Day 3.
Cosmic chemical evolution

Chiaki Kobayashi
(Univ. of Hertfordshire, UK)

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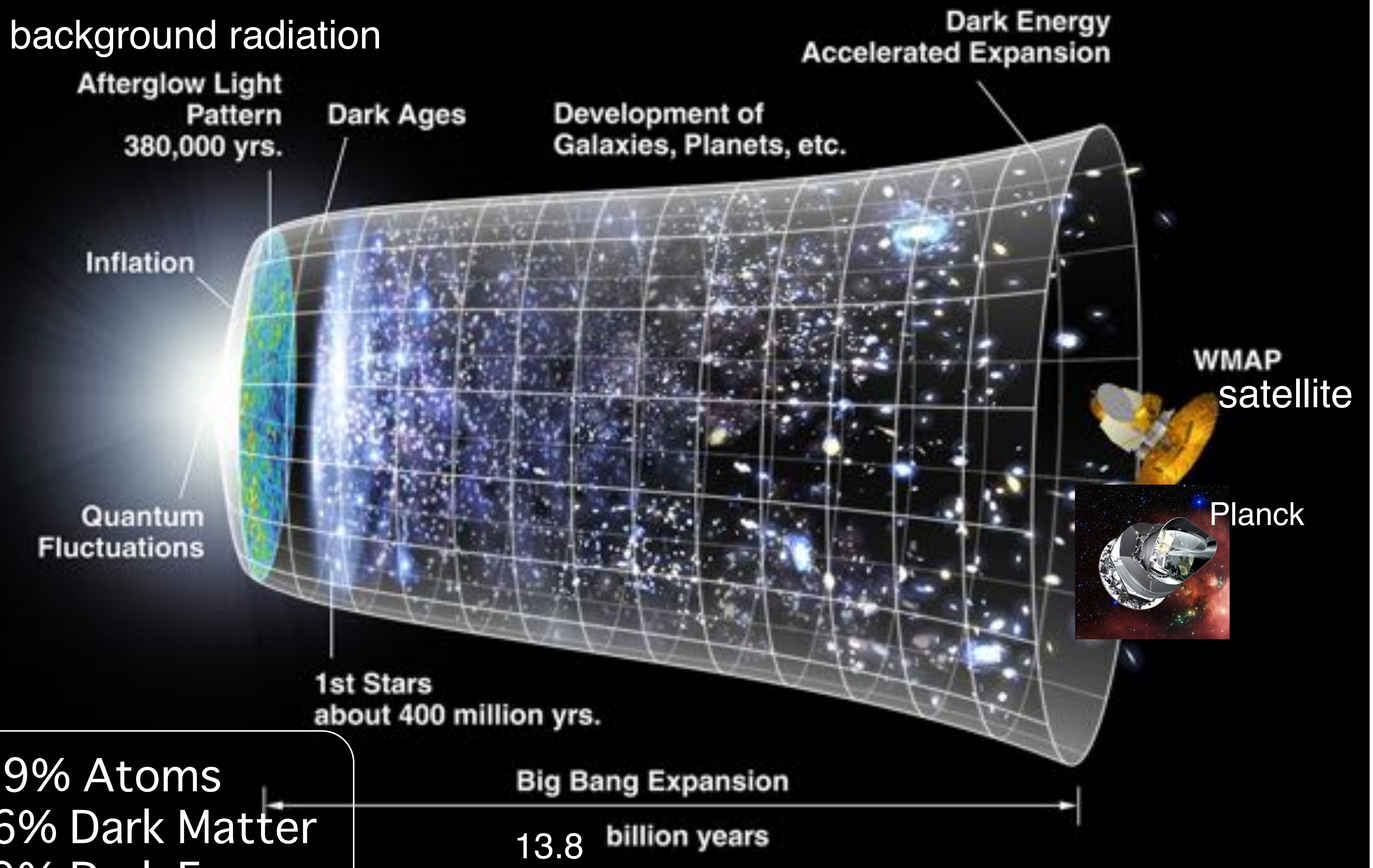
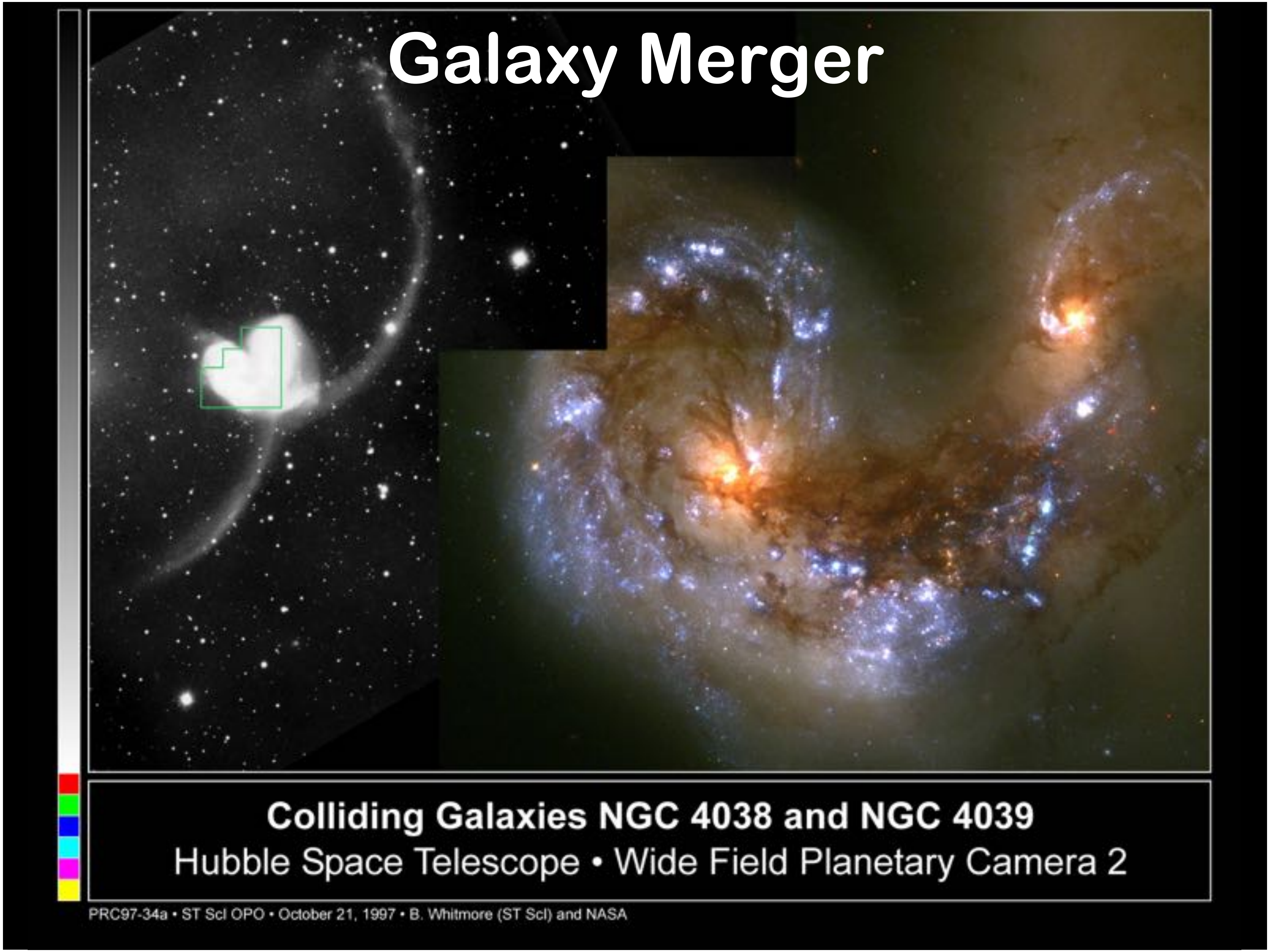
History of the Universe



4.9% Atoms
26% Dark Matter
69% Dark Energy

Galaxy Merger

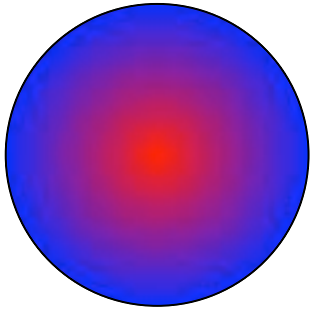


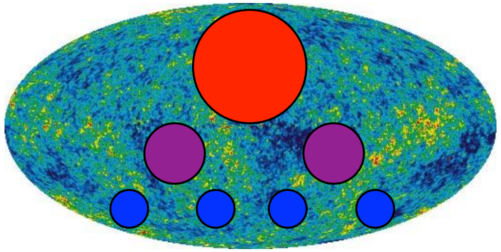
Galactic Winds

M 82 (NGC 3034) FOCAS (B, V, Hα)

Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000

3 types of galaxy models





One-zone (monolithic) models

- Instantaneous mixing approximation
- SFR/inflow/outflow with analytic formula
- Average evolution of a galaxy (or a shell of galaxy)

Semi-analytic (hierarchical) models

- Mass assembly history based on λCDM scenario
- Global properties of galaxies in a large scale

Chemo-dynamical simulations

- Inhomogeneous chemical enrichment
- Internal structures - kinematics of stars/gas, spatial distribution of elements

Other types of models

- Stochastic models (Argast+02; Ishimaru & Prantzos; Cescutti+; Wehmeyer+)
- Chemodynamical models without hydro (e.g., Minchev & Chiappini)

Basic equations of Chemodynamical Simulations

CK 2004

CK, Springel, White 2007

Taylor & CK 2014

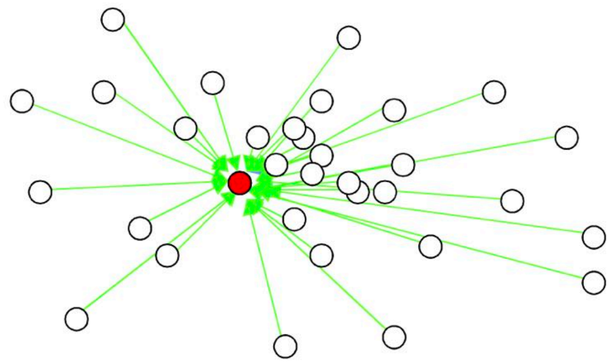
N-body methods

Gravity for DM and stars

- direct summation – O(N^2)

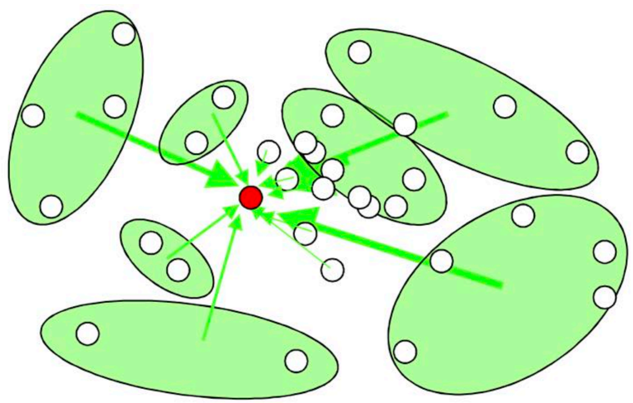
  GRAPE, GPU

$$m_i \frac{d^2 x_i}{dt^2} = \sum_{j \neq i} G m_i m_j \frac{x_j - x_i}{\left| x_j - x_i \right|^3}$$



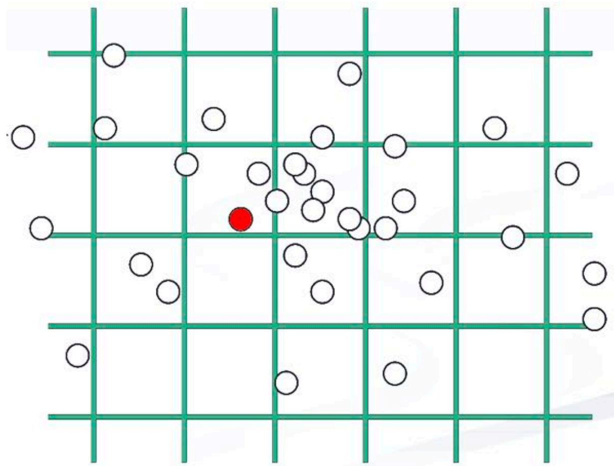
- Tree method – O(N logN)$^{-k}$

  distant particles are bundled up



- Particle-mesh method – O(N logN)

$$\nabla^2 \phi = 4\pi G \rho \rightarrow -k^2 \phi_{\mathbf{k}} = 4\pi G \rho_{\mathbf{k}} \rightarrow \phi(\mathbf{r})$$



SPH method

Smoothed Particle Hydrodynamics for gas (Gingold & Monaghan 1977; Lucy 1977; Monaghan 1992 for a review)

- equations to integrate:

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\mathbf{v} = 0$$

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla P - \nabla\Phi$$

$$\frac{Du}{Dt} = \frac{P}{\rho^2}\frac{D\rho}{Dt} + \frac{\nabla\cdot(\kappa\nabla T)}{\rho} + \frac{\Gamma - \Lambda}{\rho}$$

$$\nabla^2\Phi = 4\pi G\rho$$

$$P = (\gamma - 1)\rho u$$

SPH formulation (Navarro & White 1993)

- spline kernel *W*
- smoothing length *h*: variable both in space & time
- integration: Leap-frog method
- individual timestep

$$\langle f(\mathbf{r})\rangle = \int f(\mathbf{r}')W(\mathbf{r}-\mathbf{r}';h)d\mathbf{r}'$$

$$\langle \nabla f(\mathbf{r})\rangle = \int f(\mathbf{r}')\nabla W(\mathbf{r}-\mathbf{r}';h)d\mathbf{r}'$$

$$\langle f(\mathbf{r})\rangle = \sum \frac{m_j}{\rho(\mathbf{r}_j)} f(\mathbf{r}_j)W(\mathbf{r}-\mathbf{r}_j;h)$$

$$\langle \nabla f(\mathbf{r})\rangle = \sum \frac{m_j}{\rho(\mathbf{r}_j)} f(\mathbf{r}_j)\nabla W(\mathbf{r}-\mathbf{r}_j;h)$$

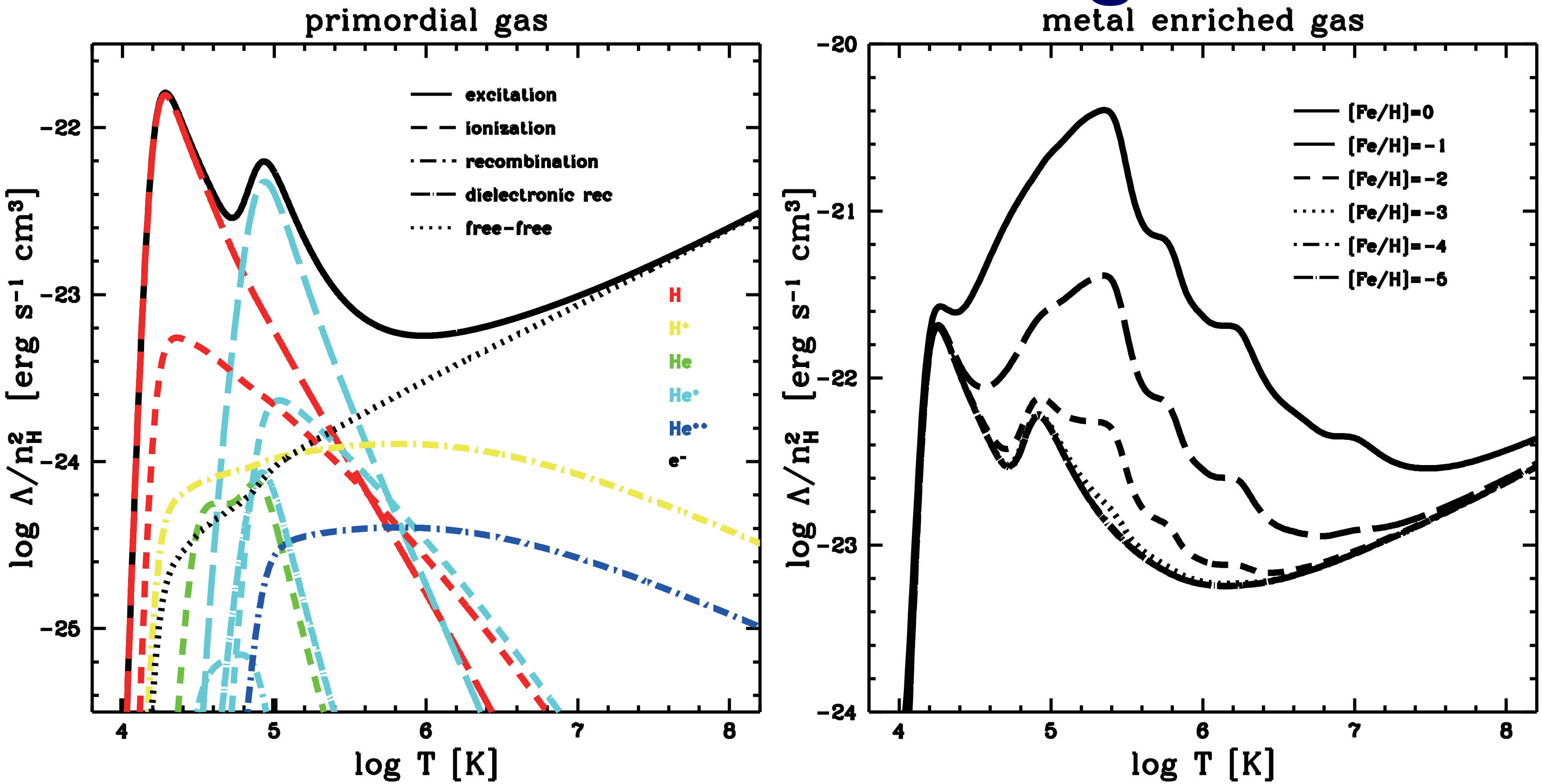
SPH

$$\rho_i = \sum m_j W(\mathbf{r}_i - \mathbf{r}_j;h)$$

$$\frac{D\mathbf{v}_i}{Dt} = -\sum m_j\left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} + \Pi_{ij}\right)\nabla_i W(\mathbf{r}_i - \mathbf{r}_j;h) - \left(\nabla\Phi\right)_i$$

$$\frac{Du_i}{Dt} = -\sum m_j\left(\frac{P_i}{\rho_i^2} + \frac{1}{2}\Pi_{ij}\right)\left(\mathbf{v}_i - \mathbf{v}_j\right)\nabla_i W(\mathbf{r}_i - \mathbf{r}_j;h) + \frac{\Gamma - \Lambda}{\rho}$$

Radiative Cooling



- Calculated by MAPPINGS III (Sutherland & Dopita 1993).
- Molecule cooling ($T<10^4$K) is not included.
- UV background heating is subtracted (Kats, Weinberg & Hernquist 96).

Star Formation

- Katz (1992)
  - converging flow
  - rapid cooling
  - Jeans unstable

$$\text{(i)}\quad (\nabla \cdot \boldsymbol{v})_i < 0, \qquad t_{\rm cool} = \frac{\rho u}{\Lambda},$$

$$\text{(ii)}\quad t_{\rm cool} < t_{\rm dyn}, \qquad t_{\rm dyn} = \frac{1}{\sqrt{4\pi G \rho}},$$

$$\text{(iii)}\quad t_{\rm dyn} < t_{\rm sound}, \qquad t_{\rm sound} = \frac{h_i}{c_s},$$

- Density criteria (Stinson+06; Governato+10, Nature)

  $\rho > \rho_{\rm crit}$

- Star formation timescale $t_{\rm sf} = \frac{1}{c} t_{\rm dyn}$, c=0.02-0.1

- Stochastic treatment for the timestep Δt
  - Form stars if random number [0,1] is smaller than

$$p \leqslant \frac{m}{m_{\rm g,0}/N_*}\left(1 - \exp\left[-\frac{\Delta t}{t_{\rm sf}}\right]\right), \quad m_{*,0} = m_{\rm g,0}/N_* \text{ with } N_* = 2.$$

Chemical Enrichment 1/2

- Ejection of mass at *t*

$$e_{m,\mathrm{SW}} = \left(\frac{\mathrm{Z}}{\mathrm{Z}_\odot}\right)^{0.8} \int_{\max[m_{2,u},m_t]}^{m_u} (1 - w_m)\phi(m)\,\mathrm{d}m, \tag{23}$$

time

$$e_{m,\mathrm{II}} = \int_{m_t}^{m_{2,u}} (1 - w_m)\phi(m)\,\mathrm{d}m, \tag{24}$$

and

$$e_{m,\mathrm{Ia}} = m_{\mathrm{CO}}\mathcal{R}_{\mathrm{Ia}}(t). \tag{25}$$

- Ejection of metals at *t*

$$e_{z_i,\mathrm{SW}} = \left(\frac{\mathrm{Z}}{\mathrm{Z}_\odot}\right)^{0.8} \int_{\max[m_{2,u},m_t]}^{m_u} (1 - w_m - p_{z_i m,\mathrm{II}})Z_i\phi(m)\,\mathrm{d}m,$$

(27)

Kobayashi et al. 06, SNII/HN, Z-dependent

$$e_{z_i,\mathrm{II}} = \int_{\max[m_{2,\ell},m_t]}^{m_{2,u}} p_{z_i m,\mathrm{II}}\phi(m)\,\mathrm{d}m + \int_{\max[m_{2,\ell},m_t]}^{m_{2,u}} (1 - w_m - p_{z_i m,\mathrm{II}})Z_i\phi(m)\,\mathrm{d}m,$$

and

Nomoto et al. 97, W7

$$e_{z_i,\mathrm{Ia}} = m_{\mathrm{CO}}p_{z_i m,\mathrm{Ia}}\mathcal{R}_{\mathrm{Ia}}(t). \tag{29}$$

Chemical Enrichment 2/2

- SW rate

$$\mathcal{R}_{\rm SW} = \int_{\max[m_{2,u}, m_t]}^{m_u} \frac{1}{m}\phi(m)\,{\rm d}m, \qquad (30)$$

- SN II/HN rate

time

$$\mathcal{R}_{\rm II} = \int_{\max[m_{2,\ell}, m_t]}^{m_{2,u}} \frac{1}{m}\phi(m)\,{\rm d}m. \qquad (31)$$

