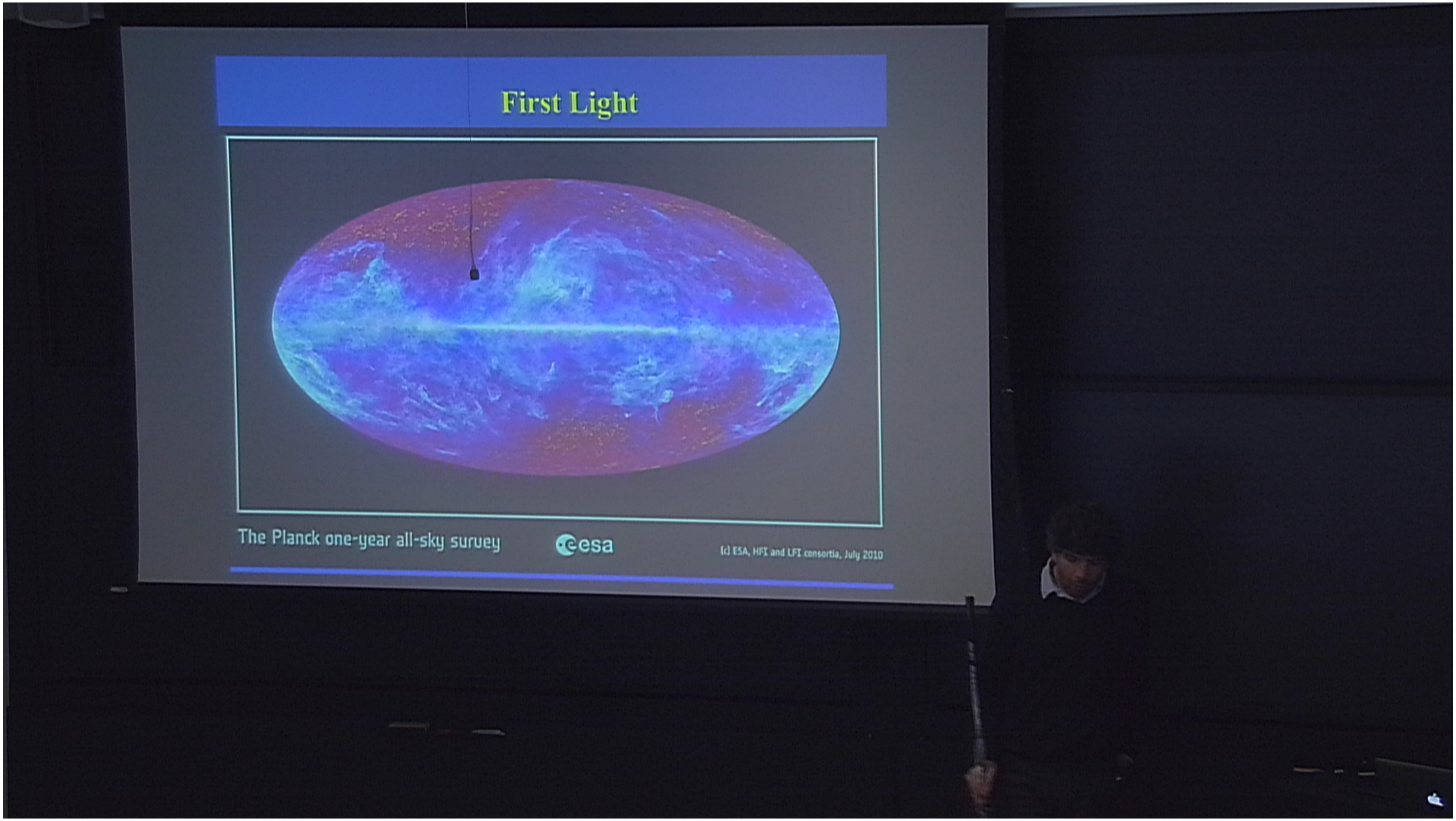
Title: Dwarf Galaxies as Cosmological Probes

Date: Nov 27, 2014 01:00 PM

URL: http://pirsa.org/14110145

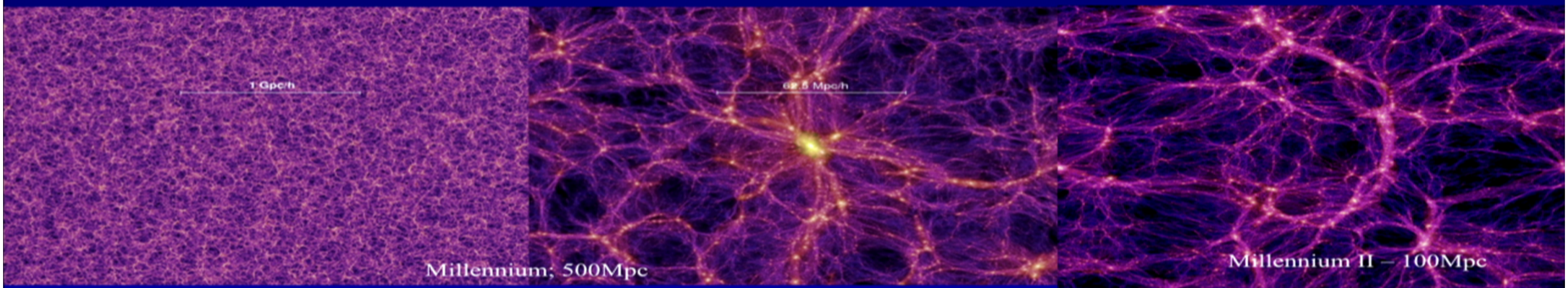
Abstract: <p>A prime challenge to our understanding of galaxy formation concerns the scarcity of dwarf galaxies compared with the numerous low-mass halos expected in the current Î›CDM paradigm. This is usually accounted for by assuming that energetic feedback from evolving stars confines dwarf galaxy formation to relatively massive halos spanning a narrow mass range. I will highlight a number of observations that may be used to test this assumption and discuss the puzzles and challenges that arise from this analysis. I will also discuss a number of challenges that Î›CDM faces on the scale of dwarf galaxies and their possible resolutions.</p>


Dwarf Galaxies as Cosmological Probes
Julio F. Navarro
CIFAR
UVic
RAVE
The Ursa Minor dwarf spheroidal


First Light
The Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 2010

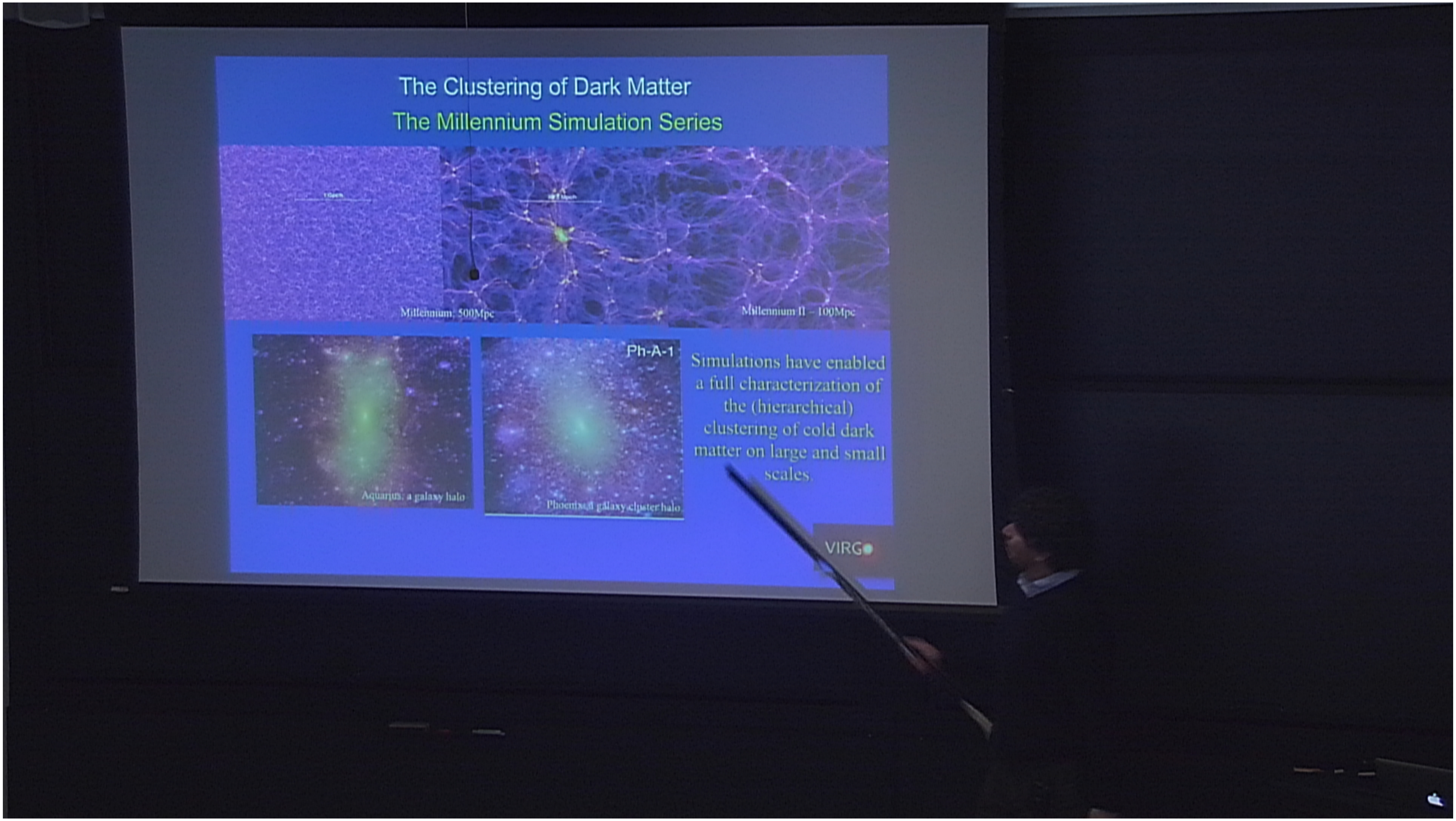
The Clustering of Dark Matter

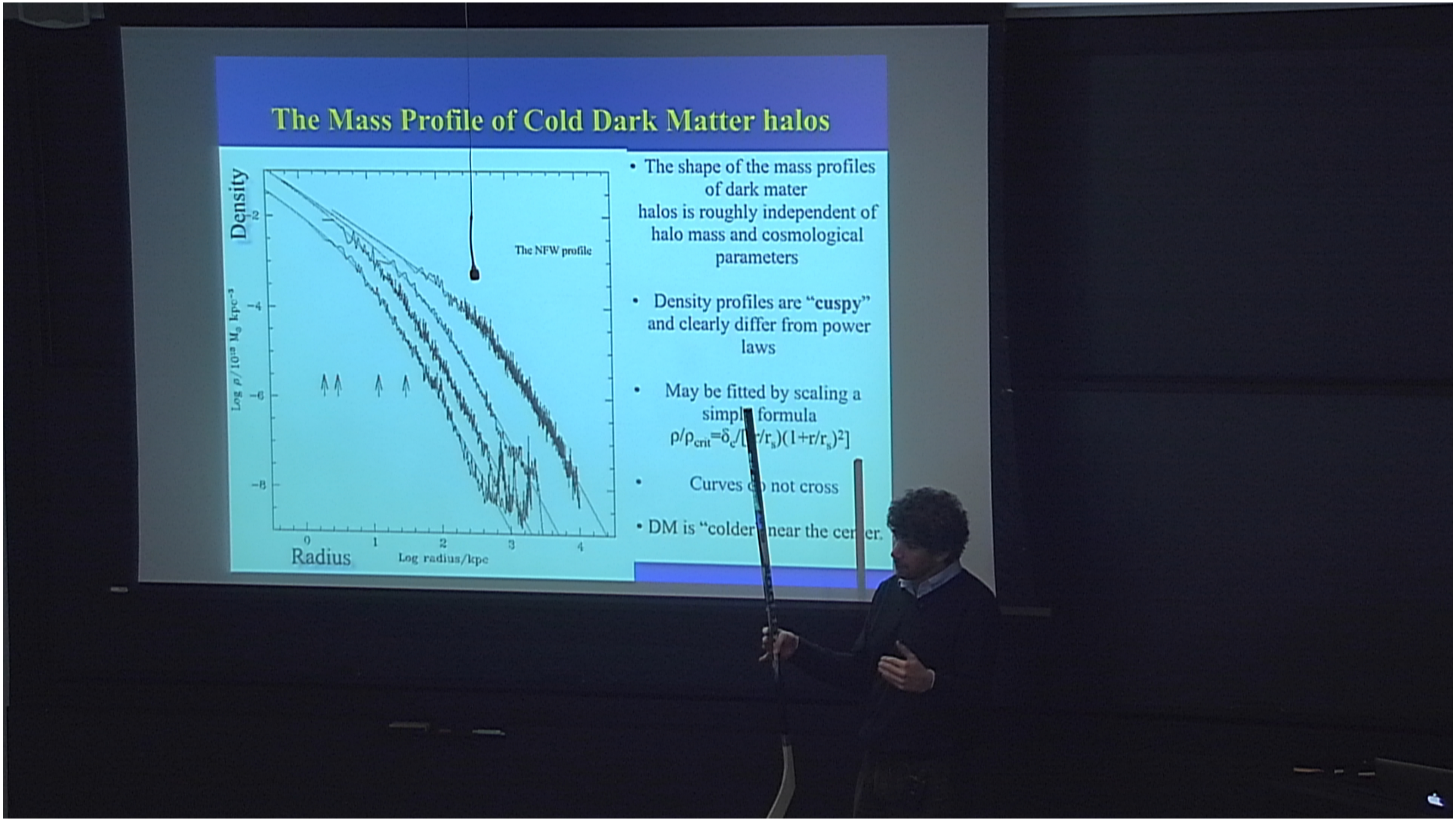
The Millennium Simulation Series

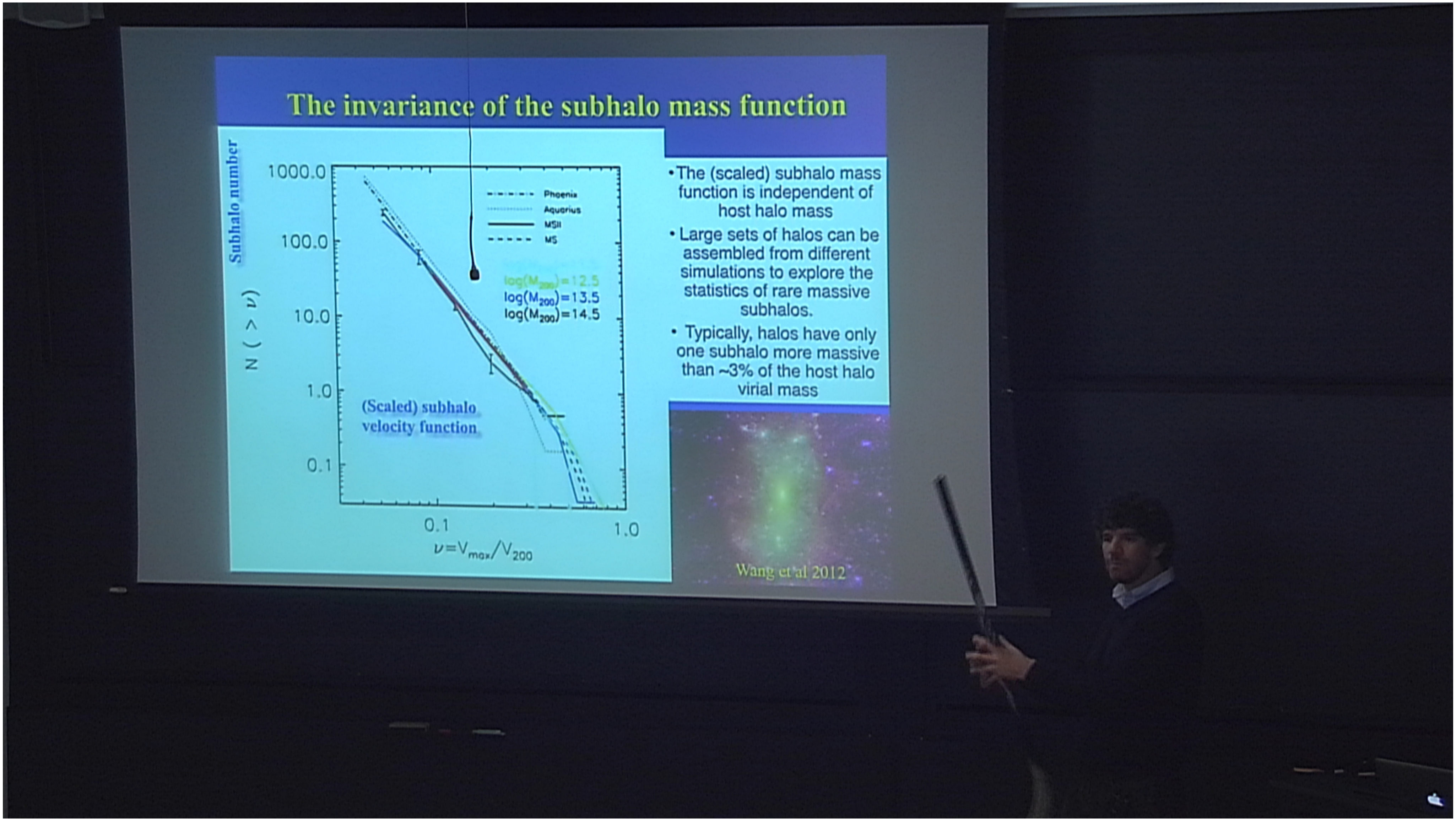


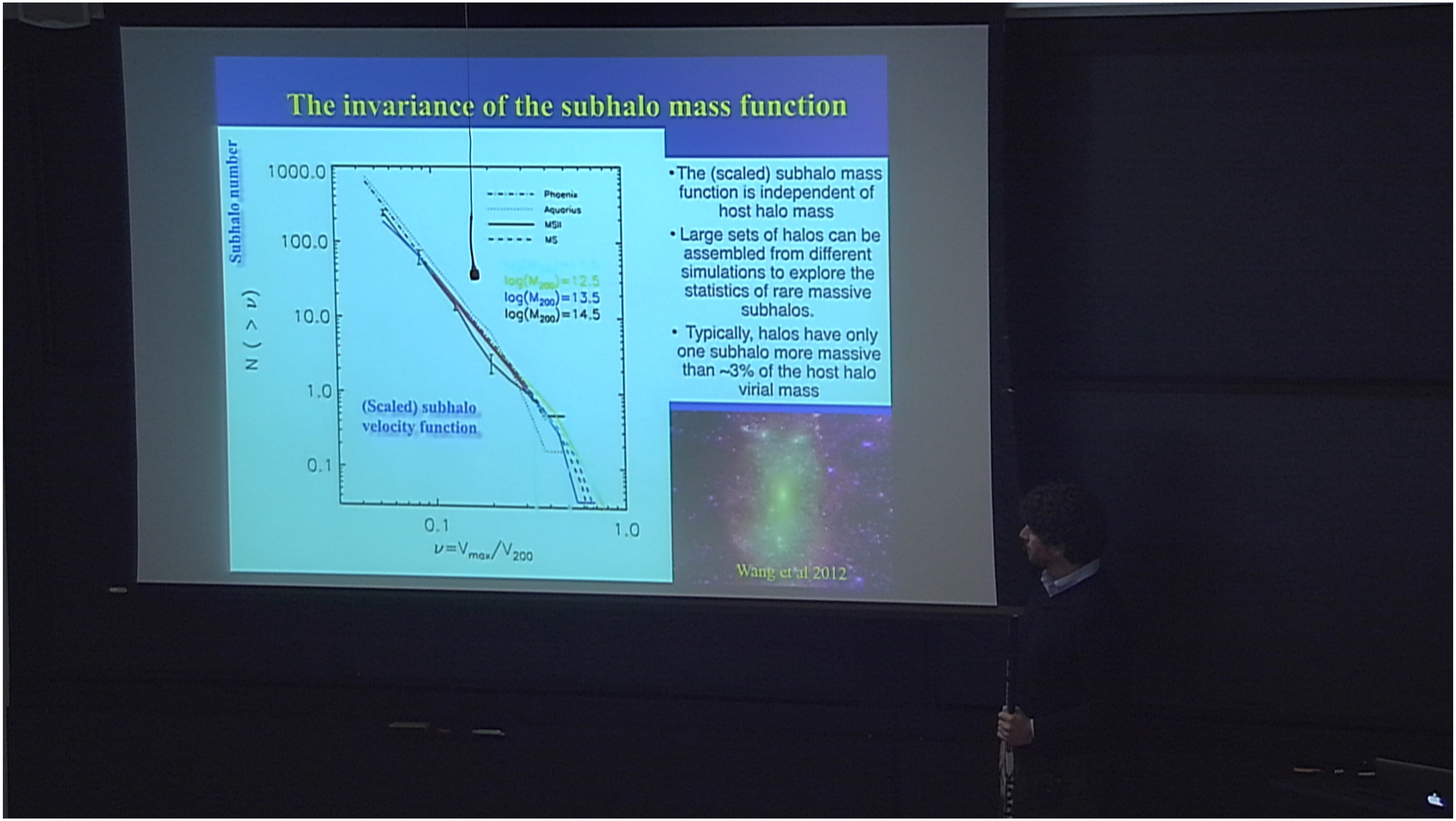
Simulations have enabled a full characterization of the (hierarchical) clustering of cold dark matter on large and small scales.

