Constraints on dark matter models from anomalous strong lens systems

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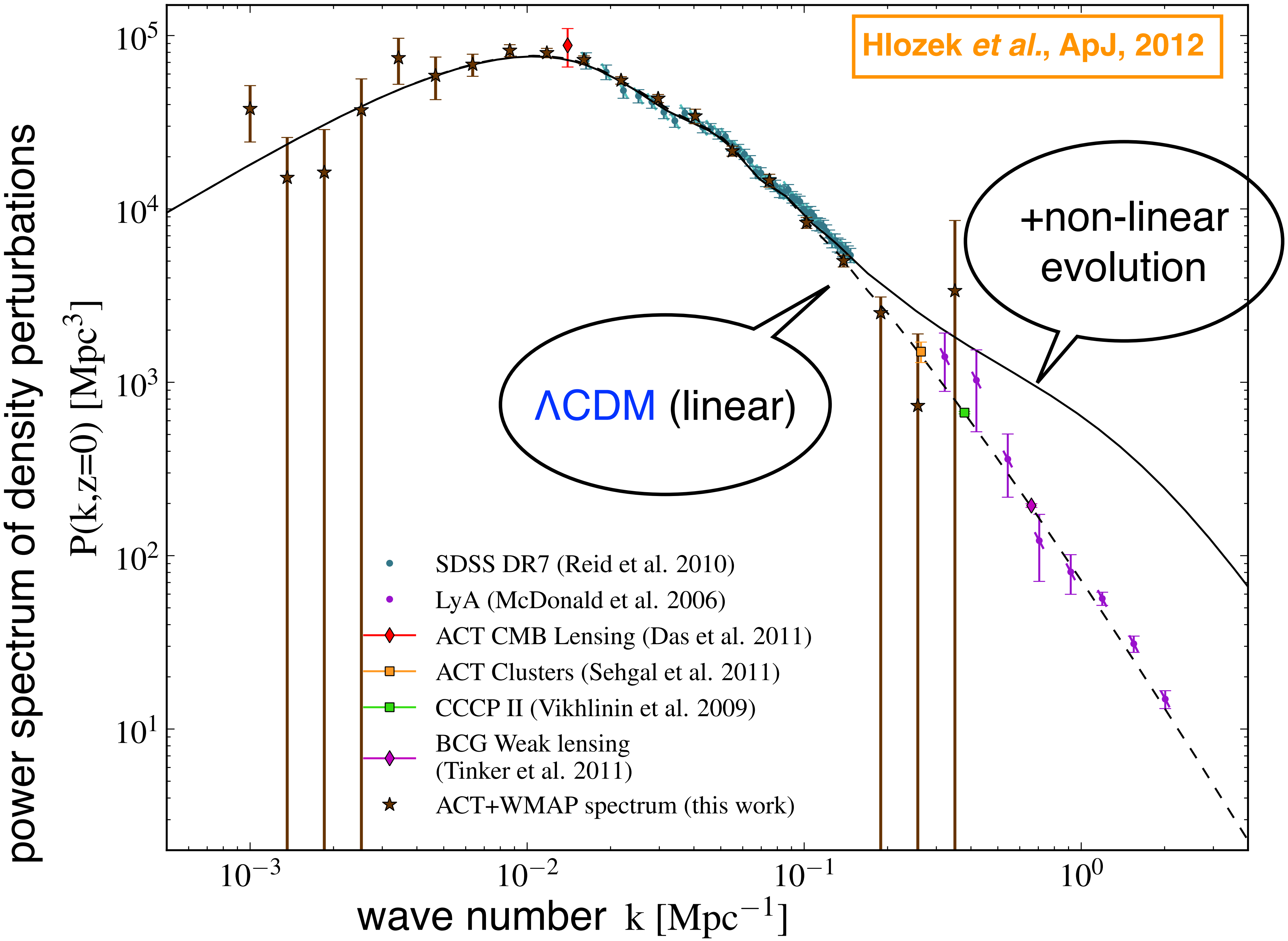
Based on
AK, K. T. Inoue, T. Takahashi, PRD, 2016