- SN Ia rate (SD scenario)

metallicity effect

$$\mathcal{R}_{\rm Ia} = b \int_{\max[m_{1{\rm p},\ell}, m_t]}^{m_{1{\rm p},u}} \frac{1}{m}\phi(m)\,{\rm d}m \int_{\max[m_{1{\rm d},\ell}, m_t]}^{m_{1{\rm d},u}} \frac{1}{m}\phi_{\rm d}(m)\,{\rm d}m. \qquad (32)$$

primary WD

secondary star

- IMFs of single and binary (secondary) stars

$$\phi(m) = m^{-x}\frac{1-x}{m_u^{1-x} - m_\ell^{1-x}} \qquad \phi_{\rm d}(m) = m^{-x} \times \frac{-x}{m_{{\rm d},u}^{-x} - m_{{\rm d},\ell}^{-x}}$$

Supernova Feedback 1/2

- Energy by stellar winds for given mass

$$e_{\rm e,SW} = \begin{cases} 0.2 \times 10^{51} \left(\frac{Z}{Z_\odot}\right)^{0.8} & (m_{2,u} < m \leqslant m_u) \\ 0.2 \times 10^{51} & (m_{2,\ell} < m \leqslant m_{2,u}) \end{cases} \quad \text{(erg)}, \qquad (17)$$

- Energy per core-collapse supernova

$$e_{\rm e,\,II} = \int_{m_t}^{m_{2,\rm u}} p_{{\rm e},m} \frac{1}{m} \phi(m)\, dm$$

$$p_{{\rm e},m} = \begin{cases} 1 & (m_{2,\ell} < m \le 20 M_{\rm sun}) \\ (1-\varepsilon_{\rm HN}) + [10,10,20,30]\varepsilon_{\rm HN} & (20,\ 25,\ 30,\ 40 M_{\rm sun}) \end{cases} \times 10^{51} (\text{erg})$$

$$\varepsilon_{\rm HN} = [0.5,\ 0.5,\ 0.4,\ 0.01,\ 0.01] \ \text{ for } Z = [0,\ 0.001,\ 0.004,\ 0.02,\ 0.05]$$

- Energy per Type Ia supernova

$$e_{\rm e,Ia} = 1.3 \times 10^{51} (m_{\rm 1d,\ell} < m \leqslant m_{\rm 1d,u}) \text{(erg)} \qquad (19)$$

Supernova Feedback

- Total energy, mass, metal ejection from a star particle *j* at time *t* to a neighbor gas particle *i*

$$E_{\mathrm{e},j}(t,Z_j) = m_*^0[e_{\mathrm{e,\,SW}}(Z_j)R_{\mathrm{SW}}(t) + e_{\mathrm{e,\,II}}(t,Z_j) + e_{\mathrm{e,\,Ia}}R_{\mathrm{Ia}}(t,Z_j)] = \sum_{i=1}^{N_{\mathrm{FB}}} E_{\mathrm{e},i}(t,Z_j)W(\mathbf{r}_i - \mathbf{r}_j; h_j)$$

$$E_{m,j}(t,Z_j) = m_*^0[e_{m,\,\mathrm{SW}}(t,Z_j) + e_{m,\,\mathrm{II}}(t,Z_j) + e_{m,\,\mathrm{Ia}}(t,Z_j)] = \sum_{i=1}^{N_{\mathrm{FB}}} E_{m,i}(t,Z_j)W(\mathbf{r}_i - \mathbf{r}_j; h_j)$$

$$E_{Z,j}(t,Z_j) = m_*^0[e_{Z,\,\mathrm{SW}}(t,Z_j) + e_{Z,\,\mathrm{II}}(t,Z_j) + e_{Z,\,\mathrm{Ia}}(t,Z_j)] = \sum_{i=1}^{N_{\mathrm{FB}}} E_{Z,i}(t,Z_j)W(\mathbf{r}_i - \mathbf{r}_j; h_j)$$

- Internal energy (and mass, metal) that gas particle *i* get from star particle j

$$\frac{du_i}{dt} = \sum_j \int_{t-dt_j}^{t} dt \frac{E_{e,j}(t,Z_j)W(\mathbf{r}_i - \mathbf{r}_j; h_j)}{\sum_{k=1}^{N_{\mathrm{FB}}} W(\mathbf{r}_k - \mathbf{r}_j; h_j)}$$

100% thermal

Other feedback methods

- artificial cooling off during heating (Governato+ 10)
- kinetic feedback (Navarro & White 93, Springel & Hernquist 03)

$$v_{\rm wind} = \sqrt{\frac{2\varepsilon_{\rm kin} E_{\rm SN}}{m}}$$

- kinetic feedback (Navarro & White 93, Springel & Hernquist 03)

$$v_{\rm wind} = 484 \text{ km/s for } p \le \frac{m}{m_{\rm g,0} / N_*}(1 - \eta \exp[-\frac{\Delta t}{t_{\rm sf}}]), \eta = 2$$

- momentum driven-winds (Dave & Oppenheimer 06)

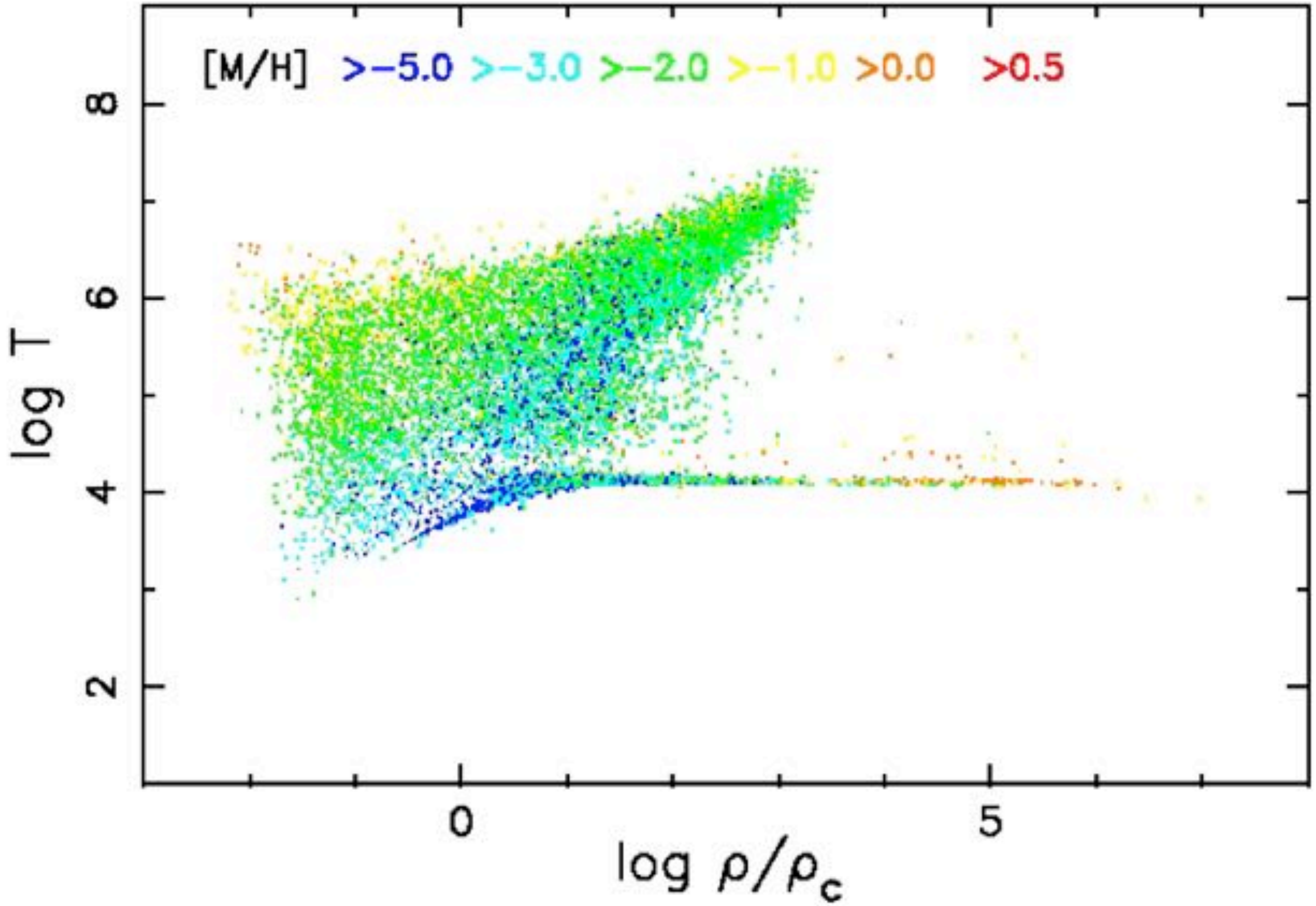
$$v_{\rm wind} = 3\sigma\sqrt{f_L - 1} + 2\sigma,\ \eta = \frac{\sigma_0}{\sigma} = 2,\ \sigma_0 = 300 \text{ km/s},\ f_L = 2 \text{ or}$$

$$f_{\rm L} = f_{{\rm L},\odot} \times 10^{-0.0029*(\log Z+9)^{2.5}+0.417694}.$$

- stochastic treatment of feedback (Dalla Vecchia & Schaye 12)
  - $\Delta\varepsilon$ (~1.82 10^{14} erg/s) is given if random number [0,1] is smaller than

$$p = f_{\rm th} \frac{\epsilon_{\rm SN\,II}}{\Delta\epsilon} \frac{m_*}{\sum_{i=1}^{N_{\rm ngb}} m_i}\ ,\ f_{\rm th}=1, N_{\rm ngb}=48$$

Density-temperature diagram



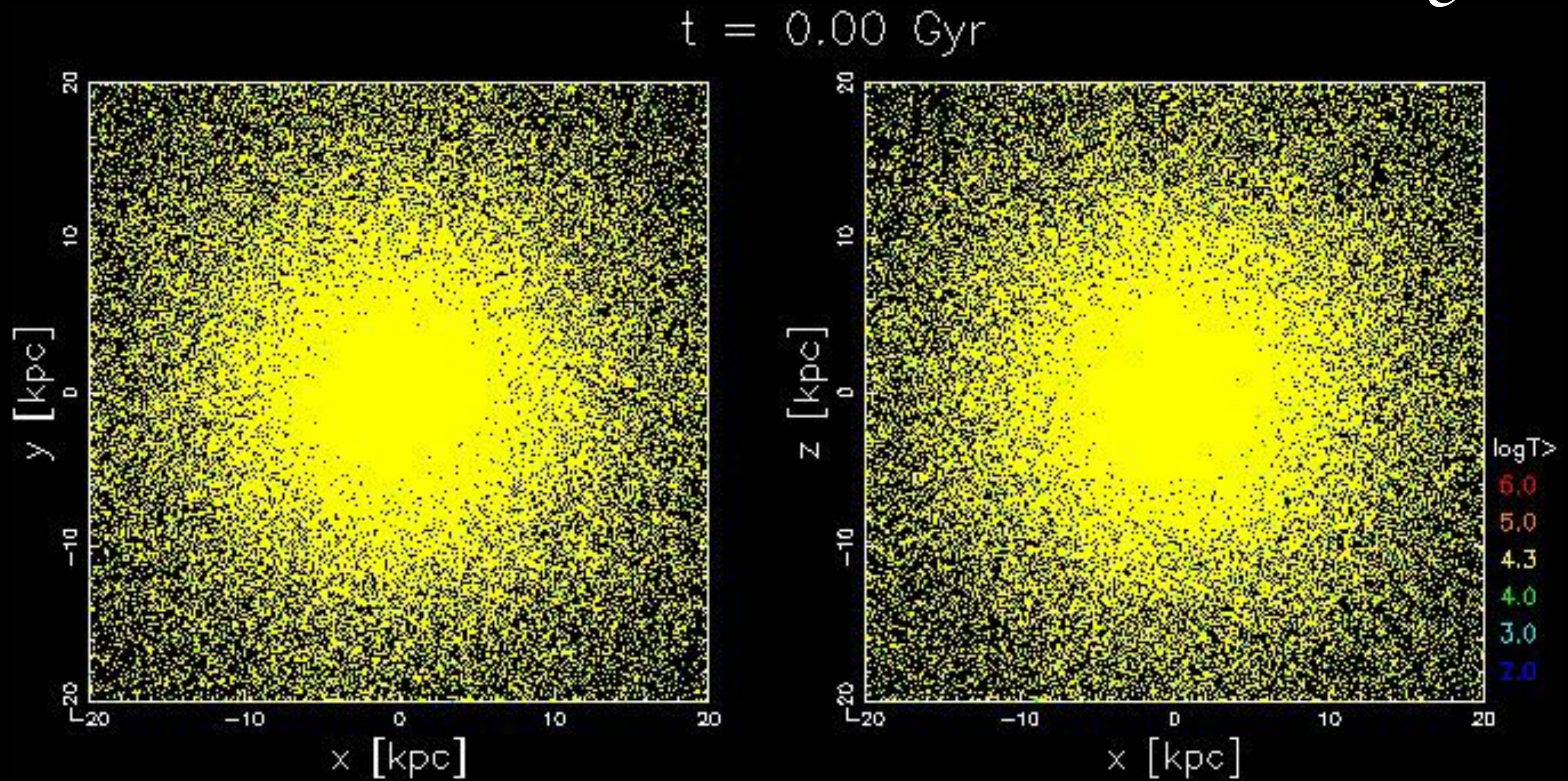
CK, Springel, & White 2007

Isolated Disk

CK, Springel, & White 2007

- Fixed NFW halo $M_{tot}=10^{10}$ /h $M_\odot$
- 10% gas, N=160000 ($m_{gas}=6.3\times10^3$ /h Mu), $\lambda=0.1$

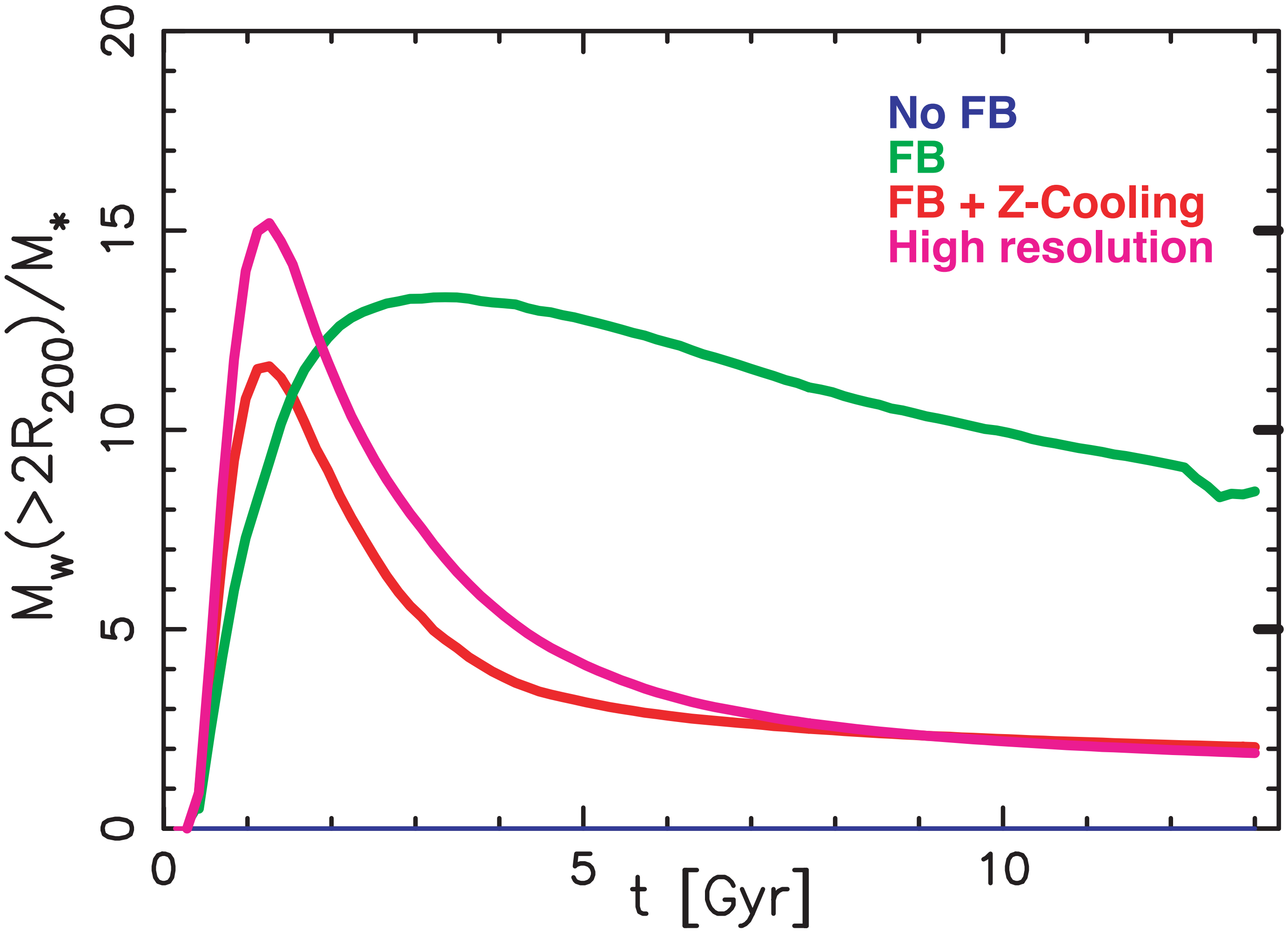
Face-on *Edge-on*



Colors: Gas Temperature, White: Stars

Wind Fraction

Wind is defined as $r>2R_{200}$



Ejected Metal Mass

$M_{z,w}/ M_{z,tot}$

44% (SN)

3% (SN)

60% (HN)

25% (HN)

2/3? (Renzini 03)

~50% gas, ~25% metals are ejected by HNe.
Resolution independent.

Other Simulation Codes

Cosmological

- Springel 00 (Gadget - SPH), Di Matteo (AGN), Scannapieco (Ia), Schaye
- Frenk, Okamoto, … (Gadget)
- Dave, Oppenheimer (Gadget)
- Mosconi, Tissera, et al. 01 (AP3MSPH, Ia)
- Teyssier 02, Devriendt (RAMSES – AMR)
- Wadsley 04 (GASOLINE –SPH), Governato, Brook
- Martinez-Serrano 08 (SPH)
- Springel 10 (AREPO)
- …

Galactic

- Steinmetz & Muller 94 (SPH)
- Raiteri, Villata & Navarro 96 (Ia)
- Carraro, Lia & Chiosi 98 (Ia)
- Hensler 90, Recchi
- Burkert, Naab 99 (N-body)
- Hernquist, Hopkins 05 (AGN)
- Mori 97
- Nakasato 03
- Gibson, Kawata 04 (Ia), Brook
- Tornatore et al. 04 (Ia)
- Elmegreen
- …

AGN feedback

Active Galactic Nuclei (AGN)

- 1950s: radio sources discovered, optical counterparts?
- 1960: 3C48, blue star with broad emission lines
- 1963: 3C273, redshift z=0.158 → distant object

Table 1. WAVE-LENGTHS AND IDENTIFICATIONS

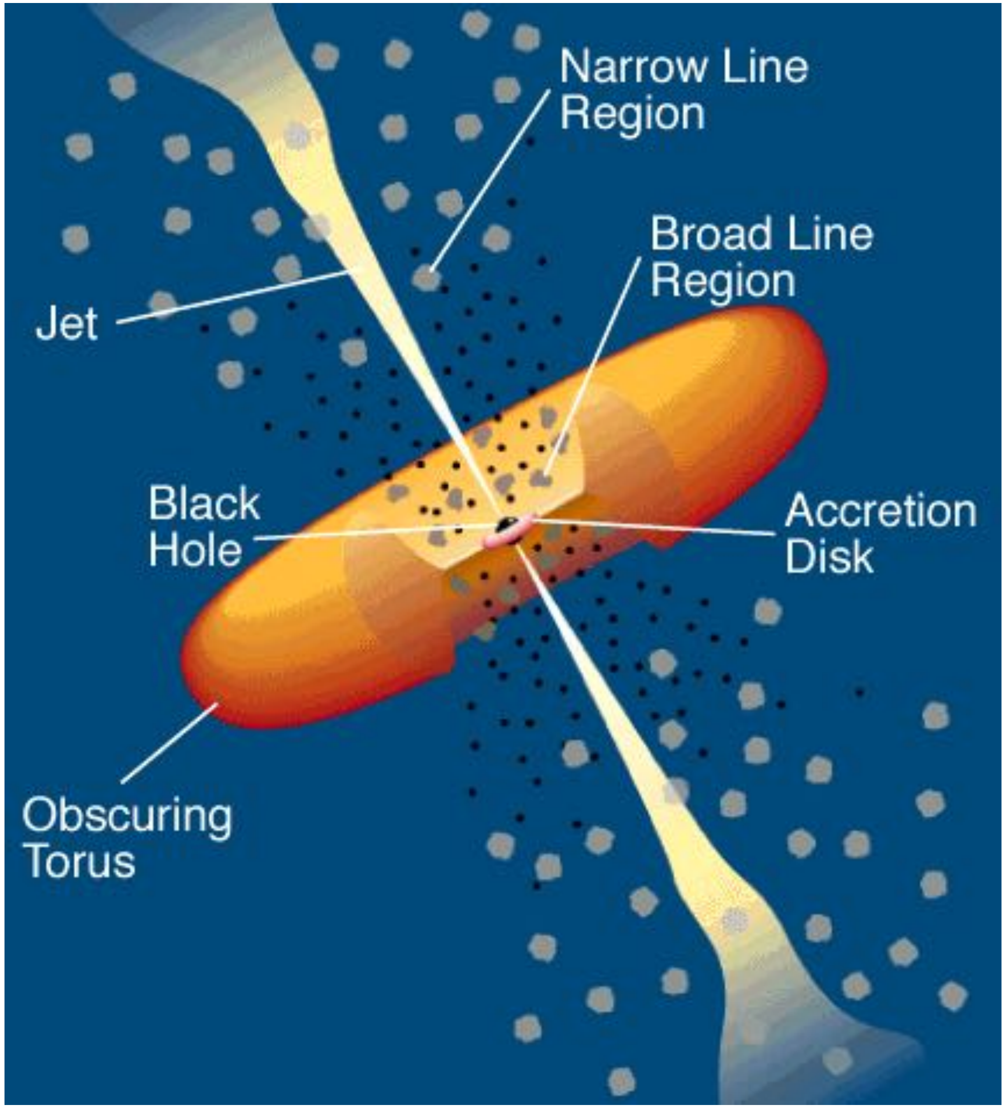
λ	$\lambda/1{\cdot}158$	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	Hϵ
4753	4104	4102	Hδ
5032	4345	4340	Hγ
5200–5415	4490–4675		
5632	4864	4861	Hβ
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

$$z \equiv \frac{\lambda_{obs}}{\lambda_{emit}} - 1$$

- very luminous, 10^{12} L_{sun}, ~ 4×10^{45} erg/s, energy-production mechanism?