VIRGO


The Clustering of Dark Matter
The Millennium Simulation Series
Millennium: 500Mpc
Millennium II – 100Mpc
Ph-A-1
Simulations have enabled a full characterization of the (hierarchical) clustering of cold dark matter on large and small scales.
Aquarius: a galaxy halo
Phoenix: a galaxy cluster halo
VIRGO


The Mass Profile of Cold Dark Matter halos
Density
Log ρ / 10^10 M⊙ kpc^-3
-2
-4
-6
-8
The NFW profile
0
1
2
3
4
Radius
Log radius/kpc
• The shape of the mass profiles of dark mater halos is roughly independent of halo mass and cosmological parameters
• Density profiles are "cuspy" and clearly differ from power laws
• May be fitted by scaling a simpl formula
ρ/ρcrit=δc/[/rs)(1+r/rs)²]
• Curves not cross
• DM is "colder near the cer er.


The invariance of the subhalo mass function
Subhalo number
N (> ν)
1000.0
100.0
10.0
1.0
0.1
Phoenix
Aquarius
MSII
MS
log(M200)=12.5
log(M200)=13.5
log(M200)=14.5
(Scaled) subhalo
velocity function
0.1
1.0
ν=Vmax/V200
•The (scaled) subhalo mass function is independent of host halo mass
• Large sets of halos can be assembled from different simulations to explore the statistics of rare massive subhalos.
• Typically, halos have only one subhalo more massive than ~3% of the host halo virial mass
Wang et al 2012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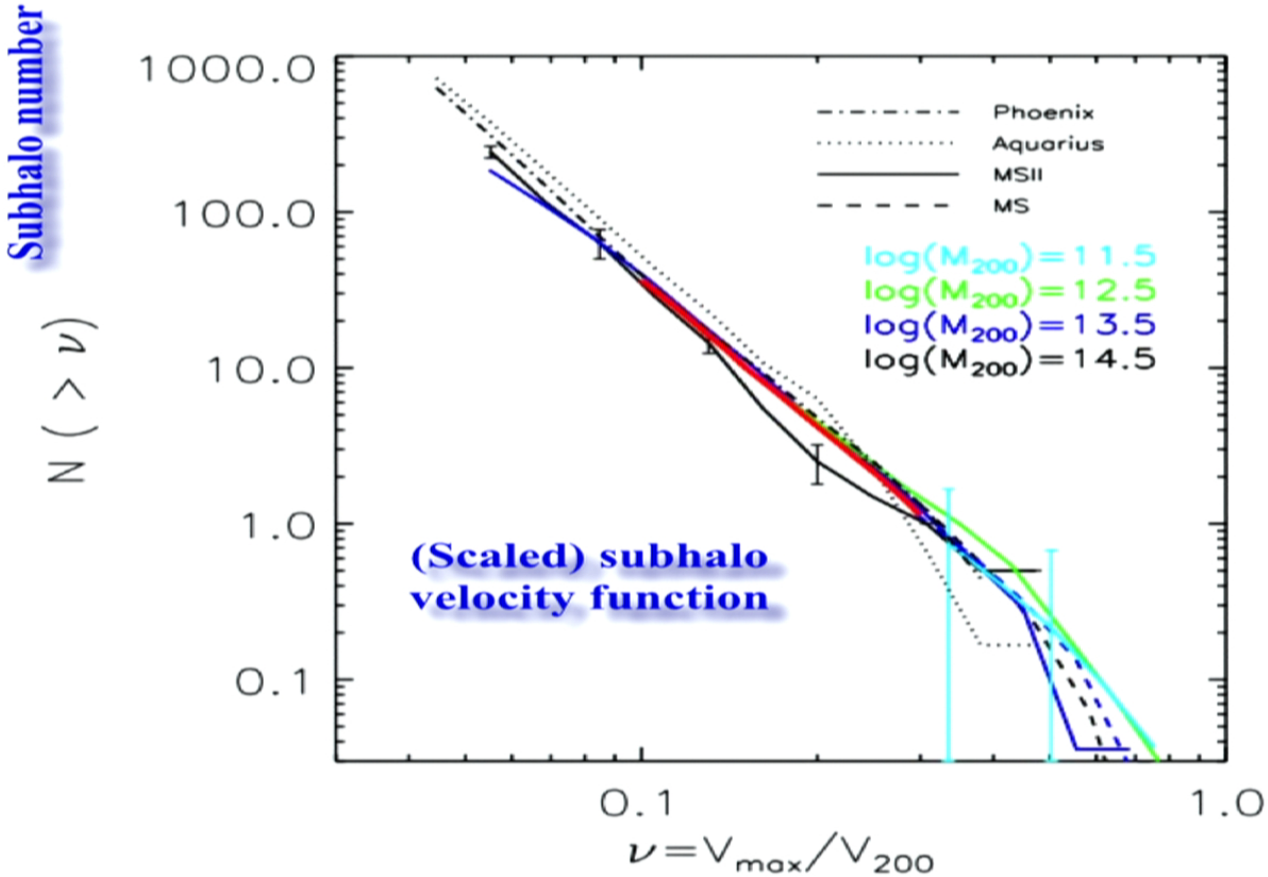

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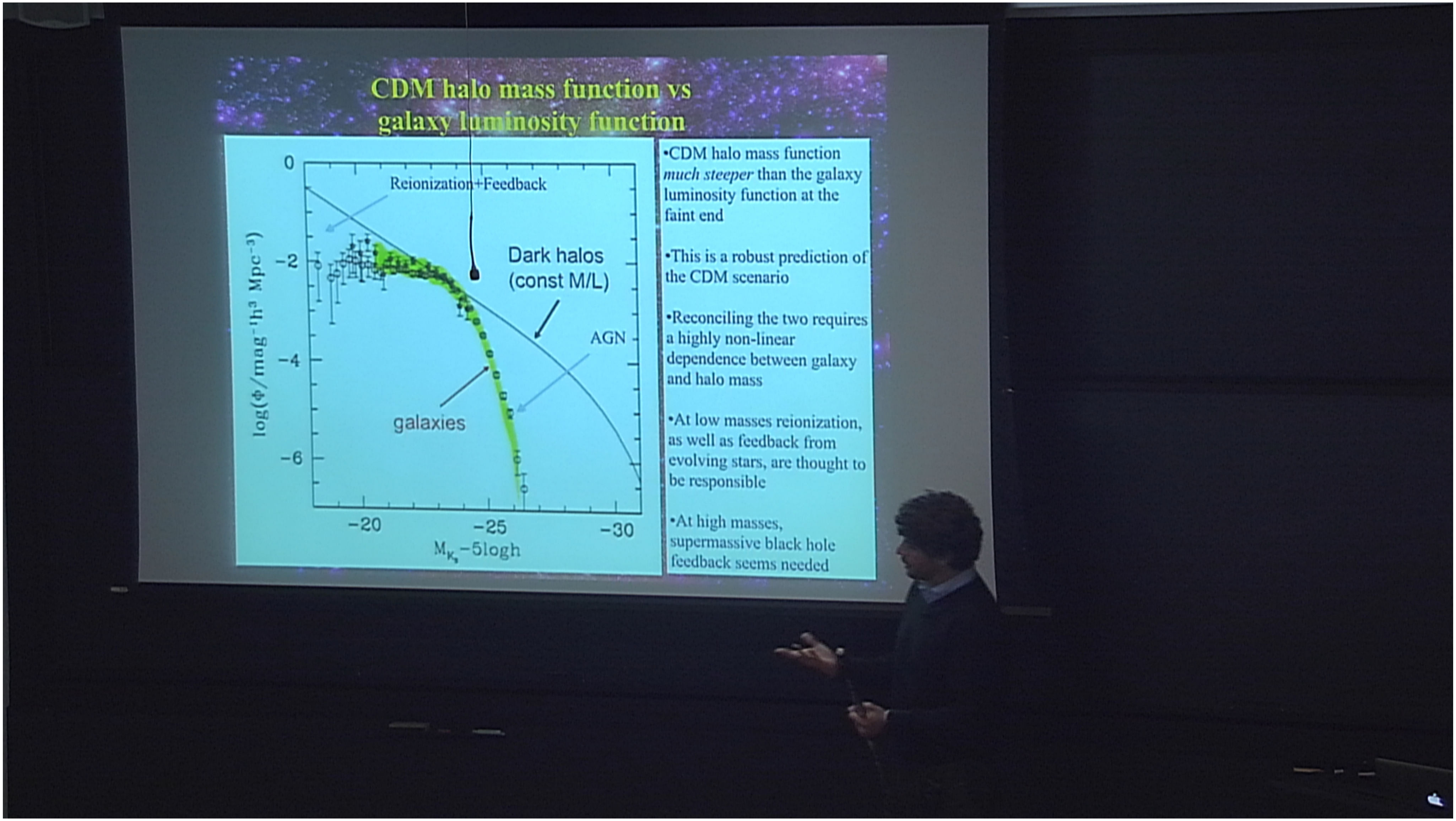

CDM halo mass function vs galaxy luminosity function
Reionization+Feedback
Dark halos (const M/L)
AGN
galaxies
log(Φ/mag⁻¹h³ Mpc⁻³)
0
-2
-4
-6
-20
-25
-30
M_Ks−5logh
•CDM halo mass function *much steeper* than the galaxy luminosity function at the faint end
•This is a robust prediction of the CDM scenario
•Reconciling the two requires a highly non-linear dependence between galaxy and halo mass
•At low masses reionization, as well as feedback from evolving stars, are thought to be responsible
•At high masses, supermassive black hole feedback seems needed

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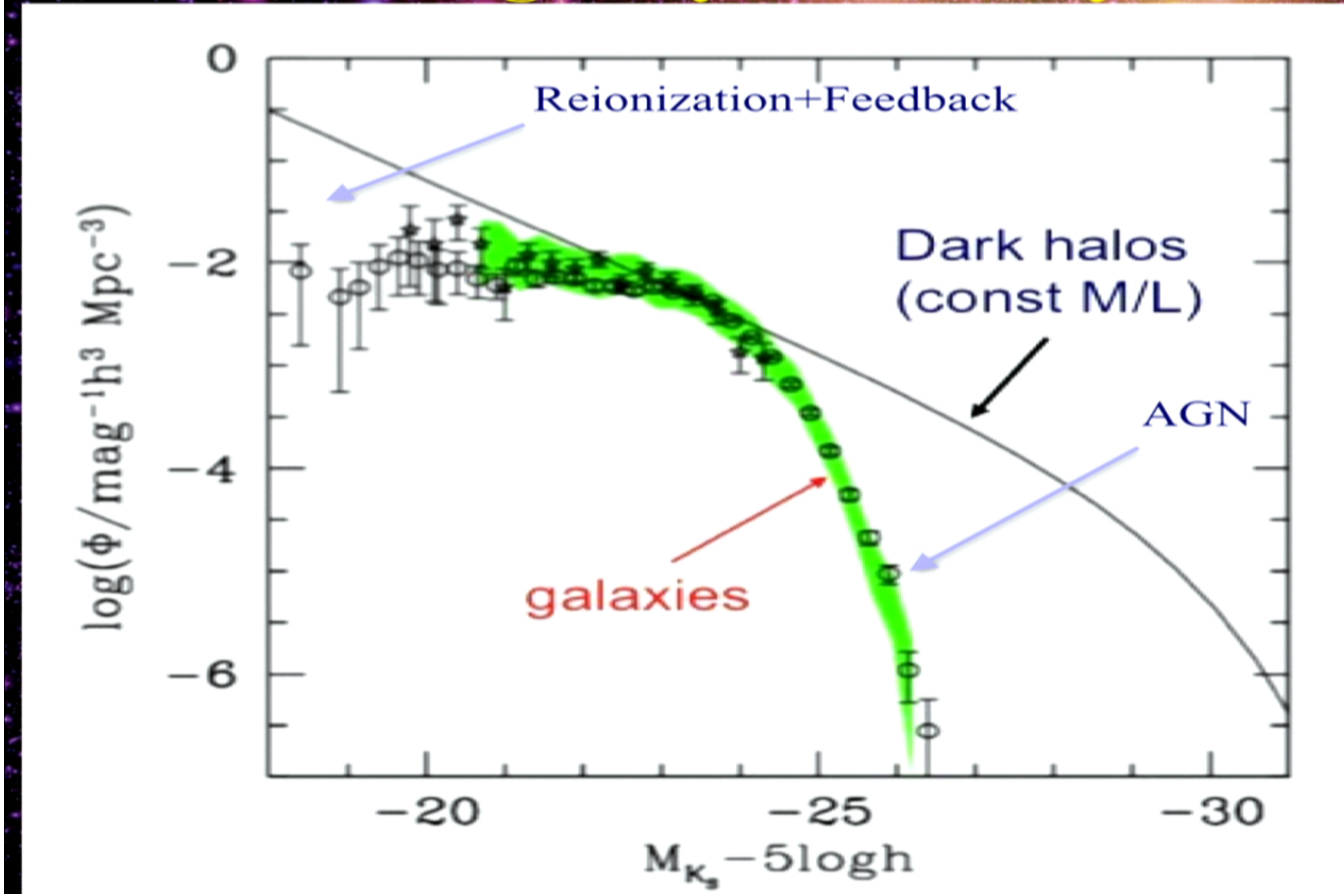

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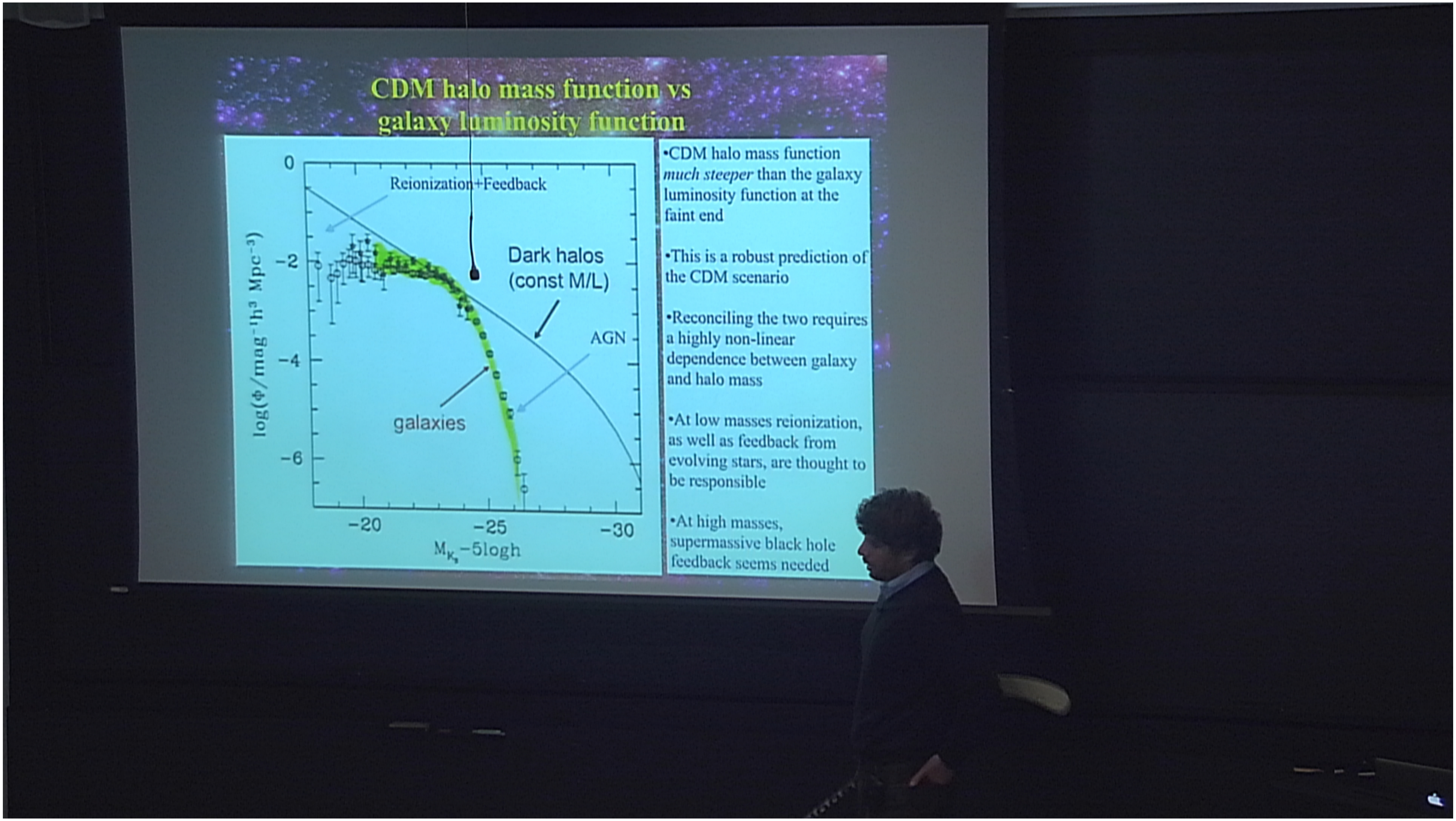
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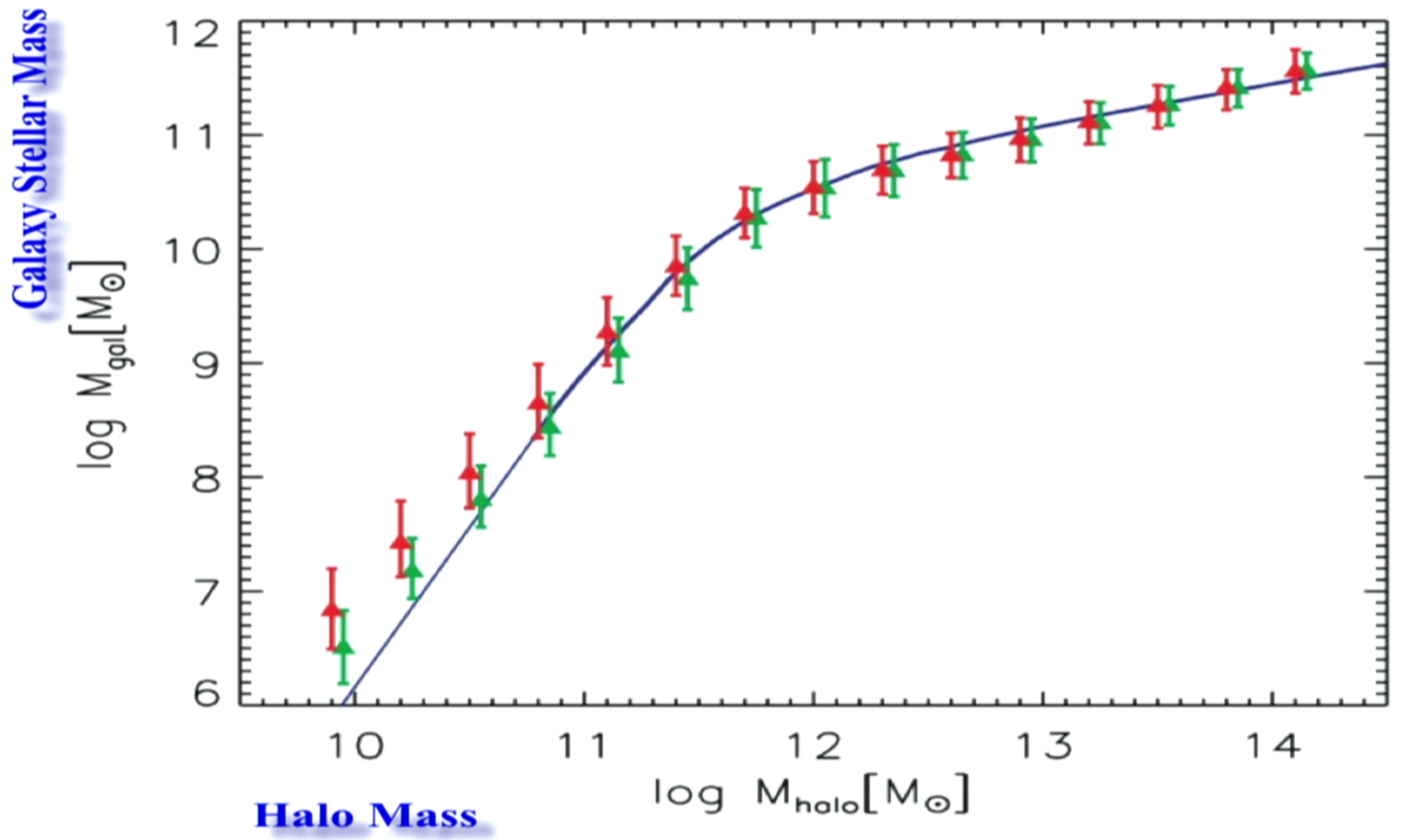
Abundance Matching: Galaxy Stellar Mass vs Halo Mass