Nov. 21, 2016 @ IPPP-Durham

Large scale structure of the Universe



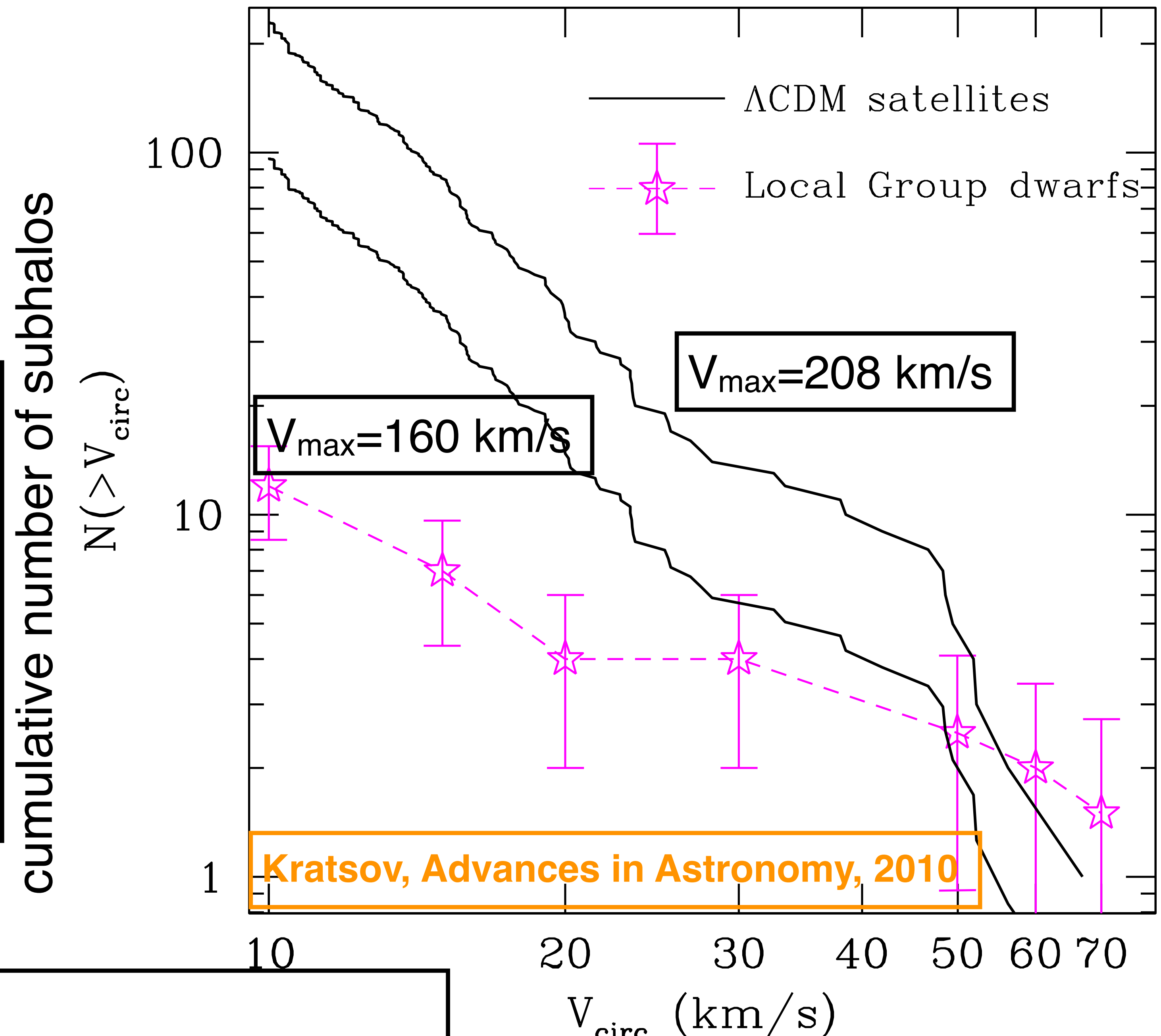
The ΛCDM model reproduces well
the large scale (>Mpc) structure of the Universe

Small scale crisis I

When *N*-body simulations in the ΛCDM model and observations are compared, problems appear at (sub)galactic scales: **small scale crisis**

missing satellite problem

N-body (DM-only) simulations in the ΛCDM model → Milky Way-size halos host **O(10)** times larger number of subhalos than that of observed dwarf spheroidal galaxies



maximal circular velocity of subhalo

(maximum) circular velocity

$$V_{\rm circ}^2(r) = \frac{GM(<r)}{r} \qquad V_{\rm max} = \max_r\{V_{\rm circ}(r)\}$$