The Unified Model of AGN

Seyfert 1 with broad & narrow emission lines



Seyfert 2 with narrow emission lines

AGN Feedback?

◆ AGN not only suppress SF but also enhance SF!

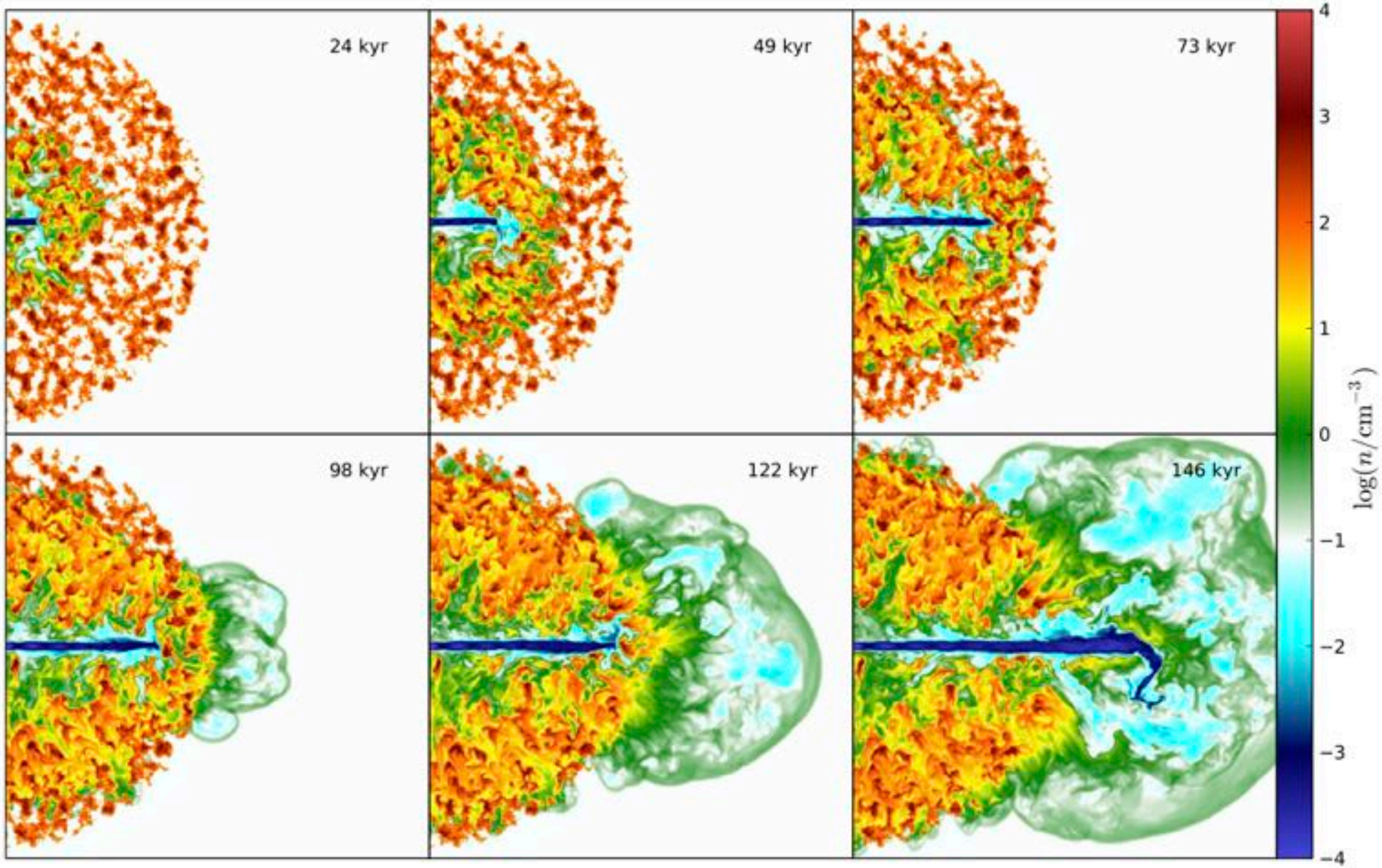
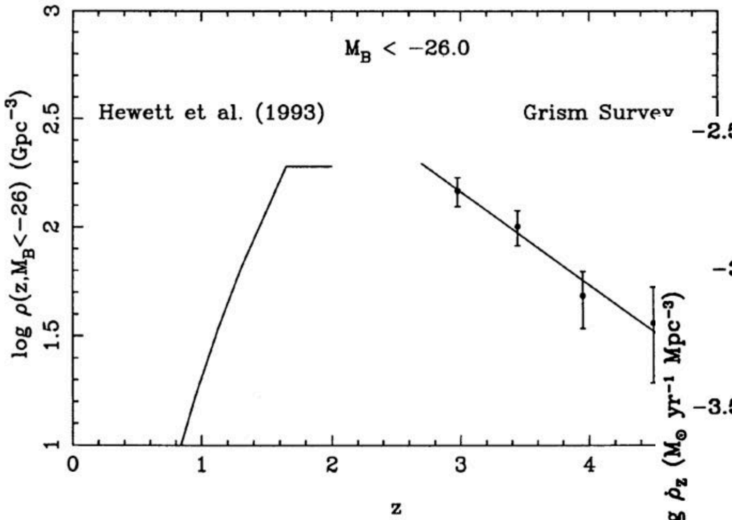


Figure 2. Evolution of density in simulation E. The width and height of each panel are 1 kpc.
(A color version, animations (A, B, C, D, E), and the complete figure set (five images) of this figure are available in the online journal.)

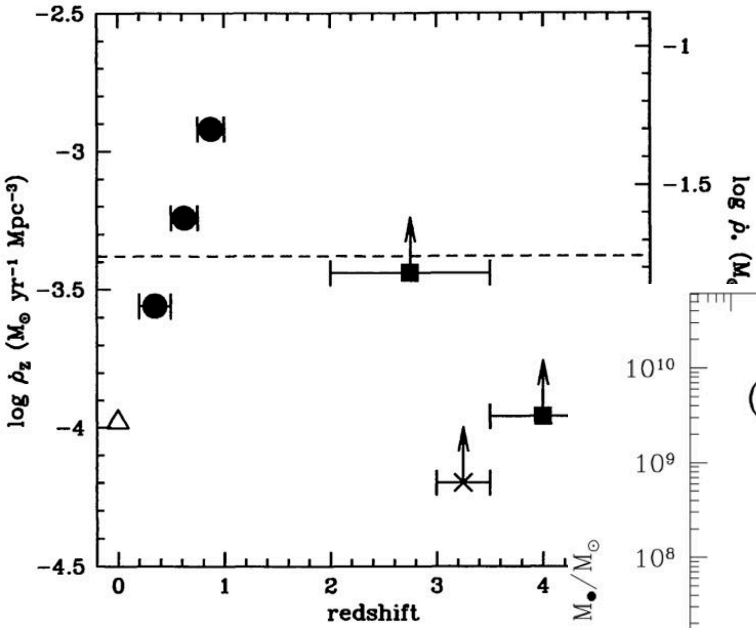
Wagner & Bicknell 2011; and many

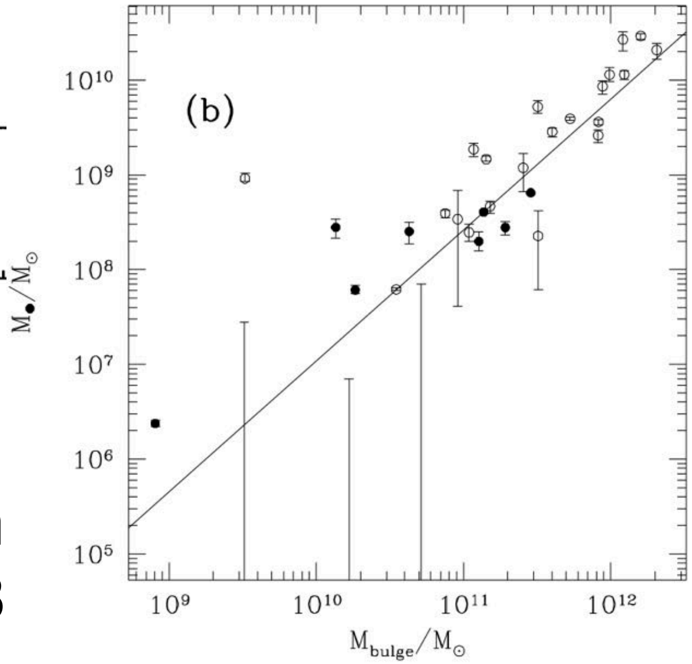
Co-evolution of SMBH & galaxies

Quasar space density
Schmidt+ 95



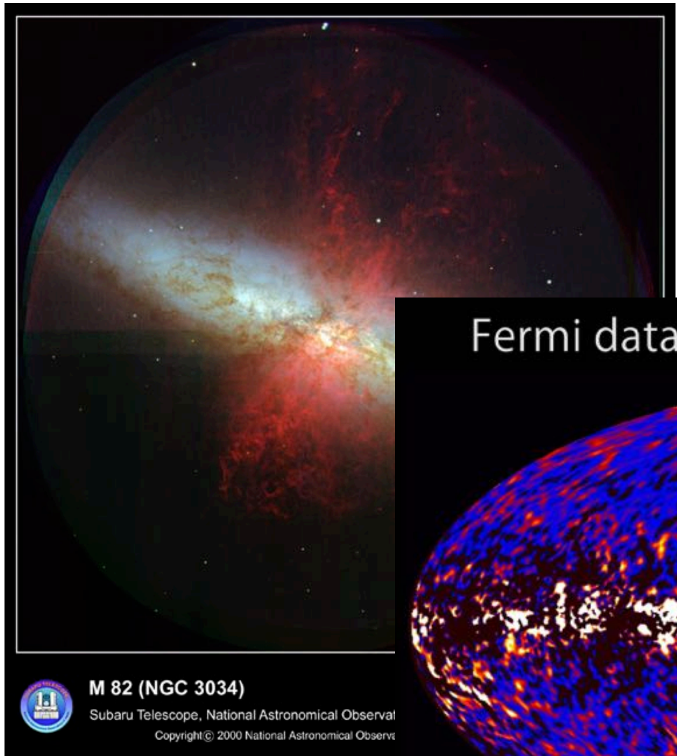
Cosmic SFR
Madau+ 96



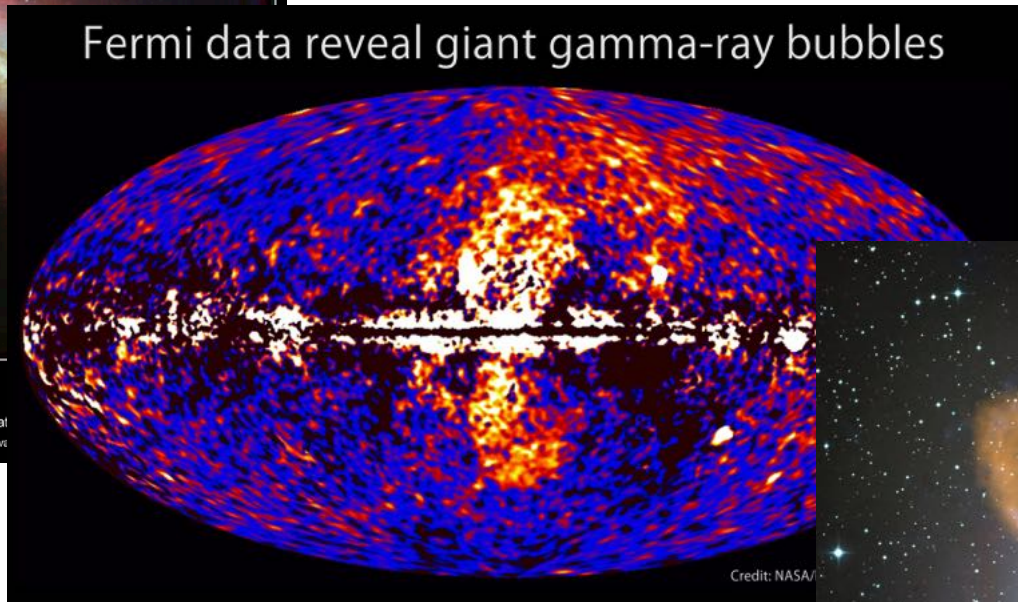


BH mass-bulge mass relation
Magorrian+ 98

Stellar + AGN winds



M_{tot}~$10^{10}M_\odot$
SFR~$10M_\odot$/yr

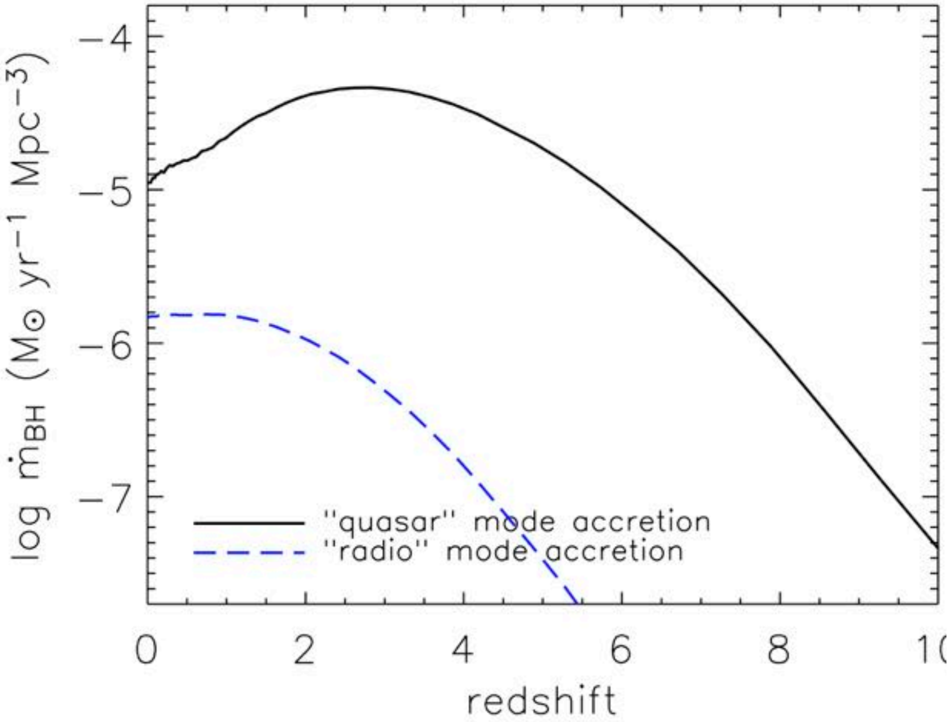


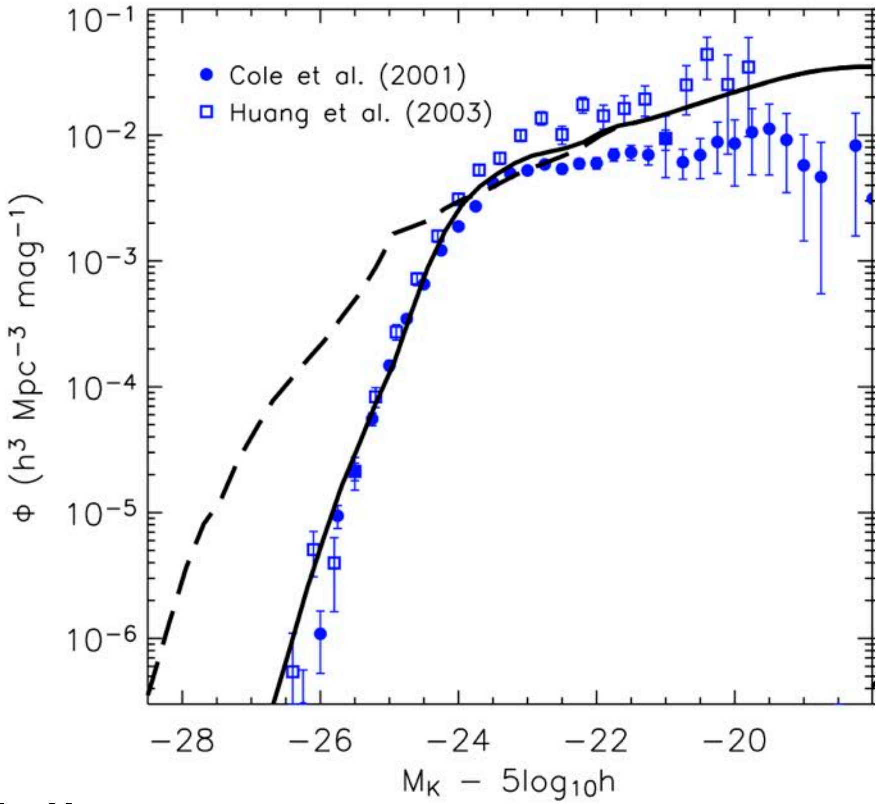
M_{halo}~0.8-$2.5 \times 10^{12}M_\odot$
M_{bulge}~$10^9M_\odot$?
M_{BH}~$10^6M_\odot$
SFR(ring)~$0.05M_\odot$/yr

M_{tot}~0.5-$1 \times 10^{12}M_\odot$
M_*~$5 \times 10^{10}M_\odot$?
M_{BH}~$5 \times 10^7M_\odot$
SFR~0?

AGN feedback in Semi-Analytic Models

- **Croton et al. 2006, Semi-analytic Model**
  - ★ quasar mode: BH growth by mergers
  - ★ radio mode: heating by hot gas accretion on BH





- No such modes in hydro-simulations (Springel, Di Matteo, Hernquist 05; Booth & Schaye 09; … Taylor & Kobayashi 14)

Standard AGN model in hydro-simulations

- Co-evolution of BH-galaxy is <u>assumed</u>.
- BH Formation (Booth & Schaye 09; also Springel, Di Matteo+ 05, Sijacki+07)
  - Regularly run a friends-of-friends group finder on all of the dark matter particles during the simulation, get DM halo mass.
  - If the halo is $>M_{halo,min}=100m_{DM}$ ($\sim10^{10}M_\odot$) and does not already contain a BH, then its most gravitationally bound baryonic particle is converted into a collisionless BH particle with $M_{seed}=0.001m_g$ ($\sim10^5M_\odot$).
- Growth
- Feedback

The first BHs?

- The first chemical enrichment is driven by ~10-50$M_\odot$ stars (faint SNe), leaving ~10$M_\odot$ BHs.
  - No signature of ~140-300$M_\odot$ stars (PISNe) observed in any chemical abundances.
- If the accretion is suppressed, <100$M_\odot$ stars form (Hosokawa+ 11). Otherwise, >300$M_\odot$ stars <u>may</u> form (Ohkubo+ 09), which collapse to 100-1000$M_\odot$ BHs.
  - Direct collapse of gas can form ~10^5 $M_\odot$ BHs (e.g., Madau & Rees 01), but rare.

- What is the role of these "first" BHs in galaxy formation?
- Can they grow into super-massive BHs at present?
- Are they enough for the down-sizing?

