Title: 21cm fluctuations in the dark ages and cosmic heat flows

Date: Aug 12, 2015 11:20 AM

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Abstract: The spin-flip transition in neutral hydrogen may be used to probe large-scale structure at high redshifts, before the first luminous objects formed. The huge number of modes potentially accessible make this a very promising avenue. I will discuss several key unknowns that could be measured with high-redshift 21cm surveys: primordial non-gaussianity, the primordial small-scale power spectrum, and dark-matter-baryon interactions. I will close by discussing CMB spectral distortions, another promising probe of early Universe physics, and illustrate how they can be used to test dark-matter interactions with standard model particles.

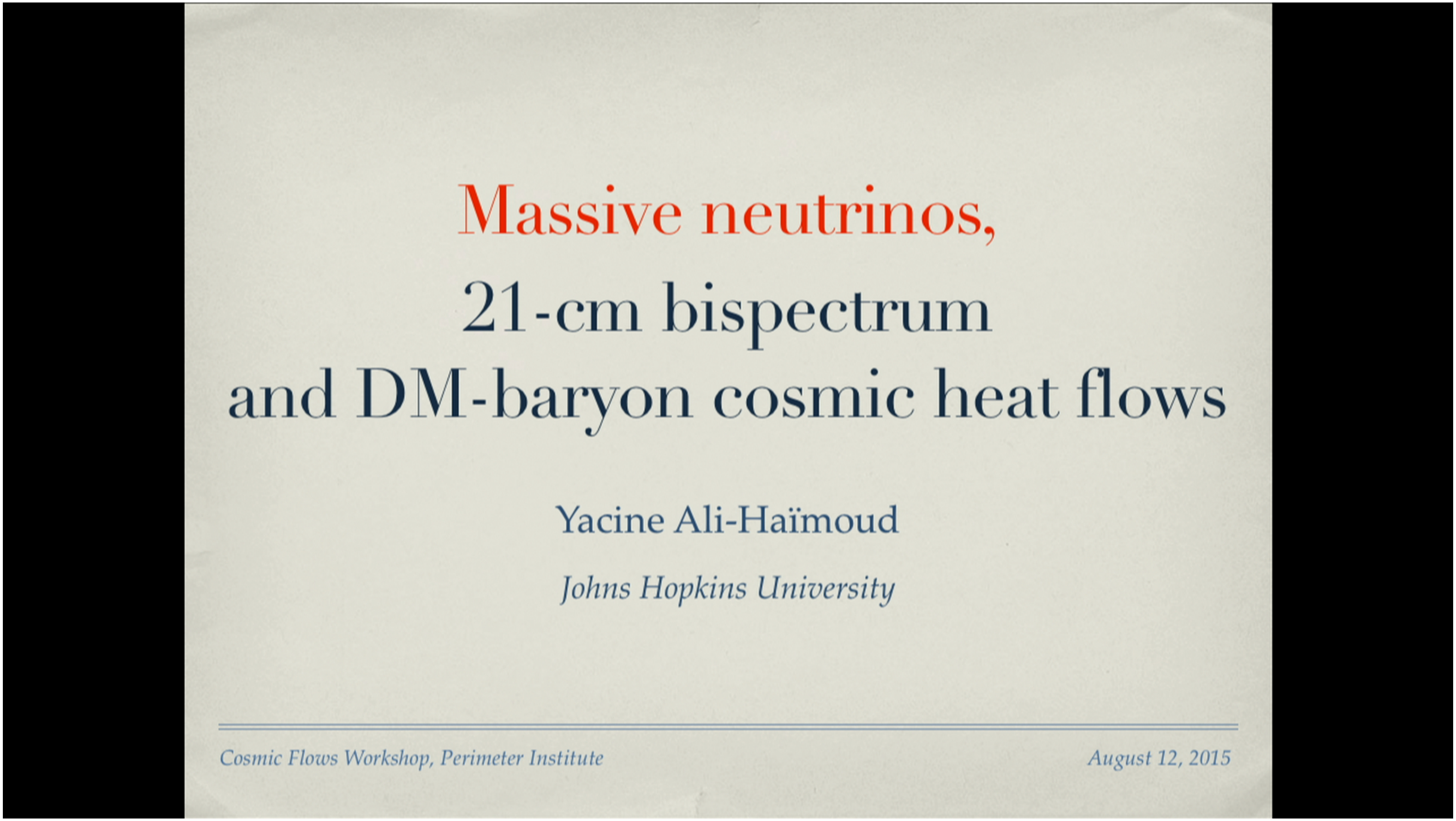
21-cm bispectrum
and DM-baryon cosmic heat flows

Yacine Ali-Haïmoud

Johns Hopkins University

Cosmic Flows Workshop, Perimeter Institute

August 12, 2015



Massive neutrinos, 21-cm bispectrum and DM-baryon cosmic heat flows

Yacine Ali-Haïmoud

Johns Hopkins University

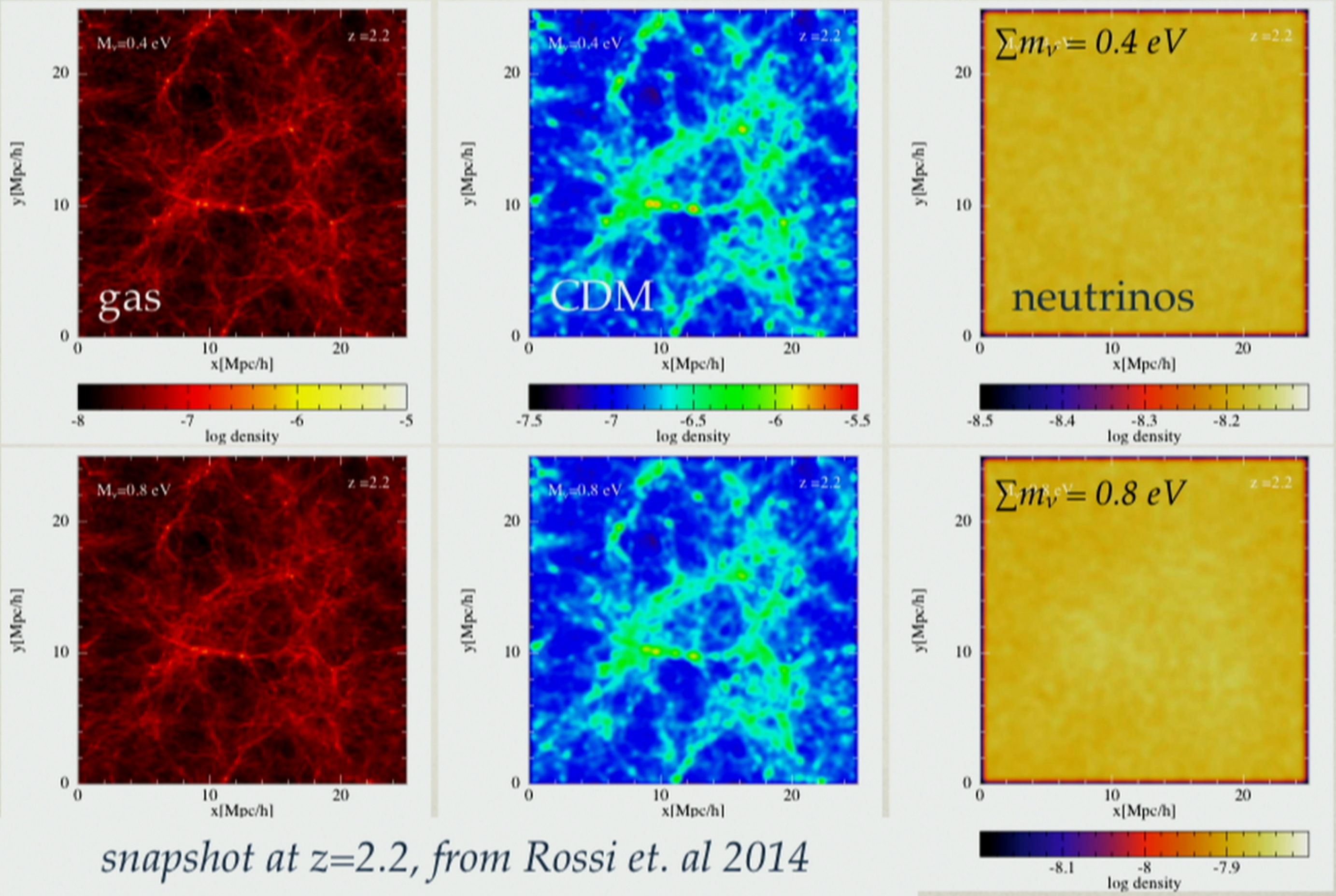
Cosmic Flows Workshop, Perimeter Institute

August 12, 2015

Part I: Massive neutrinos in the non-linear regime

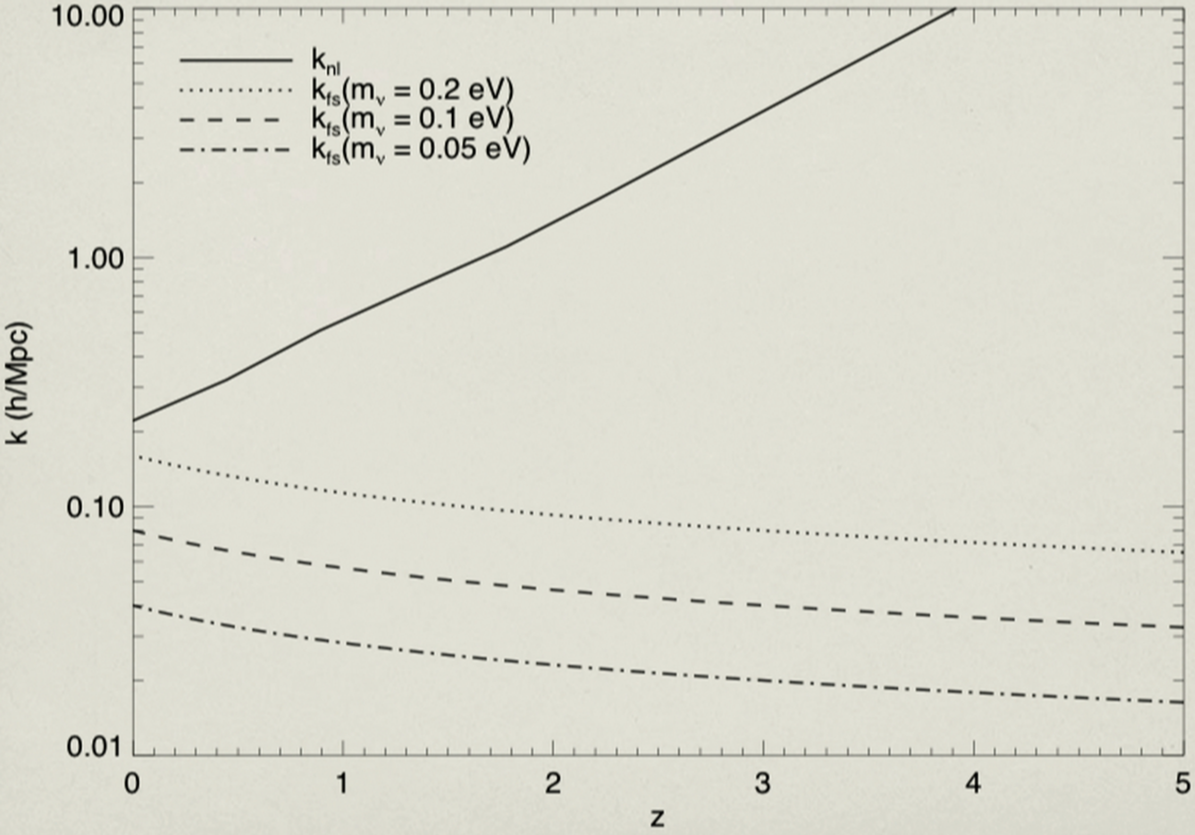
with Simeon Bird, MNRAS 2013; sequel in preparation.

