Gravitational lenses as a probe of dark matter models

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"Exploring the Energy Ladder of the Universe"

based on collaborations with
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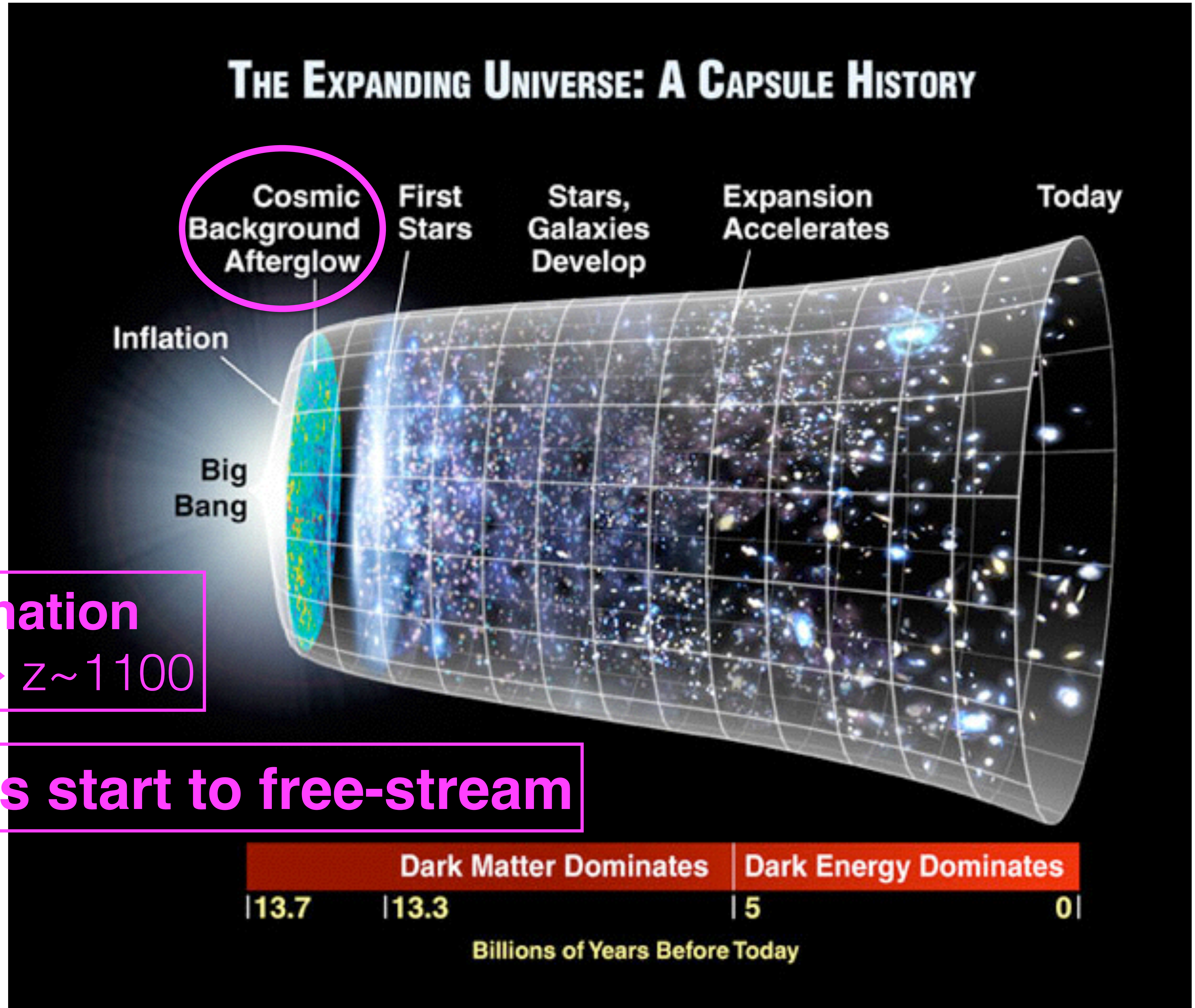
Tomo Takahashi (Saga University),
and Naoki Yoshida (Kavli Institute for the Physics and Mathematics of the Universe)

Brief introduction of structure formation

History of the Universe

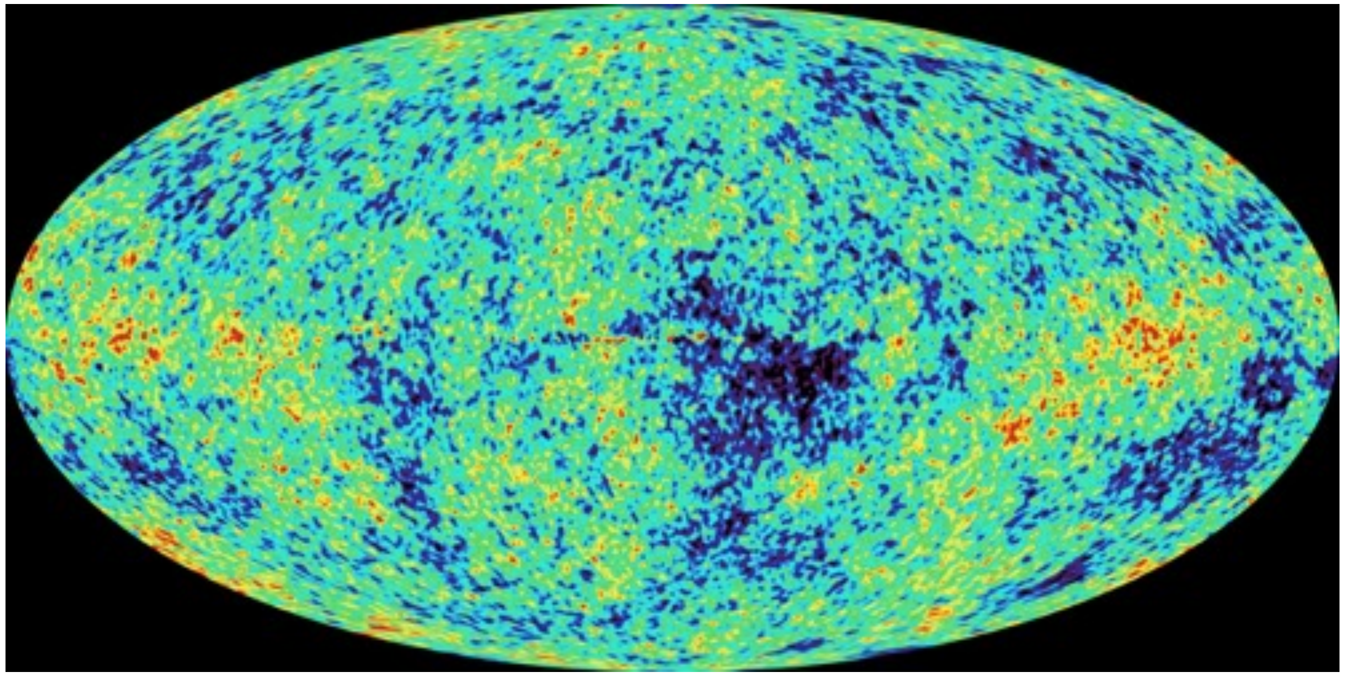


Recombination

3.8×10^5 yr ↔ $z\sim1100$

Photons start to free-stream

(Early) Sachs-Wolfe Effect



Cosmic Microwave Background (CMB): homogeneous and isotropic universe +fluctuations (~10^{-5})

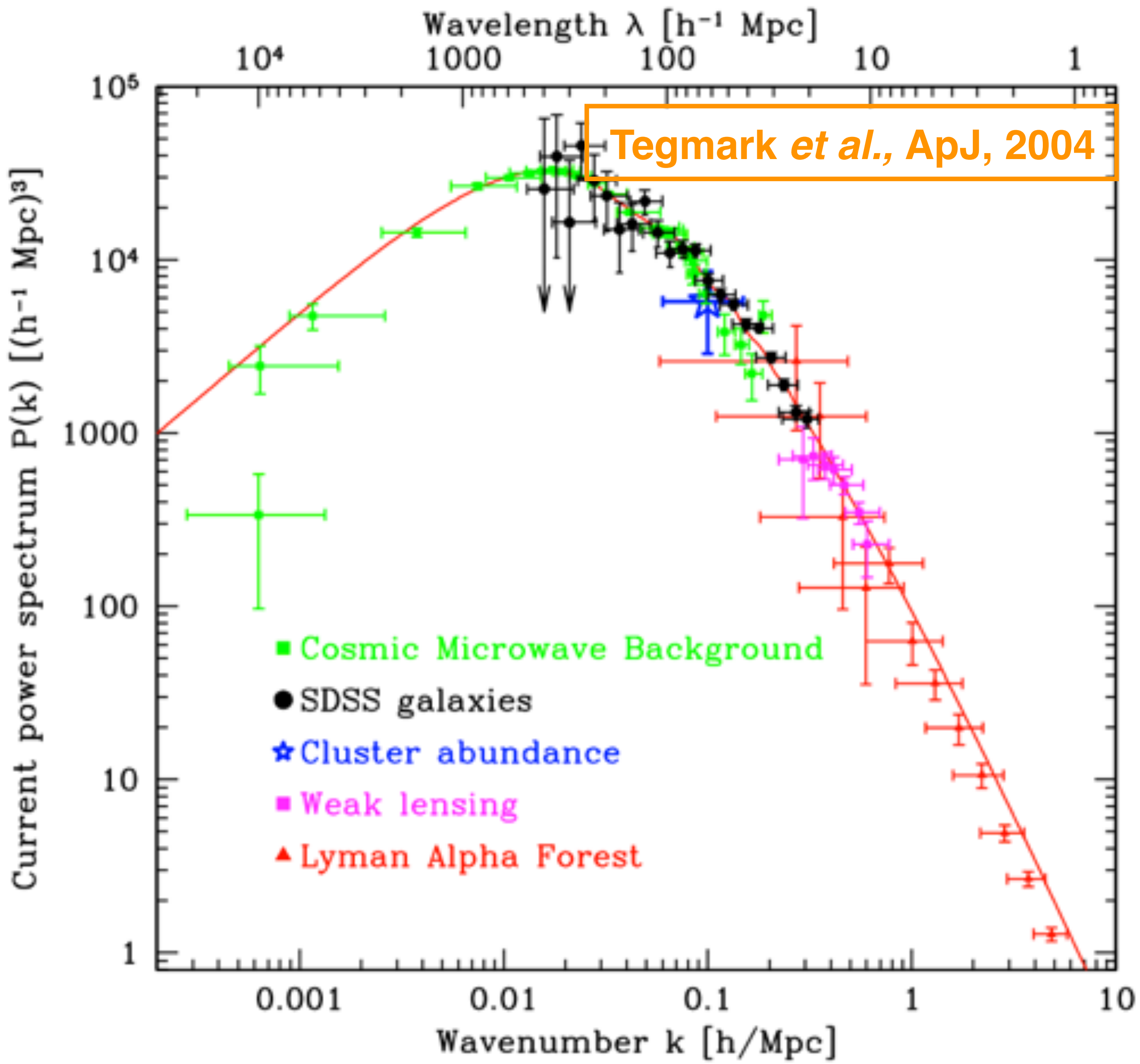
lose energy during propagation
↔ low temperature

lower temperature spots

↕

higher matter density spots

(Linear) Matter density fluctuations



matter density fluctuations

$$\delta(\mathbf{x}) \equiv \frac{\delta\rho}{\rho}(\mathbf{x}) = \int \frac{\mathrm{d}\mathbf{k}^3}{(2\pi)^3}\delta(\mathbf{k})e^{i\mathbf{kx}}$$

$$< \delta(\mathbf{k})\delta^*(\mathbf{k}') >= (2\pi)^3\delta^3(\mathbf{k}-\mathbf{k}')\mathrm{P}(\mathbf{k})$$

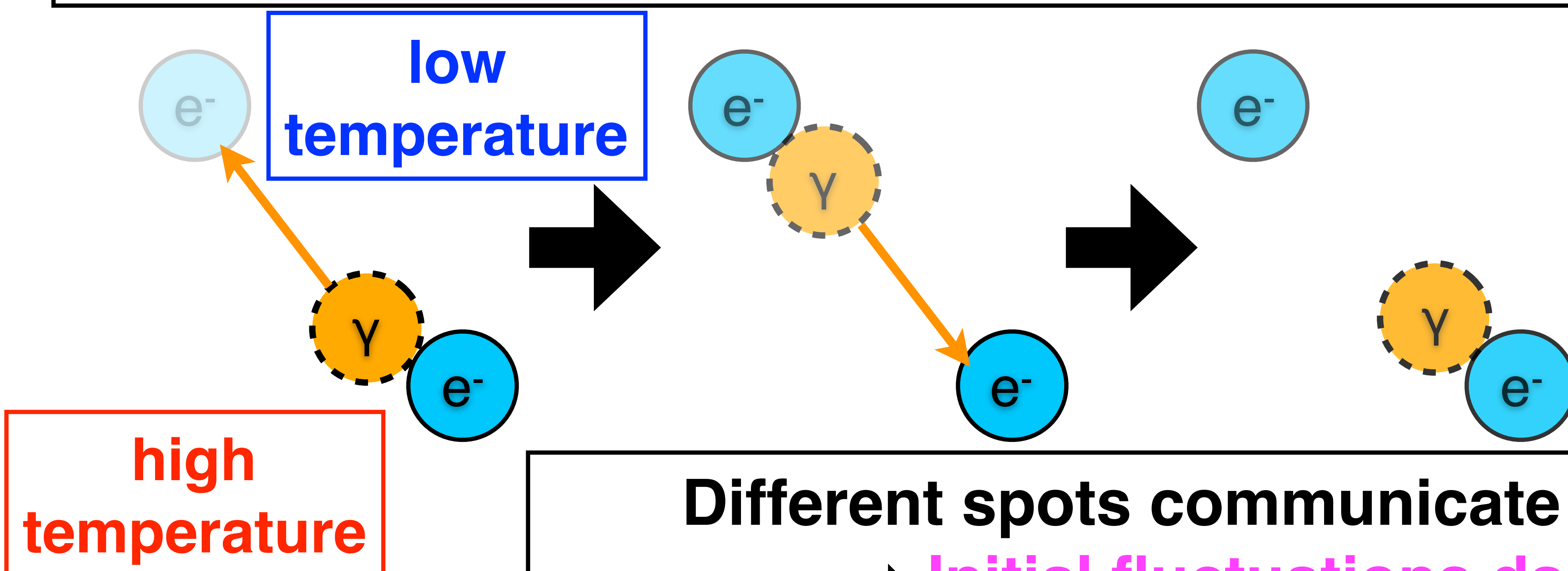
CMB anisotropies

→ matter distribution at 100 Mpc-10 Gpc (cosmic horizon) scales

Limitation of CMB: Silk damping

Photons γ and baryons e^- p^+ move together along the primordial gravitational potentials
→ **higher photon ↔ higher baryon temperature/density spots**

↔ Finite mean free path of photons $\lambda_{\rm fs} \sim \dfrac{1}{\sigma_{\rm T} n_e}$ (Thomson scattering)

