f_r),$$

Calculating the GW Background

$$h_c^2(f) = \int_0^\infty dz \, \frac{d^2N}{dz\, d\ln f_r} \, h_s^2(f_r), \qquad \frac{d^2N}{dz\, d\ln f_r} = \frac{dn_c}{dz} \frac{dt}{d\ln f_r} \frac{dz}{dt} \frac{dV_c}{dz}.$$

Calculating the GW Background

$$h_c^2(f) = \int_0^\infty dz \, \frac{d^2 N}{dz \, d\ln f_r} \, h_s^2(f_r), \qquad \frac{d^2 N}{dz \, d\ln f_r} = \frac{dn_c}{dz} \frac{dt}{d\ln f_r} \frac{dz}{dt} \frac{dV_c}{dz}.$$

$$\frac{dz}{dt} = H_0(1+z)E(z),$$

$$\frac{dV_c}{dz} = 4\pi \frac{c}{H_0} \frac{d_c^2}{E(z)},$$

Calculating the GW Background

$$h_c^2(f) = \int_0^\infty dz \, \frac{d^2N}{dz\, d\ln f_r} \, h_s^2(f_r),$$

$$\frac{d^2N}{dz\, d\ln f_r} = \frac{dn_c}{dz} \frac{dt}{d\ln f_r} \frac{dz}{dt} \frac{dV_c}{dz}.$$

$$\frac{dz}{dt} = H_0(1+z)E(z),$$

$$\frac{dV_c}{dz} = 4\pi \frac{c}{H_0} \frac{d_c^2}{E(z)},$$

$$h_c^2(f) = \int_0^\infty dz \, \frac{dn_c}{dz} \, h_s^2(f_r) \, 4\pi c \, d_c^2 \cdot (1+z) \, \tau_f .$$

Calculating the GW Background

$$h_c^2(f) = \int_0^\infty dz\, \frac{d^2N}{dz\, d\ln f_r}\, h_s^2(f_r),$$

$$\frac{d^2N}{dz\, d\ln f_r} = \frac{dn_c}{dz} \frac{dt}{d\ln f_r} \frac{dz}{dt} \frac{dV_c}{dz}.$$

$$\frac{dz}{dt} = H_0(1+z)E(z),$$

$$\frac{dV_c}{dz} = 4\pi \frac{c}{H_0} \frac{d_c^2}{E(z)},$$

$$h_c^2(f) = \int_0^\infty dz\, \frac{dn_c}{dz}\, h_s^2(f_r)\, 4\pi c\, d_c^2 \cdot (1+z)\, \tau_f.$$

$$h_c^2(f) = \sum_{\text{redshift}} \sum_{\text{binaries}} h_s^2\, \frac{4\pi\, c\, d_c^2 \cdot (1+z)}{V_{\text{sim}}}\, \tau_f.$$

Calculating the GW Background

$$h_c^2(f) = \int_0^\infty dz \, \frac{d^2N}{dz\, d\ln f_r} \, h_s^2(f_r),$$

$$\frac{d^2N}{dz\, d\ln f_r} = \frac{dn_c}{dz} \frac{dt}{d\ln f_r} \frac{dz}{dt} \frac{dV_c}{dz}.$$

$$\frac{dz}{dt} = H_0(1+z)E(z),$$

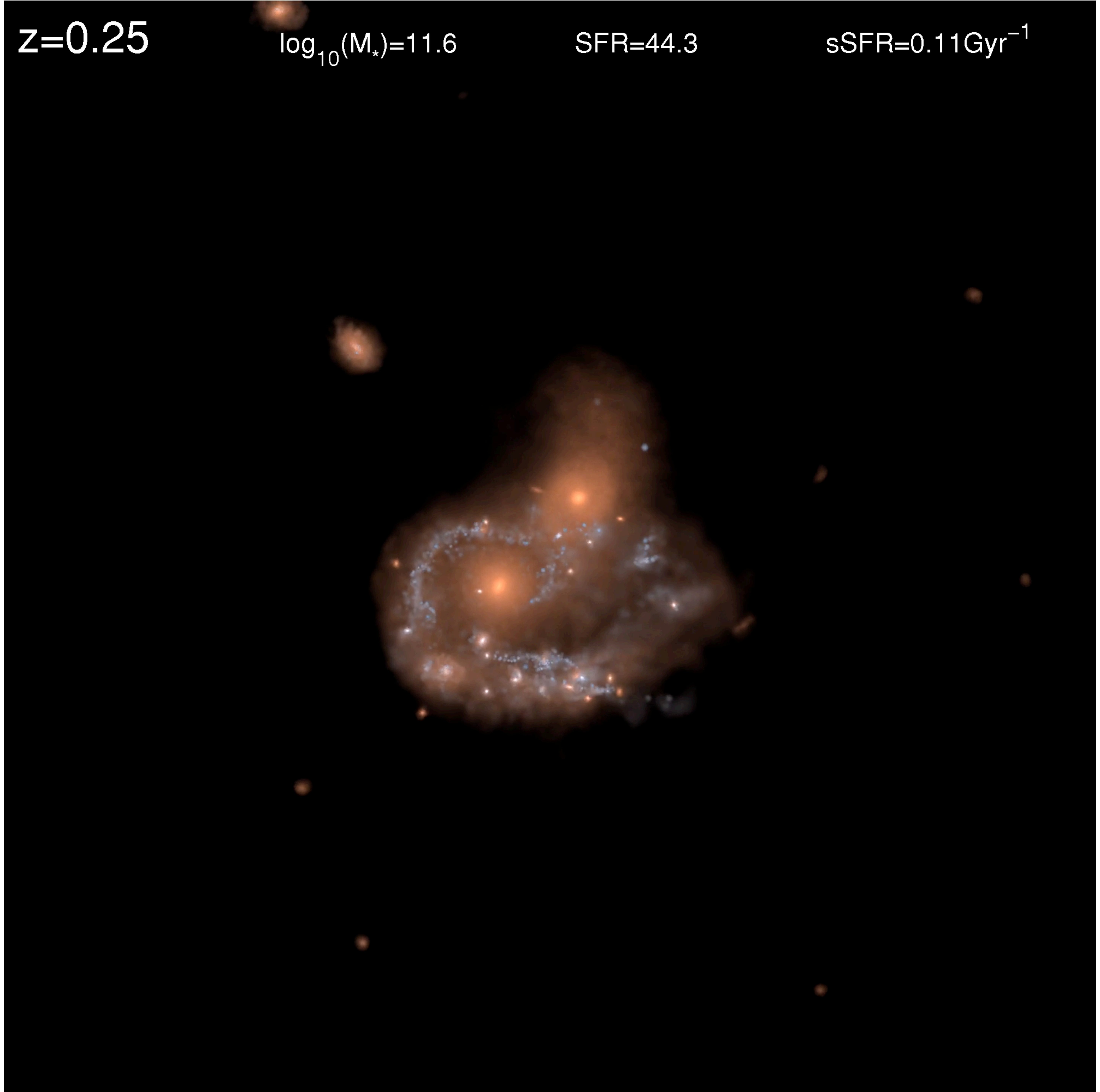
$$\frac{dV_c}{dz} = 4\pi \frac{c}{H_0} \frac{d_c^2}{E(z)},$$