New AGN model

- **BH Formation** - not merging products, but originated from primordial SF

$$\rho_{\rm g} > \rho_{\rm c}, \quad Z = 0$$ then M_{seed} (~1000$M_{\odot}$)

- **Growth** - accretion & mergers (same as in previous works; Springel, Di Matteo+ 05, Booth & Schaye 09)

$$\dot{M}_{\rm BH} = (1-\epsilon_{\rm r}) \times \min(\dot{M}_{\rm acc}, \dot{M}_{\rm Edd})$$

$$\dot{M}_{\rm acc} = \alpha \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_{\rm s}^2 + v^2)^{3/2}}, \quad \dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon_{\rm r} \sigma_{\rm T} c}$$

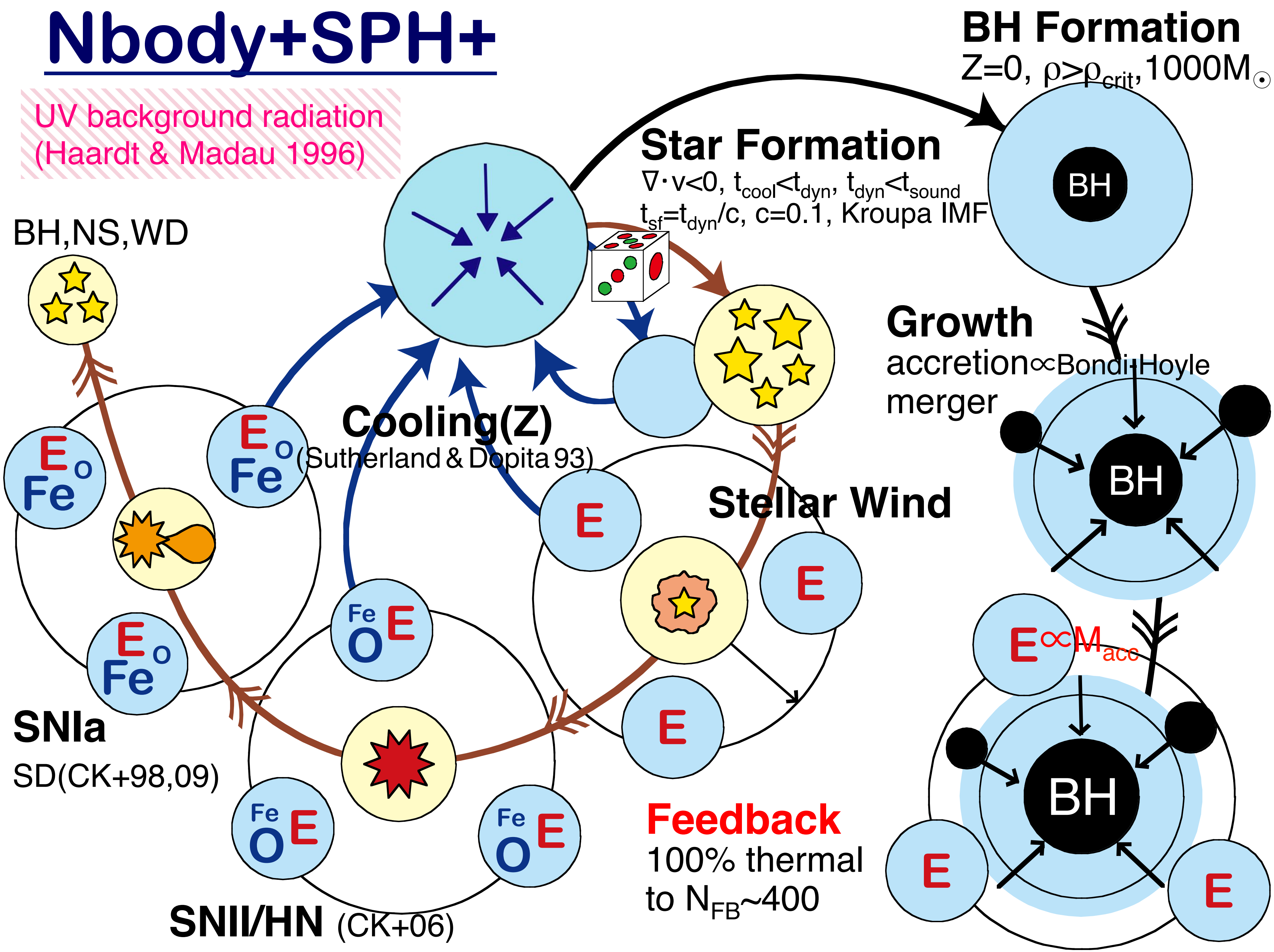
- **Feedback** – thermal

$$E_{\rm FB} = \epsilon_{\rm r} \epsilon_{\rm f} \dot{M}_{\rm acc} c^2 \Delta t$$

Cosmological Simulations

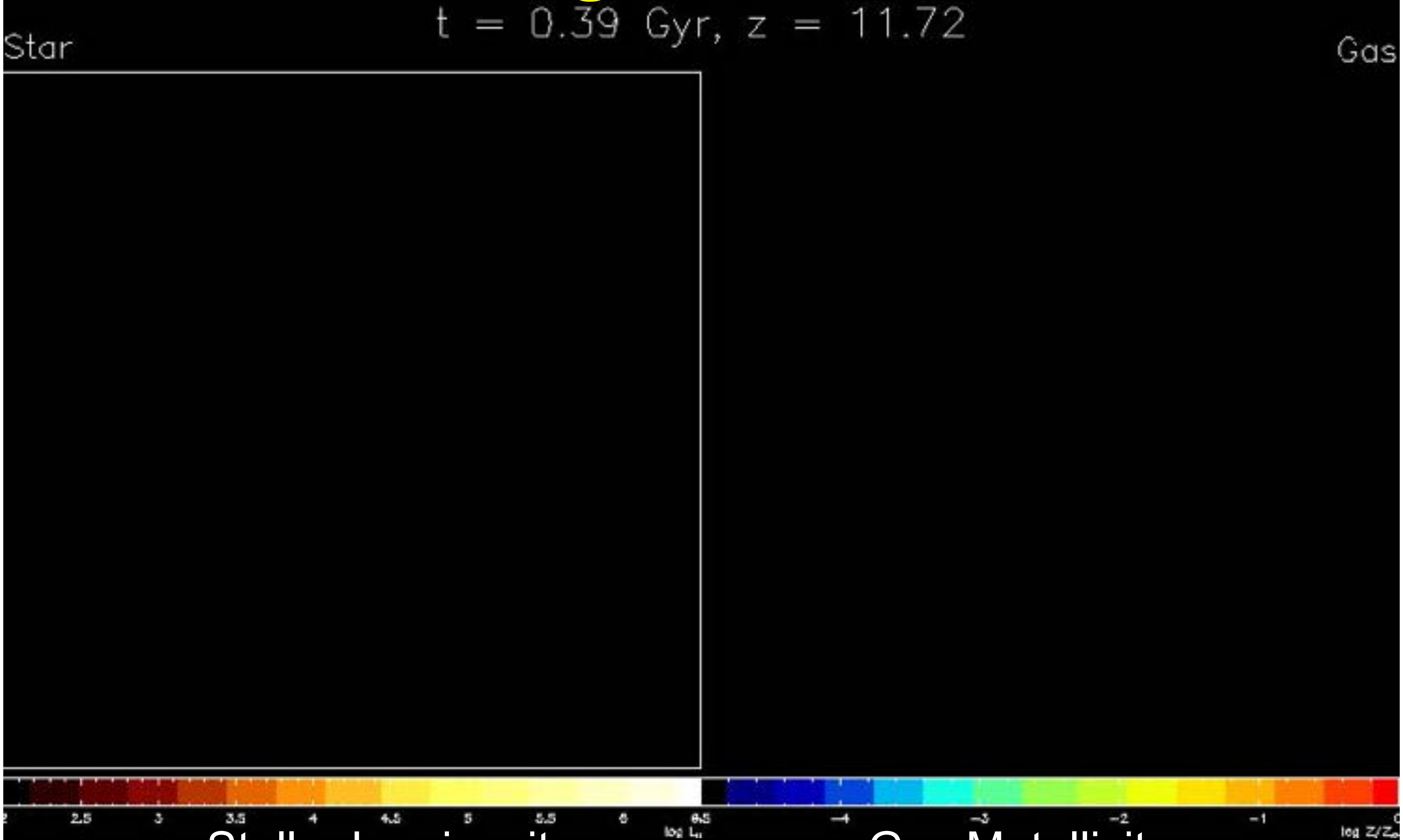
CK, Springel, White 2007

Taylor & CK 2014, 2015abcd



Nbody+SPH+
UV background radiation
(Haardt & Madau 1996)
BH Formation
Z=0, ρ>ρ_crit, 1000M_⊙
Star Formation
∇·v<0, t_cool<t_dyn, t_dyn<t_sound
t_sf=t_dyn/c, c=0.1, Kroupa IMF
BH
BH,NS,WD
Growth
accretion∝Bondi-Hoyle
merger
BH
Cooling(Z)
(Sutherland & Dopita 93)
E
O
Fe
Stellar Wind
E
SNIa
SD(CK+98,09)
E∝M_acc
BH
SNII/HN (CK+06)
Feedback
100% thermal
to N_FB~400

Cosmological Simulation

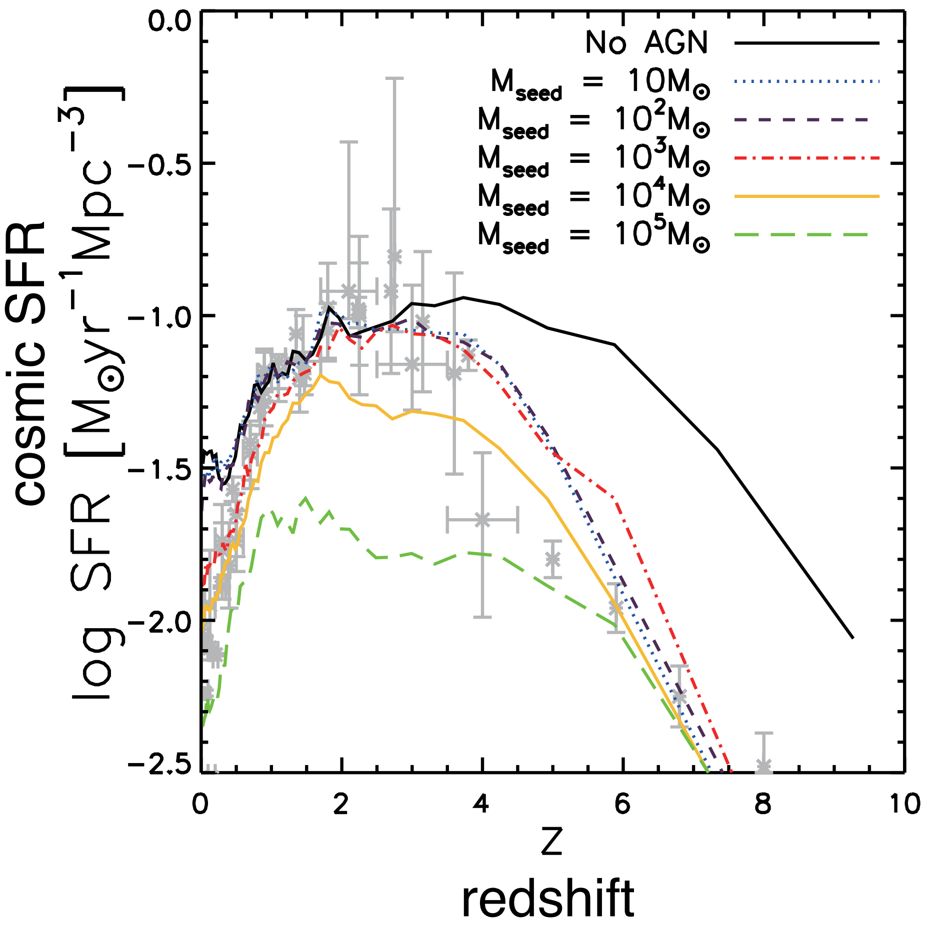


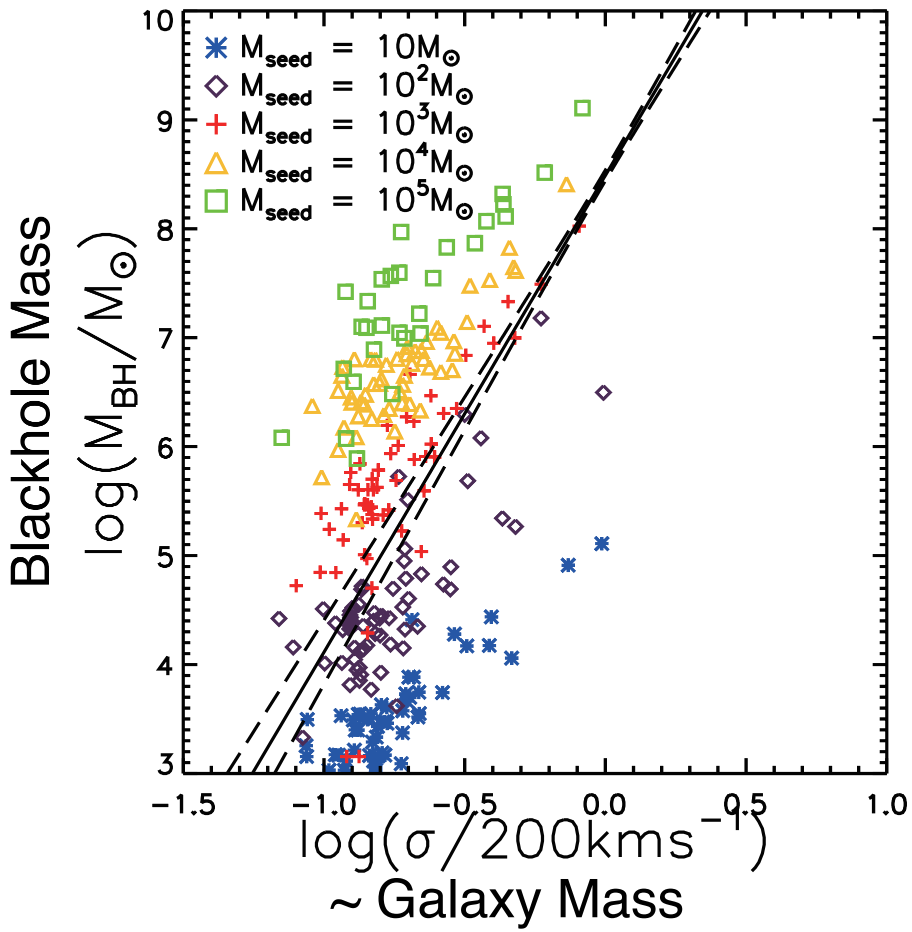
Stellar Luminosity Gas Metallicity

25Mpc; $N \sim 2 \times 240^3$; $m_{gas} \sim 10^7\ M_\odot$; $H_0=70$, $\Omega_m=0.28$, $\Omega_\lambda=0.72$, $\Omega_b=0.046$, $n=1$, $\sigma_8=0.82$

Constraining parameters

from cosmic SFRs, Magorrian relation, and galaxy size-mass relation → $\alpha = 1$, $\varepsilon_f = 0.25$, $\rho = 0.1$, $\mathbf{M_{seed} = 1000 M_\odot}$





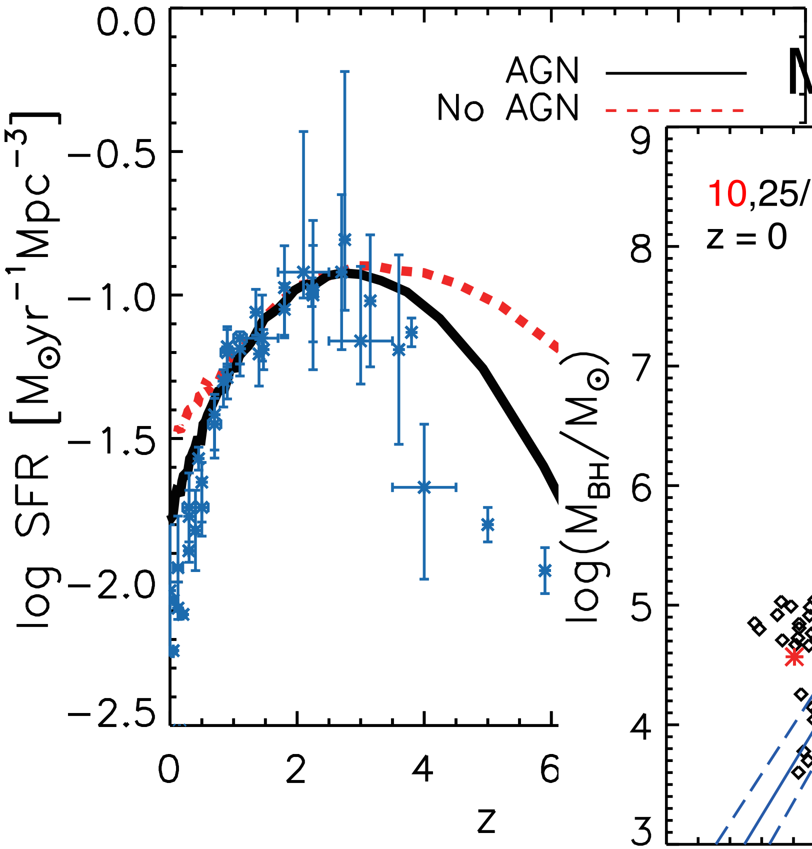
Taylor & CK 2014, MNRAS, 442, 2751

Observational Constraints

$M_{BH\ seed}$~100-1000$M_{\odot}$ better than 10, $10^{4\text{-}5}M_{\odot}$ – First Star origin

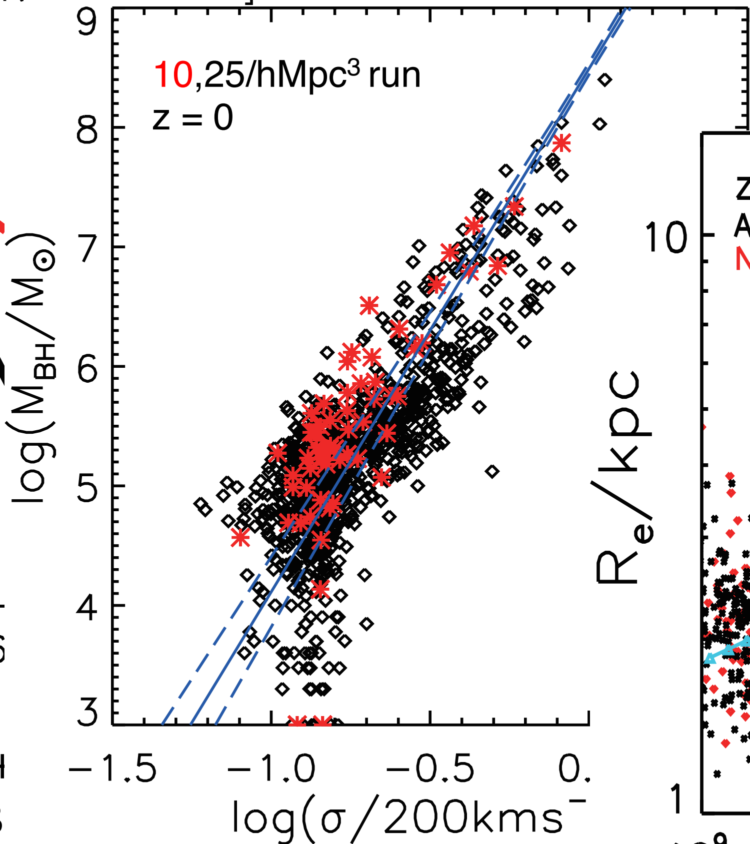
Taylor & CK 2014, MNRAS, 442, 2751;
Taylor & CK 2015a, MNRAS, 448, 1835

Cosmic SFR



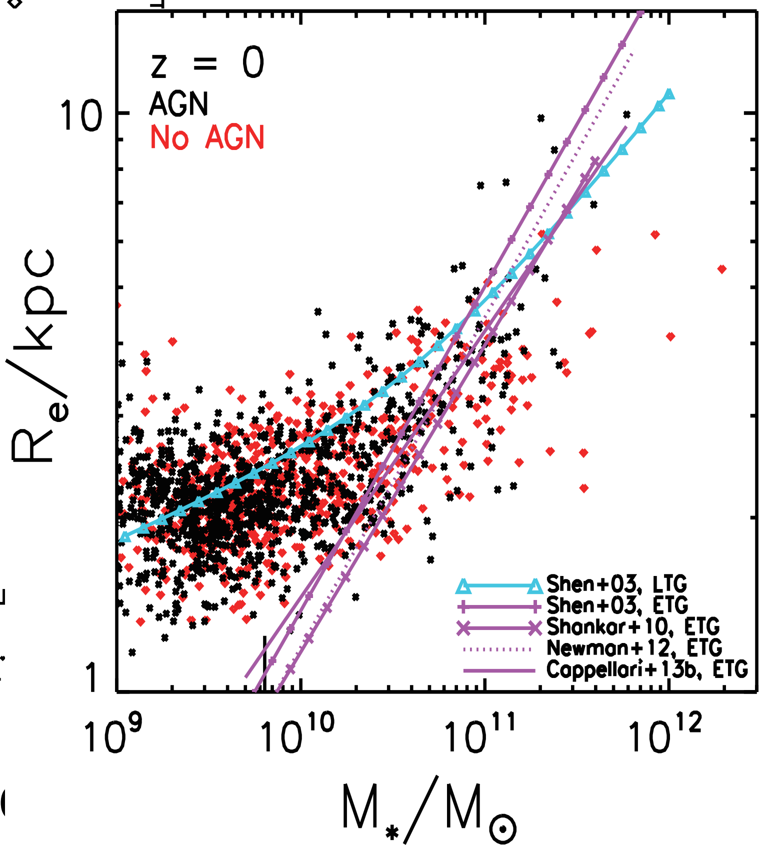
obs: Bouwens+11, Karim+
Cucciati+12, Oesch+12, B
+13, Gunawardhana+13, Sobral+13