- Steep dependence at low halo mass--a fundamental result of galaxy formation models.
- Most dwarfs form in halos of similar mass and hence similar properties —-what is the origin of their diversity then?
- Very few luminous galaxies should form in halos with mass below a "threshold" of 10^{10} M_{sun}

Guo et al 2011

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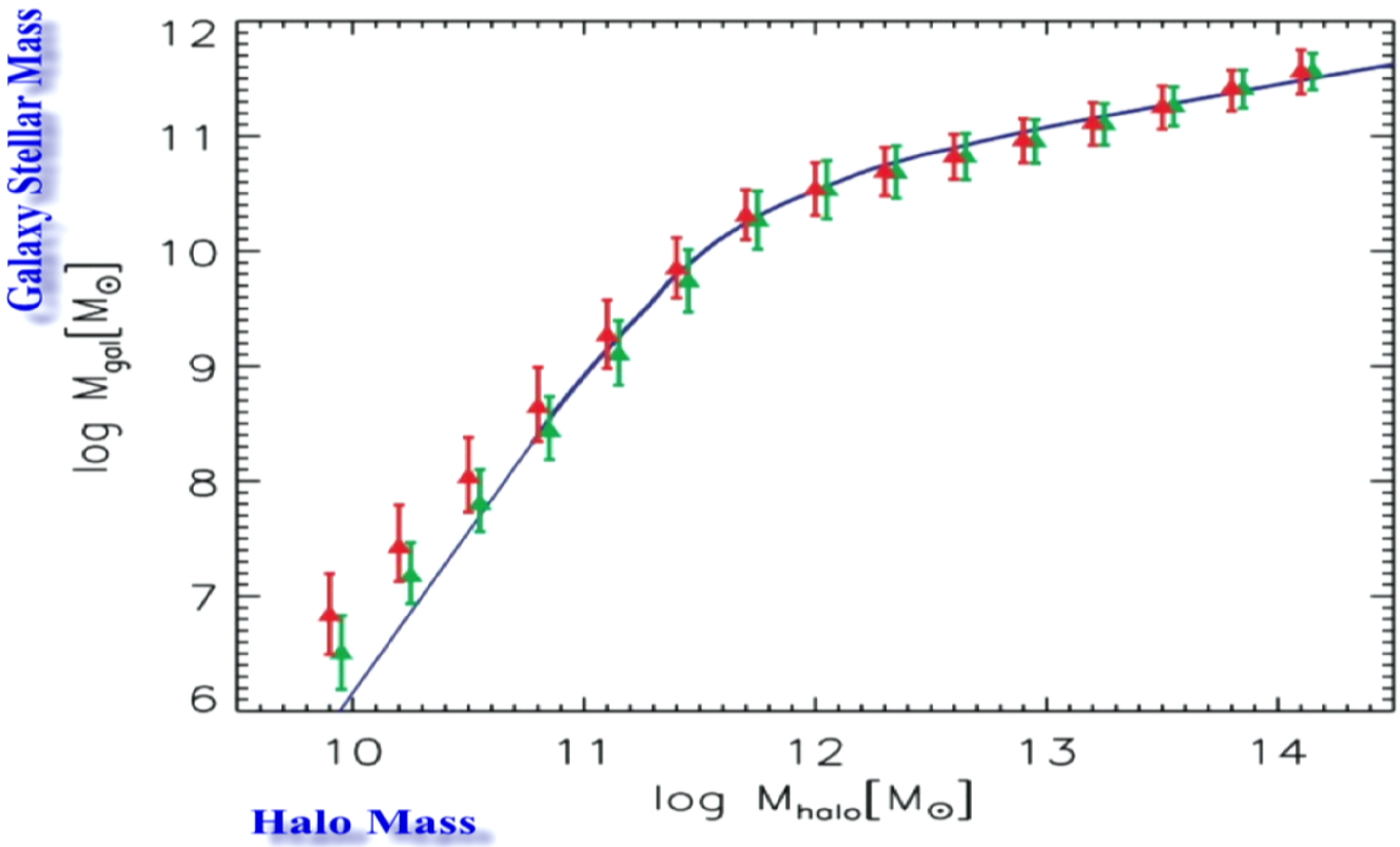

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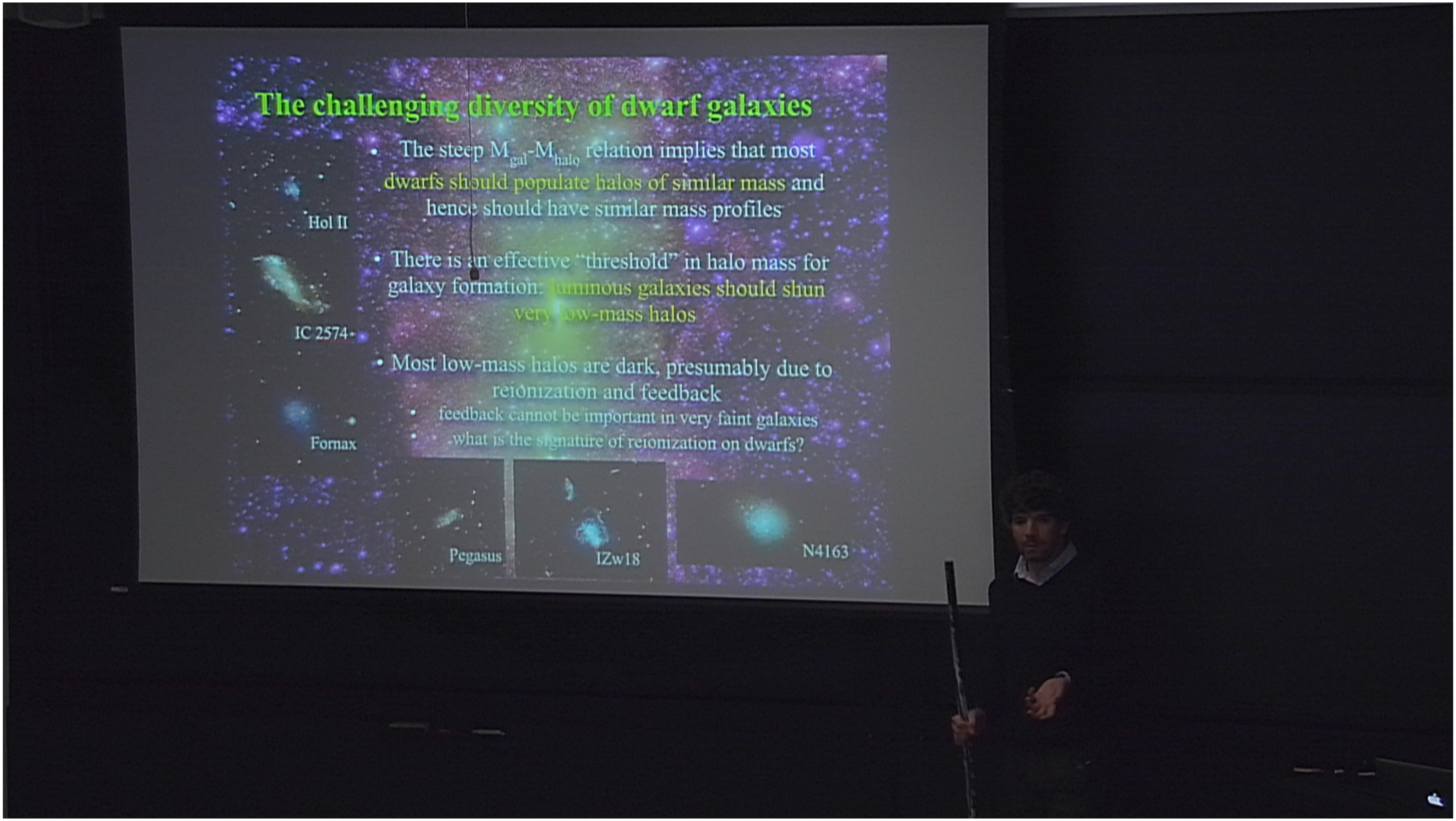
The challenging diversity of dwarf galaxies
The steep Mgal-Mhalo relation implies that most dwarfs should populate halos of similar mass and hence should have similar mass profiles
There is an effective "threshold" in halo mass for galaxy formation: luminous galaxies should shun very low-mass halos
Most low-mass halos are dark, presumably due to reionization and feedback
feedback cannot be important in very faint galaxies
what is the signature of reionization on dwarfs?
Hol II
IC 2574
Fornax
Pegasus
IZw18
N4163


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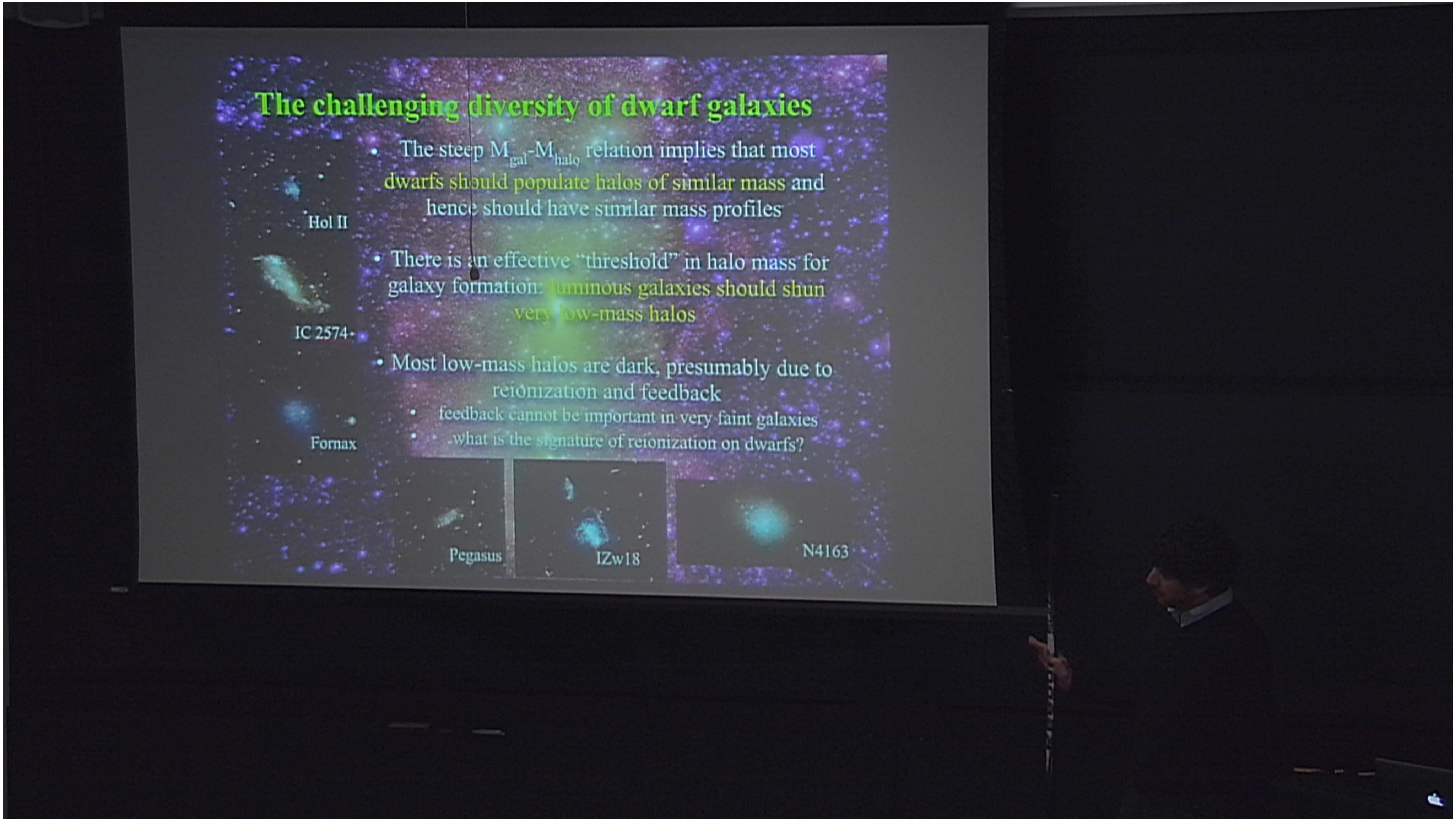
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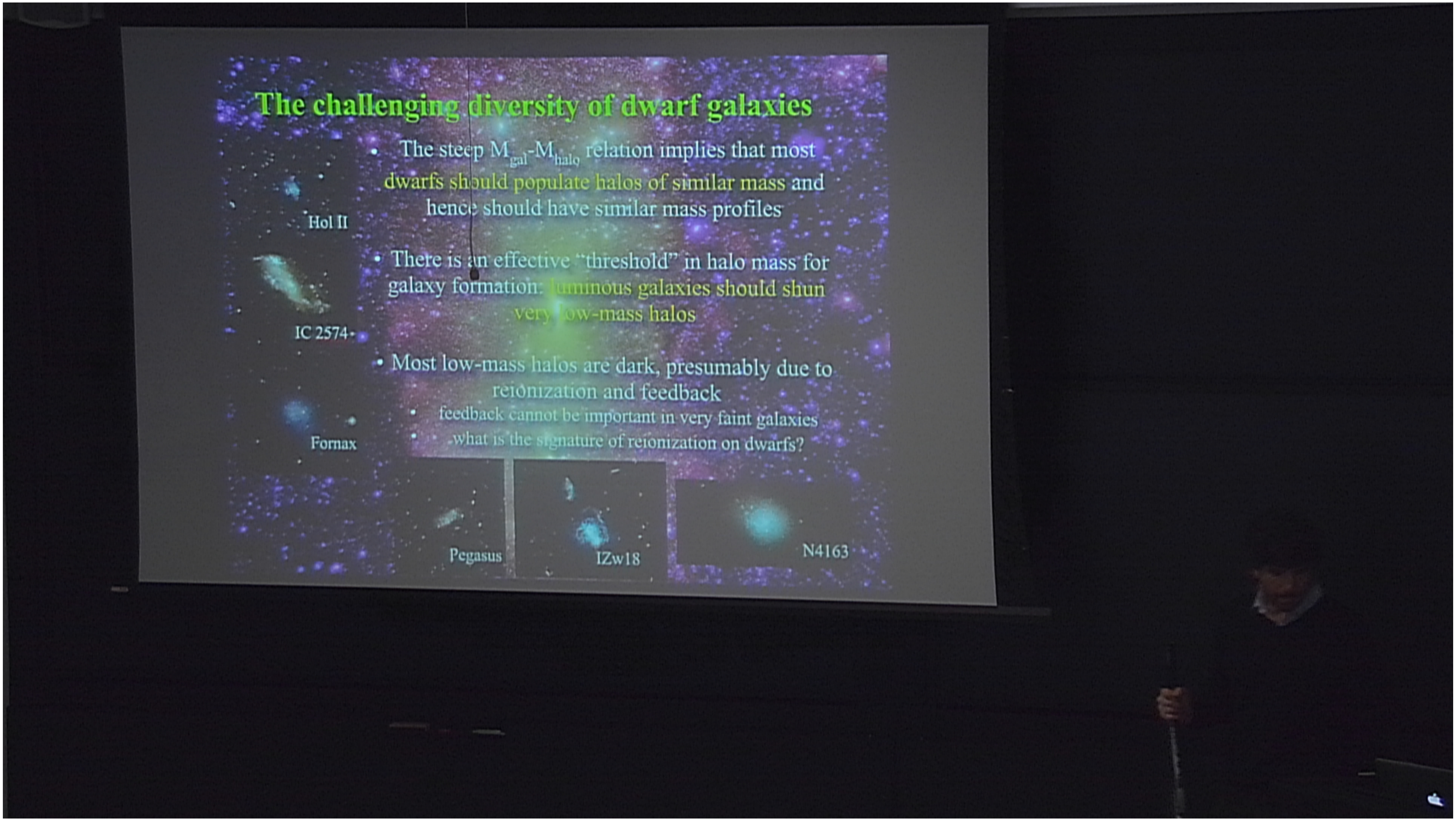
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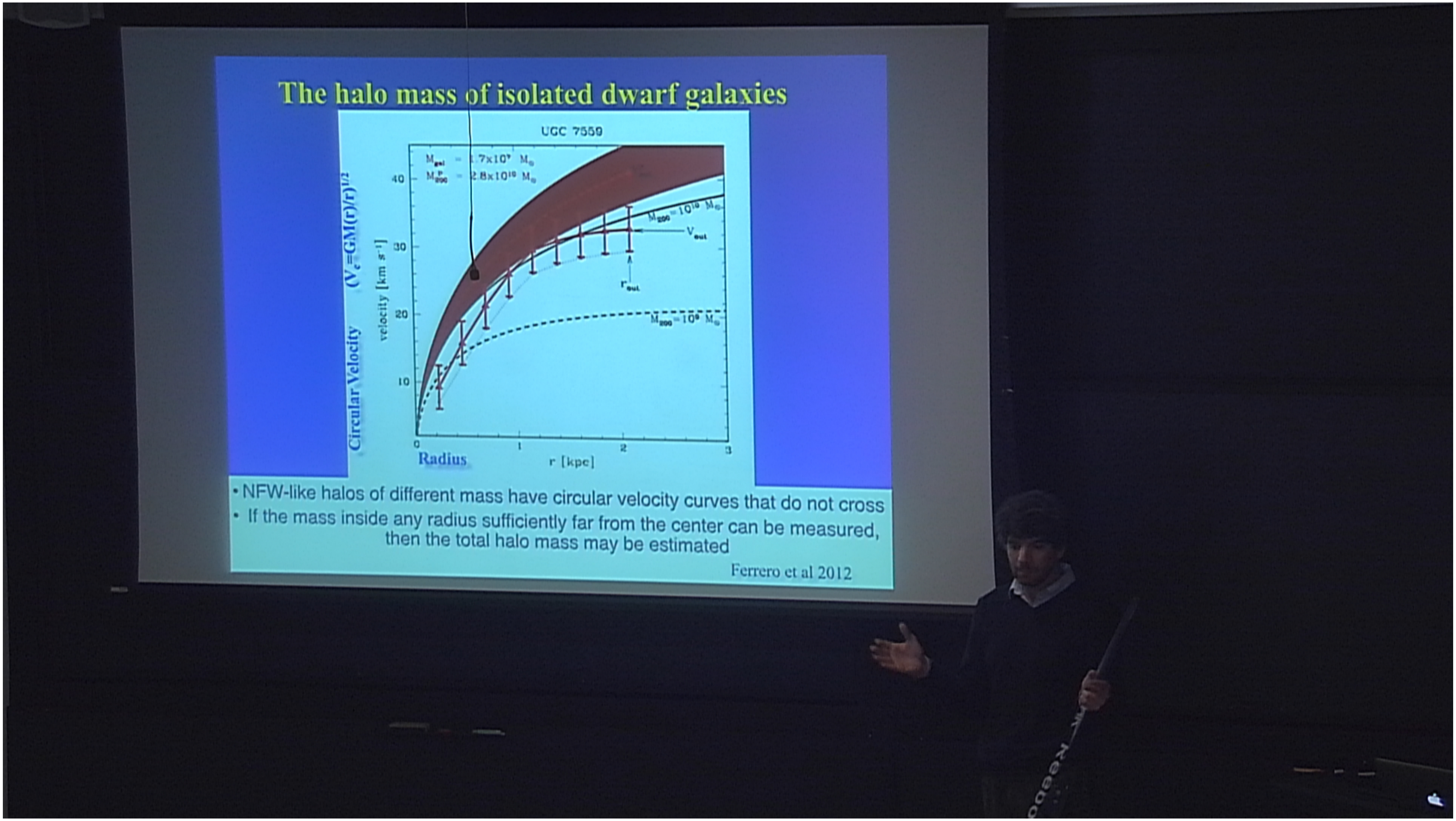
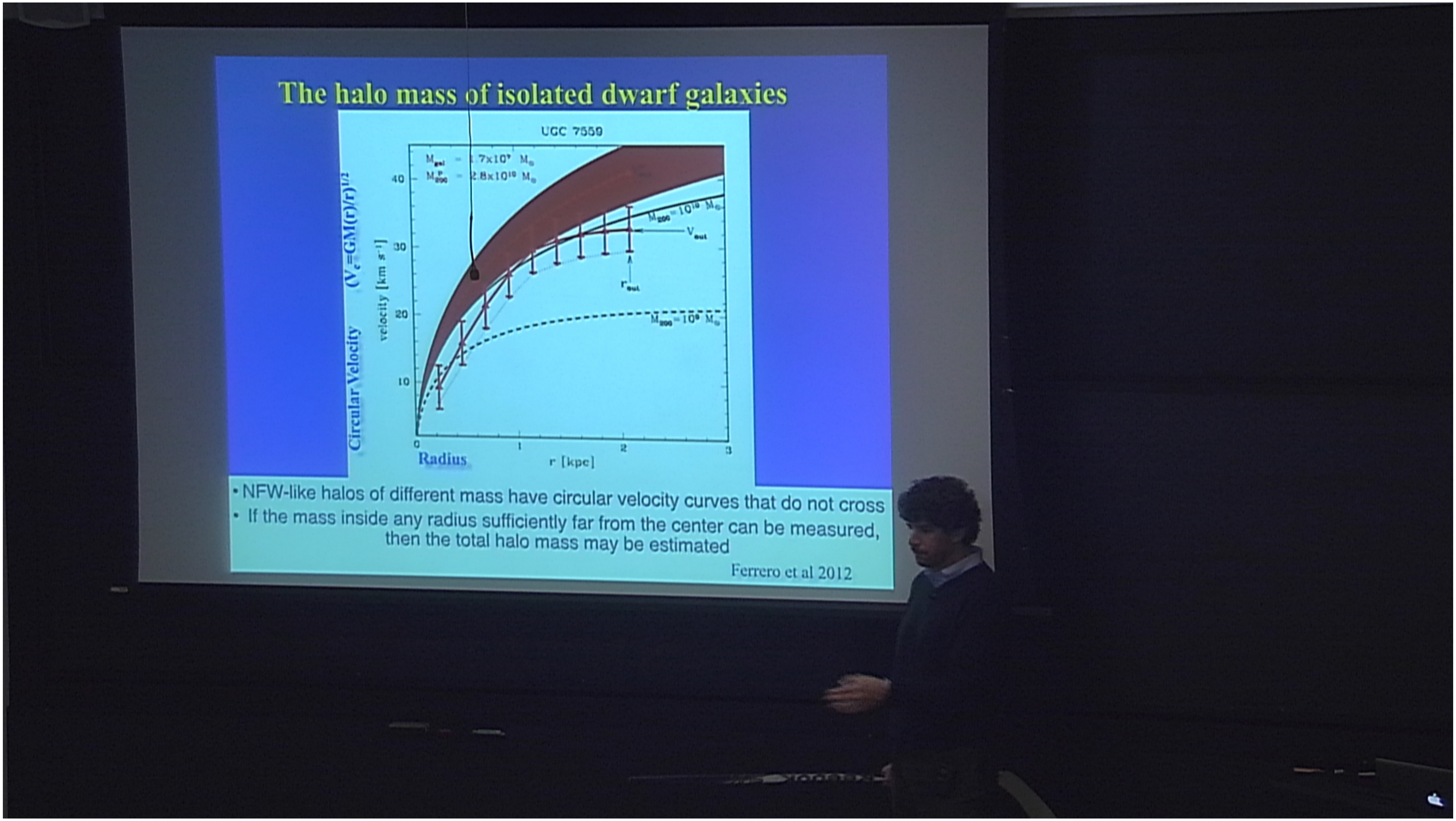