$$h_c^2(f) = \int_0^\infty dz \, \frac{dn_c}{dz} \, h_s^2(f_r) \, 4\pi c \, d_c^2 \cdot (1+z) \, \tau_f.$$

$$h_c^2(f) = \sum_{\text{redshift}} \sum_{\text{binaries}} h_s^2 \, \frac{4\pi \, c \, d_c^2 \cdot (1+z)}{V_{\text{sim}}} \, \tau_f.$$

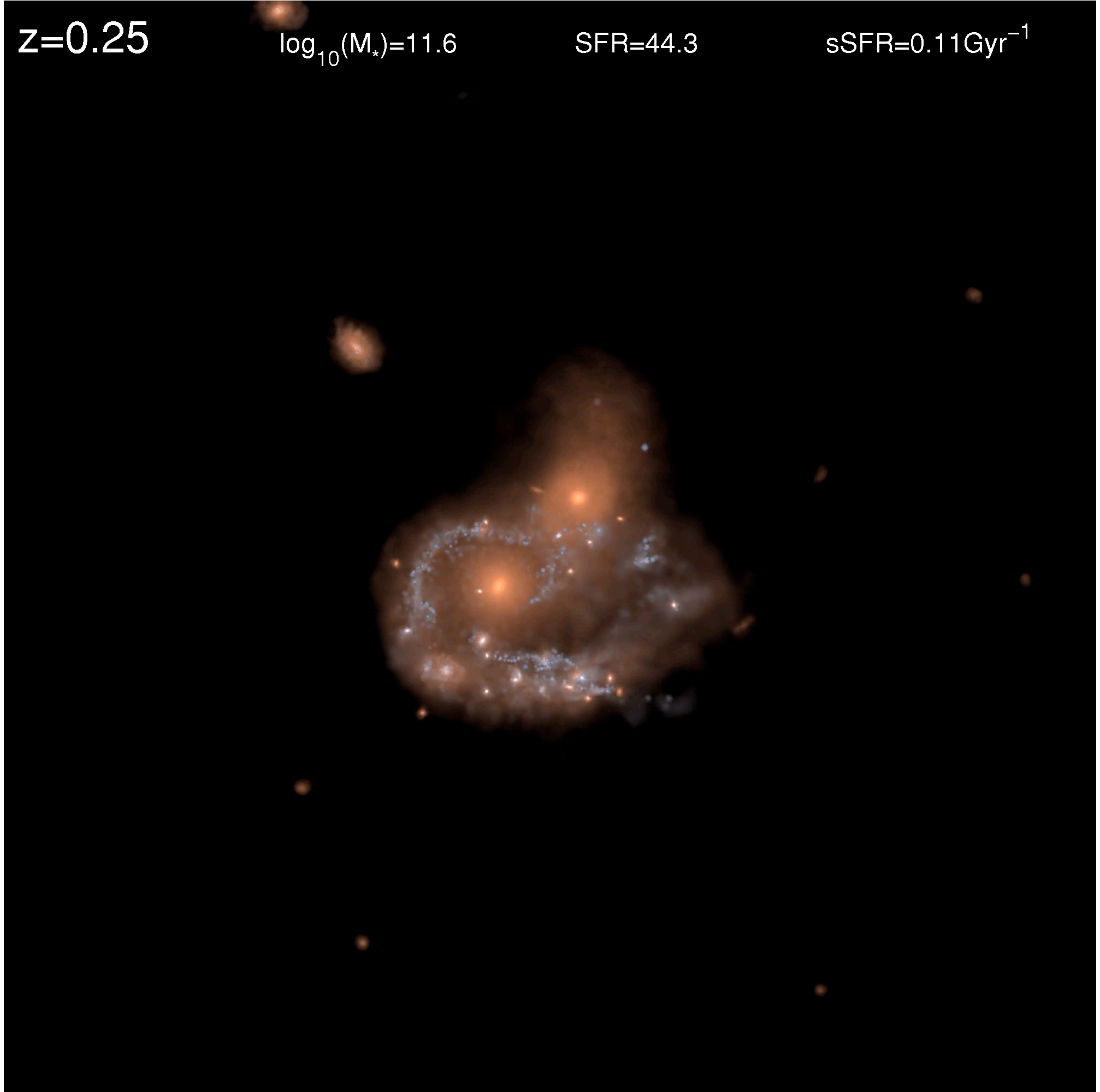
$$h_c^2(f) = \sum_{\text{redshift}} \sum_{\text{binaries}} h_s^2 \cdot \mathcal{P}(\Lambda),$$

$$\Lambda \equiv \frac{4\pi \, c \, d_c^2 \cdot (1+z)}{V_{\text{sim}}} \, \tau_f.$$



Illustris / IllustrisTNG

Vogelsberger+(2014a/b); Genel+(2014);
Nelson+2015; Sijacki+2015
Nelson+2018/2019; Springel+2018;
Marinacci+2018; Pillepich+2018



Illustris / IllustrisTNG

Vogelsberger+(2014a/b); Genel+(2014);
Nelson+2015; Sijacki+2015
Nelson+2018/2019; Springel+2018;
Marinacci+2018; Pillepich+2018