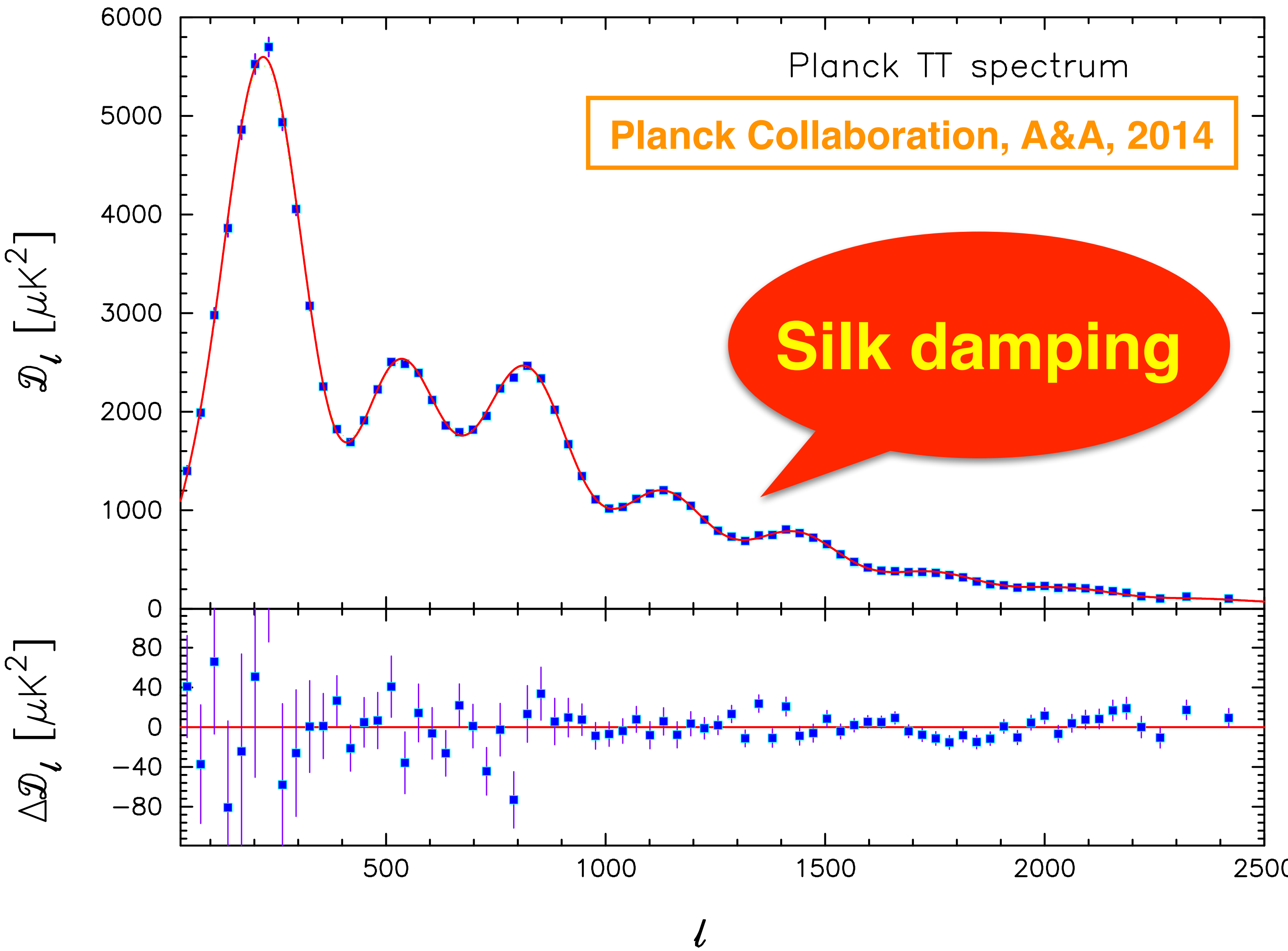


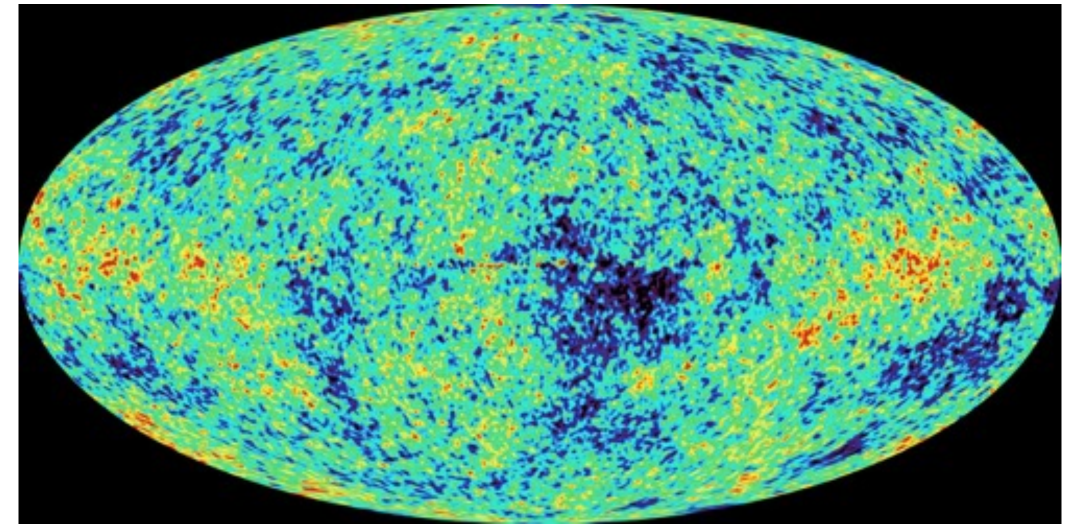
Different spots communicate each other
→ **Initial fluctuations damped**

Diffusion length-Mean free path: Random walk

$$\lambda_{\rm diff} \sim \lambda_{\rm fs}\sqrt{\sharp {\rm scat}} \qquad \sharp{\rm scat} \sim \frac{ct}{\lambda_{\rm fs}}$$

Success of ΛCDM model in CMB





Parameter	*Planck* Best fit	*Planck* 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

CMB observations of undamped modes (ℓ <2500)

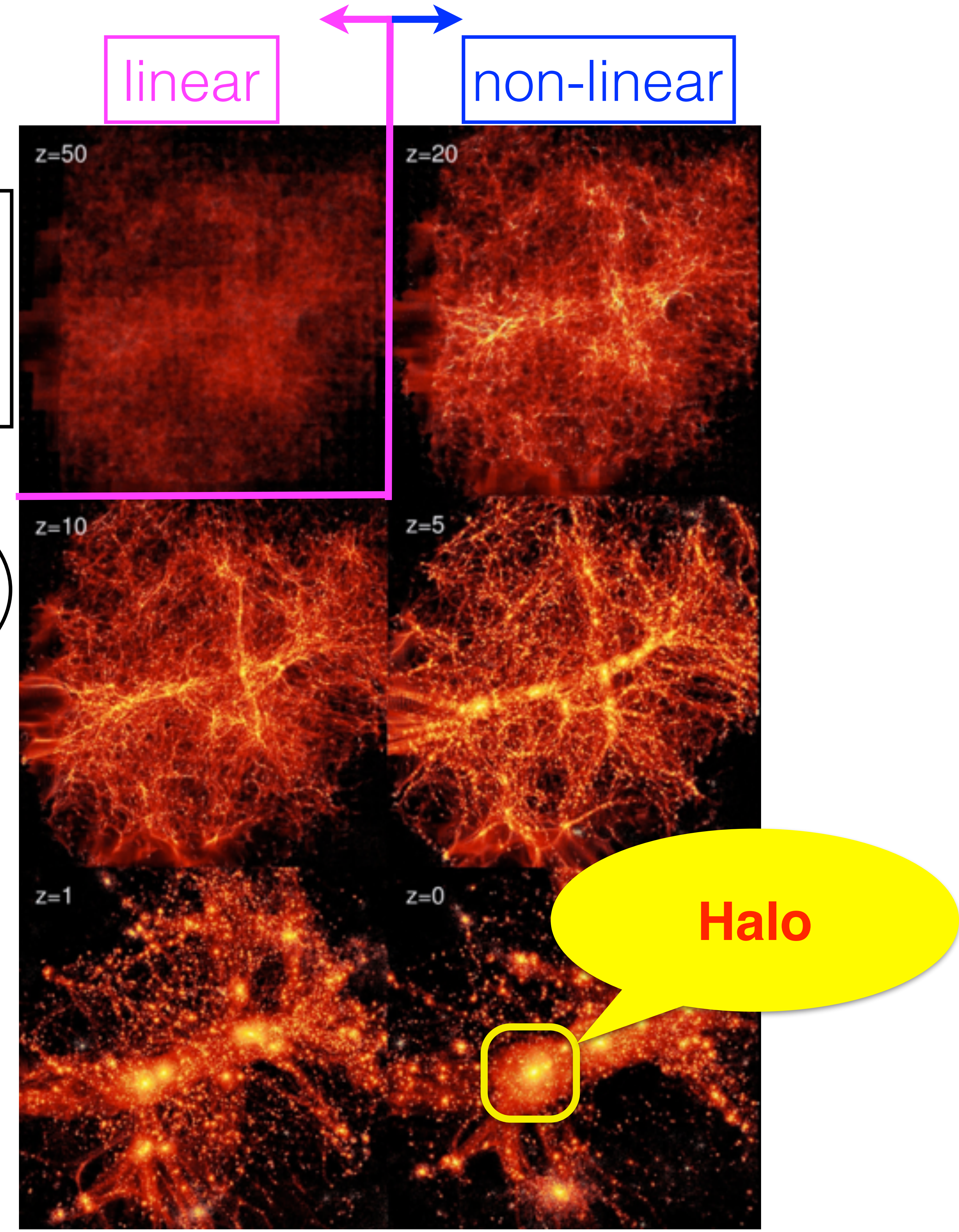
simultaneously determine six parameters of ΛCDM model and are well-reproduced

Non-linear evolution of matter distribution

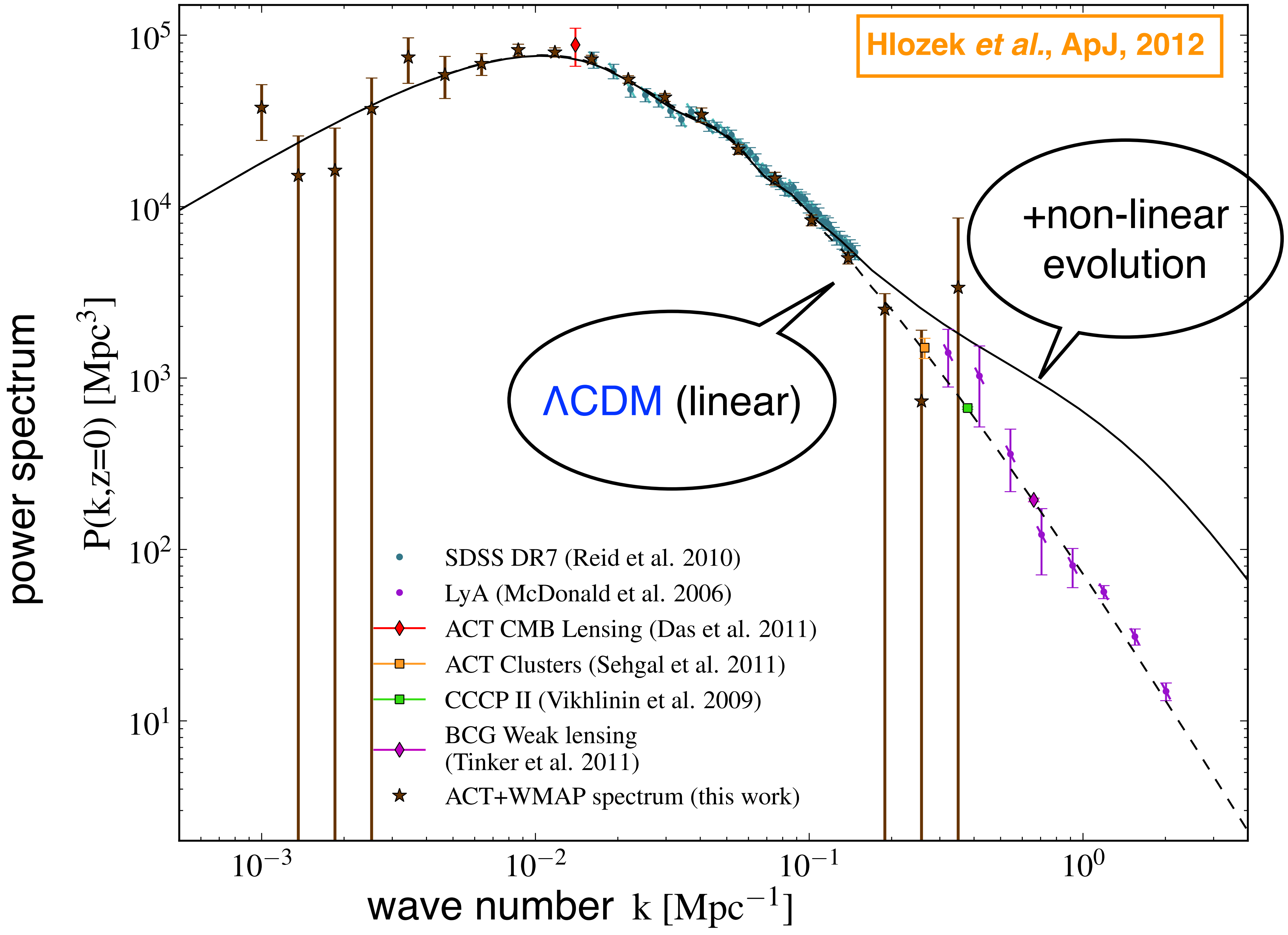
Under the matter-domination, density fluctuations grow such that $\delta \propto a$

N-body simulation
- Lagrange picture

Get non-linear ($\delta > 1$) and start to form halos, which host luminous objects like galaxies



Large scale structure of the Universe



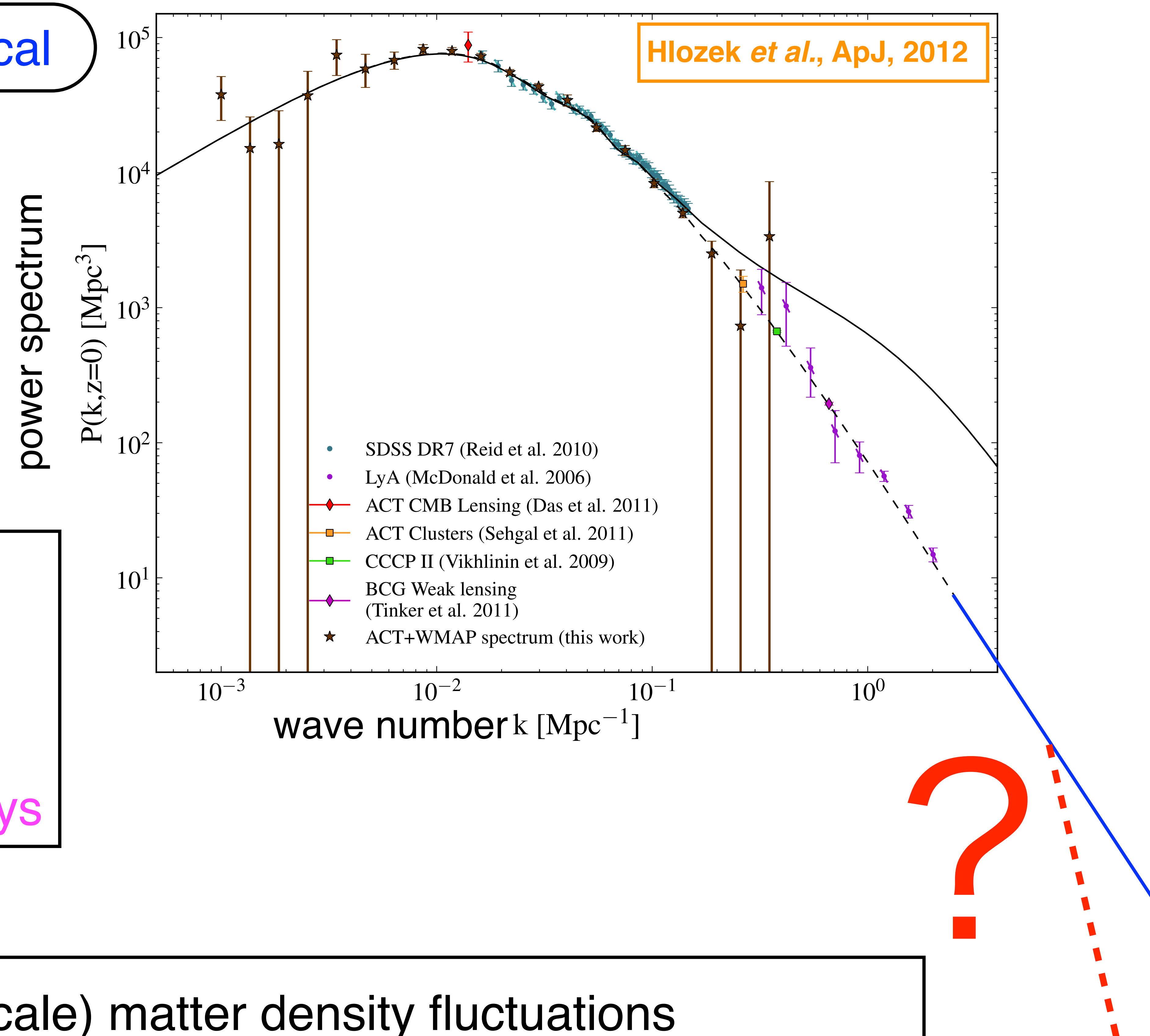
ΛCDM model reproduces
large scale (>Mpc) structure of the Universe well

