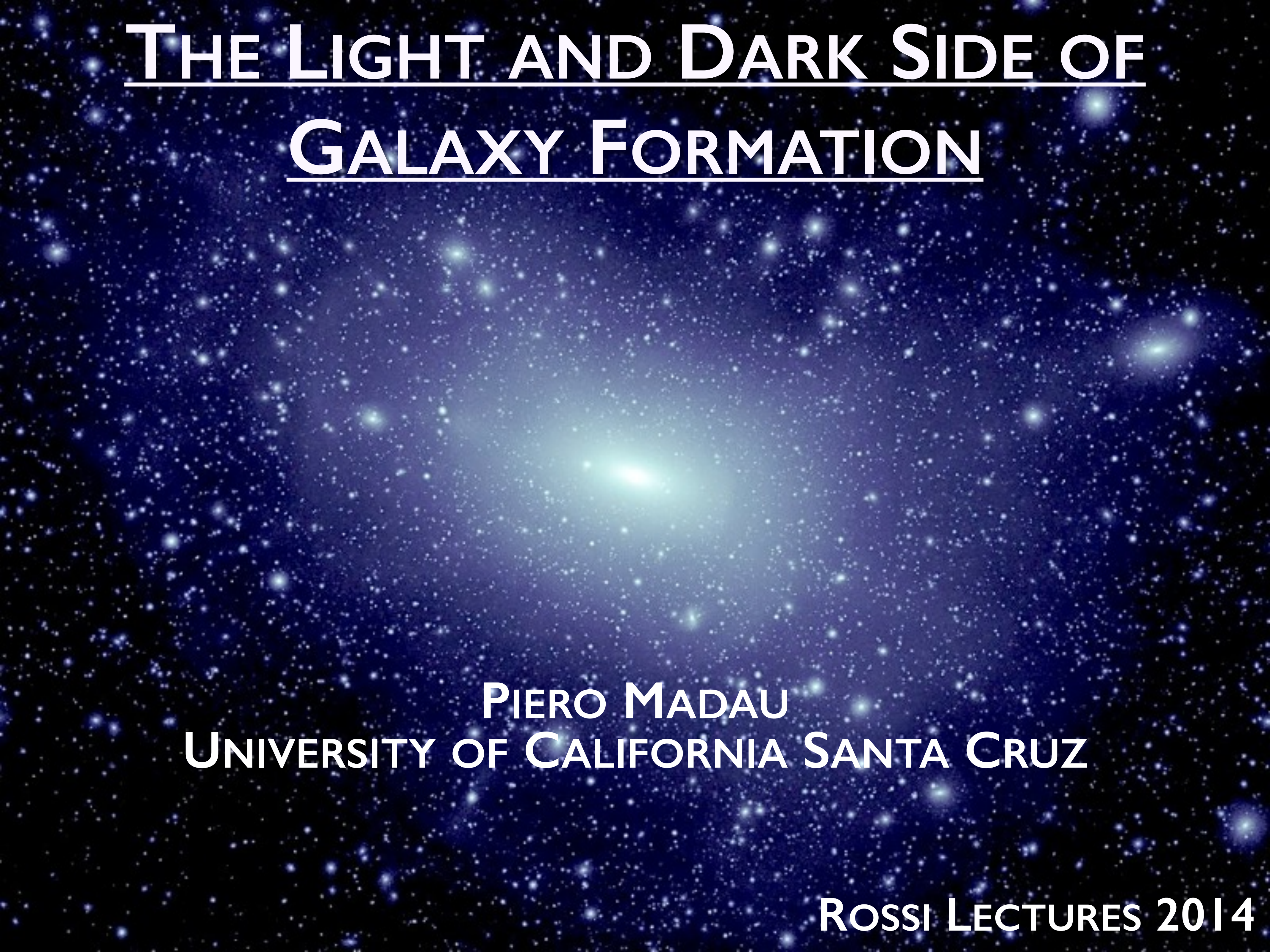
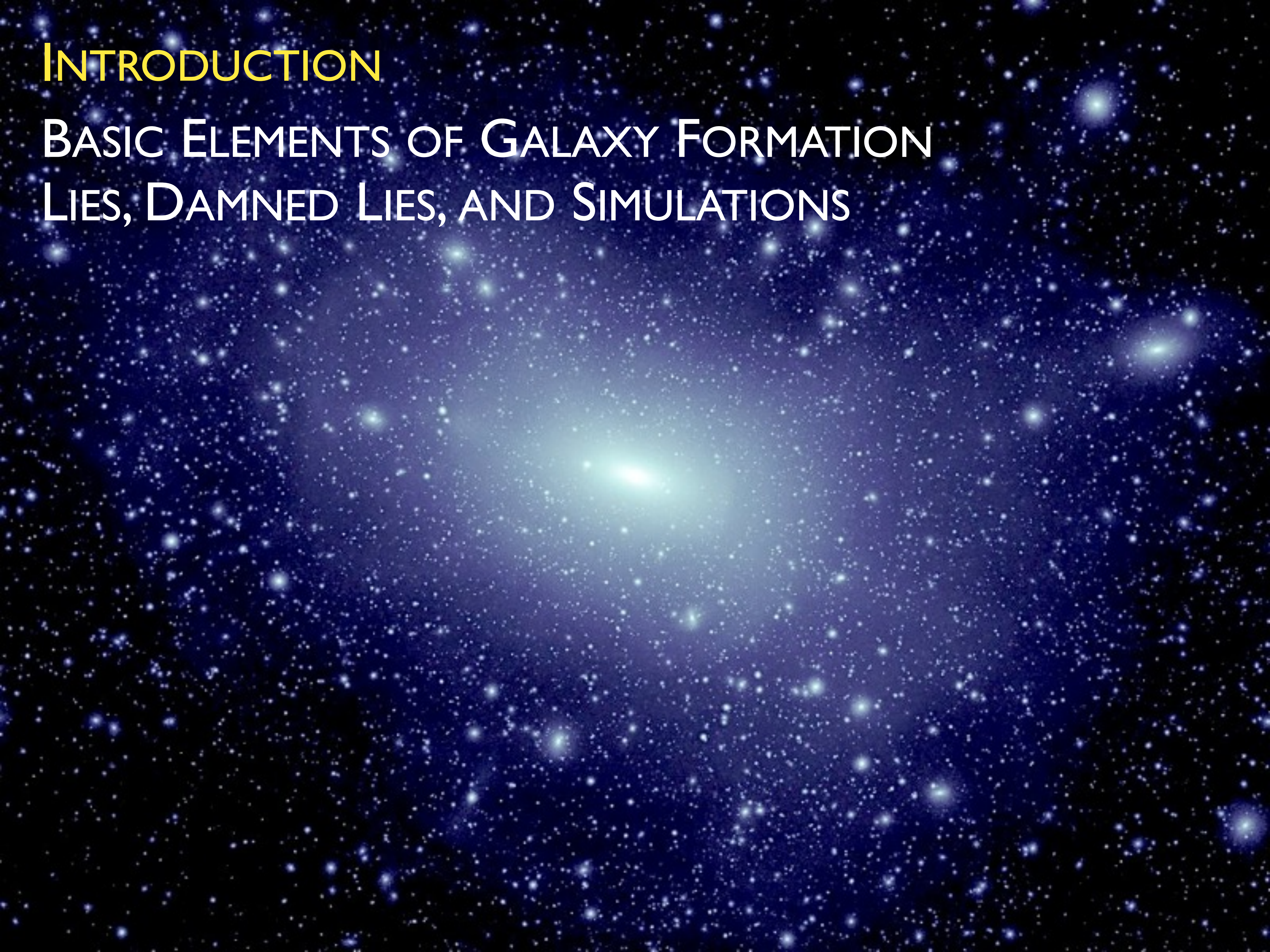

THE LIGHT AND DARK SIDE OF GALAXY FORMATION
PIERO MADAU
UNIVERSITY OF CALIFORNIA SANTA CRUZ
ROSSI LECTURES 2014

Introduction

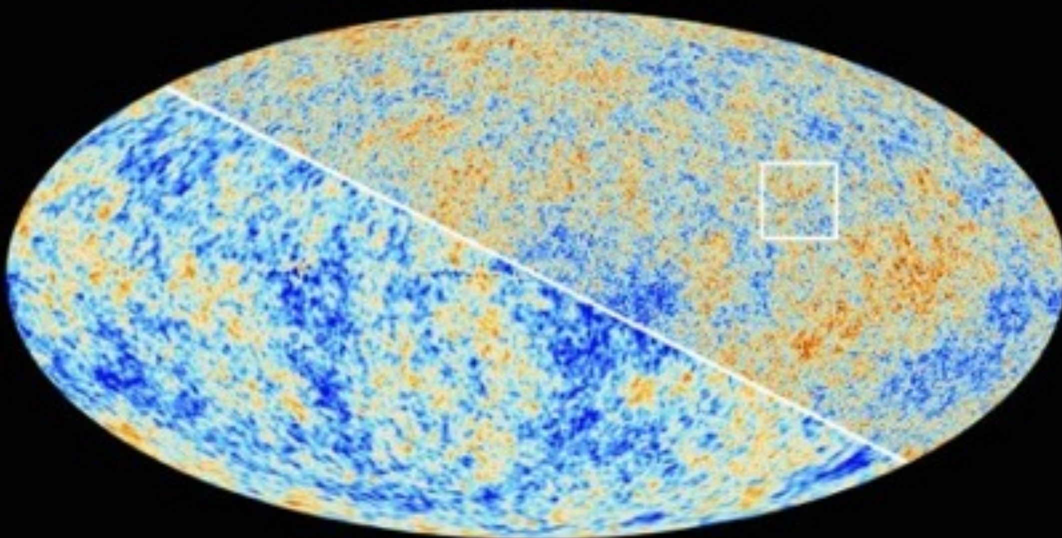
Basic Elements of Galaxy Formation

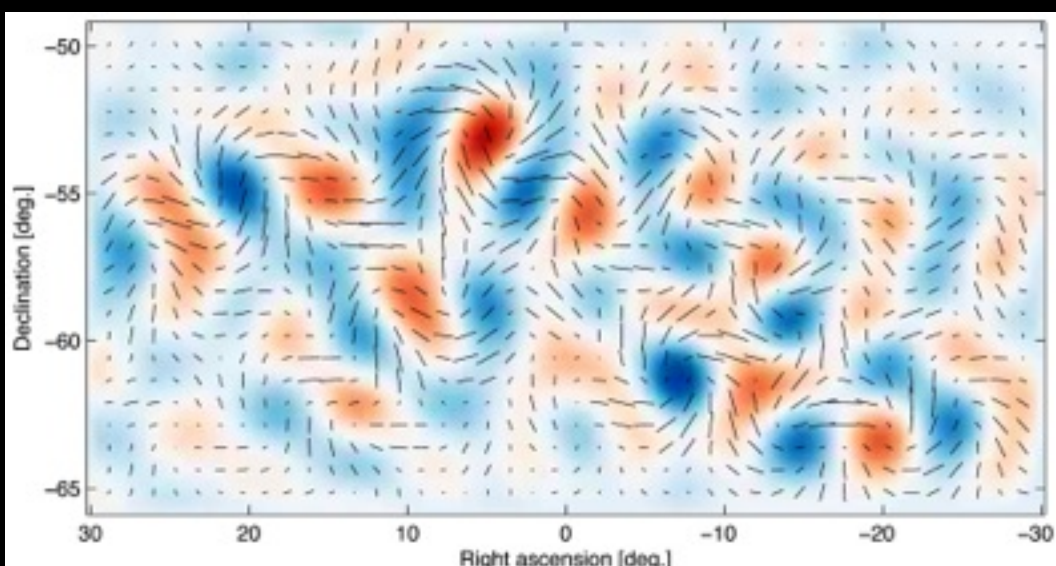
Lies, Damned Lies, and Simulations



Physics of the Early Universe

The Cosmic Microwave Background as seen by Planck and WMAP





$$A_{\mathrm{GW}} \propto H \propto E_{\mathrm{inf}}^2 \sim (10^{16}\,\mathrm{GeV})^2$$

Just Six numbers (ΛCDM)

$$\left.\begin{aligned}\Omega_\Lambda &= 0.681 \\ \Omega_b &= 0.049\end{aligned}\right\} \quad \Omega_{\mathrm{CDM}} = 0.27$$

$$H_0 = 67\,\mathrm{km/s/Mpc}$$

$$\sigma_8 = 0.835$$

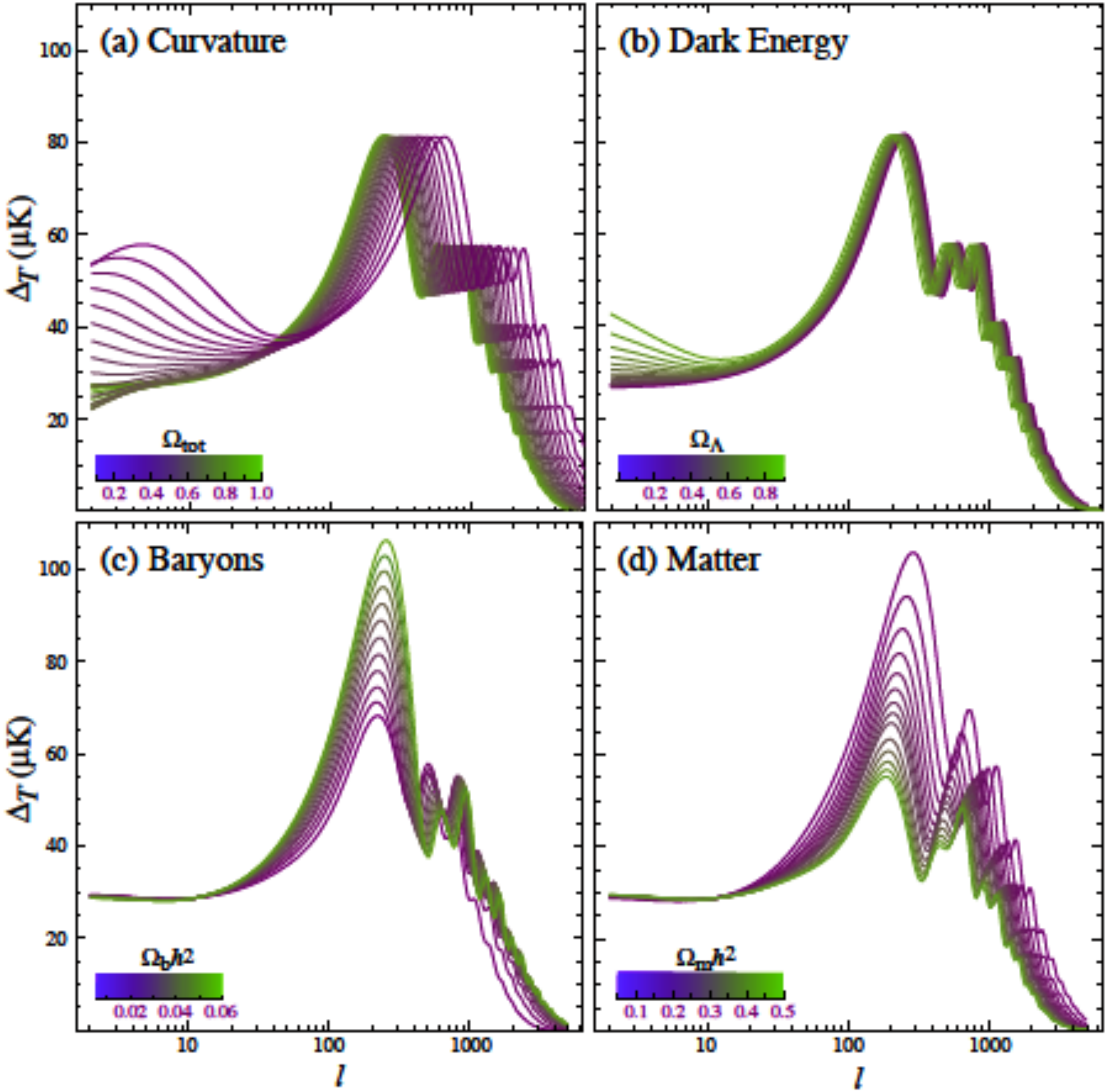
$$n_s = 0.96$$

$$\tau_e = 0.09$$

Inflation: The "bang" of the "Big Bang"

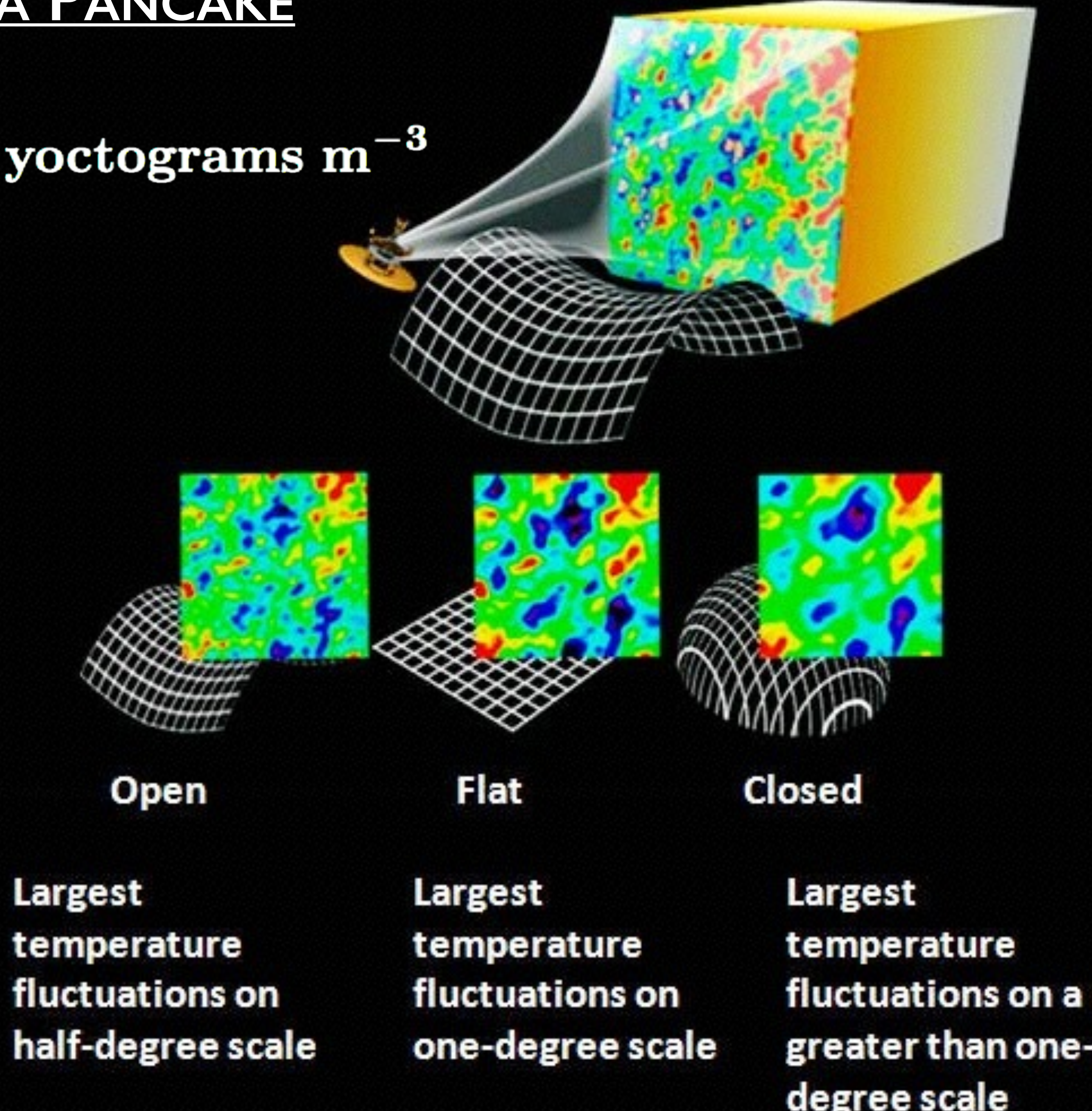
$$\frac{\text{tensor (gravitational waves)}}{\text{scalar (density perturbations)}} = 0.2 \pm 0.05$$

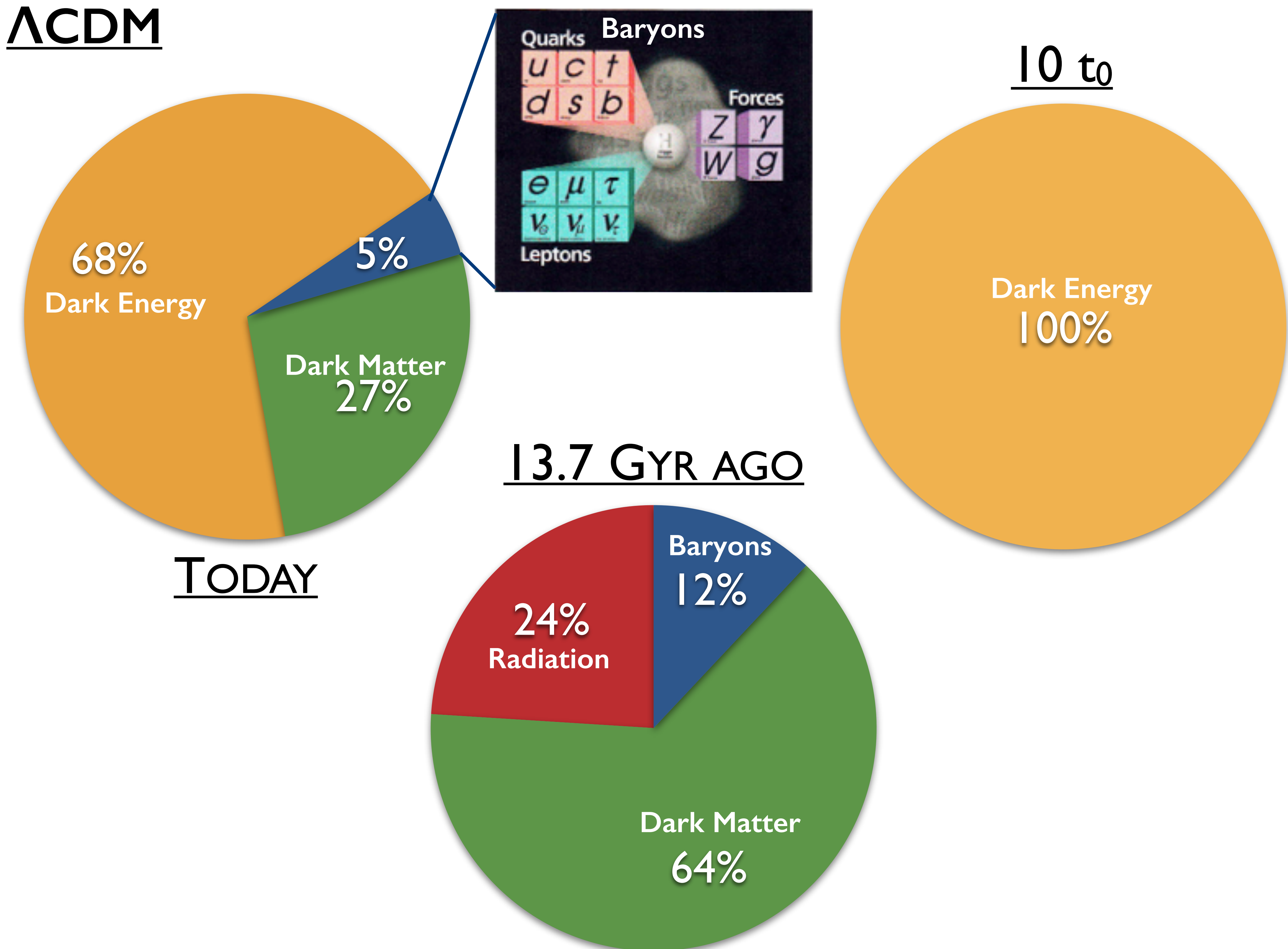
Sensitivity of acoustic temperature spectrum to cosmological parameters (Hu & Dodelson 2002)



FLAT LIKE A PANCAKE

$$\rho(t_0) = 0.84 \text{ yoctograms m}^{-3}$$




ΛCDM
68%
Dark Energy
5%
Dark Matter
27%
Today
Quarks
Baryons
u c t
d s b
Forces
Z γ
W g
e μ τ
νe νμ ντ
Leptons
13.7 Gyr ago
Baryons
12%
24%
Radiation
Dark Matter
64%
10 t0
Dark Energy
100%

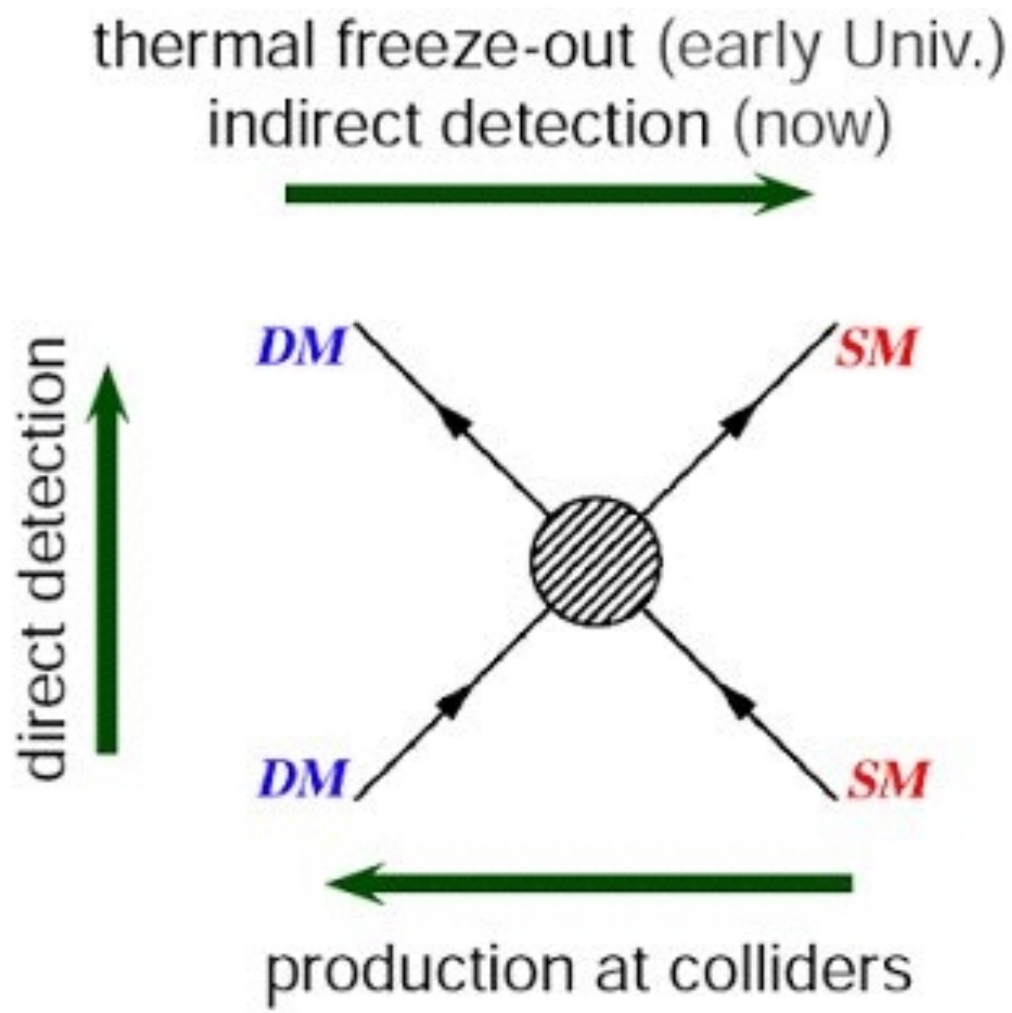
DARK MATTERS

DARK MATTER

Most of the universe can't even be bothered to interact with you.

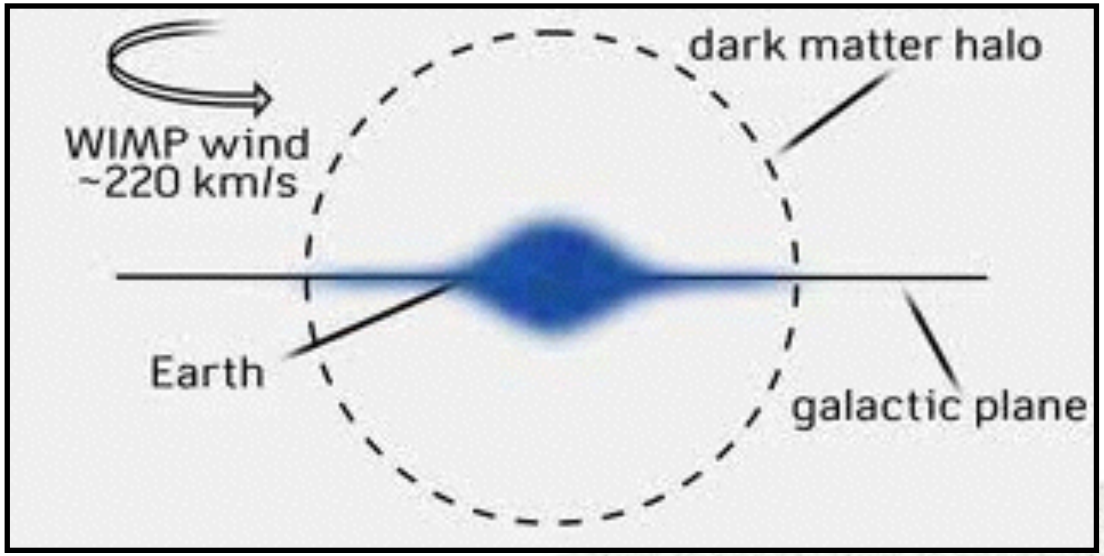
S. Carroll

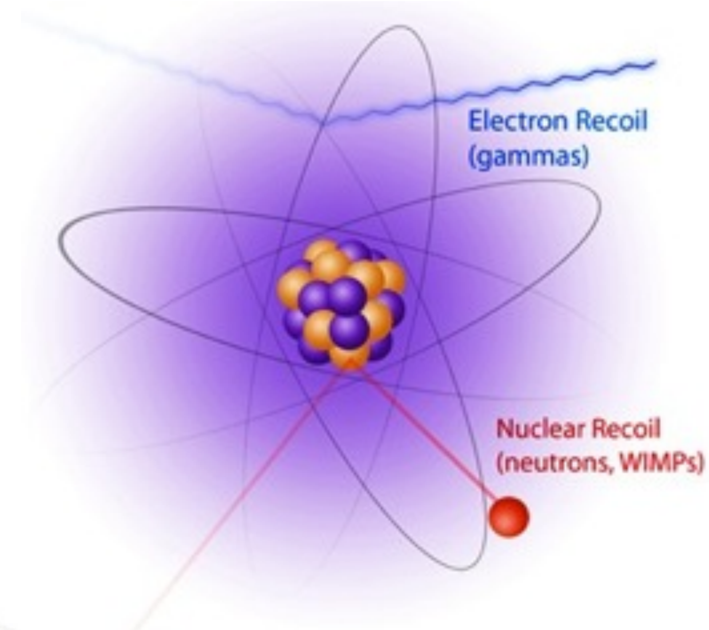
From both astrophysical and particle physics considerations, stable and heavy *Weakly Interacting Massive Particles (WIMPs)* that arise from extensions to the SM of particle physics are particularly compelling.

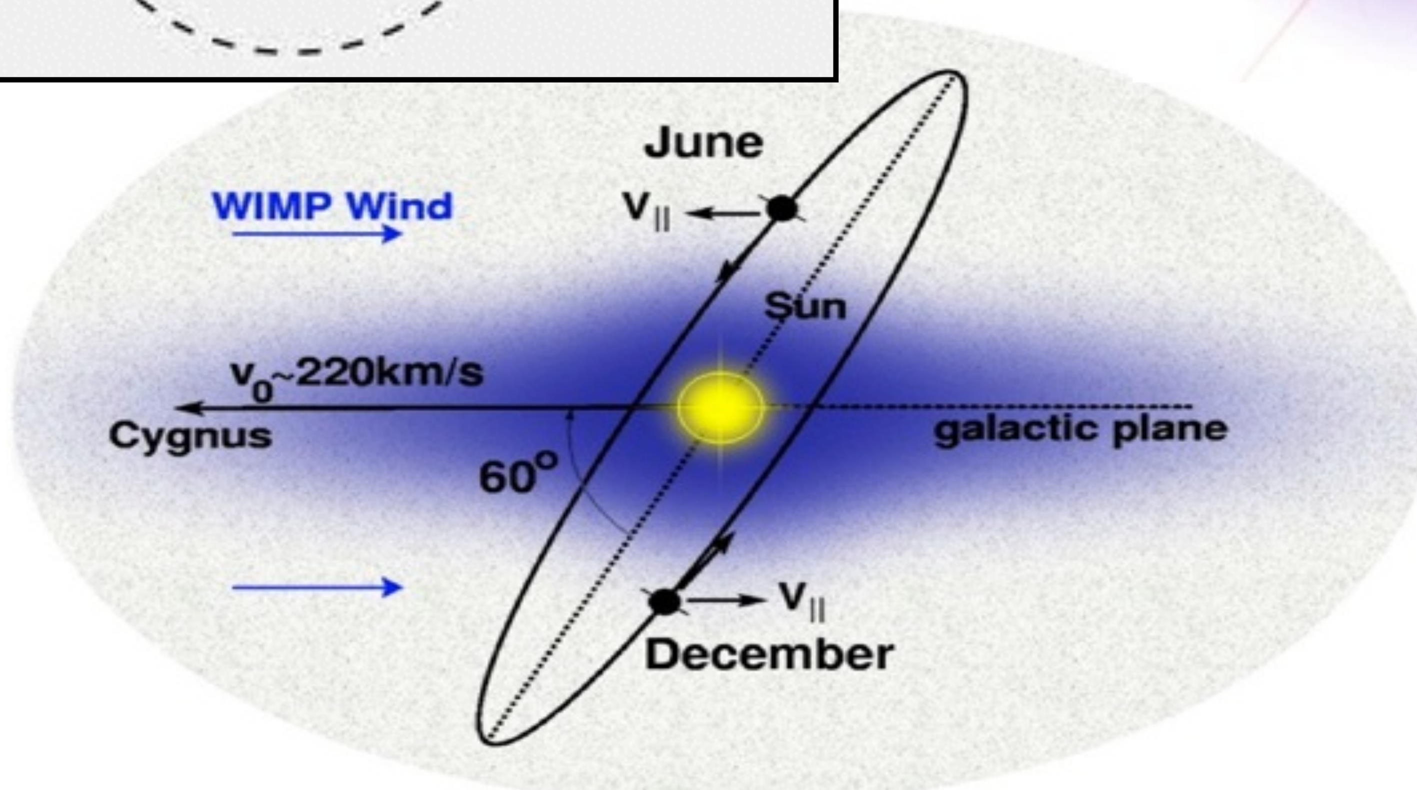


Different ways to detect DM particle interactions with standard model (SM) particles.

