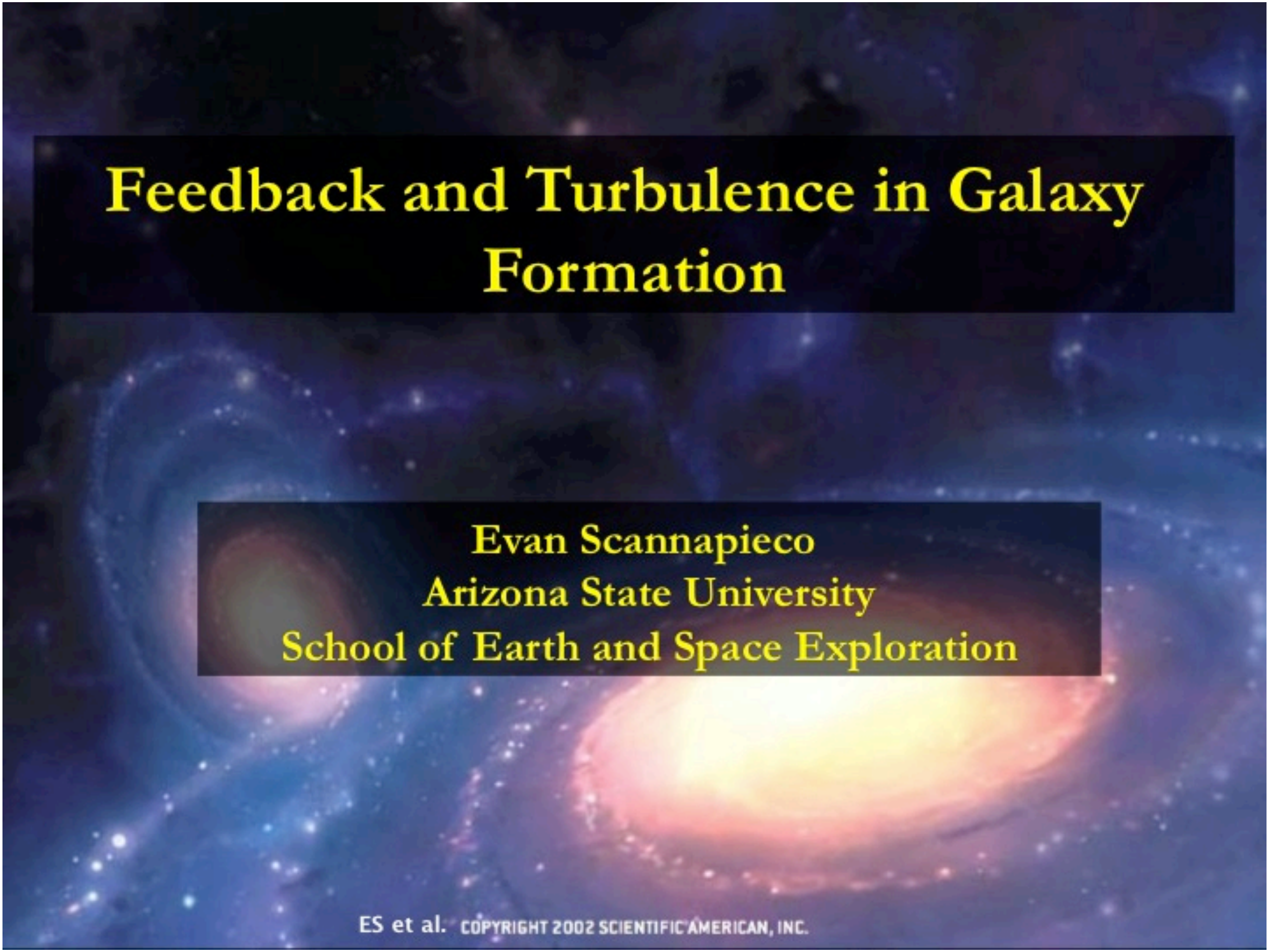


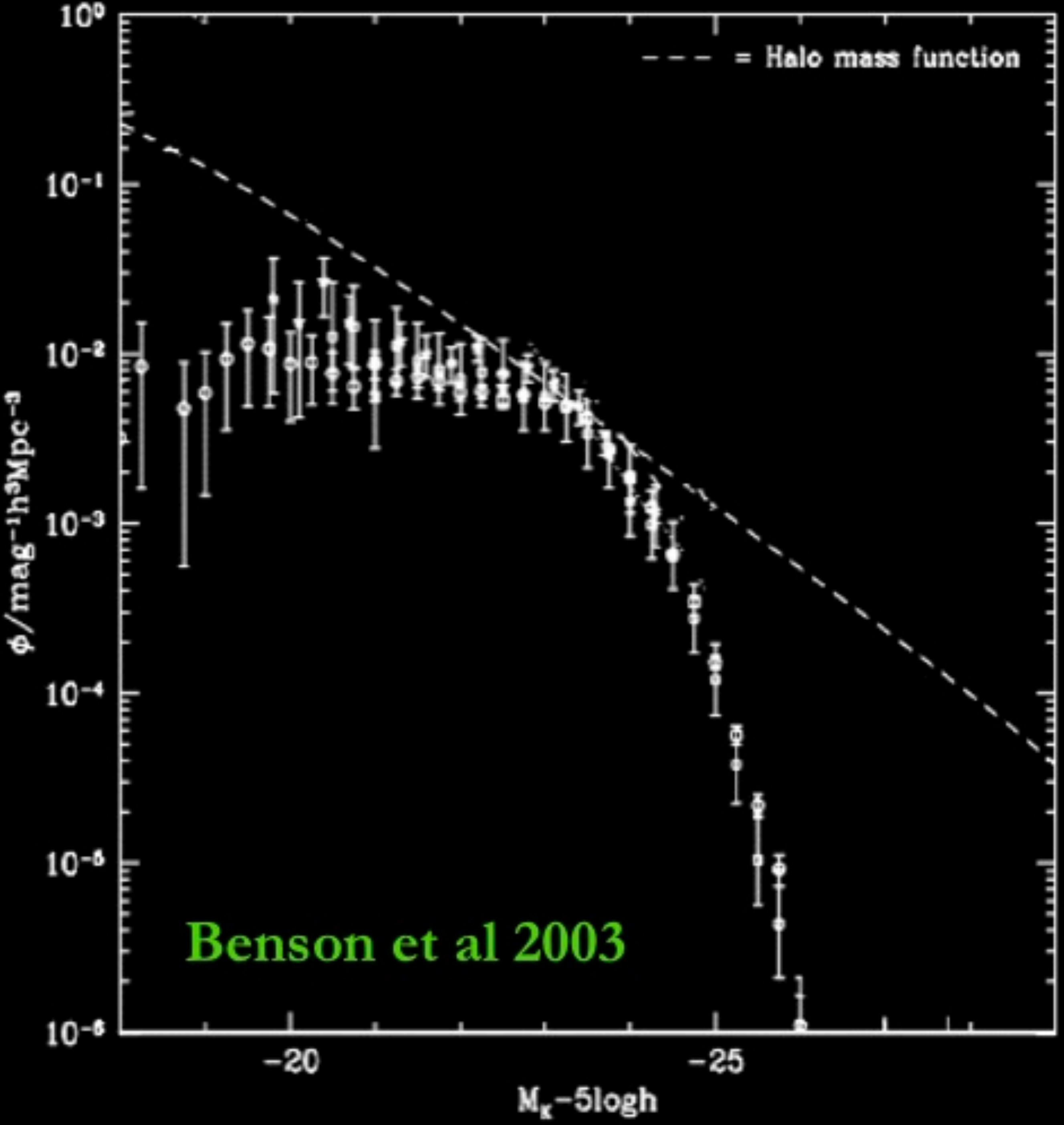
Feedback and Turbulence in Galaxy Formation

Evan Scannapieco
Arizona State University
School of Earth and Space Exploration

ES et al.

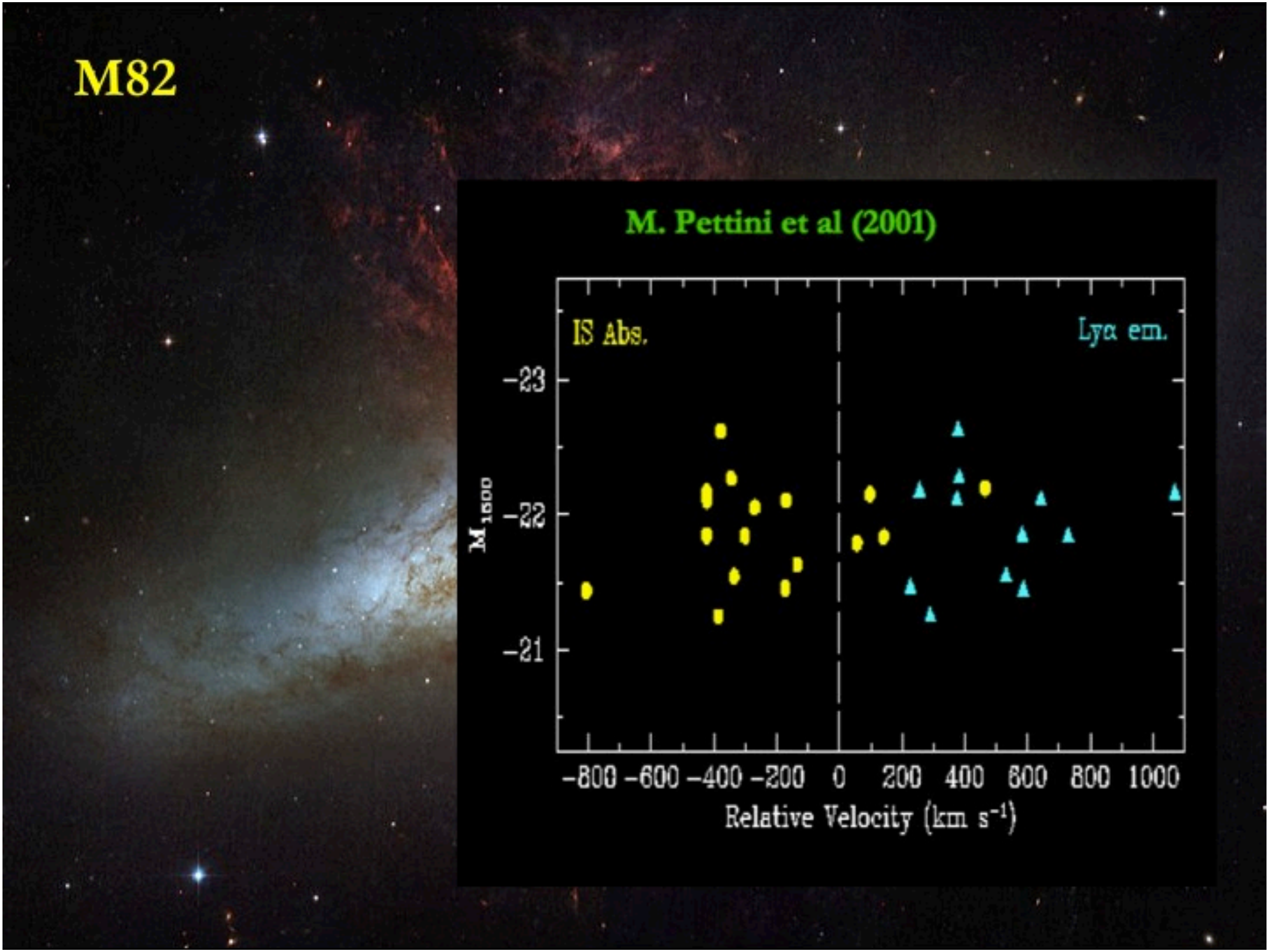
I. Prologue

ES et al.

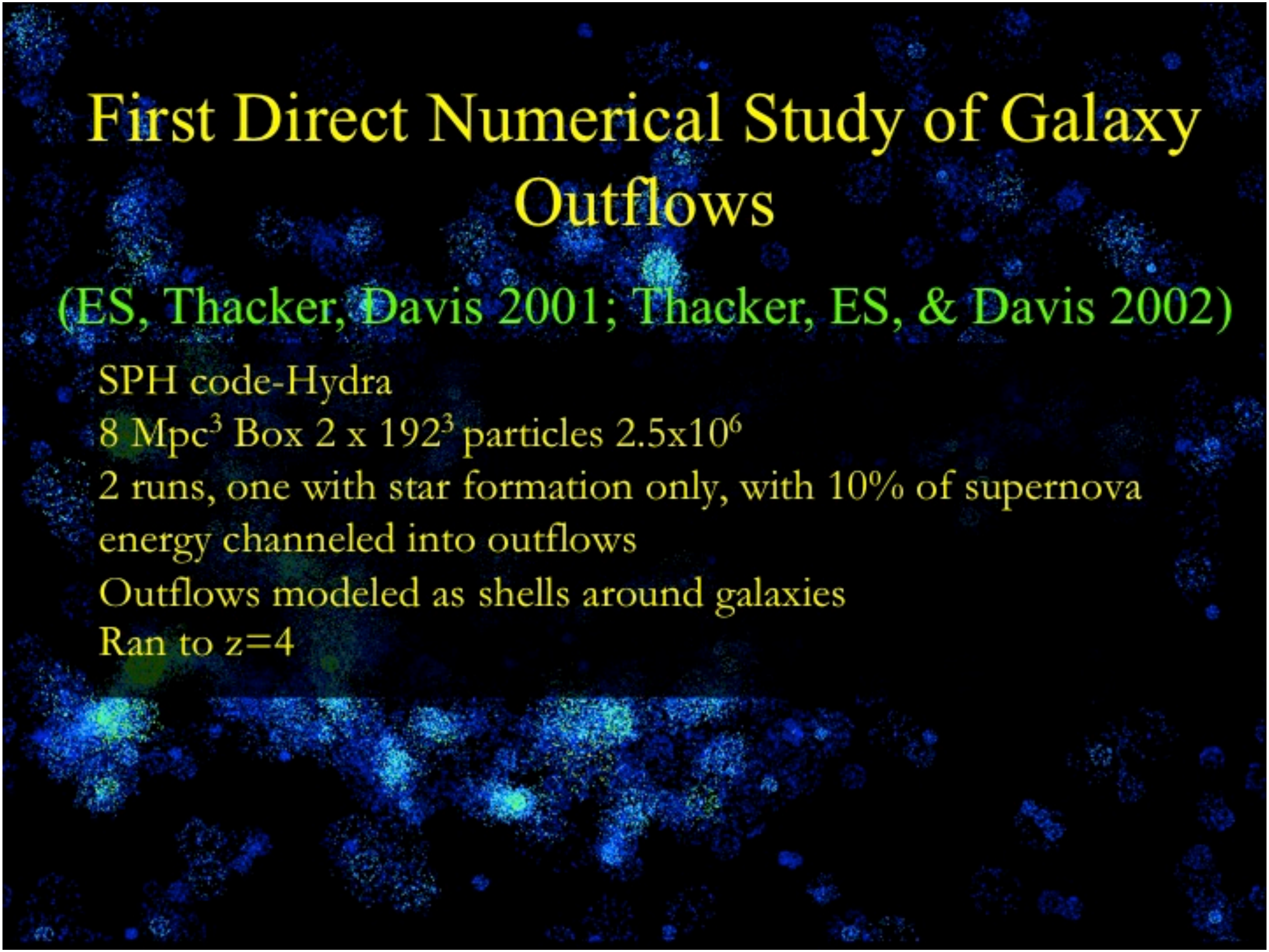


Benson et al 2003

M82



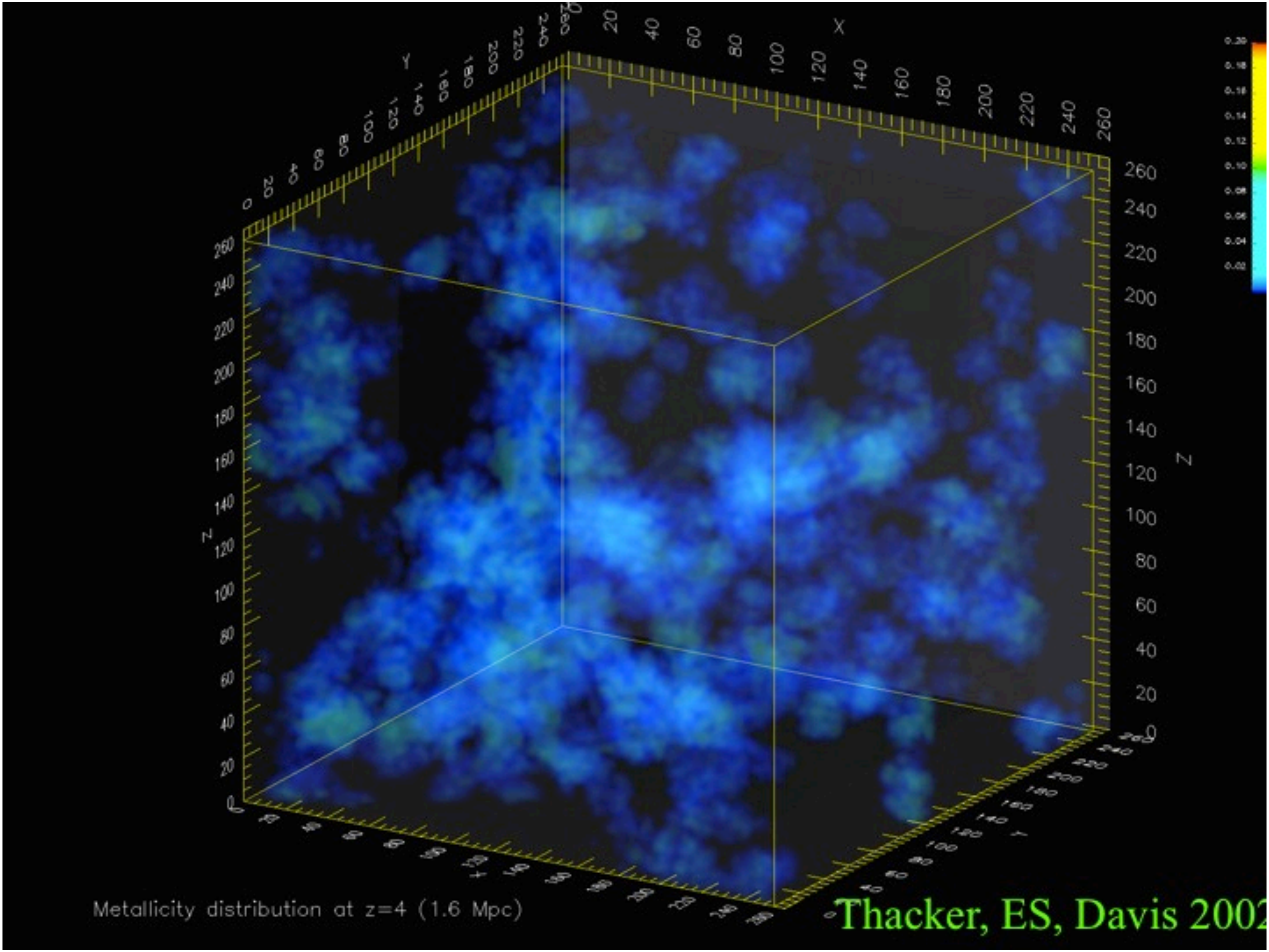
M. Pettini et al (2001)



First Direct Numerical Study of Galaxy Outflows

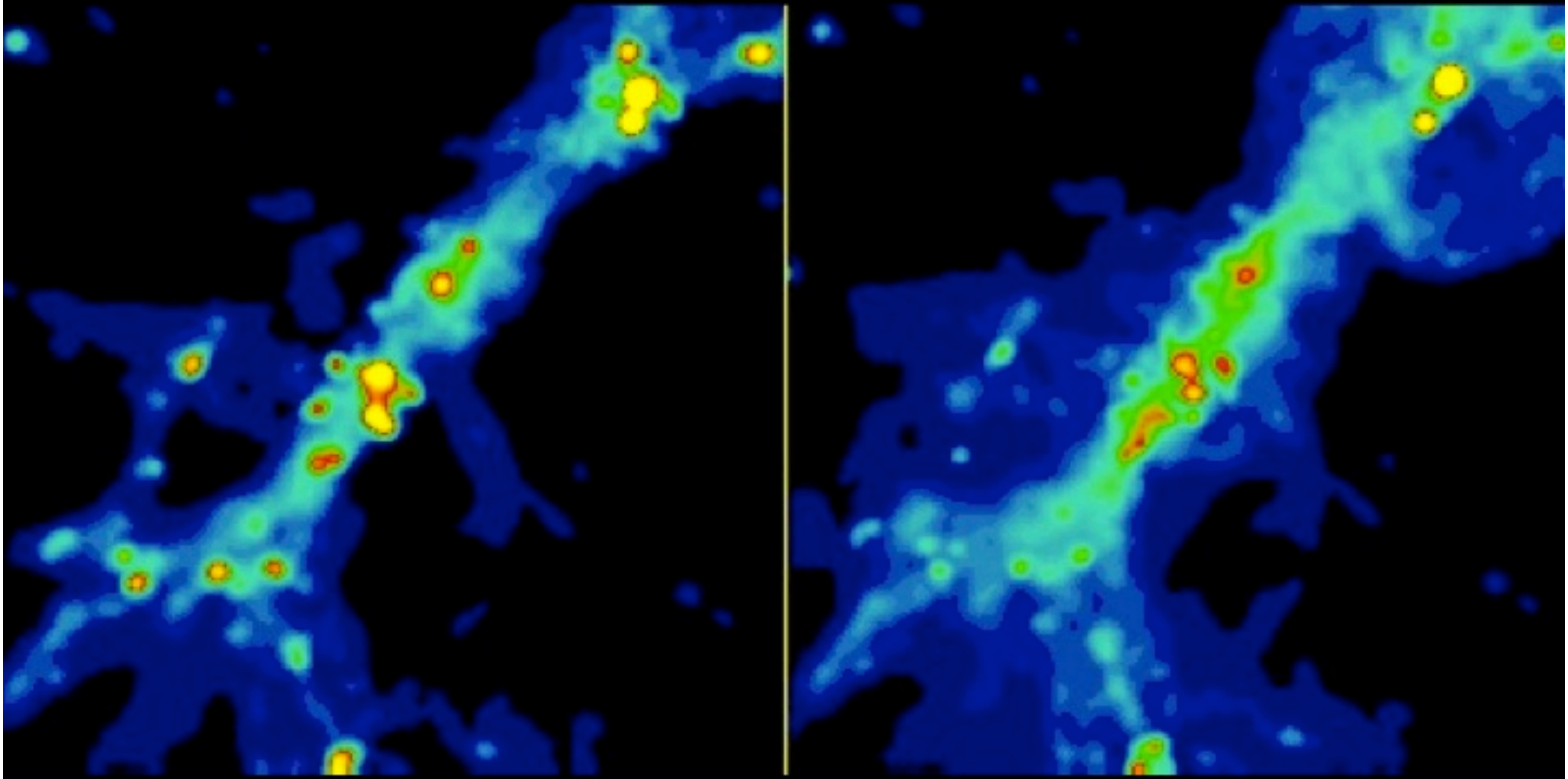
(ES, Thacker, Davis 2001; Thacker, ES, & Davis 2002)

- SPH code-Hydra
- 8 Mpc^3 Box 2 x 192^3 particles 2.5x10^6
- 2 runs, one with star formation only, with 10% of supernova energy channeled into outflows
- Outflows modeled as shells around galaxies
- Ran to z=4



Metallicity distribution at z=4 (1.6 Mpc)