Cold Dark Matter?

hypothetical

cold dark matter:
null thermal velocity
only gravitationally interacting

particle physics DM candidates:
finite (sizable) thermal velocity
interacting in many ways



(Small scale) matter density fluctuations
(deviations from **ΛCDM**) contain imprints of the nature of DM

Notes on use of large scale structure

Observation

Indirect measurement -
only luminous objects (baryons) can be detected
→ After structure formation (non-linear evolution),
baryons may not follow DM distribution
→ Difficult to detect halos that host faint objects

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-art hydrodynamic simulations and elaborate modeling of baryon processes**

Advantage of gravitational lenses

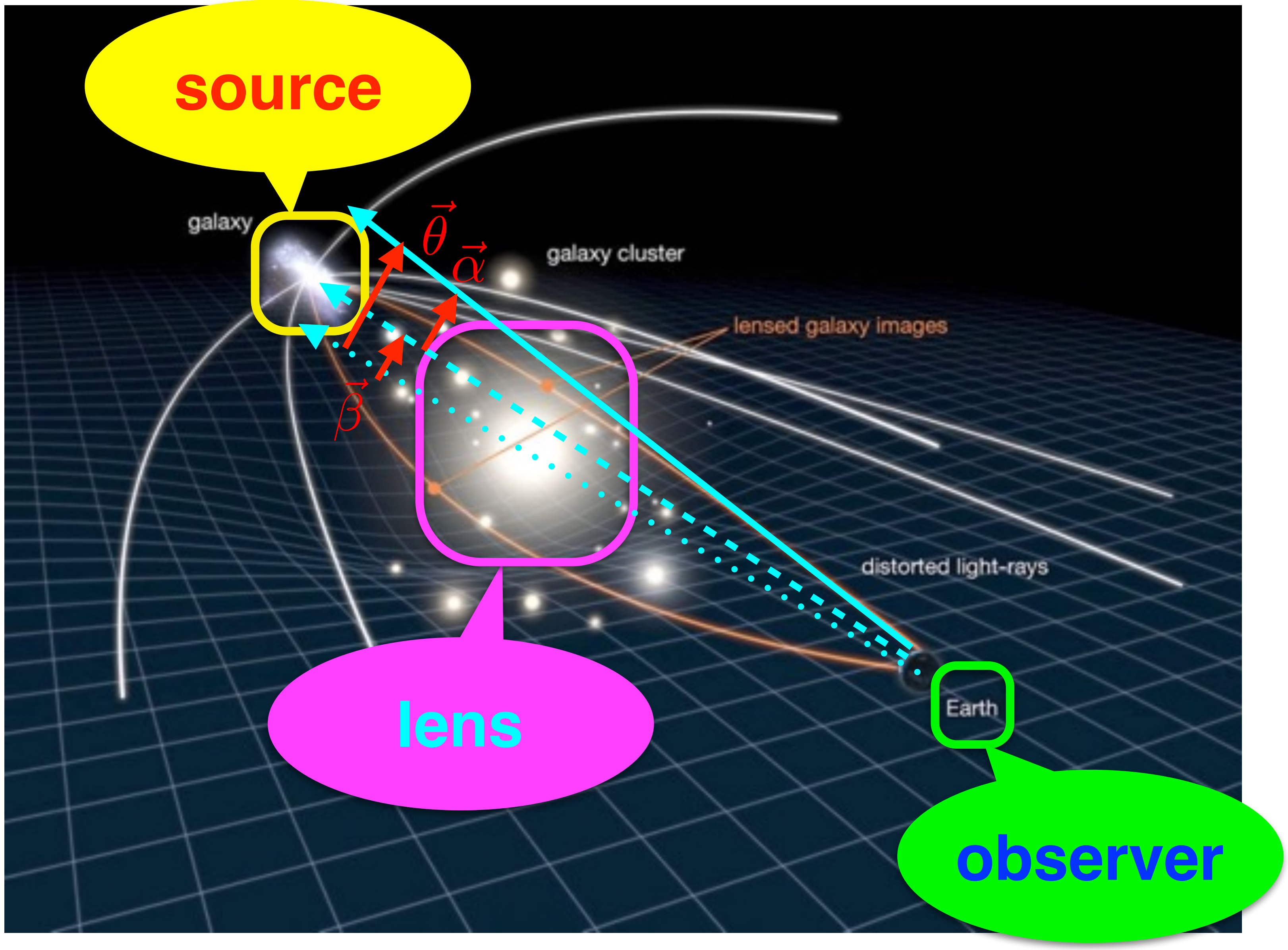
Observation

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

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-art hydrodynamic simulations and elaborate modeling of baryon processes**

Gravitational lens I



Position distortion (Born approximation)

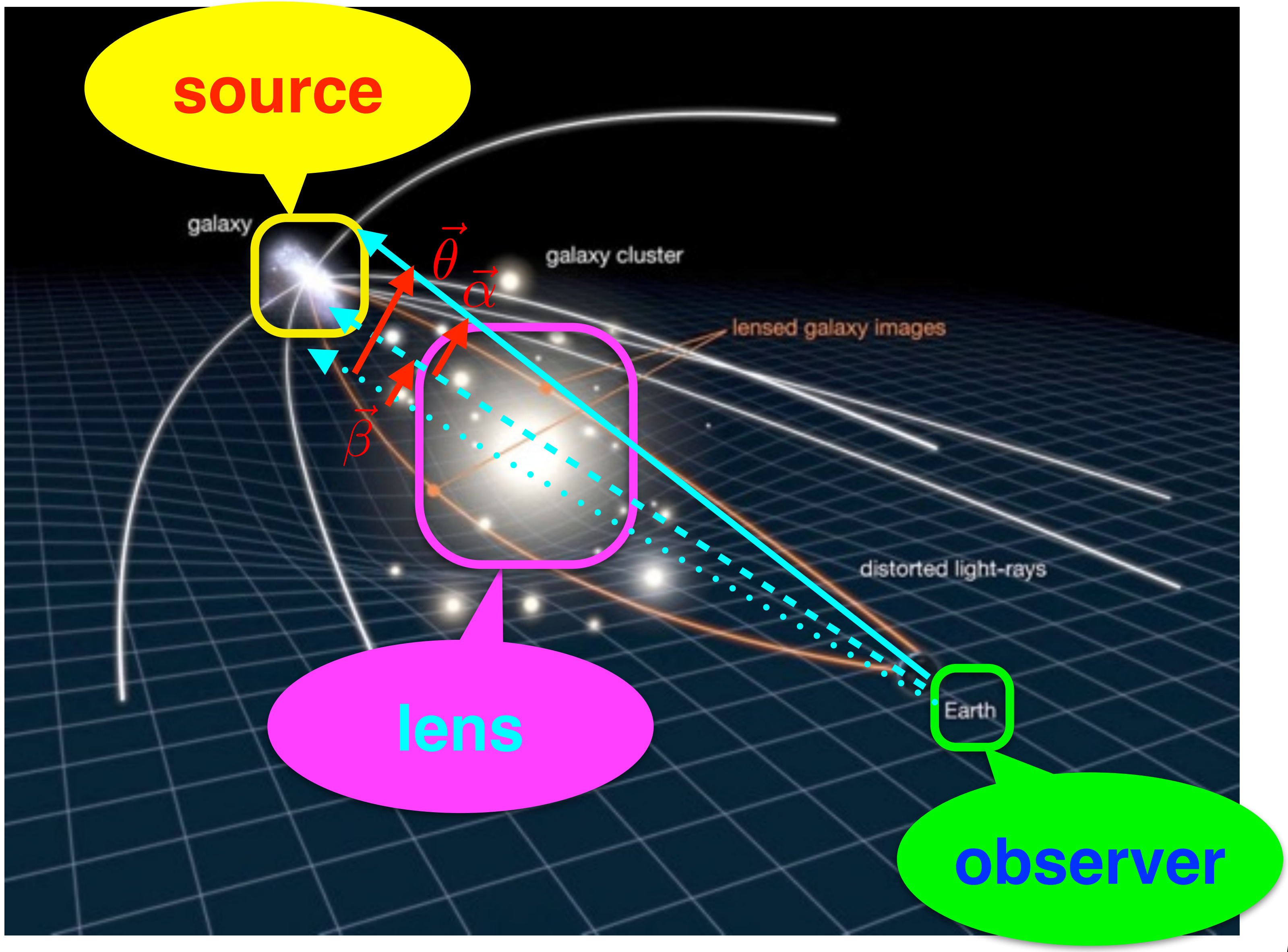
$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta}) \qquad \vec{\alpha} = \partial_{\vec{\theta}} \psi$$

$$\psi(\theta) = \frac{D_{\rm ds}}{D_{\rm d} D_{\rm s}} \frac{2}{c^2} \int \Phi(D_{\rm d}\vec{\theta}, z) dz$$

$\vec{\beta}$: original position
$\vec{\theta}$: apparent position
D: angular distance

1st derivative of gravitational potential

Gravitational lens II



Specific intensity: conserved

dE/dt/dA/(cosθ dΩ)/dν

Flux: magnified

dE/dt/dA/dν

2nd derivative of gravitational potential

κ : convergence

γ : shear

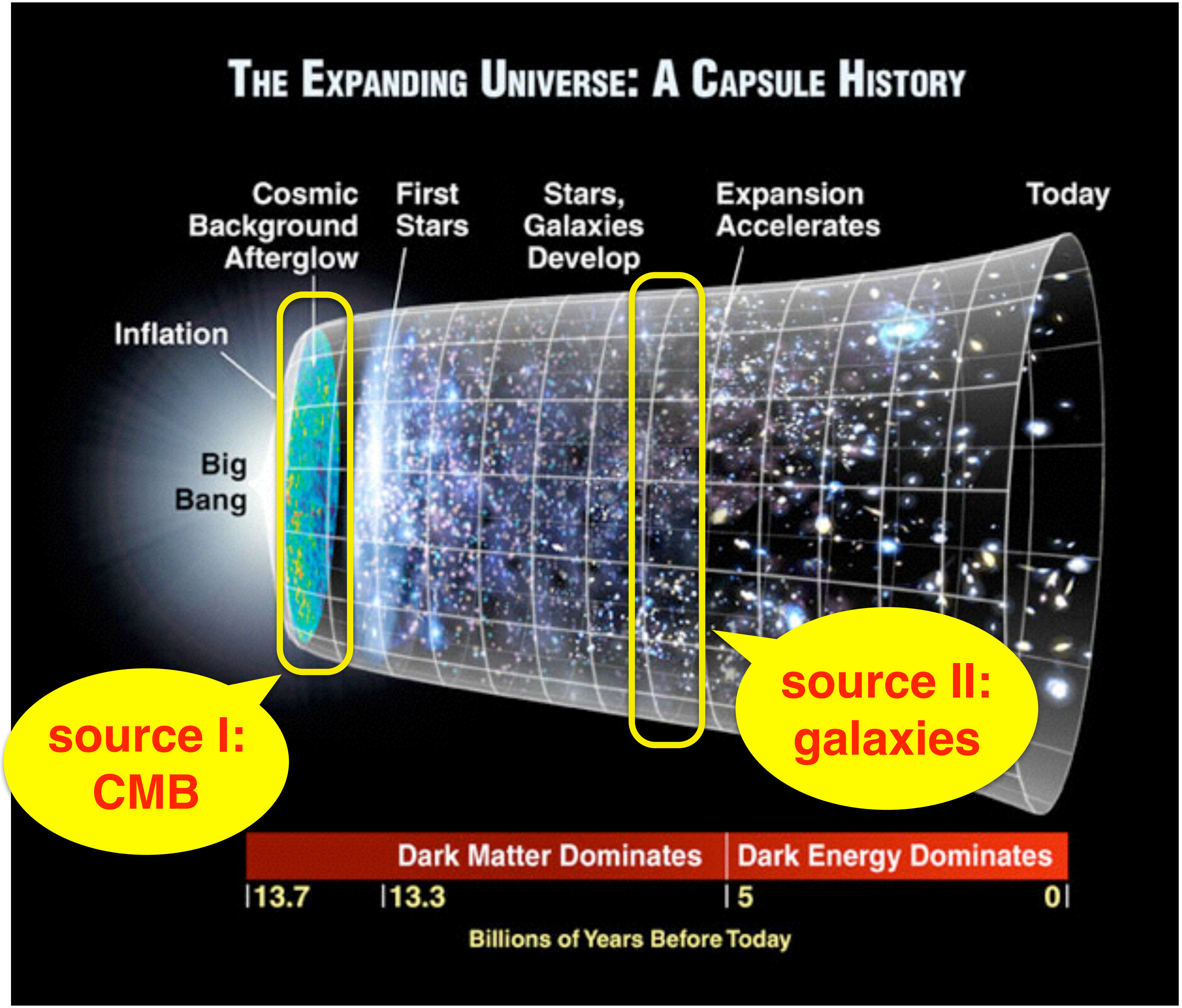
Image Distortion

$$A_{ij} = \frac{\partial \beta^i}{\partial \theta^j} \equiv \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