A Wind of WIMPs



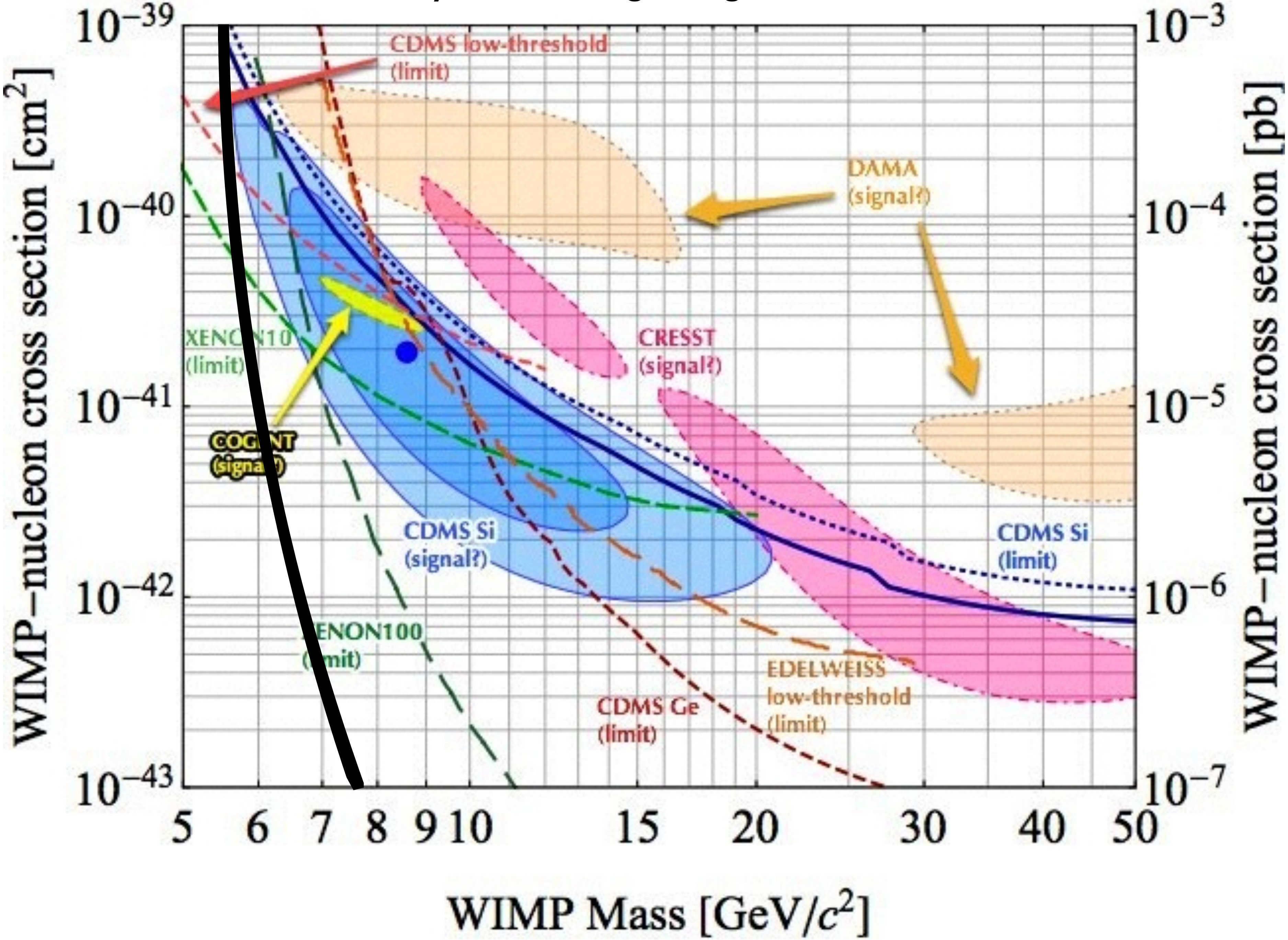




$$E_{\text{kin}} = 0.5 \times (100\,\text{GeV}) \times (220\,\text{km/s})^2 = 27\,\text{keV}$$

FIAT "LUX"

summary of best-fit signal regions and limits



SEEING THE INVISIBLE

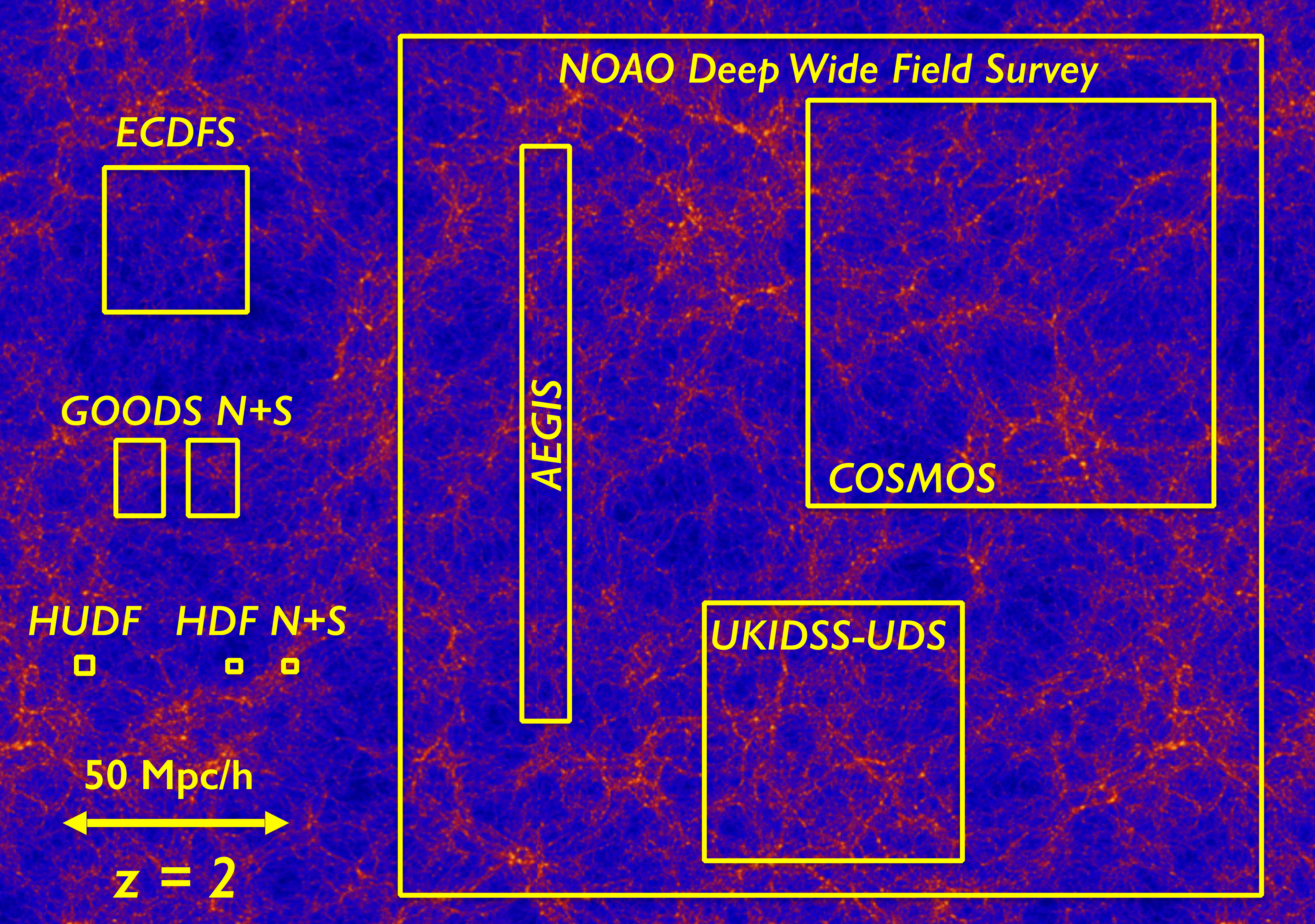
Galactic Center produces *more* *1–3* GeV *gamma-rays* than can be explained by known sources.

Excess emission is consistent with a *30–40* GeV *WIMP* annihilating into *quarks* with a thermally-averaged cross-section $\langle\sigma v\rangle = (1.4\text{–}2.0) \times 10^{-26}$ cm^3/s!

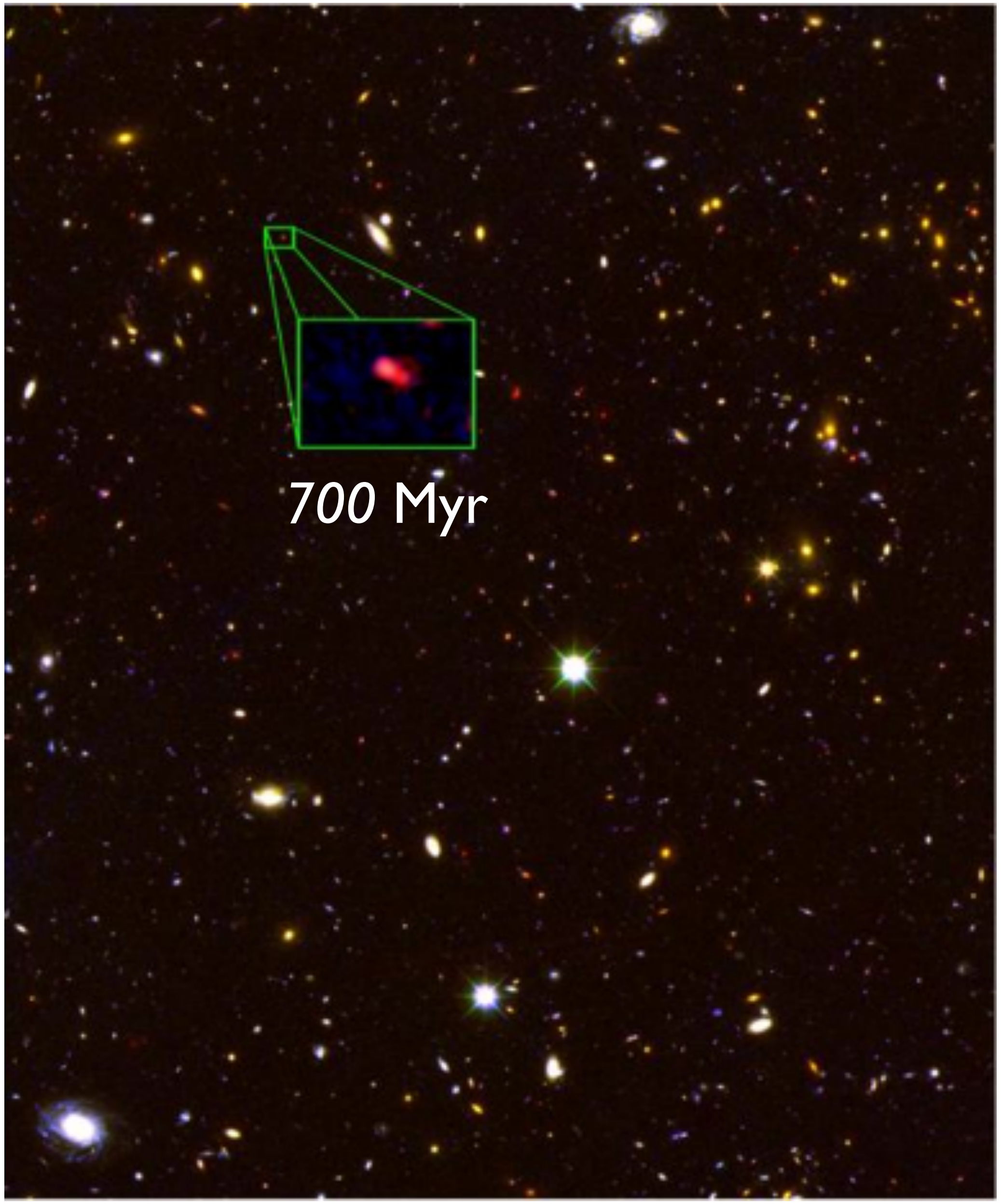
The Characterization of the Gamma-Ray Signal from the Central Milky Way:
A Compelling Case for Annihilating Dark Matter

Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]

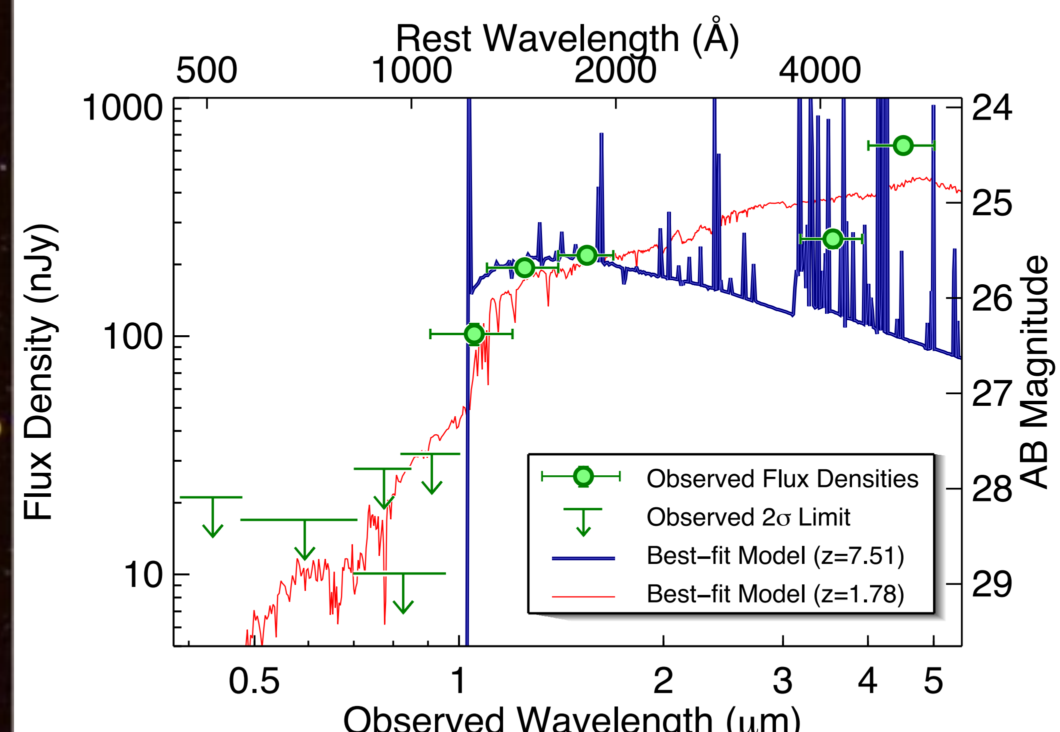
Physics of Galaxy Formation



First Galaxies

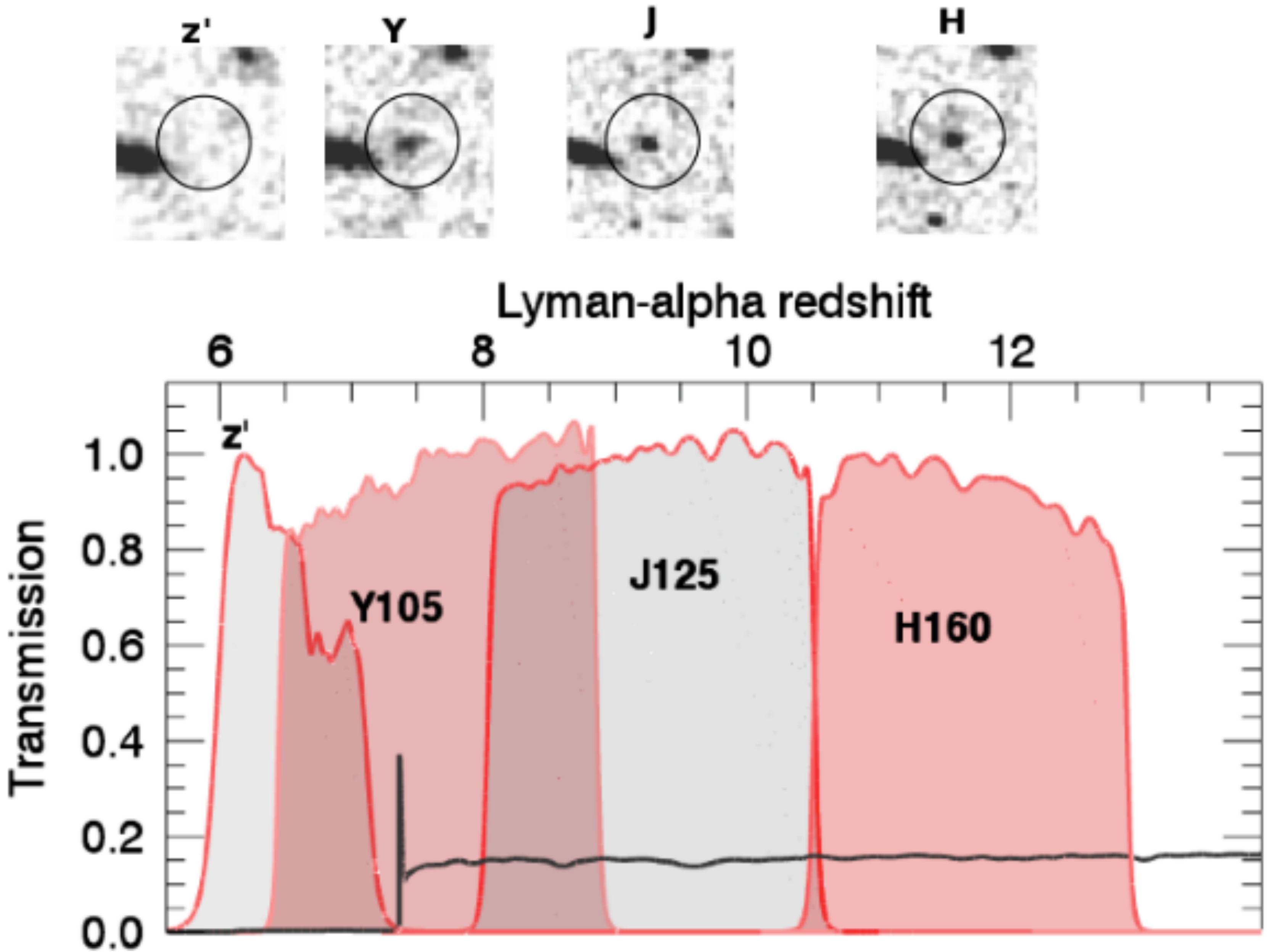


A rapidly star-forming galaxy 700 million years after the Big Bang at z=7.5!

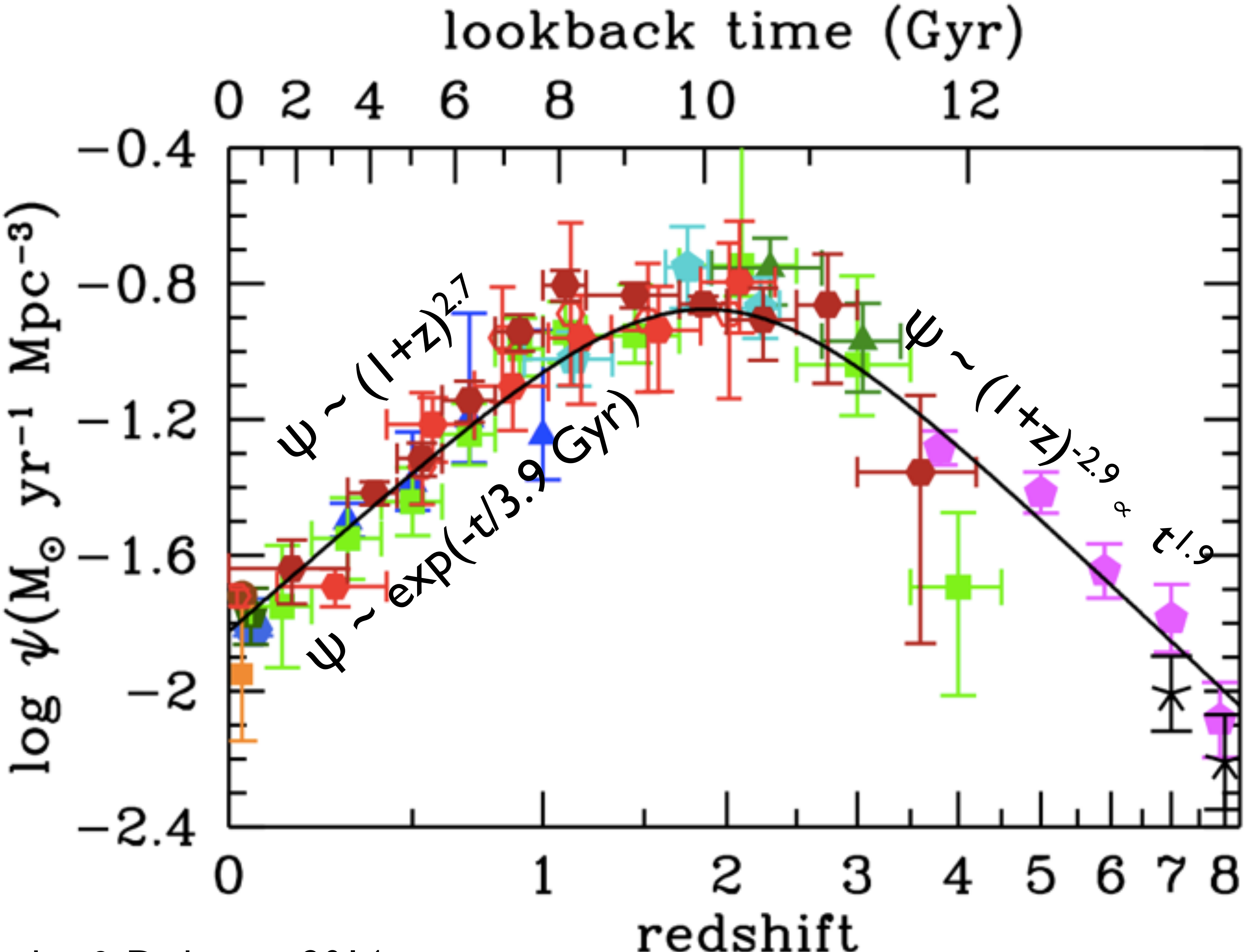


Finkelstein et al. 2013

Cosmic Dropouts

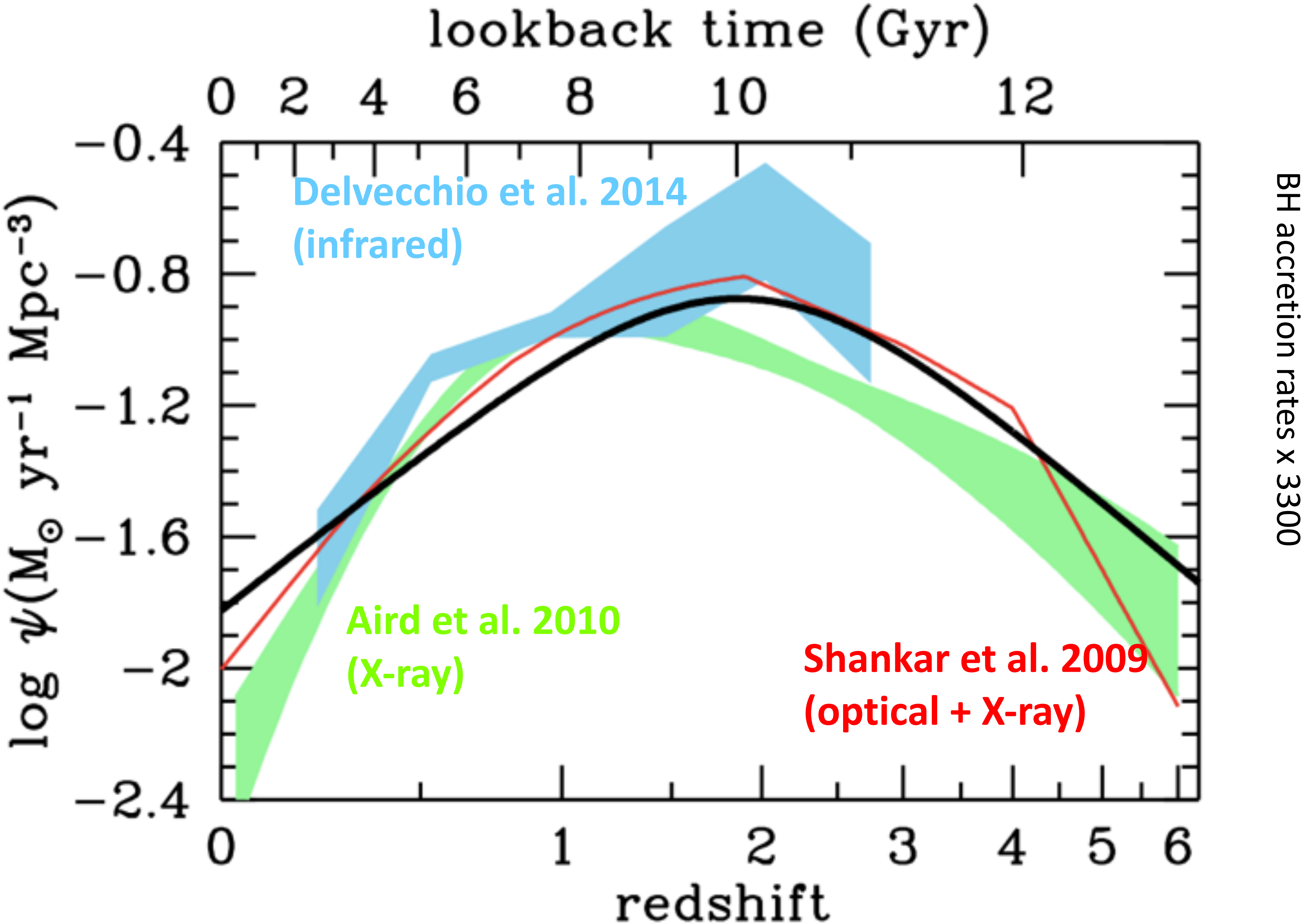


Cosmic History of Star Formation

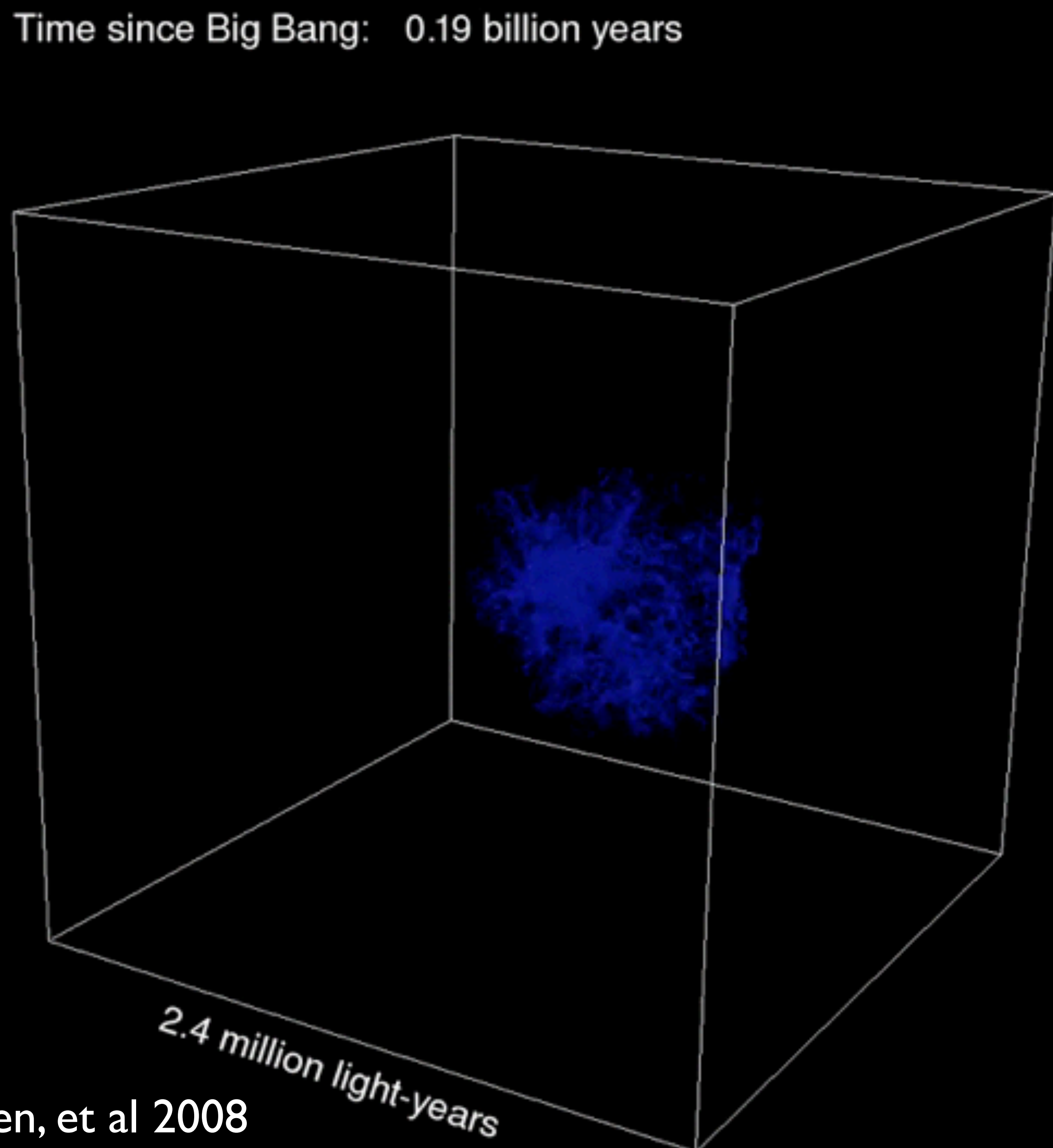


Madau & Dickinson 2014

MBH Accretion History



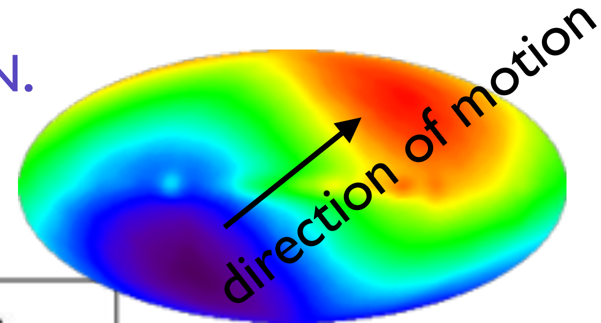
UNIVERSE IN A BOX: COSMOLOGICAL SIMULATIONS



Diemand, Kuhlen, et al 2008

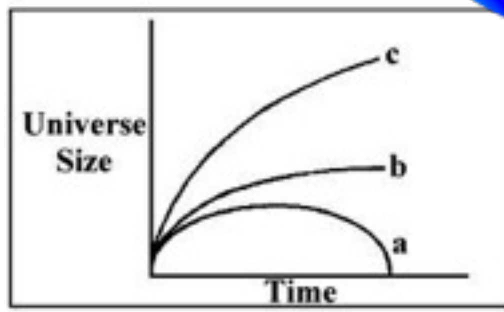
cf. When I Was an Undergrad in Arcetri...

Alan Guth had not developed Inflation.

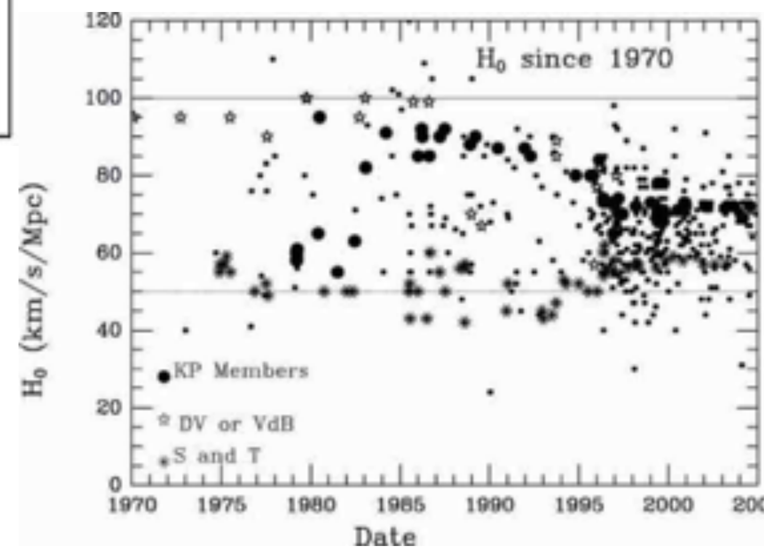


Only detected CMB anisotropy was the dipole.

Universe was decelerating.

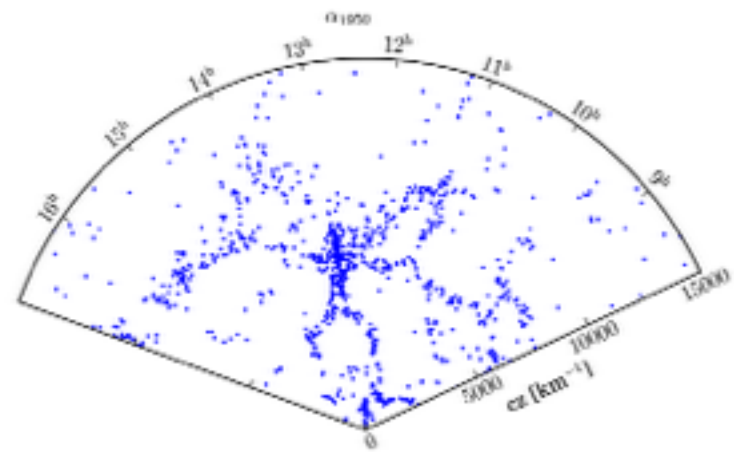


The Hubble Constant H_0 was a mess.