Thacker, ES, Davis 200

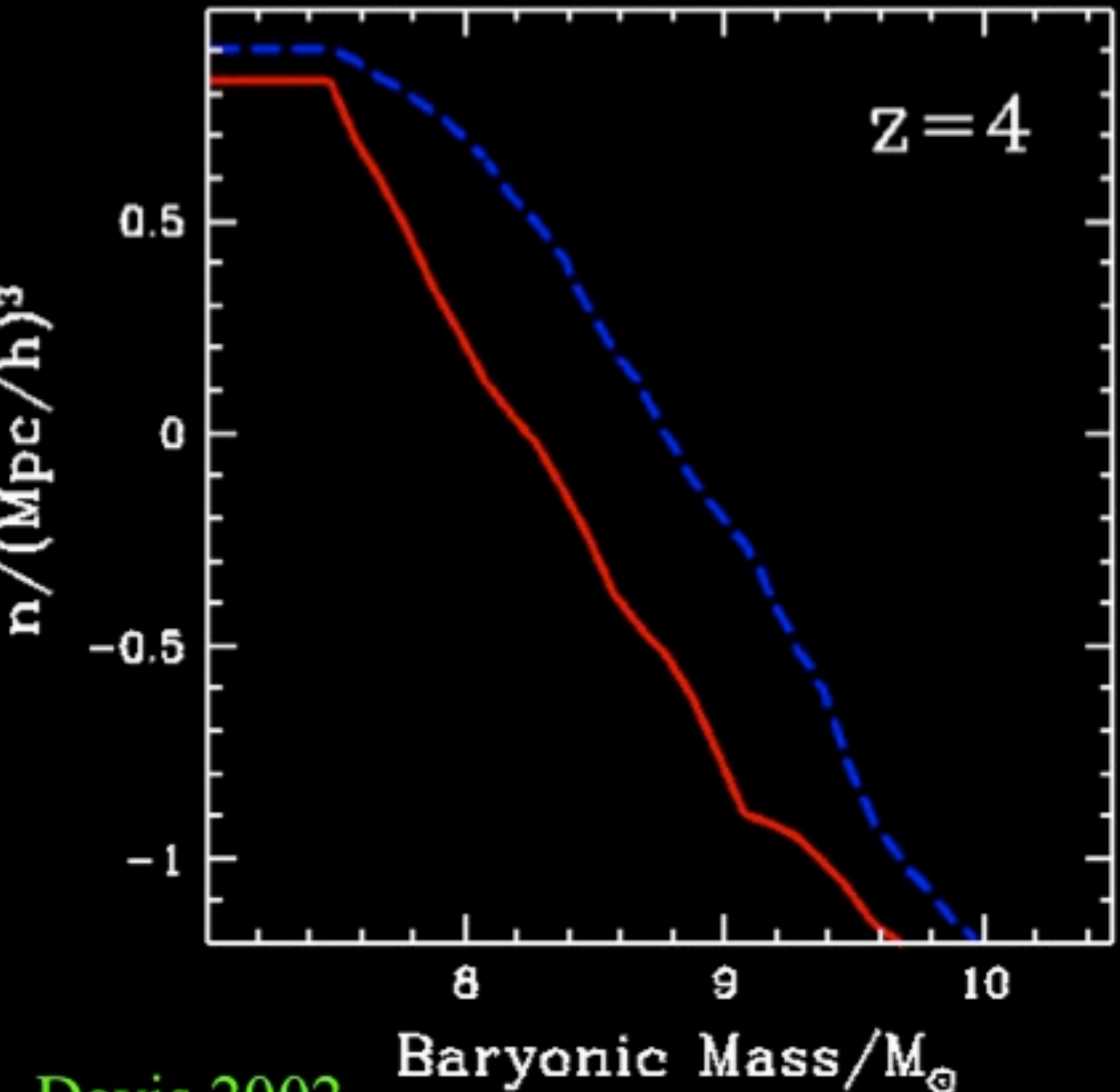


No outfalls

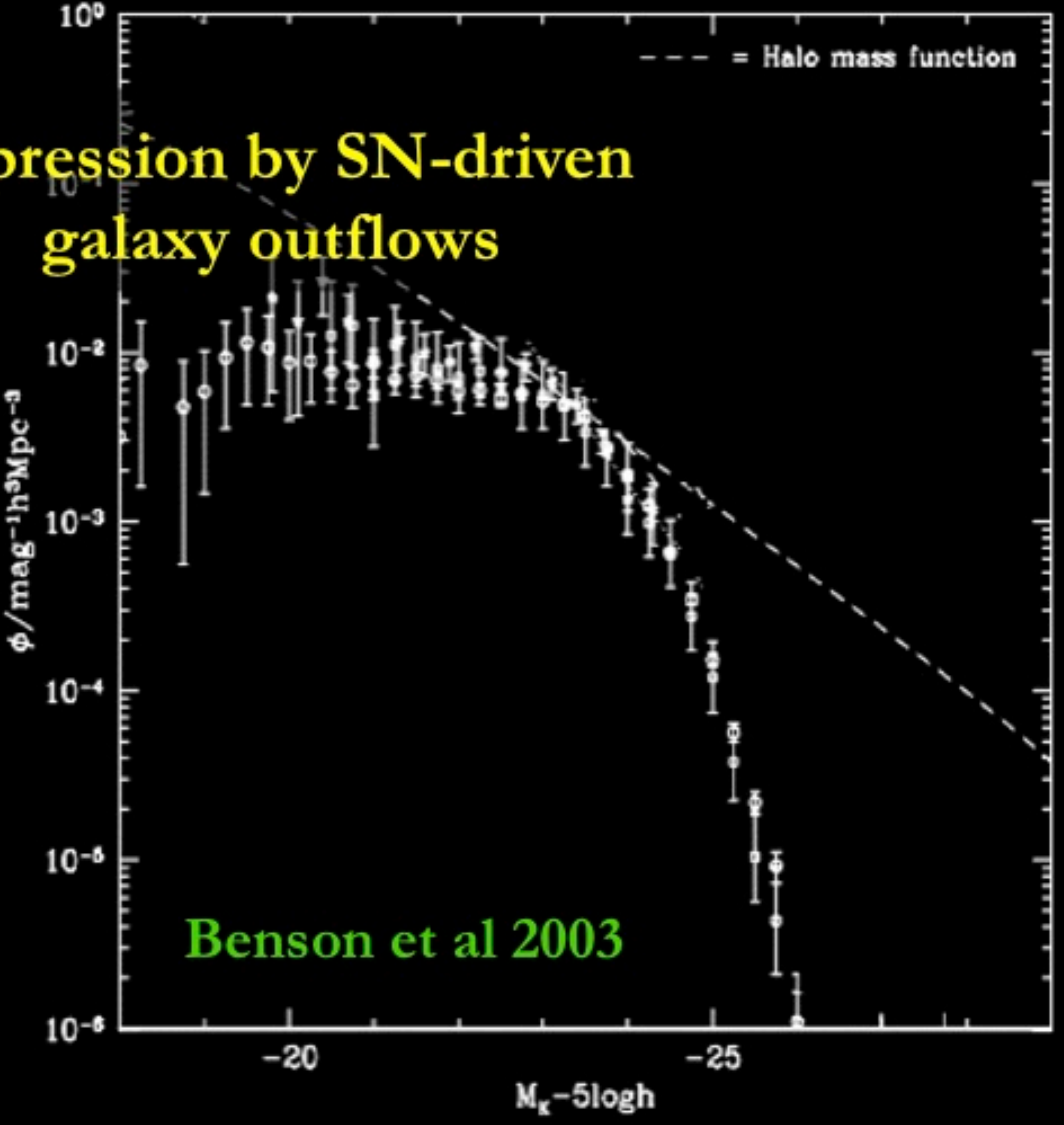
Outflows

ES, Thacker, Davis 2001

Dwarf Galaxy Suppression



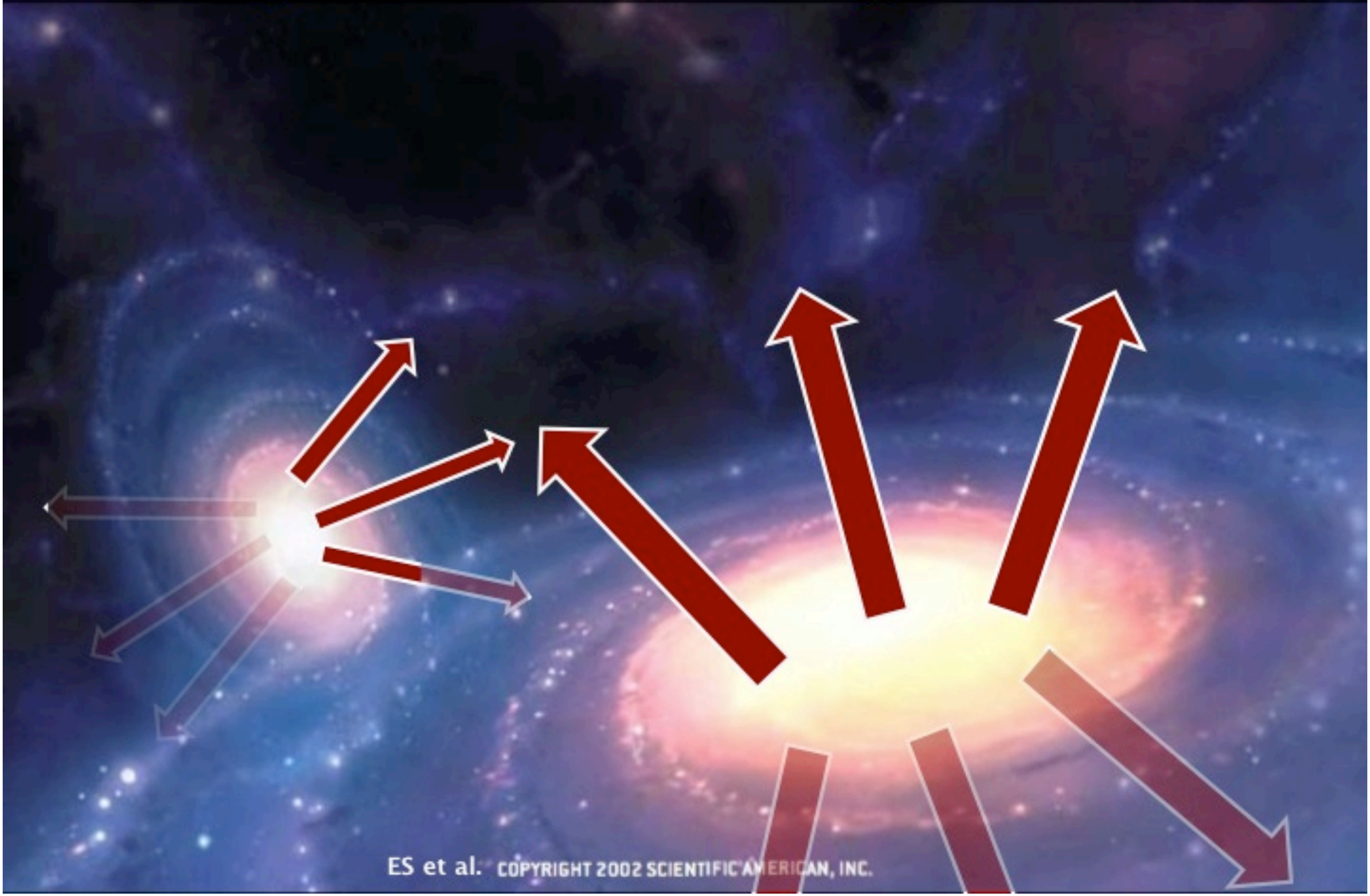
Thacker, ES, Davis 2002



Supression by SN-driven galaxy outflows

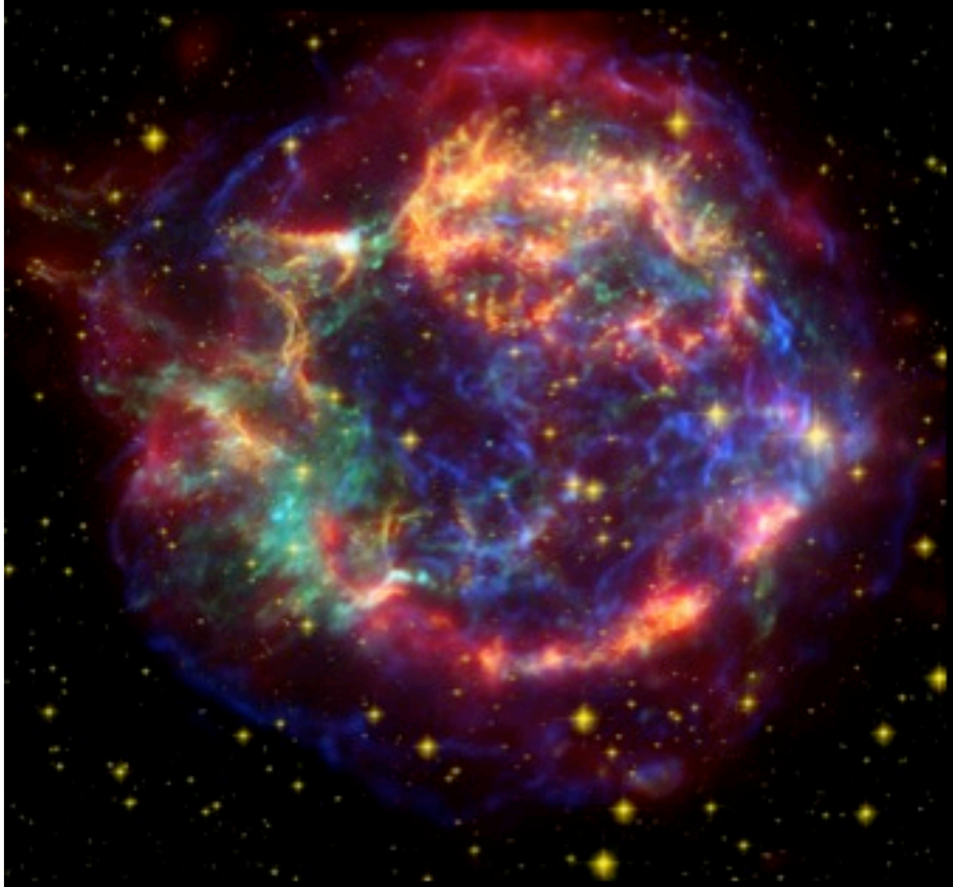
Benson et al 2003

II. Galaxy Outflows and Subgrid Turbulence

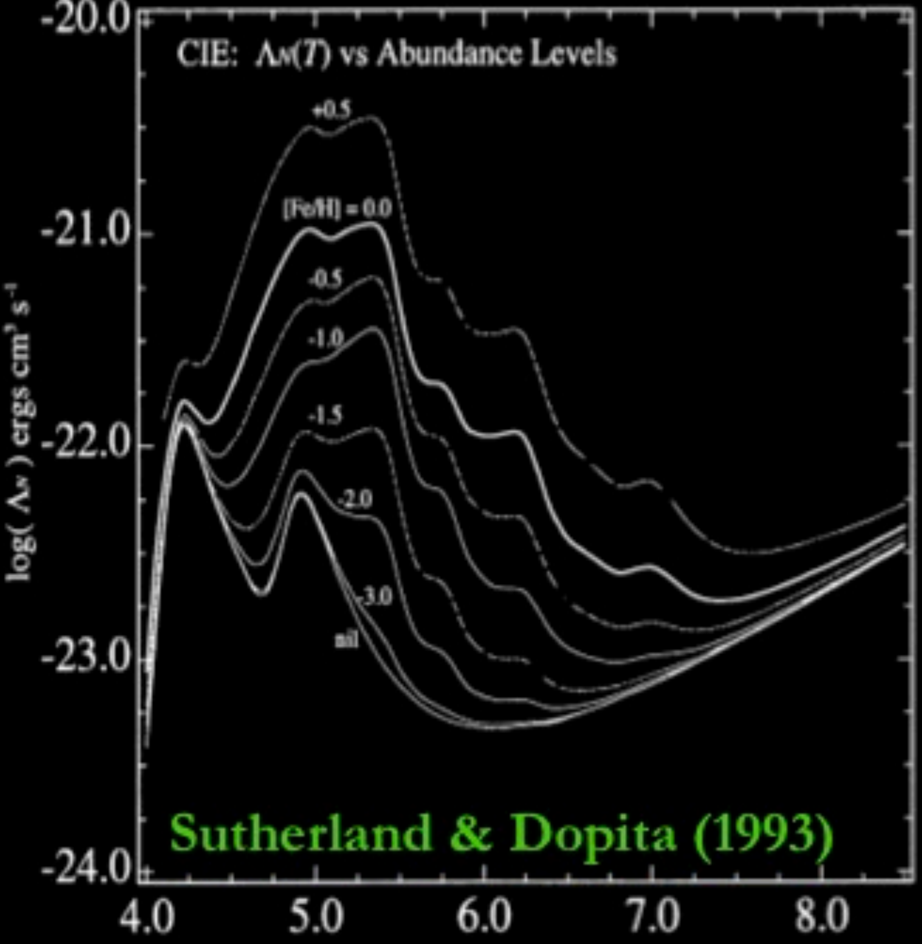


ES et al.

Supernovae & Cooling



~3 pc

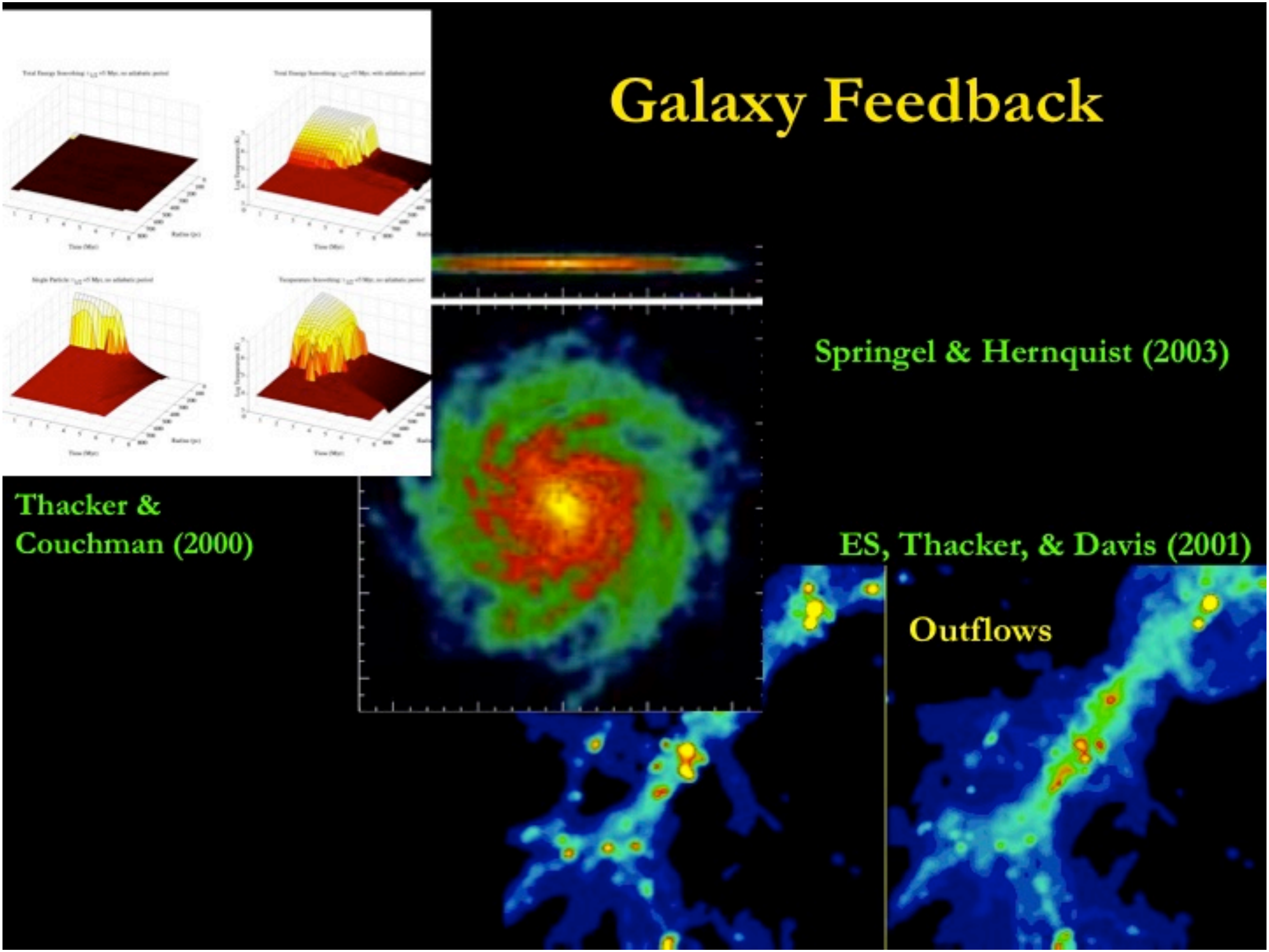


Sutherland & Dopita (1993)

Log T

Cooling times ~ 3000 years

Galaxy Feedback

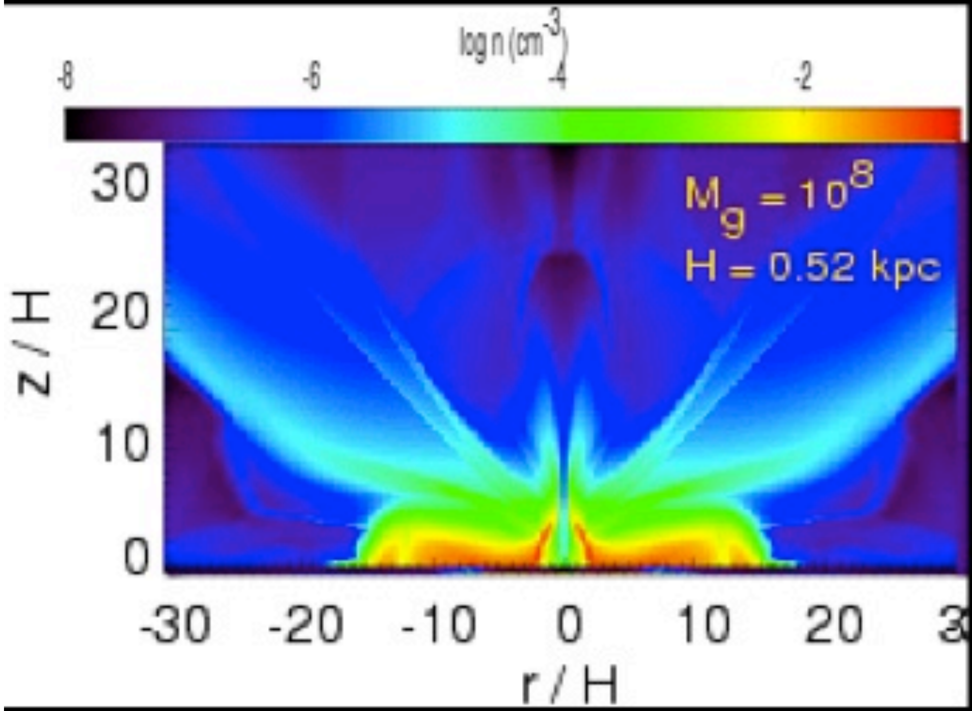


Thacker & Couchman (2000)

Springel & Hernquist (2003)

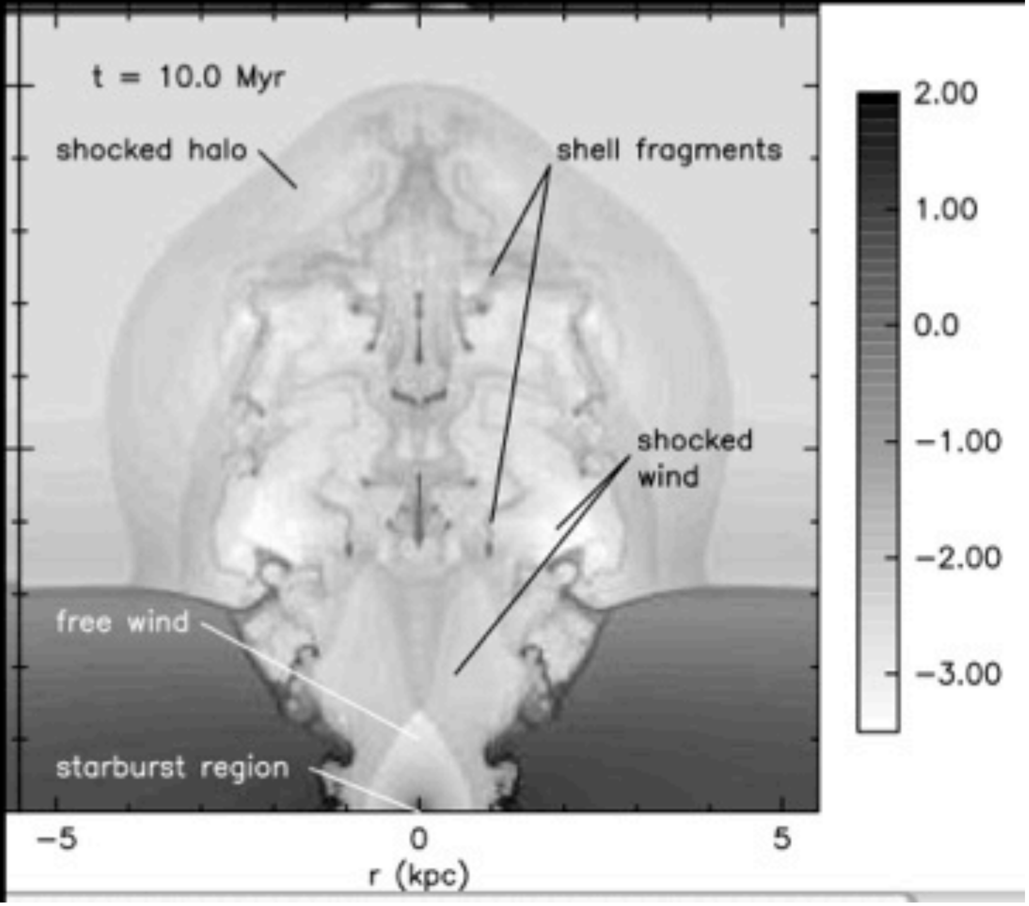
ES, Thacker, & Davis (2001)

Outflows

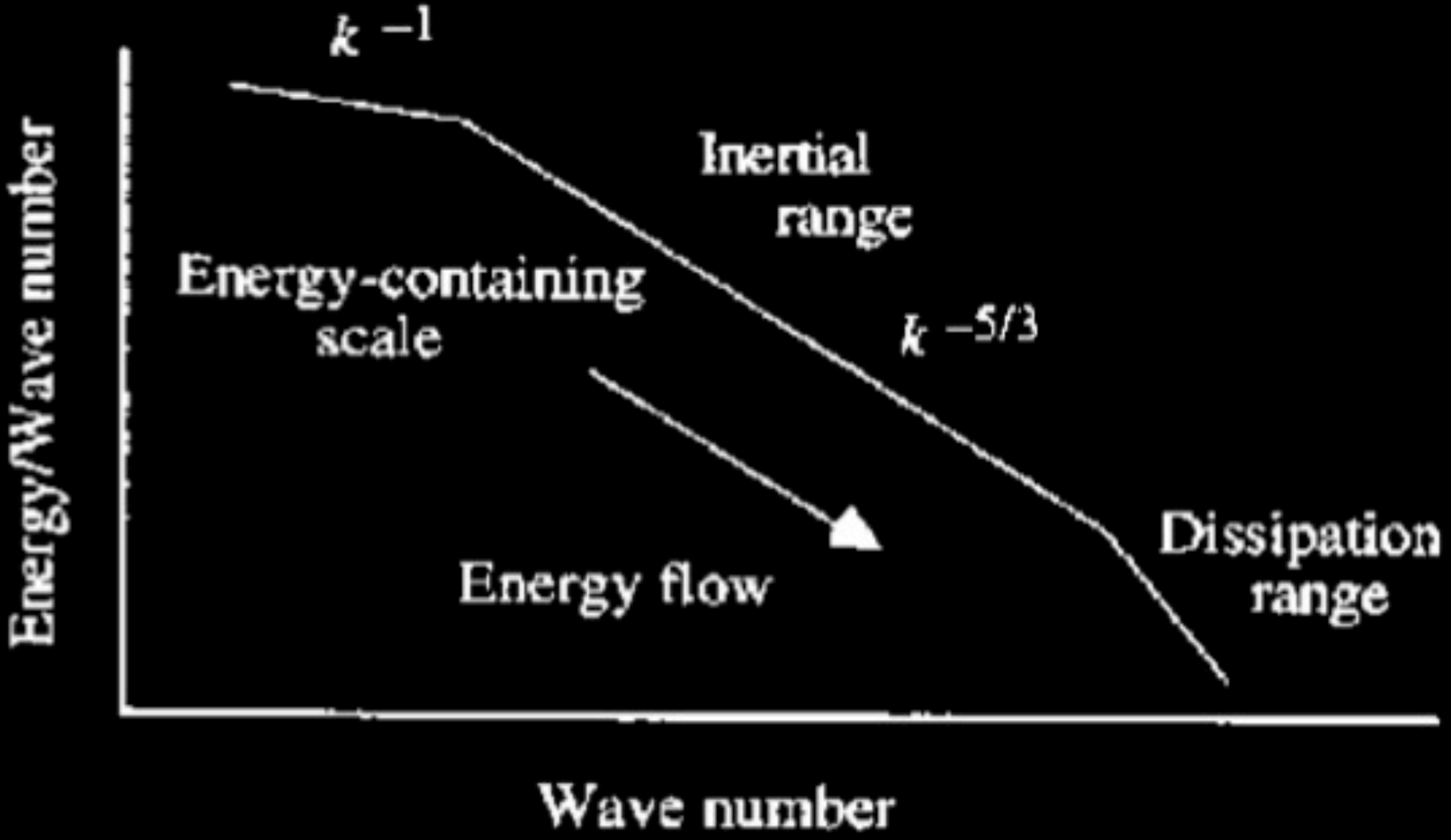


MacLow & Ferrara (1999)

Strickland & Stevens (2000)



Turbulent Dissipation Scale



Ionized Medium

Spitzer :

$L \approx 10^{-2}$ pc $V_{10}\, n^{-1}\, T_5^{5/2}$

Neutral Medium

Ambipolar Diffusion :

$L \approx 10^{-3}$ pc $V_{A,10}\, n^{-1} / x_{-6}$

Unresolved Turbulence

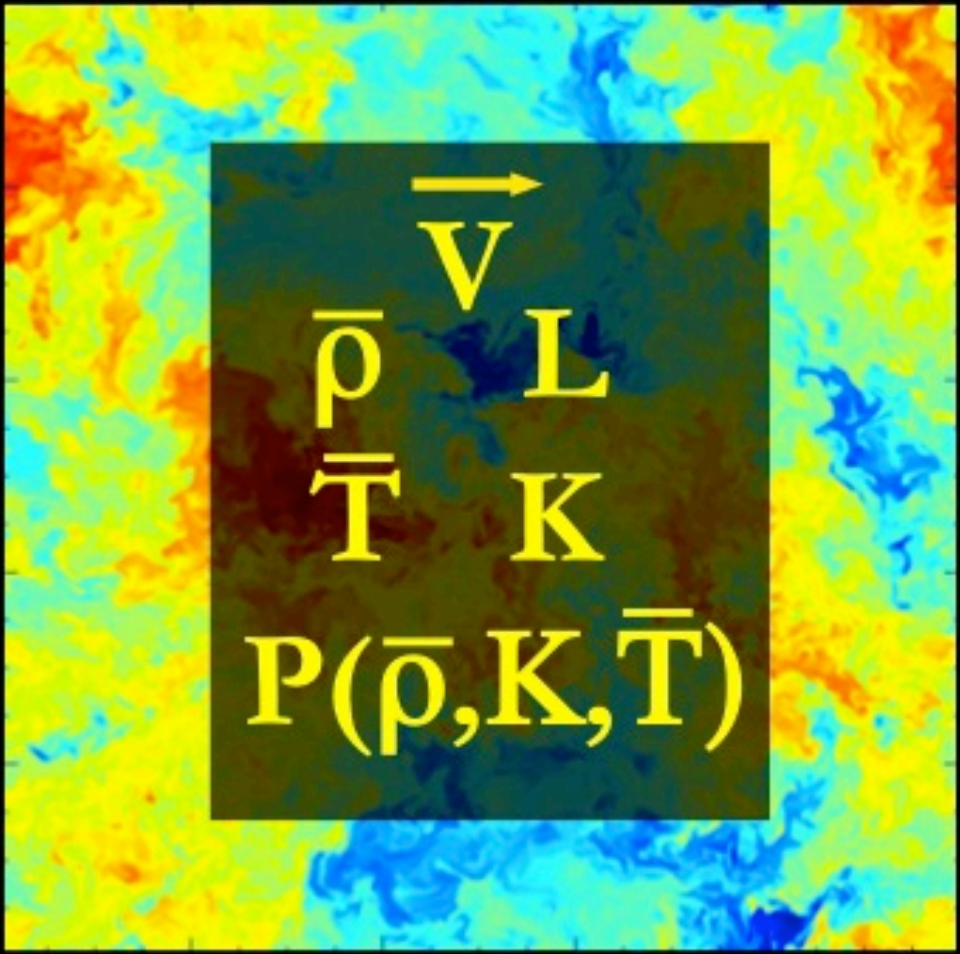
$\vec{V}$

ρ

T

$P(\rho,T)$

Cooling Time



$\vec{V}$

$\bar{\rho}$ L

$\bar{T}$ K

$P(\bar{\rho},K,\bar{T})$

Turbulent Decay Time

$L/(2K)^{1/2}$

Fluid Equations For Supersonic Turbulence

$$\frac{D\rho}{Dt} = 0$$

$$\frac{D\rho u_i}{Dt} = -\frac{\partial P}{\partial x_i}$$

$$\frac{D\rho E}{Dt} = \frac{\partial}{\partial x_j}\left(\mu_t \frac{\partial E}{\partial x_j} \right) - \frac{\partial P u_j}{\partial x_j}$$