Magnification

$$\mu = \frac{1}{\det A} = \frac{1}{(1-\kappa)^2 - \gamma_1^2 - \gamma_2^2}$$

Sources in this talk



Constraints on light gravitino mass

based on

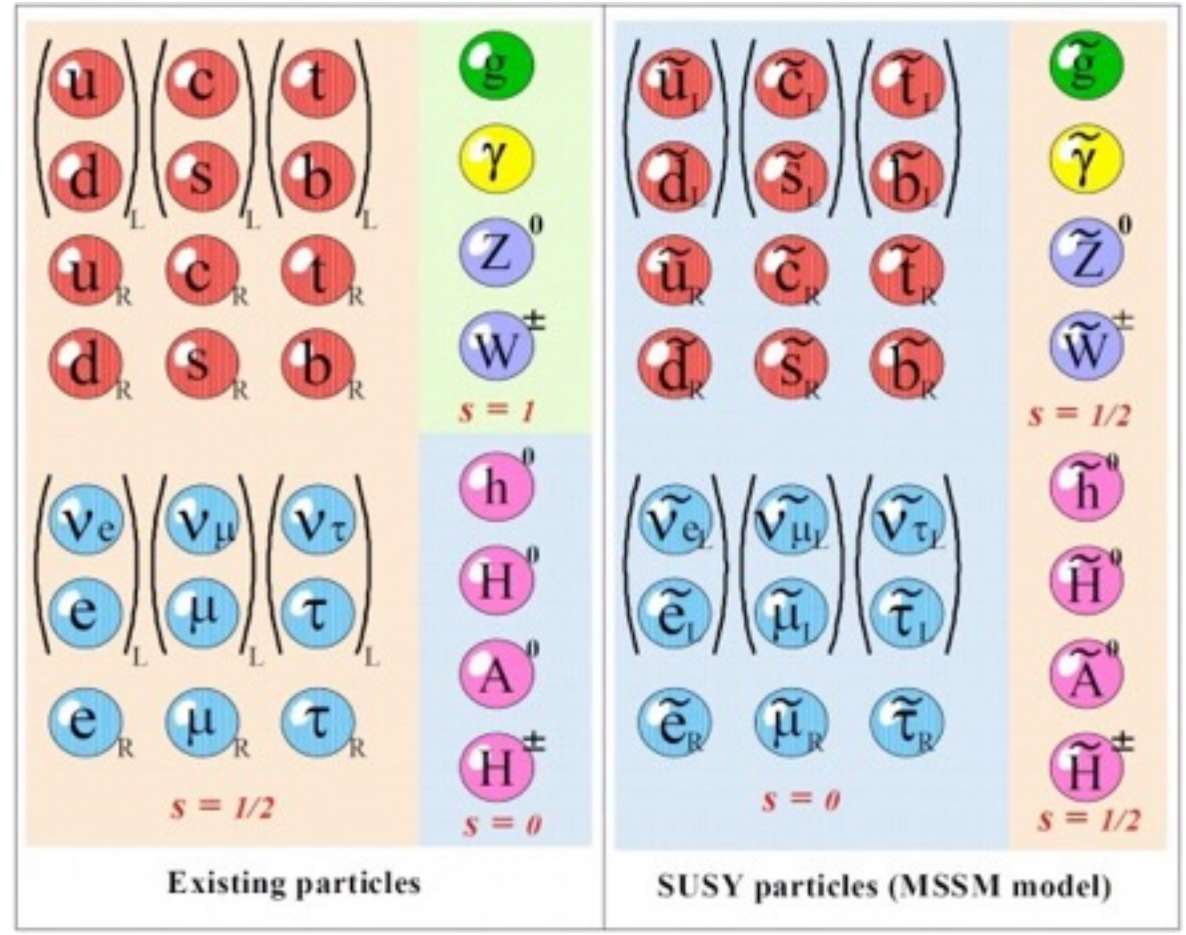
AK, M. Shirasaki, and N. Yoshida, JHEP, 2014

K. Osato, T. Sekiguchi, M. Shirasaki, **AK**, N. Yoshida, JCAP, 2016

Supersymmetry (SUSY)

Nontrivially extended Poincaré symmetry -
Boson (spin integer)
↔ Fermion (spin half-integer)

graviton (spin 2)
↔ gravitino (spin 3/2)



supersymmetric extension of Standard Model: MSSM → achieve grand unification

→ solve the hierarchy problem

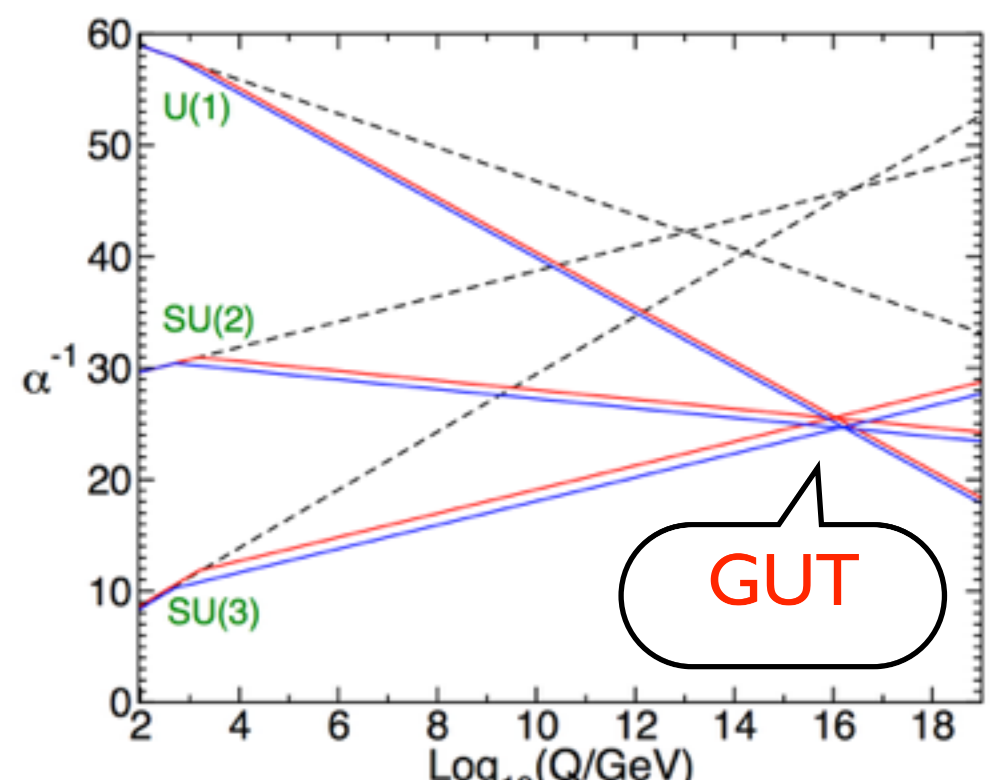
Martin, arXiv:hep-ph/9709356

$$m_{h^0}^2 = m_{h^0,0}^2 + \Delta(m_{h^0}^2)$$

model prediction (126 GeV)^2

model parameter

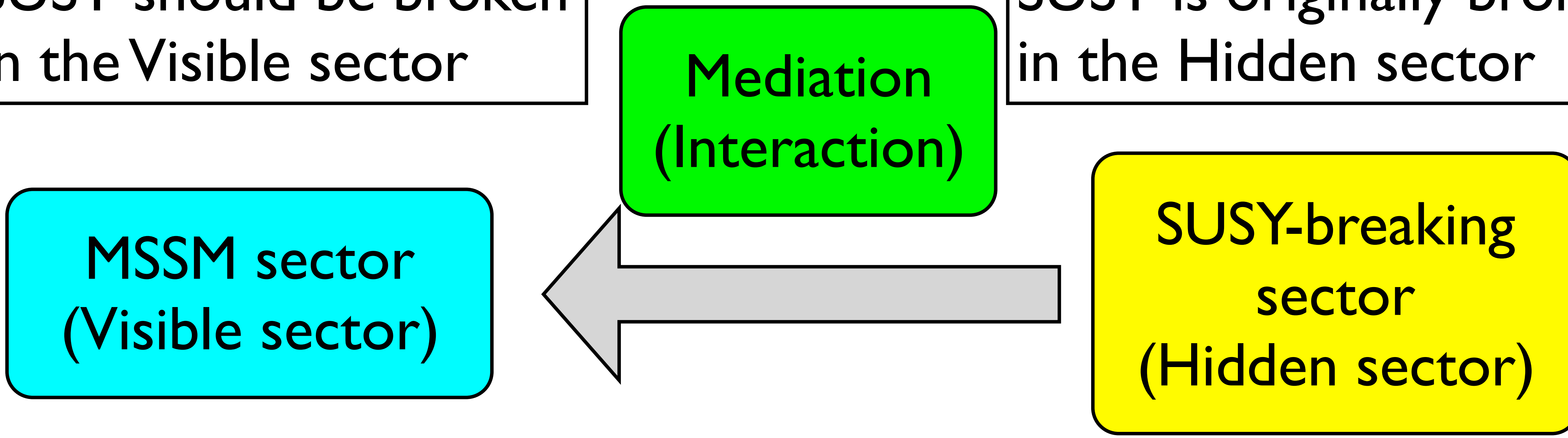
quantum correction ~(10^{17} GeV)^2



SUSY phenomenology

SUSY should be broken in the Visible sector

SUSY is originally broken in the Hidden sector



Gauge-mediated SUSY breaking(GMSB)

Messenger fields - SM gauge interaction
- coupling to SUSY breaking field

naturally ensures that flavor-blindness of SUSY breaking in MSSM

(minimal) GMSB mass spectrum

superpotential of minimal model

$$W = (\lambda S + M_{\rm mess}) \sum_{n=1}^{N_5} \Phi_n \bar{\Phi}_n$$

sfermion mass squared

$$m_{\phi_i}^2 = 2\Lambda^2 N_5 \sum_{a=1}^{3} C_a(i) \left(\frac{g_a^2}{16\pi^2} \right)^2 f(x)$$

gaugino mass

$$M_a = \frac{g_a^2}{16\pi^2} \Lambda N_5 g(x)$$

gravitino mass

$$m_{3/2} = \frac{F}{\sqrt{3} M_{\rm pl}}$$

Φ_n : messenger superfields

N_5 : # of messengers

$M_{\rm mess}$: messenger mass

$S \; (\langle S \rangle = \theta^2 F)$

: SUSY-breaking (goldstino) field

F : SUSY-breaking scale

$\Lambda (= \lambda F / M_{\rm mess})$

: MSSM SUSY-breaking scale

$$x = \Lambda / M_{\rm mess} \leq 1$$

$$f(x) = \frac{1+x}{x^2} \left[\ln(1+x) - 2{\rm Li}_2 \left(\frac{x}{1+x} \right) + \frac{1}{2} {\rm Li}_2 \left(\frac{2x}{1+x} \right) \right] + (x \to -x)$$

$$g(x) = \frac{1}{x^2} (1+x) \ln(1+x) + (x \to -x)$$

(minimal) GMSB mass spectrum

superpotential of minimal model

$$W = (\lambda S + M_{\rm mess}) \sum_{n=1}^{N_5} \Phi_n \bar{\Phi}_n$$

sfermion mass squared

gau

gravitino mass

$$m_{3/2} = \frac{F}{\sqrt{3} M_{\rm pl}}$$

Φ_n : messenger superfields

N_5 : # of messengers

distinctive feature of GMSB

$$m_\phi = \mathcal{O}(1\text{–}100)\ \mathrm{TeV}$$
$$M = \mathcal{O}(1\text{–}100)\ \mathrm{TeV}$$

$$\Rightarrow \quad m_{3/2} = \mathcal{O}(1\text{–}100)\ \mathrm{eV}$$

$$M_{\rm mess} \sim \Lambda = \mathcal{O}(10^{3\text{–}4})\ \mathrm{TeV} (\ll M_{\rm pl})$$

breaking scale

$$x = \Lambda / M_{\rm mess} \leq 1$$

$$f(x) = \frac{1+x}{x^2}\left[\ln(1+x) - 2\mathrm{Li}_2\left(\frac{x}{1+x}\right) + \frac{1}{2}\mathrm{Li}_2\left(\frac{2x}{1+x}\right)\right] + (x \to -x)$$

$$g(x) = \frac{1}{x^2}(1+x)\ln(1+x) + (x \to -x)$$

Light gravitino in cosmology

Thermal history

Produced and thermalized just after the reheating of the Universe

$T_{\mathrm{dec}3/2} = \mathcal{O}(10\text{–}100)\ \mathrm{GeV}$ ⟺ at the freeze-out of the other SUSY particles

Decouple from the thermal background and start to **free-stream with speed of light**

$(1 + z_{\mathrm{nr}3/2}) \simeq 1 \times 10^4 (m_{3/2}/1\,\mathrm{eV})(g_{*s3/2}/90)^{1/3}$

Contribute to the mass density of the Universe

Light gravitino as "hot" component

Relic gravitino

Present mass density of the gravitino

$$\Omega_{3/2}h^2 = 0.13 \left(\frac{g_{3/2}}{2}\right)\left(\frac{m_{3/2}}{100\,\mathrm{eV}}\right)\left(\frac{g_{*s3/2}}{90}\right)^{-1}$$

$\Omega_{3/2}/\Omega_{\rm DM}^{\rm CMB\,obs} = \mathcal{O}(1\text{–}10)\%$ for $m_{3/2} = \mathcal{O}(1\text{–}10)\,\mathrm{eV}$

Assume another cold and stable particle exist

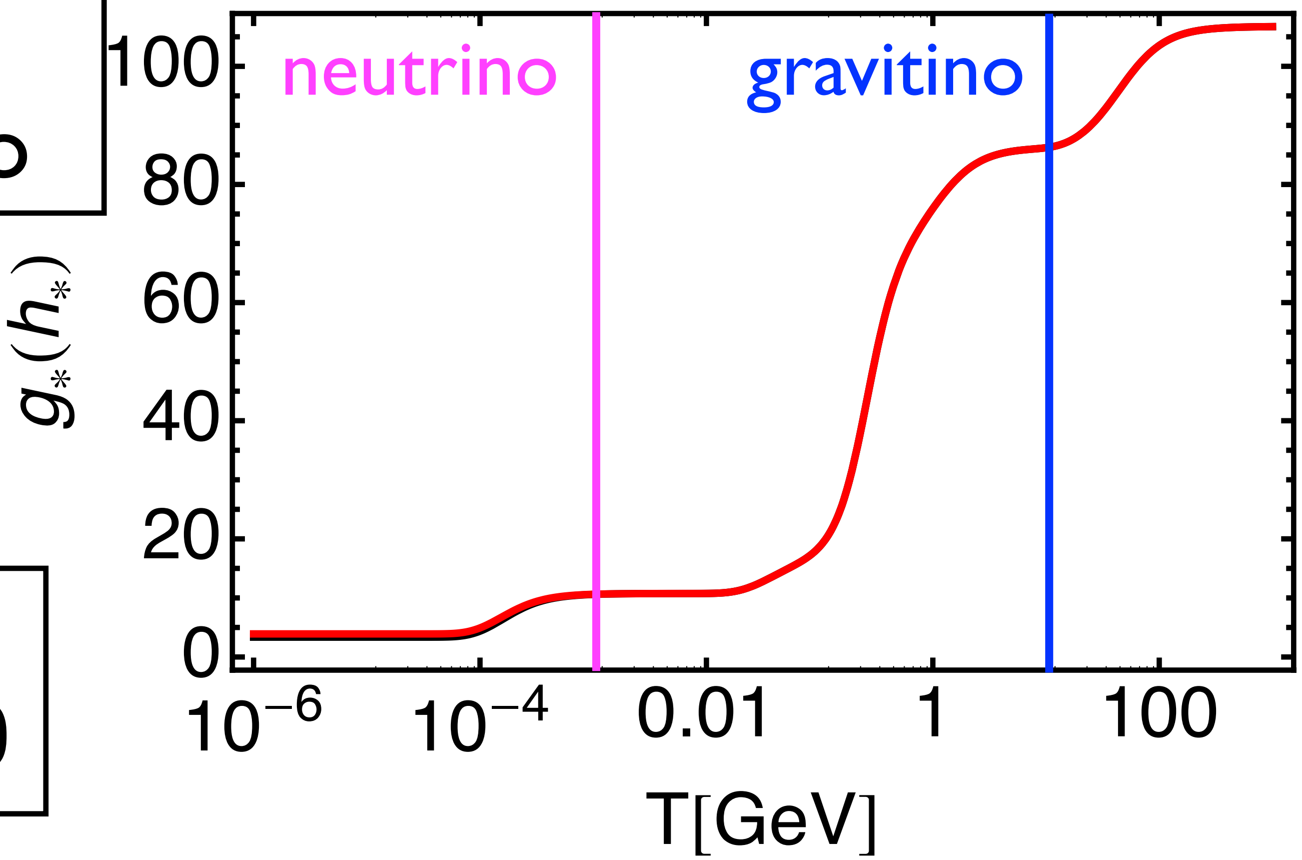
$g_{*s3/2}$: effective degrees of freedom for the entropy density at the decoupling of the gravitino