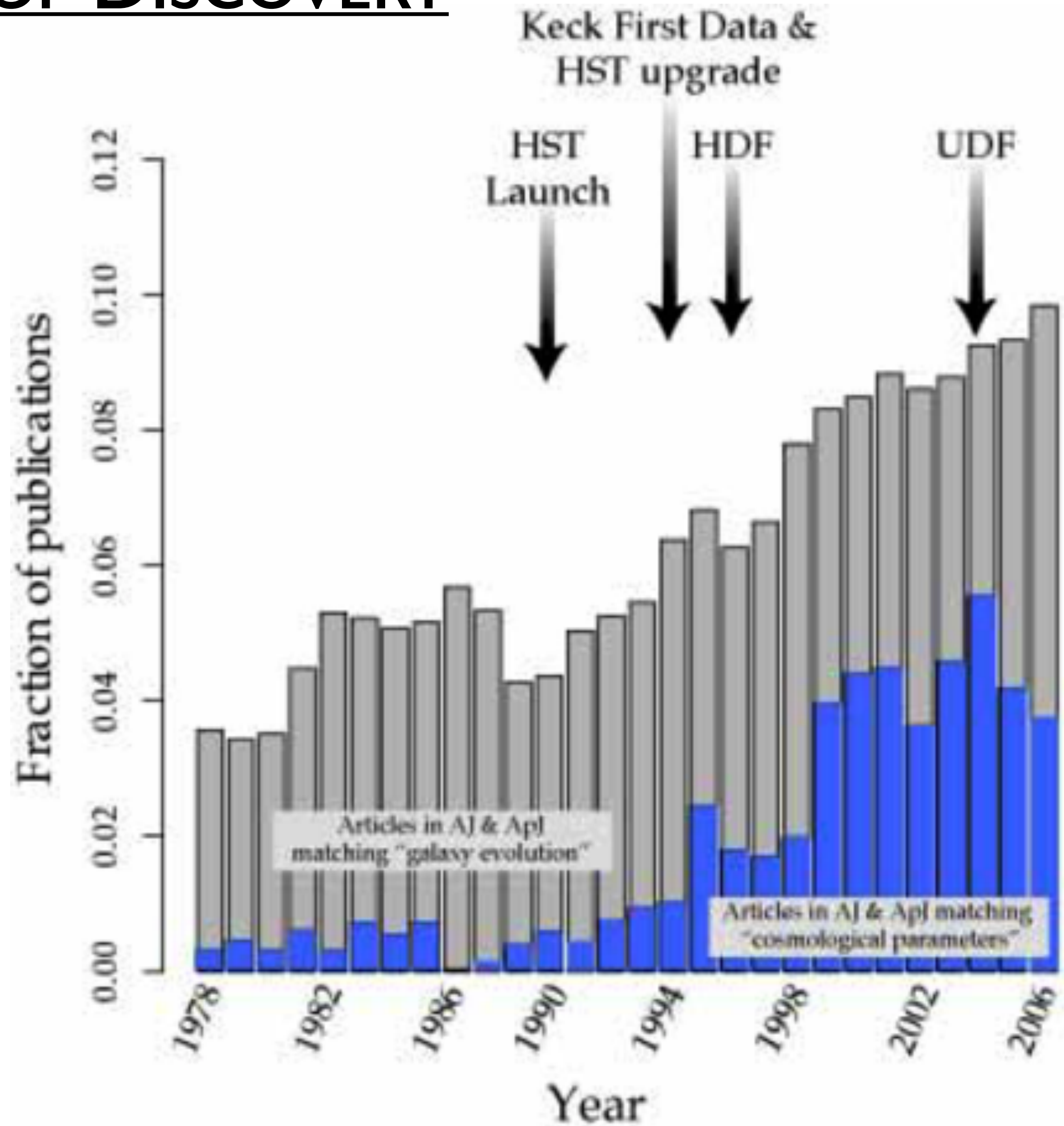
Zel'dovich was developing HDM.
There was no CDM.

CfA Redshift Survey was underway.



No known *normal* galaxies at high-redshift.

RAPID PACE OF DISCOVERY



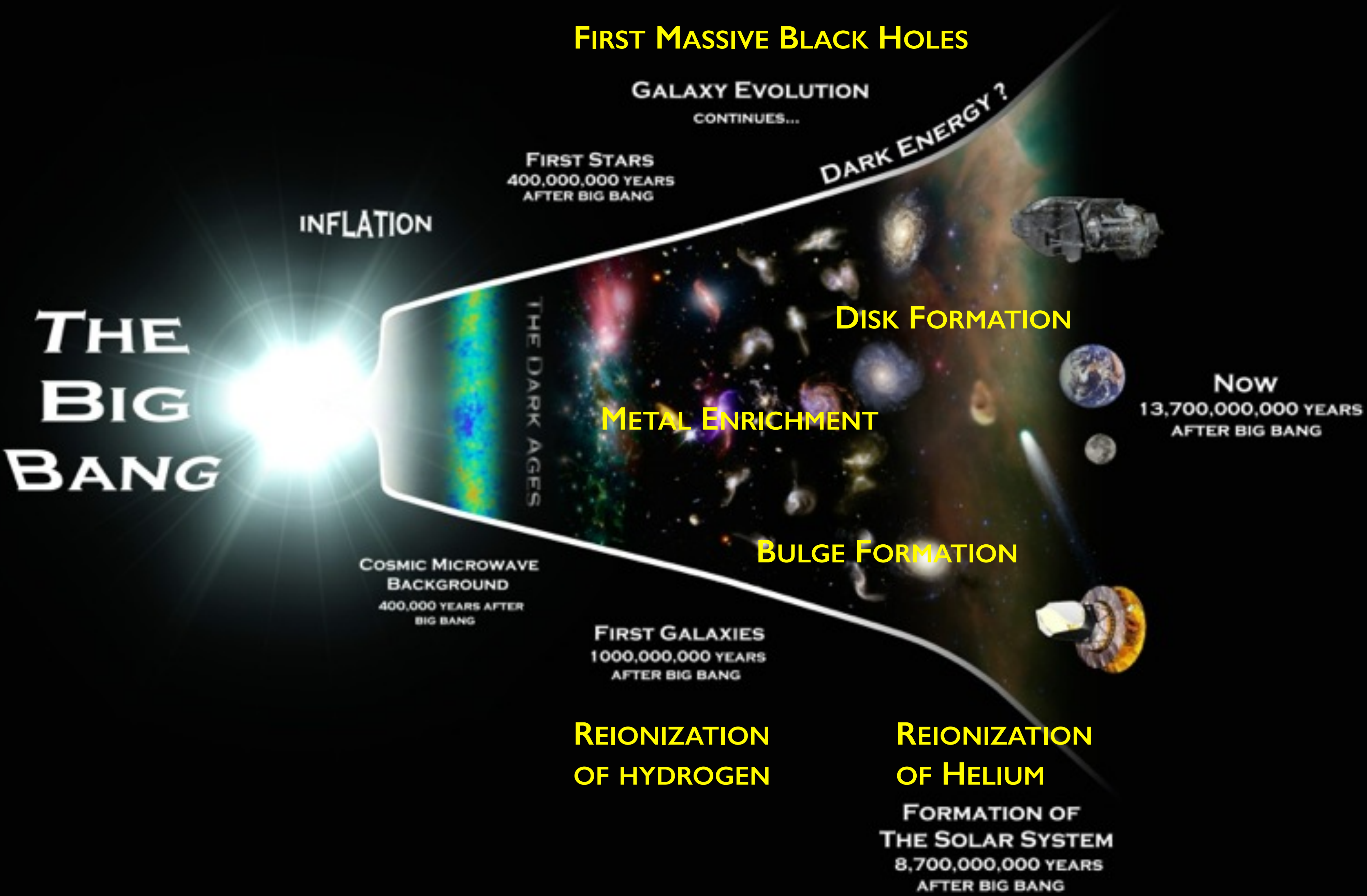
Question: do more publications in a given field mean most key questions are being answered? Should new students move into less well-developed fields?

Introduction

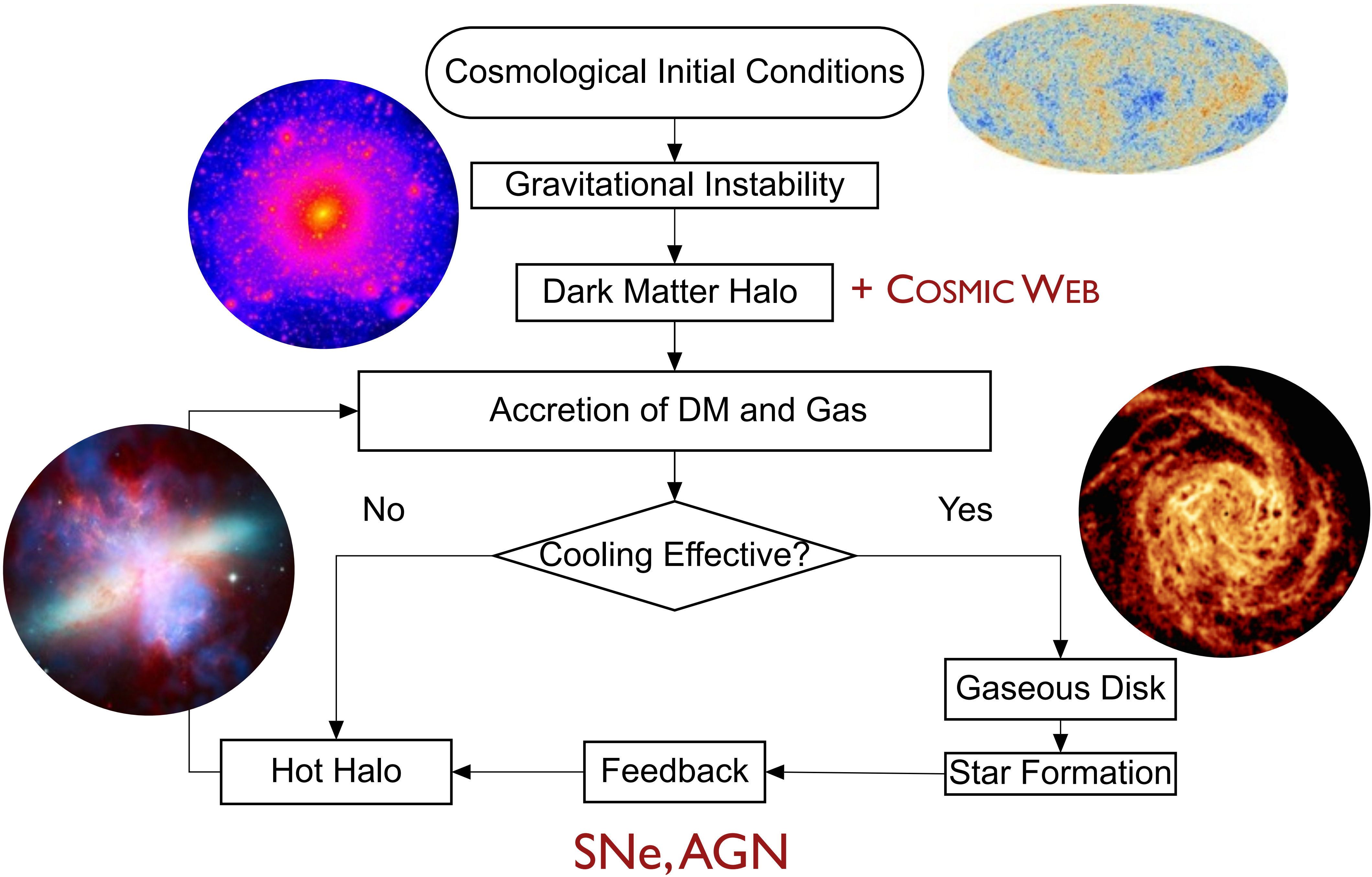
Basic Elements of Galaxy Formation

Lies, Damned Lies, and Simulations

FROM QUANTUM FOAM TO GALAXIES



A Recipe For Galaxy Formation



Standard Cosmological Model

Homogenous, Isotropic, Expanding Universe

$$ds^2 = -c^2 dt^2 + a^2(t)\left[\frac{dr^2}{1-\cancel{kr^2}} + r^2 d\Omega^2\right]$$

k=0 ⇨ Universe is flat

Hubble's Law

a source located at separation R

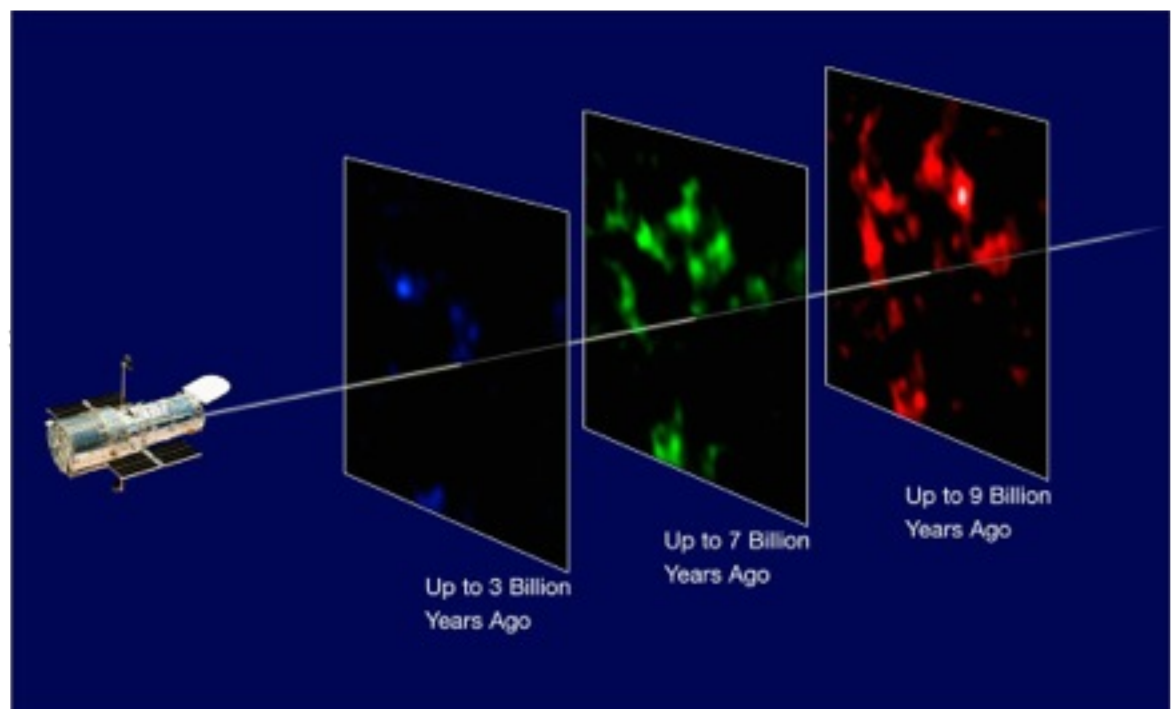
$$R = a(t)r$$

$$v = \dot{R} = \dot{a}r = \left(\frac{\dot{a}}{a}\right)R = HR$$

$$\frac{\Delta\nu}{\nu} = -\frac{v}{c} = -\frac{\dot{a}}{a}\frac{R}{c} = -\frac{\dot{a}}{a}\Delta t$$

$$\nu \propto a^{-1}$$

$$\lambda = (c/\nu) \propto a = \frac{1}{(1+z)}$$



FRIEDMANN EQUATIONS IN A FLAT UNIVERSE

$$H^2 = \frac{8\pi G}{3}\rho = H_0^2\left(\Omega_{\rm M} a^{-3} + \Omega_\Lambda + \Omega_{\rm R} a^{-4}\right)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3p/c^2\right) = -\frac{H_0^2}{2}\left(\Omega_{\rm M} a^{-3} - \Omega_\Lambda + 2\Omega_{\rm R} a^{-4}\right)$$

	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{\rm MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10}A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
$z_{\rm re}$	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
$z_{\rm drag}$	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
$r_{\rm drag}$	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
$z_{\rm eq}$	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{\rm eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{\rm drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

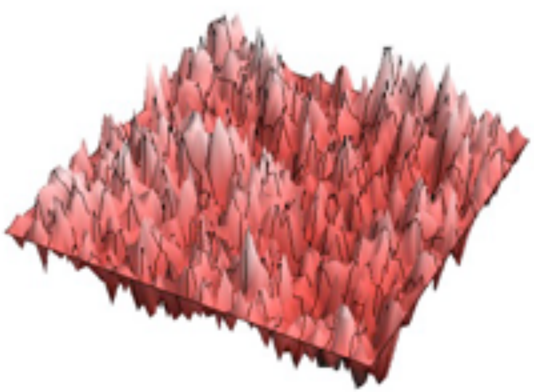
The cosmological parameters describing the Universe at recombination can be summarized on a single sheet of paper. Yet the most detailed supercomputer simulation cannot fully describe the complex structures we see today…..Why?

GRAVITATIONAL INSTABILITY IN A NUTSHELL

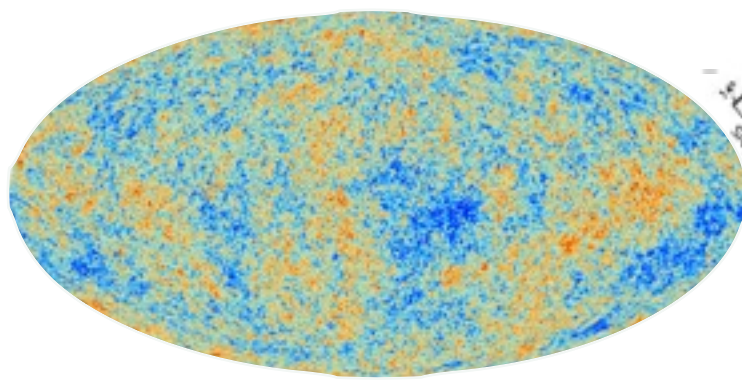
Let ρ(***x***) be the density distribution of matter at location ***x***

Let δ(***x***) be the corresponding overdensity field $\delta(\vec{x}) = \frac{\rho(\vec{x})}{\bar{\rho}} - 1$

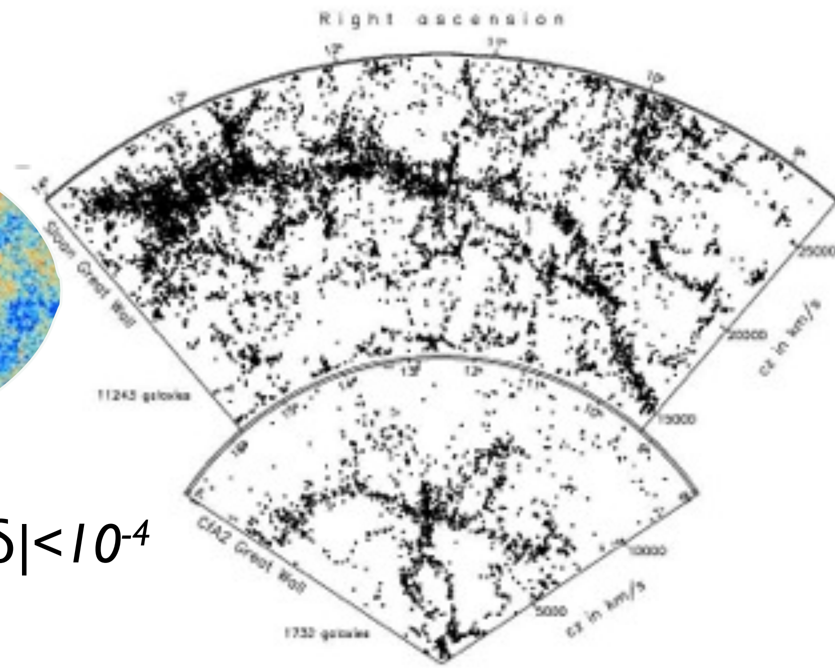
NB: δ(***x***) is the outcome of some random process in the early Universe like *quantum fluctuations of the inflaton field!*



quantum fluctuations



CMB $z=1100$, linear regime $|\delta|<10^{-4}$



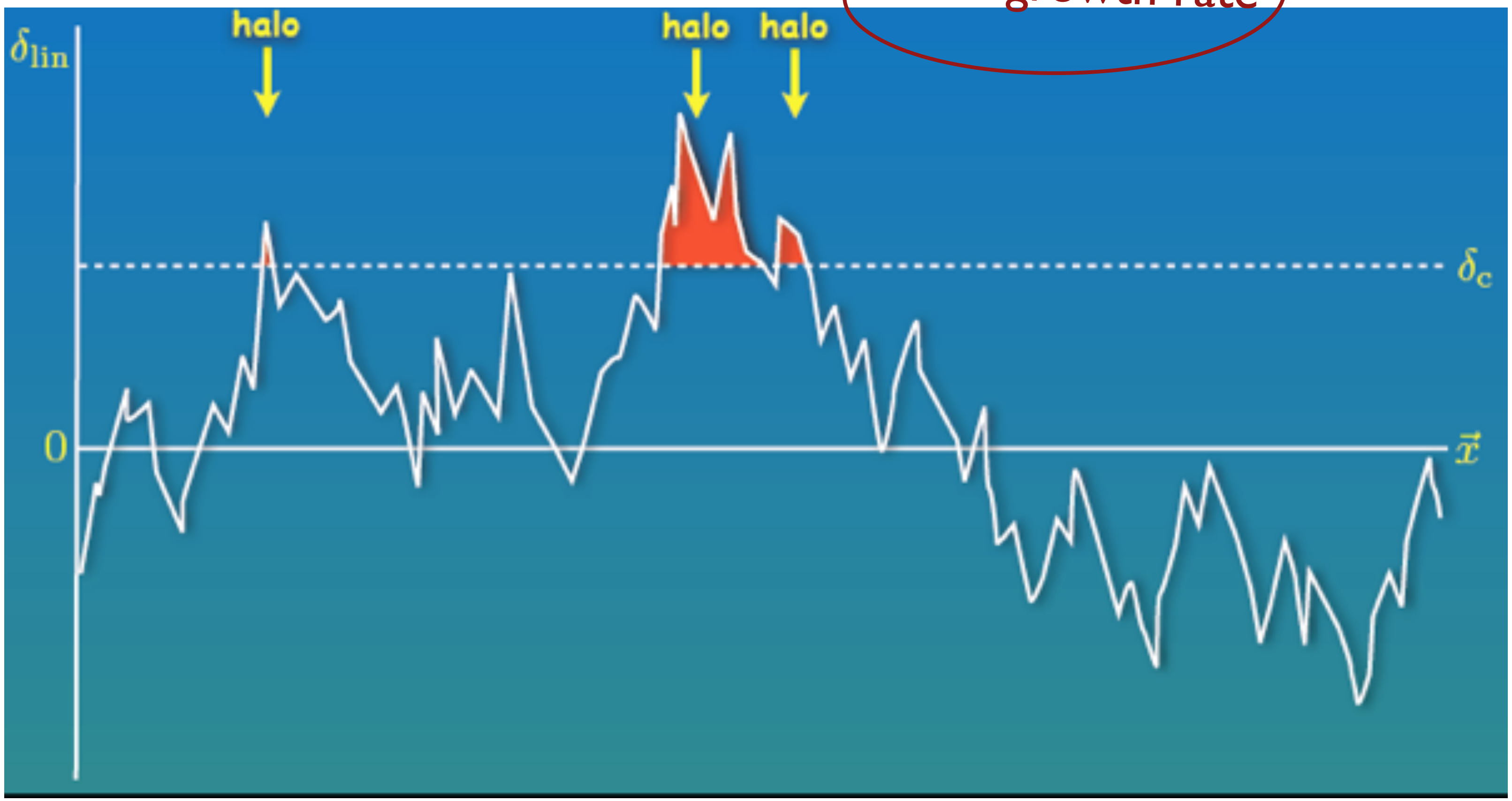
galaxy distribution $z\sim 0.1$, non-linear regime $|\delta|\gtrsim 1$

According to linear theory, the density field evolves as

$$\delta(\vec{x},t) = D(t)\delta_0(\vec{x})$$

density field linearly extrapolated to z=0

linear growth rate

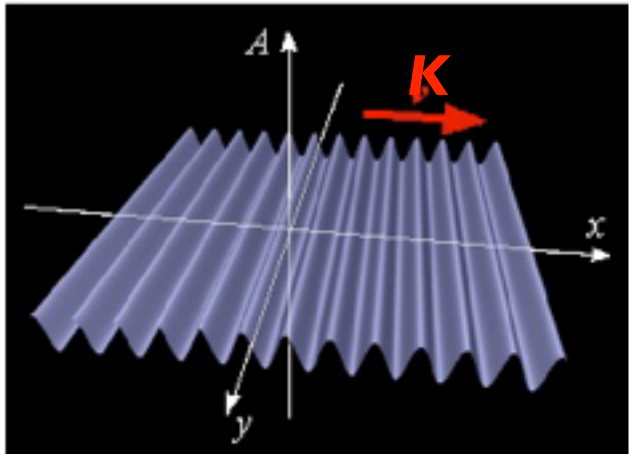


According to the spherical collapse model in a $\Omega_M=1$ Universe, regions with $\delta(x,t\}>\delta_c=1.696$ will have collapsed to produce dark matter halos by time *t*. QUESTION: which halos will collapse first?

The perturbed density field can be written as a sum of plane waves of different *wave numbers* (called *modes*) which evolve independently in the linear regime

$$\lambda = 2\pi a/k$$

$$\delta(\vec{x}) = \sum_k \delta_{\vec{k}}\, e^{i\vec{k}\cdot\vec{x}}$$



The variance of the density field can then be written as

Note: *P(k)* has units of volume!

$$\sigma^2 = \langle \delta^2 \rangle = \frac{1}{(2\pi)^3}\int P(k)d^3\vec{k} = \frac{1}{2\pi^2}\int P(k)k^2dk$$

P(k) is the power spectrum . Inflation predicts an initial power spectrum of the form

$$P(k) \propto k^n \qquad n \lesssim 1$$

SCALE INVARIANT

$$\text{Planck} \rightarrow n = 0.96$$

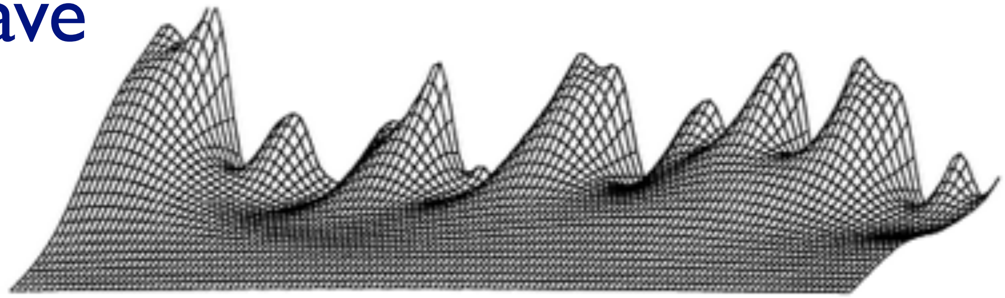
The index *n* governs the balance between large- and small-scale power in the Universe.

The meaning of different values of n can be seen by imagining the results of *smoothing* the density field by passing over it a box of some characteristic *comoving size* R and averaging the density field over the box.

This will filter out waves with $k \gtrsim 1/R$, leaving a variance

$$\langle \delta_R^2 \rangle \propto \int_0^{1/R} k^n k^2 dk \propto R^{-(n+3)}.$$

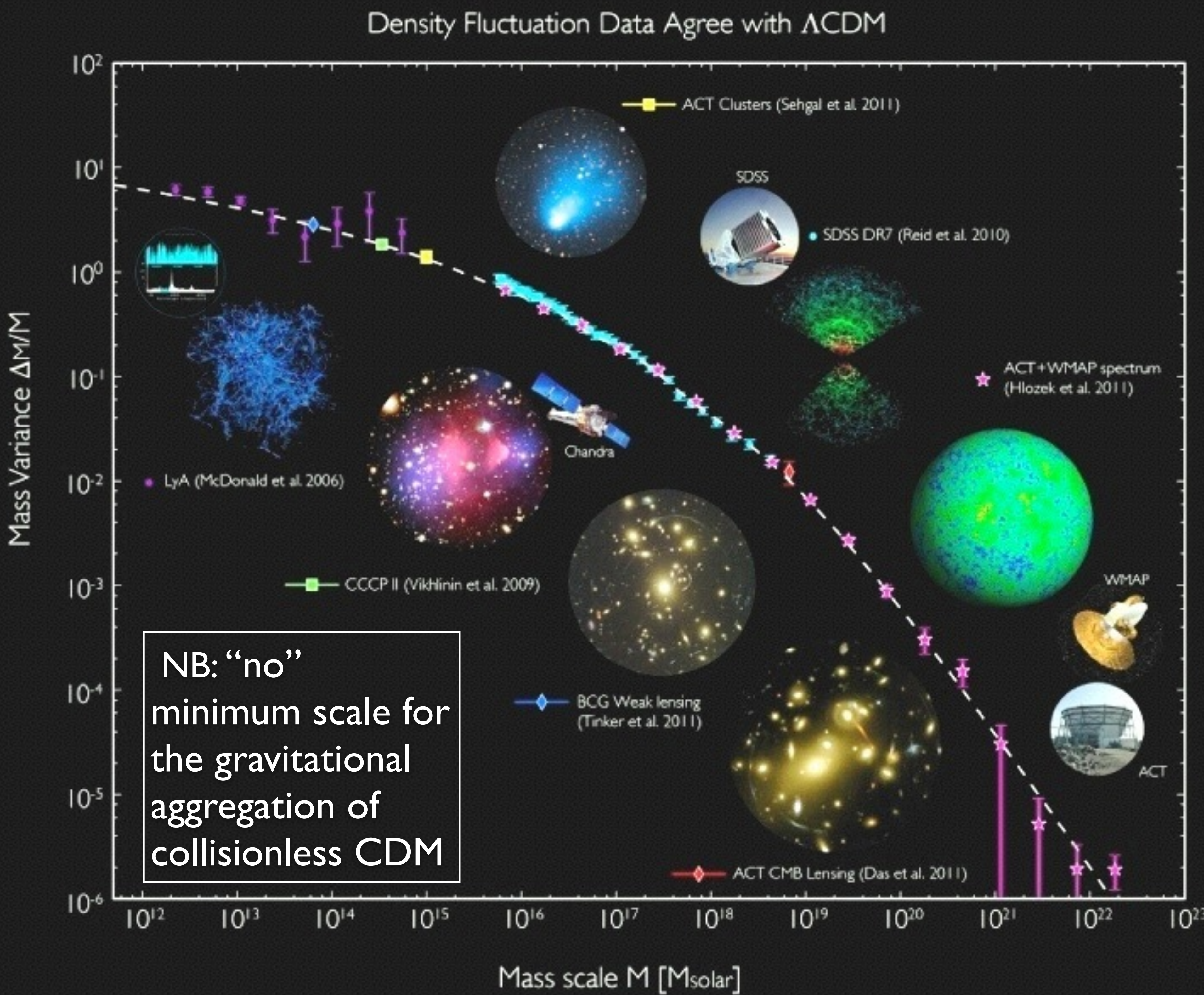
Hence, in terms of a mass , we have



$$M \propto R^3$$

$$\langle \delta_M^2 \rangle^{1/2} \propto M^{-(n+3)/6}$$

NB: we do not observe the primordial *P(k)* but *P(k)T(k)*. In CDM, *P(k)* is suppressed on small scales during the radiation-dominated era, $P(k) \sim k^{n-4}$…..


Density Fluctuation Data Agree with ΛCDM
Mass Variance ΔM/M
Mass scale M [Msolar]
ACT Clusters (Sehgal et al. 2011)
SDSS
SDSS DR7 (Reid et al. 2010)
ACT+WMAP spectrum
(Hlozek et al. 2011)
Chandra
LyA (McDonald et al. 2006)
CCCP II (Vikhlinin et al. 2009)
WMAP
BCG Weak lensing
(Tinker et al. 2011)
ACT
ACT CMB Lensing (Das et al. 2011)
NB: "no" minimum scale for the gravitational aggregation of collisionless CDM

LINEAR GROWTH OF DM PERTURBATIONS

"Hubble friction"

CDM as a zero-pressure fluid

$$\ddot{\delta}_k + 2H\dot{\delta}_k = 4\pi G\bar{\rho}\delta_k$$

static *H=0* Universe ➪ mode grows exponentially with time

$$\delta_+ \propto e^{t/t_c}$$

flat, matter-dominated Universe *H=2/3t*

$$\delta_+ \propto a = 1/(1+z)$$

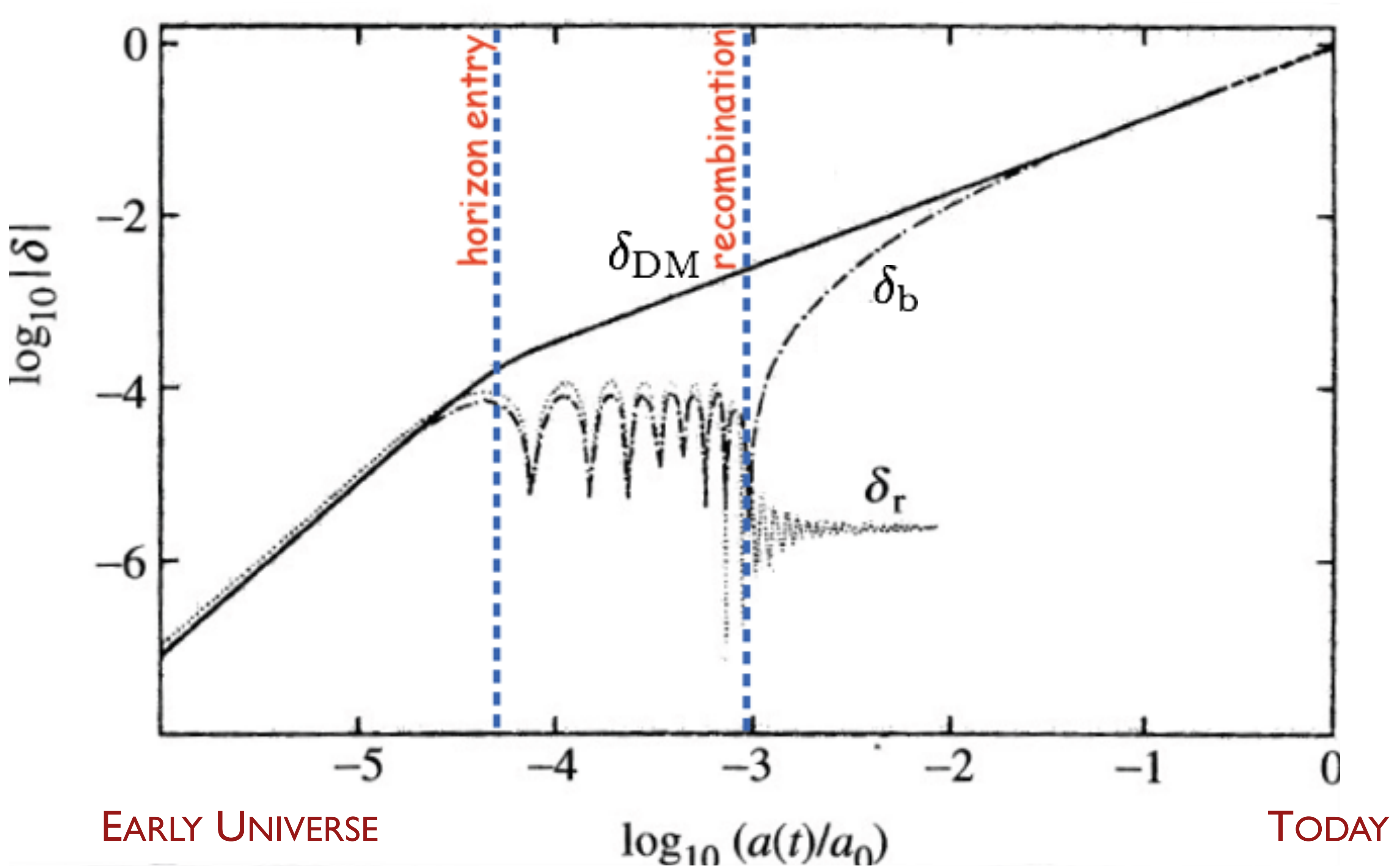
➪ growth is algebraic instead of exponential!

flat, Λ-dominated Universe *H=const*

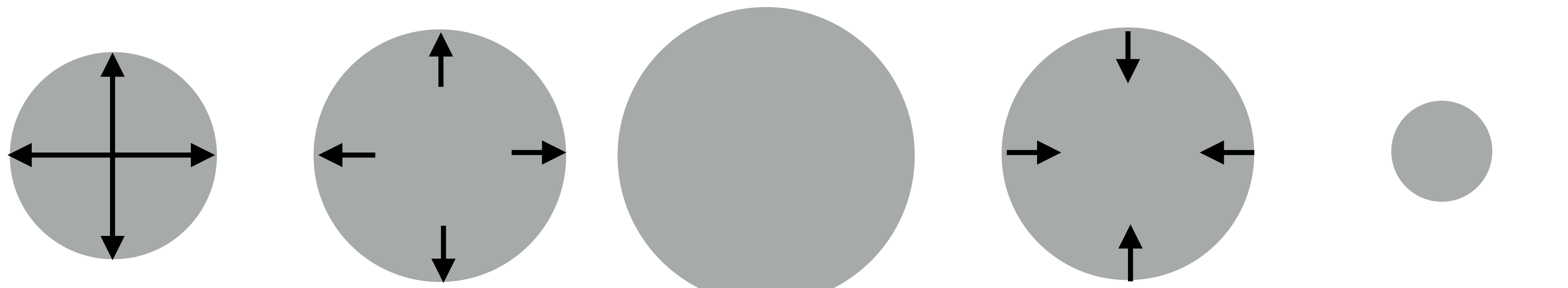
$$\ddot{\delta}_k + 2H\dot{\delta}_k = 0 \rightarrow \delta_+ = \text{const}$$

perturbations are now frozen!