The halo mass of isolated dwarf galaxies
UGC 7559
Circular Velocity
(V_c=GM(r)/r)^1/2
velocity [km s^-1]
V_out
r_out
Radius
r [kpc]
• NFW-like halos of different mass have circular velocity curves that do not cross
• If the mass inside any radius sufficiently far from the center can be measured, then the total halo mass may be estimated
Ferrero et al 2012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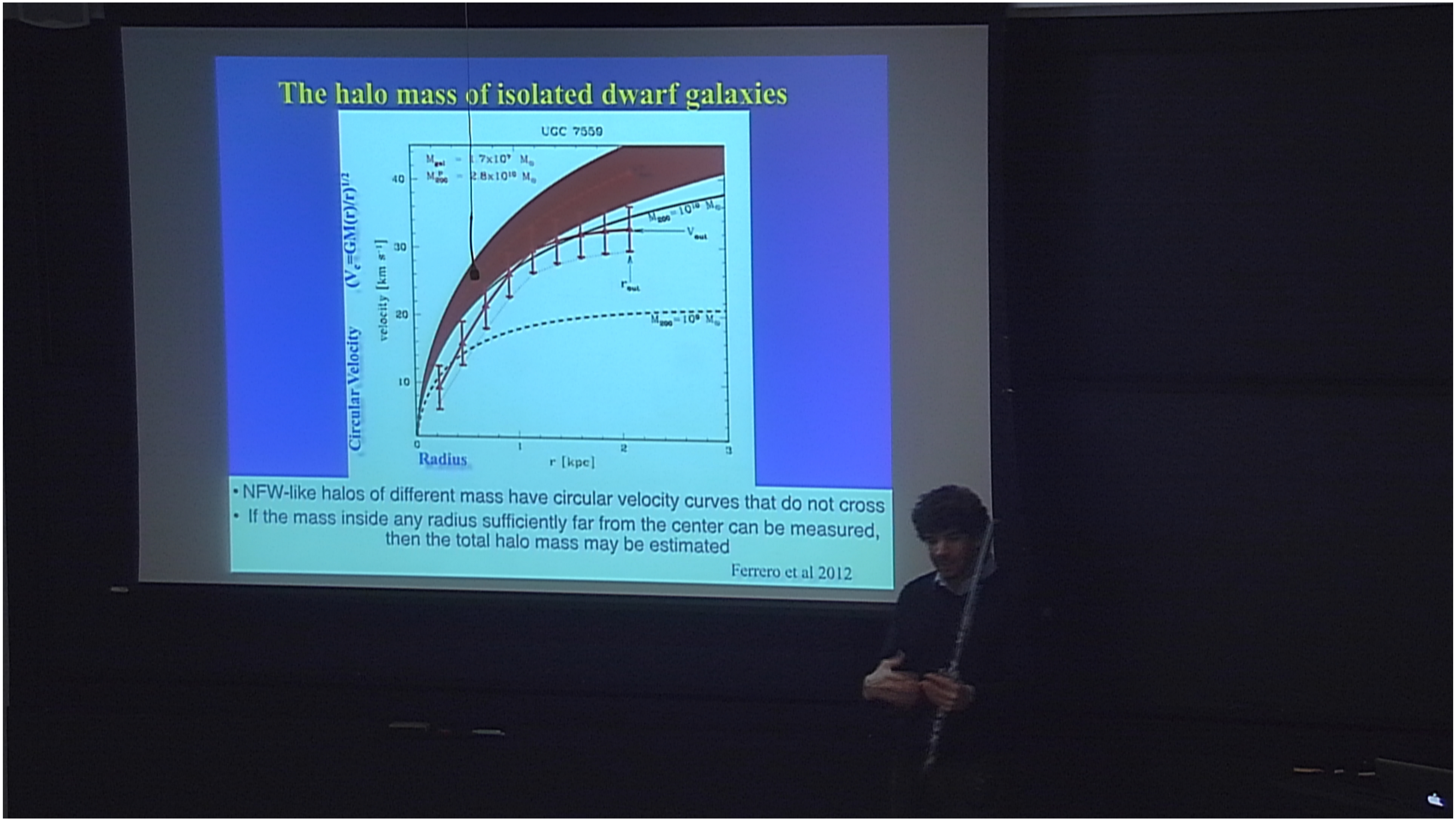
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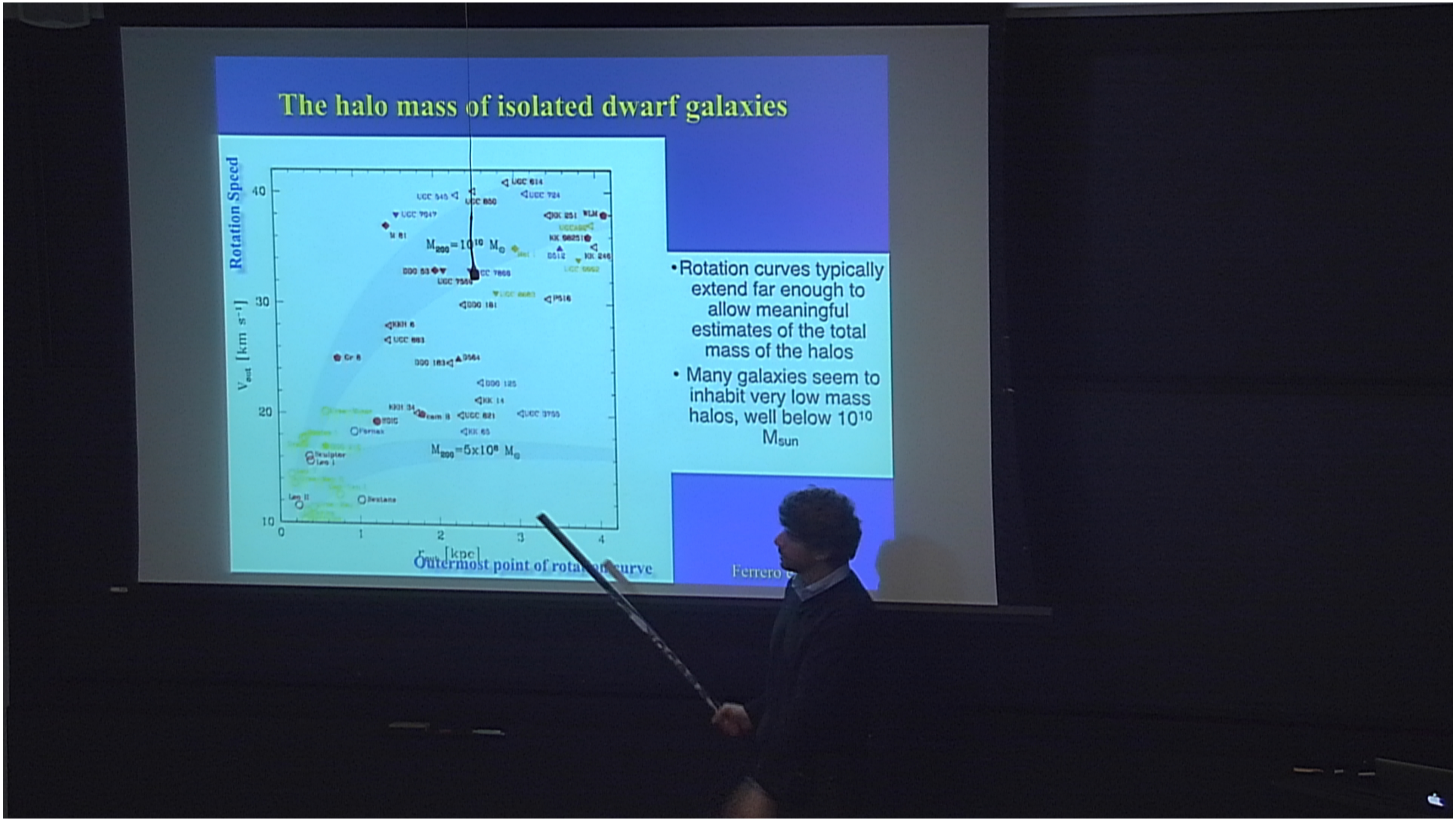
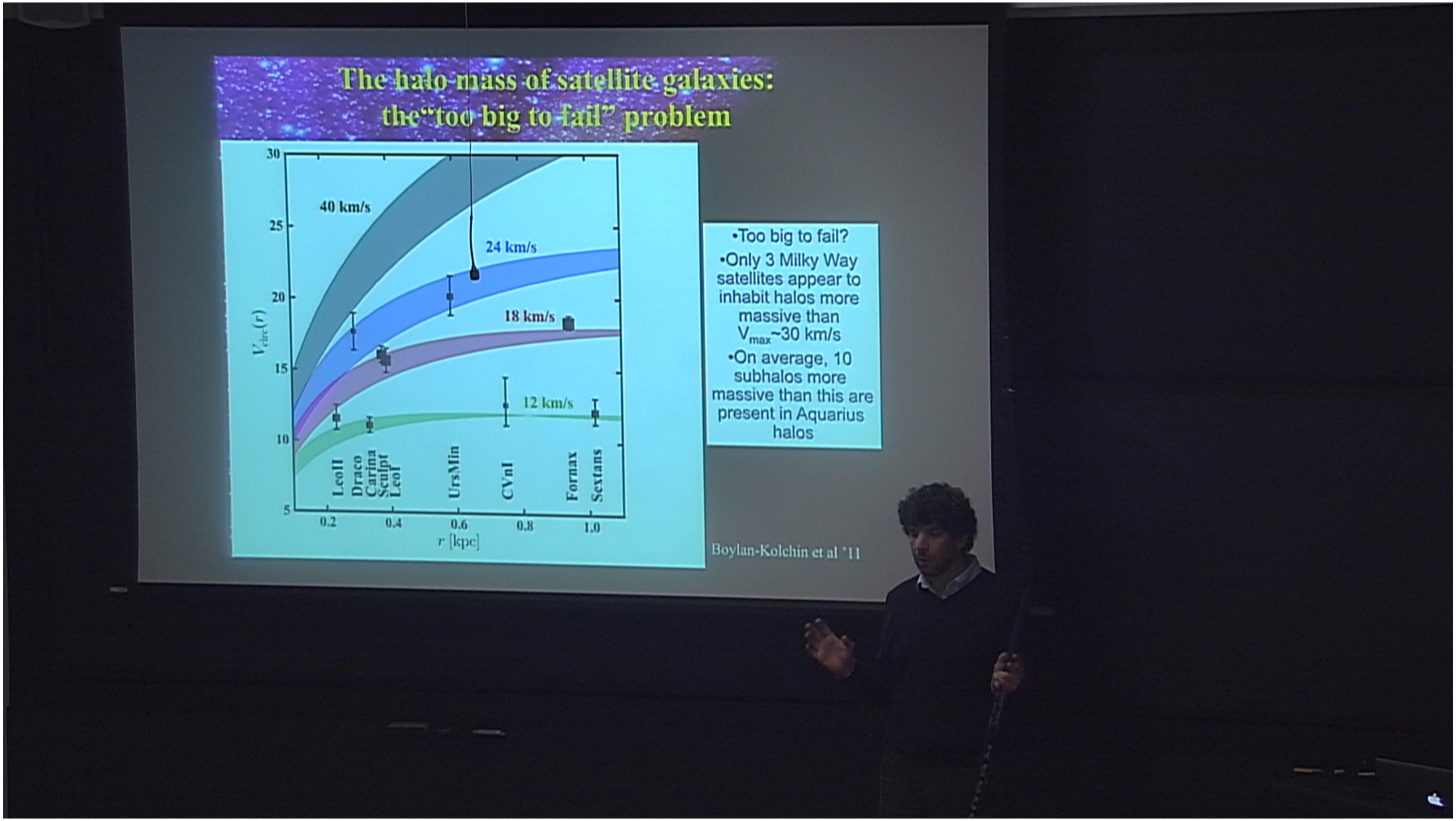
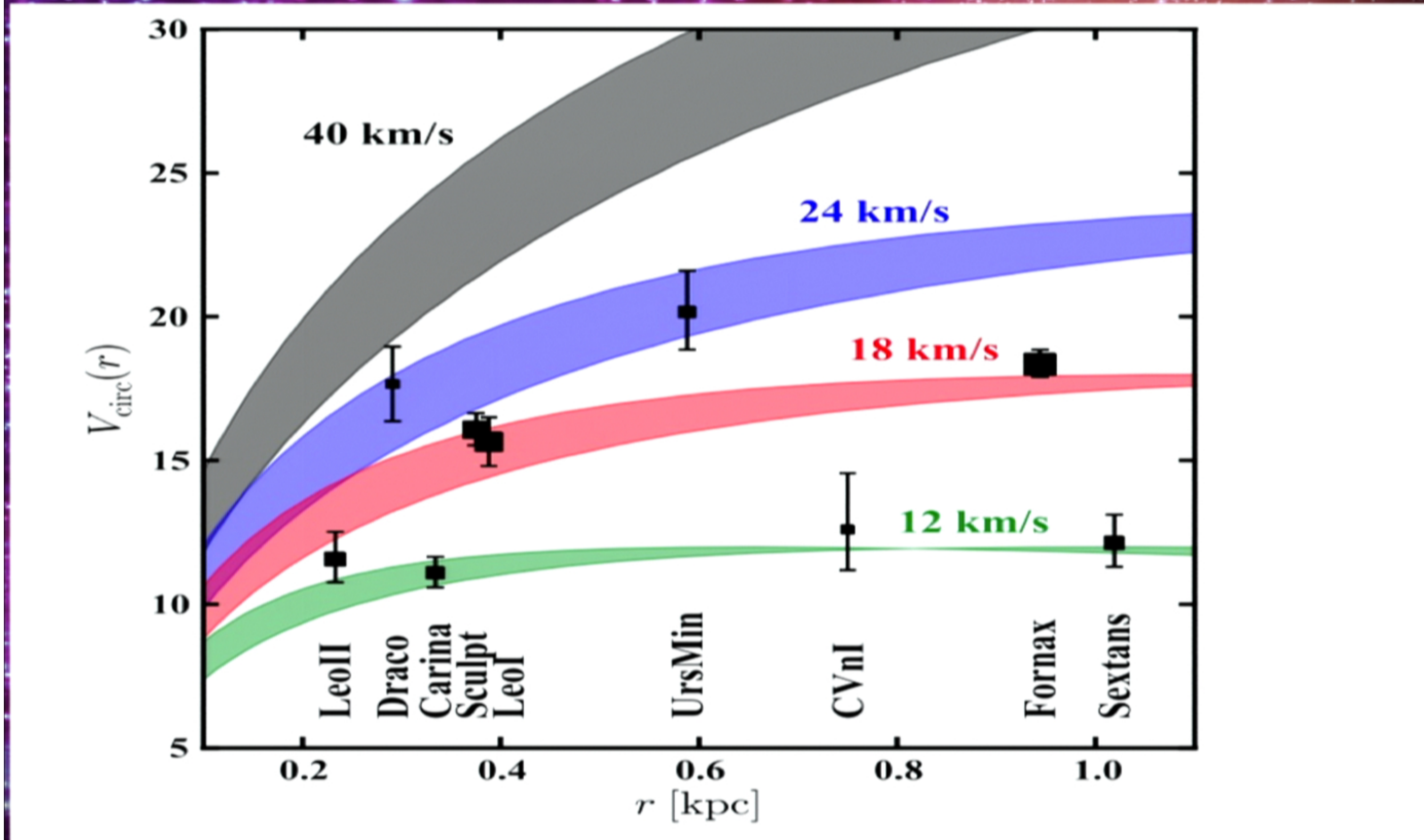

