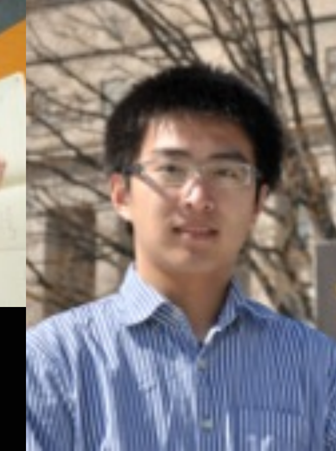


CMB spectral distortions:
Basic physics and novel sources

Daniel Grin
KICP
University of Chicago

with J.Chluba, L.Dai, M. Kamionkowski (JHU), M. Amin (KICC)

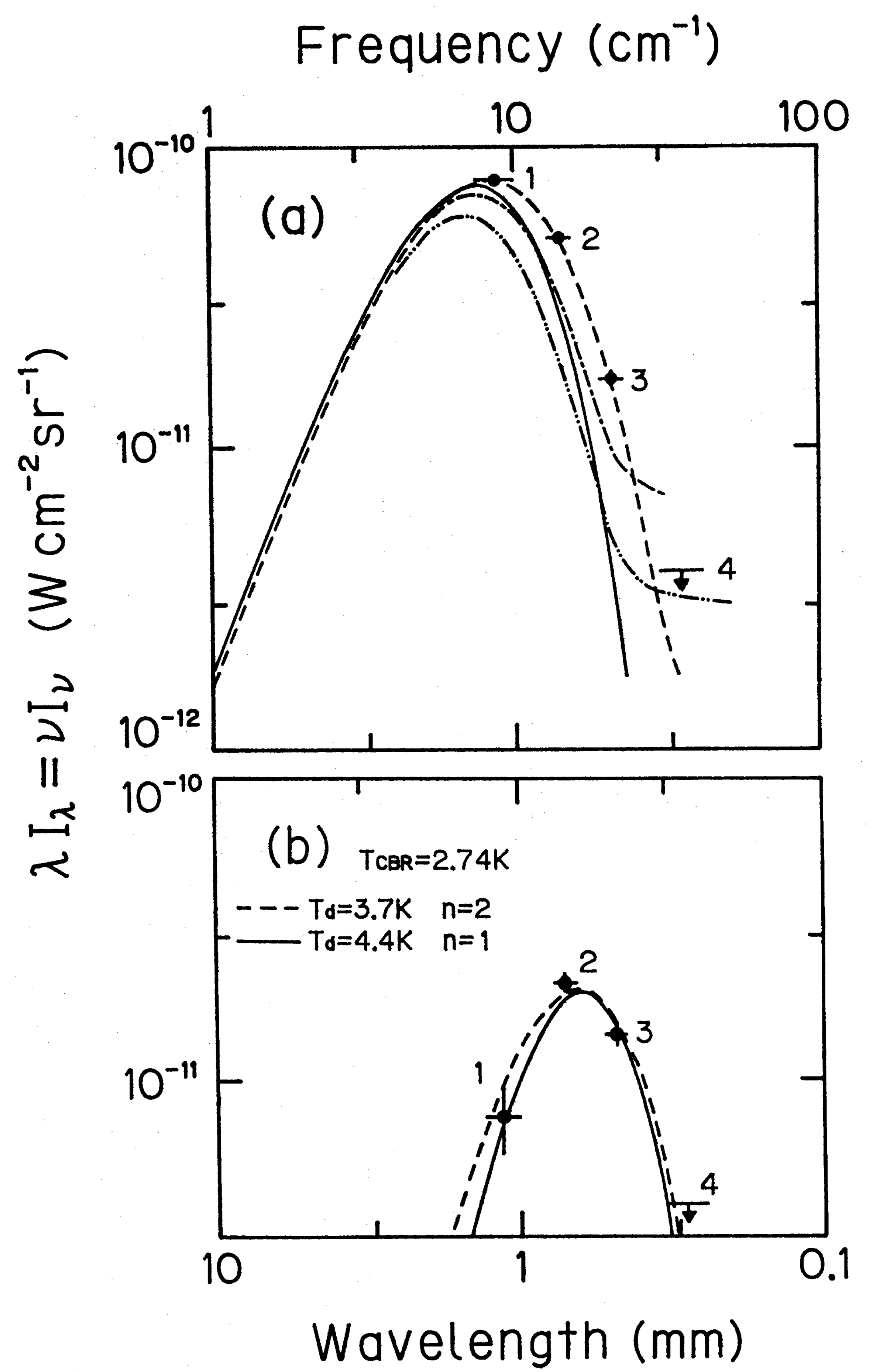
arXiv:1304.4596, MNRAS 434, 1619
arXiv: 1405.1039
arXiv: 1407.3653

Some generalities

Some generalities

First papers by Sunyaev and Zel'dovich
Review papers on spectral distortions: Les Houches lecture notes (Chluba 2013)
See work by Sunyaev, Chluba, Khatri, Ali-Haimoud, Pajer, Zaldarriaga

PHYSICS FROM 'DISTORTIONS'



Lange et al. 1987

PHYSICS FROM 'DISTORTIONS'

THE ASTROPHYSICAL JOURNAL, **344**:24–34, 1989 September 1

SPECTRAL DISTORTIONS OF THE COSMIC MICROWAVE BACKGROUND

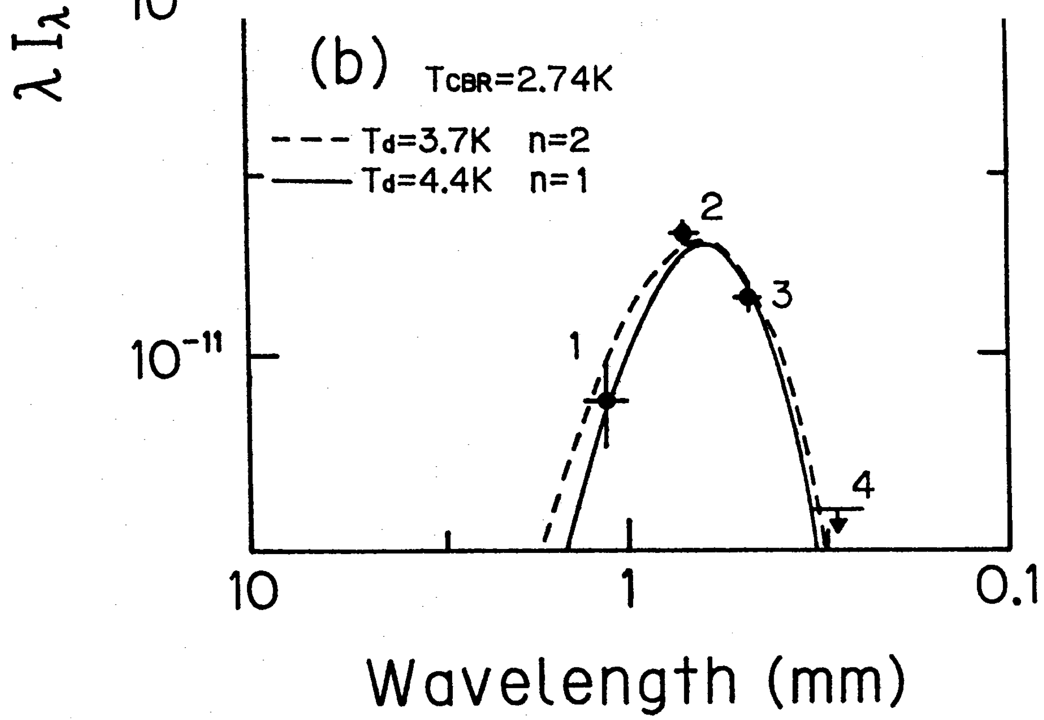
FRED C. ADAMS,[1] KATHERINE FREESE,[2] JANNA LEVIN,[2] AND JONATHAN C. MCDOWELL[1]

Received 1988 December 30; accepted 1989 February 22

ABSTRACT

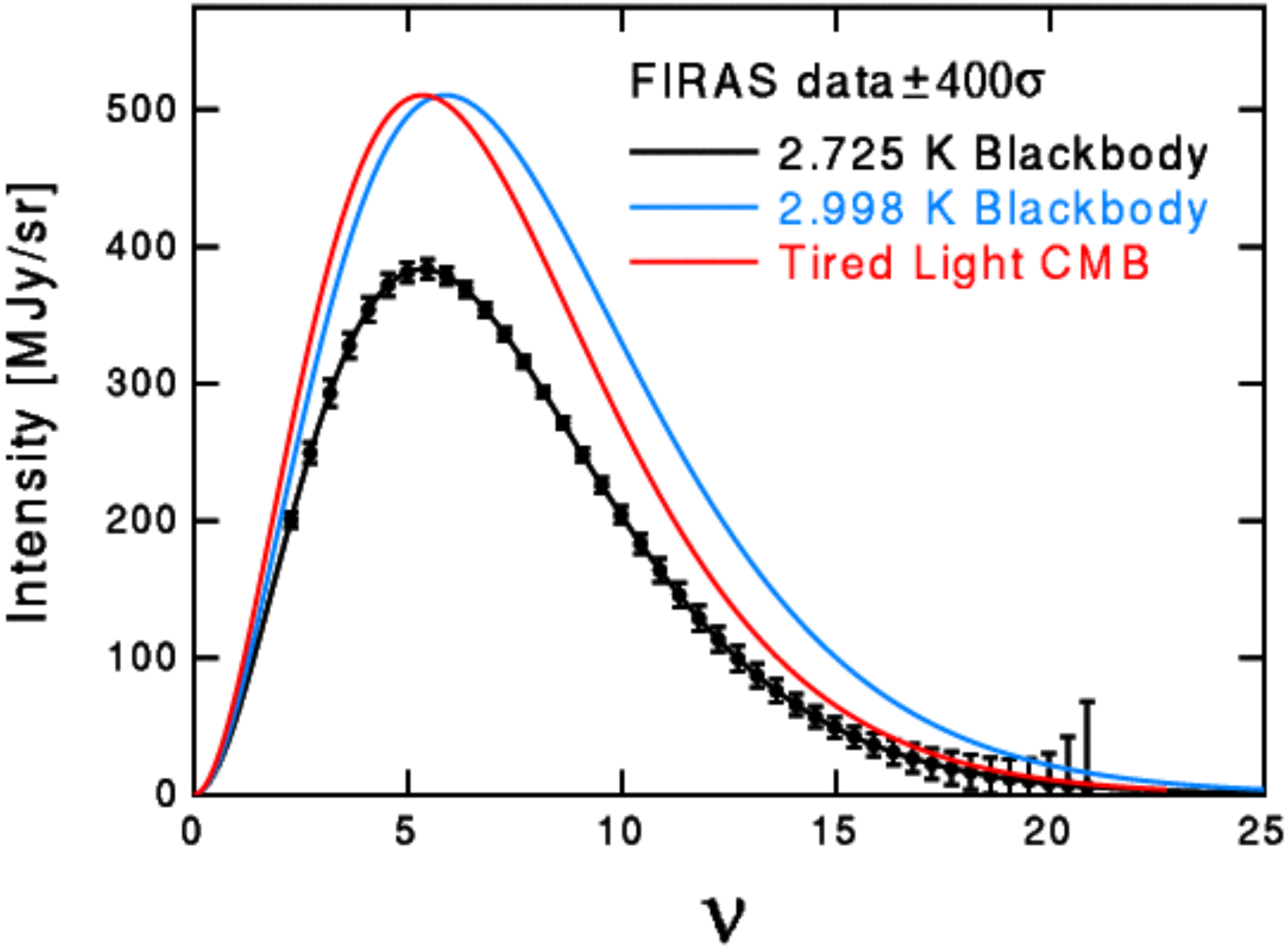
Motivated by recent experiments indicating that the spectrum of the cosmic microwave background deviates from a pure blackbody, we consider spectral distortions produced by cosmic dust. Our main result is that cosmic dust in conjunction with an injected radiation field (perhaps produced by an early generation of very massive stars) can explain the observed spectral distortions without violating existing cosmological constraints. In addition, we show that Compton y-distortions can also explain the observed spectral *shape*, but the energetic requirements are more severe.

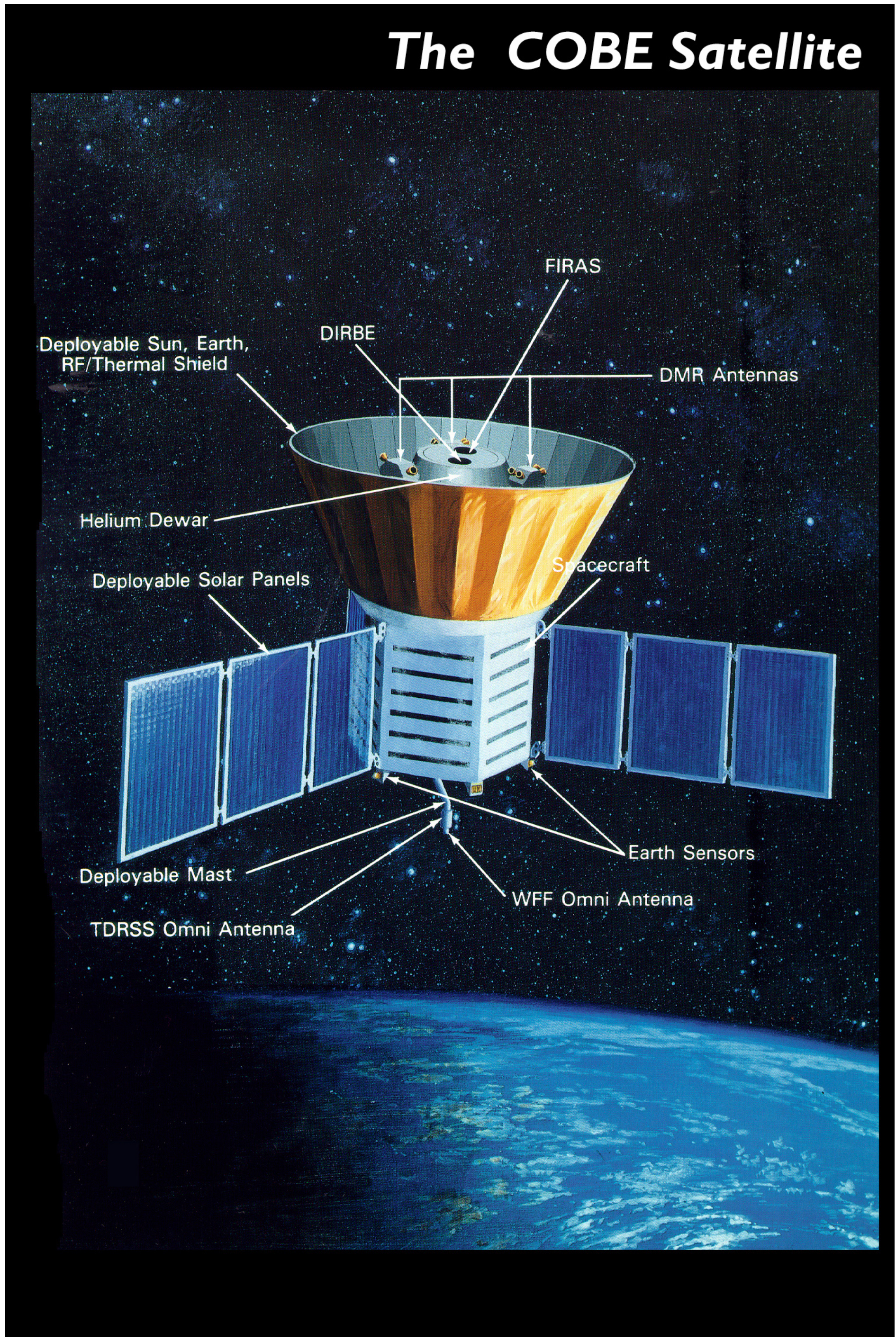
Subject headings: cosmic background radiation — cosmology — radiation mechanisms



Lange et al. 1987

COBE BLACKBODY

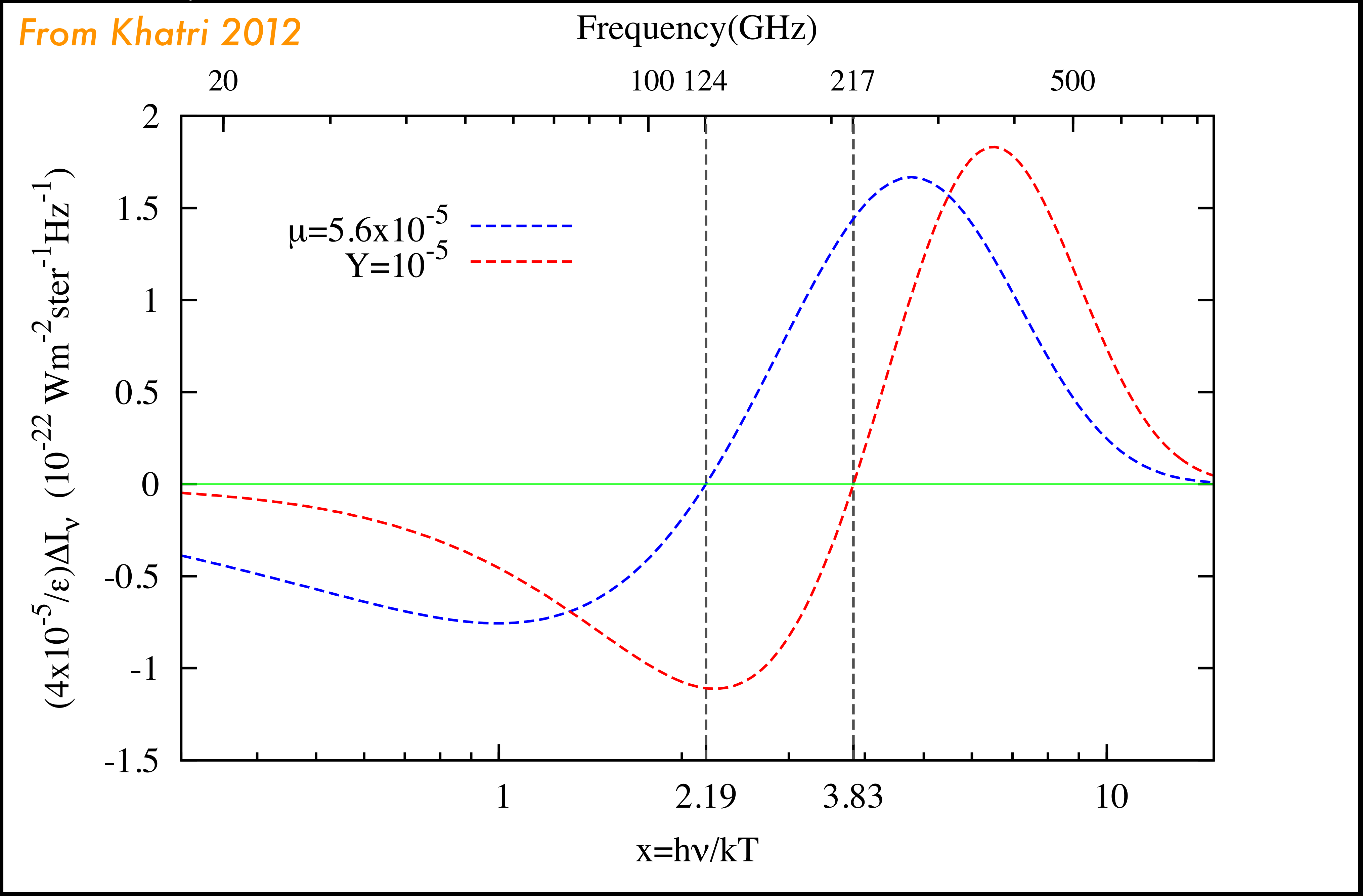




$$\mu \leq 9 \times 10^{-5}$$
$$y \leq 1.5 \times 10^{-5}$$

→ 3-4 orders of magnitude improvement now possible!!!