$g_{*s3/2} \simeq 90$ E. Pierpaoli *et al.*, PRD 1998

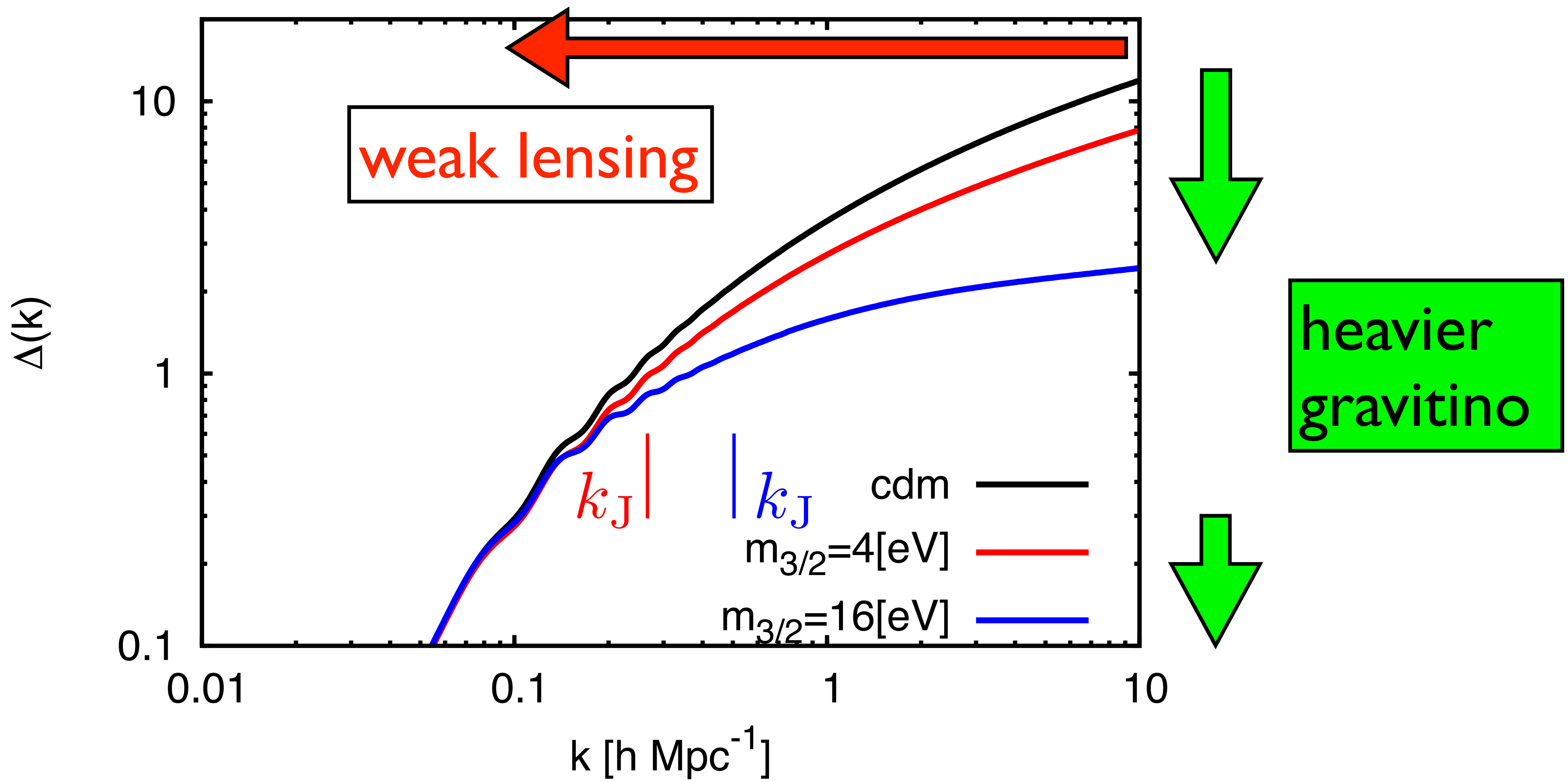
for $m_{3/2} = \mathcal{O}(1\text{–}10)\,\mathrm{eV}$

Different from the neutrino

$g_{*s\nu} \simeq 43/4$ ⟷ $g_{*s3/2} \simeq 90$



Linear matter power spectra w/ light gravitino



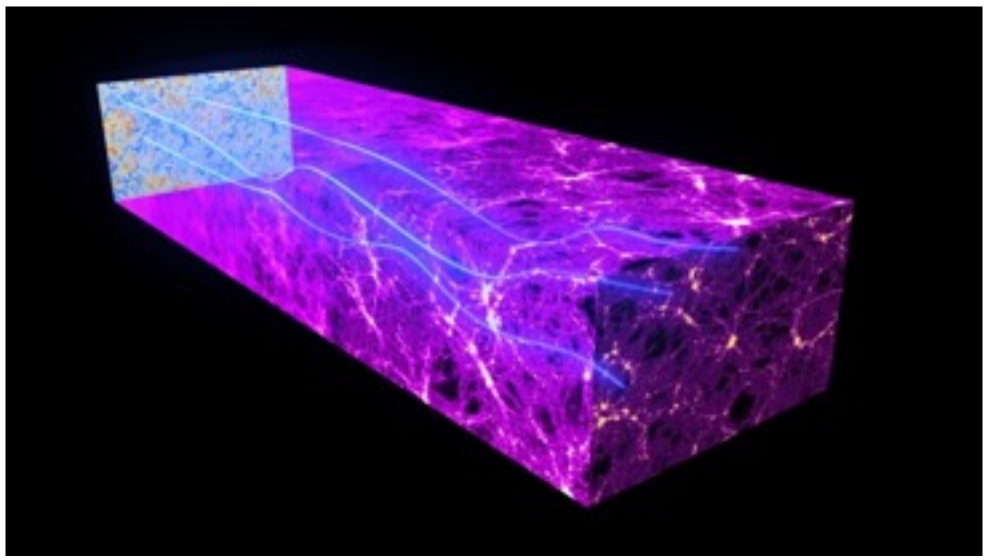
cutoff scale: $k_J = a\sqrt{\frac{4\pi G\rho_M}{\langle v^2\rangle}}\Bigg|_{a=a_{eq}} \simeq 0.86\,\mathrm{Mpc}^{-1}\left(\frac{g_{3/2}}{2}\right)^{-1/2}\left(\frac{m_{3/2}}{100\,\mathrm{eV}}\right)^{1/2}\left(\frac{g_{*s3/2}}{90}\right)^{5/6}$

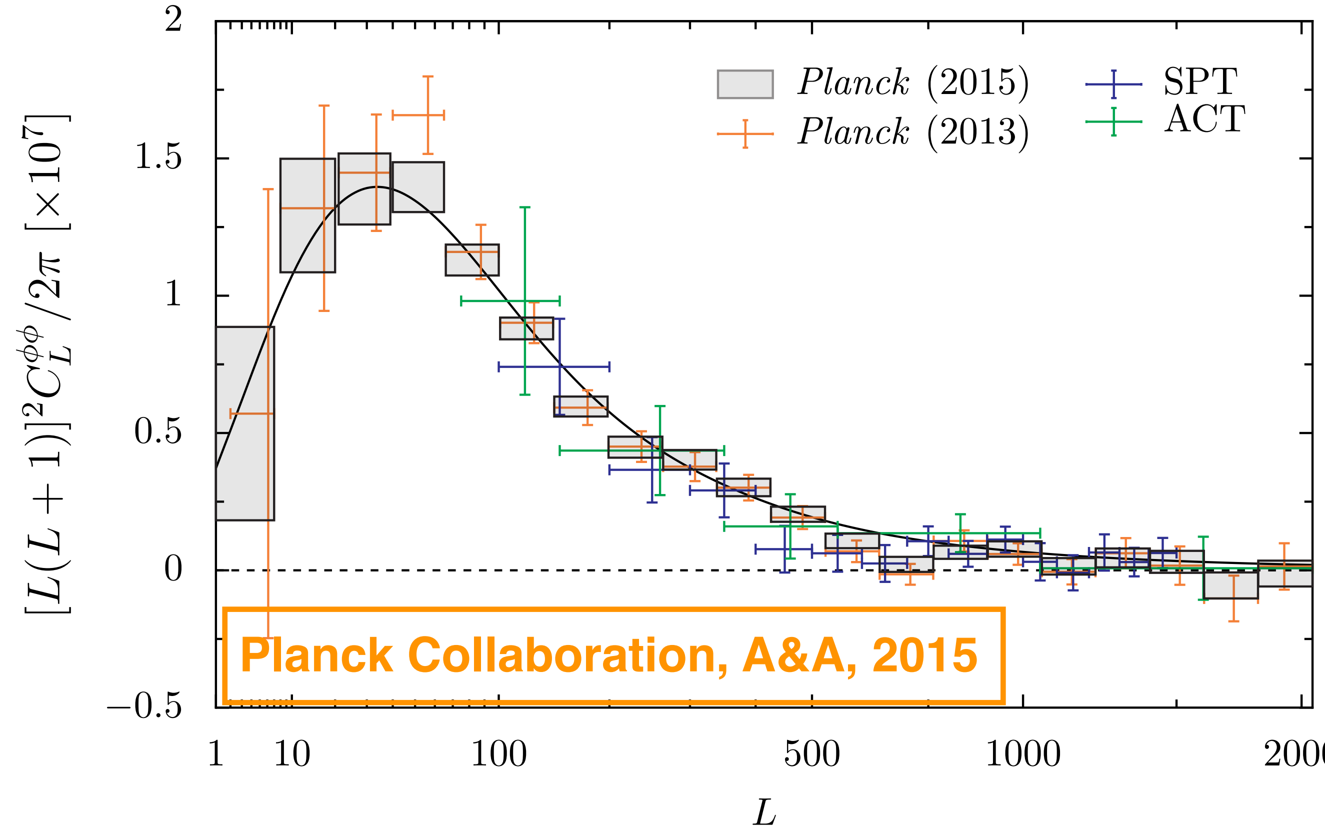
Upper bound on the gravitino mass in cosmology
⇔ Lower bound in the LHC

Cosmological data

Planck TT,TE,EE+lowP - constraint ΛCDM model parameters

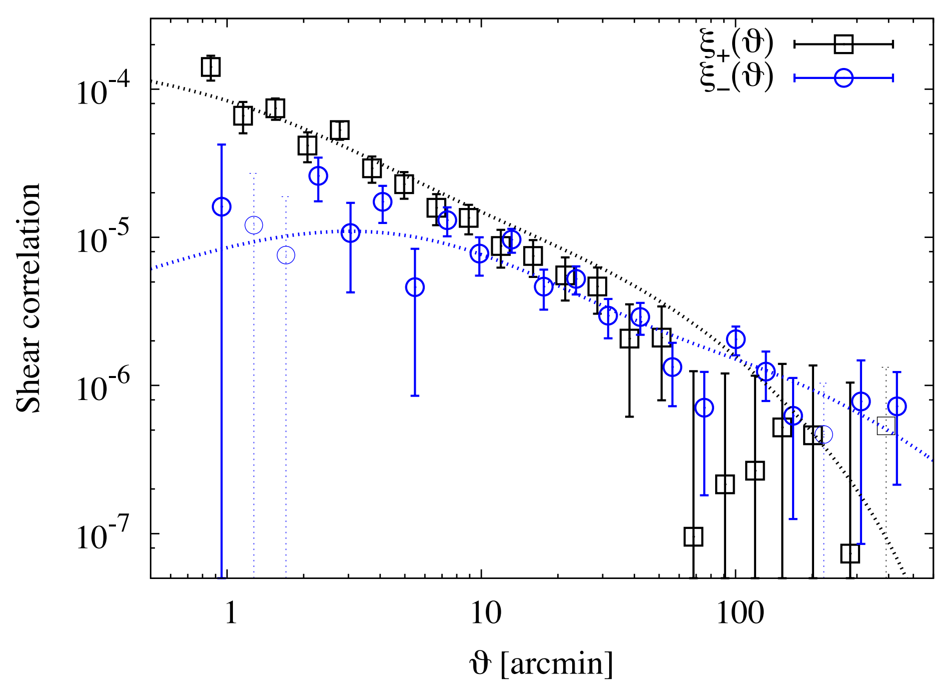
Planck lensing





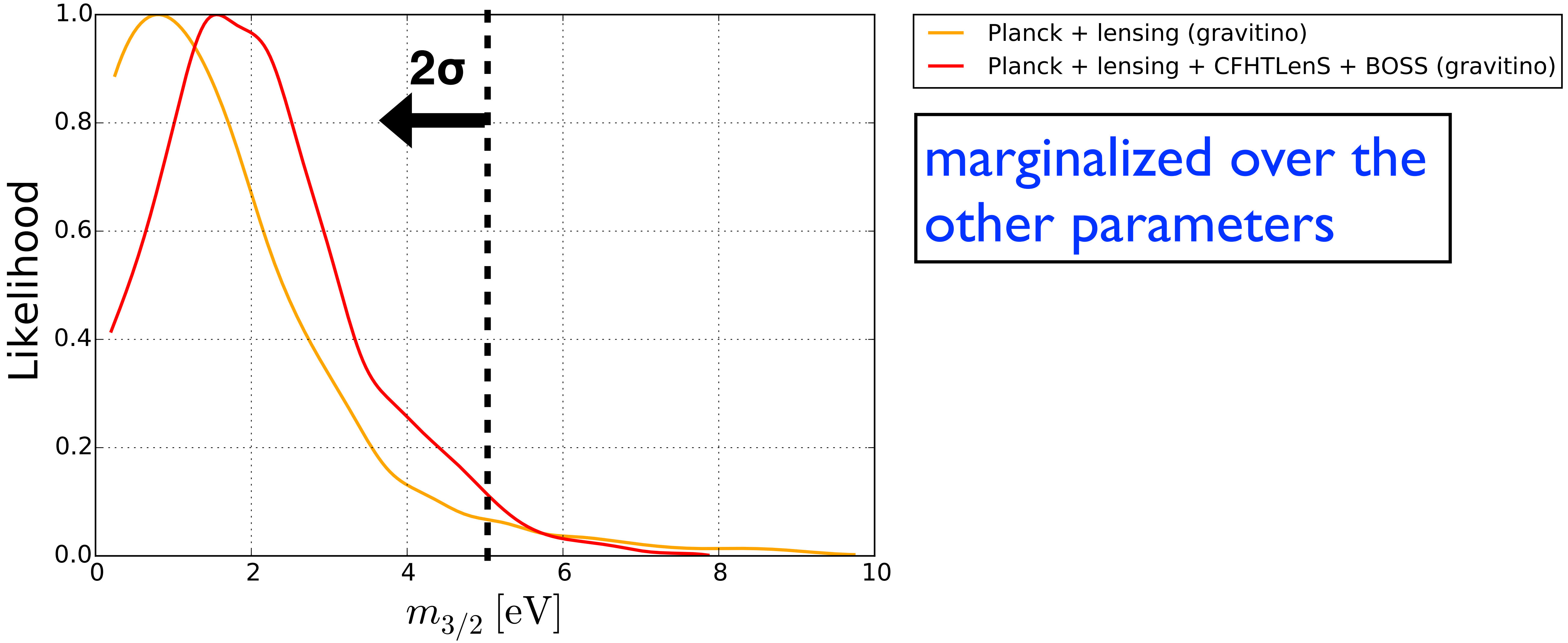
Planck Collaboration, A&A, 2015

Canada France Hawaii Lensing Survey (CFHTLenS) + BOSS



Kilbinger *et al.*, MNRAS, 2013

Results



marginalized over the other parameters

$m_{3/2} \lesssim 5\,\mathrm{eV}$ is consistent with the lens data at 95% CL

Higgs mass in MSSM

v : Higgs VEV

m_t : top quark mass

$m_{\tilde{t}}$: stop mass

$$m_{h^0}^2 = m_{h^0,0}^2 + \Delta(m_{h^0}^2)$$

model prediction (126 GeV)^2

$< m_Z^2$

(91 GeV)^2

quantum correction

$\sim m_t^4/(16\pi^2 v^2)\ln(m_{\tilde{t}}/m_t)$

$\sim \ln(m_{3/2})$

gravitino mass as large as

$m_{3/2} = \mathcal{O}(100)$ eV ($m_{\tilde{t}} = \mathcal{O}(10)$ TeV)

is needed in MSSM of perturbative GMSB ($\lambda < 1$)

