Illuminating the DM Particle from Lensed Star Transients

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Dark Matter Distinguished by Skewed Microlensing in the "Dragon Arc"

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Supported by RGC/GRF grants 17312122 and 17302023
HKU Seed Fund for Collaborative Research

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Tom Broadhurst

Keith Li Sung Kei
(PhD student)

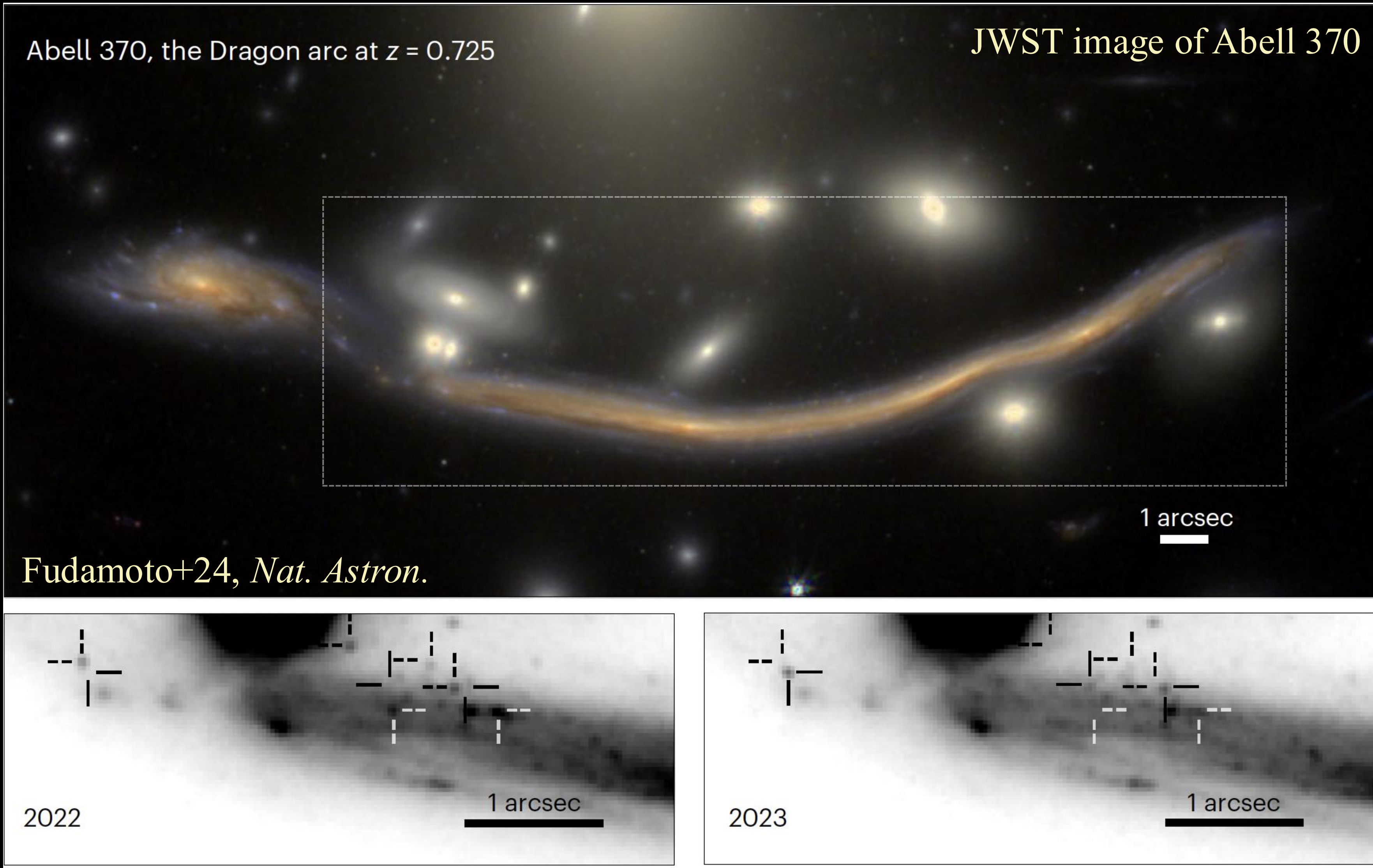
Amruth Alfred
(RGC Postdoc)

Dragon Arc

- Dragon arc was the first gravitationally-lensed arc recognized, comprising a background spiral galaxy at $z = 0.735$ gravitationally lensed by foreground galaxy cluster Abell 370 at $z = 0.375$.

Transients in the Dragon Arc

- Gravitational lensing of individual luminous stars in a background galaxy by foreground galaxy cluster augmented by foreground intracluster stars:



Cluster Macro-Lensing + Stellar Micro-Lensing

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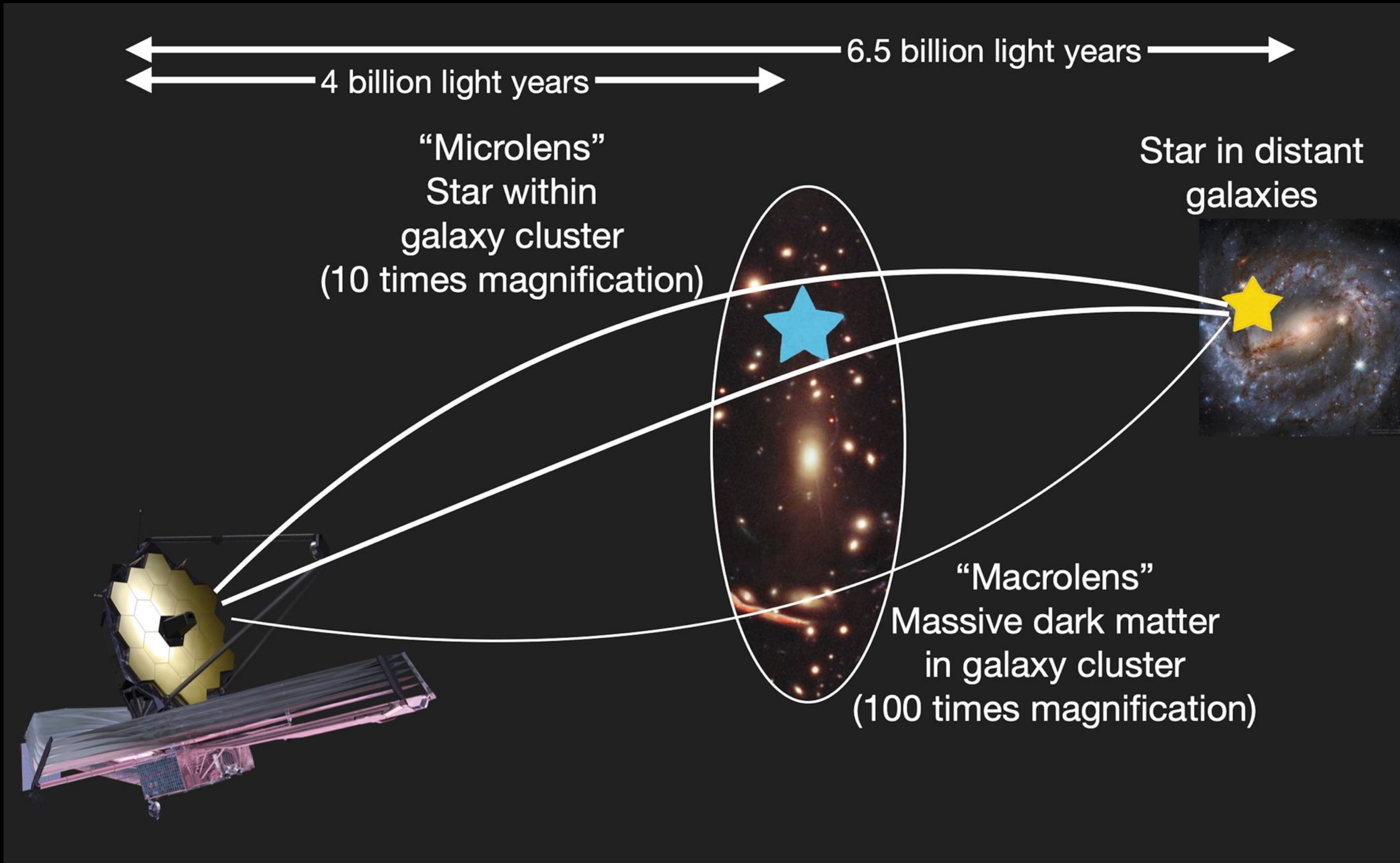
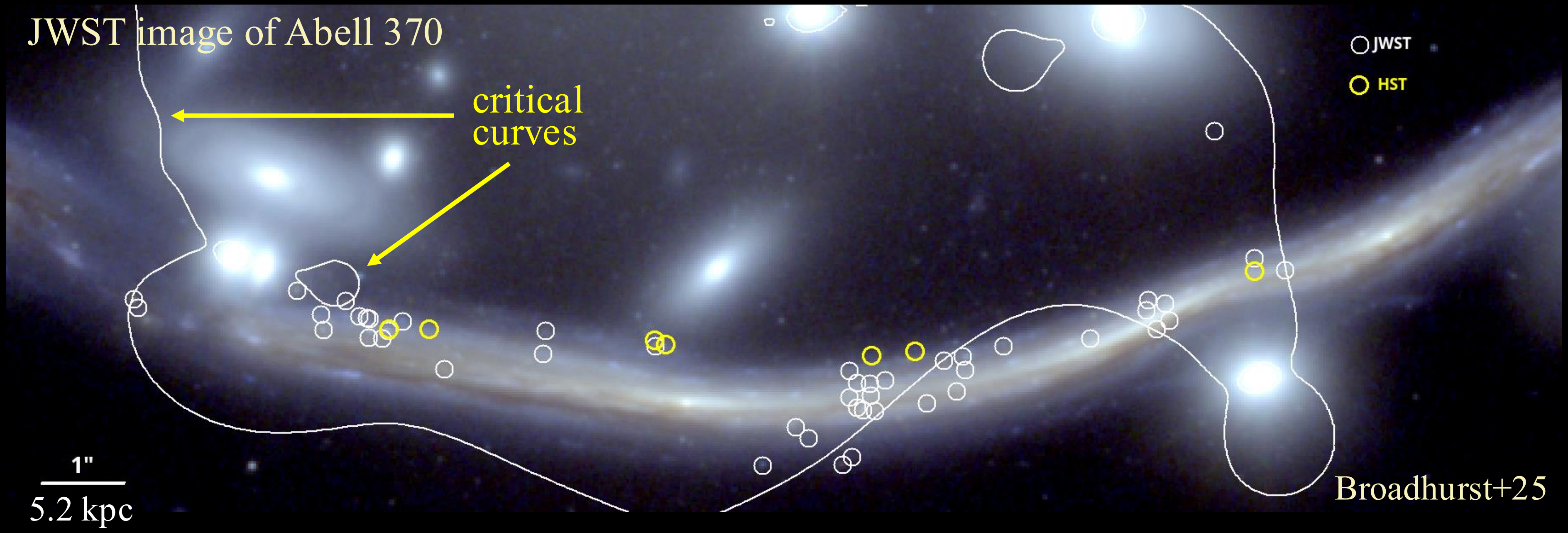


Transients in the Dragon Arc

- Circles enclose transients detected (thus far) in Dragon arc.
- White lines indicate cluster critical curve for background object at $z = 0.735$ based on lens model for Abell 370 constructed by Diego+24.



