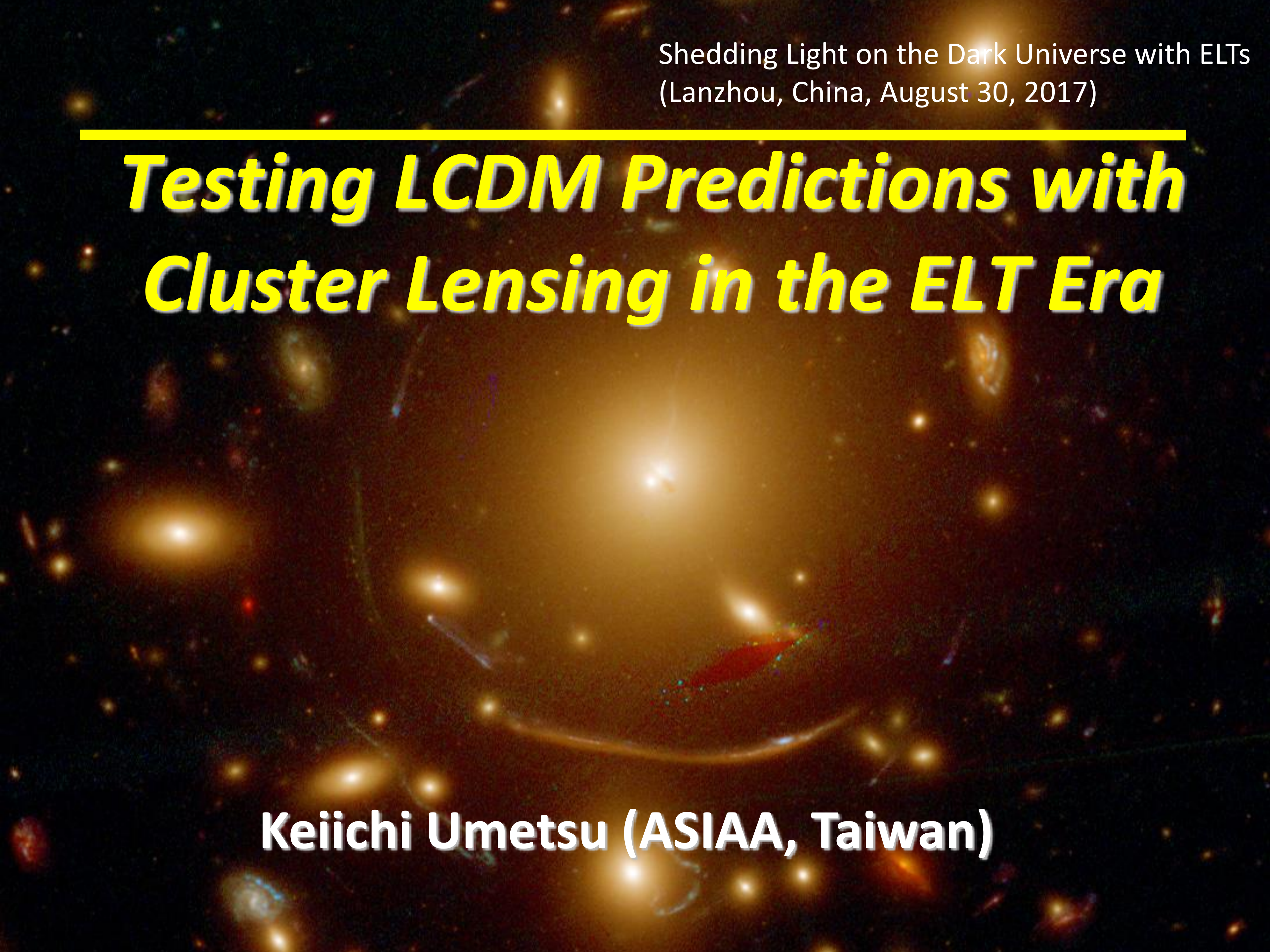


Shedding Light on the Dark Universe with ELTs
(Lanzhou, China, August 30, 2017)

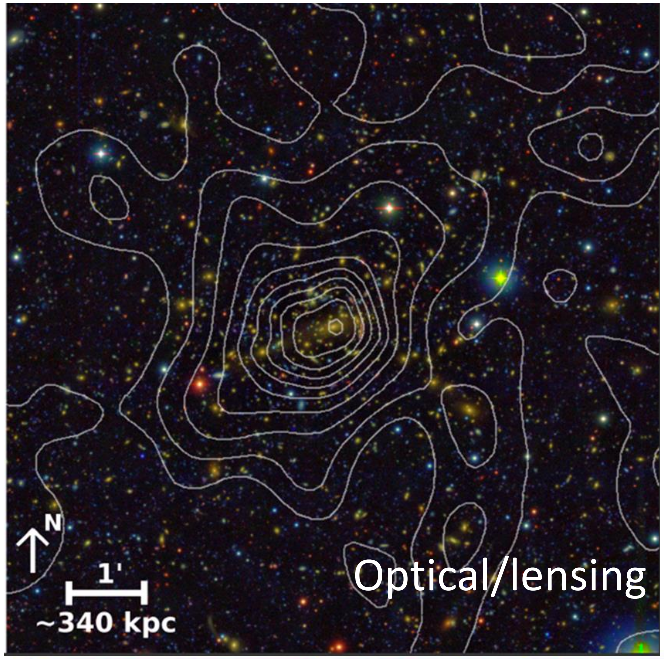
Testing LCDM Predictions with Cluster Lensing in the ELT Era

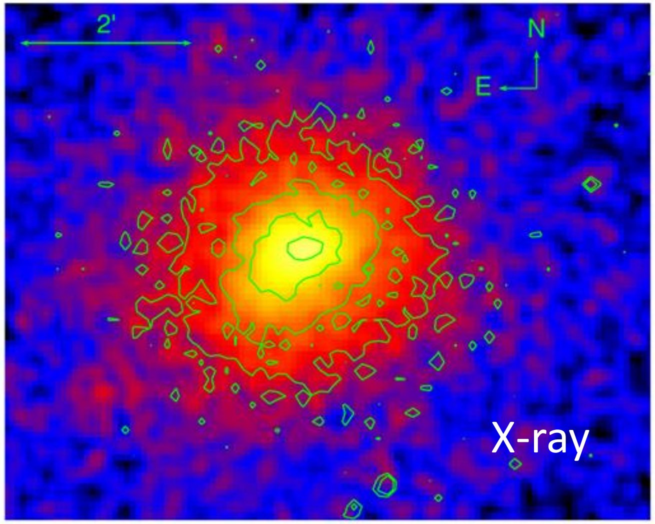
Keiichi Umetsu (ASIAA, Taiwan)

Galaxy clusters

MACS1206 (Umetsu+12)

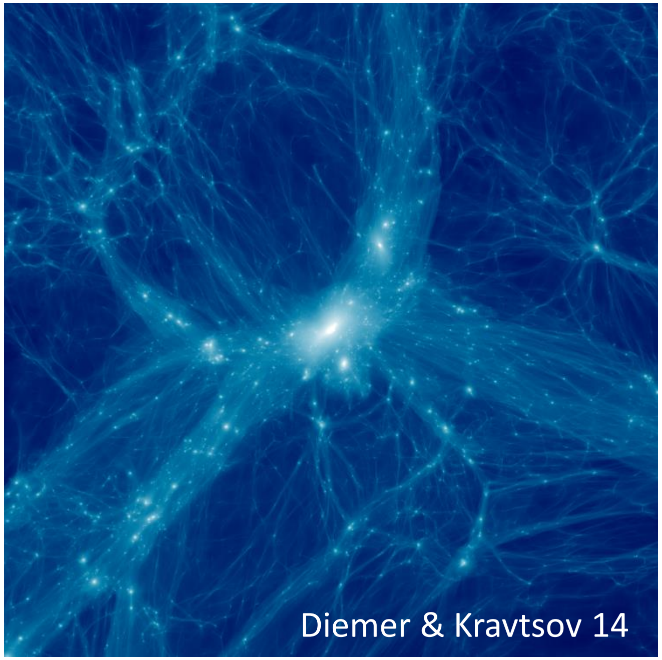
- Largest self-gravitating objects formed in the universe
- Dominated by dark matter (DM)
- Can be observed with various ways:
  - Optical/NIR
  - X-ray
  - Radio (Sunyaev-Zel'dovich effects)
  - Gravitational lensing





Clusters as DM probes

- Standard paradigm for structure formation
  - Collisionless, cold DM (CDM)
- Clusters offer fundamental tests of assumed DM properties:
  - DM density profile shape, $\rho(r)$
  - Concentration-mass relation
  - Phase-space distribution of DM
  - Triaxial halo shape
  - DM offset
  - Substructure distribution

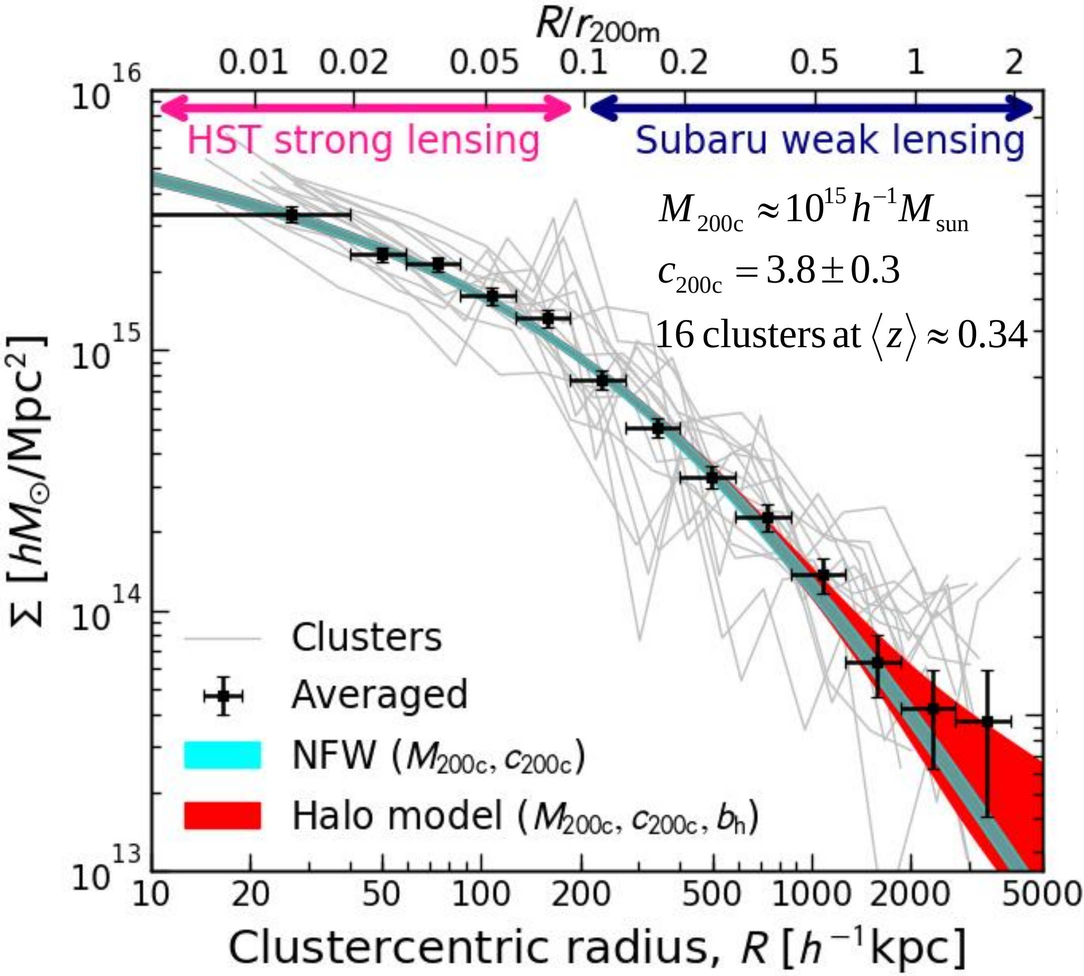


Diemer & Kravtsov 14

Bullet Cluster (Clowe+04)

