Title: Maximum entropy, the universal dark matter density profile... and its destruction

Date: Oct 16, 2012 11:00 AM

URL: http://pirsa.org/12100003

Abstract: I review some recent developments in attempting to reconcile the observed galaxy population with numerical models of structure formation in the 'LCDM' concordance cosmology. Focussing on behaviour of dwarf galaxies, I describe the infamous 'cusp-core' dichotomy -- a long-standing challenge to the LCDM picture on small scales -- and use toy models to show how it is resolved in recent numerical simulations (Pontzen & Governato 2012). I then discuss the current observational status of this picture (Teyssier, Pontzen & Read 2012; Penarrubia et al 2012).

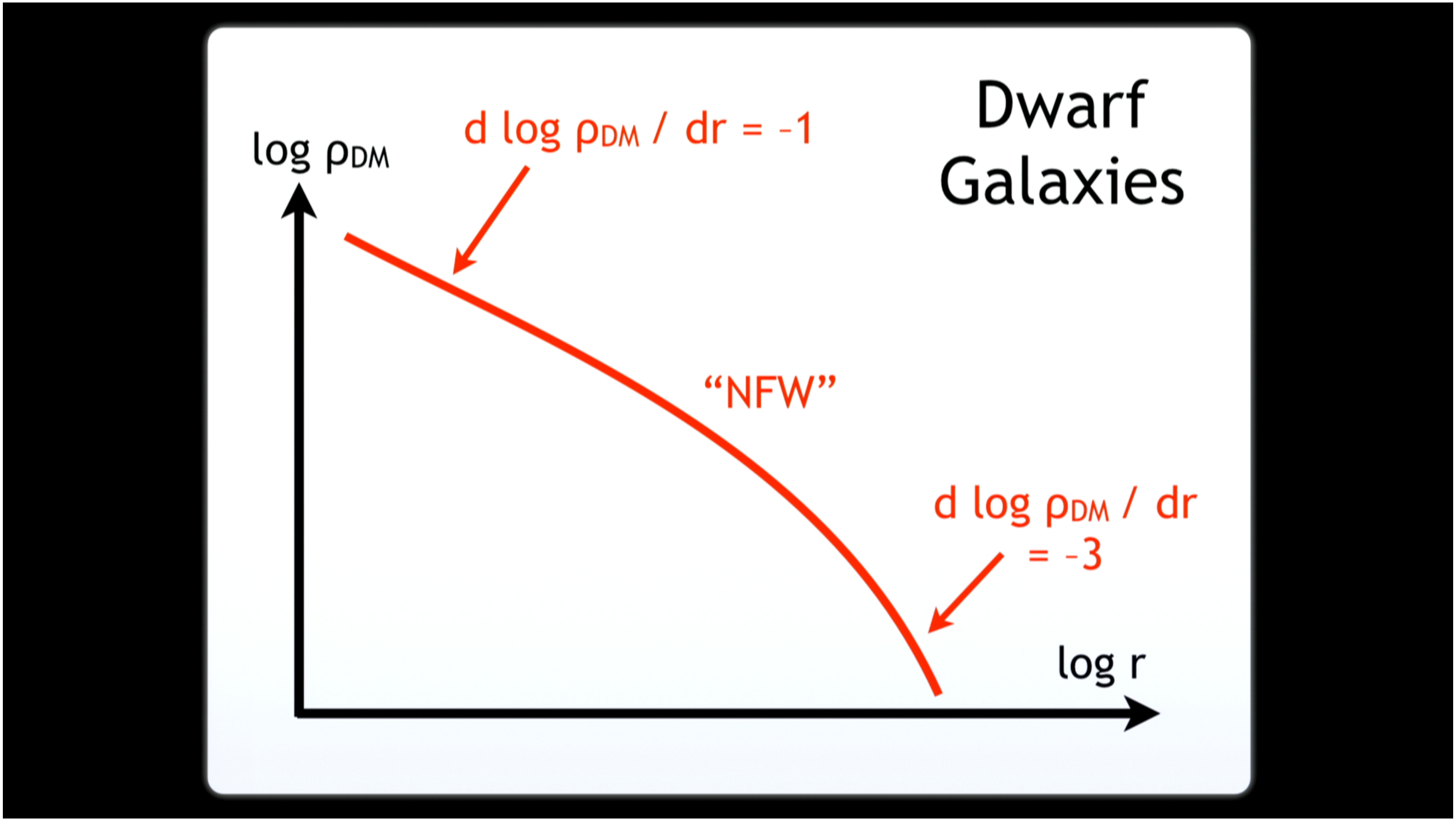
In the second half of the talk, I apply the analytic techniques developed for probing the effect of gas on dark matter dynamics to the question of how, in the absence of baryons, a universal "NFW" dark matter halo profile emerges (independent of scale or details of the initial conditions).

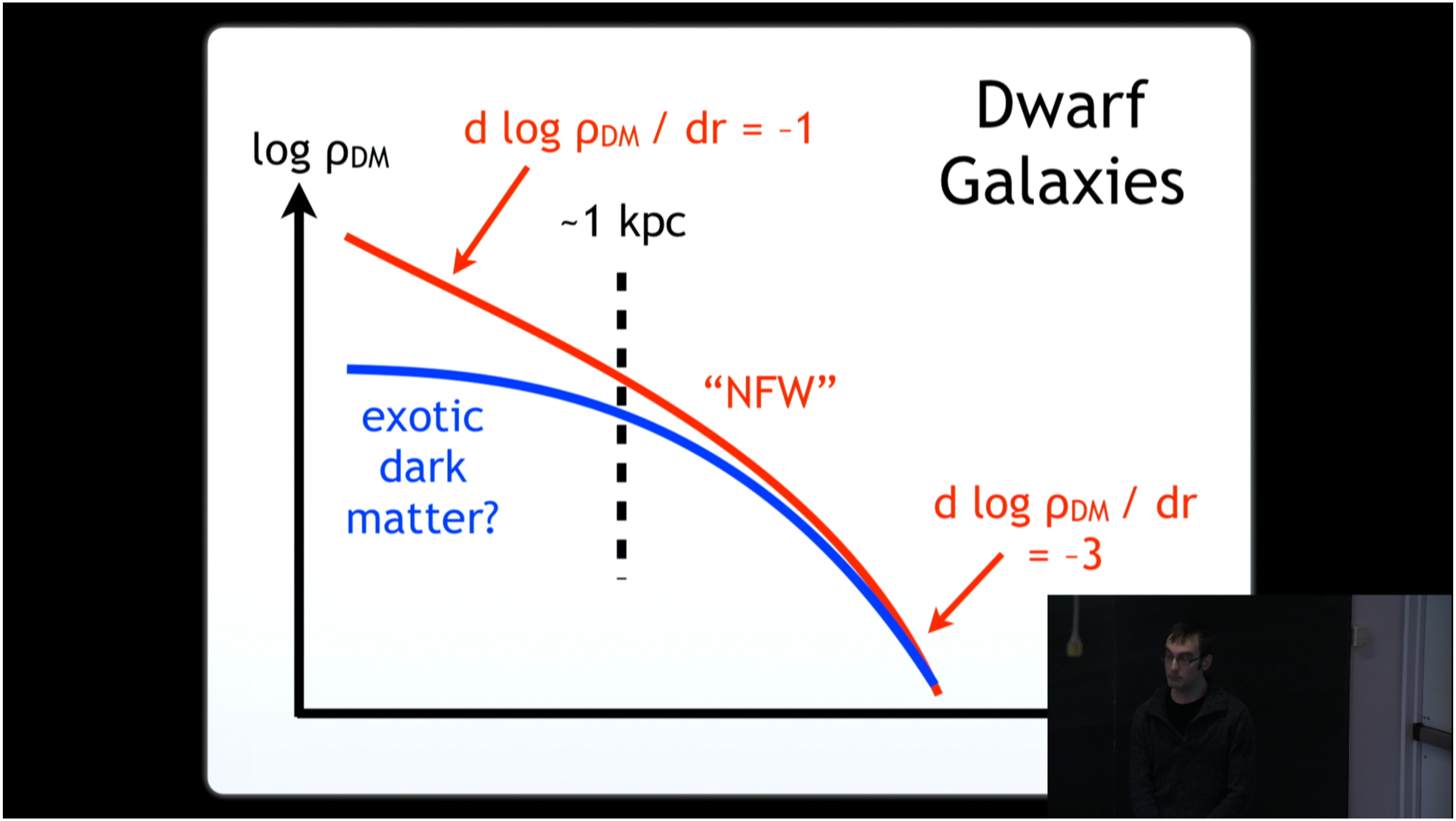
Thus the generation of NFW halos on the one hand and the destruction of their central cusps on the other can be ascribed to surprisingly similar physical arguments.

Andrew Pontzen
University of Oxford, UK

with Fabio Governato, Romain Teyssier and Jorge Peñarrubia
with thanks to Gasoline developers
(Wadsley/Quinn/Shen/Christensen)
and particular thanks to Steve Gratton

Freezing and melting: maximum entropy and universal dark matter halos


Dwarf
Galaxies
log ρDM
d log ρDM / dr = -1
"NFW"
d log ρDM / dr
= -3
log r


Dwarf Galaxies
log ρDM
d log ρDM / dr = -1
~1 kpc
"NFW"
exotic dark matter?
d log ρDM / dr = -3

1. Melting — how cusps are destroyed by feedback

2. Freezing

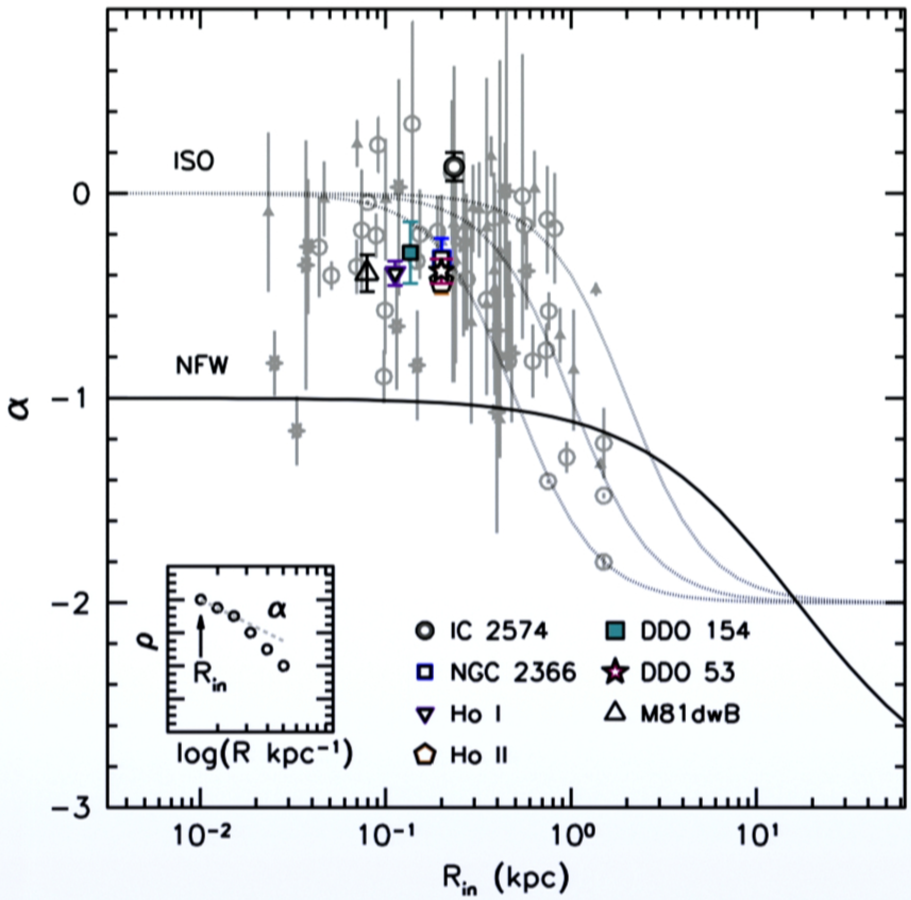
3. Melting

1. Melting — how cusps are destroyed by feedback

2. Freezing — statistical mechanics of dark matter halo formation

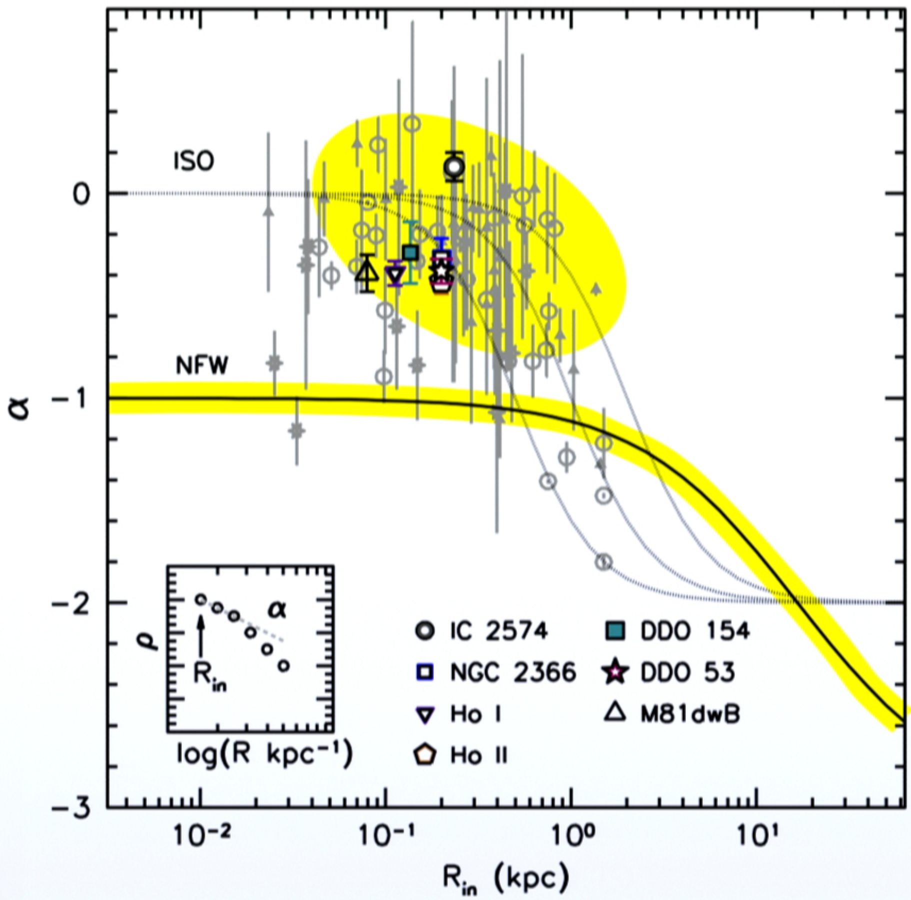
3. Melting — statistical mechanical view of feedback

Dwarf Galaxies



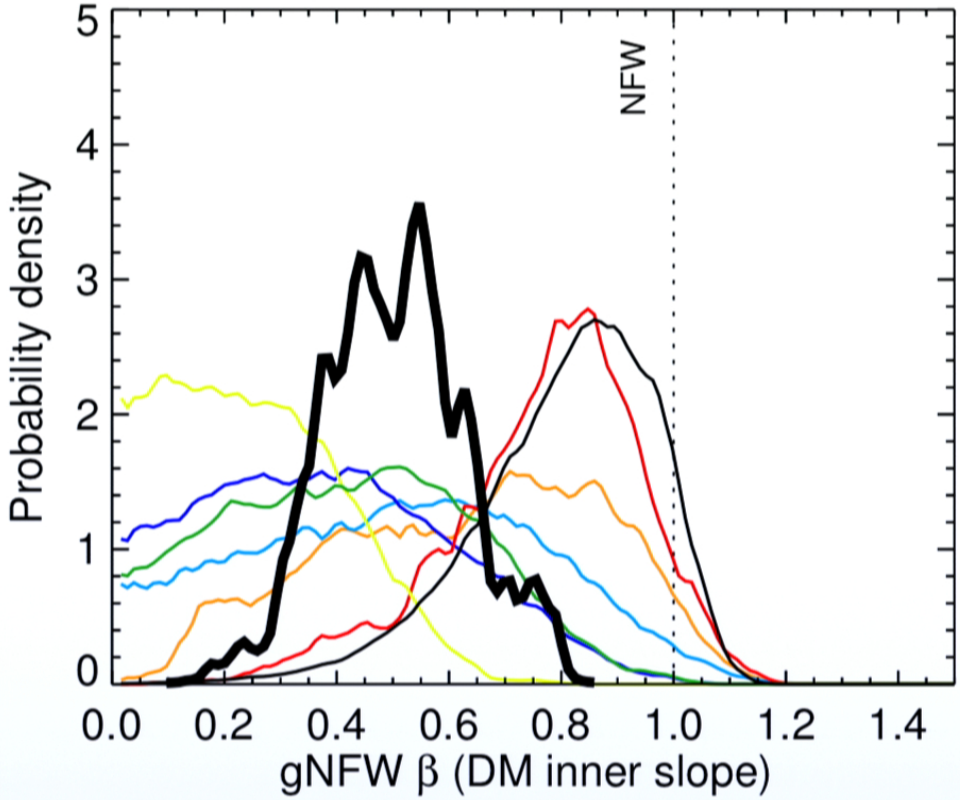
Oh et al 2011, AJ

Dwarf Galaxies



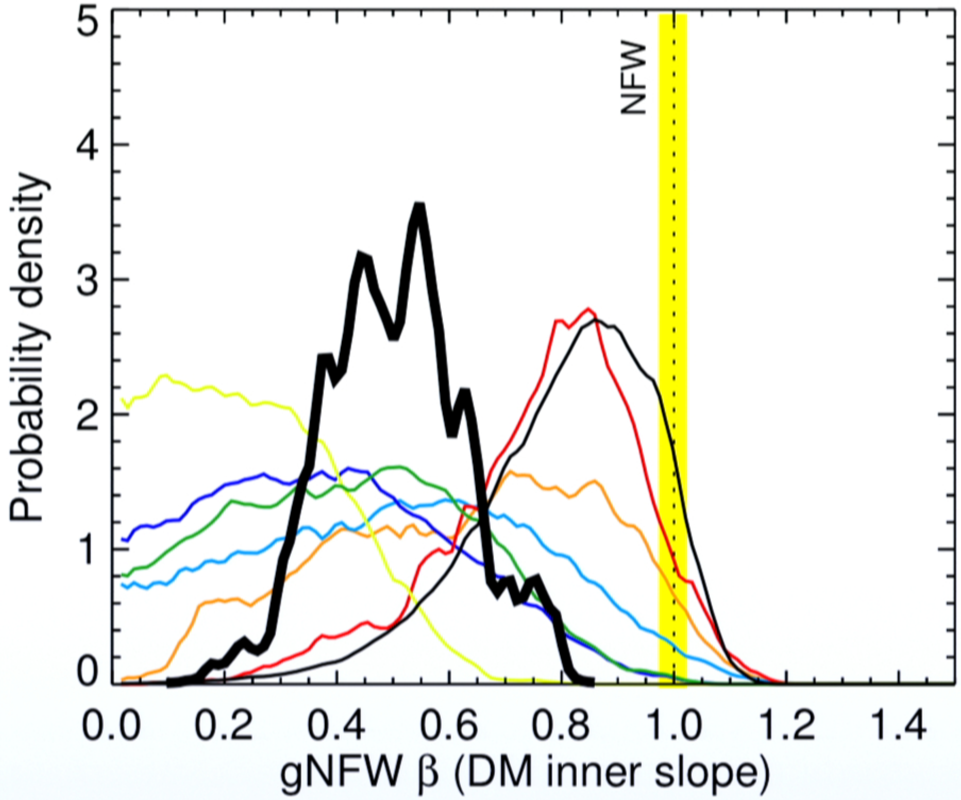
Oh et al 2011, AJ

Clusters



Newman+
ApJ submitted,
1209.1392

Clusters



Ne
ApJ s
12

Governato et al 2010

Vol 463 | 14 January 2010 | doi:10.1038/nature08640

nature

LETTERS

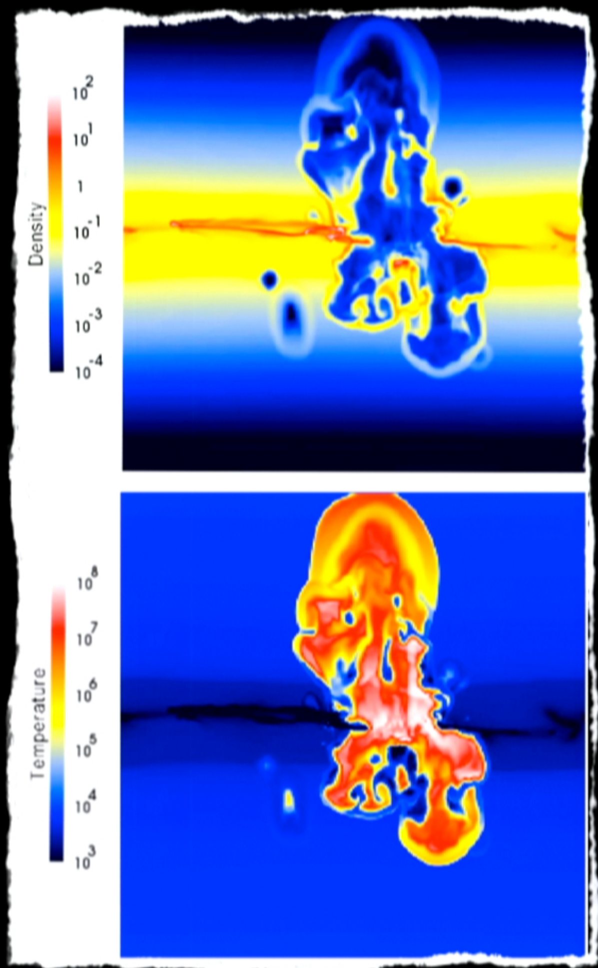
Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

F. Governato[1], C. Brook[2], L. Mayer[3], A. Brooks[4], G. Rhee[5], J. Wadsley[6], P. Jonsson[7], B. Willman[9], G. Stinson[6], T. Quinn[1] & P. Madau[8]