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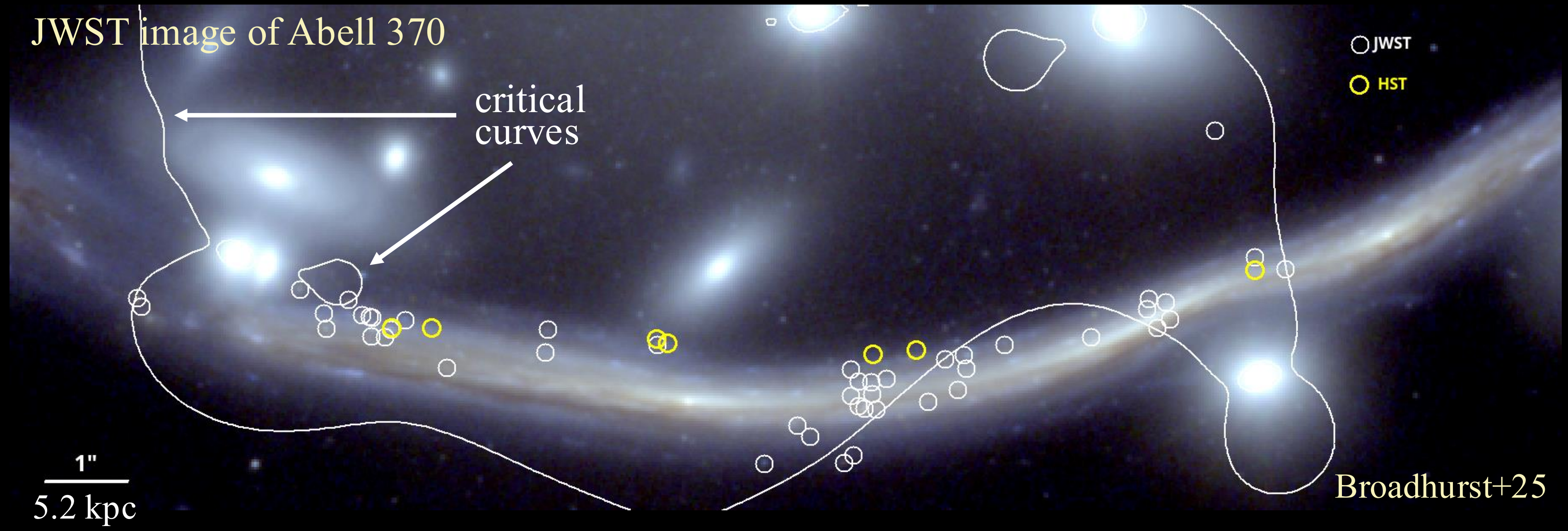
- Behavior of transients:
  - majority not at/very close to critical curve; high cluster magnification translates to small lensed area of background galaxy, hence low probability of encompassing rare luminous stars



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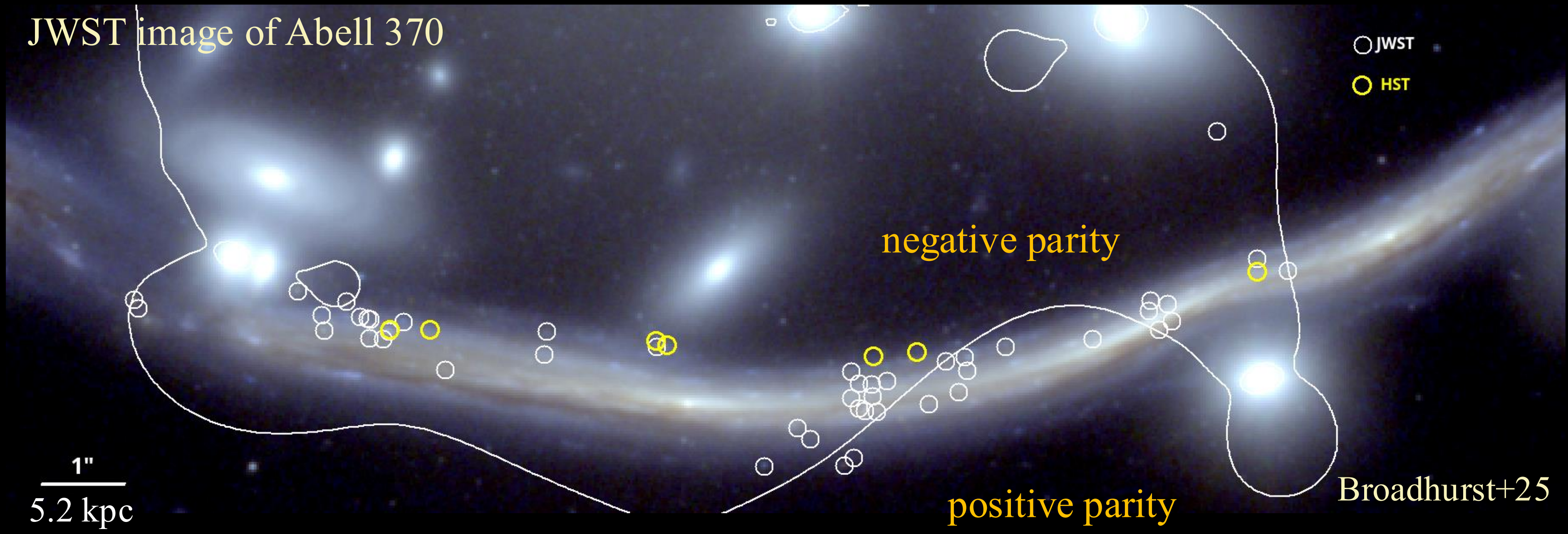
  - more at inner (negative parity) compared with outer (positive parity) side of critical curve



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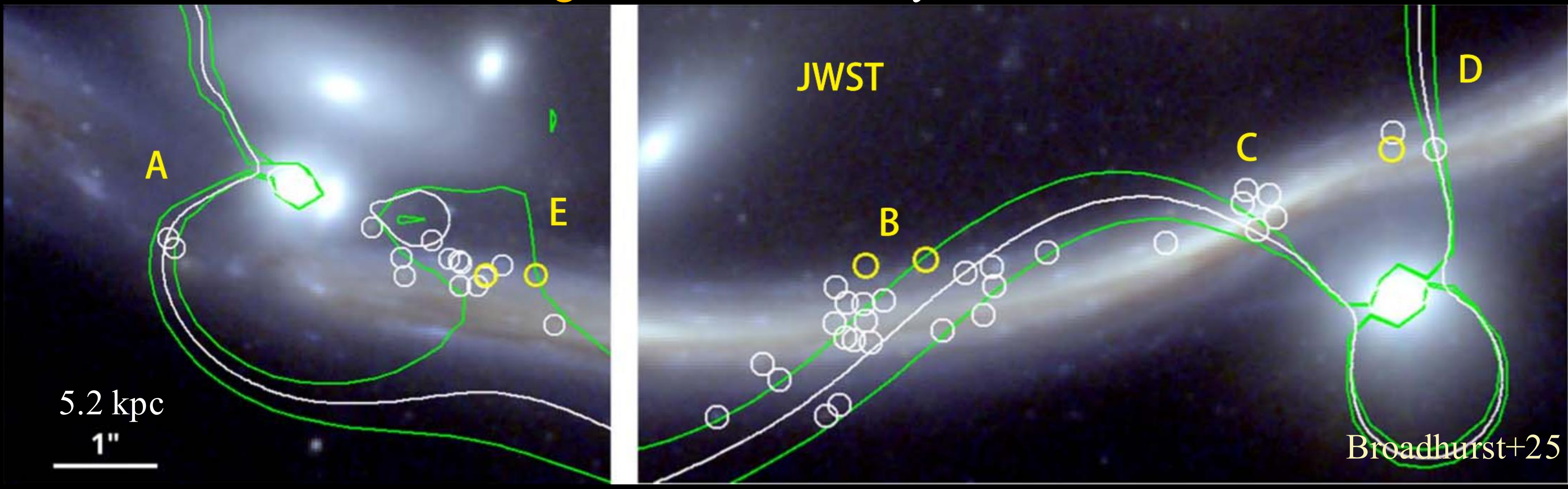
- Focus on 33 transients in regions A-D well away from cluster members.



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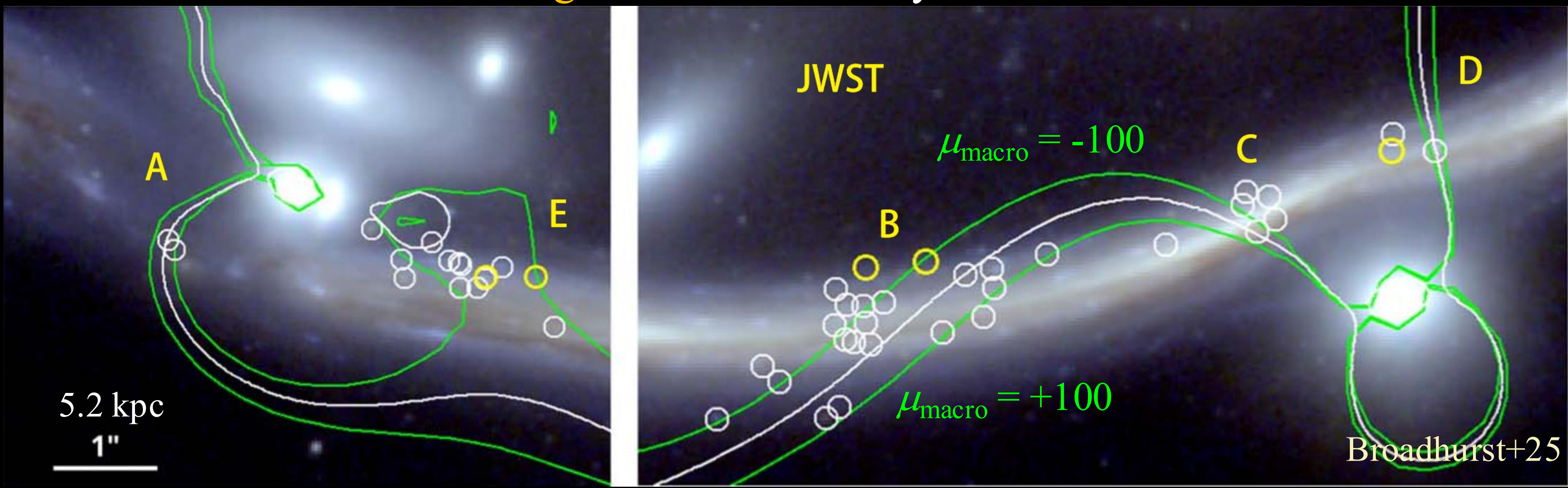
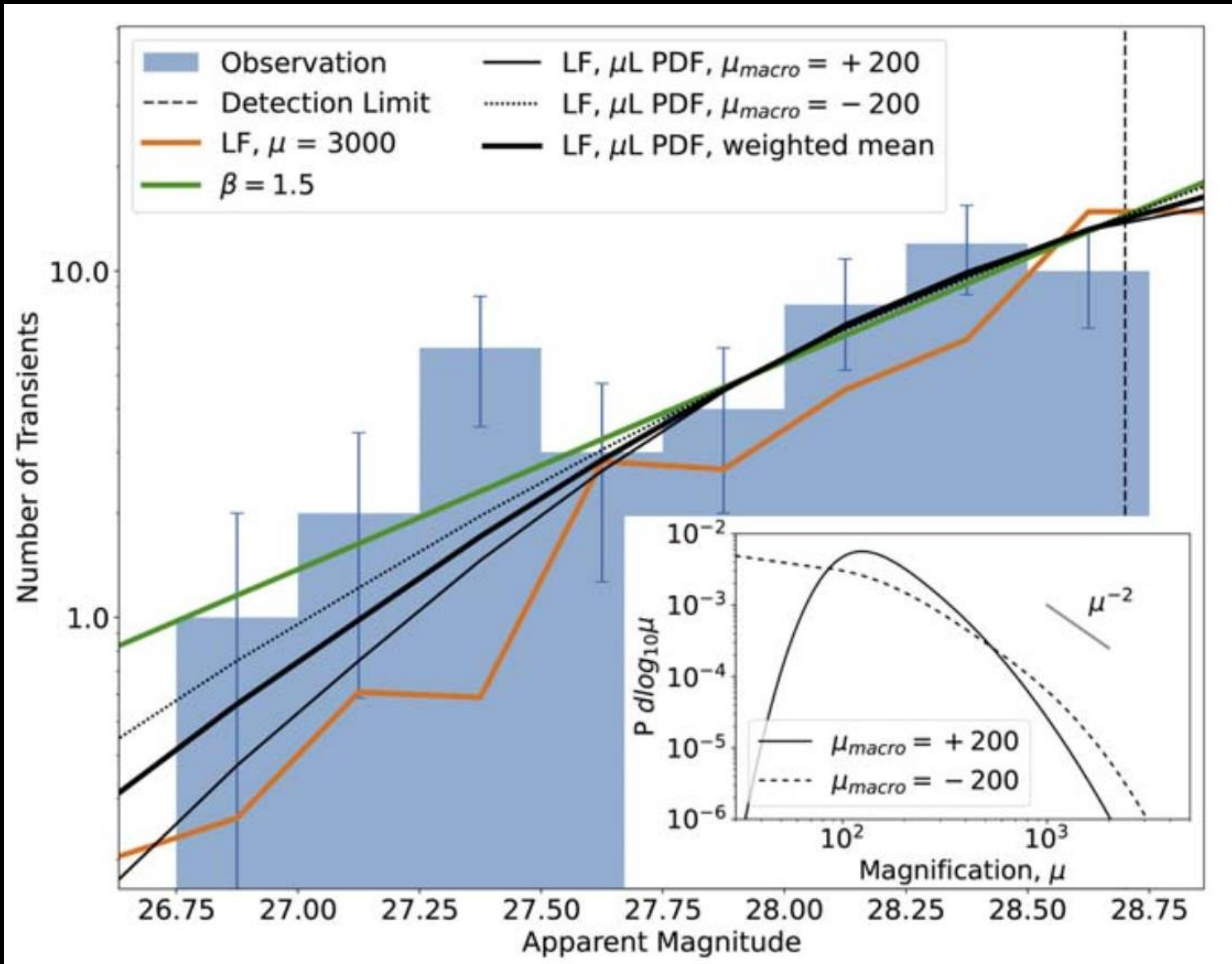
  - majority not at/very close to critical curve; high cluster magnification translates to small lensed area of background galaxy, hence low probability of encompassing rare luminous stars
  - more at inner (negative parity) compared with outer (positive parity) side of critical curve, largely bounded by $\mu_{\mathrm{macro}} = \pm 100$ within ~2 kpc of critical curve
- Focus on 33 transients in regions A-D well away from cluster members.