Ensemble cluster mass profile from lensing

- Combining strong and weak lensing allows measurements of cluster total mass profiles over a wide dynamic range (R_{min}=40kpc/h).
- The stacked ensemble profile is well described by cuspy, outward steepening density profiles as predicted for CDM-dominated halos.
- Halo concentration in good agreement with recent LCDM simulations



Umetsu et al. 2016 (CLASH), *ApJ*, 821, 116

Possible science cases for ELTs

1. **Cluster DM peculiar velocity from lensing**

→ High velocity precision spectroscopy (sub km/s) of background galaxies/QSOs strongly lensed by clusters

2. **Splashback features in phase space**

→ Spectroscopic survey of member galaxies in targeted clusters: e.g., massive clusters with high mass accretion rates (MAR)

3. **Granularity of galaxy-scale DM halos: CDM vs. ψDM**

→ High precision, high resolution photometry of QSO-galaxy strong lensing systems (lensing flux anomalies) with AO narrow-band imaging

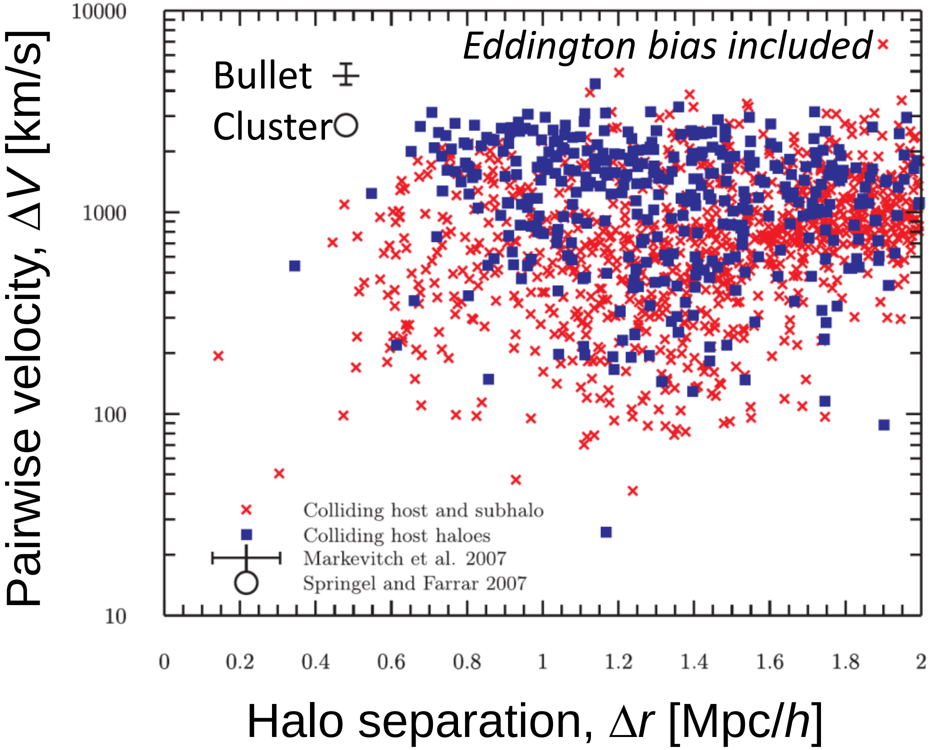
(1) Cluster dark-matter peculiar velocity from the moving lens effect

Molnar, Broadhurst, Umetsu et al. 2010, *ApJ*, 774, 70

Abundance of Bullet clusters

Pairwise velocity (extreme event) statistics of colliding clusters are sensitive to cosmology

Juropa Hubble Volume simulation at z=0.3 (Watson+14)

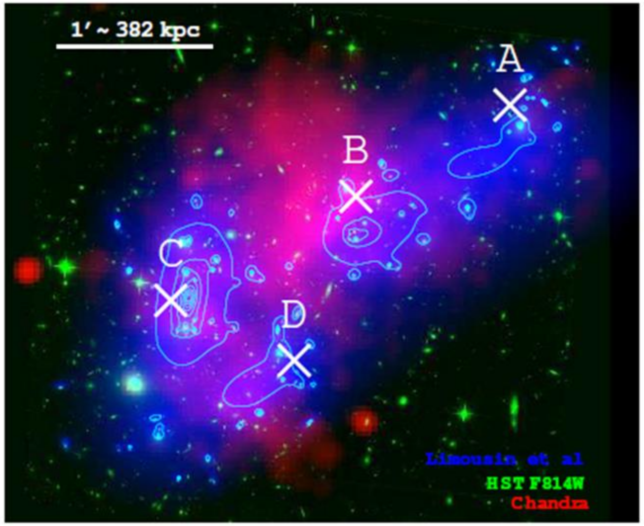


Inference of DM velocity requires hydrodynamical interpretation of gastrophysics in complex mergers

Cluster collision in the sky plane

Bullet Cluster at z=0.3 (Clowe+04)

4.2σ kSZE toward B (3500km/s) in MACS0717 at z=0.55 (Sayers+13)



Moving lens effect (Birkinshaw & Gull 83)

Lensing-analog of the Rees-Sciama 68 effect

$$\left(\frac{\Delta\nu}{\nu}\right) = -2\int \dot{\Phi}\, dt$$

Change of potential along photon path due to tangential lens motion

$$\Delta_\nu \equiv \left(\frac{\Delta\nu}{\nu}\right)_{\mathrm{BG83}} = -2\int \mathbf{V}_\perp \cdot \nabla_\perp \Phi\, dt \approx \mathbf{V}_\perp \cdot \hat{\boldsymbol{\alpha}}$$

Observable pairwise frequency shift between multiply lensed images

$$(\Delta_\nu)_{\mathrm{pair}} = \left|\Delta_{\nu,1} - \Delta_{\nu,2}\right| \approx 2V_\perp\theta_E = 3\times10^{-6}\left(\frac{V_\perp}{3000\mathrm{km/s}}\right)\left(\frac{\theta_E}{30''}\right)$$

~ 1km/s velocity shift

Total frequency shift

$$\Delta_\nu(\boldsymbol{\theta}_I) = \left[\overset{\textit{Lens}}{\boldsymbol{\beta}_T^L} - \underbrace{\boxed{\frac{D_{LS}}{D_{OS}}}\overset{\textit{Observer}}{\boldsymbol{\beta}_T^O} - \boxed{\frac{D_{OL}}{D_{OS}}\frac{1+z_L}{1+z_S}}}\overset{\textit{Source}}{\boldsymbol{\beta}_T^S}\right]\cdot\boldsymbol{\alpha},$$

with $\boldsymbol{\beta}_\mathrm{T} = \frac{\mathbf{V}_\perp}{c}$

Observer and source motions are down-weighted by geometric factors (~10m/s)

Current best velocity centroid precision ~ 1km/s with X-Shooter on 8m VLT for lensed star-forming galaxies (Christensen+10)

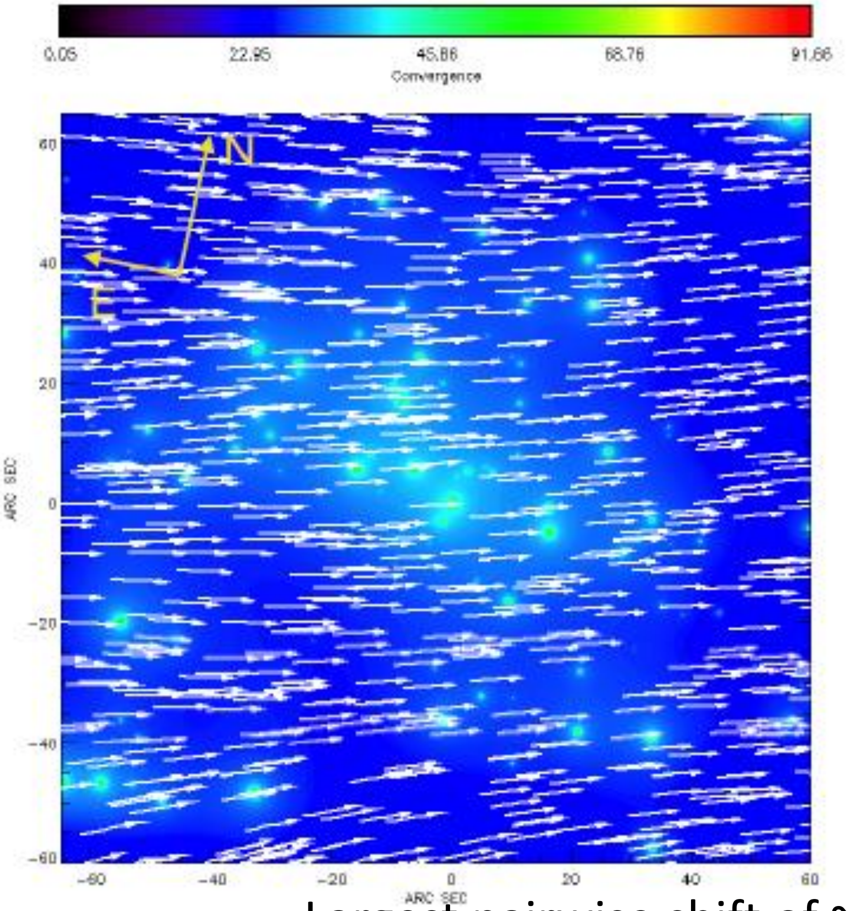
Uncertainty in tangential velocity using *N* line features per source

$$\frac{\sigma(\beta_\mathrm{T})}{\beta_\mathrm{T}} = \frac{1}{\sqrt{N}}\frac{\sigma(\Delta_\nu)}{\Delta_\nu}$$

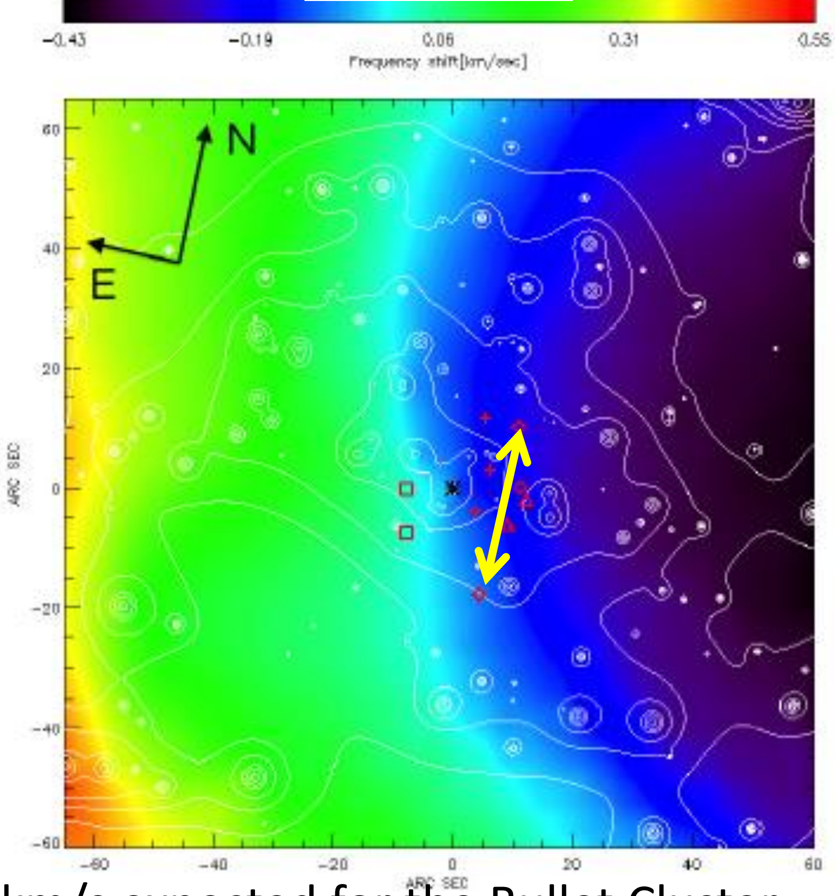
Simulated DM flow centered on the Bullet

