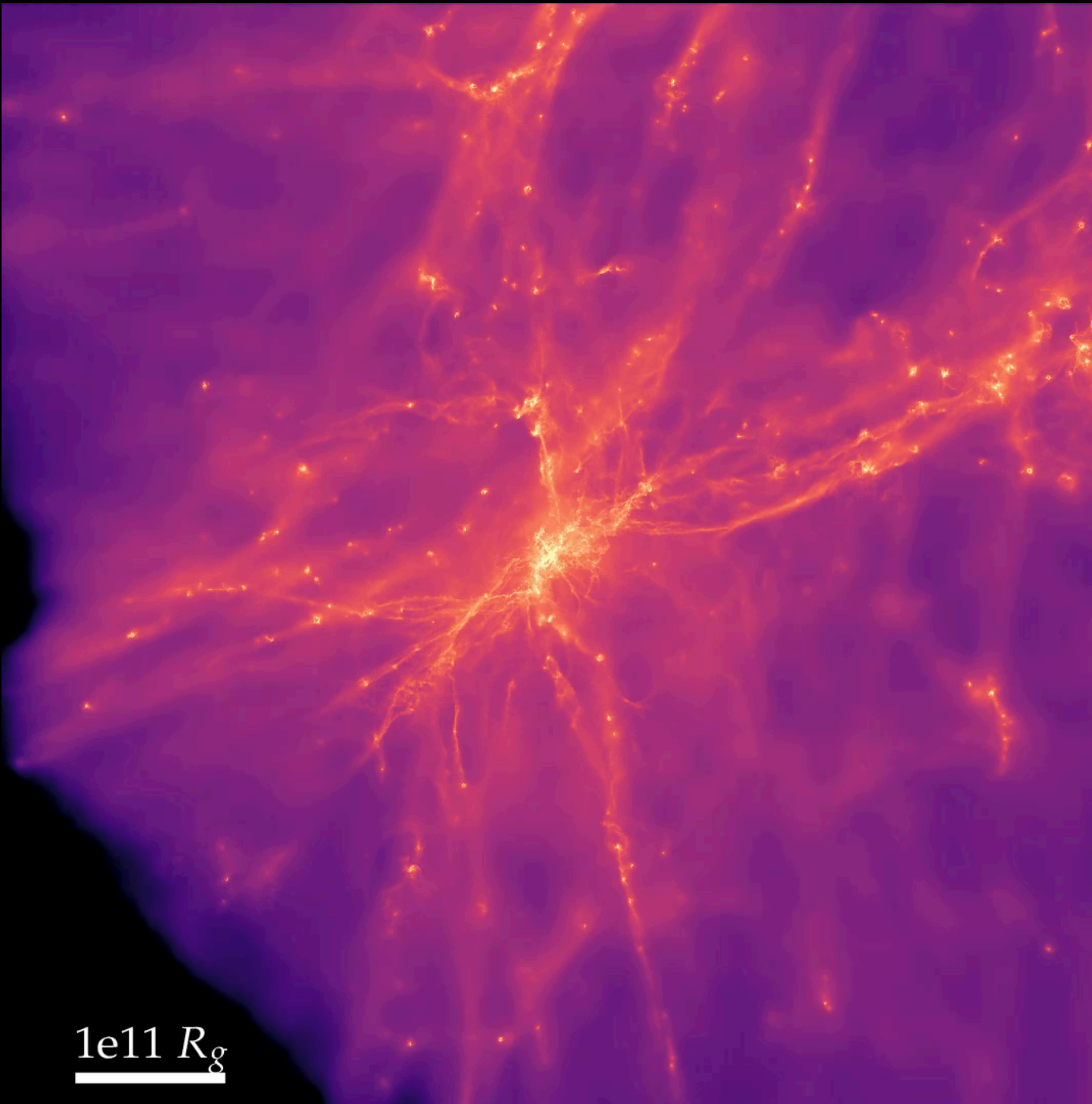


Roman & Some Unsolved Problems In Galaxy Formation

Philip F. Hopkins (Caltech), with Isabel Sands, Sam Ponnada, Raphael Skolidis, Nadine Soliman, Jaeden Bardati



1. Cosmic Rays

SNe/strong shocks

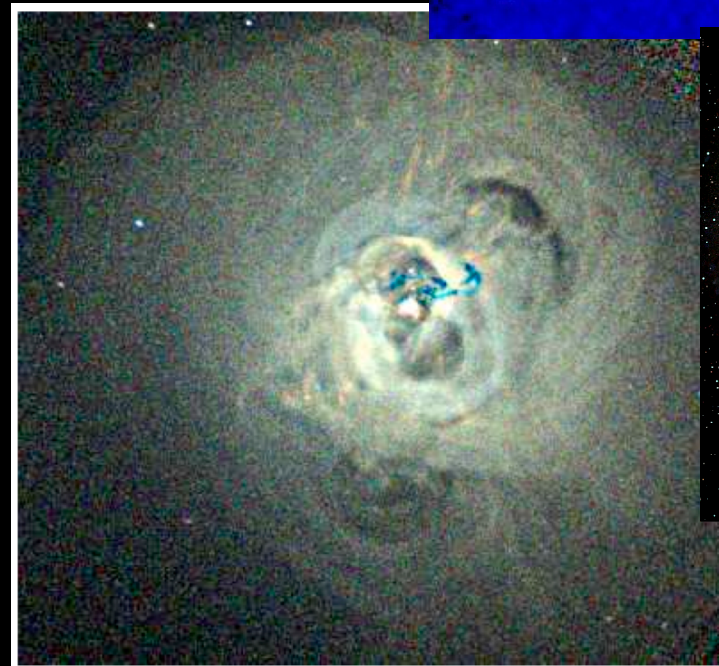
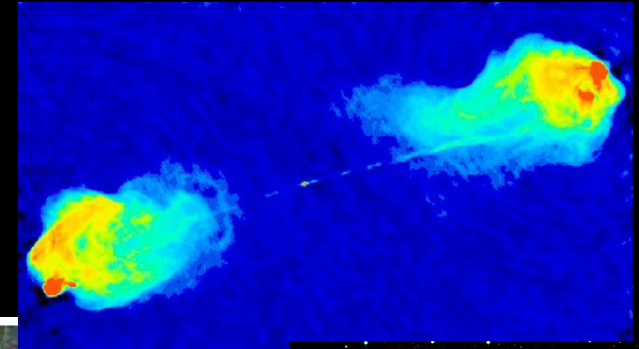
0.0098yr



10pc

Power: $\sim 10\%$ ejecta energy
(leptons $\sim 0.1 \times$ hadrons at GeV)

AGN "radio" mode

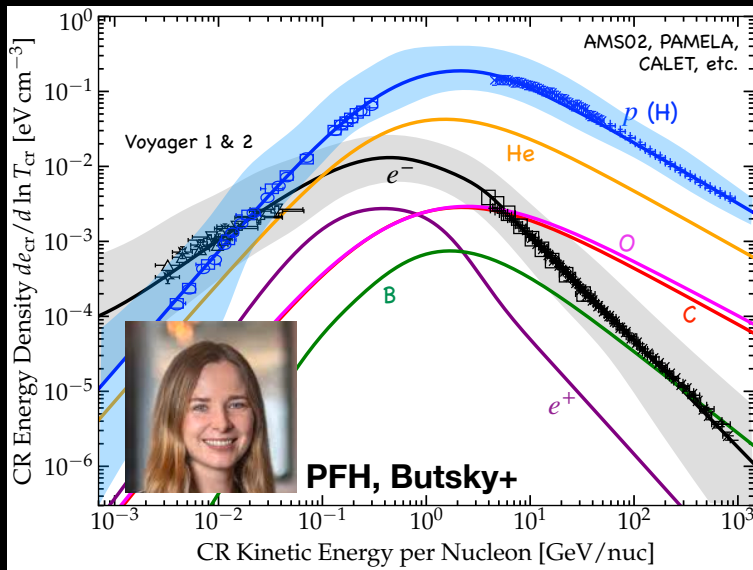


Power: $\sim \%$ of $\dot{M}_{\text{BH}} c^2$?
(jet leptons $\sim 0.05 - 50 \times$ hadrons at GeV?)

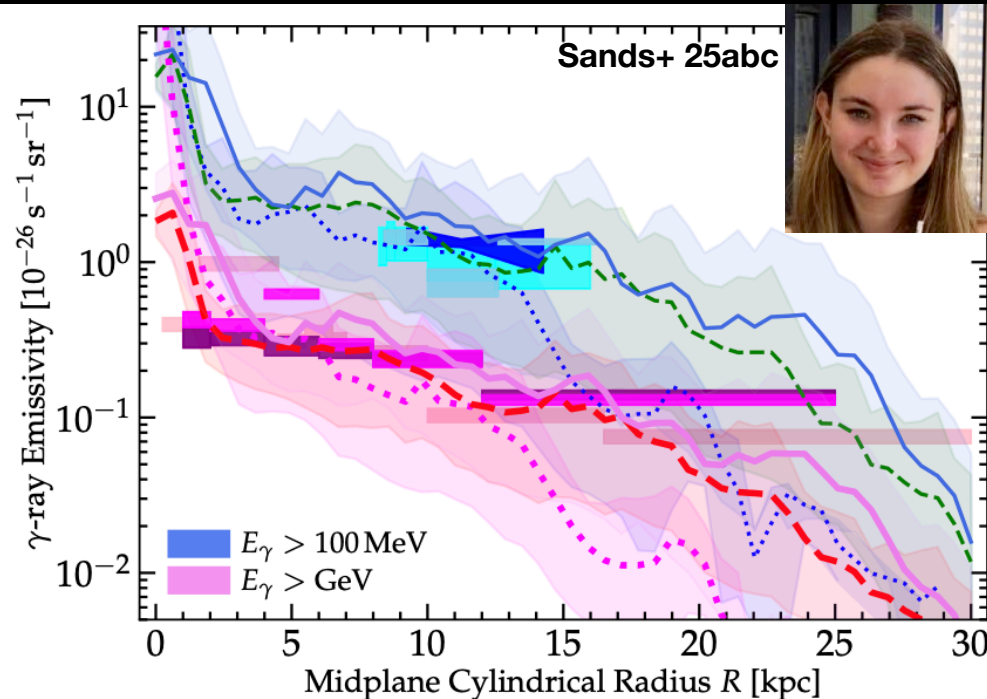
$\sim$ equipartition energy in ISM

Example: Cosmic Ray “Weather” / Inhomogeneous Transport

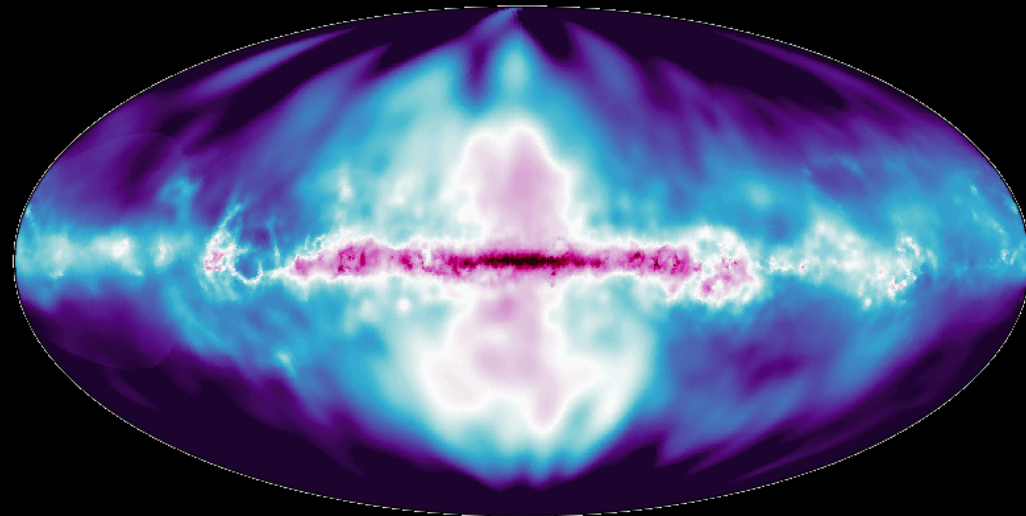
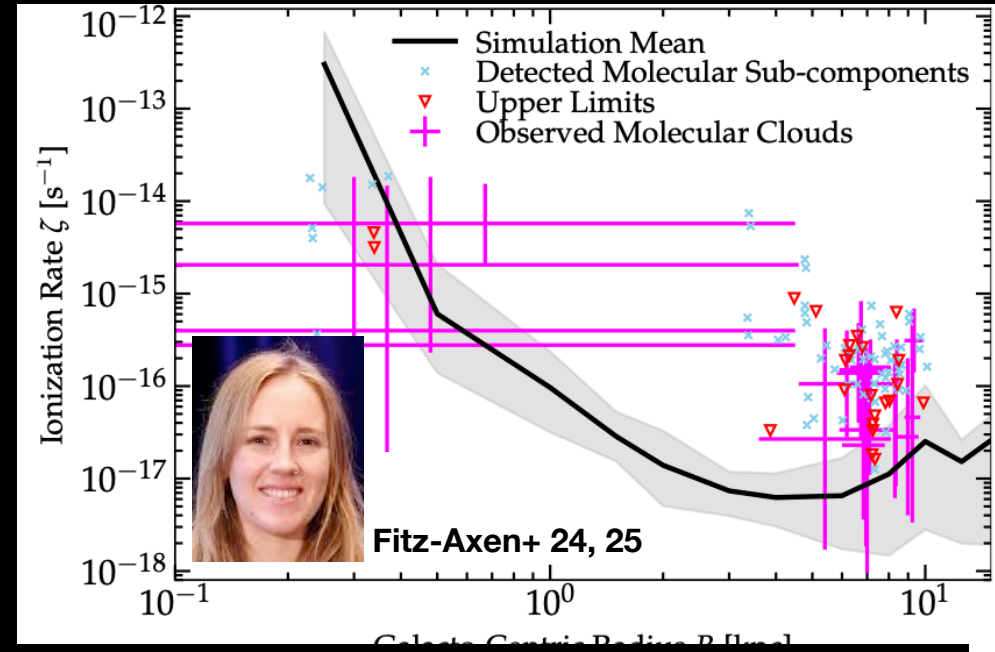
CR Spectra & Species/Isotopic Ratios...



MW γ -ray spectra & maps, Fermi bubbles, GC excess

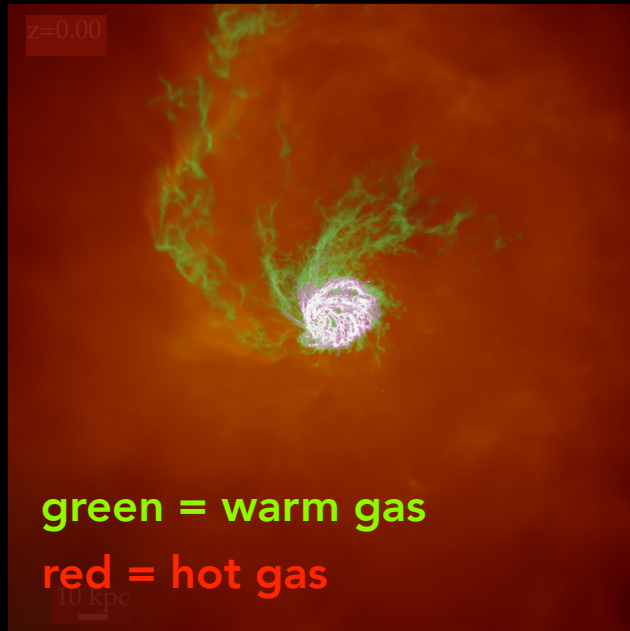


MW CR ionization: vs. GMC properties

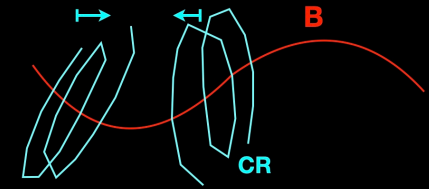
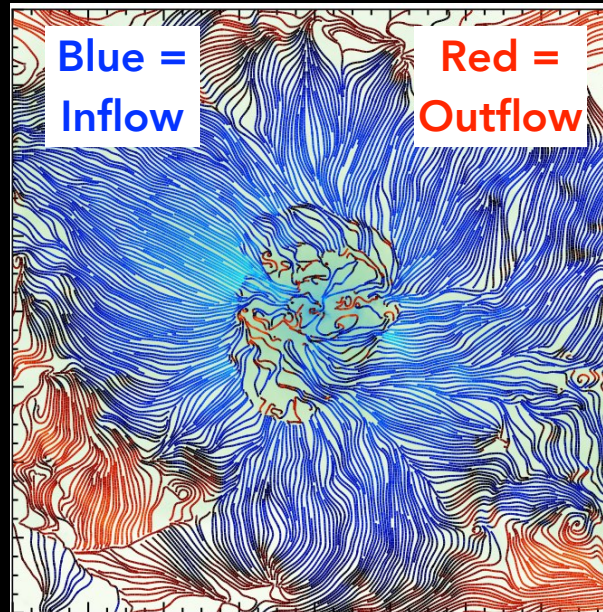


Consequences in circum/inter-galactic medium?