The halo mass of isolated dwarf galaxies
Rotation Speed
V_out [km s^-1]
M_200=10^10 M_☉
M_200=5x10^8 M_☉
r_out [kpc]
Outermost point of rotation curve
•Rotation curves typically extend far enough to allow meaningful estimates of the total mass of the halos
• Many galaxies seem to inhabit very low mass halos, well below 10^10 M_sun
Ferrero


The halo mass of satellite galaxies:
the "too big to fail" problem
40 km/s
24 km/s
18 km/s
12 km/s
$V_{circ}(r)$
r [kpc]
LeoII
Draco
Carina
Sculpt
LeoI
UrsMin
CVnI
Fornax
Sextans
•Too big to fail?
•Only 3 Milky Way satellites appear to inhabit halos more massive than V_{max}~30 km/s
•On average, 10 subhalos more massive than this are present in Aquarius halos
Boylan-Kolchin et al '11

The halo mass of satellite galaxies: the "too big to fail" problem



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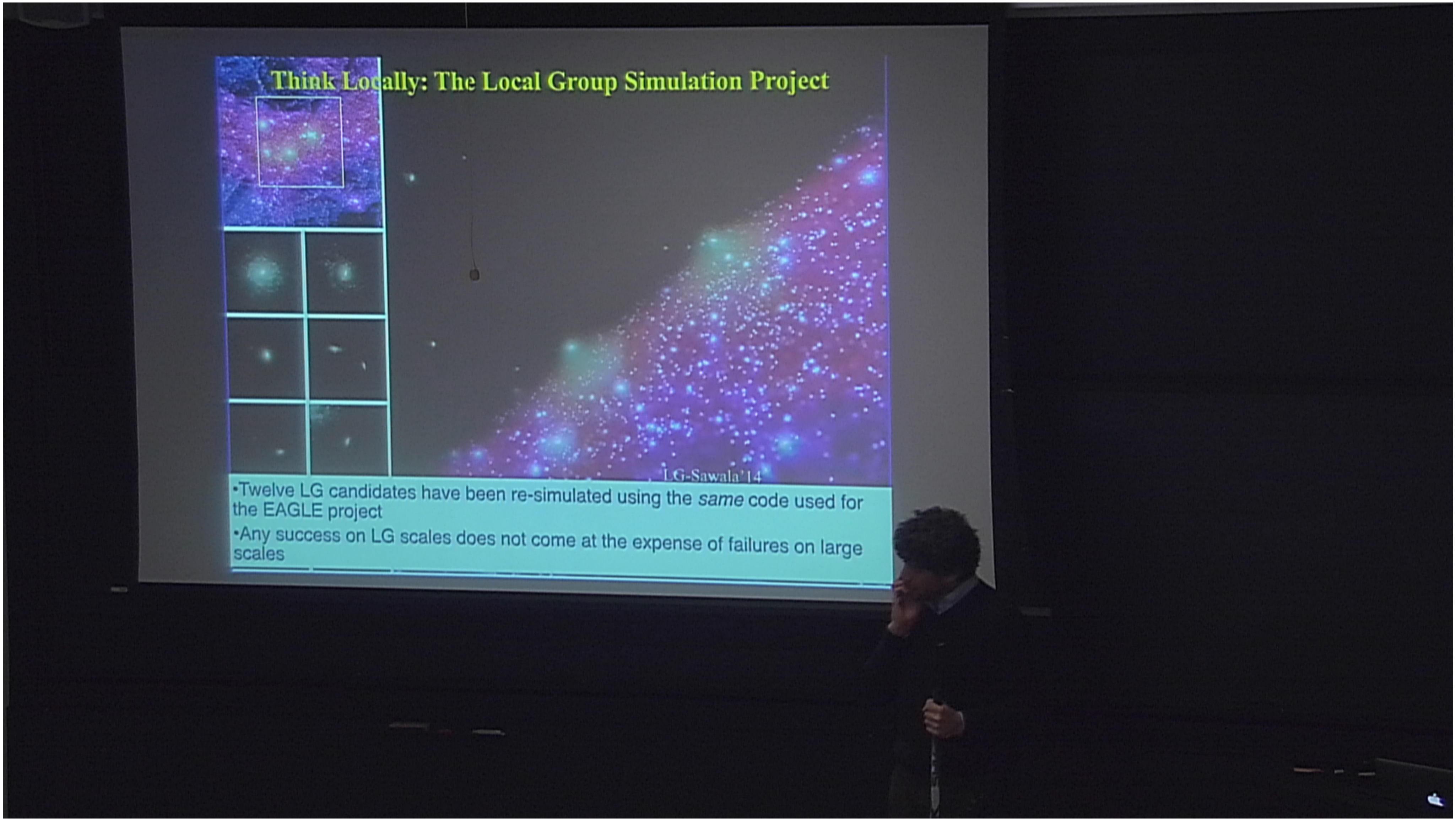
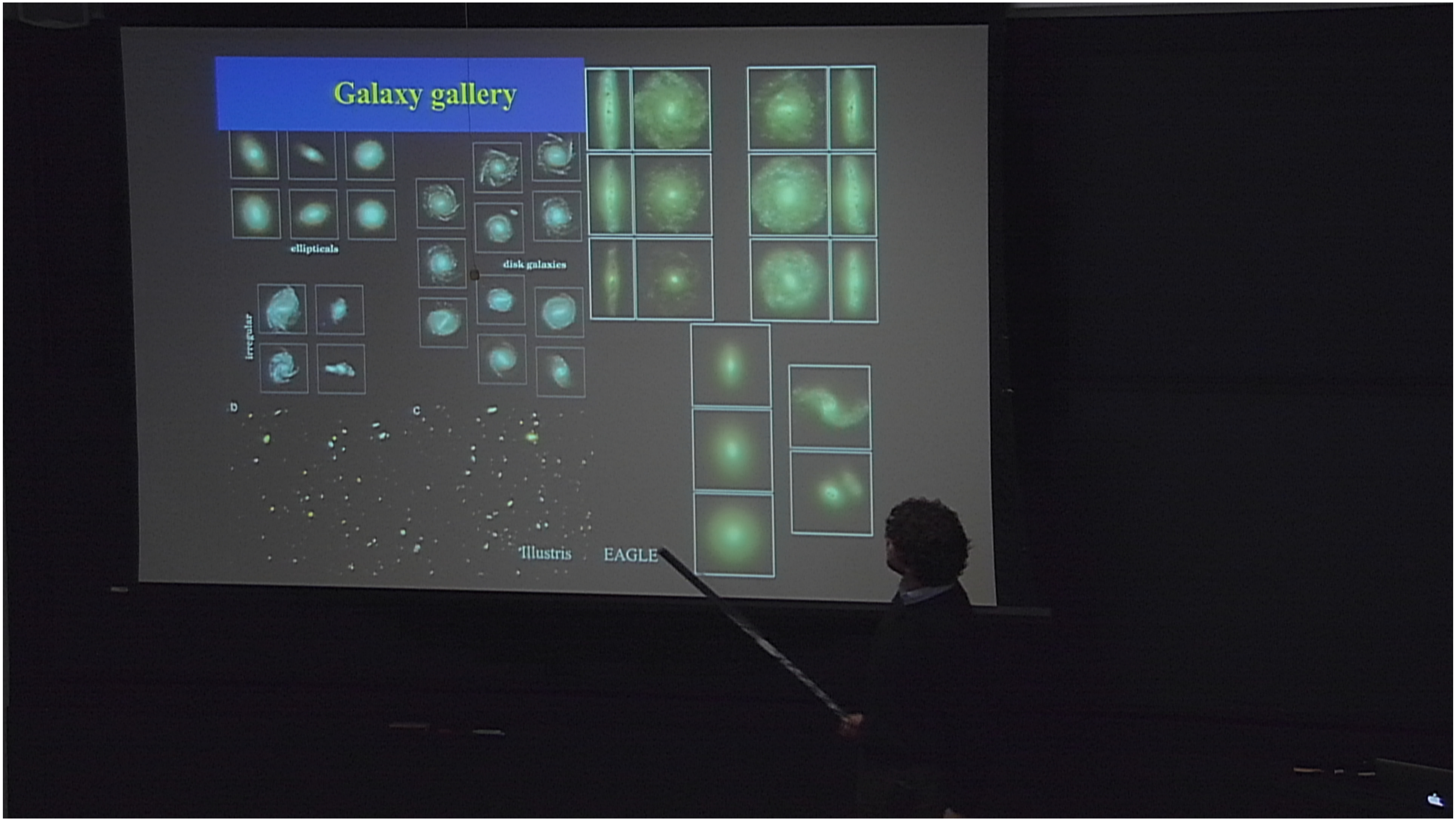
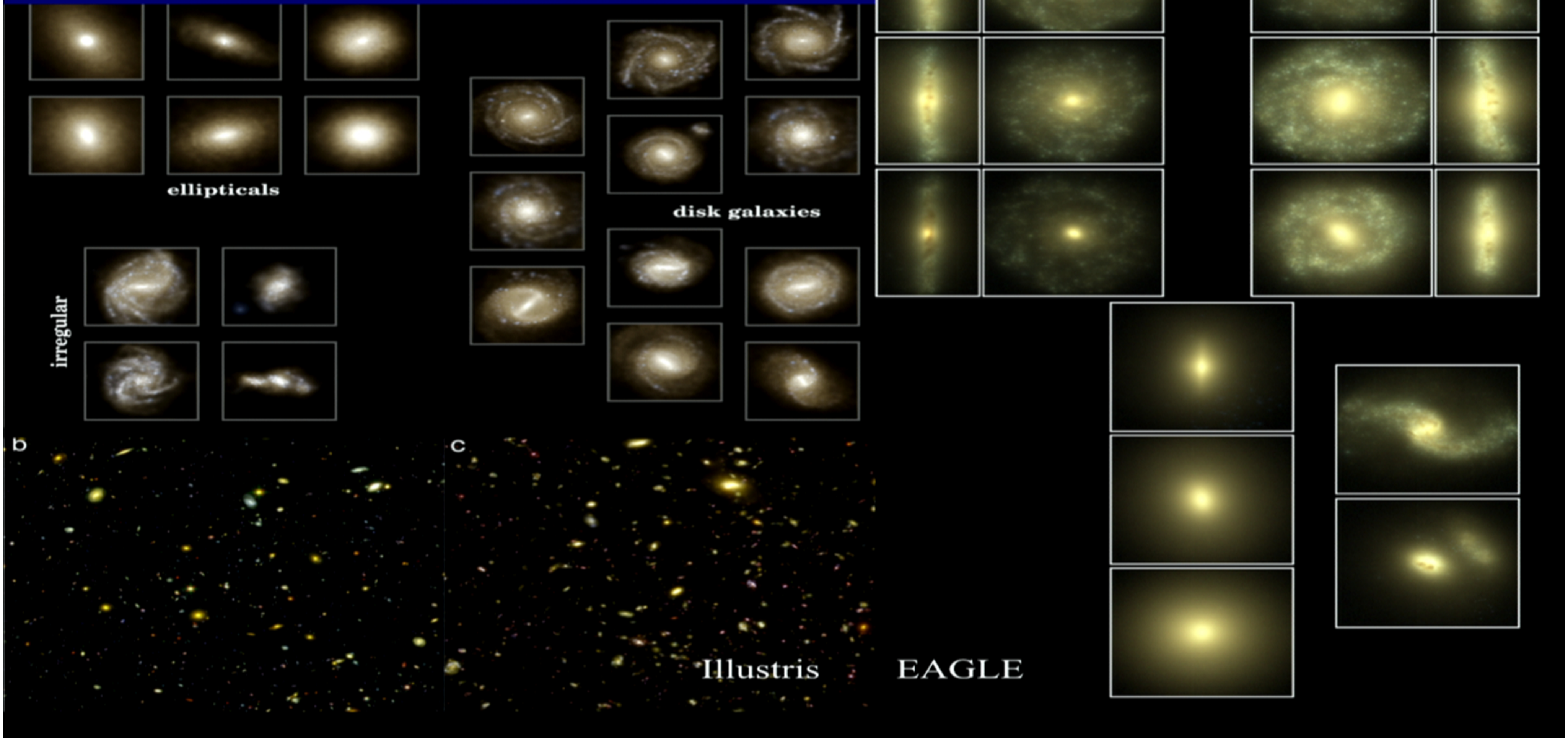
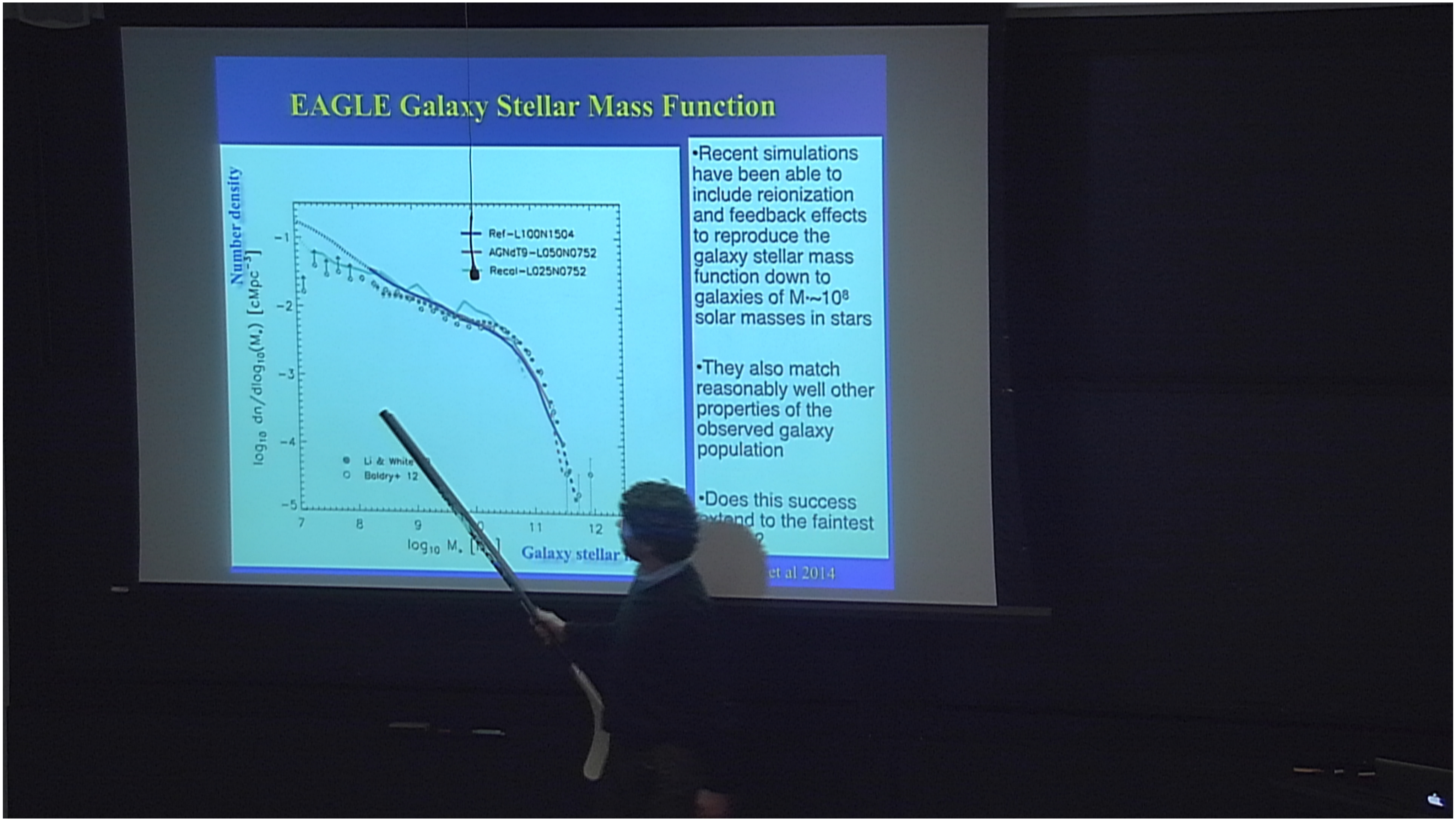

Think Locally: The Local Group Simulation Project
LG-Sawala'14
•Twelve LG candidates have been re-simulated using the *same* code used for the EAGLE project
•Any success on LG scales does not come at the expense of failures on large scales


Galaxy gallery
ellipticals
disk galaxies
irregular
b
c
Illustris
EAGLE

Galaxy gallery





EAGLE Galaxy Stellar Mass Function
Number density
$\log_{10} dn/d\log_{10}(M_*)$ [cMpc^{-3}]
Ref–L100N1504
AGNdT9–L050N0752
Recal–L025N0752
Li & White
Baldry+ 12
$\log_{10} M_*$
Galaxy stellar
•Recent simulations have been able to include reionization and feedback effects to reproduce the galaxy stellar mass function down to galaxies of M*~10^8 solar masses in stars
•They also match reasonably well other properties of the observed galaxy population
•Does this success
to the faintest
et al 2014