Ajaib *et al.*, PLB, 2012

$$W = (\lambda S + M_{\rm mess})\sum_{n=1}^{N_5}\Phi_n\bar{\Phi}_n$$

Implications

Some modification is needed for GMSB models
to reproduce simultaneously the observed Higgs mass
and gravitational lens measurements

- extension of the Higgs sector: NMSSM

Yanagida *et al.*, JHEP, 2012

- non-perturbative GMSB
  -- hidden baryons as good candidate for cold and stable particle

- non-standard cosmological history
  -- low reheating temperature $T_{\rm RH} \lesssim m_{\rm NLSP}/20$
  -- entropy production after the gravitino decoupling

Small scale crisis
vs
Quadruple lens system

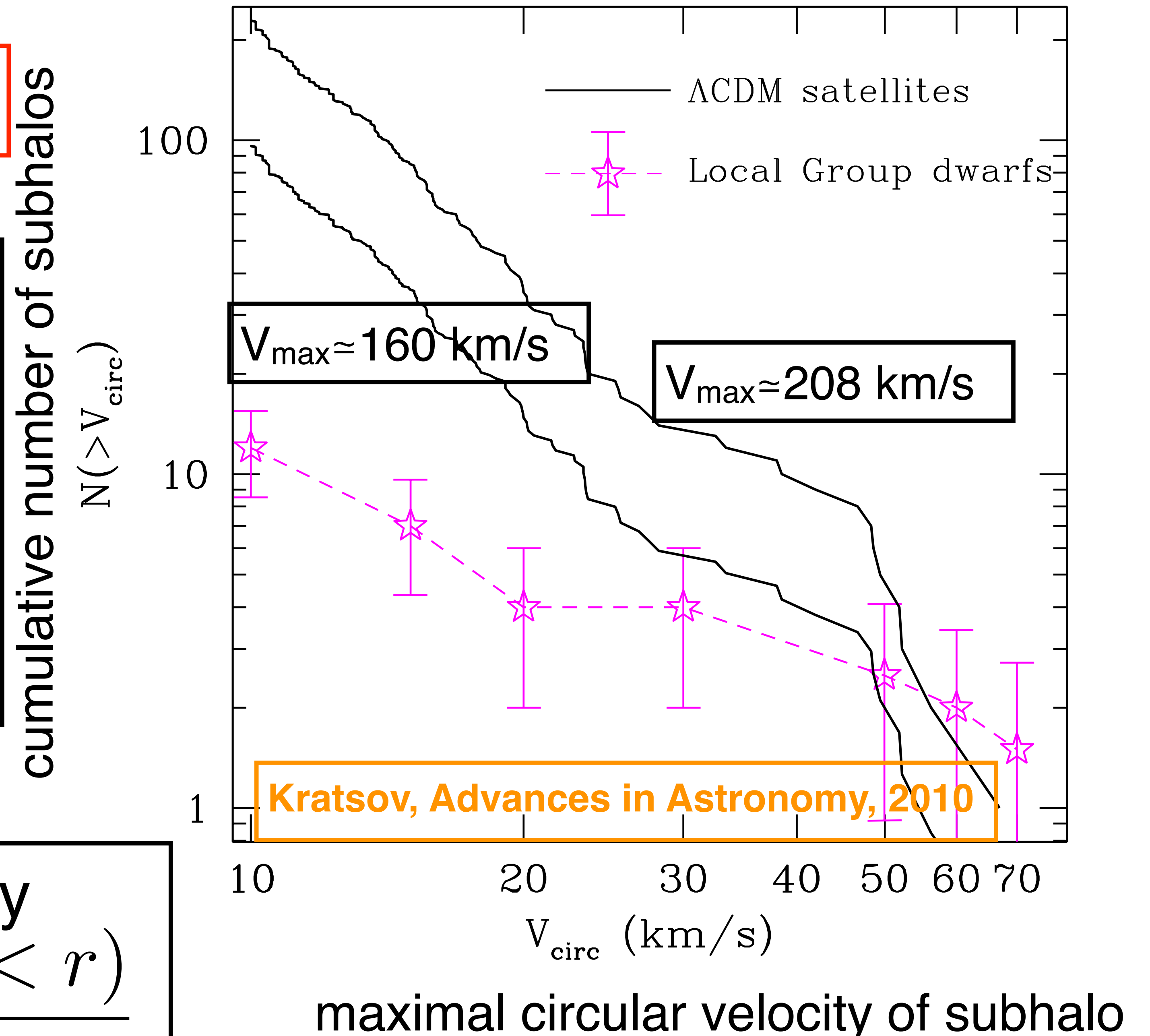
based on
A. Harada, **AK**, JCAP, 2016
AK, K. T. Inoue, T. Takahashi, arXiv:1604.01489

Small scale crisis I

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

missing satellite problem

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



circular veolocity

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

Small scale crisis II

cusp vs core problem

N-body (DM-only) simulations in ΛCDM model →
Universal DM profile independent of halo size: **NFW profile**

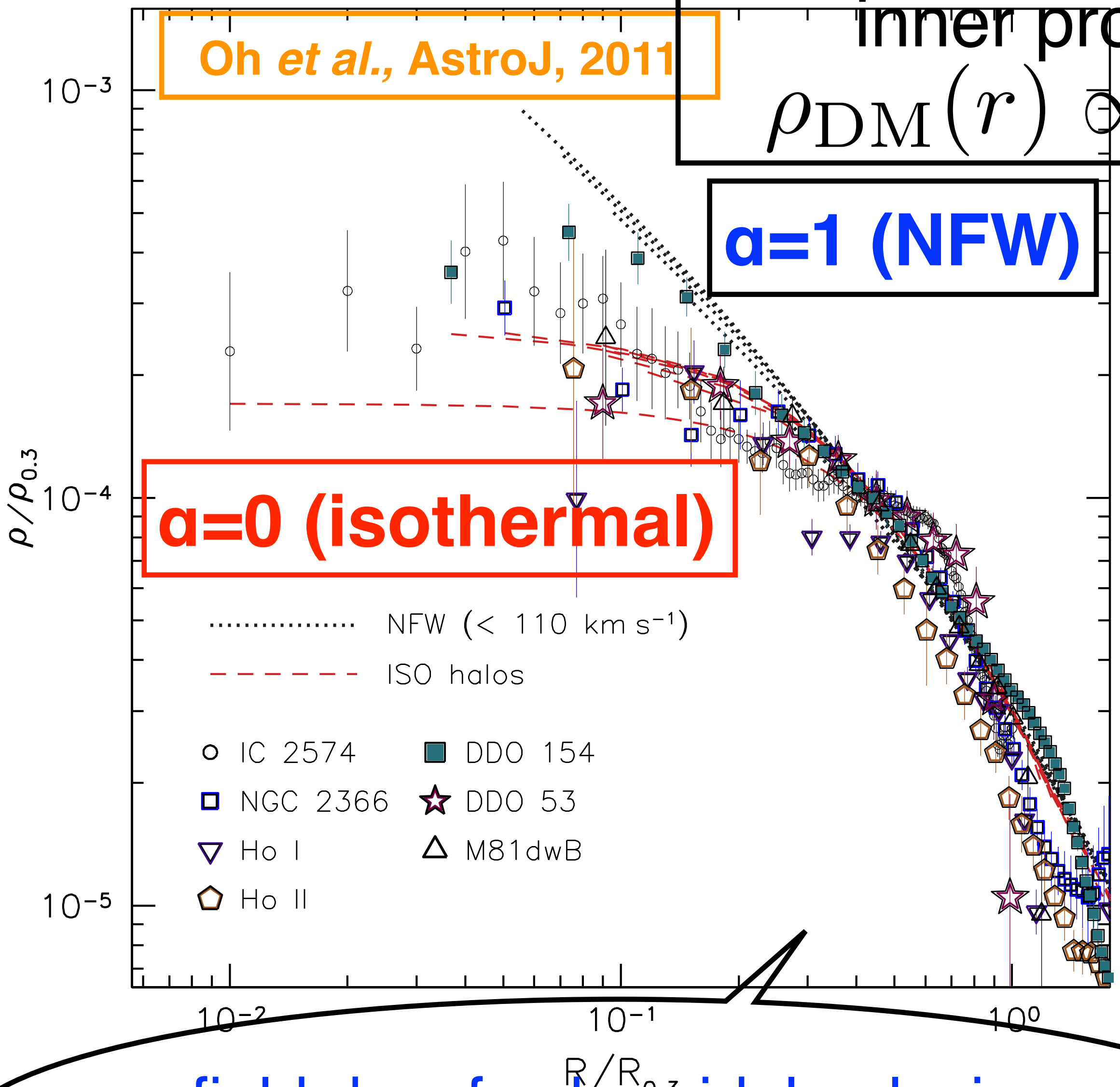
inner profile

$$\rho_{\rm DM}(r) \propto r^{-\alpha}$$

α=1 (NFW)

α=0 (isothermal)

Oh *et al.*, AstroJ, 2011



field dwarf spheroidal galaxies
~10^9 Msun

Observations infer core profile in the inner region rather than cuspy NFW profile

NFW profile

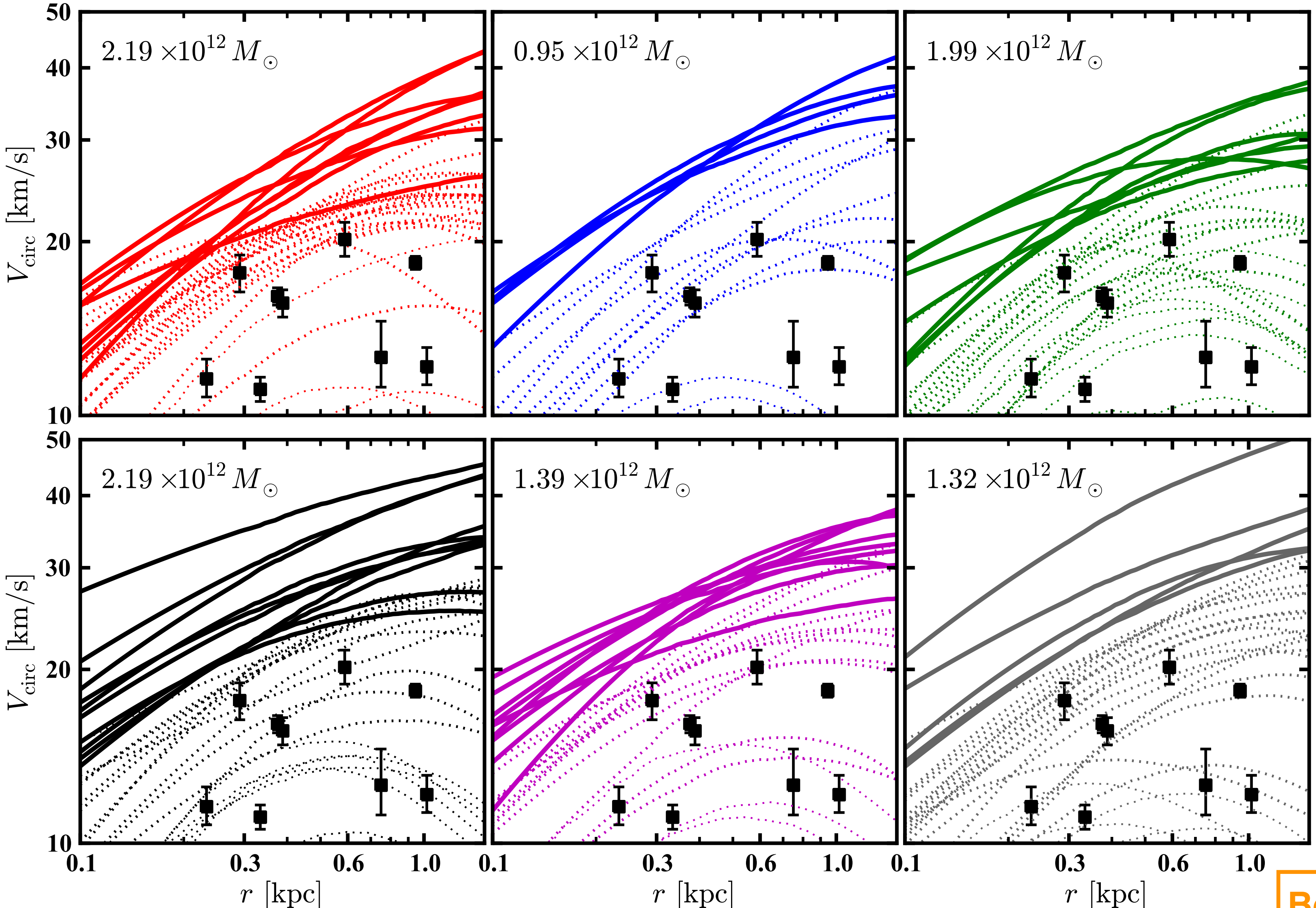
$$\rho_{\rm DM}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

isothermal profile

$$\rho_{\rm DM}(r) = \rho_{\rm DM}^0 \begin{cases} 1 \ (r \ll r_0) \\ (r_0/r)^2 \ (r \gg r_0) \end{cases}$$

Small scale crisis (III)

too big to fail problem



Boylan-Kolchin *et al.*, MNRAS, 2011

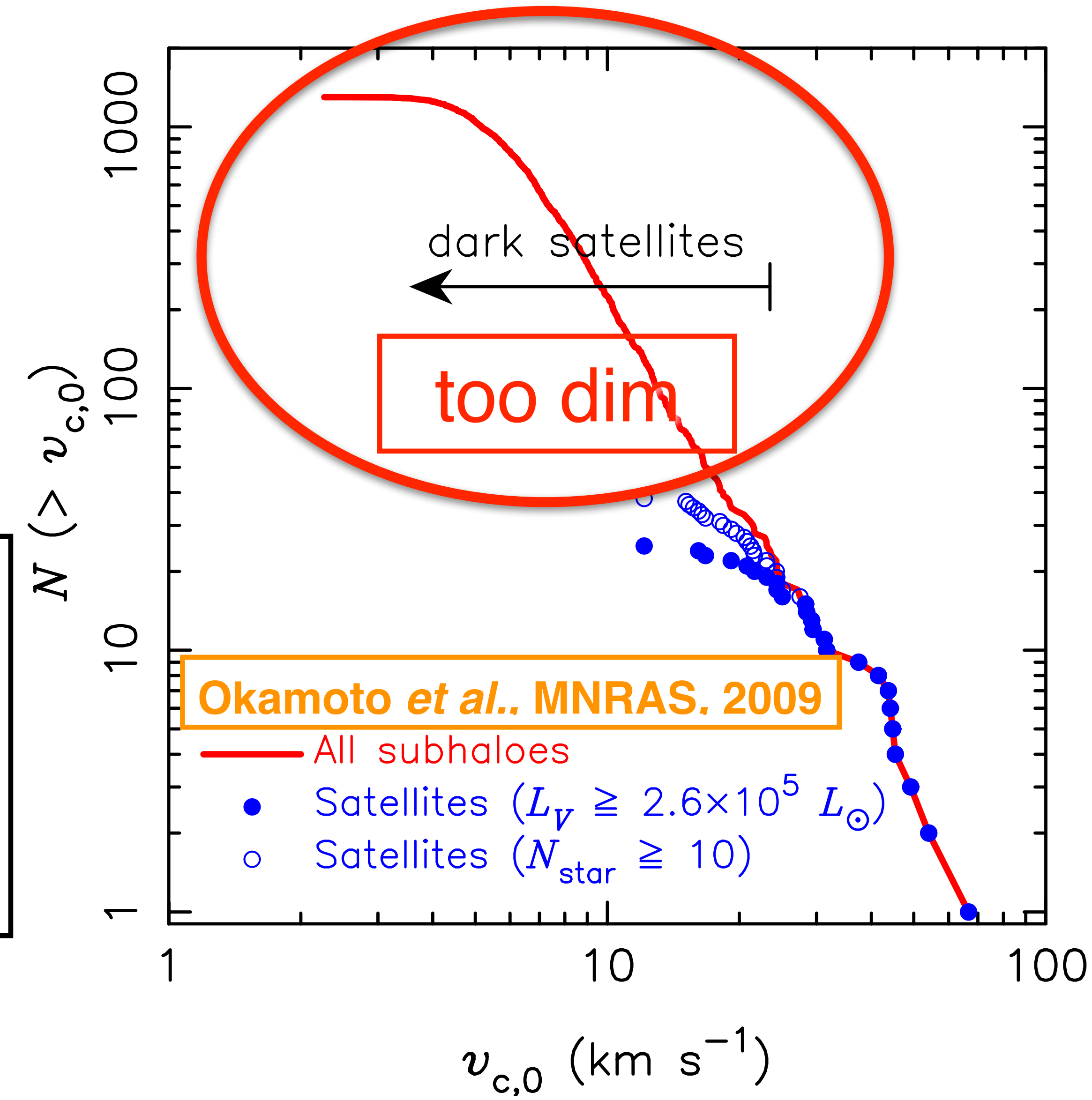
N-body (DM-only) simulations in ΛCDM model →
~10 subhalos with deepest potential wells in Milky Way-size halos do not have observed counterparts (dwarf spheroidal galaxies)