Brightness Distribution of Transients

- Derive stellar mass and hence stellar luminosity function from SED fitting (exponential decay over time in star-formation rate).



Broadhurst+25

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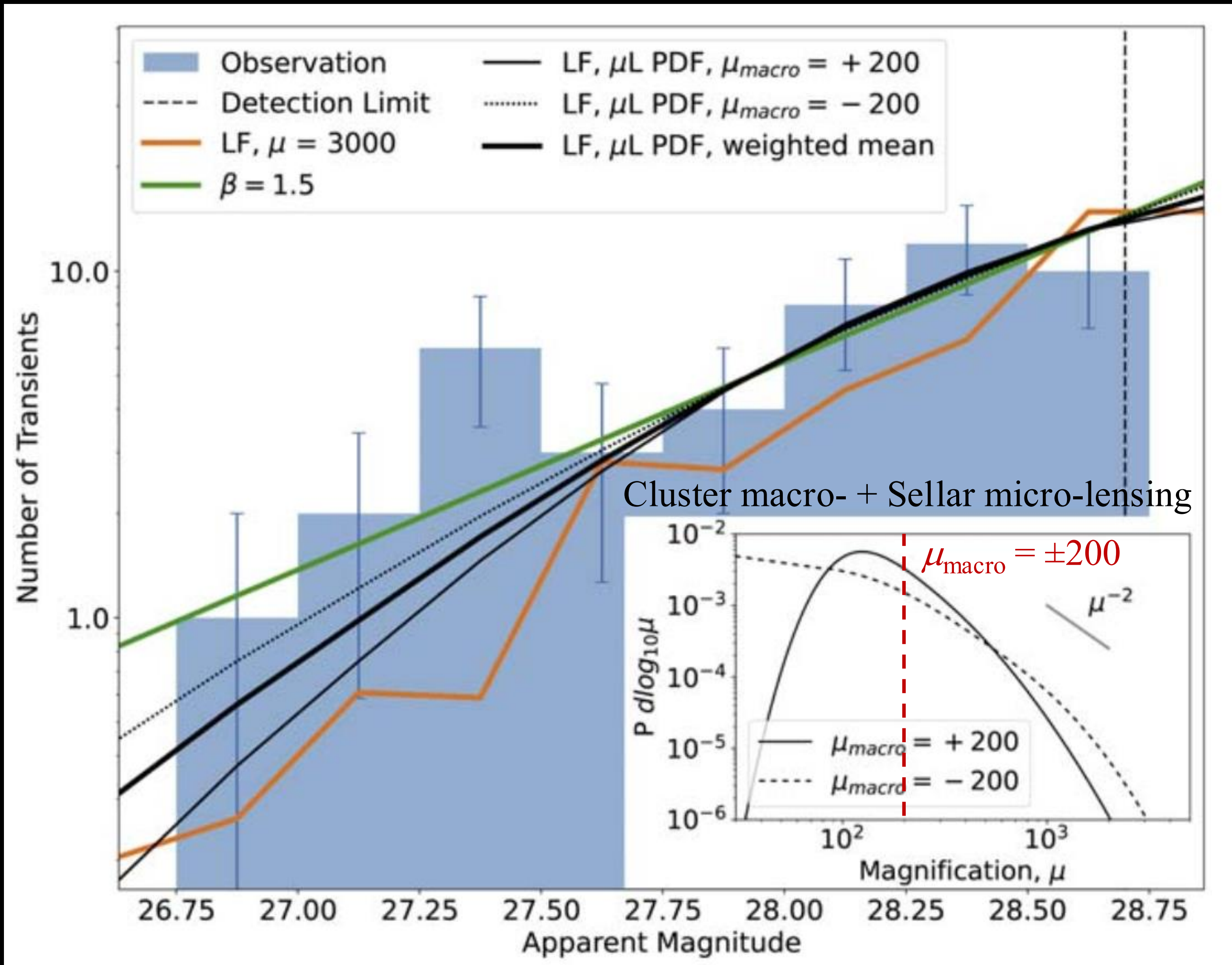

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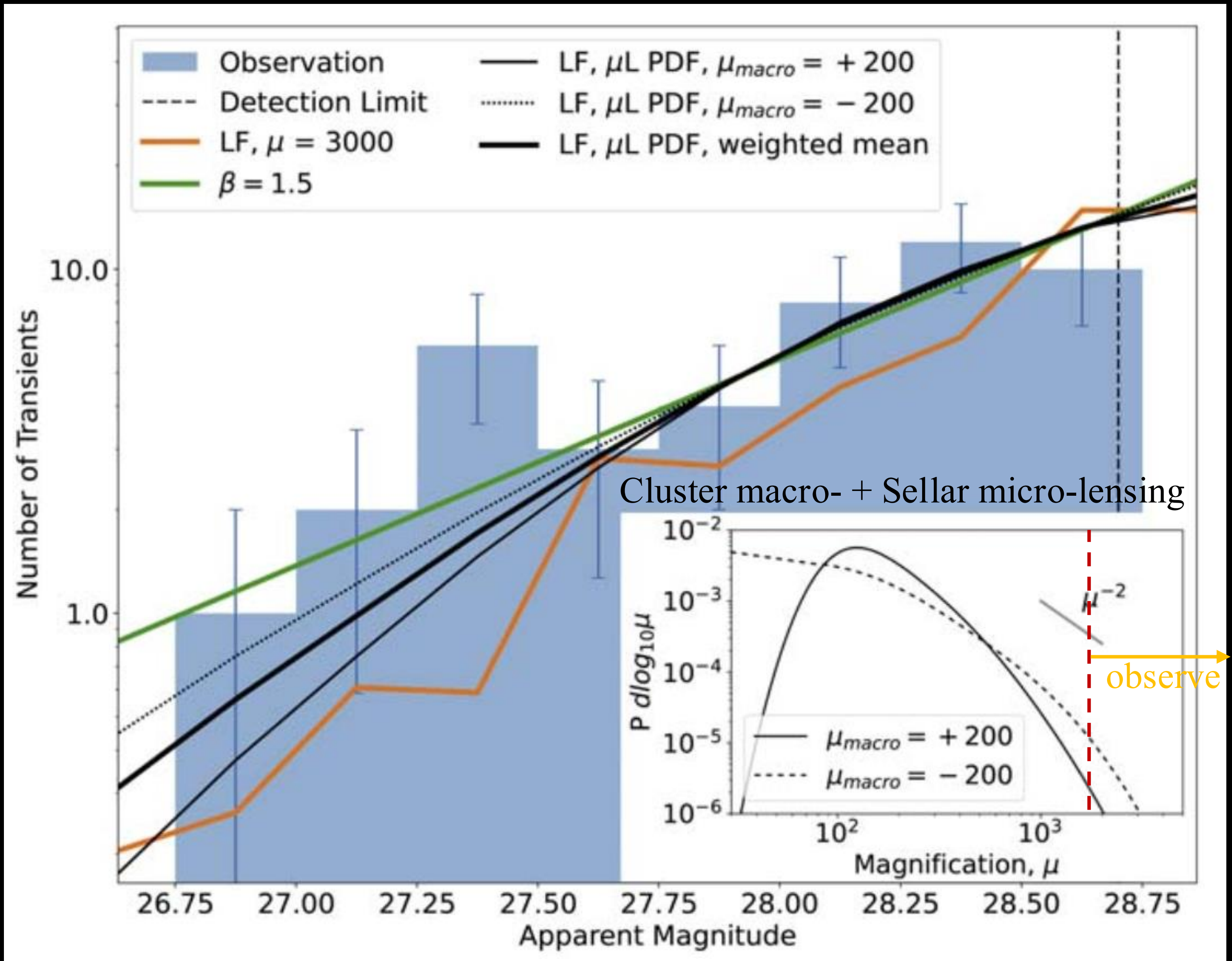

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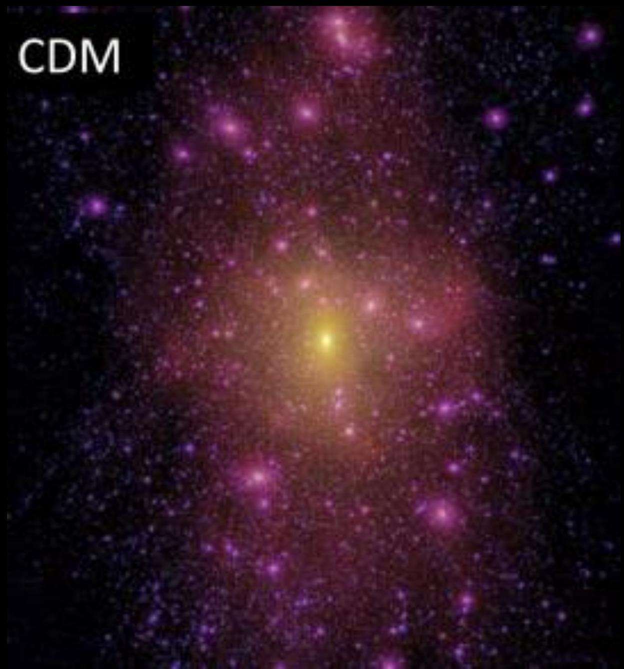
Cosmological Simulations

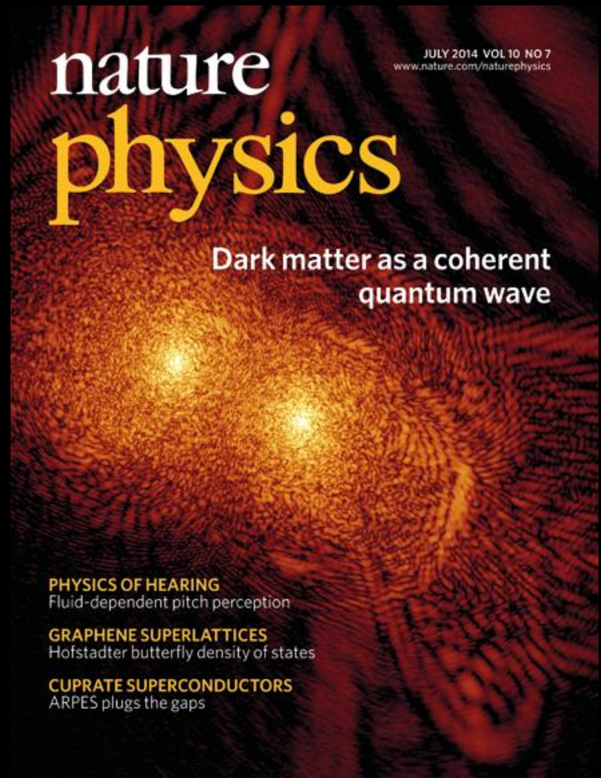
- Different small-scale structures (sub-structures) in Dark Matter – sub-halos versus pervasive density modulations – predict different spatial distributions of lensed star transients across critical curves.