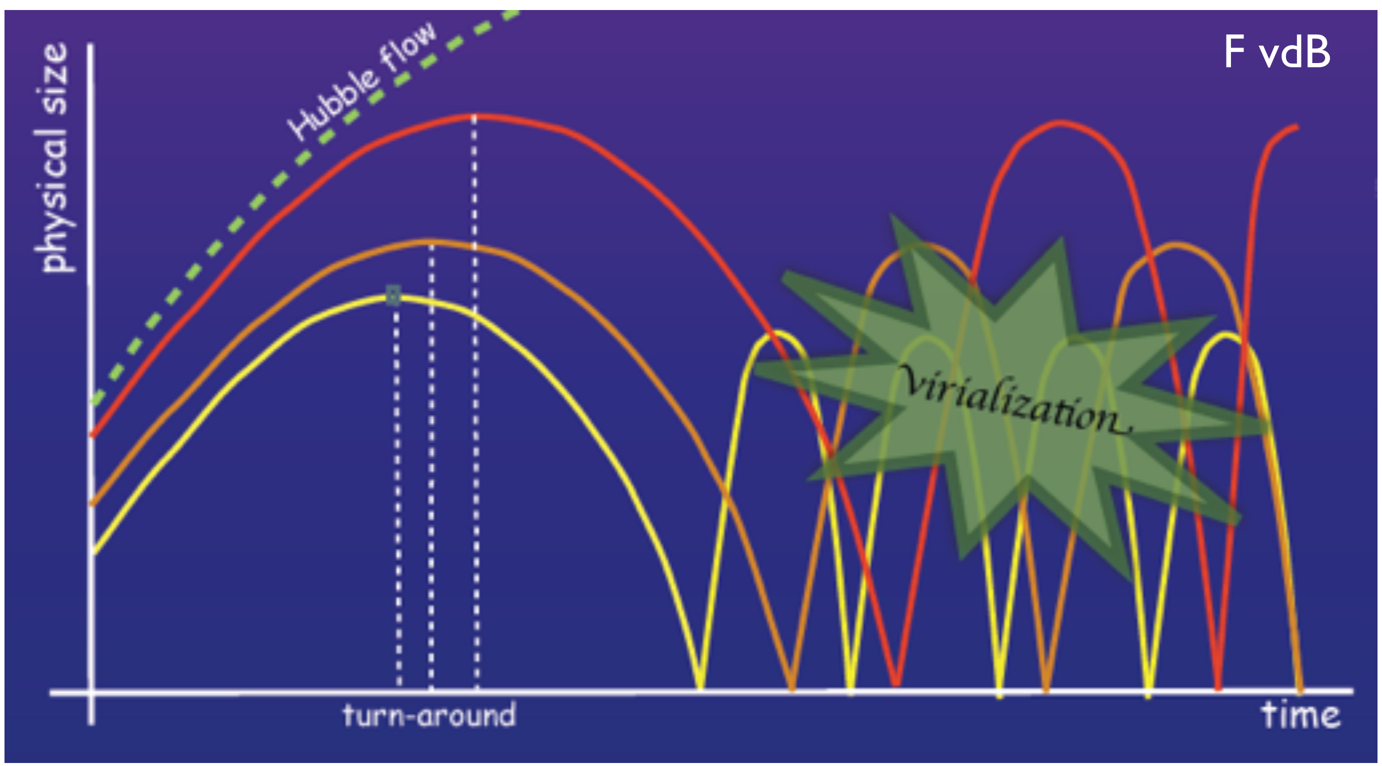
GALAXY FORMATION: A 2-STEP PROCESS



Spherical Collapse in a $\Omega_M=1$ Universe



Think of an overdensity as consisting of many individual, thin mass shells ➩ Onion Model



Because of collisionless nature of the DM, the shell crosses itself and starts to oscillate ➩ Violent Relaxation/ Virialization

$$2K + W = 0$$

Structure Formation: an N-Body simulation of Large-Scale Structure in a ΛCDM Cosmology

note the formation of pancakes,
filaments and halos, and how
voids become more spherical with time….

Timescales of Galaxy Formation

Hubble Time

$$t_{\rm H} = H^{-1} = H_0^{-1}[\Omega_M(1+z)^3 + \Omega_\Lambda]^{-1/2}$$

Free-Fall Time

$$t_{\rm ff} = \sqrt{3\pi/32G\rho}$$

$$\rho = \rho_{\rm b} + \rho_{\rm DM} \equiv \Delta\rho_{\rm crit}$$
$$t_{\rm ff} = 1.57\, t_{\rm H}/\sqrt{\Delta}$$
$$\Delta = 200 \Rightarrow t_{\rm ff} = t_{\rm H}/10$$

Cooling Time

$$t_{\rm cool} = \frac{3nk_{\rm B}T}{2n_{\rm H}^2\Lambda(T)} \propto n^{-1}$$

⇨ denser gas cools faster

3 Regimes

a) $t_{\rm cool} > t_{\rm H}$ — cooling is not important, gas in hydrostatic equilibrium

b) $t_{\rm ff} < t_{\rm cool} < t_{\rm H}$ — system evolves on cooling timescale. Gas contracts slowly as it cools.

c) $t_{\rm cool} < t_{\rm ff}$ — cooling is catastrophic, gas cannot respond to loss of pressure and falls to the center on the free-fall timescale.

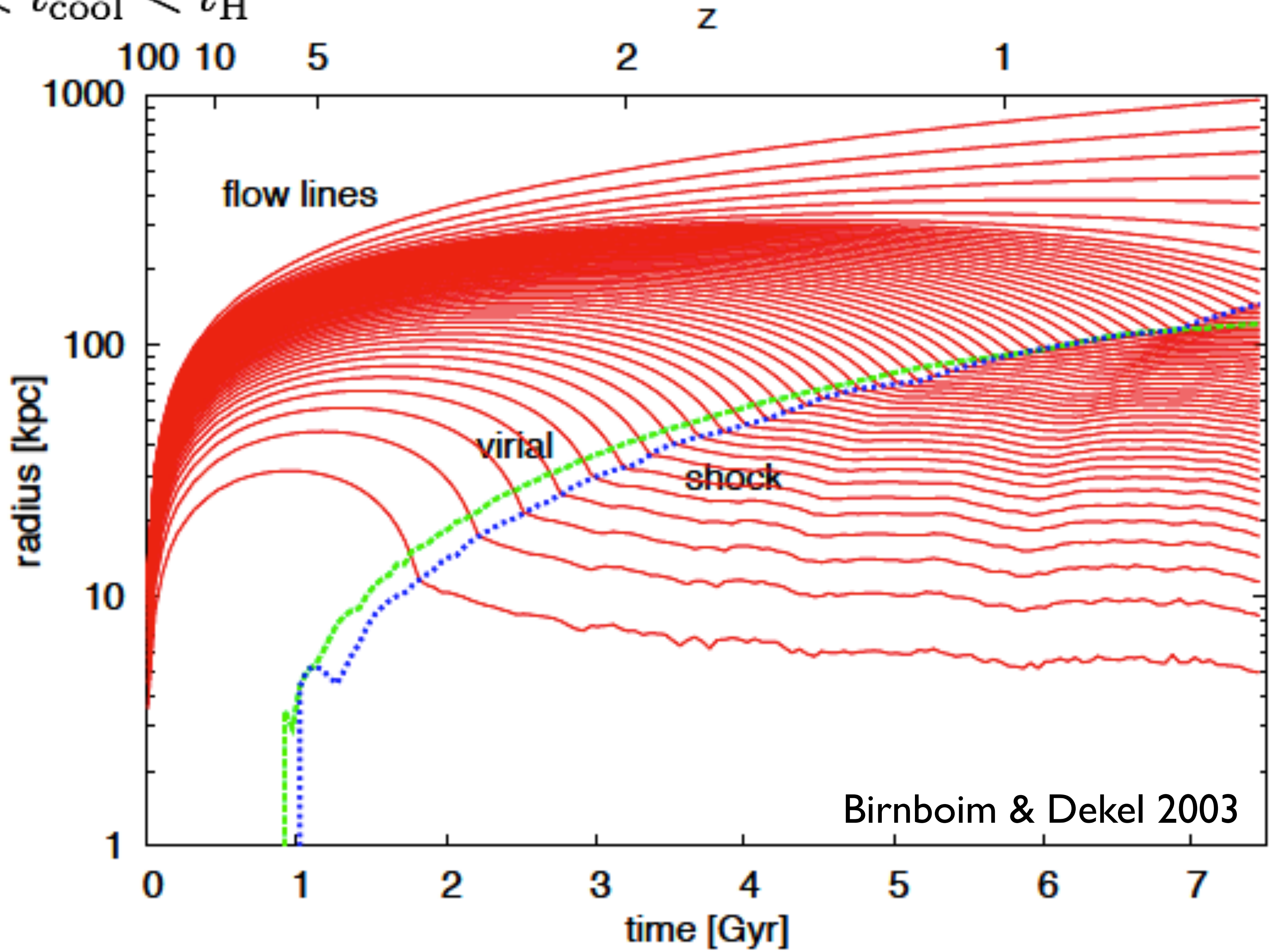
Hot Mode Accretion

EdS

$$r_{\rm vir} = 50\,{\rm kpc} \left(\frac{M_{\rm vir}}{10^{11}\,M_\odot}\right)^{1/3} \left(\frac{1+z}{3}\right)^{-1}$$

$$T_{\rm vir} = \frac{\mu m_p}{2k_B} \left(\frac{GM_{\rm vir}}{r_{\rm vir}}\right) = 3.1\times10^5\,{\rm K} \left(\frac{M_{\rm vir}}{10^{11}\,M_\odot}\right)^{2/3} \left(\frac{1+z}{3}\right)$$

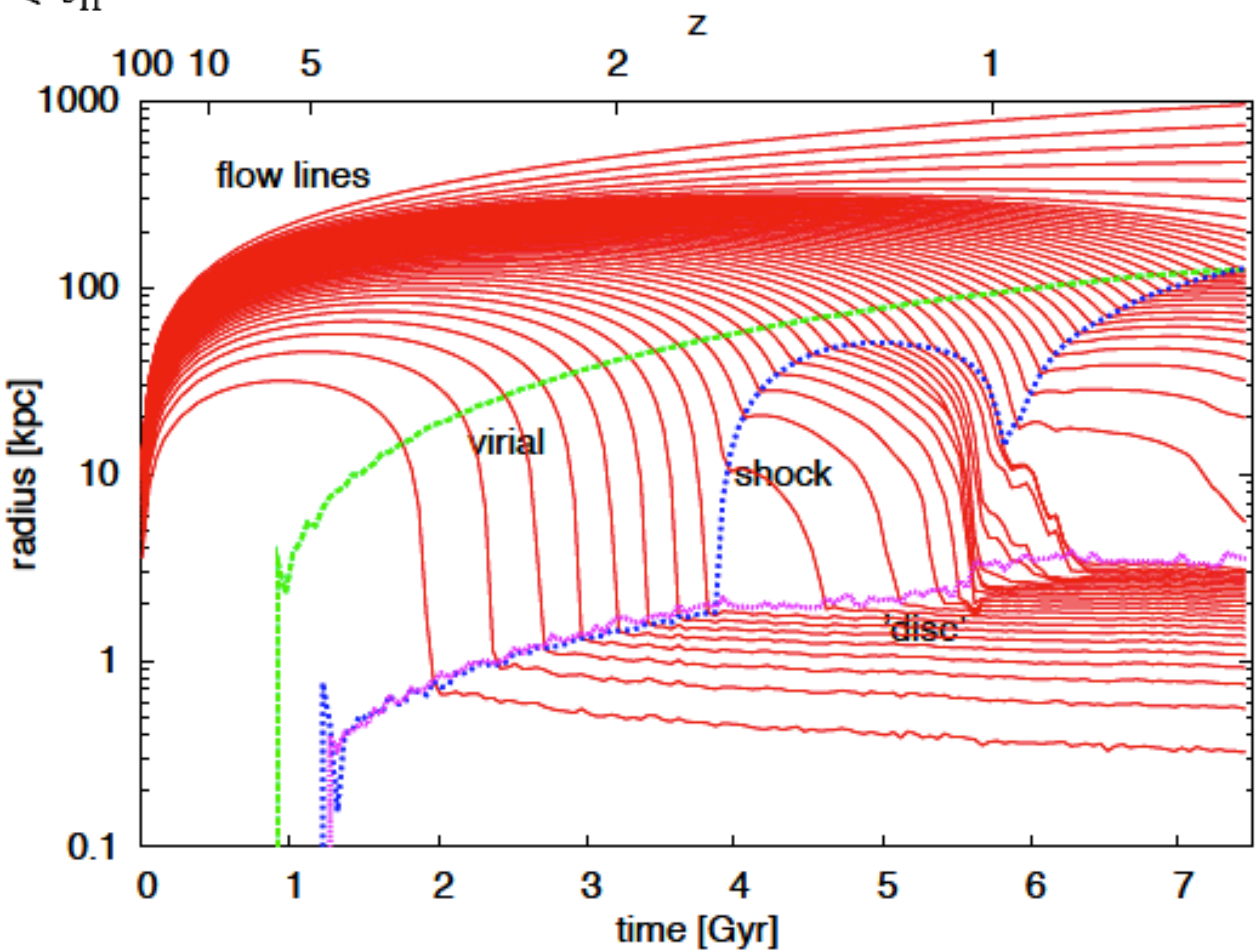
$$t_{\rm ff} < t_{\rm cool} < t_{\rm H}$$



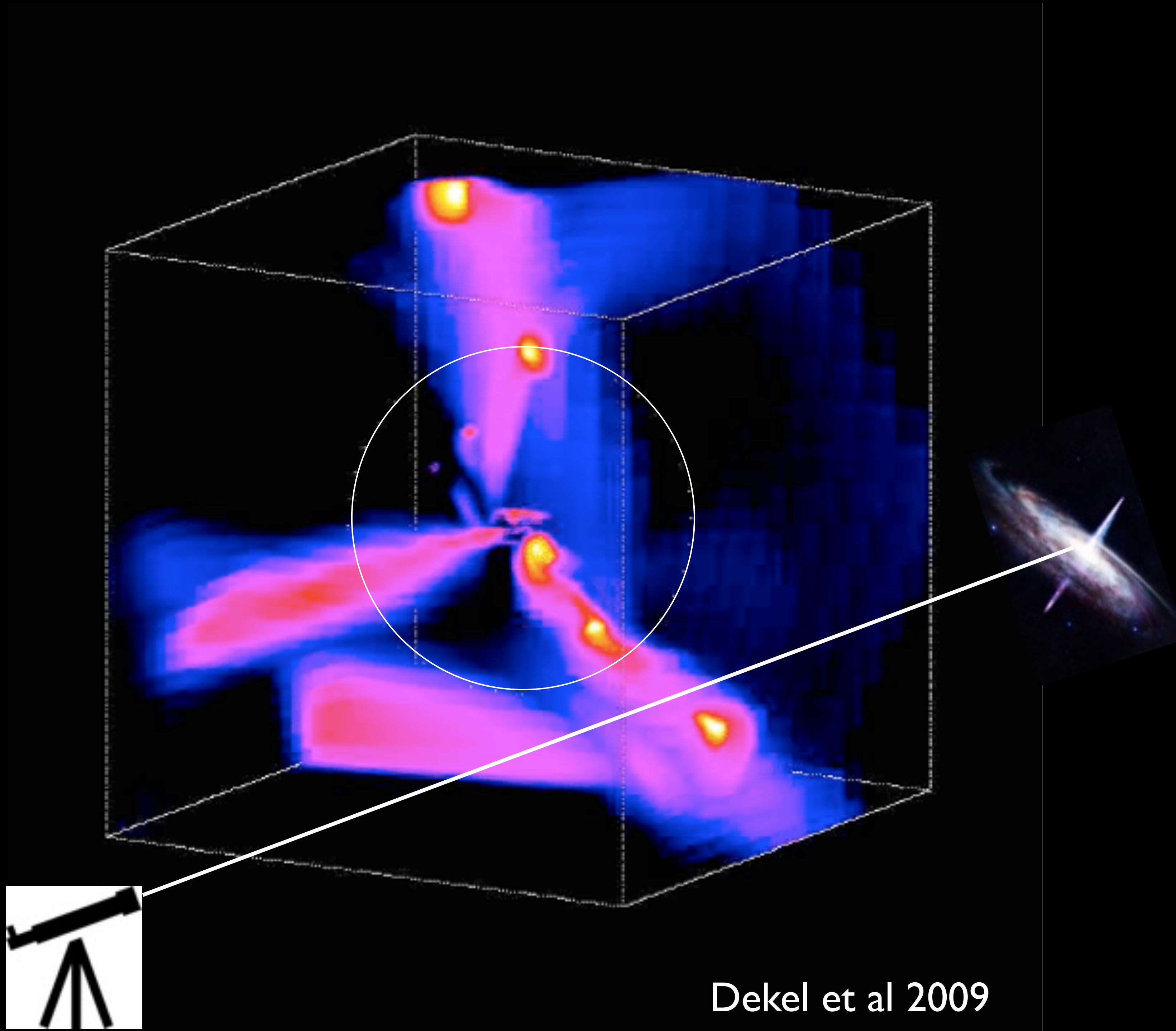
Birnboim & Dekel 2003

COLD MODE ACCRETION

$t_{\mathrm{cool}} < t_{\mathrm{ff}}$



$M_{VIR} < 10^{12}\ M_{\odot}$ LIKE IT COLD!



Dekel et al 2009

NB $t_{cool} \propto \rho_{gas}^{-1} \propto (1+z)^{-3}$

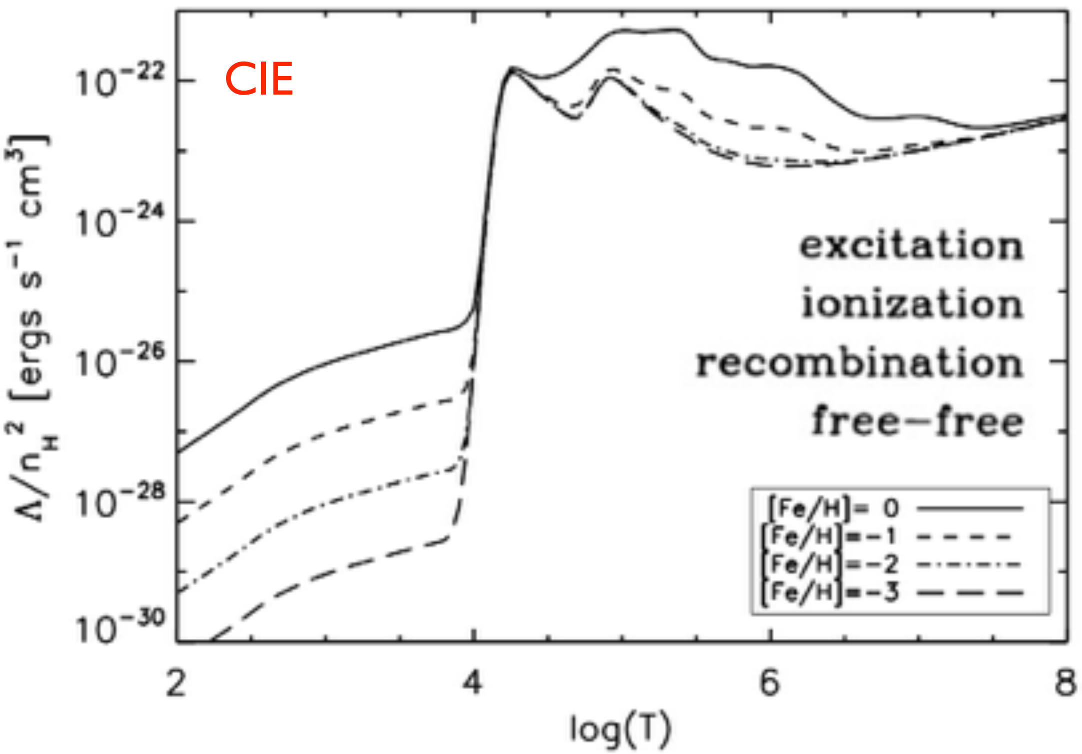
$t_{ff} \propto \rho^{-1/2} \propto (1+z)^{-3/2}$

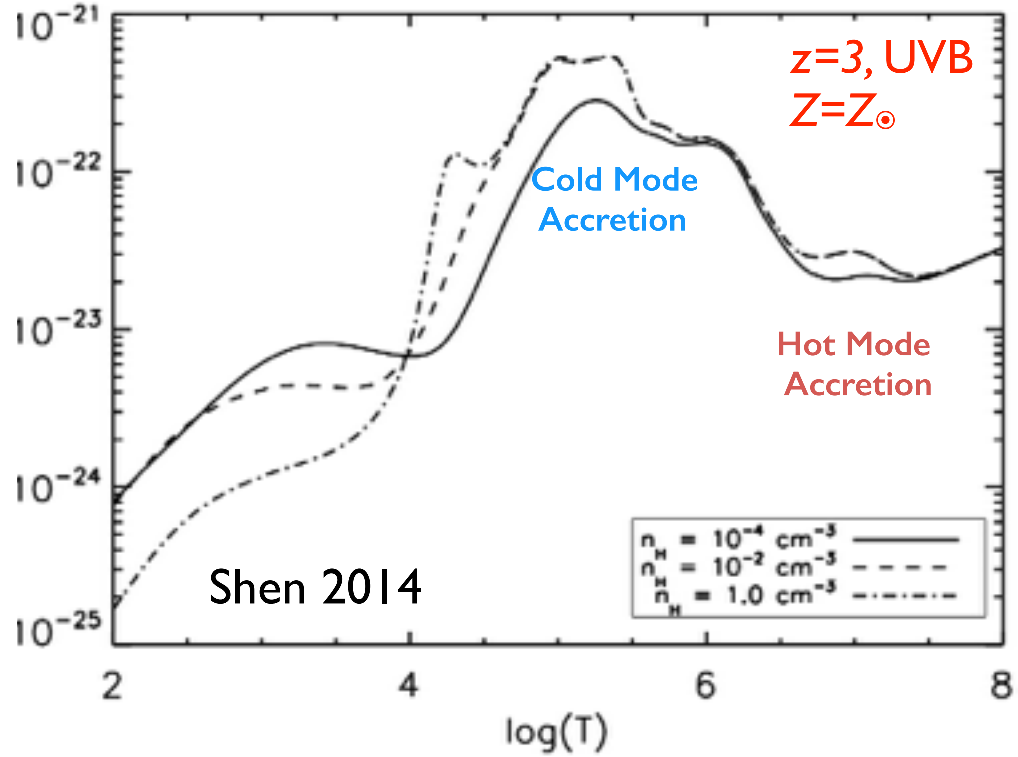
⇨ cooling is generally more efficient at high redshifts

CLASSICAL OVERCOOLING PROBLEM IN GALAXY FORMATION!

NB: $Z=Z_\odot$ cooling rate is 100 times higher than $Z=0$ at $T=10^6$ K

NB: UVB boosts low-T cooling and reduces high-T cooling

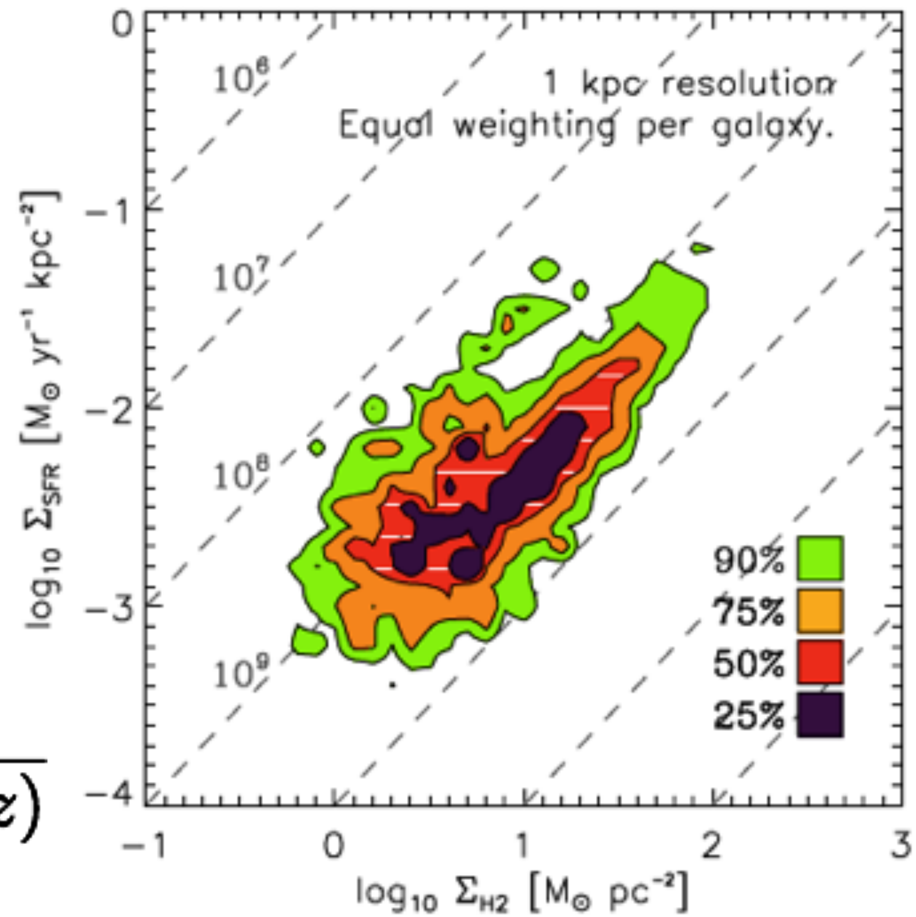




Gas Depletion Time

$$t_{\rm dep} = M_{\rm H_2}/\dot{M}_*$$

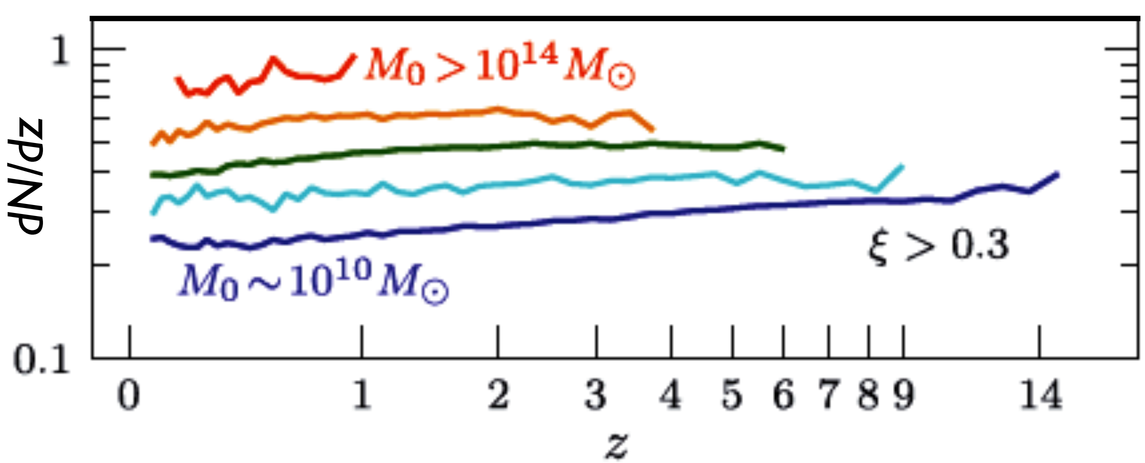
$t_{\rm dep} \approx 2\,{\rm Gyr} \gg t_{\rm ff}$ in disk galaxies



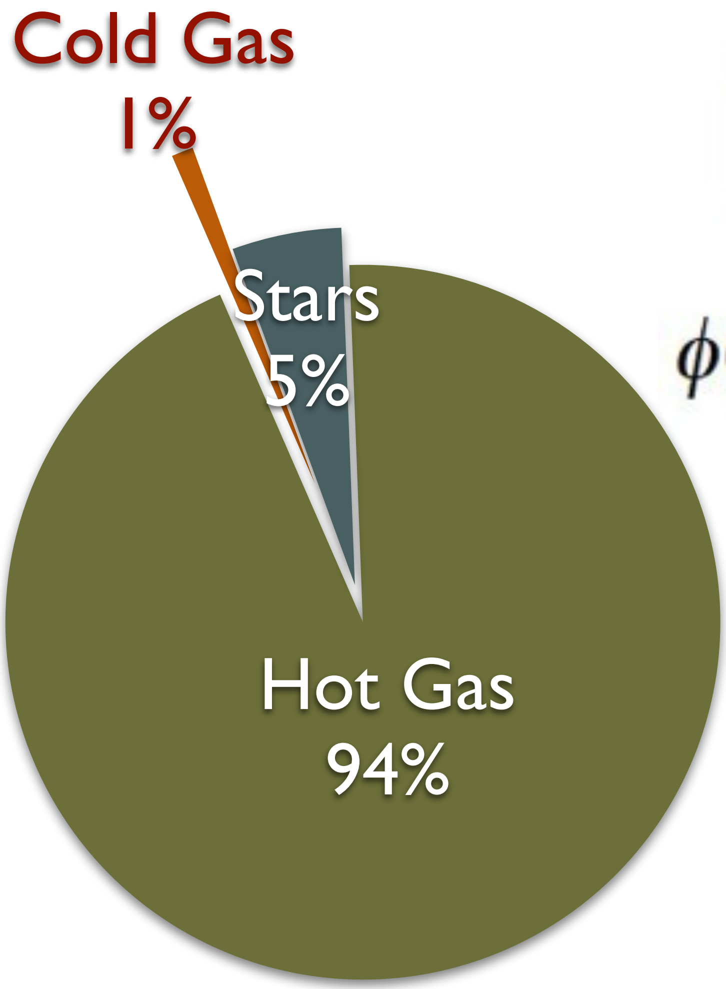
Question: Why is star formation so inefficient in disk galaxies? In particular, in those systems where $t_{\rm cool} < t_{\rm ff}$, why doesn't all the gas collapse and form stars?