Particle-based simulations



snapshot at z=2.2, from Rossi et. al 2014

Characteristic scales



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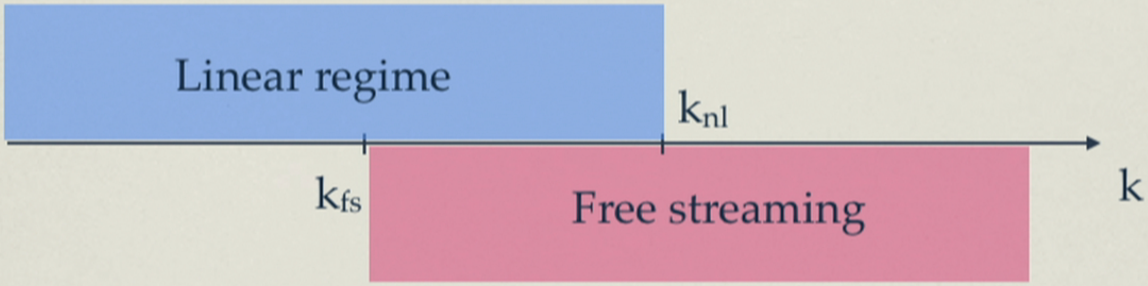
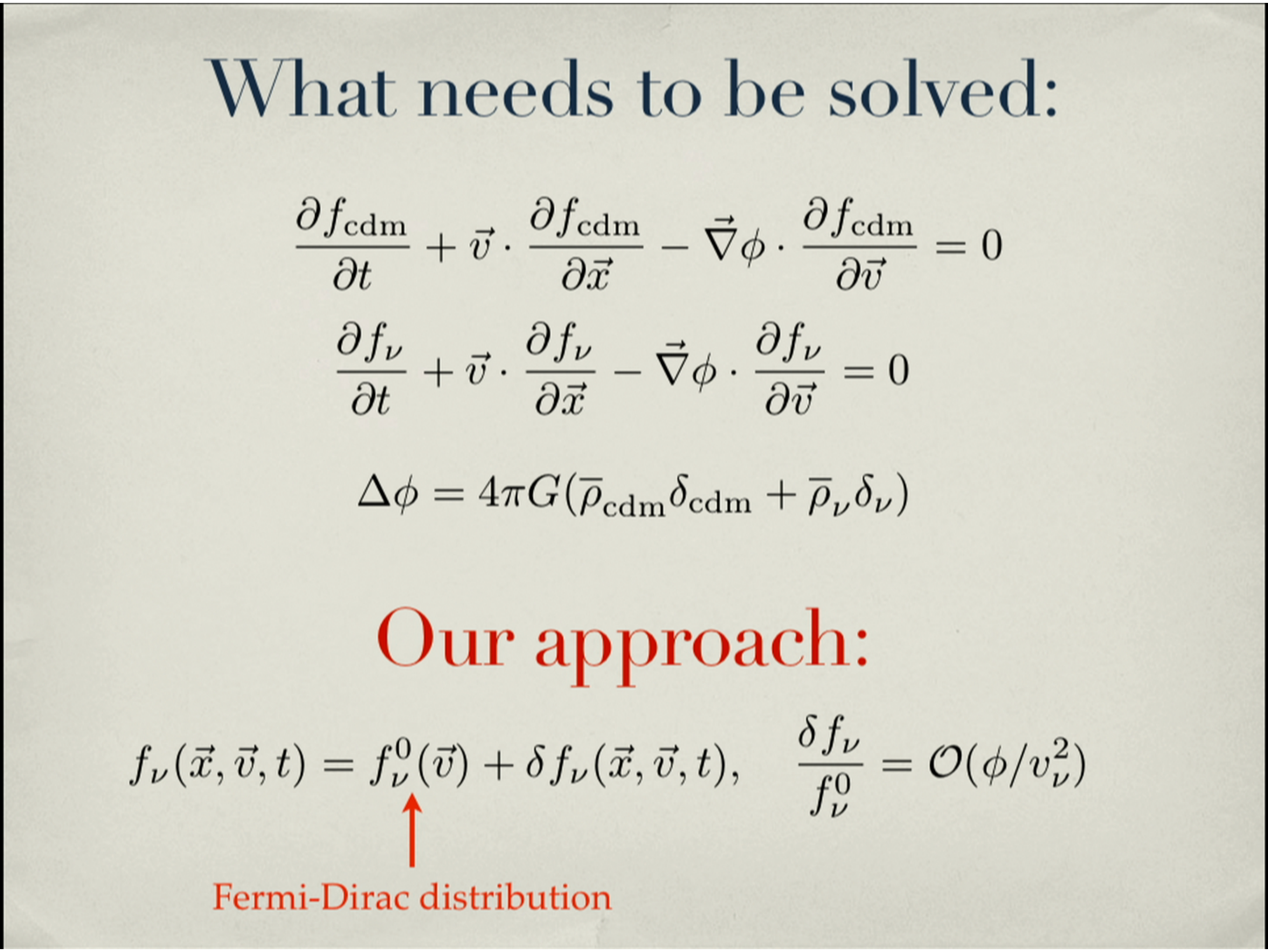


What needs to be solved:

$$\frac{\partial f_{\rm cdm}}{\partial t} + \vec{v} \cdot \frac{\partial f_{\rm cdm}}{\partial \vec{x}} - \vec{\nabla}\phi \cdot \frac{\partial f_{\rm cdm}}{\partial \vec{v}} = 0$$

$$\frac{\partial f_{\nu}}{\partial t} + \vec{v} \cdot \frac{\partial f_{\nu}}{\partial \vec{x}} - \vec{\nabla}\phi \cdot \frac{\partial f_{\nu}}{\partial \vec{v}} = 0$$

$$\Delta\phi = 4\pi G(\overline{\rho}_{\rm cdm}\delta_{\rm cdm} + \overline{\rho}_{\nu}\delta_{\nu})$$



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Our approach:

$$f_\nu(\vec{x}, \vec{v}, t) = \underset{\uparrow}{f_\nu^0}(\vec{v}) + \delta f_\nu(\vec{x}, \vec{v}, t), \quad \frac{\delta f_\nu}{f_\nu^0} = \mathcal{O}(\phi/v_\nu^2)$$

Fermi-Dirac distribution

linearize: $\delta f_\nu(\vec{k}, \vec{v}, t) = \int_{t'<t} dt' \; G(t, t', \vec{k}, \vec{v})\phi(\vec{k}, t')$

integrate over velocities:

$$\delta_\nu(\vec{k}, t) = \int_{t'<t} dt' \; F(t, t', k)\phi(\vec{k}, t')$$

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Full (non-linear) potential

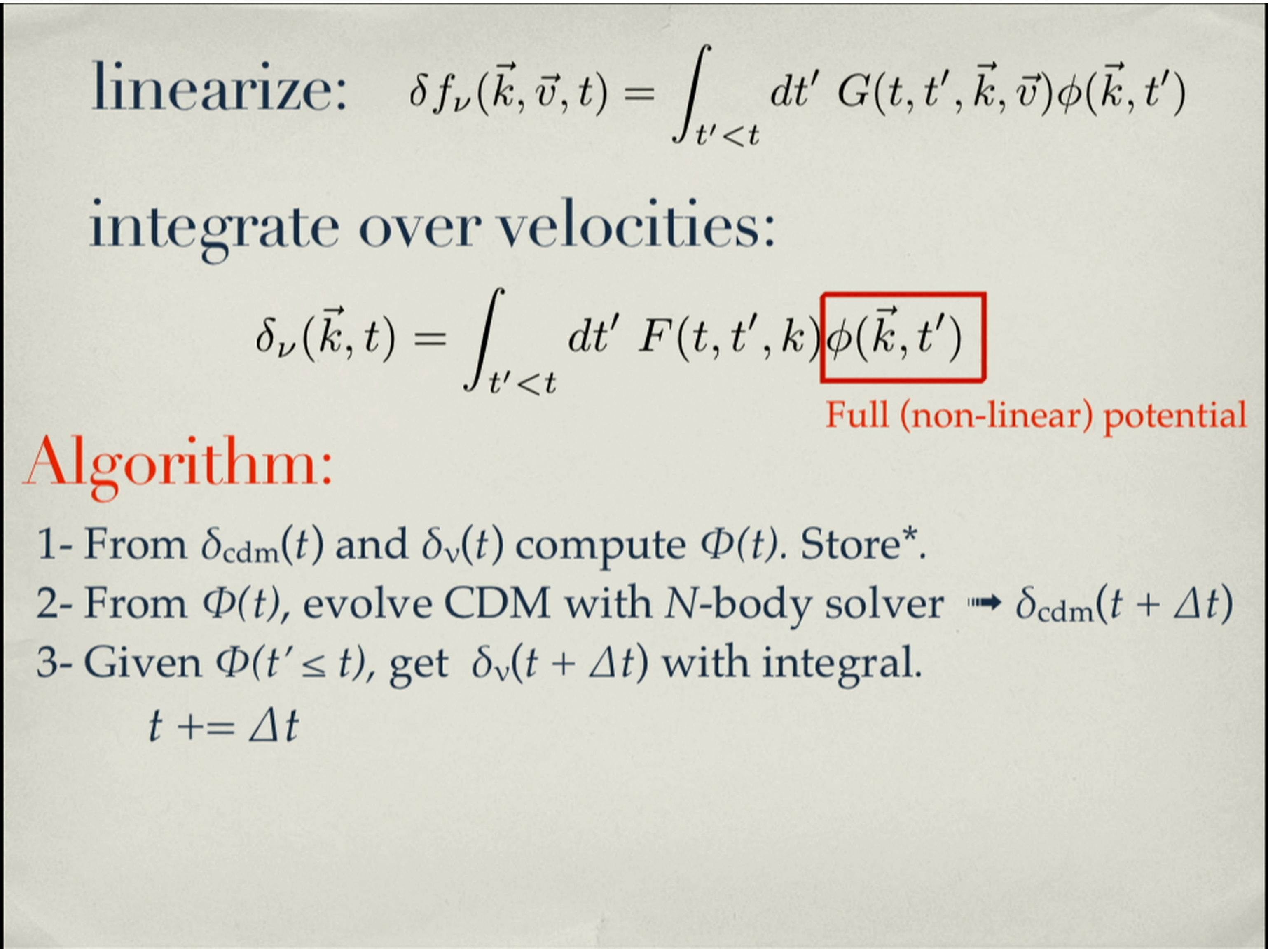
Algorithm:

1- From $\delta_{\mathrm{cdm}}(t)$ and $\delta_{\mathrm{v}}(t)$ compute $\Phi(t)$. Store*.

2- From $\Phi(t)$, evolve CDM with N-body solver ➟ $\delta_{\mathrm{cdm}}(t + \Delta t)$

3- Given $\Phi(t' \leq t)$, get $\delta_{\mathrm{v}}(t + \Delta t)$ with integral.

$t \mathrel{+}= \Delta t$



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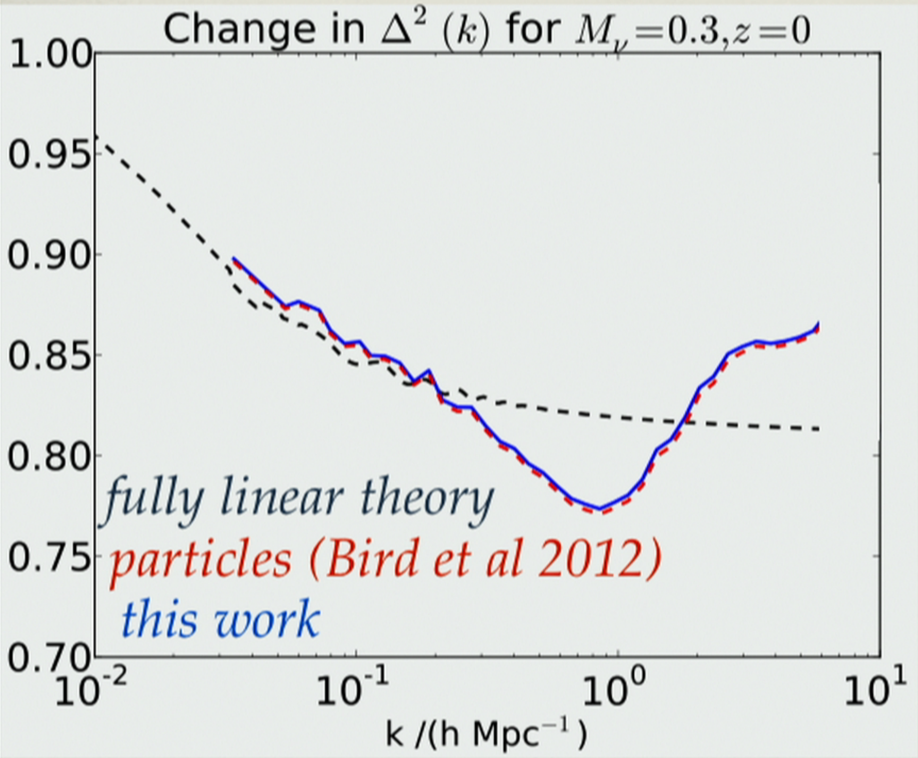
Results