Thermal +
Turbulent

ES & M. Bruggen (2010)

Fluid Equations For Supersonic Turbulence

K = Turbulent KE , L= Turbulent Length Scale

$$\frac{\mathrm{D}\bar{\rho}K}{\mathrm{D}t} = \underbrace{\frac{\partial}{\partial x_j}\left(\mu_t \frac{\partial K}{\partial x_j}\right)}_{\text{turb. diffusion}} \underbrace{- R_{i,j}\frac{\partial \tilde{u}_i}{\partial x_j}}_{\text{PdV Work}} \underbrace{+\rho \dot{E}_{\mathrm{mech}}}_{\text{Driving by SNe (etc.)}}$$

$$\underbrace{-\rho\, \mathrm{V}^2 \times (\mathrm{V}/\mathrm{L})}_{\text{Decay to thermal energy}}$$

$$\frac{\mathrm{D}\bar{\rho}L}{\mathrm{D}t} = \underbrace{\frac{\partial}{\partial x_j}\left(\mu_t \frac{\partial L}{\partial x_j}\right)}_{\text{turb. diffusion}} \underbrace{+ C_C \bar{\rho} L \frac{\partial \tilde{u}_i}{\partial x_i}}_{\substack{\text{growth of eddies} \\ \text{through motion in mean flow}}},$$

$$\underbrace{\mu_T = C_\mu \bar{\rho} L V}_{\text{turb. viscosity}}, \qquad \underbrace{V \equiv \sqrt{2K}}_{\text{turb. velocity}}$$

FLASH3.0, AMR

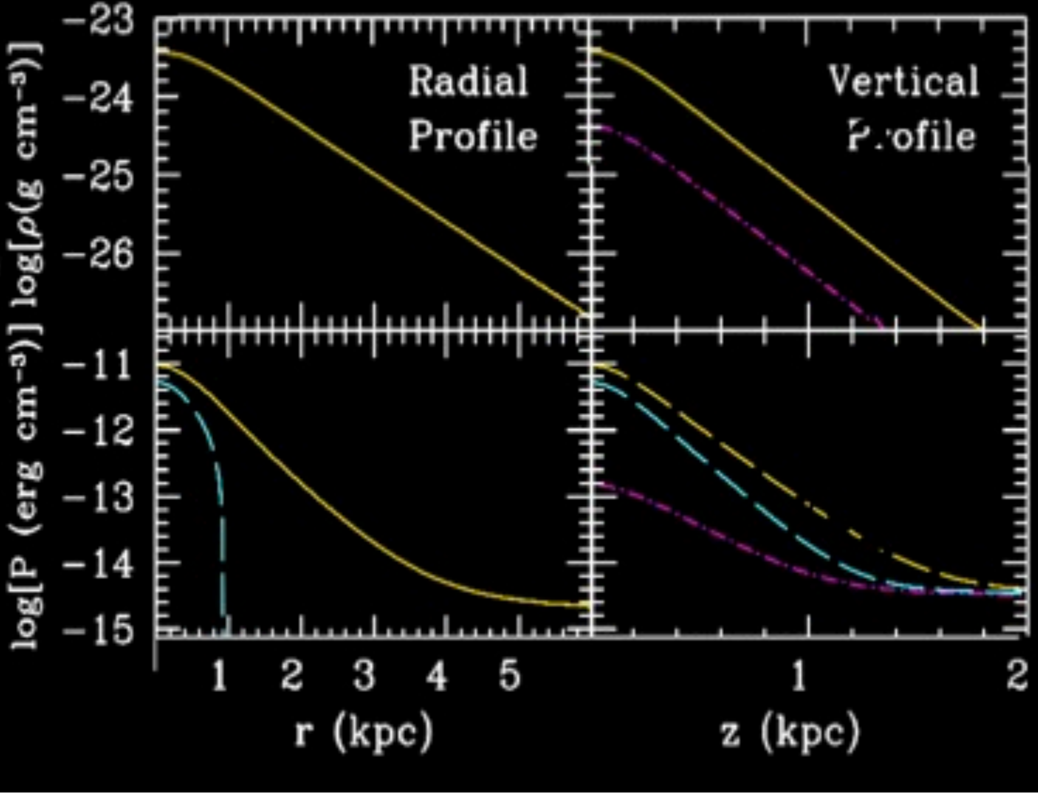
initially hydrostatic galaxy, modeled after NGC 1569

4 levels of refinement, 39 parsec res., 25 X 25 x 30 kpc box

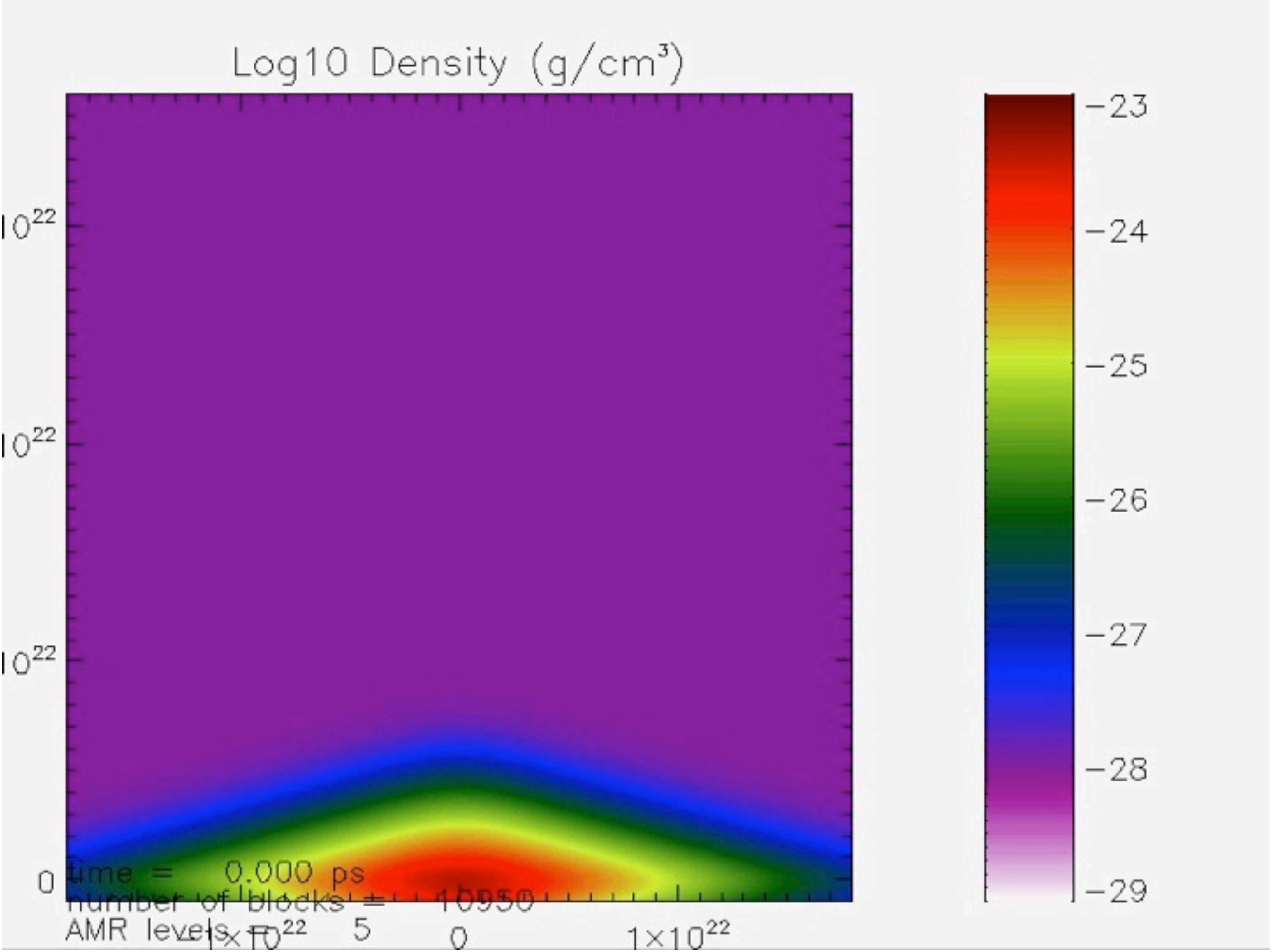
Atomic radiative cooling everywhere.

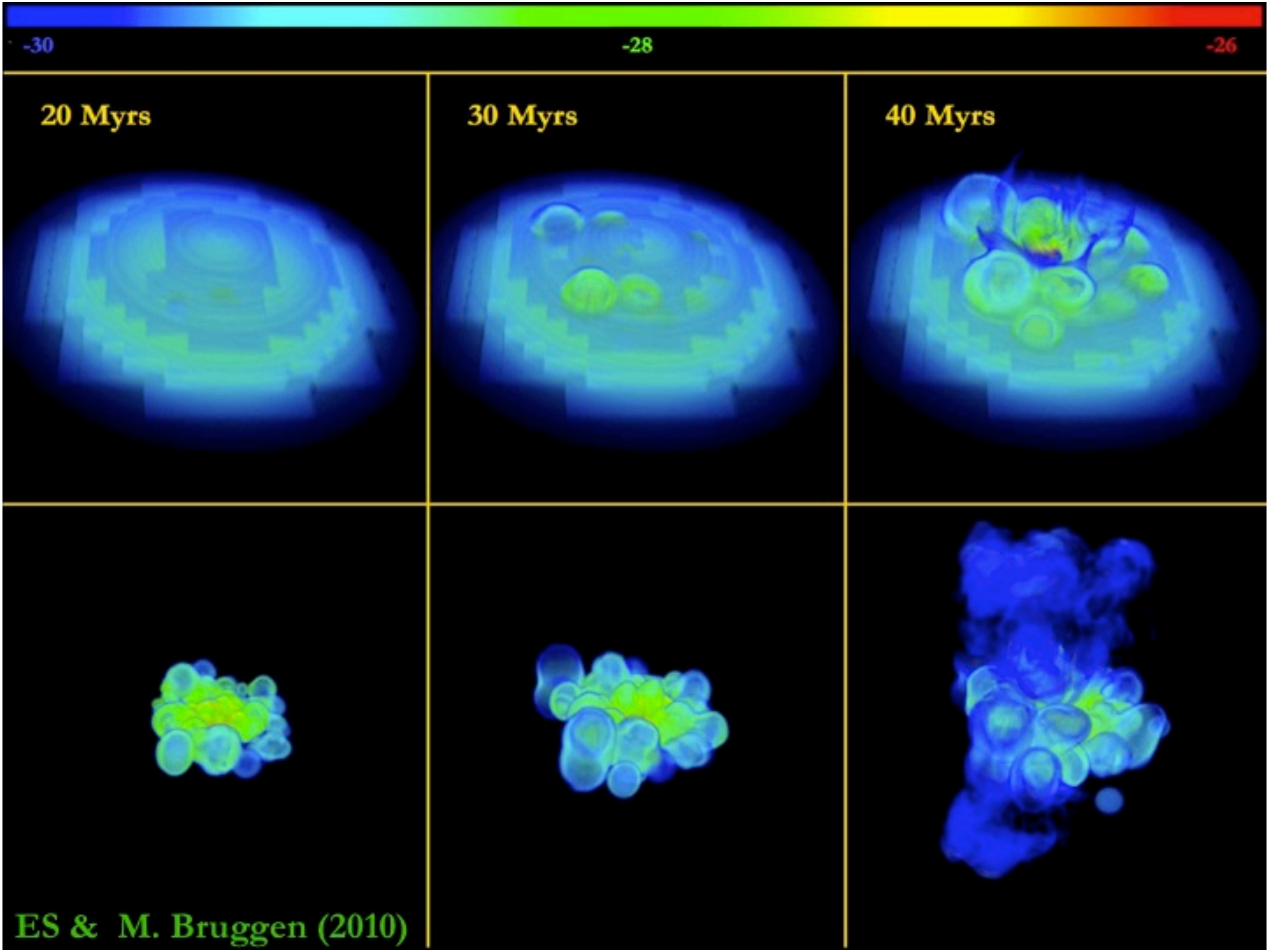
$$\Sigma_{\rm SFR} = 2.5 \times 10^{-4}\,\frac{M_\odot}{\rm yr\,kpc^2}\left(\frac{\Sigma_{\rm gas}}{10^6\,M_\odot {\rm kpc}^{-2}}\right)^{1.5}$$

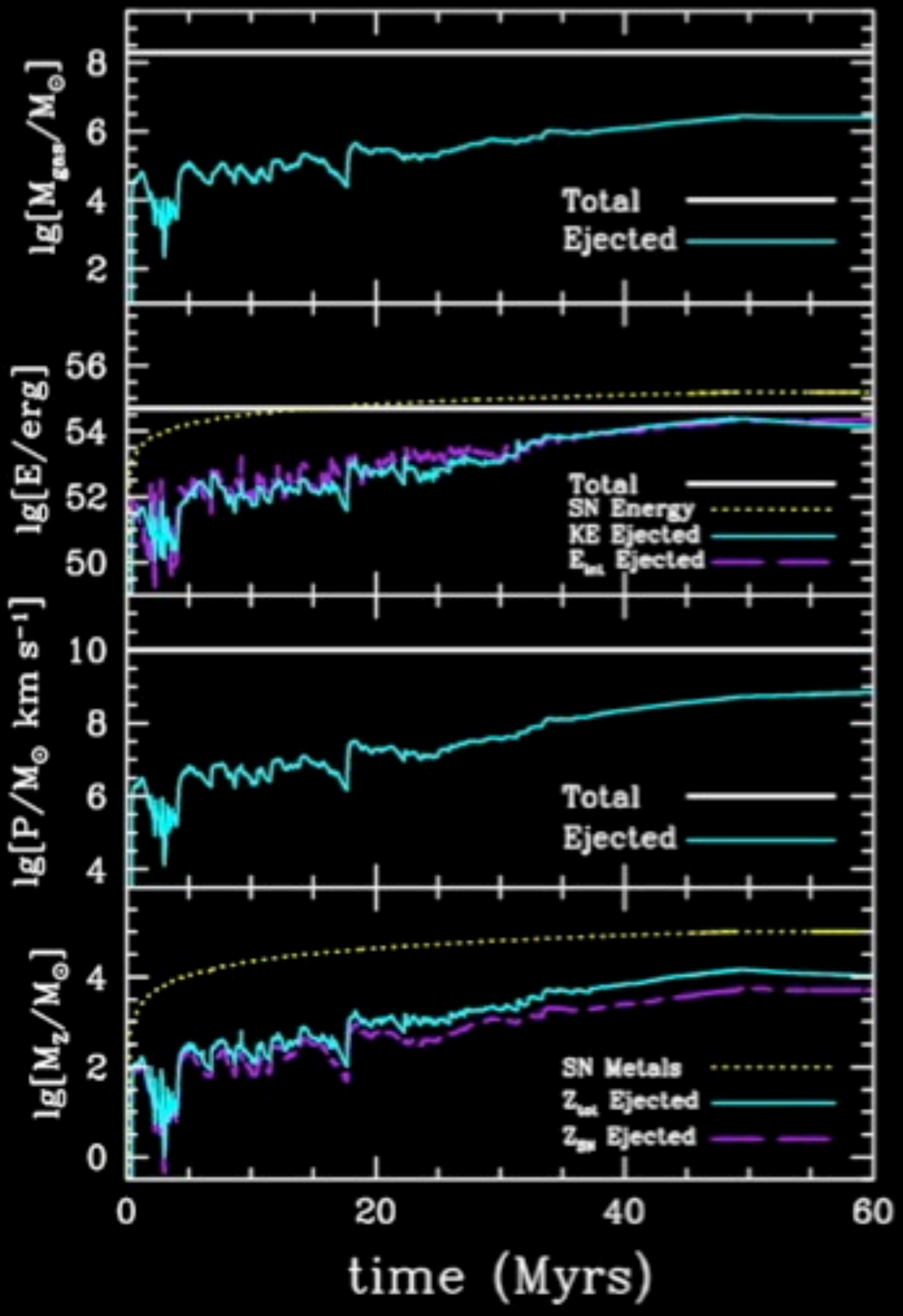
1 SN per 150 $M_\odot$



ES & M. Bruggen (2010)


Log10 Density (g/cm^3)
10^{22}
10^{22}
10^{22}
0
time =   0.000 ps
number of blocks =   10950
AMR levels =   5
-1×10^{22}
0
1×10^{22}
−23
−24
−25
−26
−27
−28
−29


-30
-28
-26
20 Myrs
30 Myrs
40 Myrs
ES & M. Bruggen (2010)



$M_\star = 8\times10^6 M_\odot$

$\approx 8\times10^6 M_{Ej}$

$E_{SN} < E_{total-ej}$

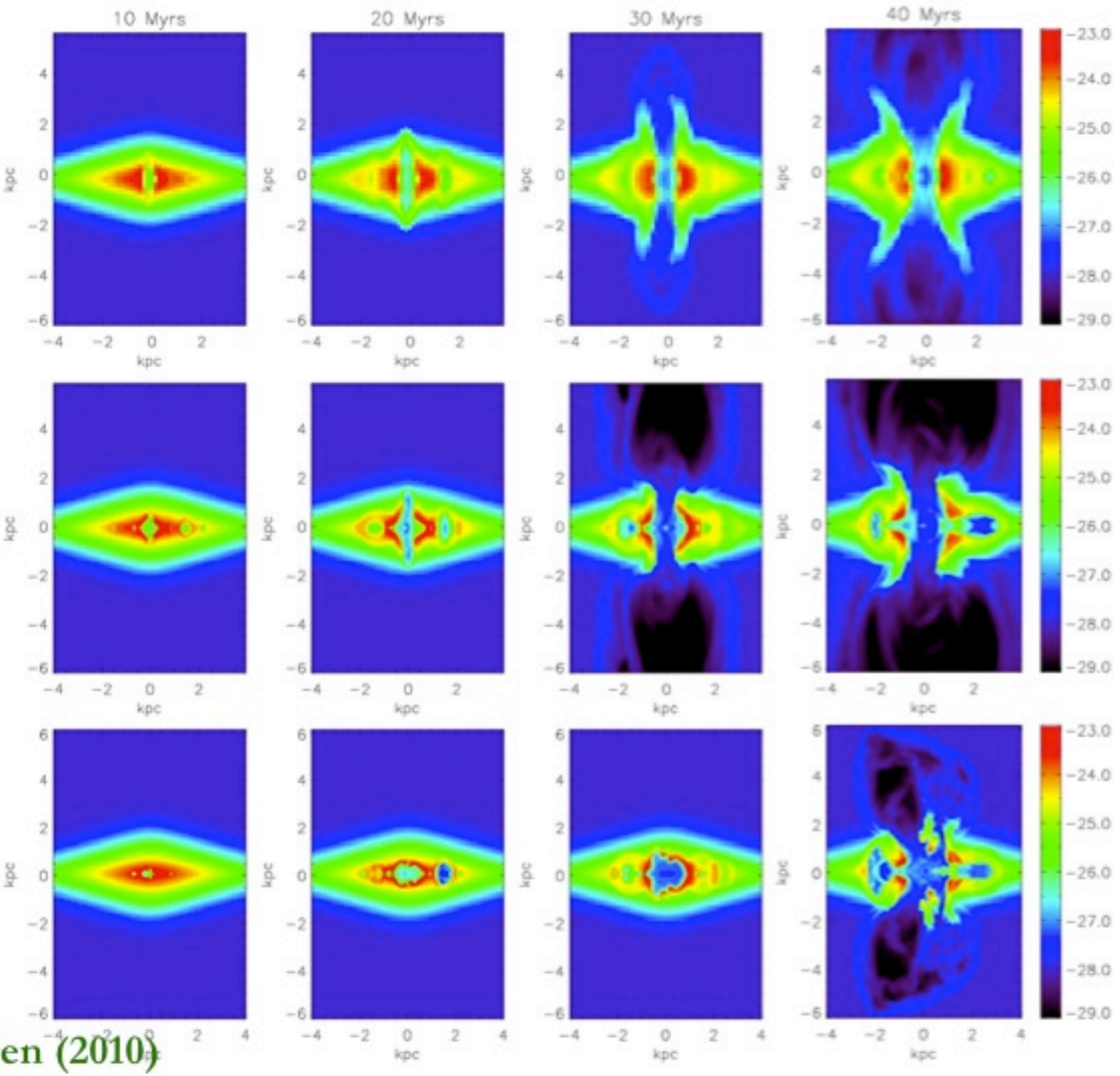
$V_{ej} \approx 50$ km/s

ES & M. Bruggen (2010)

log ρ
156 pc

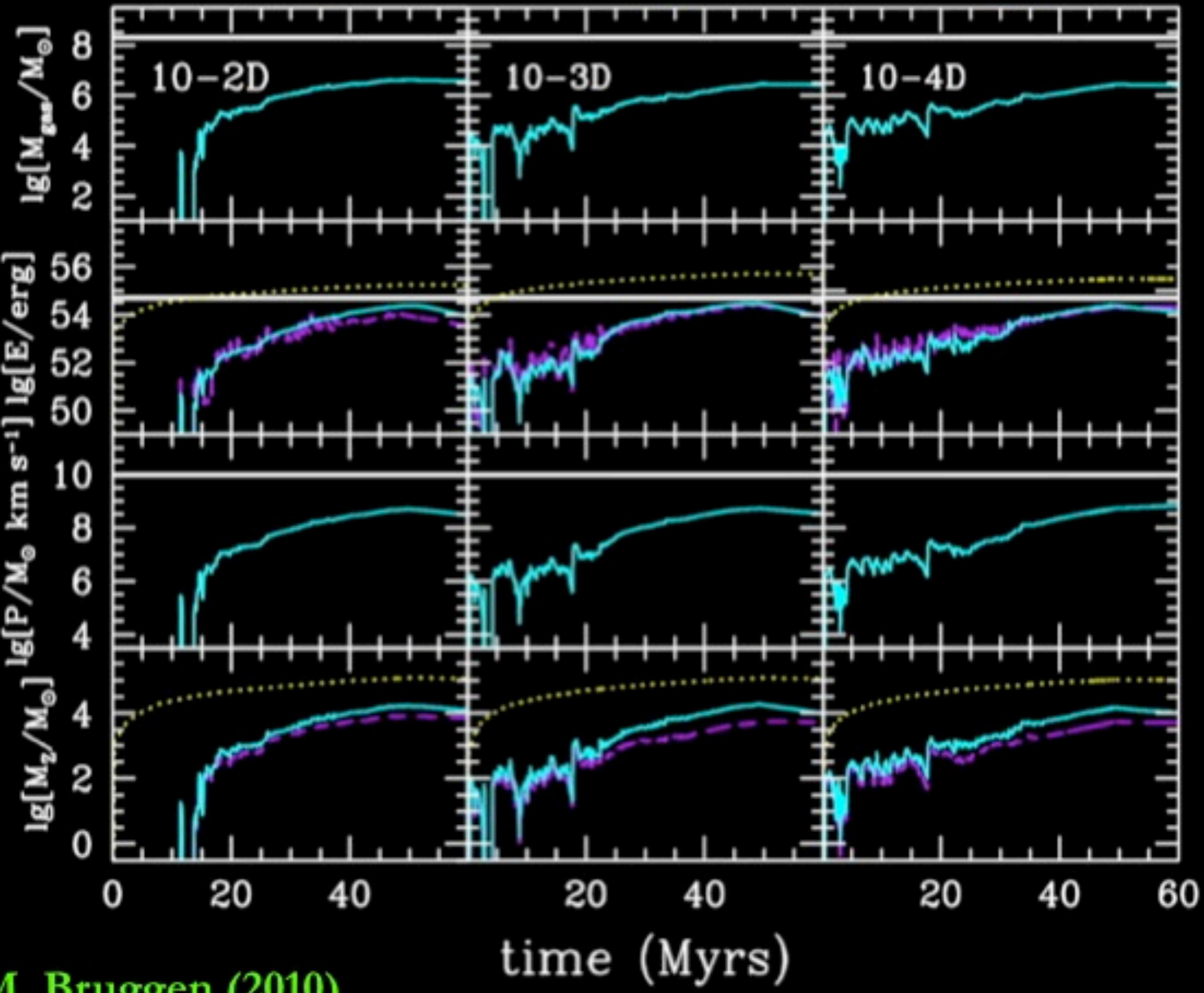
log ρ
78 pc

log ρ
39 pc



ES & M. Bruggen (2010)

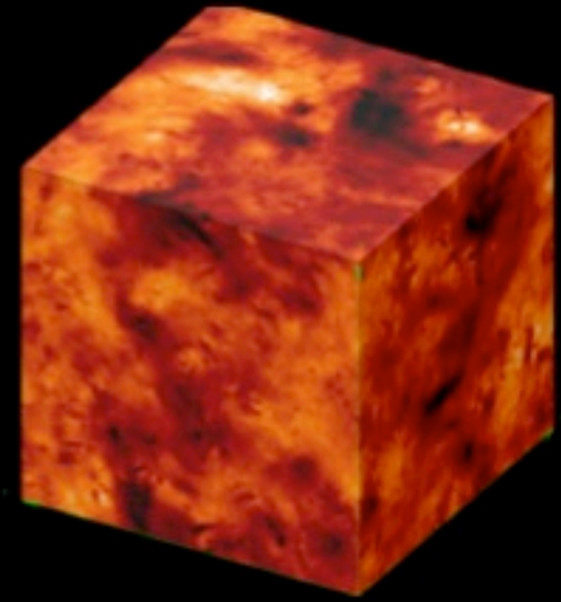
156 pc **78 pc** **39 pc**



ES & M. Bruggen (2010)

How does it look?