FLASH (DM+gas) AMR simulation of the Bullet Cluster (Molnar+13)

$$\mathbf{v}_\perp(\boldsymbol{\theta})$$



$$\left(\frac{\Delta\nu}{\nu}\right) = \mathbf{v}_\perp \cdot \hat{\boldsymbol{\alpha}}$$



400kpc/h

Largest pairwise shift of ~0.5km/s expected for the Bullet Cluster

(2) Splashback features in phase space

In collaboration with Teppei Okumura (ASIAA),
Takahiro Nishimichi (IPMU), Ken Osato (Univ of Tokyo),
Benedikt Diemer (CfA)

Splashback radius, R_{sp}: Physical halo boundary

$r > R_{\mathrm{sp}}$: infall region
$r < R_{\mathrm{sp}}$: multi-stream intra-halo region

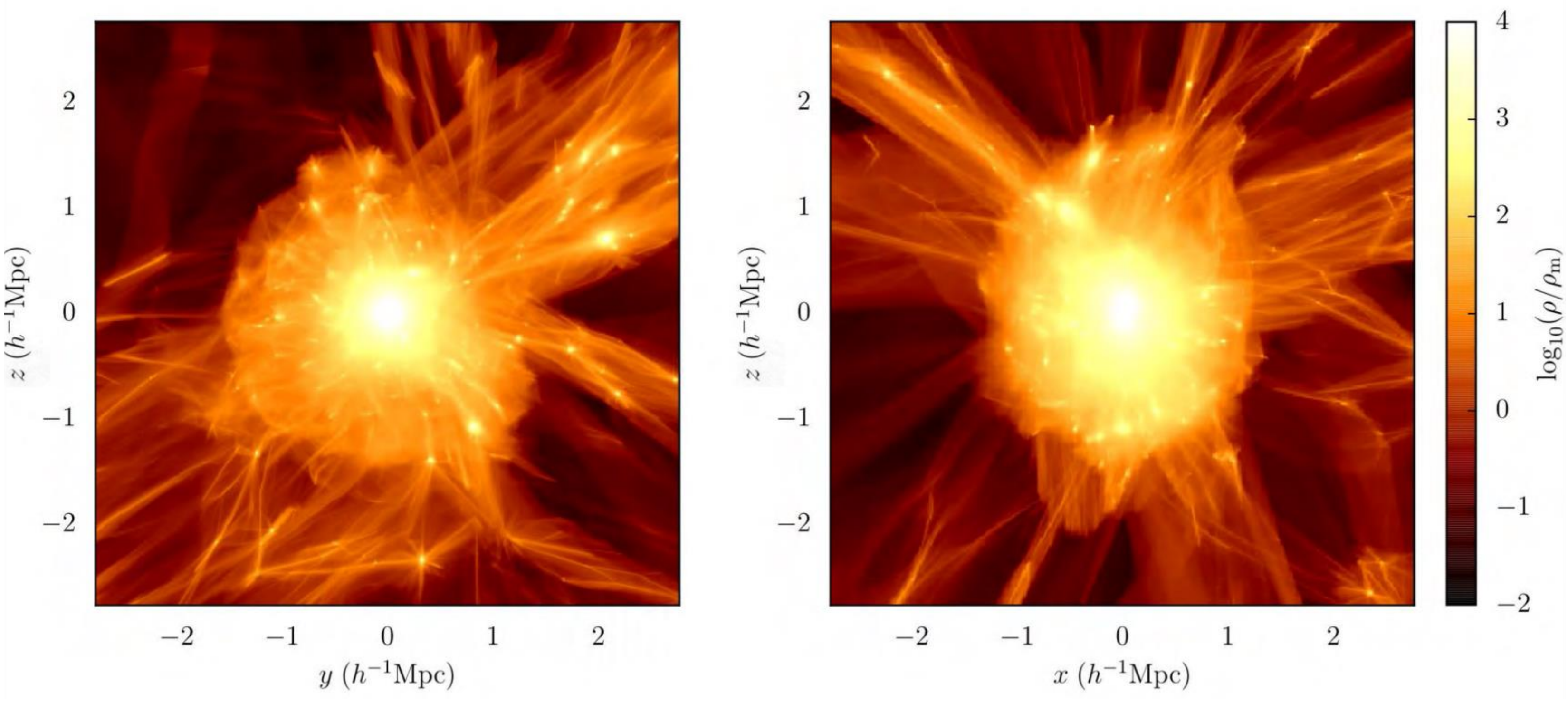
Splashback radius depends on MAR, halo peak height, cosmology (Ω_{m})

Slow accreting halos

$R_{\mathrm{sp}} > r_{200\mathrm{m}}$

Fast accreting halos

$R_{\mathrm{sp}} \sim r_{200\mathrm{m}}$

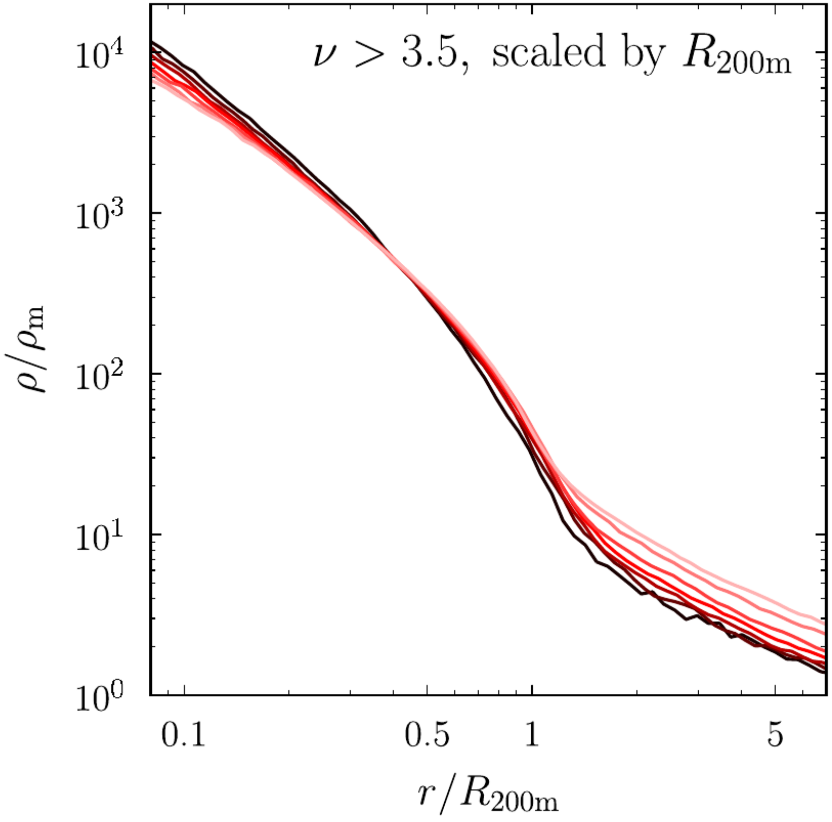


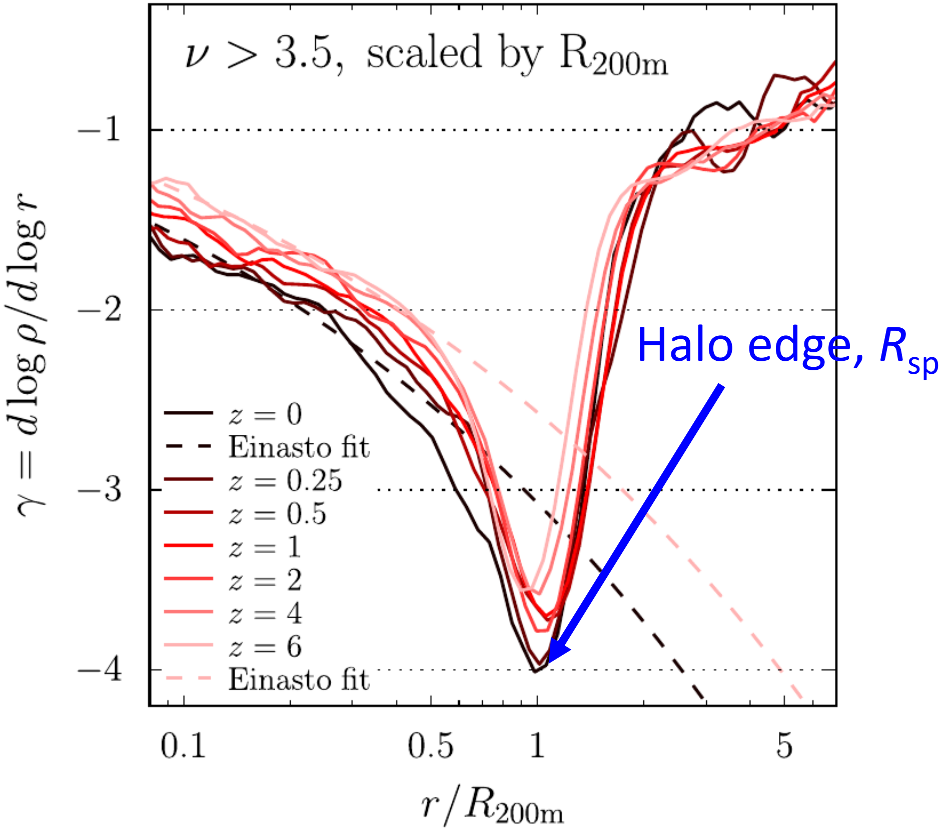
N-body simulations from S. More, Diemer, & Kravtsov 2015