Dark Matter, Gas and Stars in the Local Group
LG-Fattahi'14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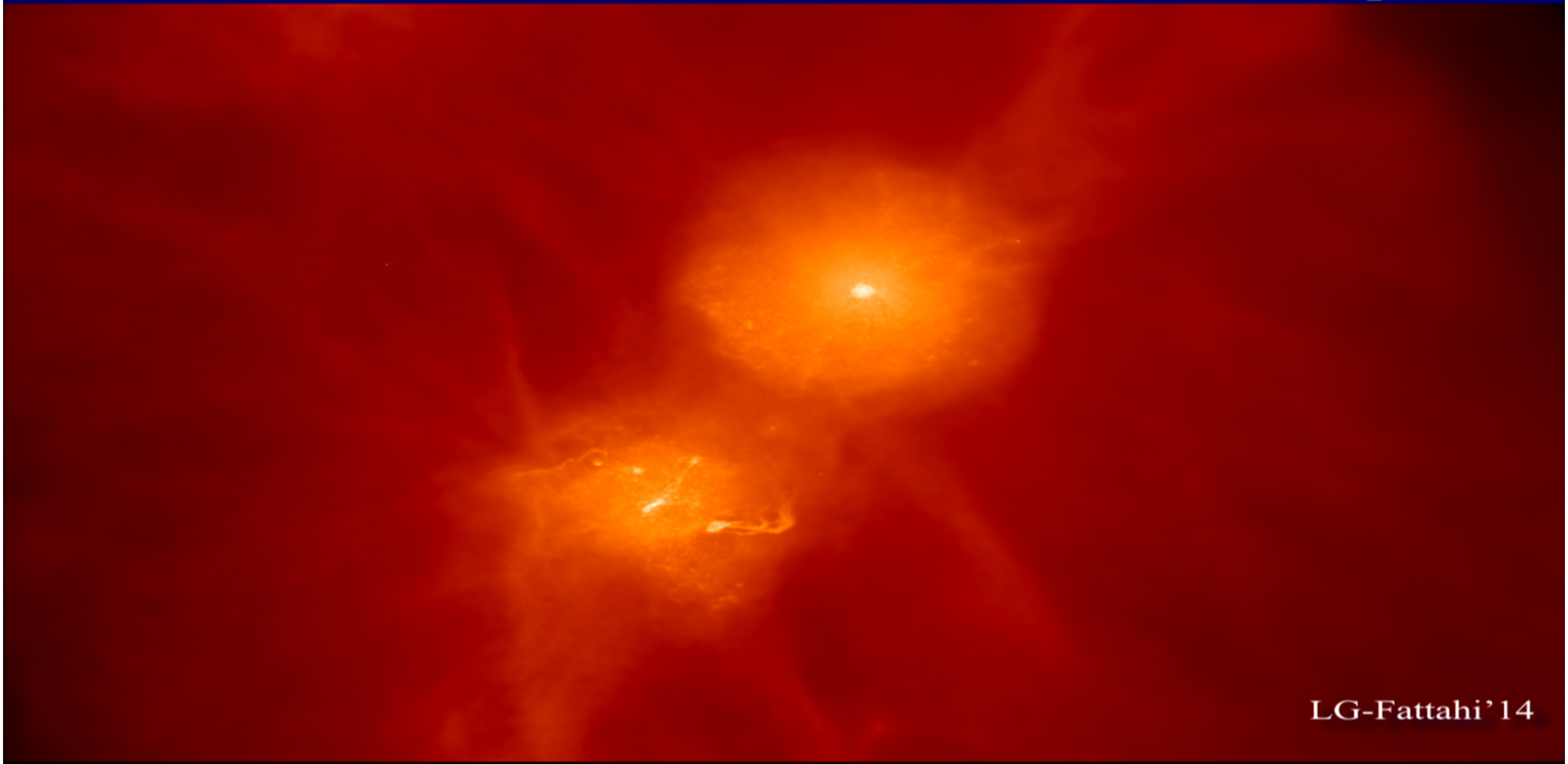


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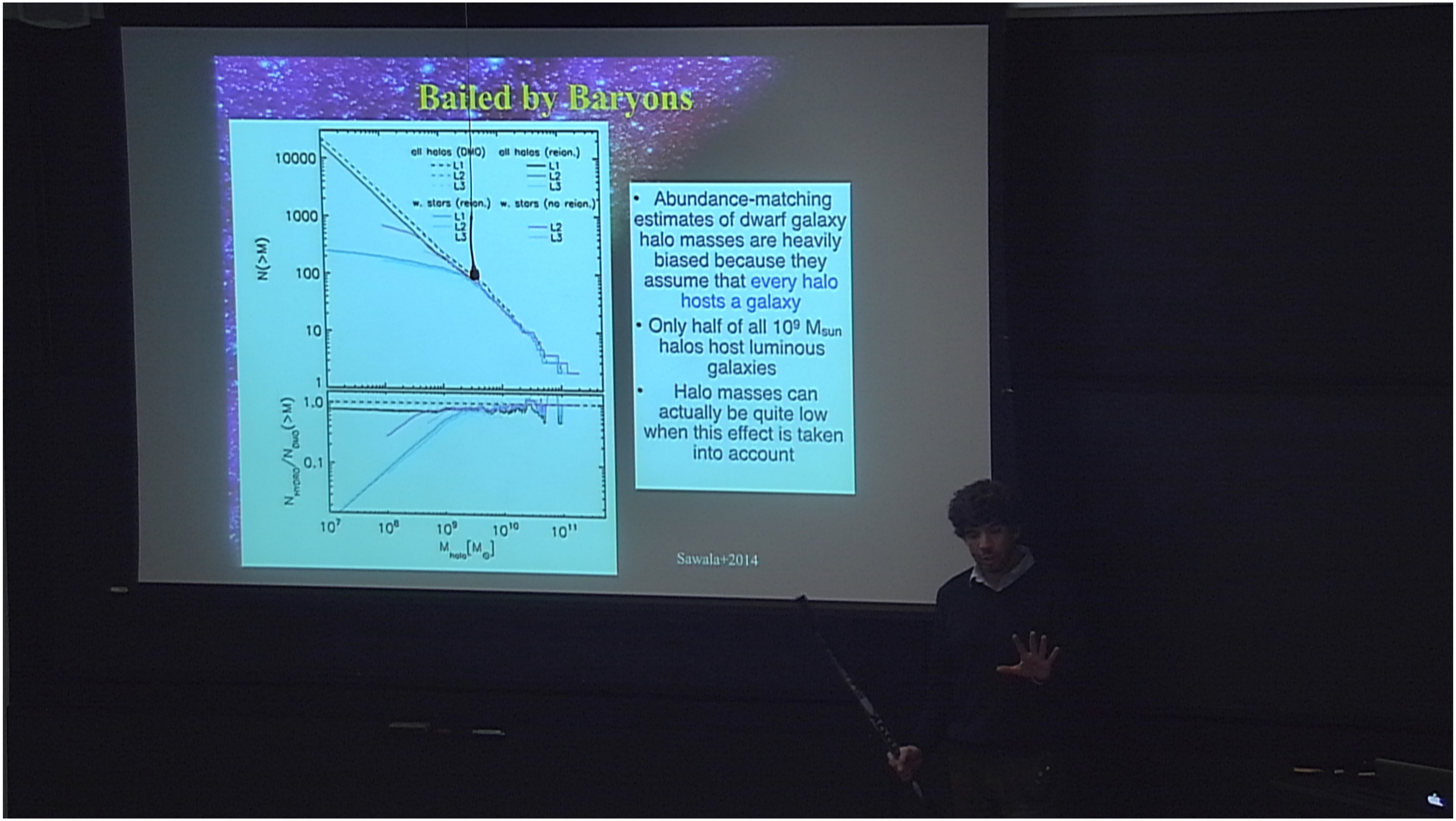
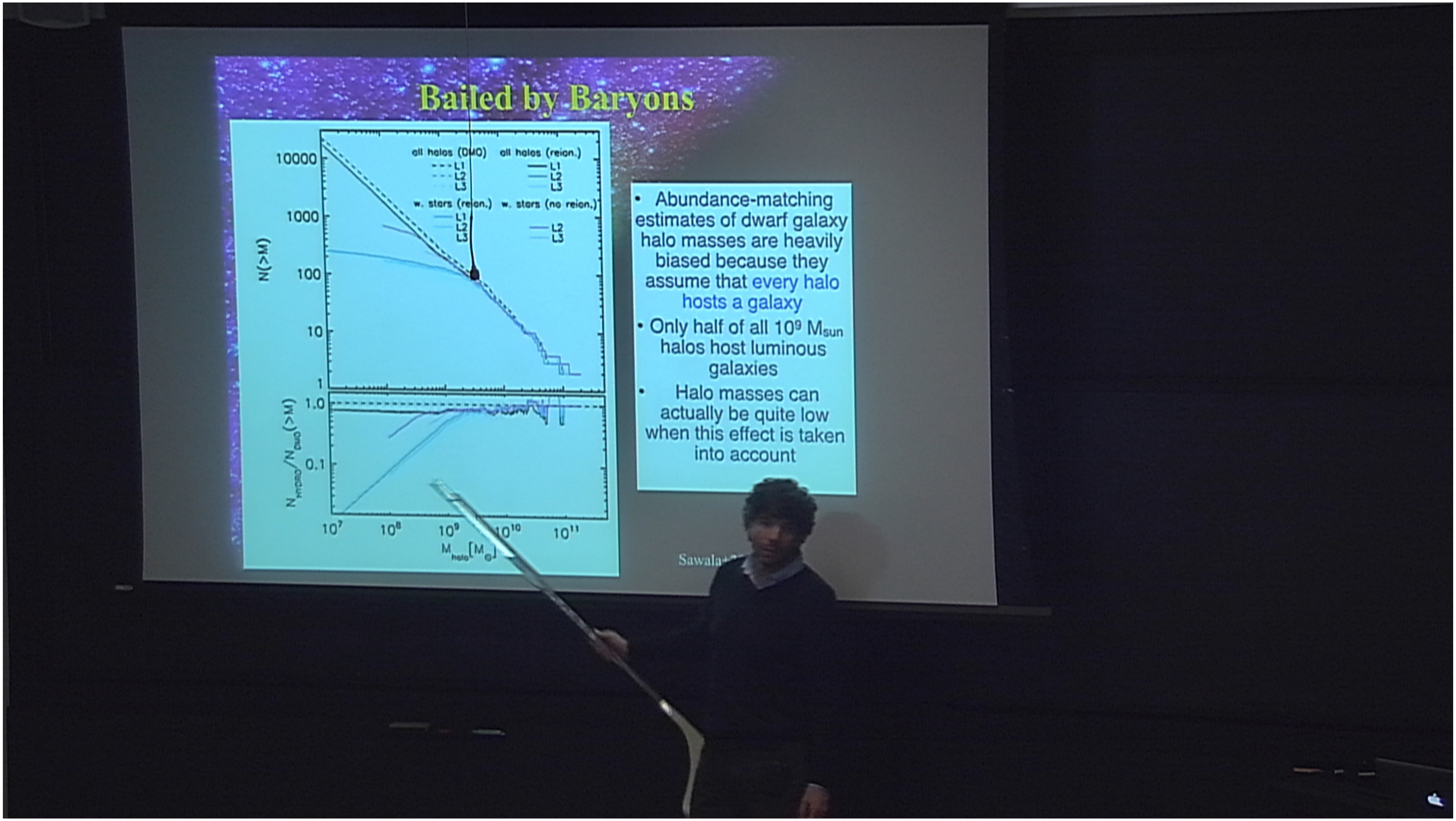

Bailed by Baryons
all halos (DMO)
all halos (reion.)
w. stars (reion.)
w. stars (no reion.)
N(>M)
$N_{HYDRO}/N_{DMO}(>M)$
$M_{halo}[M_{\odot}]$
• Abundance-matching estimates of dwarf galaxy halo masses are heavily biased because they assume that every halo hosts a galaxy
• Only half of all 10^9 M_{sun} halos host luminous galaxies
• Halo masses can actually be quite low when this effect is taken into account
Sawala+2014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L1
L2
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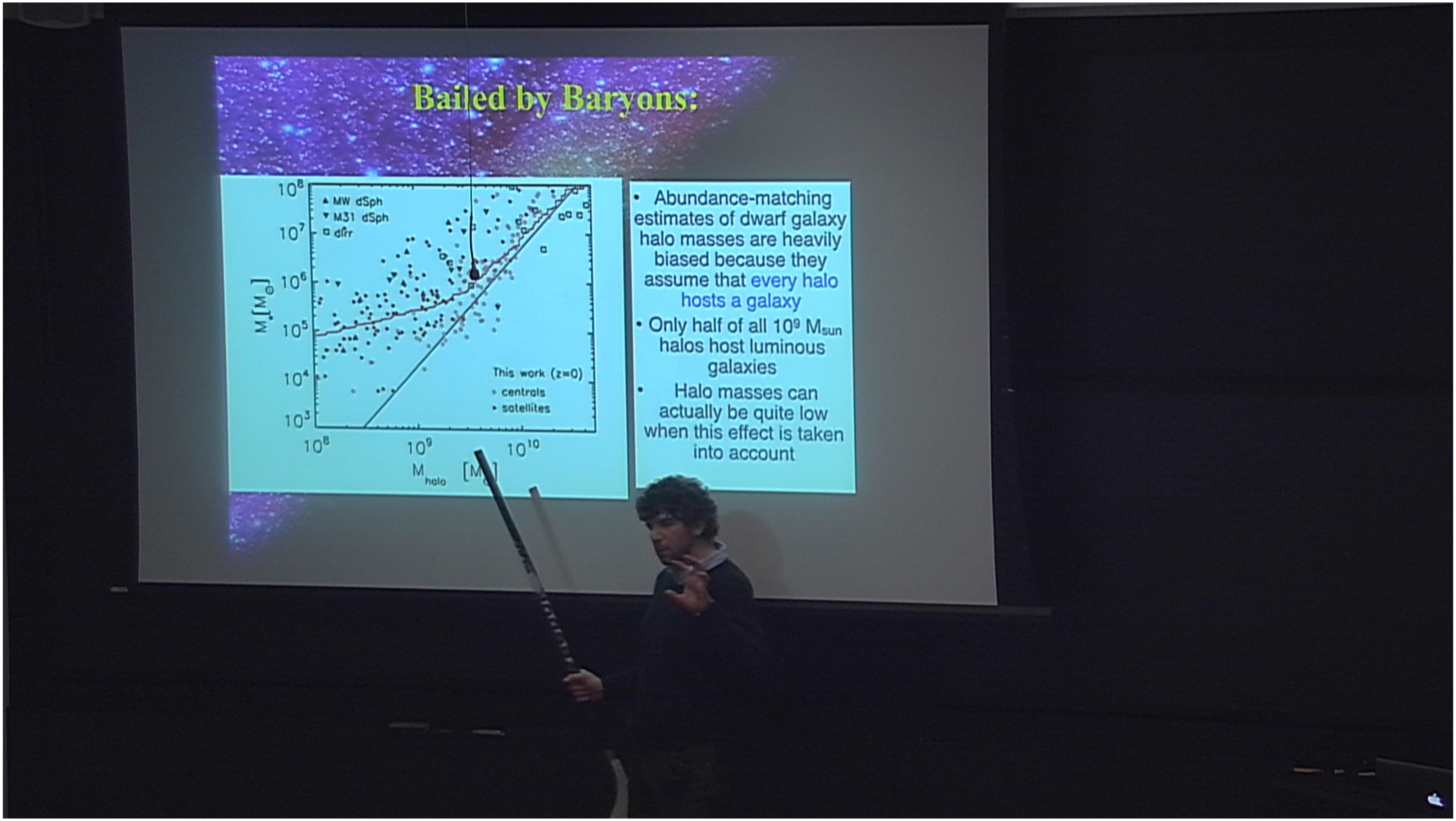
Bailed by Baryons:
MW dSph
M31 dSph
dIrr
This work (z=0)
centrals
satellites
M_halo [M_⊙]
M_*[M_⊙]
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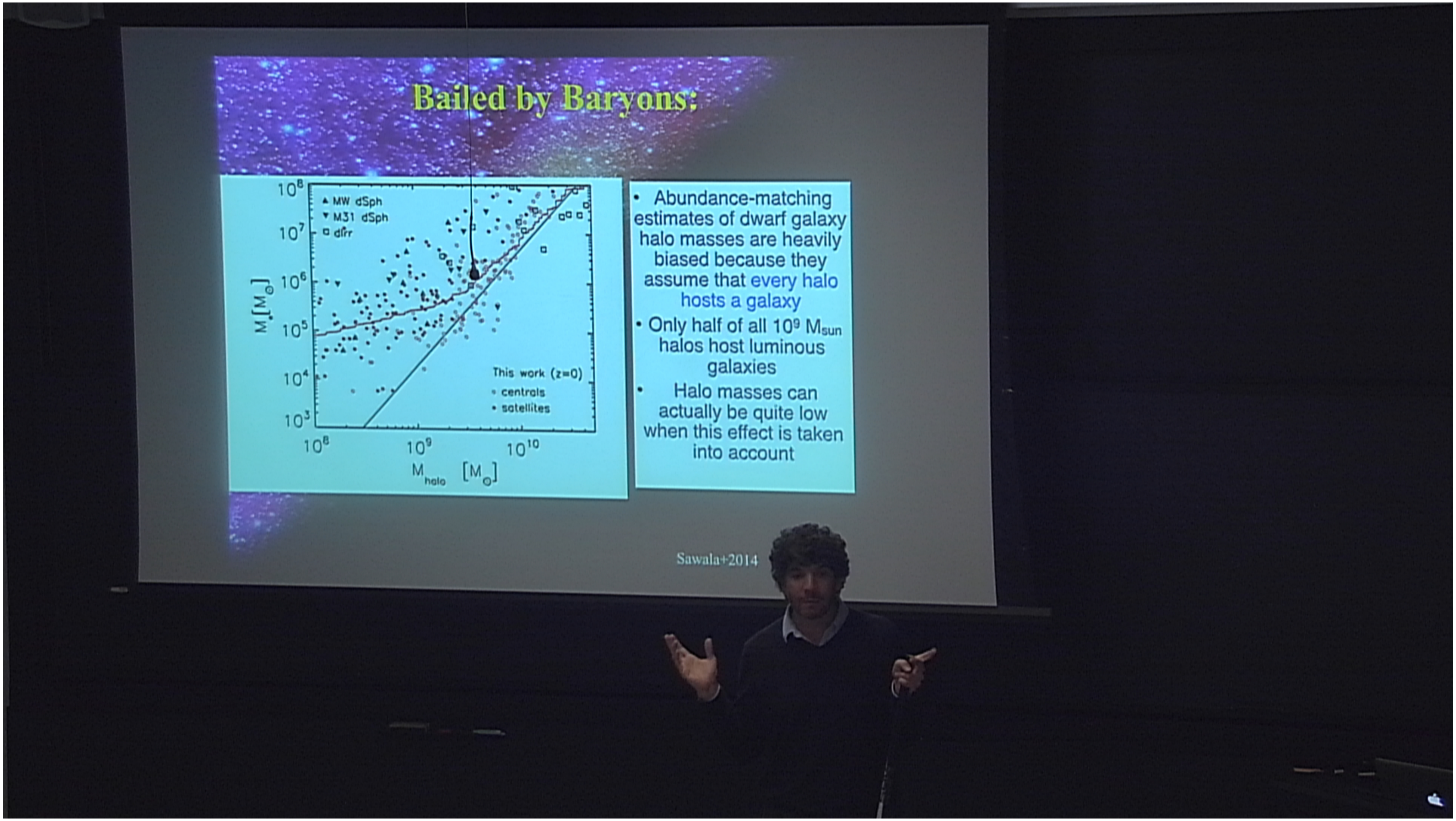
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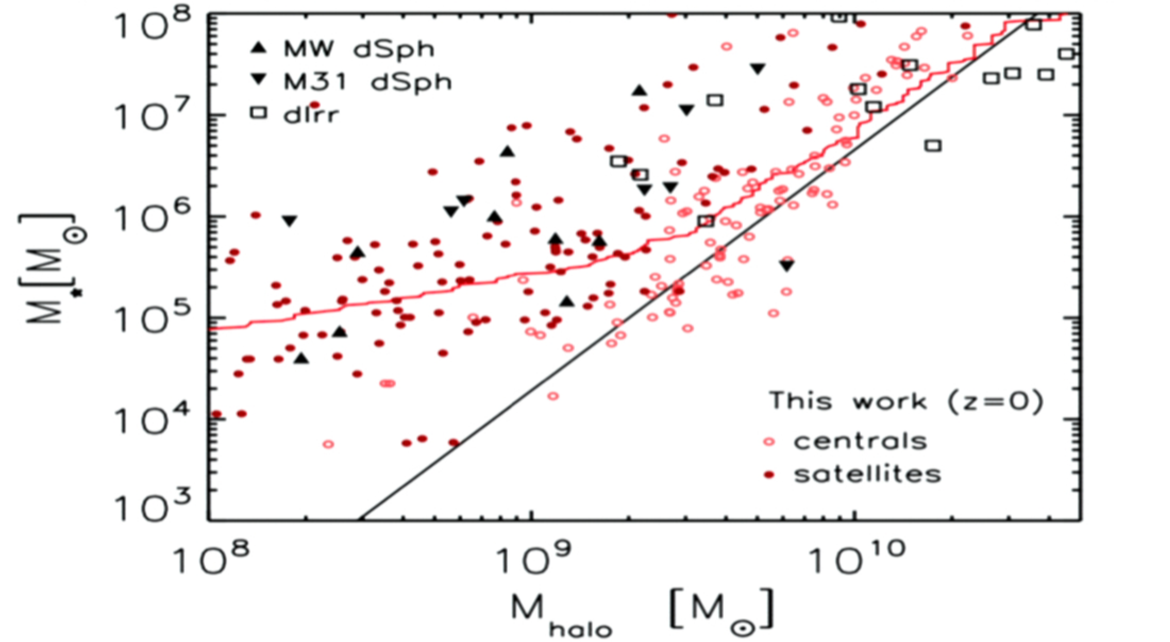