Sterile neutrino as mixed dark matter

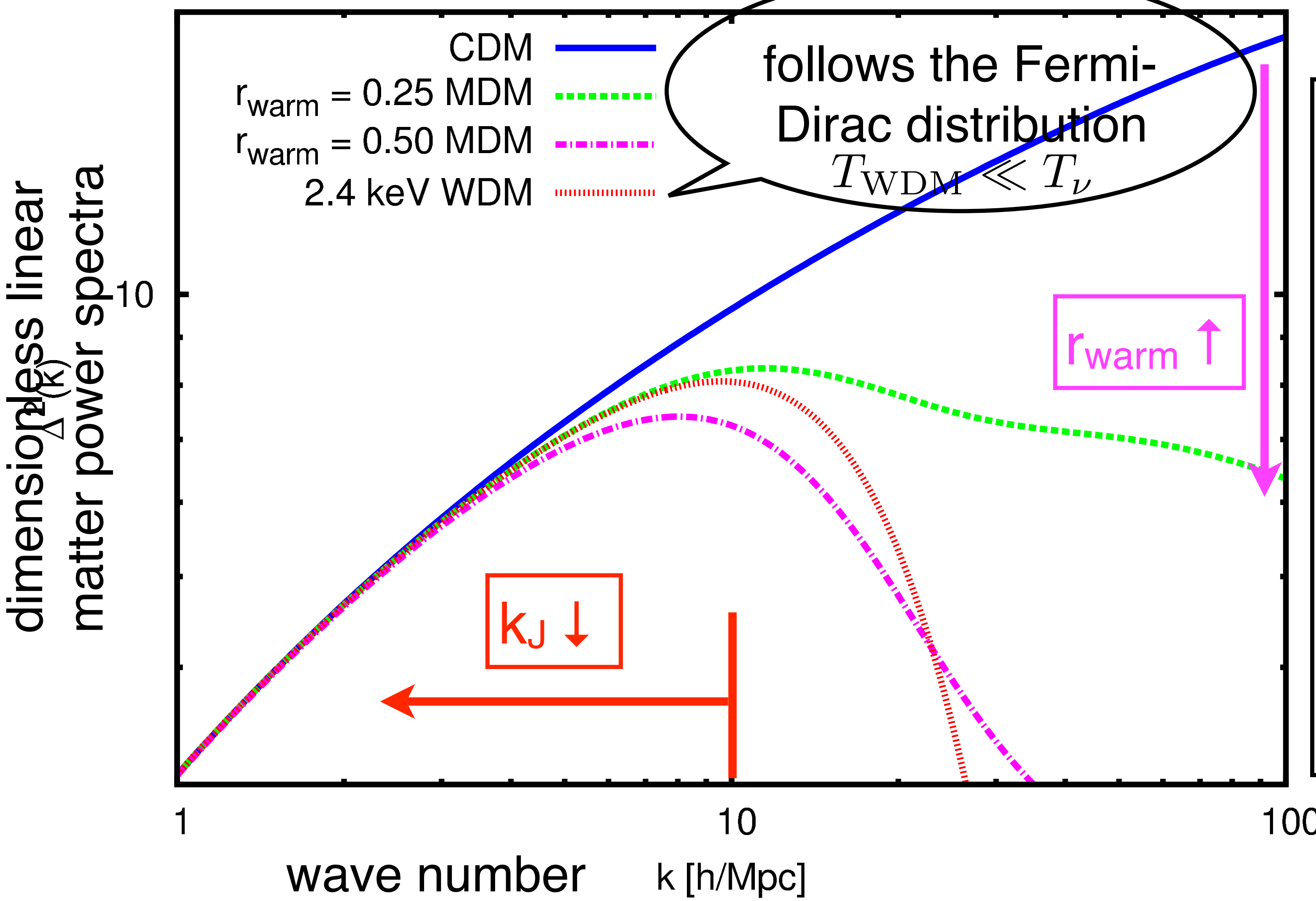
sterile neutrino radiative decay as an origin of 3.5 keV anomaly

m_s : mass
θ : mixing angle

proportional to the Fermi-Dirac distribution $T_s = T_\nu$

sterile neutrino (WDM) relic (from the Dodelson-Widrow mechanism) accounts for **20-60%** of DM mass density (rest: CDM) → CDM+WDM=**MDM**

A. Harada, AK, JCAP, 2016



Jeans scale at the matter-radiation equality:

velocity dispersion of MDM

$$k_{\rm J} = a\sqrt{\frac{4\pi G\rho_{\rm m}}{\sigma^2}}\Bigg|_{t=t_{\rm eq}}$$

$$= 64\,{\rm Mpc}^{-1}\left(\frac{m_{\rm WDM}}{2.4\,{\rm keV}}\right)^{4/3}\left(\frac{1}{r_{\rm warm}}\right)^{5/6}$$

$$= 64\,{\rm Mpc}^{-1}\left(\frac{m_s}{7\,{\rm keV}}\right)\left(\frac{0.25}{r_{\rm warm}}\right)^{1/2}$$