For almost two decades the properties of 'dwarf' galaxies have challenged the cold dark matter (CDM) model of galaxy formation[1]. Most observed dwarf galaxies consist of a rotating stellar disk[2] embedded in a massive dark-matter halo with a near-constant-density core[3]. Models based on the dominance of CDM, however, invariably form galaxies with dense spheroidal stellar bulges and steep central dark-matter profiles[4–6], because low-angular-momentum baryons and dark matter sink to the centres of galaxies through accretion and repeated mergers[7]. Processes that decrease the central density of CDM halos[8] have been identified, but have not yet reconciled theory with observations of present-day dwarfs. This failure is potentially catastrophic for the CDM model, possibly requiring a different dark-matter particle candidate[9]. Here we report hydrodynamical simulations (in a framework[10] assuming the presence of CDM and a cosmological constant) in which the inhomogeneous interstellar medium is resolved. Strong outflows from supernovae remove low-angular-momentum gas, which inhibits the formation of bulges and decreases the dark-matter density to less than half of what it would otherwise be within the central kiloparsec. The analogues of dwarf galaxies—bulgeless and

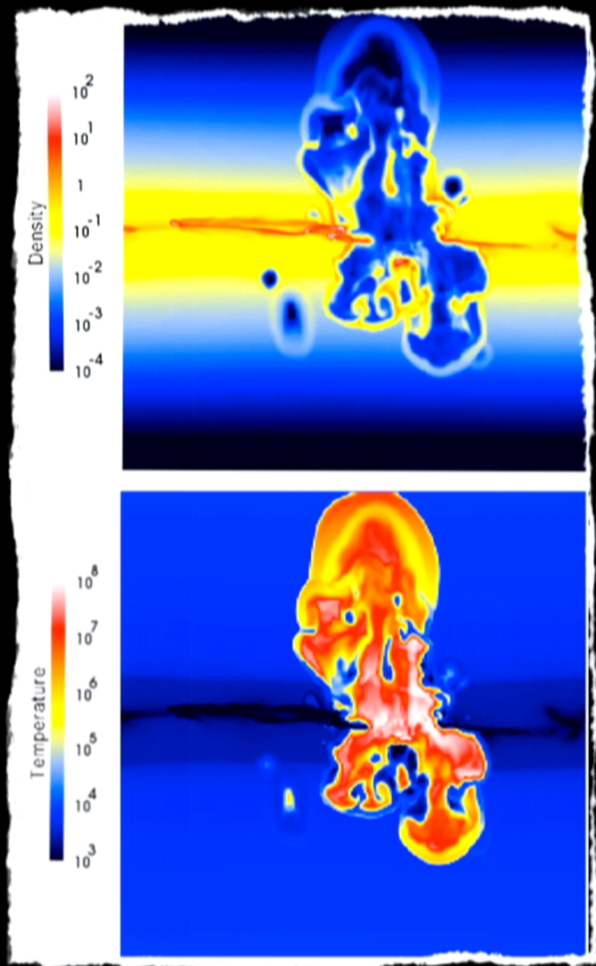
resulting feedback have been applied to the formation of high-redshift protogalaxies, leading to significant baryon loss and less concentrated systems[8,20]. Similarly, dynamical arguments[21,22] suggest that bulk gas motions (possibly supernova-induced) and orbital energy loss of gas clouds due to dynamical friction can transfer energy to the centre of the dark-matter component. Sudden gas removal through outflows then causes the dark-matter distribution to expand. These mechanisms were demonstrated to operate effectively in small high-redshift halos of total mass around $10^9 M_\odot$ ($M_\odot$ is the mass of the Sun) where they create small dark-matter cores[8]. However, such methods and the required high resolution have not been applied to cosmological hydrodynamical simulations of present-day dwarf galaxy systems ($V_{rot} \approx 60$ km s^{-1}). Showing that the properties of dwarf galaxies can be accurately predicted by the CDM scenario would end the 'small scale crisis' and further constrain the properties of the dark-matter particle candidate.

To study the formation of dwarf galaxies in a ΛCDM cosmology, we analyse a novel set of cosmological simulations. Baryonic processes are included, as gas cooling[8], heating from the cosmic ultraviolet field[23], star formation and supernova-driven gas heating



Ceverino & Klypin 08

Outflows arise naturally
in high resolution
ISM models



Ceverino & Klypin 08

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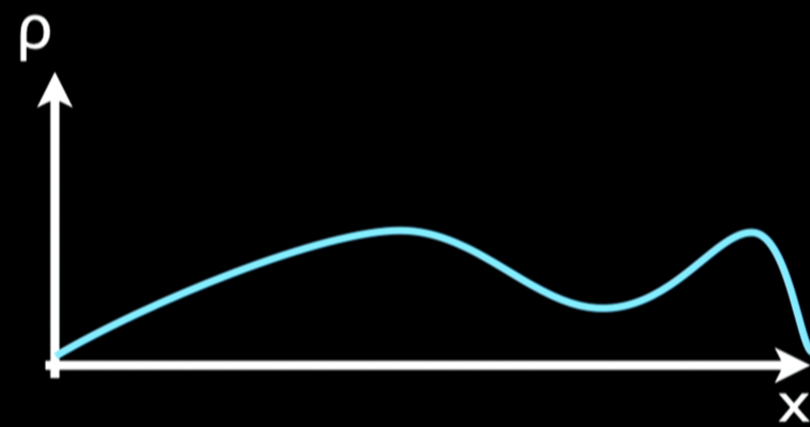

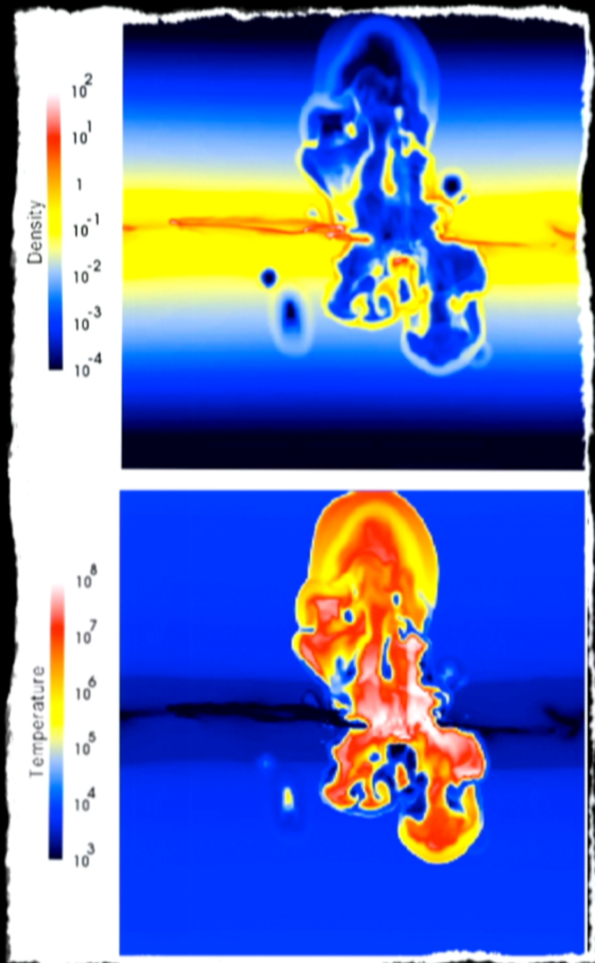

Ceverino & Klypin 08

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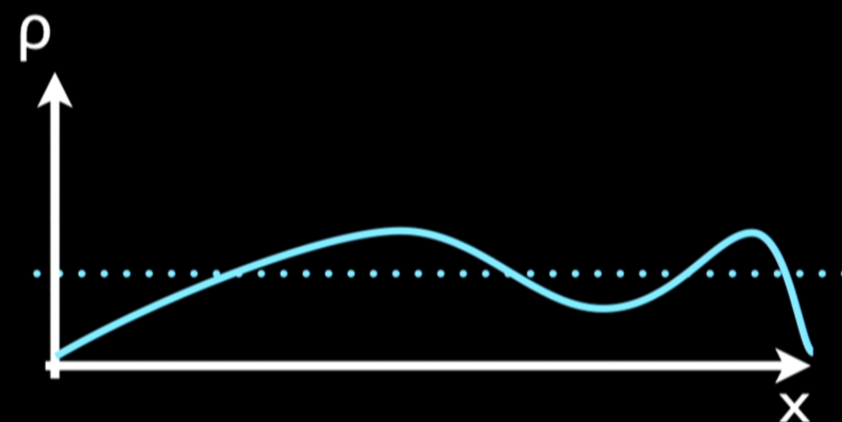
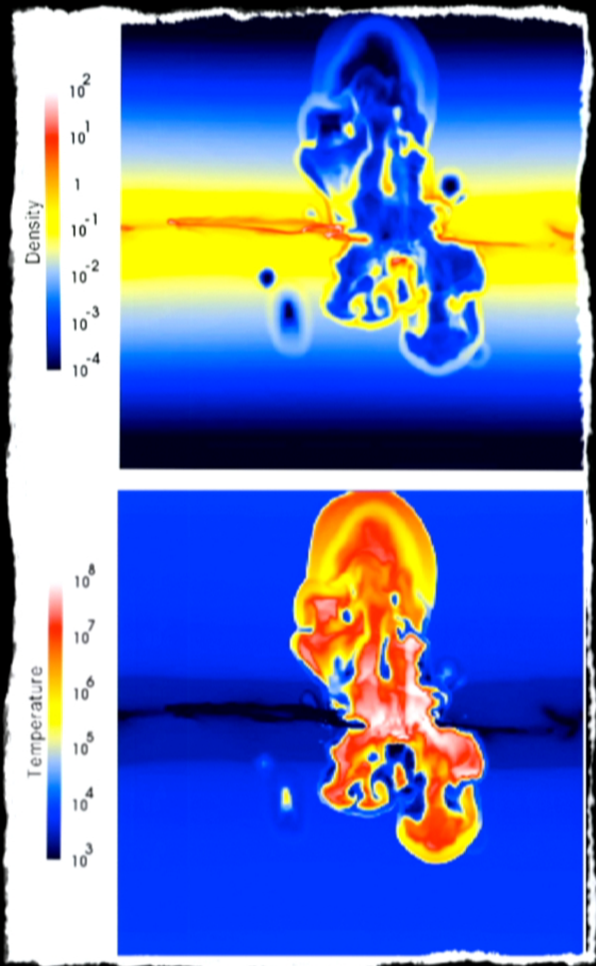
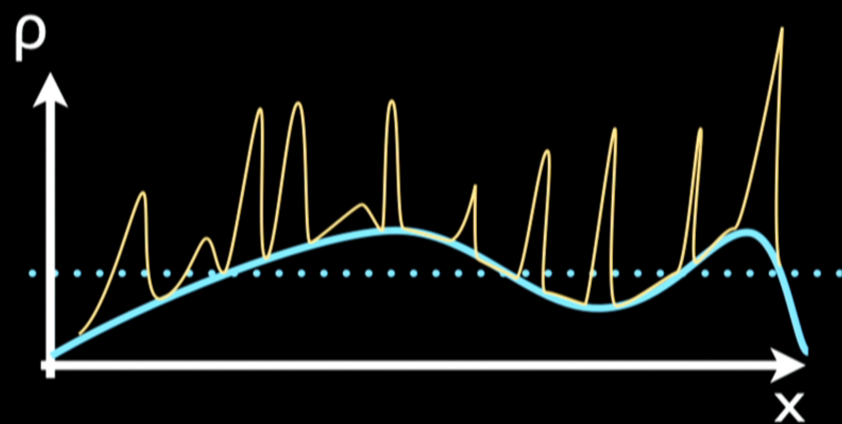


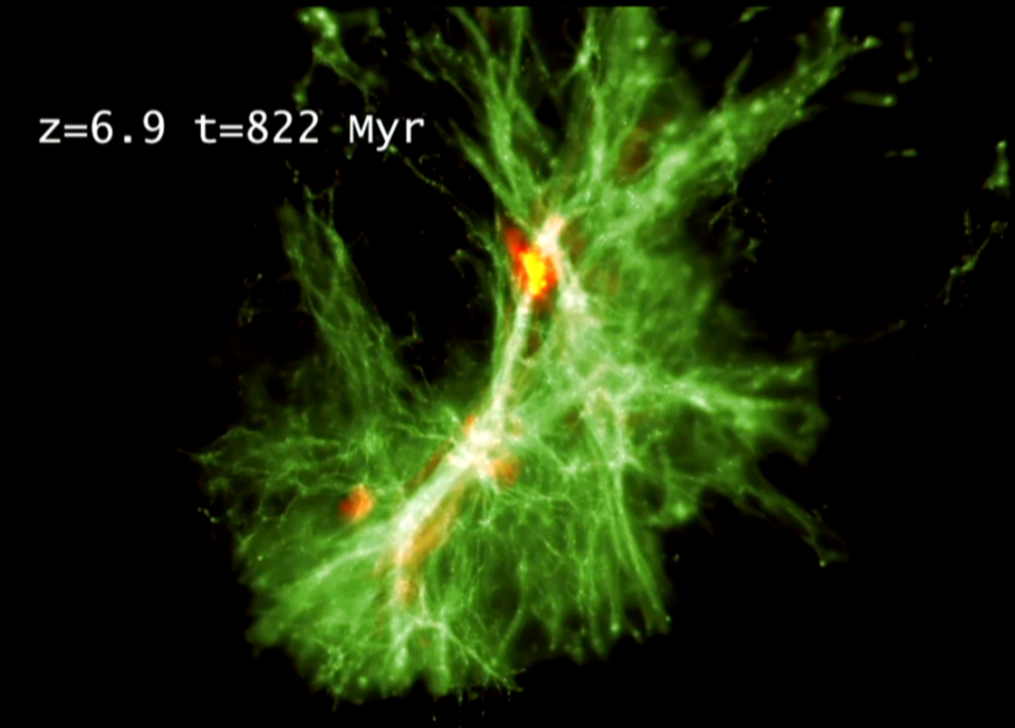


Ceverino & Klypin 08

Outflows arise naturally in high resolution ISM models

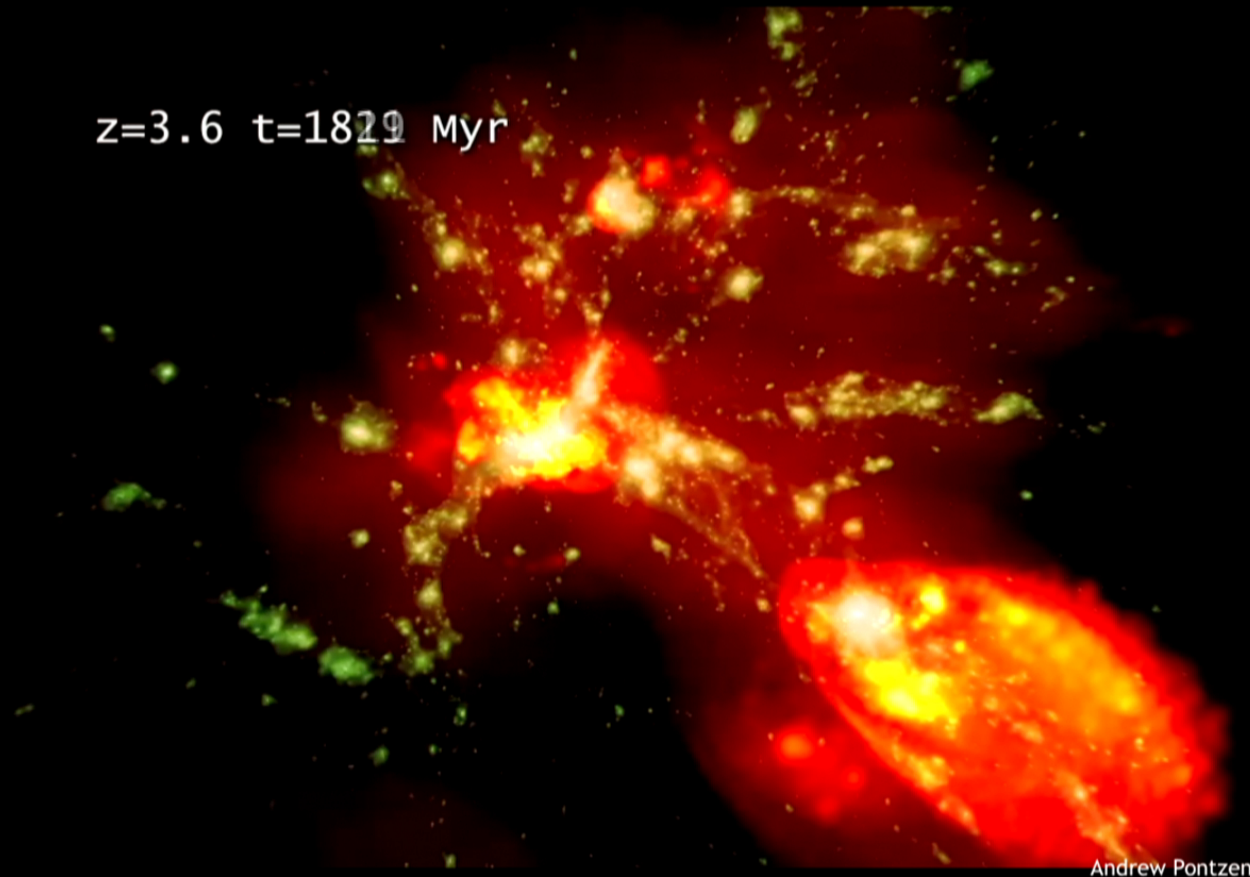


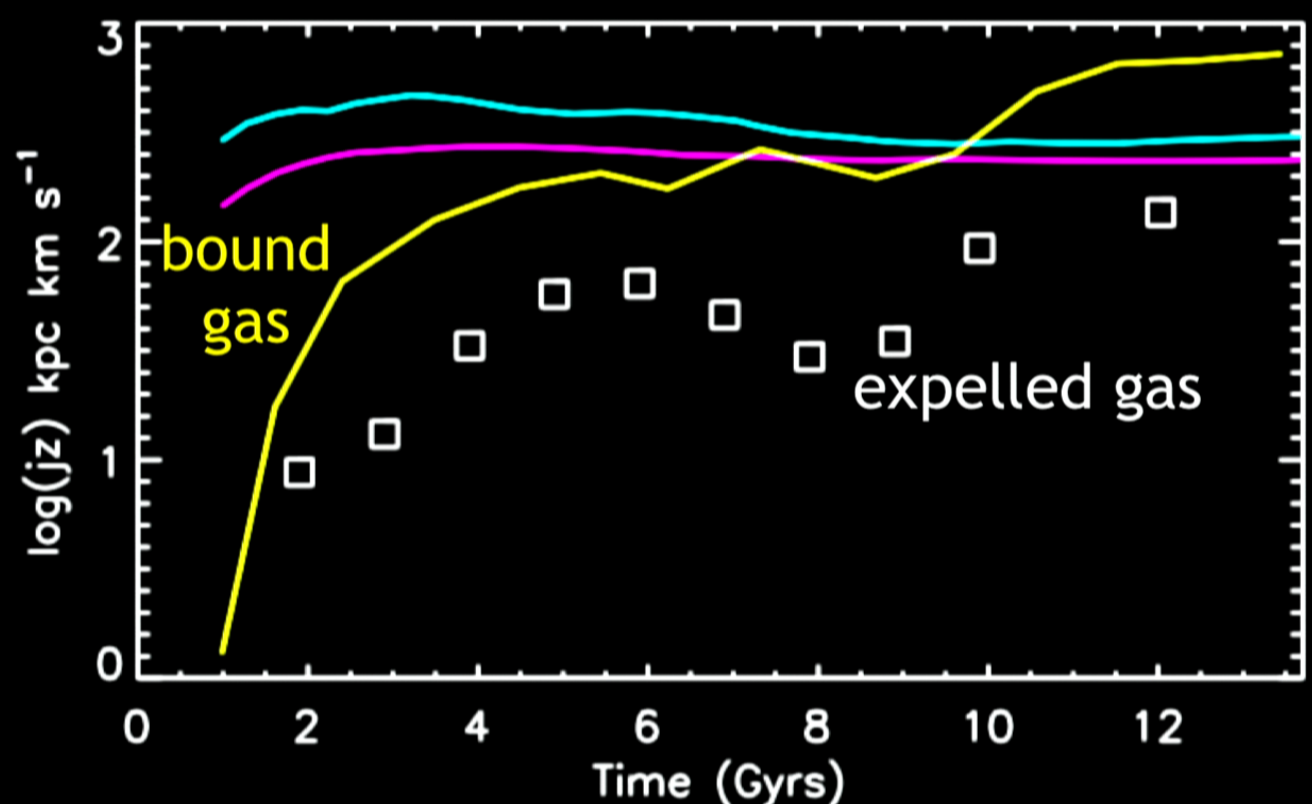
Gasoline (Wadsley/Quinn/Stadel) + Metal cooling + UV + H_2 + Thermal feedback