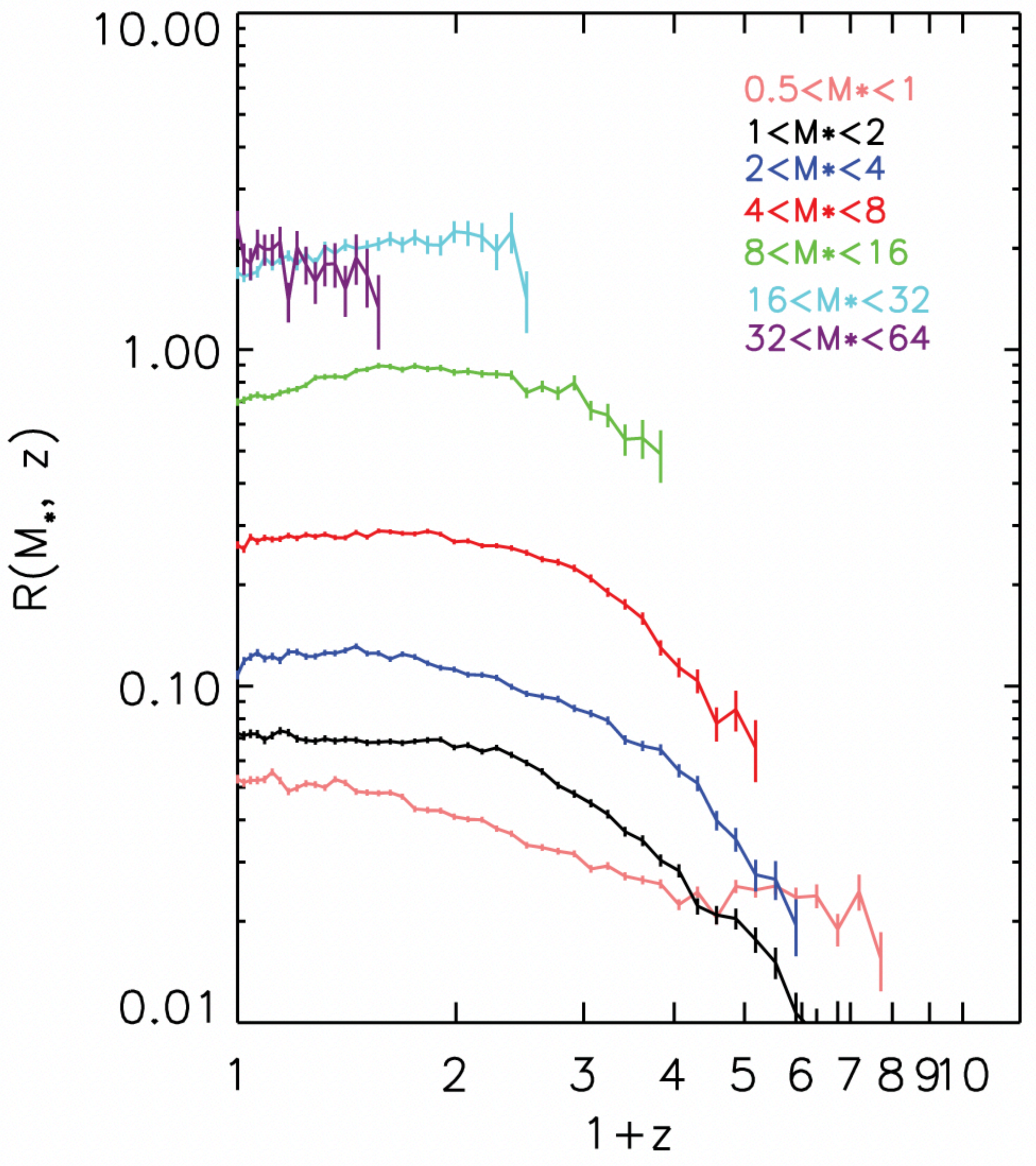
"Cosmological Simulations"

- Hydrodynamic: evolve fluids + particles explicitly,
  e.g. *illustris / illustrisTNG, Eagle, Romulus, Simba, Horizon, Gadget, Ramses, Enzo, Gasoline...*
- semi-analytic / semi-empirical methods
  - analytic models + empirical scaling relationships
- observational catalogs