Temperature Map



Velocity Streamlines



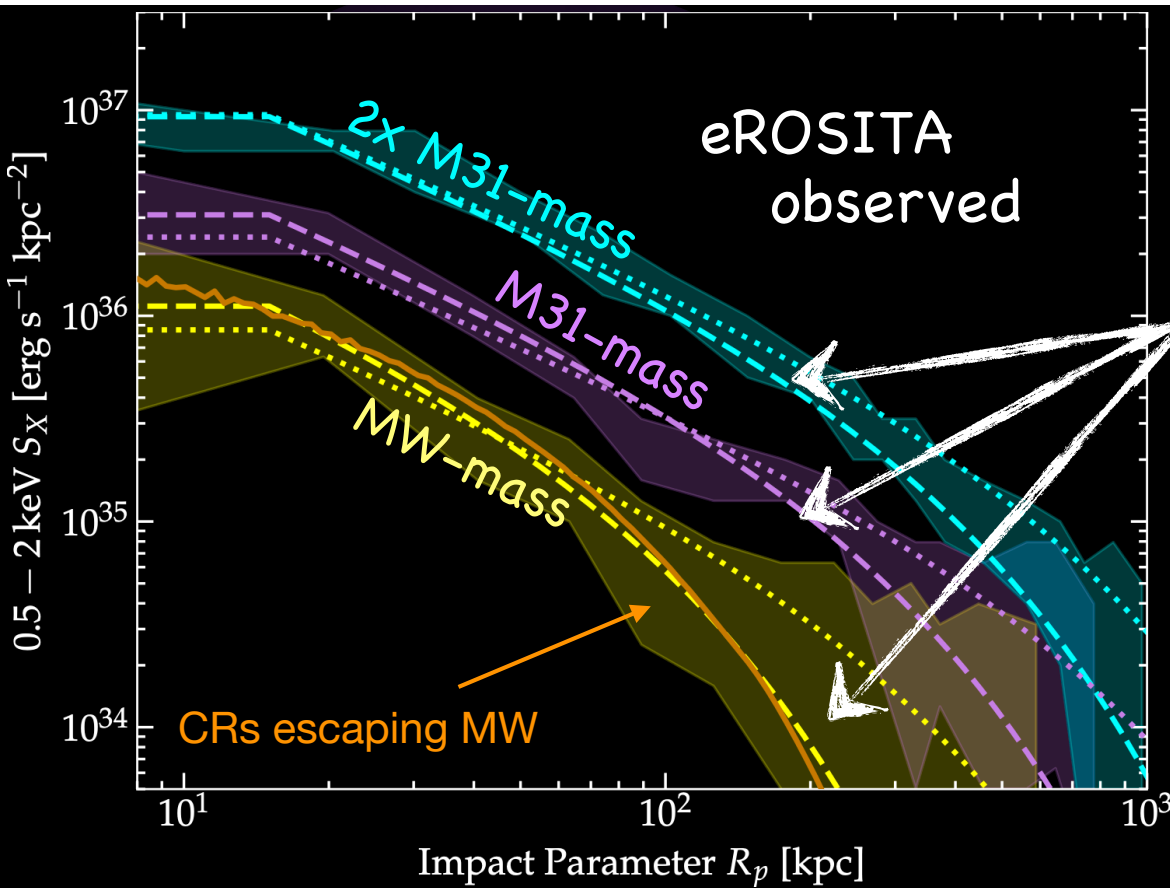
CRs do nothing
(escape CGM)

Iryna Butsky

L* galaxies: Chan+ 19
Quenching: Su+ 19, 20, 21
ISM: PFH+ 20, 21, Chan+ 22
CGM: Ji+ 21,22, Butsky+ 18,22
Eqs/Methods: PFH+ 22,23, Ji+ 22



CR halos?



Cannot be thermal (tSZ,
absorption, spectra,
baryon/metal budget):

Silich+25, Ponnada+25, Zhang+26,
Lau+25, Vladutescu-Zopp+25

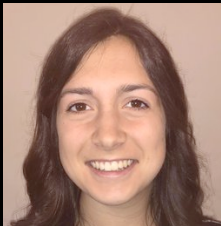
(& Yao+10, vandeVoort+16, Romero+17, Chadayammuy+22,
Wijers+22, Das+22, Truong+23, Ponti+23, ZuHone+24,
Zhang+24, Bhattacharyya+24...)

(TNG, Illustris, SIMBA, Eagle, Flamingos, Smuggle,
Magneticum, FIRE, Nihao, Marvels, TEMPEST, Foggie)

- Group scale: “S8 tension”
CRs pushing baryons at $\sim \text{Mpc}$
- Cluster scale: Are cool cores tricking us?
new radio + RMs + tSZ + ionization
= strong CR pressure & (maybe) IC X-ray?

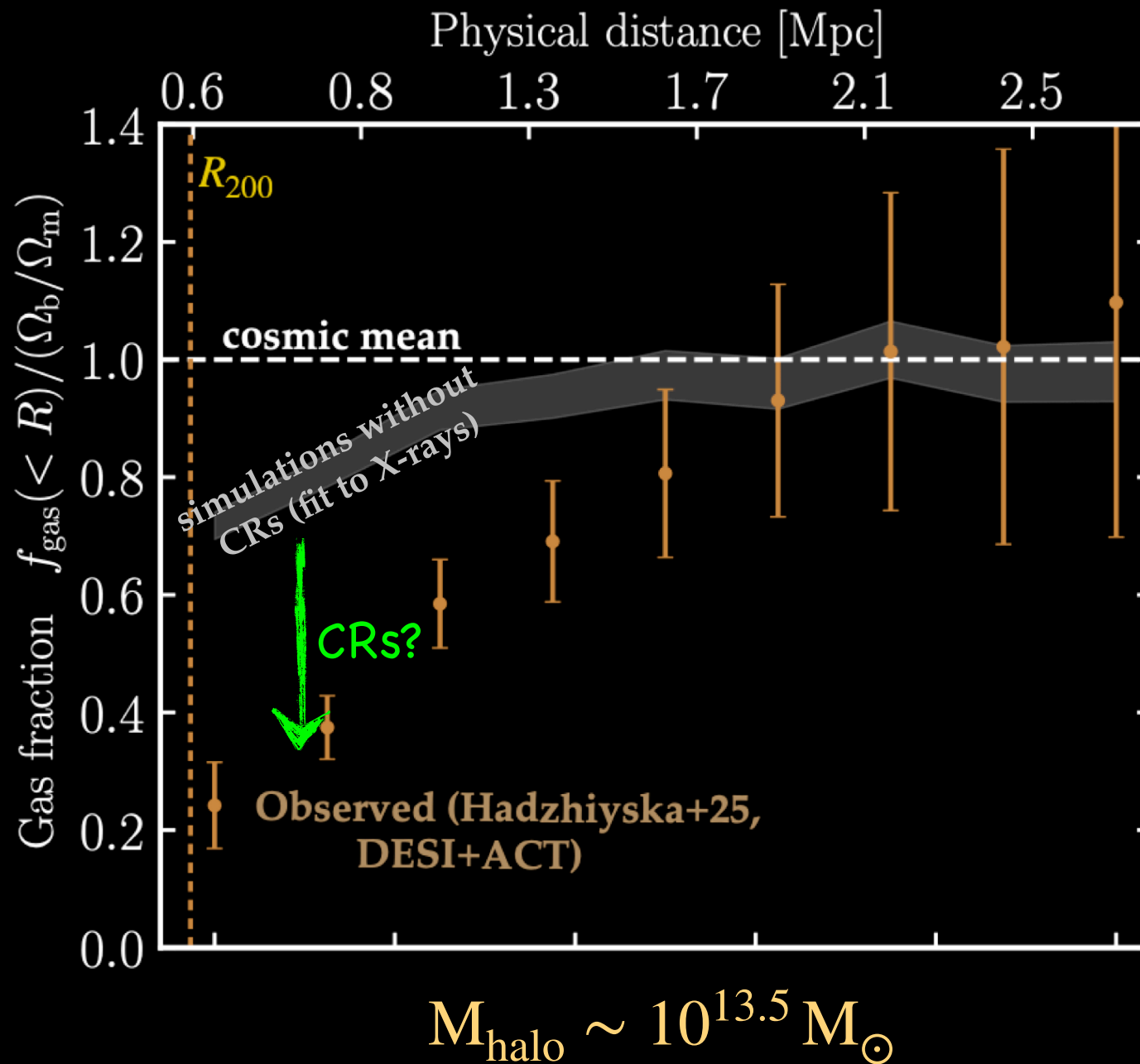


Sam Ponnada

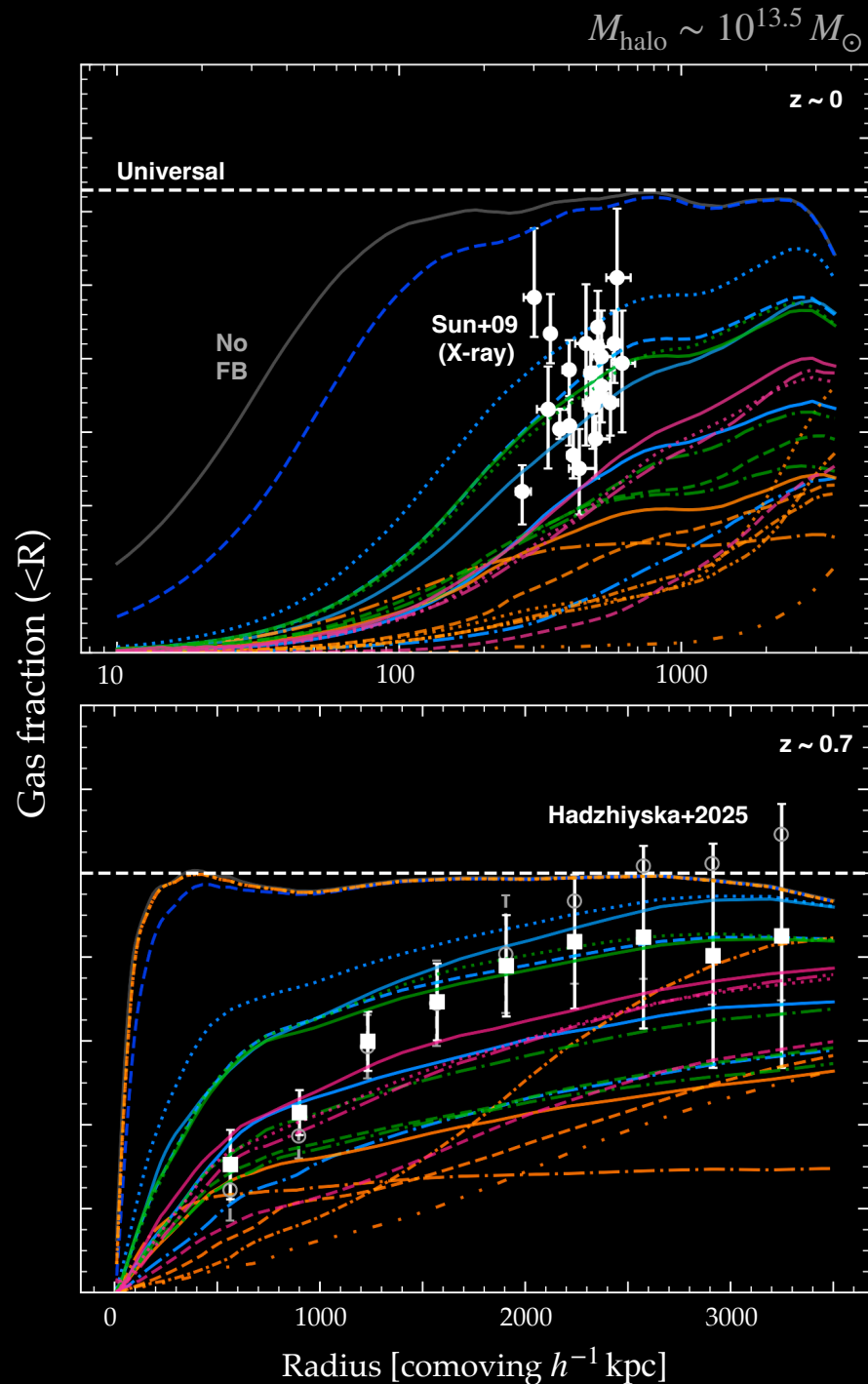


Emily Silich

Group scale: the “S8 tension”



Group scale



Vary $\dot{E}_{\text{cr}}(t, \mathbf{x})$, $\kappa_{\text{eff}}(t, \mathbf{x})$

“Weak”:

- κ/v_{st} VERY large ($v_{\text{st}} \gg 1000 \text{ km s}^{-1}$)
- E_{cr} very low ($\ll 10^{-3} M_{\text{BH}} c^2$)
- Δt_{inject} too large ($\gg \text{Gyr}$)
- t_{inject} too late ($z \lesssim 1$)

“Explosive/Thermal-like”:

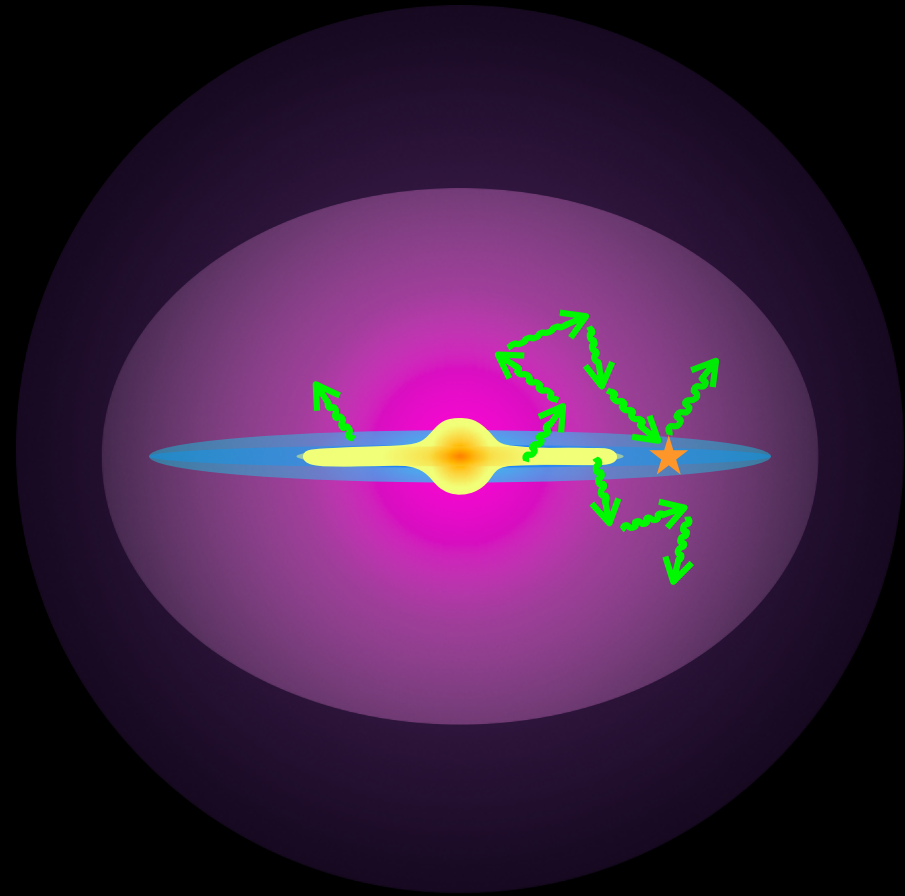
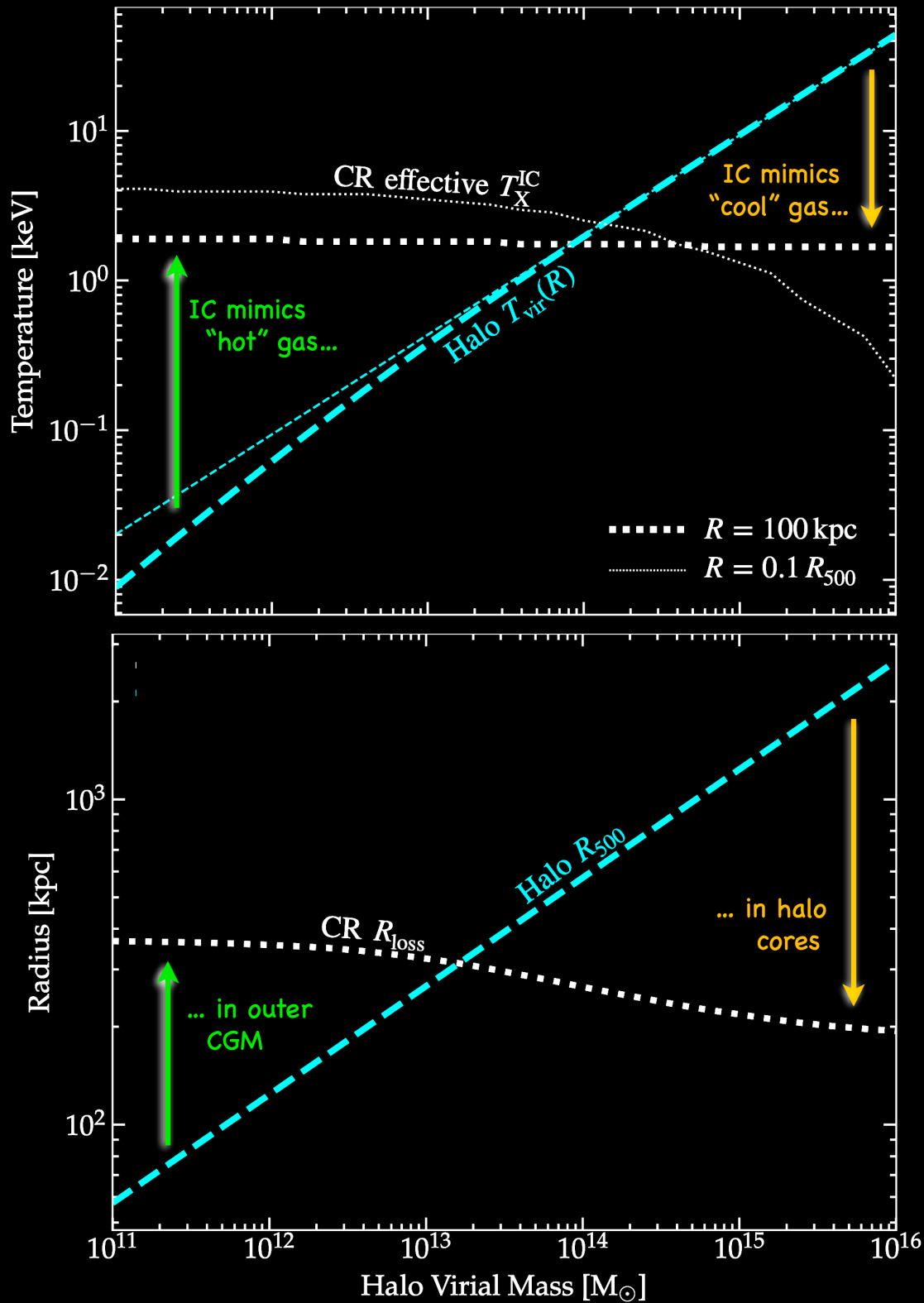
- κ small + E_{cr} large + Δt_{inject} small