I- Total matter power spectrum



Agreement with particle method:

at z = 0,

0.2% for $\sum m_\nu = 0.3$ eV

1% for $\sum m_\nu = 0.6$ eV

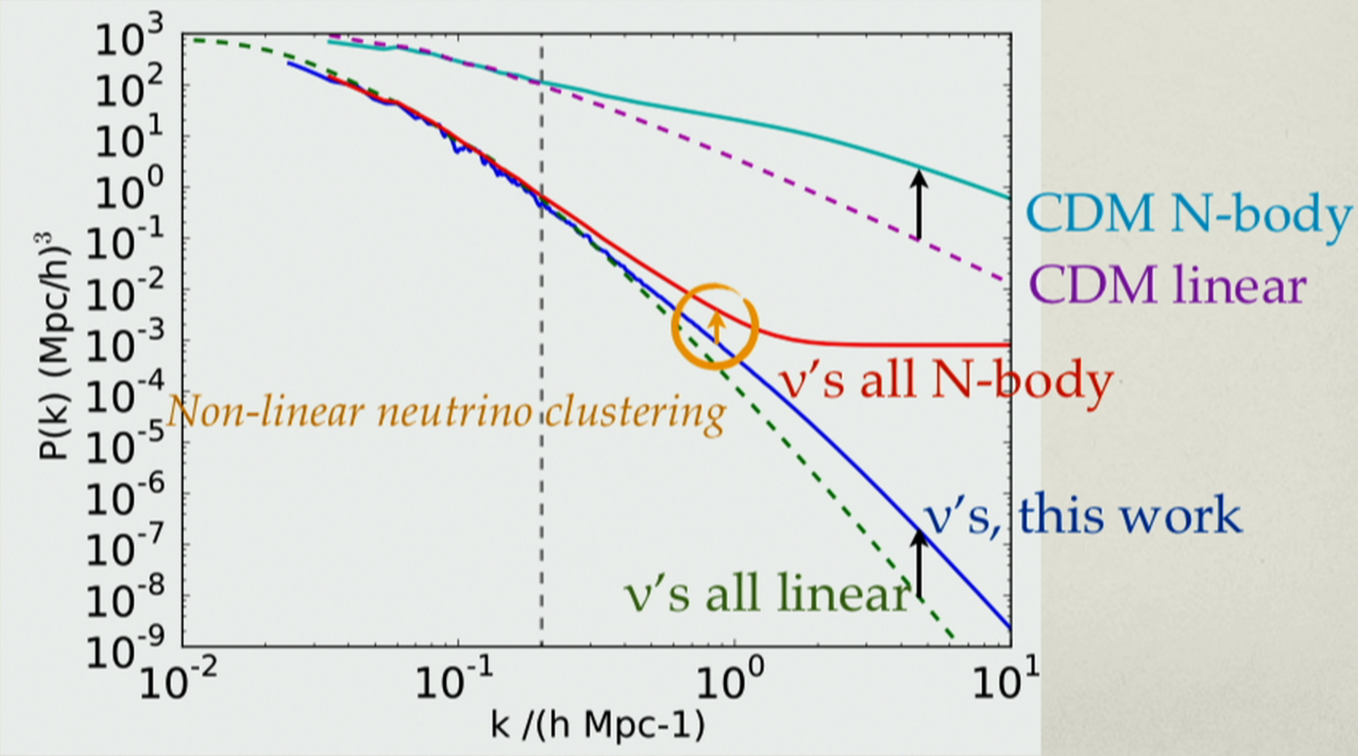
4% for $\sum m_\nu = 1.2$ eV

at z > 1, all agree to better than 1%

Results

II- Neutrino power spectrum

$$z = 0, \sum m_\nu = 0.3\ \mathrm{eV}$$



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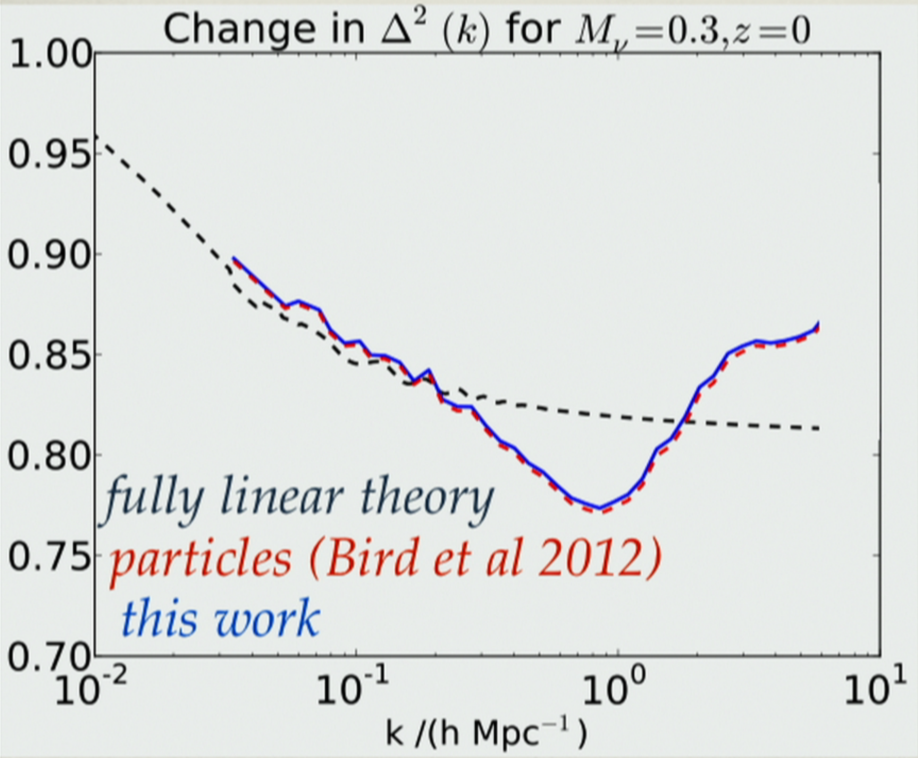
Change in $\Delta^2(k)$ for $M_\nu = 0.3, z = 0$

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* We cannot possibly store full 3-D field $\Phi(t)$.
Instead we store $P_\Phi(k, t)$ and approximate:

$$\delta_\nu(\vec{k},t) = \int_{t'<t} dt'\ F(t,t',k)\phi(\vec{k},t')$$

$$\approx \phi(\vec{k},t)\int_{t'<t} dt'\ F(t,t',k)\sqrt{P_\phi(k,t')/P_\phi(k,t)}$$

1) on large linear scales this is true

2) $F(t, t', k)$ only has support for $t\text{-}t' \lesssim 1/(k\, v_\nu) << 1/\text{Hubble}$ if $k >> k_{fs}$ (by definition).

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Can this be the reason for underestimate of $P_\nu(k)$?

NO, say these guys:

So what is going on?

Neutrinos are not all the same!

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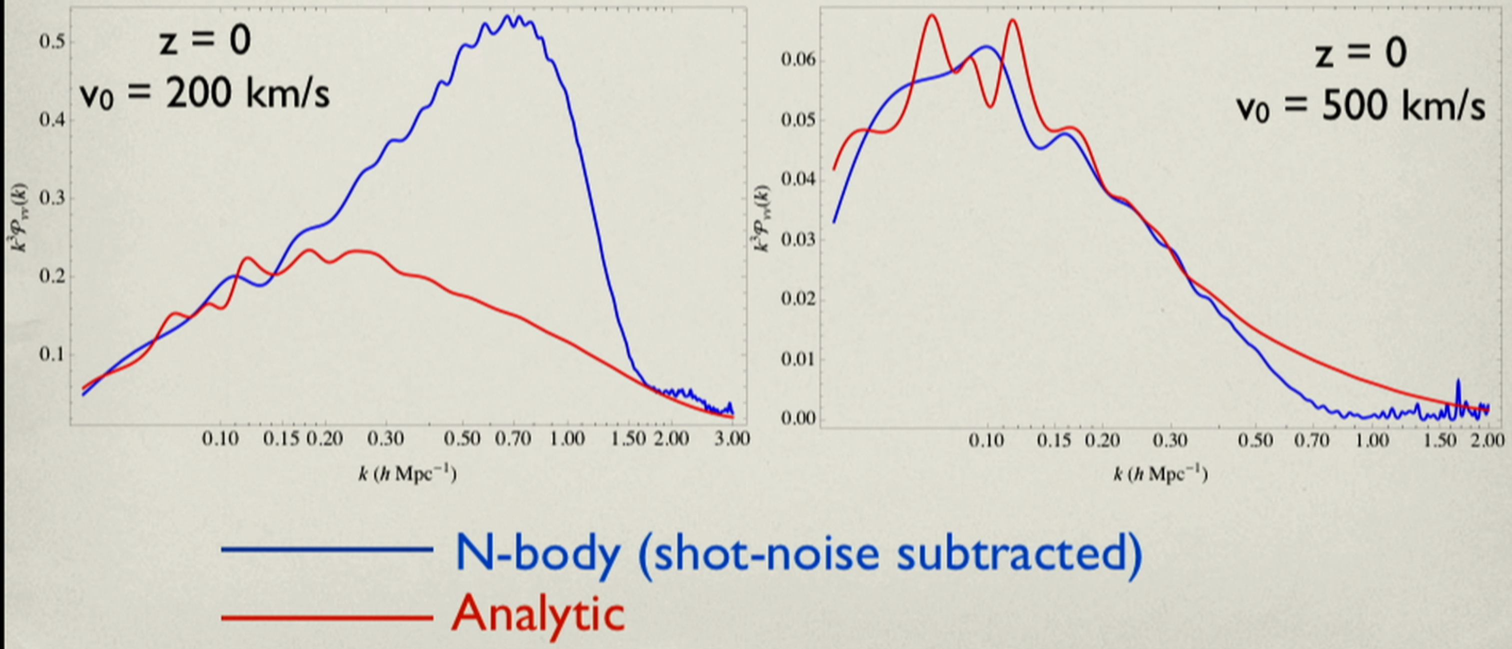
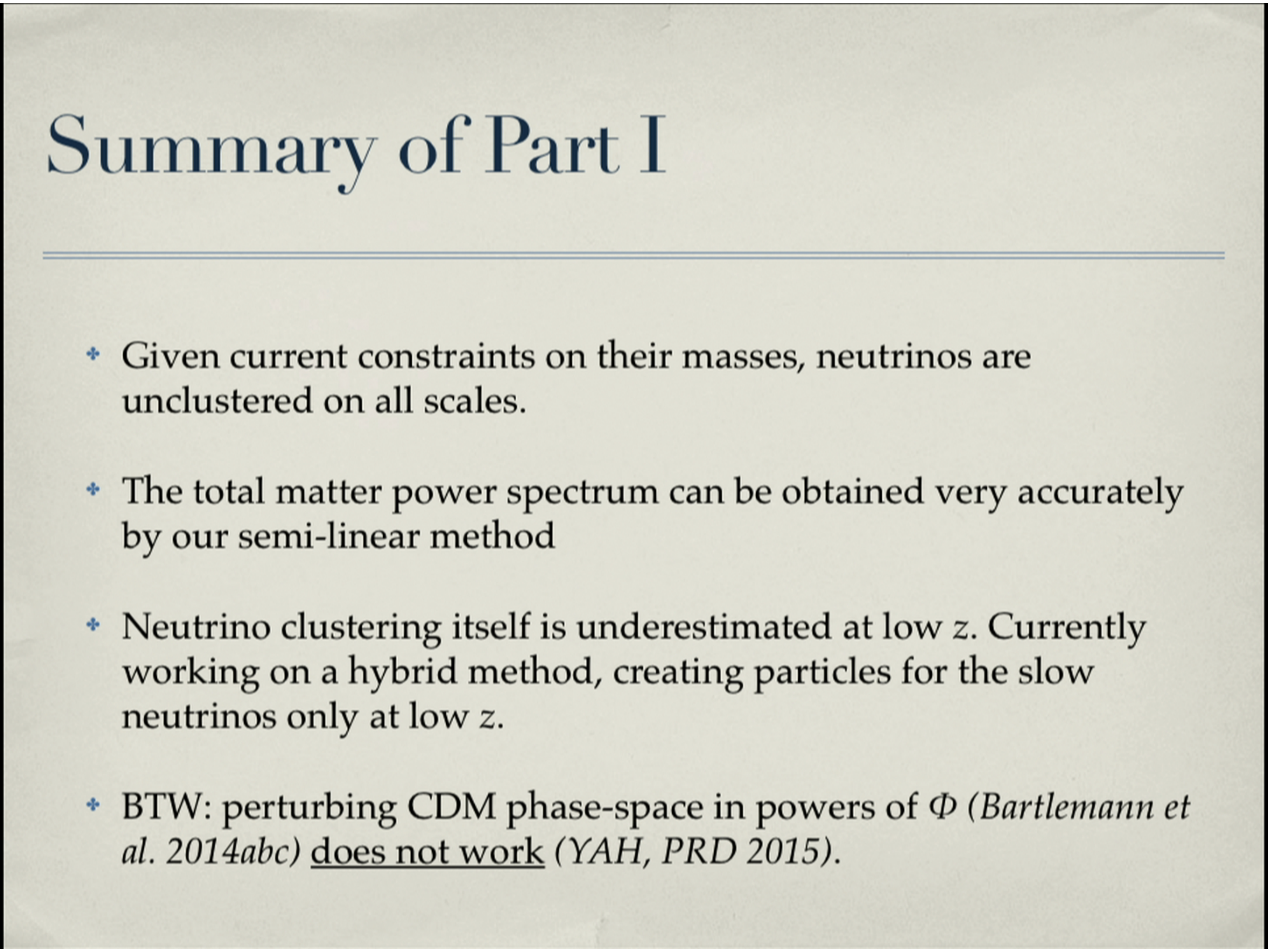
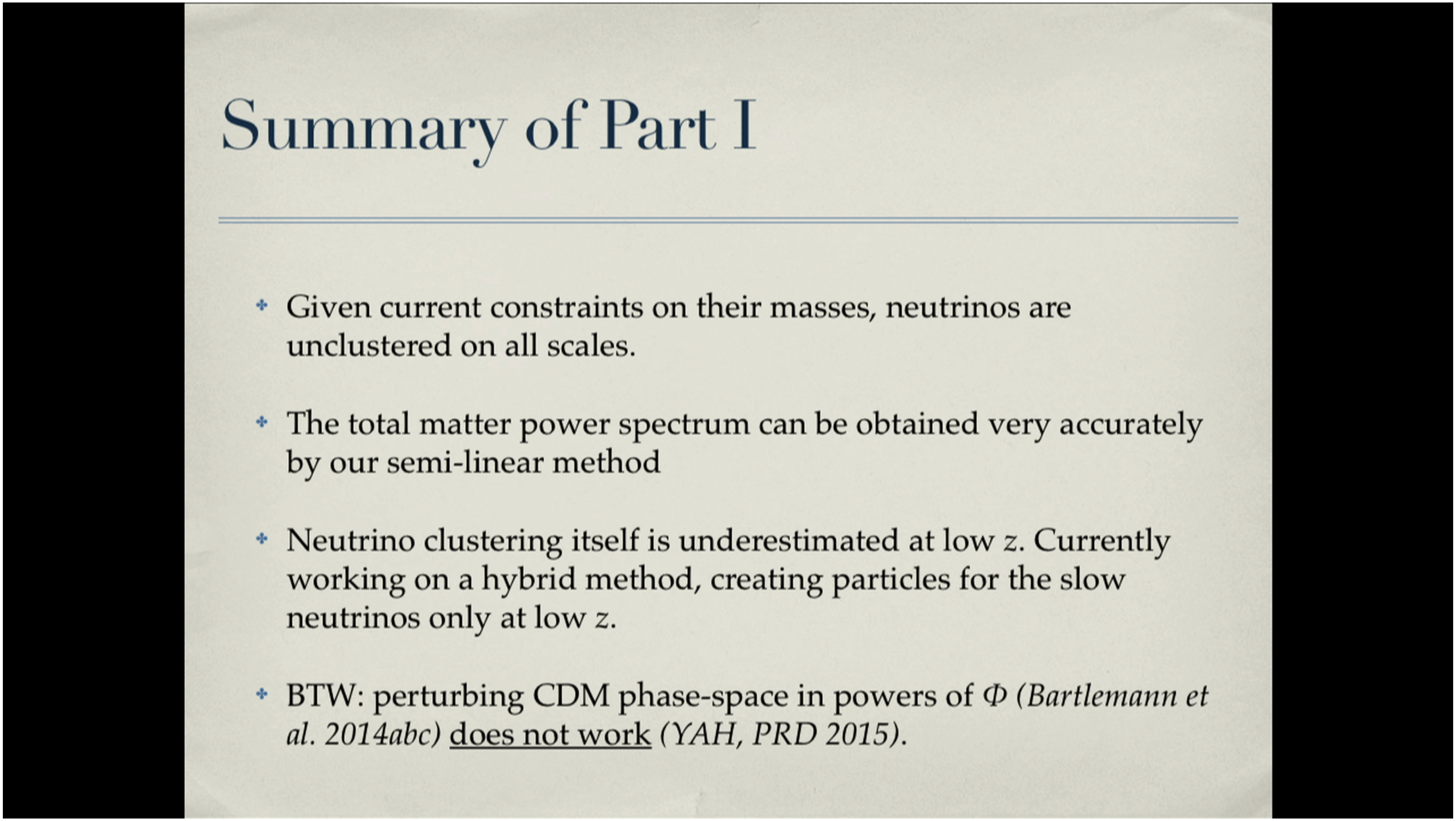