Warm Dark Matter

Cold Dark Matter

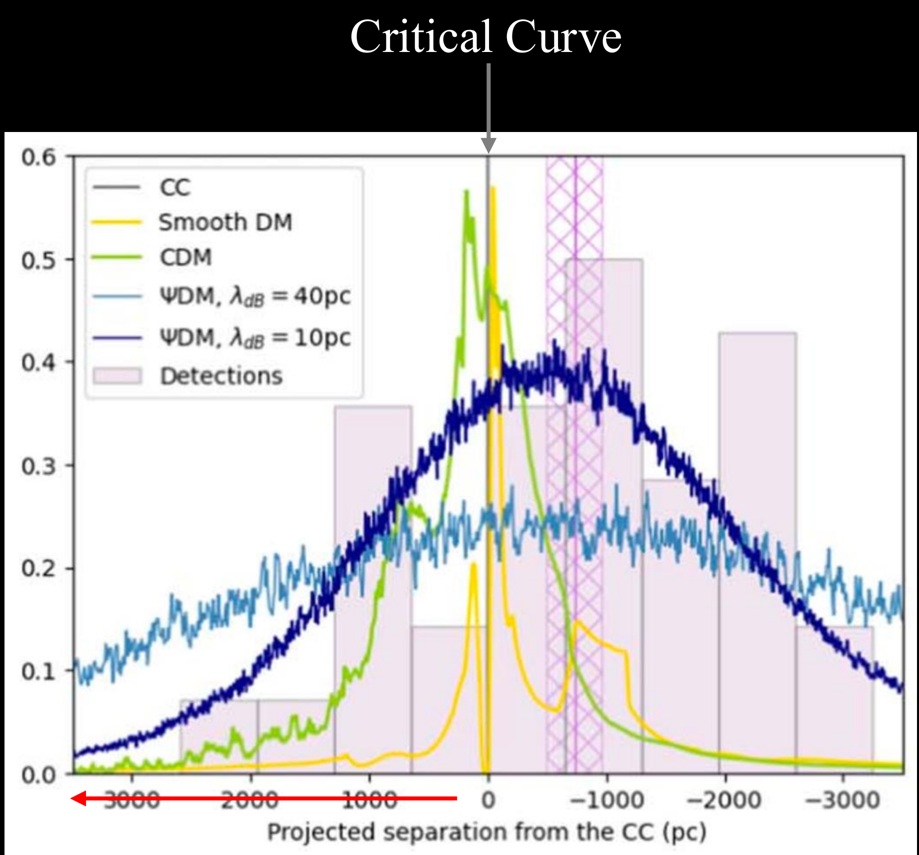


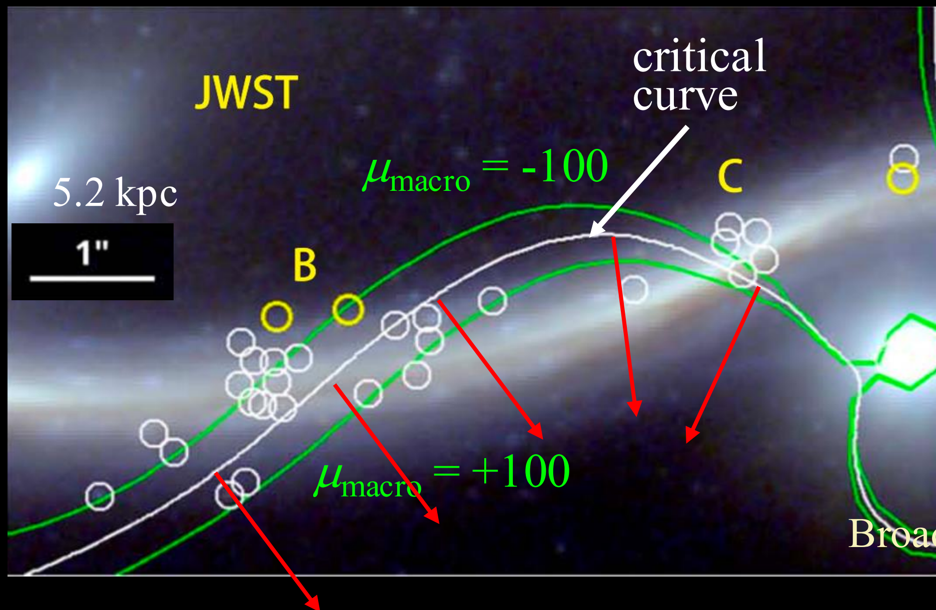
Wave-like Dark Matter



Cluster Smooth DM Halo only (warm + ultra-massive)

- NFW DM halo macro-lensing + stellar micro-lensing:





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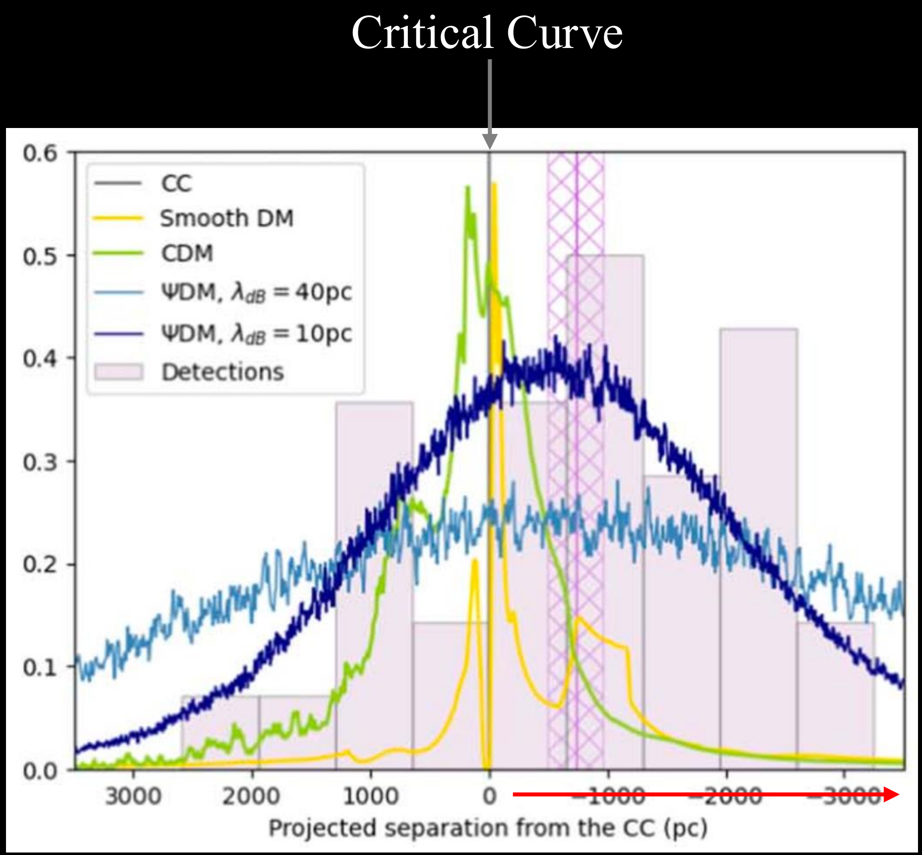

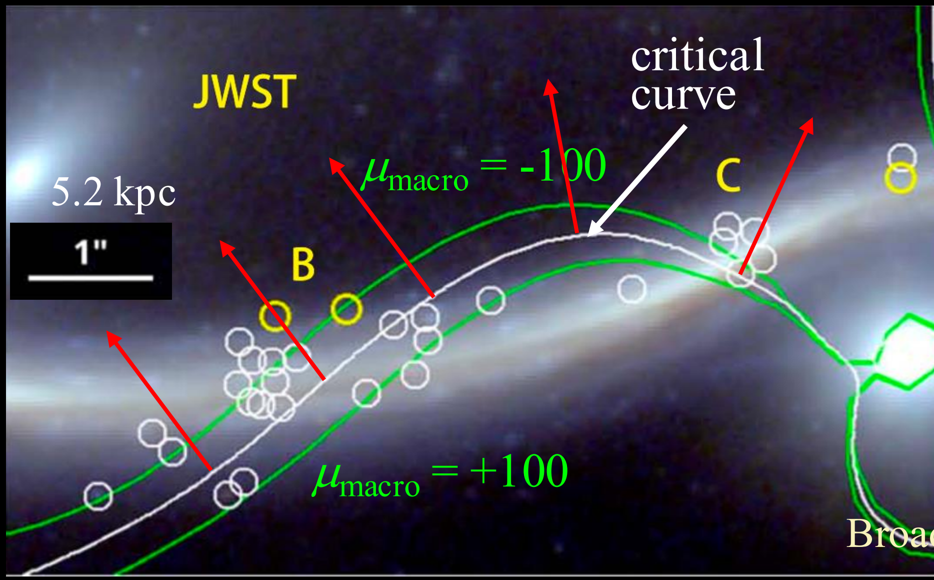

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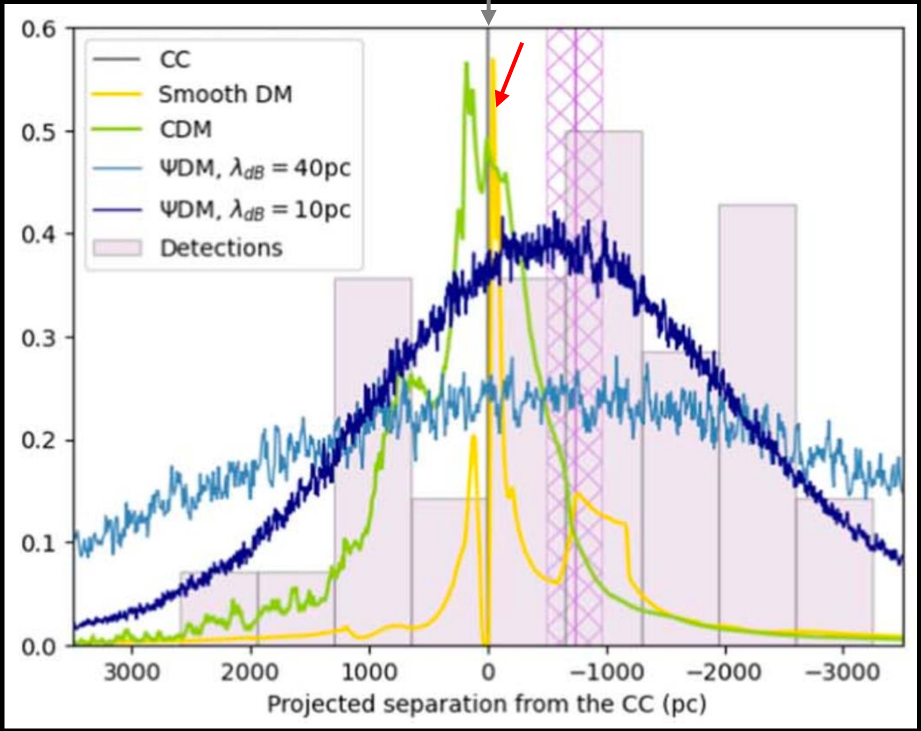
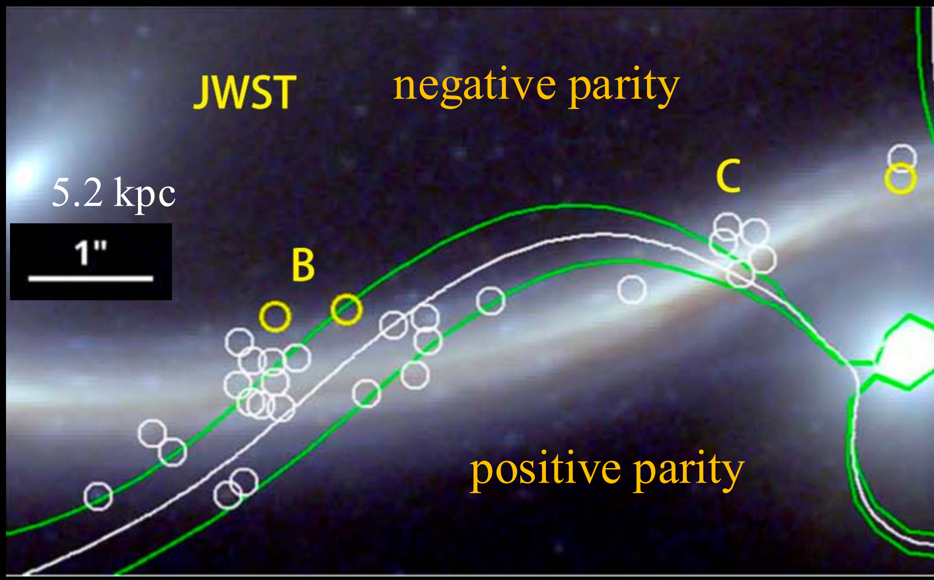
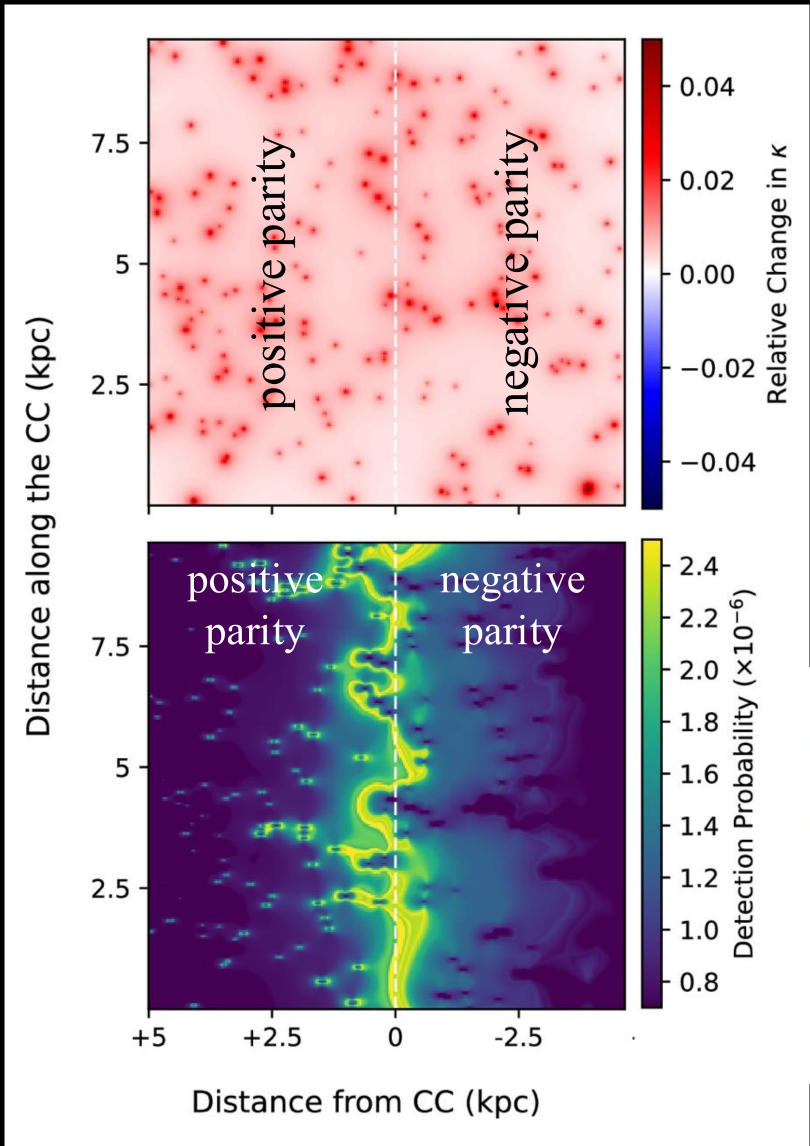
Critical Curve