“Interesting”:

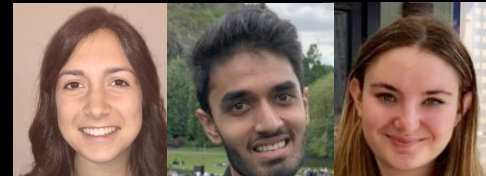
- everything else?



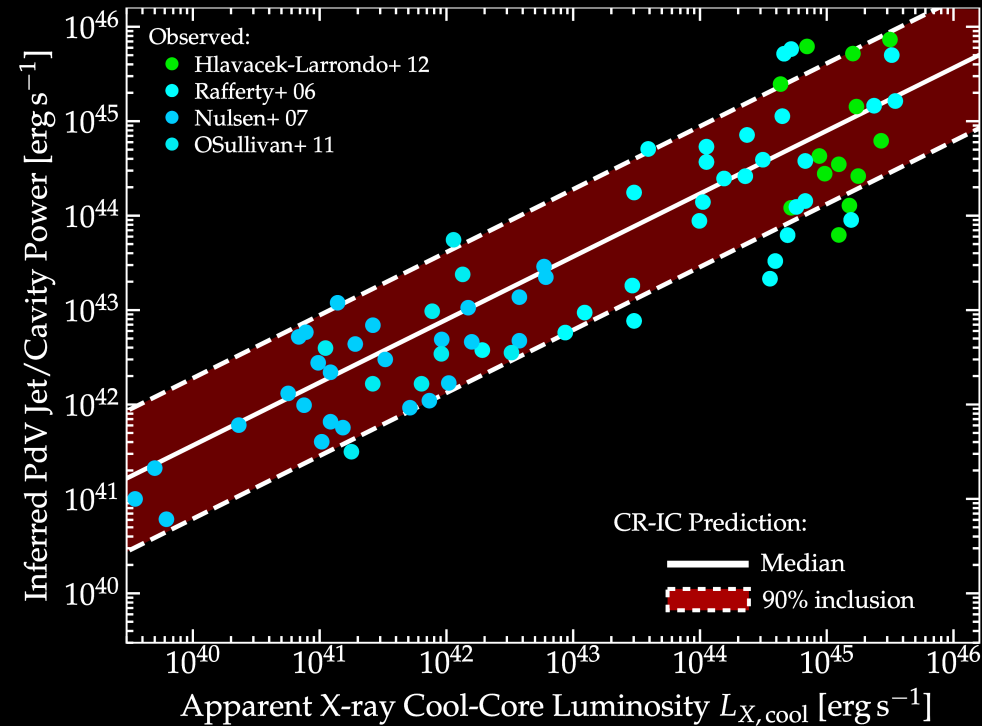
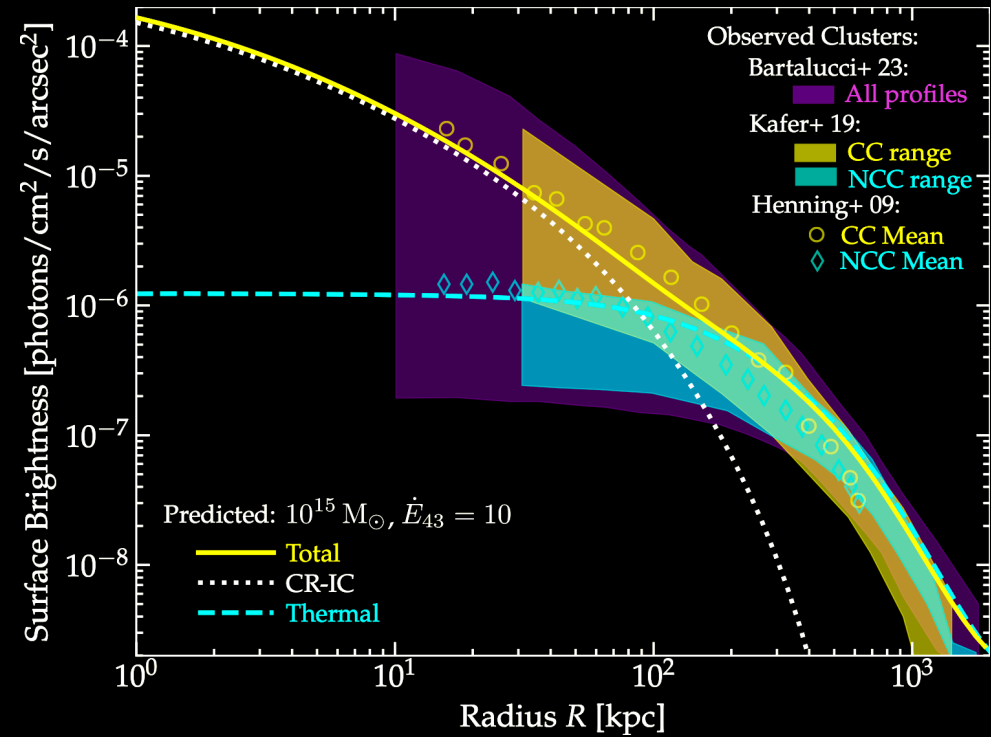
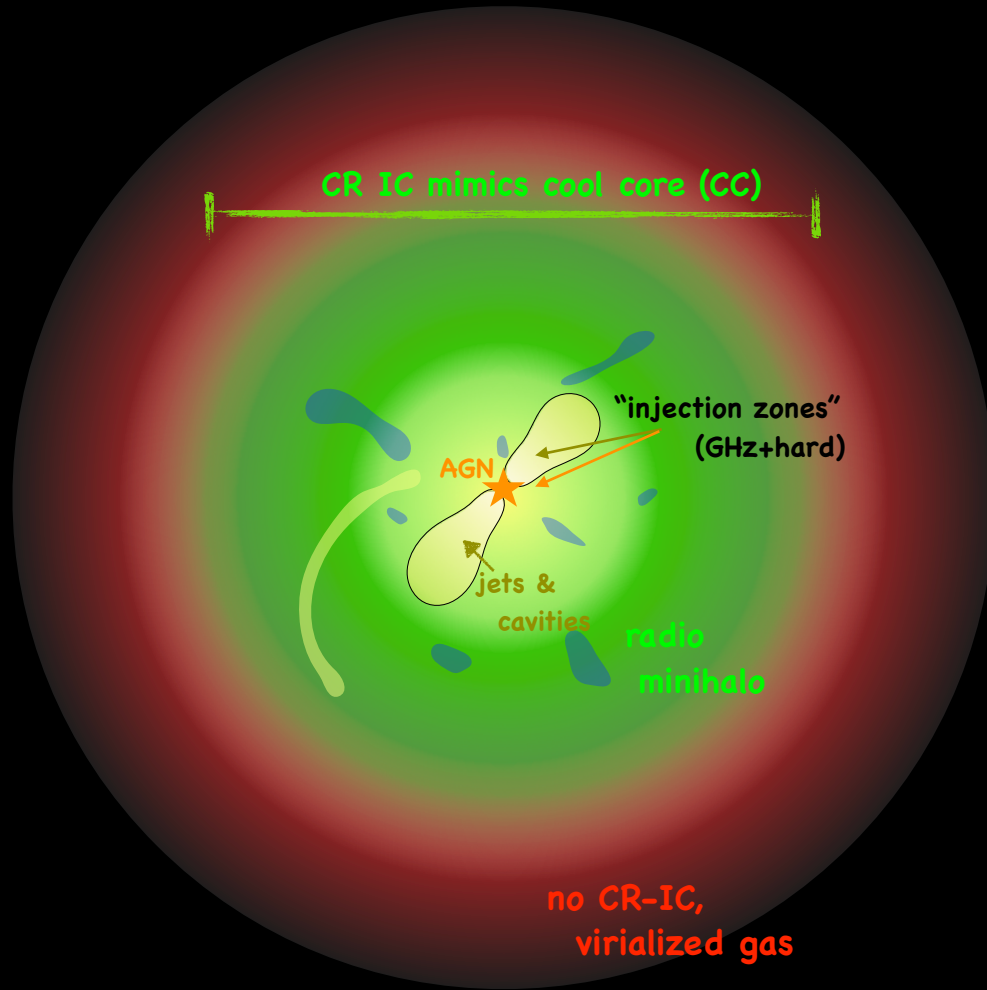
Massive Groups & Clusters



PFH, Sands, Ponnada, Silich,
Quataert, Sayers 25, 26



Clusters: What Would This Look Like?

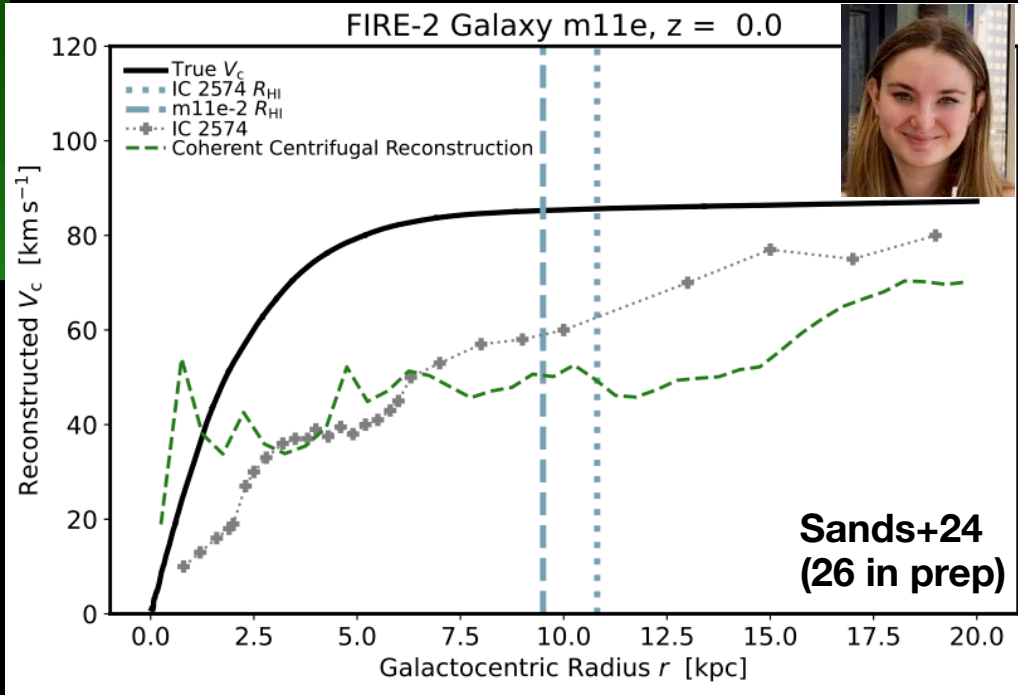
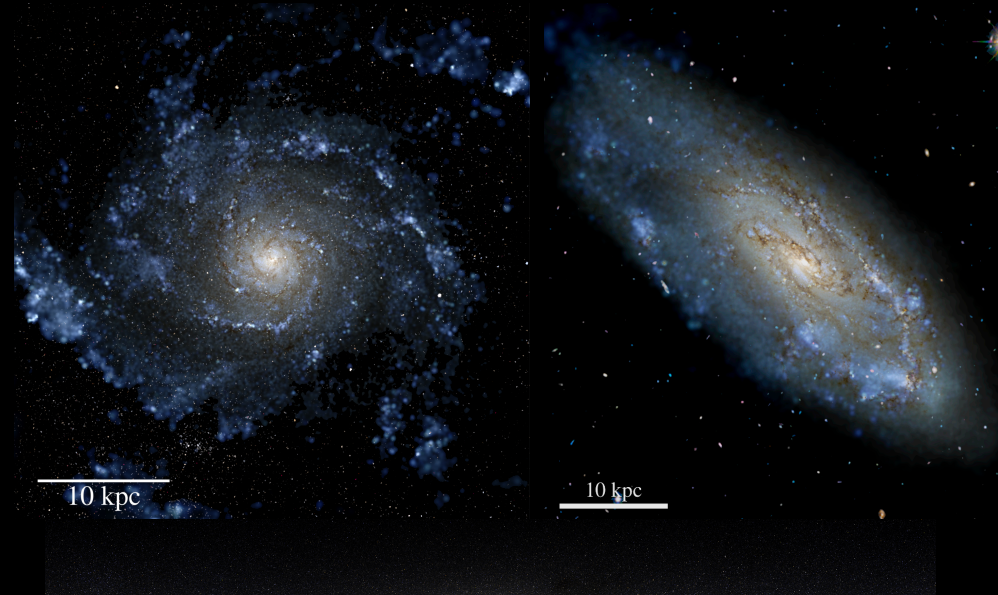


$z=5.1$

Magenta: cold
Green: warm (ionized)
Red: hot

Milky Way Progenitor Gas

2. "Bursty" Star Formation & Disk "Settling"



DM Cores/ TBTF:

Brook+ 12
Pontzen+ 12
Onorbe+ 15
Wheeler+ 15
Chan+ 15
Di Cinto+ 16
Wetzel+16, 18
Garrison-Kimmel+18
Lazar+ 20, 24

Stronger Winds/ Missing Sats:

Walch+15
Muratov+ 15
Kimm+ 15
Martizzi+ 16
Grudic+ 16
PFH+ 18

Bright High- z :

Samuel +22, 23, 26
Sun+ 23
Shen+ 23

SF Scalings:

Sparre+ 15
Hayward+ 16
Flores-Velazquez+21

Thick Disks:

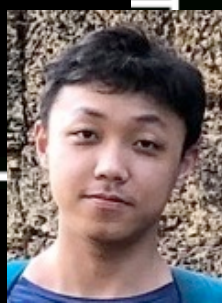
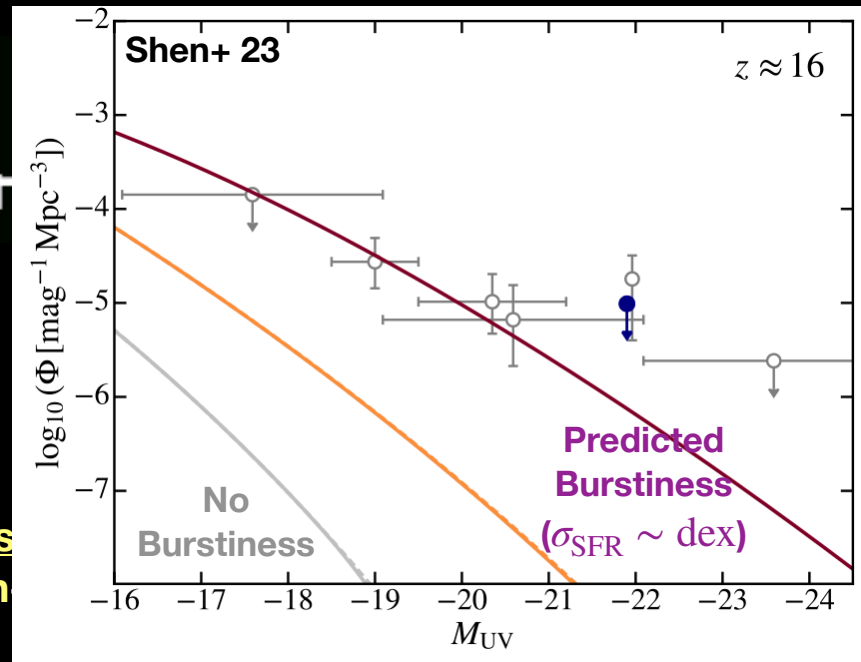
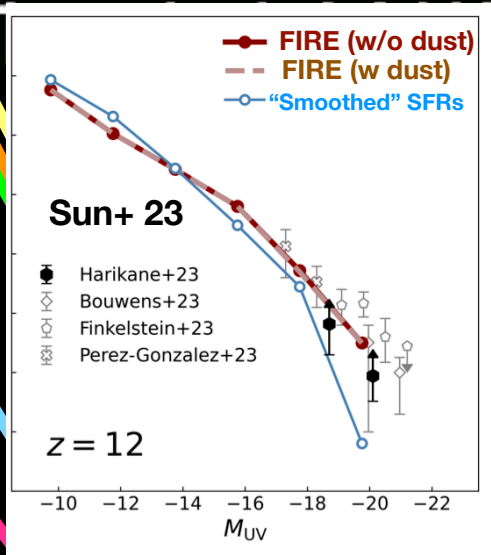
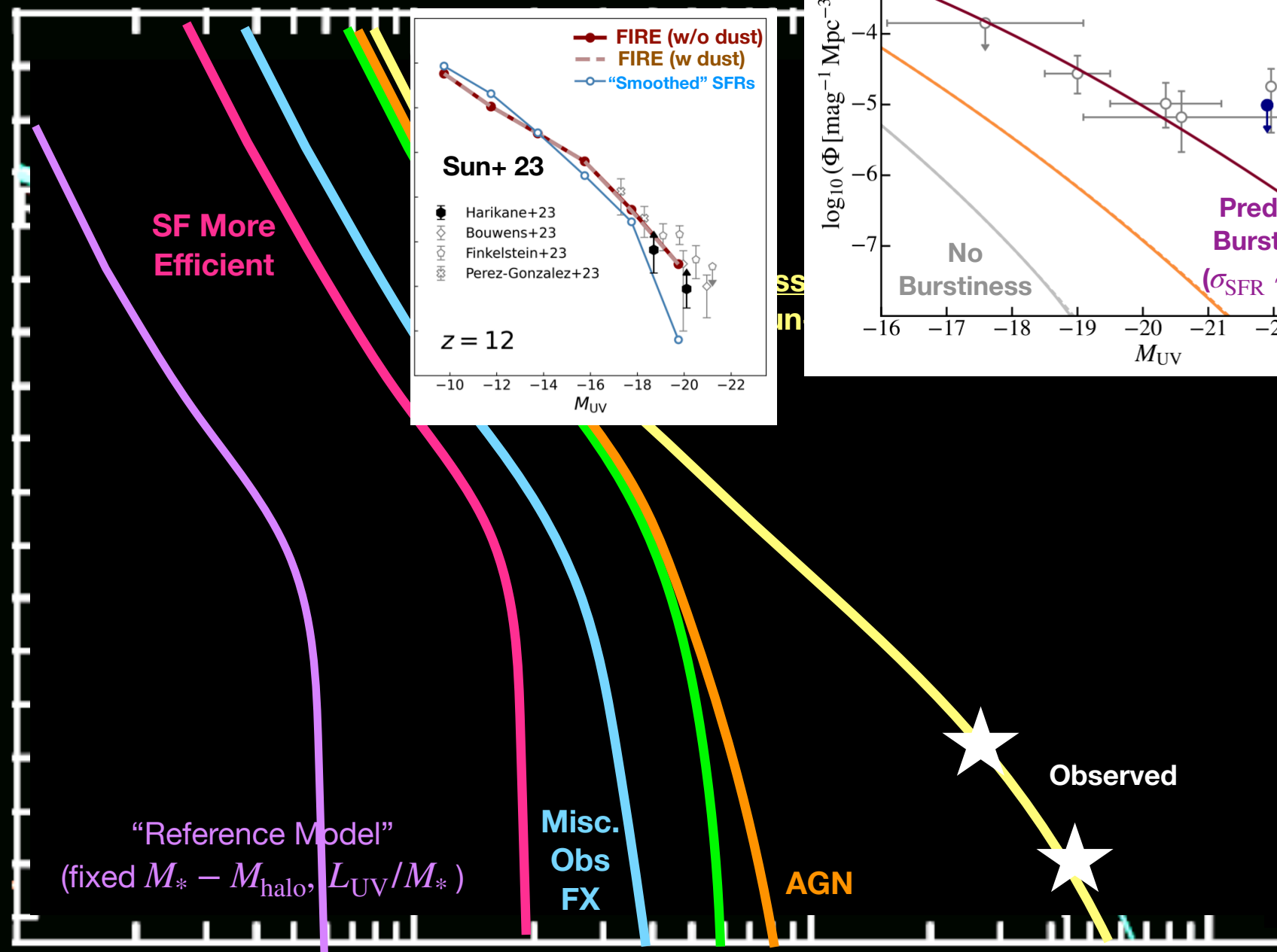
Ma+ 15,16,17,18
Wetzel+ 16
Hafen+ 20,21
Gurvich+ 21,23
Yu+ 21, 22

Dwarf kinematics, Z-Profiles, UDGs:

Wheeler+ 14
Ma+ 15, 16, 18
El-Badry+15, 17
Chan+ 17
Santos-Santos+ 18
Mercado+ 21
Sands+ 24

JWST galaxies not universe-breakers!

Number



Xuejian
(Jacob) Shen

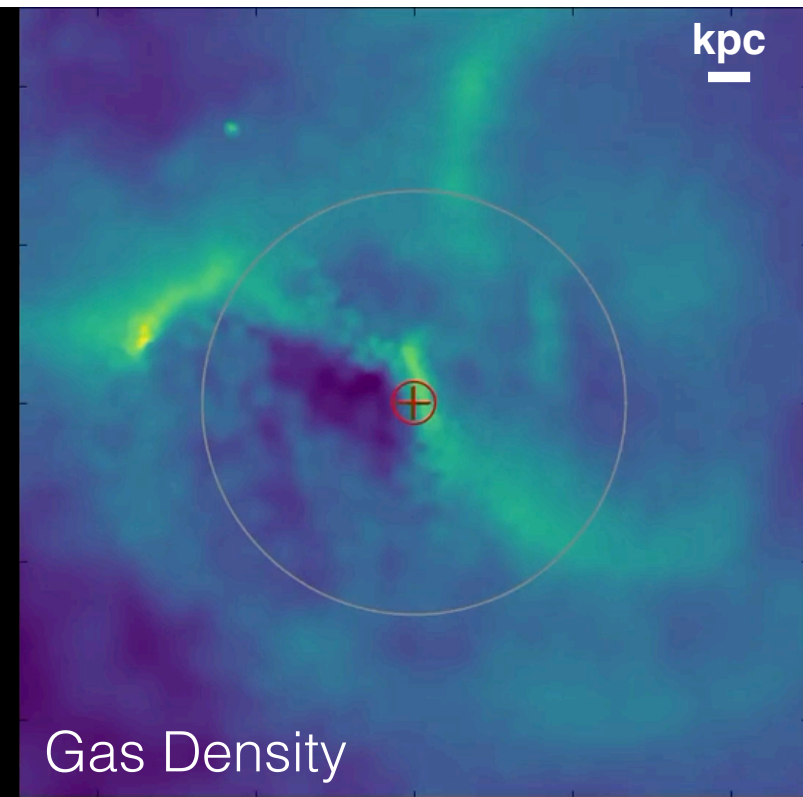
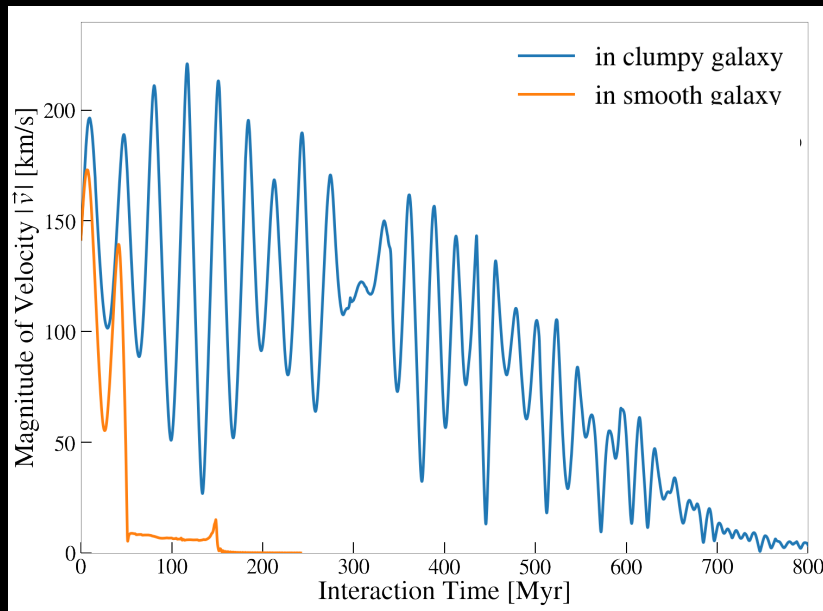
Can also cause challenges



Linhao Ma

Sinking (It's a Big Deal): 2101.02727

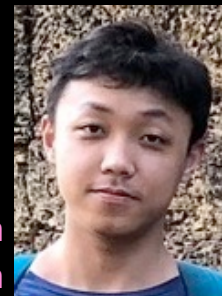
New Dynamical Friction Formula: 2208.12275



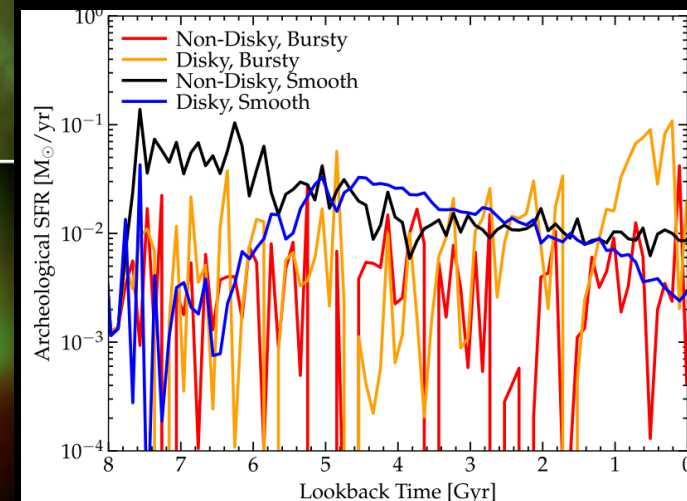
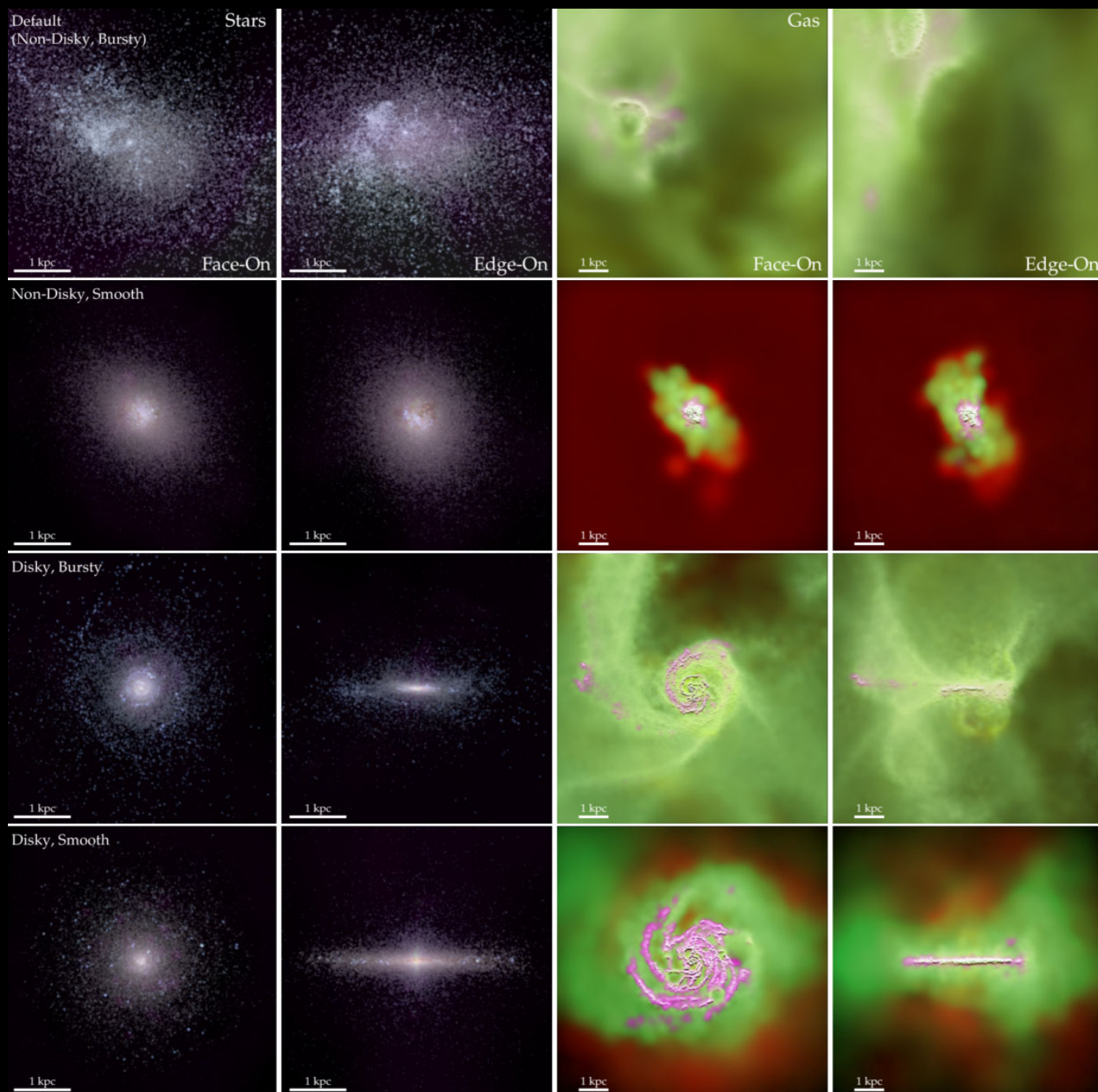
- Observed: wandering BHs (in dwarfs)
- Anchor some seeds: massive star clusters?
- Form SMBHs "late/massive": after "settling"?

What Does Control Burstiness?

PFH+Shen et al. 24
(see also Semenov+ 25, 26)



Xuejian
(Jacob) Shen



What Does Control Bursty-ness?