Summary of Part I

- Given current constraints on their masses, neutrinos are unclustered on all scales.
- The total matter power spectrum can be obtained very accurately by our semi-linear method
- Neutrino clustering itself is underestimated at low z. Currently working on a hybrid method, creating particles for the slow neutrinos only at low z.
- BTW: perturbing CDM phase-space in powers of Φ *(Bartlemann et al. 2014abc)* does not work *(YAH, PRD 2015)*.



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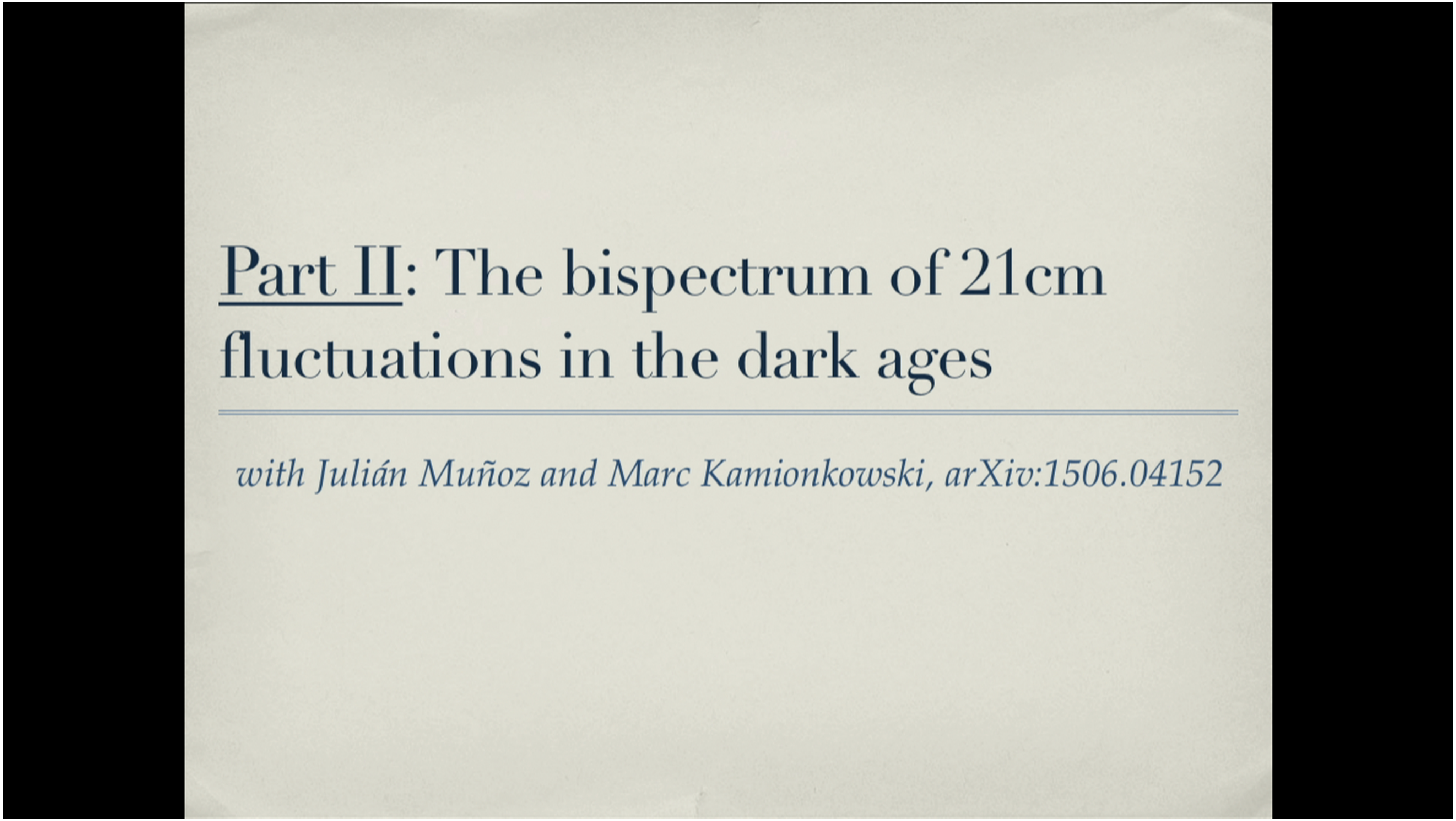
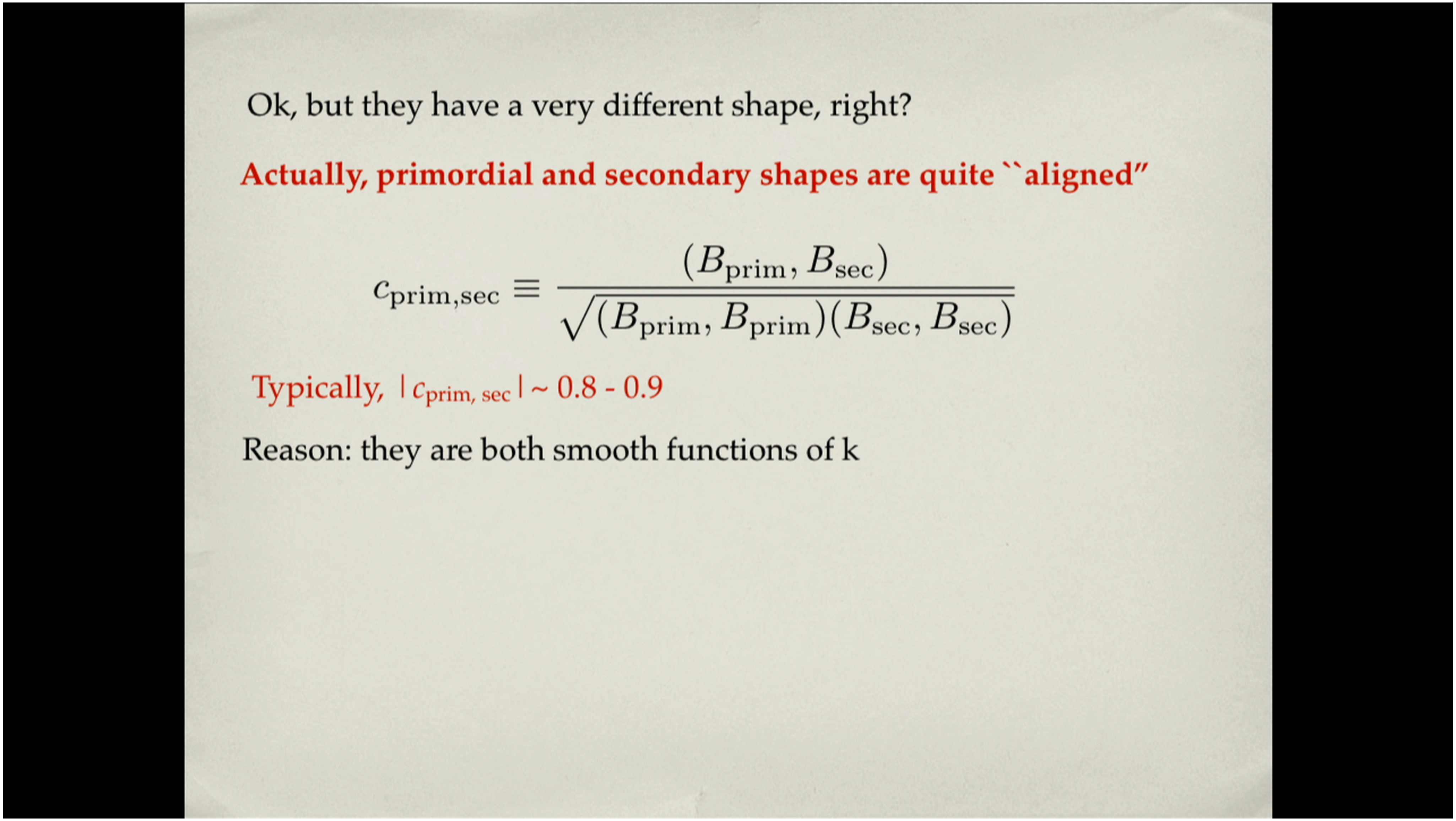