Cluster DM Halo + DM sub-Halos (cold and ultra-massive)

- NFW DM halo + DM sub-halo macro-lensing + stellar micro-lensing:



← Embed sub-halos with mass function

$$\frac{dN}{d(\log m_{\rm halo})} \propto m_{\rm halo}^{-0.9}$$

over mass range

$$10^6 - 10^8\ M_\odot$$

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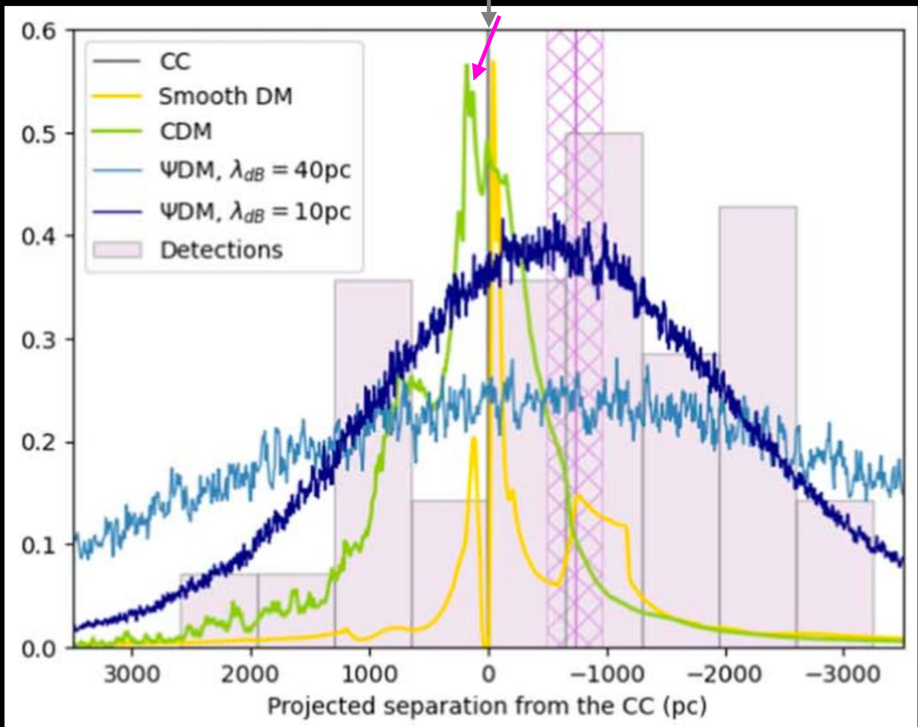
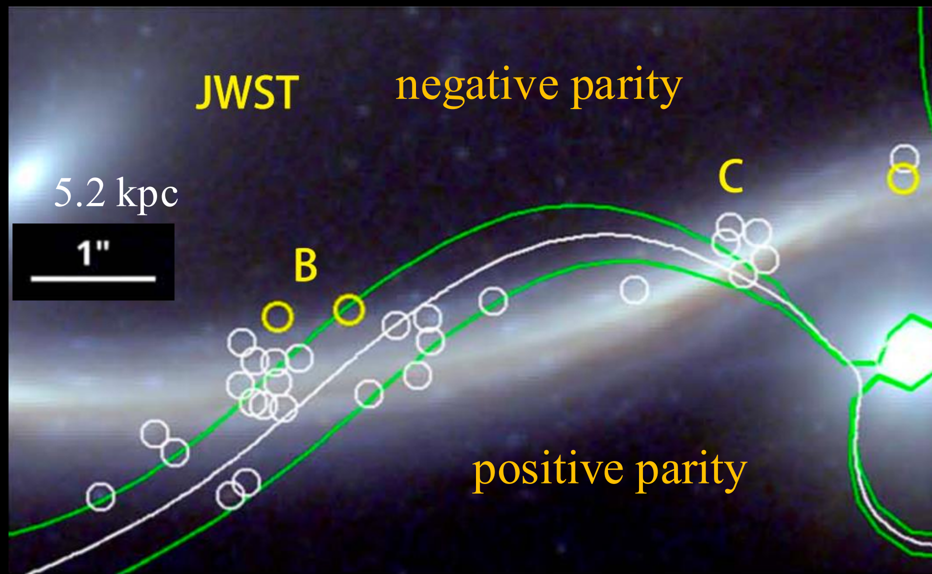
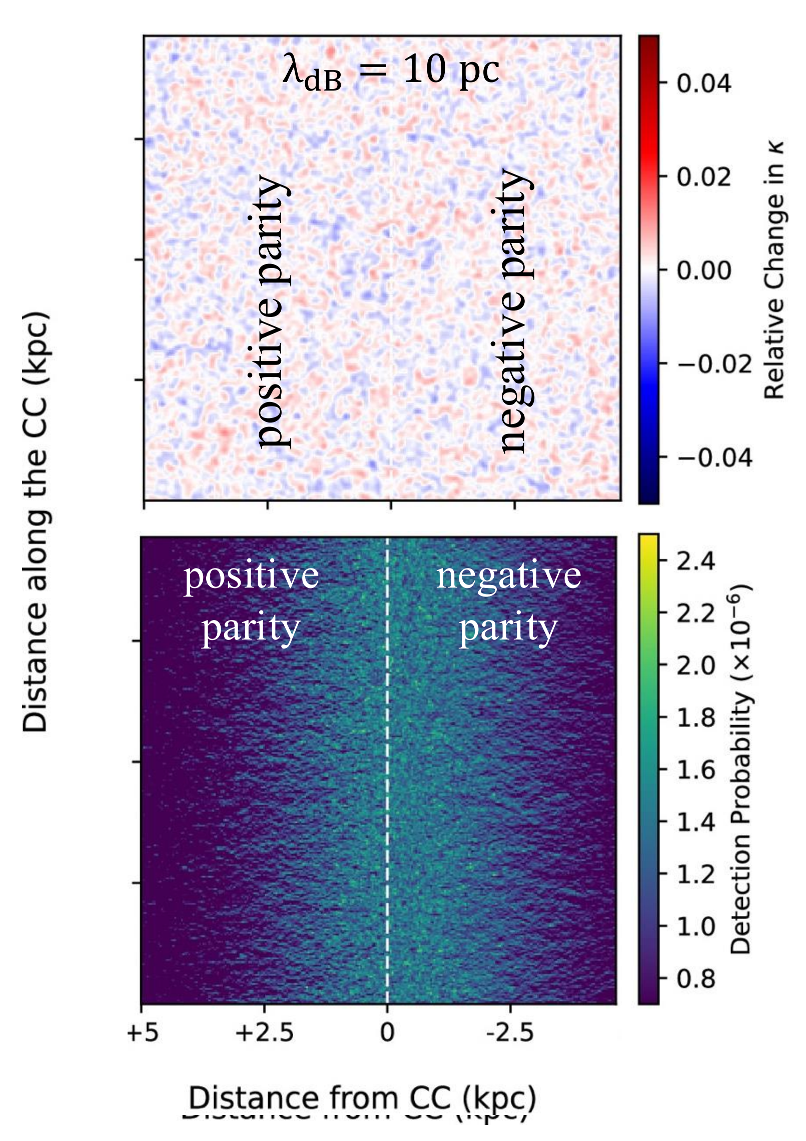




Cluster ψDM Halo (cold and ultra-light)

- Wave-like DM halo macro-lensing + stellar micro-lensing, $m_\psi \simeq 10^{-22}$ eV



← Embed Gaussian random field:
- cells sizes ~10 pc for $m_\psi \approx 10^{-22}$ eV
- 1% dispersion in density about mean

$$\lambda_{\mathrm{dB}} = 15 \left(\frac{10^{-22}\ \mathrm{eV}}{m_\psi}\right)\left(\frac{10^{15}\ M_\odot}{M_{\mathrm{halo}}}\right)^{1/3} \mathrm{pc}$$