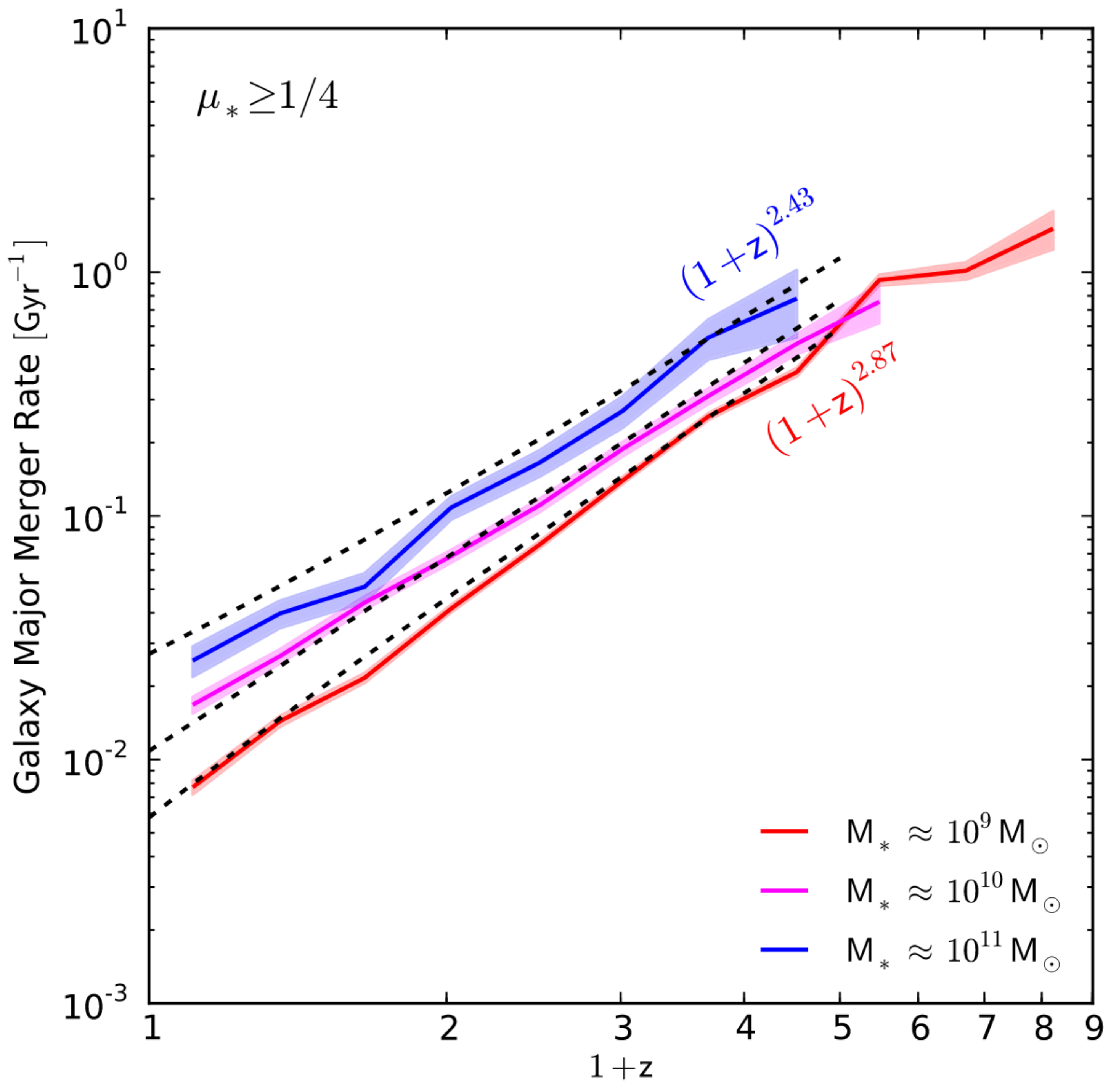
systematics

- differences between modeling styles can be significant
  e.g. galaxy–galaxy merger rates

Guo & White 2008
(millenium cosmo–DM + SAM)



Rodriguez-Gomez et al. 2015
(illustris | cosmo–hydro)



“Cosmological Simulations”

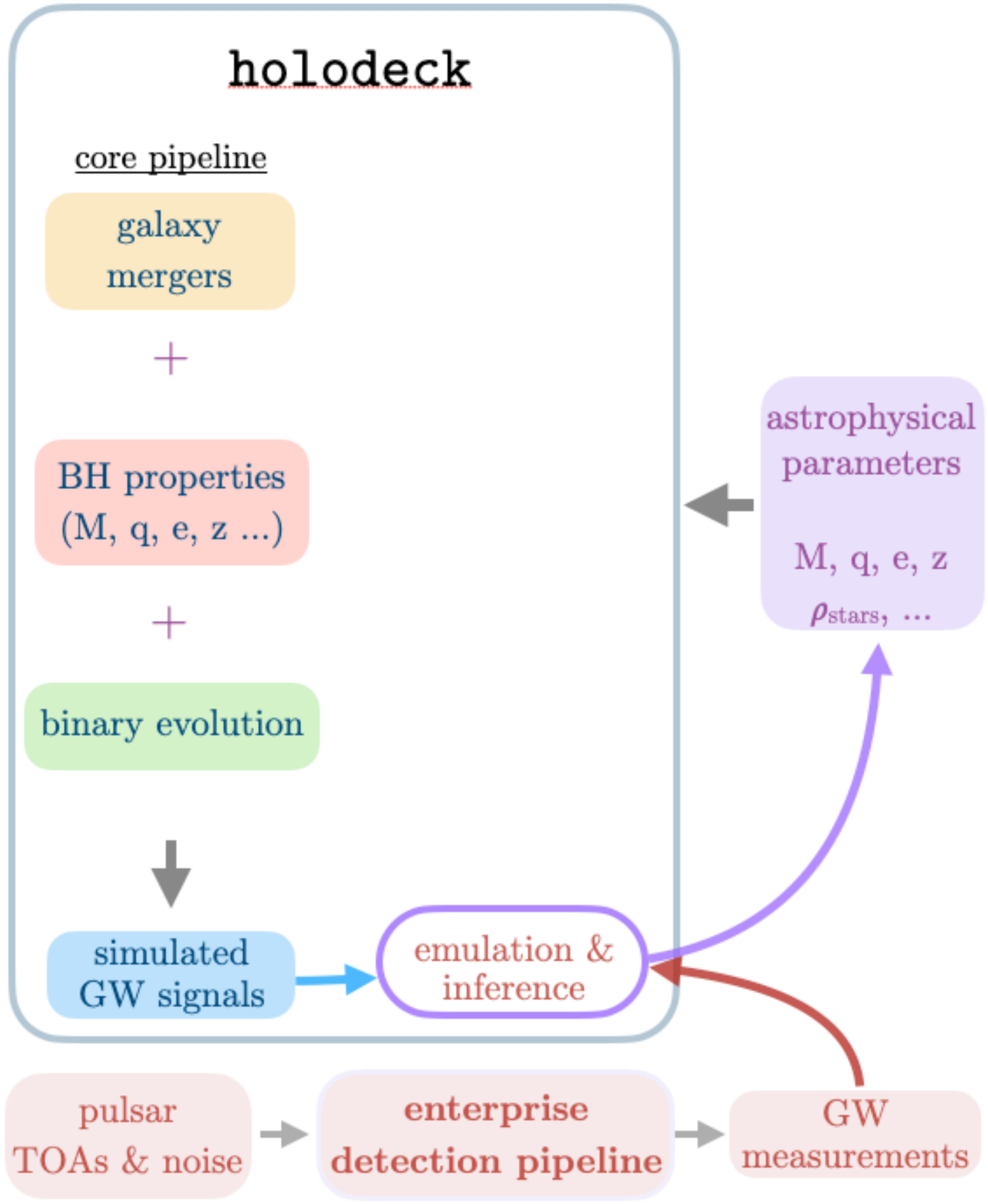
- Hydrodynamic: evolve fluids + particles explicitly,
  e.g. *illustris / illustrisTNG, Eagle, Romulus, Simba, Horizon, Gadget, Ramses, Enzo, Gasoline...*
- semi-analytic / semi-empirical methods
  - analytic models + empirical scaling relationships
- observational catalogs

"Cosmological Simulations"

- Hydrodynamic: evolve fluids + particles explicitly, e.g. *illustris* / *illustrisTNG, Eagle, Romulus, Simba, Horizon, Gadget, Ramses, Enzo, Gasoline...*
- semi-analytic / semi-empirical methods
  - analytic models + empirical scaling relationships
- observational catalogs