Part II: The bispectrum of 21cm fluctuations in the dark ages

with Julián Muñoz and Marc Kamionkowski, arXiv:1506.04152



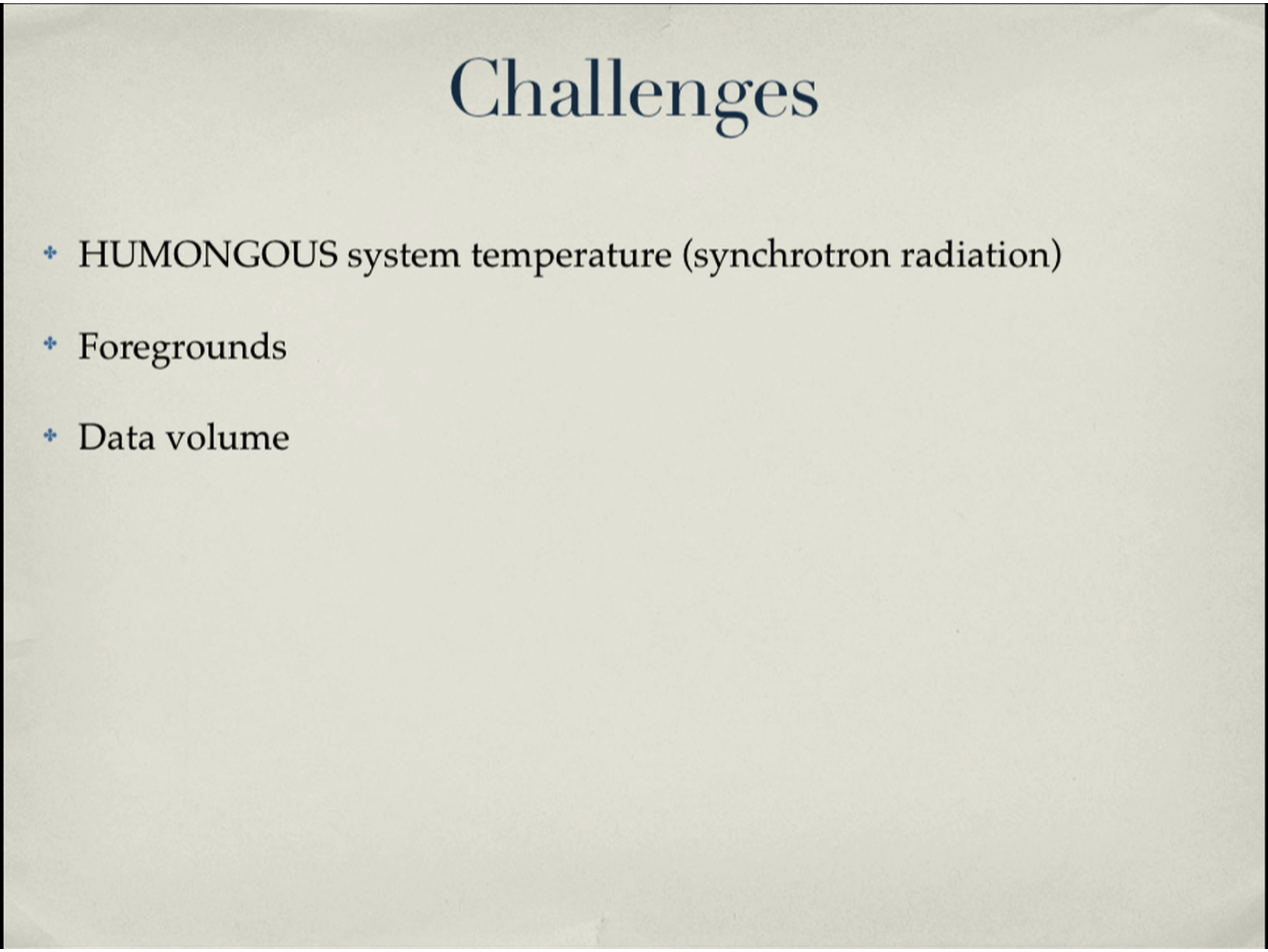
Ok, but they have a very different shape, right?

Actually, primordial and secondary shapes are quite ``aligned"

$$c_{\rm prim,sec} \equiv \frac{(B_{\rm prim}, B_{\rm sec})}{\sqrt{(B_{\rm prim}, B_{\rm prim})(B_{\rm sec}, B_{\rm sec})}}$$

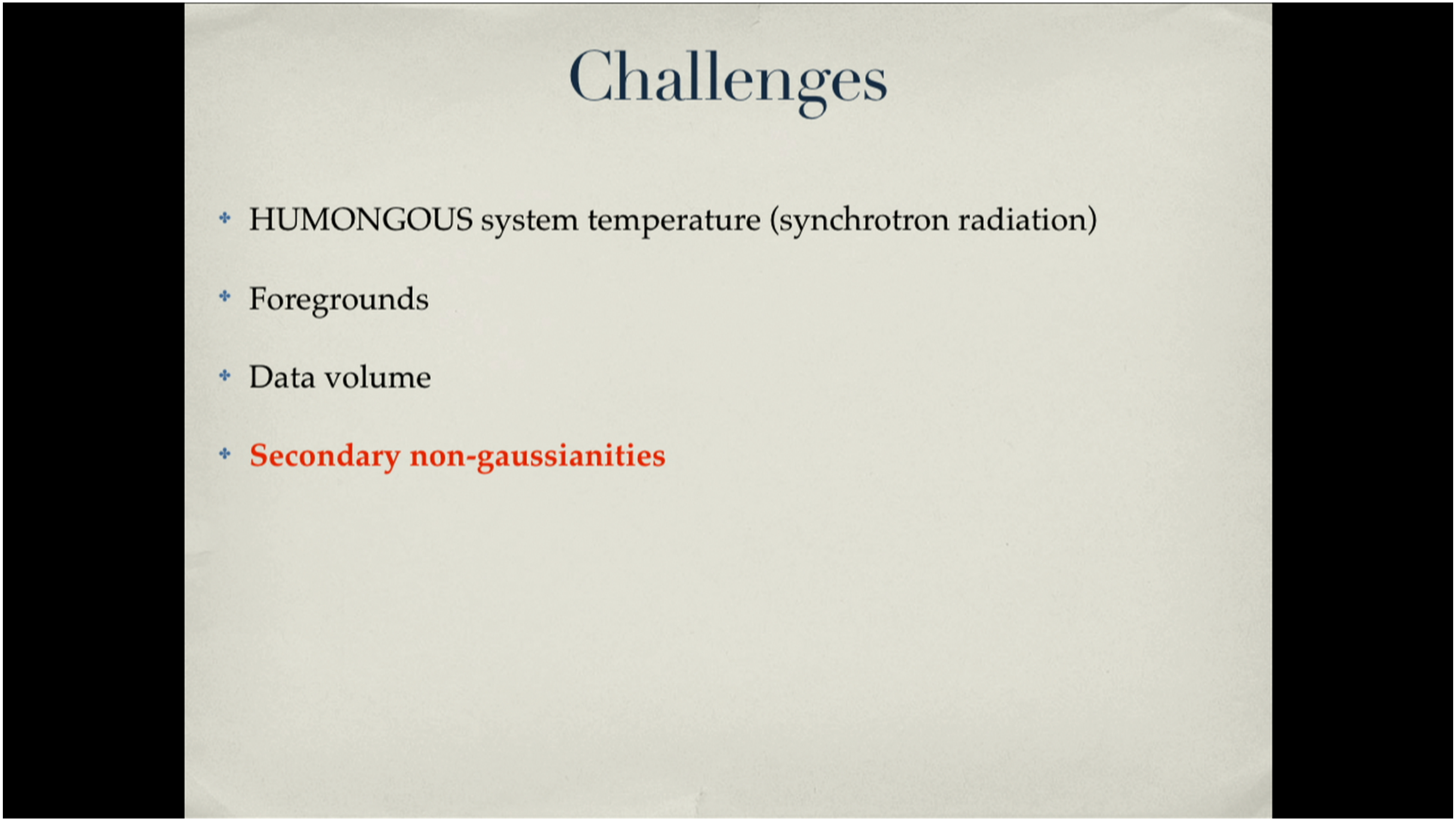
Typically, $|\, c_{\rm prim,\, sec} \,| \sim 0.8 - 0.9$

Reason: they are both smooth functions of k



Challenges

- HUMONGOUS system temperature (synchrotron radiation)
- Foregrounds
- Data volume



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- Foregrounds
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- **Secondary non-gaussianities**
- CMB case: secondaries dominated by ISW-lensing correlation

$\sigma_{f_{\rm NL}} = 5.0$ $\Delta f_{\rm NL} = 5.7$

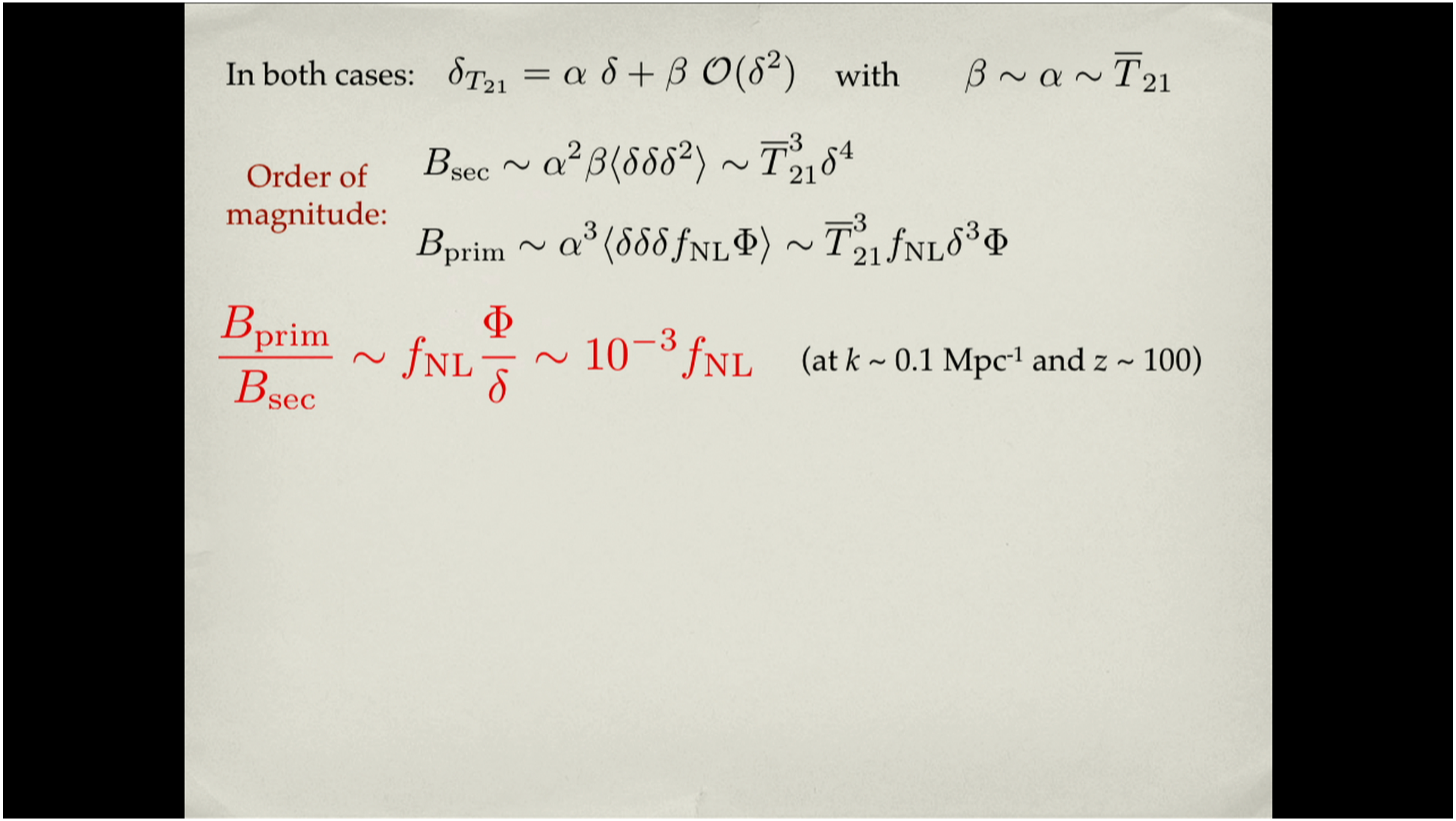
⇒ In the case of the CMB the bias from secondaries can be modeled and subtracted *(see Planck 2015 XVII)*

In both cases: $\delta_{T_{21}} = \alpha\ \delta + \beta\ \mathcal{O}(\delta^2)$ with $\beta \sim \alpha \sim \overline{T}_{21}$

Order of magnitude:

$$B_{\rm sec} \sim \alpha^2 \beta \langle \delta\delta\delta^2 \rangle \sim \overline{T}_{21}^3 \delta^4$$

$$B_{\rm prim} \sim \alpha^3 \langle \delta\delta\delta f_{\rm NL} \Phi \rangle \sim \overline{T}_{21}^3 f_{\rm NL} \delta^3 \Phi$$