We use the FLASH code with modified "Stir unit"
Periodic simulation box , 512^3 computation cells



$$
\begin{aligned}
\frac{D\rho}{Dt} &= 0, \\
\frac{D\rho u_i}{Dt} + \frac{\partial P}{\partial x_i} &= \rho g_i + \rho f_i. \\
\frac{D\rho E}{Dt} + \frac{\partial P u_j}{\partial x_j} &= \rho \dot{E}_{\mathrm{cool}} + \rho \dot{E}_{\mathrm{chem}}, \\
\frac{D\rho X_s}{Dt} &= \rho A_s \dot{R}_s.
\end{aligned}
$$

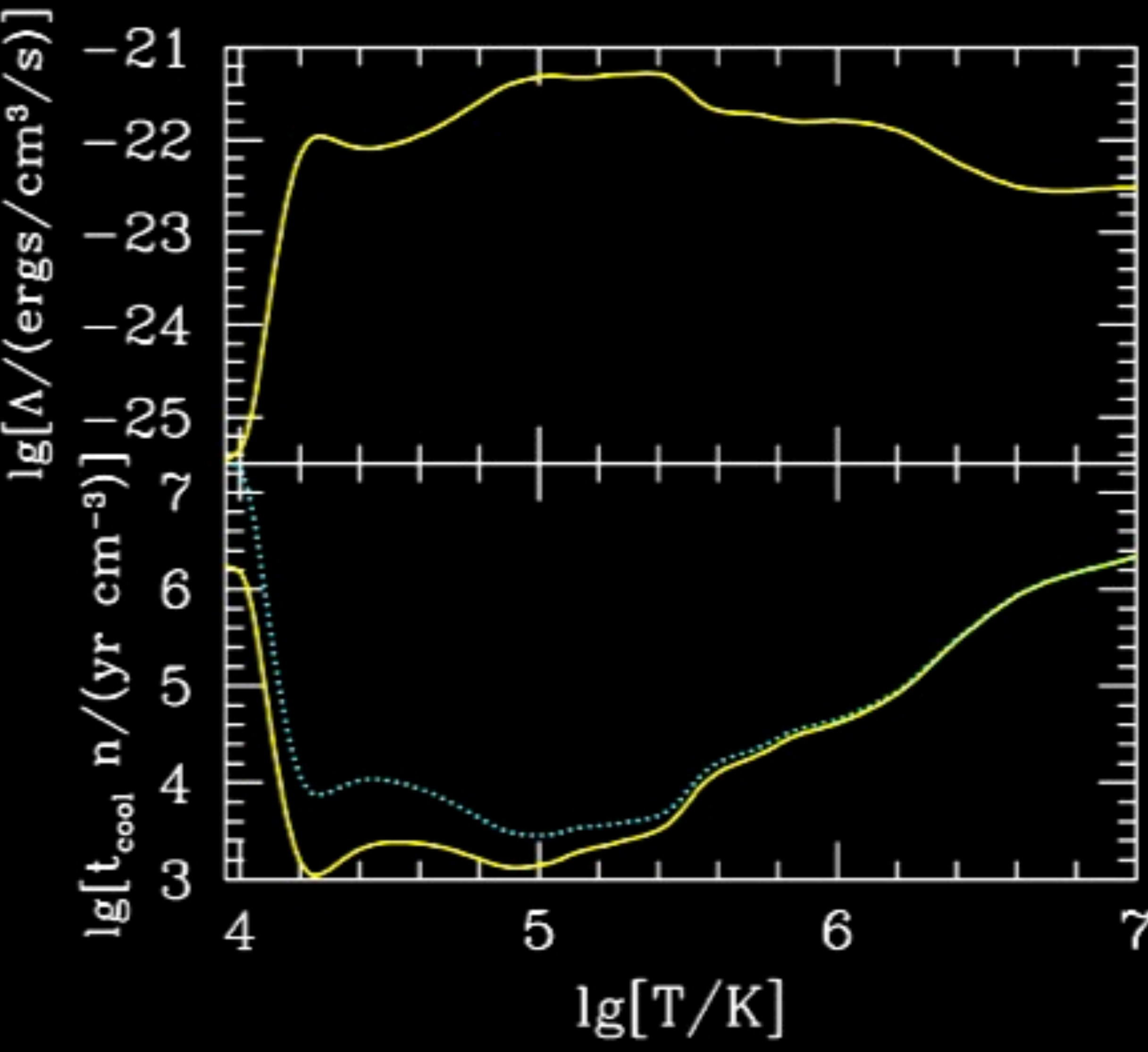
Turbulence, Cooling, & Chemistry

Ongoing with W. Gray, D. Kasen, C. Raskin

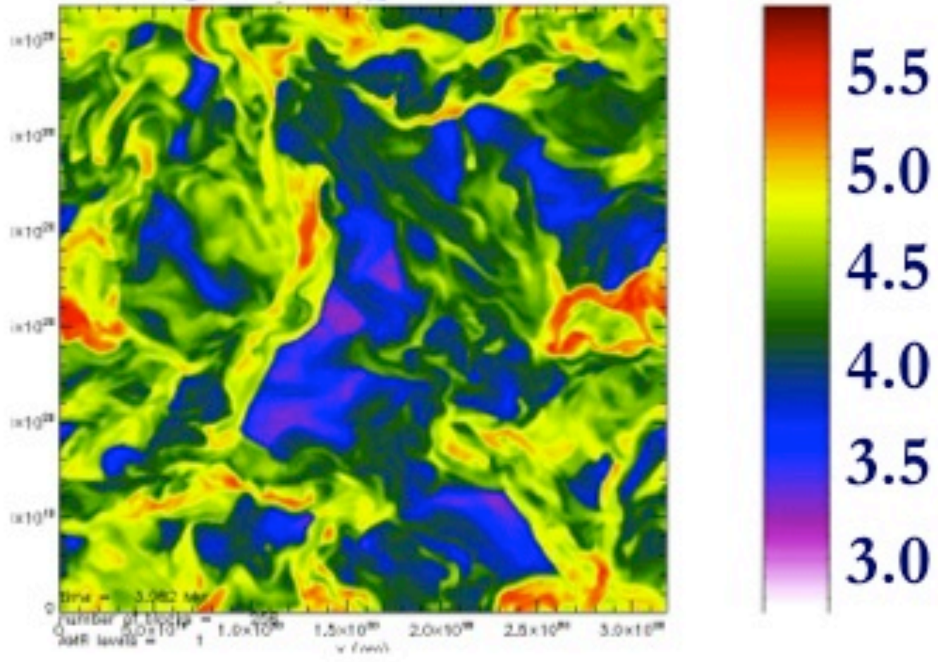
Radiative Cooling Rates in Interstellar Gas

Cooling Rate

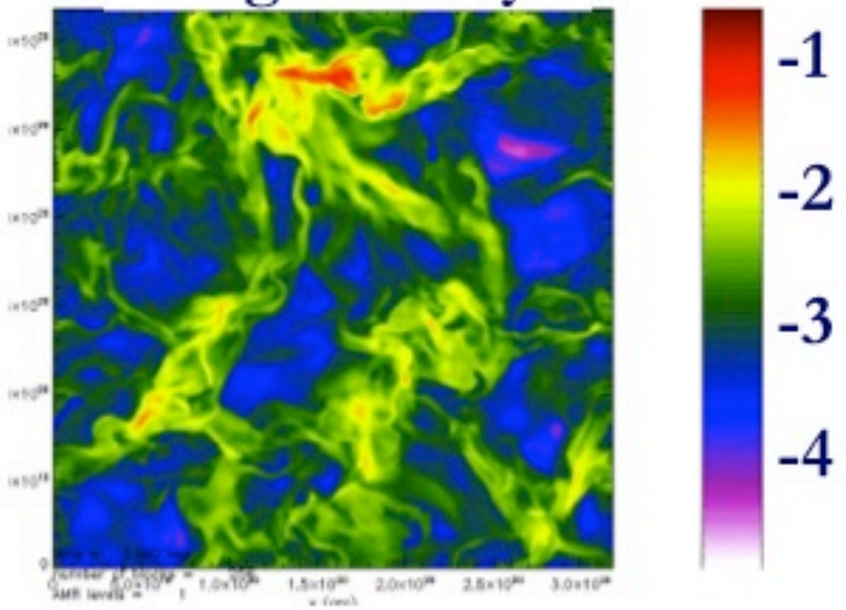
Cooling Time

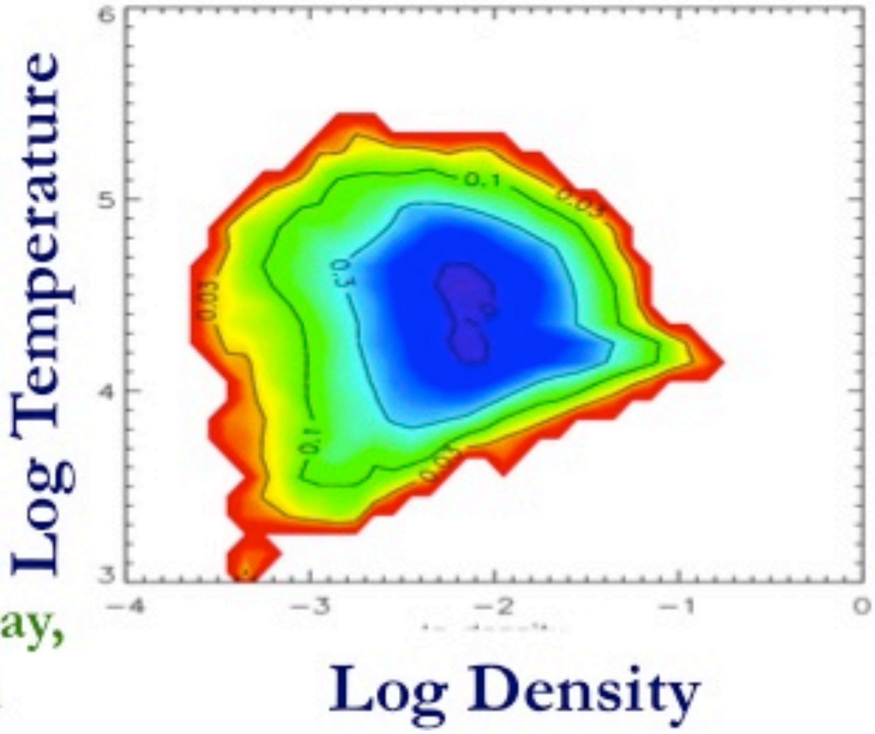


Log Temperature



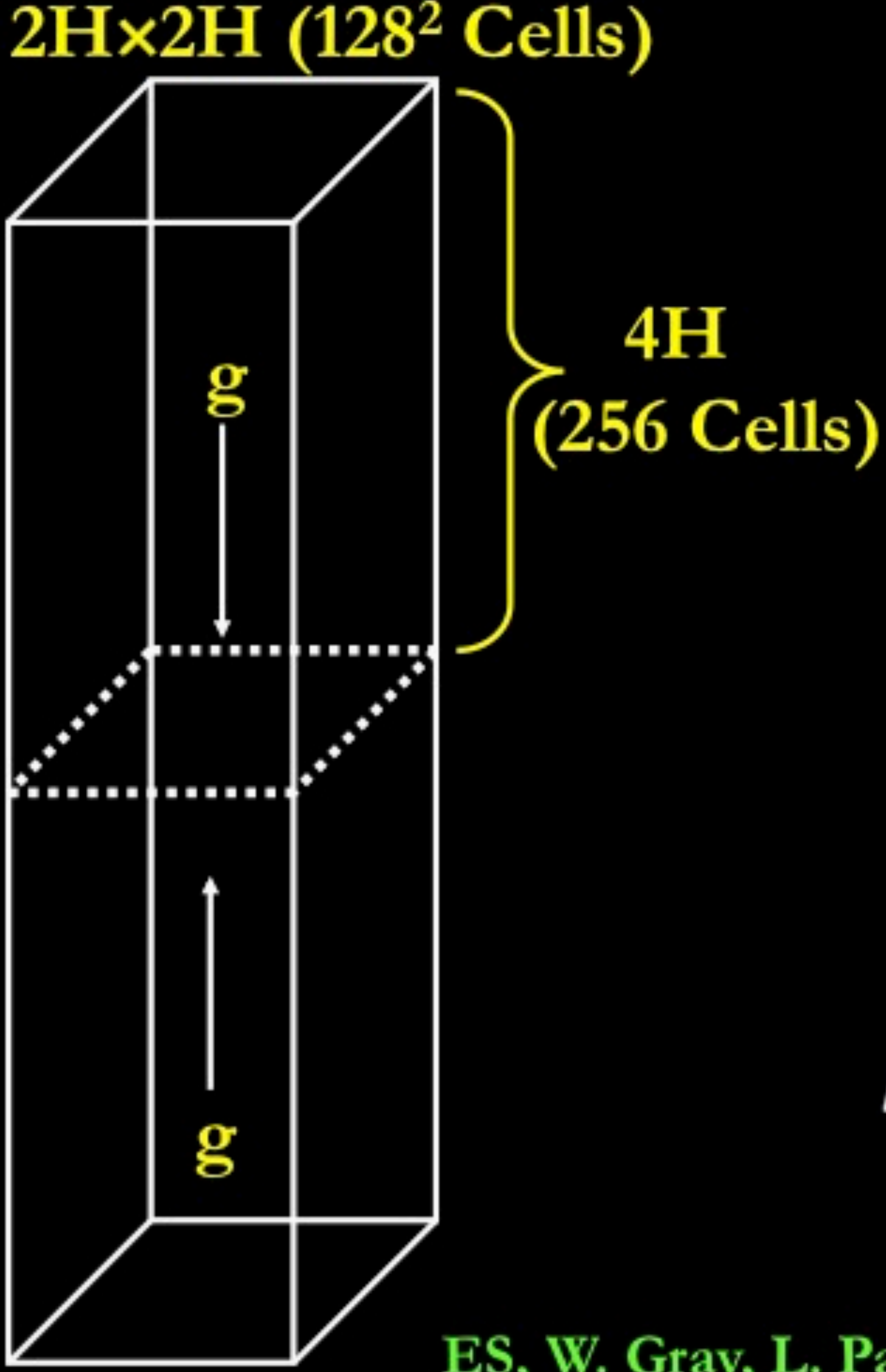
Log Density





Ongoing with W. Gray,
D. Kasen, C. Raskin

Add stratification



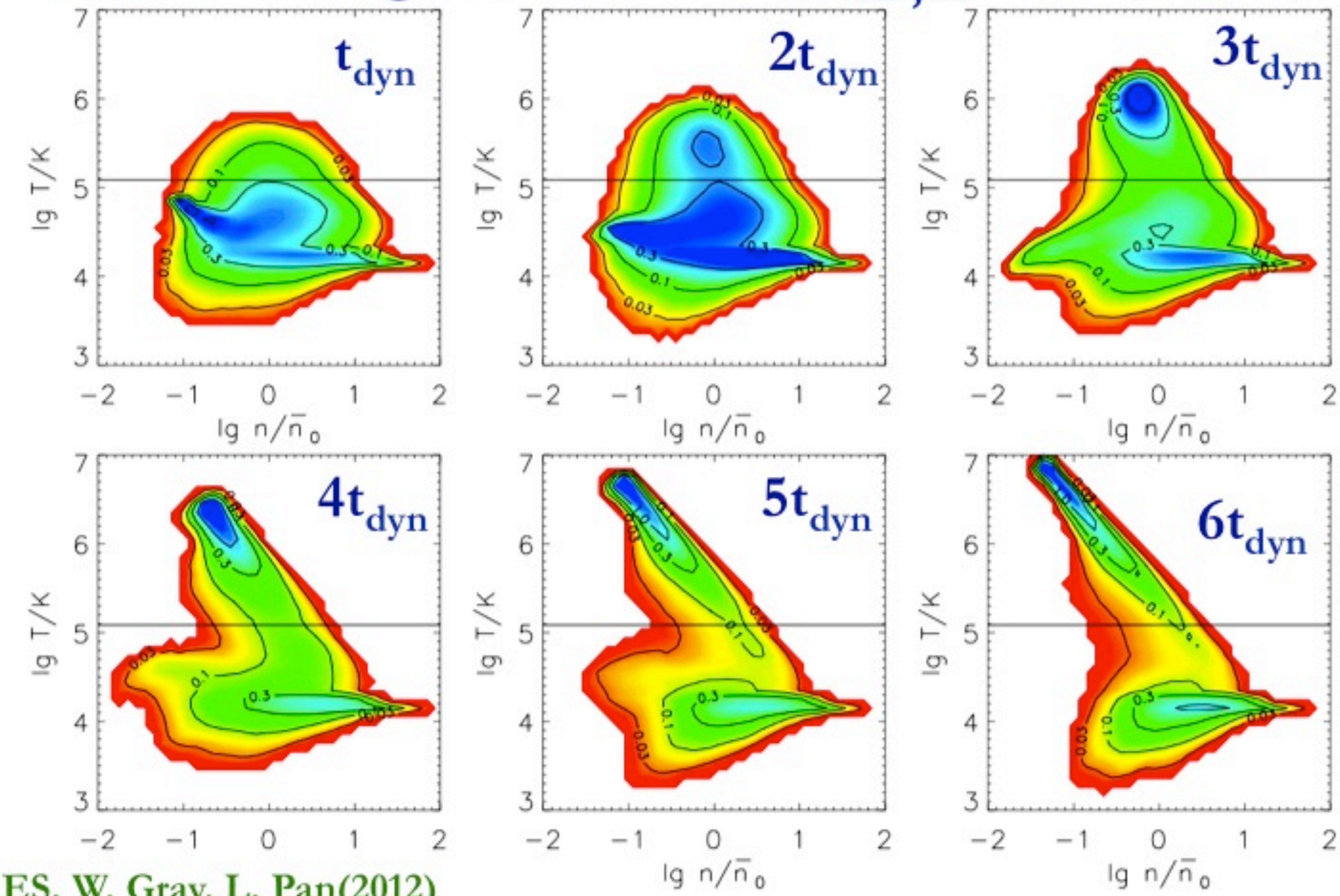
$$g = g_0 \frac{-\ z}{\sqrt{z^2 + a^2}}$$

$$a = H/2$$

$$\rho(z,t) = \rho_0 e^{-\left[\frac{(z^2+a^2)^{1/2}-a}{H}\right]}$$

ES, W. Gray, L. Pan (2012)

Mass-Weighted PDF ($\sigma_{1D,M}$=34 km/s)

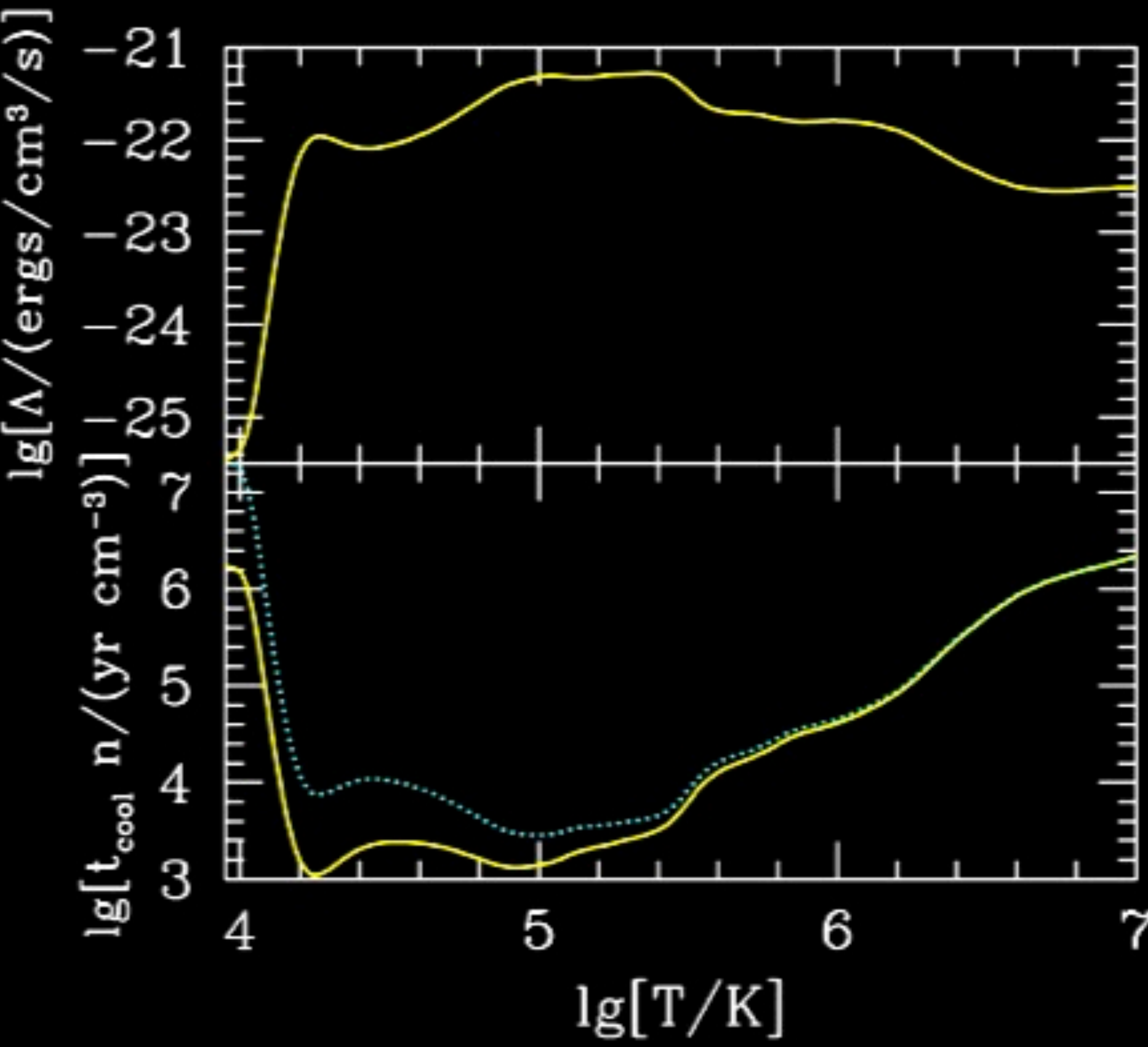


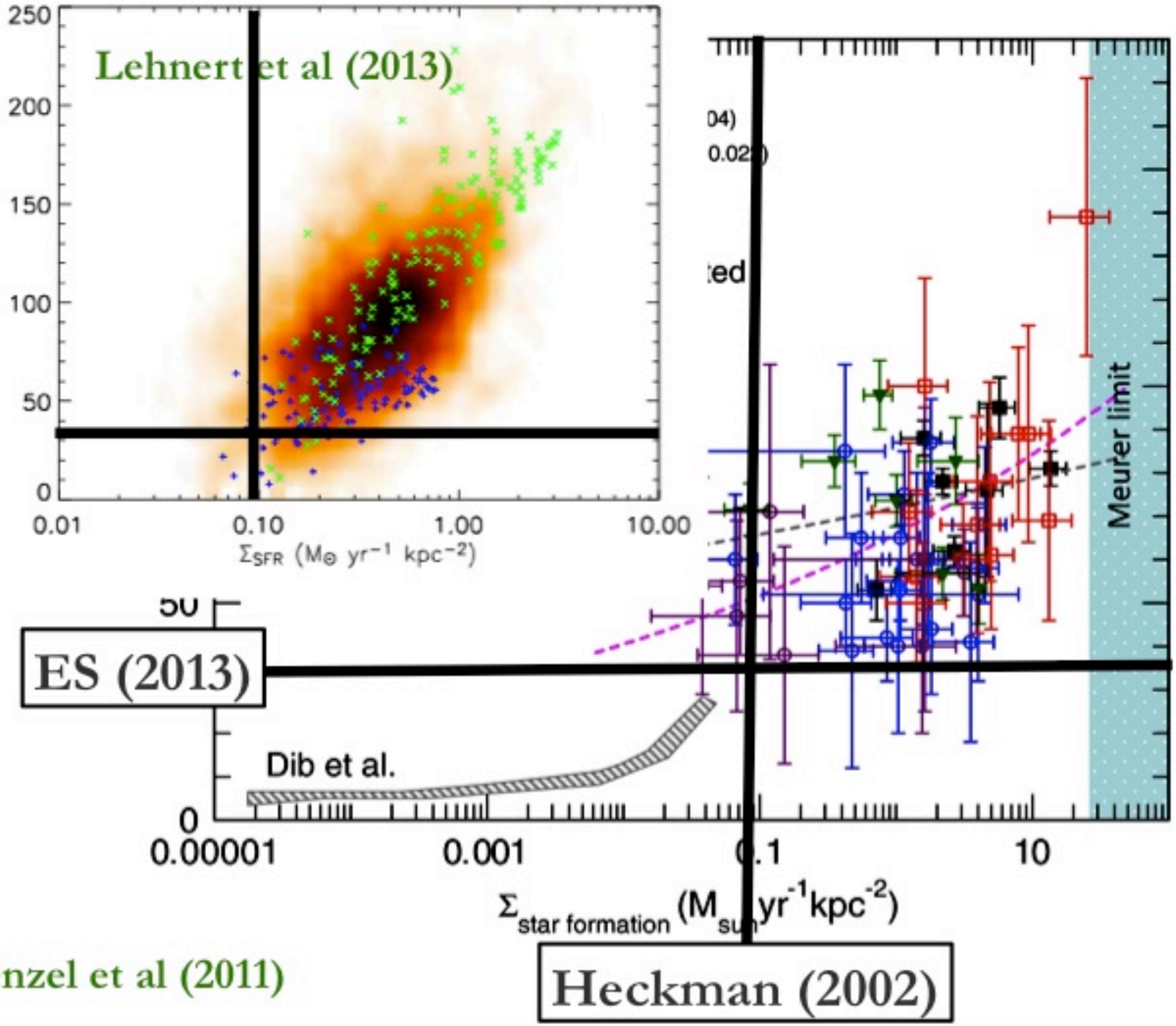
ES, W. Gray, L. Pan(2012)

Radiative Cooling Rates in Interstellar Gas

Cooling Rate

Cooling Time





Lehnert et al (2013)

ES (2013)

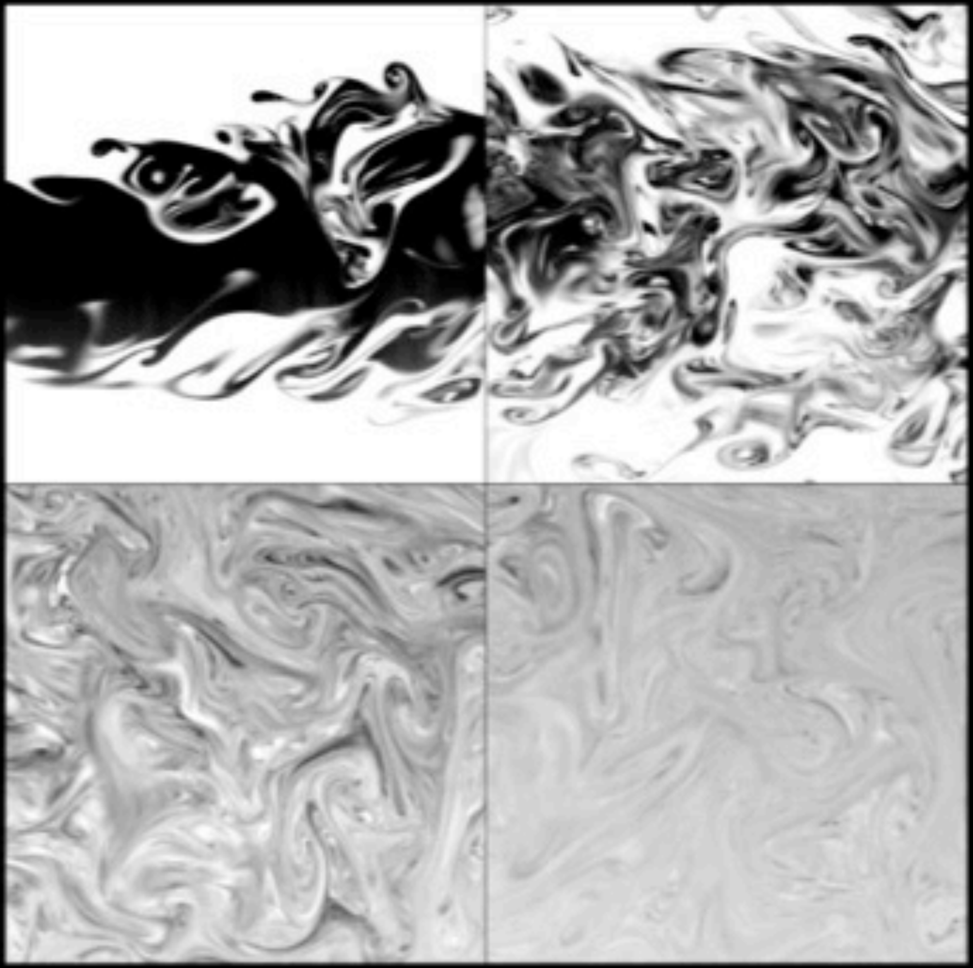
Heckman (2002)

Genzel et al (2011)

III Turbulent Mixing

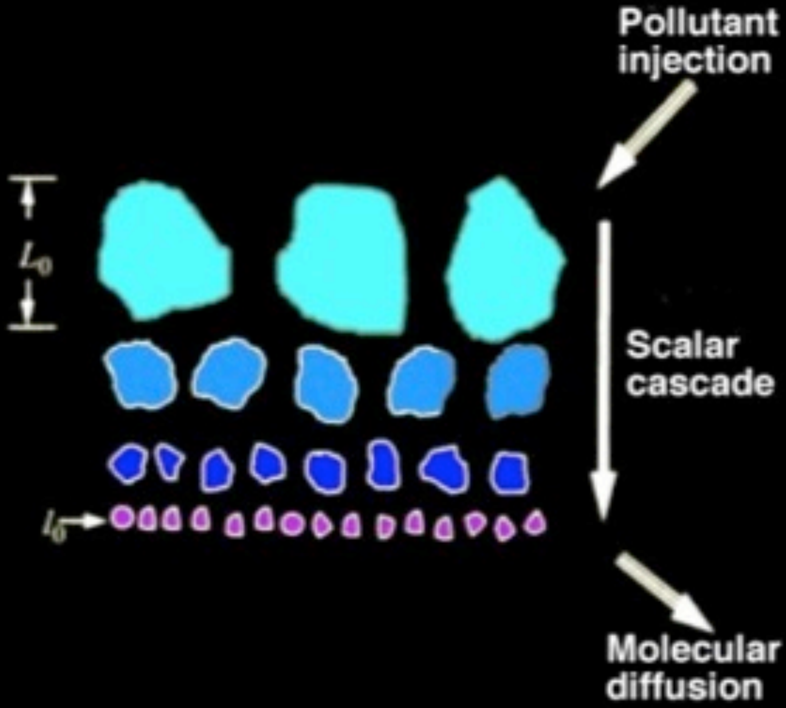
ES et al.