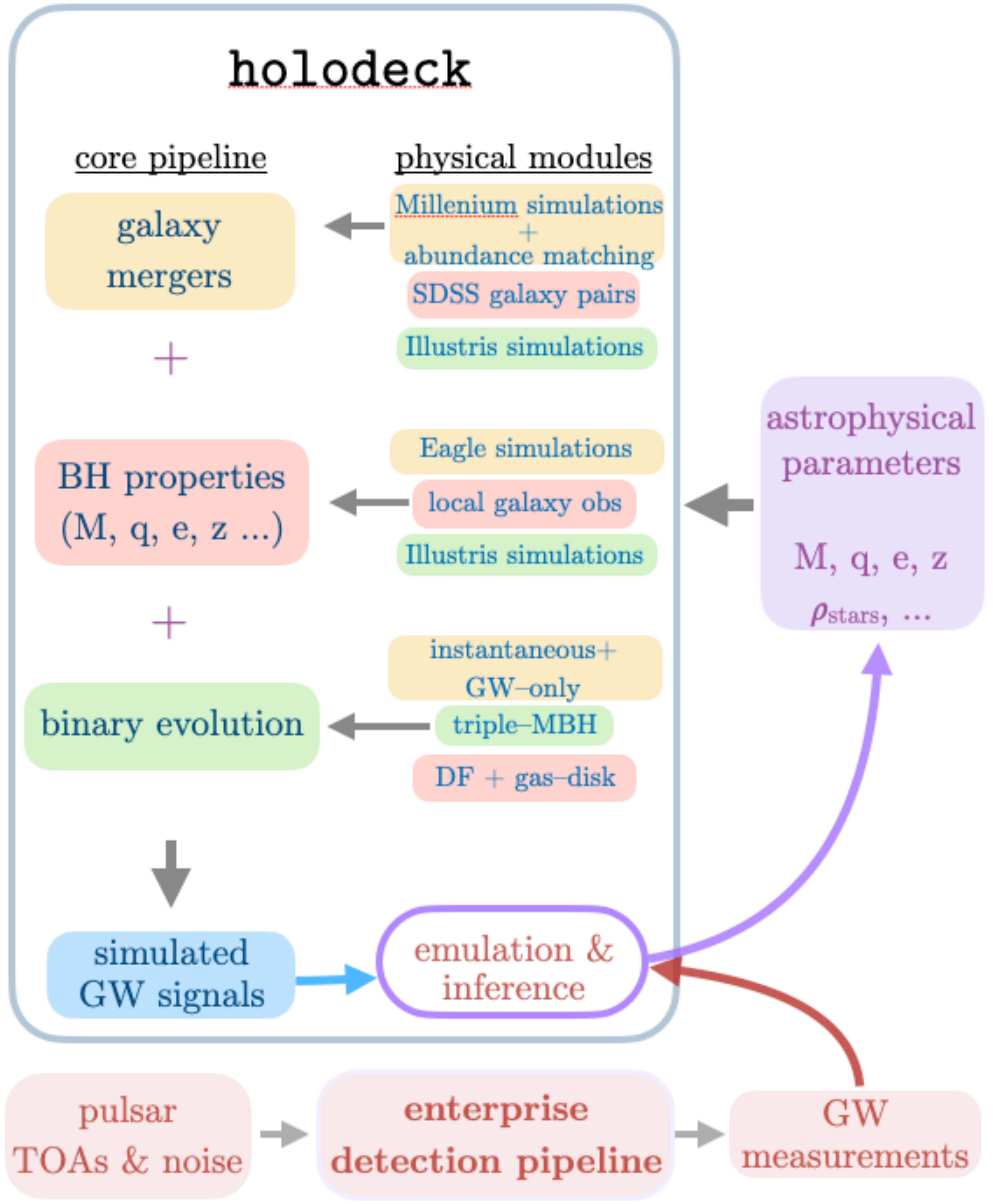
dynamical friction
GW emission
stellar scattering
circumbinary disk coupling
separation (pc)
10^4
10^2
1
10^{-3}
frequency (nHz)
1
10
100
$\dot{\mathbf{M}}$
$\vec{\mathbf{J}}$
$d\vec{v}/dt$
$\vec{v}$
a_0
a_1

structure



holodeck
core pipeline
galaxy mergers
+
BH properties (M, q, e, z ...)
+
binary evolution
simulated GW signals
emulation & inference
astrophysical parameters
M, q, e, z
$\rho_{\rm stars}$, ...
pulsar TOAs & noise
enterprise detection pipeline
GW measurements

structure



holodeck
core pipeline
physical modules
galaxy mergers
Millenium simulations + abundance matching
SDSS galaxy pairs
Illustris simulations
+
BH properties (M, q, e, z ...)
Eagle simulations
local galaxy obs
Illustris simulations
+
binary evolution
instantaneous+ GW–only
triple–MBH
DF + gas–disk
astrophysical parameters
M, q, e, z
ρ_{stars}, ...
simulated GW signals
emulation & inference
pulsar TOAs & noise
enterprise detection pipeline
GW measurements

motivation

- NANOGrav's 15yr astrophysics interpretation paper
  - **unified**: collaboration-wide effort (instead of individual's binary models)
  - **robust**: marginalization over *systematic* uncertainties
  - **reproducible**: comprehensive review, maintenance & upgrades; open source*

current

- Expansion to LISA
  - plug-and-play with alternative simulations or parametrizations
- Multimessenger GW+EM constraints
  - GW measurements
  - EM binary candidates (e.g. periodic variables, Graham+2015, Charisi+2015)
  - AGN properties (e.g. luminosity function, galaxy scaling relations)