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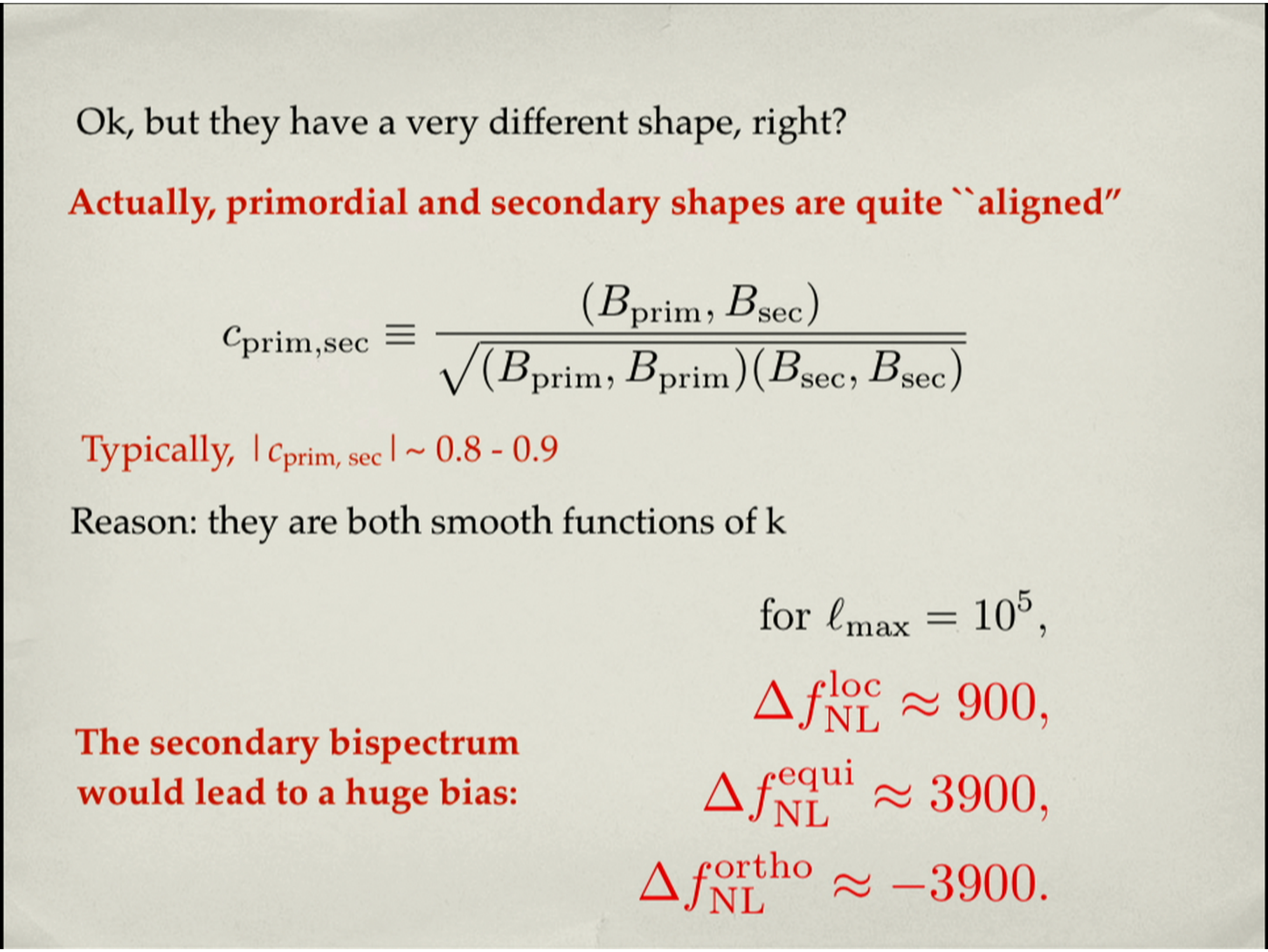
$$\frac{B_{\rm prim}}{B_{\rm sec}} \sim f_{\rm NL} \frac{\Phi}{\delta} \sim 10^{-3} f_{\rm NL}$$ (at $k \sim 0.1$ Mpc^{-1} and $z \sim 100$)



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Typically, $|c_{\rm prim,\, sec}| \sim 0.8 - 0.9$

Reason: they are both smooth functions of k

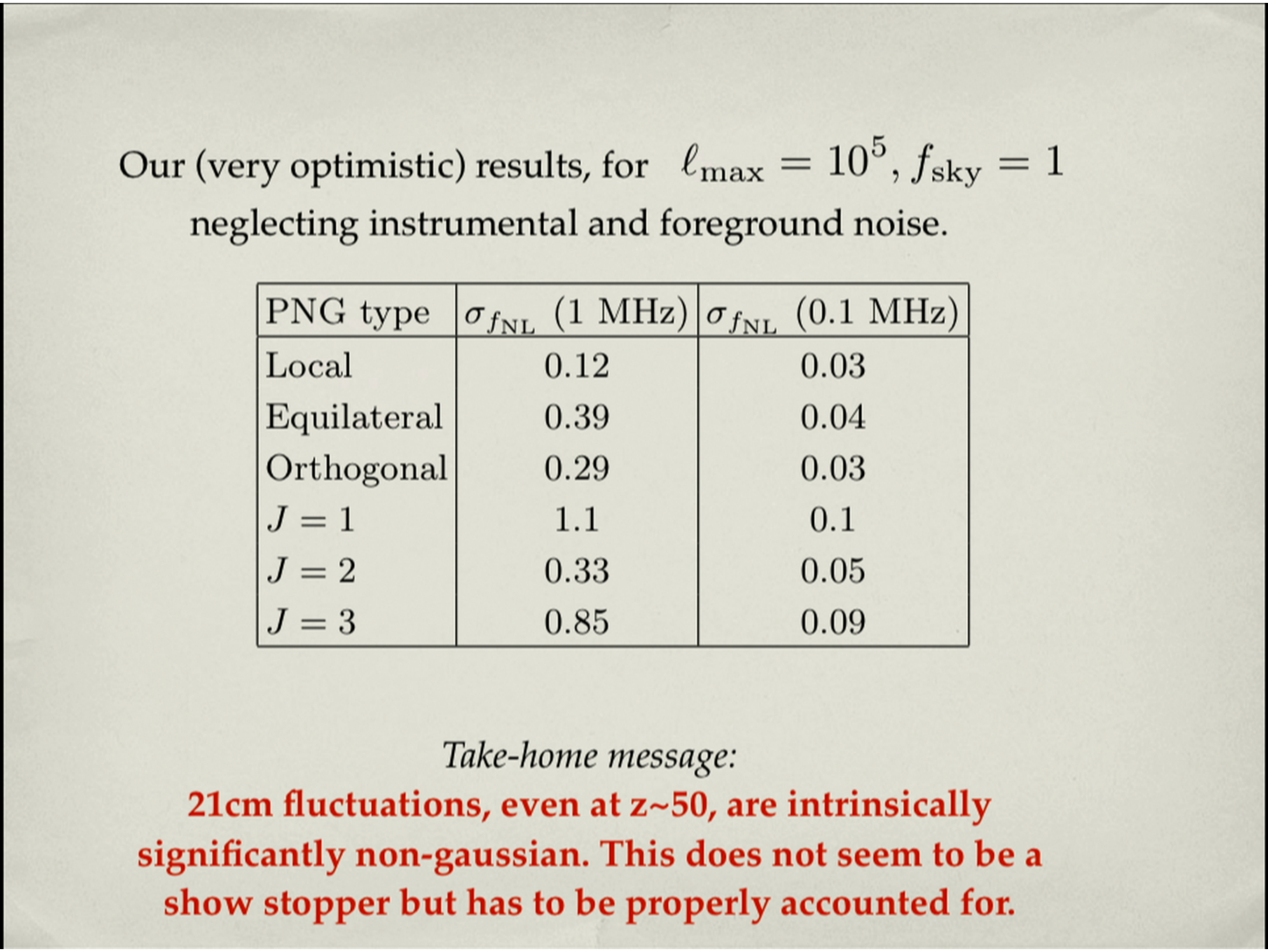
$$\text{for } \ell_{\rm max} = 10^5,$$

The secondary bispectrum would lead to a huge bias:

$$\Delta f_{\rm NL}^{\rm loc} \approx 900,$$

$$\Delta f_{\rm NL}^{\rm equi} \approx 3900,$$

$$\Delta f_{\rm NL}^{\rm ortho} \approx -3900.$$



Our (very optimistic) results, for $\ell_{\rm max} = 10^5, f_{\rm sky} = 1$
neglecting instrumental and foreground noise.

PNG type	$\sigma_{f_{\rm NL}}$ (1 MHz)	$\sigma_{f_{\rm NL}}$ (0.1 MHz)
Local	0.12	0.03
Equilateral	0.39	0.04
Orthogonal	0.29	0.03
$J = 1$	1.1	0.1
$J = 2$	0.33	0.05
$J = 3$	0.85	0.09

Take-home message:

21cm fluctuations, even at z~50, are intrinsically significantly non-gaussian. This does not seem to be a show stopper but has to be properly accounted for.

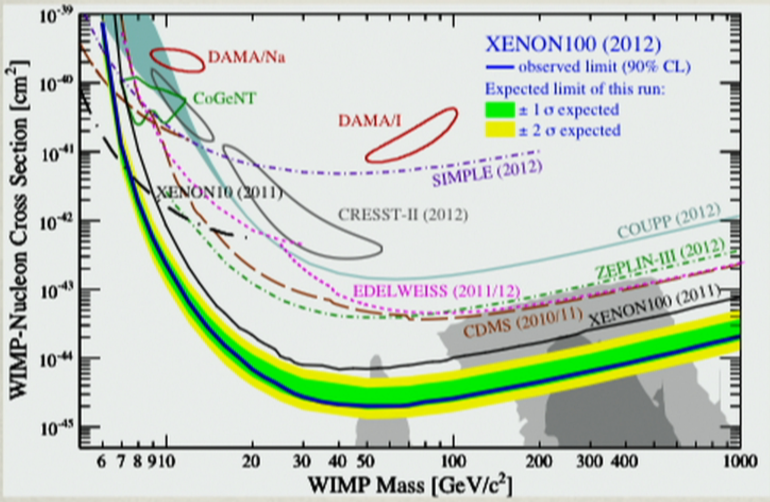
Part III: Constraints on dark matter interactions with standard model particles from CMB spectral distortions.

with Jens Chluba & Marc Kamionkowski, PRL 2015 (arXiv: 1506:04745)