μ AND Y-TYPE DISTORTION



EQUILIBRATING PROCESSES

- Chemical equilibrium epoch

$$e^- + X \leftrightarrow e^- + X + \gamma \quad \text{Bremmstrahlung}$$

$$e^- + \gamma \leftrightarrow e^- + \gamma + \gamma \quad \text{Double Compton scattering}$$

- Comptonization (μ) epoch

$$e^- + \gamma \leftrightarrow e^- + \gamma \quad \text{Energy-exchanging Compton scattering}$$

- Thomson (y) epoch

$$e^- + \gamma \leftrightarrow e^- + \gamma \quad \text{Elastic Compton scattering}$$

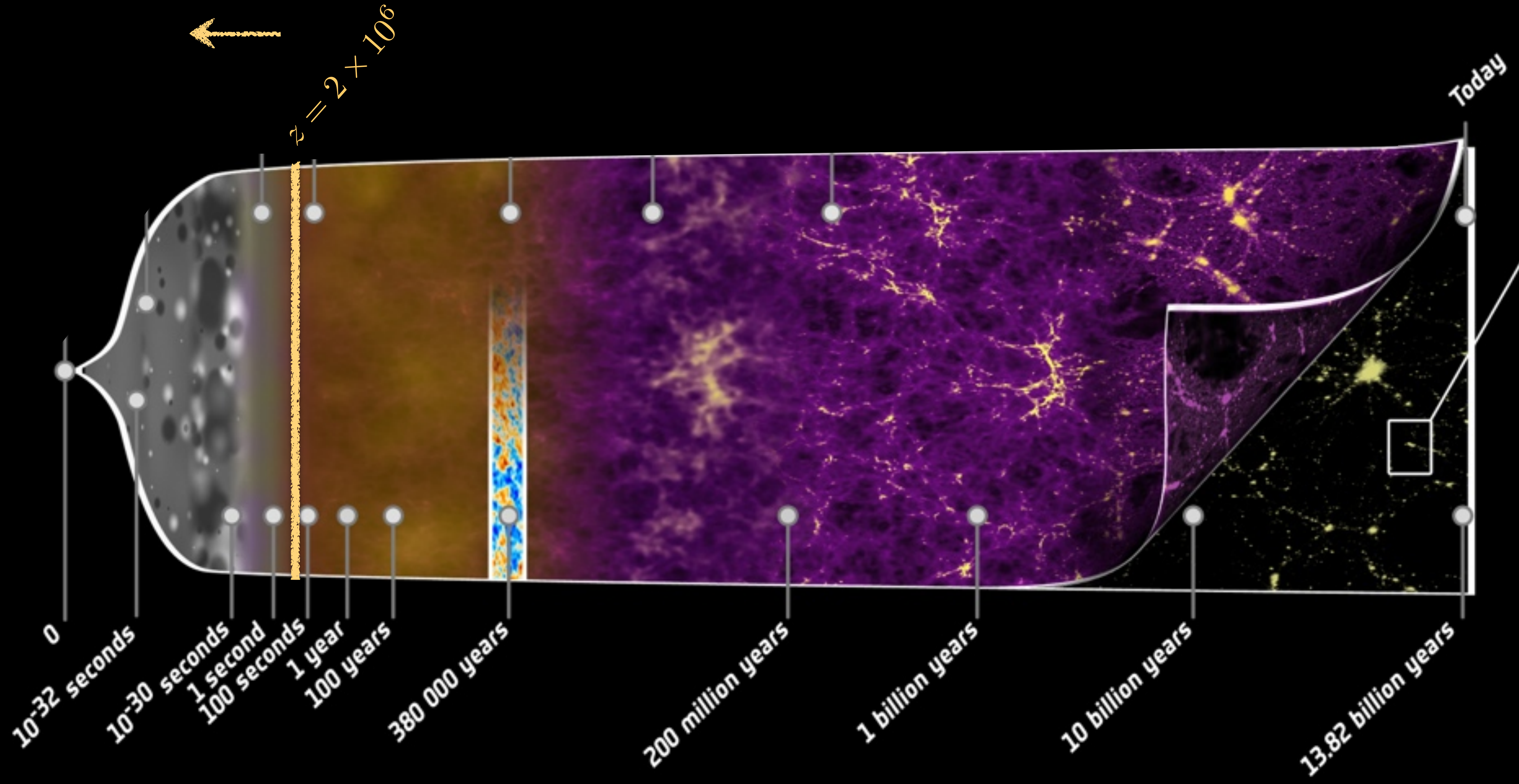
Seminal work by Sunyaev/Zeldovich (1970)
recent work by Chluba, Khatri, Sunyaev....
see also Wayne Hu's PhD thesis for a review

PHYSICS OF SPECTRAL DISTORTIONS

blackbody

$$\frac{1}{\exp\left[\frac{h\nu}{kT}\right]-1}$$

number change
energy change



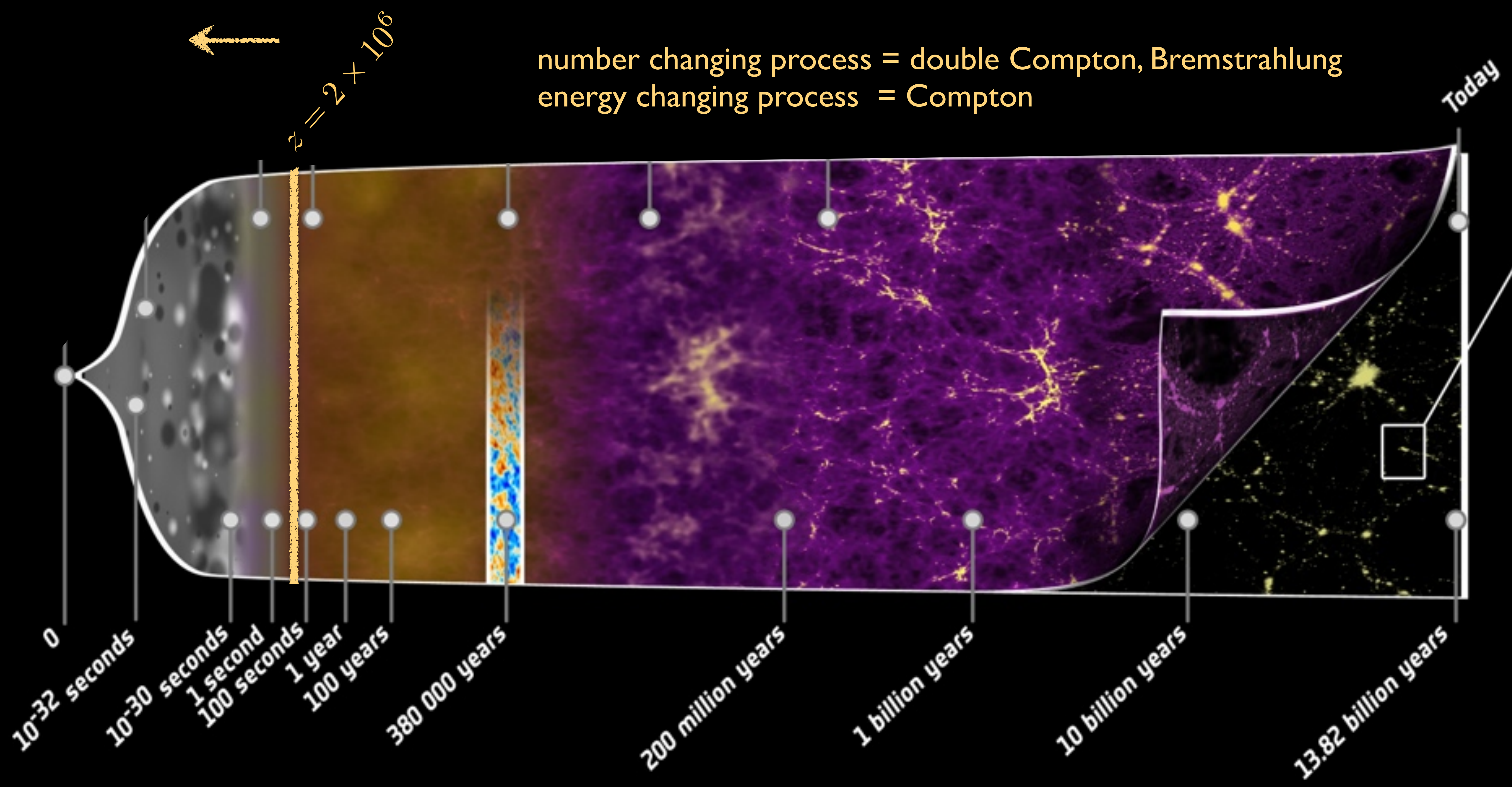
PHYSICS OF SPECTRAL DISTORTIONS

blackbody

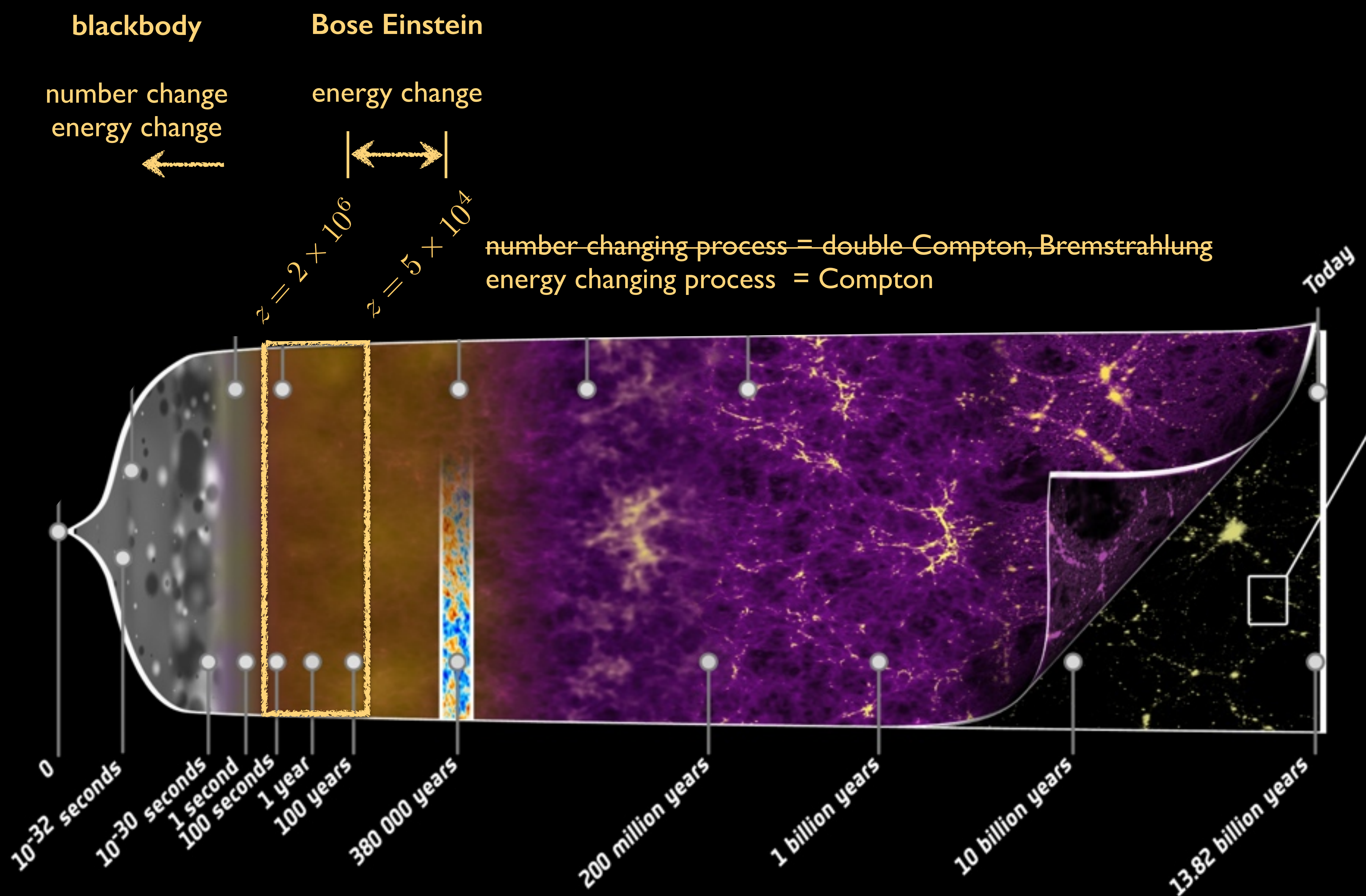
$$\frac{1}{\exp\left[\frac{h\nu}{kT}\right] - 1}$$

number change
energy change

number changing process = double Compton, Bremstrahlung
energy changing process = Compton



PHYSICS OF SPECTRAL DISTORTIONS



PHYSICS OF SPECTRAL DISTORTIONS

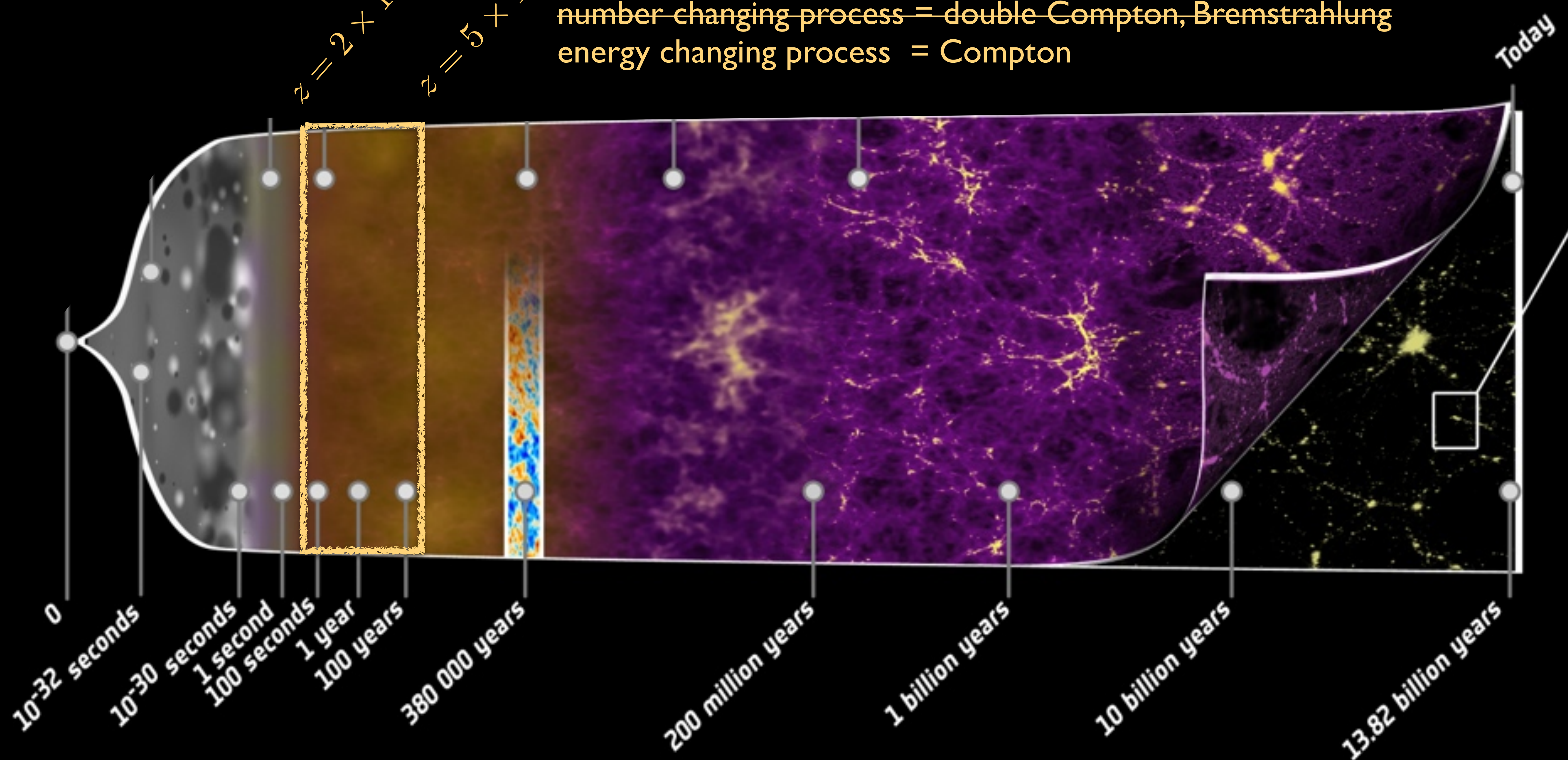
blackbody	Bose Einstein
number change energy change ←	energy change |←→|