Magorrian relation



obs: Kormendy & Ho 2(

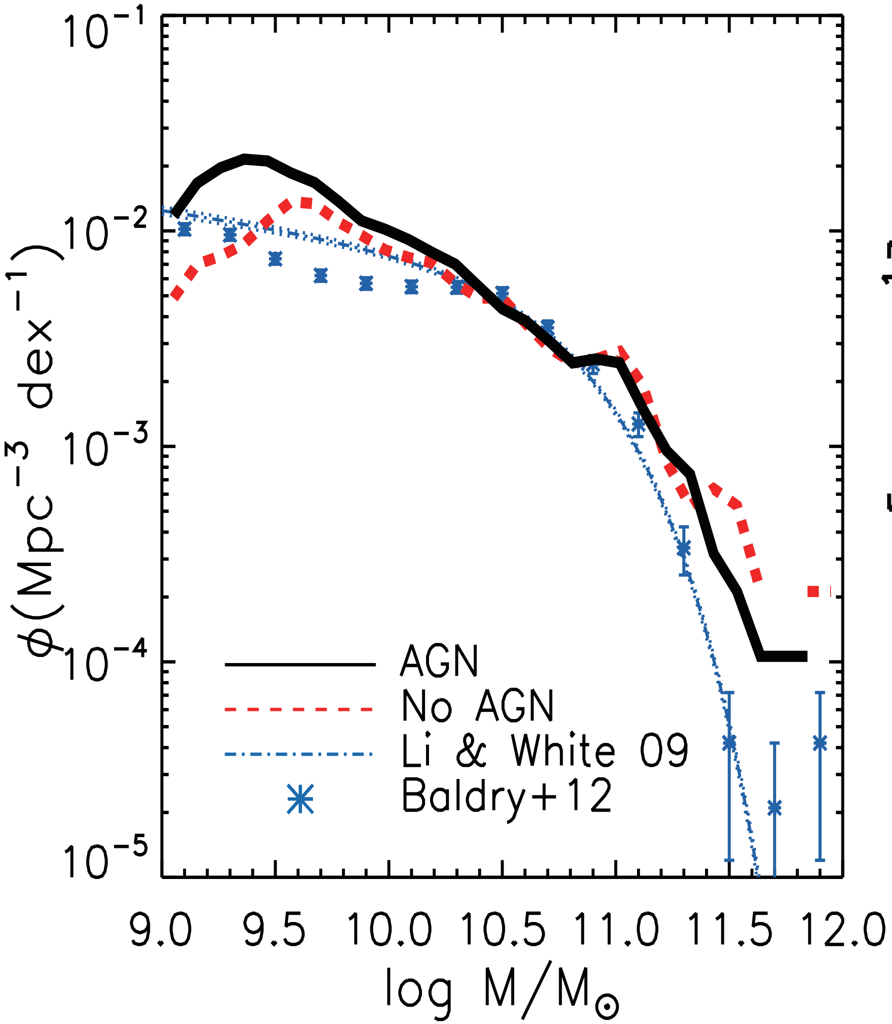
Size-mass relation



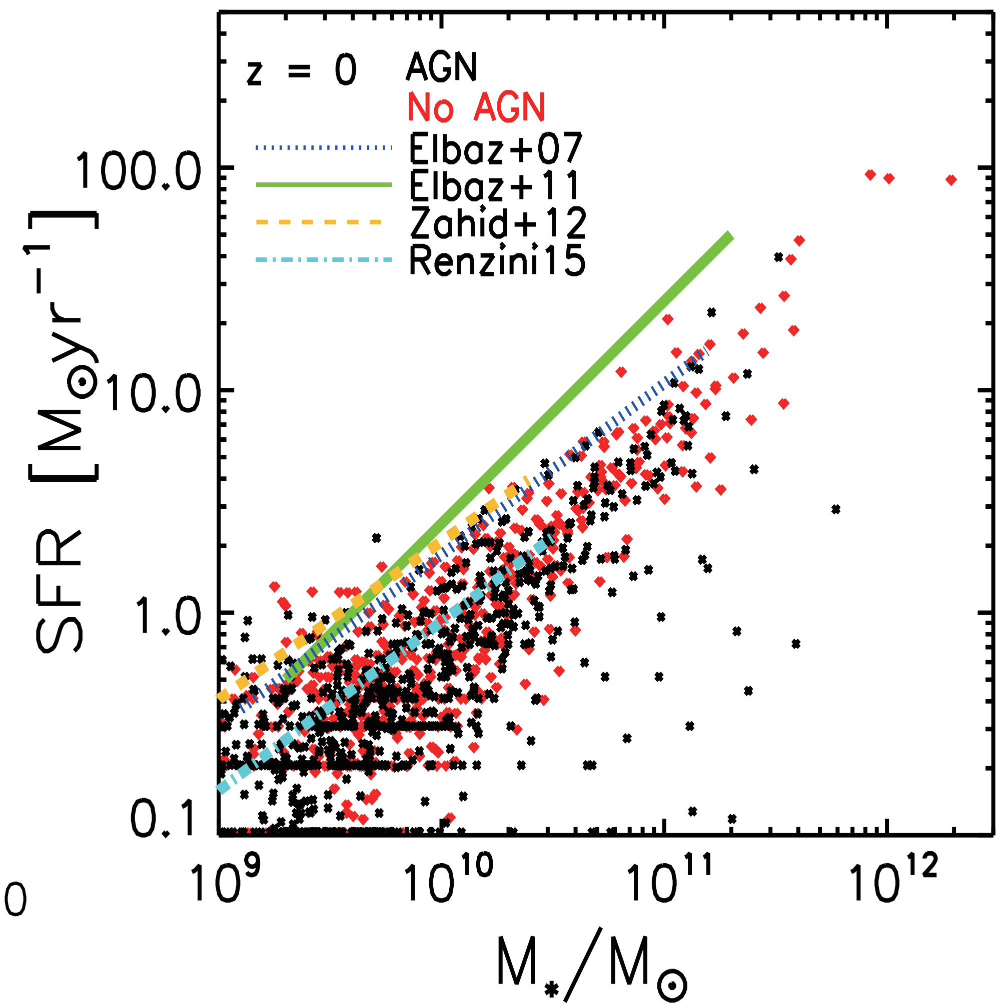
Simulation Outcome

Not used for parameter determination

Stellar Mass Function

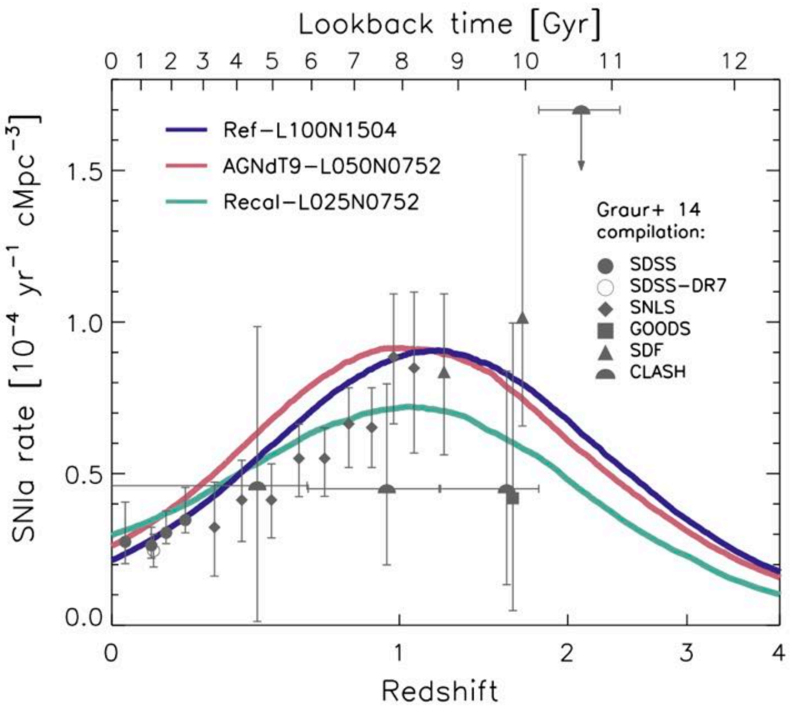


Star Formation Main Sequence



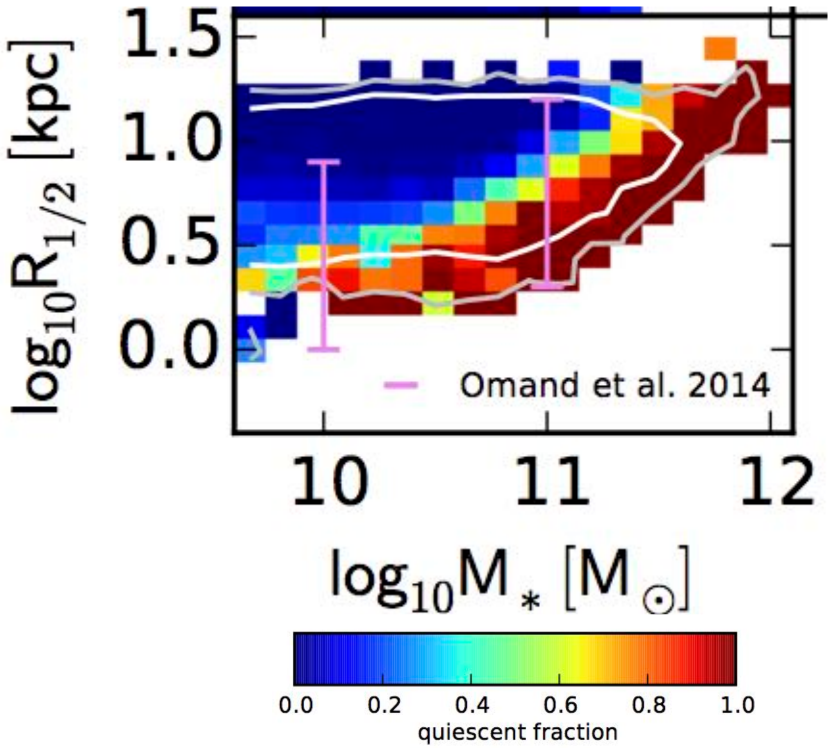
Other Big Simulations

- EAGLE w Gadget-3 (100Mpc)
  - Cosmic SFR?
- Illustris w AREPO (106.5Mpc)
  - Size-Mass relation?

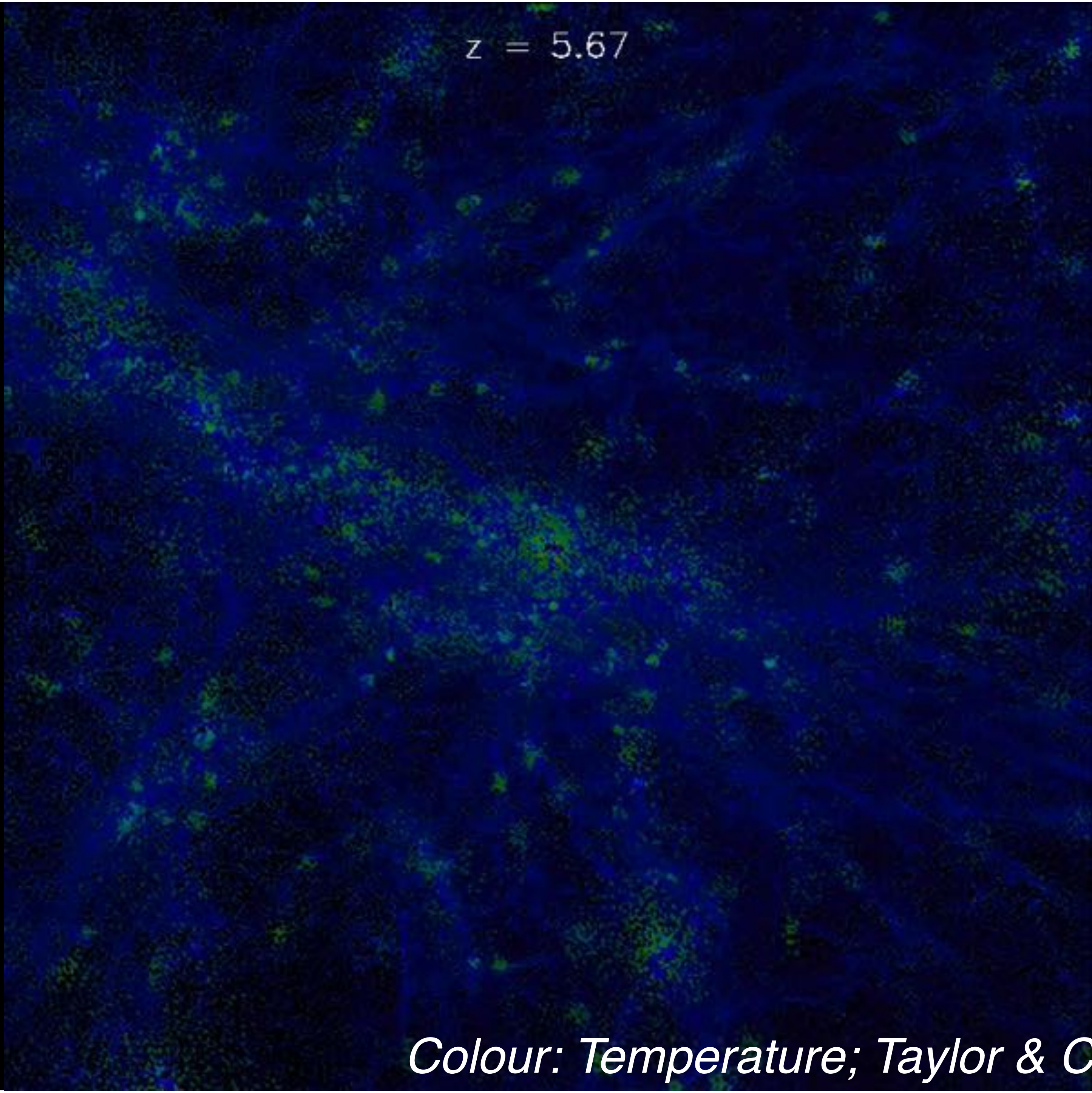


Schaye et al. 14

obs: Omand et al. 2014



Snyder et al. 15

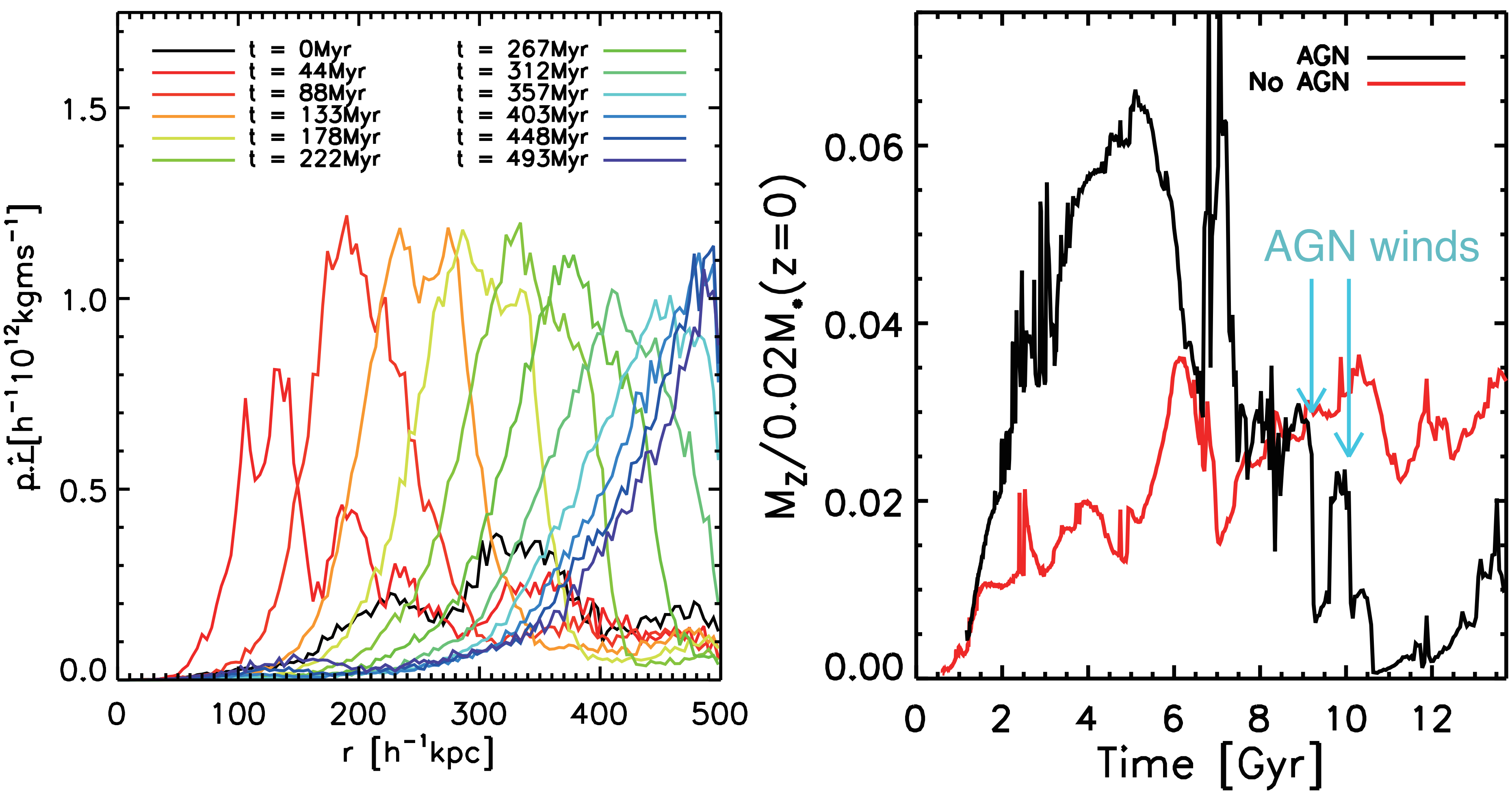


Colour: Temperature; Taylor & CK 2014

38

AGN-driven outflows

Taylor & CK 2015b, MNRAS, 452, L59



- AGN-driven winds remove the remaining gas (3% of baryon) and ~2% of total produced metals.

Metallicity of galaxies

Star Forming Galaxies

- Emission line ratios – [OII],Hβ, [OIII],Hα,[NII],[SII]
- Photoionization models - MAPPINGS (Sutherland & Dopita 199), Cloudy (Ferland et al. 1998)
- Stellar population synthesis models - Starburst99 (Leitherer et al. 1999)
- Degeneracy between Z and ionization parameter q
- Solar Abundance = 8.69 (Allende Prieto et al. 2001), 8.66 (Asplund et al. 2004)

Metallicity = 12 + log (O/H)

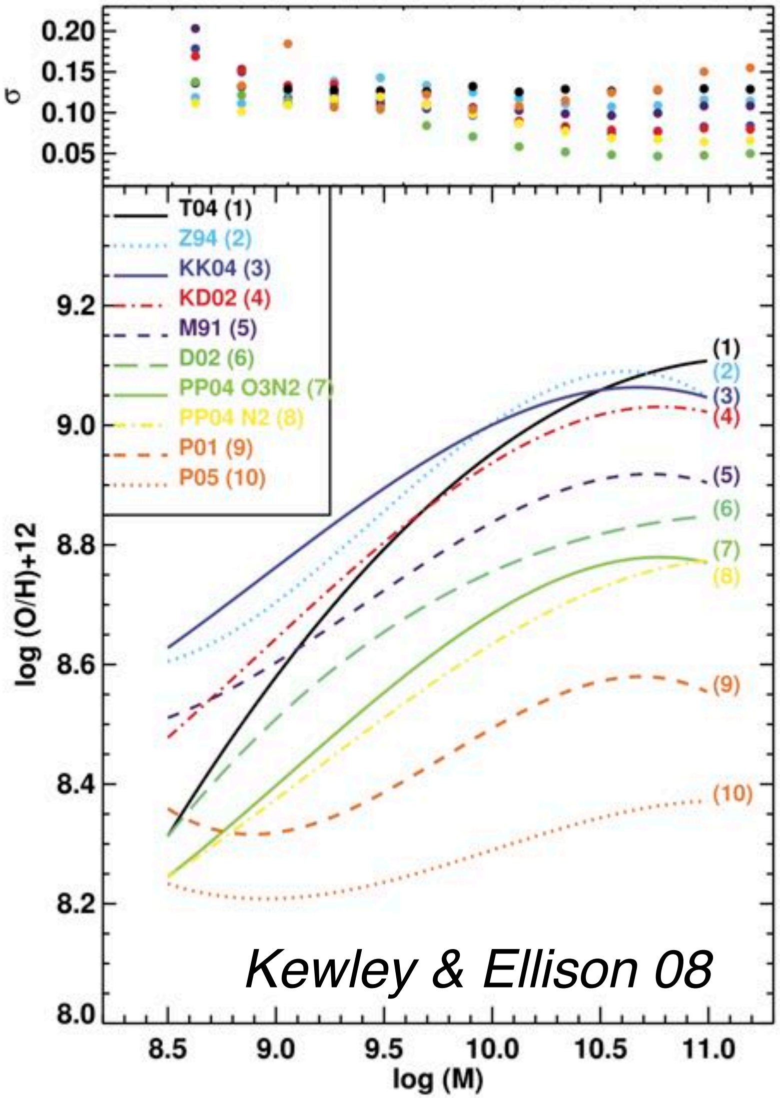
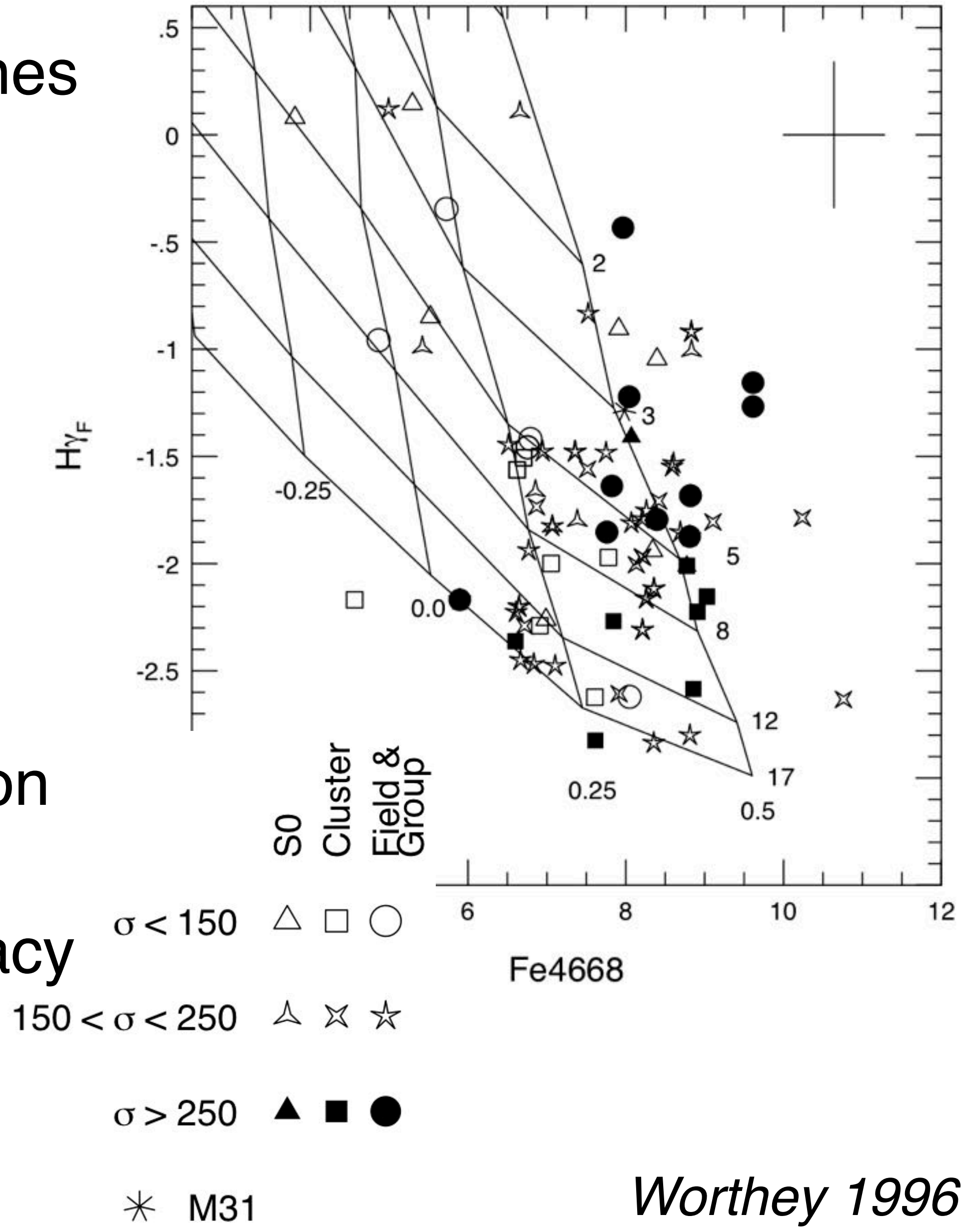


FIG. 2.—Robust best-fit *M-Z* relations calculated using the different metallicity calibrations listed in Table 1, except the T_e method. The top panel shows the rms scatter in metallicity about the best-fit relation for each calibration in 0.1 dex bins of stellar mass. The *y*-axis offset, shape, and scatter of the *M-Z* relation differ substantially, depending on which metallicity calibration is used.