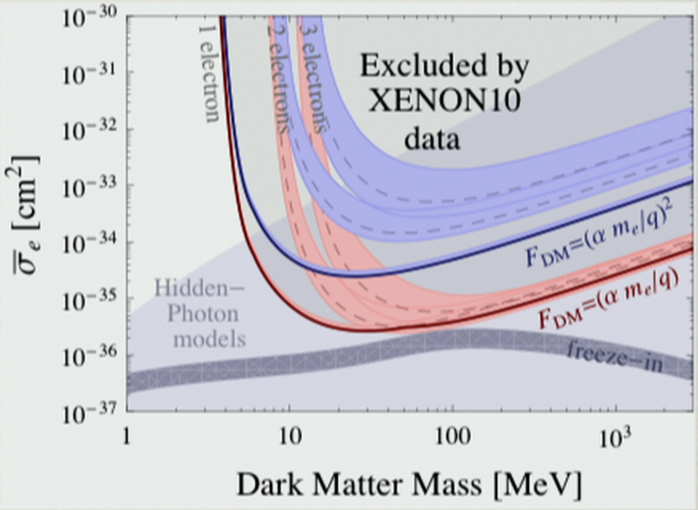
Direct detection constraints

DM-nucleon: constraints
only for m_{DM} > several GeV

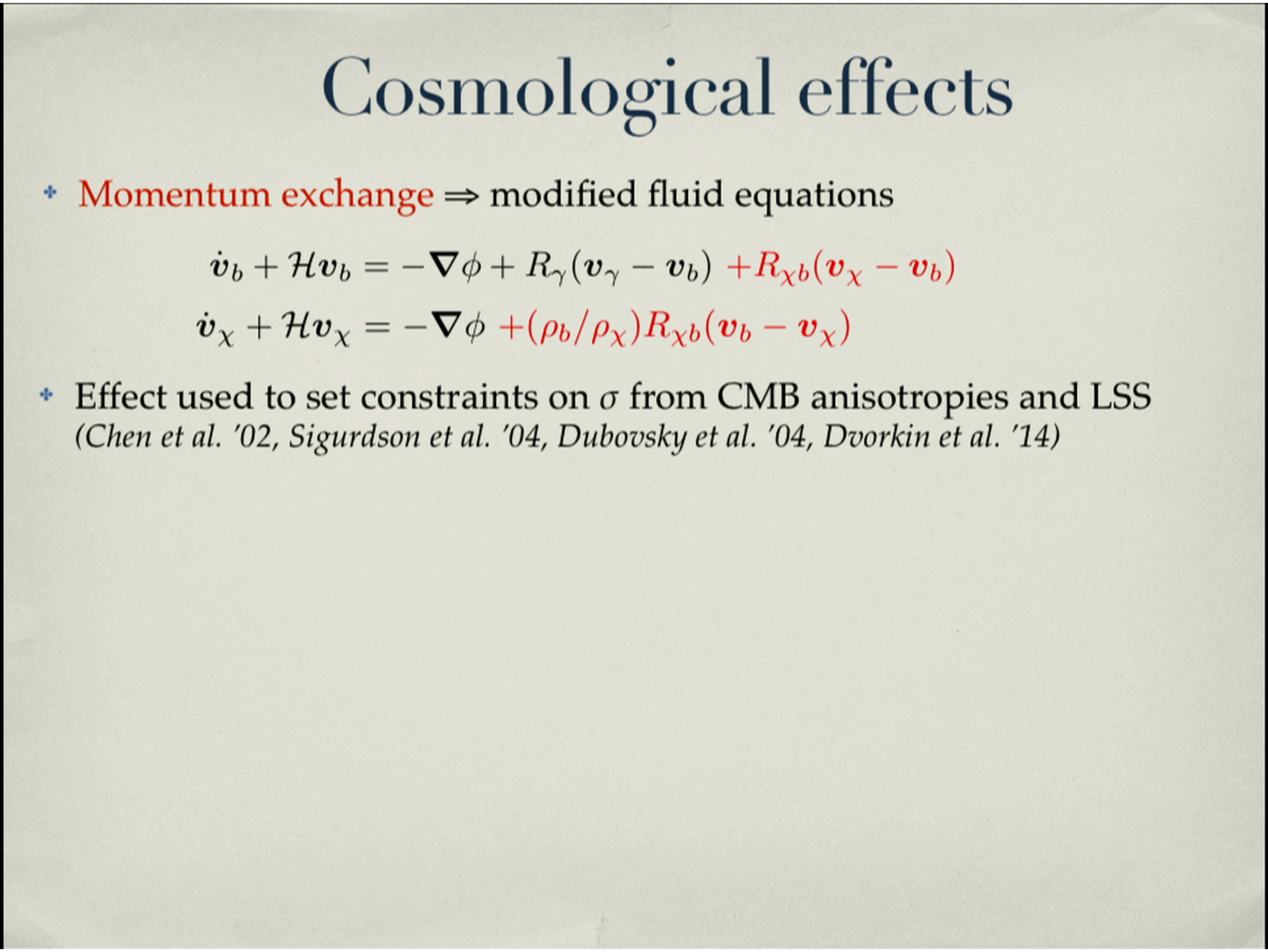
DM-electron: constraints
only for m_{DM} > several MeV



XENON100 collaboration 2012



Essig et al. 2012



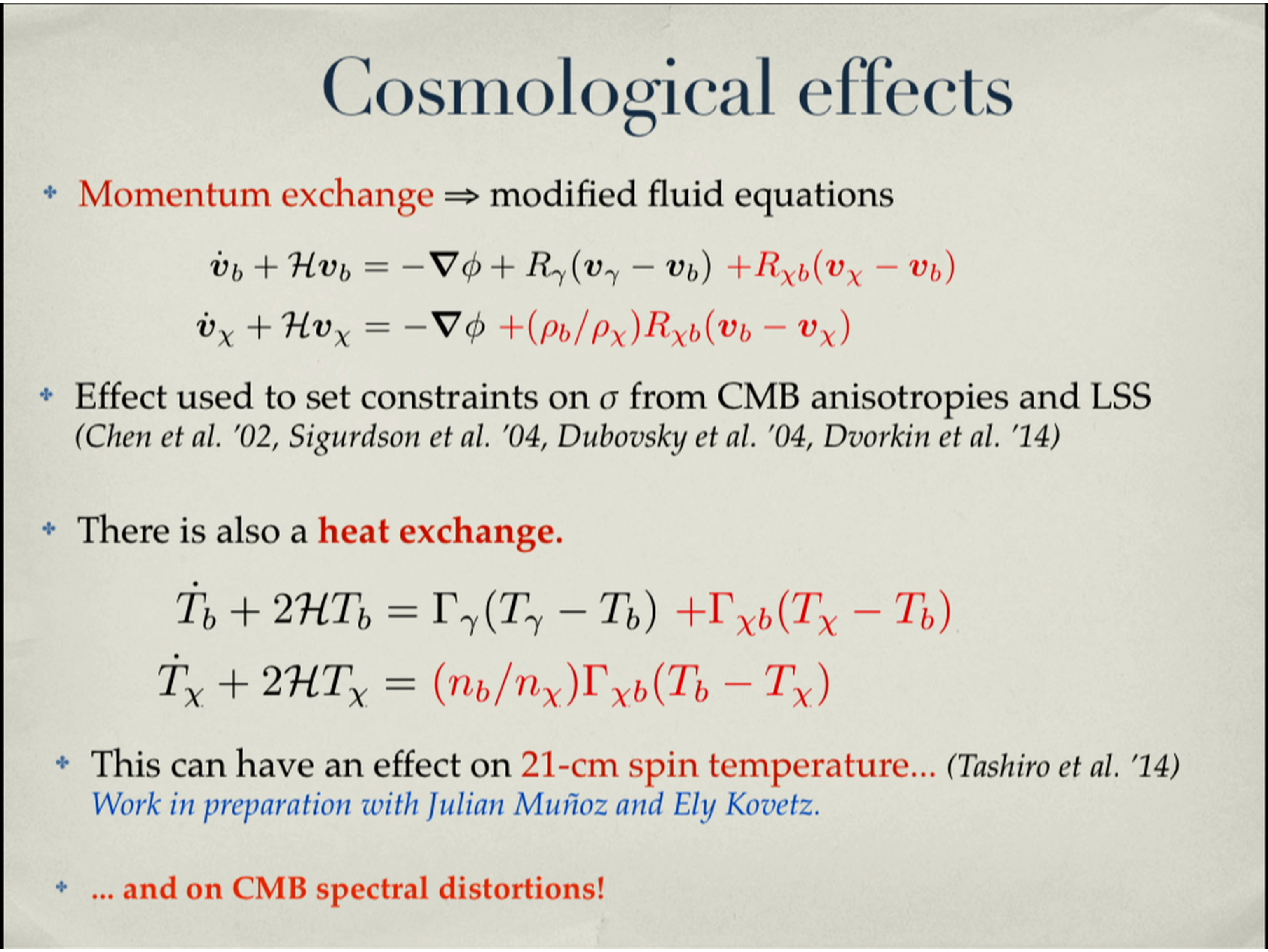
Cosmological effects

- Momentum exchange ⇒ modified fluid equations

$$\dot{\boldsymbol{v}}_b + \mathcal{H}\boldsymbol{v}_b = -\boldsymbol{\nabla}\phi + R_\gamma(\boldsymbol{v}_\gamma - \boldsymbol{v}_b) + R_{\chi b}(\boldsymbol{v}_\chi - \boldsymbol{v}_b)$$

$$\dot{\boldsymbol{v}}_\chi + \mathcal{H}\boldsymbol{v}_\chi = -\boldsymbol{\nabla}\phi + (\rho_b/\rho_\chi)R_{\chi b}(\boldsymbol{v}_b - \boldsymbol{v}_\chi)$$

- Effect used to set constraints on σ from CMB anisotropies and LSS *(Chen et al. '02, Sigurdson et al. '04, Dubovsky et al. '04, Dvorkin et al. '14)*



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- Effect used to set constraints on σ from CMB anisotropies and LSS *(Chen et al. '02, Sigurdson et al. '04, Dubovsky et al. '04, Dvorkin et al. '14)*

- There is also a **heat exchange.**

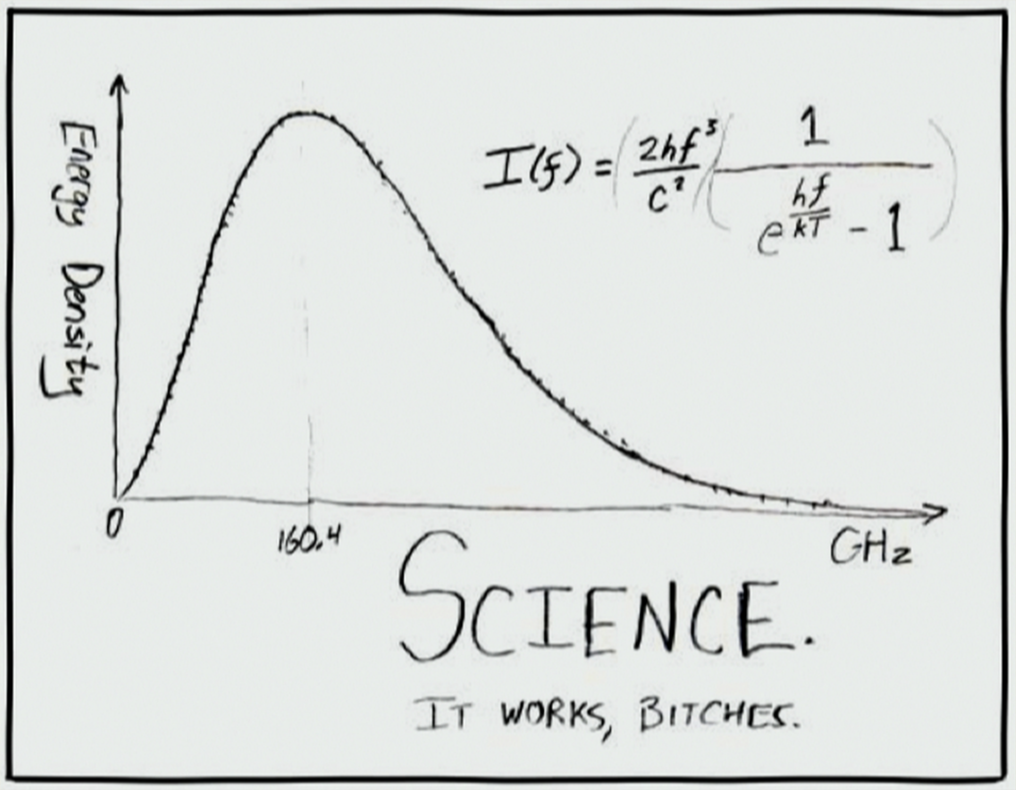
$$\dot{T}_b + 2\mathcal{H}T_b = \Gamma_\gamma(T_\gamma - T_b) + \Gamma_{\chi b}(T_\chi - T_b)$$

$$\dot{T}_\chi + 2\mathcal{H}T_\chi = (n_b/n_\chi)\Gamma_{\chi b}(T_b - T_\chi)$$

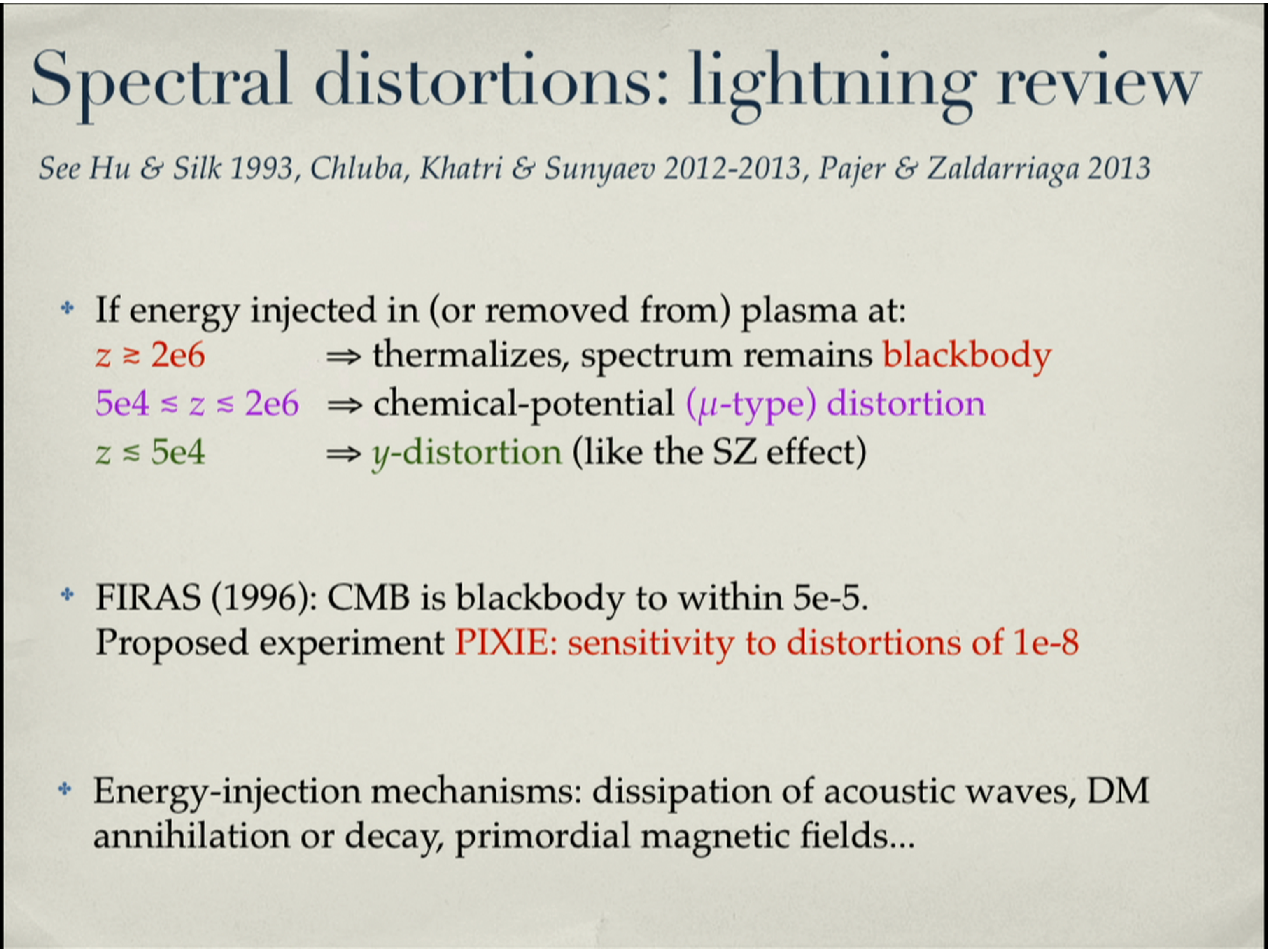
- This can have an effect on 21-cm spin temperature... *(Tashiro et al. '14)* *Work in preparation with Julian Muñoz and Ely Kovetz.*