100's of controlled experiments:

ARBITRARY:

- Cooling curves, temperatures
- Masses, gas fractions, accretion rates
- Stellar evol times, FB “strength”
- SF laws, CGM gas properties, spin
- Potential shapes/depths

SHALLOW POTENTIAL

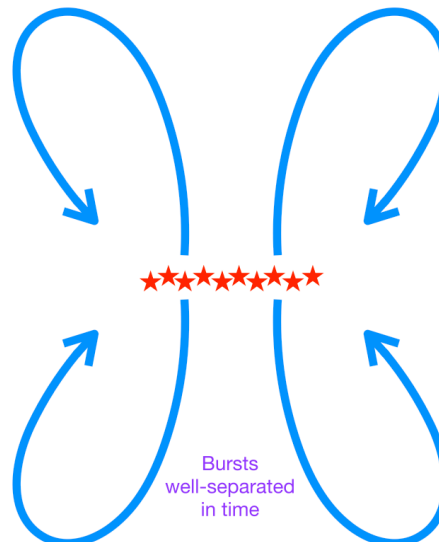
“Overshoot” easy



Outflows travel far



Recycling times long



DEEP POTENTIAL

“Overshoot” difficult



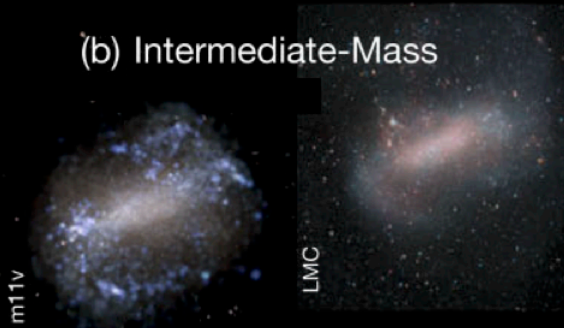
Outflow travel limited



Recycling times short



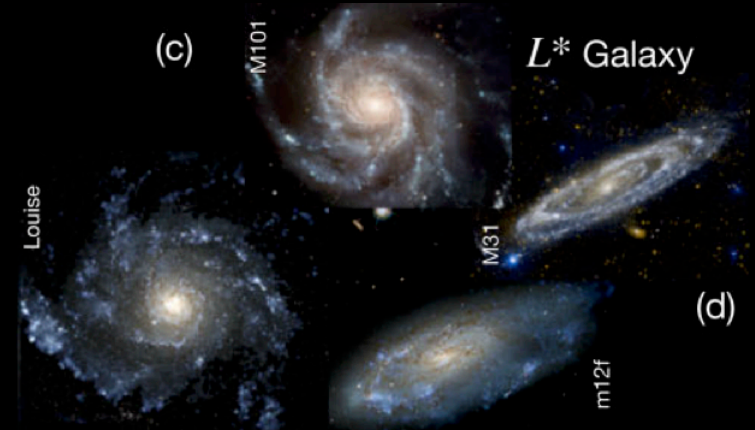
(b) Intermediate-Mass



- shallow, more concentration potential
- bursty SF, thick gas & stellar disks form

$V_{\text{esc}} \uparrow$
 Outer disk height $\downarrow$
 Gas fraction $\downarrow$
 "Overshoot" chance $\sim \sigma/V_{\text{esc}} \downarrow$

(c) L^* Galaxy

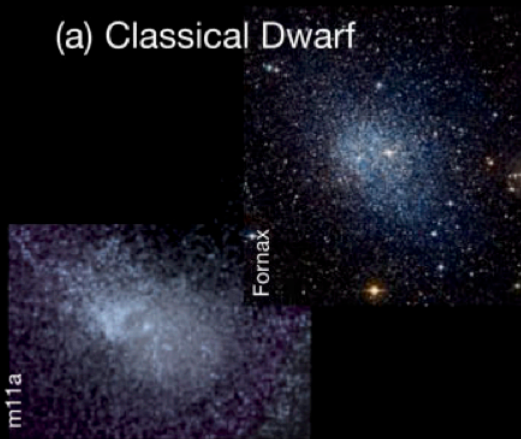


(d)

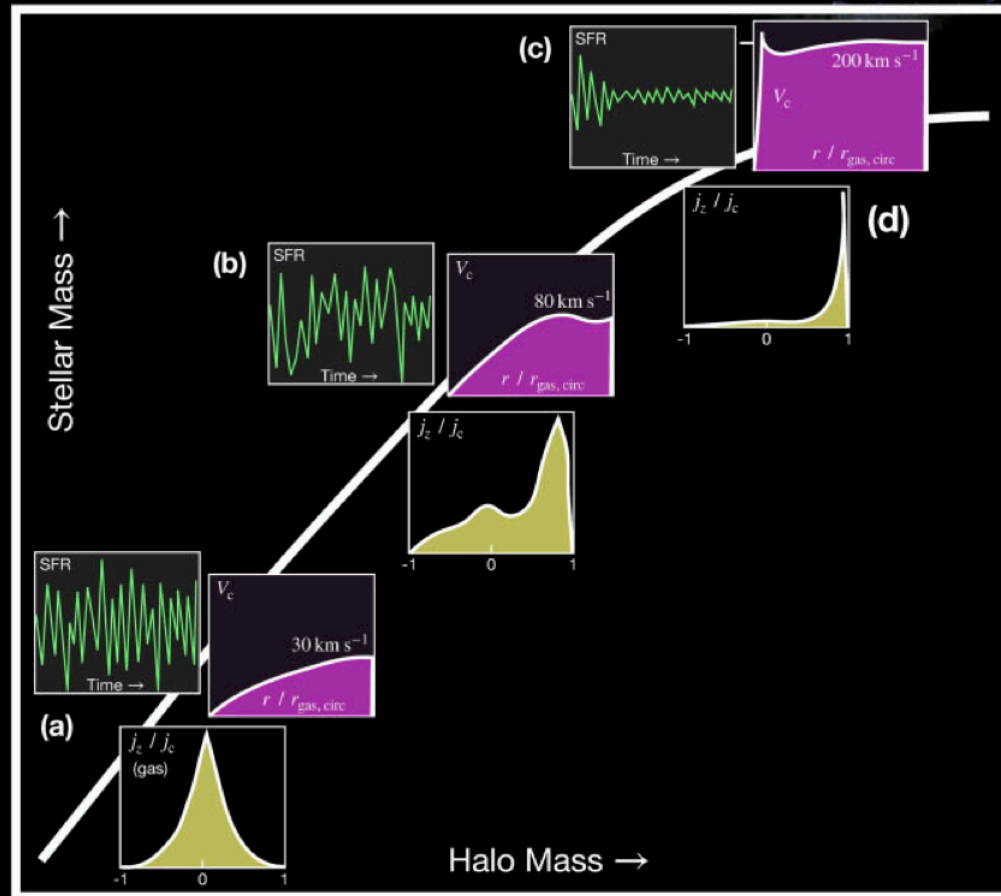
- deeper potential, outflows confined
- smooth SF, thinner gas & stellar disks

Potential, $V_{\text{esc}} \uparrow$
 FB Efficiency $\downarrow$
 Baryonic concentration $\uparrow$

(a) Classical Dwarf



- shallow, un-concentrated potential
- bursty SF, no gas or stellar disk



$V_{\text{esc}} \uparrow$
 Disk height $\downarrow$
 Stellar thin disk builds up
 Quenching?
 Mergers?

(e) Massive Galaxy



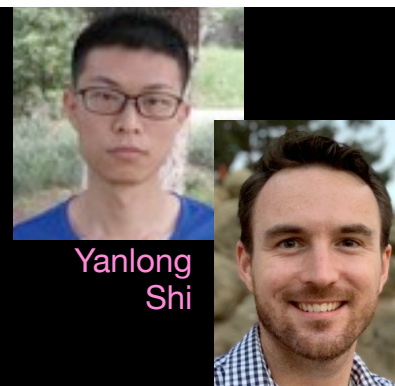
- gas rich disks become thinner
- gas poor stellar disks destroyed by mergers

3. "Seeds" & Early Growth of SMBHs:

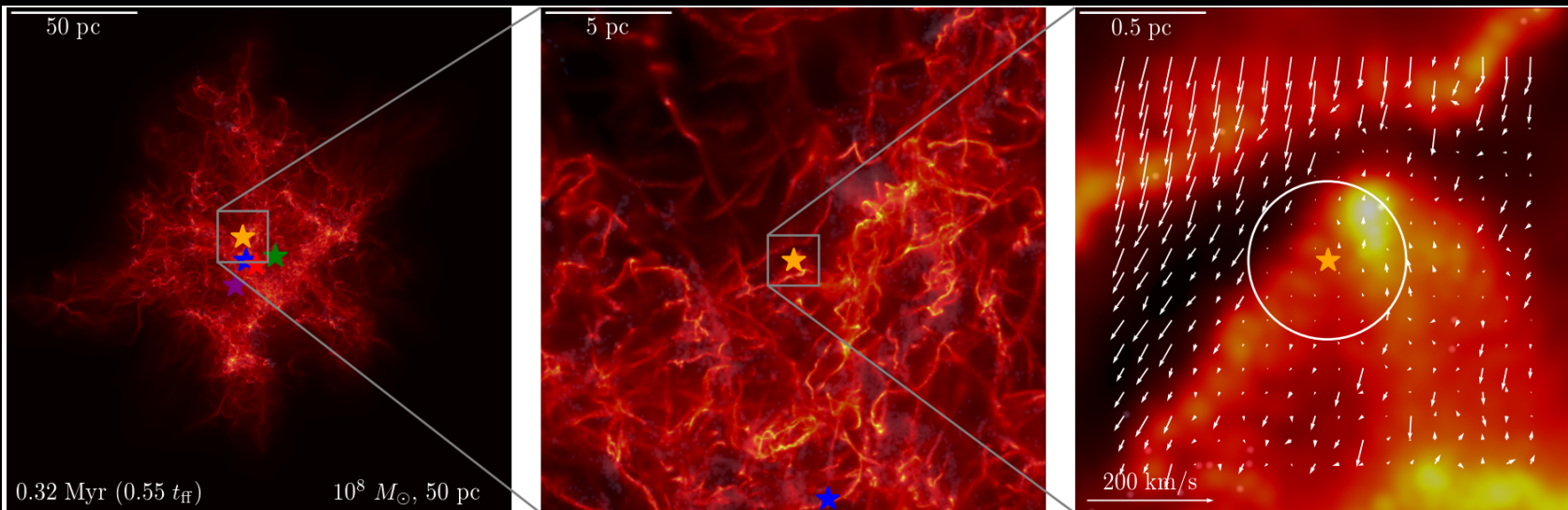
- **Hyper-Eddington Accretion:** Y. Shi+ '23 & '24
Dense massive galaxy nuclei, $\sim 1000\times$ Eddington
onto $1 - 100 M_{\odot}$ BHs

.... or: even *more extreme* seeds!

- **Runaway Stellar Mergers:** Shi, Grudic, PFH+ '21
Dense, massive GCs? $\ll 1000 M_{\odot}$
- **Dissipative Dark Matter Collapse:** Xiao, J. Shen+ 21
Up to $\sim 10^8 - 10^{10}$ in extreme early DM halos



Xuejian
(Jacob) Shen



Super-Eddington: IMBHs & LRDs?

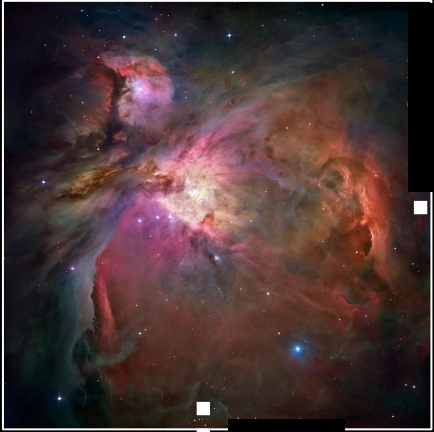
Shi+24,26

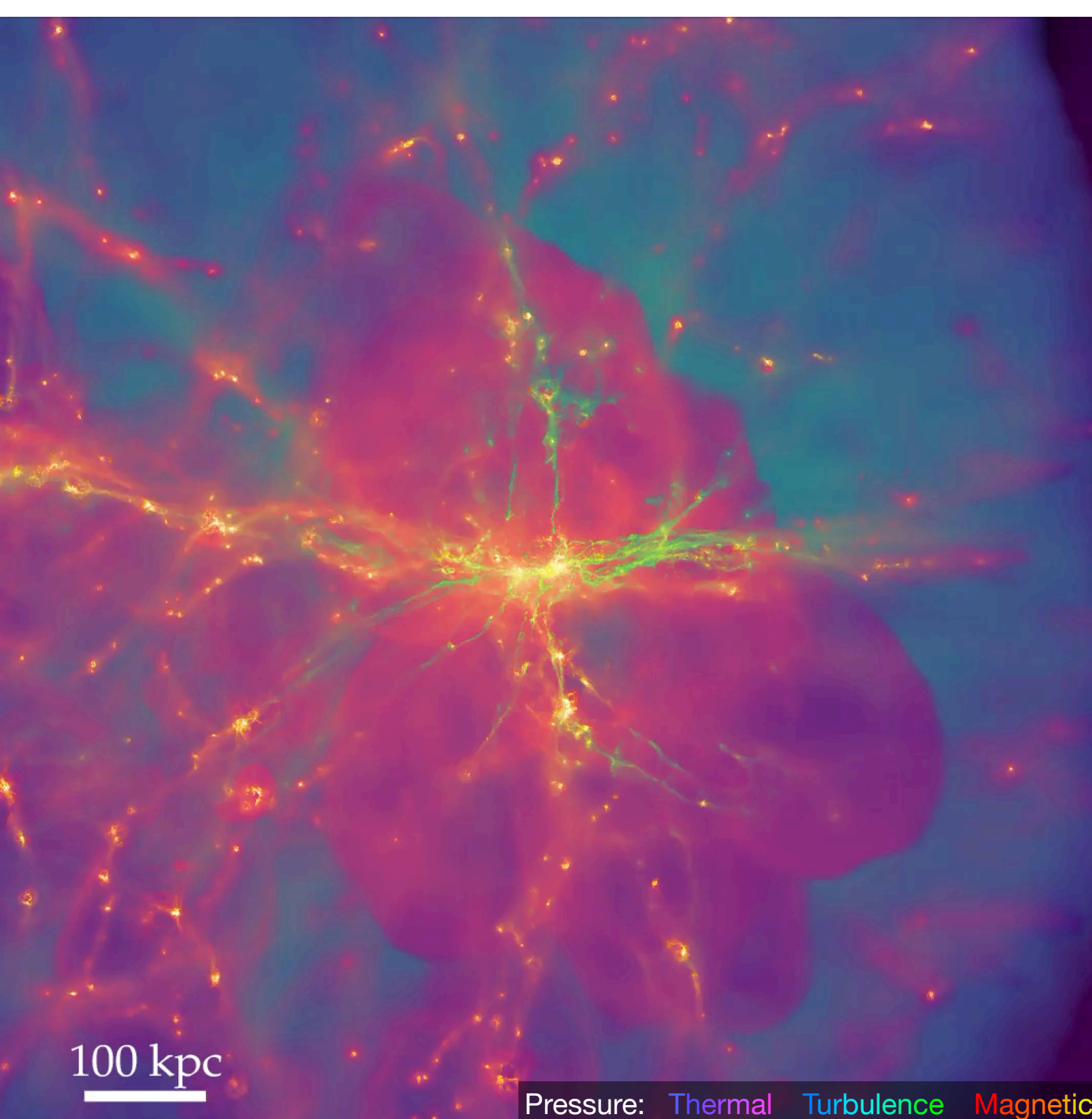
(also : Biernack+17;
Rodriguez+20; Bruel+23,25;
Gonzalez+24; Rantala+26;
Paiella+25; Spurzem+23; Kritos+24;
McLean+26; Liempos+26)



Bardati+ (envelopes *resolved*)

Gas Complex





4. AGN feedback

- Non-equilibrium ion/atomic/molecular **thermo-chemistry**
- **Multi-band NLTE** EUV-FIR **radiation** (& **opacities**)
- Non-ideal **MHD** (conduction, viscosity, Hall, ambipolar, Ohmic)
- Self-gravity & high-order orbits
- FIRE star formation & stellar feedback (low-resolution)
- STARFORGE star formation & feedback

Intergalactic
Medium

$\sim \text{Mpc}$

Circumgalactic
Medium

Galactic
ISM

To the horizon!

Kaaz+ 24

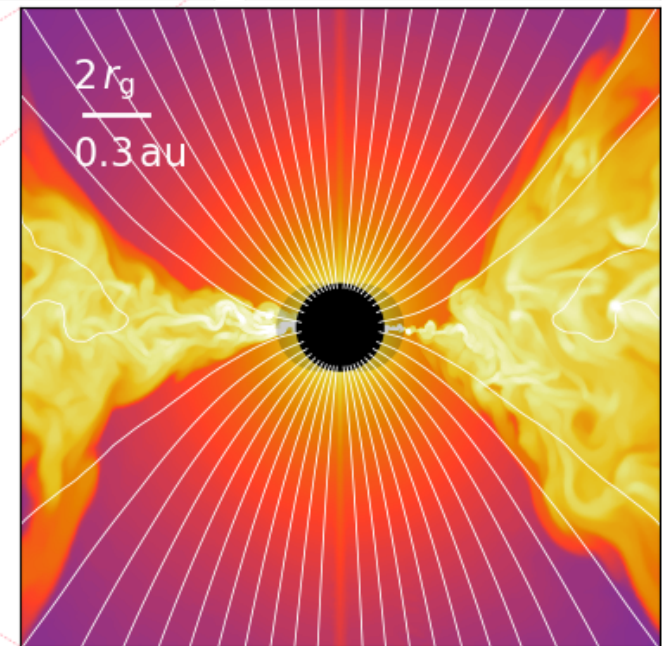
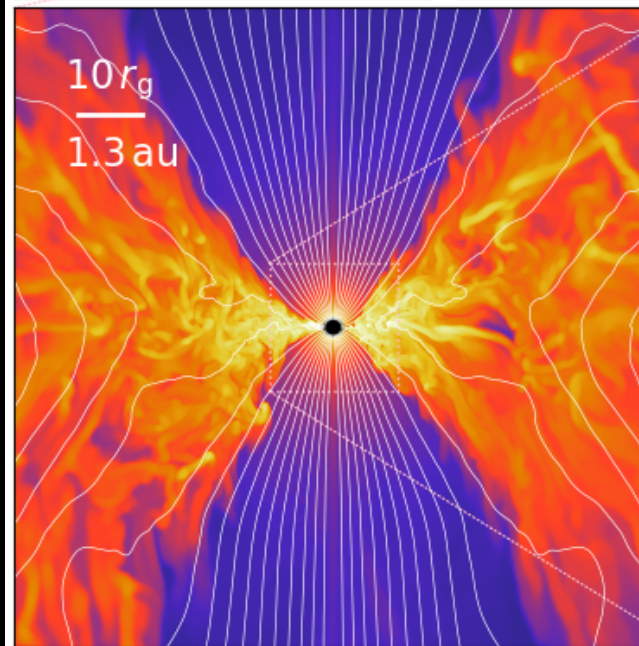
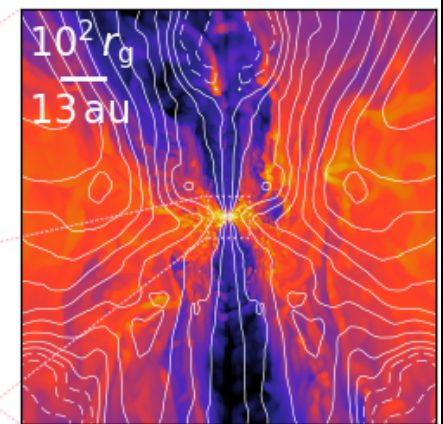
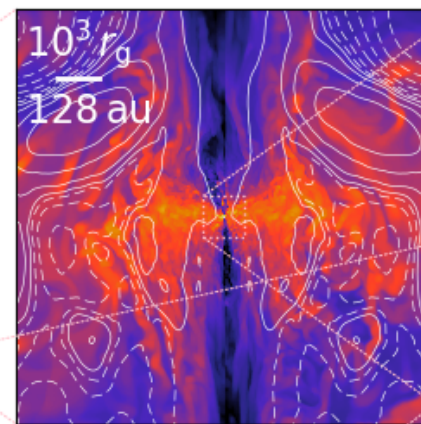
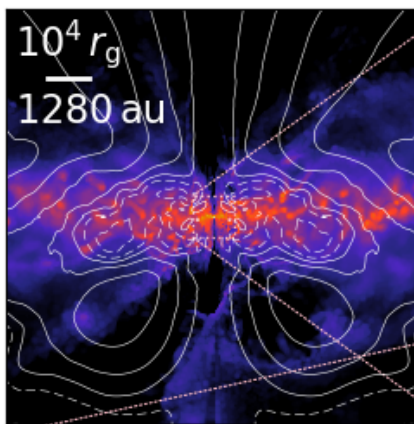
$1e11 R_g$