Andrew Pontzen

Gasoline (Wadsley/Quinn/Stadel) + Metal cooling + UV + H_2 + Thermal feedback





Brook+ 2011

cf Binney 01, van den Bosch 01

Flores & Primack 1994

Navarro, Eke, Frenk 1996

El Zant 2001

El Zant 2004

Pasetto et al 2010,
Goerdt et al 2010,
Cole et al 2011

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Mashchenko et al 2006/2008

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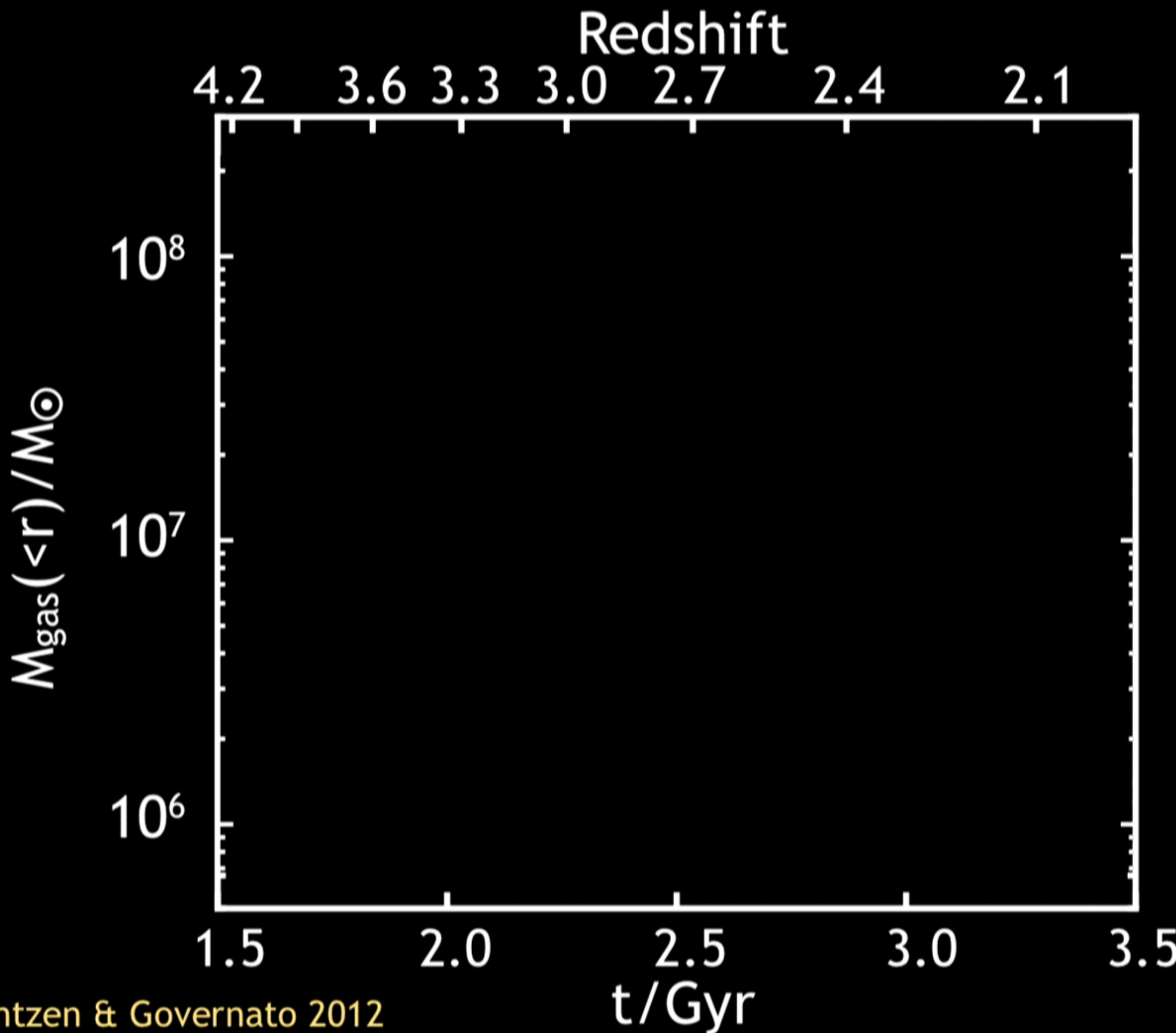
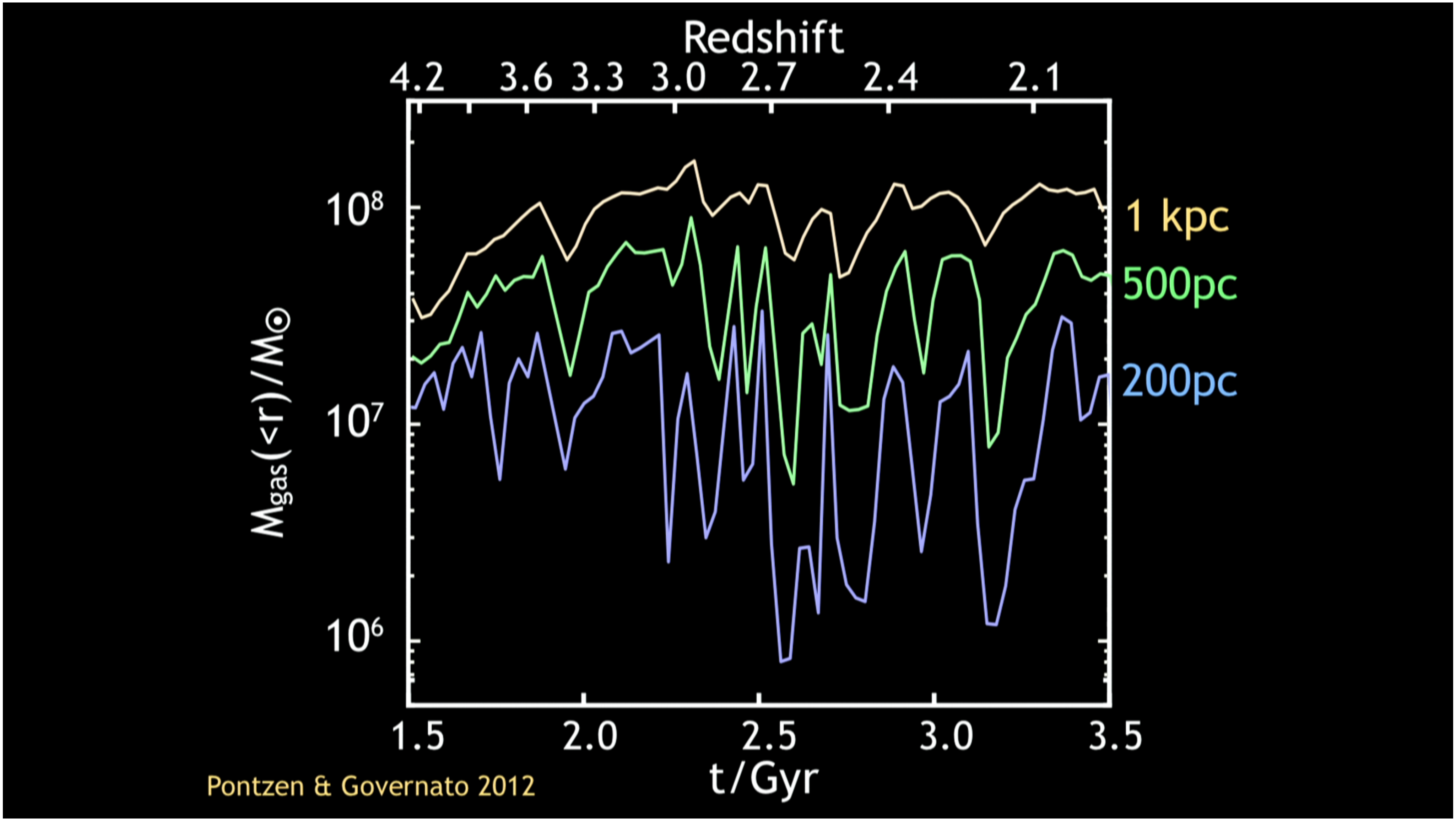
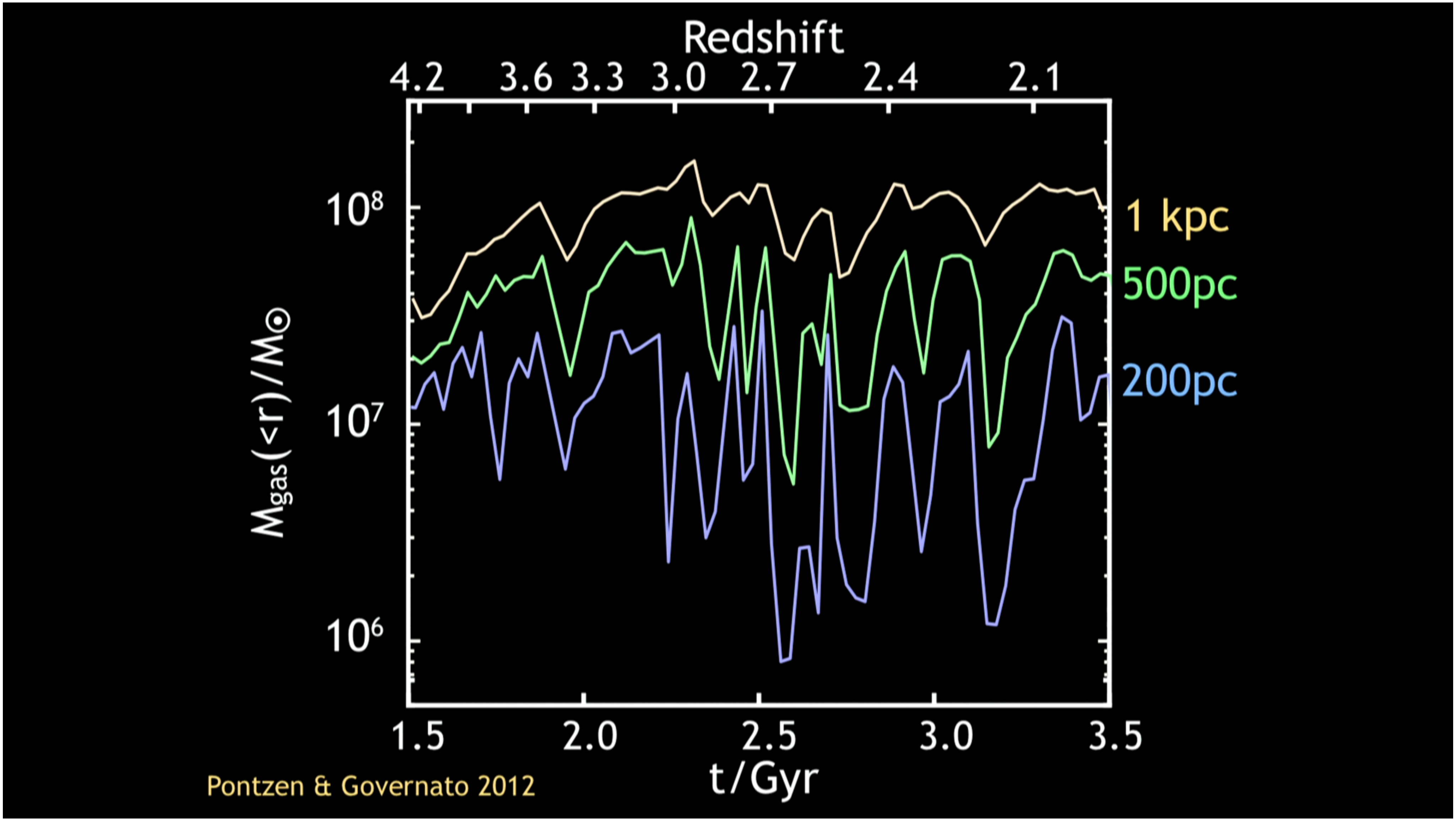
Cole et al 2011



Pontzen & Governato 2012


Redshift
4.2
3.6
3.3
3.0
2.7
2.4
2.1
10^8
10^7
10^6
Mgas(<r)/M☉
1 kpc
500pc
200pc
1.5
2.0
2.5
3.0
3.5
t/Gyr
Pontzen & Governato 2012


Redshift
4.2
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3.3
3.0
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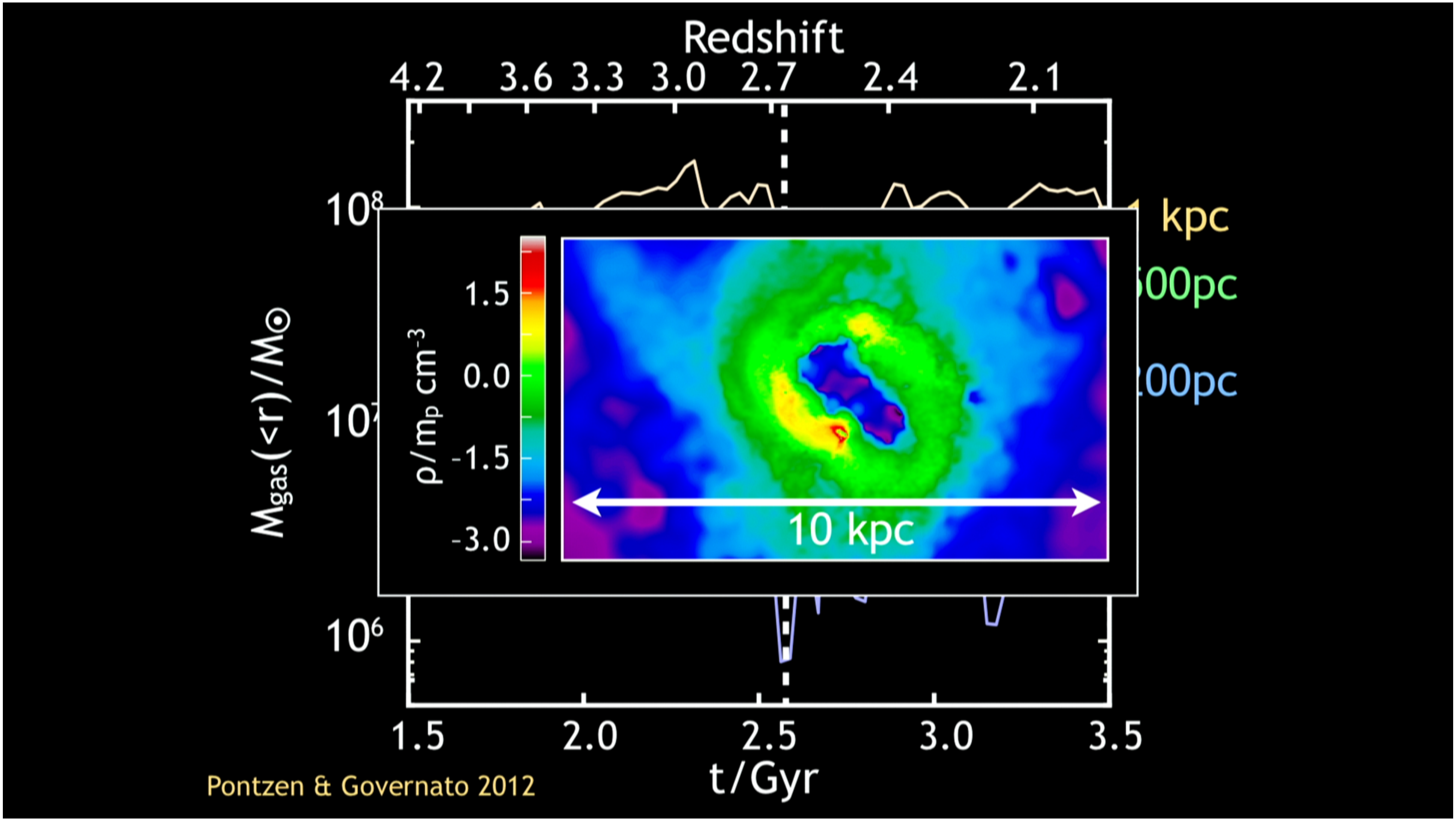
2.4
2.1
10^8
10^7
10^6
$M_{gas}(<r)/M_\odot$
1 kpc
500pc
200pc
1.5
2.0
2.5
3.0
3.5
t/Gyr
Pontzen & Governato 2012


Redshift
4.2
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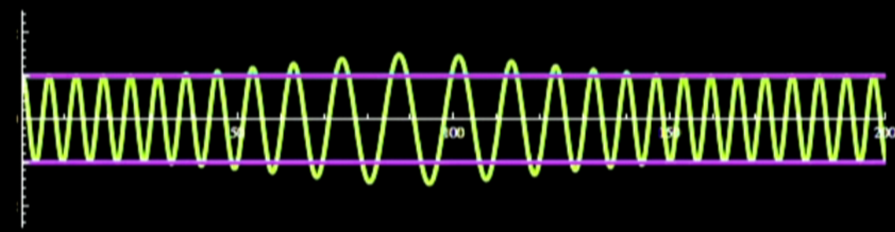
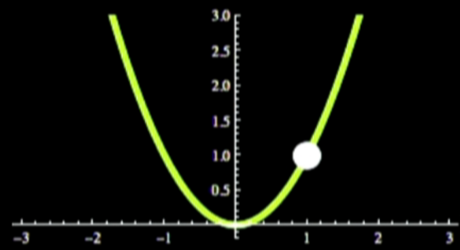
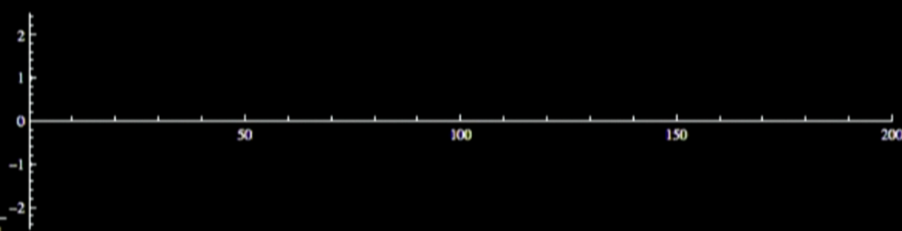
3.0
2.7
2.4
2.1
10^8
10^7
10^6
$M_{gas}(<r)/M_\odot$
kpc
00pc
00pc
1.5
0.0
-1.5
-3.0
$\rho/m_p\ cm^{-3}$
10 kpc
1.5
2.0
2.5
3.0
3.5
t/Gyr
Pontzen & Governato 2012

Adiabatic

$$E_f = E_i$$







Pontzen & Governato 2012

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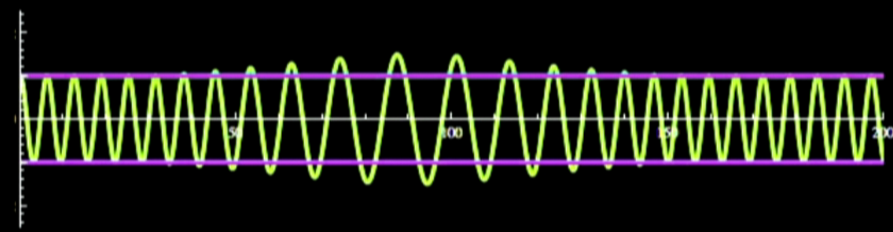
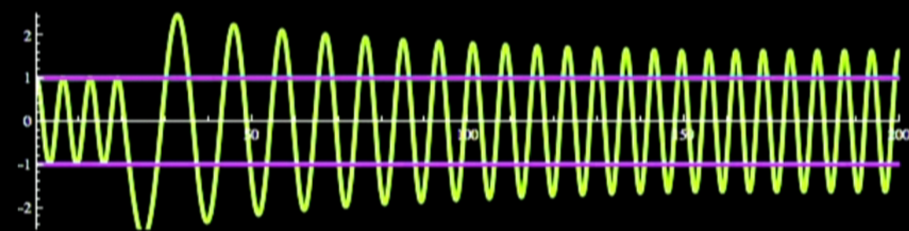


Sudden, then adiabatic

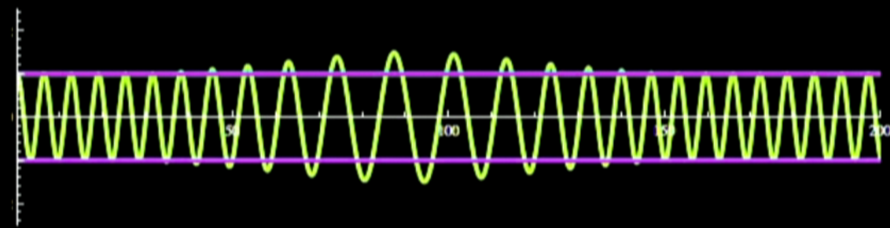
$$\frac{\langle E_f \rangle}{E_i} = \frac{1}{2}\left(\frac{\omega_1}{\omega_0} + \frac{\omega_0}{\omega_1}\right)$$



Pontzen & Governato 2012

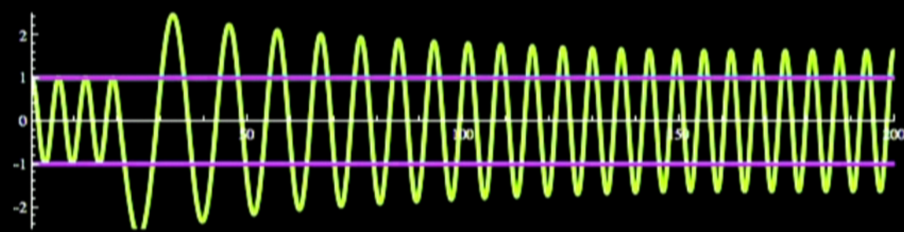
Adiabatic

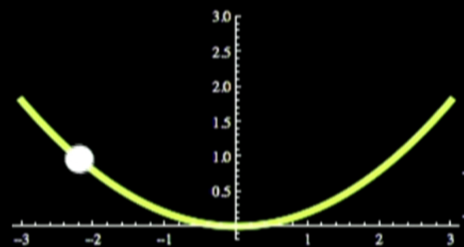
$$E_f = E_i$$

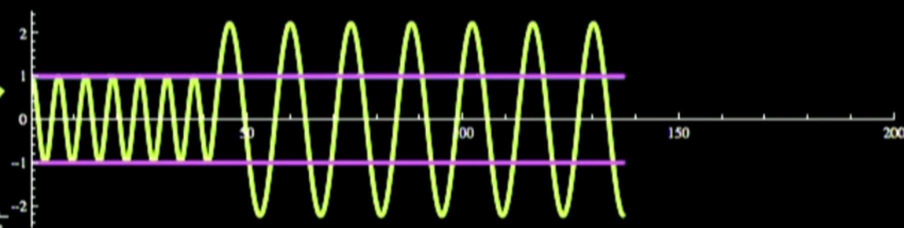


Sudden, then adiabatic

$$\frac{\langle E_f \rangle}{E_i} = \frac{1}{2}\left(\frac{\omega_1}{\omega_0} + \frac{\omega_0}{\omega_1}\right)$$



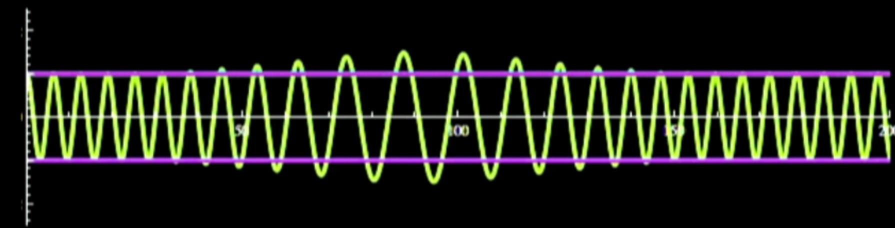




Pontzen & Governato 2012

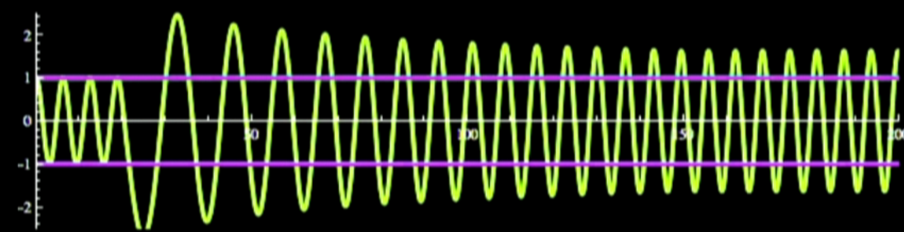
Adiabatic

$$E_f = E_i$$



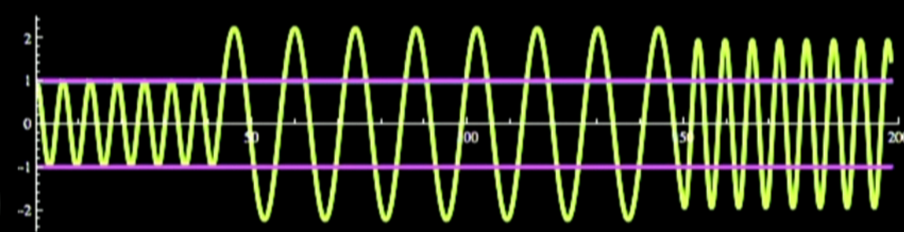
Sudden, then adiabatic

$$\frac{\langle E_f \rangle}{E_i} = \frac{1}{2}\left(\frac{\omega_1}{\omega_0} + \frac{\omega_0}{\omega_1}\right)$$