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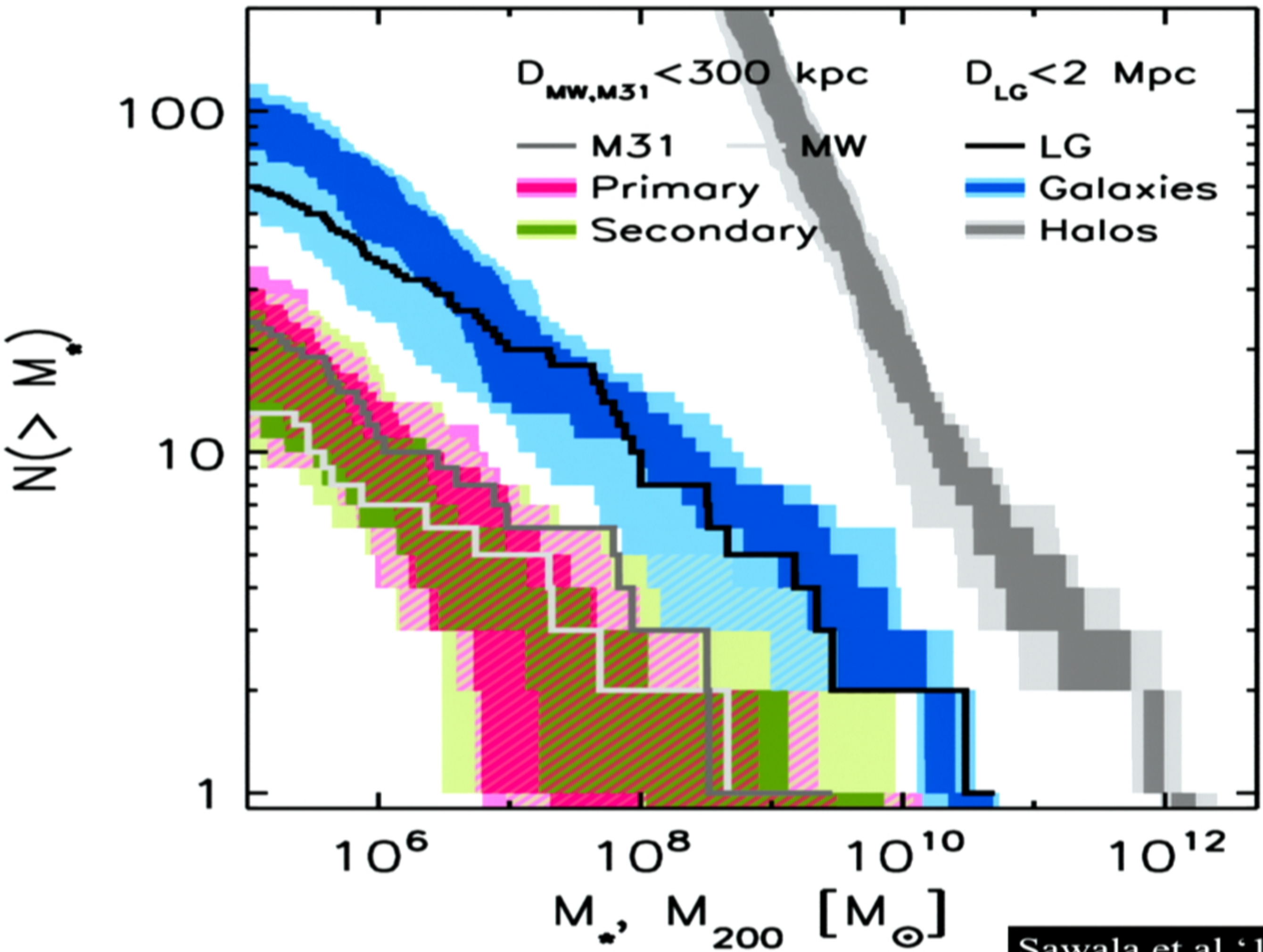
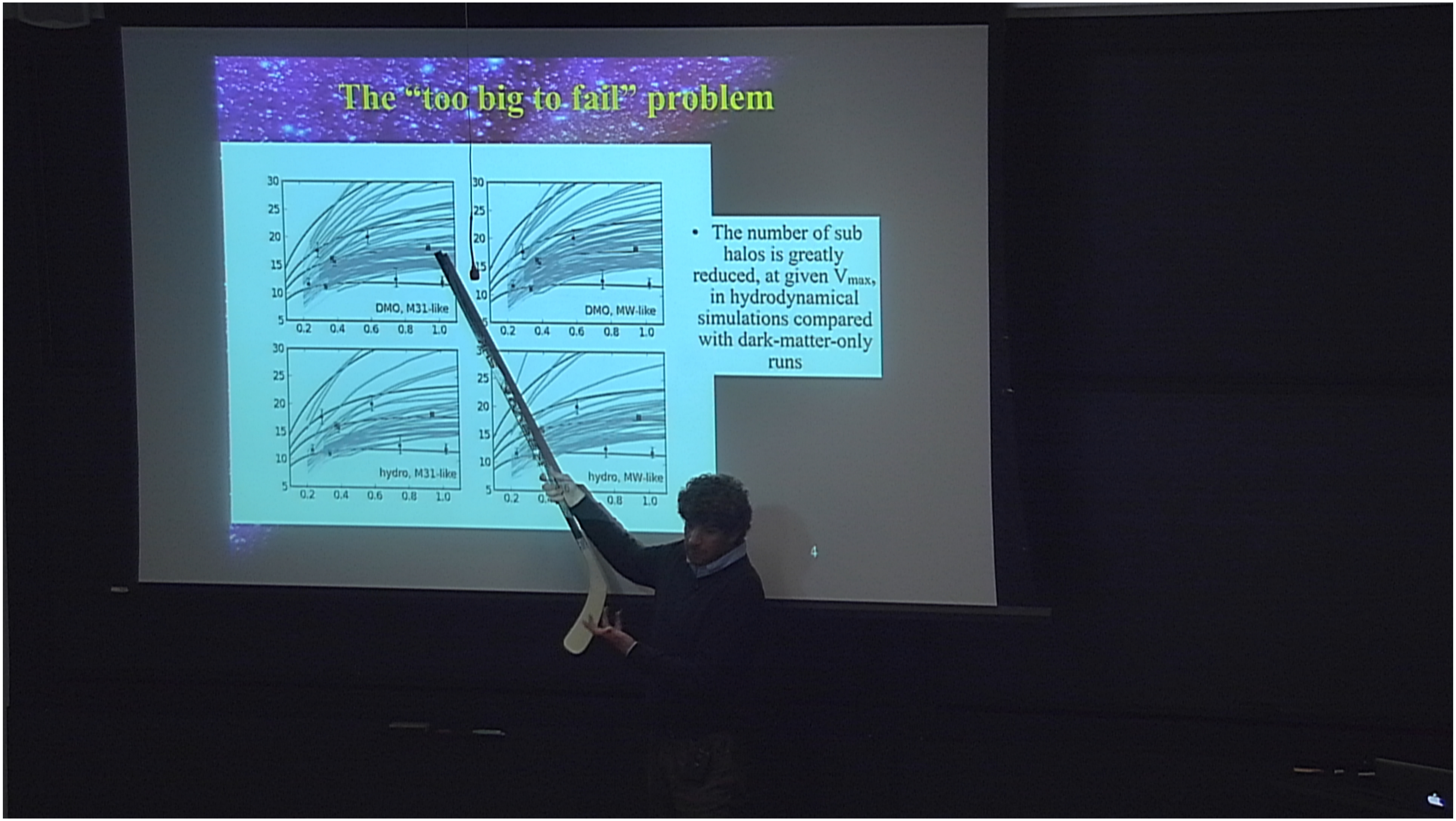
Sawala+2014

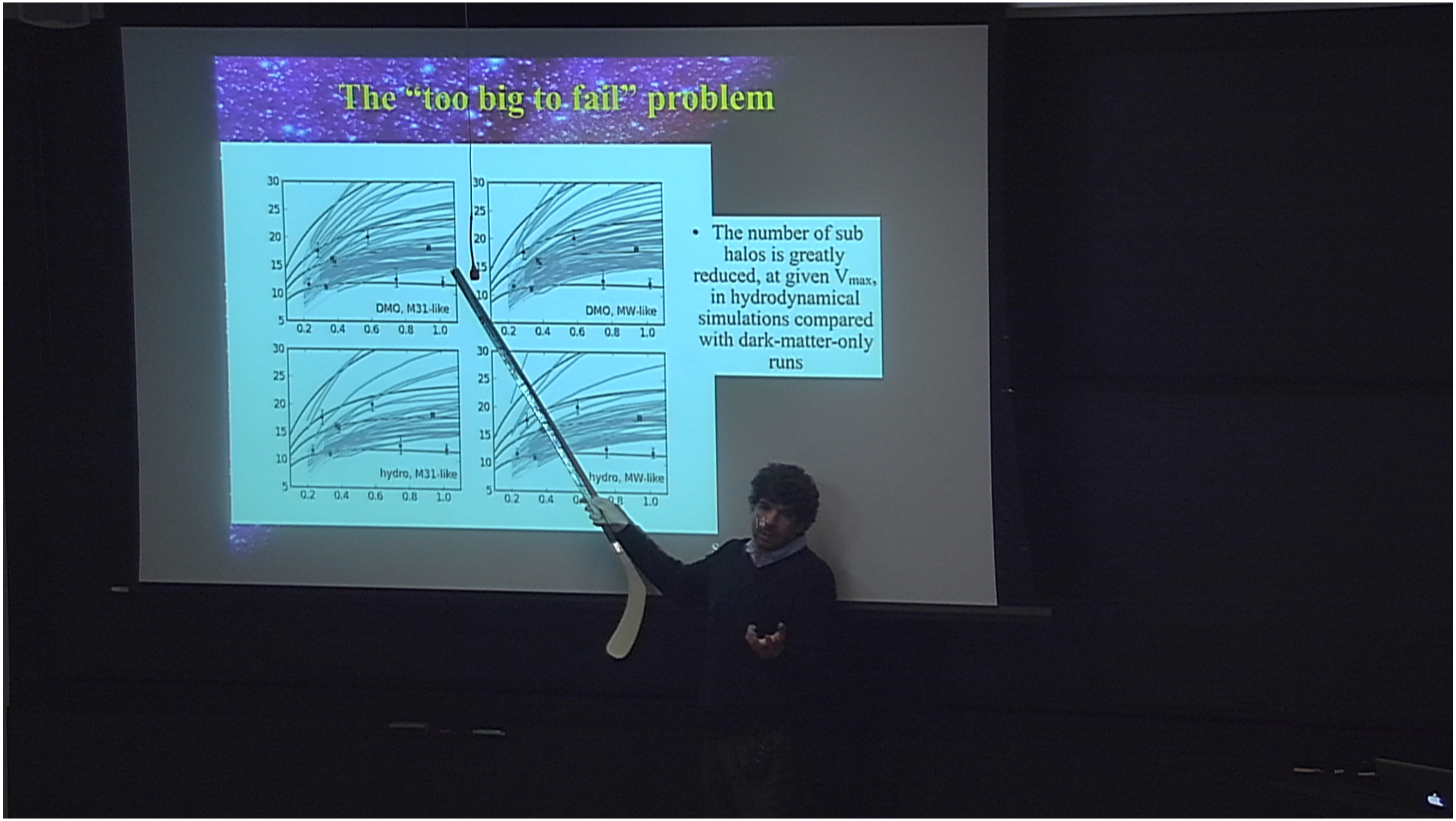
The "missing satellites" problem



Sawala et al '14

- The Local Group re-simulations match quite well the observed number of satellites of each primary and the number of dwarfs within ~2 Mpc from the LG barycentre, down to stellar masses of order ~10^5 M_{sun}