Inner Disk

$10 R_g$

sub-AU

Nick Kaaz



$1e4 R_g$

Outer
Accretion Disk

$1e5 R_g$

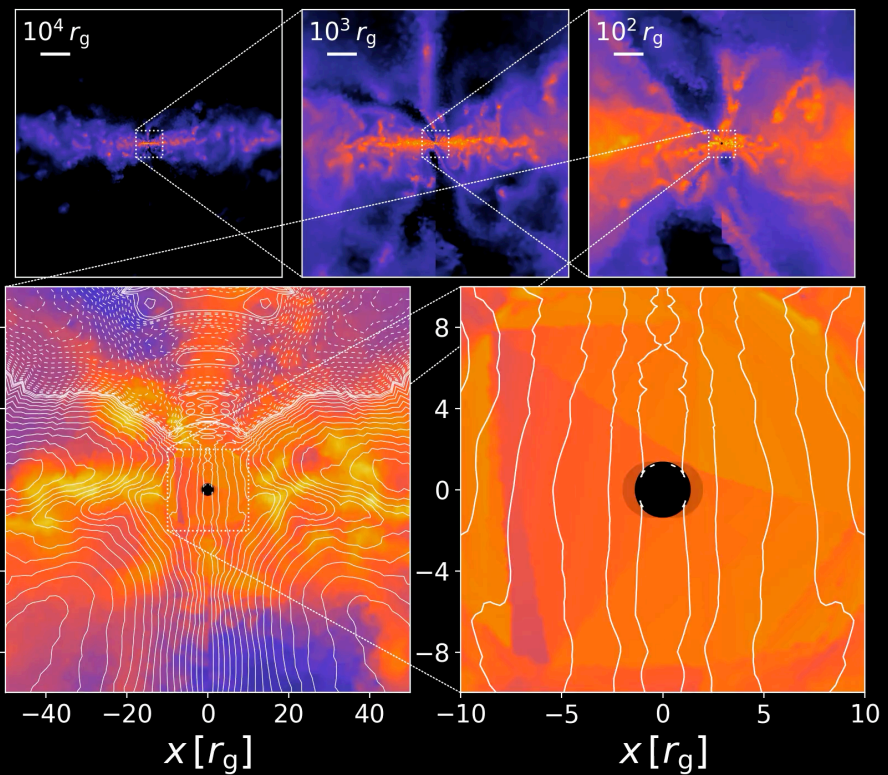
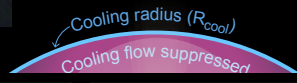
AGN Feedback?

Jets

Kung-Yi Su



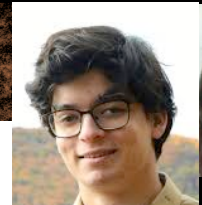
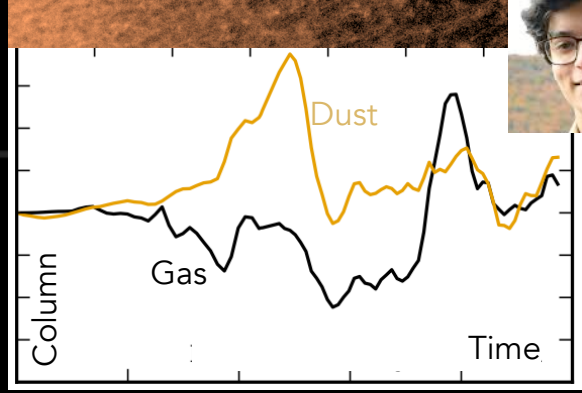
- * Which jets quench? ('21, '25)
- * Jets vs Eddington & IMBHs ('23)
- * Jets vs mass ('24)
- * Multi-zone sims (w Hyerin Cho '24, '25)
- * CGM signatures (w Roy '23, Qutob '24)



Nick Kaaz

- * GRMHD Jets from zooms ('24)
- * "Stifled" on $\sim 100 R_g$ ('25)

Radiation



Jaeden Bardati



Nadine Soliman

- * Variability ('23,26)
- * BLR+Torus winds & SEDs (25,26)

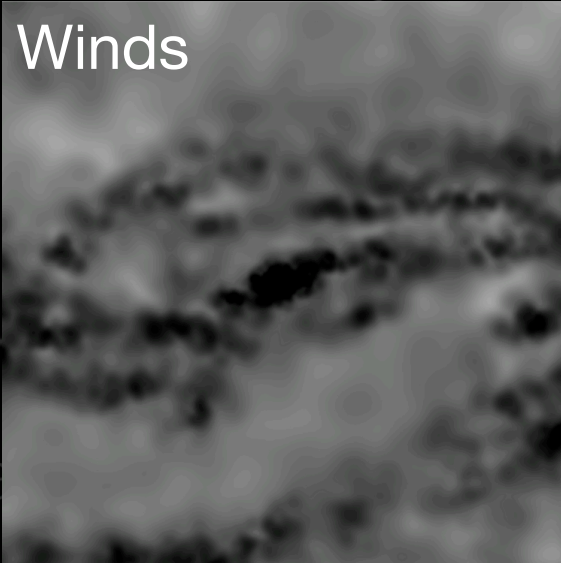
Sam Ponnada

- * FIR-Radio ('24)
- * Synchrotron jet tests ('25)



Cosmic Rays

Winds



Jonathan Mercedes-Feliz

- * FB-driven SF ('24)
- * Positive FB? ('23)

Rachel Cochrane



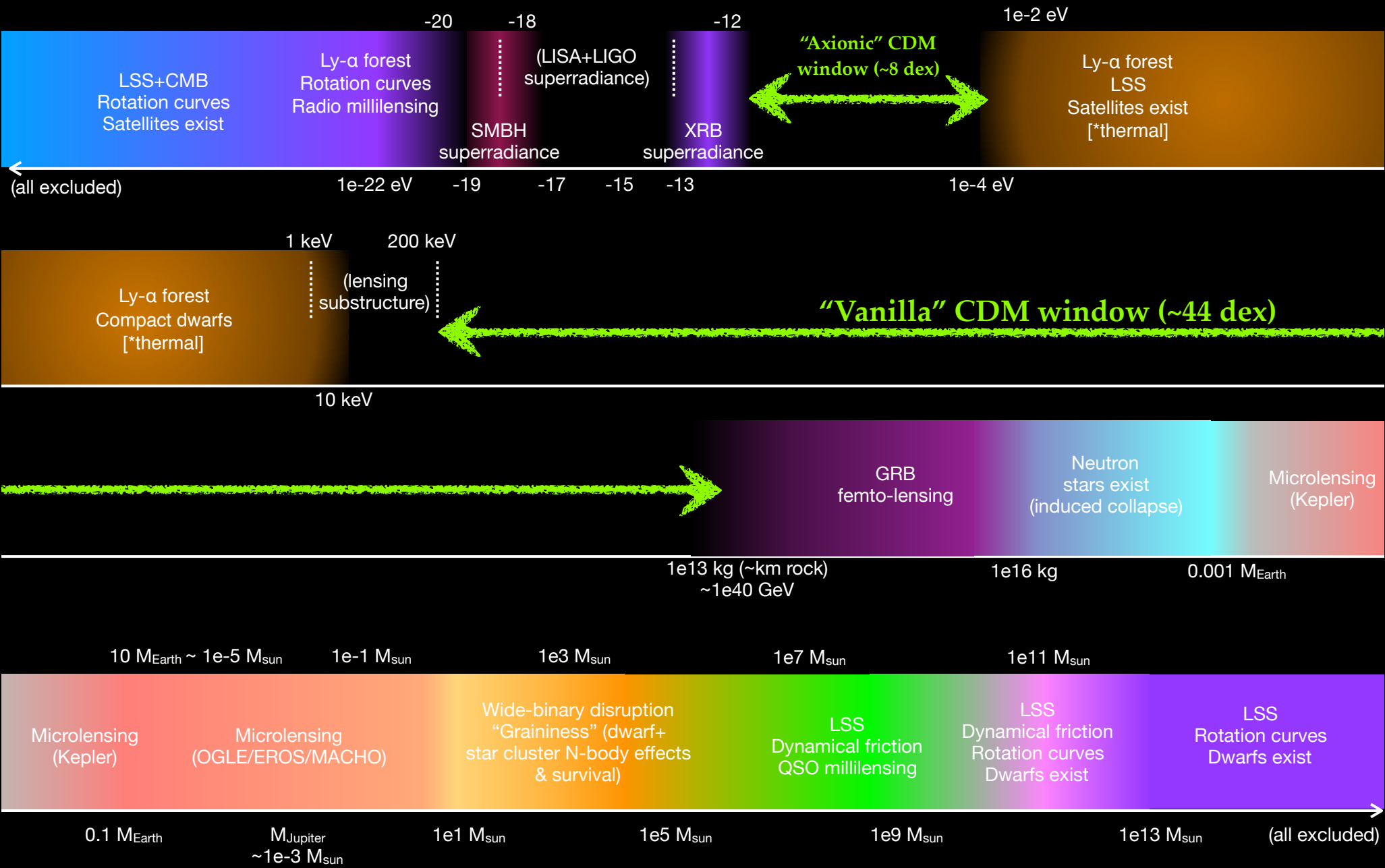
- * Winds alter galaxy R_{eff} ('23)

Yanlong Shi

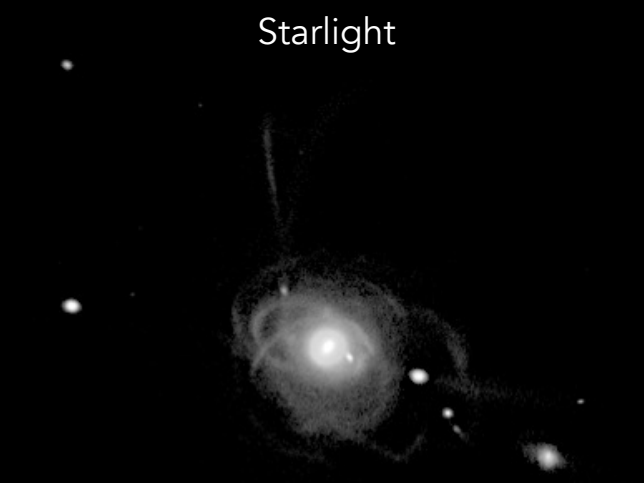
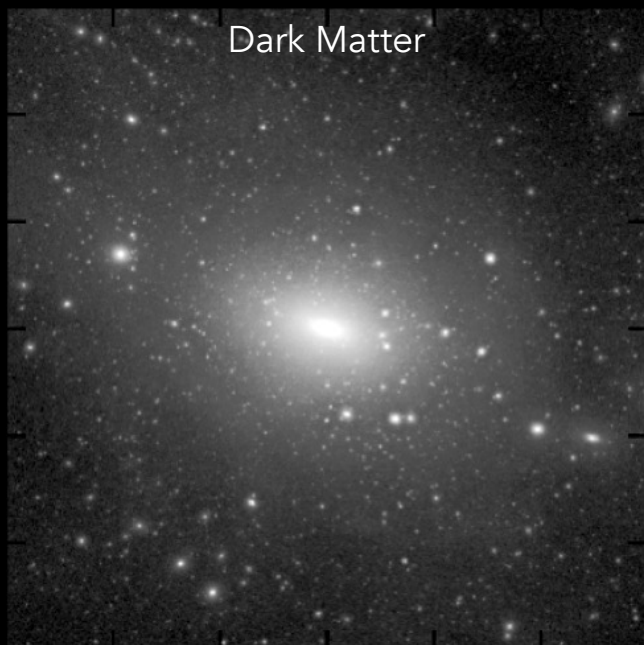
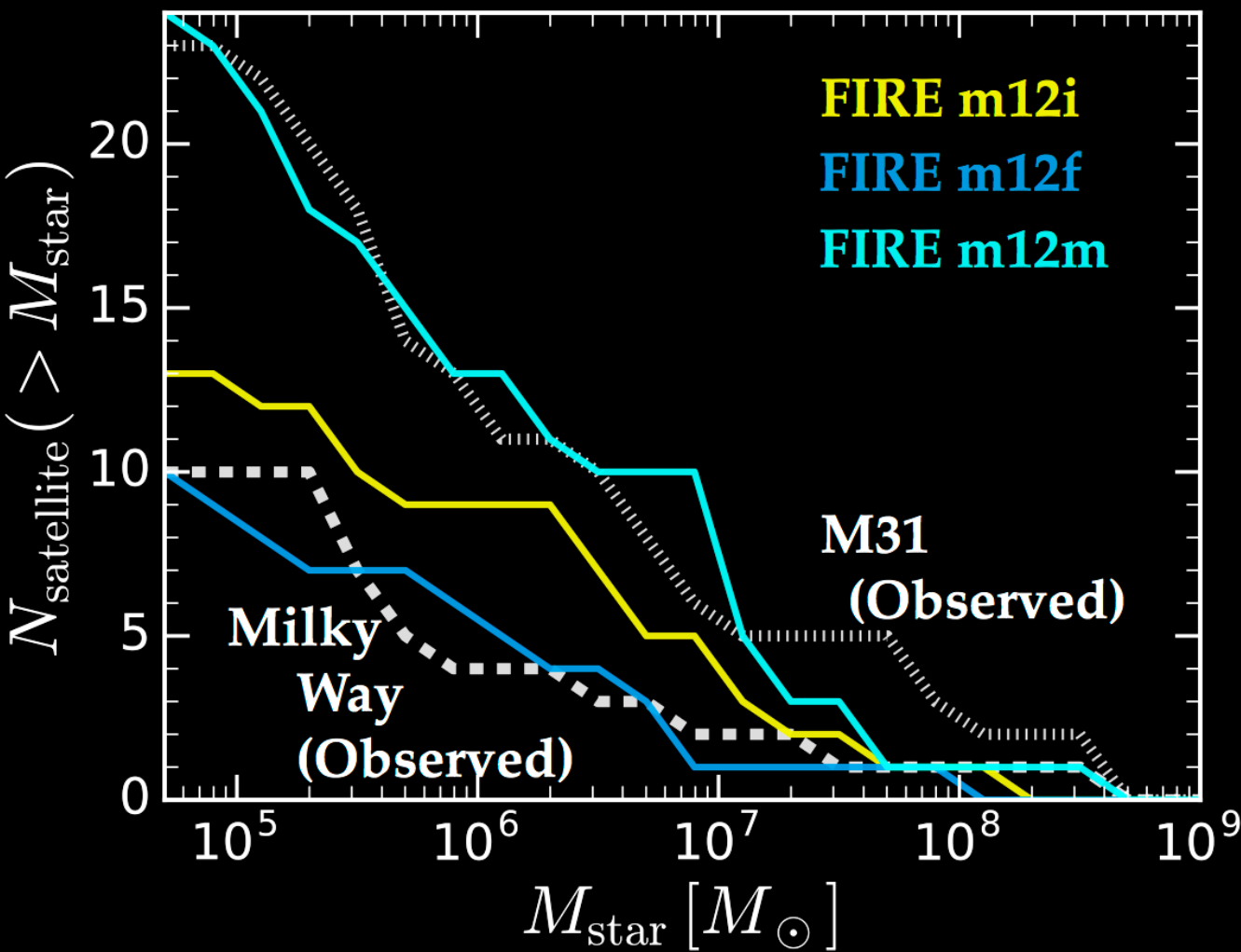
- * In IMBHs & LRDs ('24)