Sudden, then sudden

$$\frac{\langle E_f \rangle}{E_i} = \left(1 + \frac{1}{4}\left[\frac{\omega_1^2 - \omega_0^2}{\omega_0^2}\right]^2\right)$$



Pontzen & Governato 2012

The radial action:

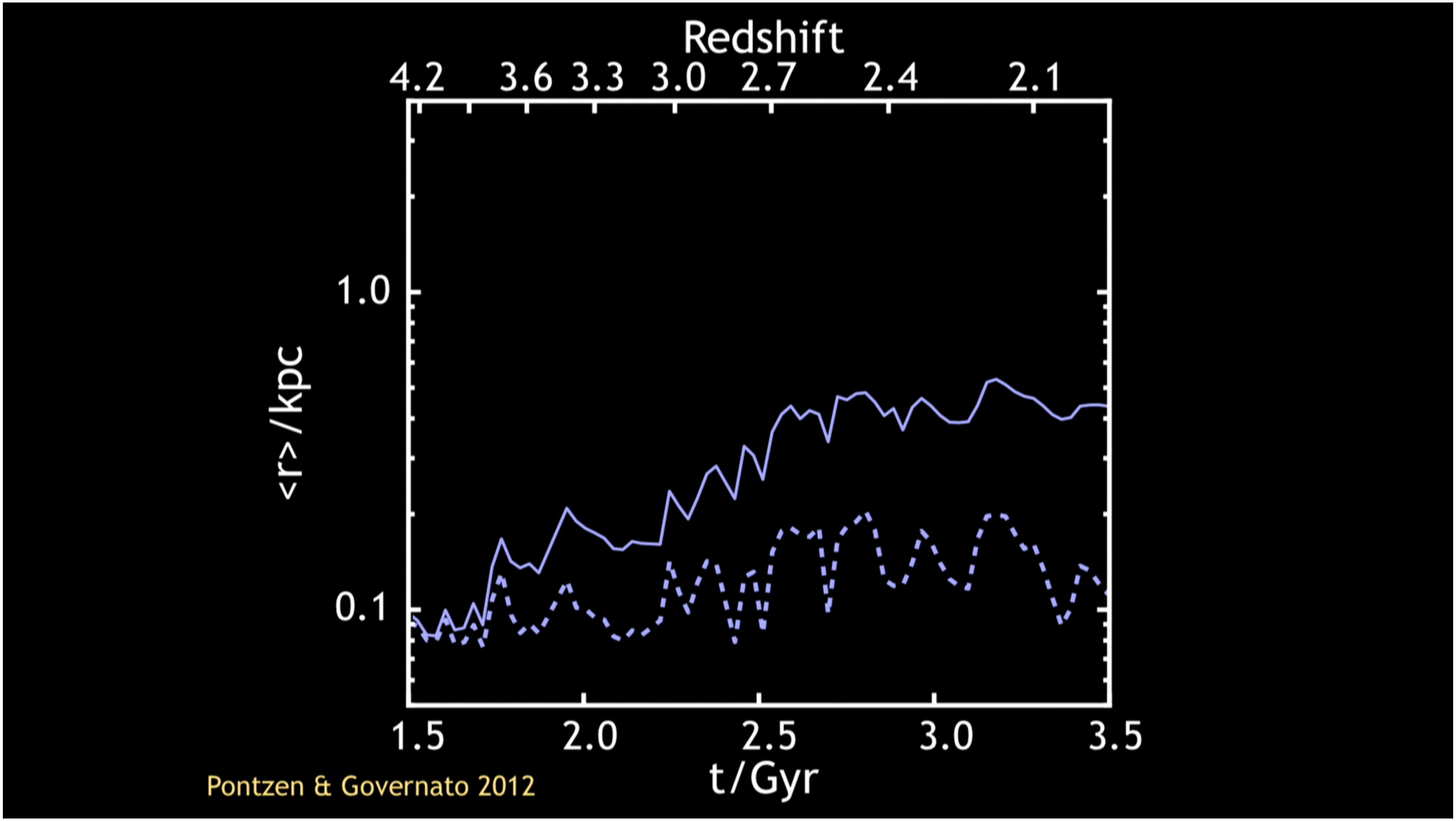
$$J_r = \frac{1}{\pi} \int \mathrm{d}r \, \sqrt{2E - 2\Phi(r) - j^2/r^2}$$

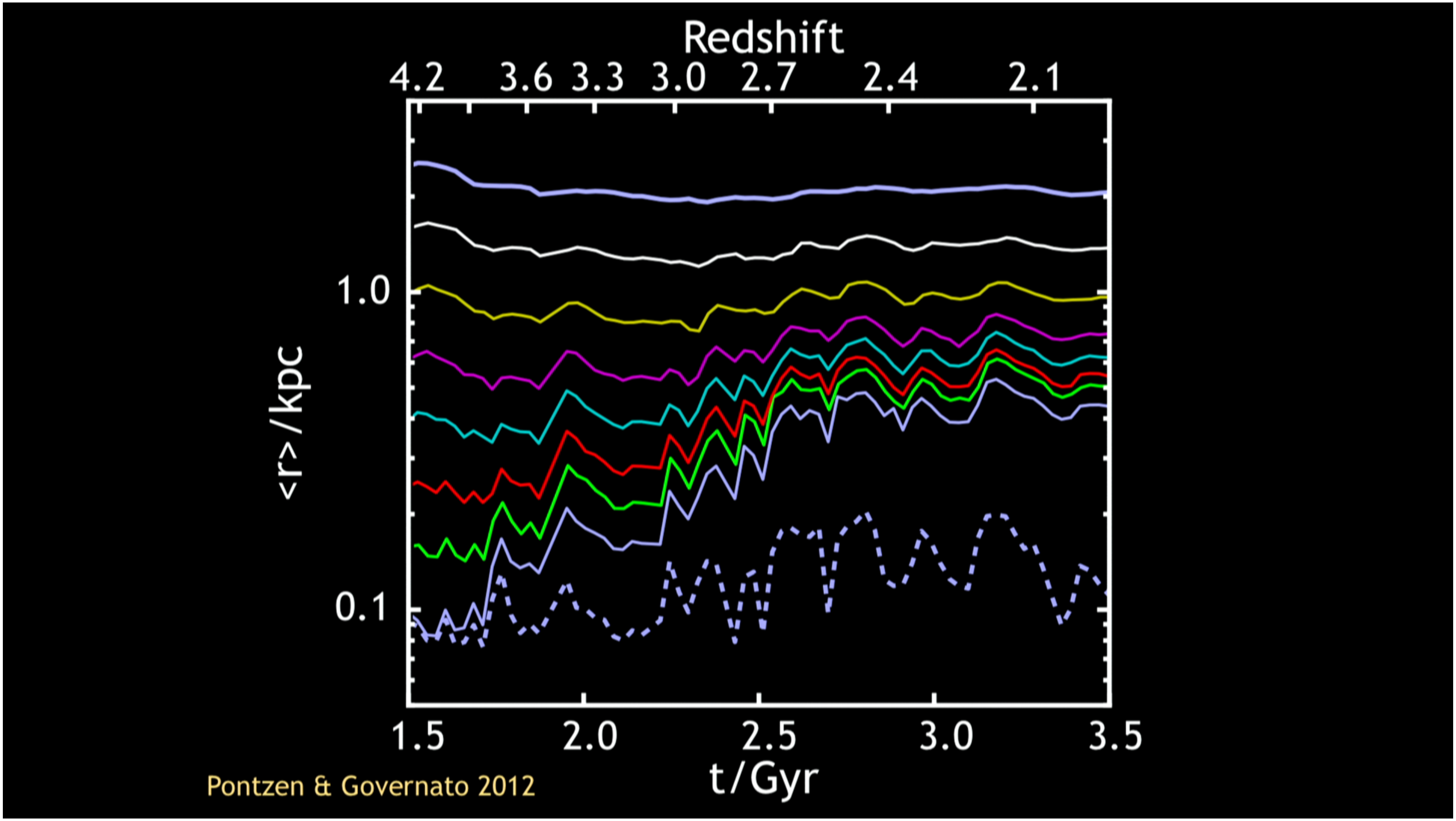
The radial action:

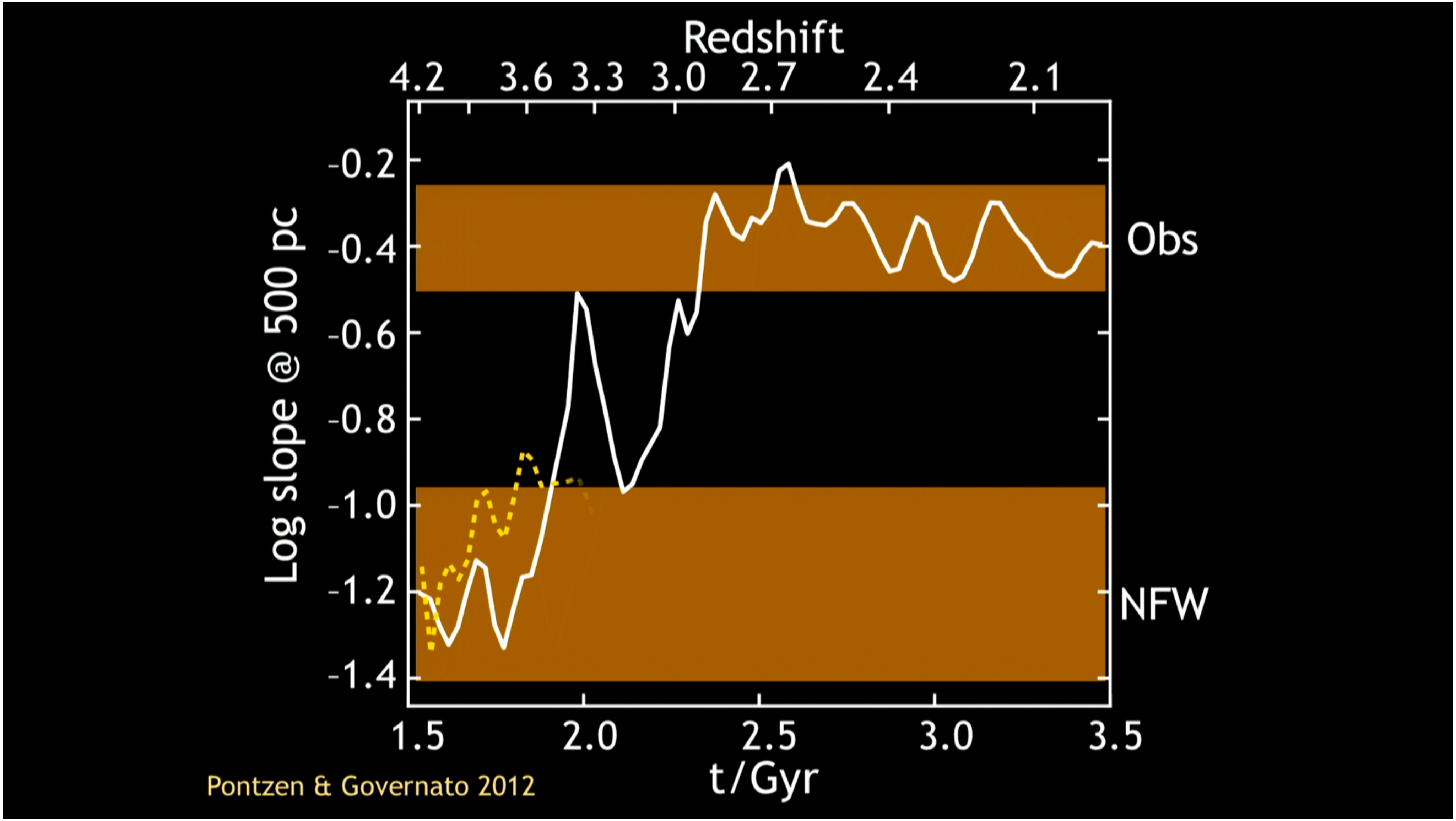
$$J_r = \frac{1}{\pi}\int \mathrm{d}r\,\sqrt{2E - 2\Phi(r) - j^2/r^2}$$

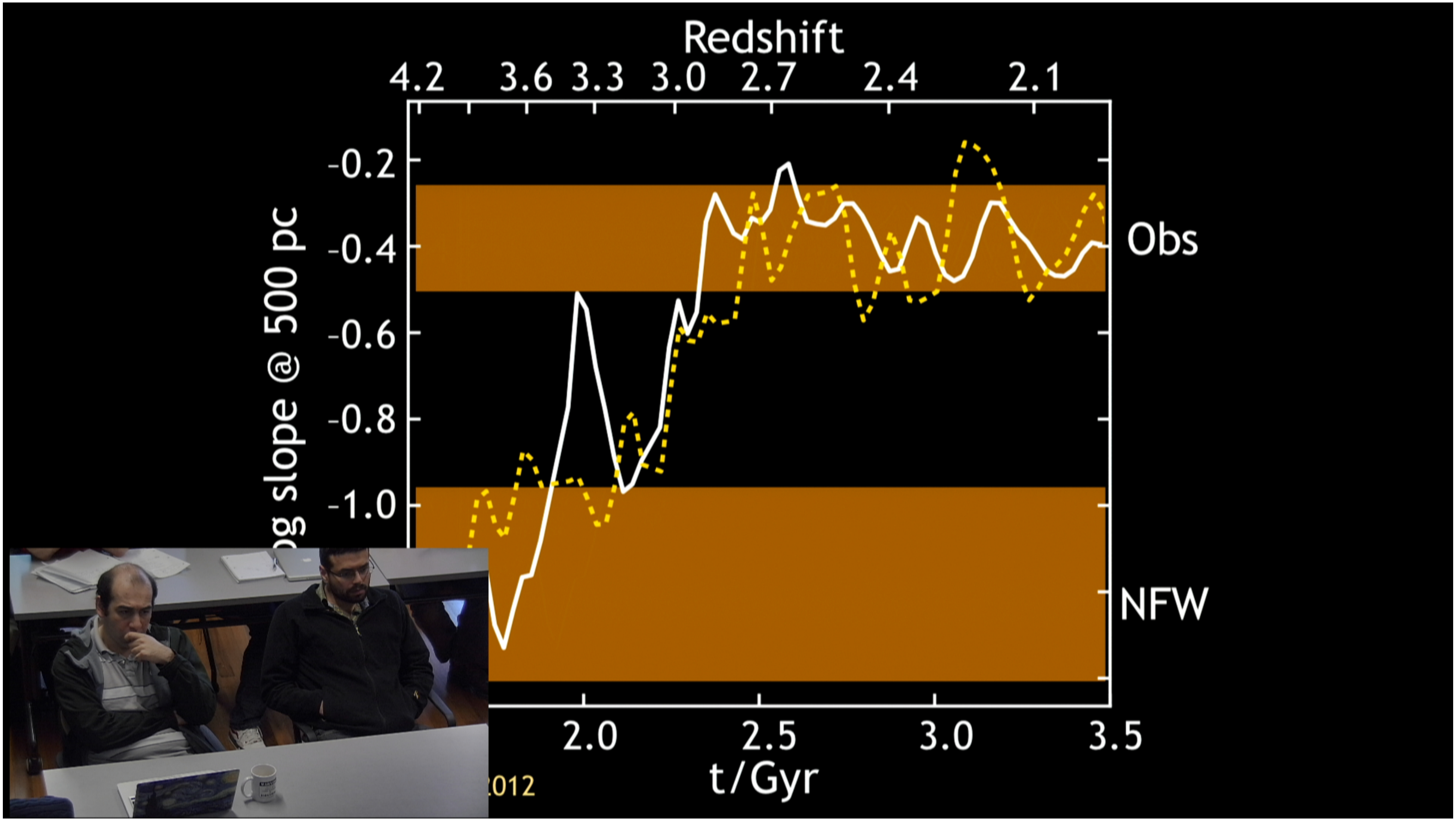
Slow ('adiabatic') changes:

J_r=constant, j=constant


Redshift
4.2
3.6
3.3
3.0
2.7
2.4
2.1
1.0
0.1
<r> /kpc
1.5
2.0
2.5
3.0
3.5
t/Gyr
Pontzen & Governato 2012


Redshift
4.2
3.6
3.3
3.0
2.7
2.4
2.1
1.0
0.1
<r> /kpc
1.5
2.0
2.5
3.0
3.5
t/Gyr
Pontzen & Governato 2012


Redshift
4.2
3.6
3.3
3.0
2.7
2.4
2.1
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
Log slope @ 500 pc
Obs
NFW
1.5
2.0
2.5
3.0
3.5
t/Gyr
Pontzen & Governato 2012


Redshift
4.2
3.6
3.3
3.0
2.7
2.4
2.1
-0.2
-0.4
-0.6
-0.8
-1.0
Obs
NFW
2.0
2.5
3.0
3.5
t/Gyr

Dwarf MW Cluster

$M_{200} = 2.8 \times 10^{10}\ M_\odot$, $r_{200} = 98$ kpc

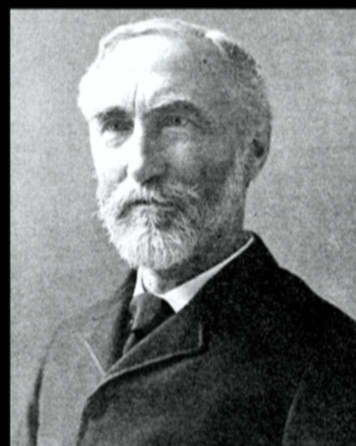
$M_{200} = 8.0 \times 10^{11}\ M_\odot$, $r_{200} = 301$ kpc

$M_{200} = 8.7 \times 10^{13}\ M_\odot$, $r_{200} = 1.43$ Mpc

Pontzen & Governato
arXiv:1210.1849

Statistical mechanics

maximize $\int f \ln f$ …why?

Statistical mechanics

maximize $\int f \ln f$ subject to fixed <E>,

$$f \propto \exp -\beta E$$

'violent relaxation'
(Lynden-Bell 1967)

J_r, j, j_z conserved under slow changes of potential

Statistical mechanics

maximize $\int f \ln f$ subject to fixed $\langle E \rangle$,

$$f \propto \exp -\beta E$$

'violent relaxation'
(Lynden-Bell 1967)

J_r, j, j_z conserved under slow changes of potential

$\langle J_r \rangle$, $\langle j \rangle$, $\langle j_z \rangle$ conserved under **any** changes of potential

Statistical mechanics

maximize $\int f \ln f$ subject to fixed $\langle J_r \rangle$, $\langle j \rangle$, $\langle j_z \rangle$ & $\langle E \rangle$

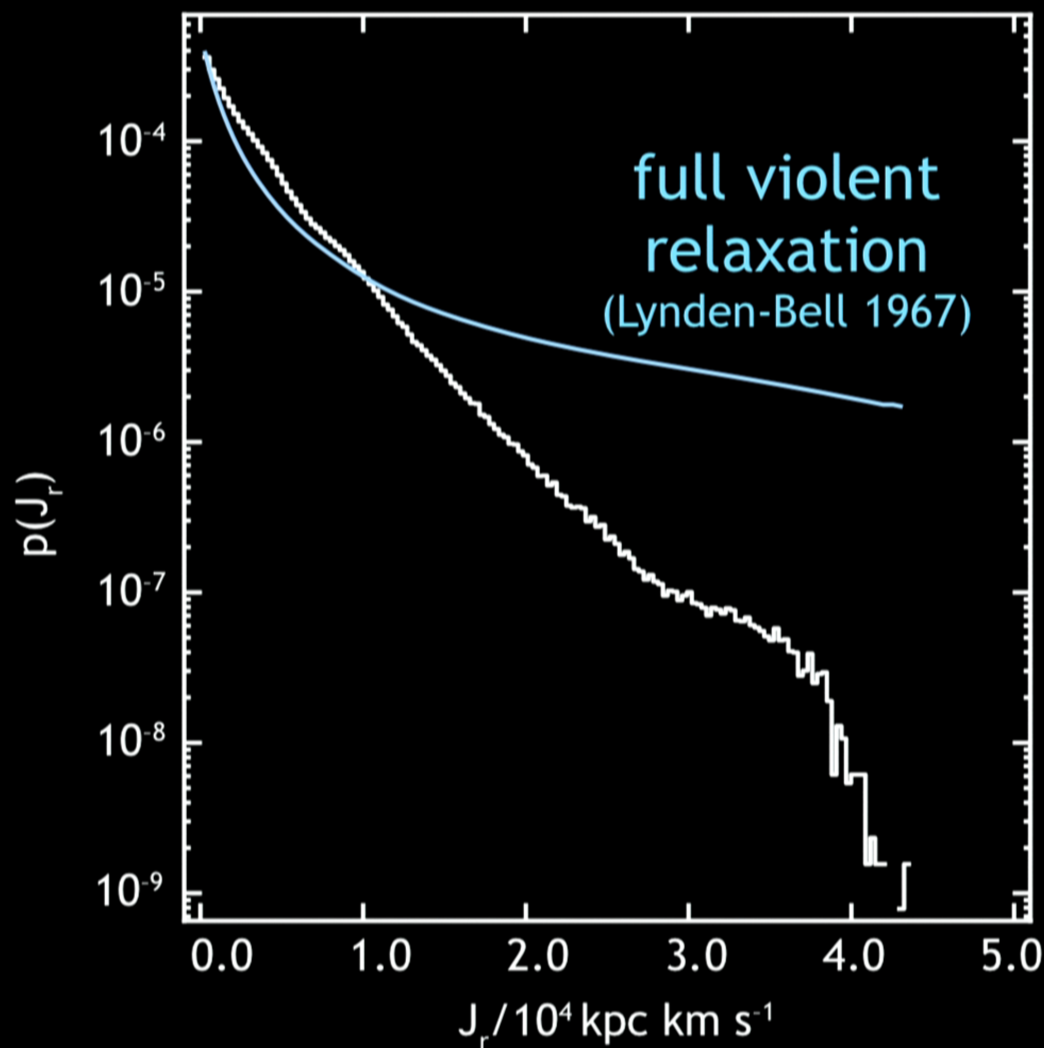
$$f \propto \exp\left(-\beta_r J_r - \beta_j j - \beta_z j_z - \beta_E E\right)$$