$z = 2 \times 10^6$ $z = 5 \times 10^4$

$$\frac{1}{\exp\left[\frac{h\nu}{kT} + \mu\right] - 1}$$

~~number changing process = double Compton, Bremstrahlung~~

energy changing process = Compton



PHYSICS OF SPECTRAL DISTORTIONS

blackbody

number change
energy change

←

Bose Einstein

energy change

|←→|

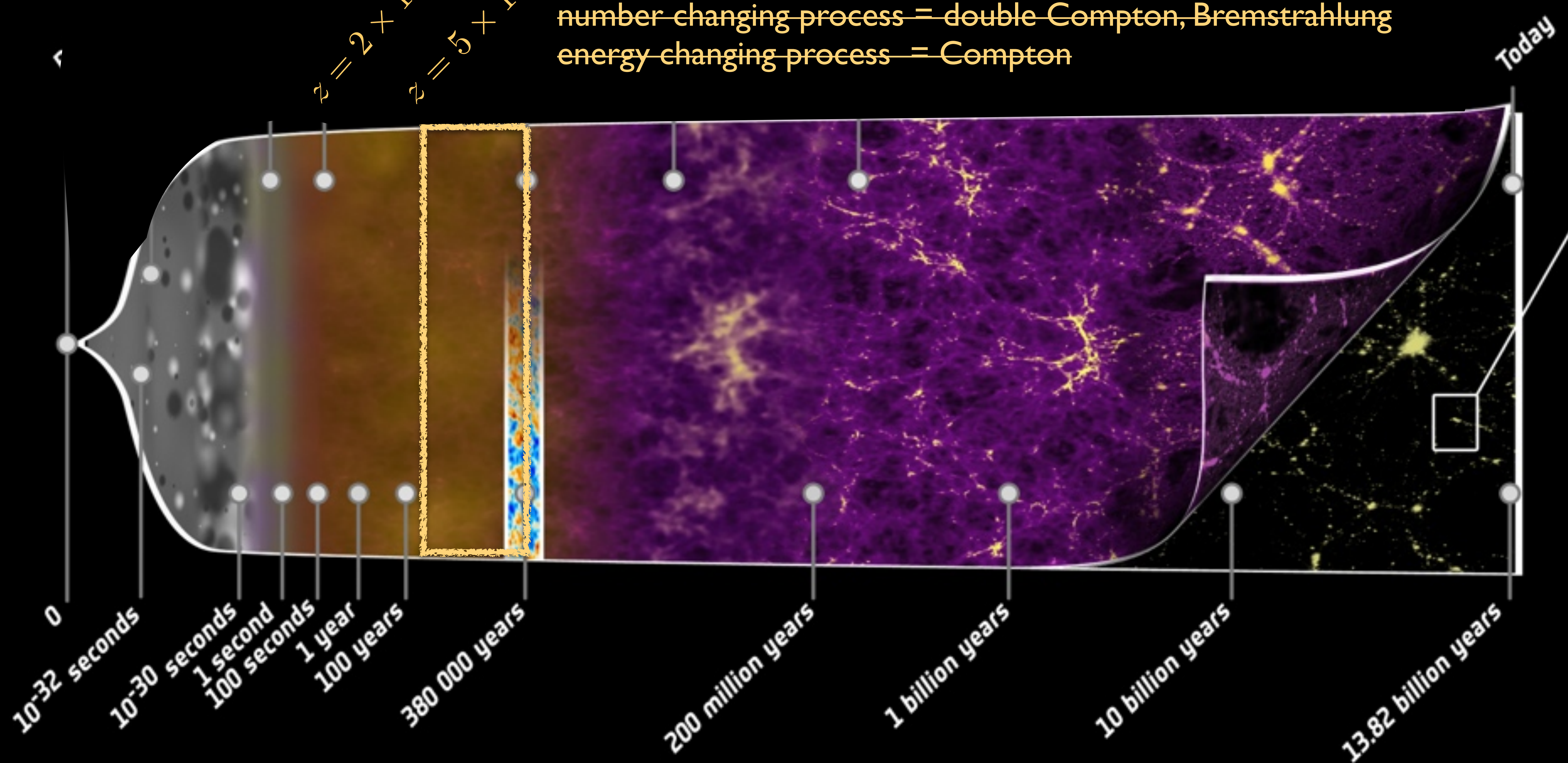
$z = 2 \times 10^6$

$z = 5 \times 10^4$

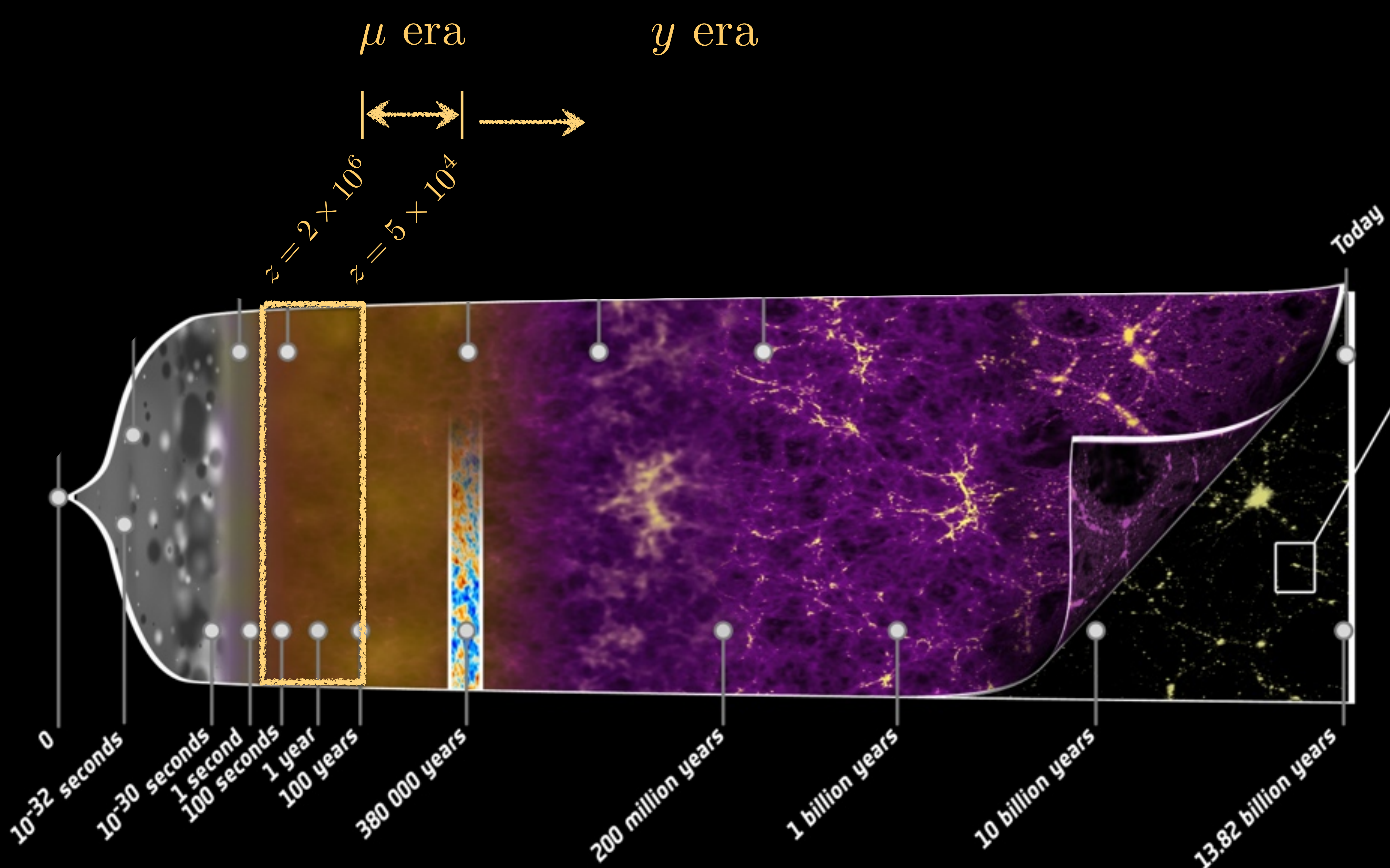
Compton y+BB

→

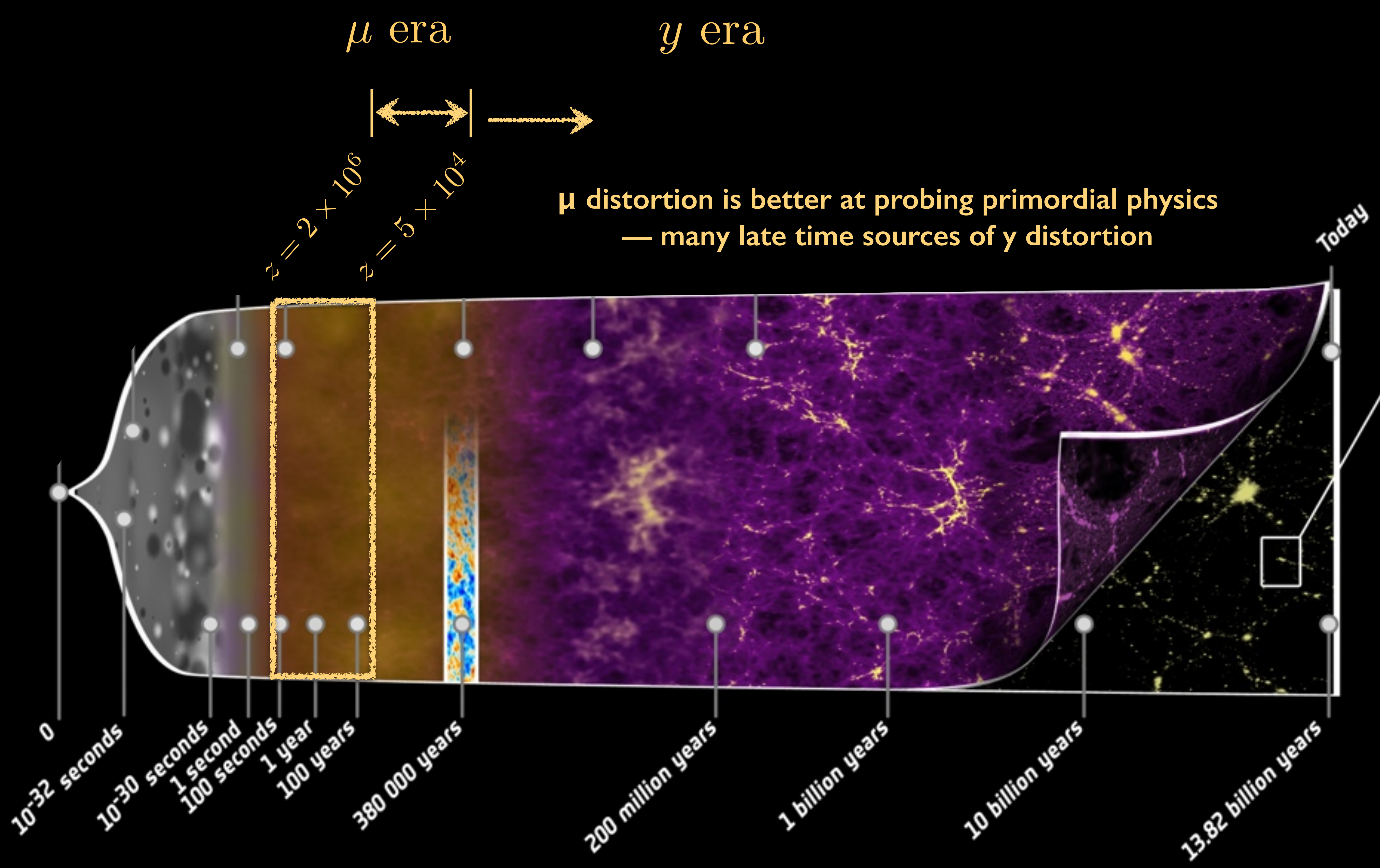
~~number changing process = double Compton, Bremstrahlung~~
~~energy changing process = Compton~~



PHYSICS OF SPECTRAL DISTORTIONS



PHYSICS OF SPECTRAL DISTORTIONS



Energy injection

- Dark matter annihilation (photons produced directly or through cascades)

Chluba 2009

- Dark matter decay
- Damping of acoustic modes

Chluba/Erickcek/Ben-Dayan 2012

  - Features in power spectrum
- Reionization (z~6) $y \sim 10^{-7}$ overwhelms primordial y
- Gauge boson production from cosmic strings

Tashiro and Vachaspati 2012

- Primordial magnetic field damping

Marsh/Silk/Tashiro 2013

SDS AND SMALL-SCALE POWER SPECTRUM

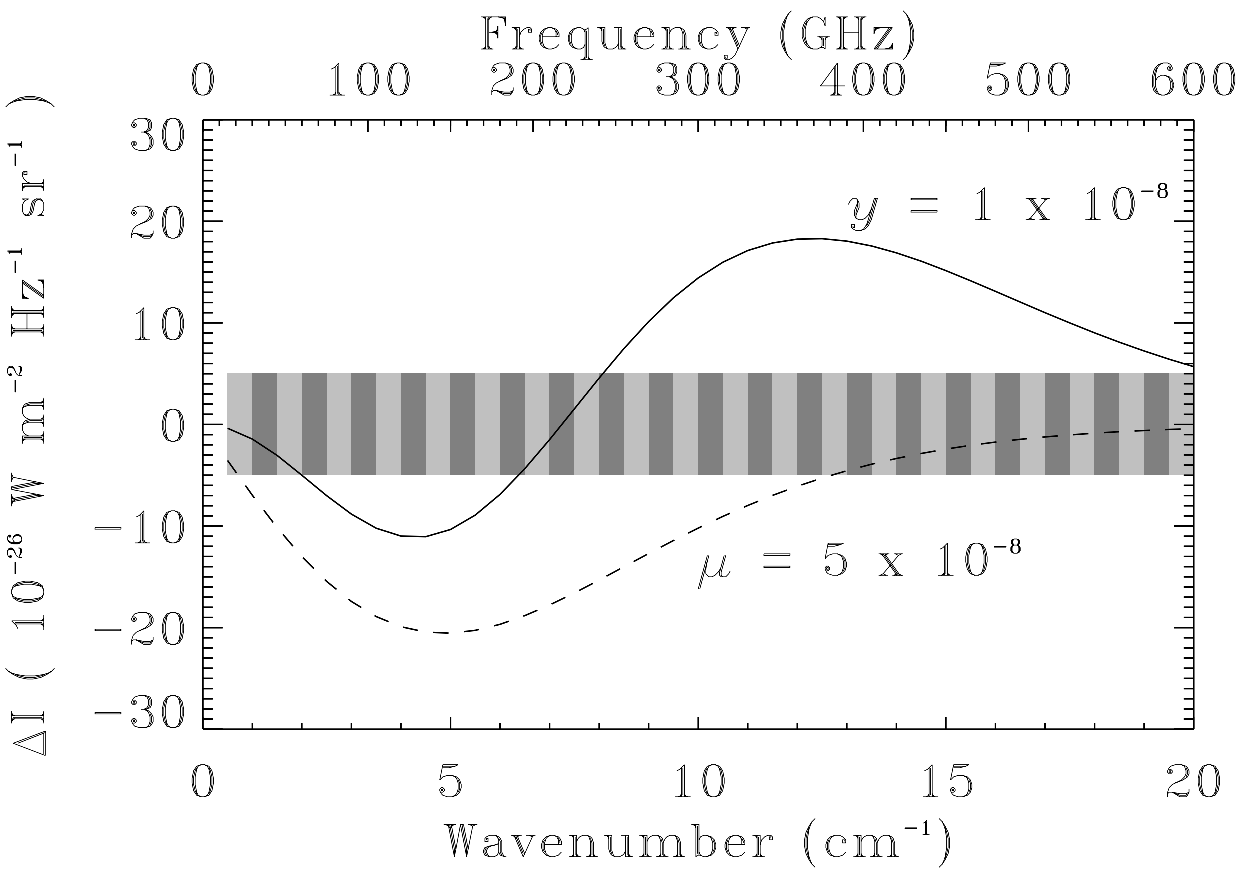
- Damping of acoustic modes

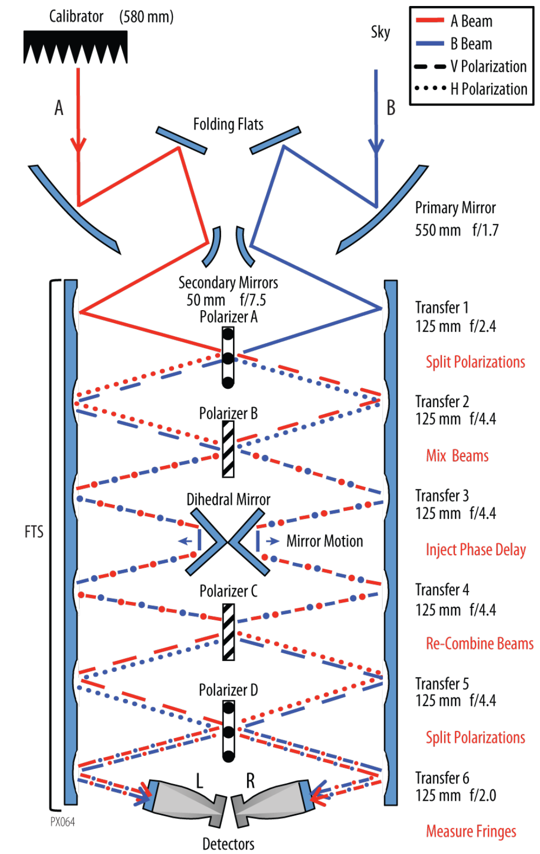
  Chluba/Erickcek/Ben-Dayan 2012

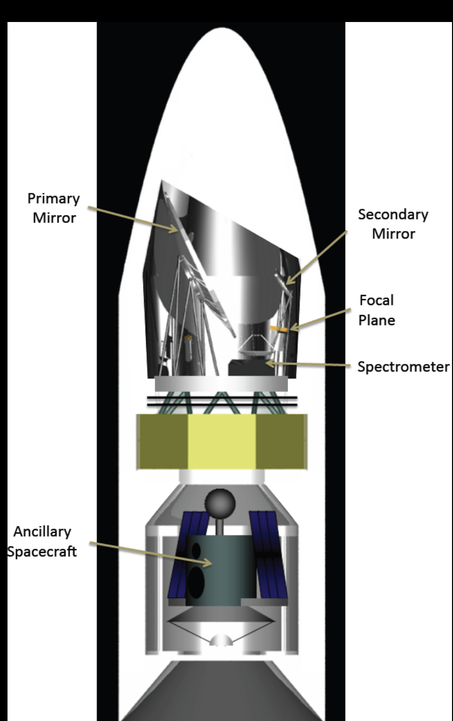
  - Steps in primordial power spectrum
  - Bumps in primordial power spectrum
  - Features from inflationary particle production
  - Running mass inflaton

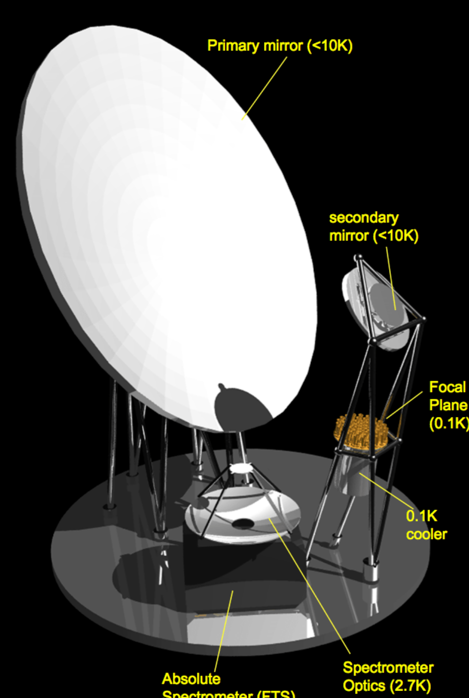
EXPERIMENTAL HORIZON

PIXIE (Explorer proposal, $200M)