The "too big to fail" problem
DMO, M31-like
DMO, MW-like
hydro, M31-like
hydro, MW-like
• The number of sub halos is greatly reduced, at given Vmax, in hydrodynamical simulations compared with dark-matter-only runs
4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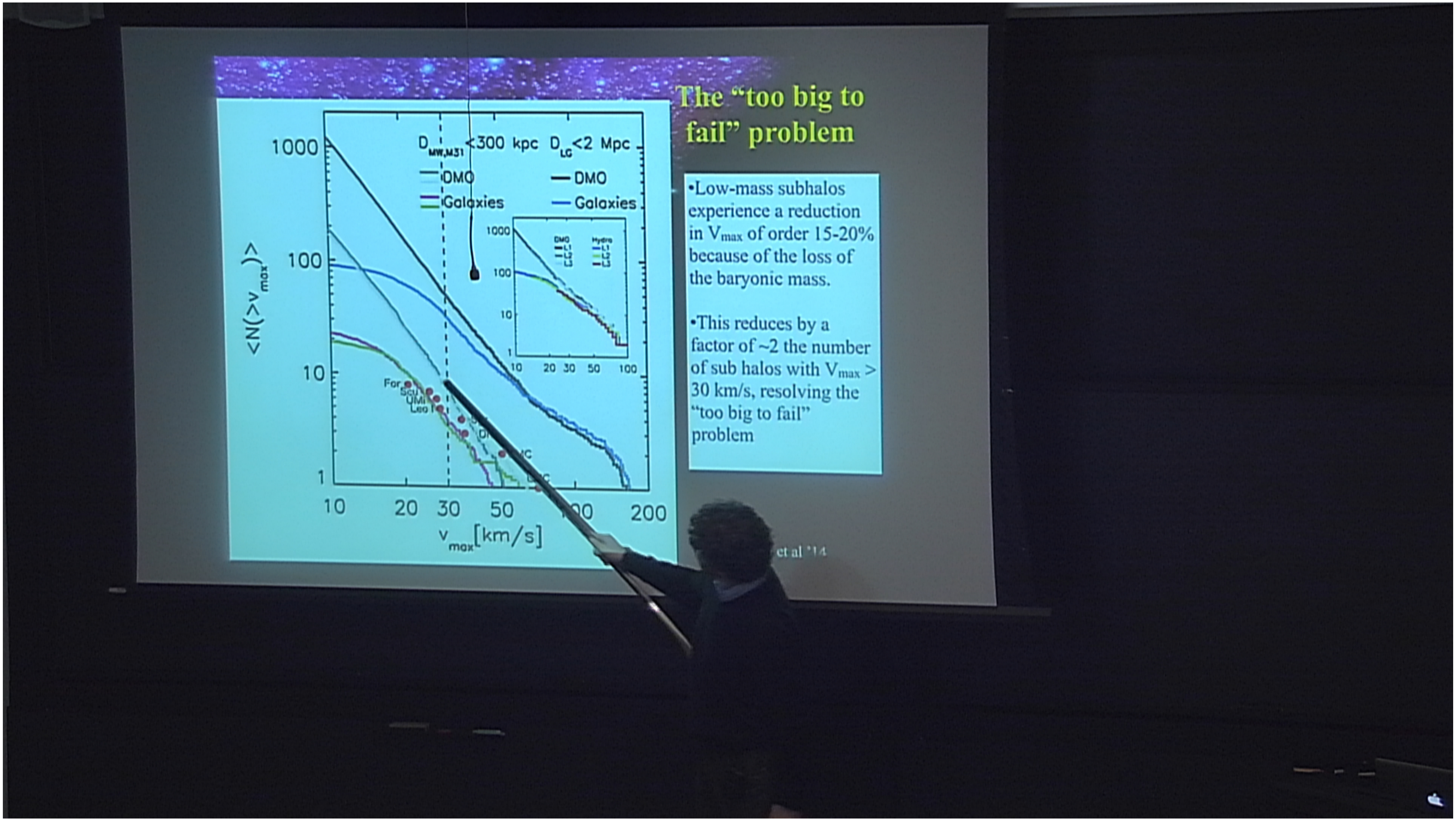
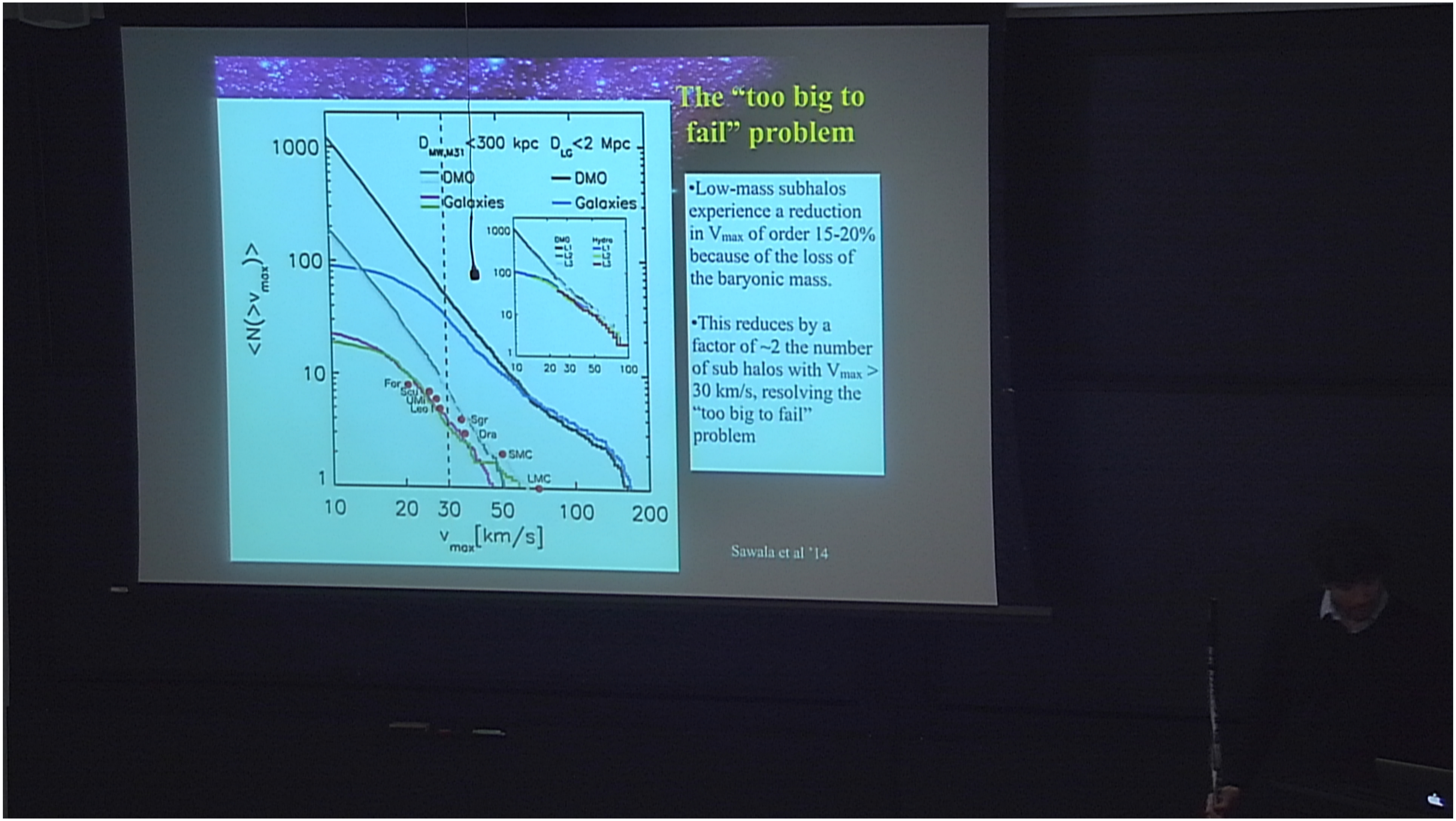
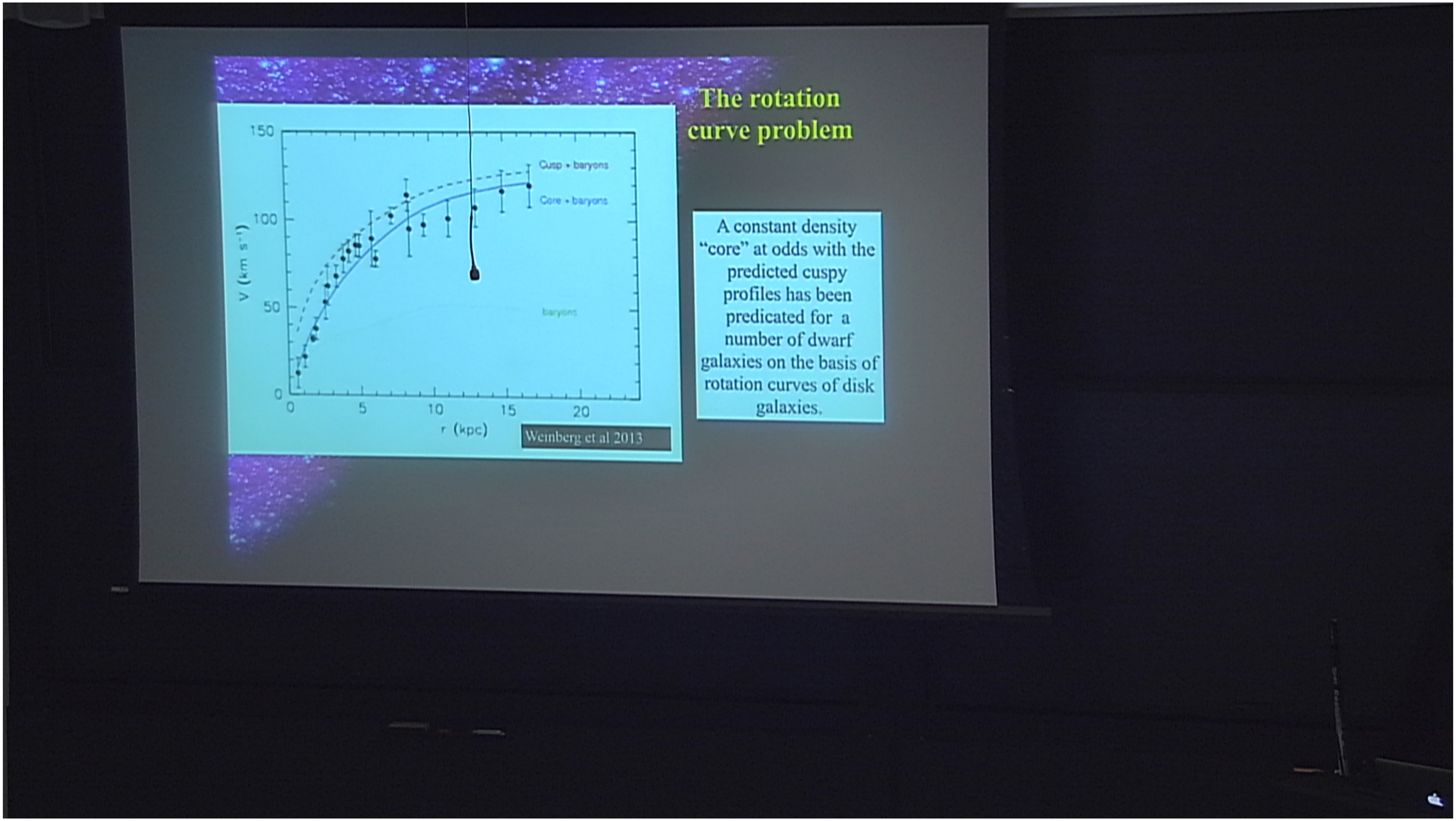
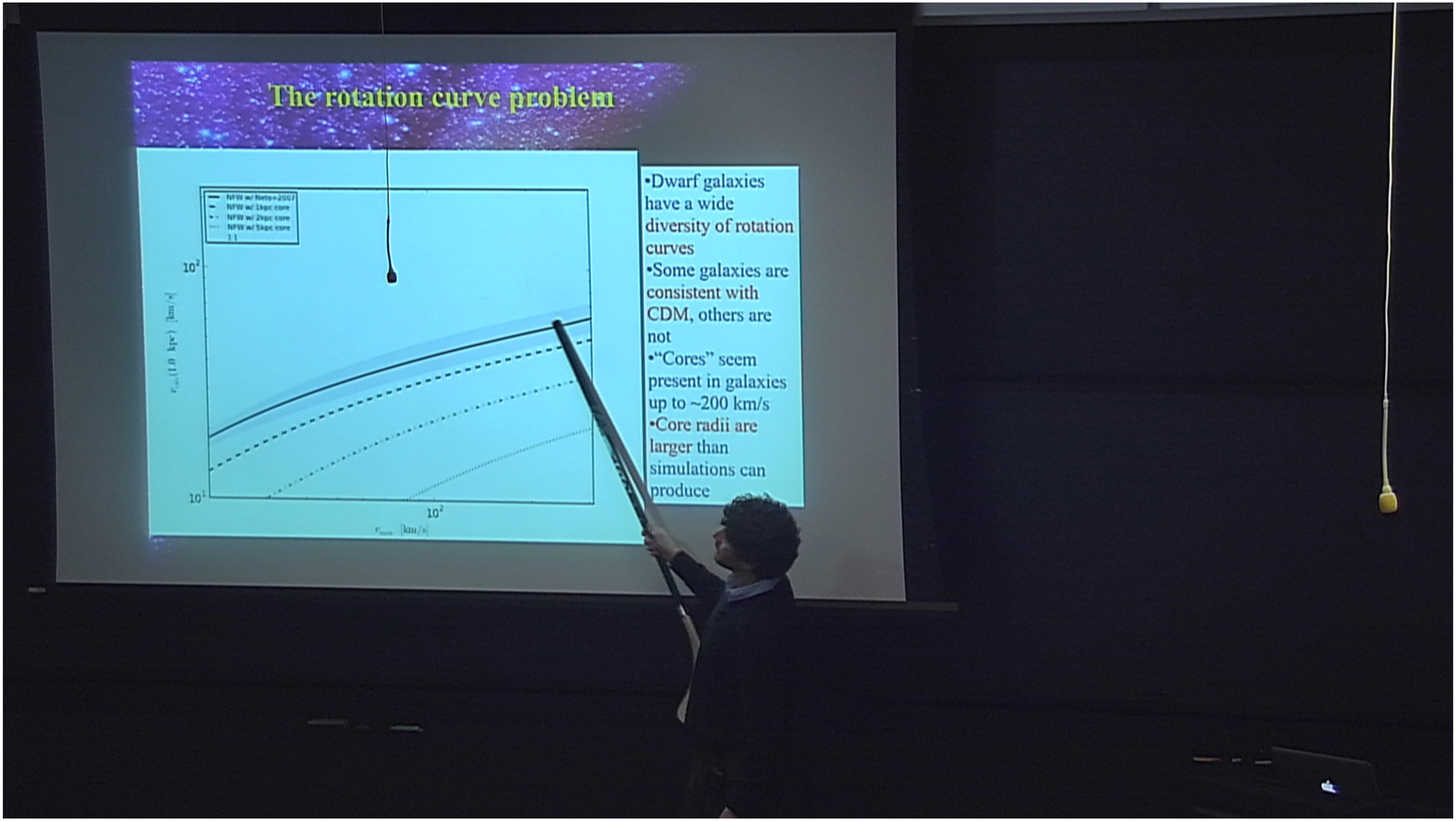
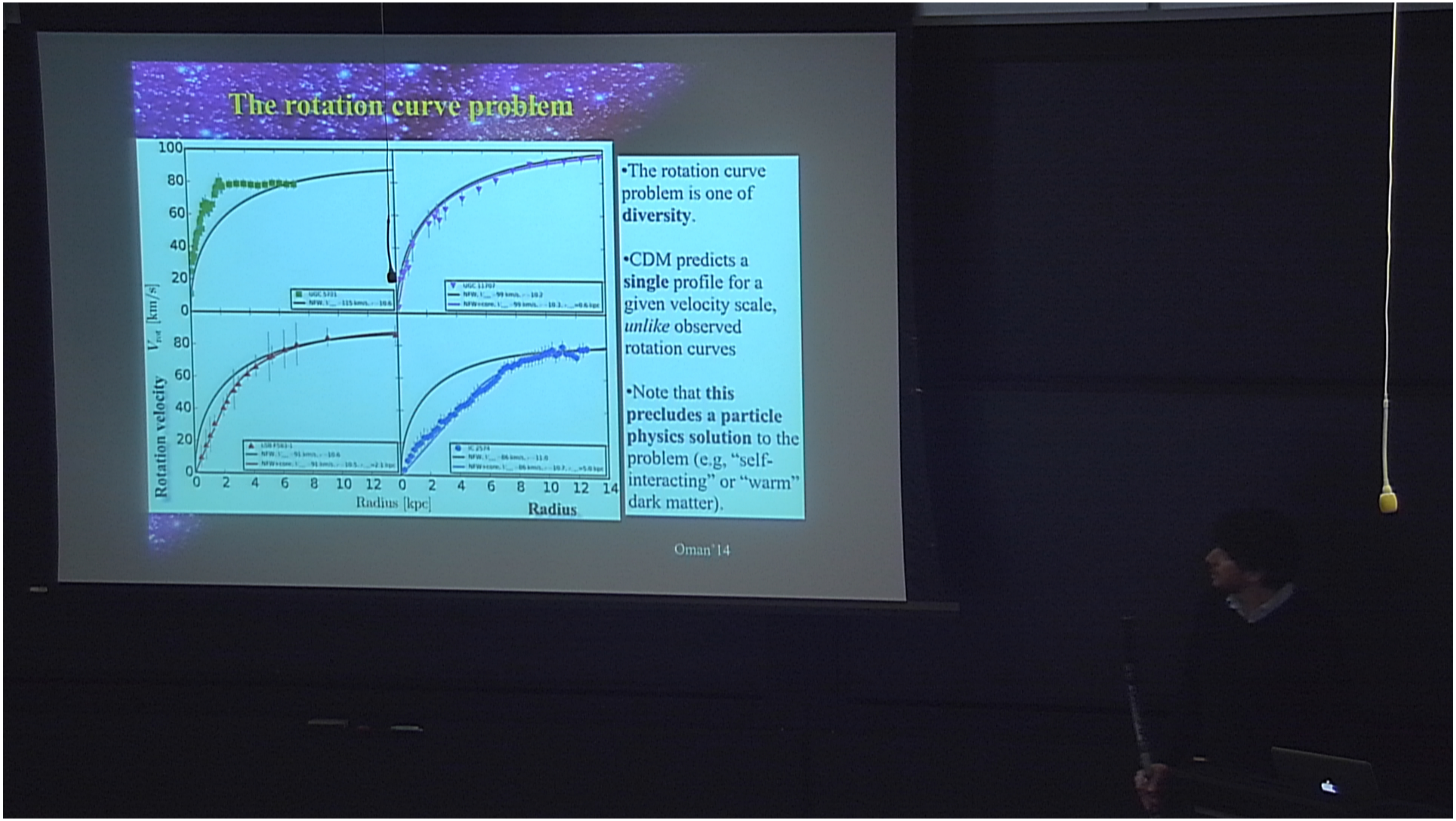


The "too big to fail" problem
•Low-mass subhalos experience a reduction in Vmax of order 15-20% because of the loss of the baryonic mass.
•This reduces by a factor of ~2 the number of sub halos with Vmax > 30 km/s, resolving the "too big to fail" problem
$D_{MW,M31}$<300 kpc
D_{LG}<2 Mpc
DMO
Galaxies
DMO
Galaxies
<N(>vmax)>
vmax [km/s]
1000
100
10
1
10
20
30
50
200
For
Scu
UMi
Leo I
DMO
Hydro
L1
L2
L3
et al '14

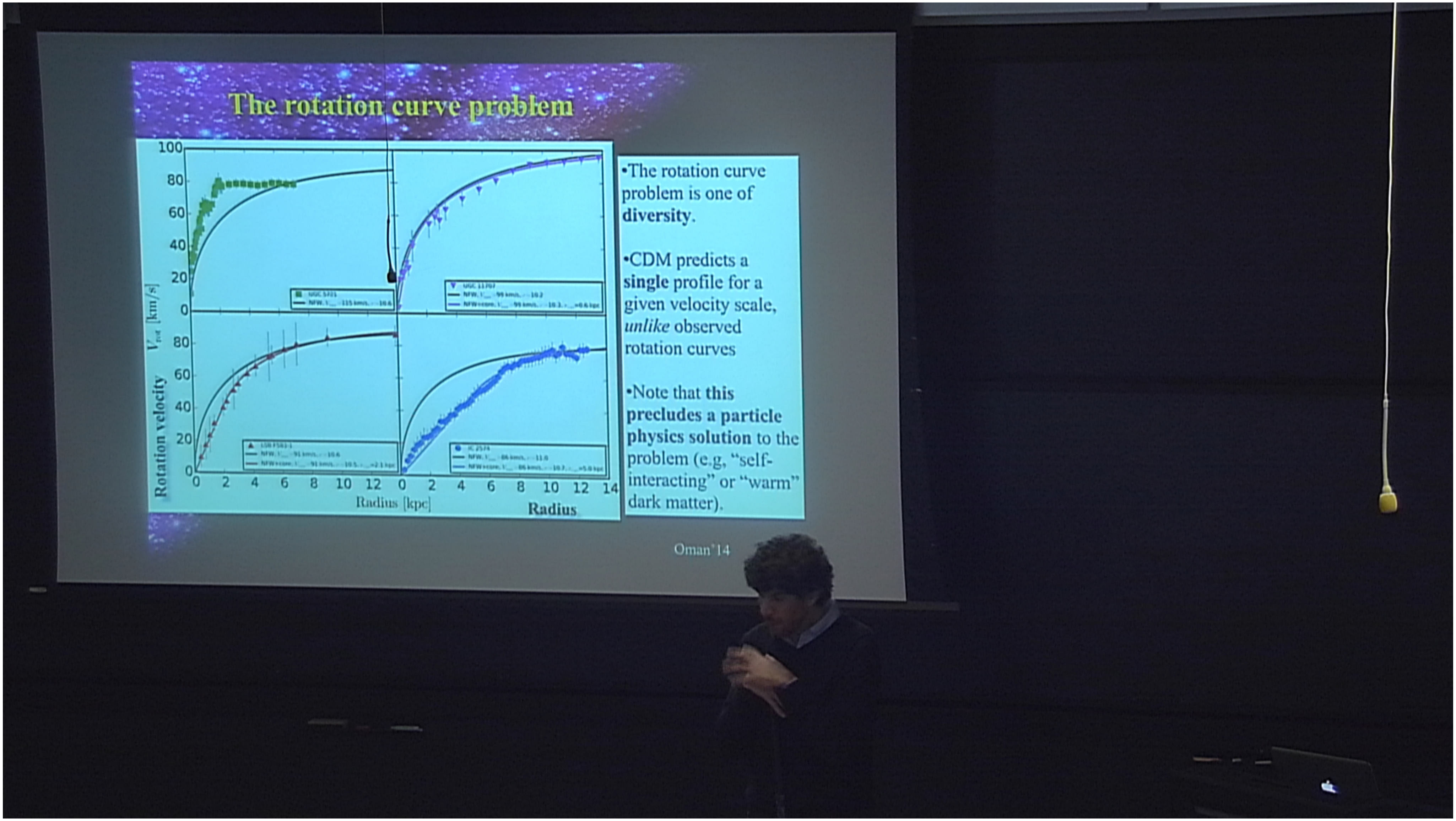

The "too big to fail" problem
•Low-mass subhalos experience a reduction in Vmax of order 15-20% because of the loss of the baryonic mass.
•This reduces by a factor of ~2 the number of sub halos with Vmax > 30 km/s, resolving the "too big to fail" problem
Sawala et al '14
DMW,M31<300 kpc
DLG<2 Mpc
DMO
Galaxies
DMO
Galaxies
<N(>vmax)>
vmax[km/s]
1000
100
10
1
10
20
30
50
100
200
For
Scl
UMi
Leo I
Sgr
Dra
SMC
LMC
DMO
Hydro
L1
L2
L3


The rotation curve problem
A constant density "core" at odds with the predicted cuspy profiles has been predicated for a number of dwarf galaxies on the basis of rotation curves of disk galaxies.
Cusp + baryons
Core + baryons
baryons
V (km s⁻¹)
r (kpc)
Weinberg et al 2013


The rotation curve problem
NFW w/ Neto+2007
NFW w/ 1kpc core
NFW w/ 2kpc core
NFW w/ 5kpc core
1:1
•Dwarf galaxies have a wide diversity of rotation curves
•Some galaxies are consistent with CDM, others are not
•"Cores" seem present in galaxies up to ~200 km/s
•Core radii are larger than simulations can produce



The rotation curve problem
•The rotation curve problem is one of **diversity**.
•CDM predicts a **single** profile for a given velocity scale, *unlike* observed rotation curves
•Note that **this precludes a particle physics solution** to the problem (e.g, "self-interacting" or "warm" dark matter).
Oman'14
Rotation velocity
Radius [kpc]
Radius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Rotation velocity
Radius [kpc]
Radius
Oman'14