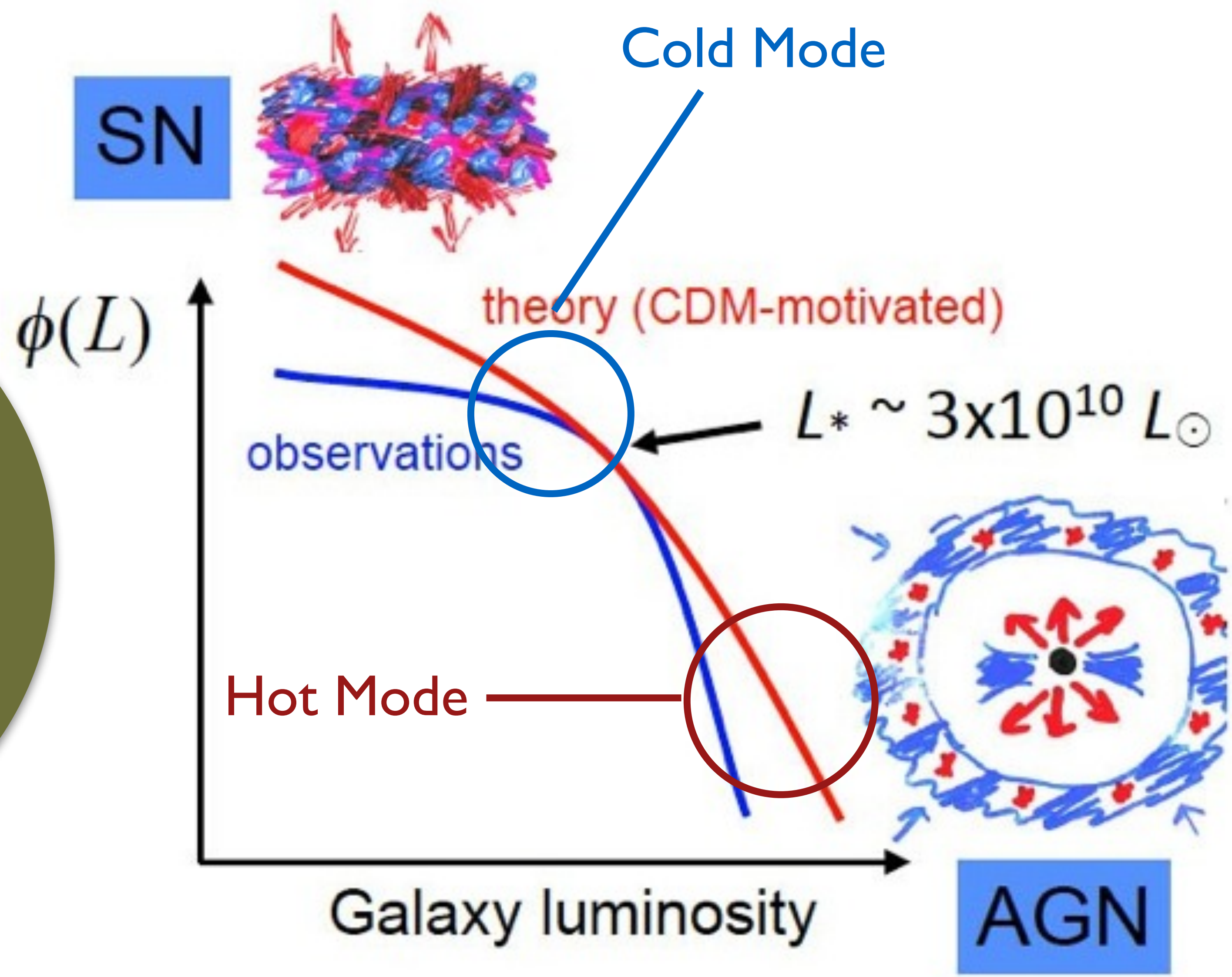
Merging Time

$$t_{\rm merg} = \frac{t_{\rm H}}{(1+z)(dN/dz)}$$



BARYONS MATTER: FEEDBACK





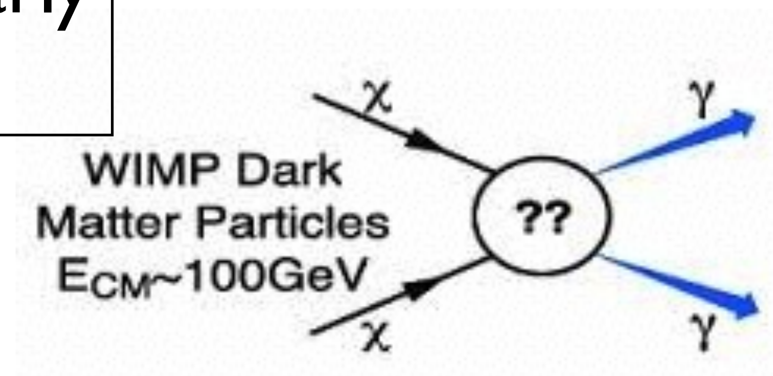
Introduction

Basic Elements of Galaxy Formation

Lies, Damned Lies, and Simulations

COSMIC RELICS

DM=some X particle created in the early Universe that has *no em. interaction*



NON-THERMAL RELICS

produced by a non-thermal mechanism, e.g. axions, WIMPZILLA

THERMAL RELICS

produced in TE with other components, e.g. neutralinos, neutrinos, WIMP

HOT

$$3k_BT_D > m_Xc^2$$

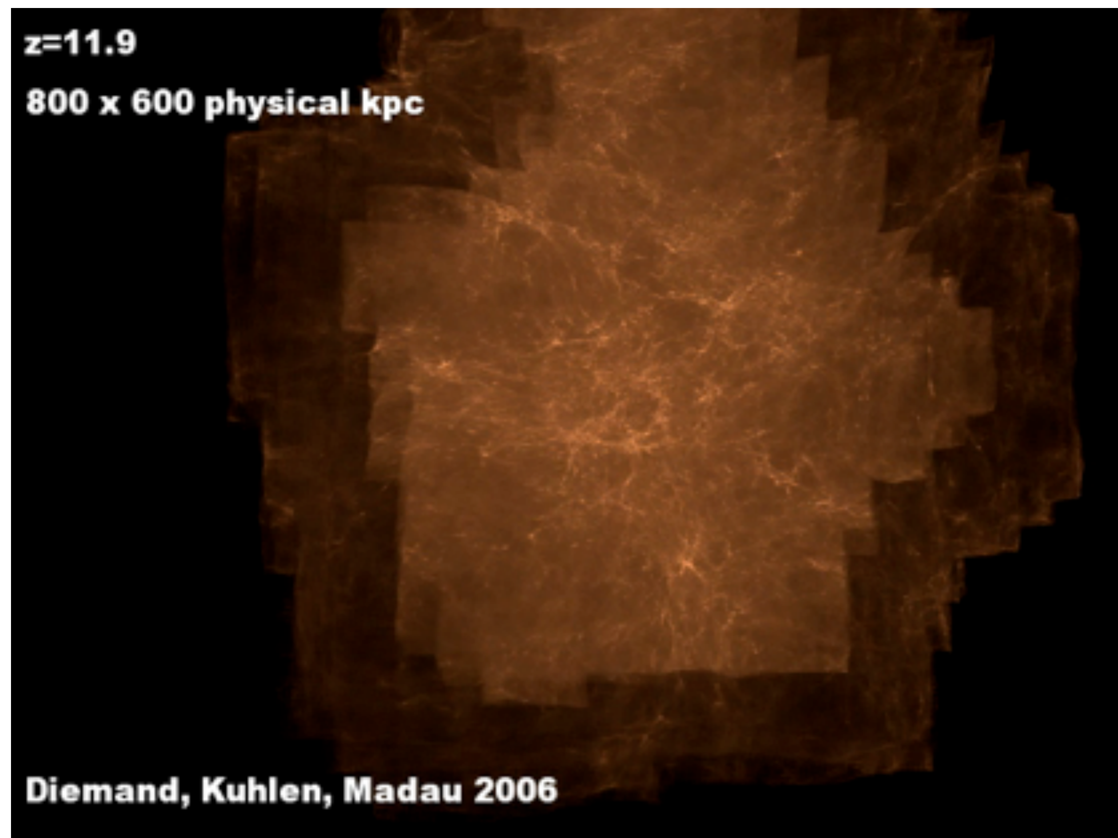
COLD

$$3k_BT_D < m_Xc^2$$

N-Body Cosmological Simulations of a Galaxy Halo

- assume all Ω_M is in cold WIMPs, and sample it with *N* particles.
- bad approximation in the center of a massive galaxy where baryons dominate, OK for ultra-faint dwarfs (*M/L~1000*).
- simple physics (just gravity) & good CPU scaling ➪ high spatial and temporal resolution.
- no free parameters (ICs known from CMB and LSS)

➪ ACCURATE SOLUTION TO AN IDEALIZED PROBLEM



HIERARCHICAL N-BODY TREE CODES

OCTREE gravity calculation

$O(N^2) \Rightarrow O(N \log N)$

Newton's equations of motion in co-moving coordinates

$$\frac{d\vec{x}}{dt} = \vec{v}$$

$$\frac{d\vec{v}}{dt} + 2H(a)\vec{v} = -\frac{1}{a^2}\vec{\nabla}\phi.$$

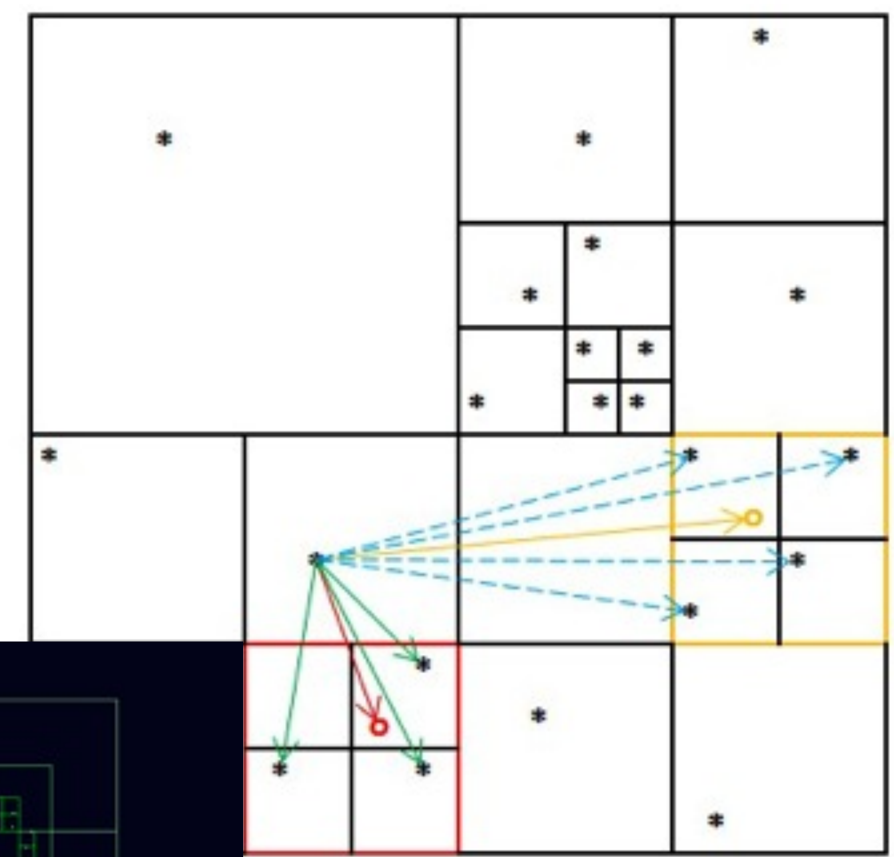
Cosmology, the expansion of the universe

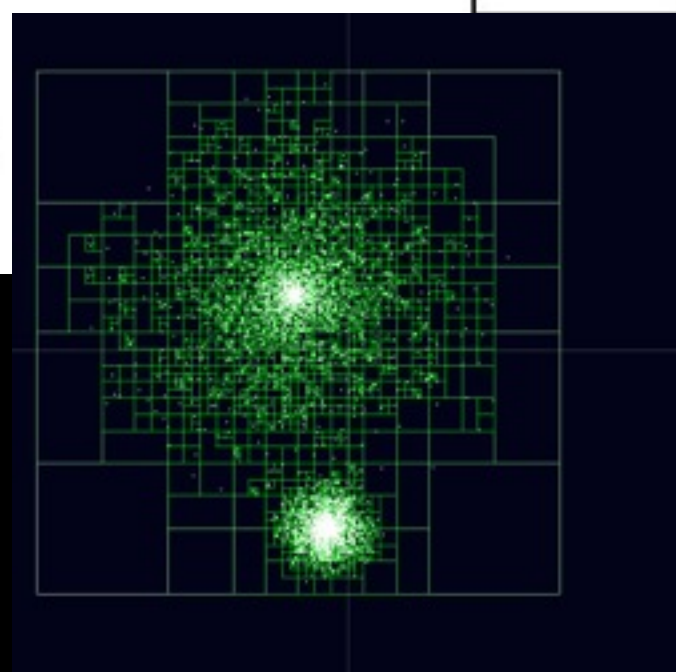
$$H(a) = \dot{a}/a \quad \text{(Hubble constant)}$$

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G\rho_b(t) + \frac{\Lambda}{3} \quad \text{(2}^{\text{nd}}\text{ Friedman equation)}$$

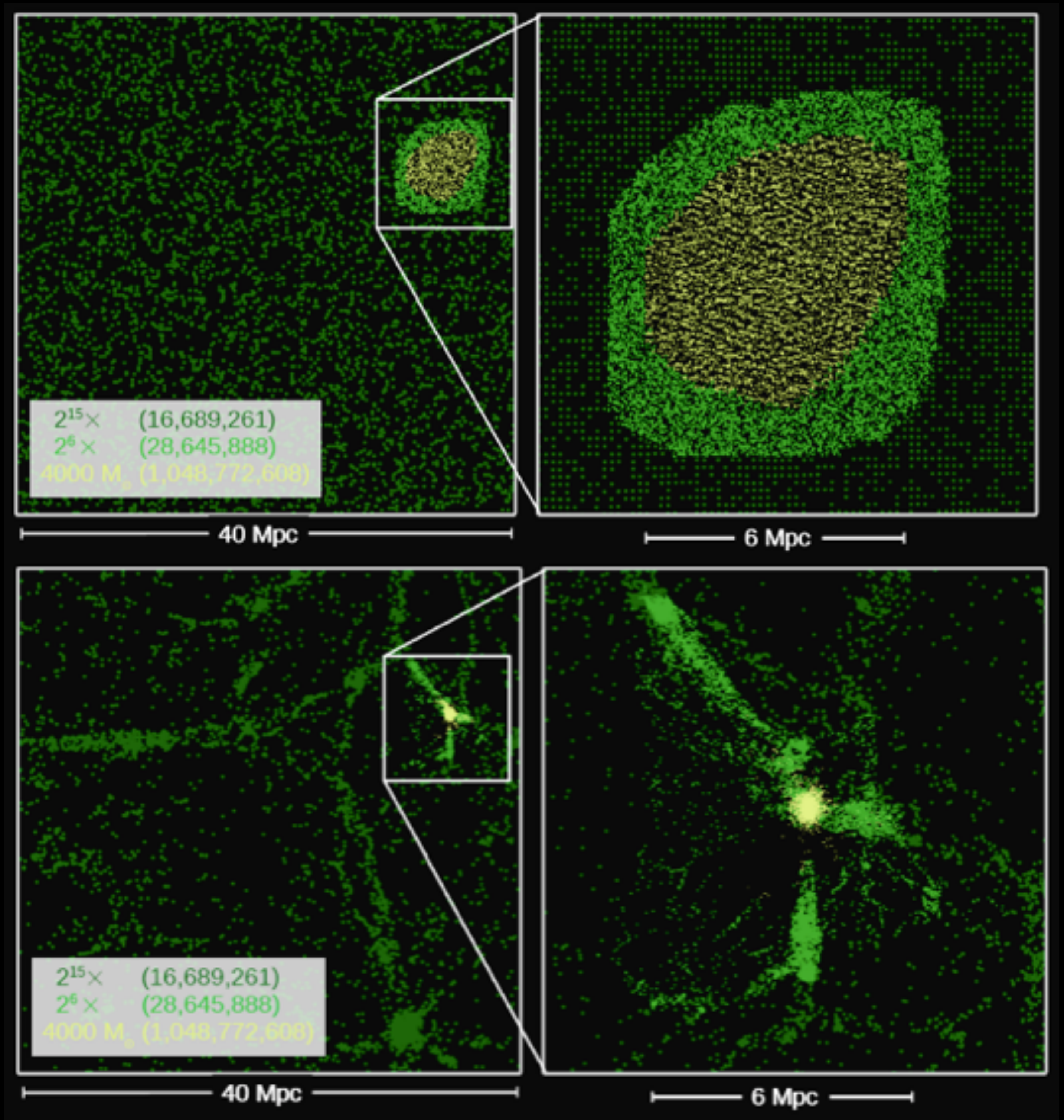
Gravitational potential

$$\nabla^2\phi = 4\pi G\rho a^2 - \Lambda a^2 + 3a\ddot{a}$$
$$= 4\pi G(\rho - \rho_b)a^2$$





Zooming-in



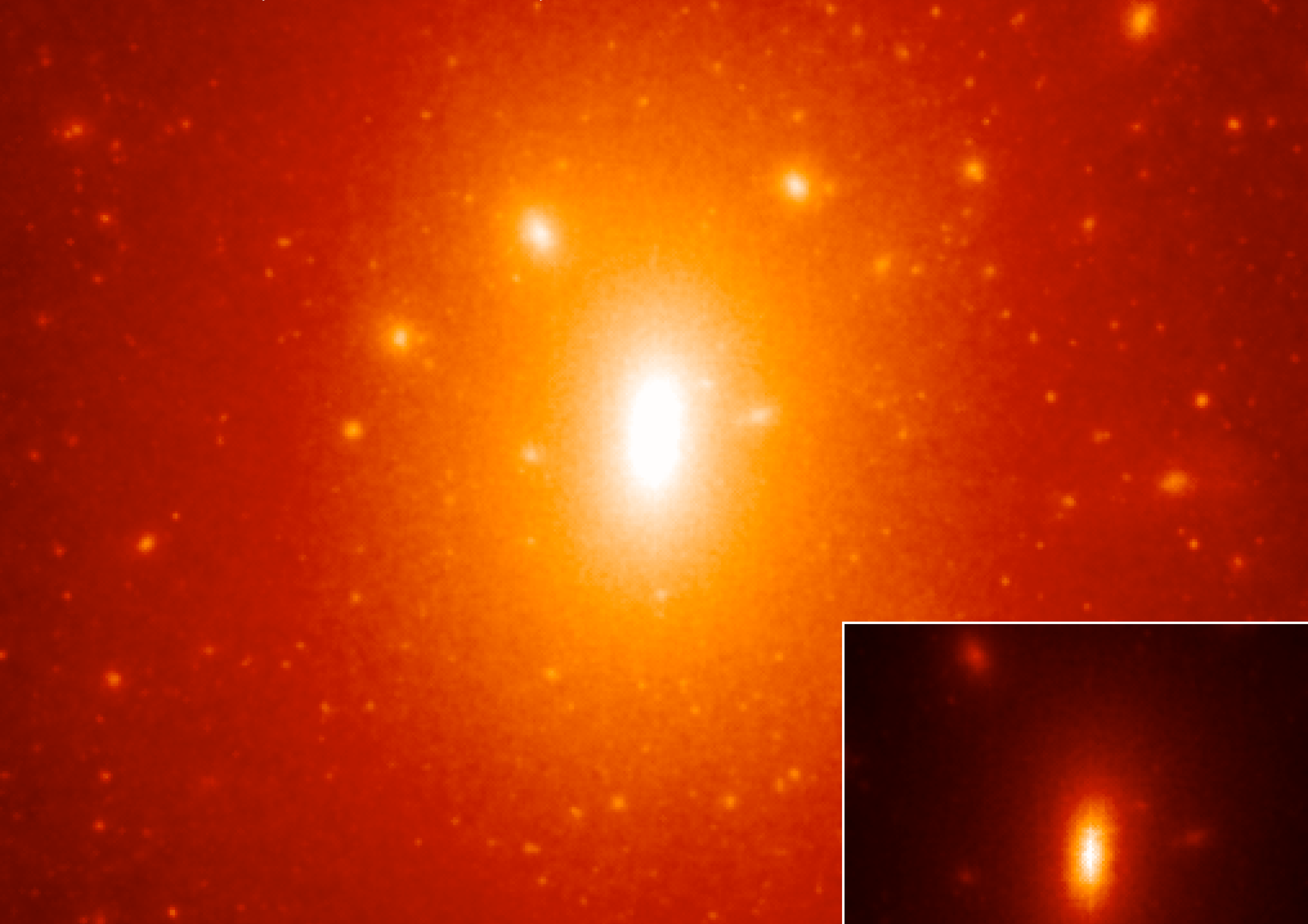
$2^{15}\times$ (16,689,261)
$2^{6}\times$ (28,645,888)
4000 $M_\odot$ (1,048,772,608)
40 Mpc
6 Mpc
$2^{15}\times$ (16,689,261)
$2^{6}\times$ (28,645,888)
4000 $M_\odot$ (1,048,772,608)
40 Mpc
6 Mpc

Structure Formation: an *N*-Body simulation of the Assembly of a Milky Way Halo

note the accretion of matter along filaments and the clumpiness of the final DM distribution…..

Stadel, Potter et. al. 2008

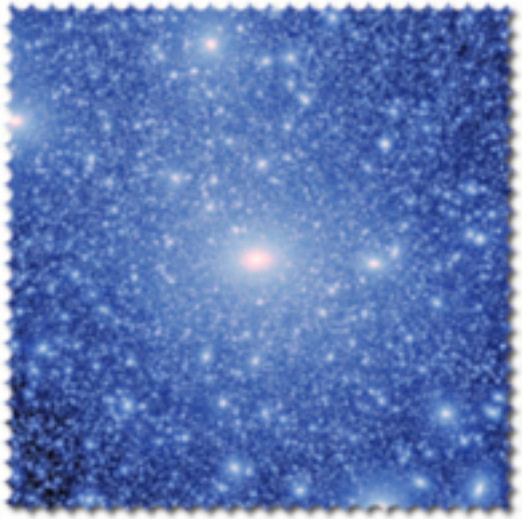
Resolution, Resolution, Resolution



Resolution, Resolution, Resolution

Resolution, Resolution, Resolution

Incompletely Phase-Mixed Material

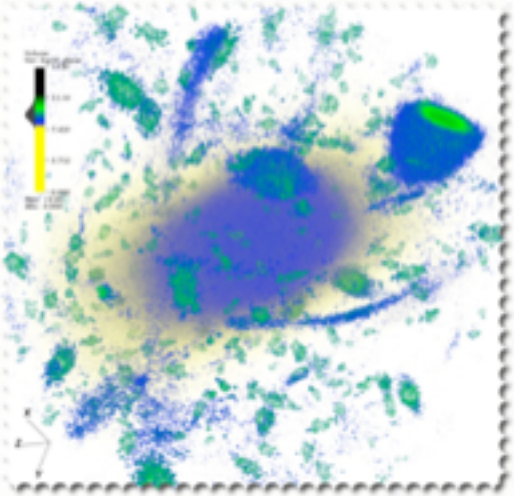


Clumps

DM Indirect Detection

Annihilation Rate

$$\int_{\text{line of sight}} \rho_{\text{DM}}^2 \, d\ell$$

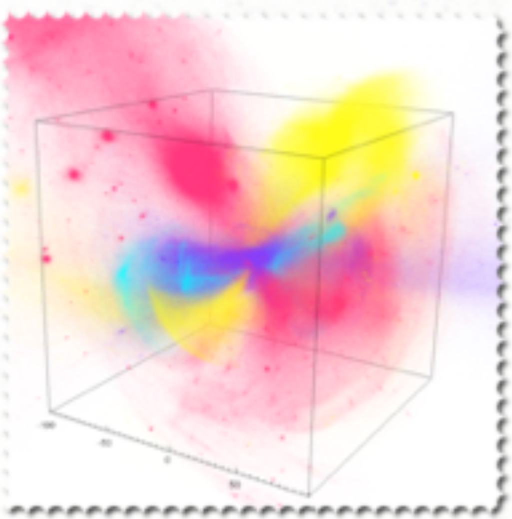


Streams

Direct Detection

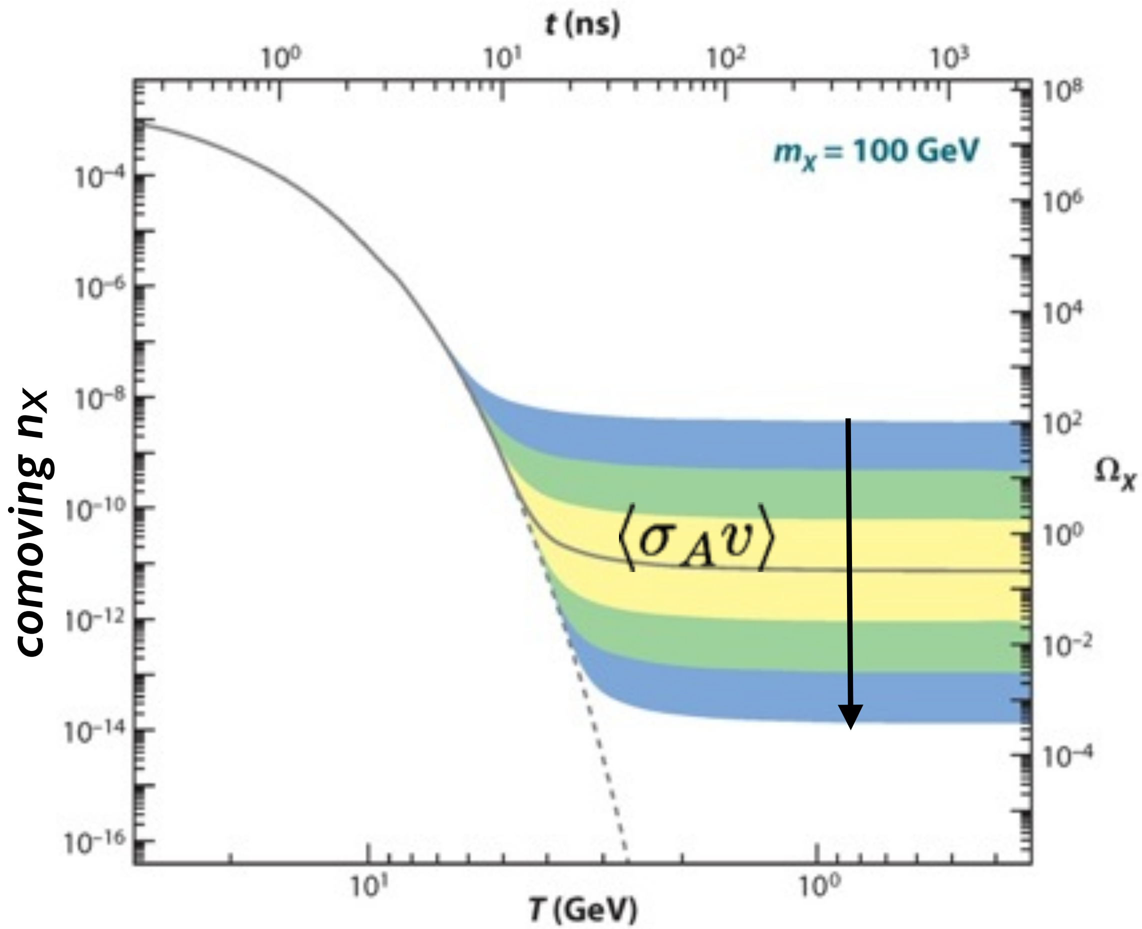
Nucleon Scattering Rate

$$\rho_{\text{DM}} \int_{v_{\min}}^{\infty} \frac{f(v)}{v} \, dv$$



Debris Flows (Shells, Sheets, Plumes)

THE WIMP MIRACLE



BOLTZMANN EQ.

$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma_A v \rangle (n_X^2 - n_{X,\mathrm{eq}}^2)$$

DECOUPLING

$$\Gamma = n_X \langle \sigma_A v \rangle < H$$

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm^3 s^{-1}}}{\langle \sigma_A v \rangle} \qquad \Omega_\chi h^2 \simeq 0.11$$

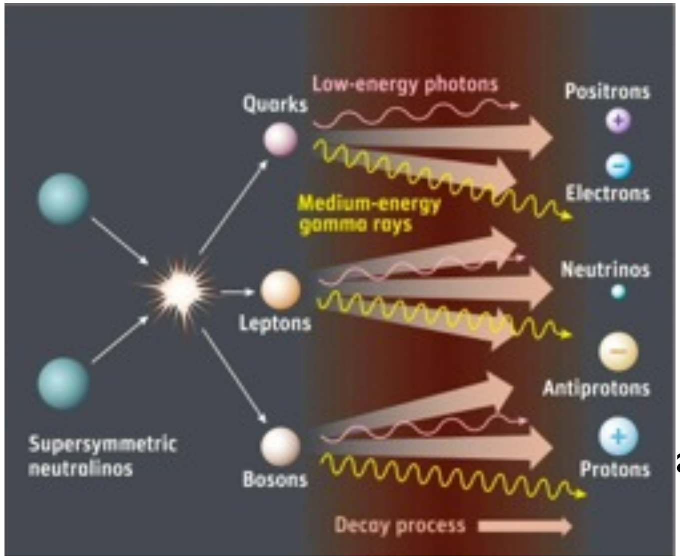
$$\langle \sigma_A v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm^3 s^{-1}} \quad \sigma_W \sim \alpha^2 / m_W^2$$

Willman I: $r_s = 180\,\mathrm{pc},\ \rho_s = 0.4\,\mathrm{M}_\odot\ \mathrm{pc}^{-3}$

$m_\chi = 150\,\mathrm{GeV}$ $\qquad d = 38\,\mathrm{kpc}$

$$L_{\rm ann}^{\rm WI} = \frac{\langle \sigma v \rangle}{m_\chi} \left(\frac{4\pi}{3}\right) r_s^3 \rho_s^2 \sim 10^{35}\ \mathrm{ergs\ s^{-1}}$$

WIMP Annihilation Signal

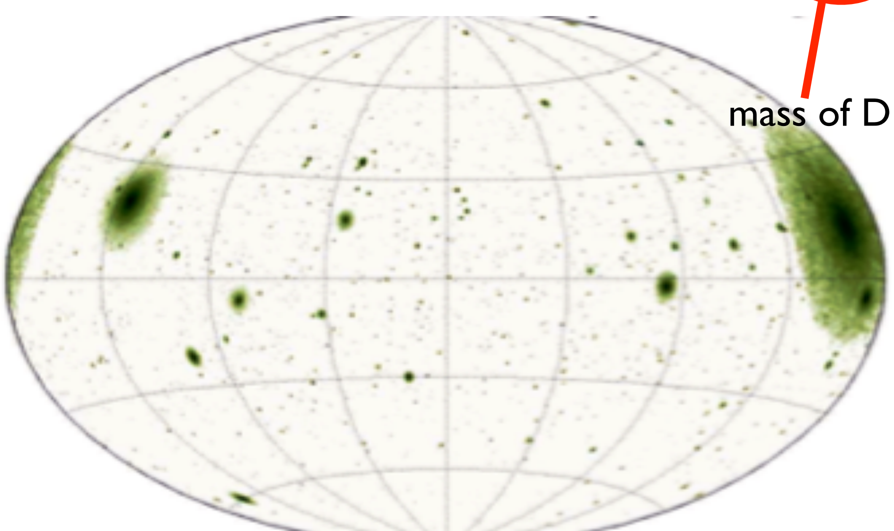


annihilation cross-section x thermal velocity

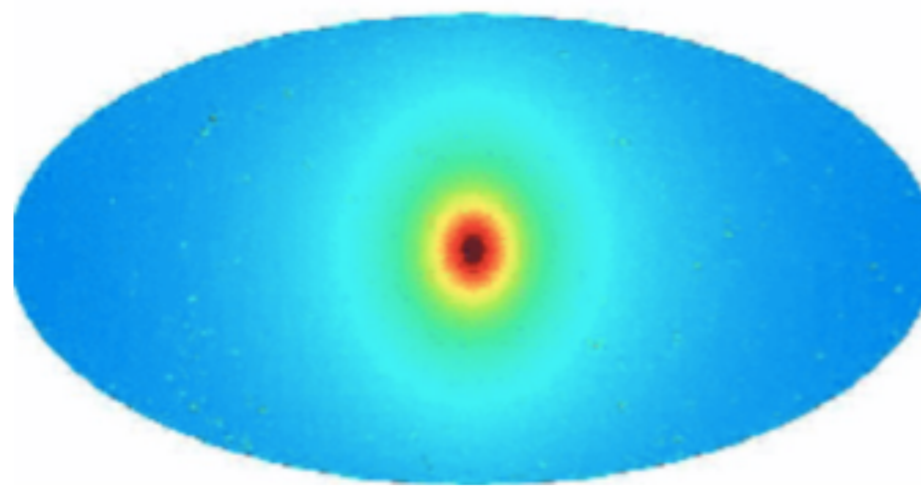
γ-photons produced per annihilation

$$N_\gamma = \left[\int_{\text{line of sight}} \rho_{\rm DM}^2 \, dl(\psi)\right] \frac{\langle \sigma v \rangle}{M_\chi^2} \left[\int_{E_{th}}^{M_\chi} \left(\frac{dN_\gamma}{dE}\right)_{\rm SUSY} A_{\rm eff}(E) dE\right] \frac{\Delta\Omega}{4\pi} \tau_{\rm exp}$$

mass of DM particle

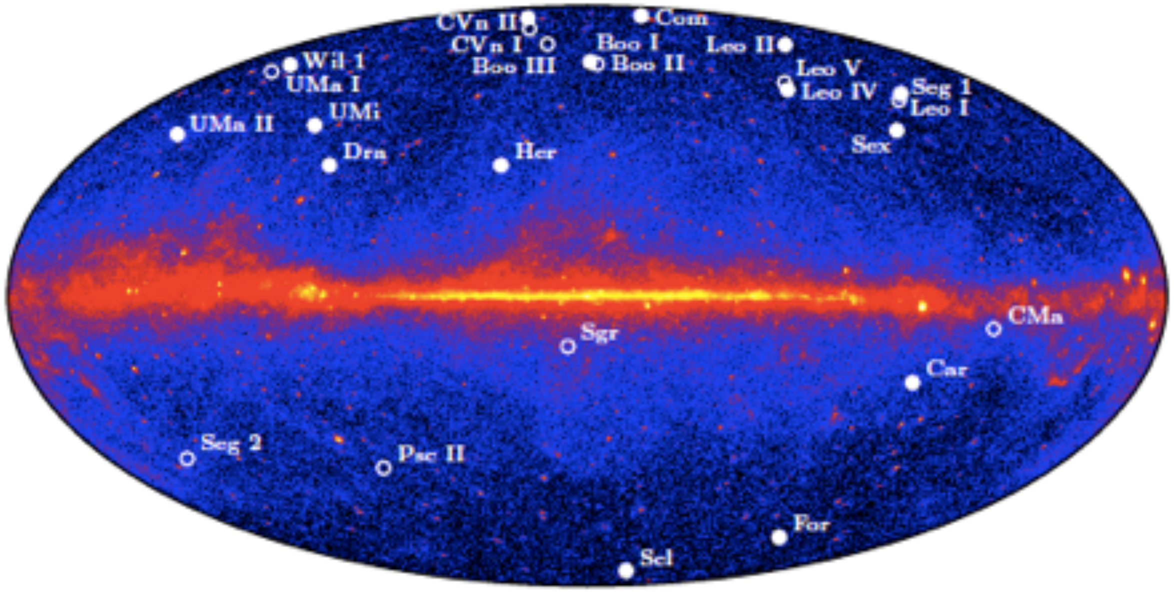


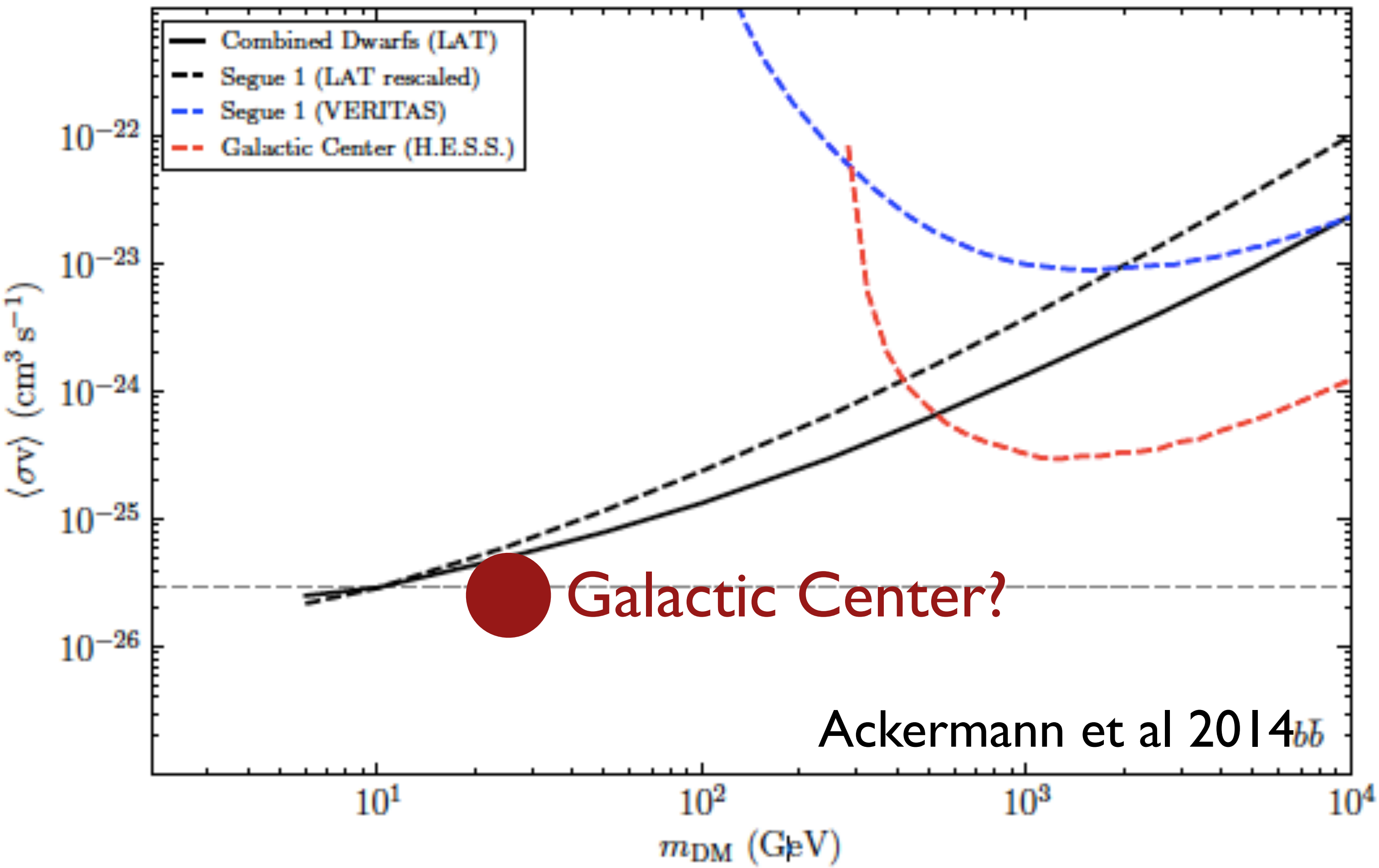
Kuhlen et al. 2008, Anderson et al. 2010