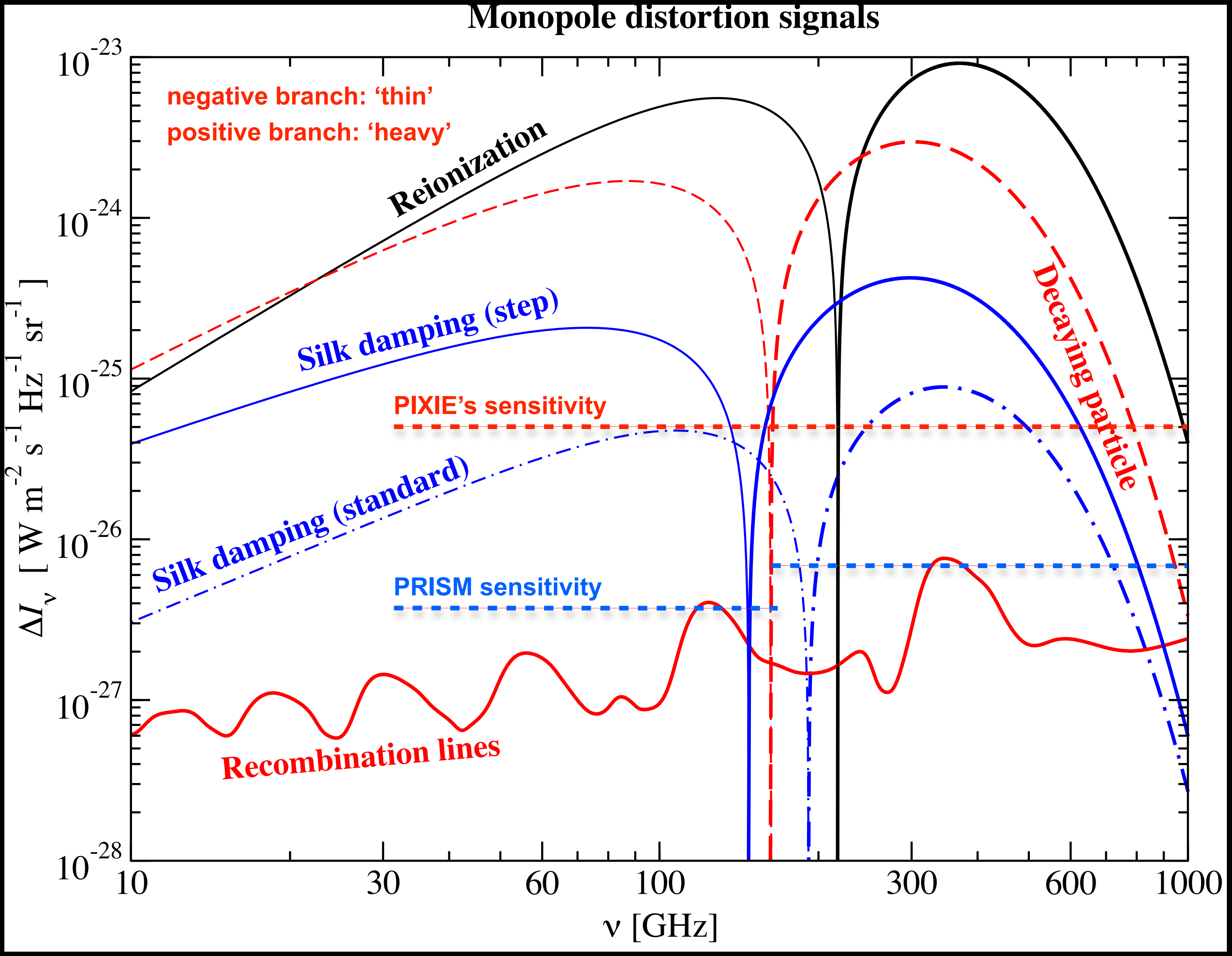






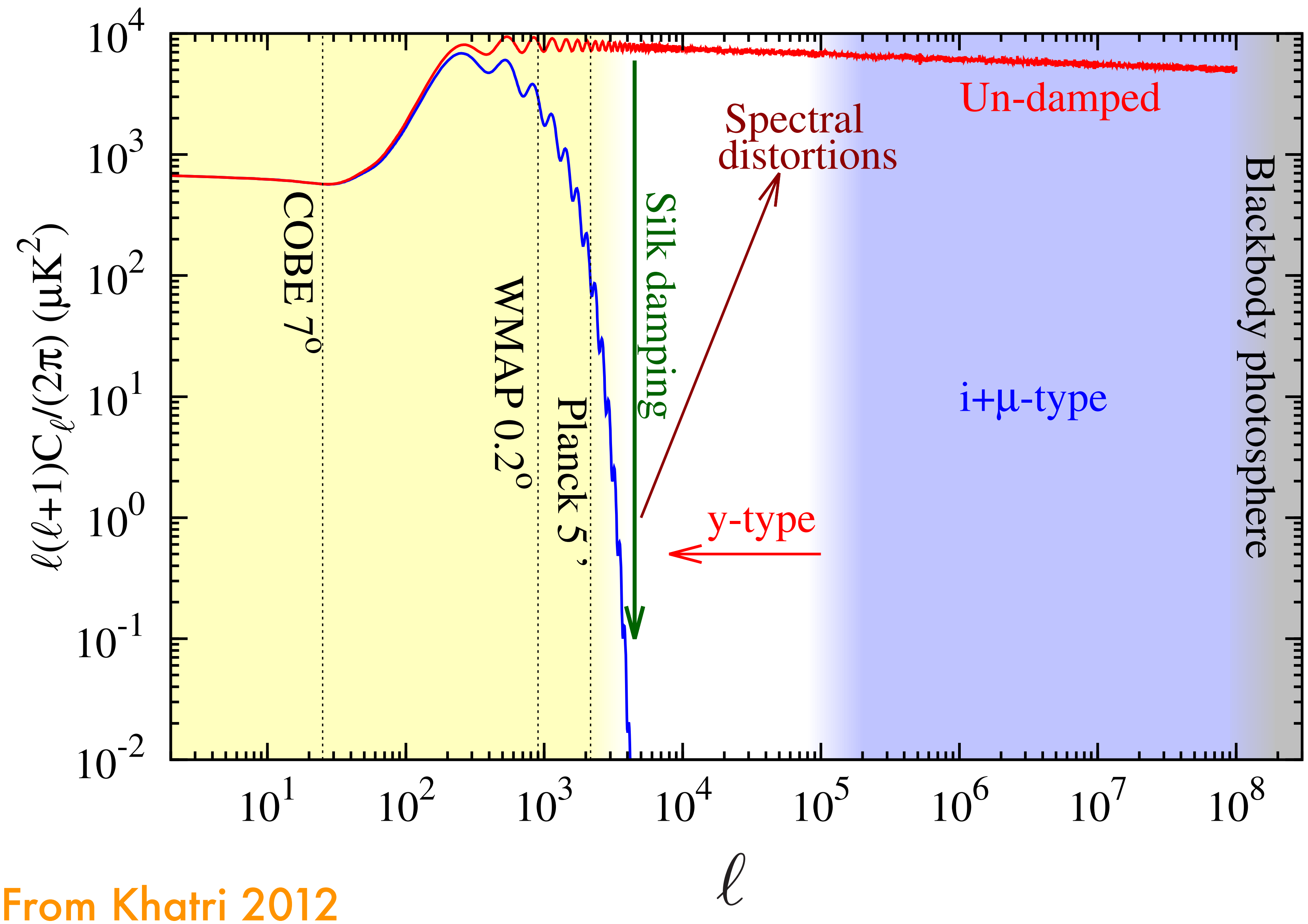
PRISM [50 cm spectrophotometer +imager: 4m telescope, 7600 bolometers, ~30 frequency bands] (billions and billions....)

EXPECTED SIGNALS/SENSITIVITY



recombination lines predicted by Zel'dovich/Kurt/Sunyaev (1969), reviewed in Sunyaev/Chluba 0710.2879

SILK DAMPING AND DISTORTION FROM ADIABATIC MODES



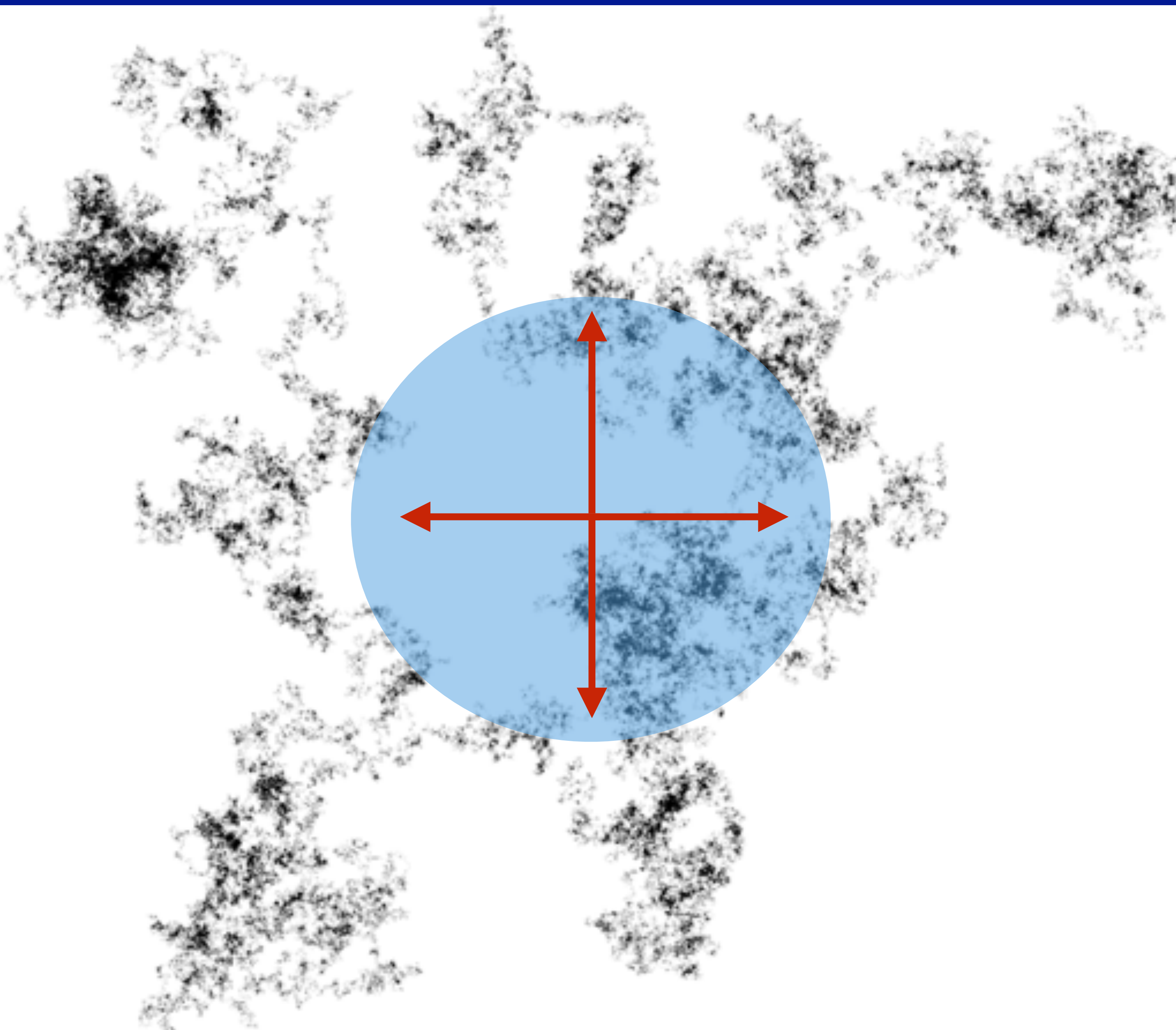
From Khatri 2012

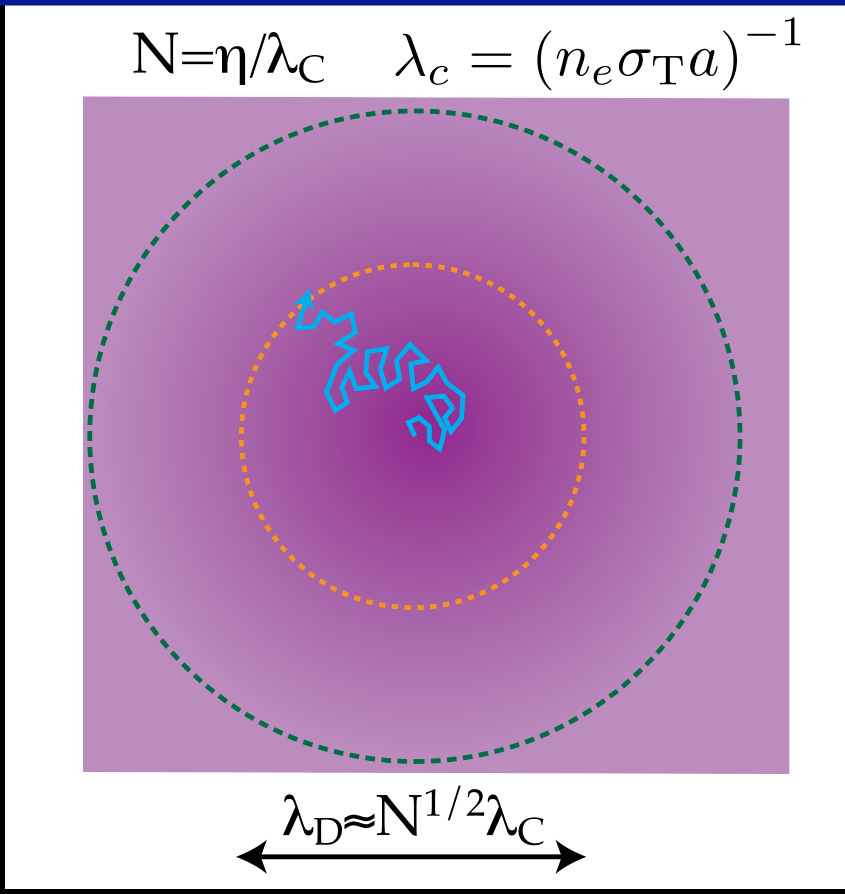
Mode dissipation mixes black bodies – these distortions begin their life as y distortions, the epoch determines the rest

NEARLY Scale-invariant LCDM cosmology →

$\mu \sim 2 \times 10^{-8}$
$y \sim 4 \times 10^{-9}$

SUPERPOSITION OF BLACKBODIES THROUGH DIFFUSION





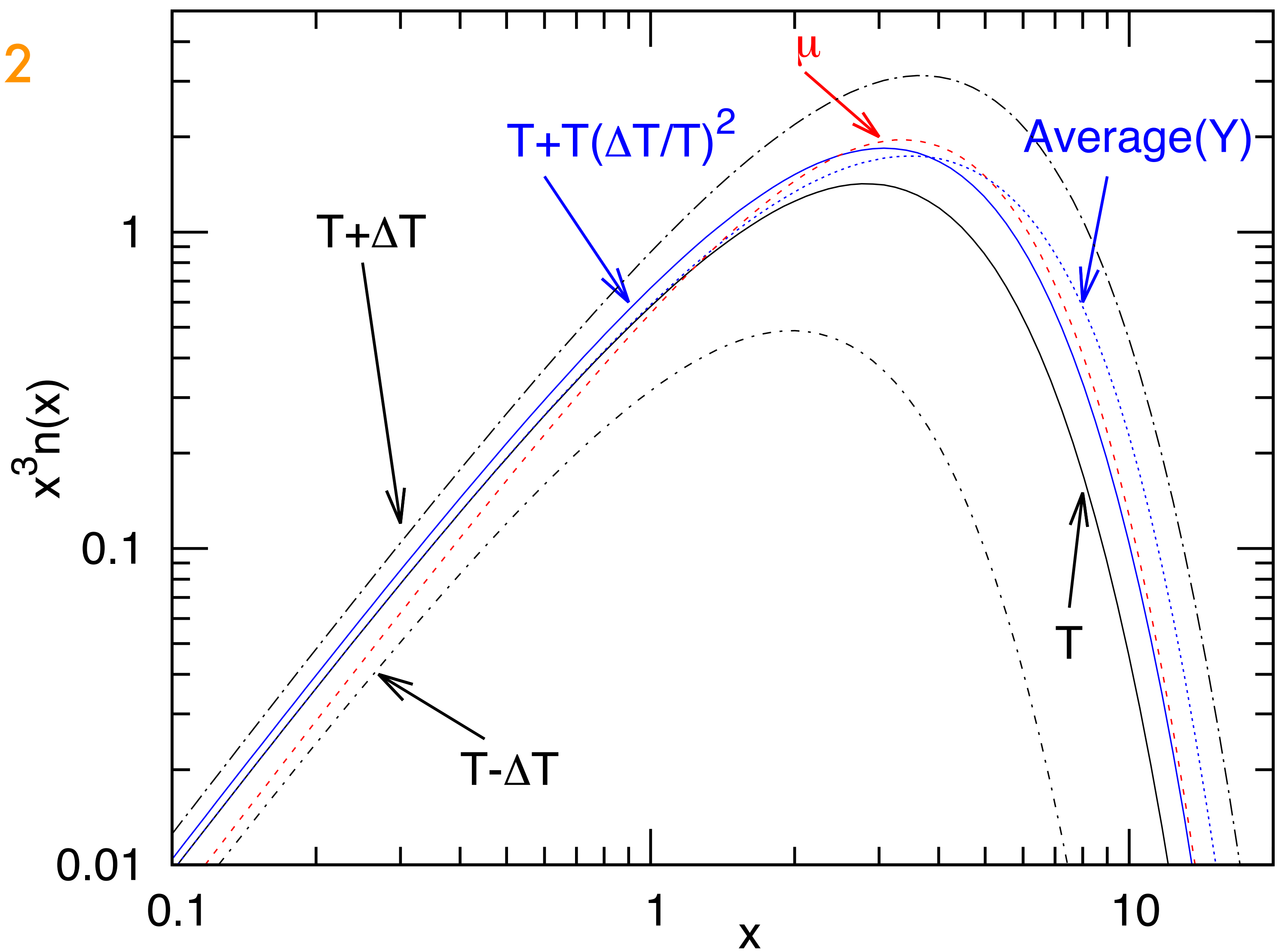
$$k_D \sim 4 \times 10^{-6}\,(1+z)^{3/2}\ \mathrm{Mpc}^{-1}$$

- ✳Free electron sees average spectrum – not BB
- ✳Rescatters into homogeneous component (spectral distortion)
- ✳l=2 is first piece that *cannot be gauged away: from diffusion*

SUPERPOSITION OF BLACKBODIES

pointed out in Chluba/Sunyaev 2004

From Khatri 2012



HEATING FROM ACOUSTIC MODE DISSIPATION

- Energy lost to Silk damping: $\frac{d}{dt}\frac{\Delta E_\gamma}{E_\gamma} = 4 n_e \sigma_T \int \frac{k^2 dk}{2\pi^2} P_i(k)$

$$\left\{ \frac{(3\Theta_1 - v)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2(\Theta_2^{\rm P} + \Theta_0^{\rm P}) + \sum_{l\geq 3}(2l+1)\,\Theta_l^2 \right\}$$