5. Dark Sector Physics



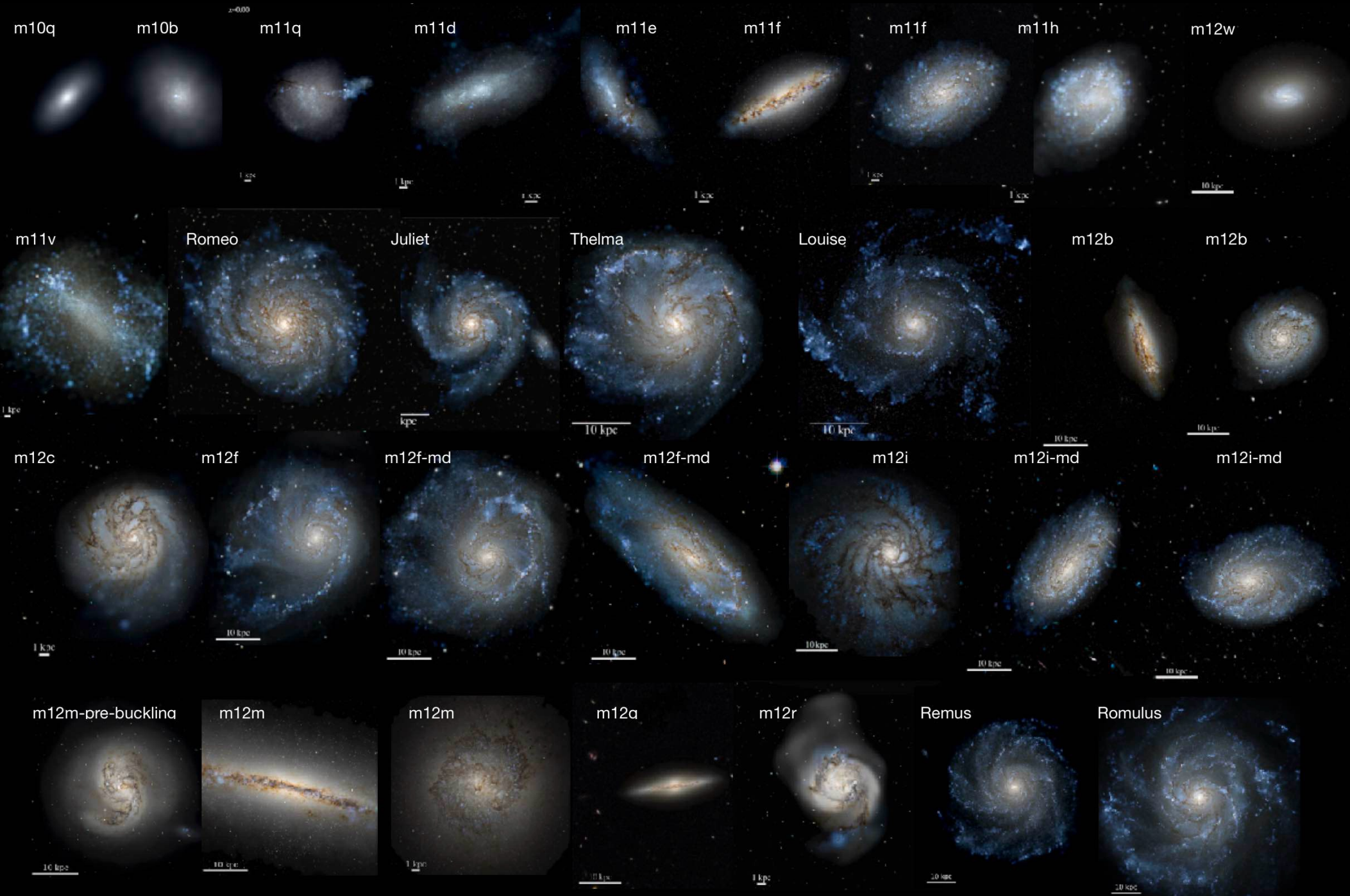
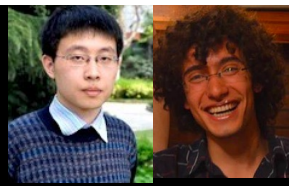
No real “missing satellites” or “too big to fail” or “cusp core” problem[s]



Garrison-Kimmel+ (arXiv:1806.04143)

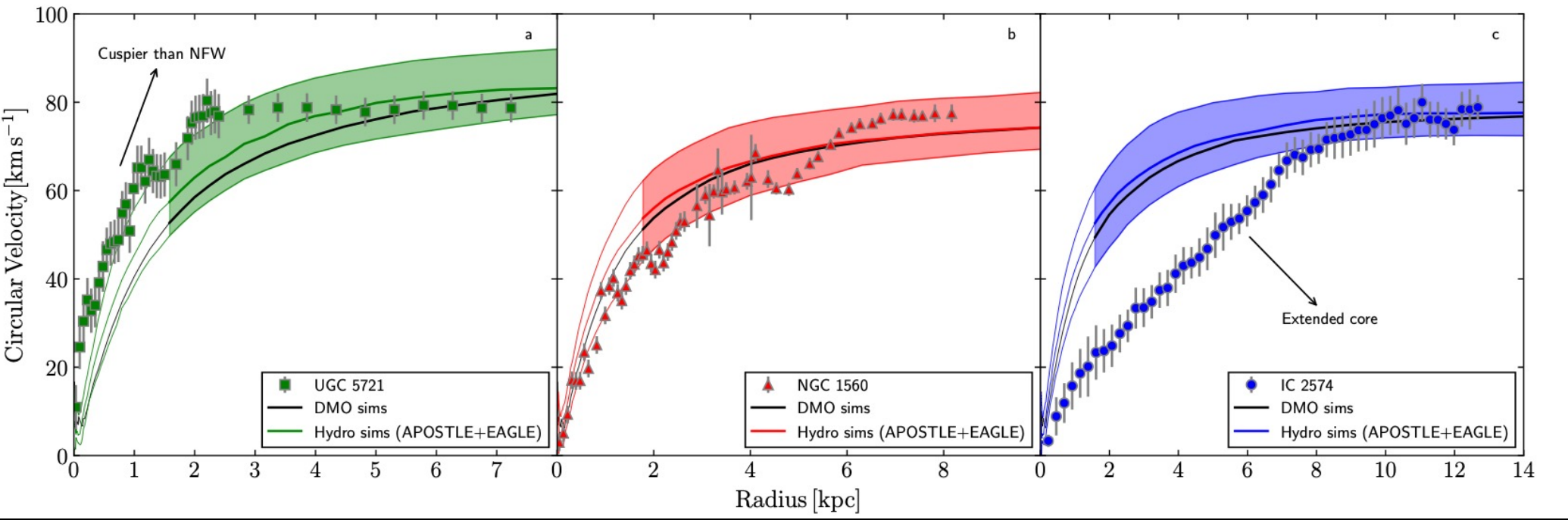
Many Morphological Types "Straightforward"