Possible solution I

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

↕

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

Possible solution II

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

↕

alternative models ↔ nature of DM

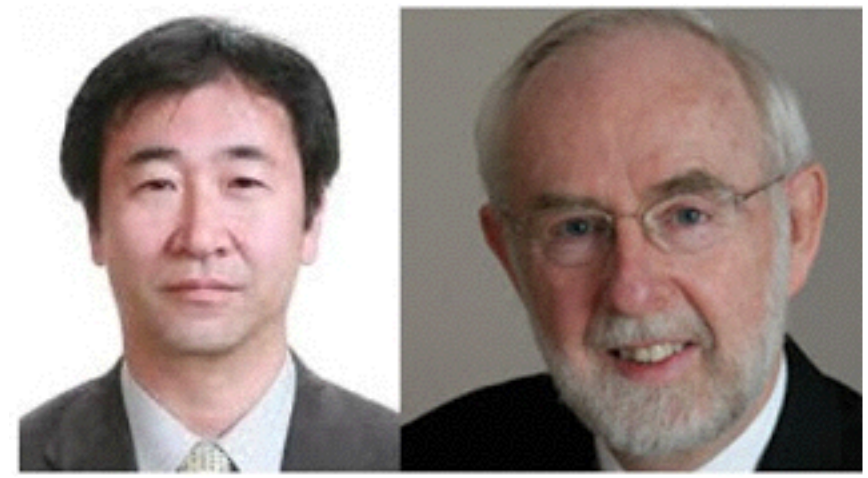
- **warmness** - thermal velocities induce pressure of DM fluid and prevent gravitational growth (Jeans analysis)

- **interactions with SM particles** - DM fluid couples to photons/neutrinos (moving with speed of light) in a direct/indirect manner.

- **self-interaction** - induced heat transfer of DM fluid heats DM particles in inner region and flatten inner profile

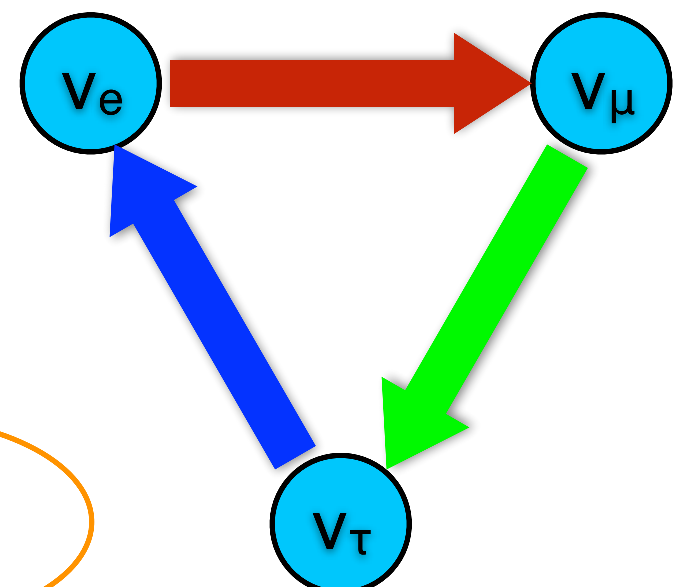
Warmness of DM: sterile neutrino

right-handed neutrino
inferred by observed **neutrino oscillation**
- heavier than active ones
through the see-saw mechanism



m_s : mass
θ : mixing angle

$m_s = 7\,\mathrm{keV}$
$\sin^2(2\theta) \sim 10^{-9}$



Nobel Prize 2015
Takaaki Kajita
and
Arthur B McDonald

radiative decay $\tau \sim 10^{27}\ \mathrm{s}$

$\nu_s \rightarrow \nu + \gamma$ X-ray

anomalous line of 3.5 keV ? ⟷ **not confirmed**

E. Bulbul *et al.*, ApJ, 2014 **A. Boyarsky *et al.*, PRL, 2014**

XMM-Newton, Chandra

T. Tamura *et al.*, PASJ, 2015
N. Sekiya *et al.*, PASJ, 2015

Suzaku

May sterile neutrino DM reconcile **missing satellite problem and anomalous X-ray line simultaneously?**

Sterile neutrino as mixed dark matter

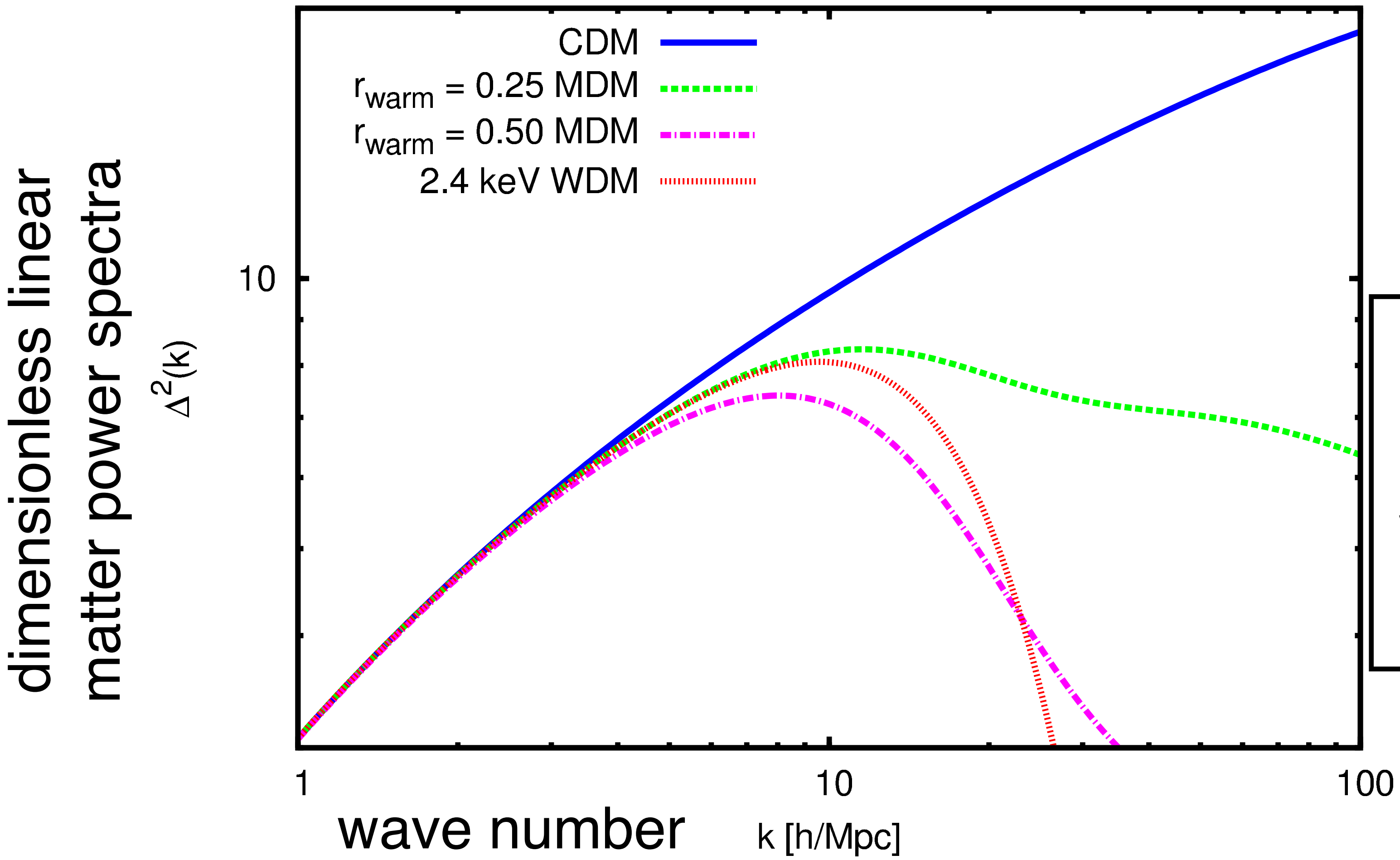
sterile neutrino radiative decay as an origin of 3.5 keV anomaly

Abazajian, PRL, 2014

large lepton asymmetry $n_L/n_\gamma \sim 10^{-4}$ (c.f. $n_B/n_\gamma \sim 10^{-10}$)

Kamada *et al.*, JCAP, 2016

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



Linear matter power is suppressed at galactic scales, while the suppression is weaker than in pure WDM models