- CosmoTherm (Chluba 2013) -- follows 80 moments, all relevant reactions

NEW PROBE OF SMALL-SCALE PERTURBATIONS

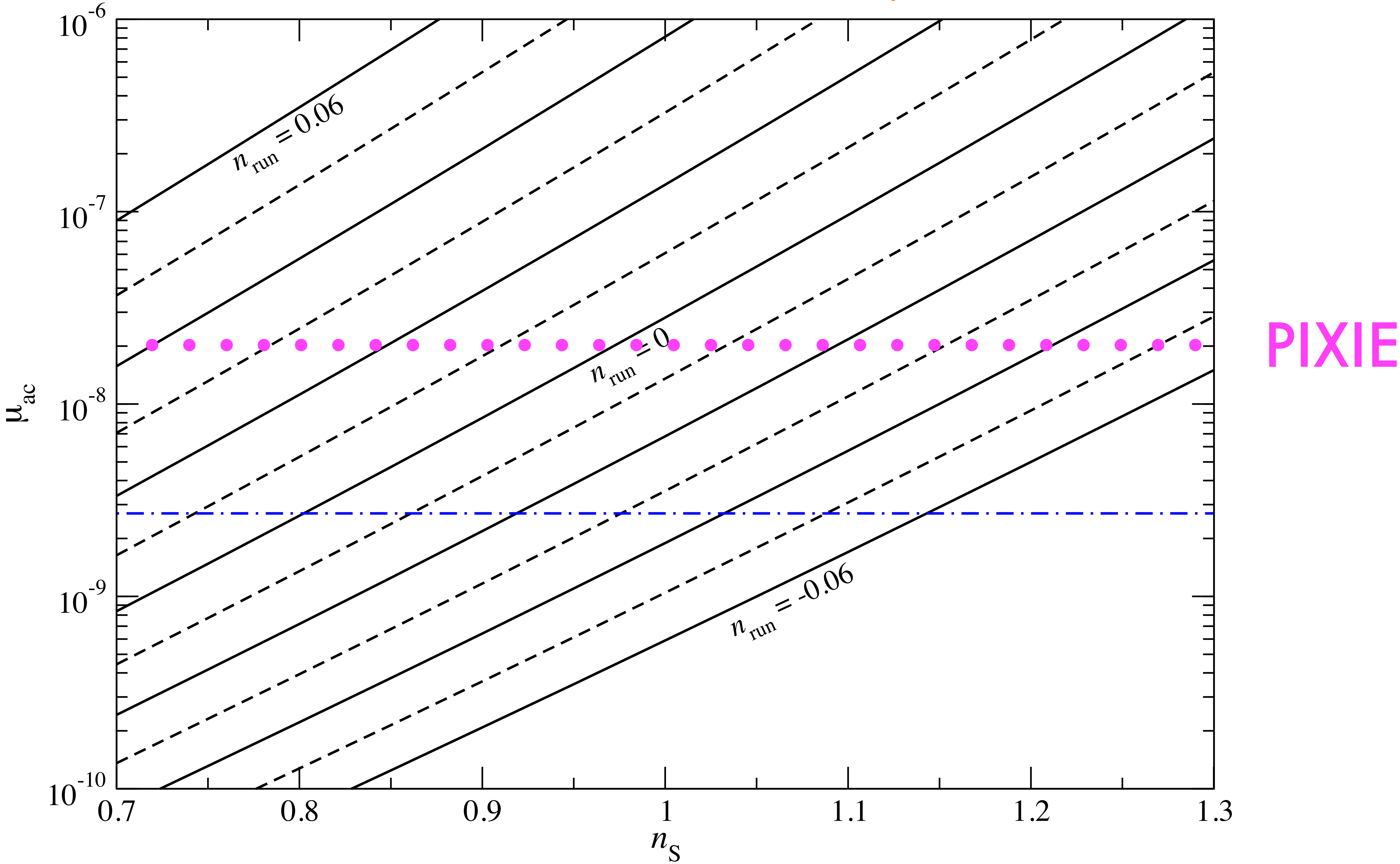
- ✳ CMB/LSS $0.01\ \mathrm{Mpc}^{-1} \ll k \ll 0.3\ \mathrm{Mpc}^{-1}$
- ✳ CMB $0.001\ \mathrm{Mpc}^{-1} \ll k \ll 0.2\ \mathrm{Mpc}^{-1}$
- ✳ Lyman-α forest $0.1\ \mathrm{Mpc}^{-1} \ll k \ll 10\ \mathrm{Mpc}^{-1}$
- ✳ 21-cm cosmology $0.01\ \mathrm{Mpc}^{-1} \ll k \ll 100\ \mathrm{Mpc}^{-1}$
- ✳ Y-distortions [but confusion from reionization!]

$$1\ \mathrm{Mpc}^{-1} \ll k \ll 50\ \mathrm{Mpc}^{-1}$$

- ✳ μ-distortions $50\ \mathrm{Mpc}^{-1} \ll k \ll 10^4\ \mathrm{Mpc}^{-1}$

SILK DAMPING AND DISTORTION FROM ADIABATIC MODES

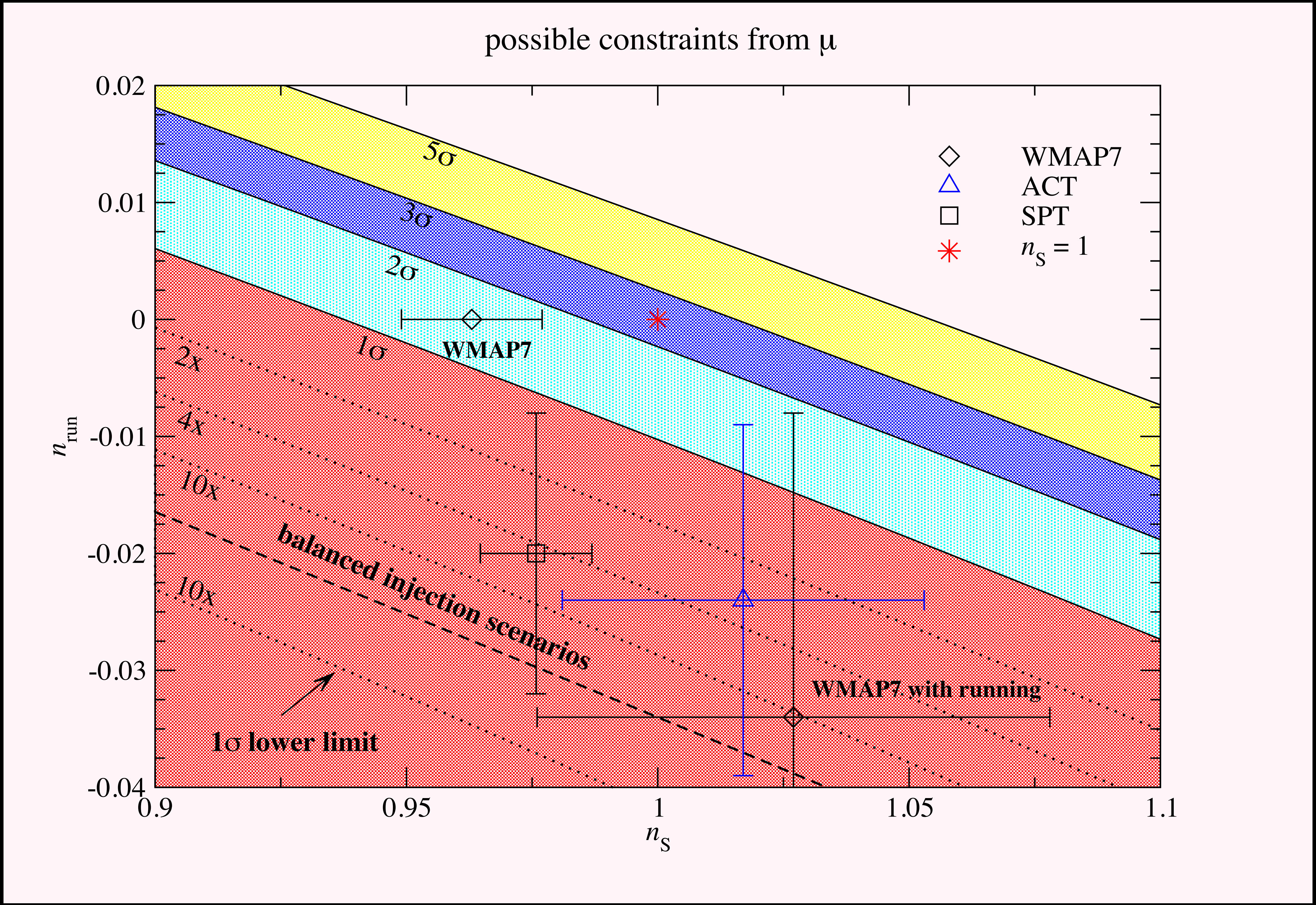
Nearly scale-invariant LCDM cosmology → $\mu \sim 2 \times 10^{-8}$



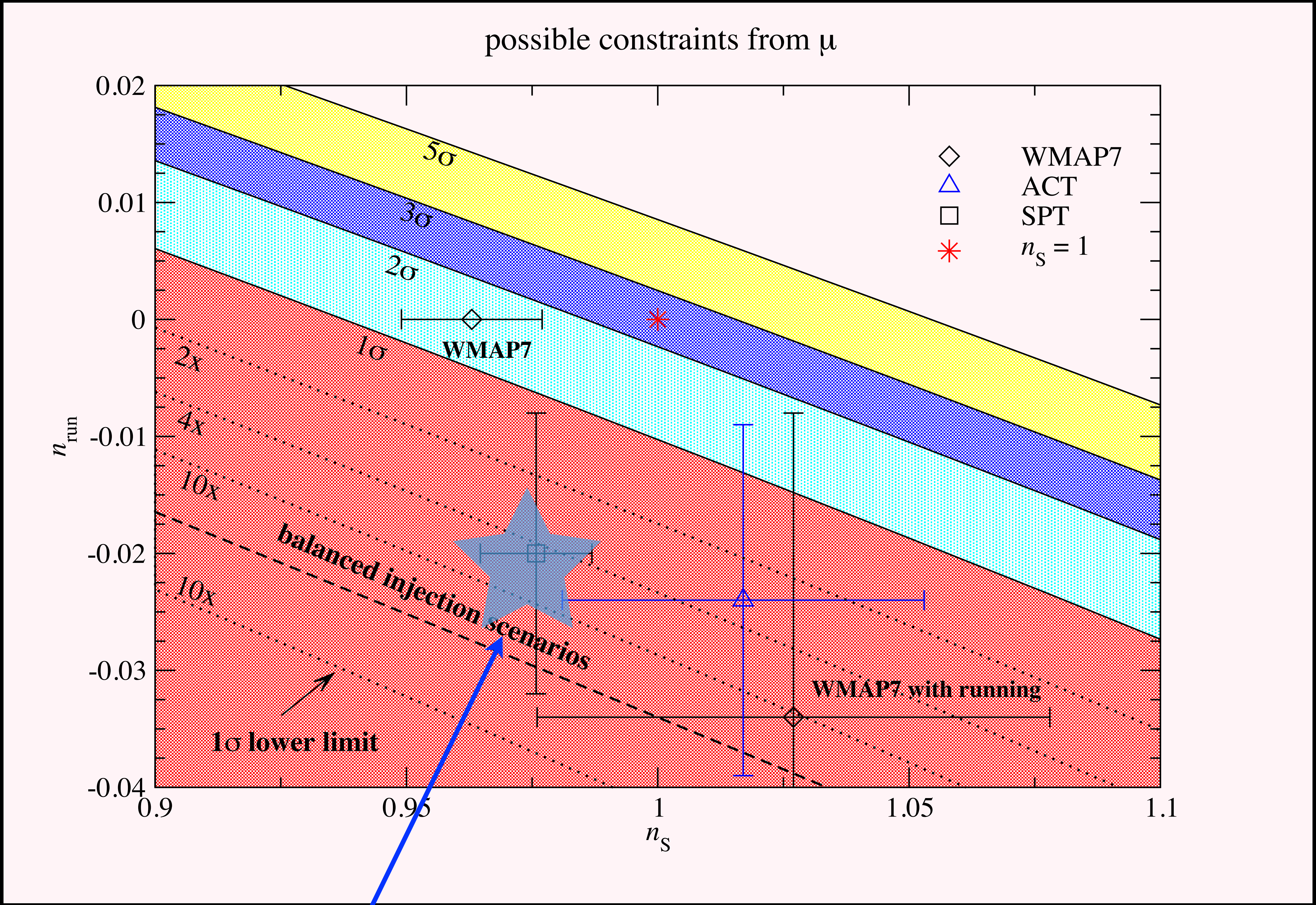
ADIABATIC COOLING

From Chluba 2012

Details of spectrum matter!



Details of spectrum matter!



BICEP+PLANCK?

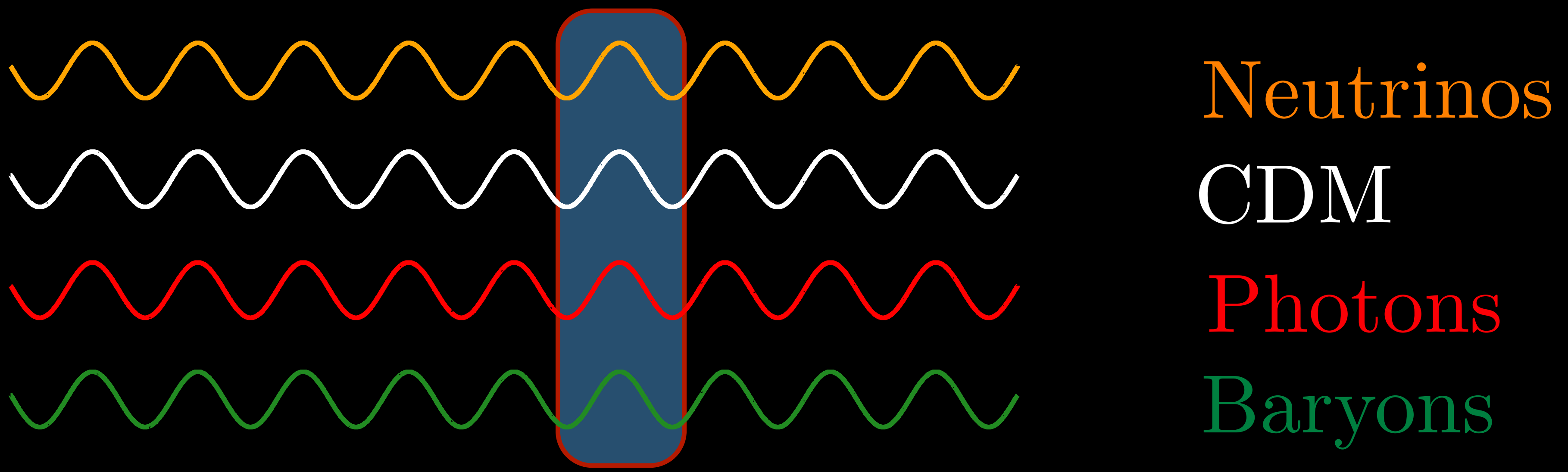
Spectral distortions from primordial isocurvature