Ma+ '16
El-Badry+ '17, 18

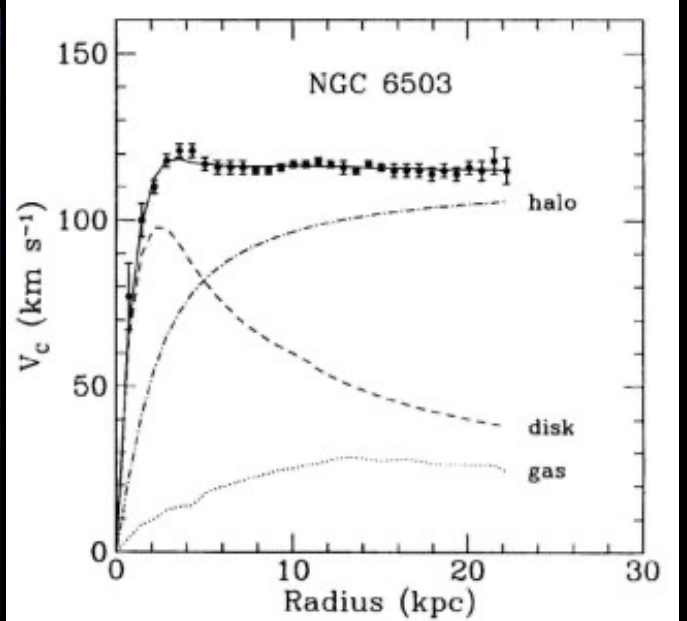


Example: Diversity Problem & Rotation Curves

Oman+ 15,
SPARC+ 17/18/19/20,
Sales+ 22

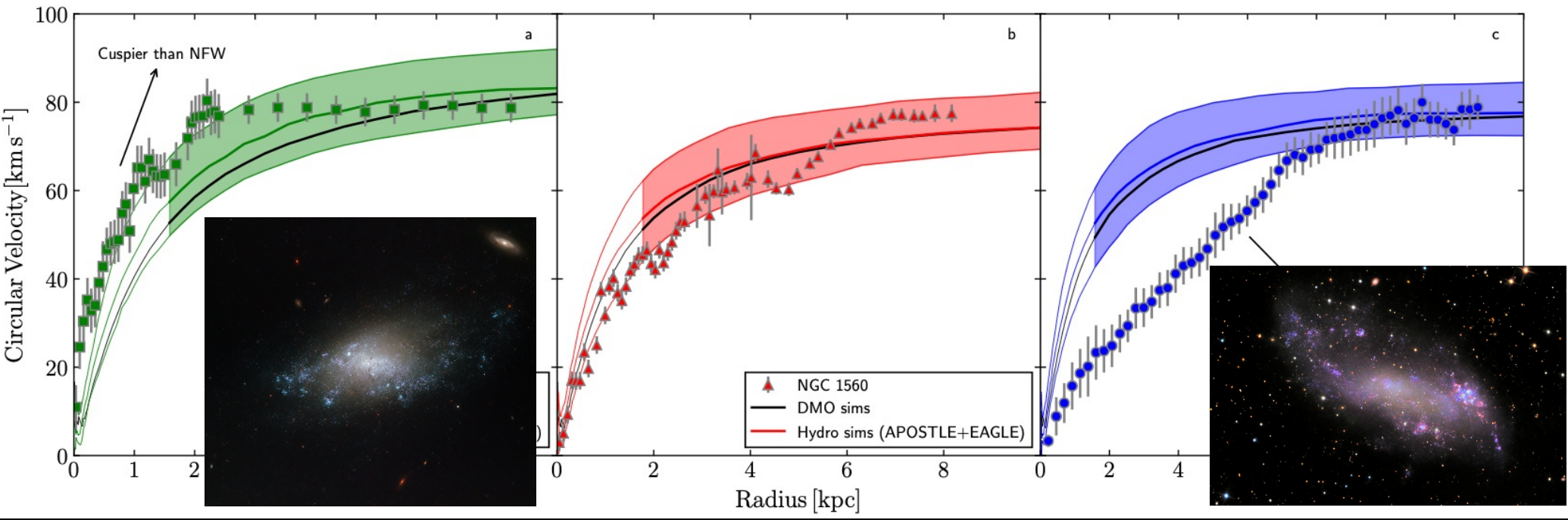


“Classic”
rotation curve

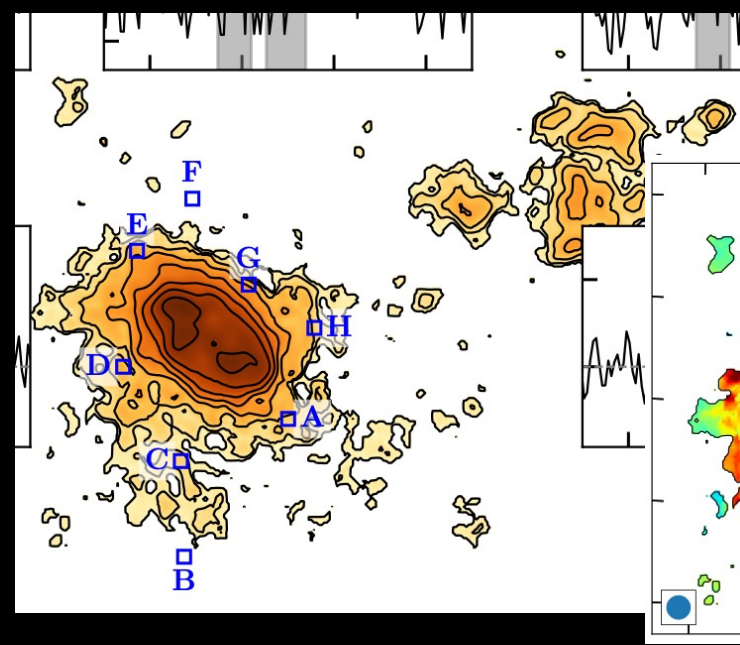


Example: Diversity Problem & Rotation Curves

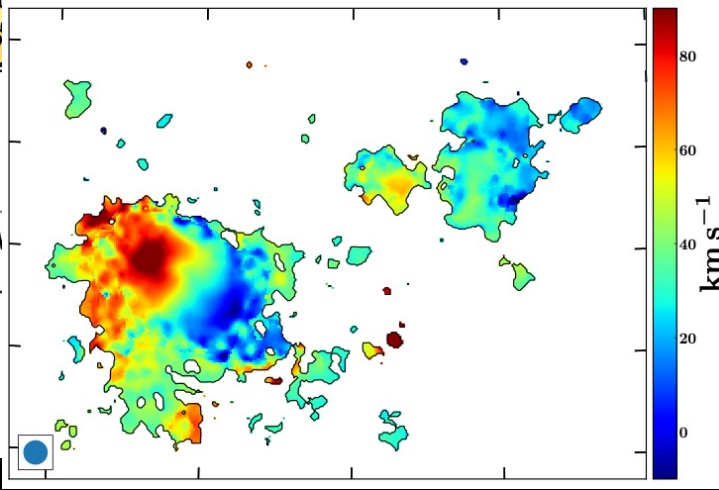
Oman+ 15,
SPARC+ 17/18/19/20,
Sales+ 22



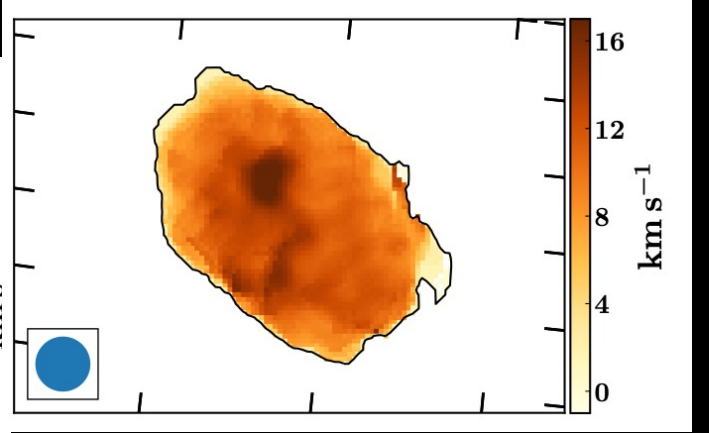
HI Map



Velocity Map

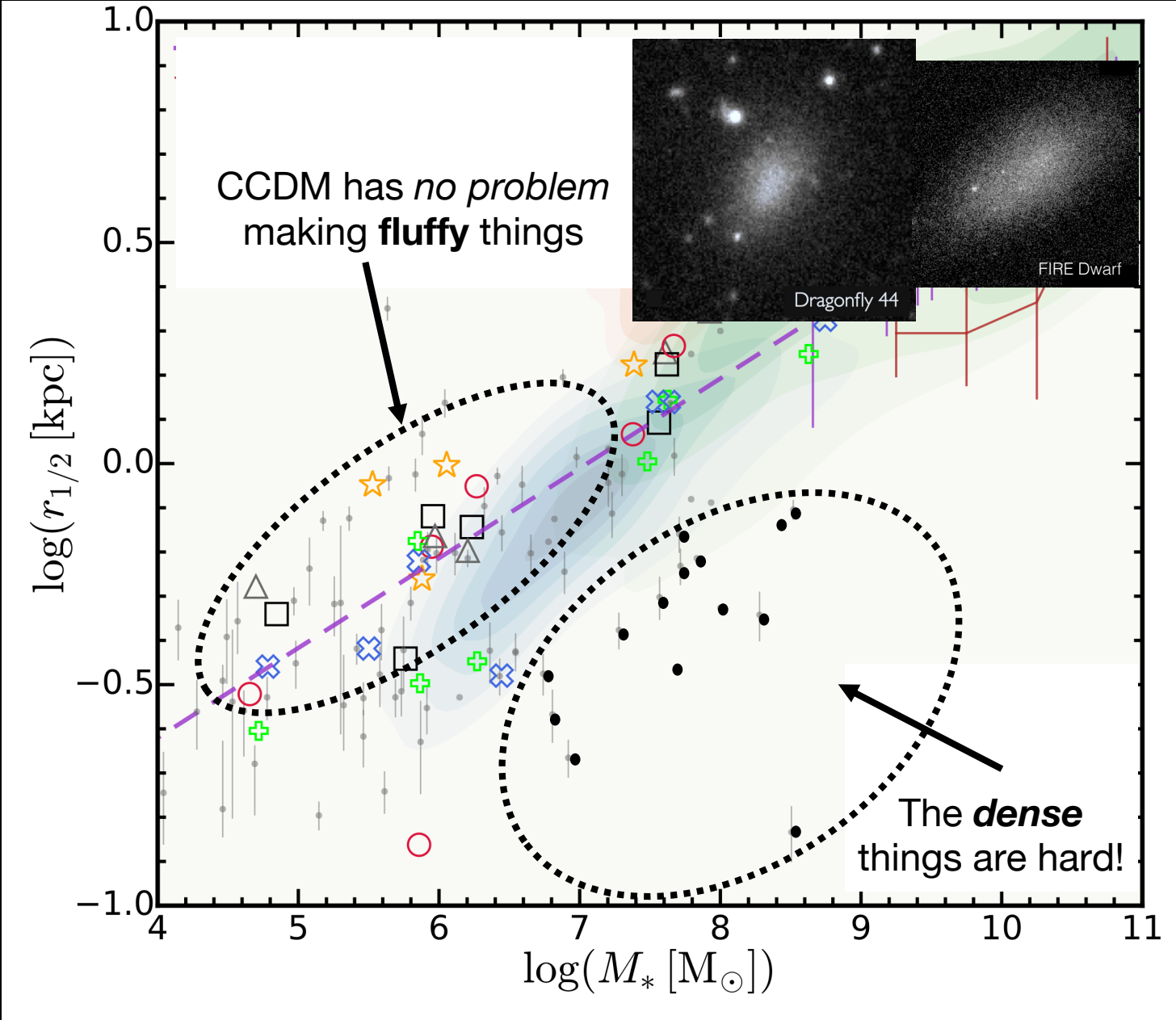


Dispersion Map



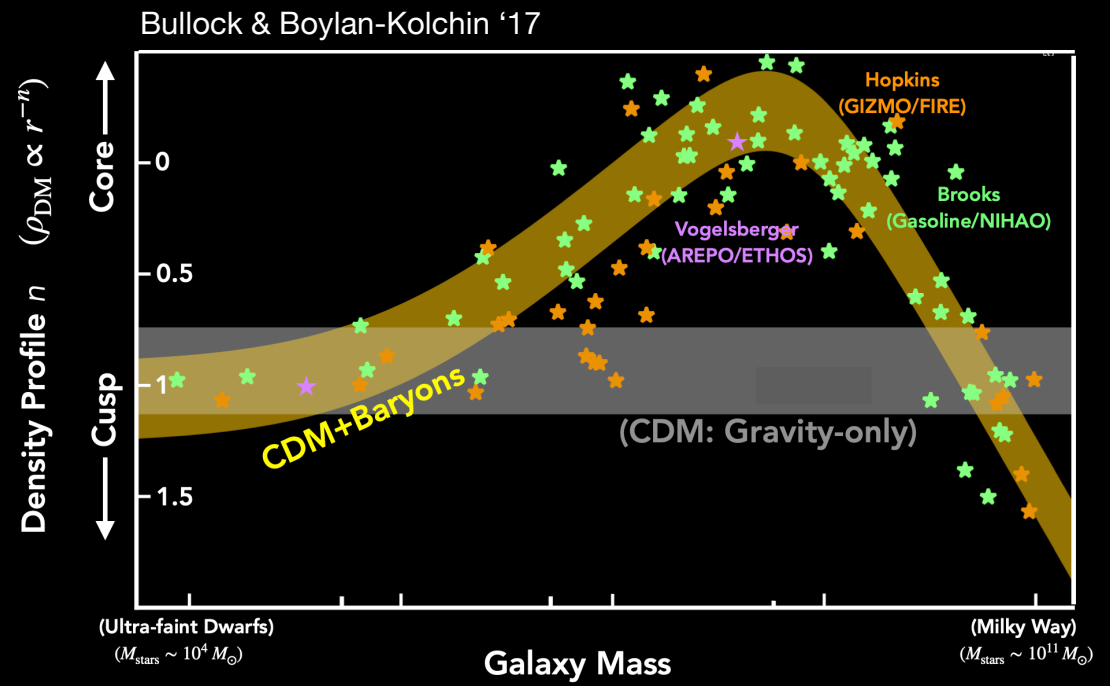
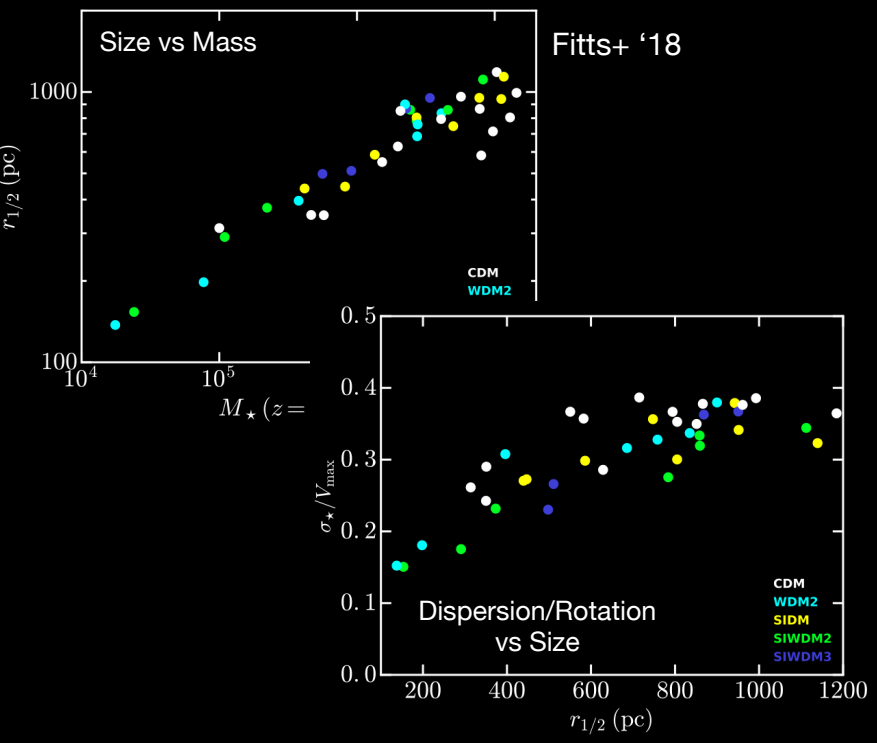
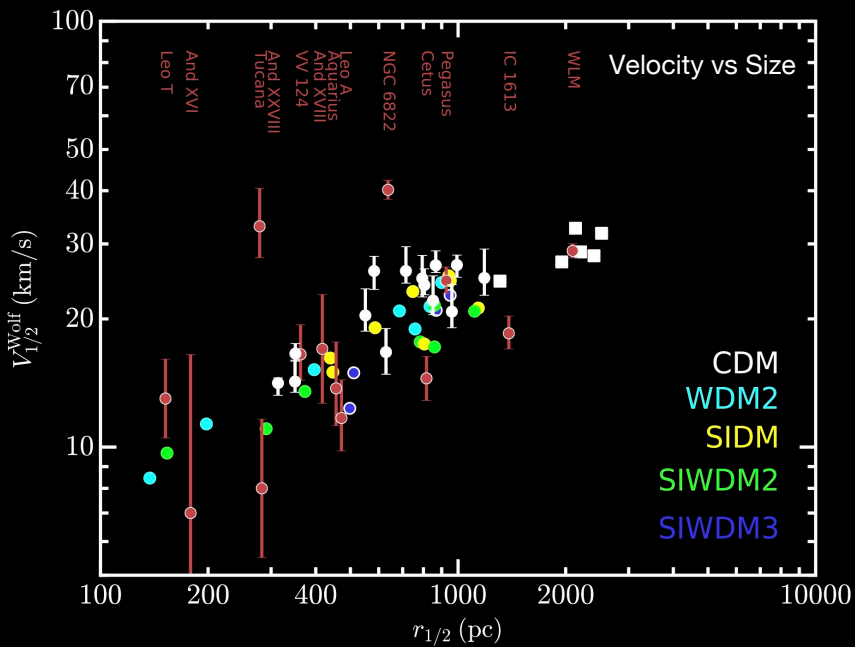
Dense Objects (at low masses) are Actually the Challenge

ONE SUBSET OF THE "DIVERSITY" PROBLEM?



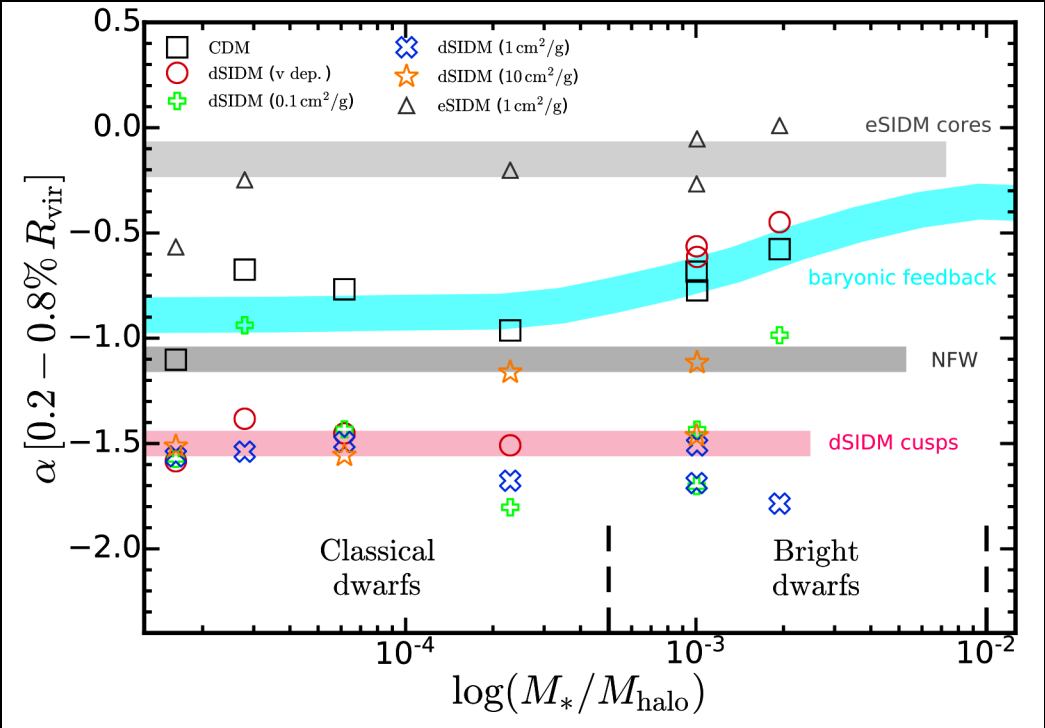
Baryons self-regulate: many predictions are surprisingly robust

GOOD AND BAD FOR US

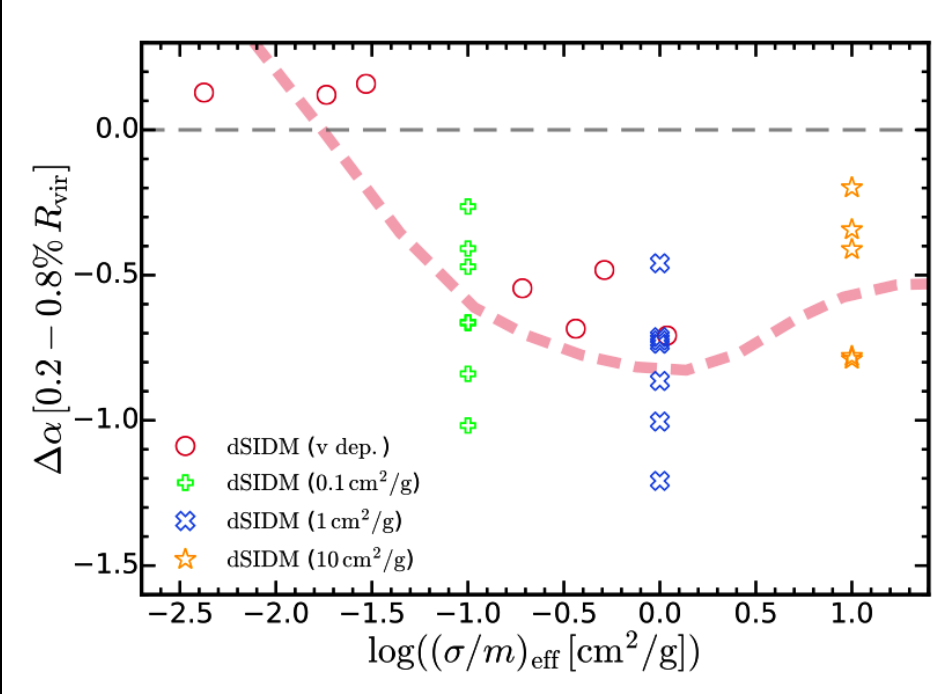


Highly Non-Monotonic Behaviors

Shen+ '21,22



dSIDM



very low σ low σ intermediate σ high σ

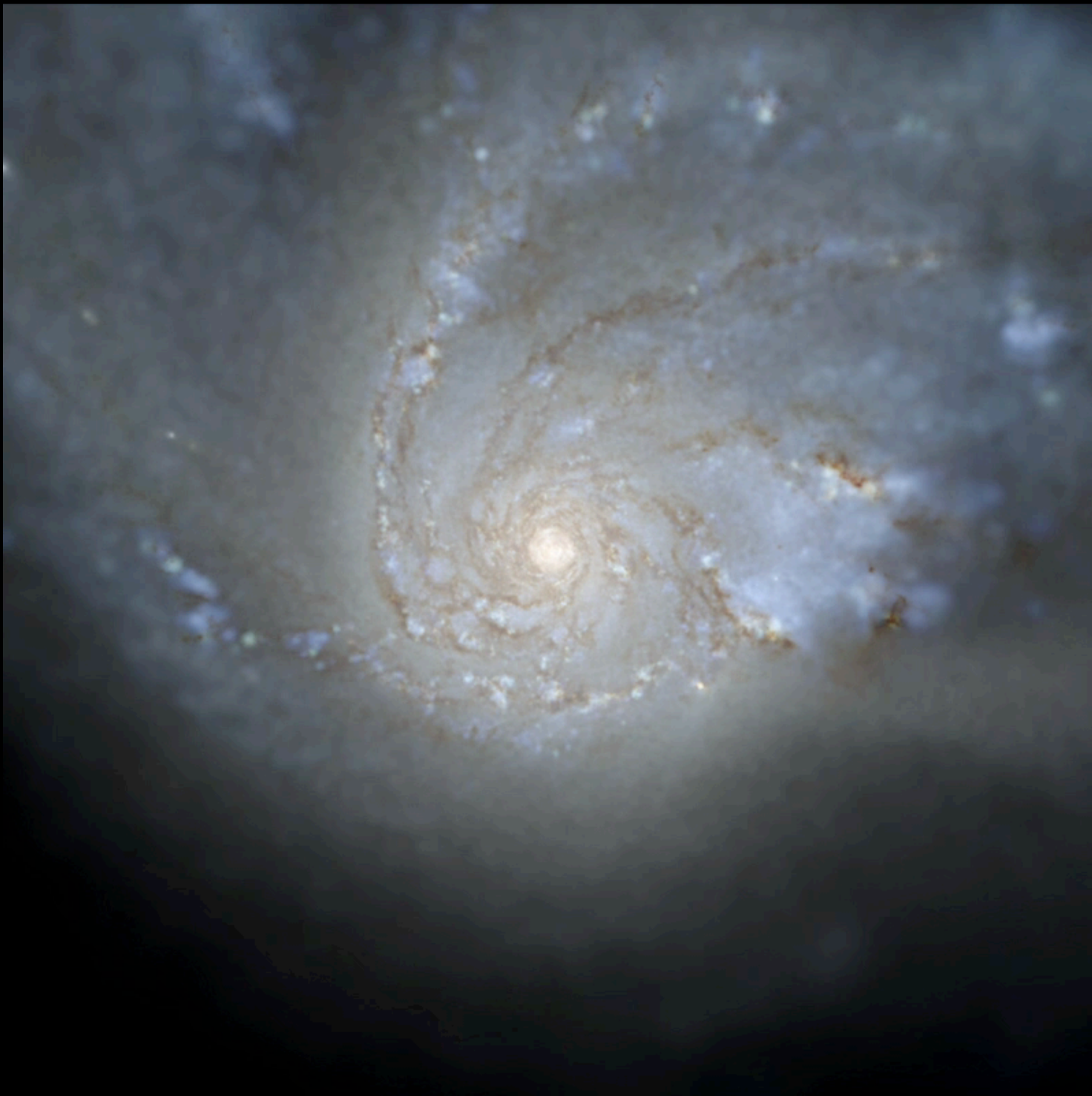
(also Alysons talk)
eSIDM:

cusps
(CDM-like)

small cores

big cores

cusps
(gravothermal)



Thanks!