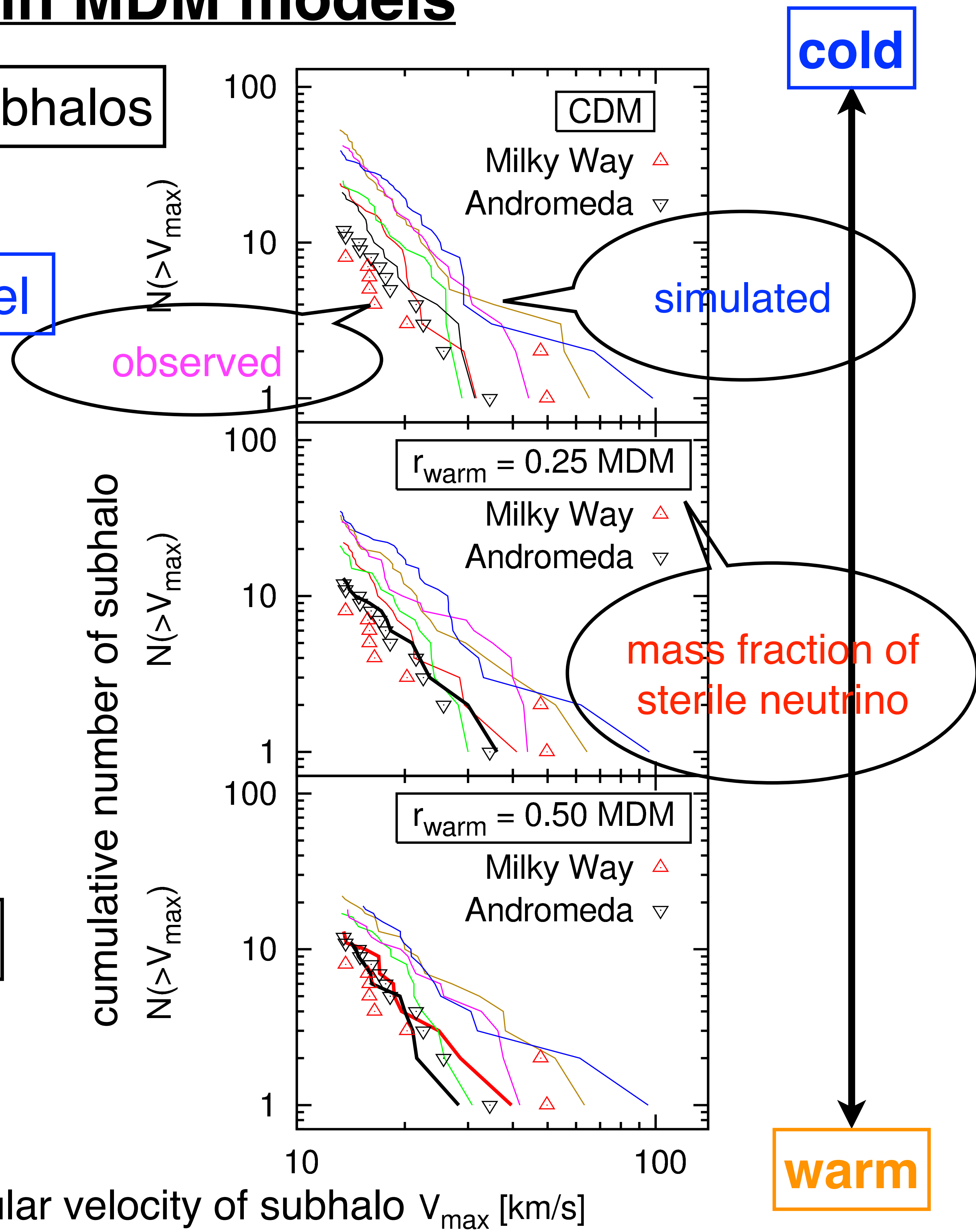
Missing satellite problem in MDM models

cumulative velocity function of subhalos

Too many subhalos in CDM model

1 out of 6 halos may reproduce the number of observed dwarf spheroidal galaxies

2 out 6 halos appear concordant



Possible solution I

Above Discussions are based on *N*-body (**DM-only**) simulations in the ΛCDM model

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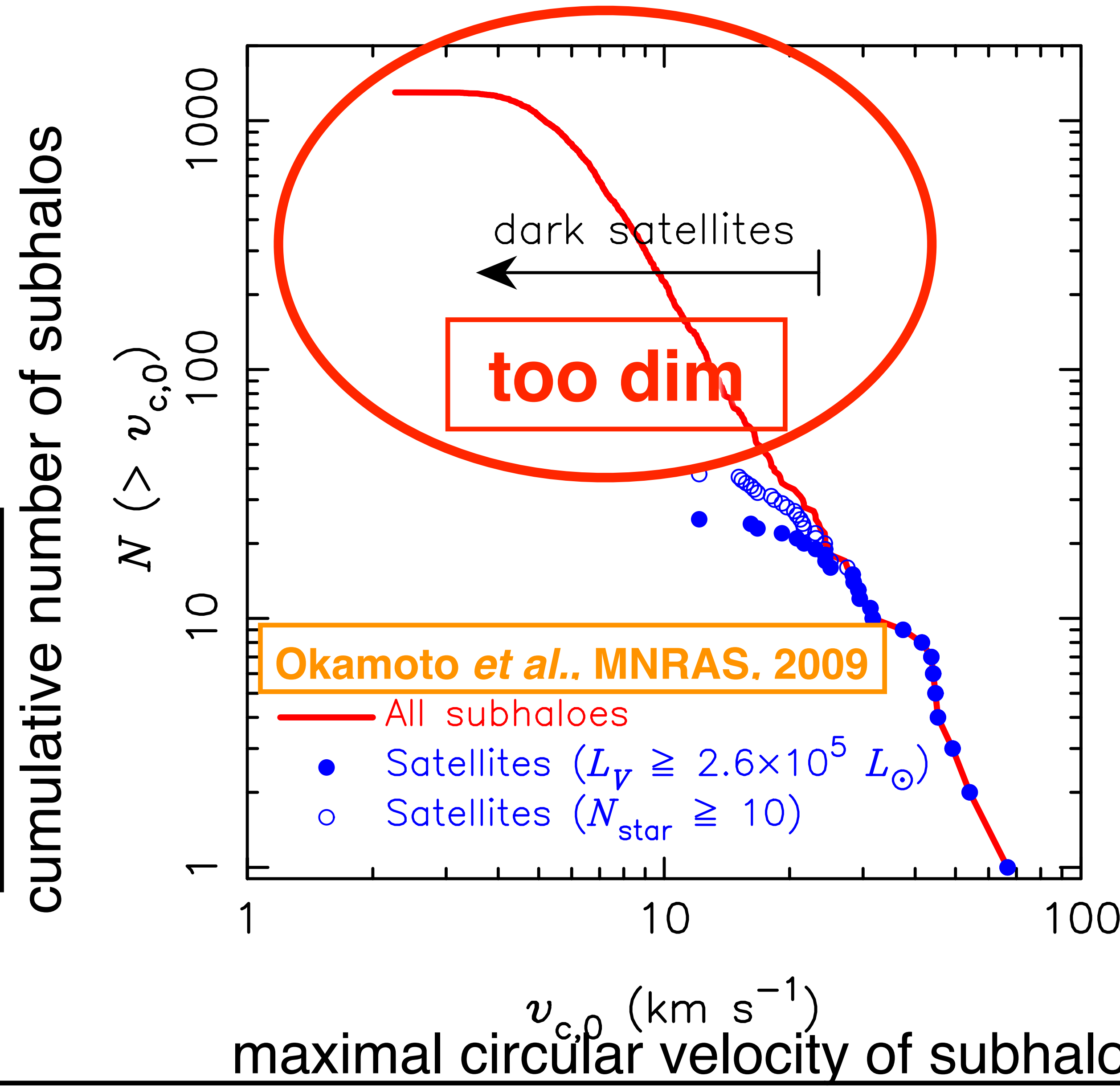
Gravitational potentials are shallower at smaller scales →
BARYONIC HEATING and **COOLING** processes may be important