'constrained violent relaxation'

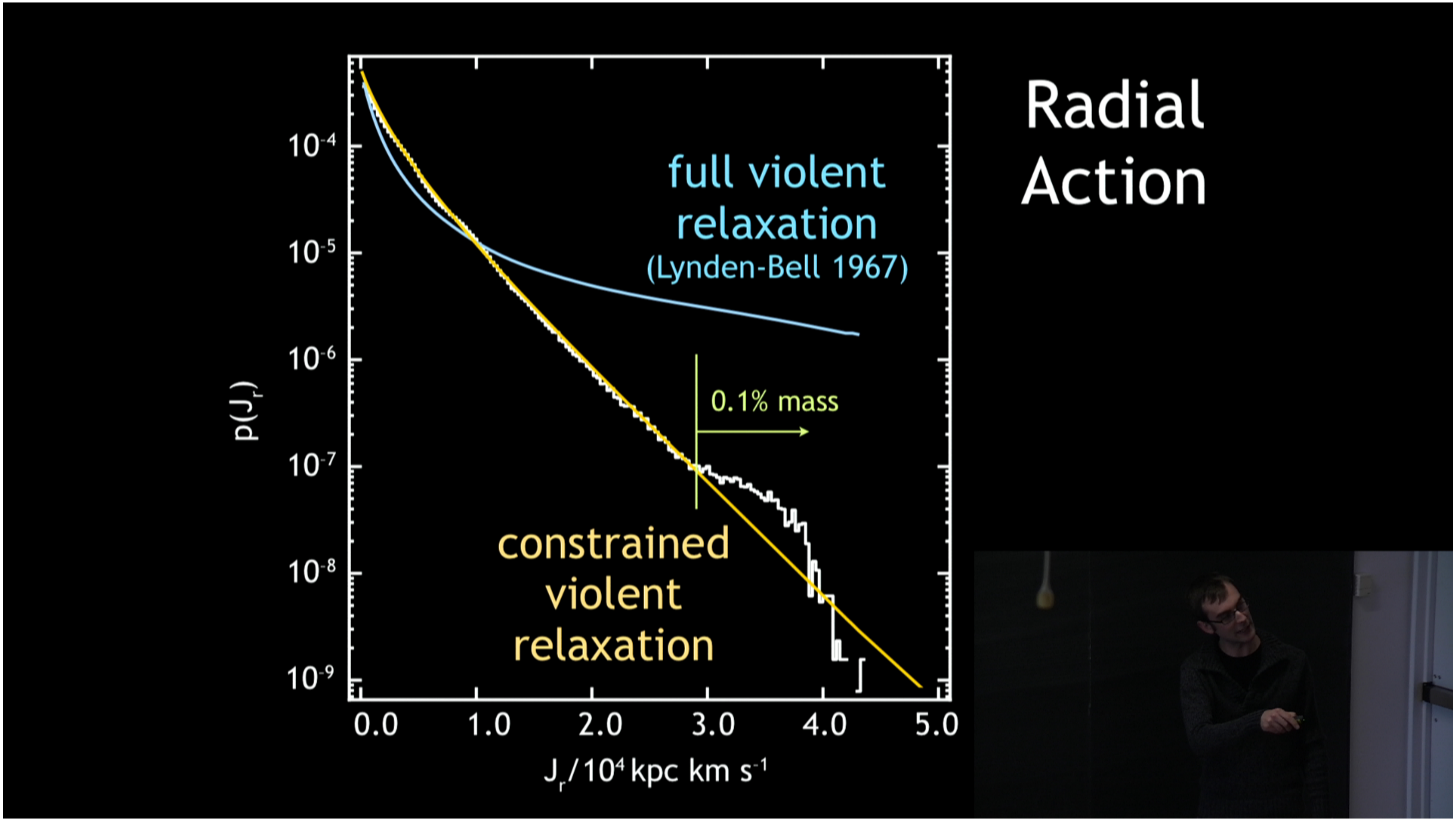
J_r, j, j_z conserved under slow changes of potential

$\langle J_r \rangle$, $\langle j \rangle$, $\langle j_z \rangle$ conserved under **any** changes of potential

Radial Action

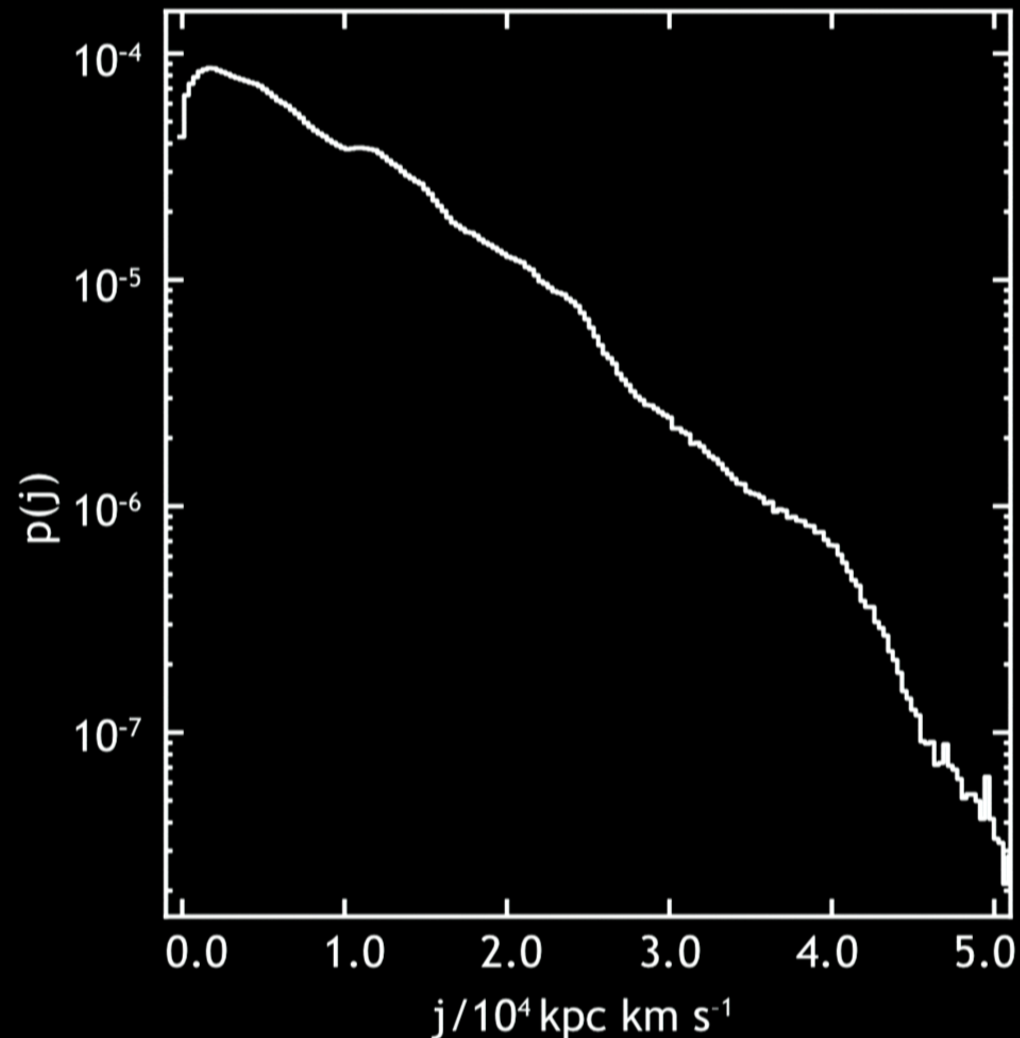


Pontzen & Governato arXiv:1210.1849



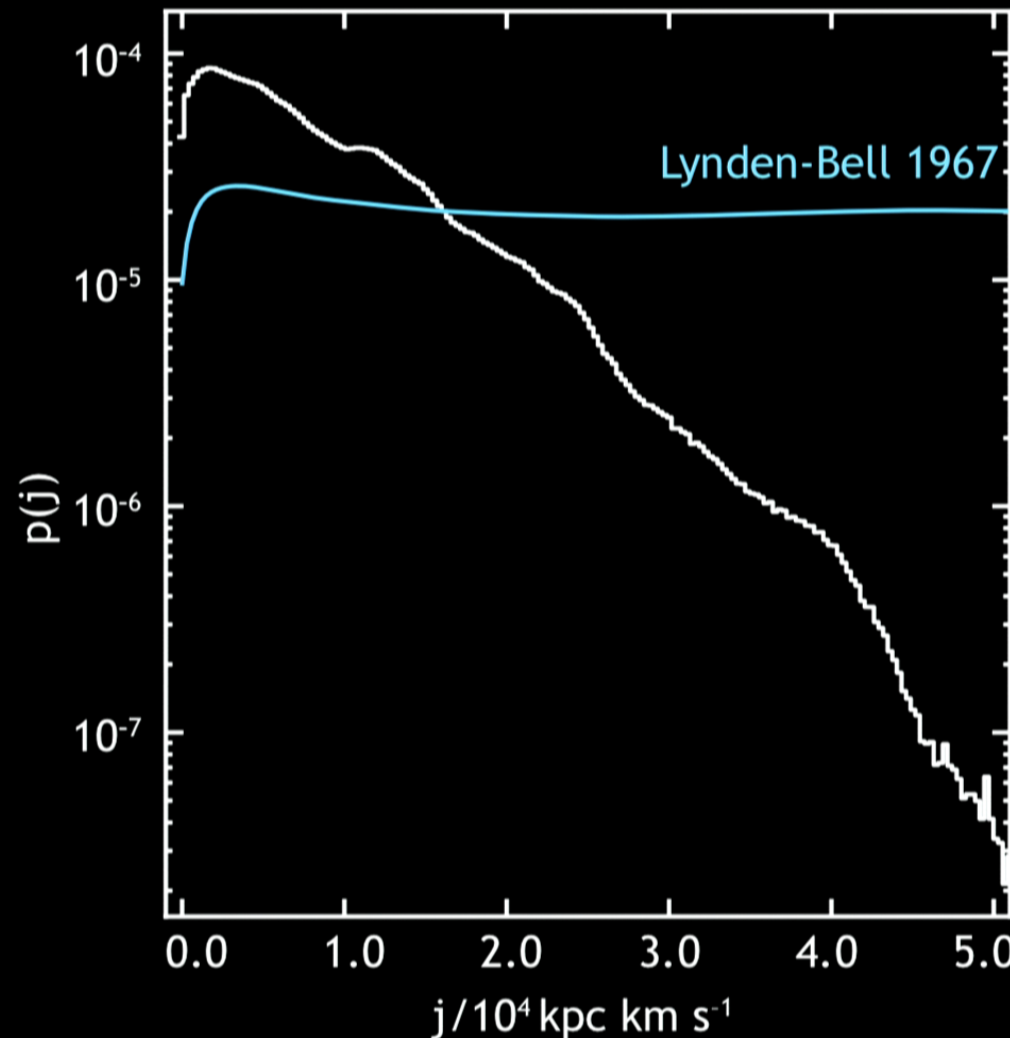
Radial
Action
full violent
relaxation
(Lynden-Bell 1967)
0.1% mass
constrained
violent
relaxation
$p(J_r)$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.0
1.0
2.0
3.0
4.0
5.0
$J_r / 10^4$ kpc km s^{-1}