Splashback feature in real space

DM density steepening relative to Einasto/NFW

$R_{\mathrm{sp}} \sim r_{200\mathrm{m}}$ for high-mass forming halos



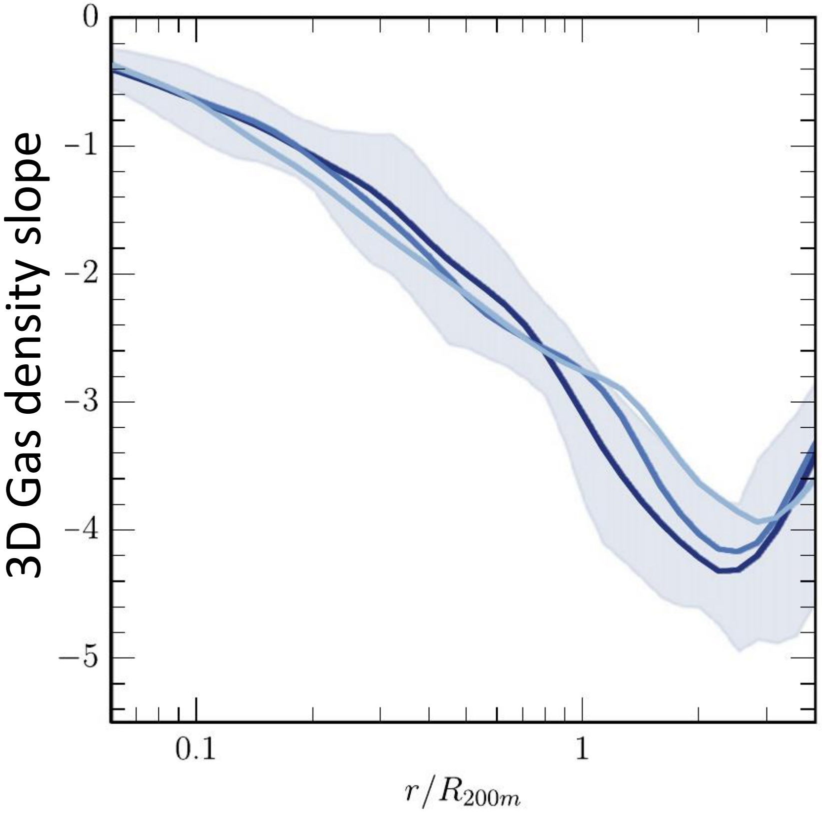


Halo edge, R_{sp}

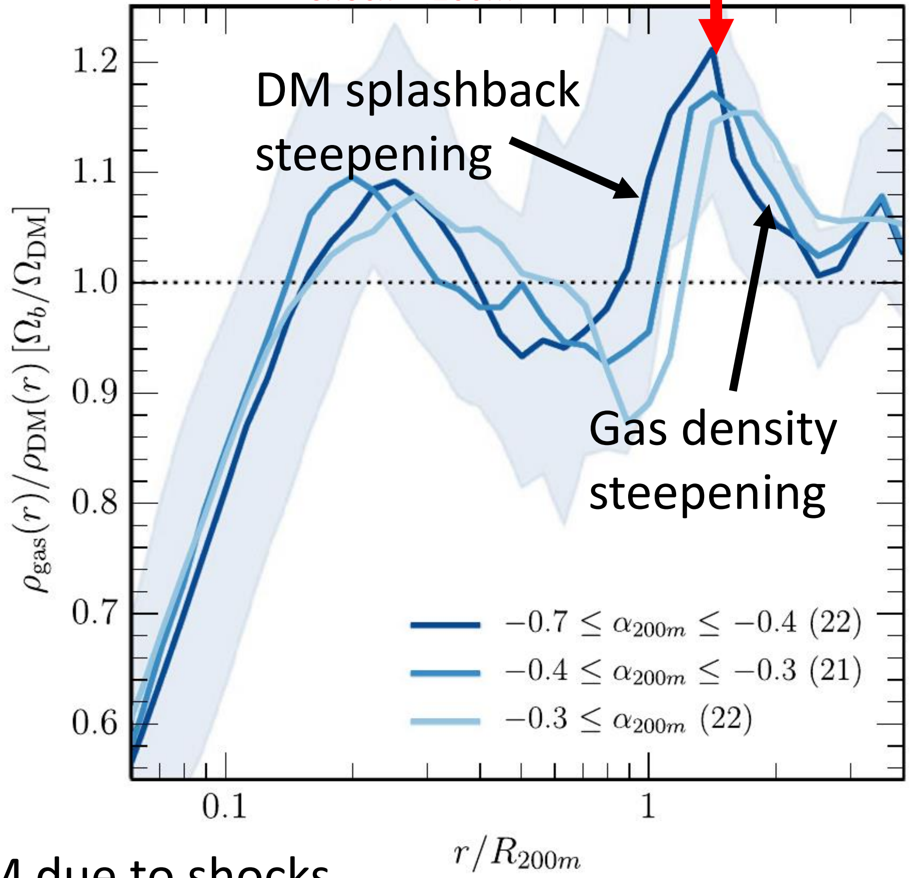
N-body simulations from Diemer & Kravtsov 2014 (DK14)

Cluster outskirts: DM vs. hot gas

Ensemble cluster halos from cosmological hydro simulations (*Omega*500, Lau+15)



Accretion shock radius, $\langle R_{shock}/r_{200m}\rangle \sim 1.6$


DM splashback steepening

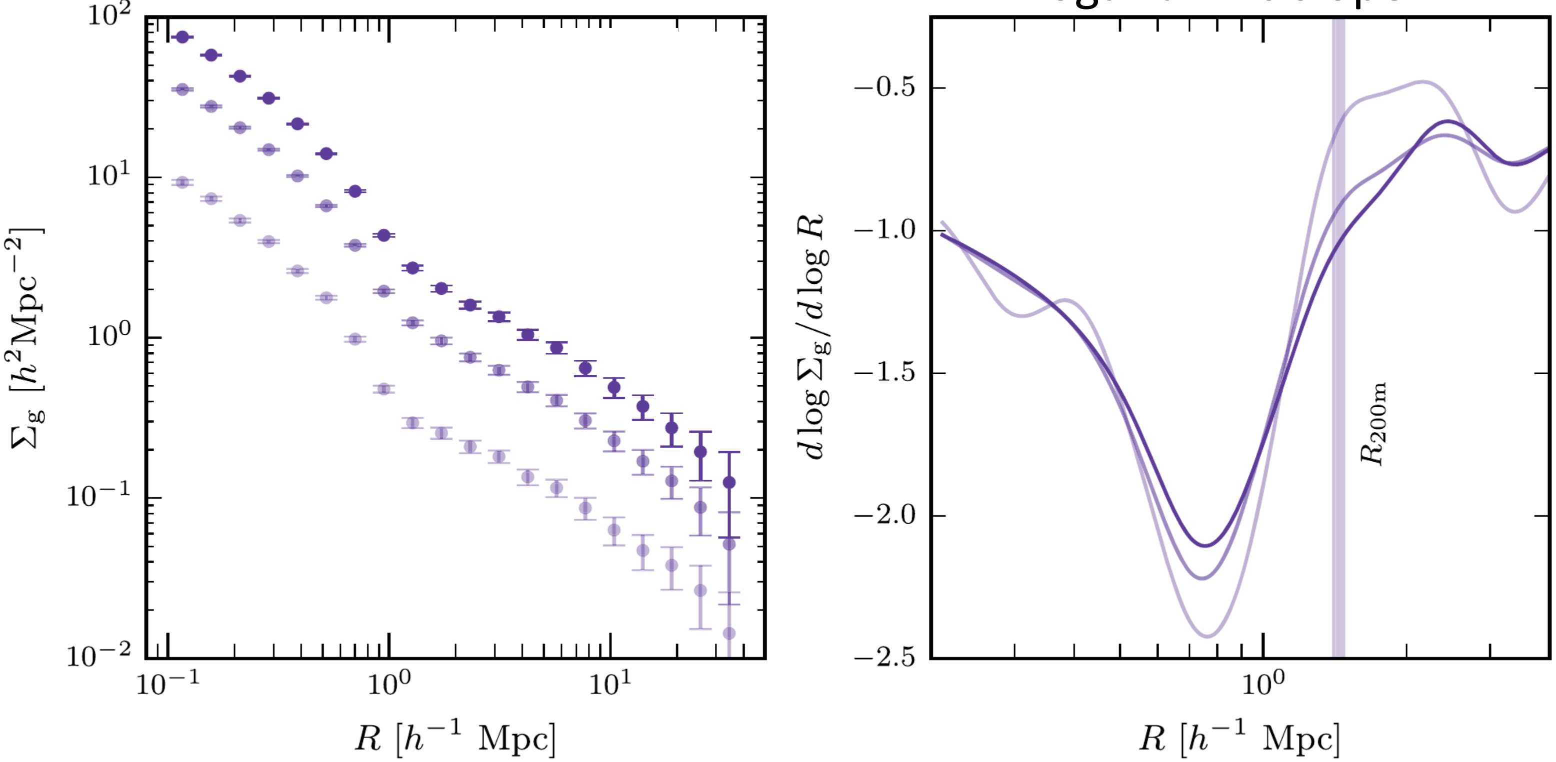
Gas density steepening

Collisional gas accretes slower than DM due to shocks and ram pressure, leading to 10% departures in gas/DM density ratio from the cosmic mean value

Lau et al. 2015

Splashback in SDSS cluster satellite galaxies

Projected galaxy distribution around SDSS/DR8 redMaPPer clusters (S. More+16)



Cluster-satellite density correlation

Logarithmic slope

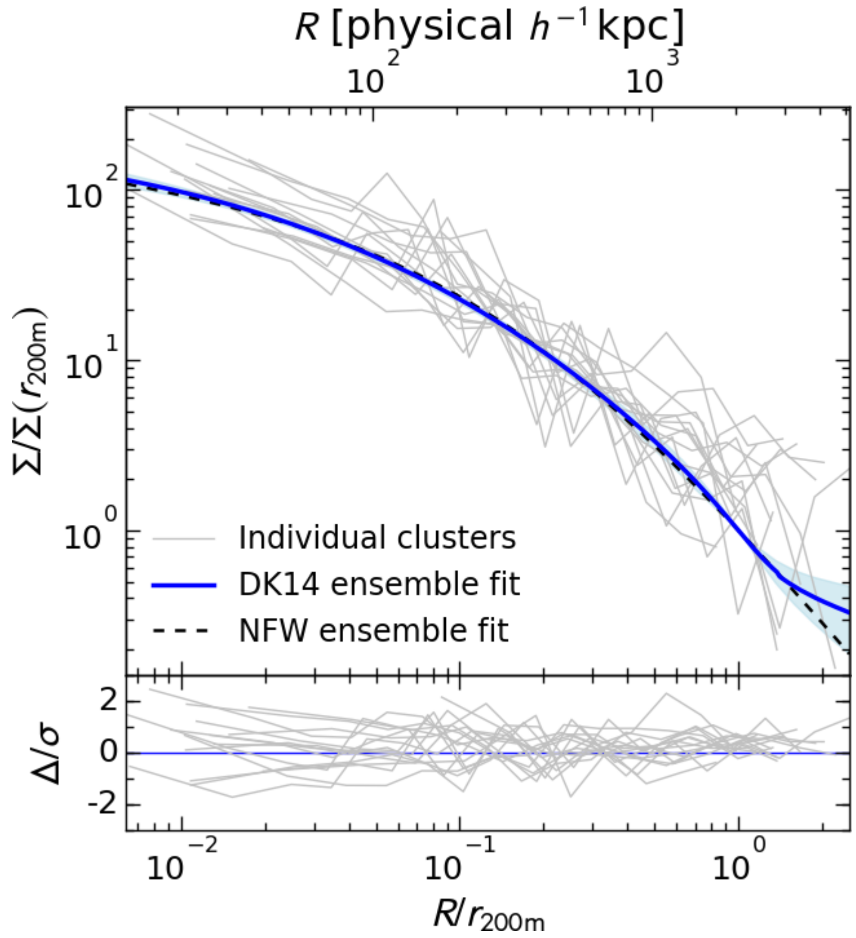
$$\boxed{R_{sp}/r_{200m} = 0.84 \pm 0.03 \text{ at } M_{200m} = 1.9\times10^{14} M_{sun}/h \quad (z = 0.24)}$$

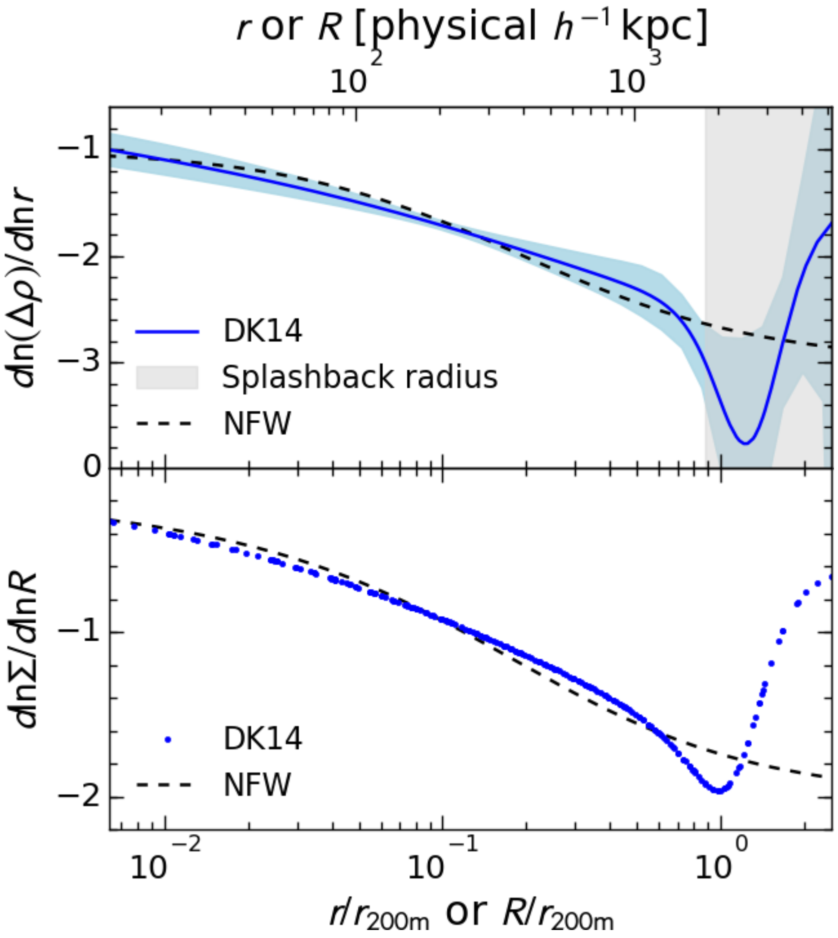
S. More et al. 2016

- Steepest slope found at significantly smaller radius than predicted R_{sp}/r_{200m} ~ 1.1
- Projection effects in cluster membership identification (Zu+16; Busch & White 17)