- **... and on CMB spectral distortions!**

Spectral distortions: lightning review



Credit: xkcd



Spectral distortions: lightning review

See Hu & Silk 1993, Chluba, Khatri & Sunyaev 2012-2013, Pajer & Zaldarriaga 2013

- If energy injected in (or removed from) plasma at:
  $z \gtrsim$ 2e6 ⇒ thermalizes, spectrum remains blackbody
  5e4 $\lesssim z \lesssim$ 2e6 ⇒ chemical-potential (μ-type) distortion
  $z \lesssim$ 5e4 ⇒ y-distortion (like the SZ effect)

- FIRAS (1996): CMB is blackbody to within 5e-5.
  Proposed experiment PIXIE: sensitivity to distortions of 1e-8

- Energy-injection mechanisms: dissipation of acoustic waves, DM annihilation or decay, primordial magnetic fields...

Energy extraction process

(Chluba & Sunyaev '12)

- Left alone, non-relativistic baryons would cool down adiabatically

$$T_b\Big|_{\mathrm{ad}} \propto a^{-2} \;\Rightarrow\; \dot{T}_b\Big|_{\mathrm{ad}} = -2HT_b$$

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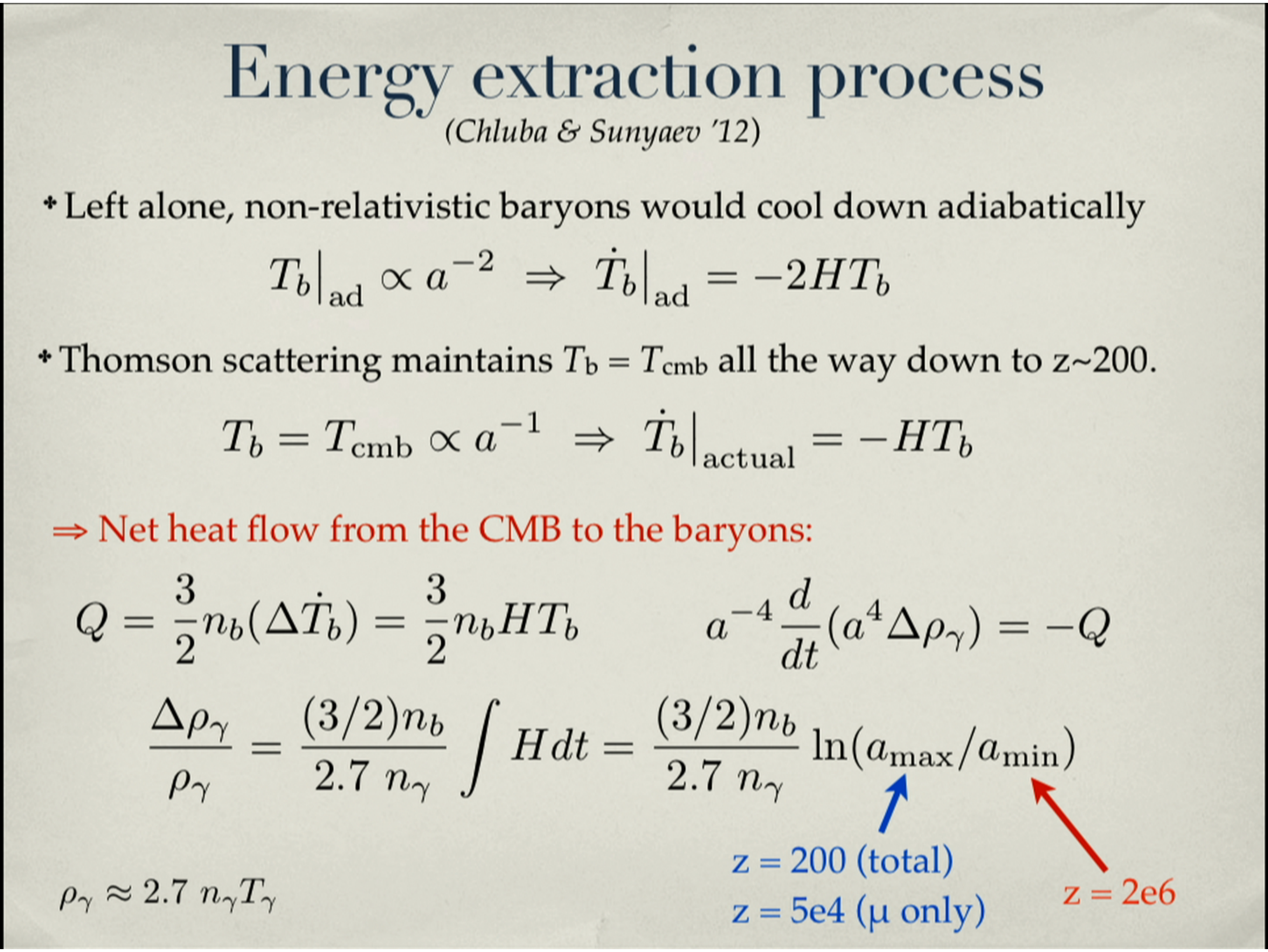
⇒ Net heat flow from the CMB to the baryons:

$$Q = \frac{3}{2} n_b (\Delta \dot{T}_b) = \frac{3}{2} n_b H T_b \qquad a^{-4}\frac{d}{dt}(a^4 \Delta\rho_\gamma) = -Q$$

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = \frac{(3/2)n_b}{2.7\; n_\gamma}\int H\,dt = \frac{(3/2)n_b}{2.7\; n_\gamma}\ln(a_{\mathrm{max}}/a_{\mathrm{min}})$$

$\rho_\gamma \approx 2.7\; n_\gamma T_\gamma$



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z = 200 (total)

z = 5e4 (μ only)

z = 2e6

$\rho_\gamma \approx 2.7\, n_\gamma T_\gamma$

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⇒ Net heat flow from the CMB to the baryons:

$$Q = \frac{3}{2}n_b(\Delta\dot{T}_b) = \frac{3}{2}n_b H T_b \qquad a^{-4}\frac{d}{dt}(a^4\Delta\rho_\gamma) = -Q$$

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = \frac{(3/2)n_b}{2.7\ n_\gamma}\int H\,dt = \boxed{\frac{(3/2)n_b}{2.7\ n_\gamma}}\ln(a_{\rm max}/a_{\rm min})$$

$\sim 10^{-10}$

z = 200 (total)

z = 5e4 (μ only)

z = 2e6

$$\rho_\gamma \approx 2.7\, n_\gamma T_\gamma$$

Adding scattering DM to the mix

- If DM is non-relativistic by z = 2e6 ($m_{DM} \gtrsim$ keV) and
- scatters off photons: identical effect
- scatters of nuclei or electrons: Thomson scattering must maintain the entire "plasma" in equilibrium. Increased heat capacity due to additional particles. Indirect thermal coupling to CMB.

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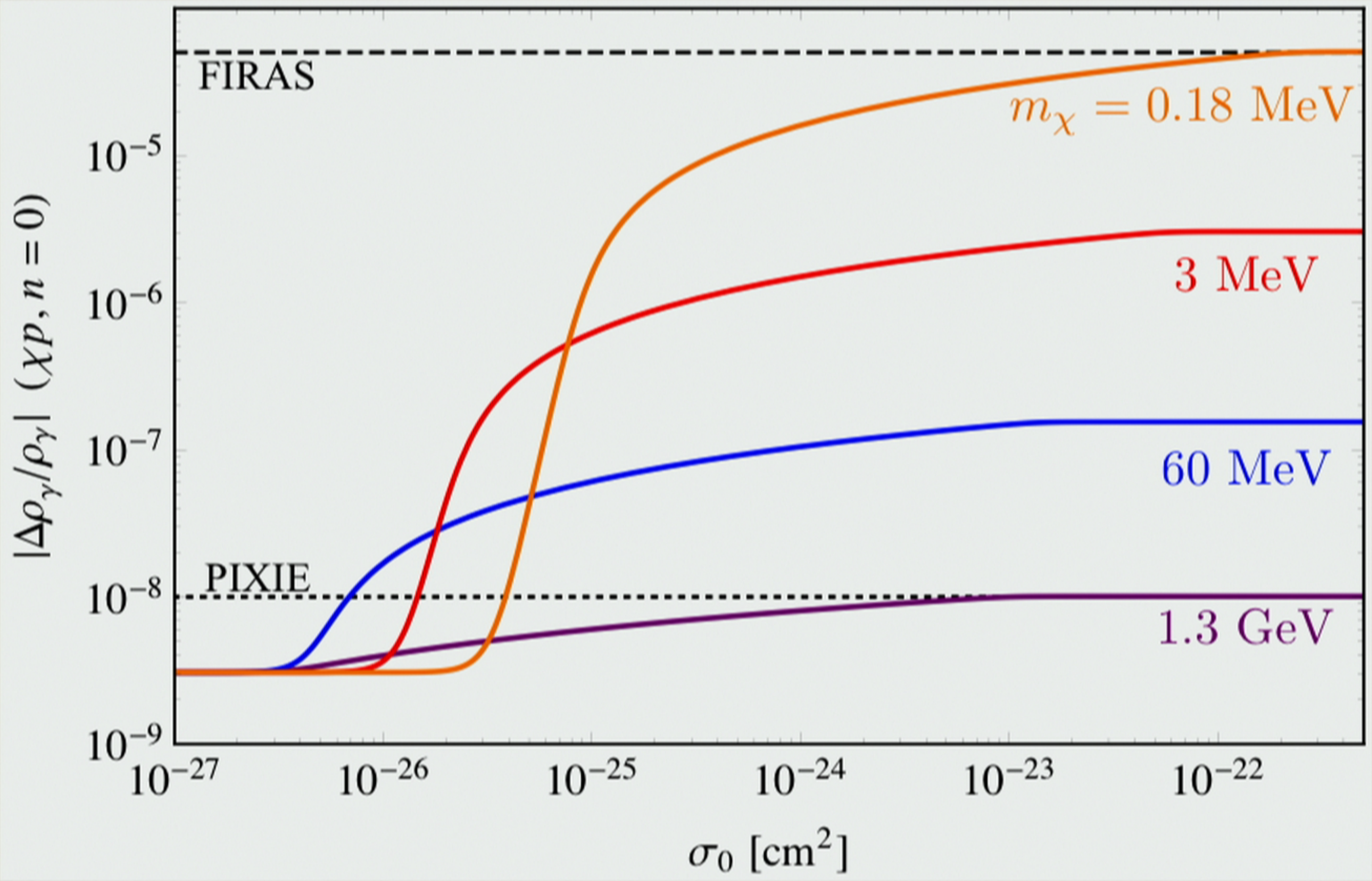
- In both cases:

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} \sim \frac{n_{\rm DM}}{n_\gamma} \log(a_{\rm decoupling}/a_{\rm min})$$

$\propto 1/m_{\rm DM}$

can probe light DM

depends on cross-section



For velocity-independent scattering (but we studied general power-law dependence)