Angular momentum

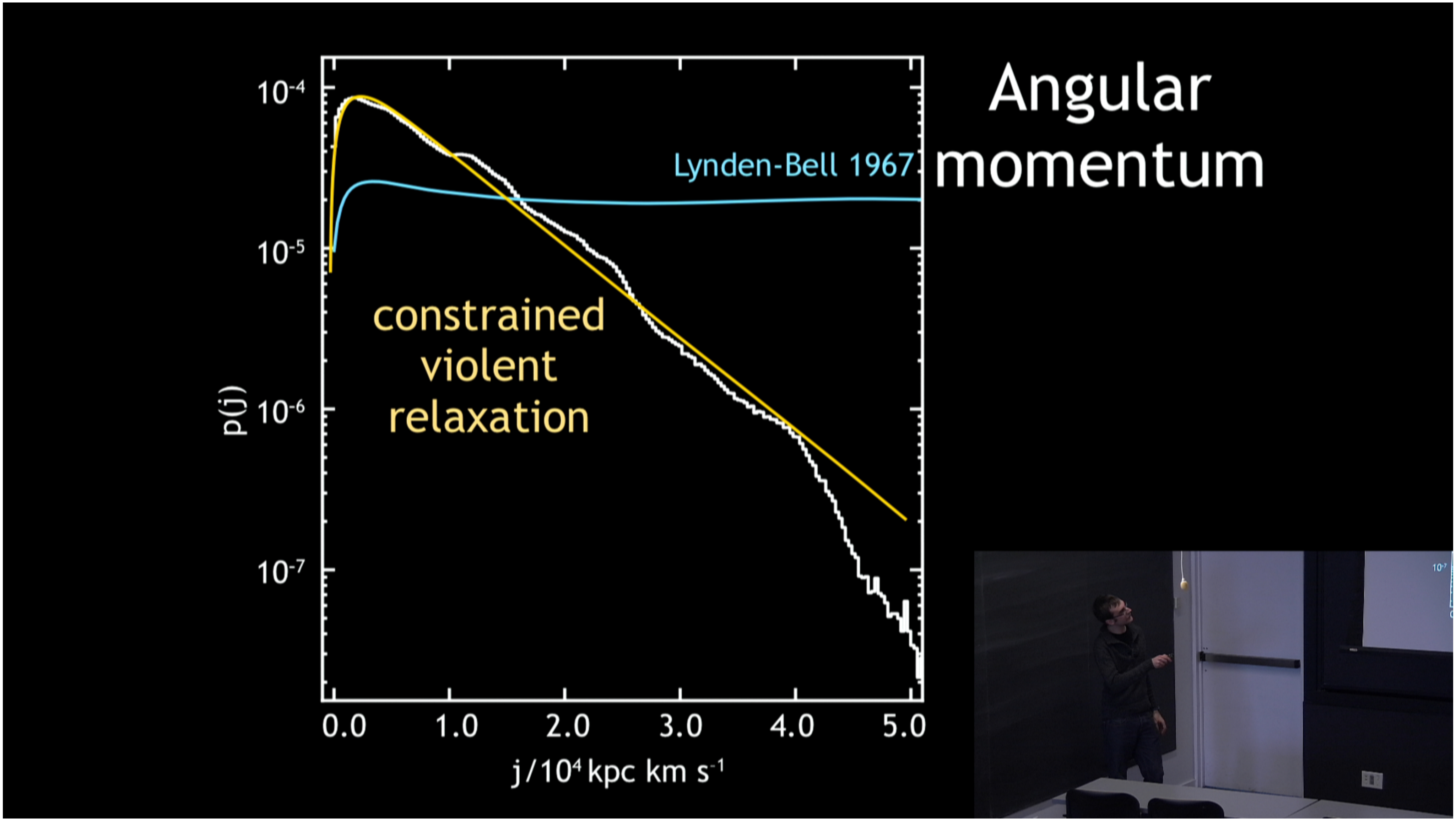


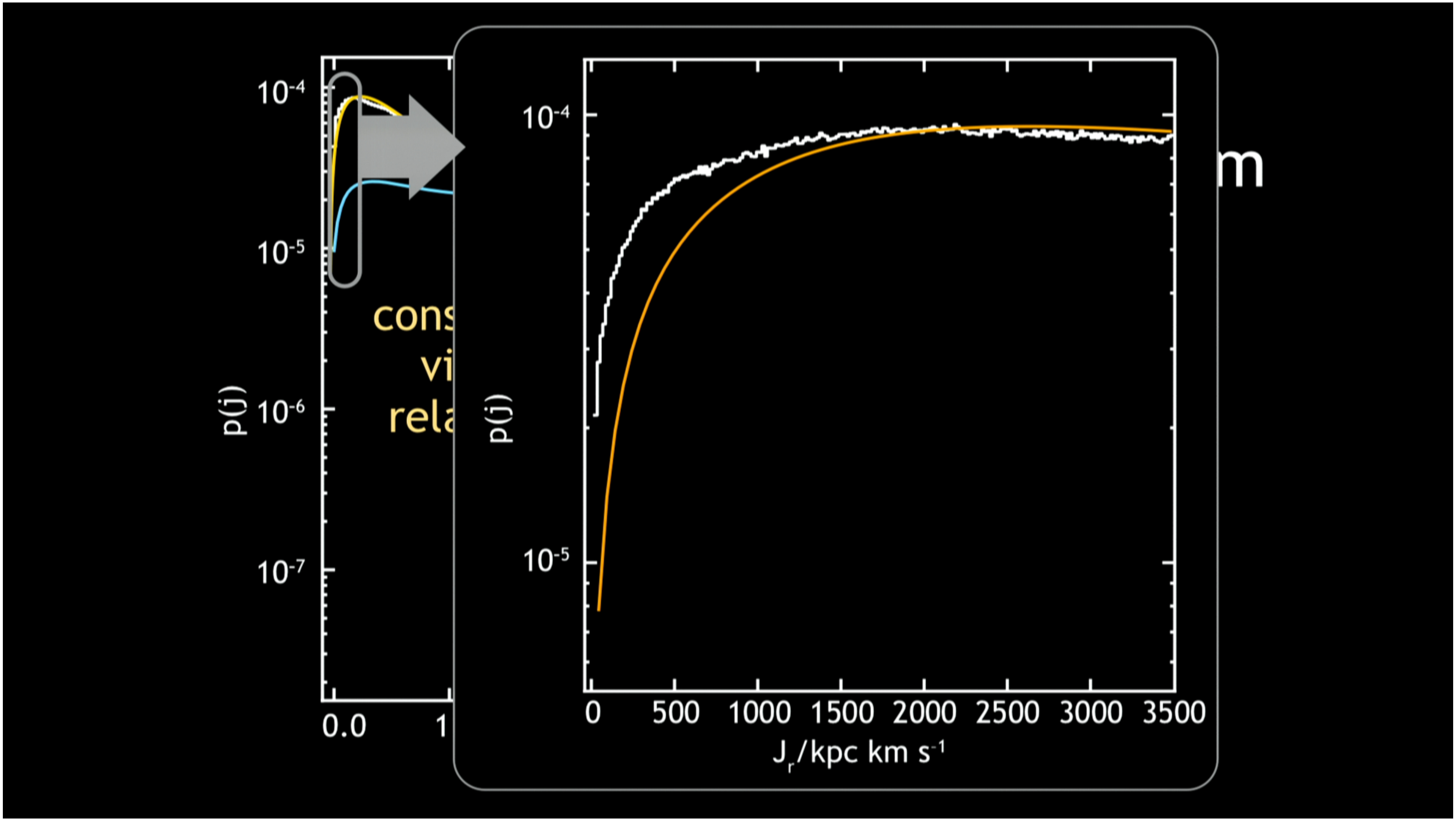
Pontzen & Governato arXiv:1210.1849

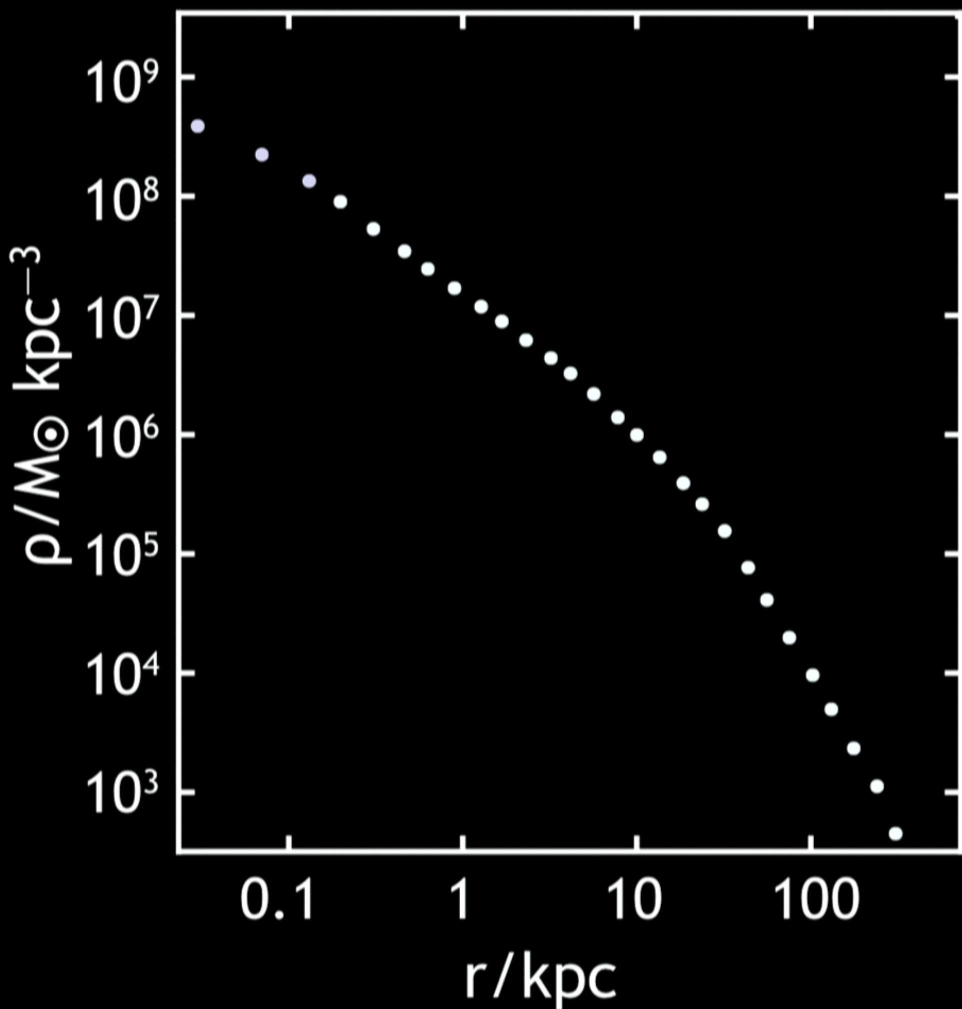
Angular momentum



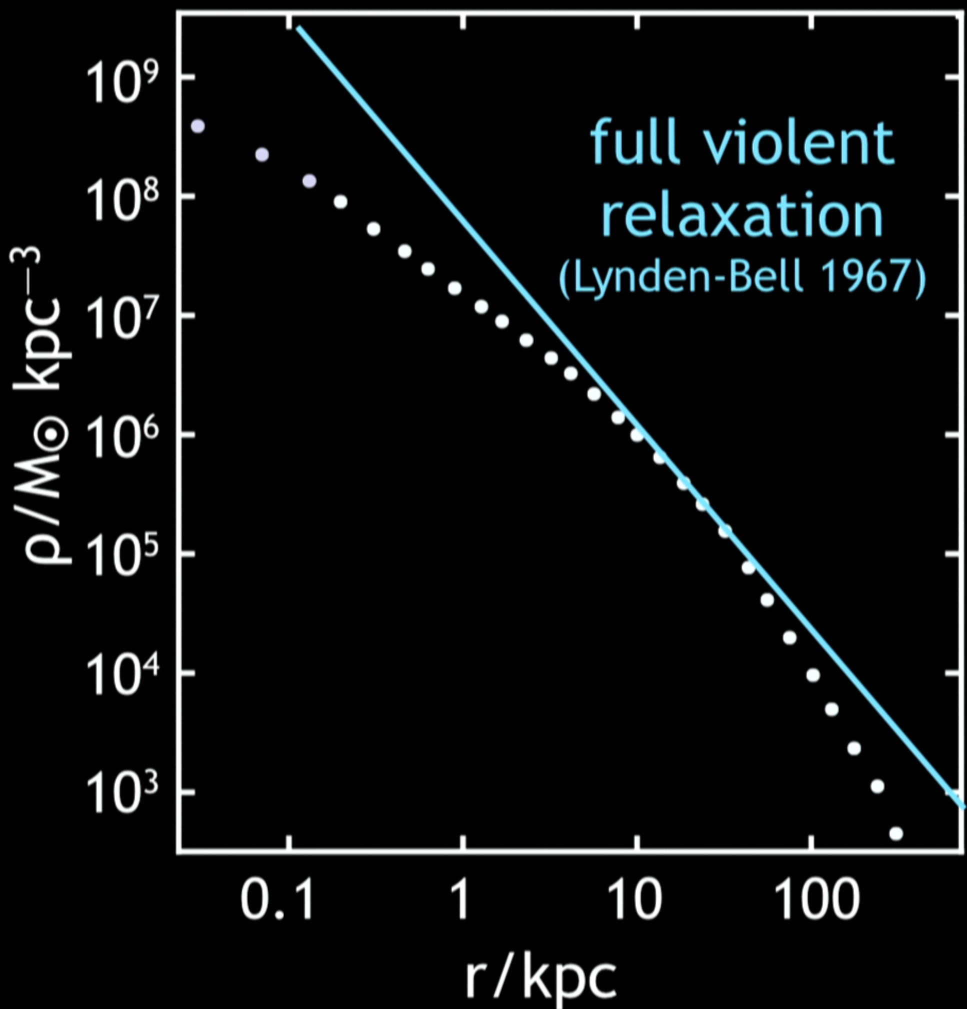
Pontzen & Governato arXiv:1210.1849

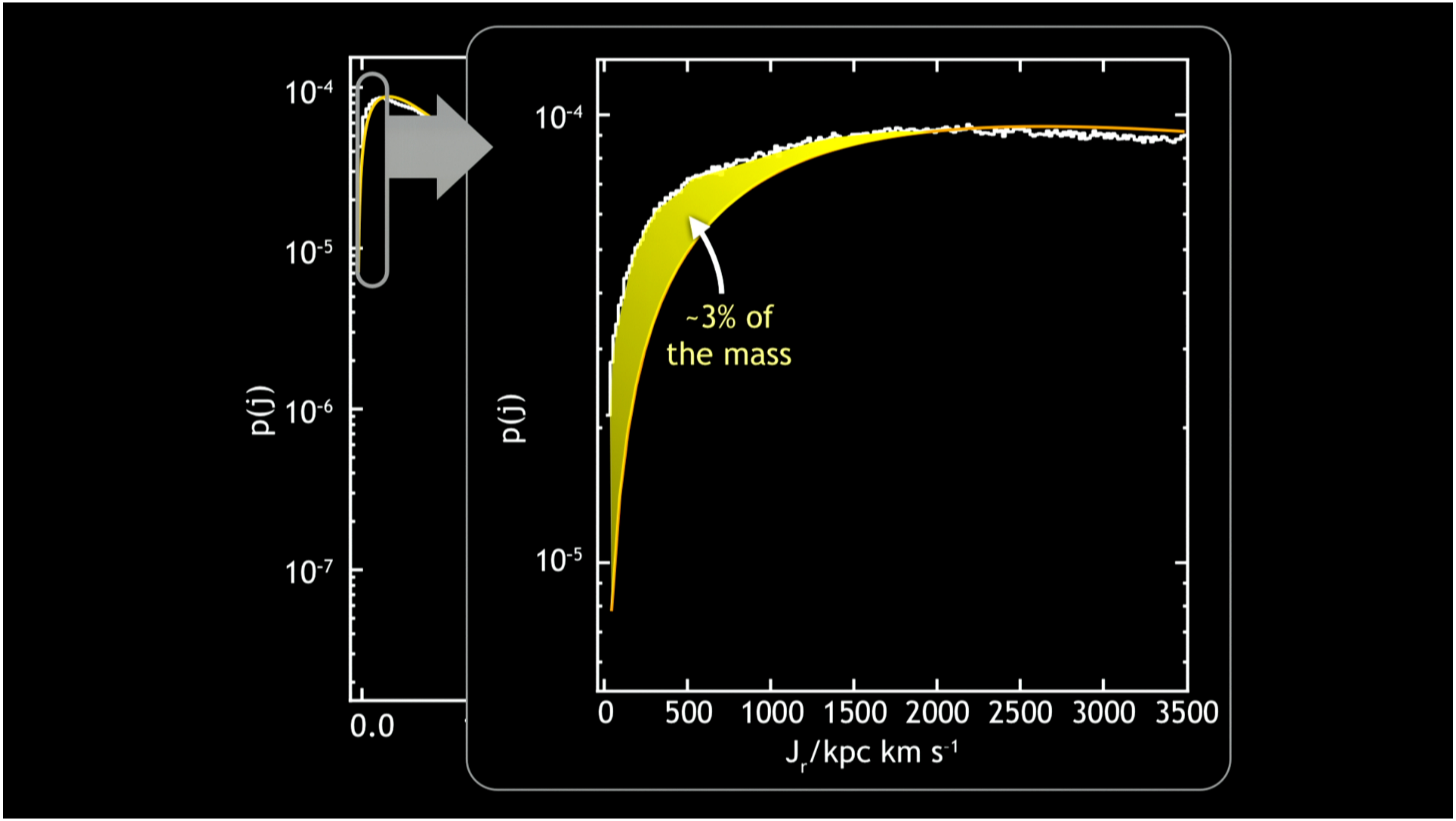

Angular momentum
Lynden-Bell 1967
constrained violent relaxation
p(j)
10-4
10-5
10-6
10-7
0.0
1.0
2.0
3.0
4.0
5.0
j / 10⁴ kpc km s⁻¹


10-4
10-5
10-6
10-7
p(j)
0.0
1
cons
vi
rela
m
10-4
10-5
p(j)
0
500
1000
1500
2000
2500
3000
3500
Jr/kpc km s-1

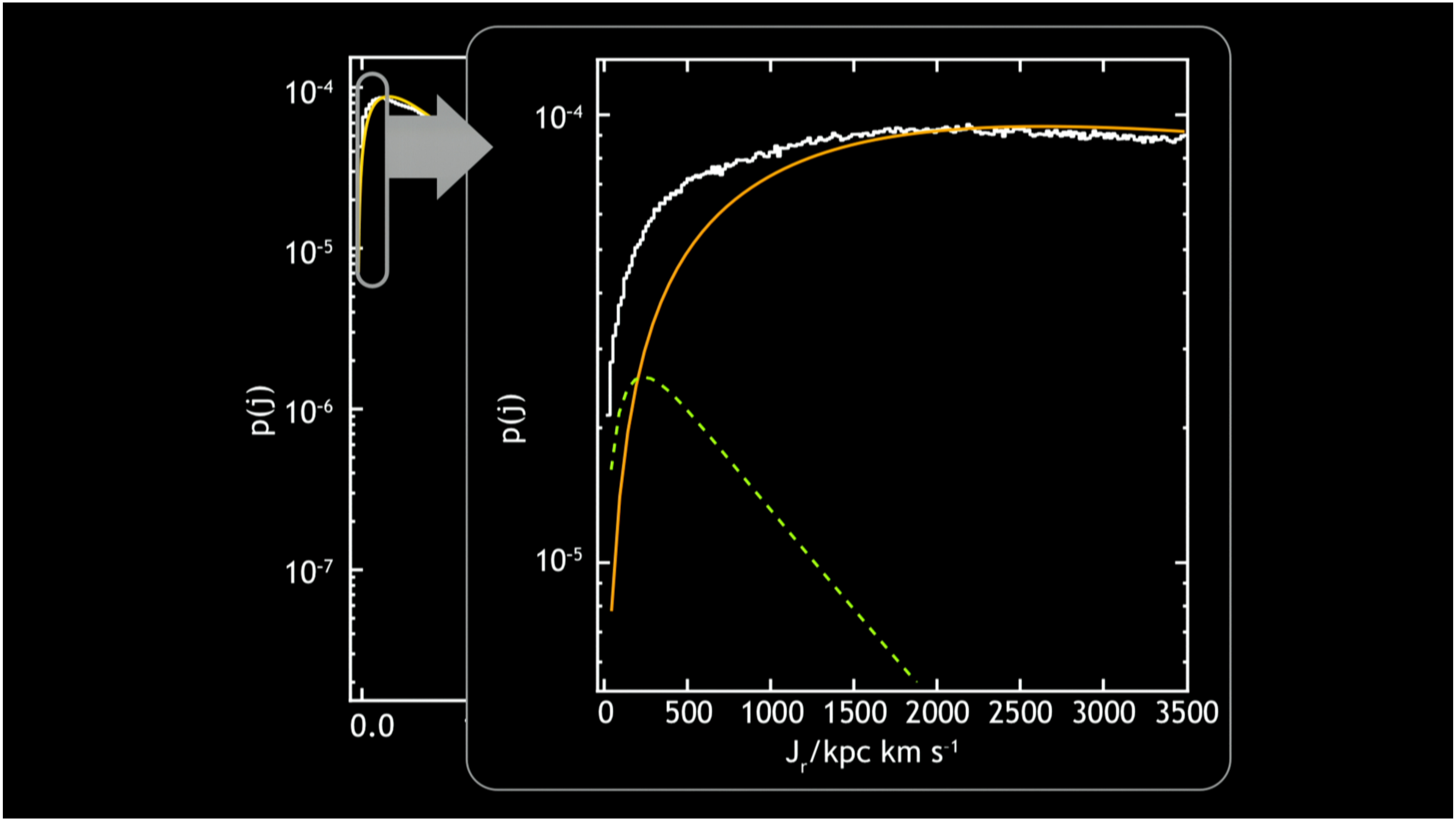


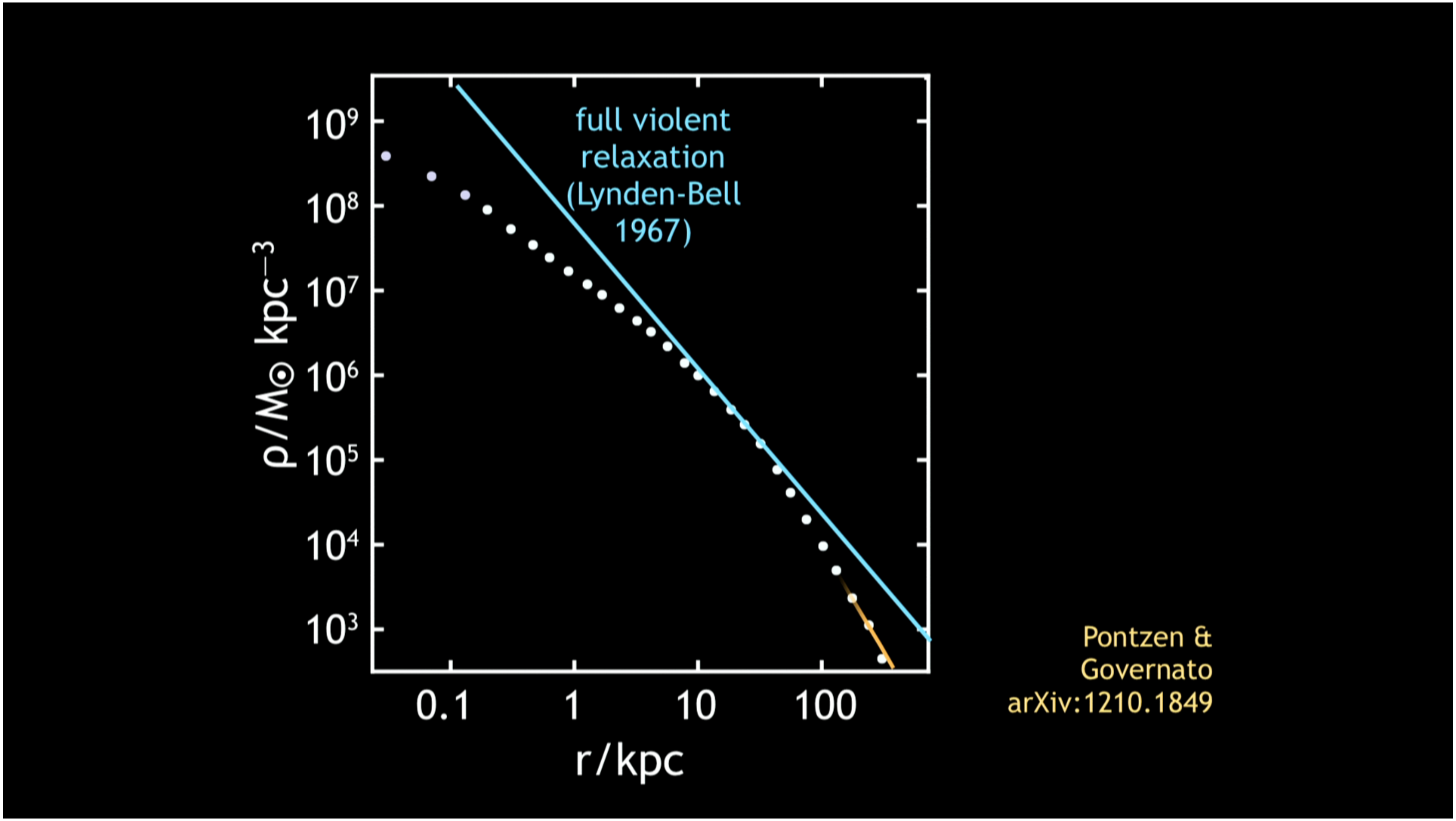
Pontzen &
Governato
arXiv:1210.1849

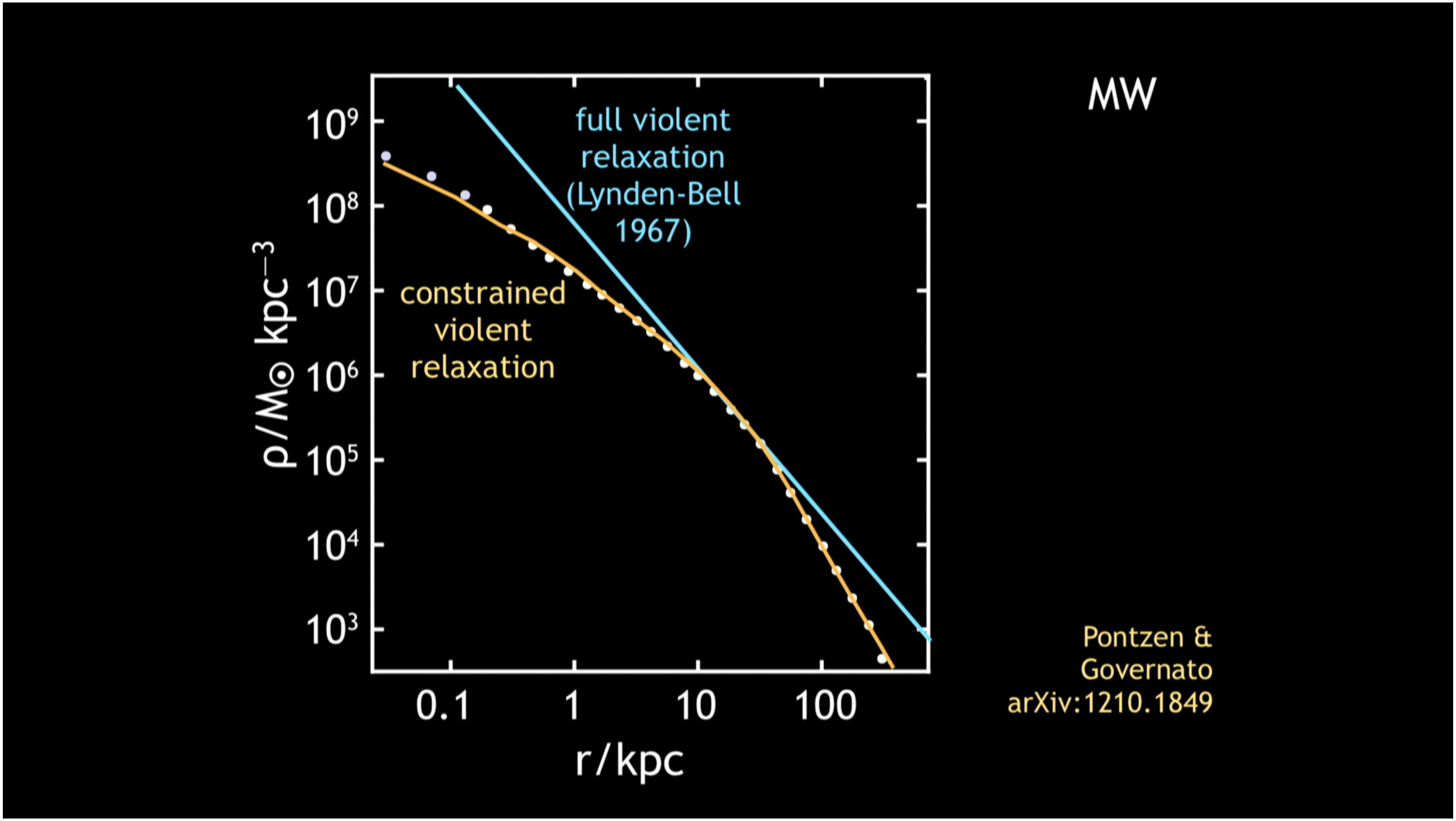

full violent
relaxation
(Lynden-Bell 1967)
ρ/M⊙ kpc⁻³
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
0.1
1
10
100
r/kpc

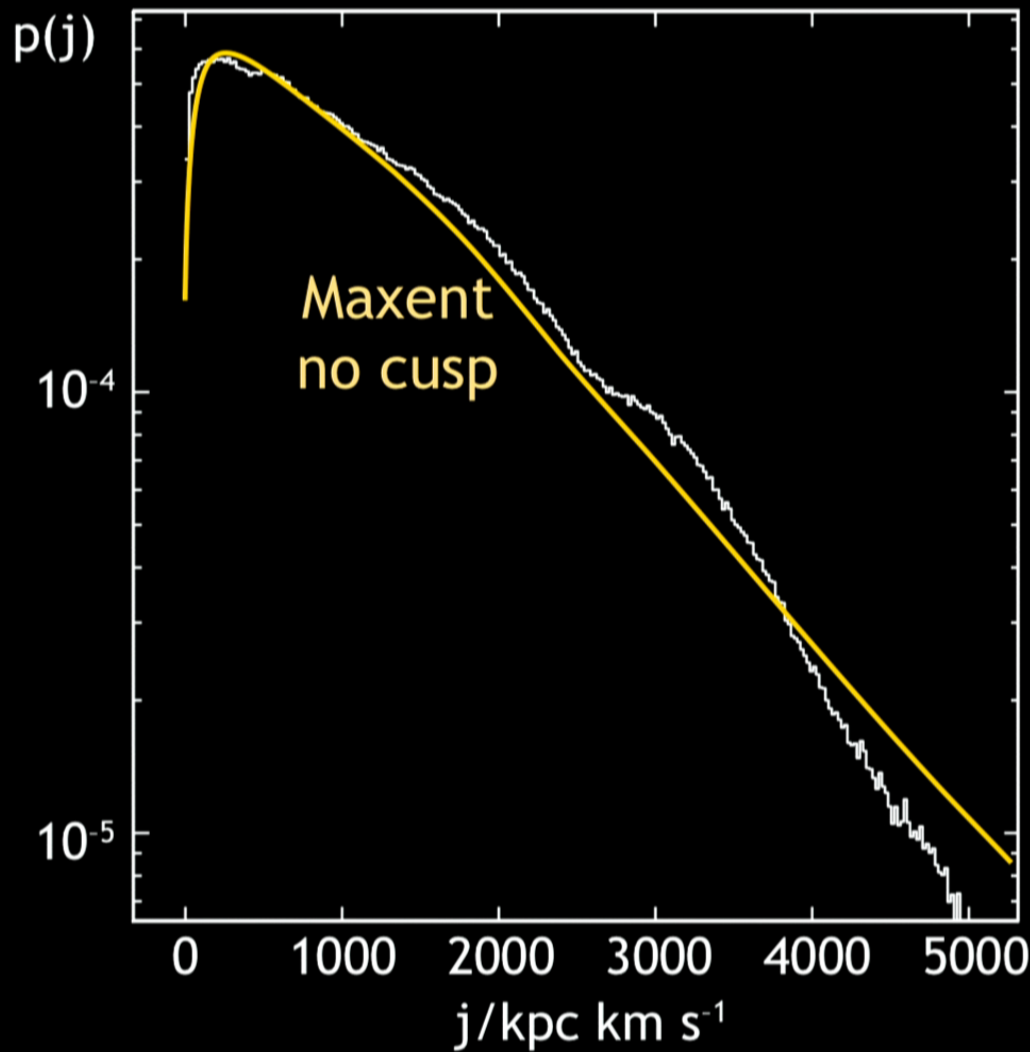


10-4
10-5
10-6
10-7
p(j)
0.0
p(j)
10-4
10-5
~3% of
the mass
0
500
1000
1500
2000
2500
3000
3500
J_r/kpc km s^{-1}