CLASH cluster lensing constraints on $R_{\rm sp}$

Simultaneous model fit to "scaled" Σ profiles of 16 X-ray-selected CLASH clusters

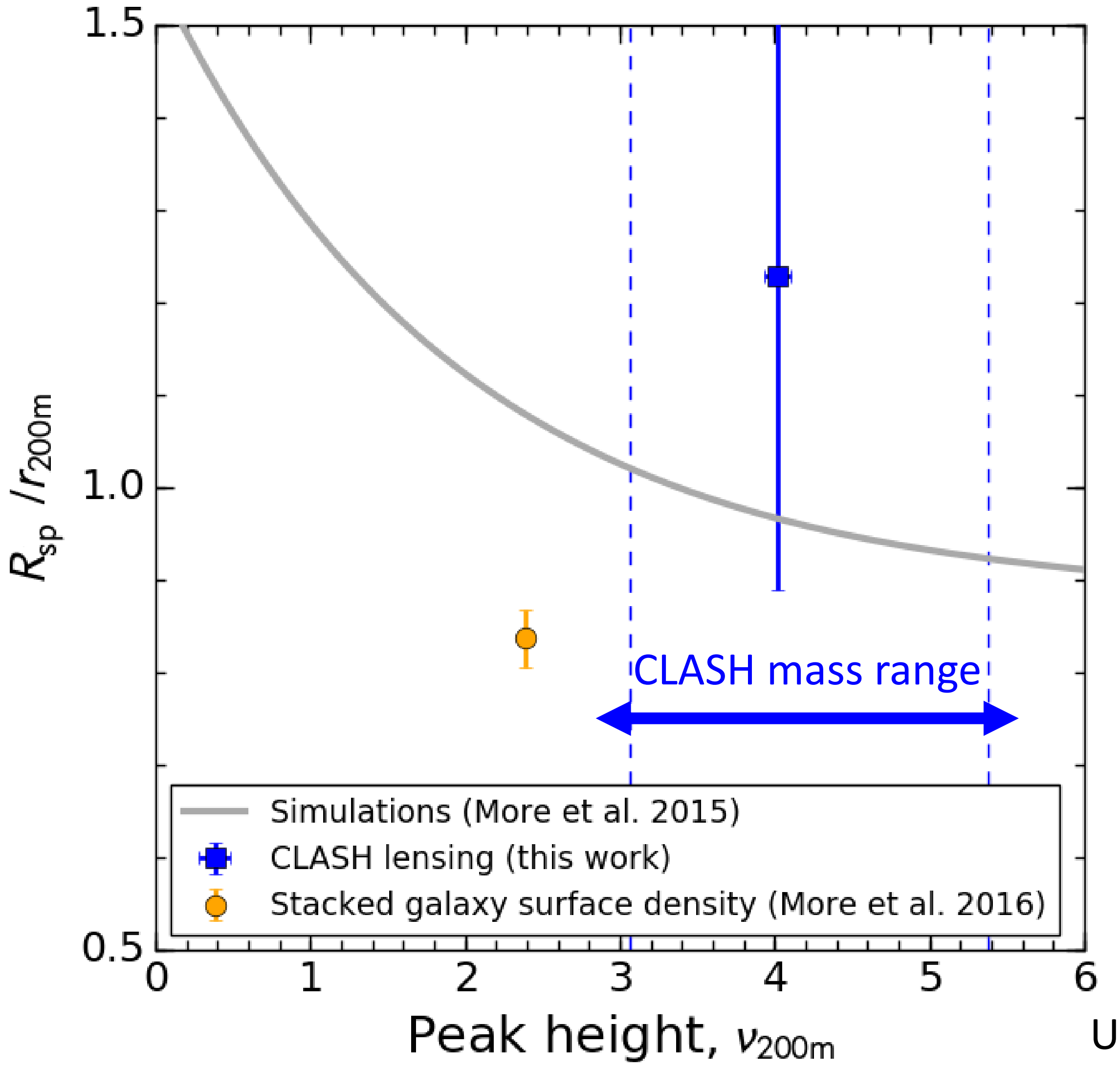




$$\boxed{R_{\rm sp}/r_{\rm 200m} > 0.89\,(1\sigma) \text{ at } M_{\rm 200m} = 1.3\times10^{15}\,M_{\rm sun}/h \quad (z=0.34)}$$

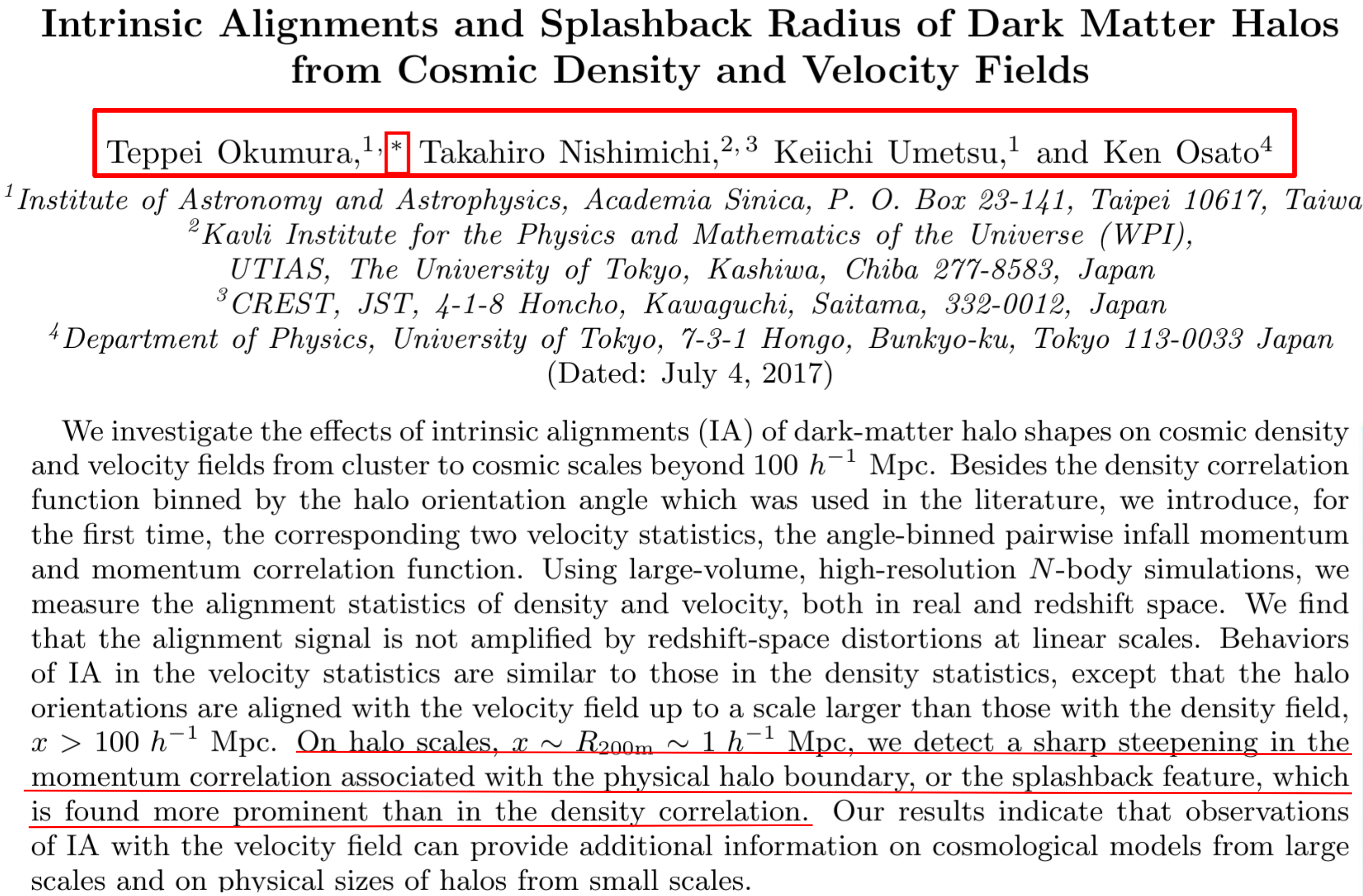
Umetsu & Diemer 17,
ApJ, 836, 231

Density steepening: Observations vs. simulations



Umetsu & Diemer 17,
ApJ, 836, 231

Splashback feature in real & velocity space



Intrinsic Alignments and Splashback Radius of Dark Matter Halos from Cosmic Density and Velocity Fields

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[4] *Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 Japan*

(Dated: July 4, 2017)

We investigate the effects of intrinsic alignments (IA) of dark-matter halo shapes on cosmic density and velocity fields from cluster to cosmic scales beyond 100 h^{-1} Mpc. Besides the density correlation function binned by the halo orientation angle which was used in the literature, we introduce, for the first time, the corresponding two velocity statistics, the angle-binned pairwise infall momentum and momentum correlation function. Using large-volume, high-resolution N-body simulations, we measure the alignment statistics of density and velocity, both in real and redshift space. We find that the alignment signal is not amplified by redshift-space distortions at linear scales. Behaviors of IA in the velocity statistics are similar to those in the density statistics, except that the halo orientations are aligned with the velocity field up to a scale larger than those with the density field, $x > 100\ h^{-1}$ Mpc. On halo scales, $x \sim R_{200\mathrm{m}} \sim 1\ h^{-1}$ Mpc, we detect a sharp steepening in the momentum correlation associated with the physical halo boundary, or the splashback feature, which is found more prominent than in the density correlation. Our results indicate that observations of IA with the velocity field can provide additional information on cosmological models from large scales and on physical sizes of halos from small scales.

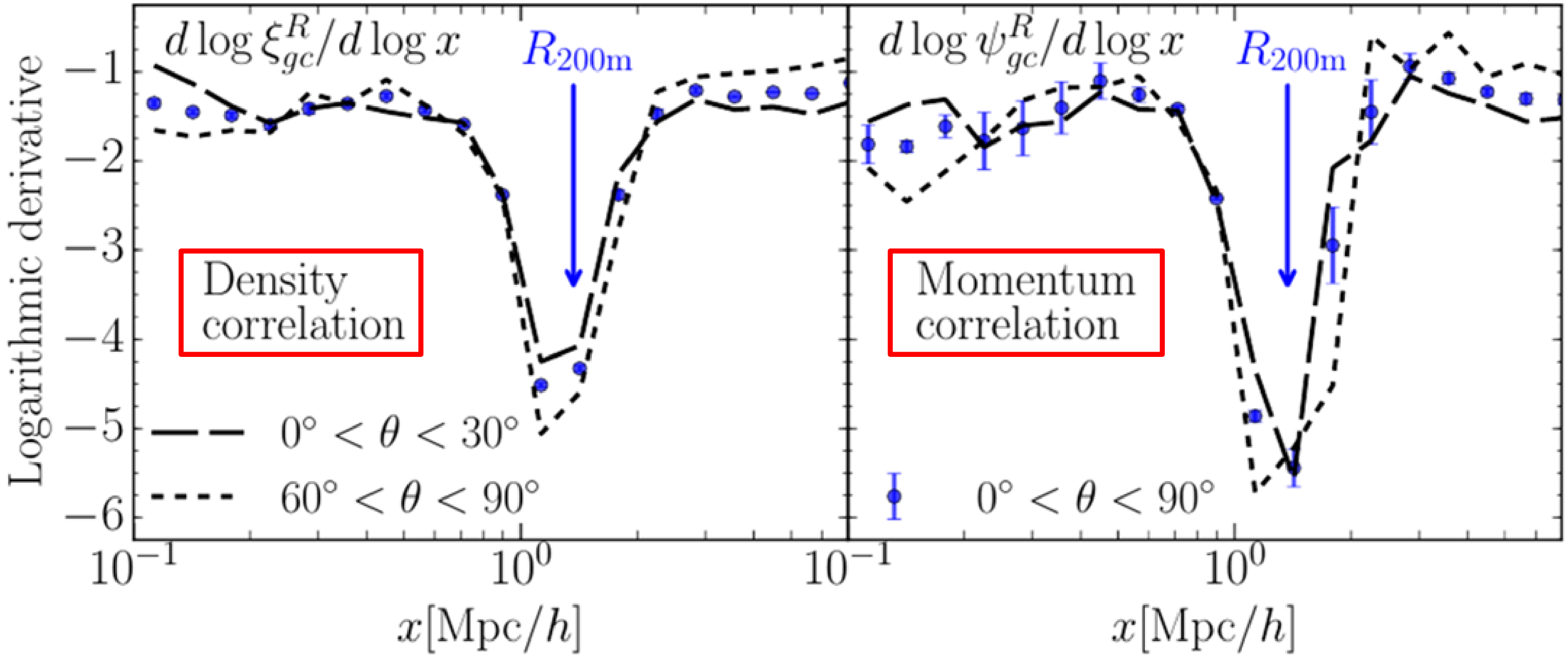
arXiv:1706.08860

KU & T. Okumura, Dec 2014

Cluster-satellite correlations in simulations

$$\xi_{\mathrm{gc}}(\mathbf{x}) := \langle \delta_{\mathrm{g}}(\mathbf{r}_1)\delta_{\mathrm{c}}(\mathbf{r}_2) \rangle$$