Baryonic processes

- **heating from ionizing photons** - ionizing photons emitted and spread around reionization of the Universe heat and evaporate gases

- **mass loss by supernova explosions** - supernova explosions blow gases from inner region → DM redistribute along shallower potential

Advantage of gravitational lenses

Observation

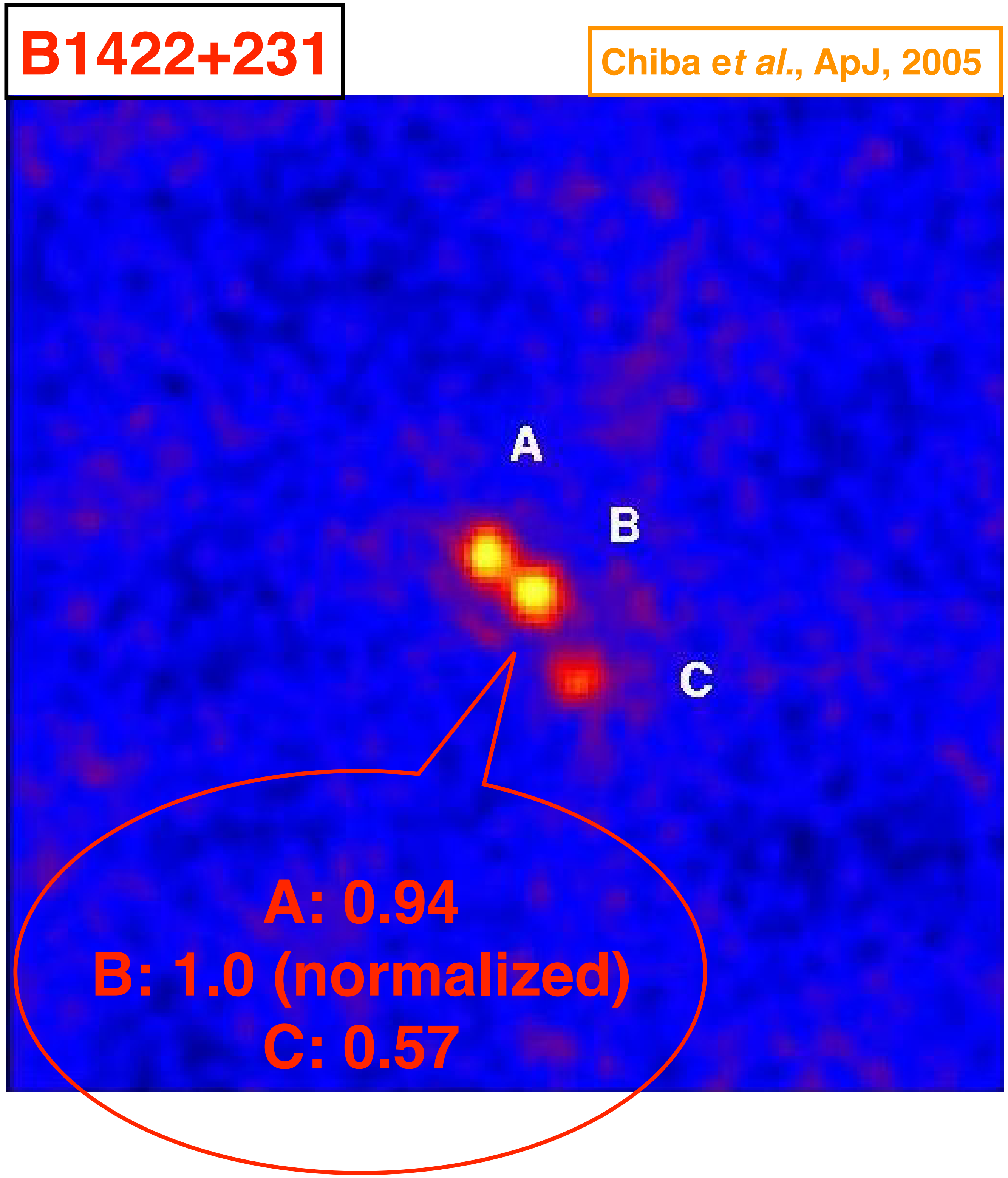
Direct measurement -
gravitational potentials: the **WHOLE** matter (DM+baryons) distribution