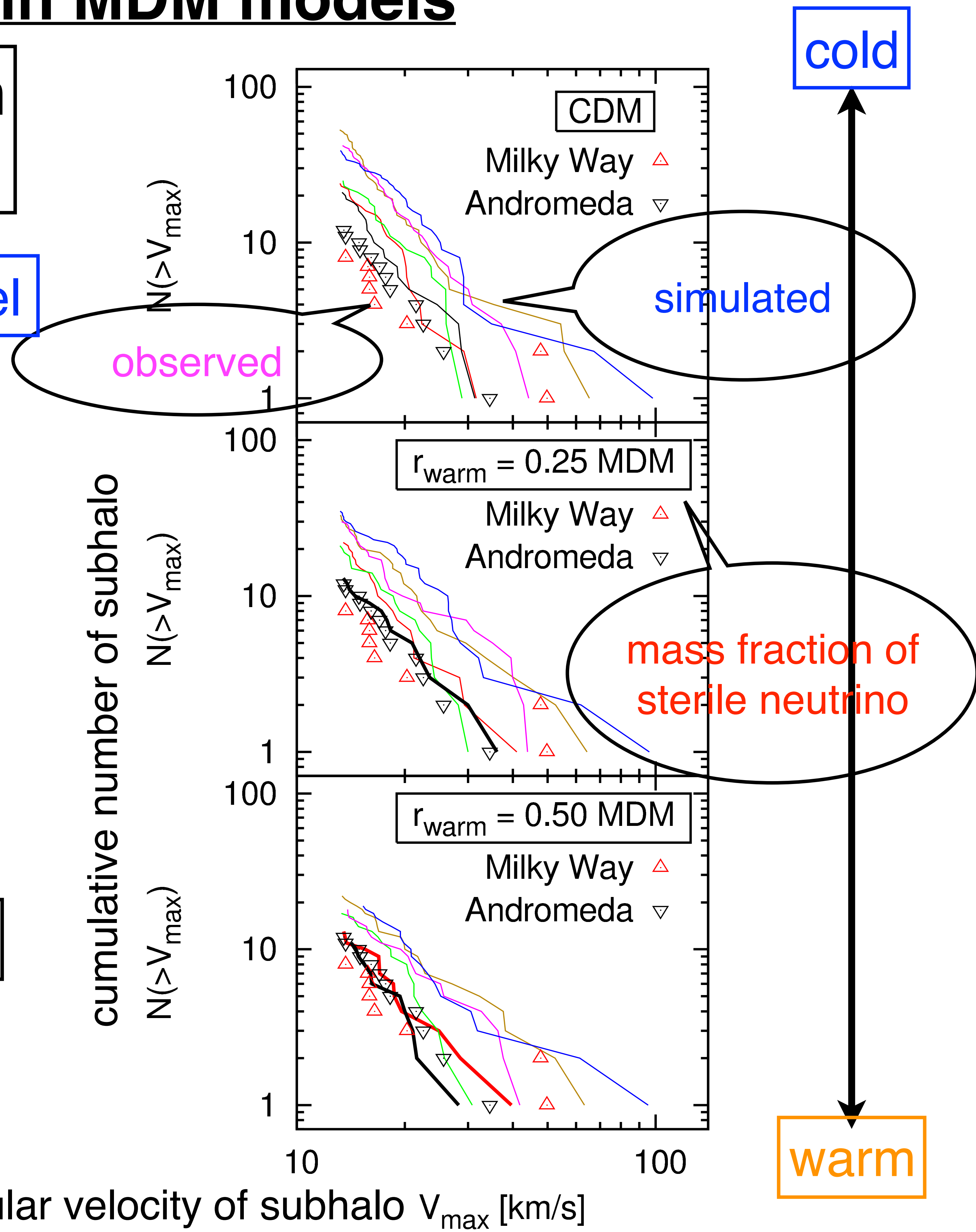
Missing satellite problem in MDM models

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

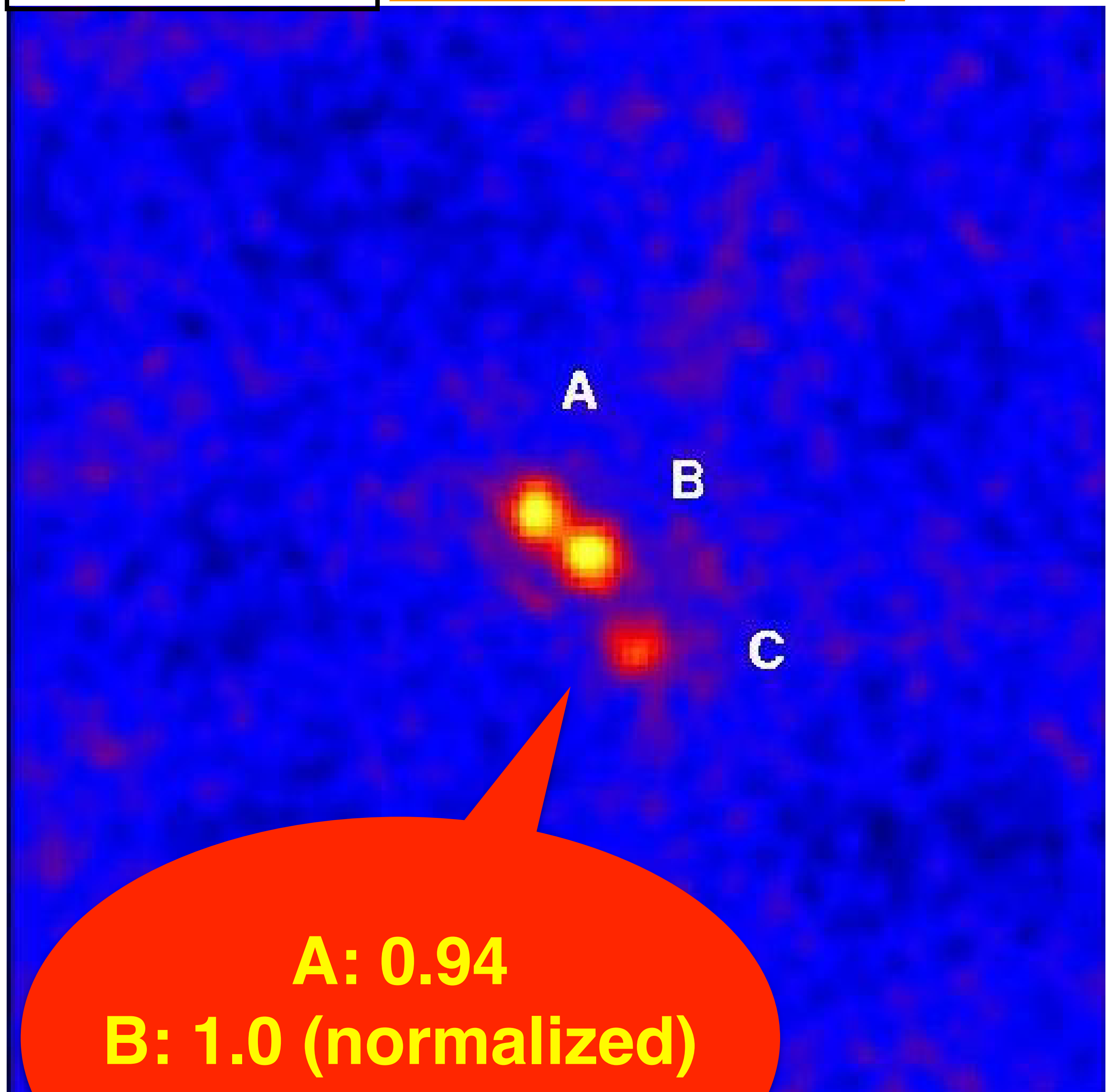
2 out 6 halos appear concordant



Anomalous Flux Ratio

B1422+231

M. Chiba *et al.*, ApJ, 2005



A: 0.94
B: 1.0 (normalized)
C: 0.57

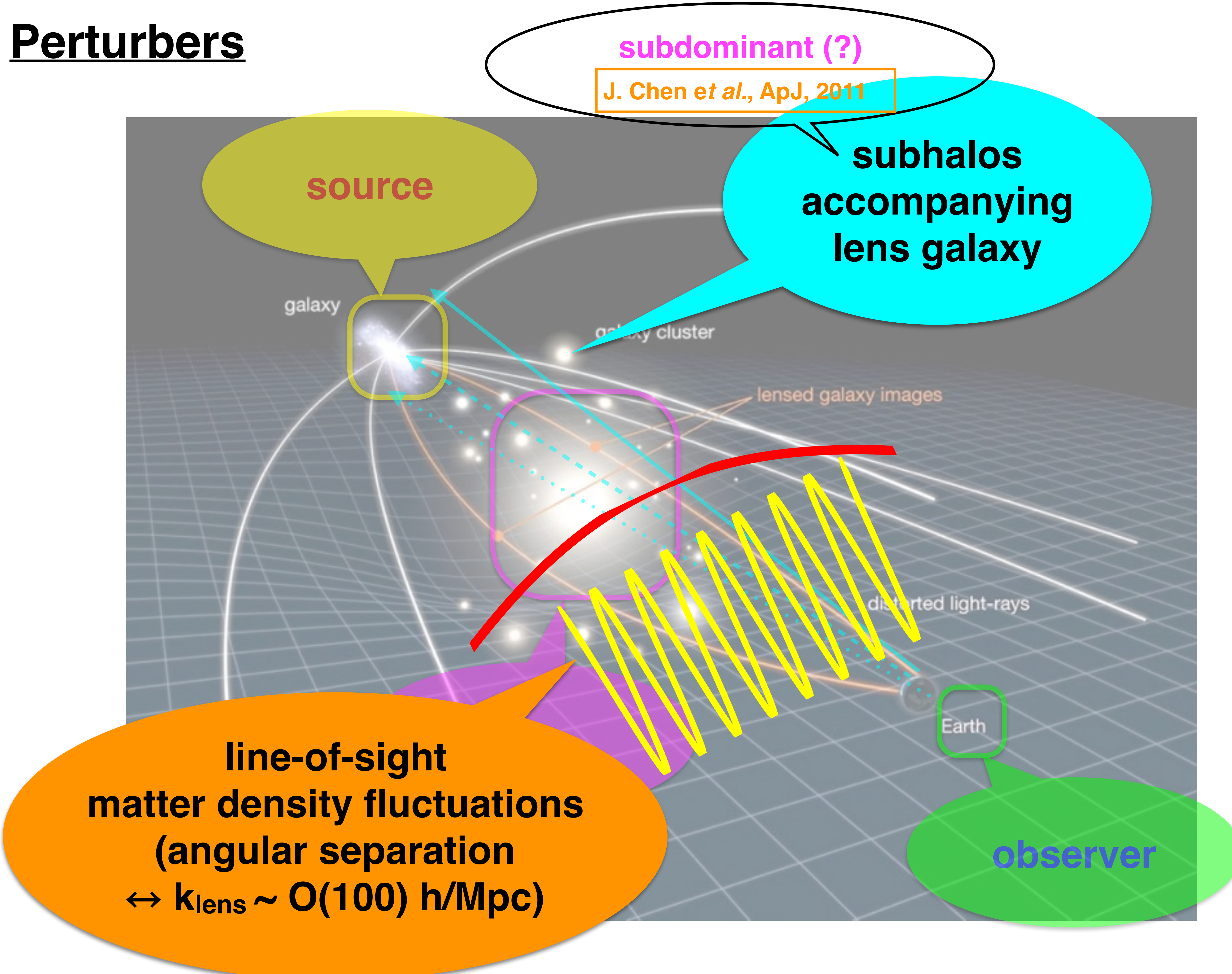
Singular isothermal profile for lens galaxy provides a good-fit for lens positions

1st derivative of gravitational potential

2nd derivative of gravitational potential

Derived flux ratio $(A+C)/B \simeq 1$ is not concordant with observed value $(A+C)/B \simeq 1.5$ (2σ or more)

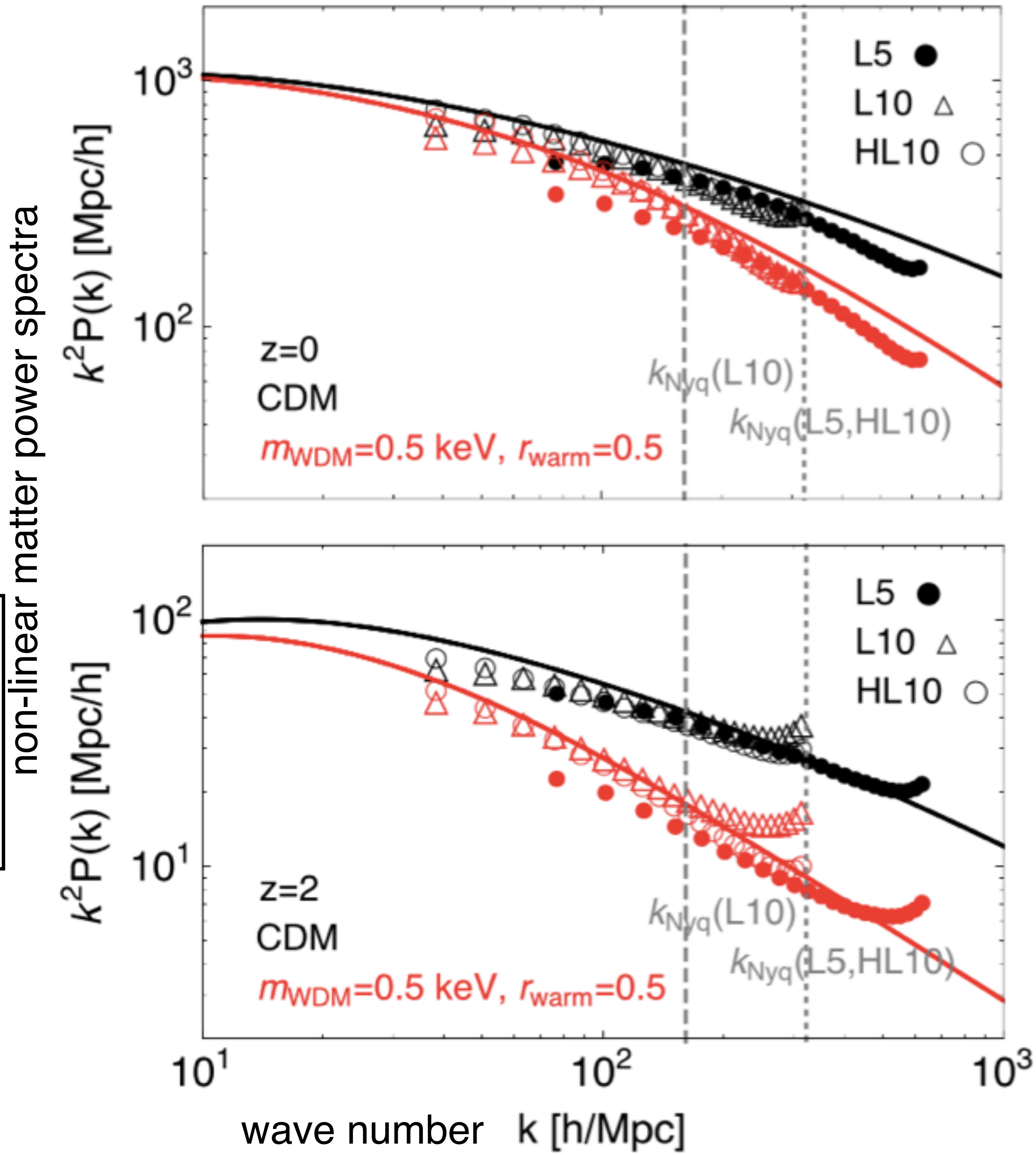
Perturbers


subdominant (?)
J. Chen et al., ApJ, 2011
source
galaxy
subhalos accompanying lens galaxy
lensed galaxy images
Earth
line-of-sight matter density fluctuations (angular separation ↔ k_{lens} ~ O(100) h/Mpc)
observer

Line-of-sight matter density fluctuations

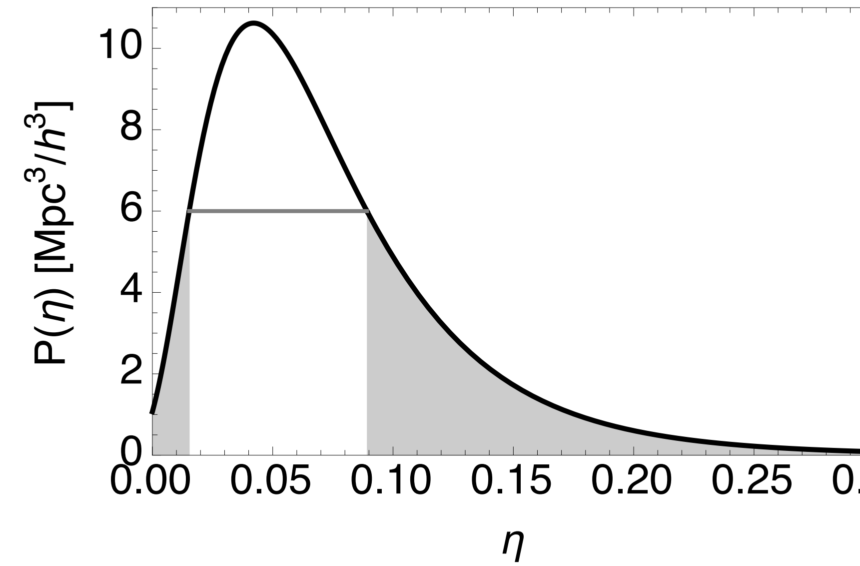
N-body simulation to measure non-linear matter power spectra

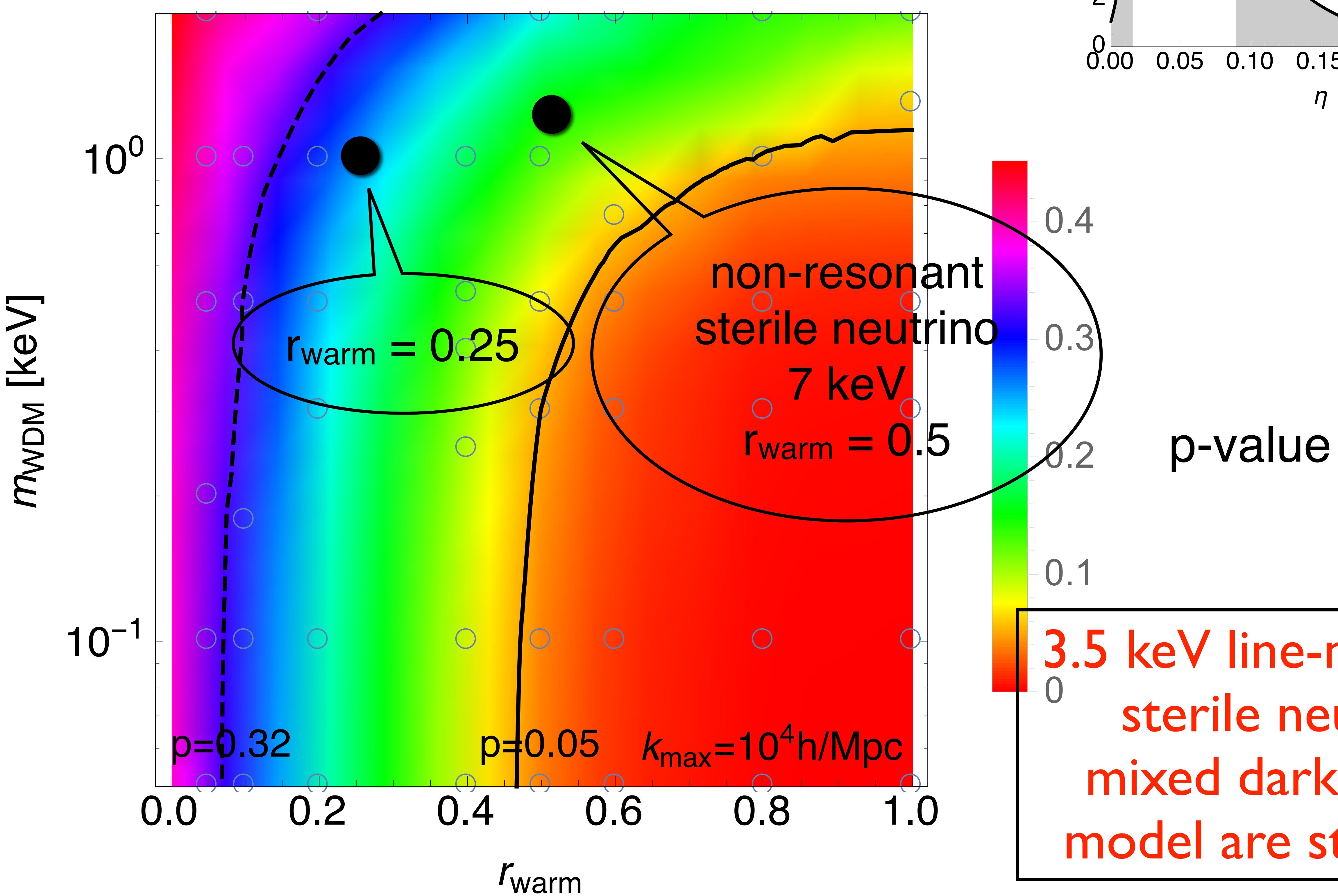
perturbed magnification η: a convolution of non-linear matter spectra with some Kernel



Likelihood

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





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

Conclusions and Prospects

Conclusions

- Through the small-scale matter distribution, we can explore the existence of long-lived particles produced in the early Universe (being careful of baryonic processes)

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

- To be compatible with the very light gravitino and the Higgs mass, GMSB is needed to have an extended Higgs sector or some non-standard thermal history of the Universe

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

Prospects

- Weak lens surveys are now on-going (DES, HSC-Wide, …) and higher-quality data will be available soon

- SMG lens samples are expected to be found in on-going ALMA data

- In any case, more precise understanding of structure formation (non-linear evolution) in non-CDM models is indispensable
  -- need a help of analytic approach