Springel et al. 2009

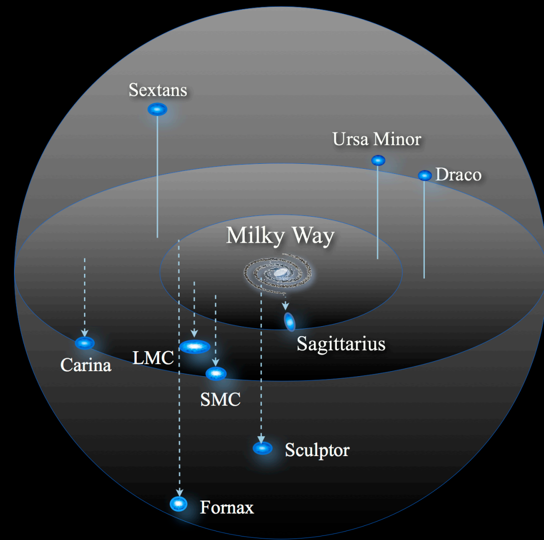
FERMI'S 25 DWARFS

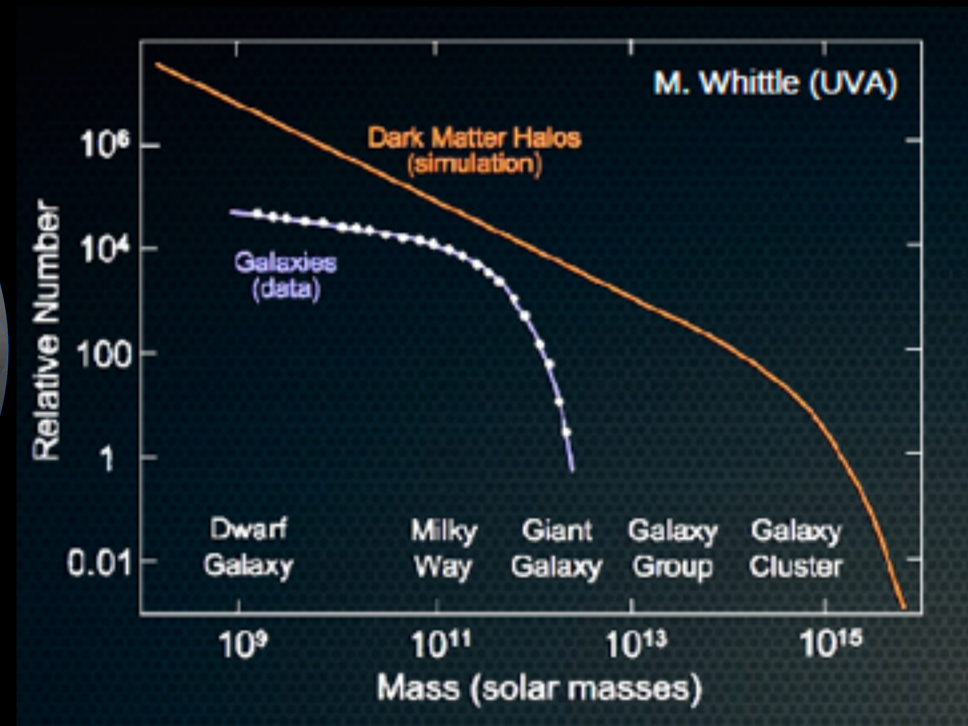




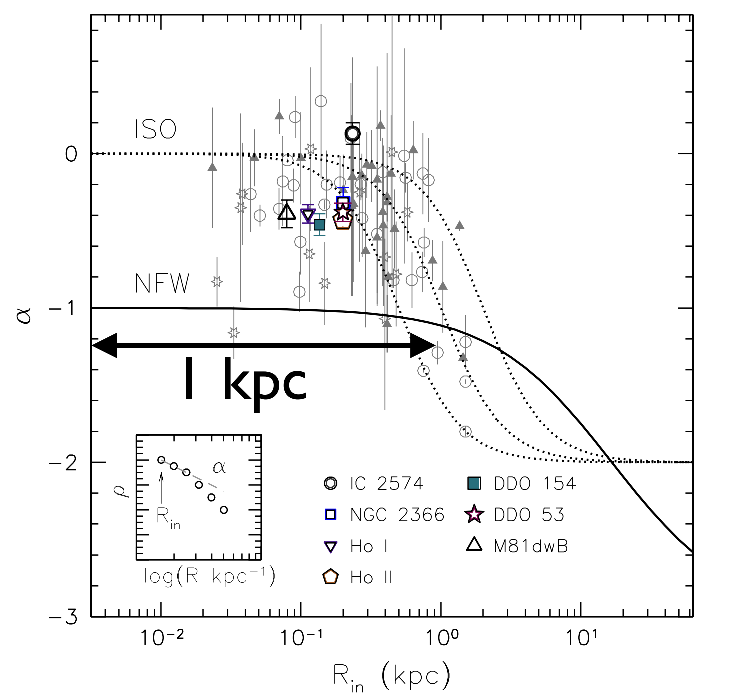
The Small-Scale Crisis

Missing Satellite Problem

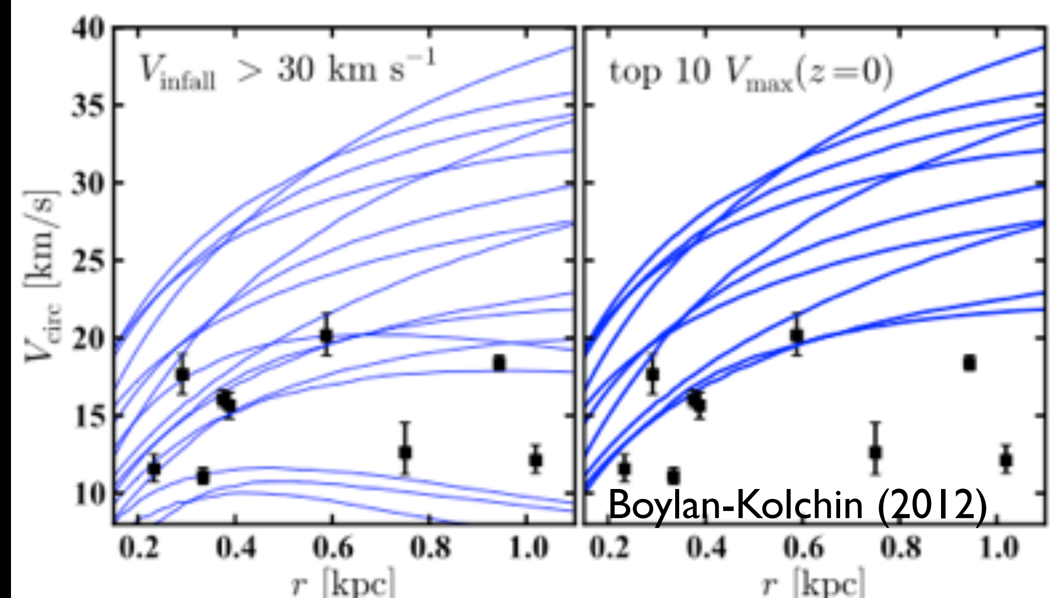




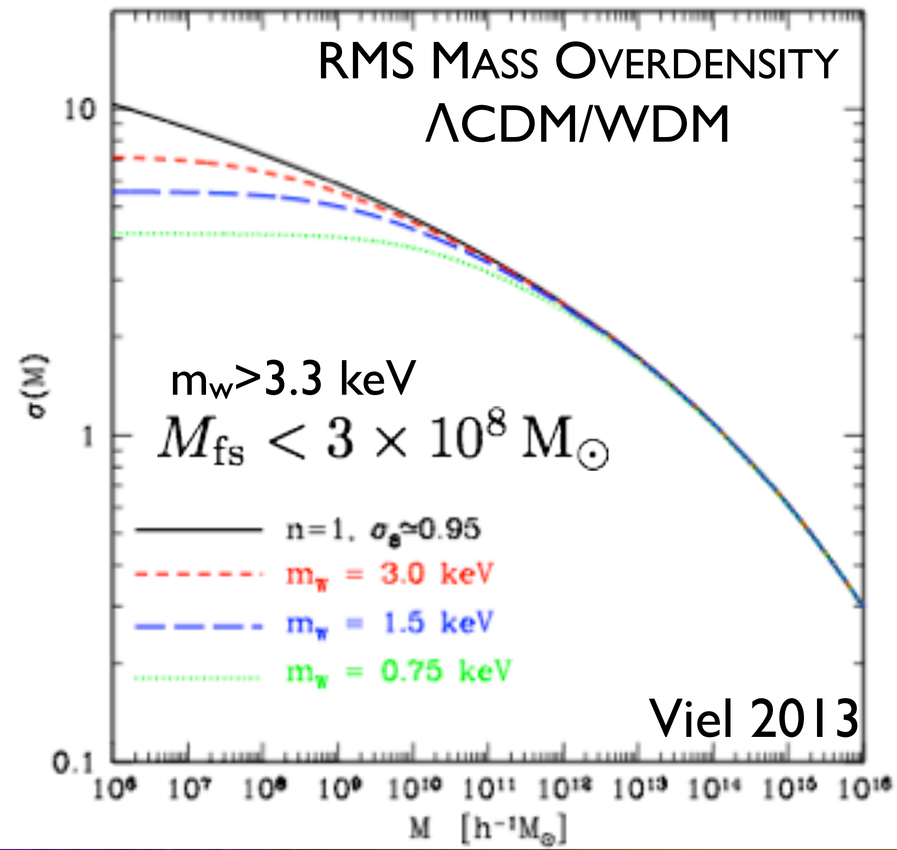
Cusp/Core Problem



Too-Big-Too-Fail Problem

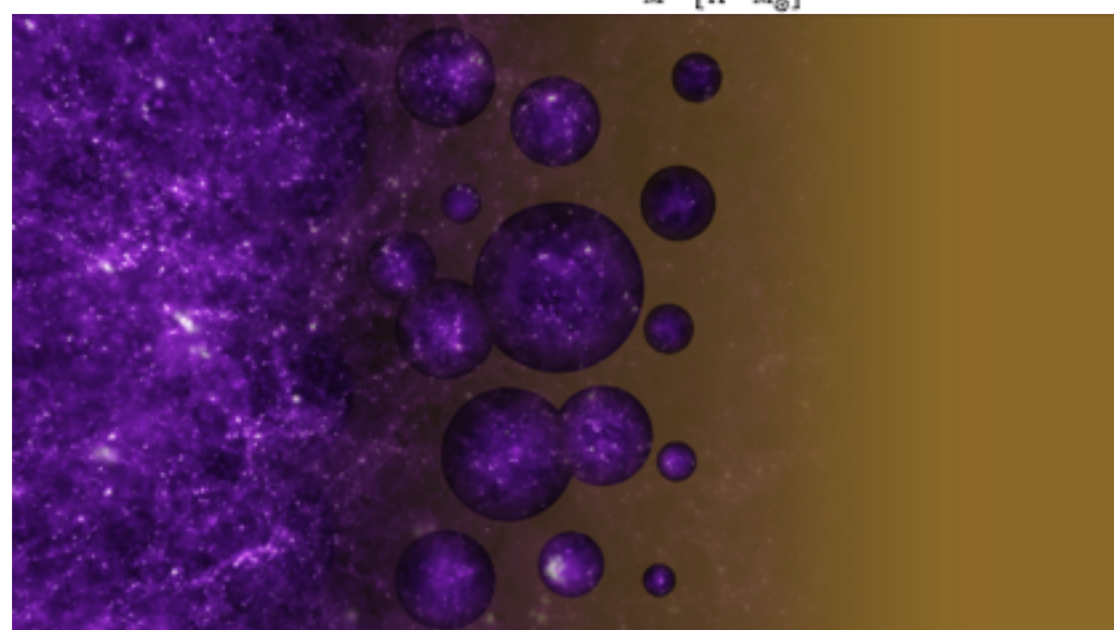


Why Do We Care About Dwarfs?



- DGs are cosmic DM laboratories: probe the power spectrum on small scales and offer a unique test of the particle nature of the dark matter.

- DGs are the champions of the epoch of first light: first generation of cosmic structures to go nonlinear ➪ believed to be responsible for the reionization and chemical enrichment of the early universe.



ERIS SIMULATION OF A MW GALAXY

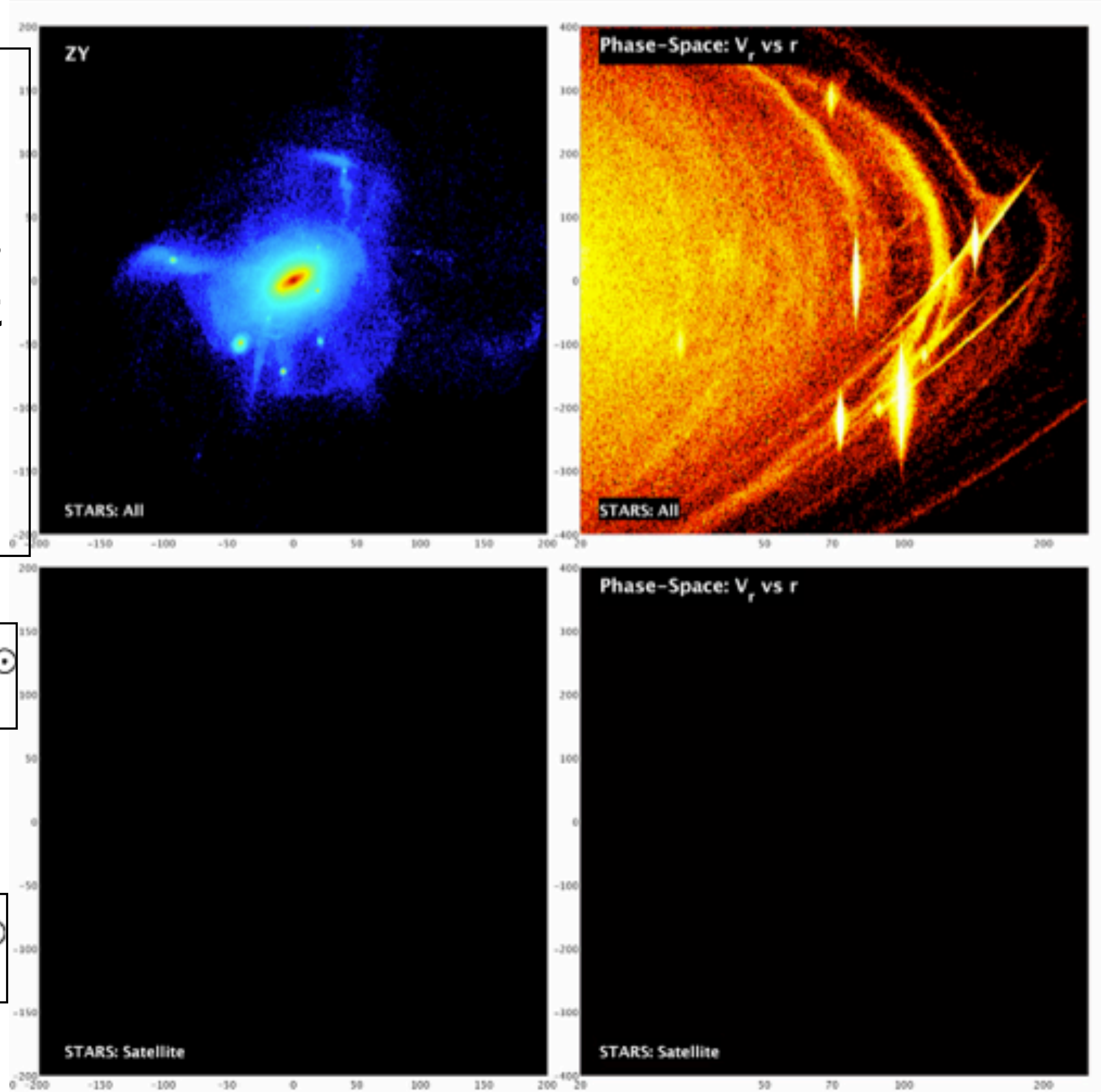
$M_{\rm vir} = 8 \times 10^{11}\,{\rm M}_\odot$
$N = 13{\rm M\ (DM)} + 13{\rm M\ (SPH)}$

Guedes et al 2011

- DGs are the building blocks of massive galaxies: their remnants provide a powerful test of the hierarchical assembly of cosmic structures.

$z_i = 0.77, M_{\rm vir} = 9 \times 10^9\,{\rm M}_\odot$
$M_* = 2.6 \times 10^8\,{\rm M}_\odot$

$z = 0, M_{\rm vir} = 3.4 \times 10^7\,{\rm M}_\odot$
$M_* = 2.2 \times 10^7\,{\rm M}_\odot$

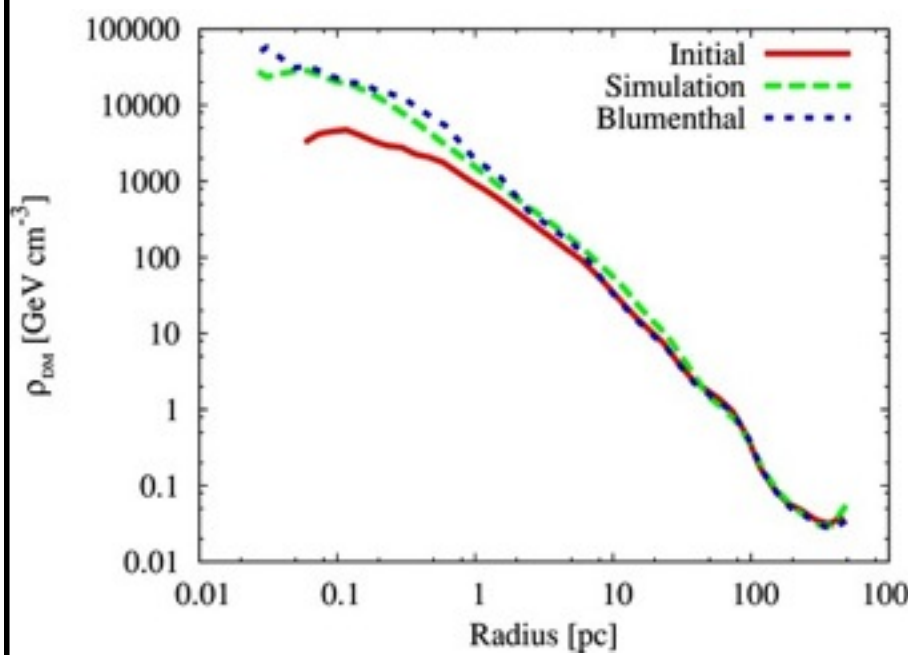


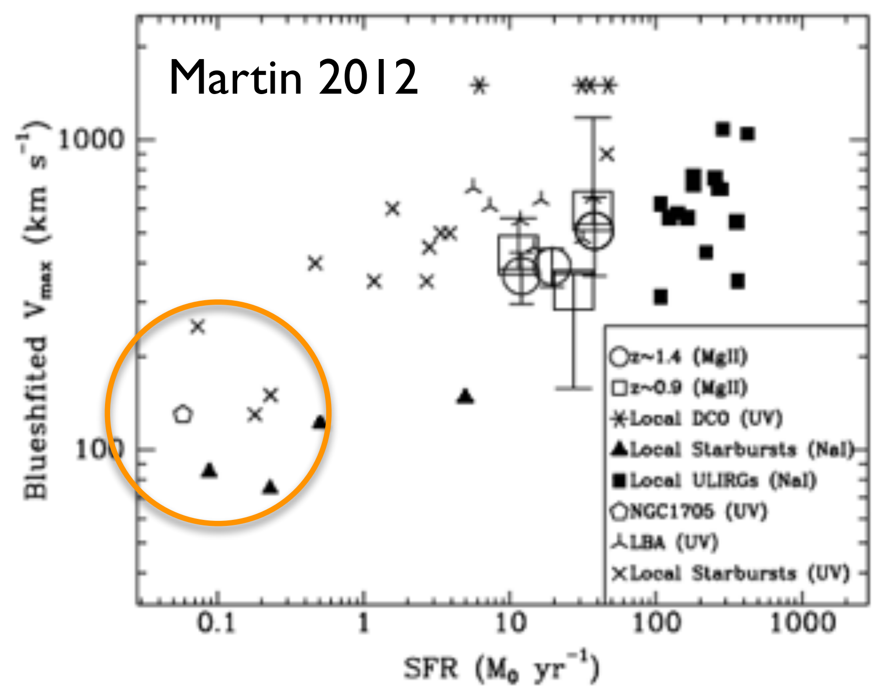
Pillepich et al 2014

ATTRACTIVE SOLUTION TO THE DG PROBLEM: BARYONS

• Until recently any direct effect of the baryonic component on the DM was limited to a minor *adiabatic* correction, i.e. baryonic processes modulate the SFR without changing the underlying DM scaffolding.

• This picture has recently been subverted. Spectroscopic observations have revealed the ubiquity of *galaxy-scale outflows*, even in dwarfs with $SFR \ll 1 M_{\odot}/yr$. It has been realized that these processes have a *non-adiabatic* impact on the host DM halo.





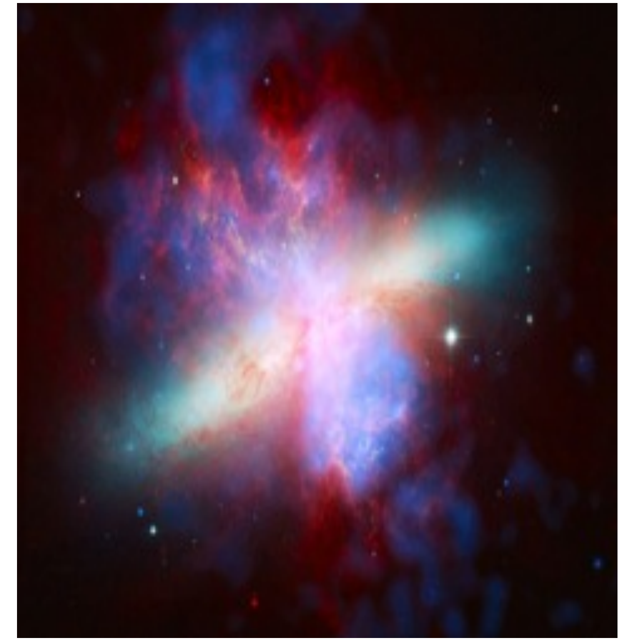
CAN SUPERNOVA FEEDBACK FIX DM DENSITIES? EXPLAIN LOW SFEs?

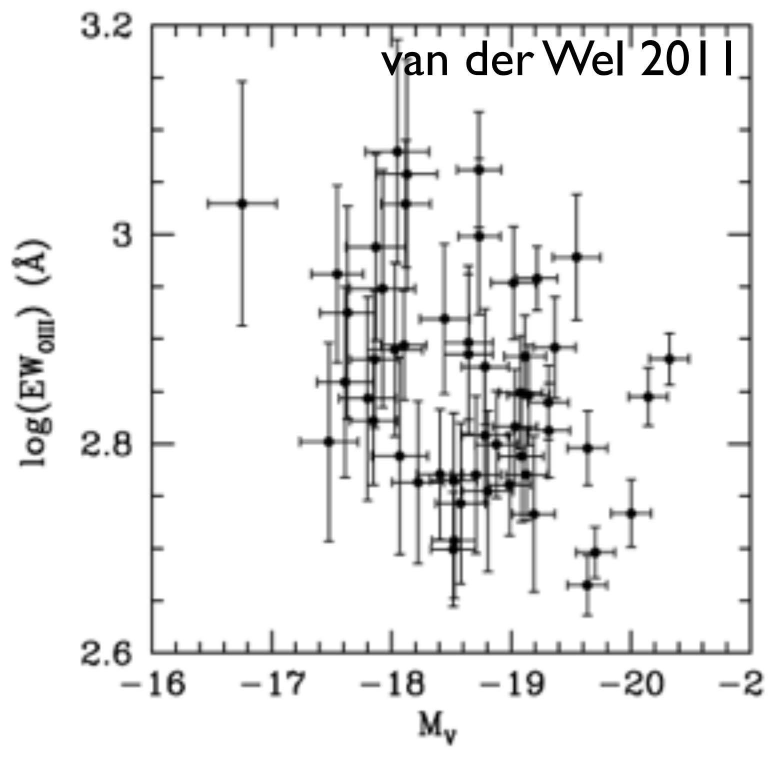
● Capturing the baryonic and feedback processes that regulate the *metabolism* of DGs requires cosmological hydro simulations of high dynamic range.

● Gas in such *low-Z* systems does not settle into a *thin, cold disk,* and their shallow potential wells make the ISM more prone to disruption from energetic SNe.

● Star formation may proceed in a *bursty* manner that is different from that of larger mass spirals.

● Stellar feedback drives *galactic outflows* that modulate the stellar buildup, lower f_{gas} and alter the chemical evolution of DGs.





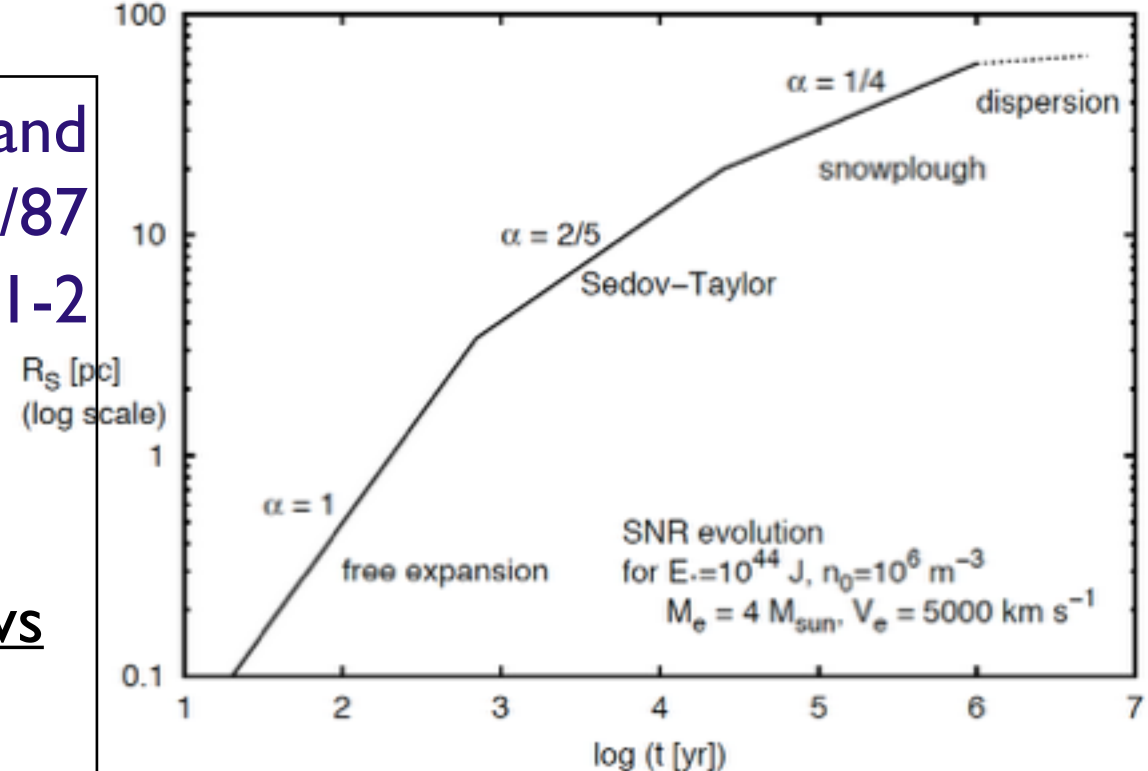
Feedback

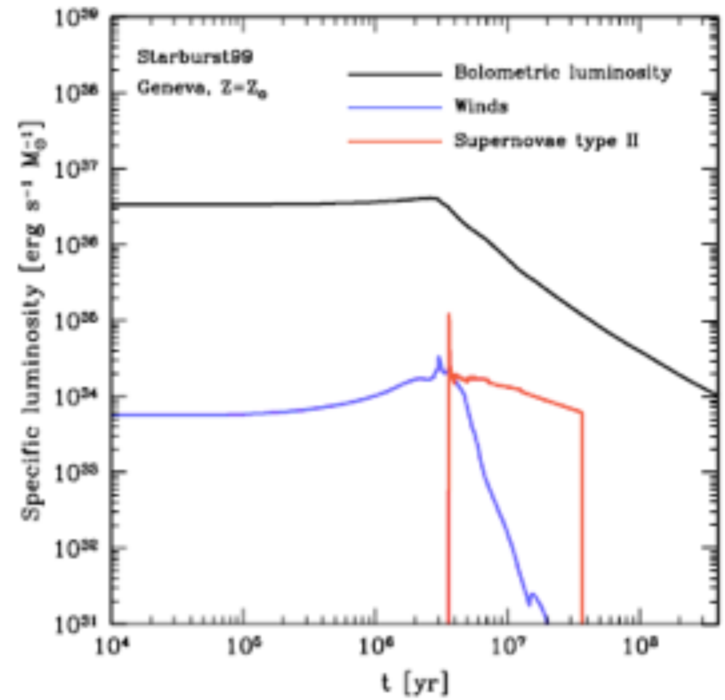
● Each SN deposits metals and $E \simeq 10^{51}$ ergs (Kroupa IMF ➪ 1 SN/87 M☉) into the nearest neighbors (1-2 SPH particles).

● SN feedback: heated gas has its cooling shut off ➪ <u>galactic ouflows</u>

$t_{\mathrm{blast}} = 10^{6.85}\ E_{51}^{0.32}\ n^{-0.16} P_{04}^{-0.2}$ yr
$R_{\mathrm{blast}} = 10^{1.74}\ E_{51}^{0.32}\ n^{0.34} P_{04}^{-0.7}$ pc
($t_{\mathrm{cool}} \sim T^{1/2}$ above 1 keV)

<u>minimalistic feedback</u>: cf. explicit wind particles/mass+metal loading/ 2-phase subgrid ISM/radiation pressure on dust/AGN feedback/ hydro decoupling (e.g. Vogelsberger et al. 2013).