$$\psi_{\mathrm{gc}}(\mathbf{x}) := \langle [1+\delta_{\mathrm{g}}(\mathbf{r}_1)][1+\delta_{\mathrm{c}}(\mathbf{r}_2)] v_{\mathrm{g}}^{z}(\mathbf{r}_1) v_{\mathrm{c}}^{z}(\mathbf{r}_2) \rangle \quad \text{with } x = \mathbf{r}_2 - \mathbf{r}_1$$



- Steepening in momentum correlation (slope ~ -5) more prominent than in density correlation (slope ~ -4)
- Need high-resolution kSZE to measure ψ_{gc}

Okumura+17, arXiv:1706.08860

Satellite velocity dispersion

$$\sigma_{v,\mathrm{gc}} := \left\langle [1+\delta_{\mathrm{g}}(\mathbf{r}_1)][1+\delta_{\mathrm{c}}(\mathbf{r}_2)][v^z_{\mathrm{g}}(\mathbf{r}_1)-v^z_{\mathrm{c}}(\mathbf{r}_2)]^2 \right\rangle$$

Okumura+17,
arXiv:1706.08860

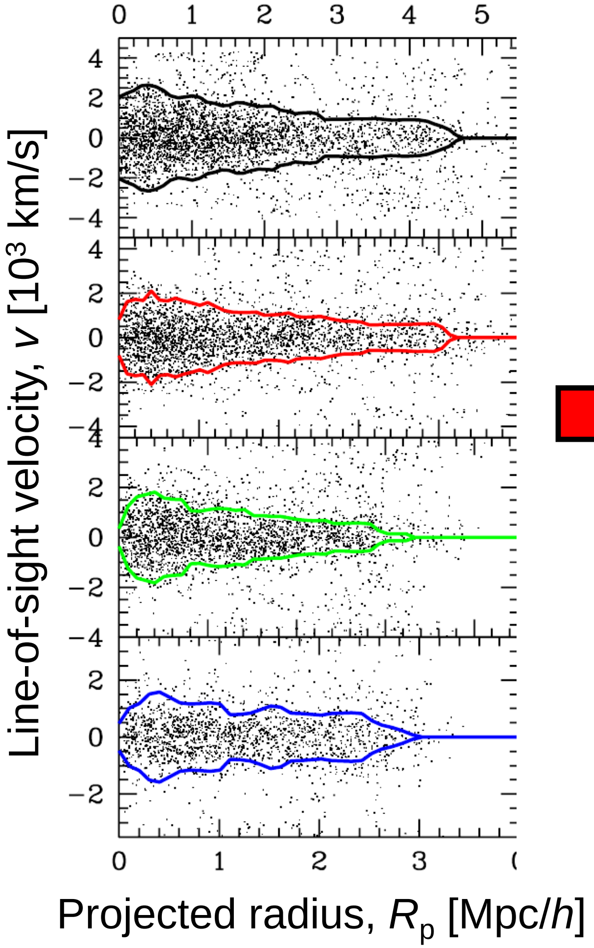
Accessible in principle from spectroscopic observations in projection

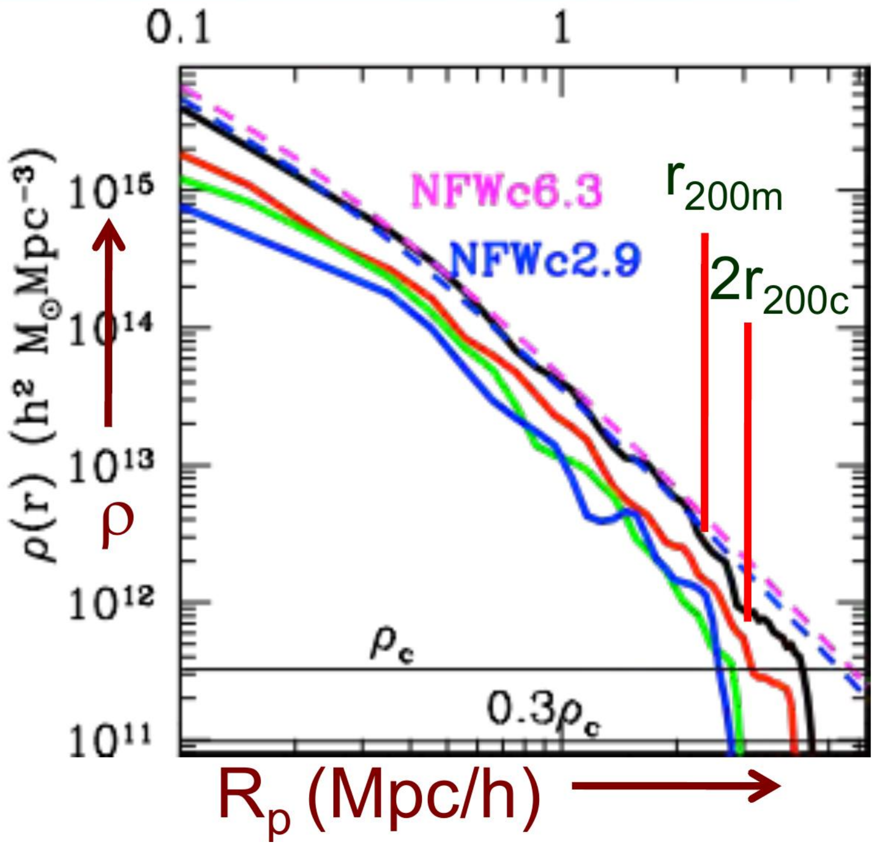
Figure courtesy of Teppei Okumura

Stacked infall patterns in projected phase space

Stacked ensembles of 58 X-ray-selected clusters at 0.1<*z*<0.3
(Hectspec Cluster Survey with MMT) by Rines+13

Dynamical caustic: escape velocity

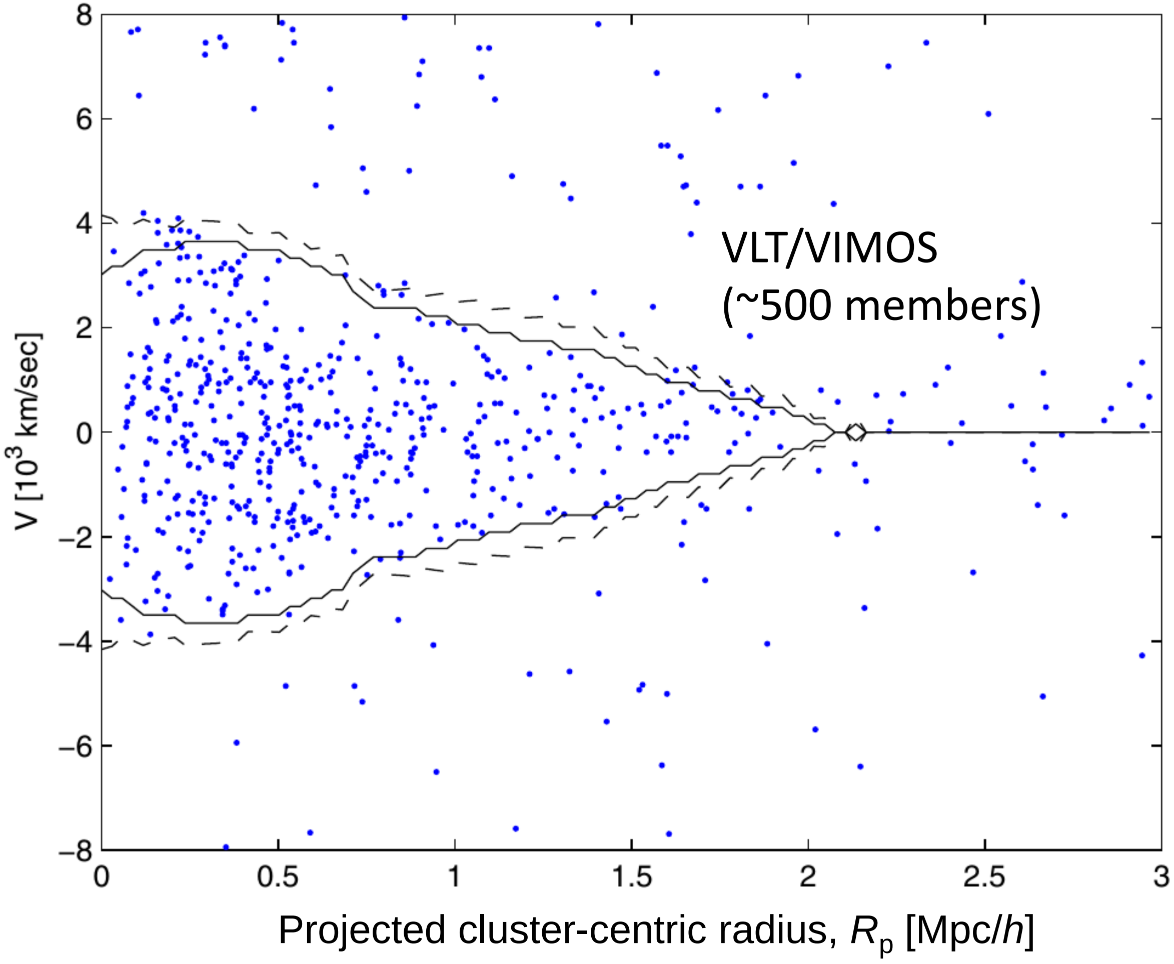




Rines et al. 2013

Halo edge in Superlens A1689

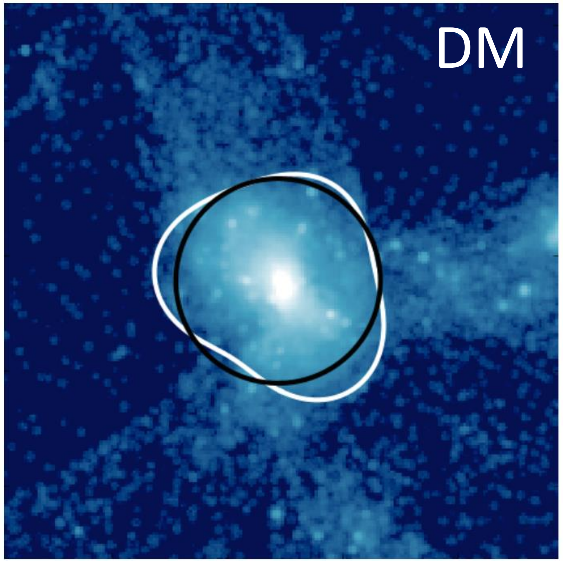
Phase-space identification of cluster edge radius, ~2.1Mpc/h, thanks to high density contrast of the superrich cluster A1689

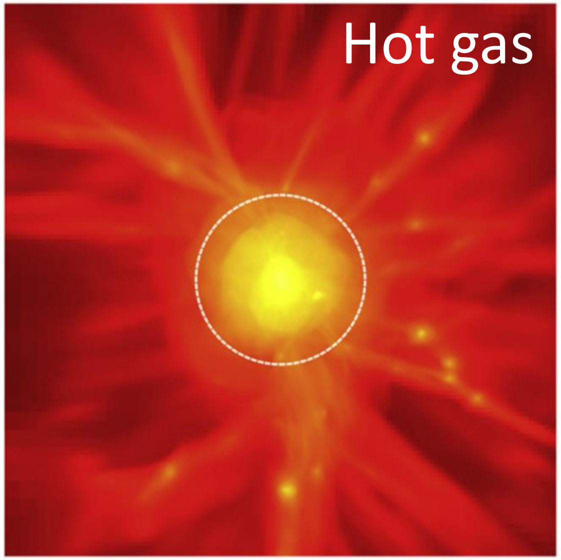


VLT/VIMOS (~500 members)

Lemze, Broadhurst, Rephaeli, Barkana, & Umetsu 2009, *ApJ*, 701, 1336

Joint observations of splashback and accretion shock features?