Mixing in Incompressible Turbulence



Mixing of a jet of dye
Duplat and Villermaux (2008)

Classic phenomenology (Obukohov-Corrsin)



Mixing timescale $\tau_{\mathrm{mix}} \sim \mathrm{L}/\mathrm{V}_{\mathrm{t}}$

Mixing in supersonic turbulence:

1. What is the role of compressible modes?
2. How does the mixing timescale change with the flow Mach number?

Simulations of Mixing in Supersonic Turbulence

We use the FLASH code with modified “Stir unit” for flow and scalar driving. Periodic simulation box , 512^3 computation cells

Turbulent flows:

-Driven and maintained by a solenoidal forcing at large scales
-Amplitude of the force adjusted to obtain 6 Mach #s from 0.9 to 6
$1 \leq k \leq 3$
-Isothermal equation of state.

Metals:

-Same driving scheme used representing new sources of pollutants at large scales.

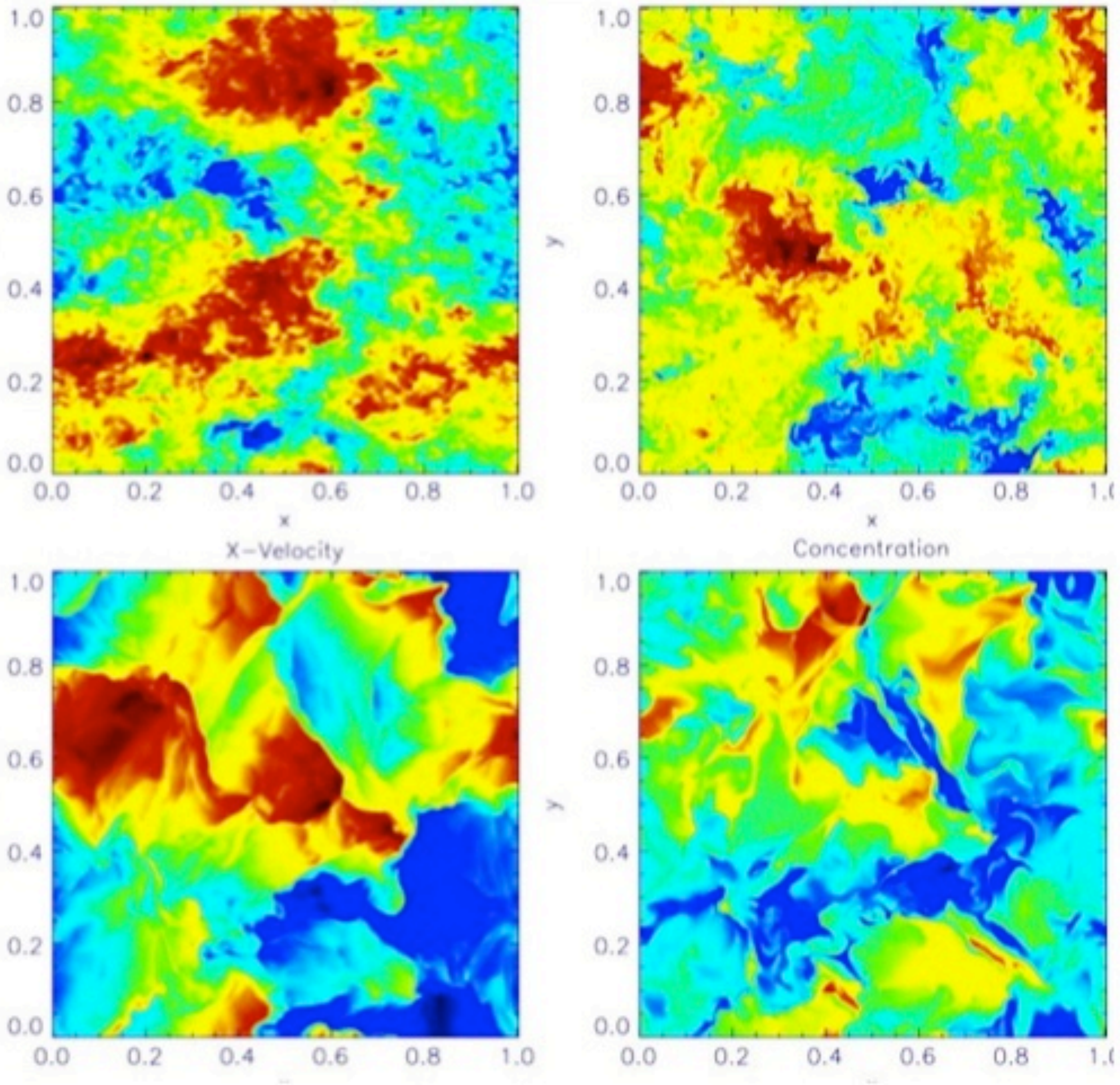
Pan & ES (2010)

x-velocity

concentration

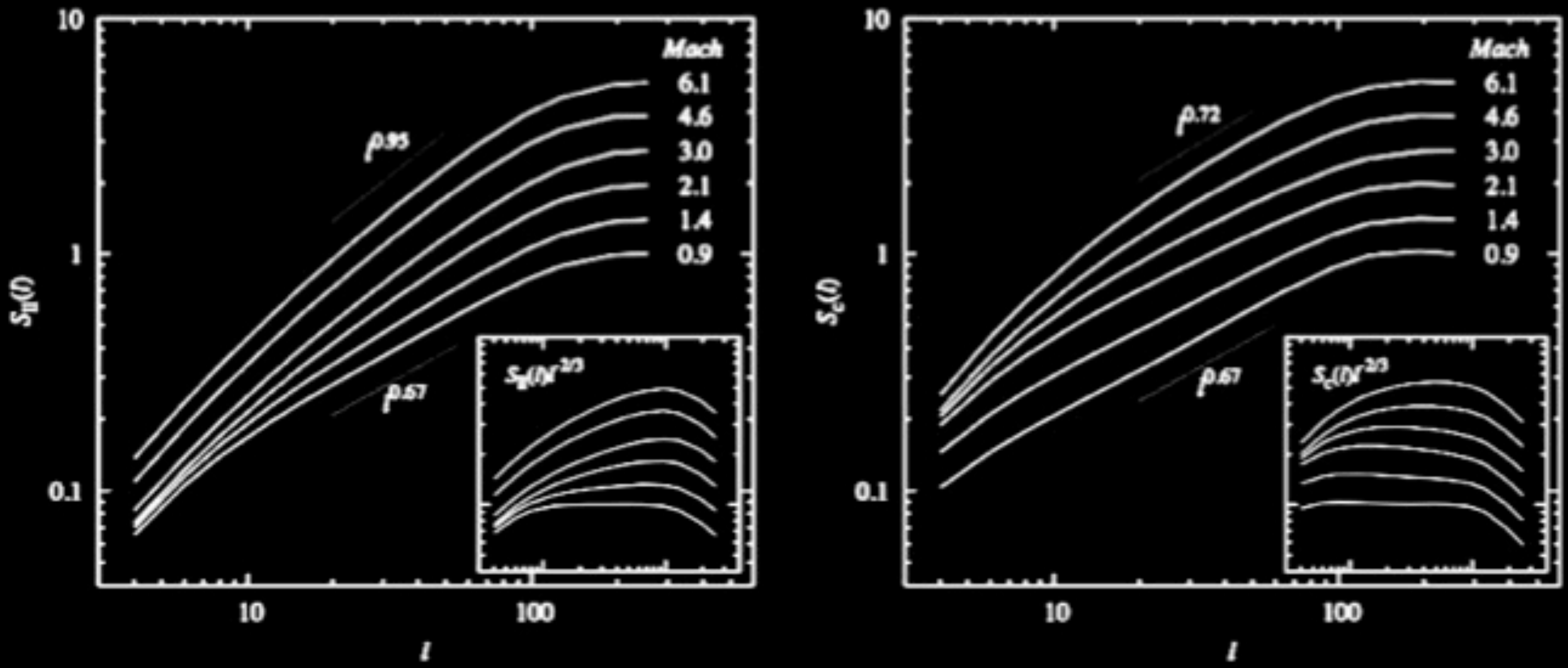
M = 0.9

M = 6.1



Pan & ES (2010)

2nd Order Velocity and Scalar Structure Functions

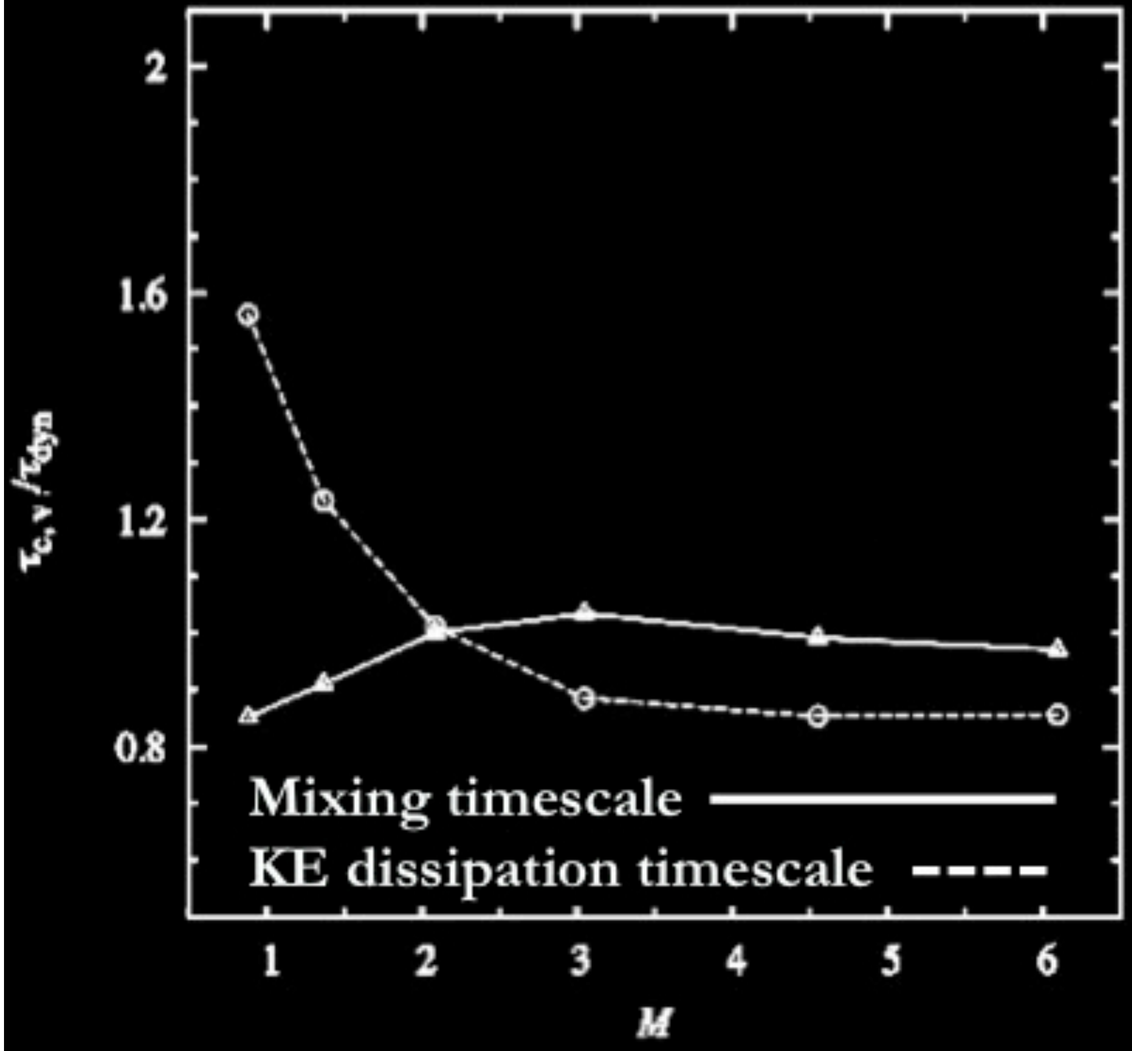


1. The velocity structure function steepens from 2/3 to 0.95 at M = 6.1, primarily due to increasing shocks

2. The slope of the scalar structure function first decreases from 2/3 at M=0.9 to 0.6 at M=2.1. However, at M >3, the slope increases, due to the effect of strong compressible modes on scalar structures.

Pan & ES (2010)

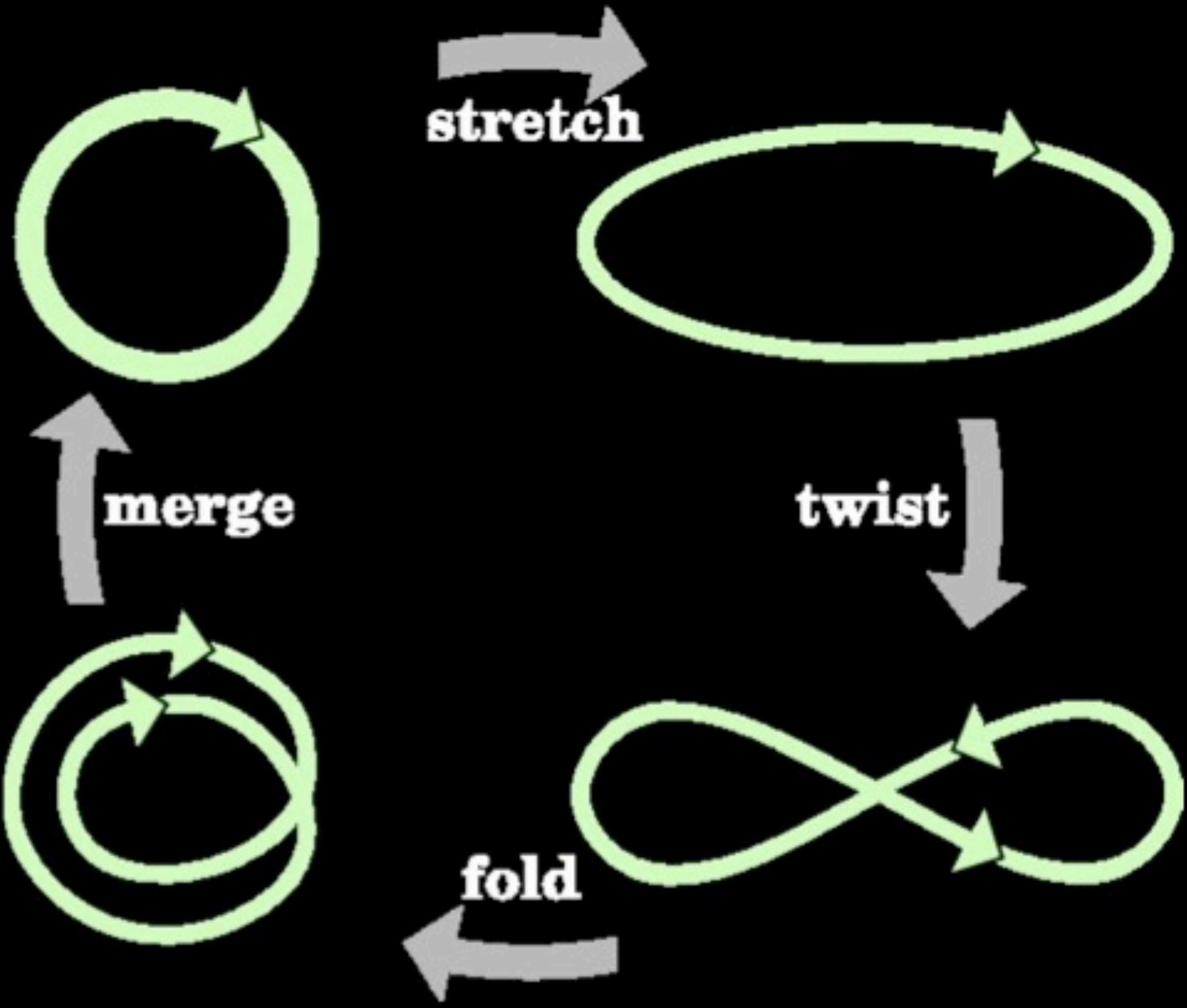
Mixing and Energy Dissipation Timescales

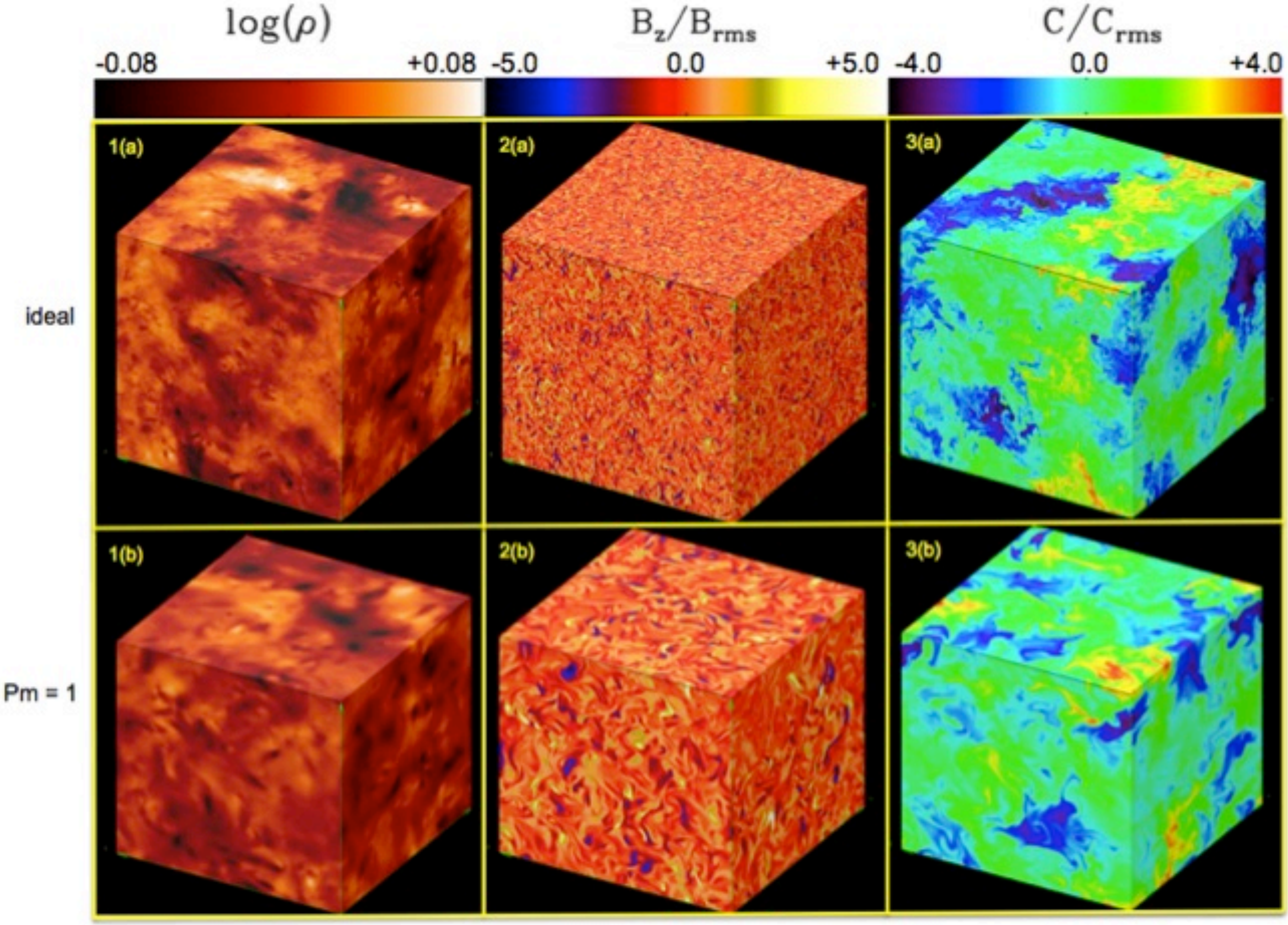


- Energy dissipation rate increases with Mach #
- Mixing rate decreases with M: compressible modes are less efficient at producing small scalar structures

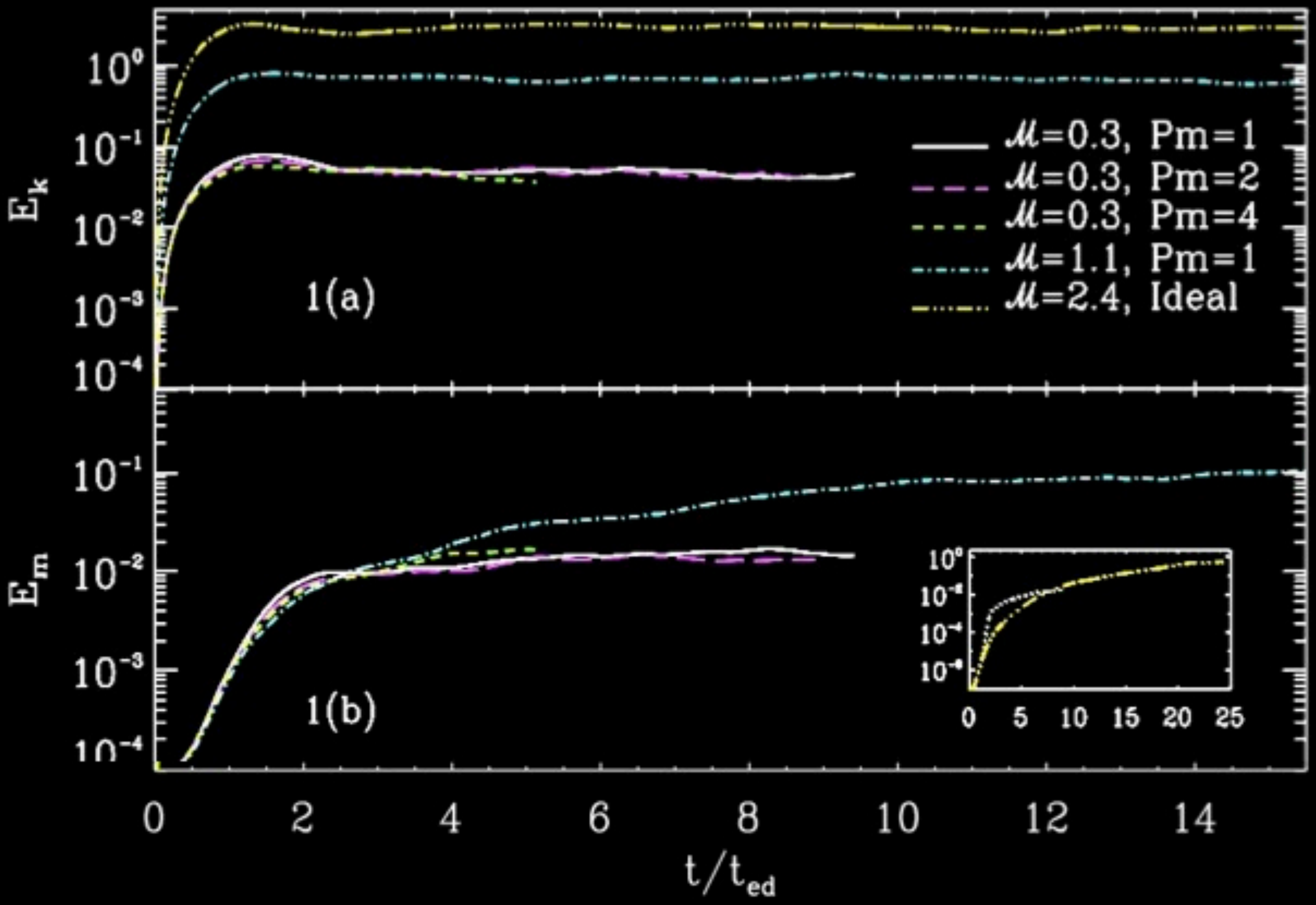
Pan & ES (2010)

Mixing in Magnetized Media

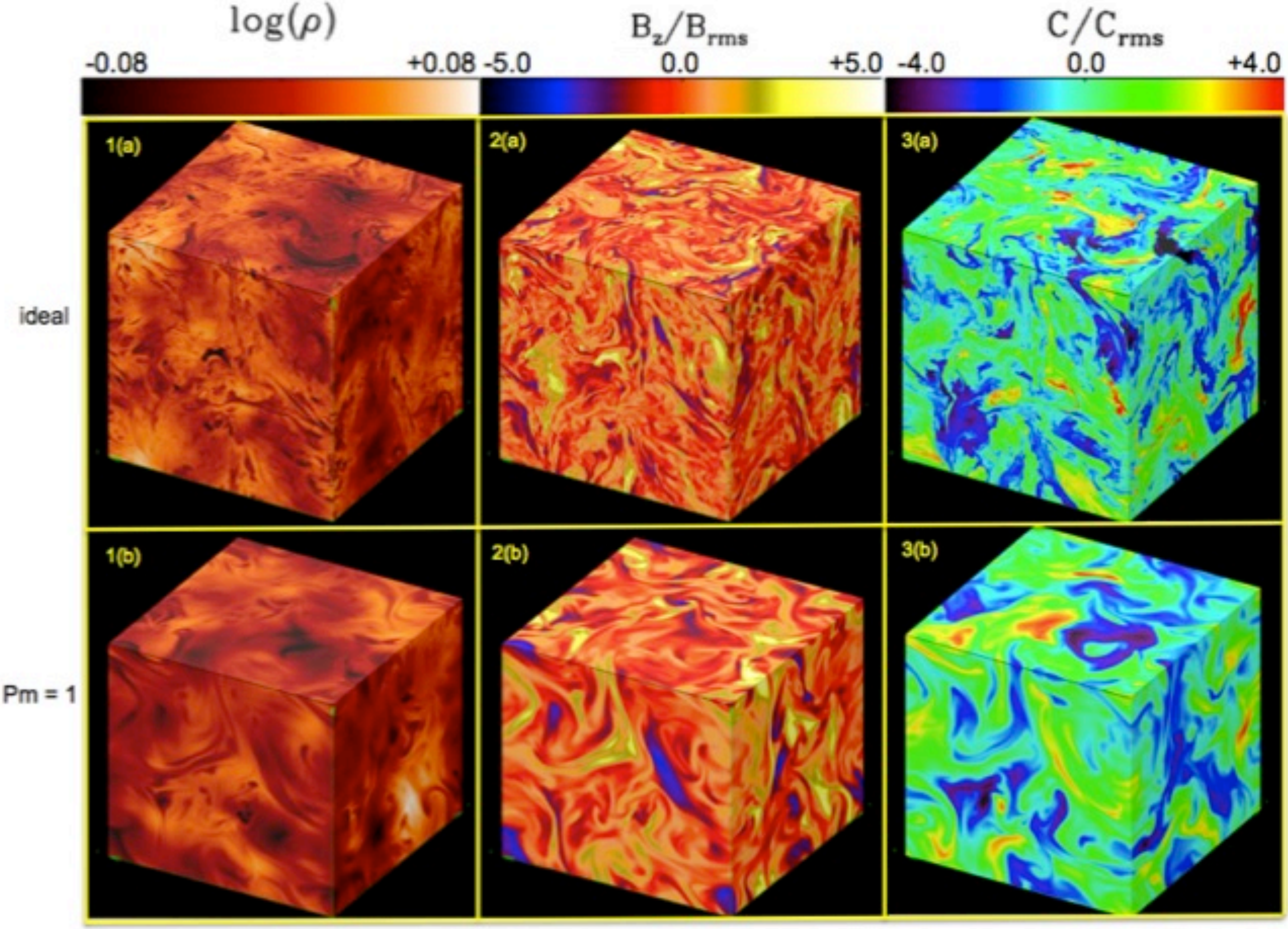




Sur, Pan, & ES (2014)