with J.Chluba

arXiv:1304.4596, MNRAS 434, 1619

Zoology of initial conditions

Adiabatic



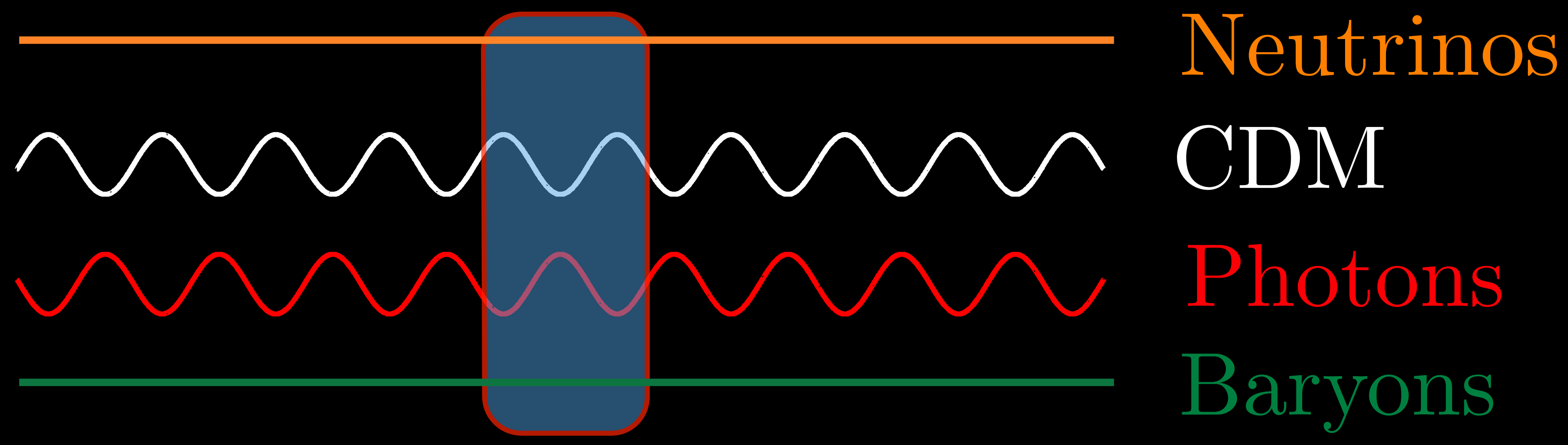
$$\Delta\Phi \neq 0$$

$$S_i = 0$$

$$S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}$$

Zoology of initial conditions

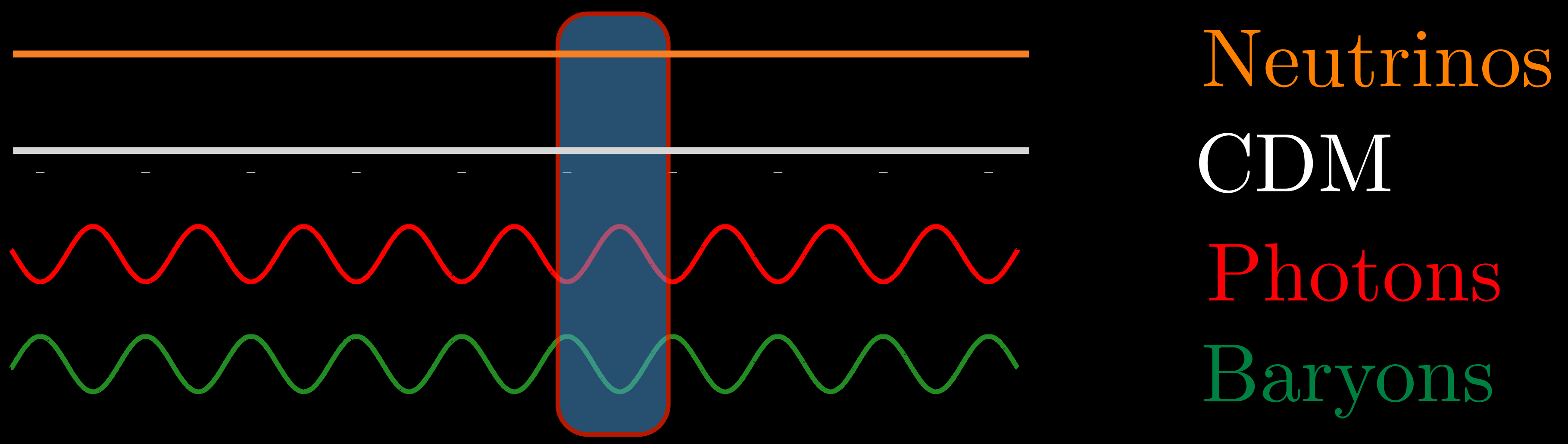
CDM
isocurvature



$$S_c \neq 0 \;\; \Delta\Phi = 0$$

Zoology of initial conditions

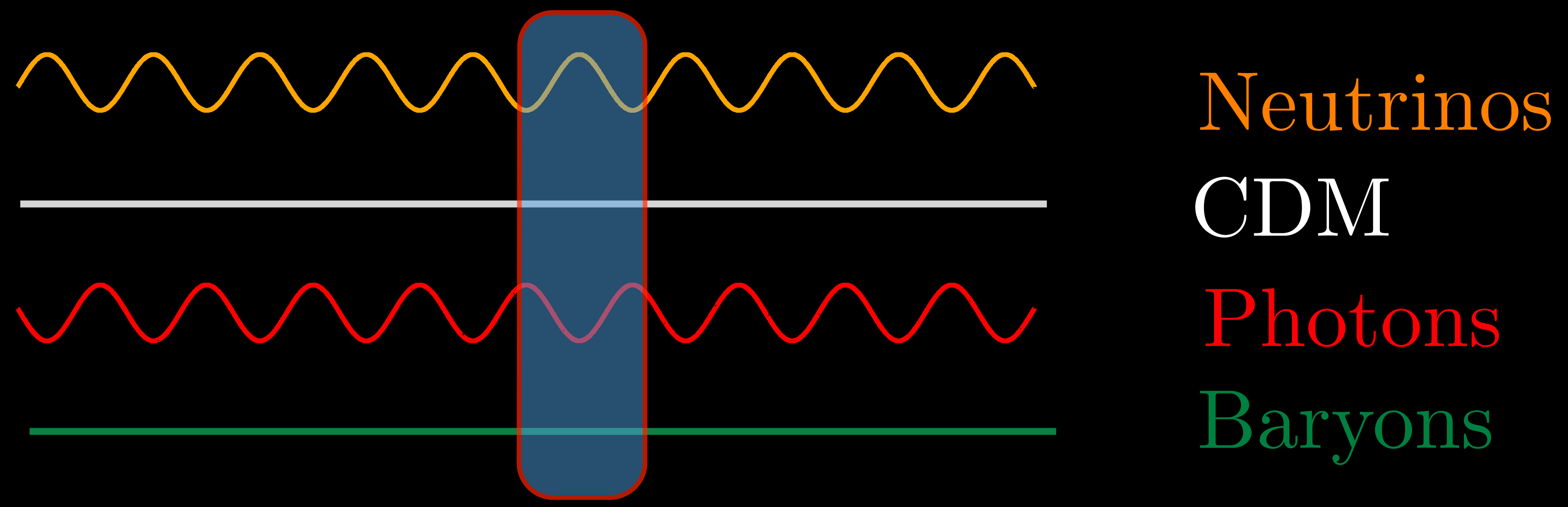
Baryon isocurvature



$$S_b \neq 0 \ \Delta\Phi = 0$$

Zoology of initial conditions

ν
isocurvature

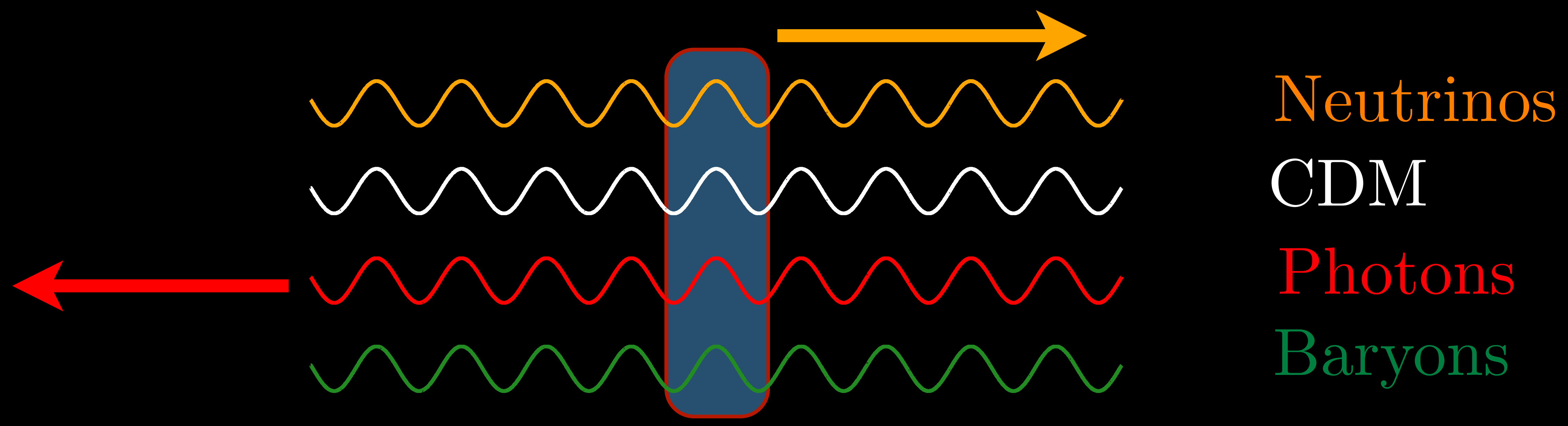


$$S_\nu \neq 0 \quad \Delta\Phi = 0$$

Velocity isocurvature modes

Example:

ν velocity isocurvature

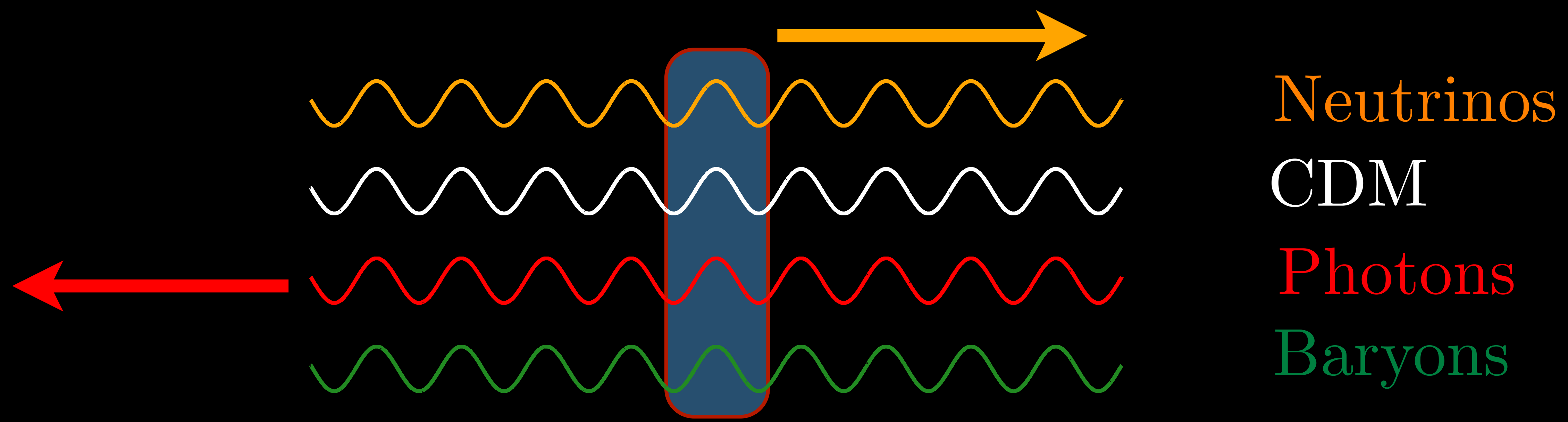


Momentum density also gravitates!

Velocity isocurvature modes

Example:

ν velocity isocurvature



Momentum density also gravitates!

All density initial conditions can be expressed in terms of these!
These conditions are not conserved under fluid evolution

TWO FLAVORS OF CDM ISOCURVATURE

- Axion-type isocurvature: S_c uncorrelated with ζ

  Axion exists, fluctuates, $\rho_{\mathrm{axion}} \ll \rho_{\mathrm{inflaton}}$

- Curvaton-type isocurvature: S_c correlated with ζ
  - Curvaton dominates after inflation, seeds adiabatic ζ
  - Baryons/CDM produced before ζ growth complete: isocurvature from mismatch

CURVATON MODELS AND ISOCURVATURE

- Hard for an inflationary model to do everything you want

$$\frac{k^3 P_{\mathcal{R}}(k)}{2\pi^2} = \frac{H_k^2}{8\pi^2 M_{\rm pl}^2 \epsilon} \qquad \epsilon = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2$$

- Instead, have a spectator σ (curvaton) that briefly dominates after inflation
- Sources entropy fluctuation in species that are generated before curvaton dom.

$$S_{\rm c} = \delta_{\rm c} - \frac{3}{4}\delta_{\rm rad} = -\frac{3}{4}\delta_{\rm rad}$$

- Curvaton dominates, decays, adiabatic (correlated with isocurvature) results

$$\zeta = \frac{\rho_\sigma}{3\rho_{\rm tot}}\delta_\sigma$$

Axions carry isocurvature

- If PQ symmetry broken during/before inflation

$$\sqrt{\langle a^2 \rangle} = \frac{H_{\rm I}}{2\pi}$$

Quantum zero-point fluctuations!

- Subdominant species seed isocurvature fluctuations

$$\zeta \propto \frac{\rho_a}{\rho_{\rm tot}} \frac{\delta \rho_a}{\rho_a} \ll 10^{-5}$$

$$S_{a\gamma} = \frac{\delta n_a}{n_a} - \frac{\delta n_\gamma}{n_\gamma} = \frac{\delta \rho_a}{\rho_a} - \frac{3}{4} \frac{\delta \rho_\gamma}{\rho_\gamma} \sim 10^{-5}$$

- WMAP 7-year constraints (Komatsu/Larson et al 2010)

$$P_{\mathrm{S_c}}^{\mathrm{axion}}/P_\zeta \lesssim 0.13 \qquad P_{\mathrm{S_c}}^{\mathrm{curvaton}}/P_\zeta \lesssim 0.01$$

✳ WMAP 7-year constraints (Komatsu/Larson et al 2010)

$$P_{S_c}^{\rm axion}/P_\zeta \lesssim 0.13 \qquad P_{S_c}^{\rm curvaton}/P_\zeta \lesssim 0.01$$

✳ Constraints relax if assumptions (scale-invariance, single isocurvature mode) relaxed: Bean et al. 2009

r_{iso}	CI	NID	NIV
	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$
	< 0.13	< 0.08	< 0.14

→

CI+NID+NIV	No BBN/bias
0.44 ± 0.09	0.51 ± 0.09

✳ Planck 1st-year temperature constraints (Et al *et al*..., 2013)

$$4.6 \times 10^{-3} \lesssim \frac{P_{\rm iso}}{P_{\rm tot}} \lesssim 1.6 \times 10^{-2}$$

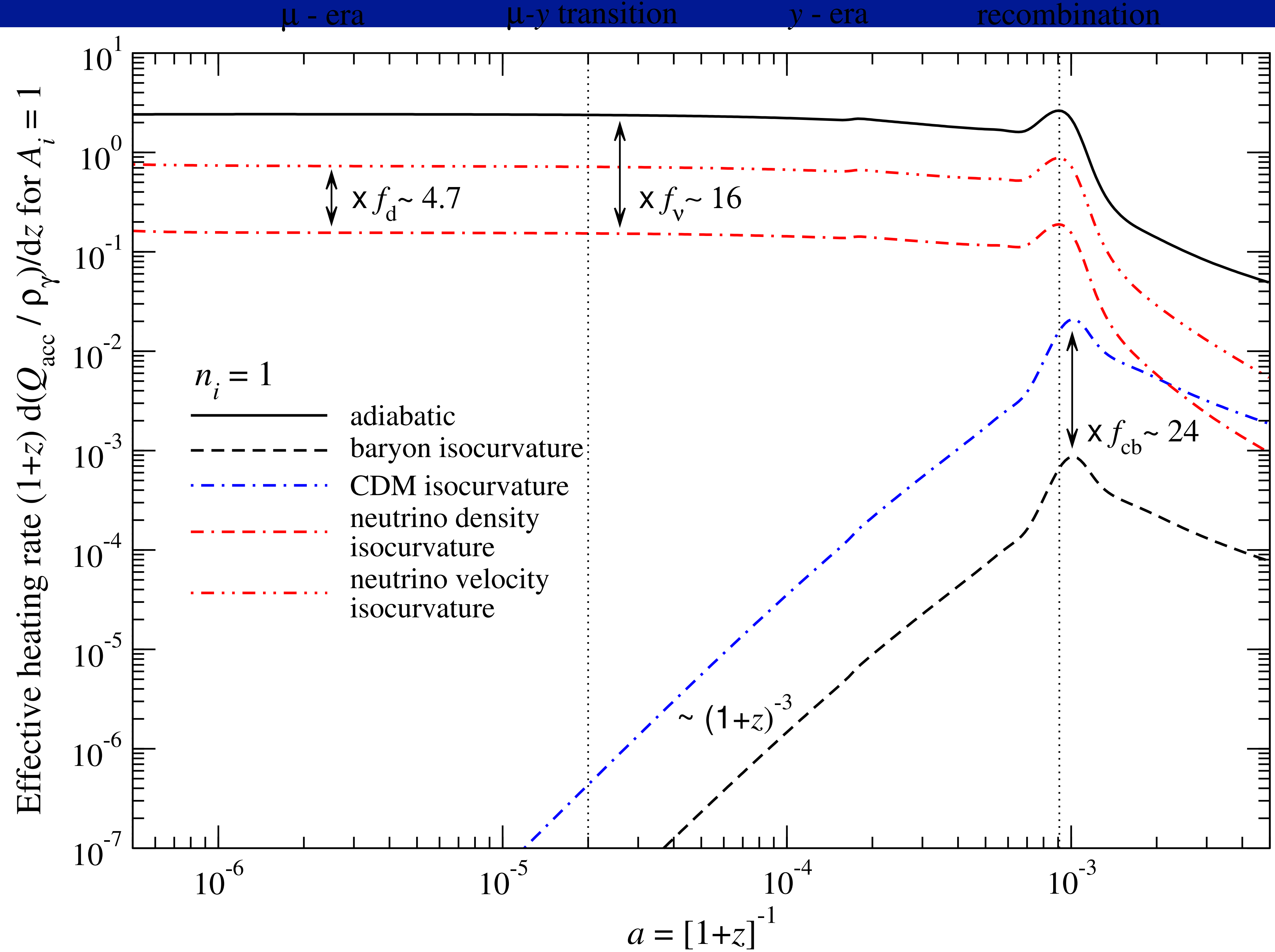
✳ Constraints relax if assumptions (scale-invariance, single isocurvature mode) relaxed: Bean et al. 2009

	CI	NID	NIV
r_{iso}	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$
	< 0.13	< 0.08	< 0.14