Collisionless splashback features (~ R_{sp})

- Steepening in satellite density
- Steepening in lensing signal
- Steepening in velocity caustic (+σ_v)

Accretion shock features (~ R_{shock})

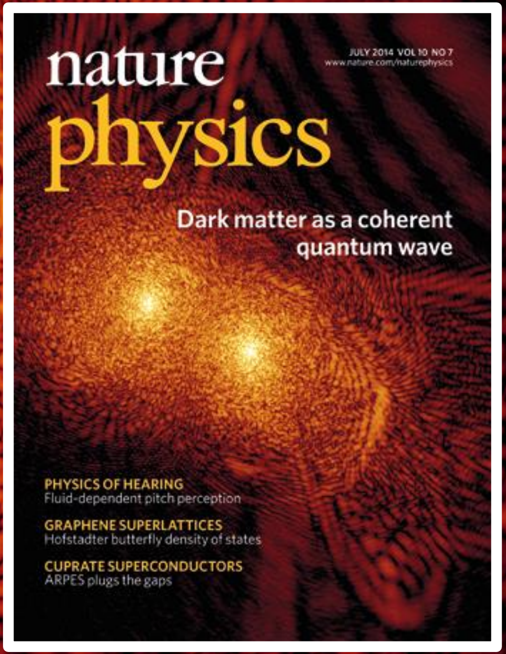
- Maximum peak in gas entropy @R_{shock}
- Steepening in gas density

Theoretical requirements

- Quantitative understanding of splashback feature in phase space (e.g., Okumura+17)
- Establish the relation between DM and gas features from simulations (e.g., Lau+15, Diemer+17)

(3) Granularity of galaxy-scale dark matter halos: CDM vs. ψDM

Schive, Chiueh, & Broadhurst
2014, *Nature Physics*, 10, 496


nature physics

JULY 2014 VOL 10 NO 7
www.nature.com/naturephysics

Dark matter as a coherent quantum wave

PHYSICS OF HEARING
Fluid-dependent pitch perception

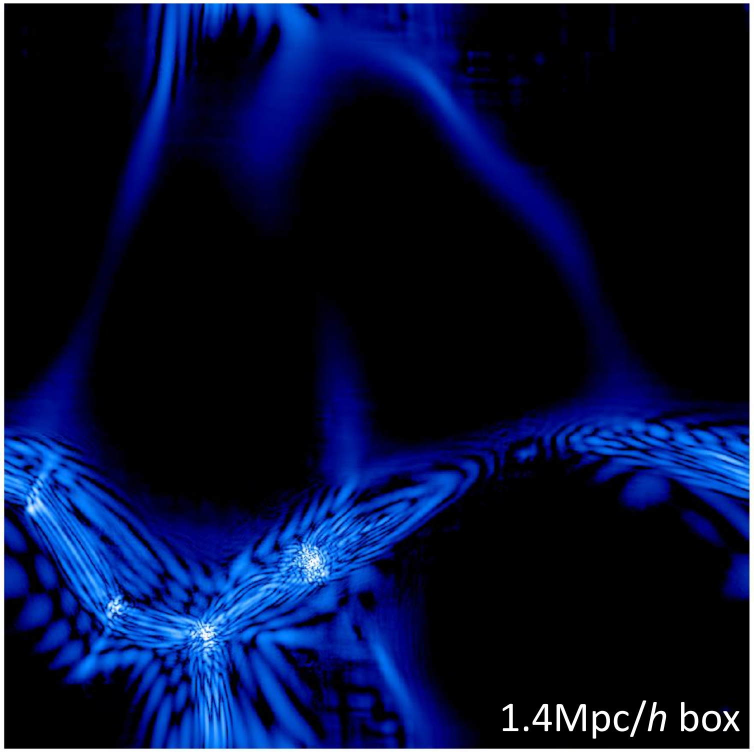
GRAPHENE SUPERLATTICES
Hofstadter butterfly density of states

CUPRATE SUPERCONDUCTORS
ARPES plugs the gaps

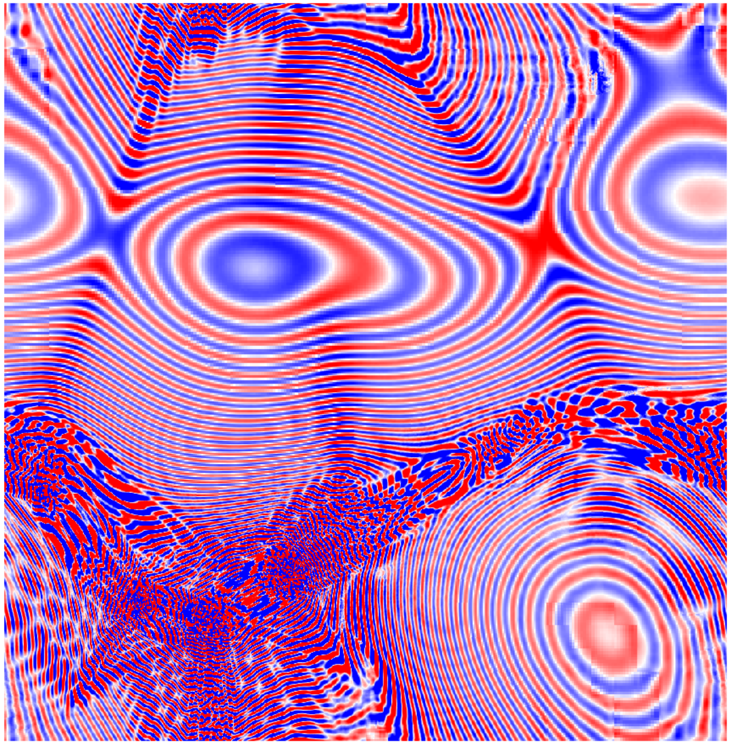
Hsi-Yu Schive (U of Illinois)
James Chan (NTU)
Tzihong Chiueh (NTU)
Tom Broadhurst (Ikerbasque, Spain)

Quantum fluid ψDM in nonlinear regime: Numerical challenges

Density



Wave function

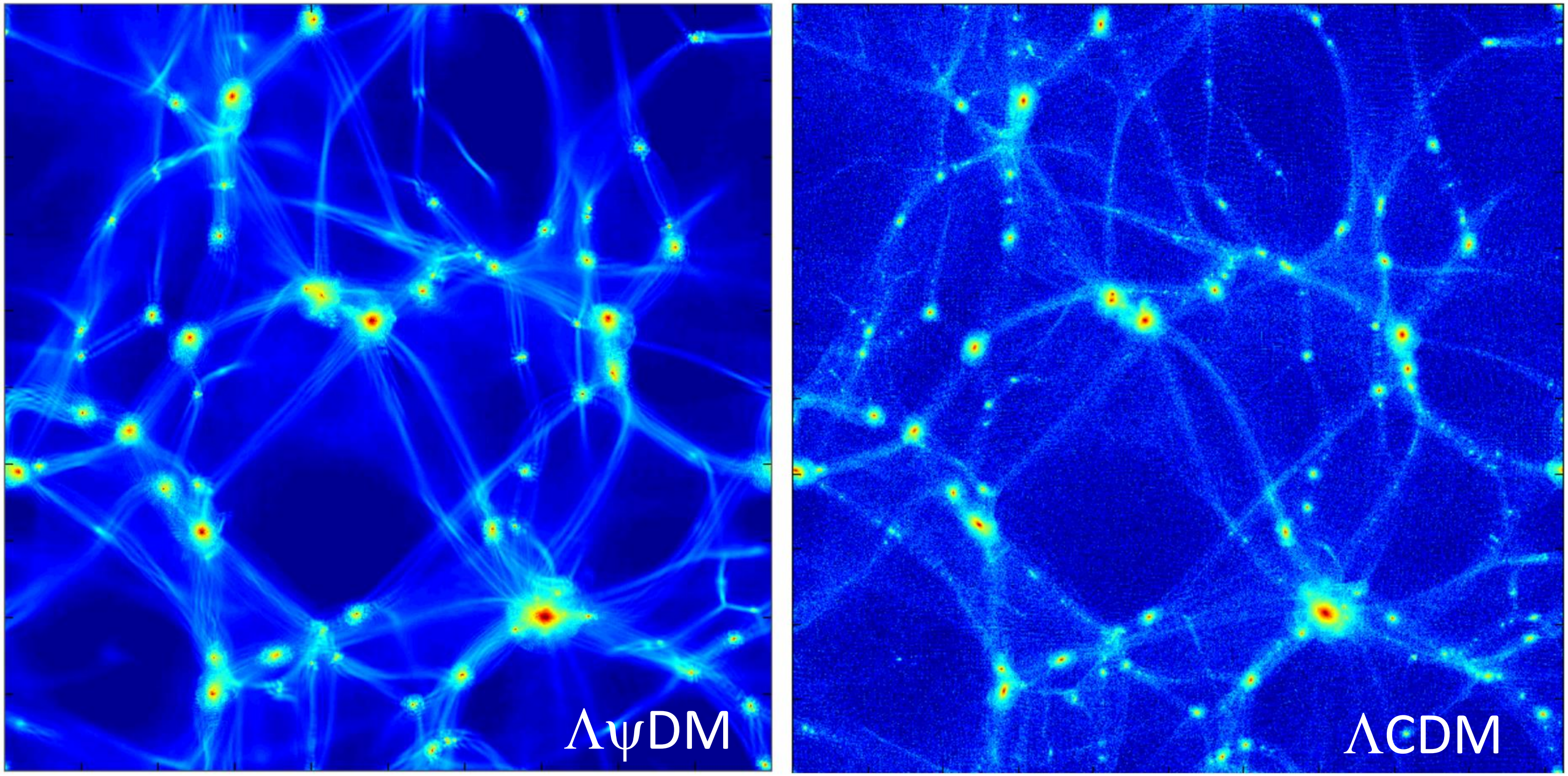


de Broglie λ <~ kpc for astrophysical Bose-Einstein condensates with m_B~ 10^{-22}eV

→Ultra-high resolution ($\lambda \propto 1/v$, 200km/s → 100pc) and extremely small time-step ($\Delta t \propto \Delta x^2$) are required!!