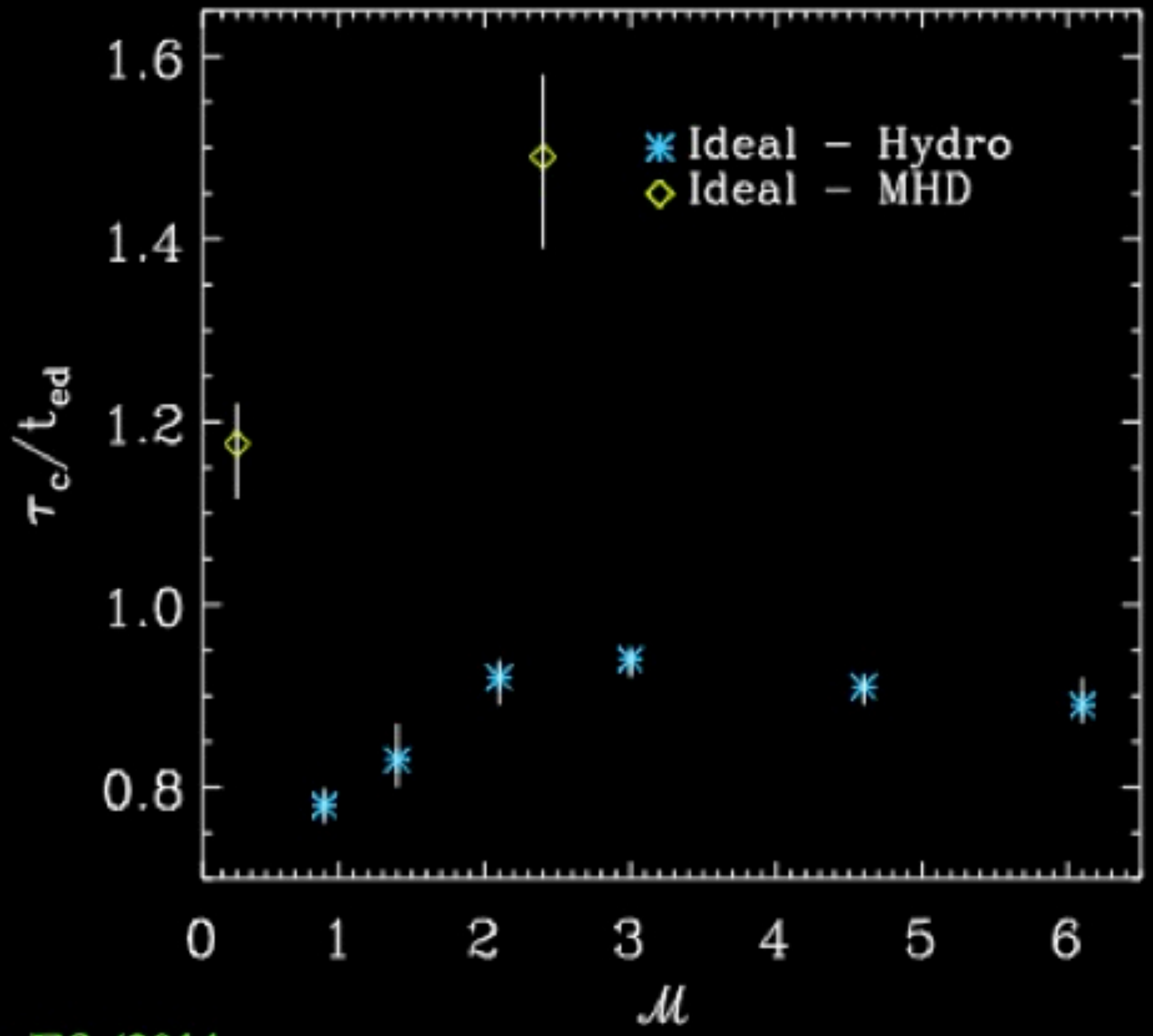


Sur, Pan, & ES (2014)

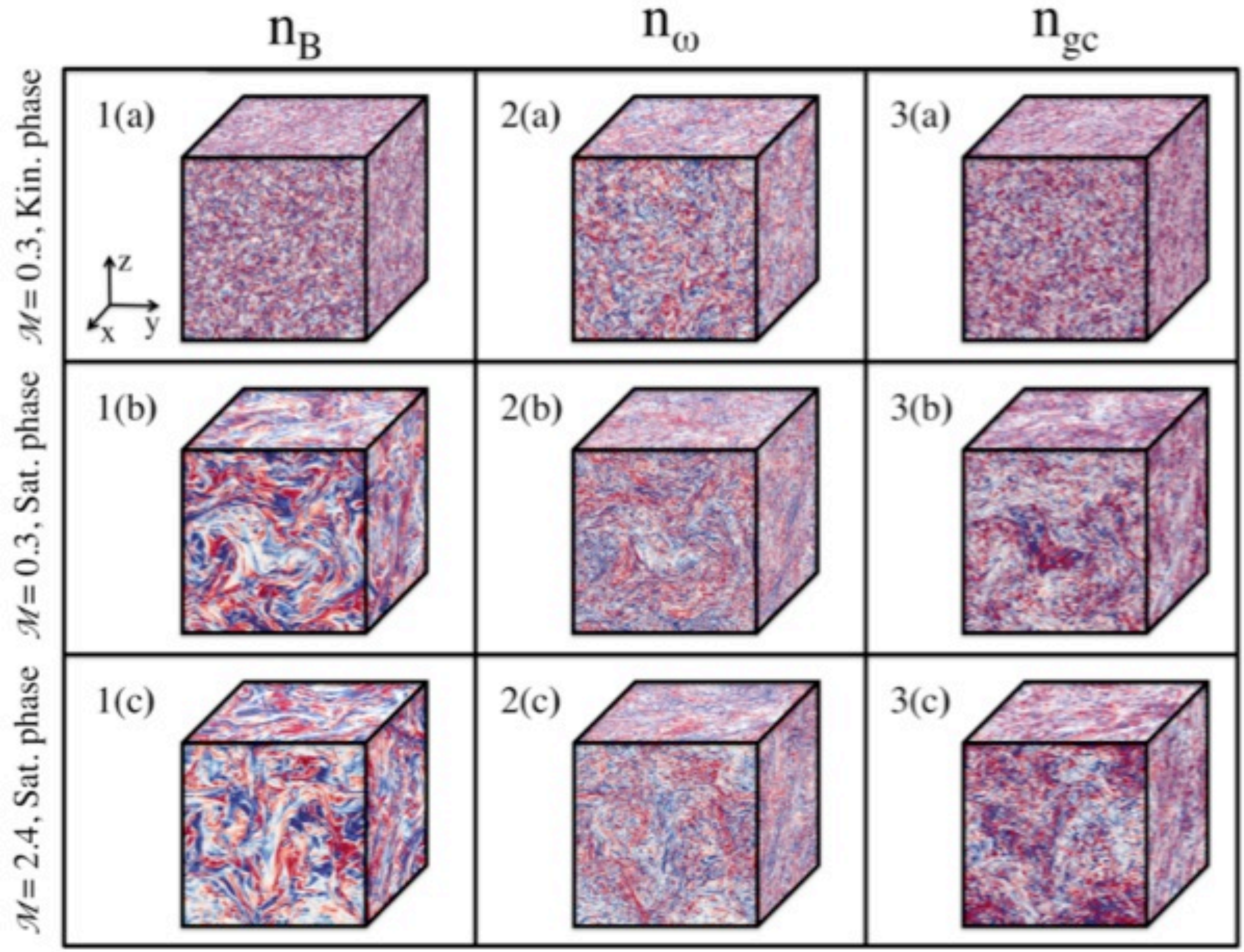


Sur, Pan, & ES (2014)

Mixing Timescales

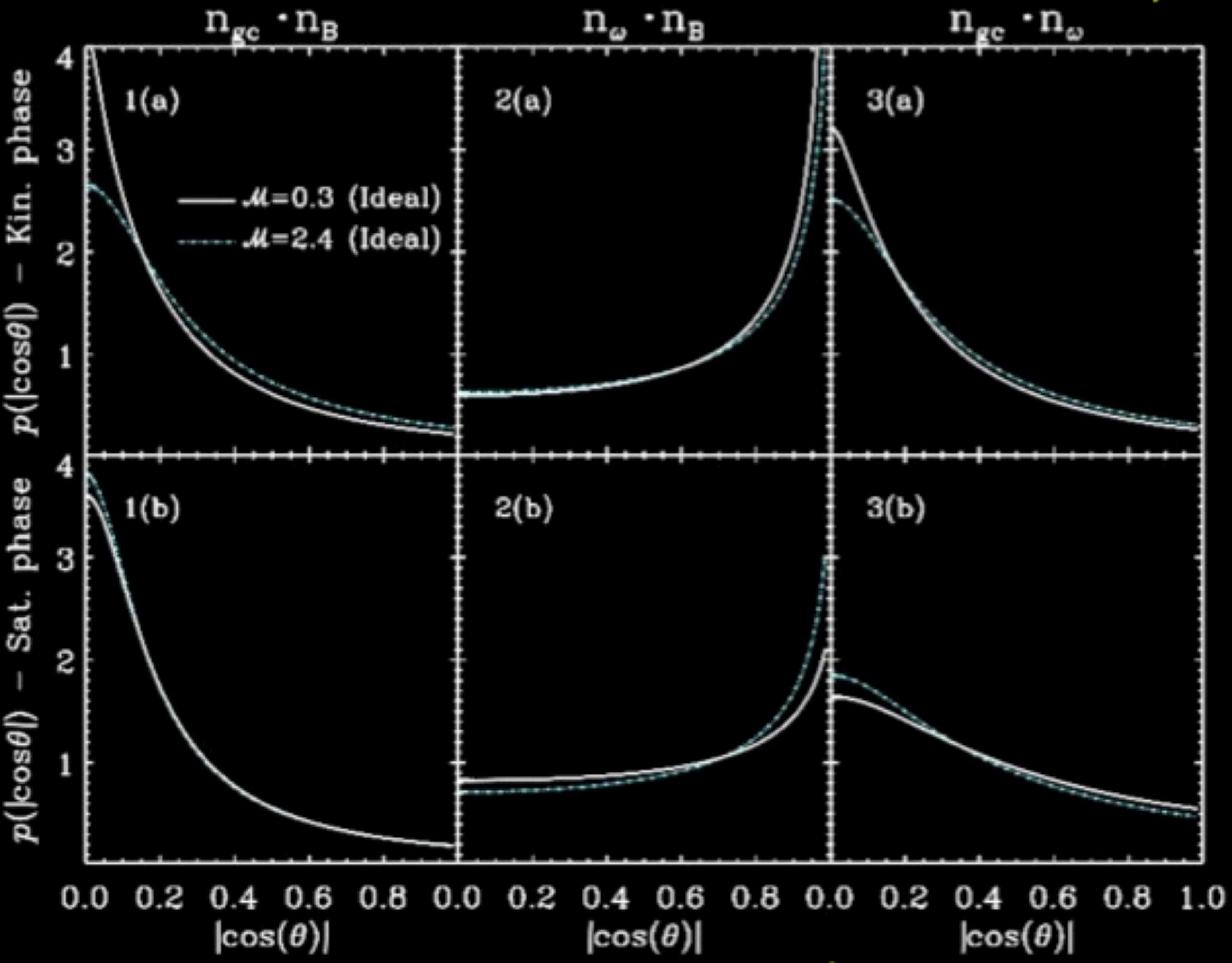


Sur, Pan, & ES (2014)



Sur, Pan, & ES (2014)

∇C & B-field   Vorticity & B-field   ∇C & Vorticity

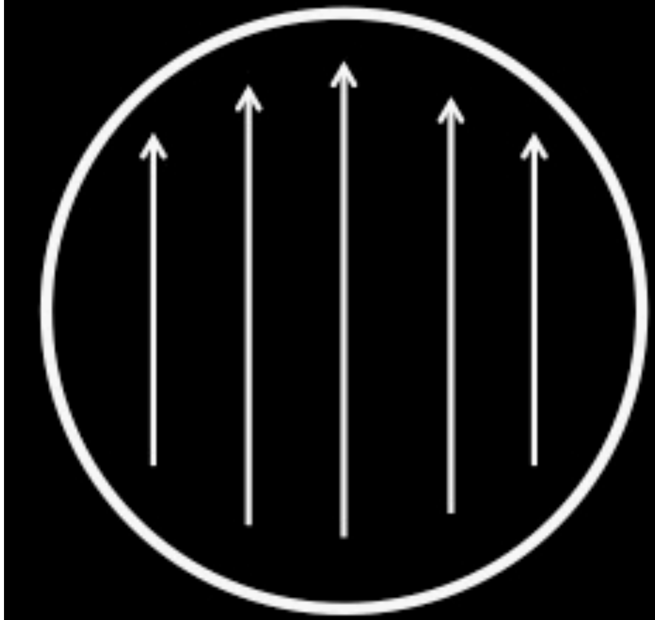


More Aligned

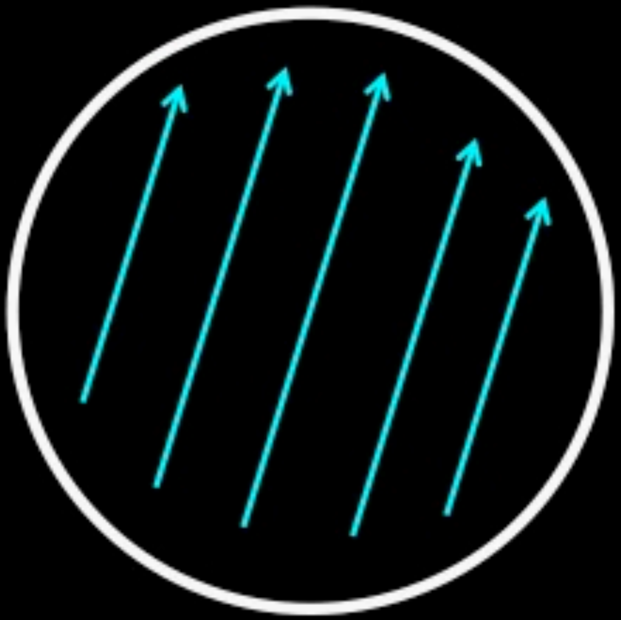
Sur, Pan, & ES (2014)

Impact of Turbulence

Vorticity

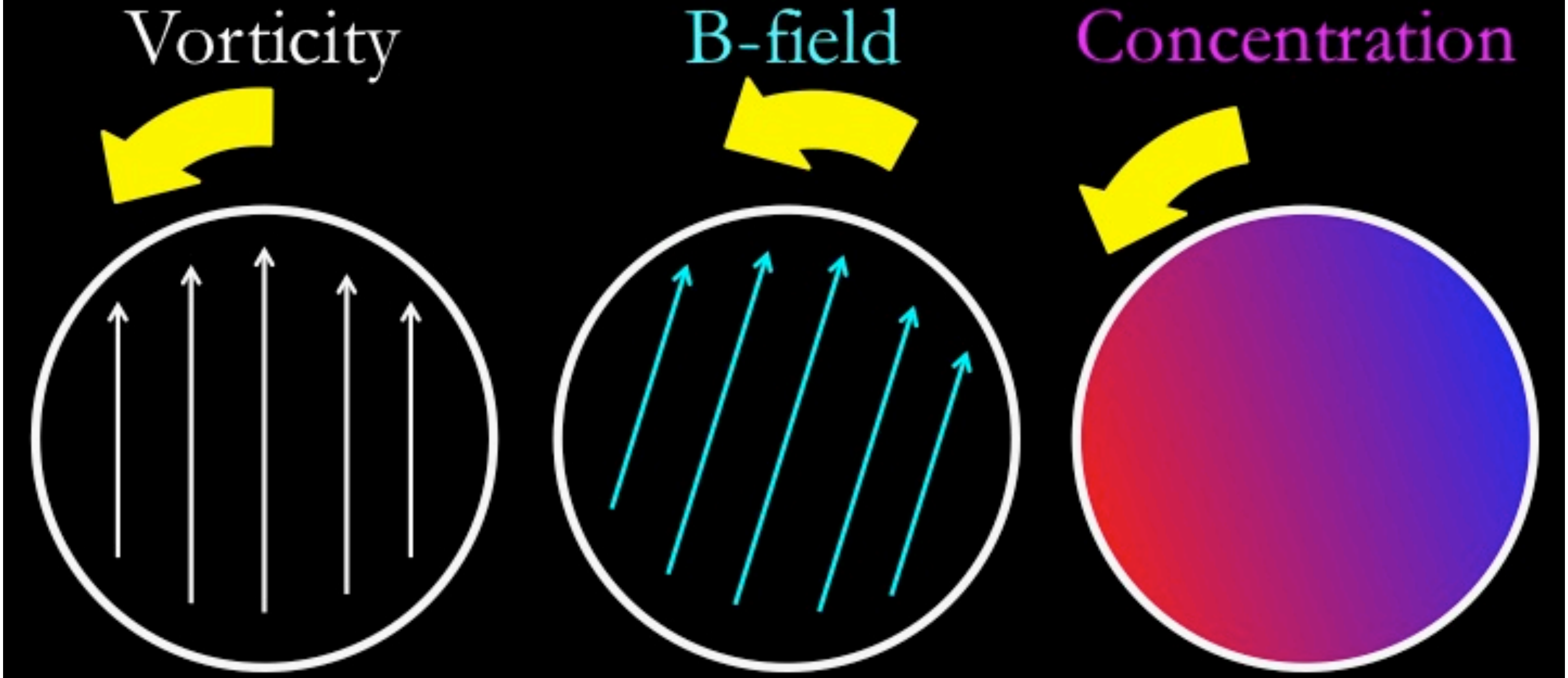


B-field

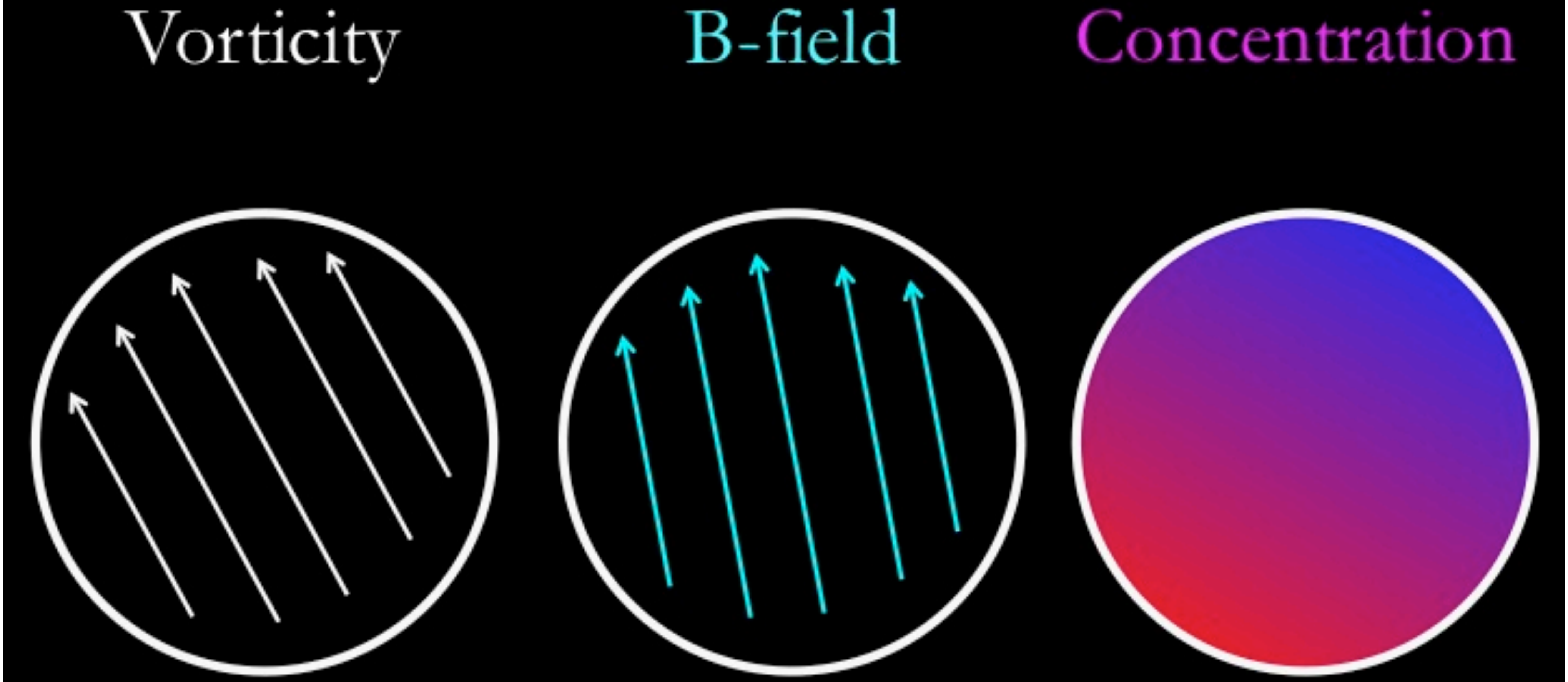


Concentration

Rotation

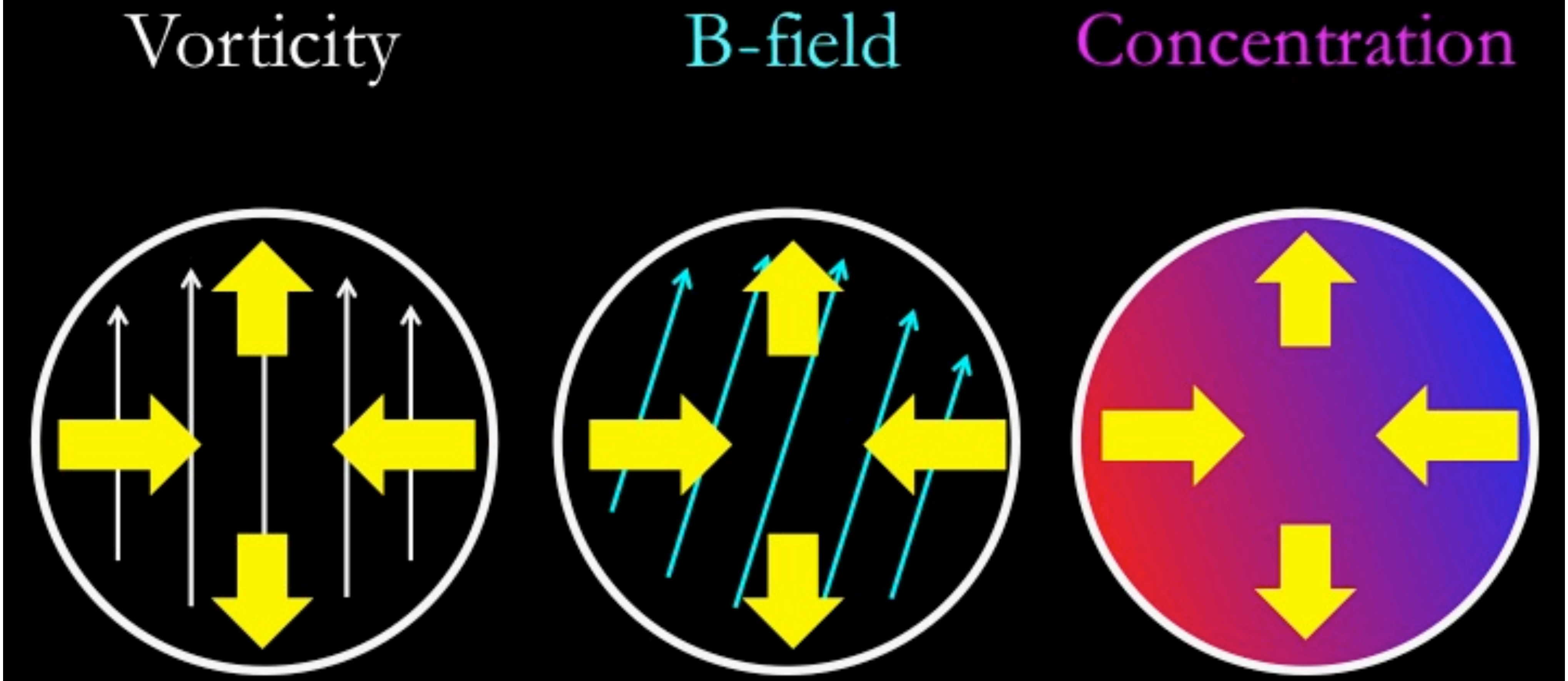


Rotation



Fields Strengths unchanged

Strain



Vorticity

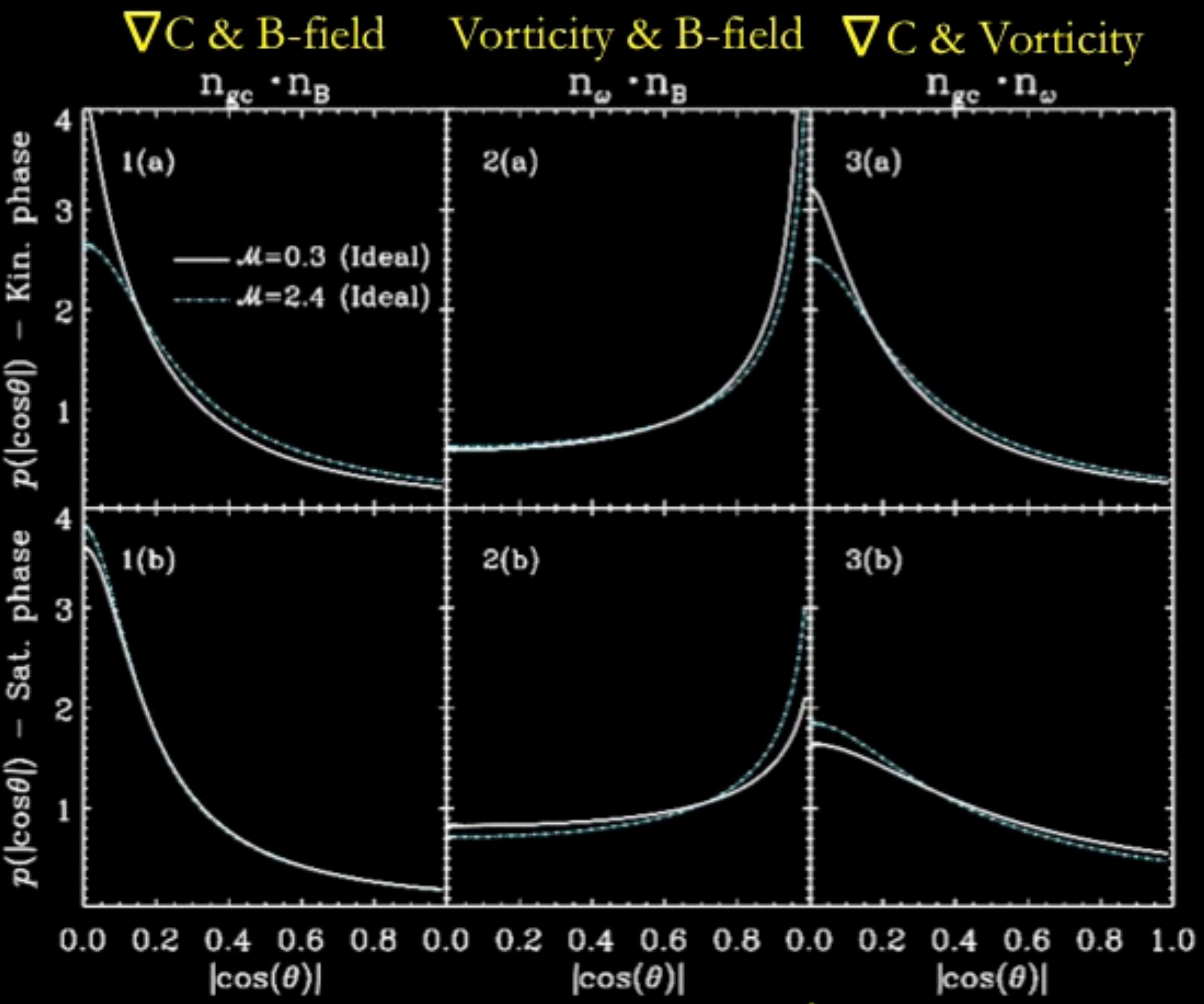
B-field

Concentration

Strain

Vorticity B-field Concentration

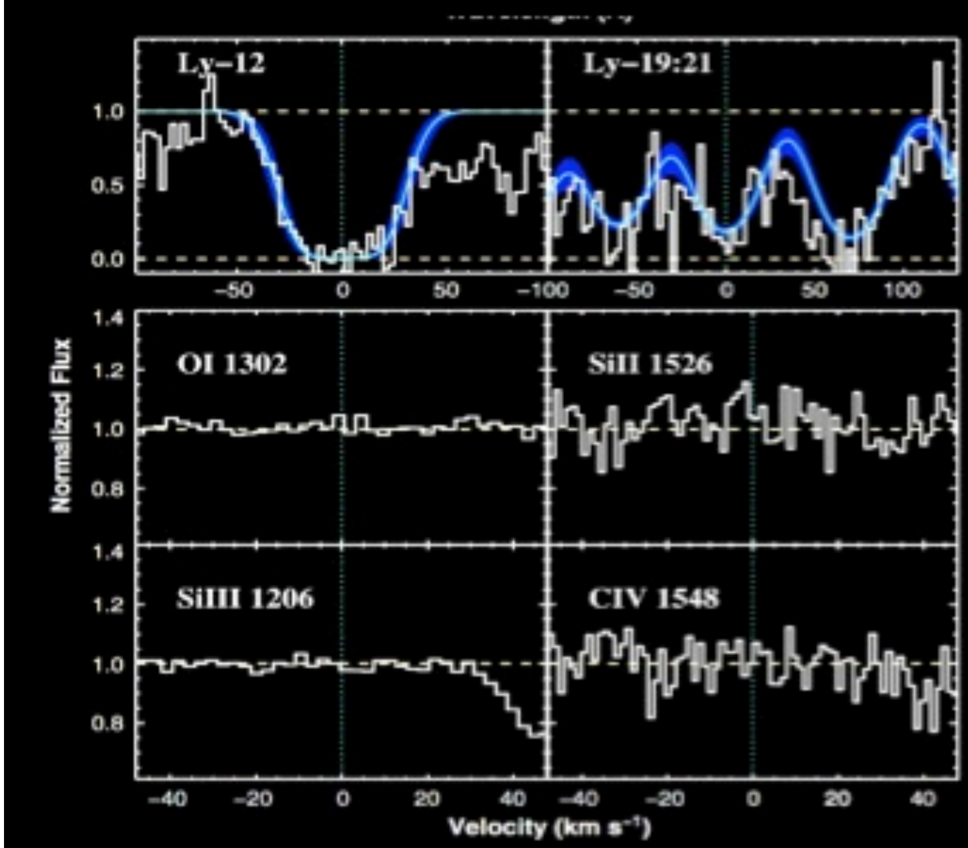
Grows ⇕ Grows ⇕ ∇Grows ⇔

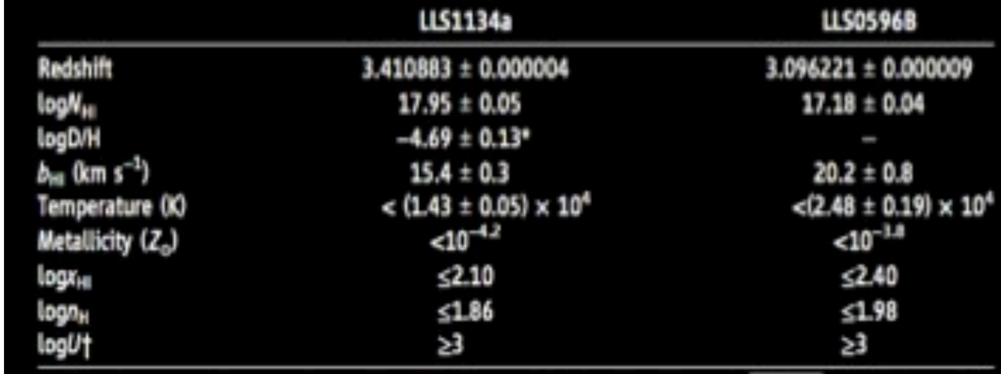


More Aligned

Sur, Pan, & ES (2014)