Early-type Galaxies (ETG)

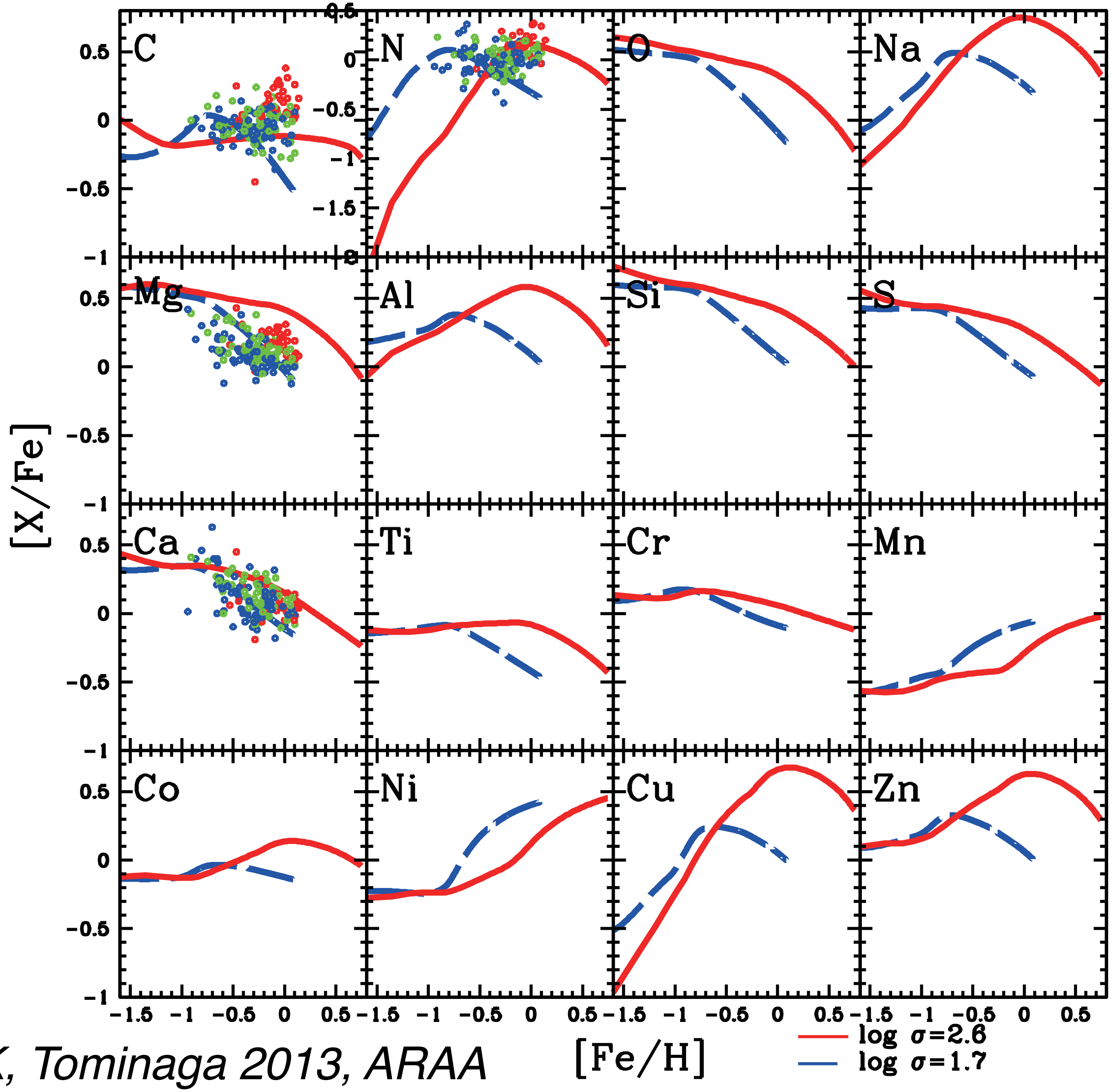
- Integrated Absorption Lines → Lick indices Mg_2, Mg_b, Fe5270, Fe5335, Hβ, Hγ
- Population synthesis models – Worthey 1994, Thomas, Maraston & Bender 2003
- Broadening of velocity dispersion
- Contamination of emission lines
- Age-Metallicity Degeneracy

Metallicity [M/H]



Worthey 1996

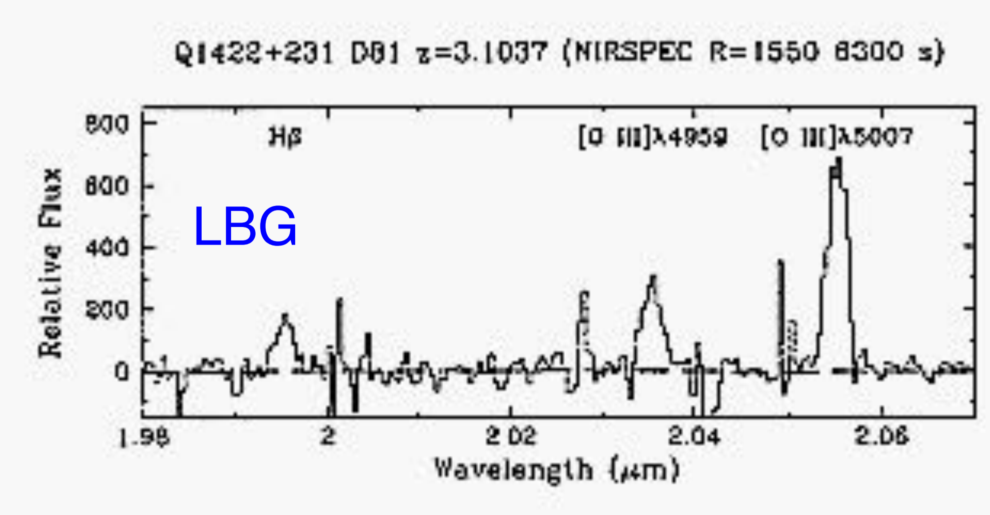
[X/Fe]-[Fe/H] relations of ETGs



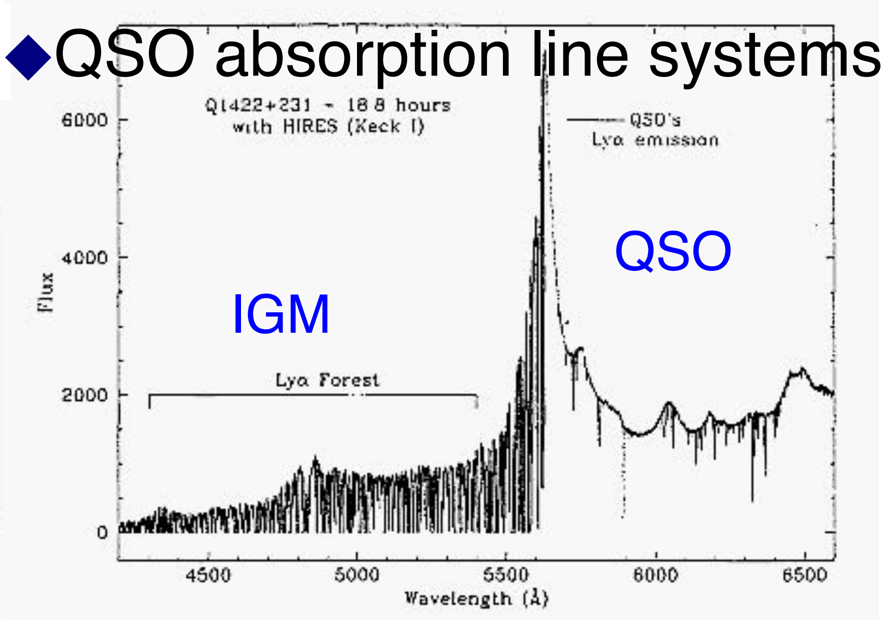
Nomoto, CK, Tominaga 2013, ARAA

Abundances at high-redshifts

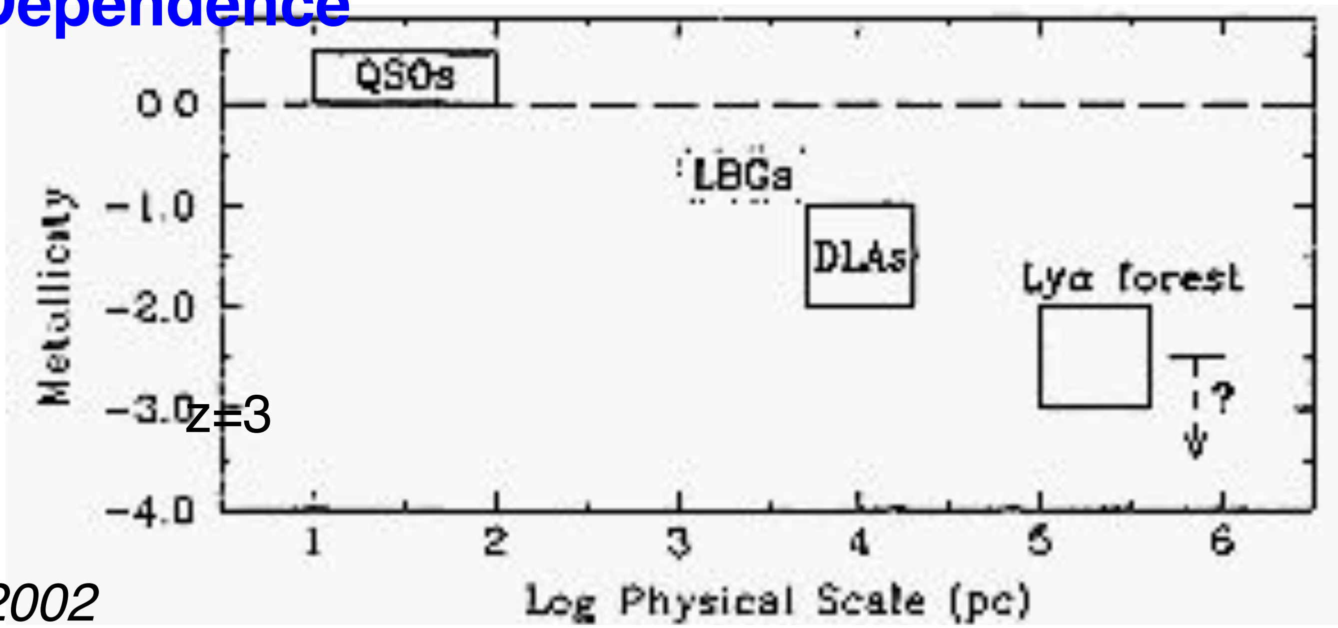
- ◆Lyman-break Galaxies



- ◆QSO absorption line systems

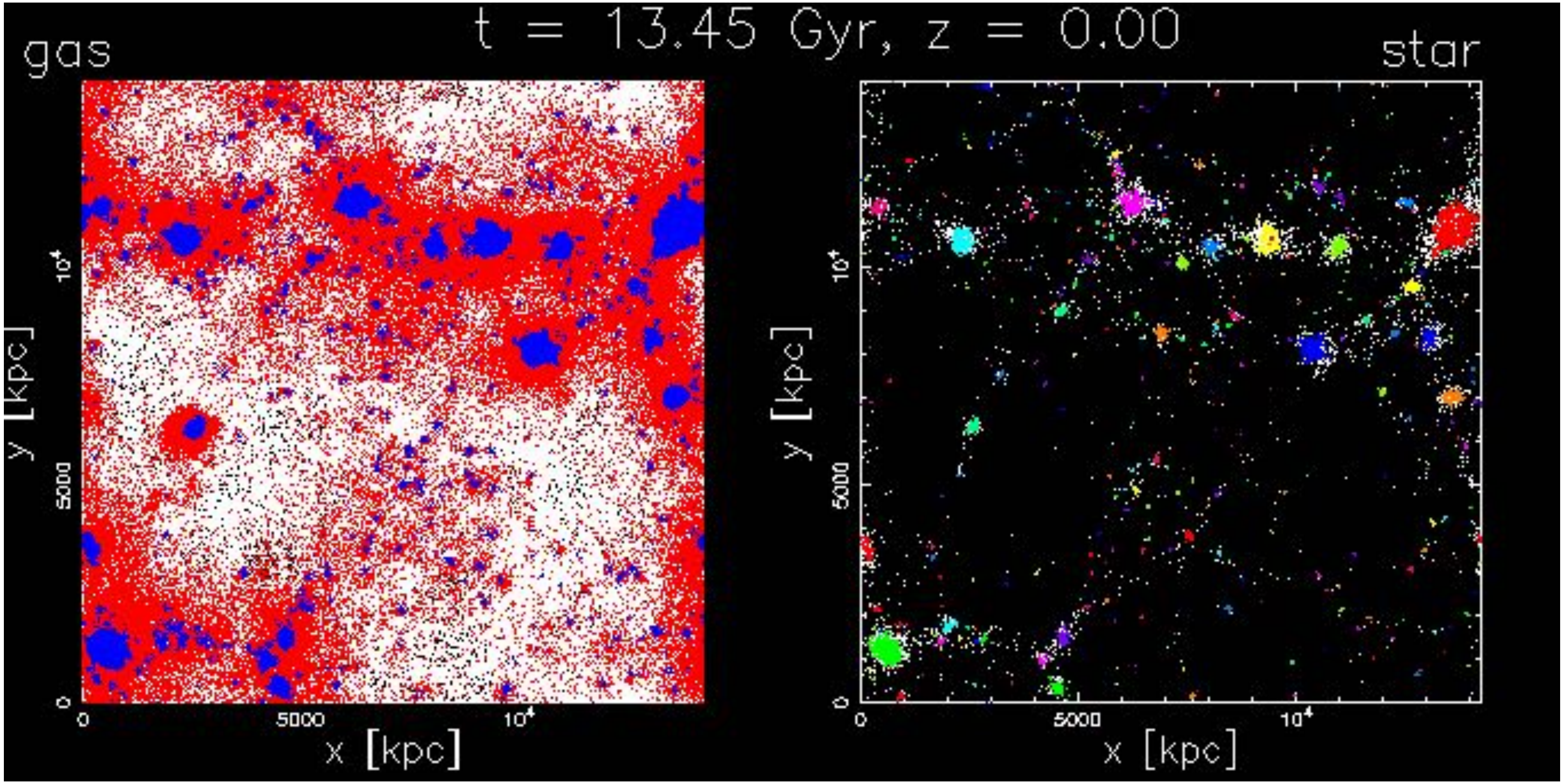


- ◆**Scale Dependence**



Pettini 2002

The origin of MZR

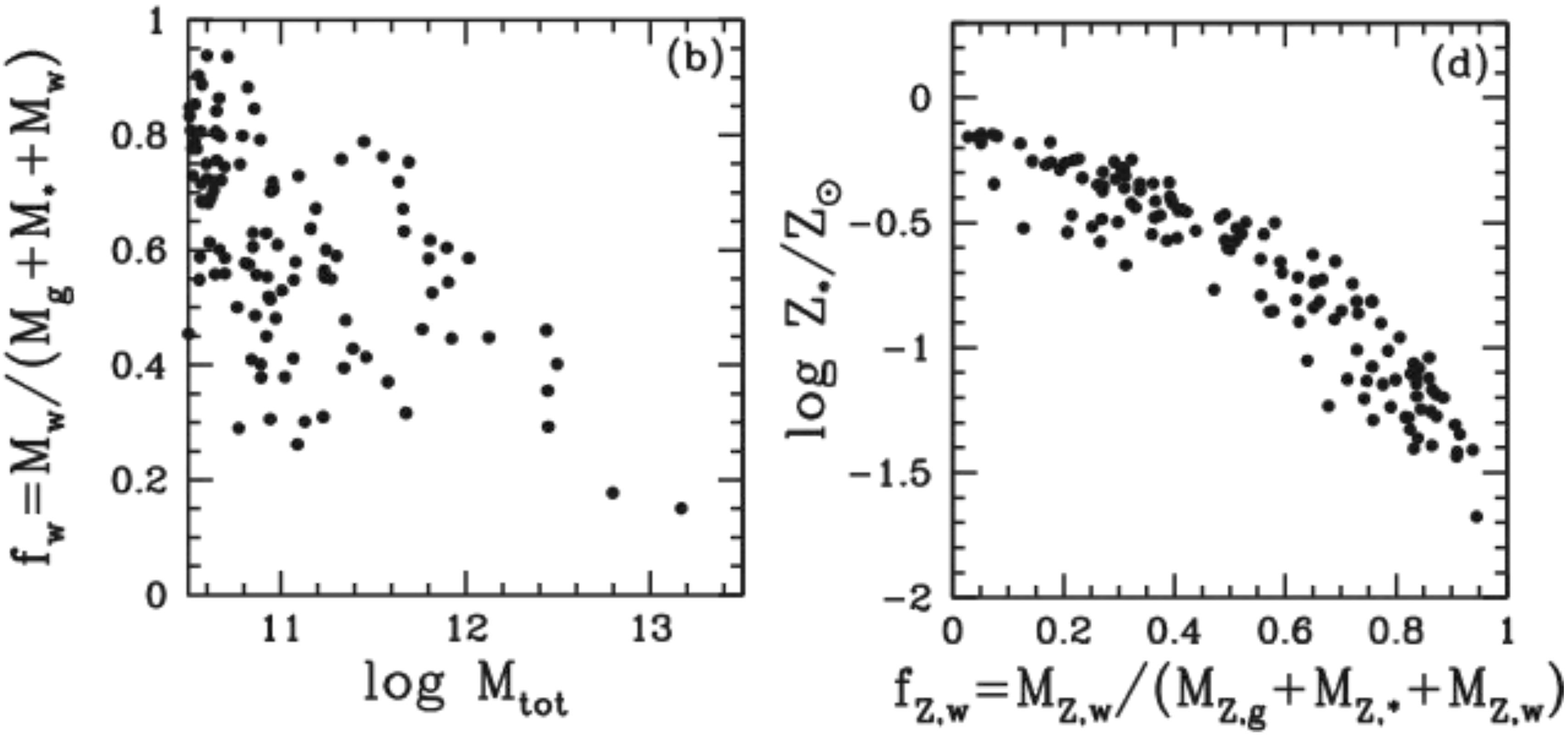


Gas in galaxies, identified by FOF
Wind Gas, is not in galaxy,
but has been in some galaxies

M_*/M_b=0.10
$M_{g,gal}/M_b$=0.10
M_w/M_b=0.20

CK+ 07

The origin of MZR



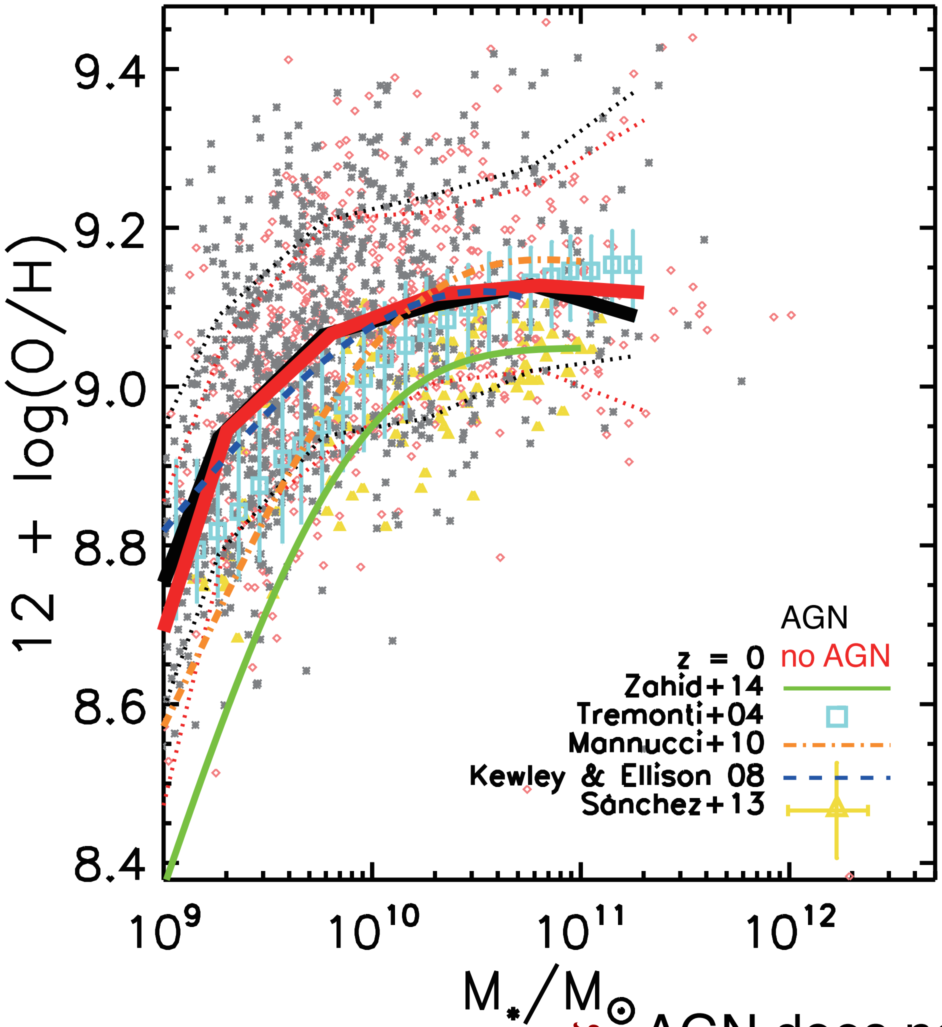
- Metals are effectively ejected from (present) dwarfs.
- The origin of the mass-metallicity relation --- Mass-dependent Galactic Winds.