We propose a **NEW GRAVITATIONAL LENS MEASUREMENT** to probe sub-galactic scale structure

Theory

- Non-linear evolution - perturbation theory breaks down
→ time/resource-consuming *N*-body simulations (and detailed comparison with analytic approach)
- co-evolution of DM halos and baryon processes (supernova explosions, galaxy formation…)
→ state-of-the-art hydrodynamic simulations and elaborate modeling of baryon processes

Anomalous flux ratio



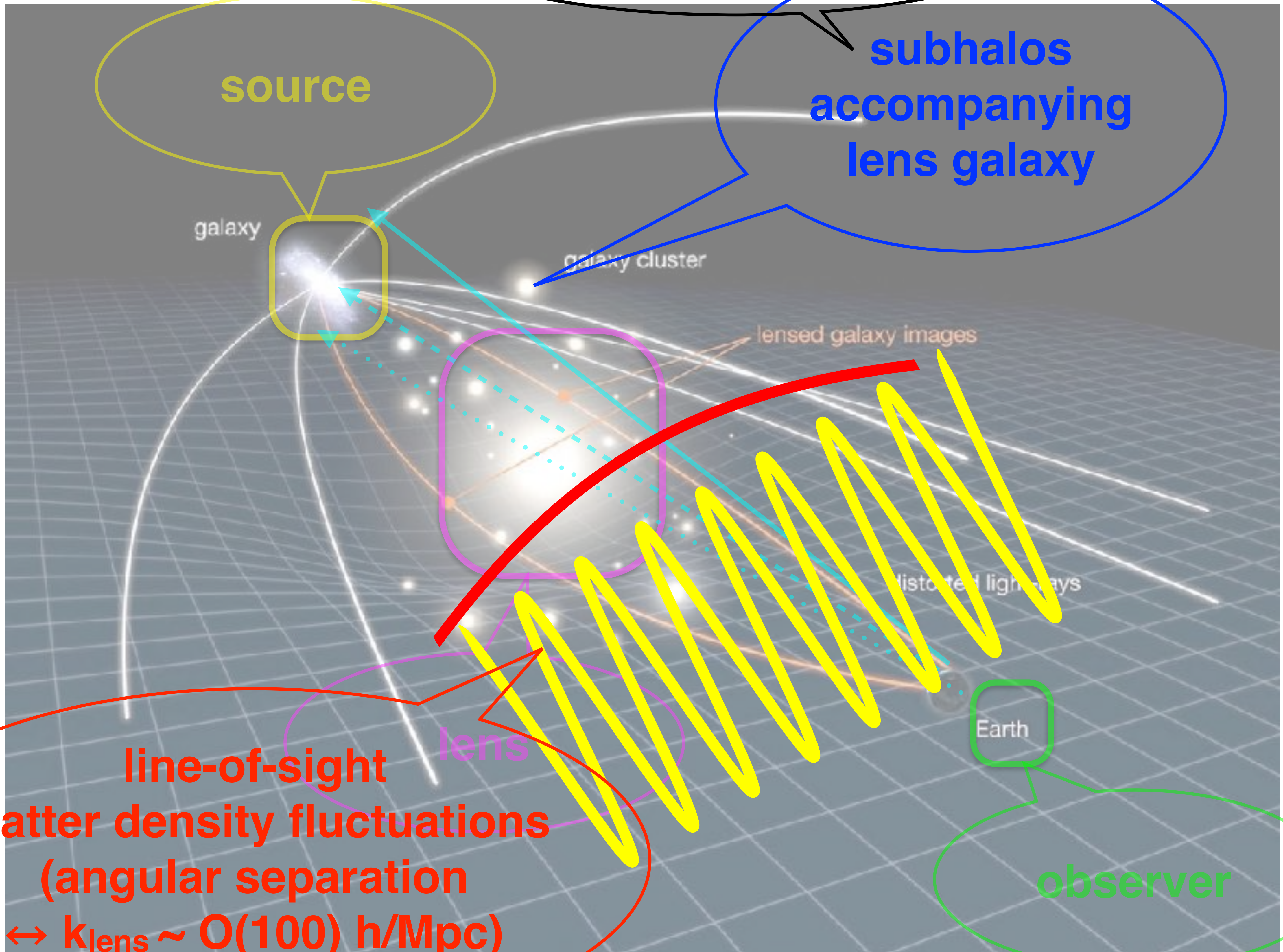
Singular isothermal ellipsoid (SIE) for lens galaxy provides a good-fit for **RELATIVE POSITIONS OF LENSED IMAGES**

1st derivative of gravitational potential

2nd derivative of gravitational potential

Derived FLUX RATIO (A+C)/B =1 is **NOT CONSISTENT WITH** observed value (A+C)/B =1.5 (2σ or more)