future

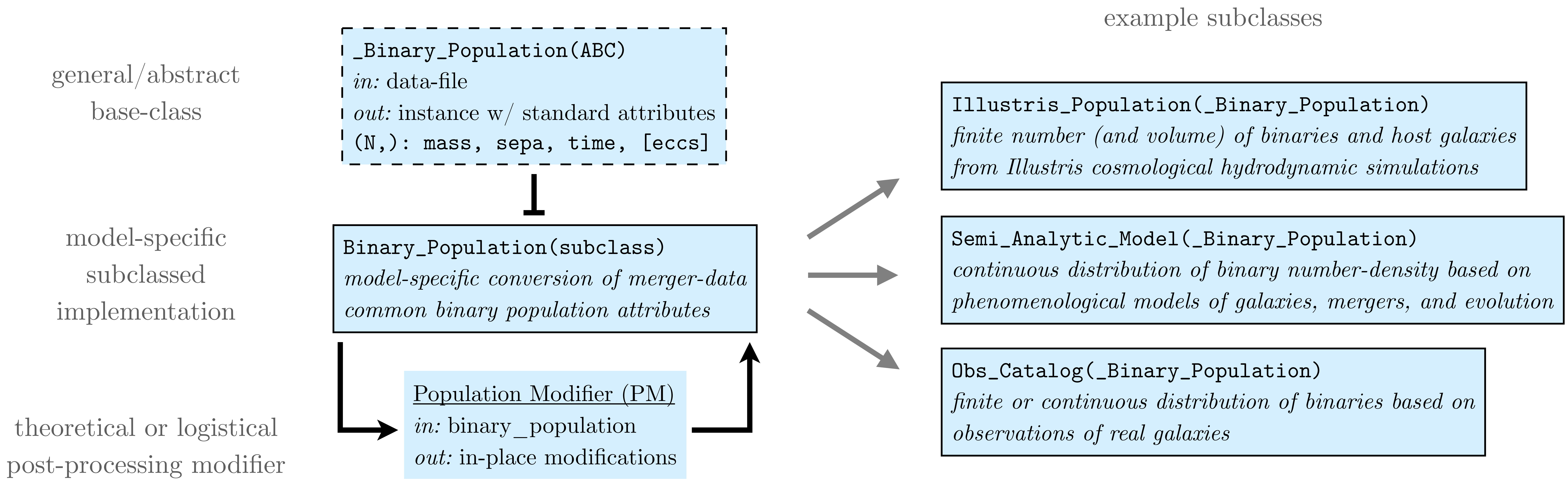
requirements

- **rapidly map: astrophysical parameters => GW signals**
  (e.g. M–Mbulge, Mdot, stellar scattering efficiencies, ...)
    - [cosmo sims =>] binary evo => GW library => emulation

- **systematic characterization/inclusion of uncertainties**
  (e.g. galaxy-galaxy merger rates, BH–host relations, ...)
    - both parametric/statistical variations & numerous model classes
      (e.g. hydro sims; semi-analytic models)

implementation

- python, class-based framework with `numba` accelerated modules



`holodeck`: core methodologies

<u>Illustris</u>
large-separation
galaxy or MBH pairs

host galaxy properties

accretion rates

<u>Semi-Analytic Models (Siyuan Chen)</u>

stellar-mass function ⇒ *MBH mass*
⇒ *pair fraction* ⇒ *merger time*
⇒ **MBH pairs**

<u>2MASS Catalog (Andrew Casey-Clyde)</u>

brightness ⇒ *stellar-mass* ⇒ *MBH mass*
⇒ *pair fraction* ⇒ *merger time*
⇒ **MBH pairs**

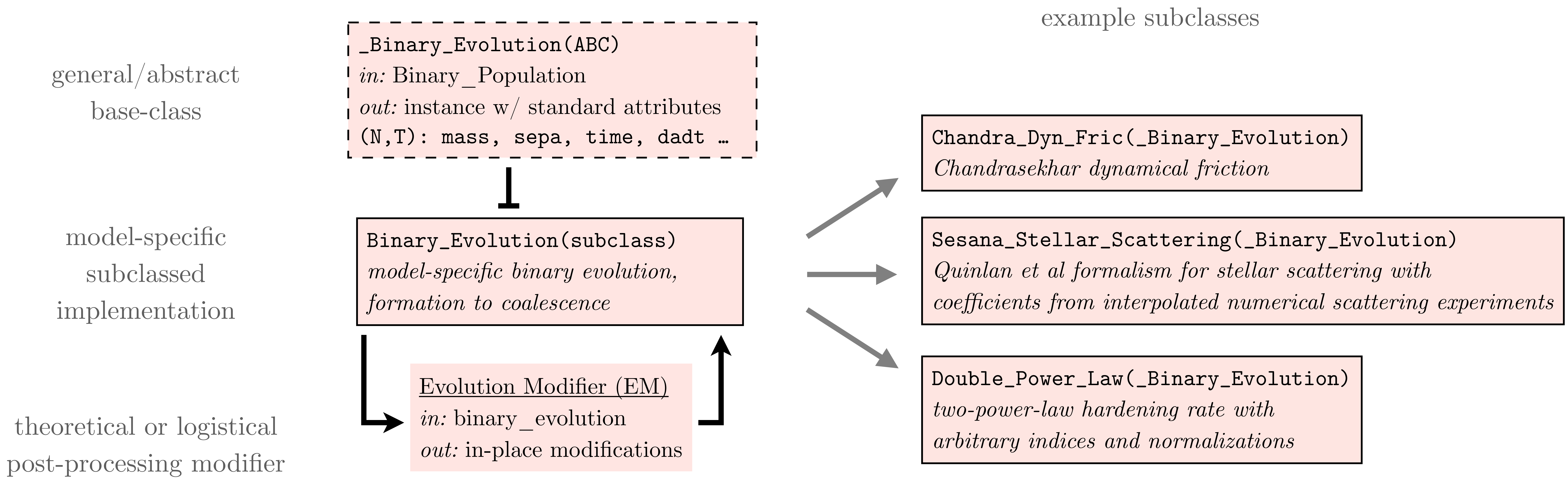
`Illustris_Population(_Binary_Population)`
finite number (and volume) of binaries and host galaxies from Illustris cosmological hydrodynamic simulations

`Semi_Analytic_Model(_Binary_Population)`
continuous distribution of binary number-density based on phenomenological models of galaxies, mergers, and evolution

`Obs_Catalog(_Binary_Population)`
finite or continuous distribution of binaries based on observations of real galaxies