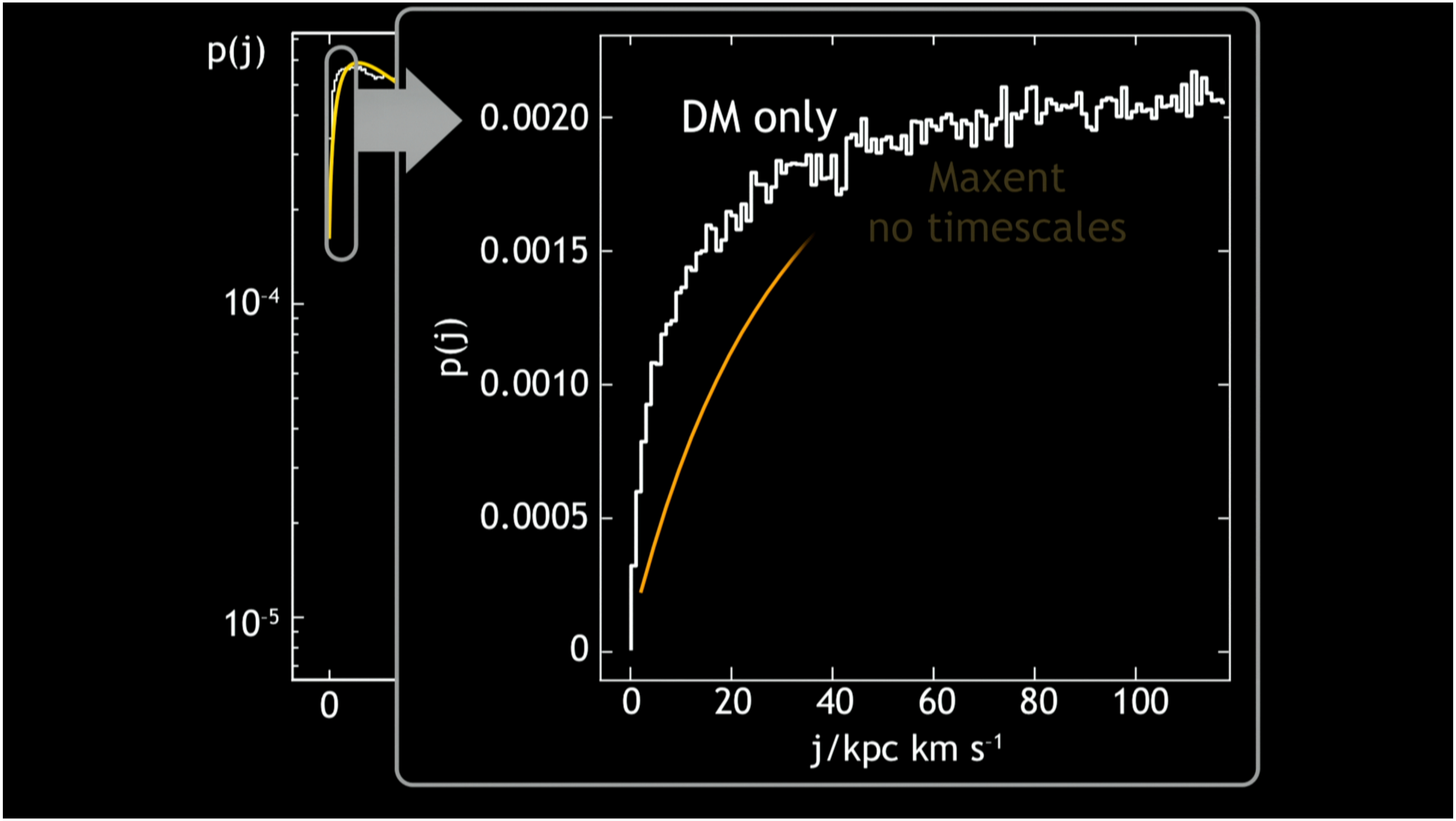

10-4
10-5
10-6
10-7
p(j)
0.0
10-4
10-5
p(j)
0 500 1000 1500 2000 2500 3000 3500
J_r/kpc km s-1


full violent
relaxation
(Lynden-Bell
1967)
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
ρ/M⊙ kpc⁻³
0.1
1
10
100
r/kpc
Pontzen &
Governato
arXiv:1210.1849

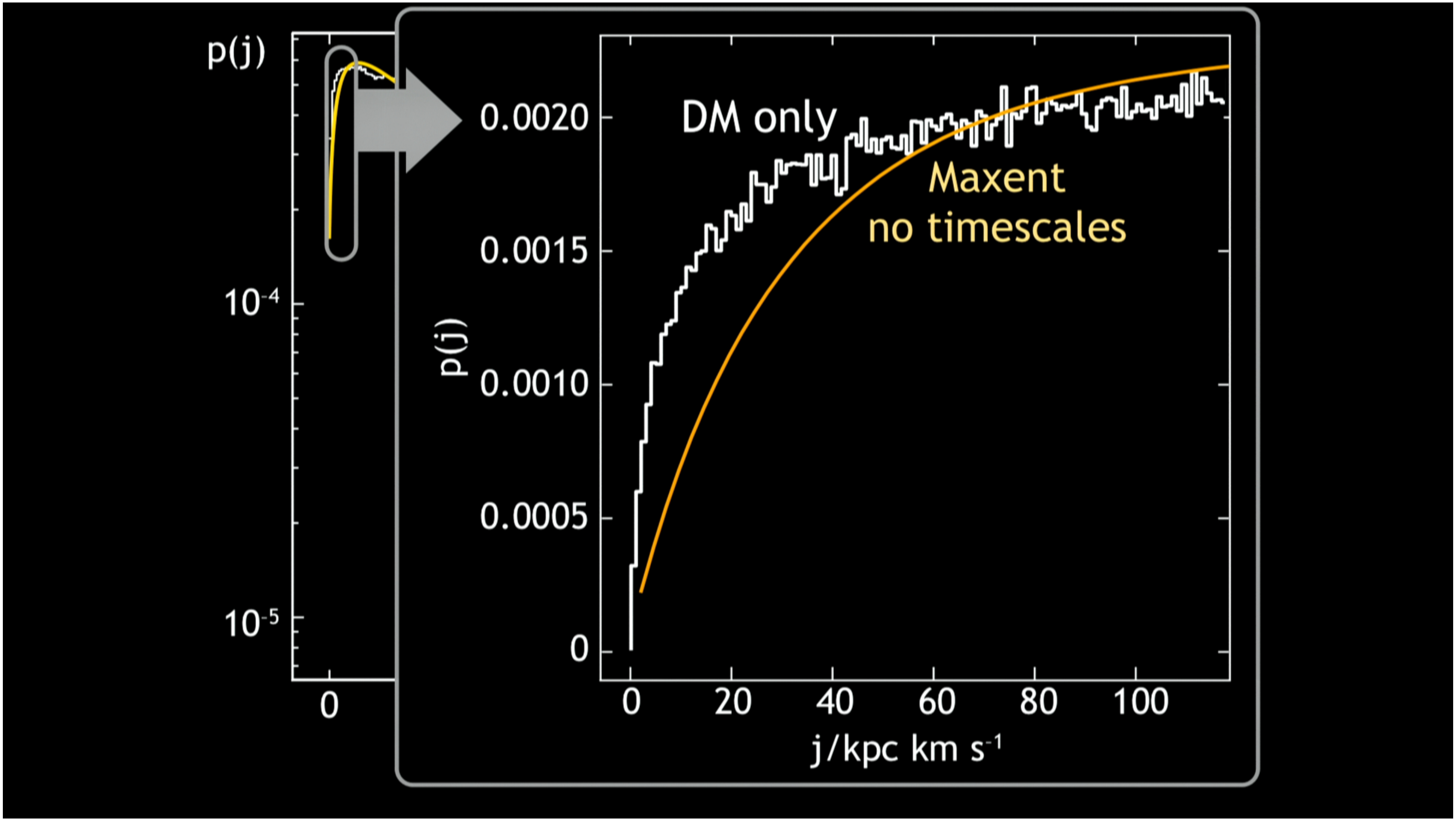

MW
full violent
relaxation
(Lynden-Bell
1967)
constrained
violent
relaxation
10^9
10^8
10^7
10^6
10^5
10^4
10^3
$\rho/M_\odot\ \mathrm{kpc}^{-3}$
0.1
1
10
100
r/kpc
Pontzen &
Governato
arXiv:1210.1849

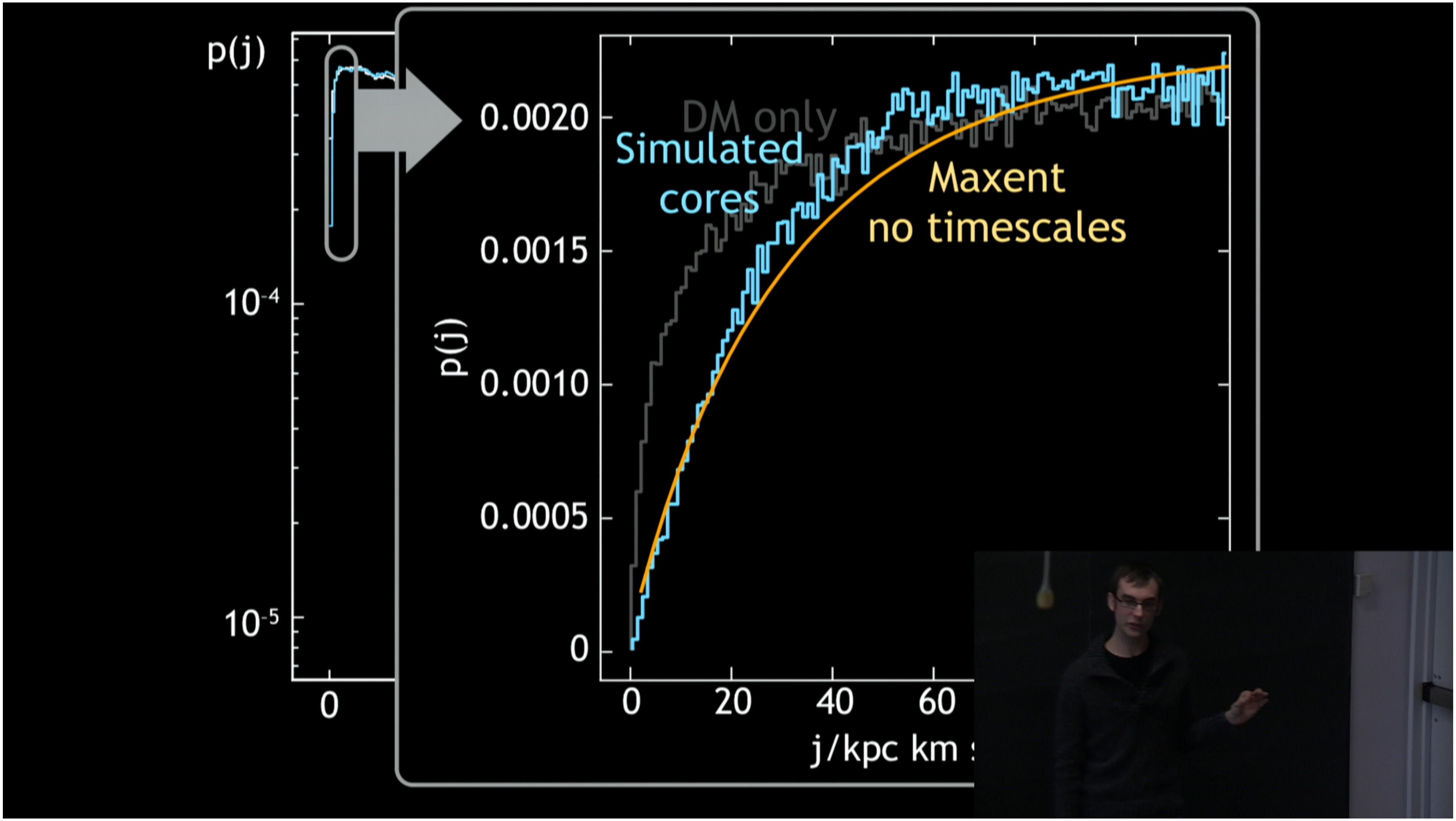


Dwarf:
angular
momentum



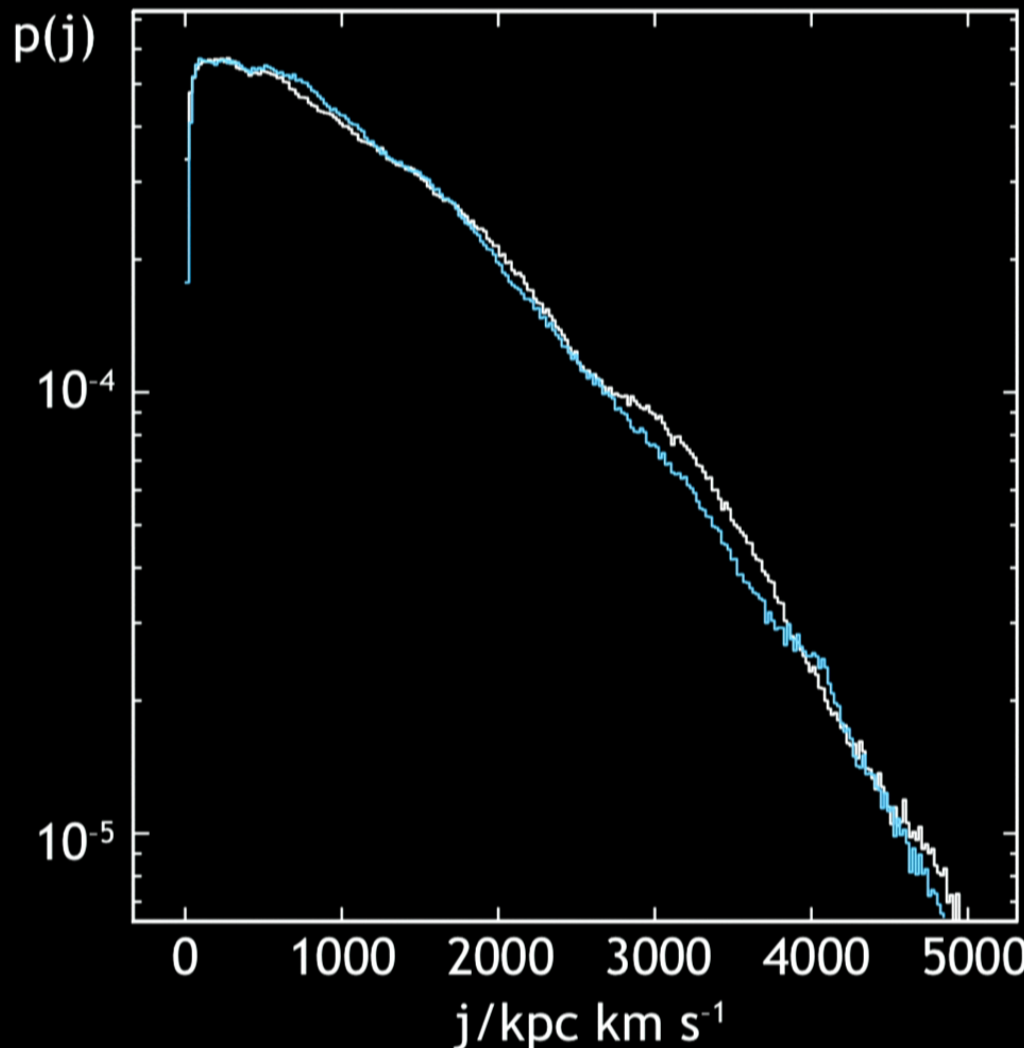
p(j)
10^-4
10^-5
0
DM only
Maxent
no timescales
p(j)
0.0020
0.0015
0.0010
0.0005
0
0
20
40
60
80
100
j/kpc km s^-1

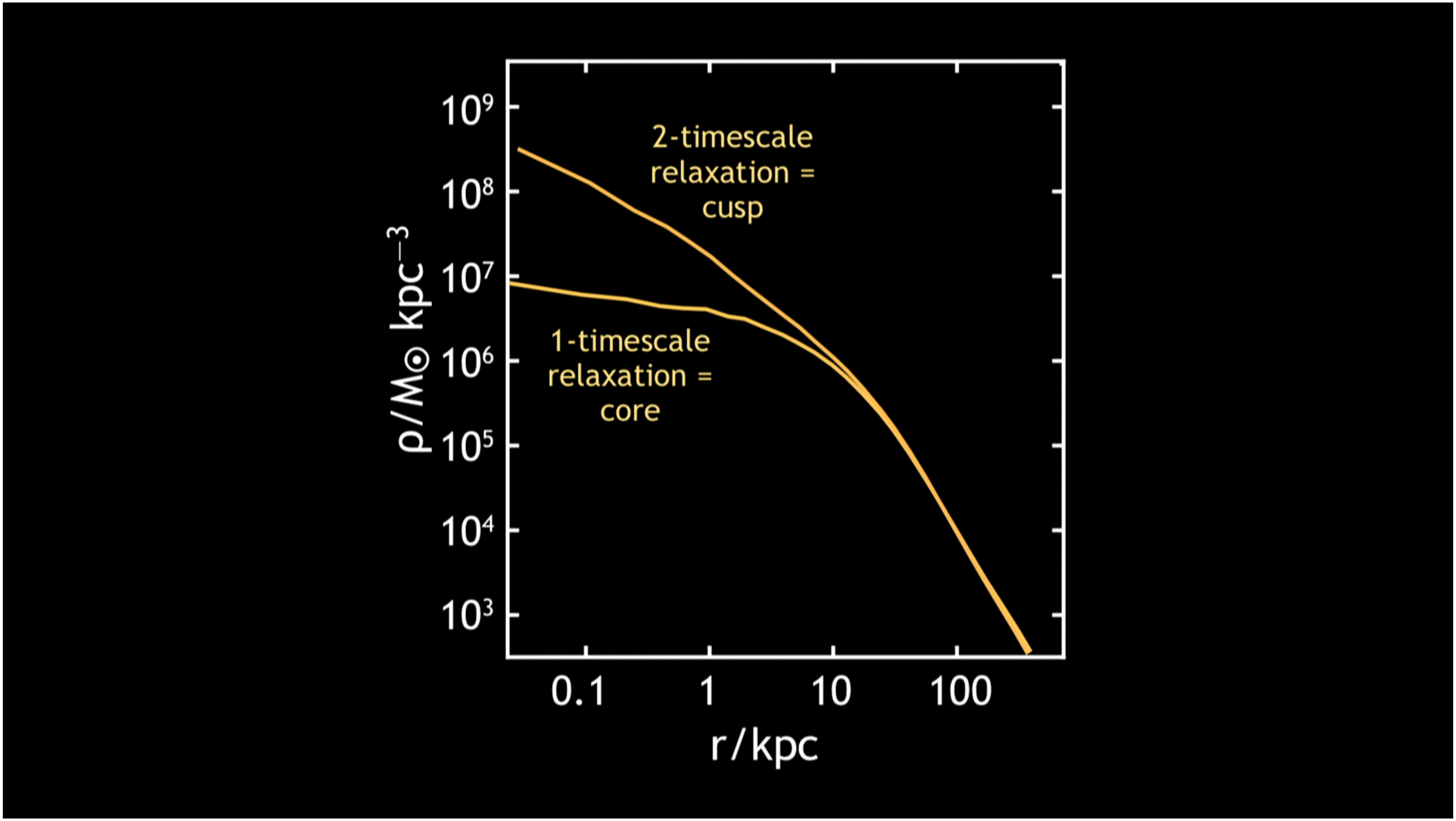

p(j)
10^-4
10^-5
0
DM only
Maxent
no timescales
p(j)
0.0020
0.0015
0.0010
0.0005
0
0
20
40
60
80
100
j/kpc km s^-1



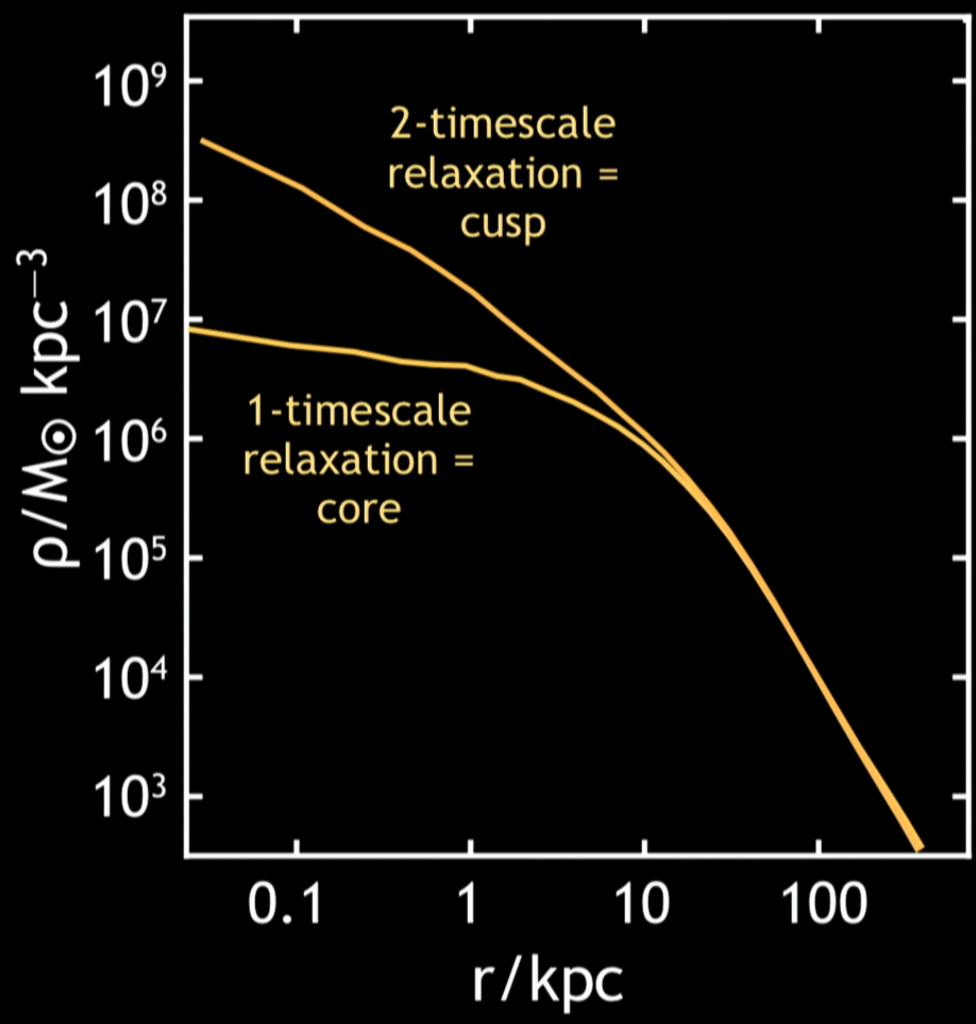
p(j)
10^{-4}
10^{-5}
0
0.0020
0.0015
0.0010
0.0005
0
p(j)
DM only
Simulated cores
Maxent no timescales
0
20
40
60
j/kpc km

Dwarf: angular momentum





2-timescale
relaxation =
cusp
1-timescale
relaxation =
core
10^9
10^8
10^7
10^6
10^5
10^4
10^3
$\rho/M_\odot\ \mathrm{kpc}^{-3}$
0.1
1
10
100
r/kpc


2-timescale
relaxation =
cusp
1-timescale
relaxation =
core
$\rho/M_\odot\ kpc^{-3}$
10^9
10^8
10^7
10^6
10^5
10^4
10^3
0.1
1
10
100
r/kpc

1. Our dark matter reshaping mechanism now seen in multiple simulations. Highly bursty SF (or AGN) is key; do real galaxies do this?