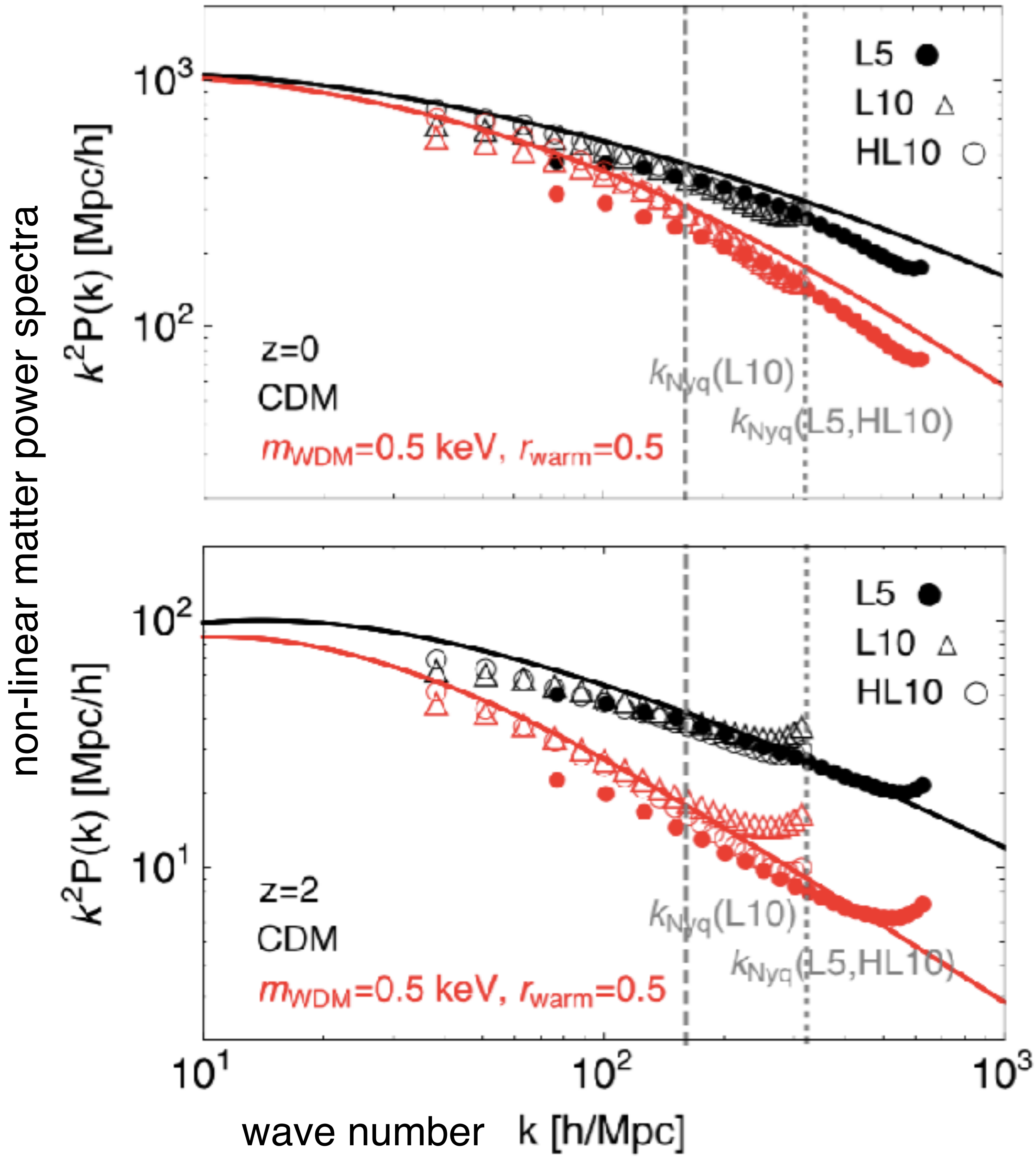
Possible Perturbers



Line-of-sight matter density fluctuations

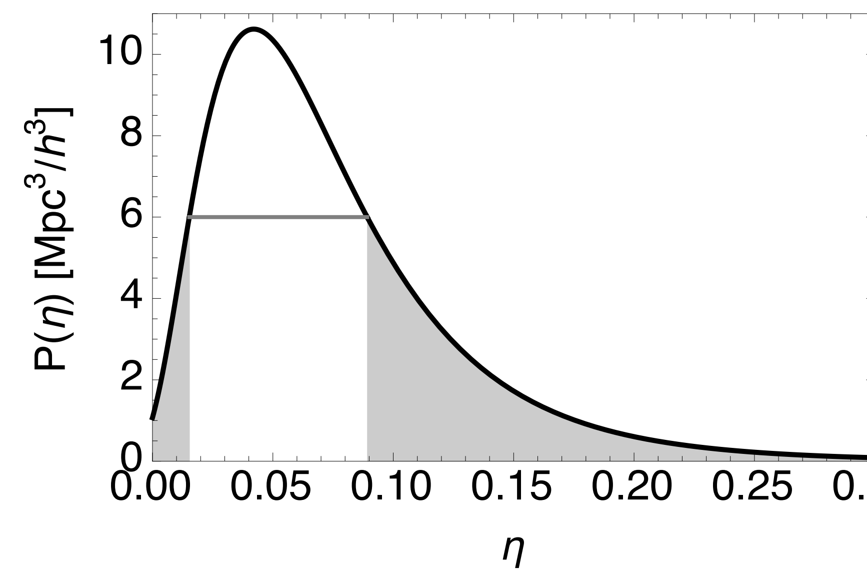
N-body simulation
to measure non-linear
matter power spectra