implementation

- python, class-based framework with `numba` accelerated modules

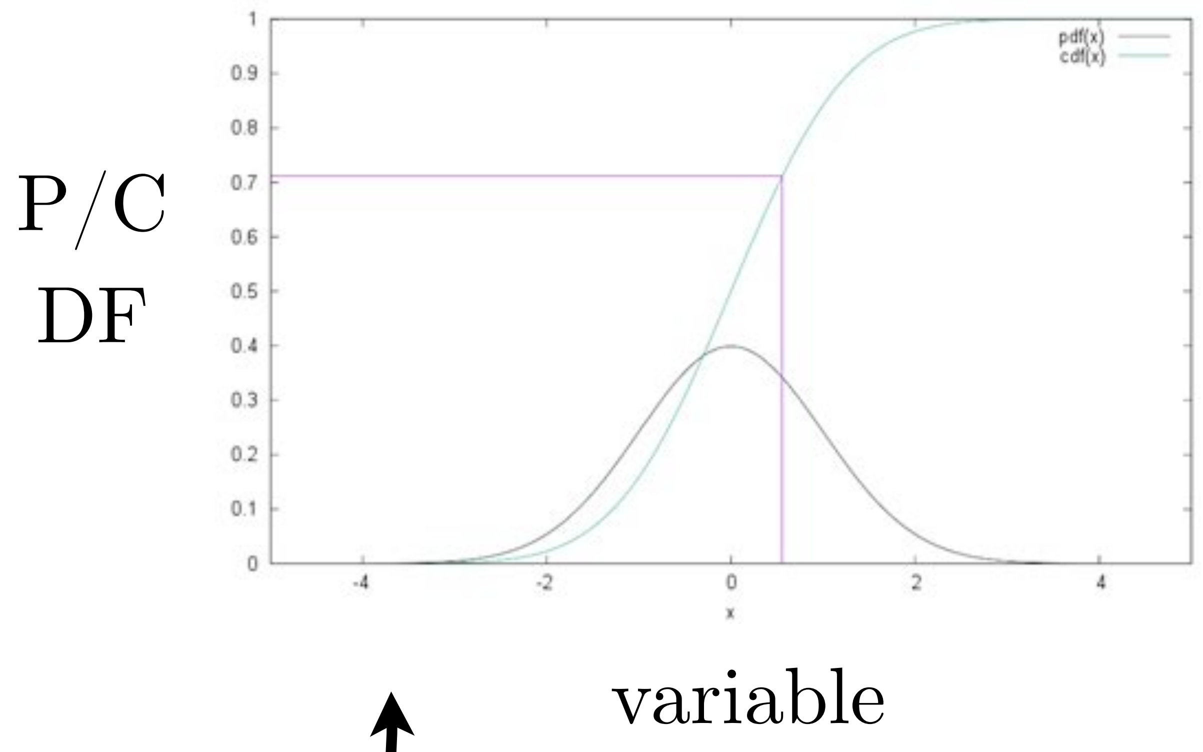


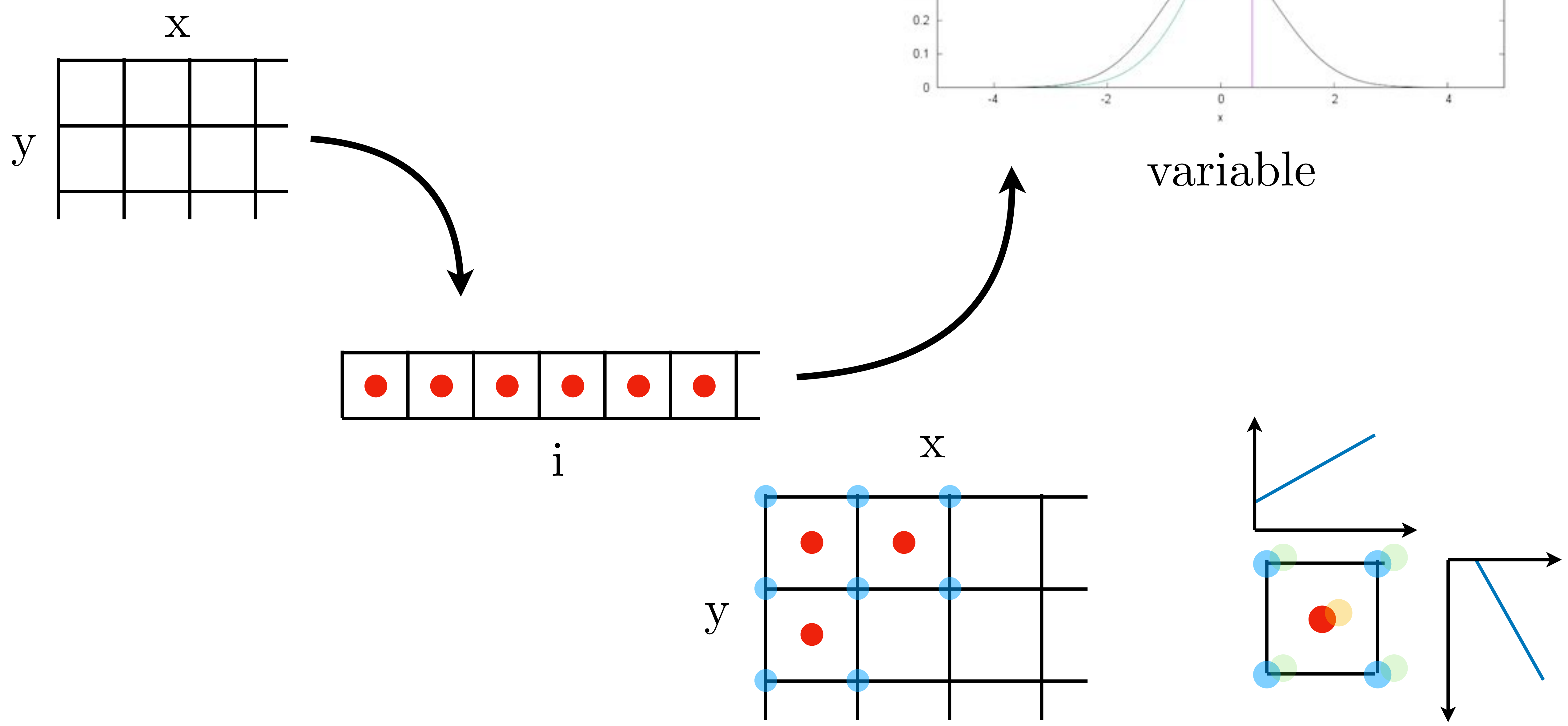
`kalepy` sampling

$$\frac{d^4 N_{\mathrm{BH}}}{dM\, dq\, dz\, d\ln f_o}$$

4D "continuous" (discretized)
distribution of binaries

inversion sampling



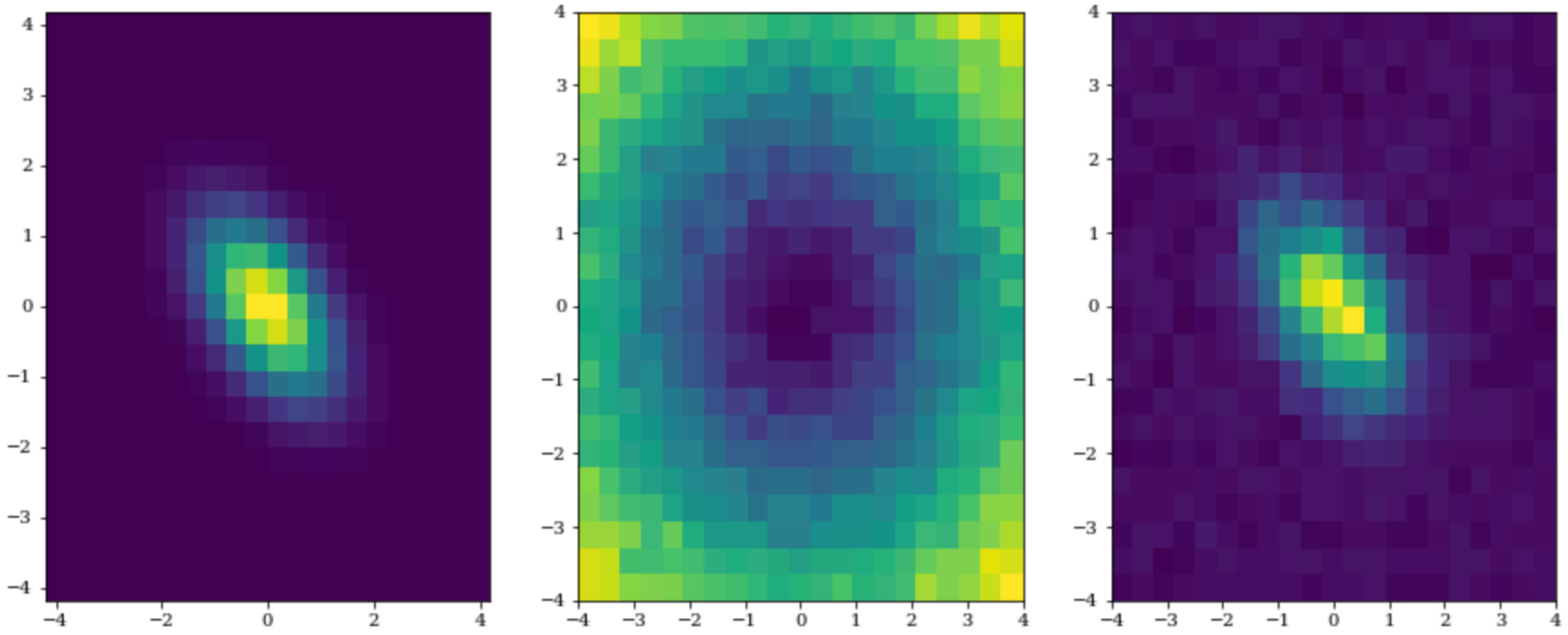


`kalepy` sampling