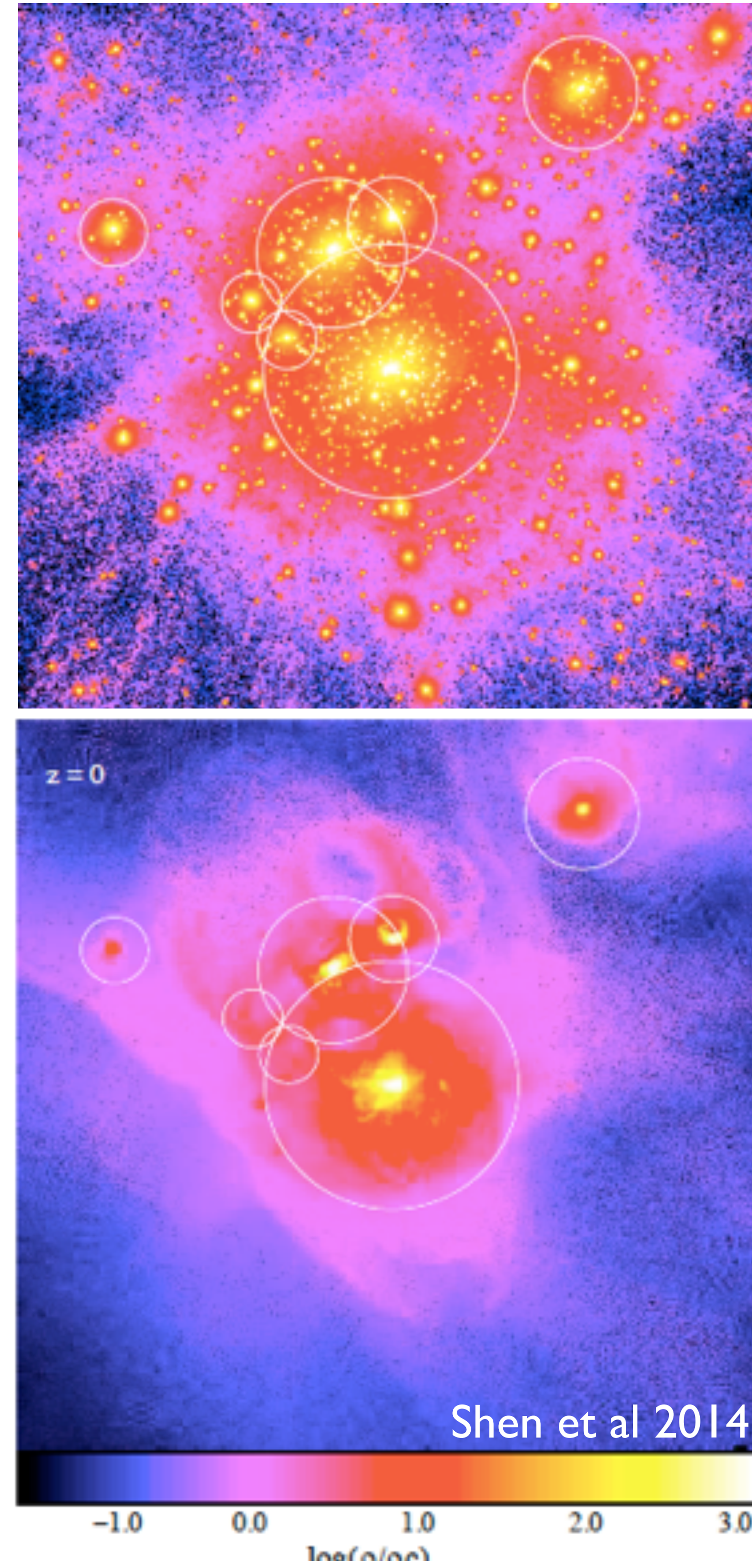
A Group of Seven Dwarfs

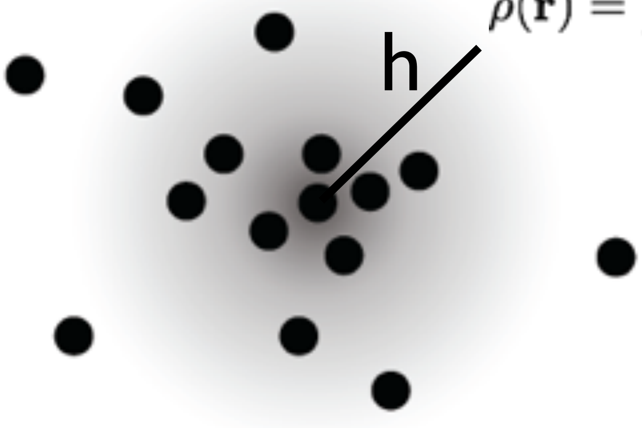
- LCDM cosmological SPH simulation run to *z=0*
- mass resolution $m_{\rm DM} = 1.6 \times 10^4\,{\rm M}_\odot$ $m_* = 1000\,{\rm M}_\odot$

- gravitational softening=86 ppc
- metal-dependent gas cooling
- UVB heating & photoionization
- high SF gas density threshold of 100 cm^{-3} ⇨ SF is clustered

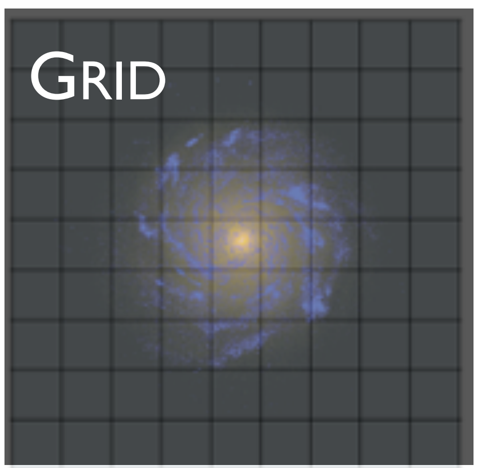
$$d\rho_*/dt = 0.1 \times (\rho_{\rm gas}/t_{\rm dyn}) \propto \rho_{\rm gas}^{3/2}$$

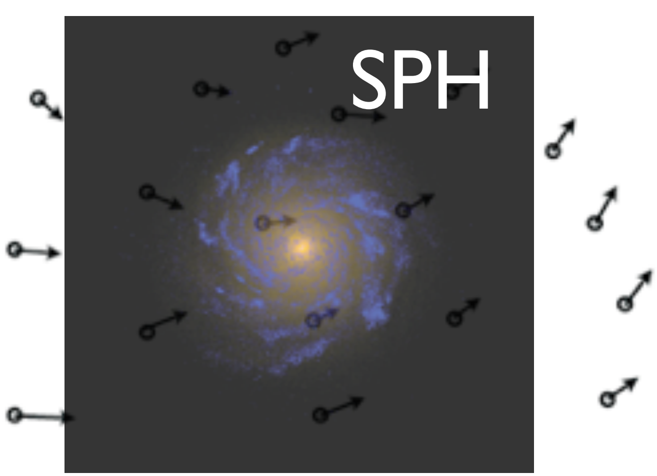
$$\lambda_{\rm J,th} = (\pi c_s^2/G\rho)^{1/2} \approx 50 T_3^{1/2}\ {\rm pc}$$





$\rho(\mathbf{r}) = \sum_{j=1}^{N} m_j W(|\mathbf{r}-\mathbf{r}_j|, h)$





Key Features of SPH

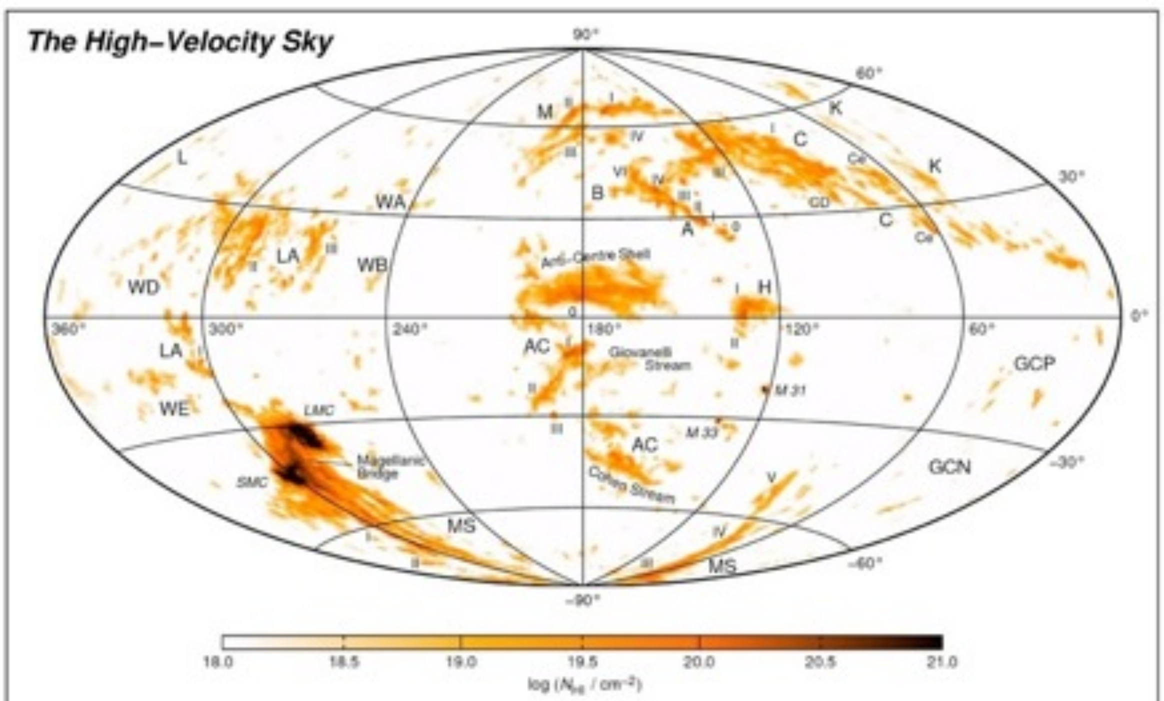
- An exact solution to the continuity equation.
- RESOLUTION follows mass, particle nature gives natural compatibility with N-body codes.
- ZERO intrinsic dissipation/numerical diffusion. Need to add some explicitly to: 1) capture shocks; 2) avoid suppression of fluid mixing.
- EXACT conservation of mass, momentum, angular momentum, entropy.
- ADVECTION done perfectly. Galilean invariance -- important in cosmological simulations where highly supersonic bulk flows are common.
- Does not CRASH ("screw-ups" indicated by noise rather than code crash).
- Gas particles have "NAMES".

Turbulent Diffusion of Metals and Thermal Energy

$$(dc/dt)_D = (1/\rho)\nabla \cdot (D\nabla c)$$

$$D = 0.05\,\rho|S_{\mathrm{ij}}|\,h^2$$

S_{ij}=trace-free velocity shear tensor ➪ no diffusion for compressive or purely rotating flow (Shen et al 2010)

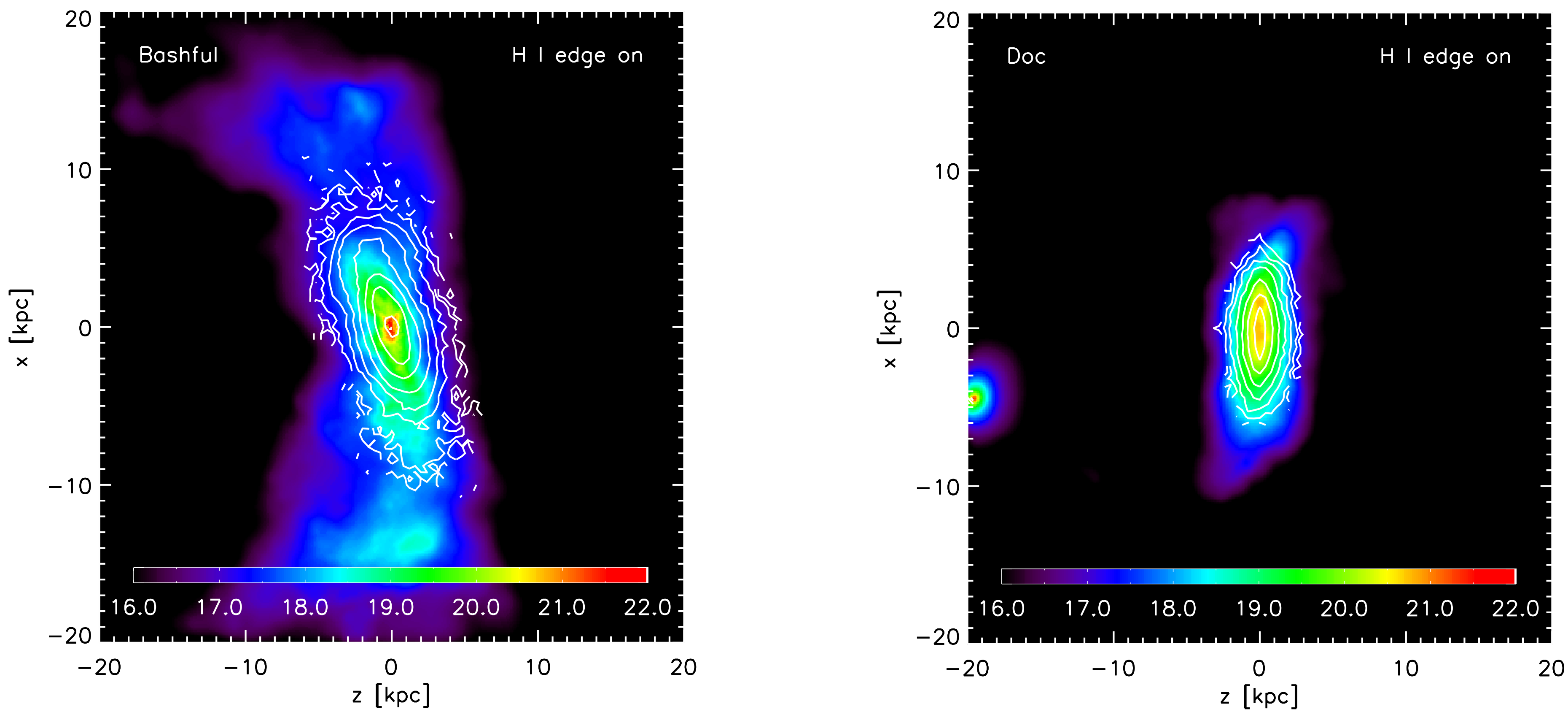


Tobias Westmeier, CSIRO Australia Telescope National Facility

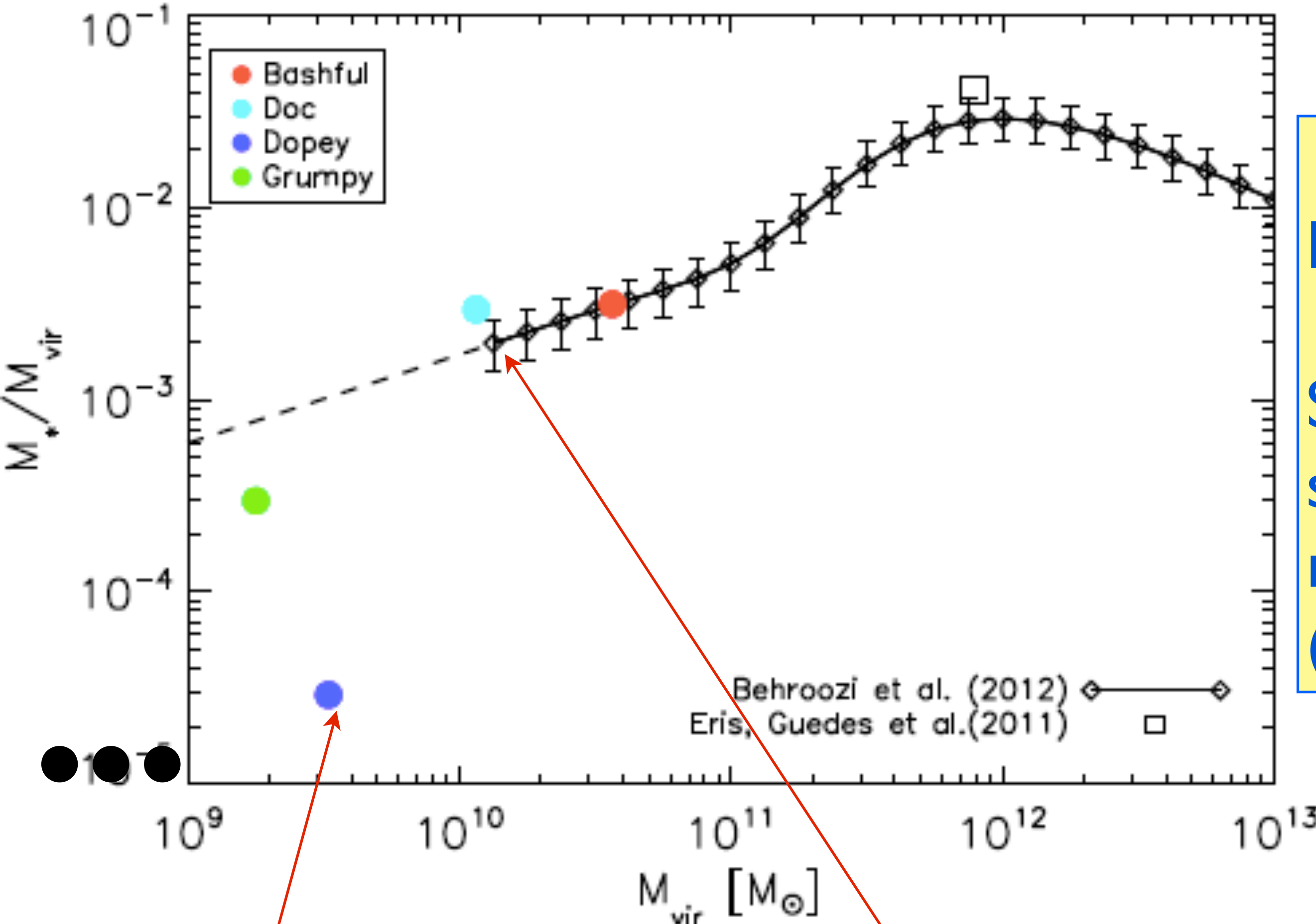
Based on the Leiden/Argentine/Bonn Survey (Kalberla et al. 2005, A&A 440, 775) and the Milky Way model of P. Kalberla (Kalberla et al. 2007, A&A, in press).

Word of Caution: MW Halo Gas Does Not Mix Well!

Name	M_{vir} $[M_\odot]$	R_{vir} [kpc]	V_{max} $[km\,s^{-1}]$	M_* $[M_\odot]$	M_{gas} $[M_\odot]$	M_{HI} $[M_\odot]$	M_V
Bashful	3.59×10^{10}	85.23	50.7	1.15×10^{8}		2.34×10^{7}	−15.5
Doc	1.16×10^{10}	50.52	38.2	3.40×10^{7}		1.98×10^{7}	−14.0
Dopey	3.30×10^{9}	38.45	22.9	9.60×10^{4}		1.96×10^{6}	−8.61
Grumpy	1.78×10^{9}	29.36	22.2	5.30×10^{5}		5.40×10^{5}	−11.0
Happy	6.60×10^{8}	22.49	15.6	—		—	—
Sleepy	4.45×10^{8}	19.71	14.8	—		—	—
Sneezy	4.38×10^{8}	19.62	13.2	—		—	—



THE STELLAR MASS FRACTION OF DGS AT Z=0.



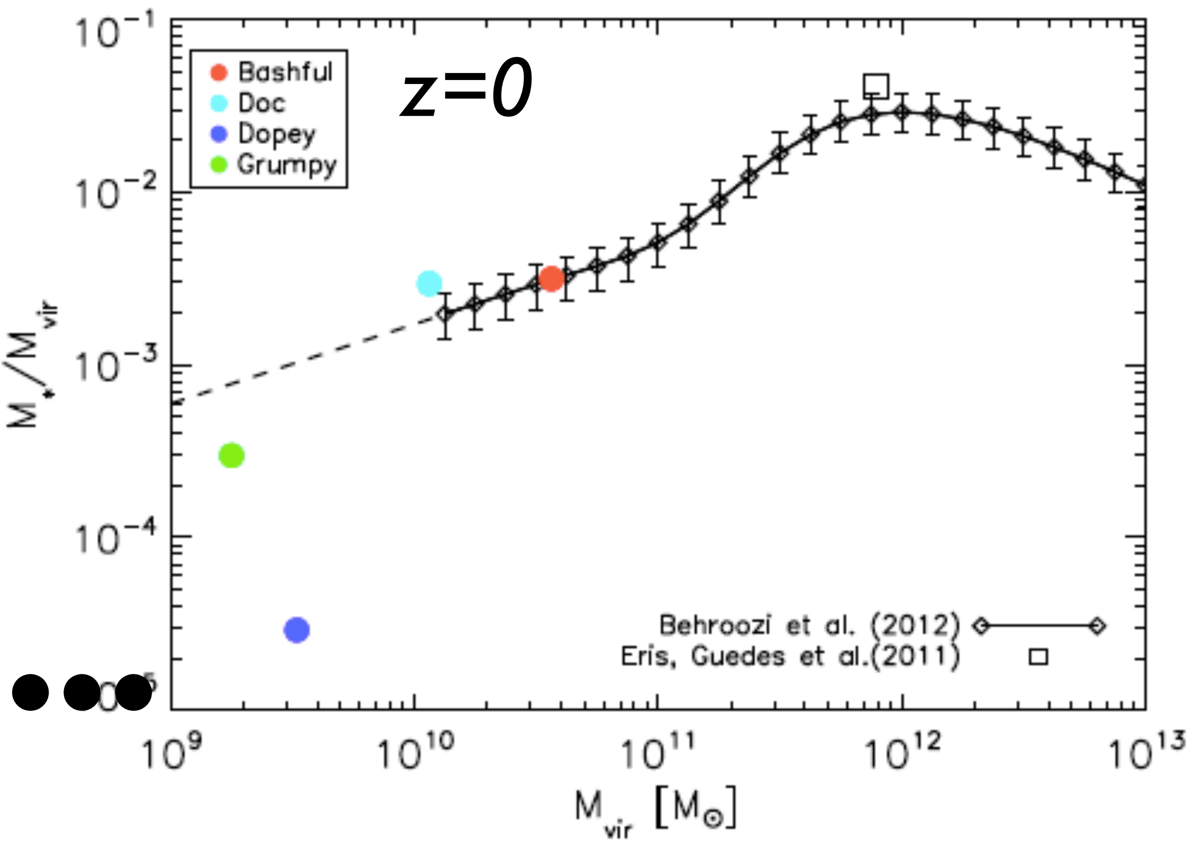
Empty square: Eris.

Solid line: the present-day stellar mass-halo mass relation of Behroozi et al. (2013).

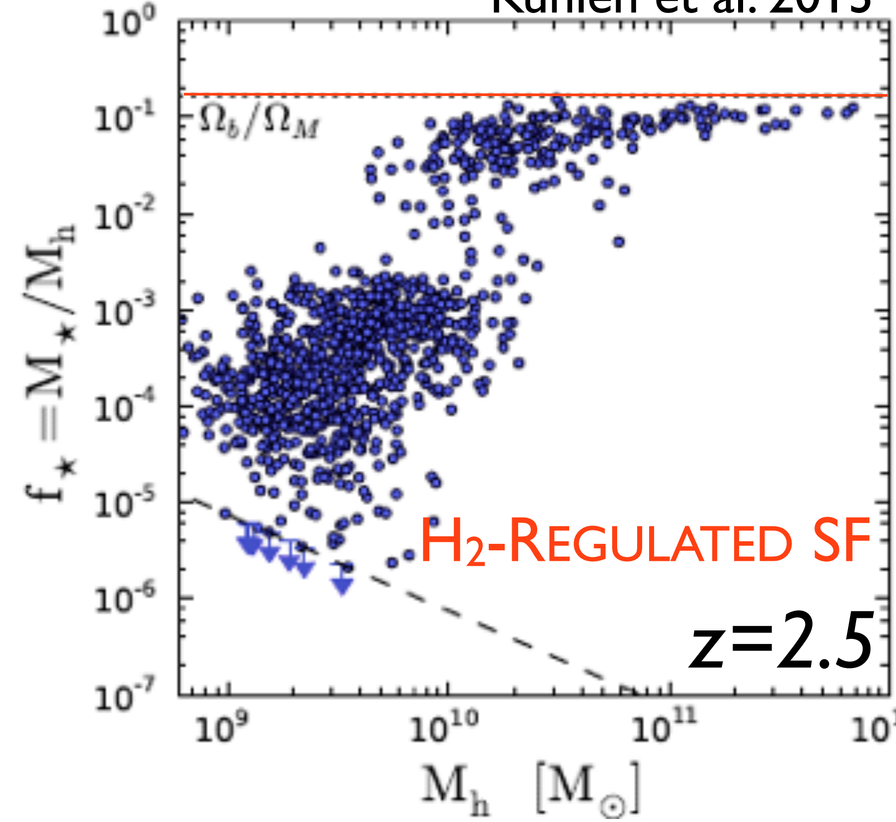
SF EFFICIENCIES STRONGLY MODULATED BY THE DEPTH OF THE POTENTIAL WELL!

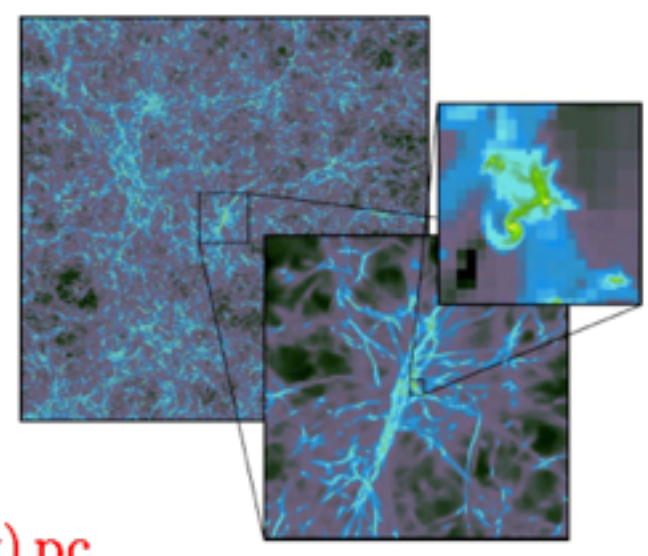
GASOLINE VS. ENZO

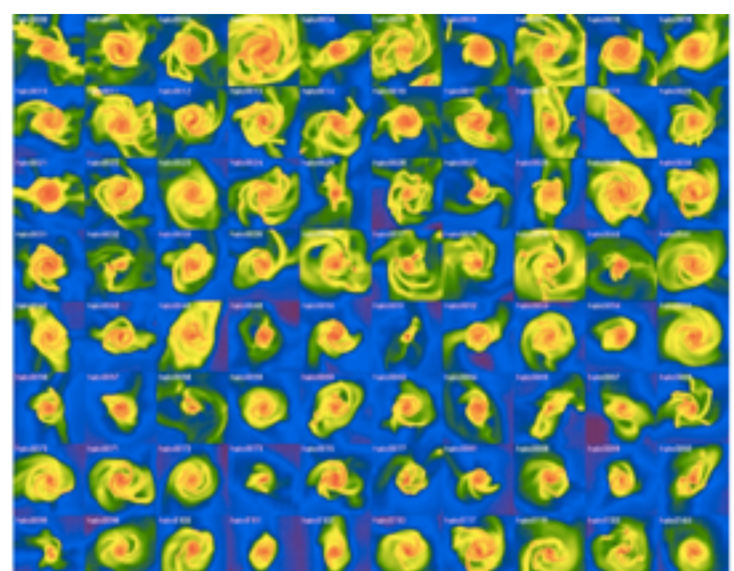
$\dot{\rho}_* \propto \rho_{\rm gas}^{3/2}$ vs. $\dot{\rho}_* \propto f_{\rm H2}\rho_{\rm gas}^{3/2}$



Kuhlen et al. 2013





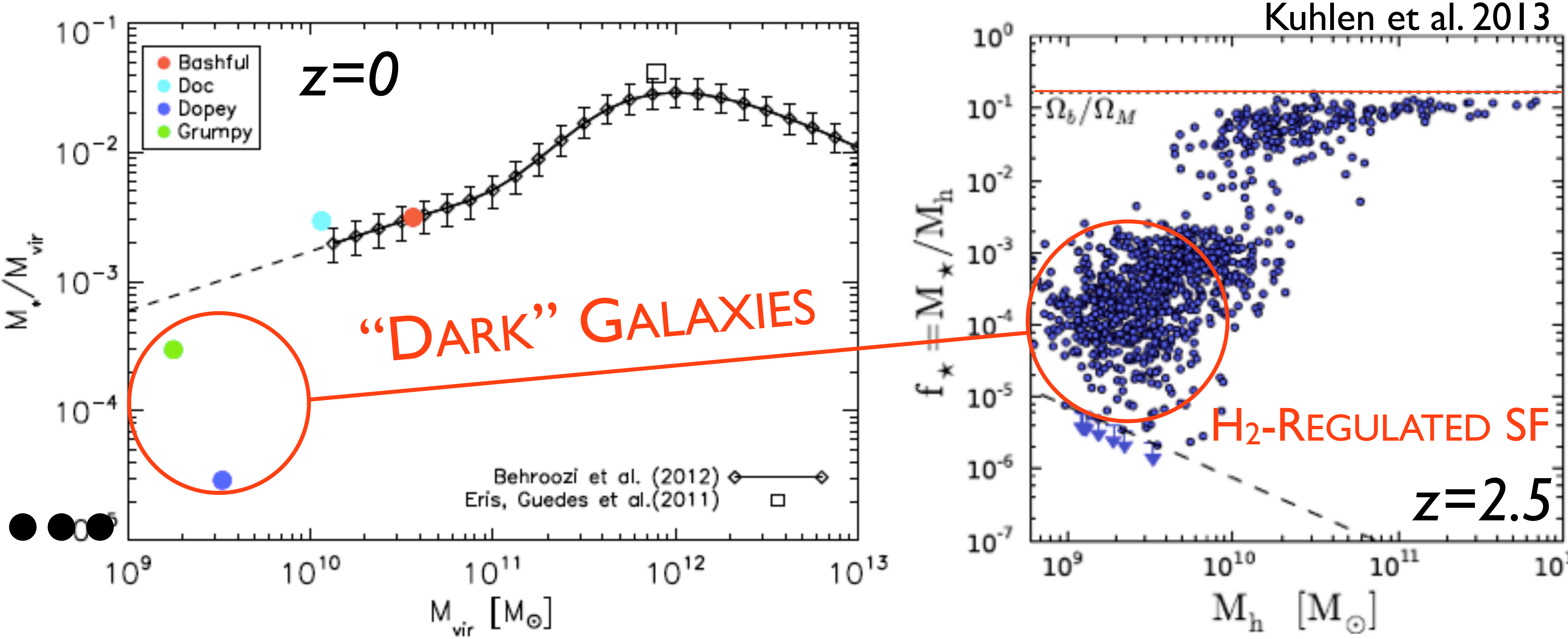


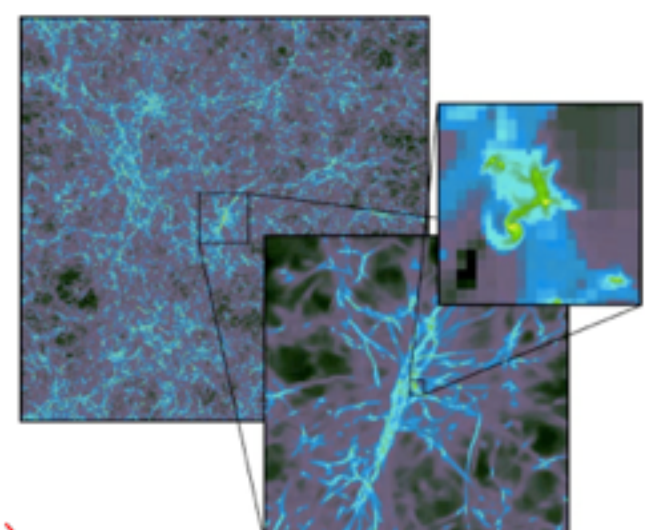
$\Delta x = 380/(1+z)\,{\rm pc}$

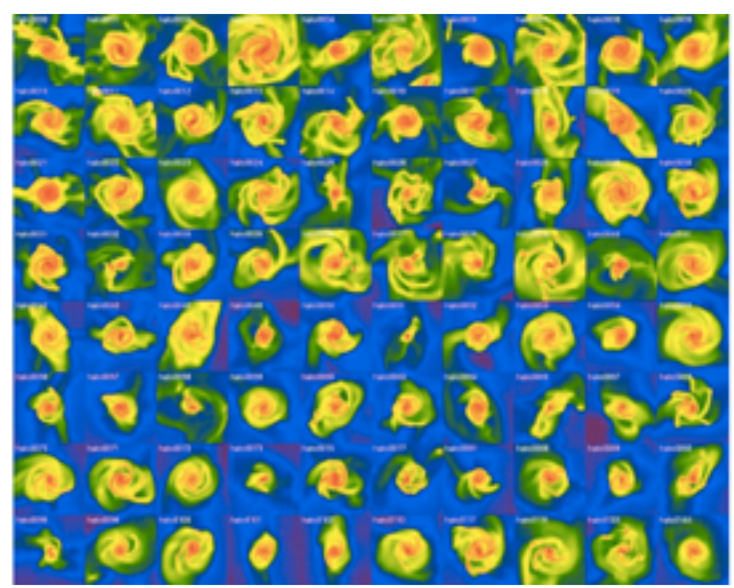
GASOLINE VS. ENZO

$$\dot{\rho}_* \propto \rho_{\rm gas}^{3/2} \quad \text{vs.} \quad \dot{\rho}_* \propto f_{\rm H2}\rho_{\rm gas}^{3/2}$$