CK+ 07

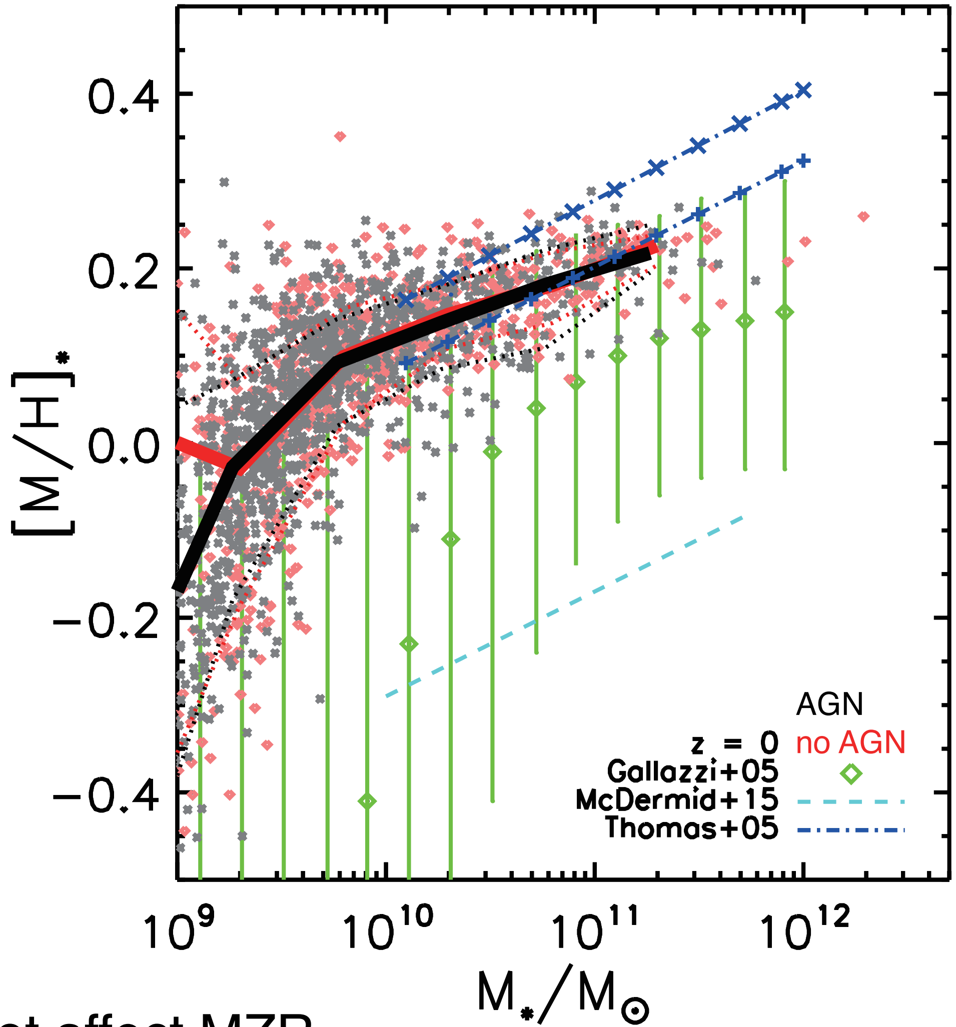
Mass Metallicity Relations (MZR)

Taylor & CK 2015a, MNRAS, 448, 1835

Gas-phase Oxygen Abundance, SFR weighted

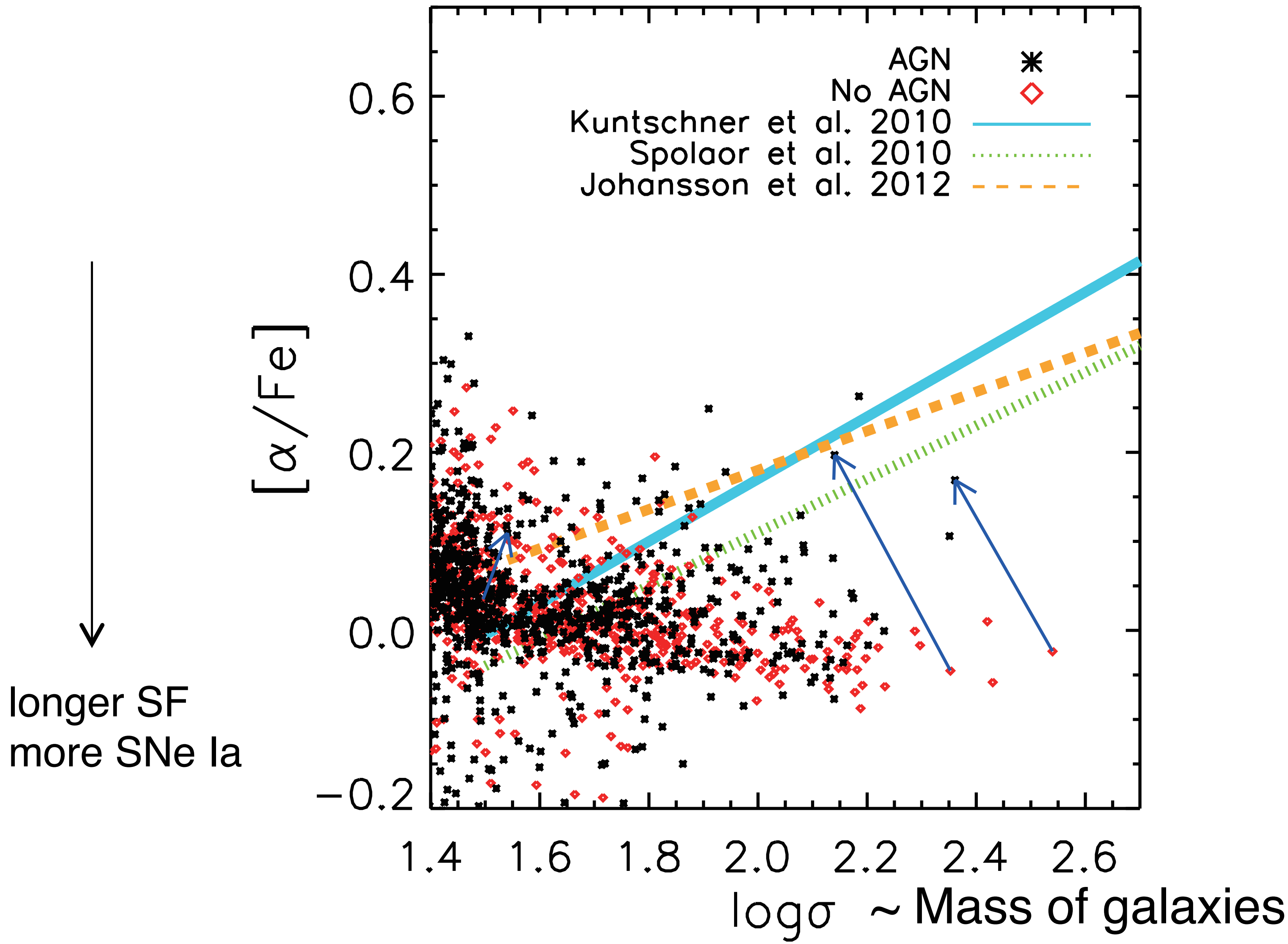


Stellar Metallicity, luminosity weighted



AGN does not affect MZR.

[α/Fe]-mass relation of ellipticals



Taylor & CK 2015, MNRAS, 448, 1835

Other models

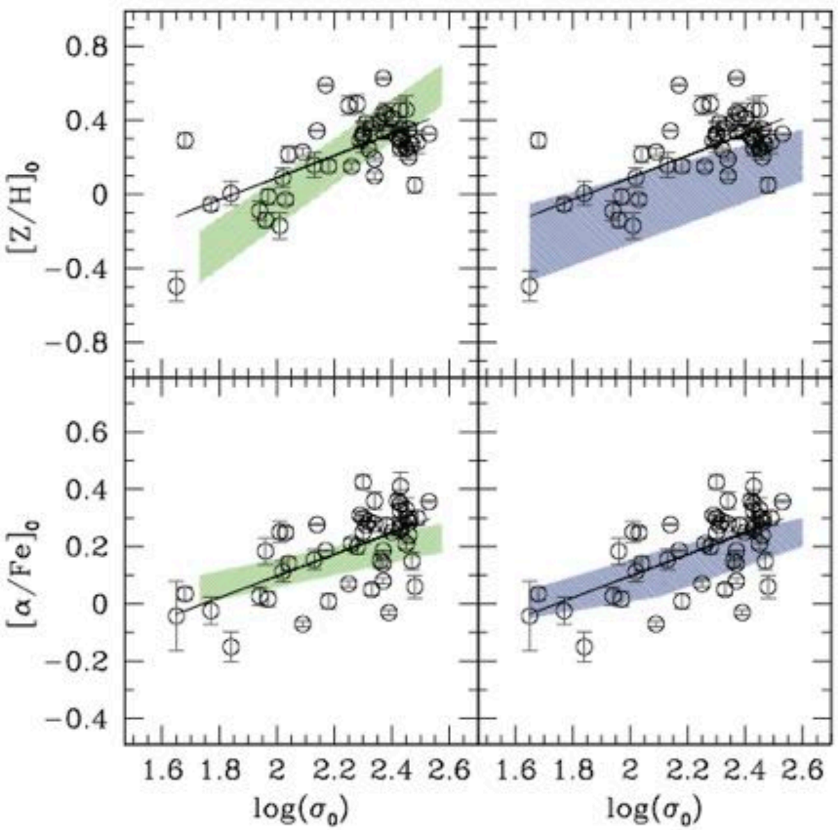


Figure 9. Comparison between observed and predicted $[Z/H]_0$–mass and $[\alpha/Fe]_0$–mass relationships. Open black circles represent central values of our sample galaxies. The black solid line is the weighted least-squares linear fit to the data points. In the left plots, we plot the predictions from Arrigoni et al. (2009) (green shading). In the right plots, the models of Calura et al. (2009) are shown (blue shading).

- Matteucci 1994, GCE
  - Inverse wind?
- Arrigoni et al. 10, SAM
  - flat IMF (x=1.1)
  - yields: Woosley & Weaver 95
  - SNIa: bimodal DTD (inconsistent with obs. in the solar neighborhood)
- Calura & Menci 09, SAM
  - SFR-dependent IMF
  - yields: Woosley & Weaver 95
  - SNIa: Matteucci & Greggio 86
- Yates et al. 13, SAM
  - Chabrier (03) IMF
  - yields: Portinari+ 98
  - SNIa: power-law DTD

Cosmic evolution

Cosmic evolution

- ✴Time evolution of scaling relations
  (Size/metallicity/BH mass – galaxy mass)

  → JWST (>2018)

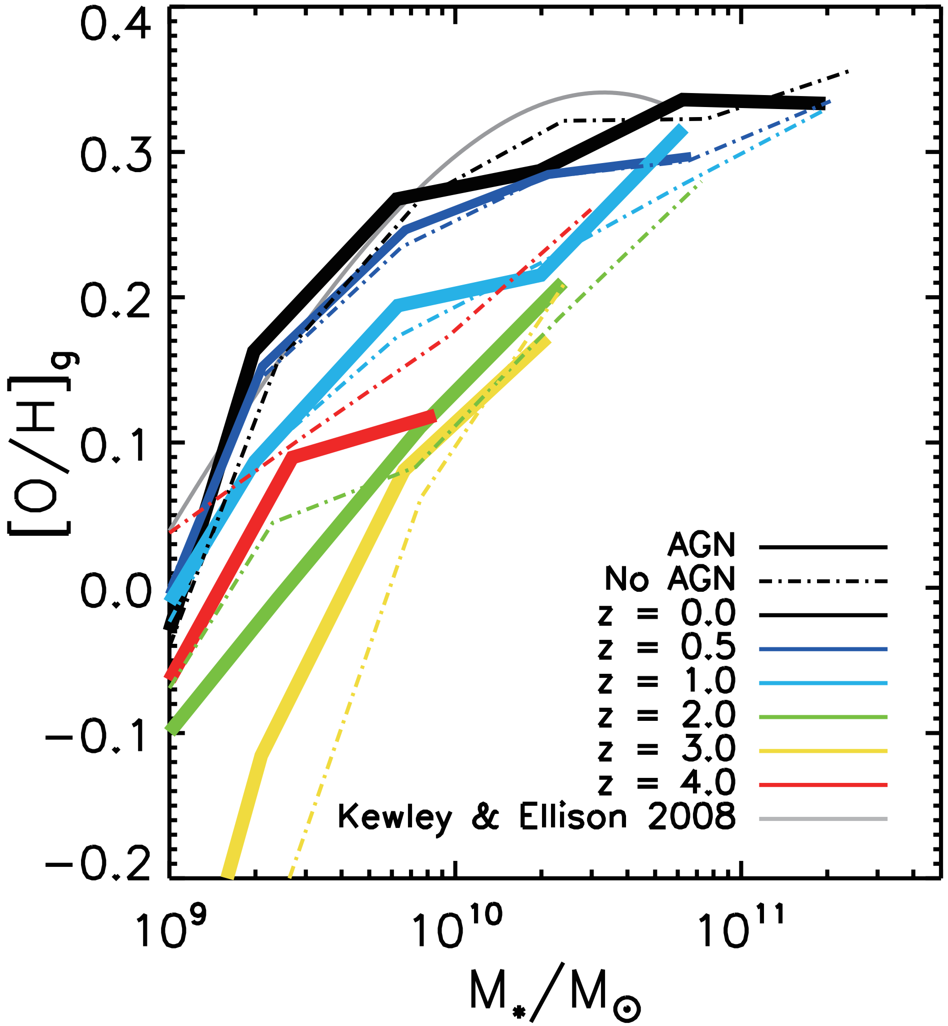
- ✴Internal structures (2D map of gas, stars, and elements) within galaxies

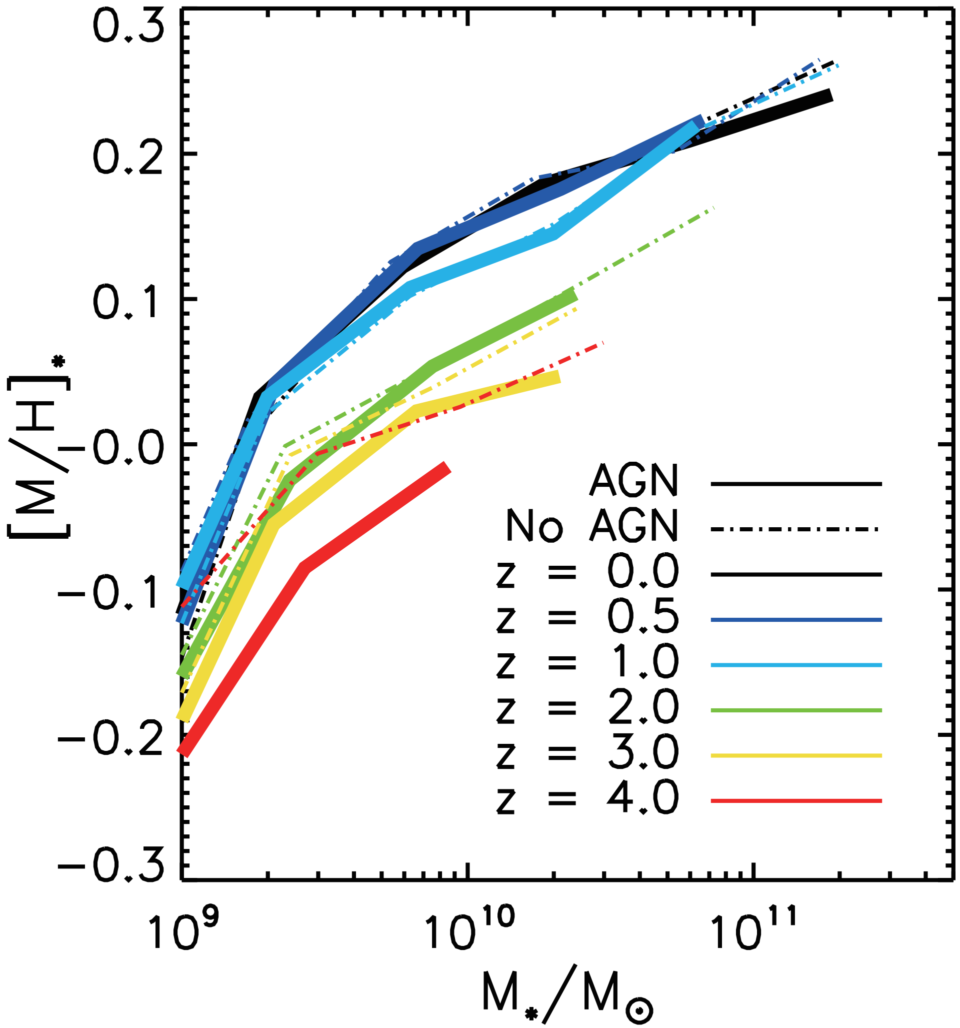
  → IFU (Integral field unit)

Time evolution of M-Z relation

Taylor & CK 2016a, arXiv1608.06685

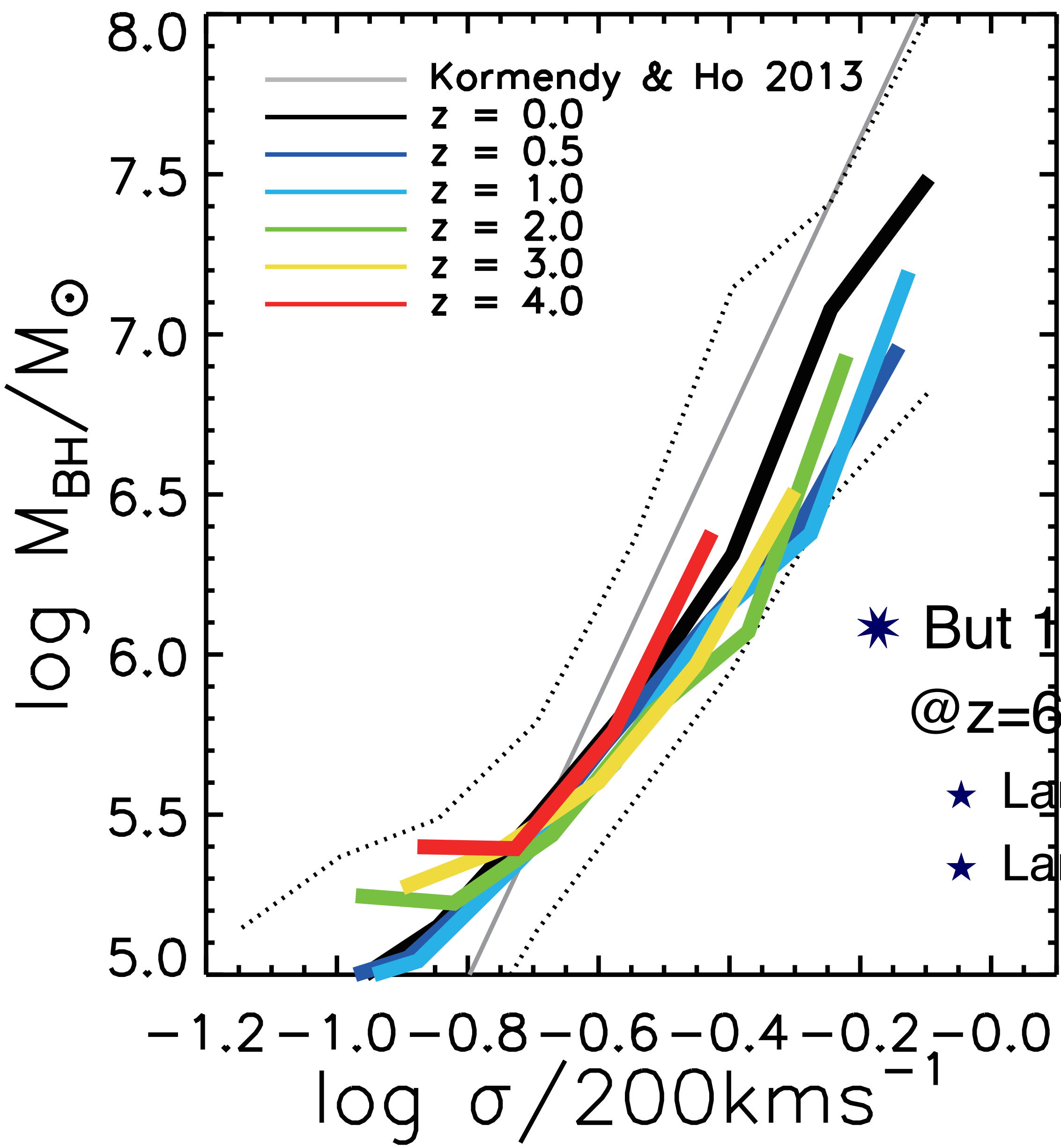
- Gas: Steeper slope is at higher-z.
- Stars: Normalization shifts.