PG12: 1106.0499; Governato et al 1202.0554; Teyssier et al 1206.4895
Zolotov et al 1207.0007; Peñarrubia et al 1207.2772

Andrew Pontzen, Oxford Astrophysics

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Pontzen & Governato 1210.1849

Andrew Pontzen, Oxford Astroph

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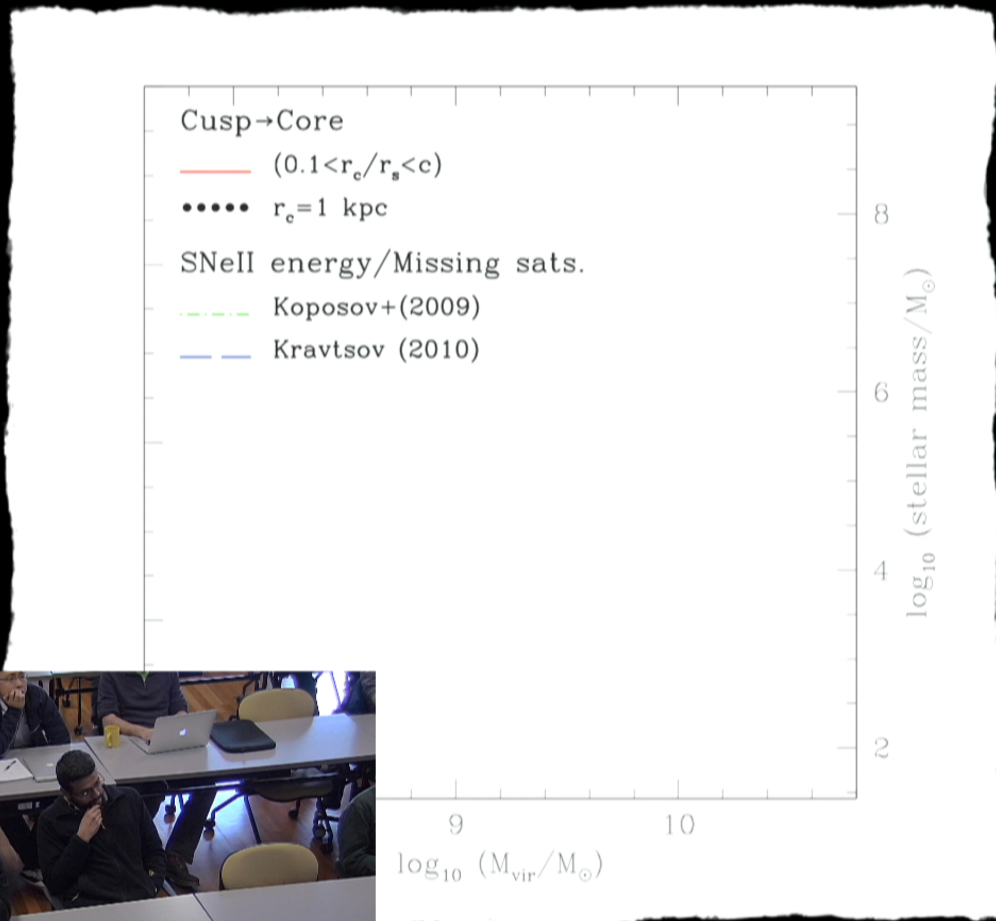
Pontzen & Governato 1210.1849

3. Astrophysical core formation makes relaxation more complete. How about particle physics cores (e.g. SIDM)?

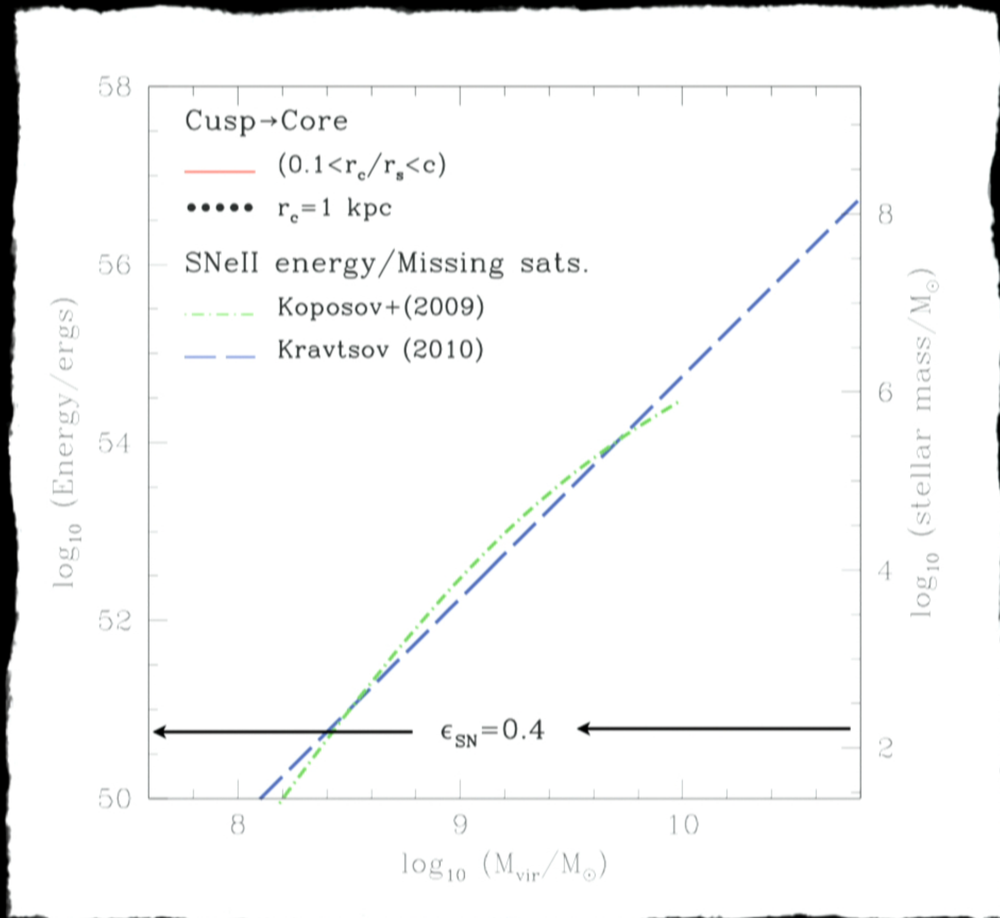
Andrew Pontzen, Oxford Astrophysics



Scalings?

Penarrubia,
Pontzen & Walker
1207.2772

Scalings?



Penarrubia,
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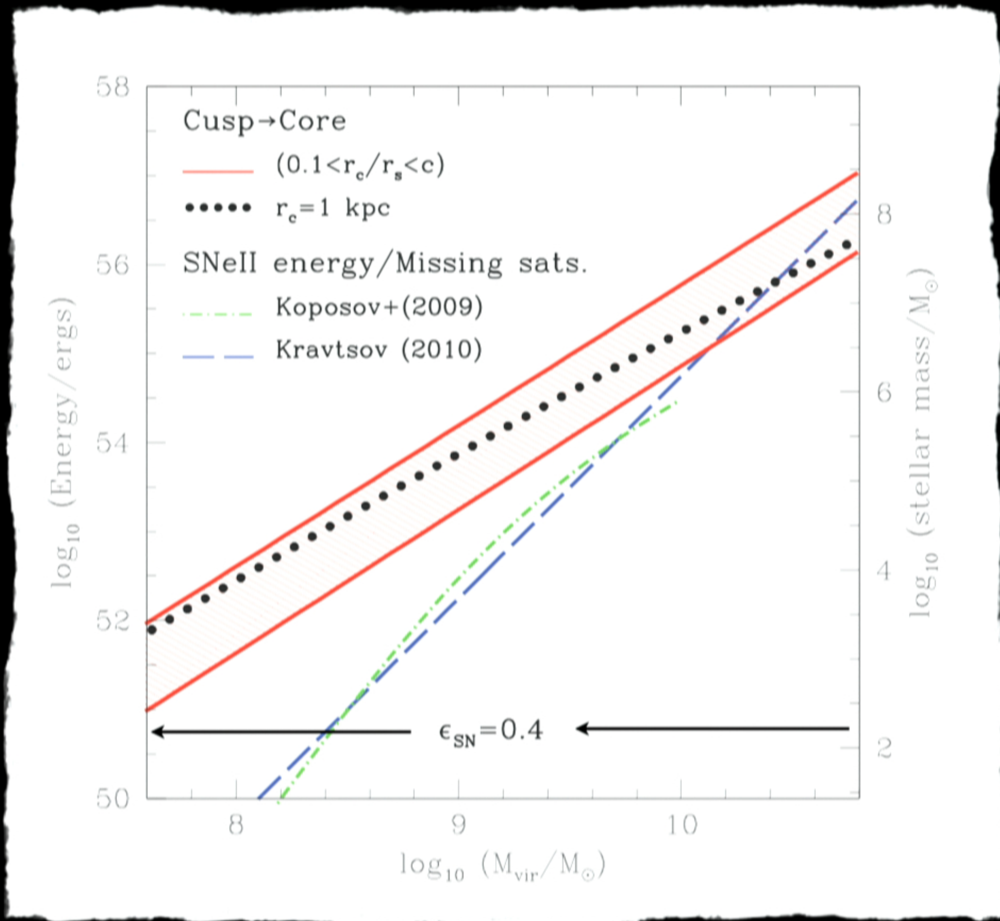
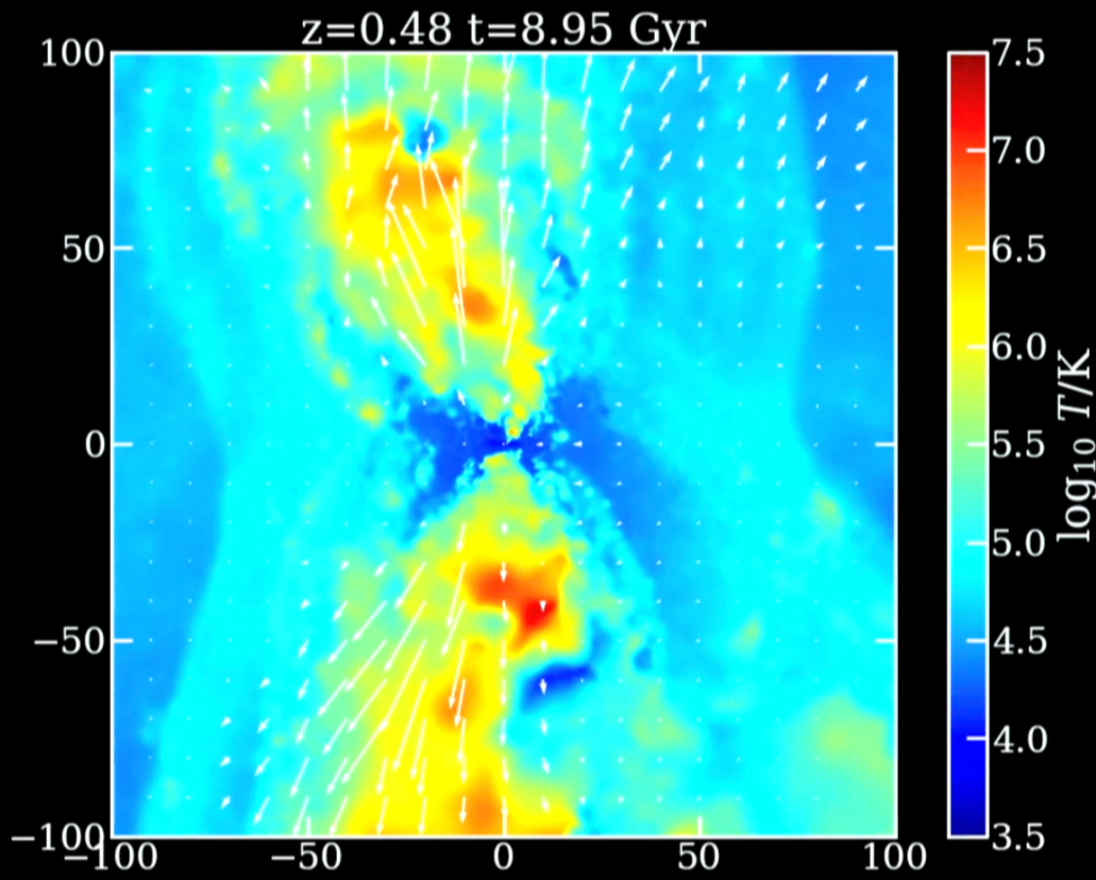


Scalings?

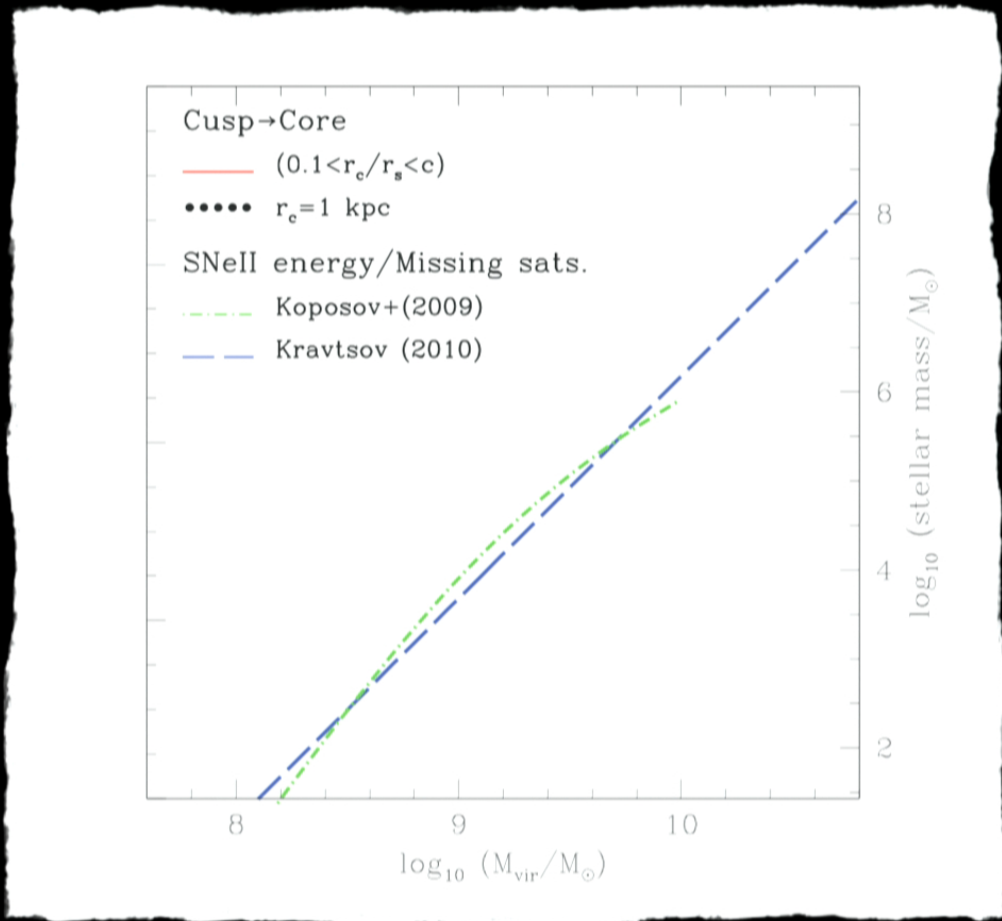
Penarrubia,
Pontzen & Walker
1207.2772

Outflows?

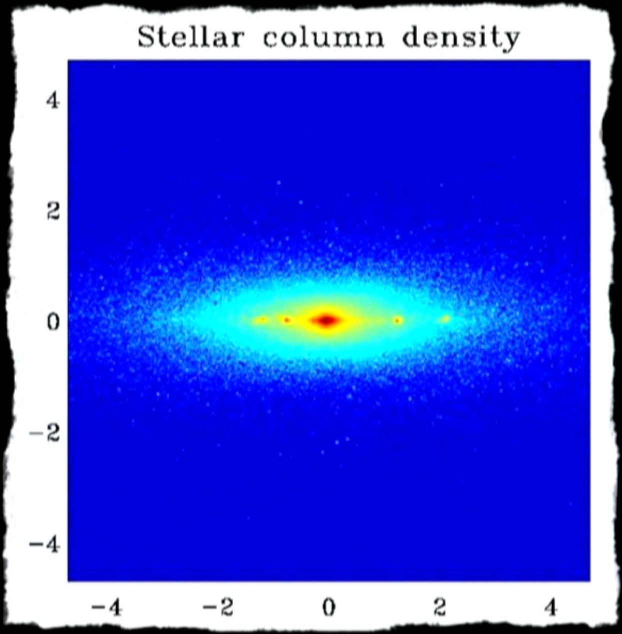


Pontzen et al
in prep 2013

Scalings?



Penarrubia, Pontzen & Walker 1207.2772

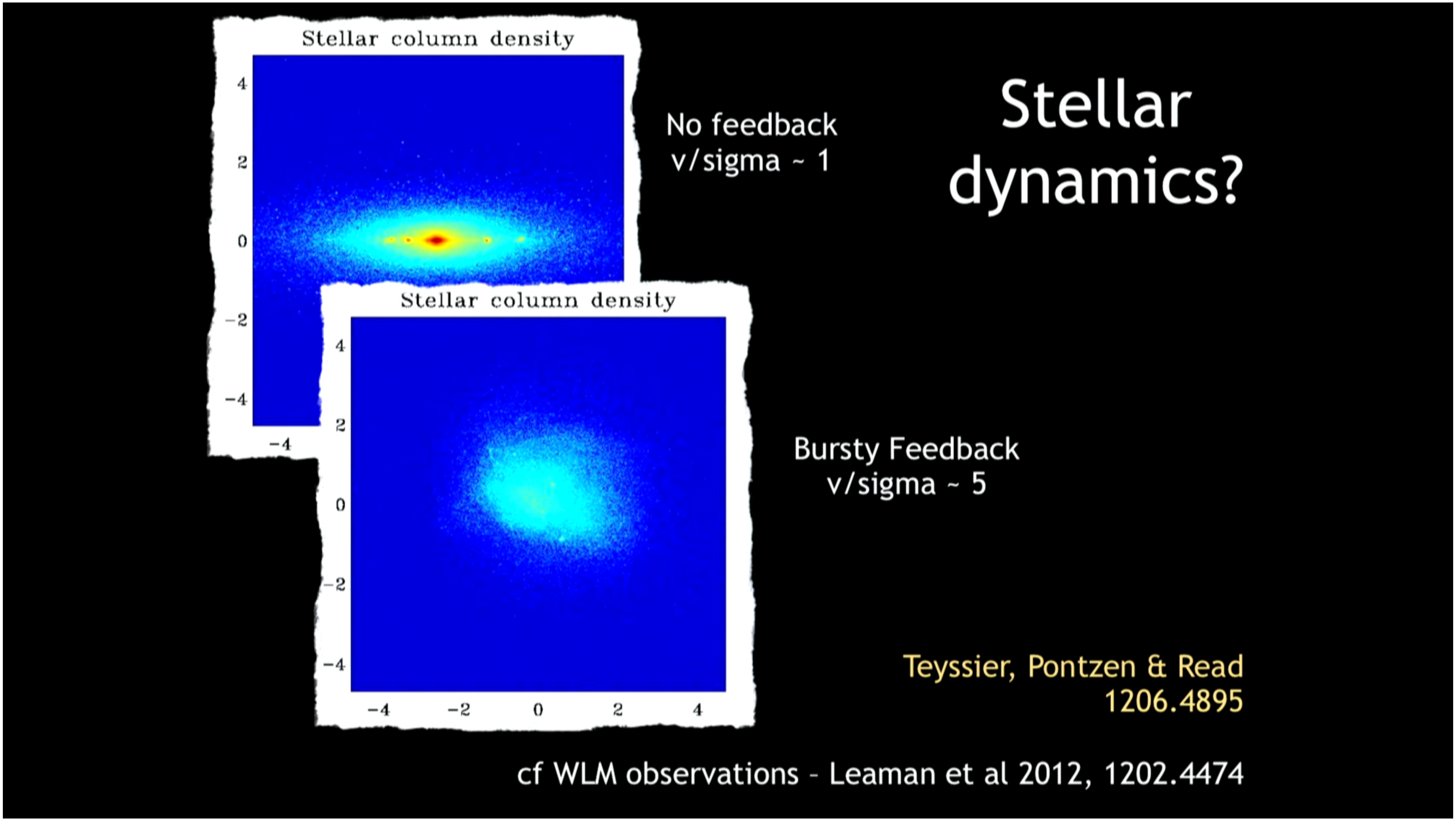


No feedback
v/sigma ~ 1

Stellar dynamics?

Teyssier, Pontzen & Read
1206.4895

cf WLM observations – Leaman et al 2012, 1202.4474


Stellar dynamics?
Stellar column density
No feedback
v/sigma ~ 1
Stellar column density
Bursty Feedback
v/sigma ~ 5
Teyssier, Pontzen & Read
1206.4895
cf WLM observations - Leaman et al 2012, 1202.4474