Kuhlen et al. 2013

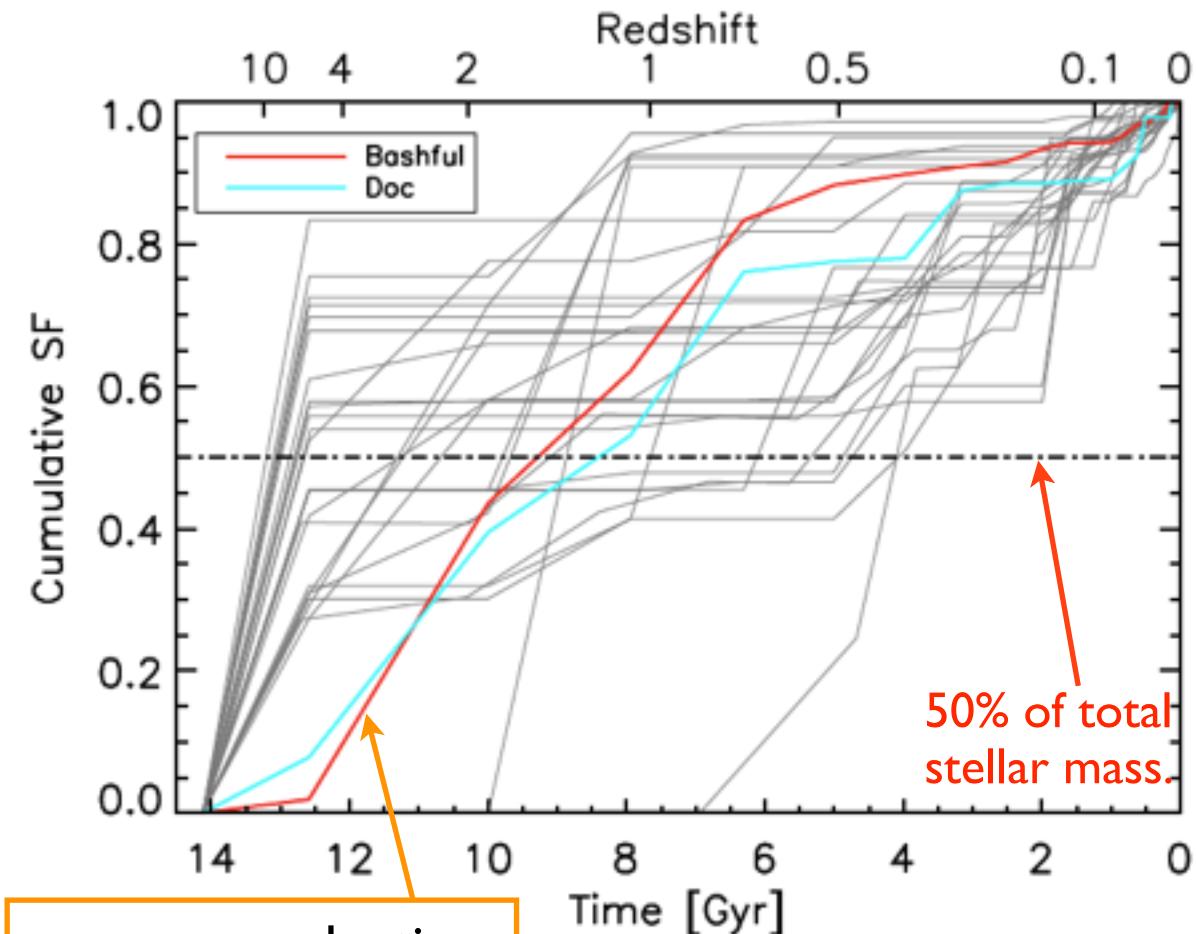


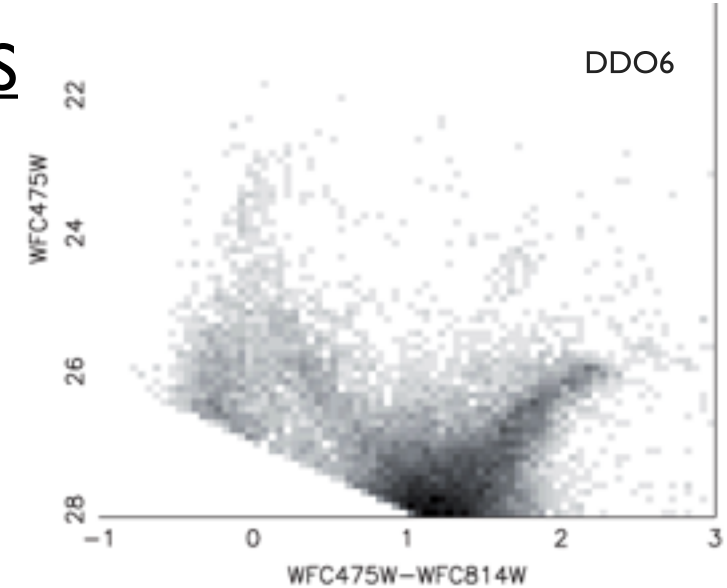




$\Delta x = 380/(1+z)\,\mathrm{pc}$

Resolved Star Formation Histories





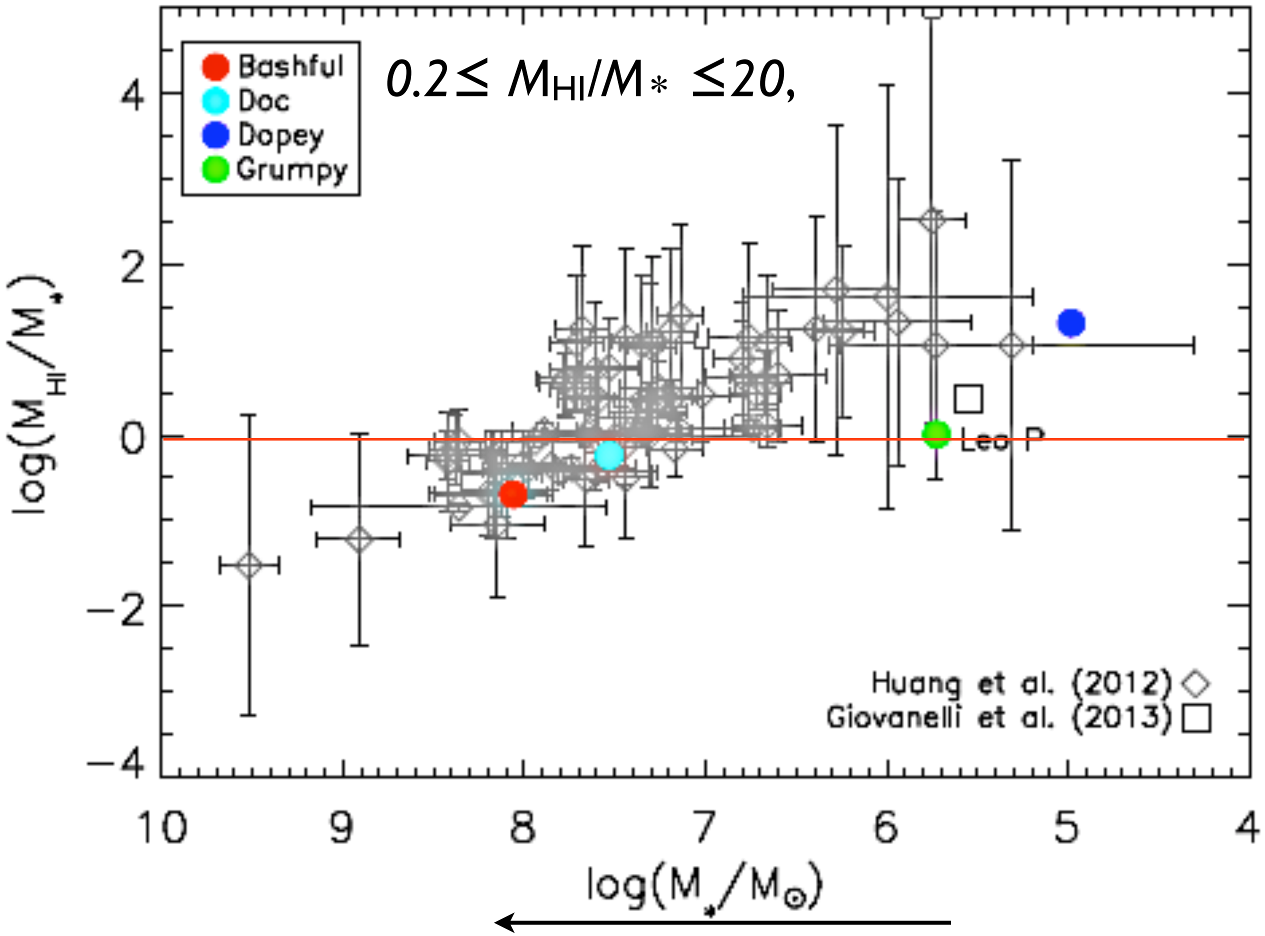
no overproduction of stars at high-z

Individual dIrrs in the ANGST sample (Weisz et al. 2011).

Average ANGST dIrr formed bulk of its stars prior to $z=1$, exhibits ancient star formation (>10 Gyr ago) and lower levels of activity over the last 6 Gyr.

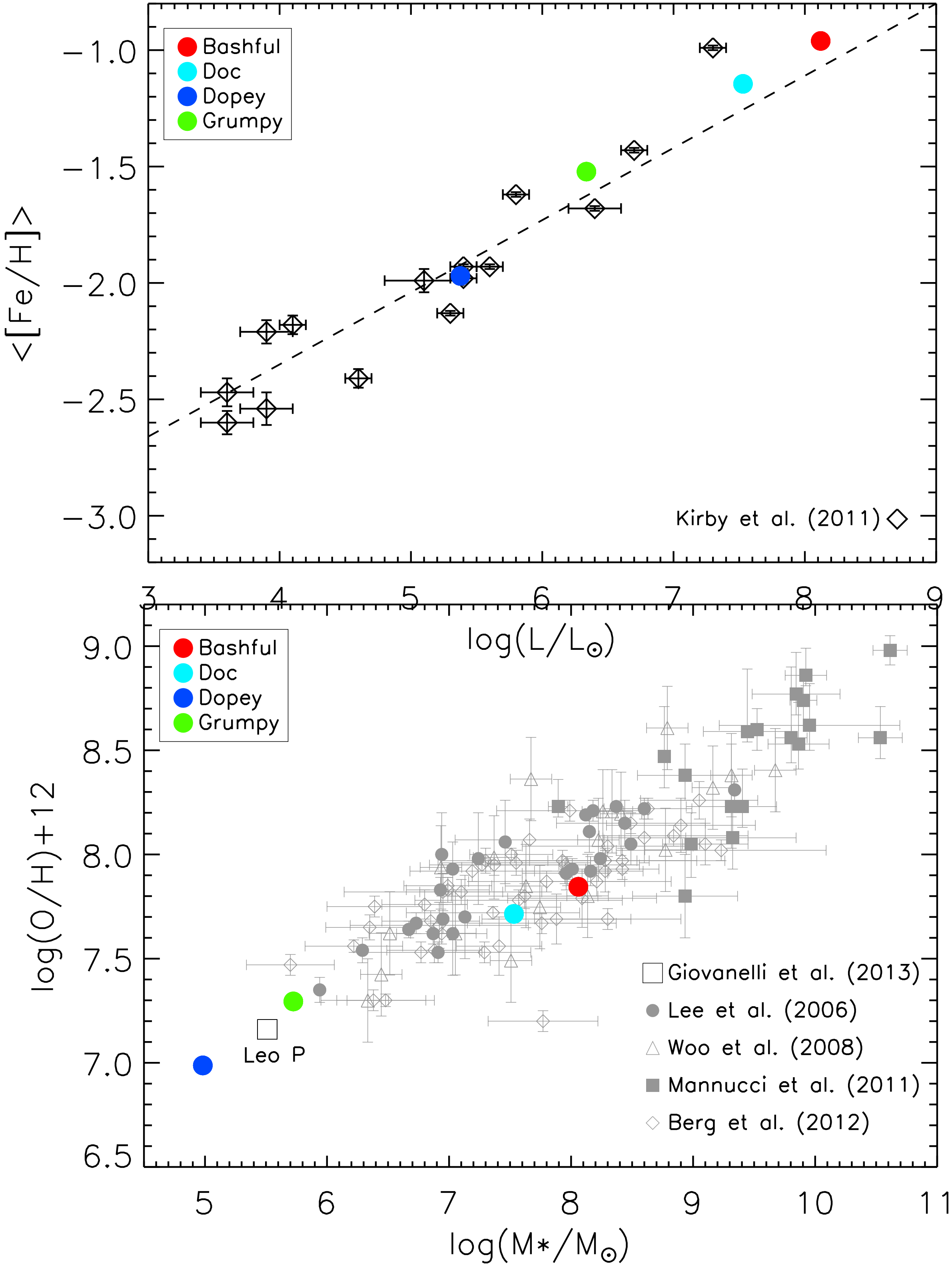
Cold Gas Fraction

Low stellar-mass galaxies in ALFALFA DG sample are HI gas rich.



Low star formation efficiencies *are not the result of blowing away* all the baryons. Baryons are retained *but are unable to make stars* because of the more realistic description of where stars form (in high density clouds) and how feedback regulates the thermodynamics of the ISM.

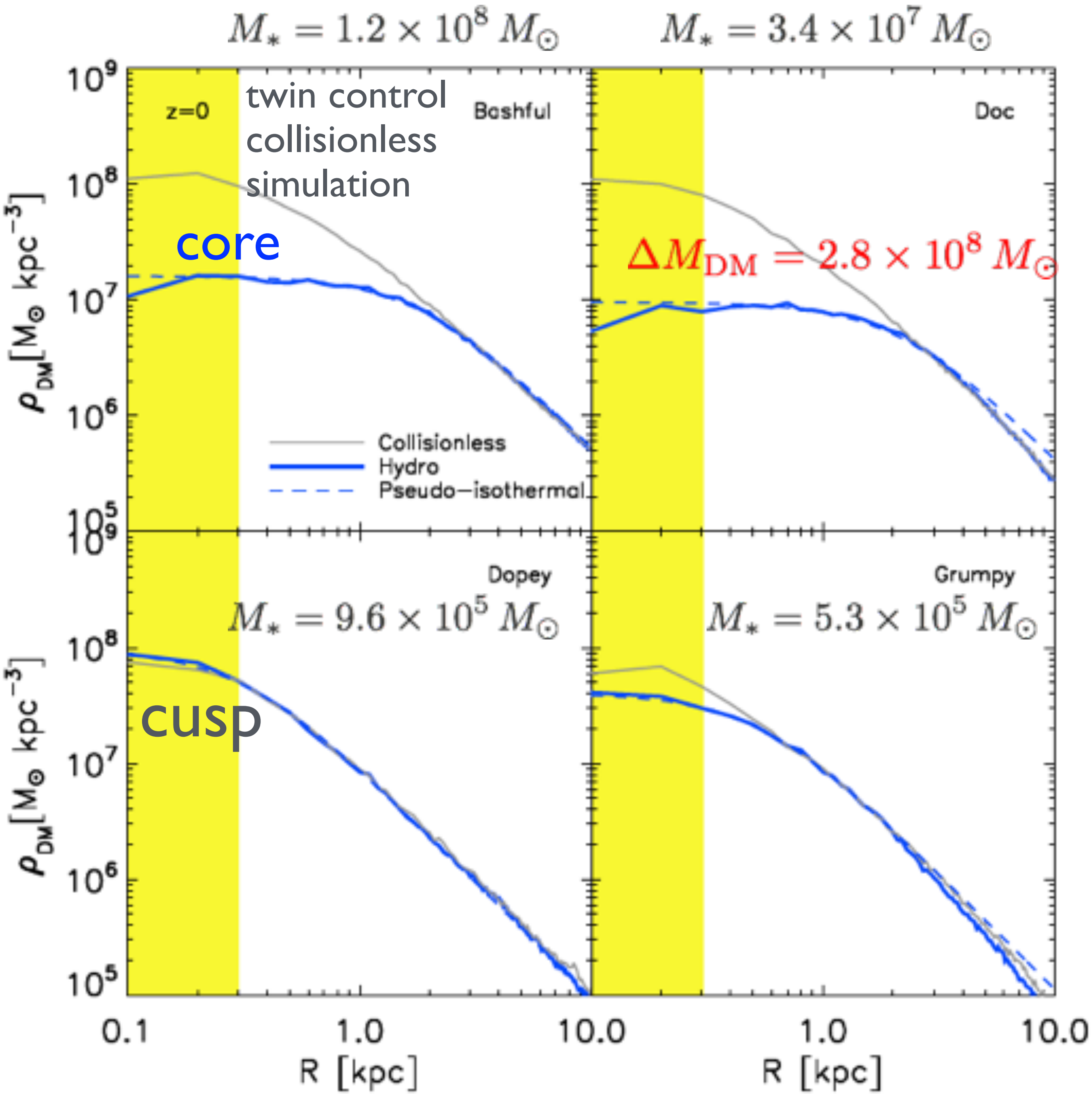
METAL POOR



Stellar metallicity *V*-band luminosity relation for Milky Way's dSphs (Kirby et al. 2011).

The stellar mass-gas phase metallicity relation of DGs. Fraction of all the metals ever produced retained increases with decreasing stellar mass = 10%—90% for Bashful-Dopey.

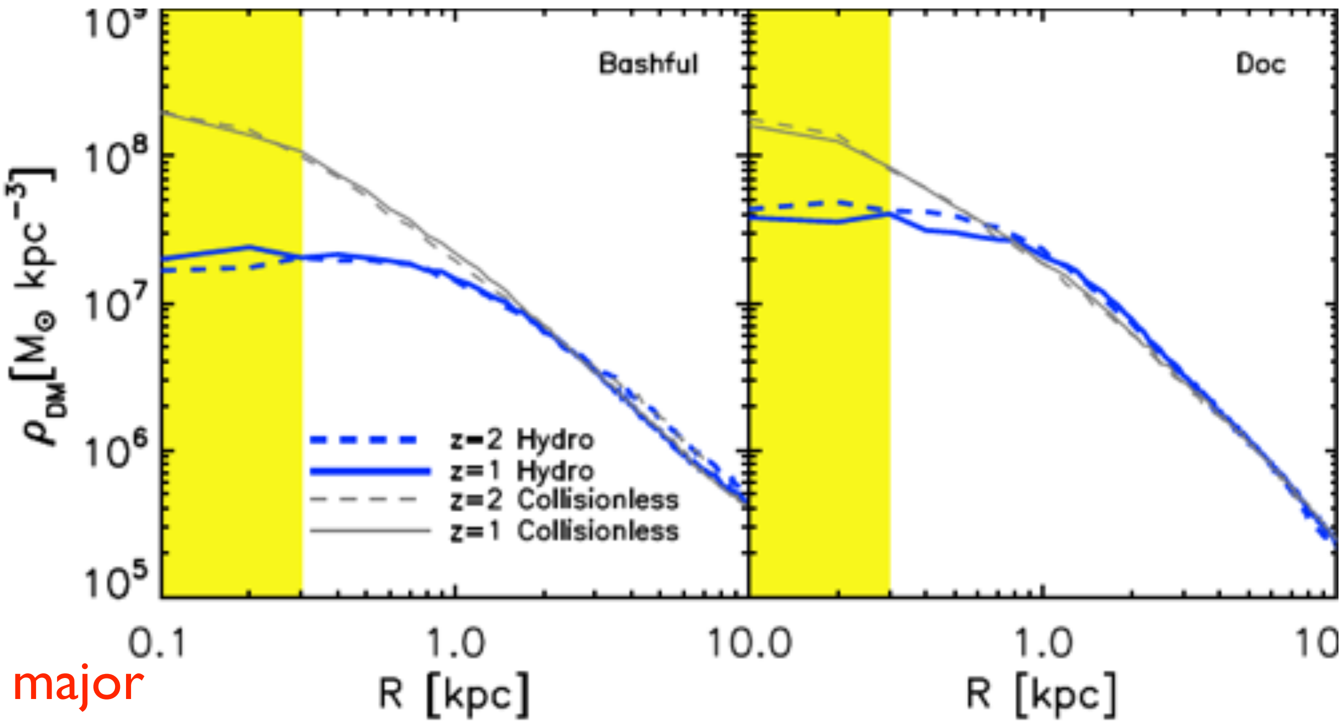
CORED PROFILE



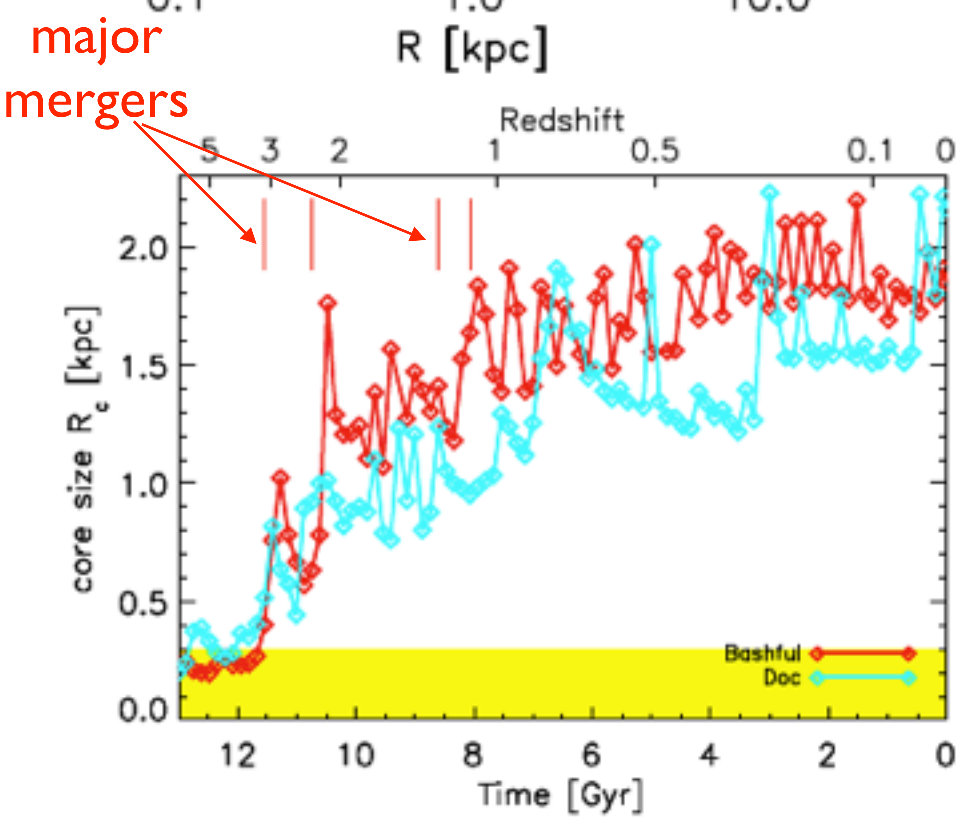
$$\rho_{\rm DM} = \frac{\rho_0}{1 + (R/R_c)^2}$$

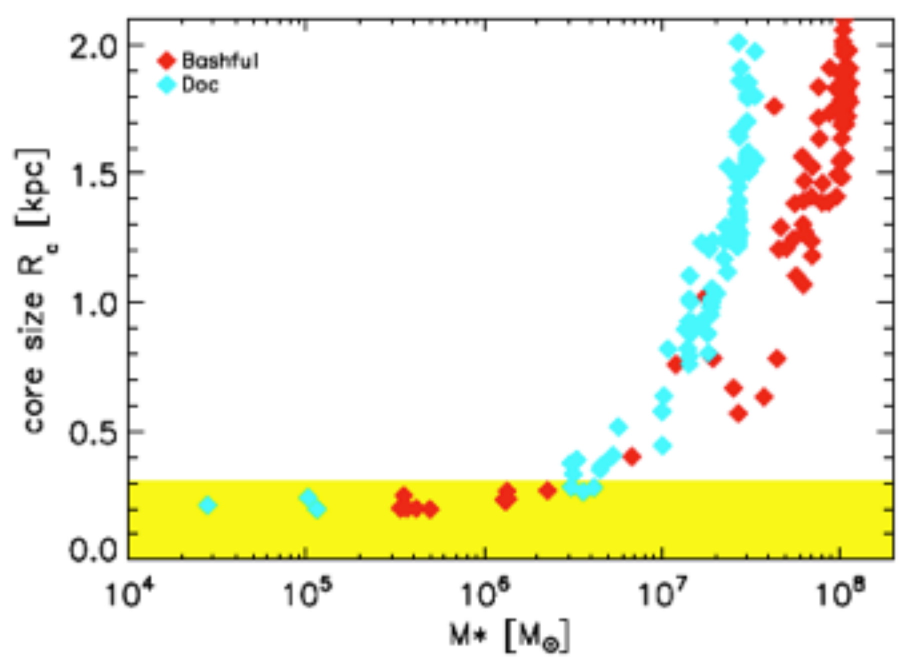
$$R_c = 1.8\,{\rm kpc}$$

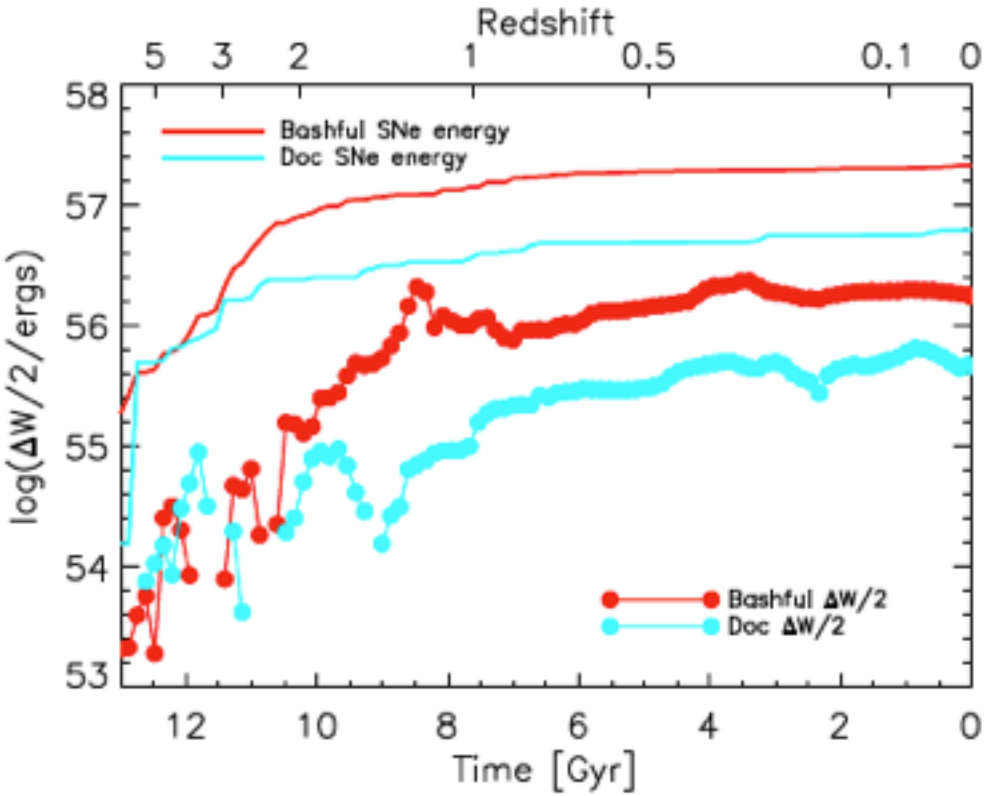
$$= 2.1\,{\rm kpc}$$



- kpc-size cores form early
- cusps are not restored following galaxy mergers
- SN feedback effectively removes DM cusps in DGs with $M_* > 10^6\ M_\odot$



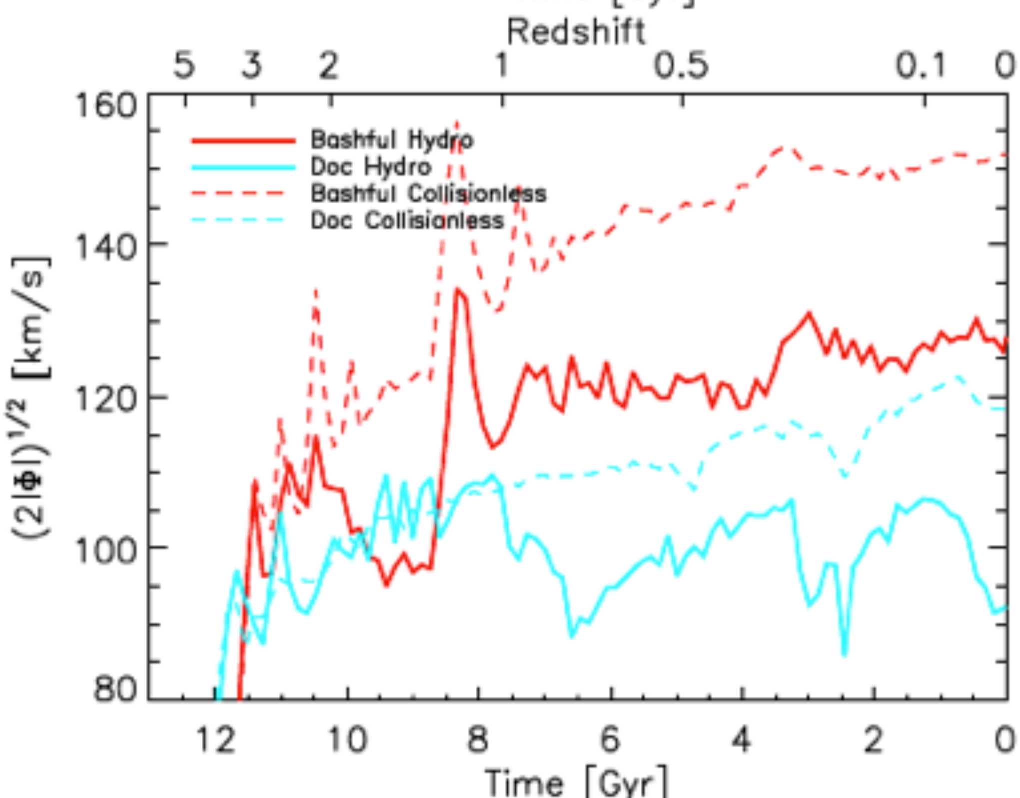




$$W = -4\pi G \int_0^{R_{\rm vir}} \rho_{\rm DM} M(<R) R dR$$

$$\frac{\Delta W}{2} = \frac{W_{\rm core} - W_{\rm cusp}}{2}.$$

minimum energy required for cusp-core transformation

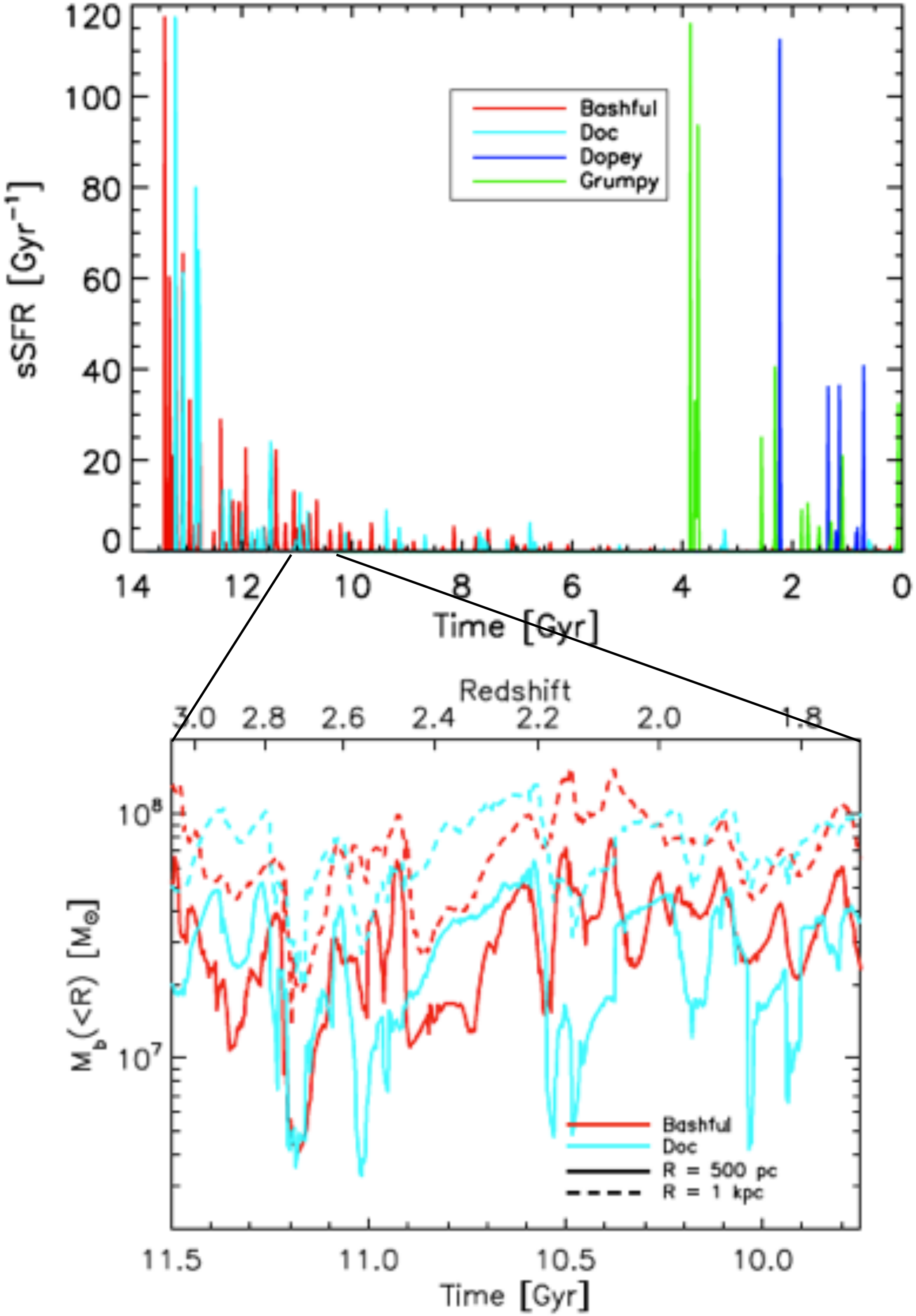


$$\Delta E_{\rm SN} \gg \Delta W/2$$

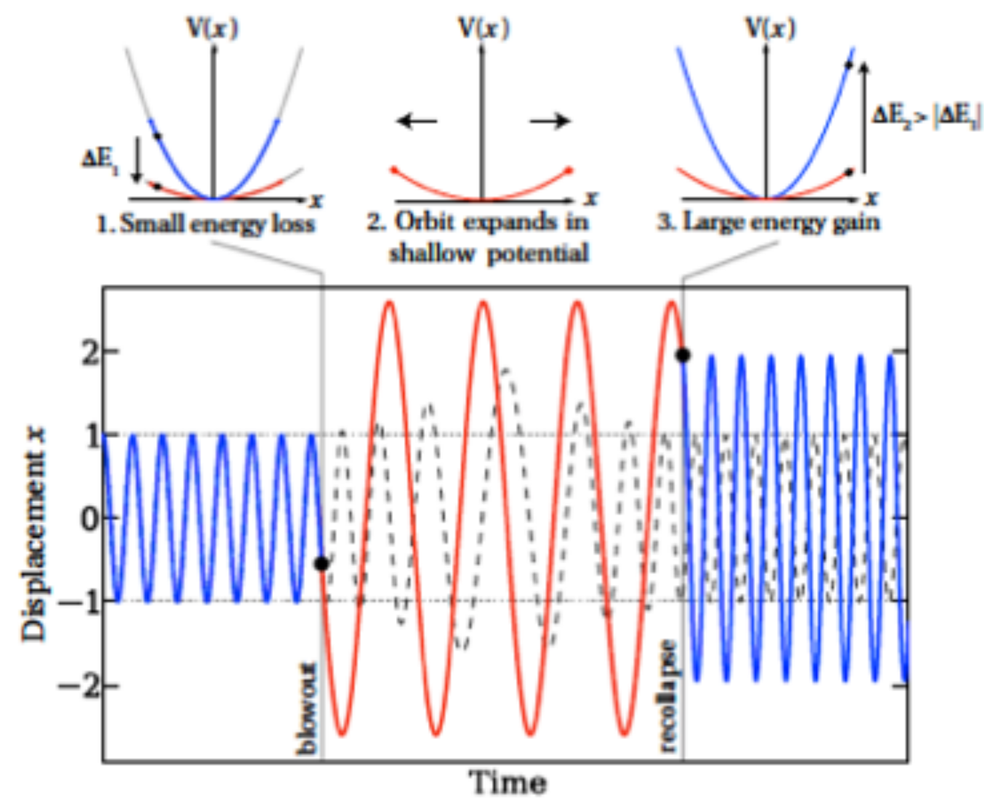
$$\sqrt{2|\phi(R=0)|} \sim \rm const$$

at late epochs

Bursty Star Formation & Potential Fluctuations



The bursty star formation histories of DGs. Bottom left panel: fluctuating baryonic (gas+stars) central masses of the two simulated DGs.



Pontzen & Governato 2012

The End