proportional sampling

$$E[f(x)] = \int f(x)p(x)dx = \int f(x)\frac{p(x)}{q(x)}q(x)dx \approx \frac{1}{n}\sum_i f(x_i)\frac{p(x_i)}{q(x_i)}$$

distribution (p) samples (q) reconstruction (p/q)

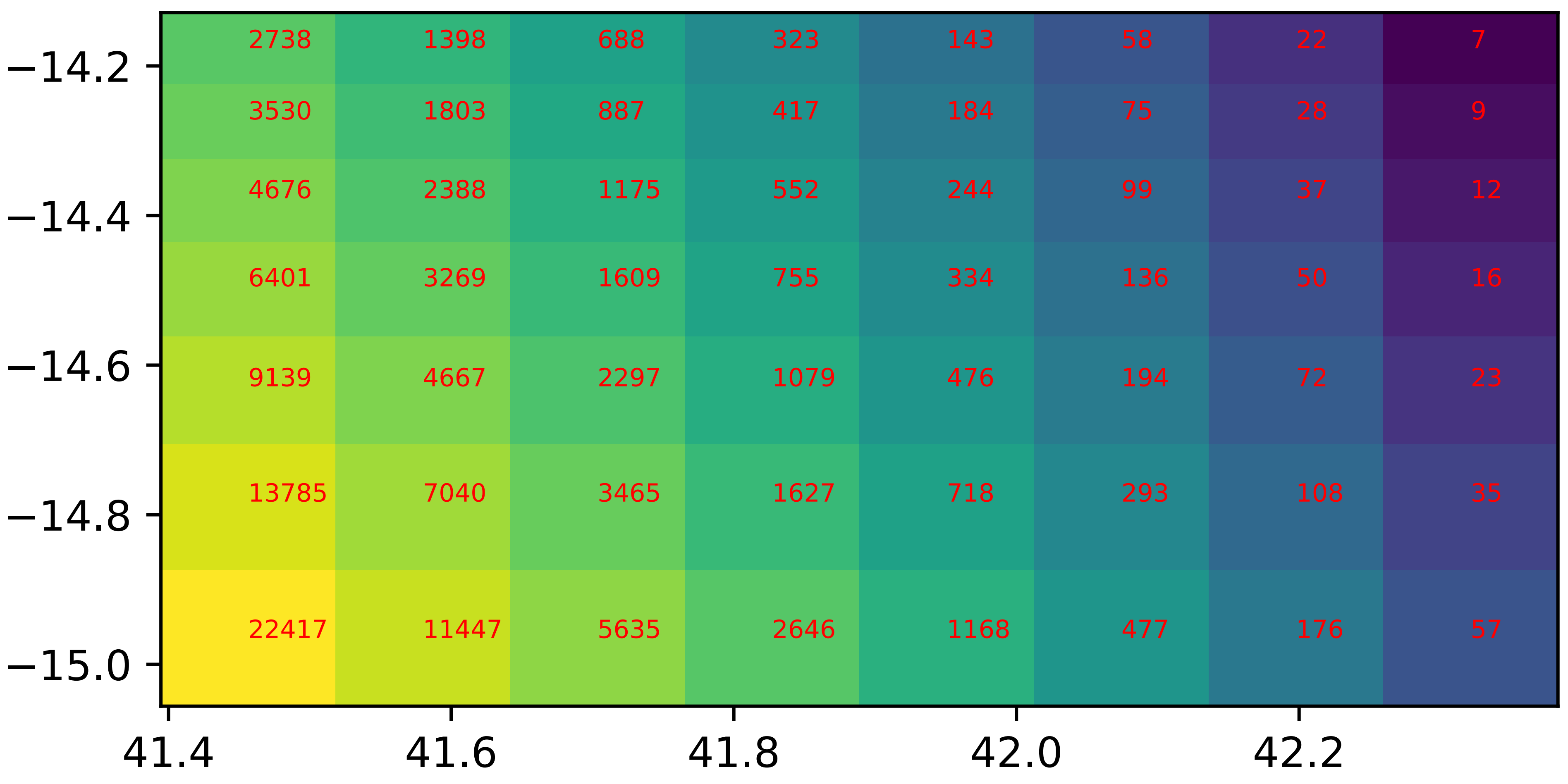


`kalepy` sampling

“outlier” sampling

for bins with $N > N_0$ $[O(10 – 100)]$, use centroids, not samples

distribution



samples