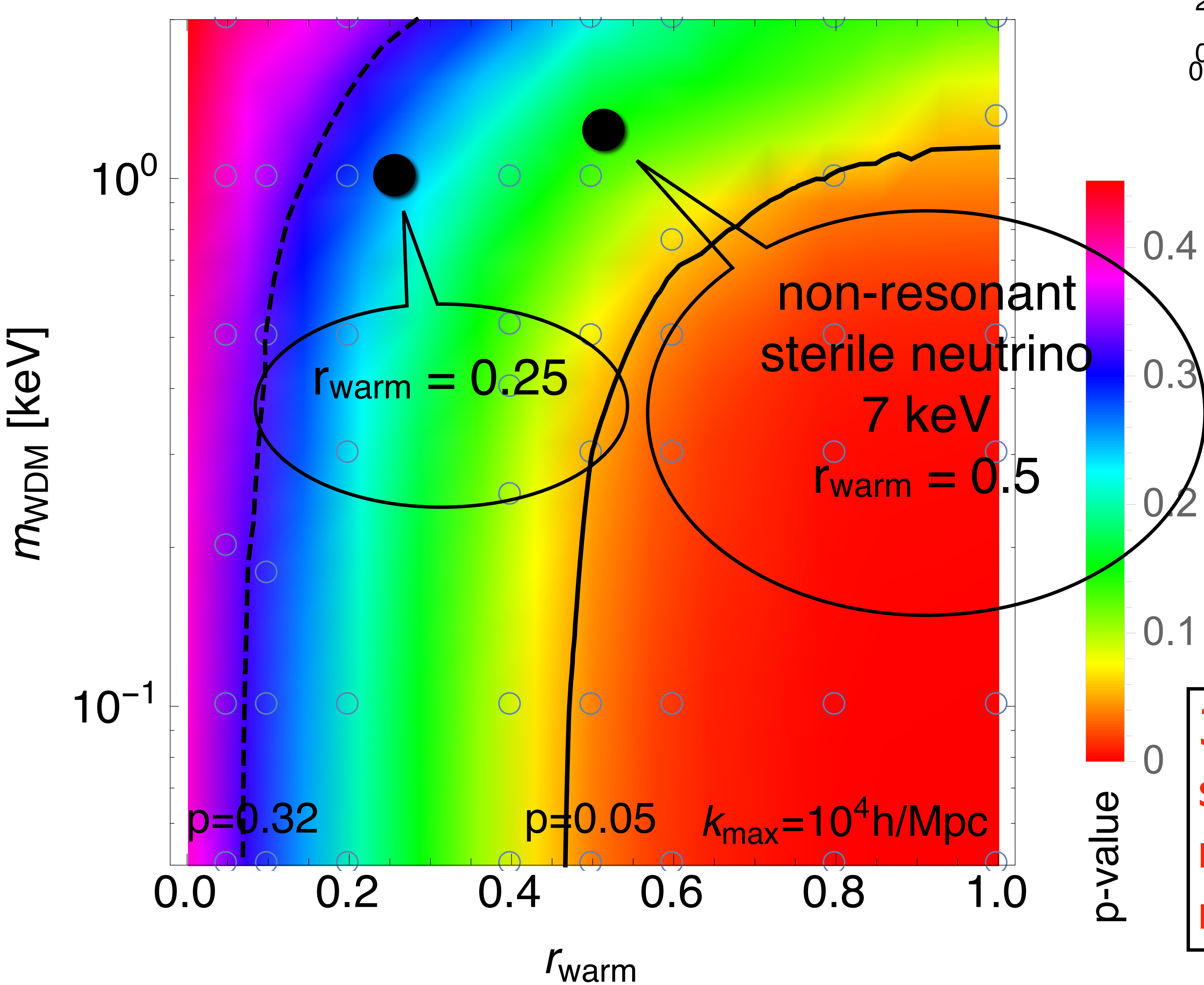
perturbed magnification
η: a convolution of
non-linear matter spectra
with a certain Kernel



Likelihood

p-value: probability of finding a sample that is more unlikely than the observed value





conversion ($r_{\rm warm}$, k_J fixed):

$$m_{\rm WDM} = 1.0\,{\rm keV} \times \left(\frac{m_s}{7\,{\rm keV}}\right)\left(\frac{r_{\rm warm}}{0.25}\right)^{1/4}$$

3.5 keV line-motivated sterile neutrino mixed dark matter model are still viable

Summary and prospect

- Gravitational lens is a powerful tool to probe
the (relatively) small-scale clustering property of the Universe

- 3.5 keV-line motivated (sterile neutrino) mixed DM models
likely reproduce simultaneously the small number of
the observed dwarf spheroidal galaxies
and anomalous flux in QSO quadrupole lens systems

- Sub-millimeter galaxy lens samples are expected to be found
in on-going ALMA data

- More precise understanding of structure formation
(non-linear evolution) in non-CDM models is indispensable
→ need a help of analytic approach