Schive, Chiueh, & Broadhurst 14

ψDM vs. CDM: large scale features



ψDM on AMR grid (GAMER)

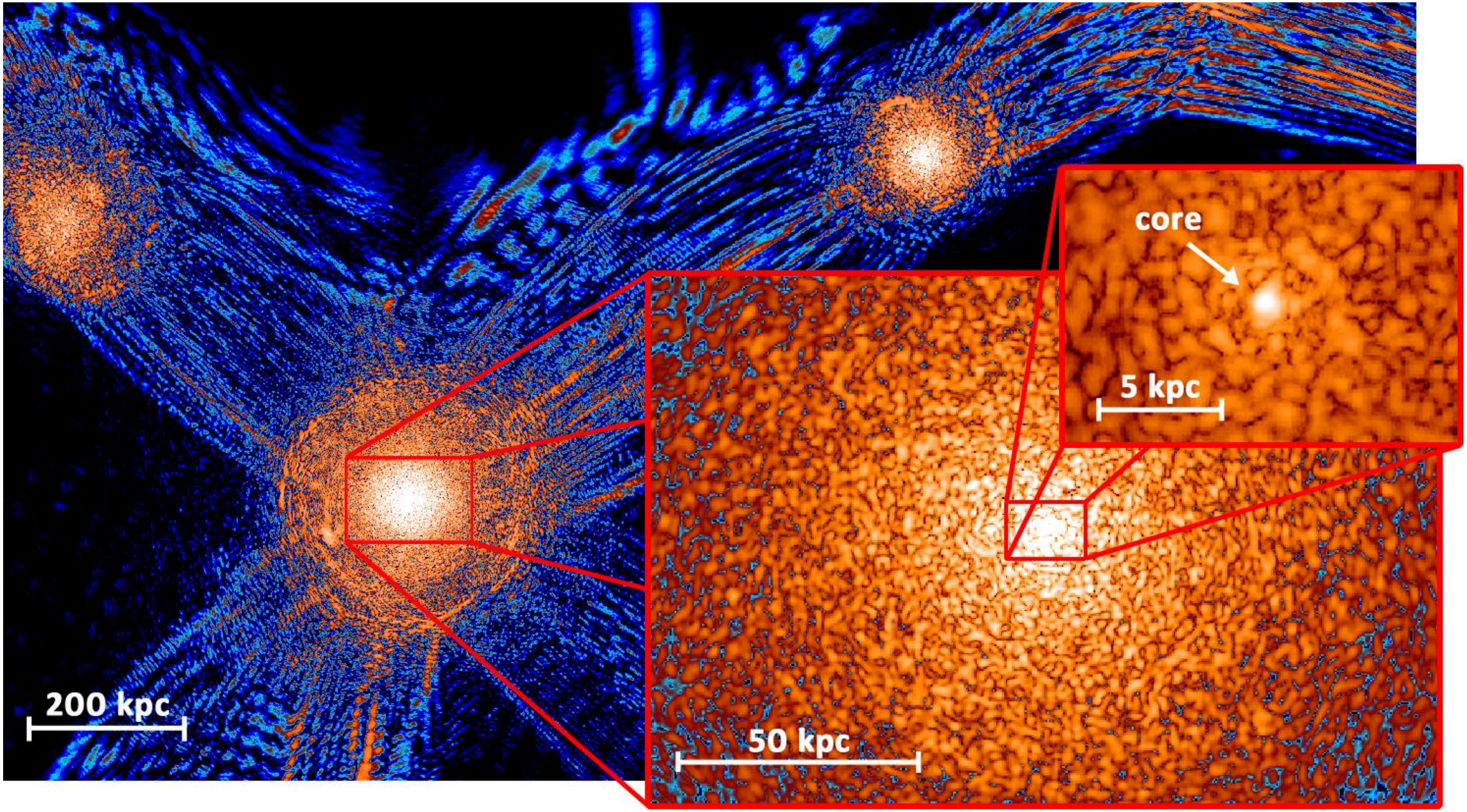
Particle CDM (GADGET-2)

50Mpc/*h* box

Large scale structures indistinguishable from collisionless CDM

Schive, Chiueh, & Broadhurst 14

Nonlinear structure of wavelike ψDM halos: Density granules and solitonic core

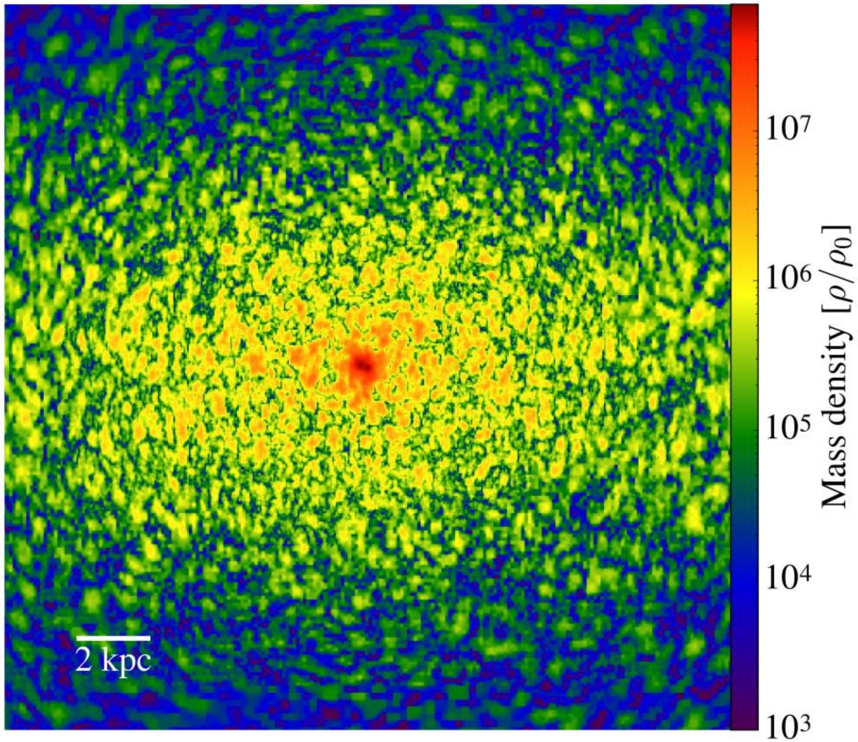


Schive, Chiueh, & Broadhurst 14

Granularity of ψDM halos

The halo density field is 100% modulated with ψDM, which is the most obvious difference from particle CDM and WDM

$M_{\rm halo}$ ~ 1.6e11$M_{\rm sun}$, z=0.3
$M_{\rm DM}/M_*$ ~ 0.93 within $R_{\rm Ein}$ ~ 0.9kpc (z_s=3)



Soliton core size ~ Halo granule size

The halo granule scale is set by the halo mass:

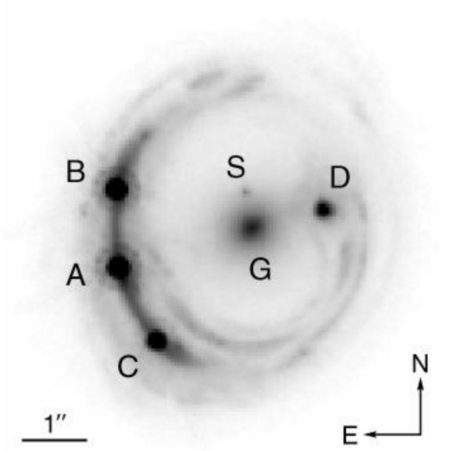
$$\frac{M_{\rm core}}{M_{\rm halo}} \propto a^{-1/2} M_{\rm halo}^{-2/3}$$

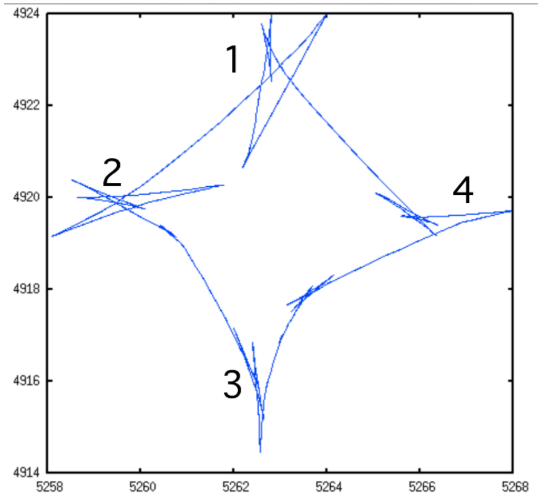
(Schive+14, *PRL*, 113, 261302)

- $M_{\rm core}$ ~ 5x$10^8 M_{\rm sun}$, $r_{\rm core}$~160pc for a Milky-Way-sized halo
- Quantum effects less important for high-mass halos (e.g., clusters)

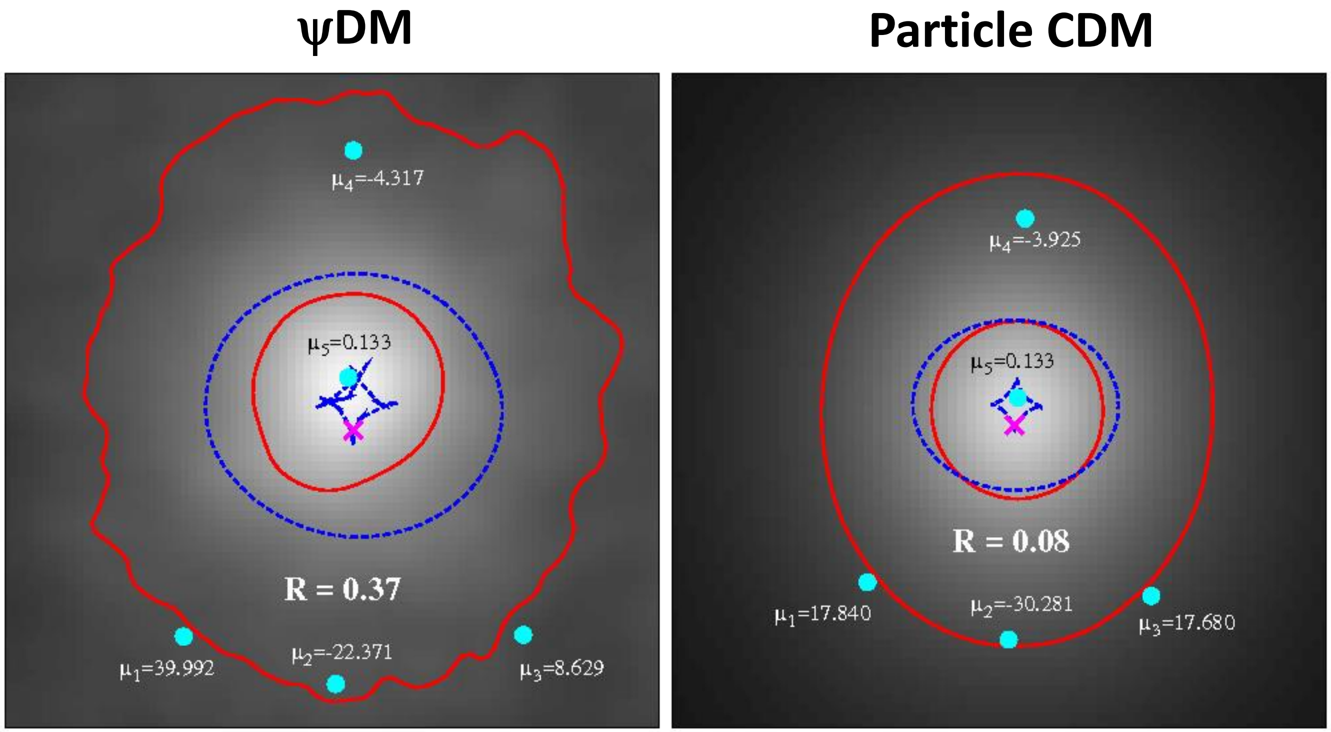
Predictions: Flux anomalies due to ψDM halo granules

Lensing flux anomalies common for quasars strongly lensed by galaxies: $\mu_1+\mu_3-|\mu_2|$ should =0, but usually 10-50% residual





Caustic structure more complex in ψDM – changing image brightness and positions on scale of ~0.1—1 kpc



2kpc (~0.5”) across the image

High angular resolution, narrow-line imaging of QSOs with ELTs to avoid micro lensing

Figure courtesy of J. Chan, H.-Y. Schive, T. Chiueh

Summary

1. **Cluster DM peculiar velocity from the moving lens effect**
   - High velocity precision spectroscopy (sub km/s) of background galaxies/QSOs strongly lensed by clusters
2. **Splashback features in phase space**
   - Spectroscopic survey of cluster outskirts for splashback featres in phase space, together with joint lensing and X-ray observations
3. **Granularity of galaxy-scale DM halos: ψDM vs. CDM**
   - High precision, high resolution photometry of QSO-galaxy strong lensing systems with AO narrow-band imaging to test wavelike ψDM vs. CDM