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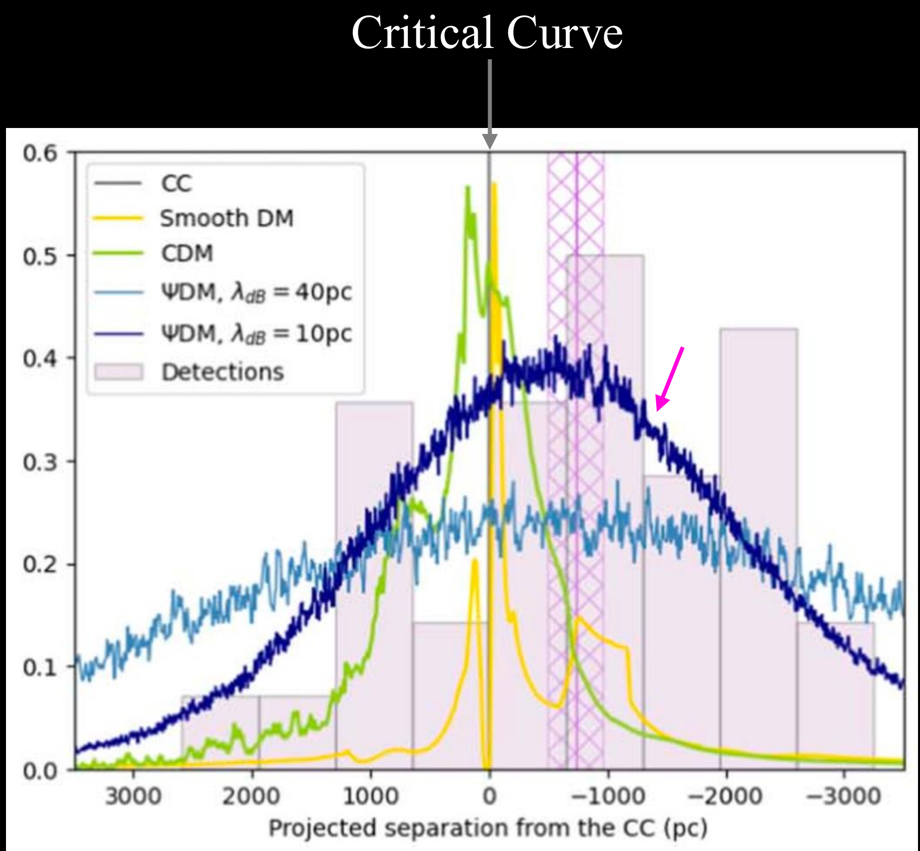
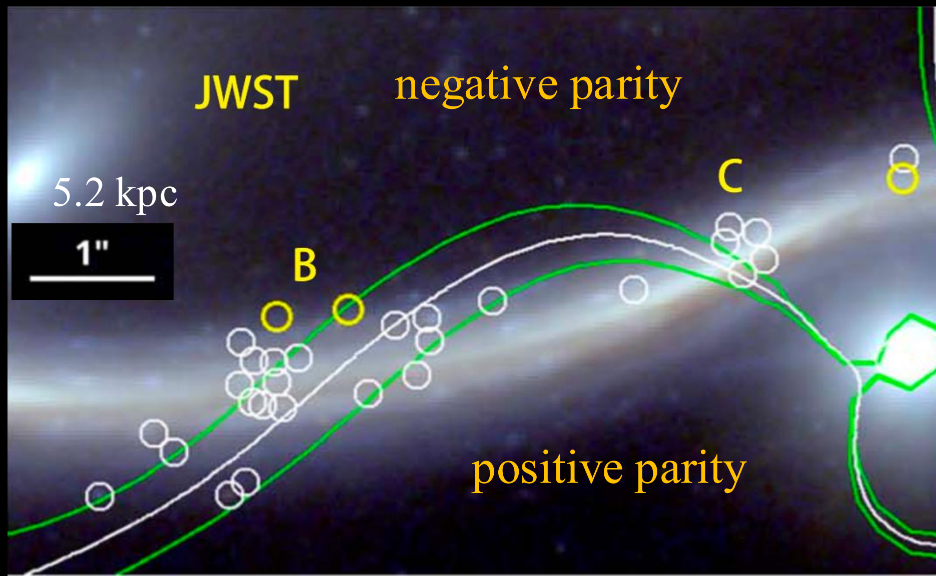
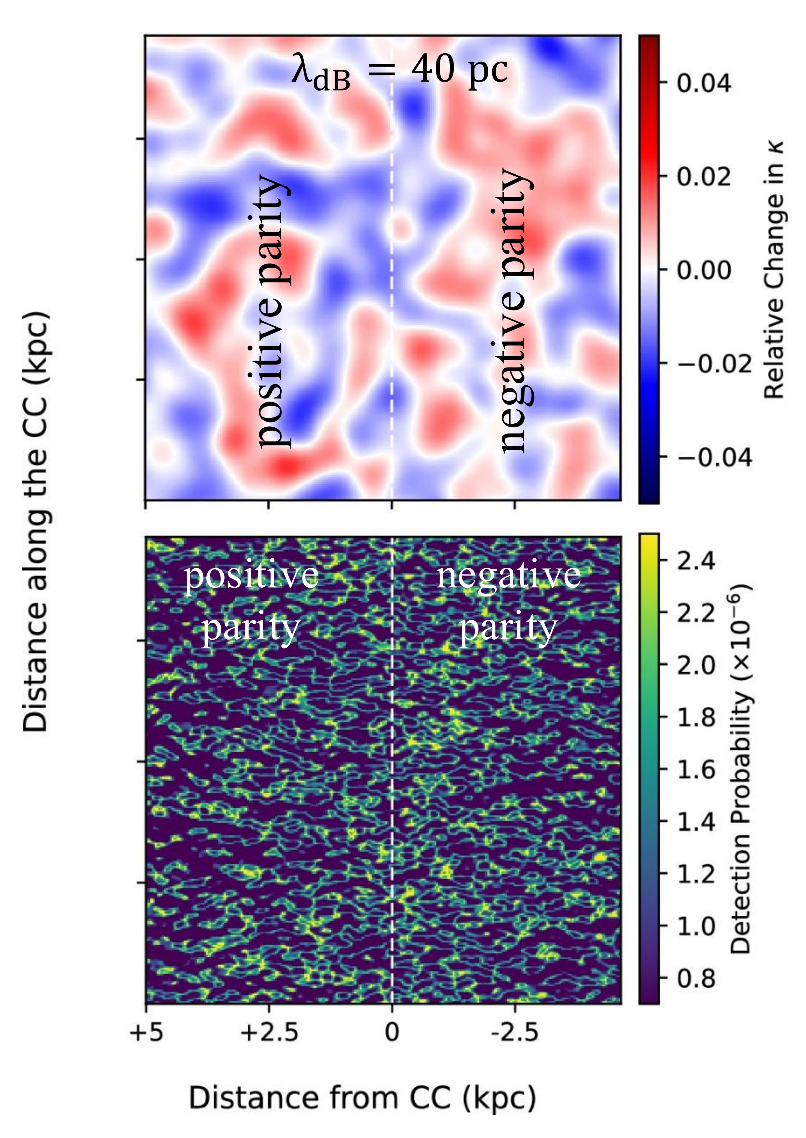




Cluster ψDM Halo (cold and ultra-light)

- Wave-like DM halo macro-lensing + stellar micro-lensing, $m_\psi \simeq 0.25 \times 10^{-22}$ eV



← Embed Gaussian random field:
- cells sizes ~40 pc for $m_\psi \approx 0.25 \times 10^{-22}$ eV
- 1% dispersion in density about mean

$$\lambda_{\rm dB} = 15 \left(\frac{10^{-22}\ {\rm eV}}{m_\psi}\right)\left(\frac{10^{15}\ M_\odot}{M_{\rm halo}}\right)^{1/3} {\rm pc}$$

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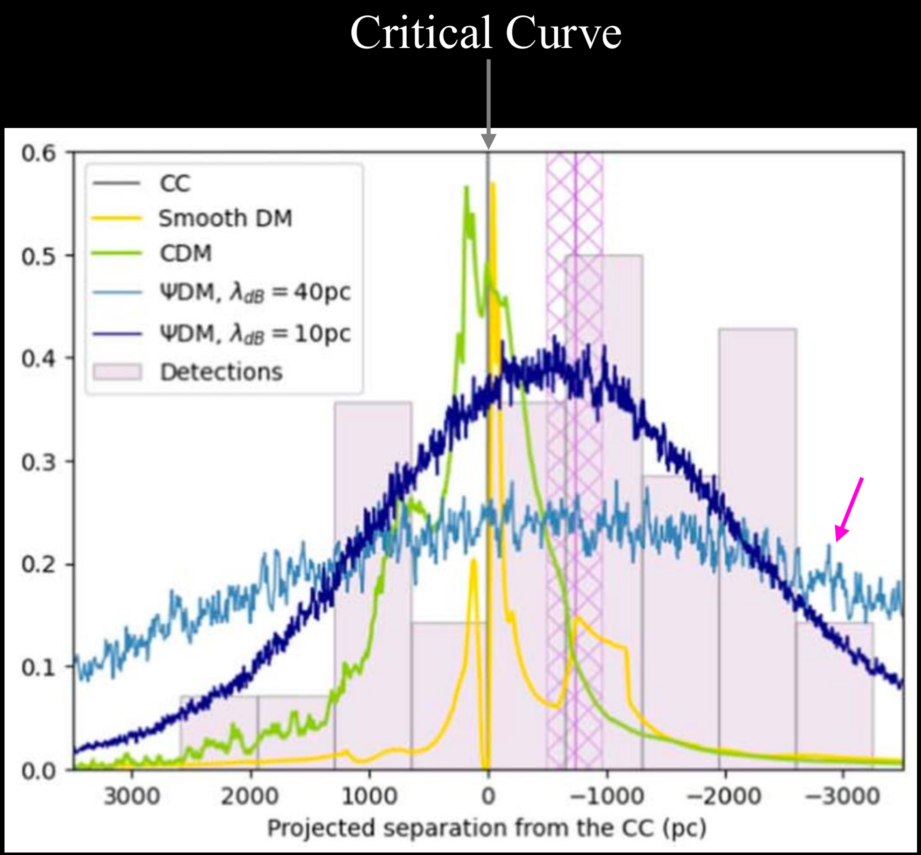
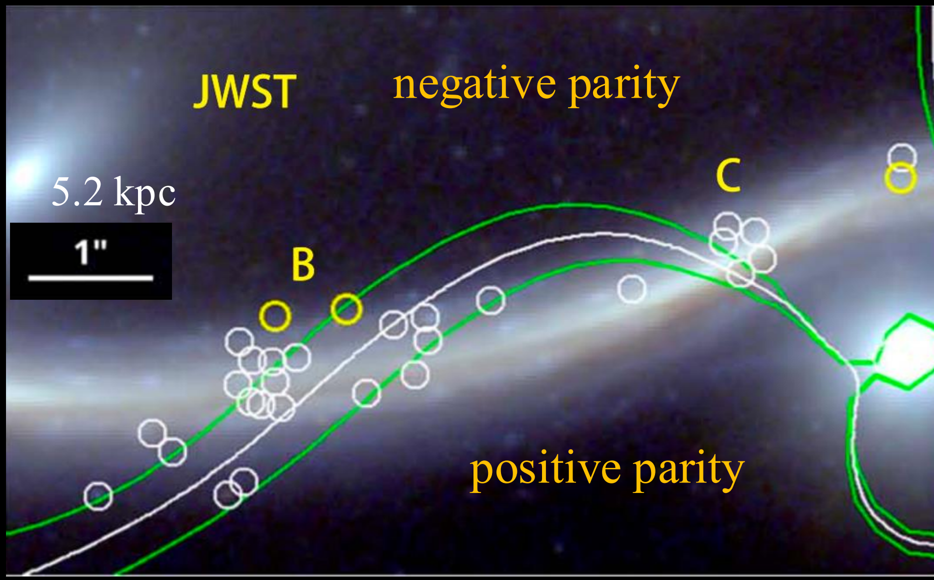
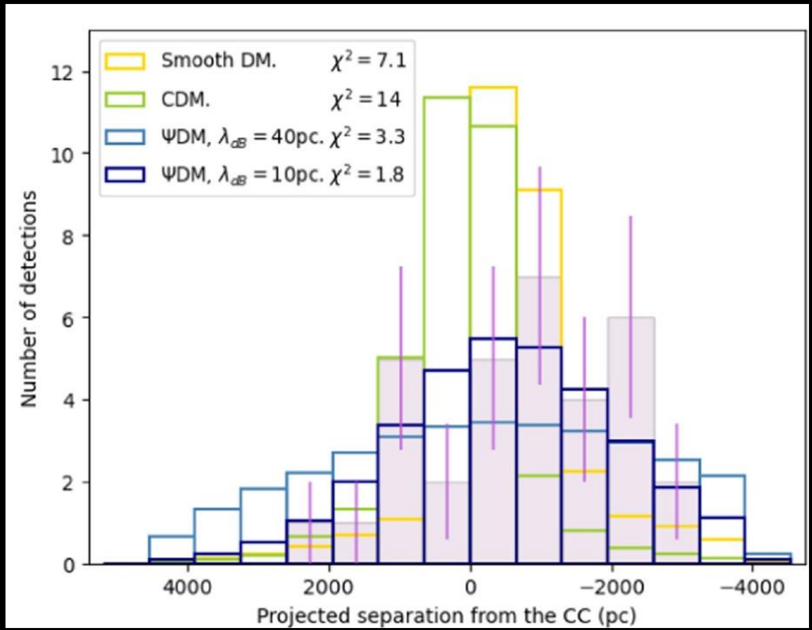
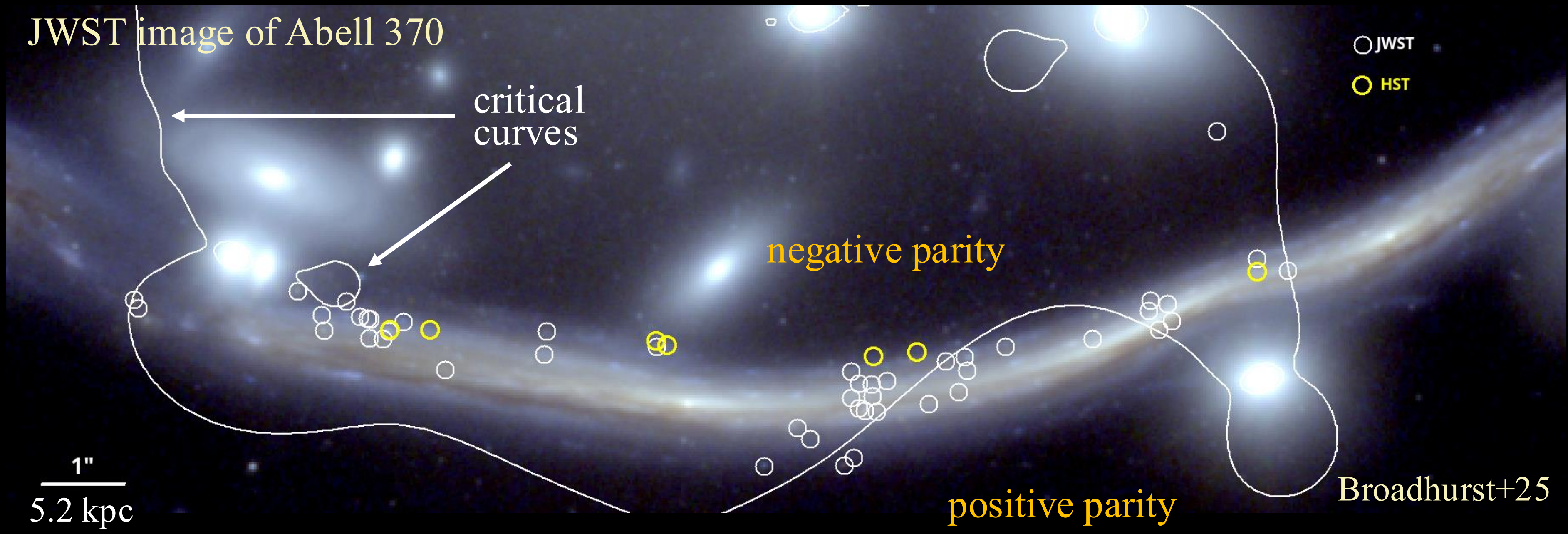