Evolution of the Metal Free Fraction





	LLS1134a	LLS0596B
Redshift	3.410883 ± 0.000004	3.096221 ± 0.000009
$\log N_{HI}$	17.95 ± 0.05	17.18 ± 0.04
logD/H	−4.69 ± 0.13*	–
b_{HI} (km s^{-1})	15.4 ± 0.3	20.2 ± 0.8
Temperature (K)	$< (1.43 \pm 0.05) \times 10^4$	$<(2.48 \pm 0.19) \times 10^4$
Metallicity ($Z_\odot$)	$<10^{-4.2}$	$<10^{-3.8}$
$\log x_{HI}$	≤2.10	≤2.40
$\log n_H$	≤1.86	≤1.98
logU†	≥3	≥3

Fumagalli et al (2011) see also Simcoe (2012)

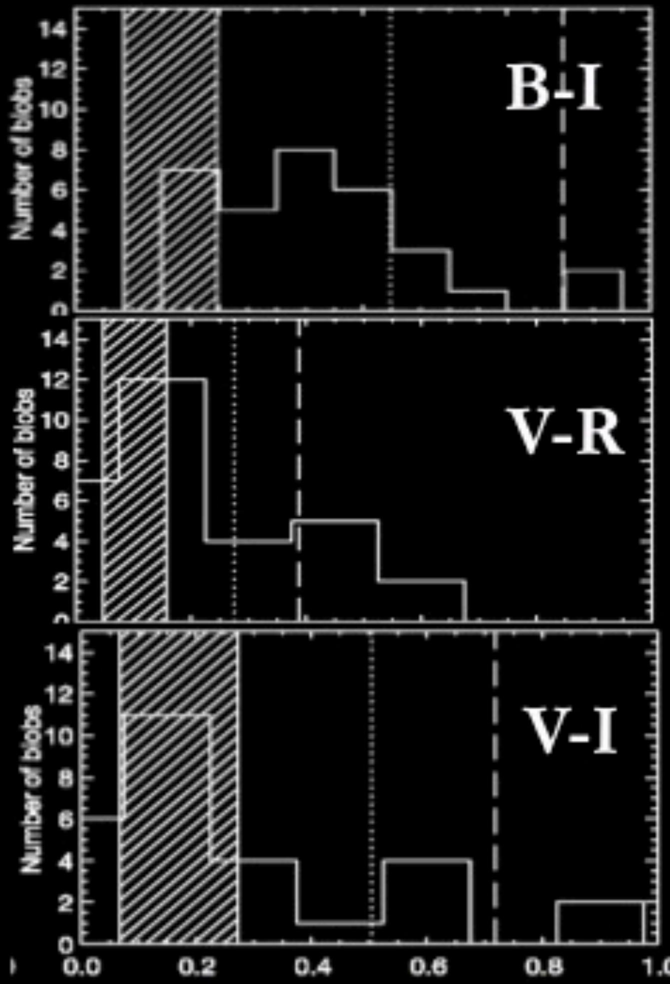


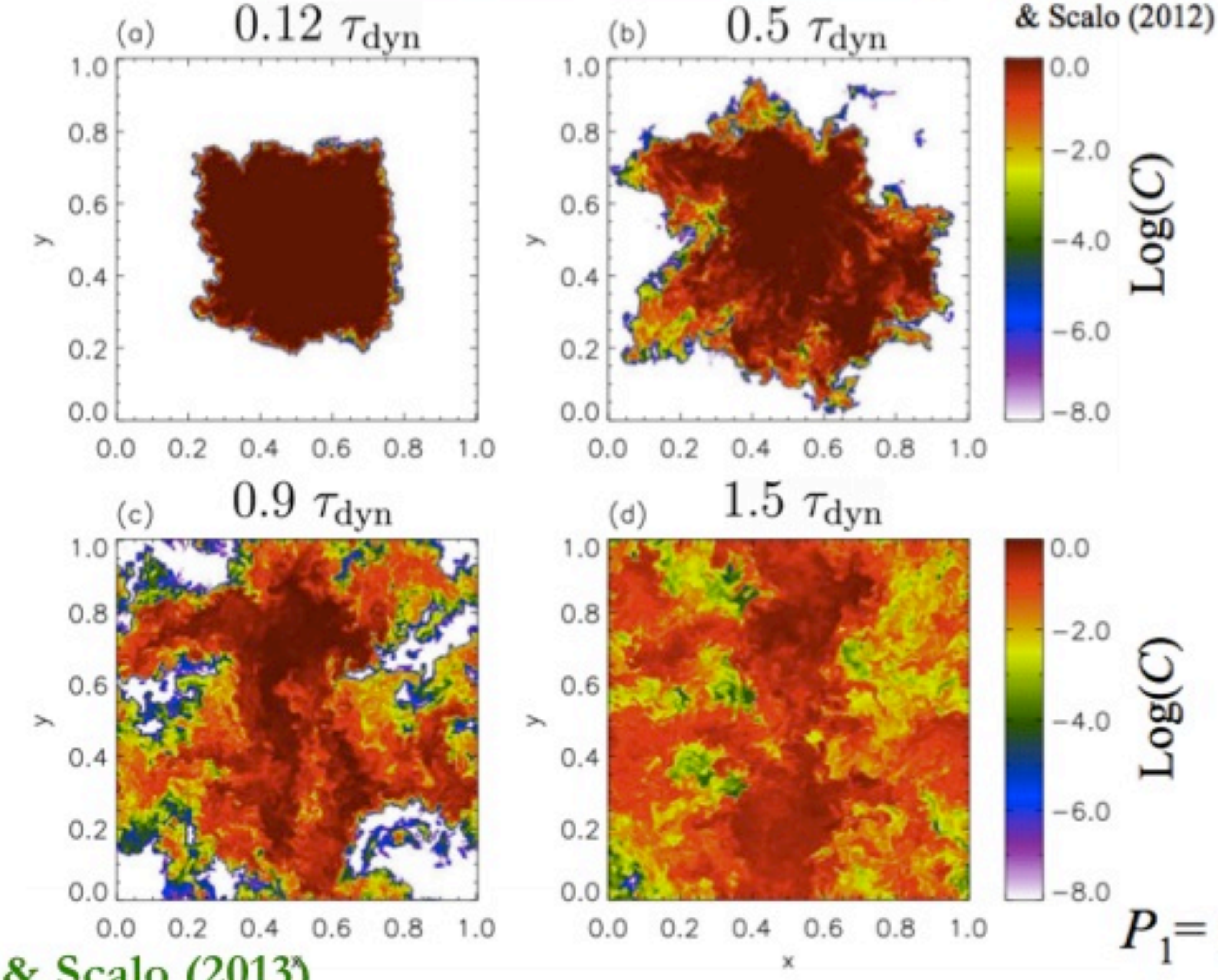
Figure 2 The shaded ranges indicate the range of expected colours as various properties of the metal-free population are varied, such as their age (between 10^5–10^8 yr), the IMF (for the three models given in ref. 17), and star-formation history (between a burst and continuous star formation at a constant rate). All three colour histograms suggest that about 20% of the blobs need to be made of purely population III stars.

Haiman & Jimenez (2006)

Evolution of Primordial Gas in Supersonic Turbulence

Simulation Results: $M = 0.9$

LP., Scannapieco & Scalo (2012)

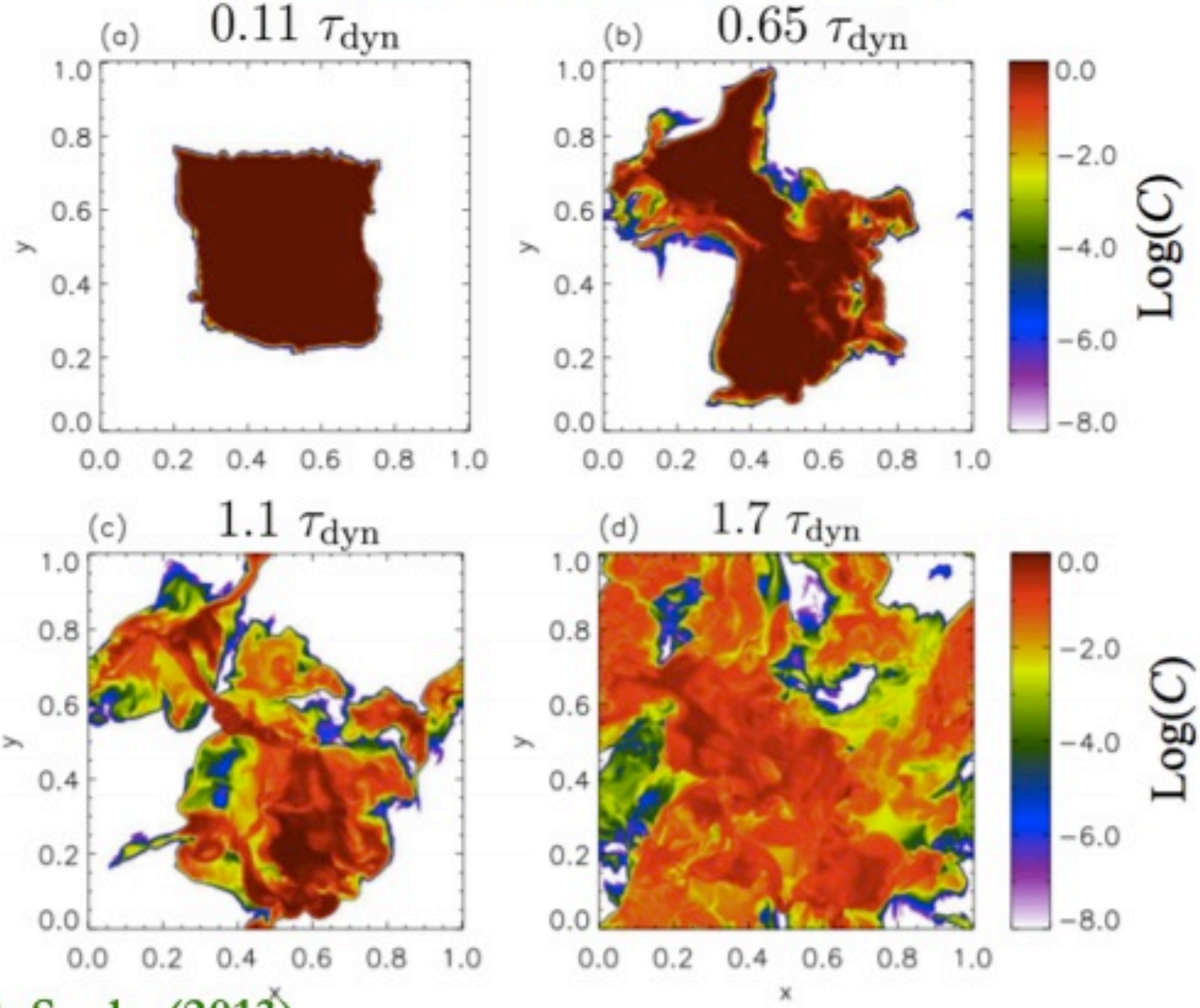


$P_1 = 0.1$

Pan, ES, & Scalo (2013)

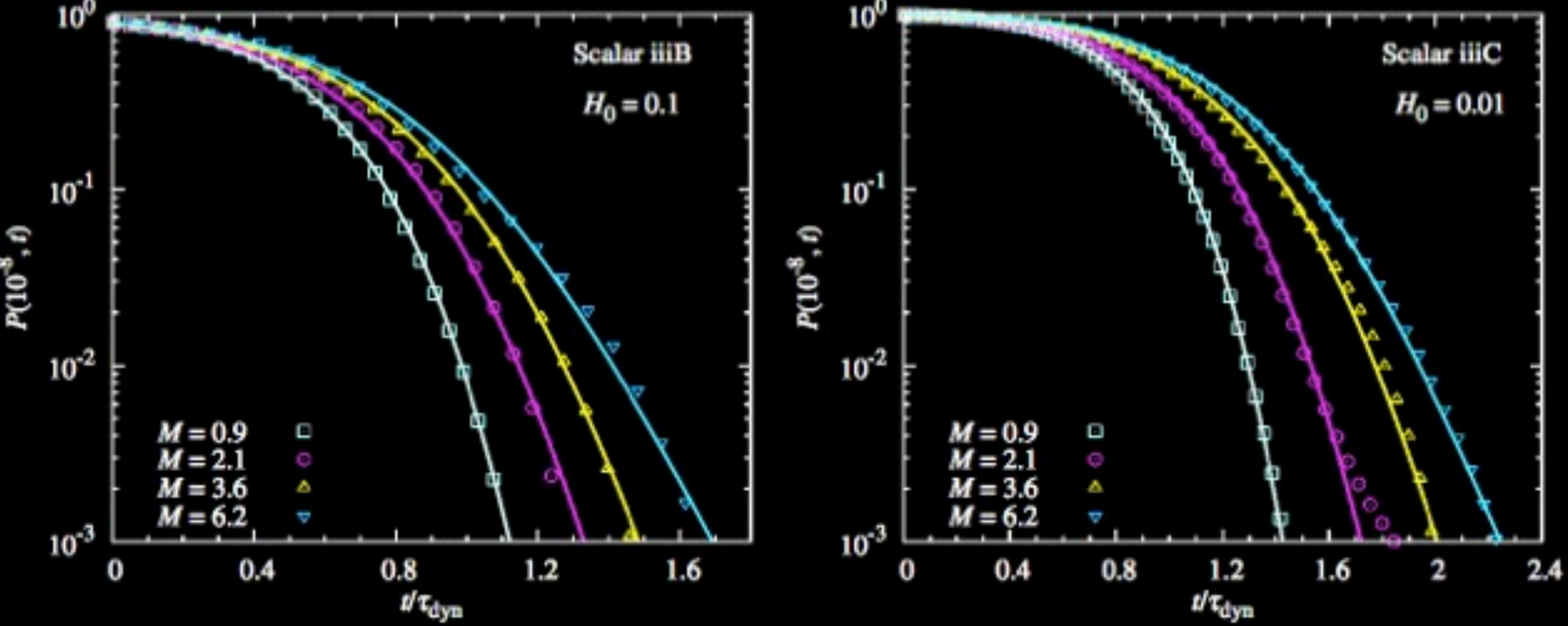
Evolution of Primordial Gas in Supersonic Turbulence

Simulation Results: $M = 6.2$



Pan, ES, & Scalo (2013)

Evolution of Primordial Gas in Supersonic Turbulence



Results are extremely well fit by a "convolution" model in with two parameters, one a timescale, and one related to the fractal dimension of scalar structures

Pan, ES, & Scalo (2013)

Subgrid Model for Evolution Primordial Fraction

$$\frac{D(\rho P)}{Dt} = -\frac{n_{\rm s}}{\tau_{\rm scon}} P(1 - P^{1/n_{\rm s}}) - \dot{\rho}_{\rm ejecta} P$$

P - Primordial Fraction

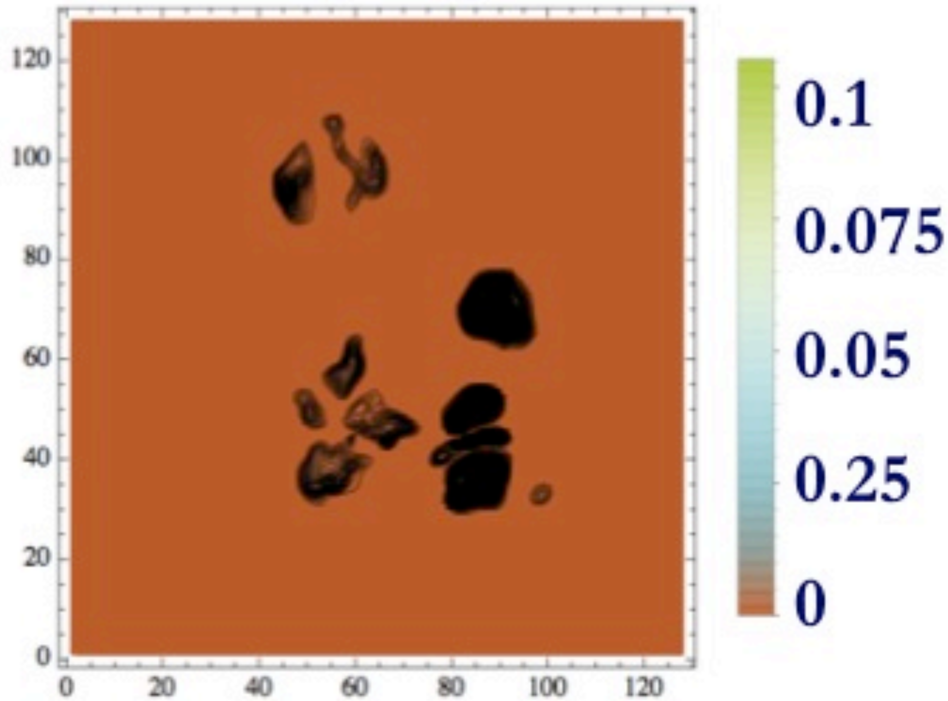
ρ – Density

$\dot{\rho}_{\rm ejecta}$ – Rate at which ejecta is being added to a cell

$n_{\rm s}$, $\tau_{\rm scon}$ – Fit functions to local turbulent Mach number and Z/Z_c provided in Pan, ES, & Scalo (2013)

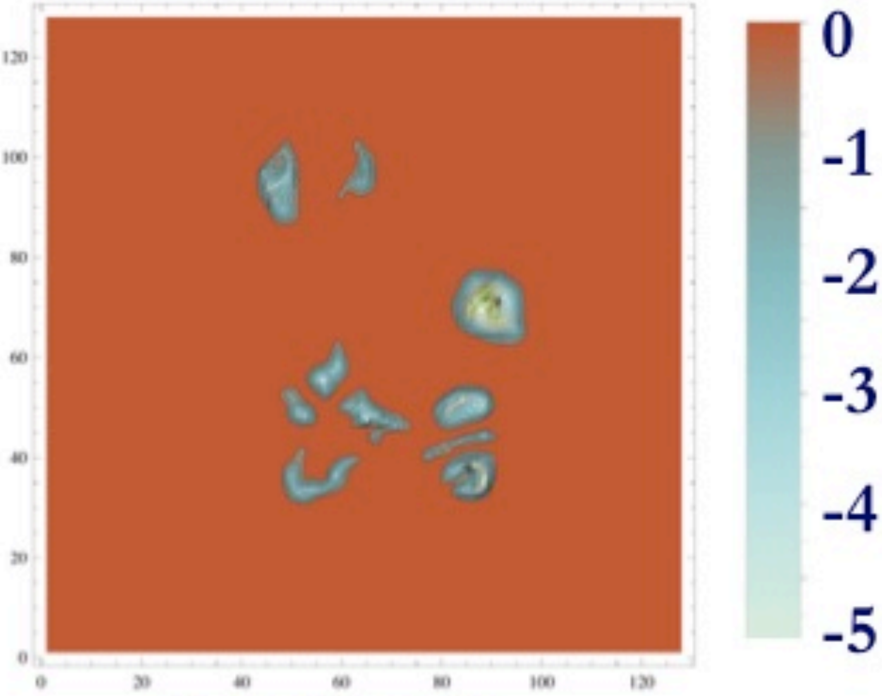
Pan, ES, & Scalo (2013)

Evolution of Primordial Fraction (Test run @ z=9)



$Z/Z_\odot$

0.3 cMpc/h



Log P

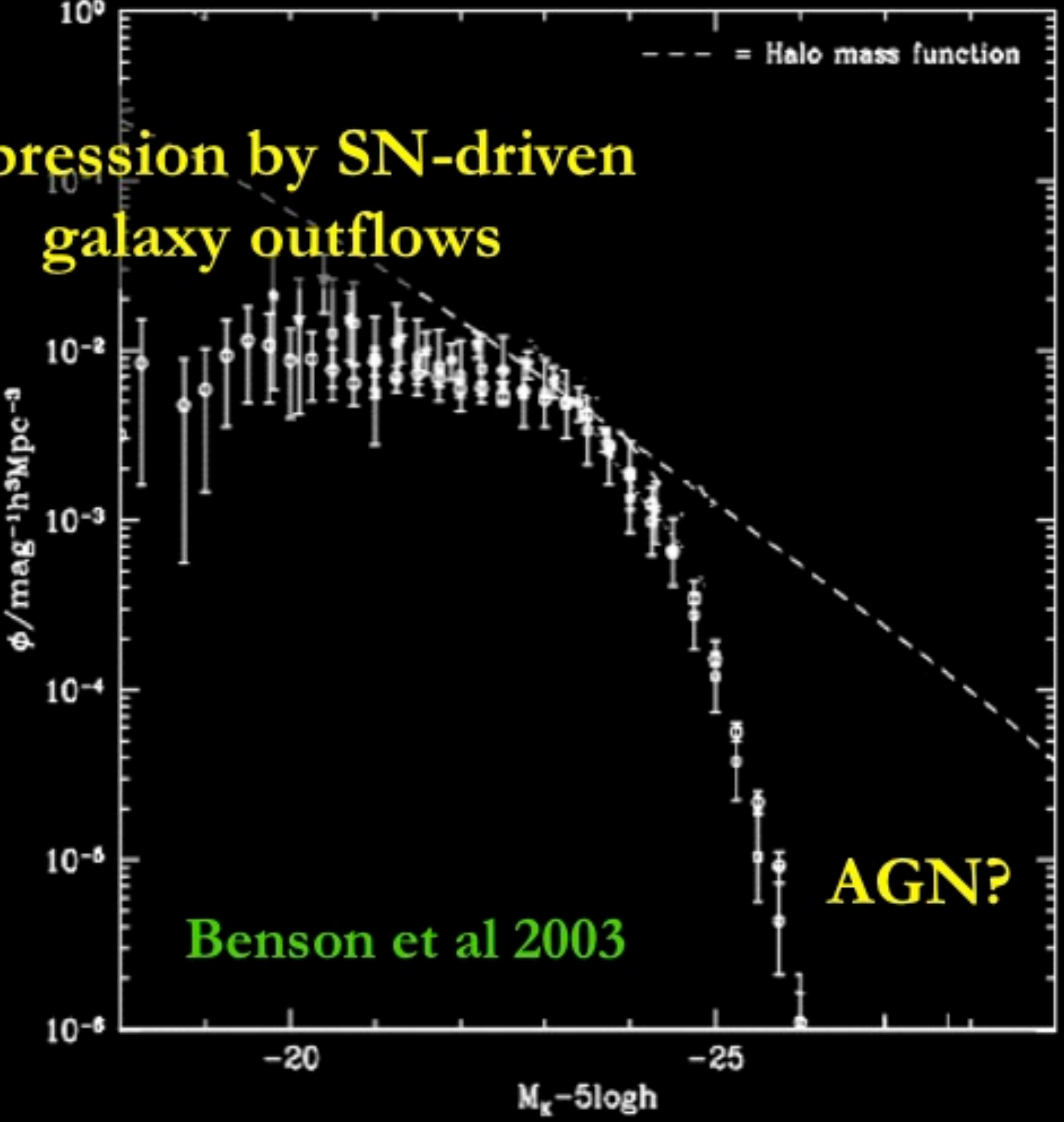
0.3 cMpc/h

We are implementing this now into the RAMSES code,
looking to set up examples of high-redshift galaxies
Happy to work on further applications of this with anyone.

with R. Sarmento, ES

IV. Constraining AGN Outflows

ES et al.