Time evolution of M_{BH}-σ relation

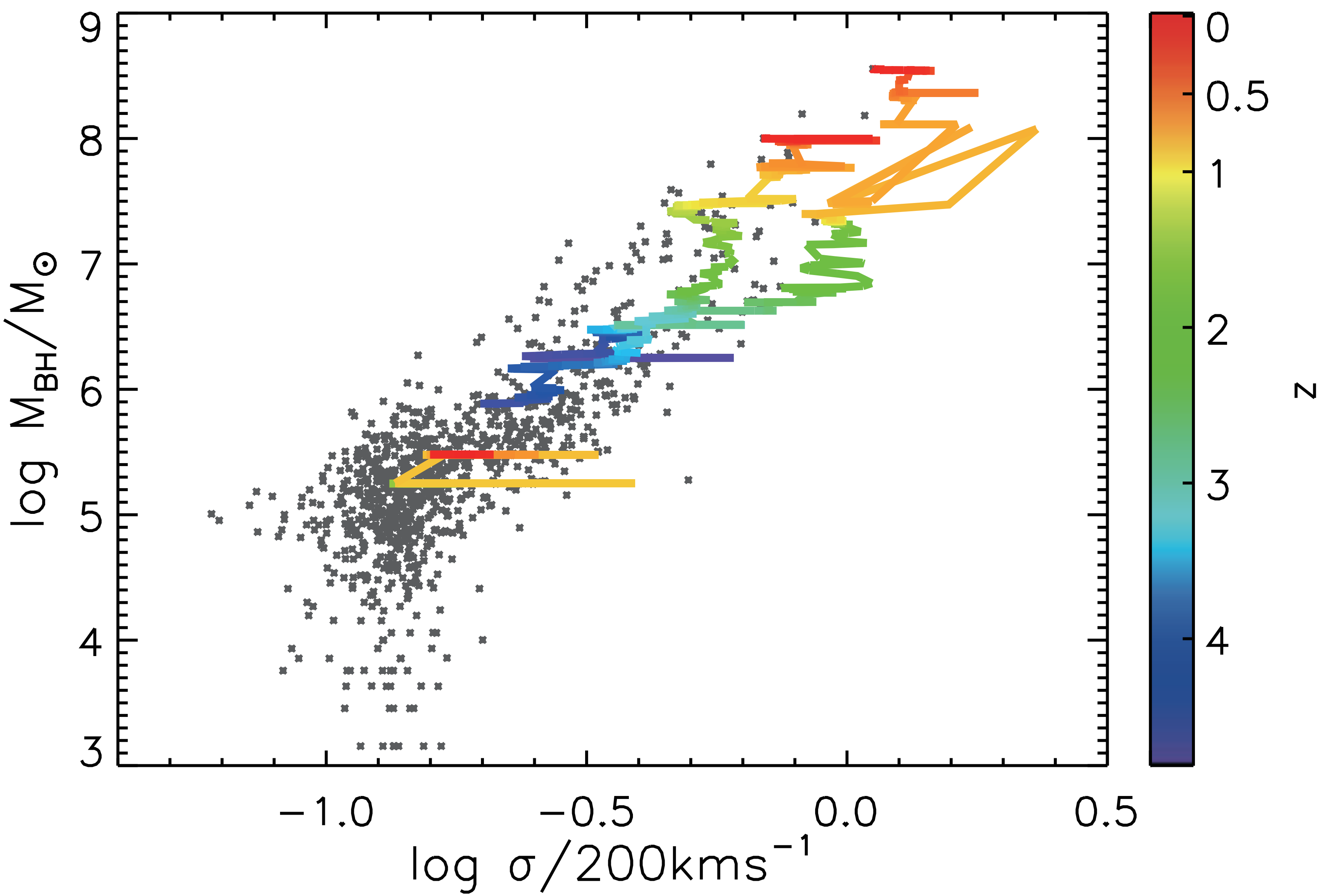
Taylor & CK 2016, ArXiv1608.06685



- But $10^{10} M_\odot$ BH @z=6.3 (Wu+ 15)
  - Larger Volume?
  - Larger Seed??

Time evolution of M_{BH}-σ relation

Taylor & CK 2016, ArXiv1608.06685

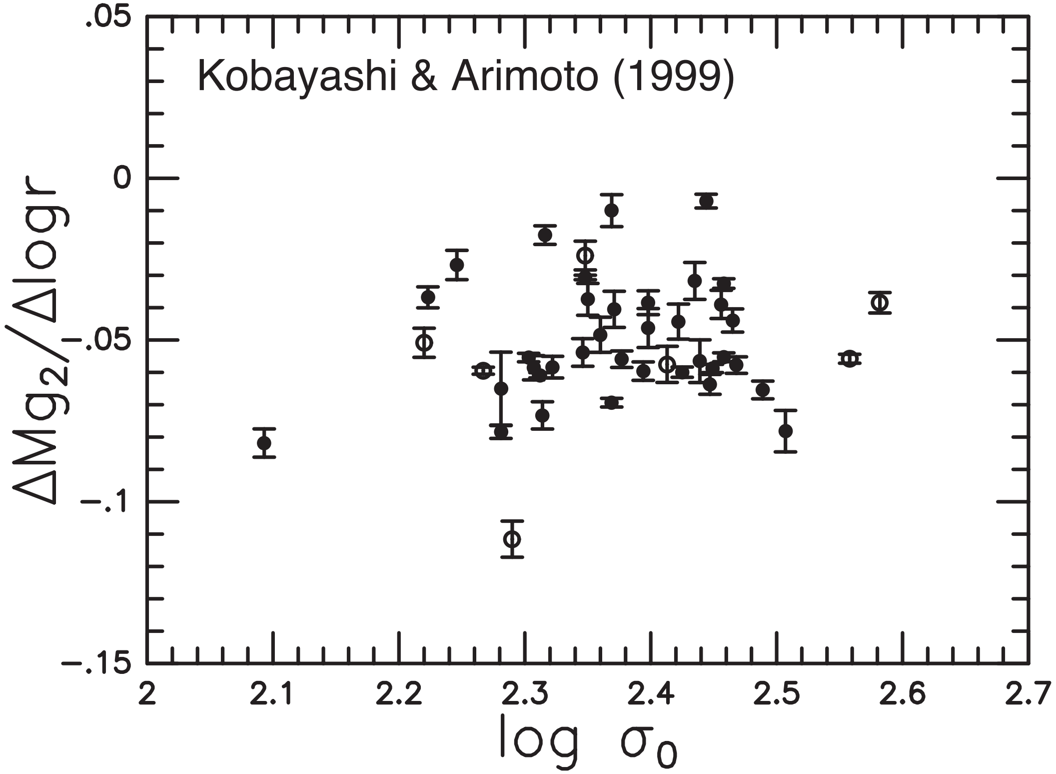


THE ASTROPHYSICAL JOURNAL, 527:573–599, 1999 December 20

Metallicity gradients

GRADIENTS OF ABSORPTION-LINE STRENGTHS IN ELLIPTICAL GALAXIES

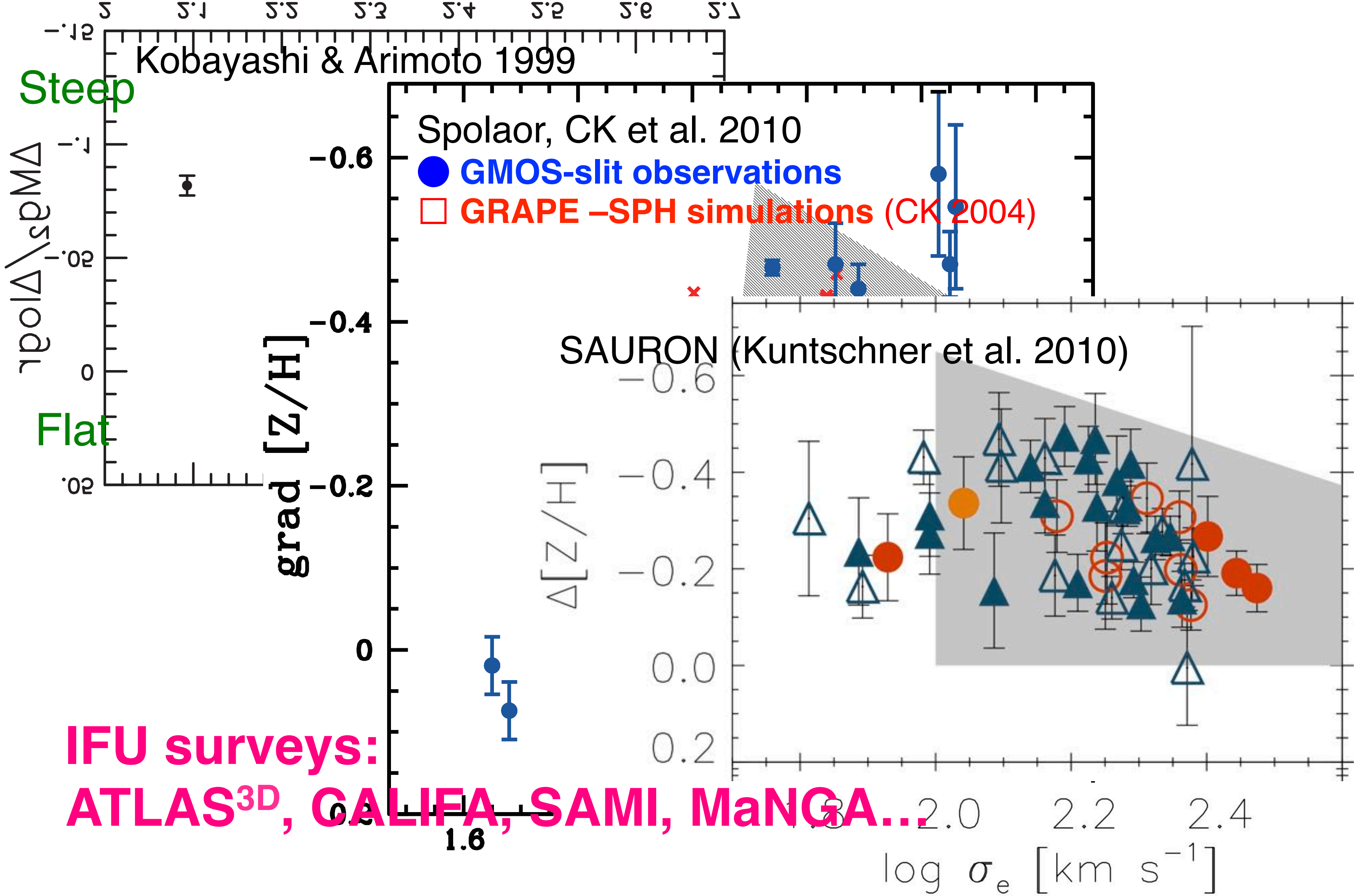
CHIAKI KOBAYASHI
Department of Astronomy, School of Science, University of Tokyo 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; chiaki@astron.s.u-tokyo.ac.jp
AND
NOBUO ARIMOTO
Institute of Astronomy, School of Science, University of Tokyo 2-21-1, Osawa, Mitaka, Tokyo 181-8588, Japan; arimoto@mtk.ioa.s.u-tokyo.ac.jp
Received 1998 May 27; accepted 1999 July 19



For example, if the Worthey (1994) calibration is adopted, one finds that the typical metallicity gradient of elliptical galaxies is $\Delta \log Z/\Delta \log r \simeq -0.3$. The radial gradient of metallic line strength can be naturally explained by the dissipative collapse picture. However, the measured gradients are less steep than those predicted by numerical simulations of the collapse model. For example, Larson's hydrodynamical simulations gave $\Delta \log Z/\Delta \log r \sim -0.35$ (Larson 1974a) and -1.0 (Larson 1975), and Carlberg's N-body simulations gave $\Delta \log Z/\Delta \log r \sim -0.5$ (Carlberg 1984). This discrepancy could be interpreted if mergers flatten an original gradient; indeed numerical simulations showed that the gradient in a disk galaxy should be halved after three successive mergers of galaxies with similar sizes (White 1980). However, both simulations of the dissipative collapse and successive mergers leave room for the improvement because some essential physical processes, such as star formation, thermal feedback from supernovae, and metal enrichment, were not taken into account.

Also, Organo+ 2005, Spolaor+ 10, Kuntschner+ 10, CALIFA, SAMI, MaNGA

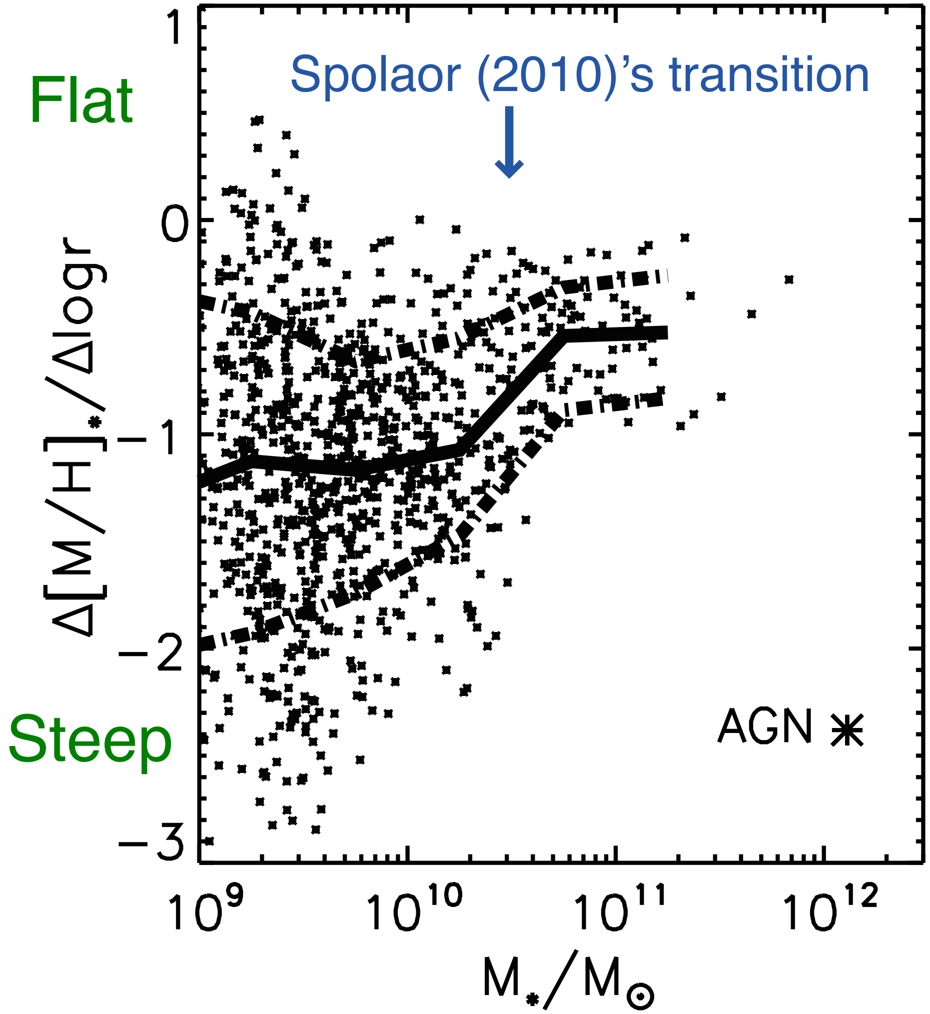
Metallicity Gradients vs Mass

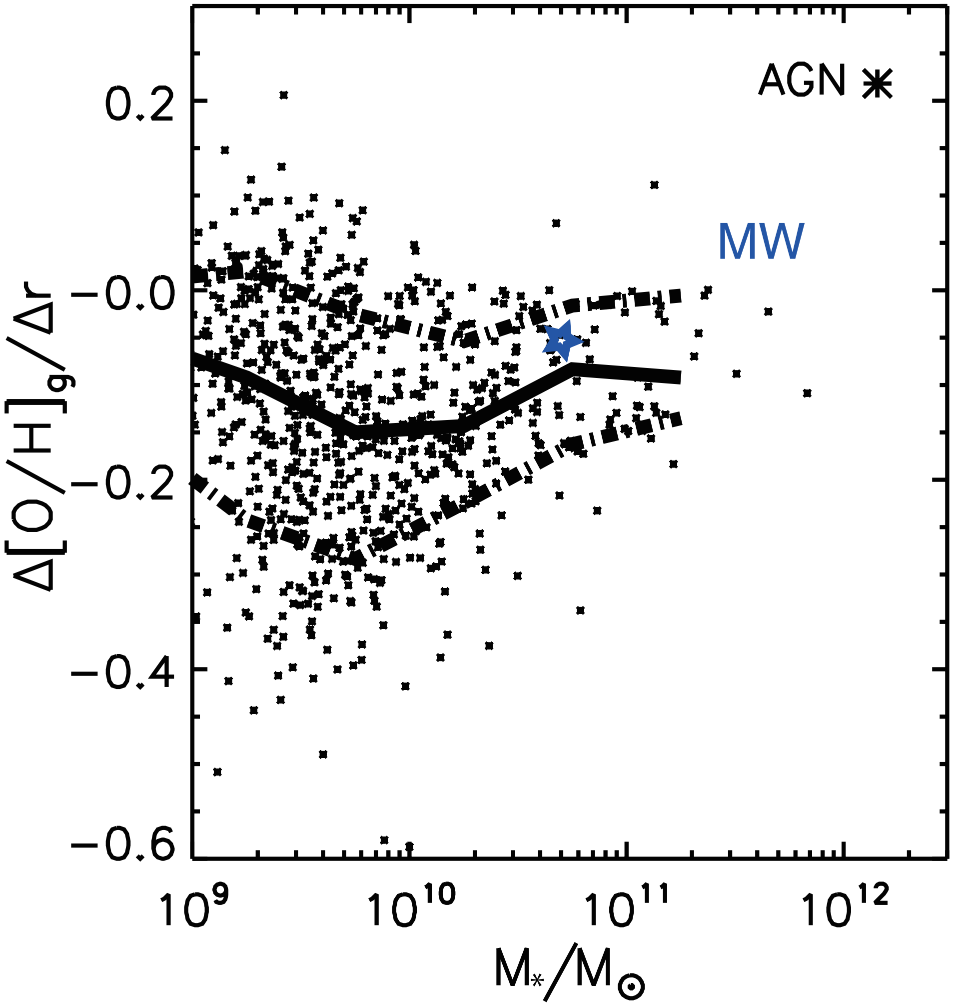


IFU surveys:
ATLAS^{3D}, CALIFA, SAMI, MaNGA…

Metallicity Gradients vs Mass

ATLAS^{3D}, CALIFA, SAMI, MaNGA… *Taylor & CK 2015d, submitted*

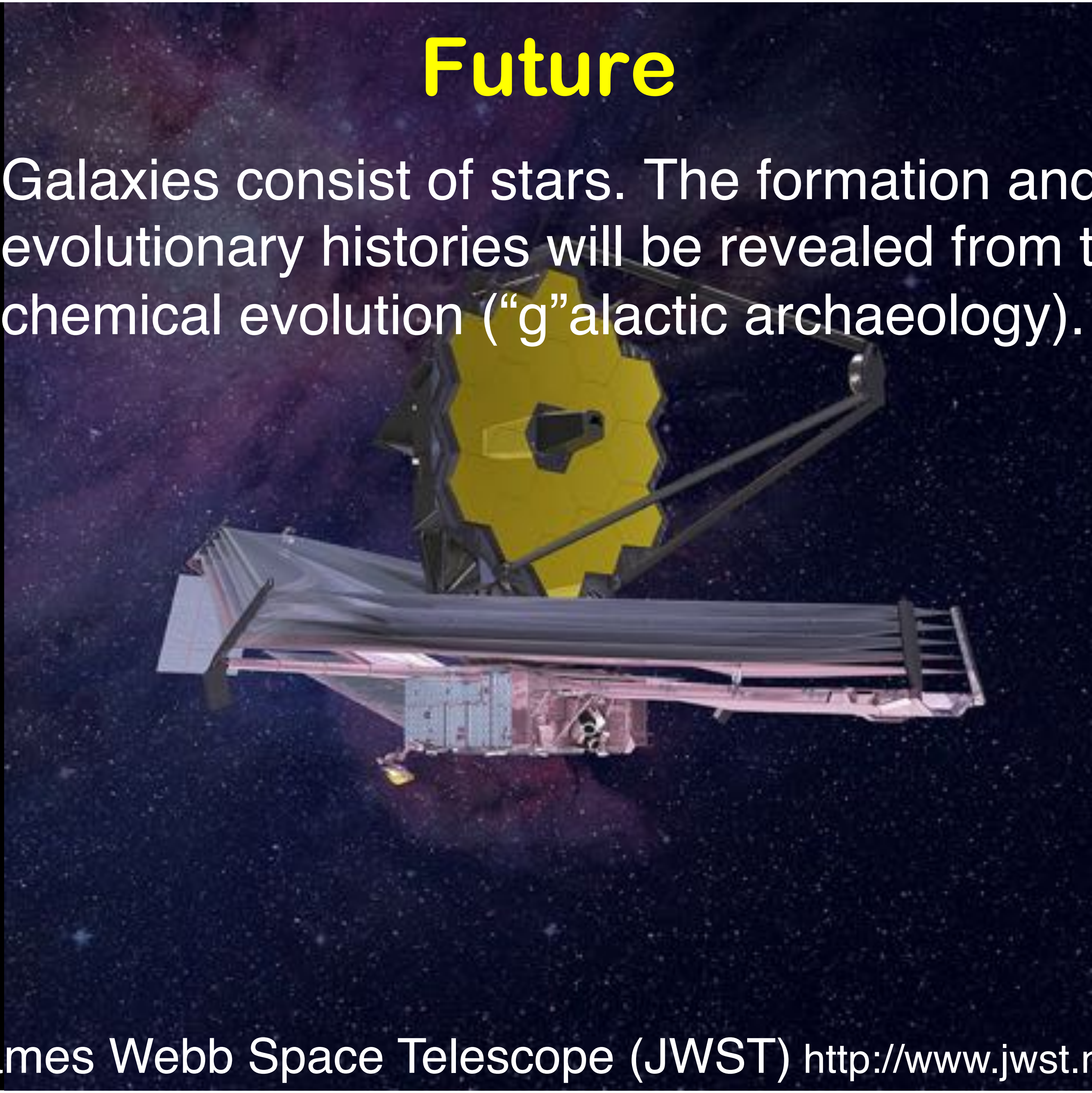




Measured in MAX(2re,10kpc), V-luminosity/SFR weighted

Future

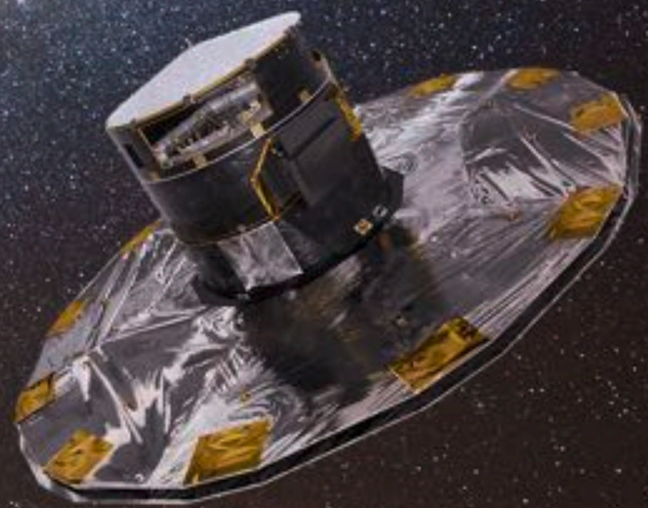
- Galaxies consist of stars. The formation and evolutionary histories will be revealed from their chemical evolution (“g”alactic archaeology).



James Webb Space Telescope (JWST) http://www.jwst.nasa.gov

Now

- Meantime, let's update our knowledge of stellar physics and the Milky Way, from elemental abundances and kinematics of stars with precision spectroscopy.



GAIA spacecraft http://sci.esa.int/gaia/