Necessity for Ultra-Light DM particles

- Only weakness in our inference:
  Is the locus of the critical curve correct?





Transients in the Jupiter Arc

- Transients in a background galaxy at $z = 0.94$ gravitationally lensed by foreground galaxy cluster MACS J0416.1-2403 at $z = 0.397$.

HST+JWST (red) image of MACS J0416.1-2403

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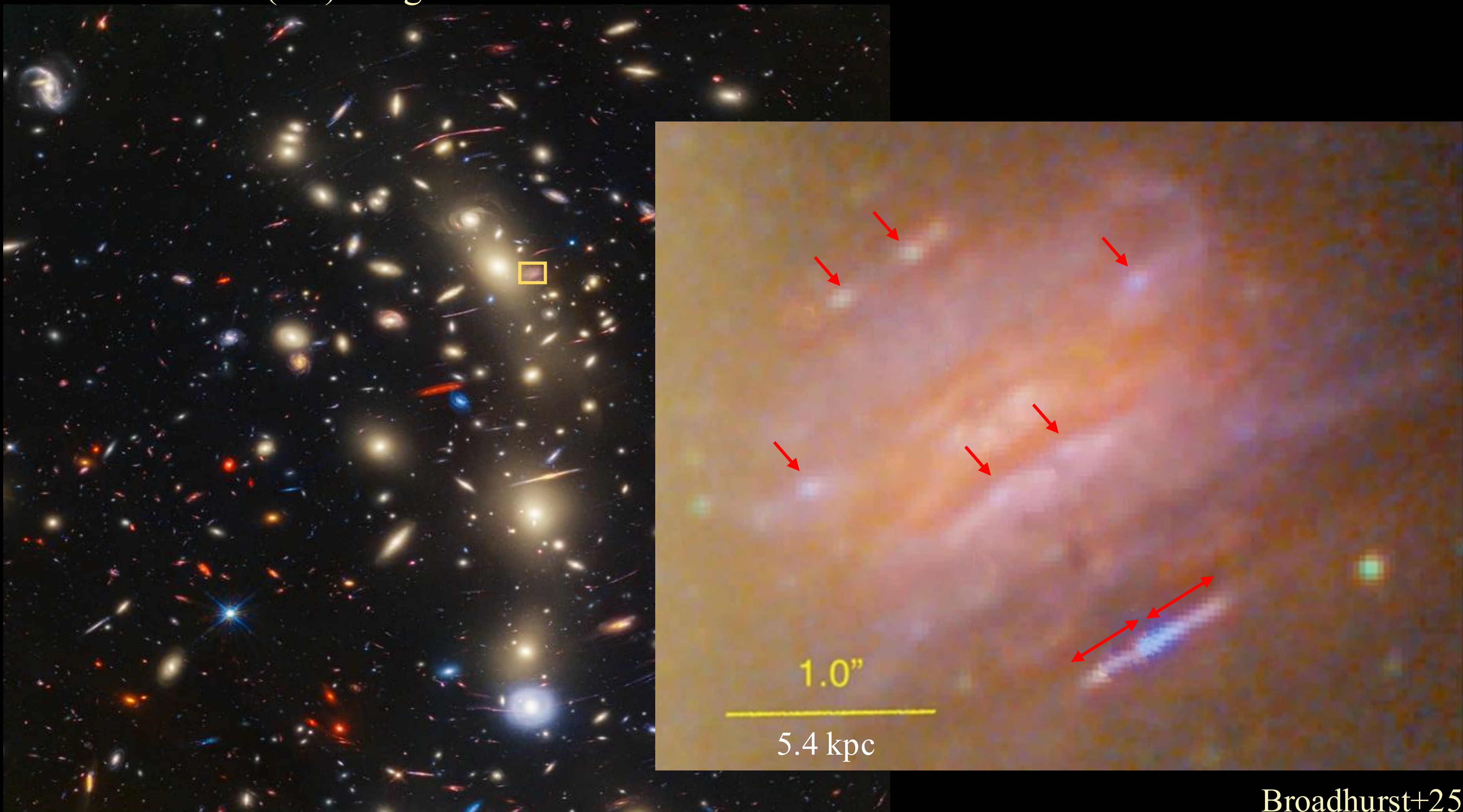

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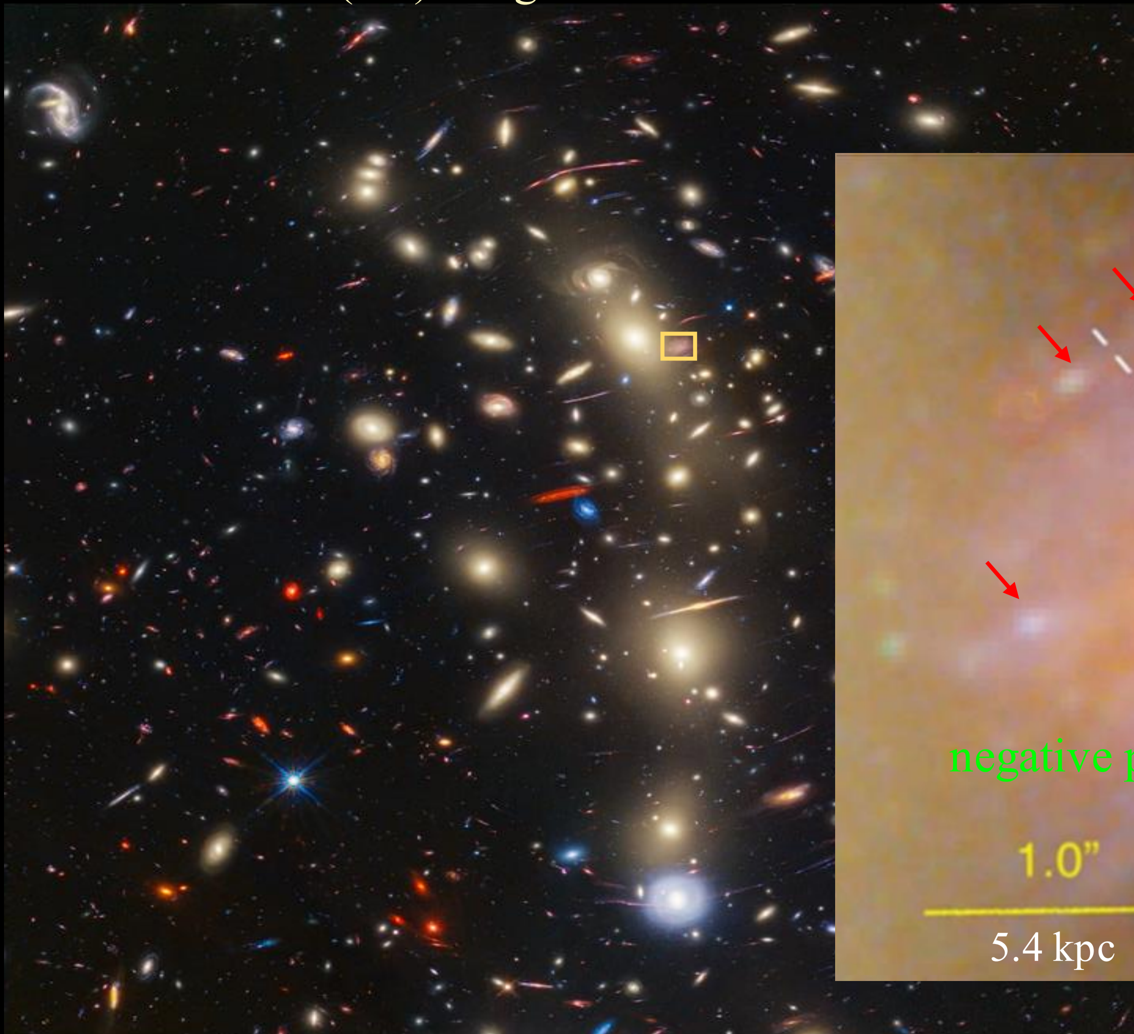