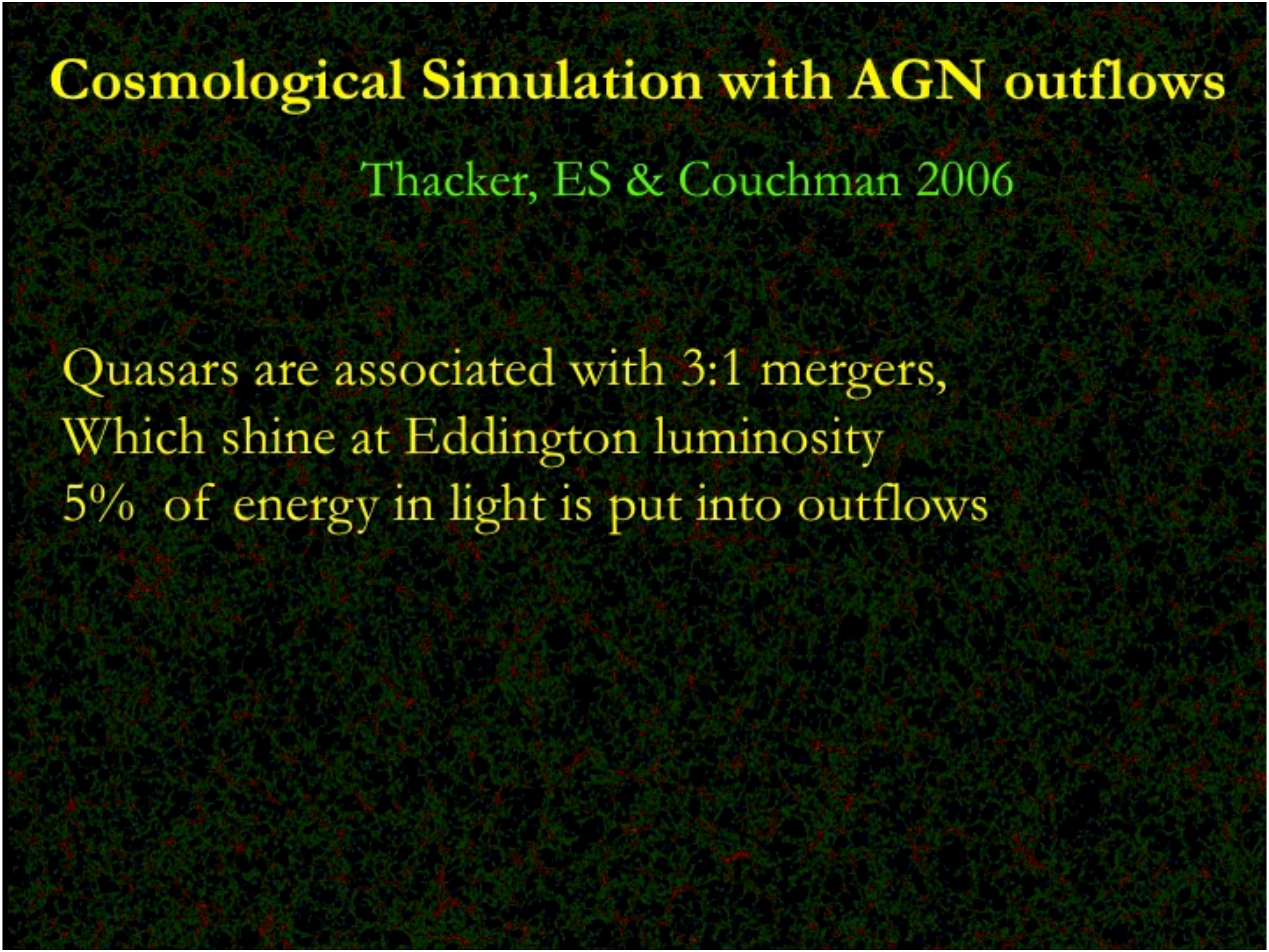
Supression by SN-driven galaxy outflows

AGN?

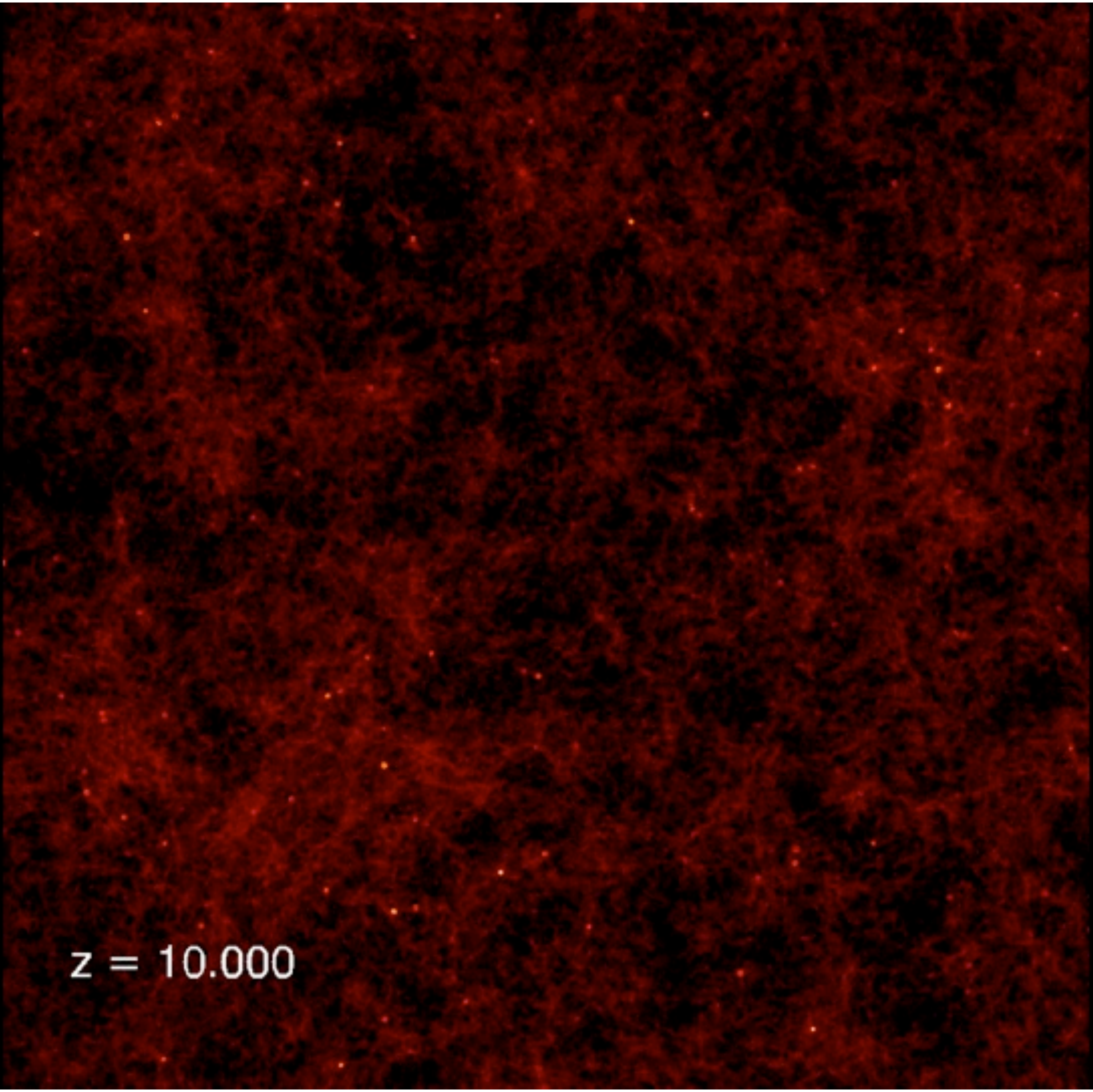
Benson et al 2003

Cosmological Simulation with AGN outflows

Thacker, ES & Couchman 2006

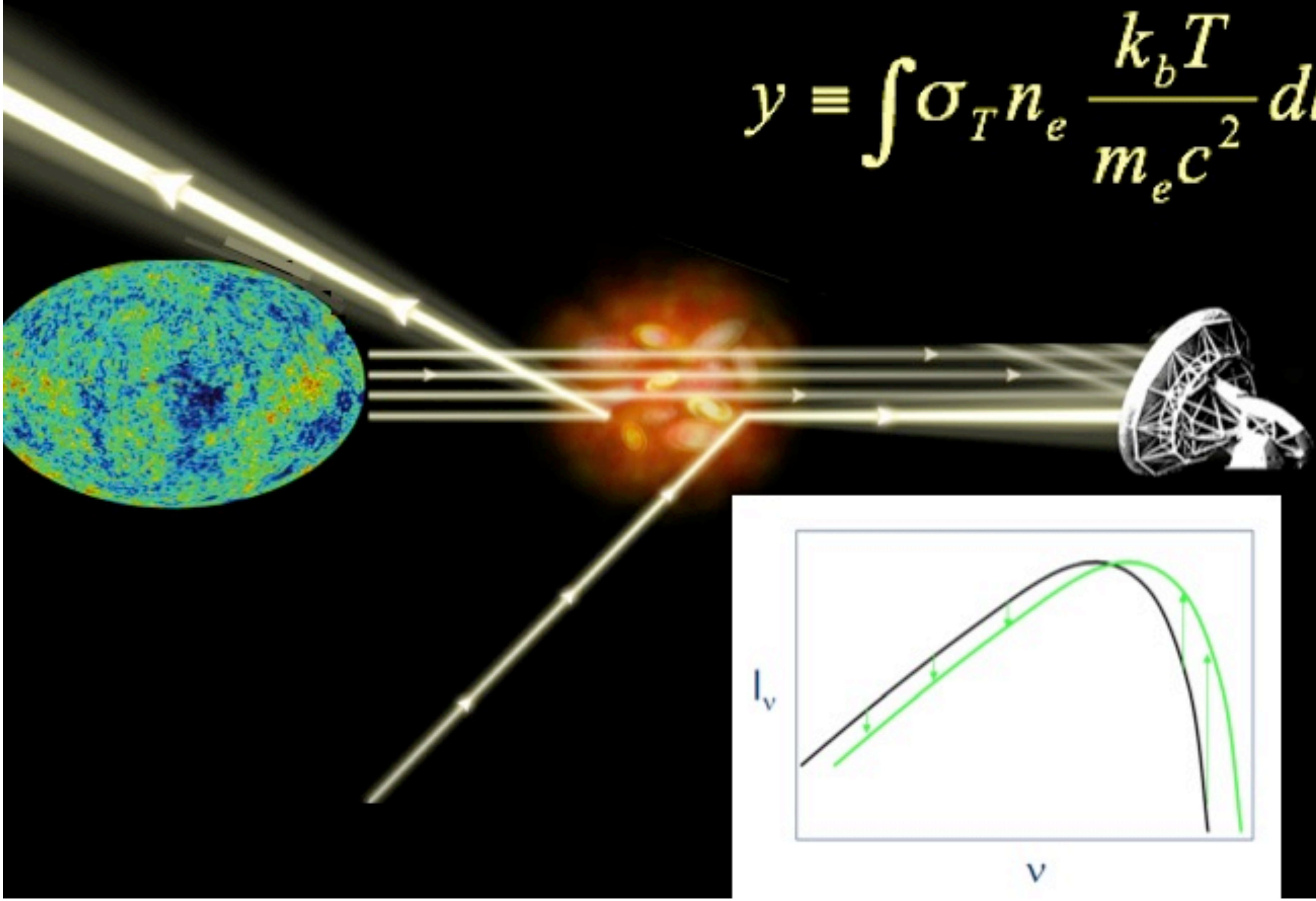


Quasars are associated with 3:1 mergers,
Which shine at Eddington luminosity
5% of energy in light is put into outflows

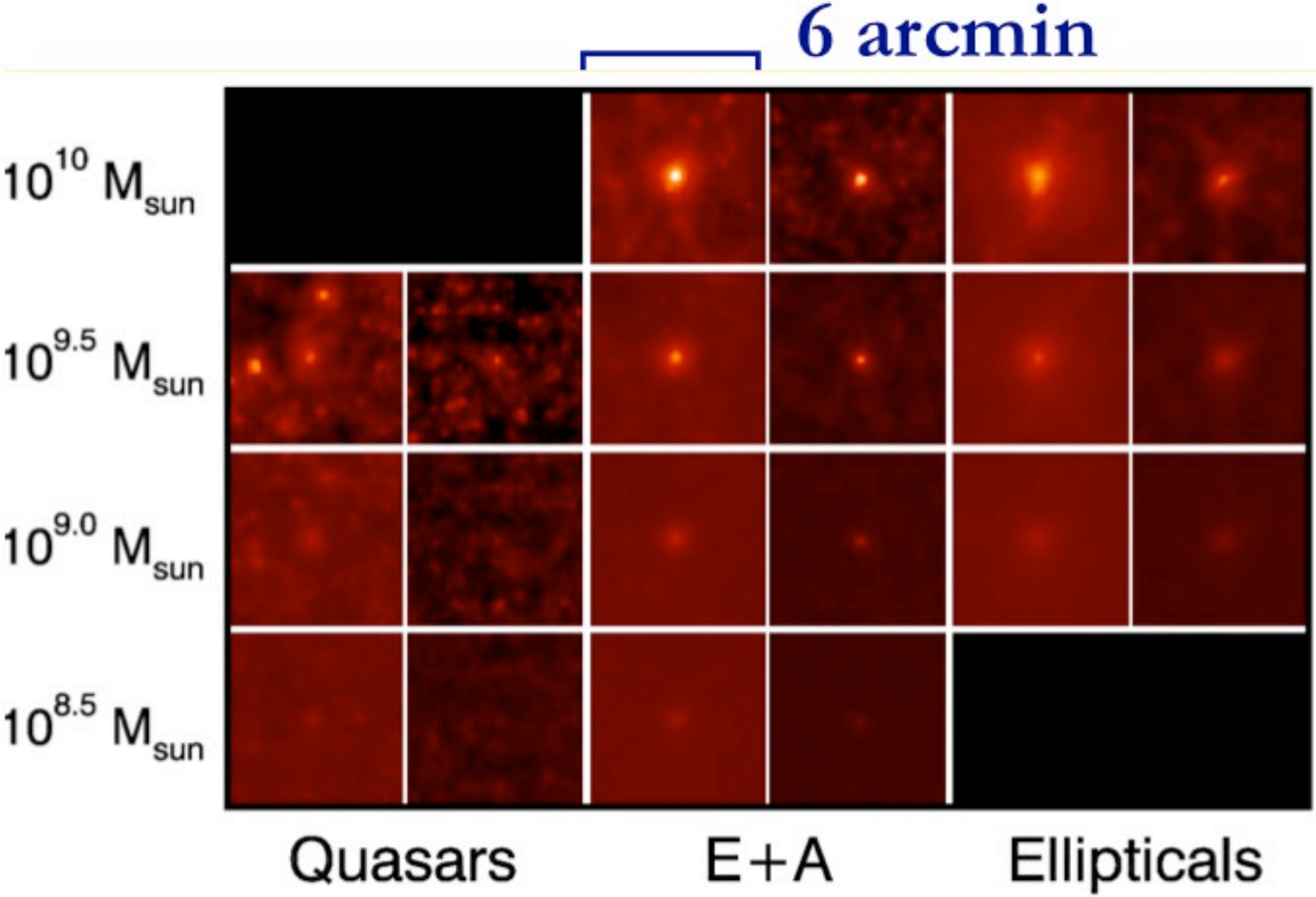

z = 10.000

Sunyaev Zel'dovich Effect

$$y \equiv \int \sigma_T n_e \frac{k_b T}{m_e c^2} dl$$



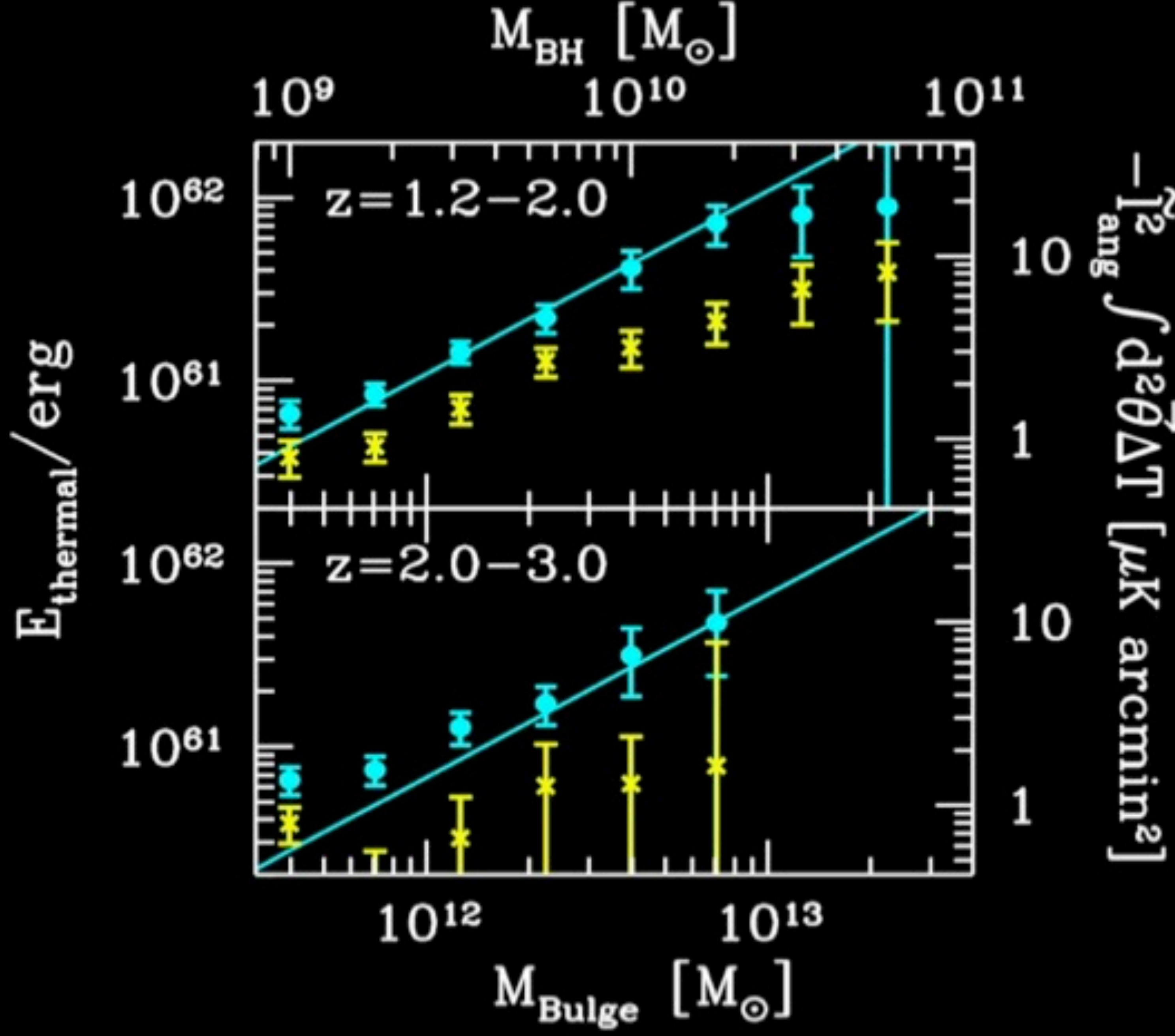
Cross-Correlations



Signal is Proportional to Energy

$$\int d\vec{\theta} y(\vec{\theta}) = \frac{\sigma_T}{m_e c^2} \frac{1}{l_{\rm ang}^2} \int dV n_e(V) k [T_e(V) - T_{\rm CMB}]$$

$$E_{\rm thermal} = -4.8 \times 10^{60}\,{\rm ergs}\ \ \tilde{l}_{\rm ang}^2 \frac{\int d\vec{\theta} \Delta T(\vec{\theta})}{\mu K\,{\rm arcmin}^2}$$

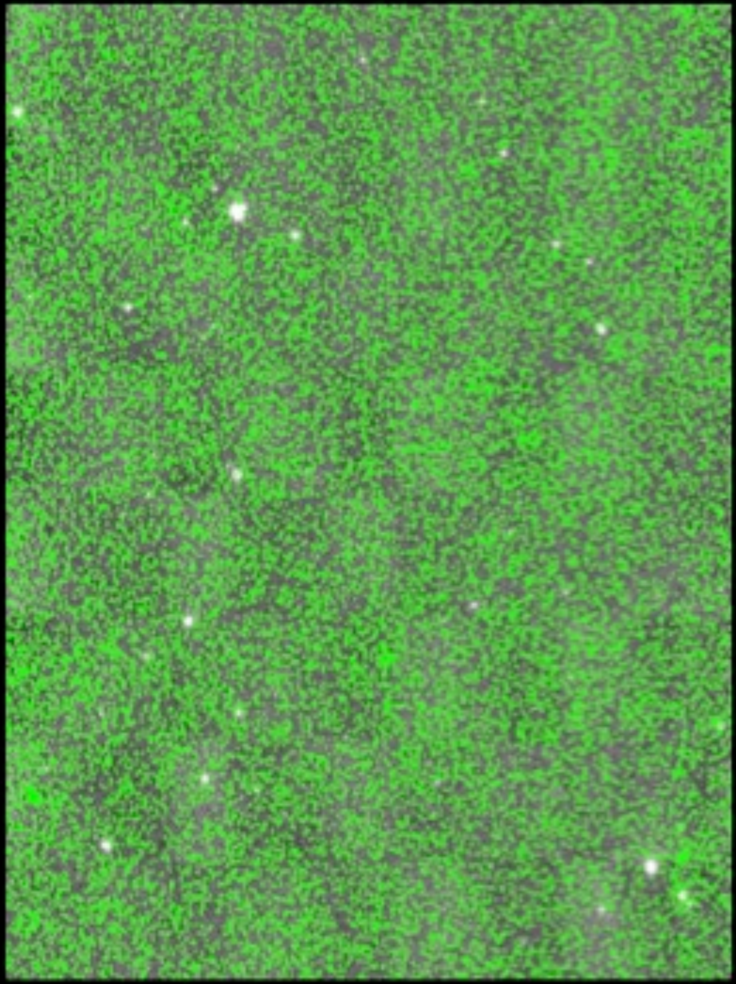


M_{BH} [$M_\odot$]
10^9
10^{10}
10^{11}
z=1.2−2.0
z=2.0−3.0
10^{62}
10^{61}
10^{62}
10^{61}
$E_{thermal}$/erg
10
1
10
1
$-\tilde{l}^2_{ang}\int d^2\vec{\theta}\Delta T$ [μK arcmin^2]
10^{12}
10^{13}
M_{Bulge} [$M_\odot$]

VISTA Hemisphere Survey

5-σ AB mag. limits:

$J = 21.5$, $H = 21.2$, $K = 20.4$

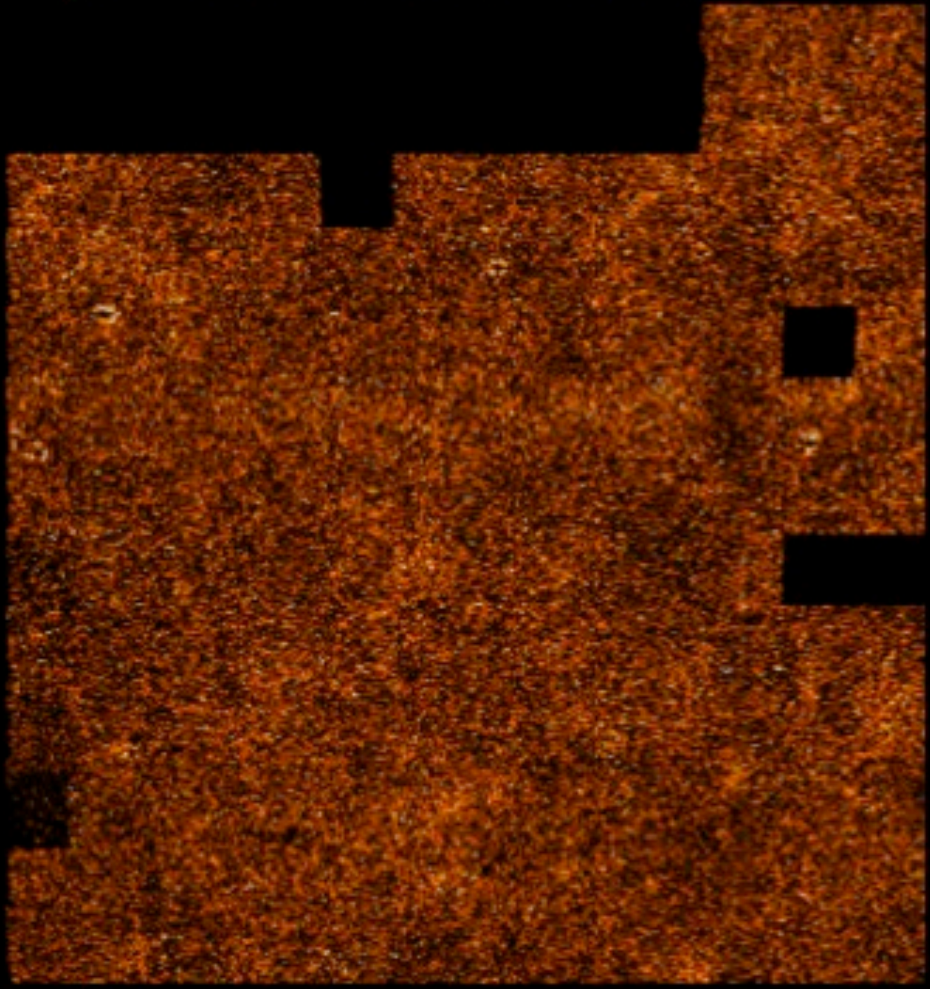


1.89°×1.43°

Blanco Cosmology Survey

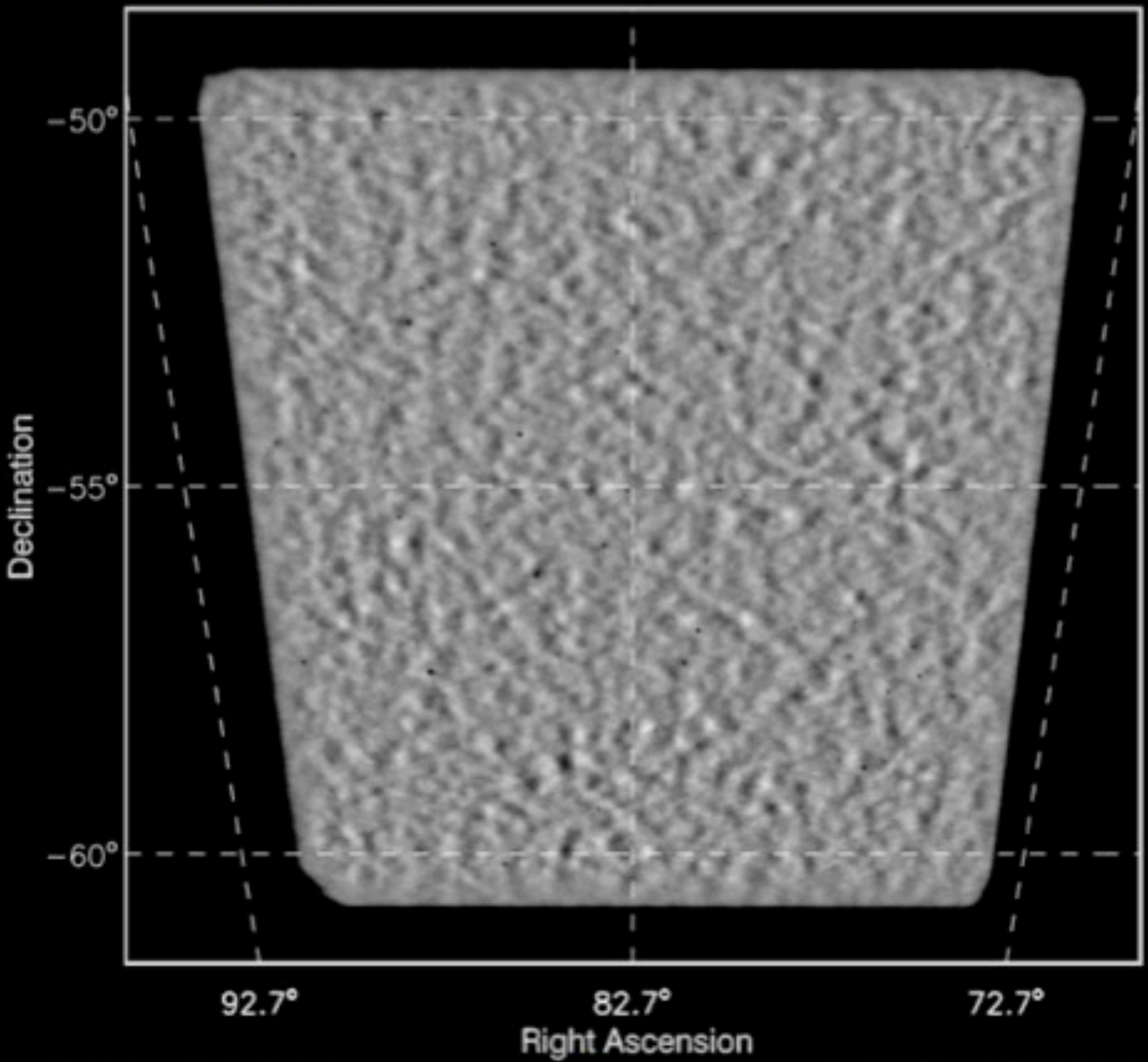
5-σ AB mag limits:

g=23.3, r=23.4, i=23.0, z=21.3



RA: 76° to 89°, dec -49° to -56°

95 deg^2 public *SPT* data



17 μK arcmin at 150 GHz

THANKS!

ES et al.