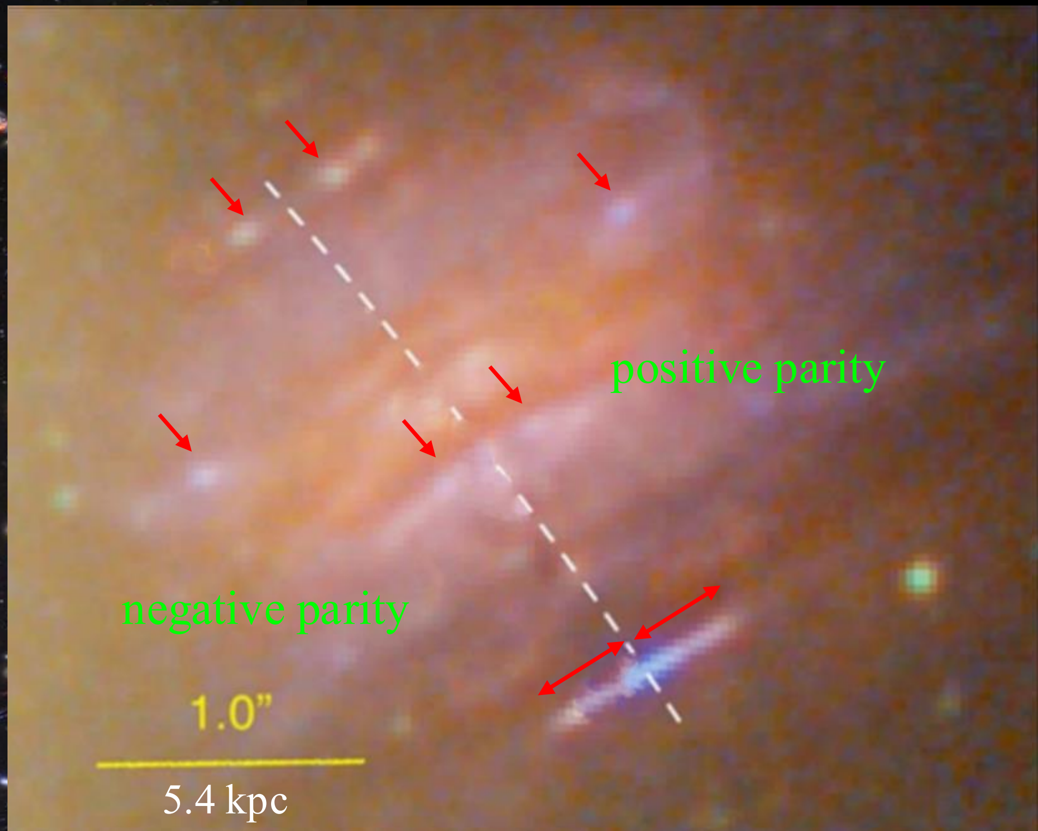

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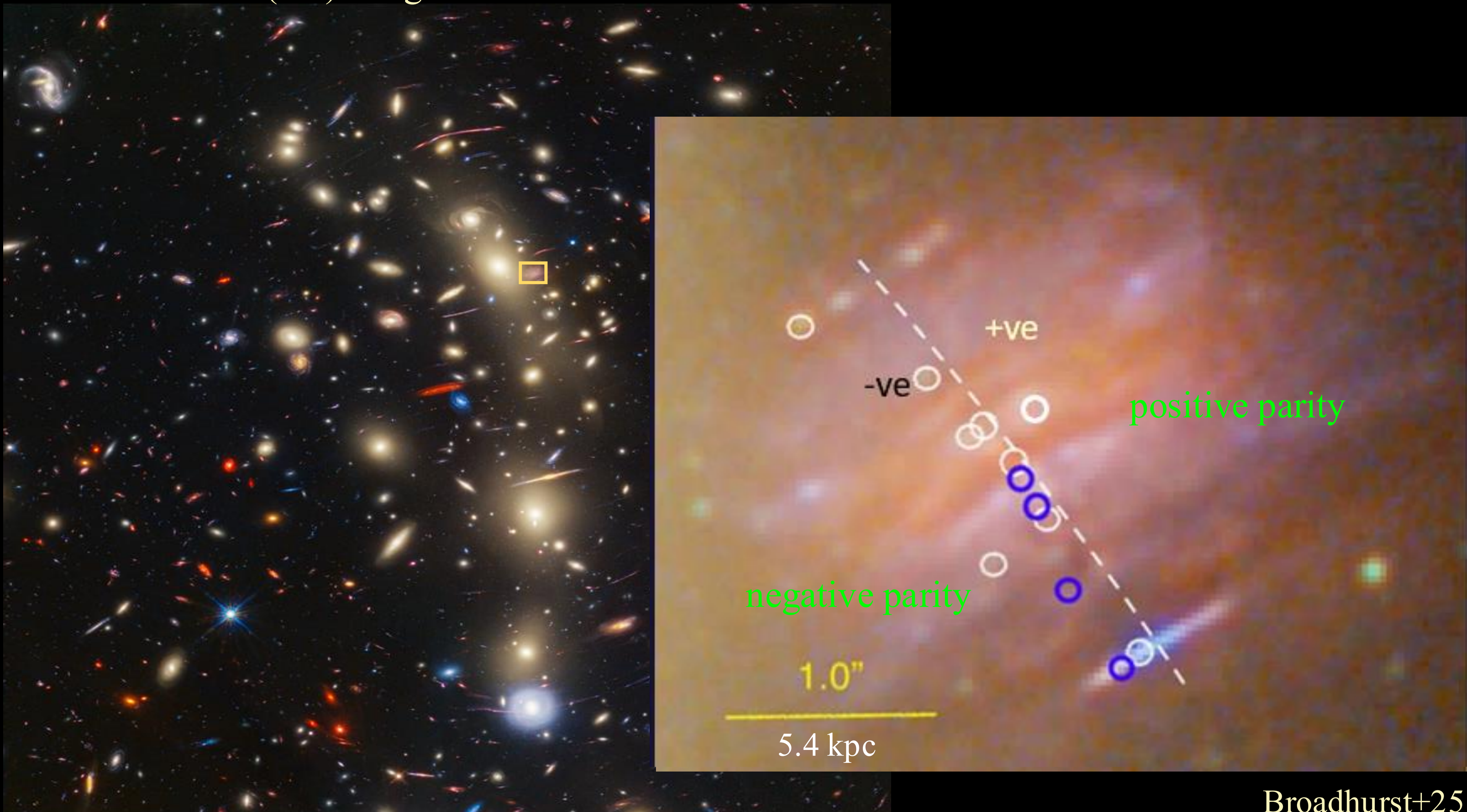

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EPILOGUE

Ultra-Massive vs Ultra-Light Dark Matter Particle

- To alleviate missing satellite problem, require DM particle mass ~10^{-22} eV to suppress DM halos having masses <10^8 $M_\odot$ (Schive, Chiueh, & Broadhurst 2014, Nat. Phys.)
- To explain inferred sizes of cores in dwarf galaxies, require DM particle mass ~10^{-22} eV (Schive+14)
- Structural/dynamical evidence for solitonic cores in dwarf galaxies, requiring DM particle mass ~10^{-22} eV (Pozo+21,+24a,+24b)
- Dynamical evidence of a dark solitonic core of 10^9 $M_\odot$ in the Milky Way, requiring DM particle mass ~10^{-22} eV (Martino+20)
- Prolate galaxies in the early Universe
- Flux power spectrum of Ly-α forest incompatible with DM particle mass < 10^{-21} eV (Armengaud+17, Iršič+17, Leong+19)

- DM particle mass ~10^{-22} eV is natural scale for spin 0 (scalar) particle, for which the best motivated example is the QCD Axion (Hui+21, *ARA&A*)

Ultra-Massive vs Ultra-Light Dark Matter Particle

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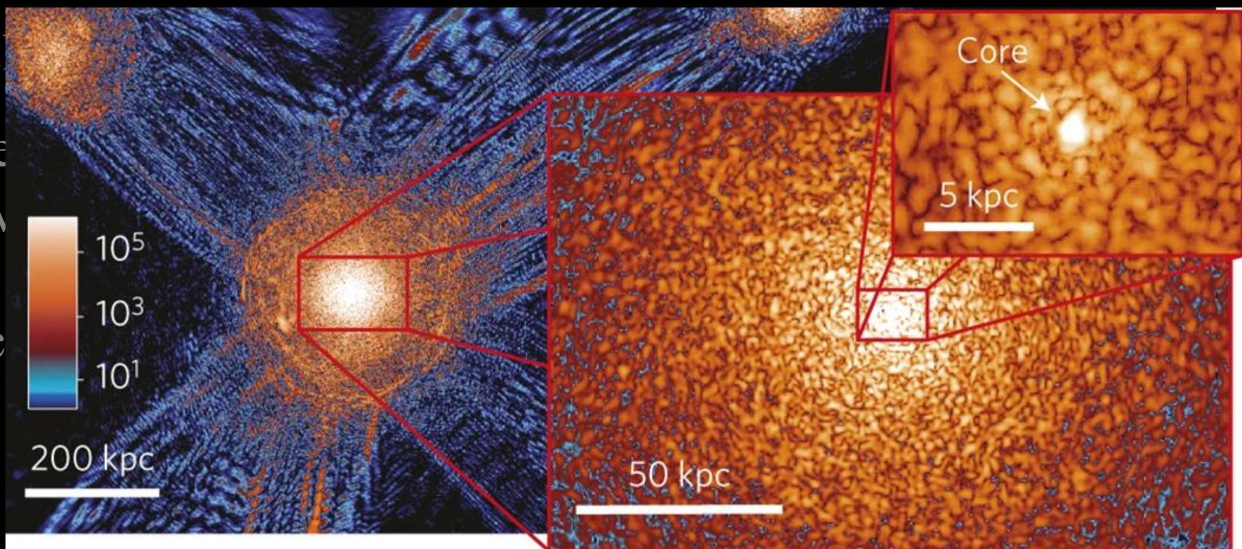

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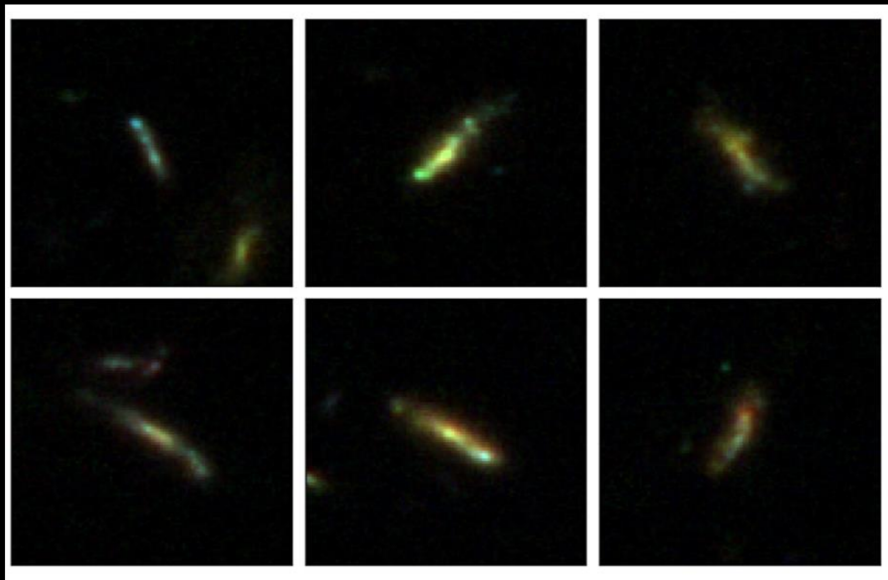

requiring DM particle mass $\sim 10^{-22}$ eV

- Prolate galaxies in the early Universe
- Flux power spectrum of Ly-α forest in
  $< 10^{-21}$ eV (Armengaud+17, Iršič+17,
- DM particle mass $\sim 10^{-22}$ eV is natural

Dark matter filaments at high redshift: cold, warm or fuzzy?

Hydrodynamical simulations of warm and fuzzy dark matter reproduce the observed shapes of early galaxies more faithfully than counterpart simulations with cold dark matter, showing the sensitivity of galaxy shapes to the underlying filamentary network.

Nature of Dark Matter

Ultra-massive

- CMB Anisotropy
- Large-scale structure of the Universe
- Predicts too many low-mass halos
  (missing satellite problem)
- Predicts cusps in galaxies
  (cusp-core problem)
- Leaves lensing anomalies
- In contradiction with lensed star transients
  across cluster critical curves
- Oblate galaxies in early Universe

Ultra-light

- CMB Anisotropy
- Large-scale structure of the Universe
- Suppression of low-mass halos
  (alleviates missing satellite problem)
- Predicts cores in galaxies
  (resolves cusp-core problem)
- Alleviates lensing anomalies
- Consistent with lensed star transients
  across cluster critical curves
- Prolate galaxies in early Universe

Nature of Dark Matter

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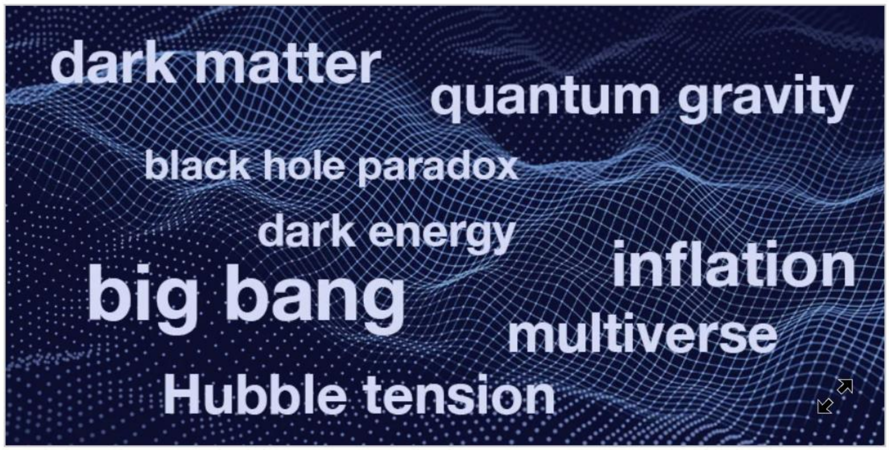

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Nature of Dark Matter