→

CI+NID+NIV	No BBN/bias
0.44 ± 0.09	0.51 ± 0.09

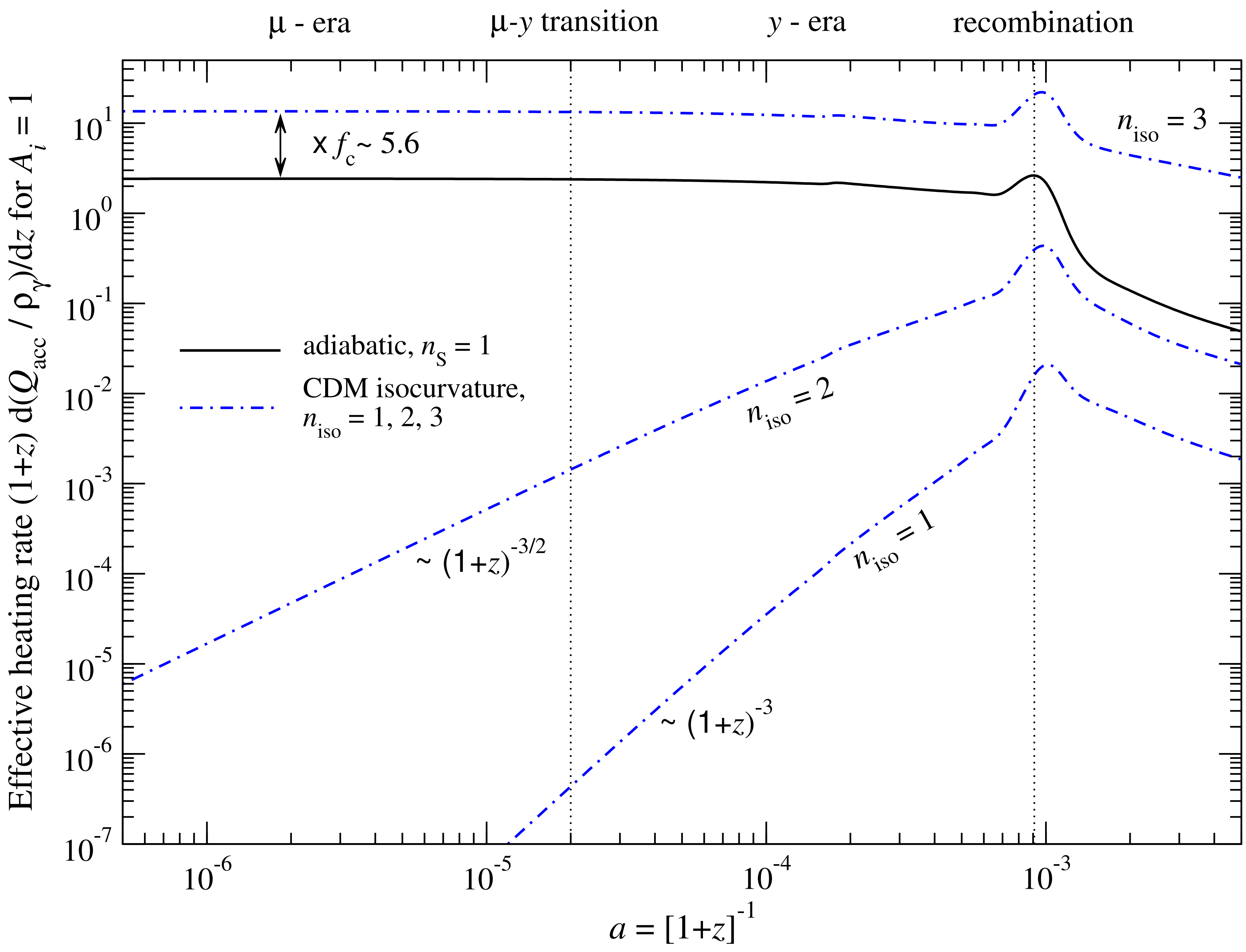
HEATING AND DISTORTION FROM ALTERNATE INITIAL CONDITIONS



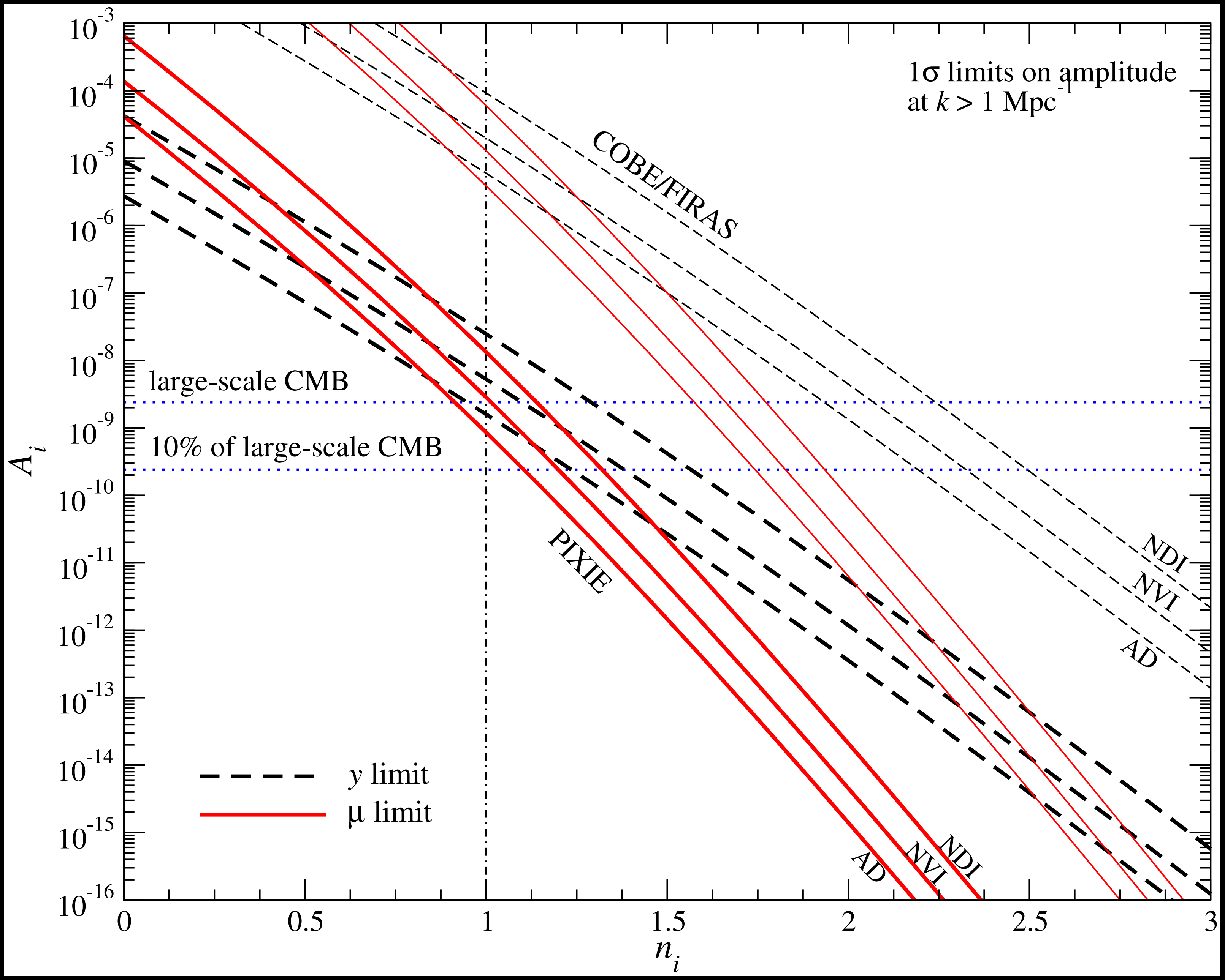
Isocurvature in relativistic species yields more energy injection during μ-era

Isocurvature in non-relativistic species less suppressed during matter domination

RESULTS DEPEND ON POWER SPECTRUM OF ISOCURVATURE MODES



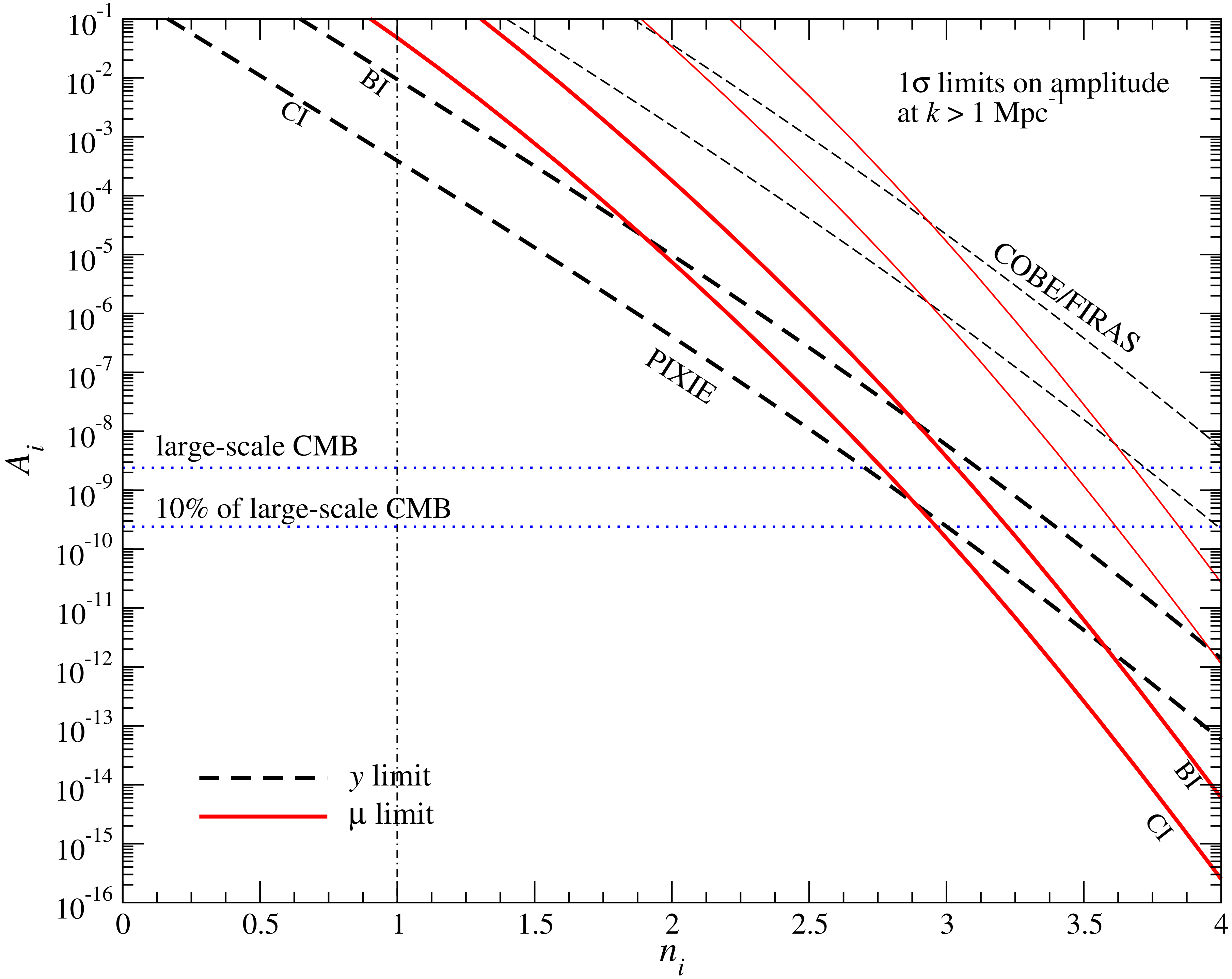
Distortions probe spectral slope and/or initial conditions of primordial fluctuations



$$\mu \leq 10^{-8}$$
$$y \leq 2 \times 10^{-9}$$

→ PIXIE SENSITIVITY

Distortions probe spectral slope and/or initial conditions of primordial fluctuations



Small field models

* Small-field inflationary models with non-monotonic $\left(\frac{V'}{V}\right)^2$ (Ben-Dayan/Brustein 2010) can evade Lyth Bound

$$\Delta\phi \geq m_{\rm pl}\sqrt{\frac{r}{4\pi}}$$

Experimentally relevant!

* Model predicts $\mu \sim 10^{-6}$ (Chluba/Erickcek/Ben-Dayan 2012)

Phase transitions and spectral distortions from scaling seeds

with M. Amin

arXiv: 1405.1039

Phase transitions and spectral distortions from scaling seeds

with M. Amin

arXiv: 1405.1039

Background on scaling seeds: Durrer et al. (Physics Reports 2001)
See work by Durrer, Kunz, Stebbins, Albrecht, Hu, White, Ferreira, Joyce, Melchiorri, Magueijo,Shellard

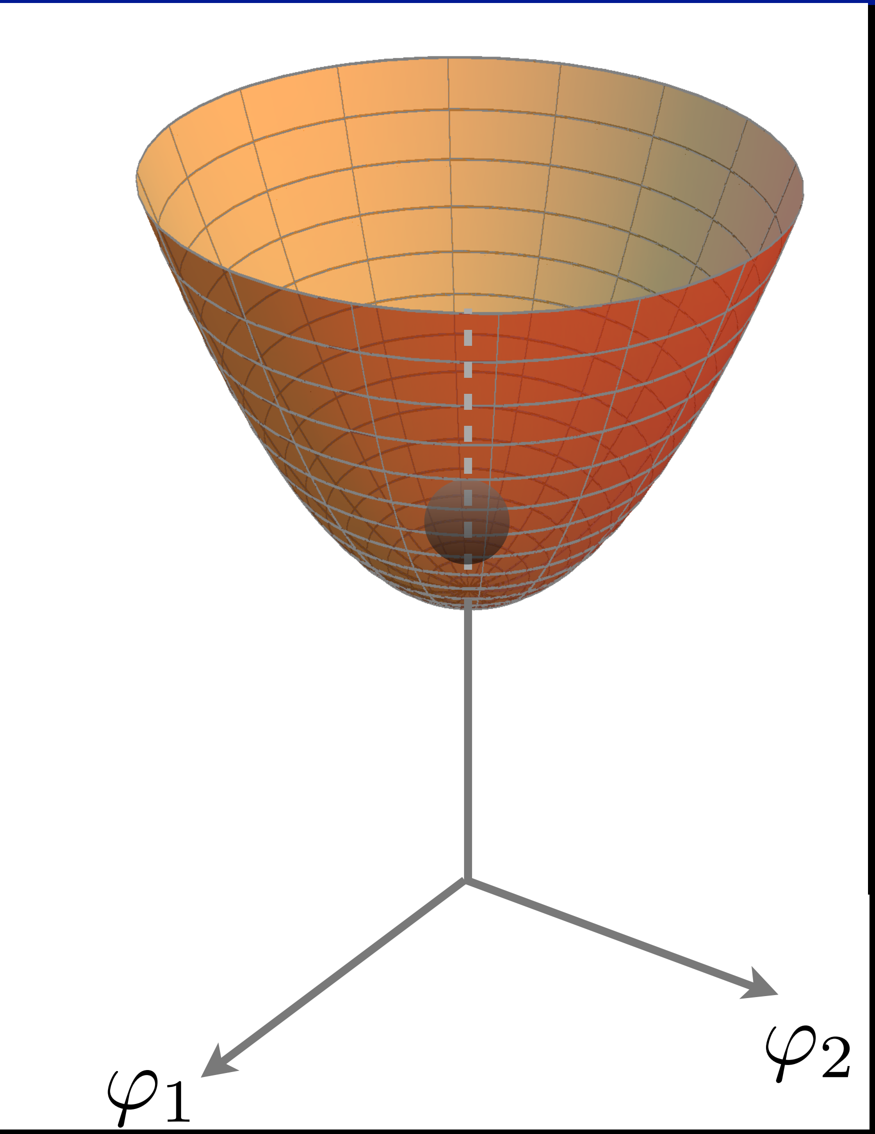
Phase transitions and spectral distortions from scaling seeds

with M. Amin

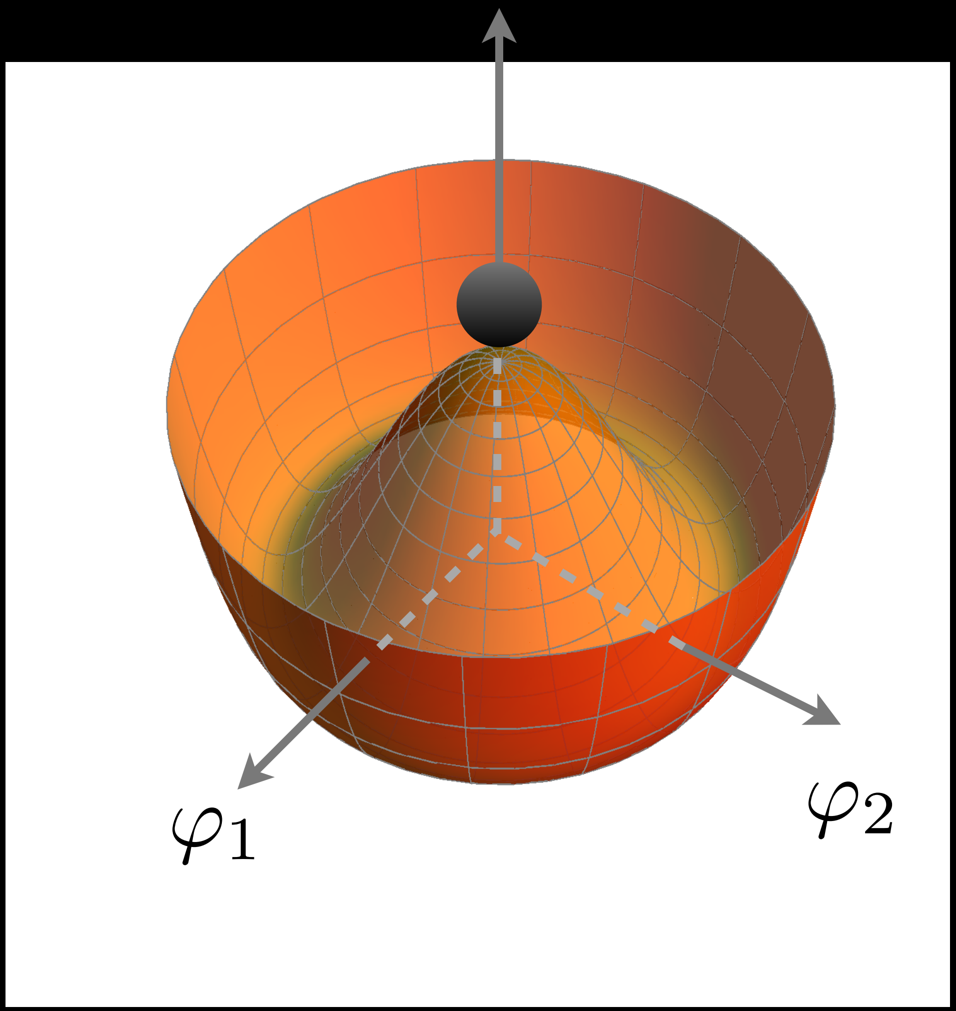
arXiv: 1405.1039

Phase transitions and spectral distortions

STABLE



UNSTABLE

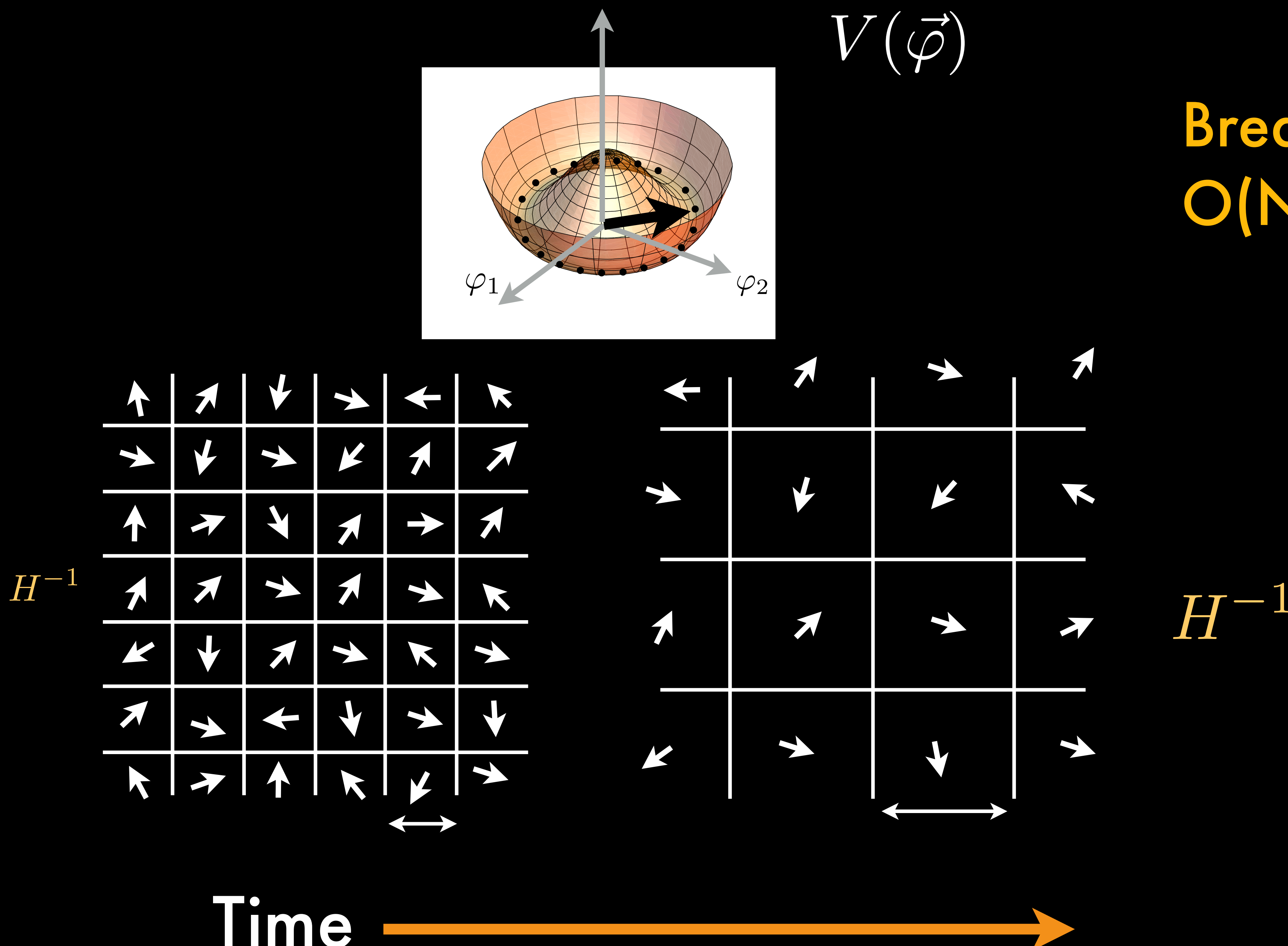


DECREASING TEMPERATURE →

Break a global O(N) symmetry

Scaling-seed network:

N>4 [otherwise, dangerous defects]



Break a global O(N) symmetry

Details: Non-linear source

- Back-reaction of metric on scaling seeds neglected
  - 'Stiff approximation': *Stebbins and Veeraraghavan 1996*
  - Field lives on vacuum manifold with free orientation

$$\sum_i |\phi_i|^2 = v^2 \qquad \Box\vec{\varphi} + \left(\frac{\partial^\mu\vec{\varphi}\cdot\partial_\mu\vec{\varphi}}{v^2}\right)\vec{\varphi} = 0$$

Details: Non-linear source

- Back-reaction of metric on scaling seeds neglected
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  - Field lives on vacuum manifold with free orientation

$$\sum_i |\phi_i|^2 = v^2$$

$$\Box\vec{\varphi} + \left(\frac{\partial^\mu\vec{\varphi}\cdot\partial_\mu\vec{\varphi}}{v^2}\right)\vec{\varphi} = 0$$

$$\text{spatial average} = \frac{C}{\eta^2}$$

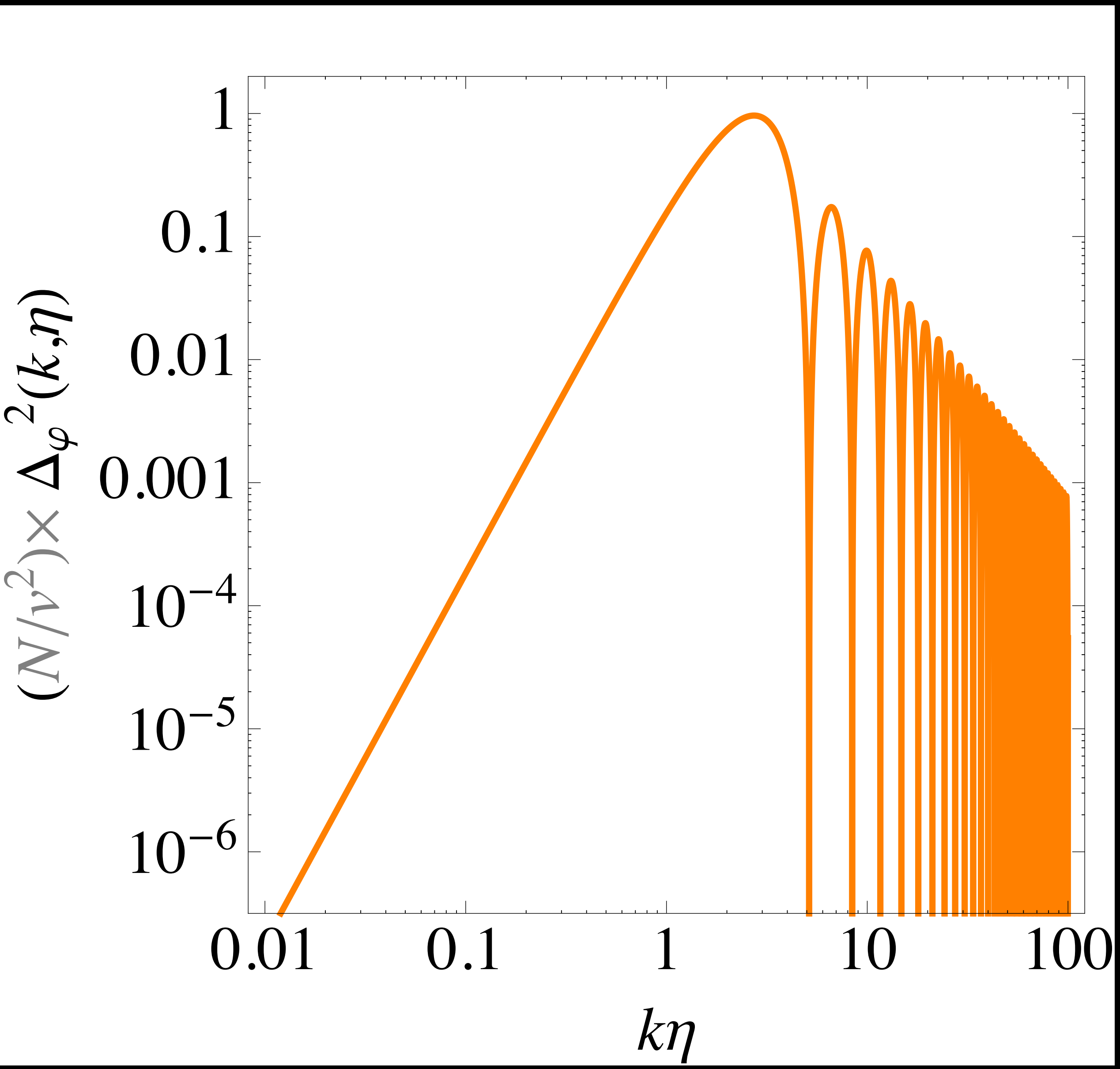
Details: Non-linear source

- Back-reaction of metric on scaling seeds neglected
  - 'Stiff approximation': *Stebbins and Veeraraghavan 1996*
  - Field lives on vacuum manifold with free orientation

$$\sum_i |\phi_i|^2 = v^2 \qquad\qquad \Box\vec{\varphi} + \left(\frac{\partial^\mu \vec{\varphi}\cdot\partial_\mu\vec{\varphi}}{v^2}\right)\vec{\varphi} = 0$$

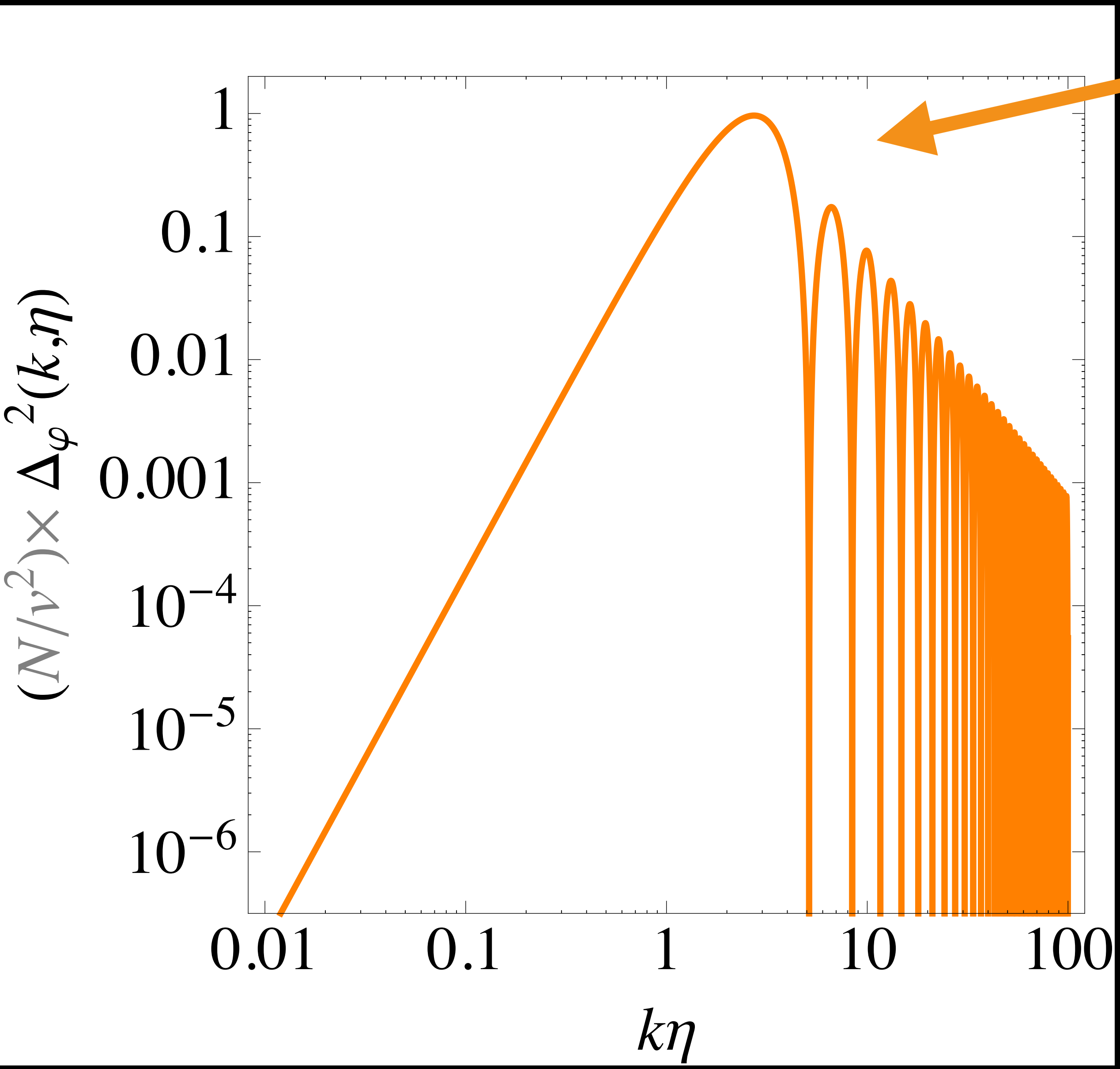
- Scaling *ansatz*- simulations and analytic arguments show adequacy in large-N limit

Seed-correlation power-spectrum



Seed-correlation power-spectrum

Maximal fluctuation on horizon scale



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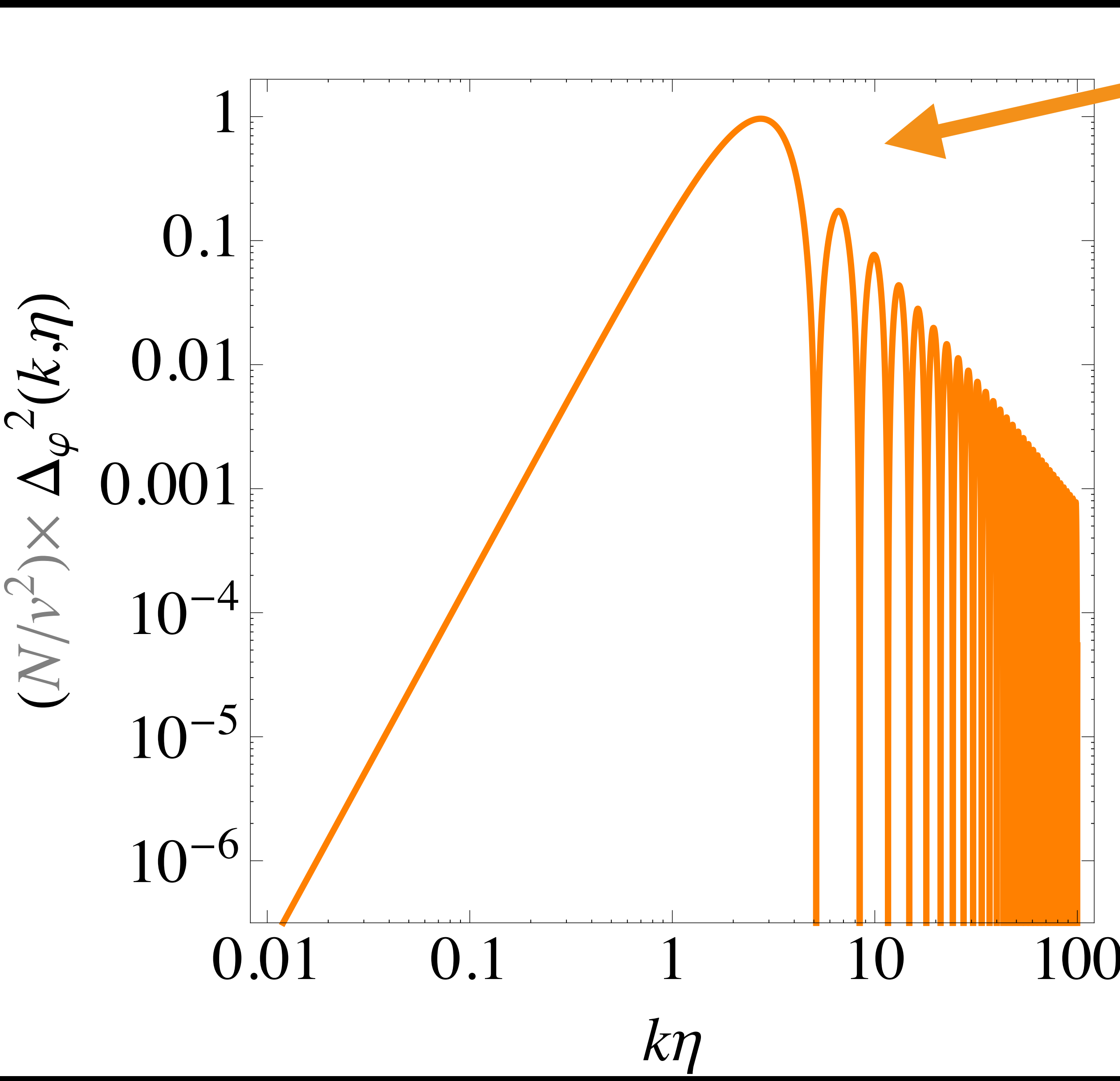
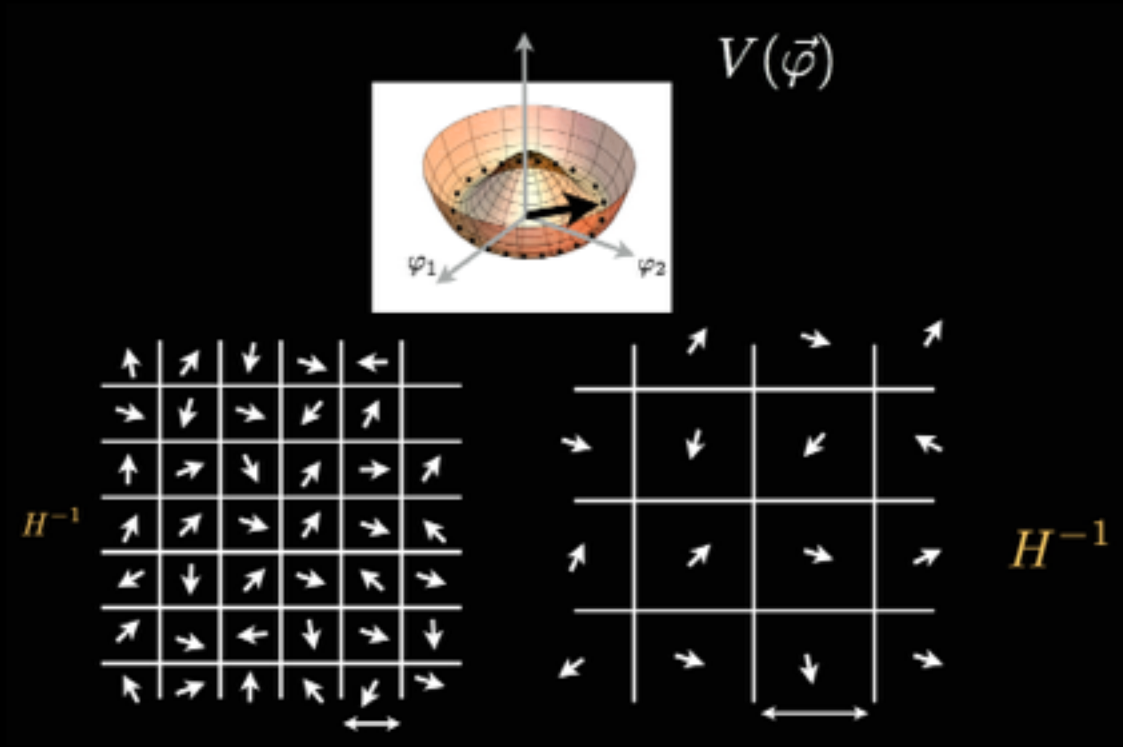


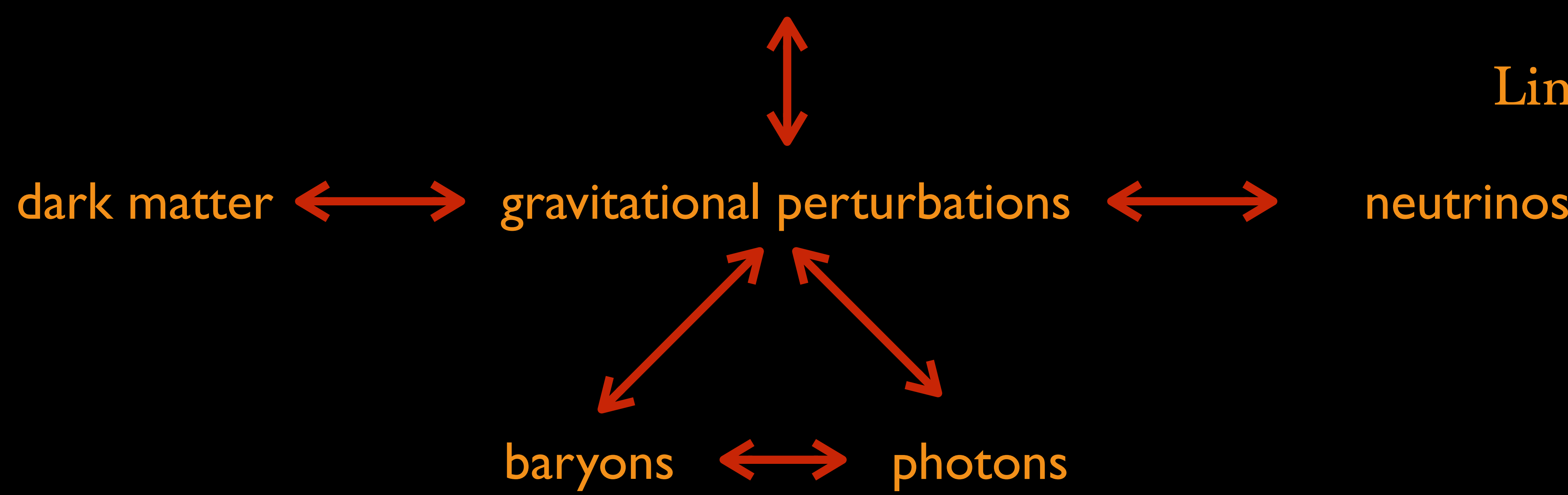
Compute gravitational potential fluctuations

System to follow

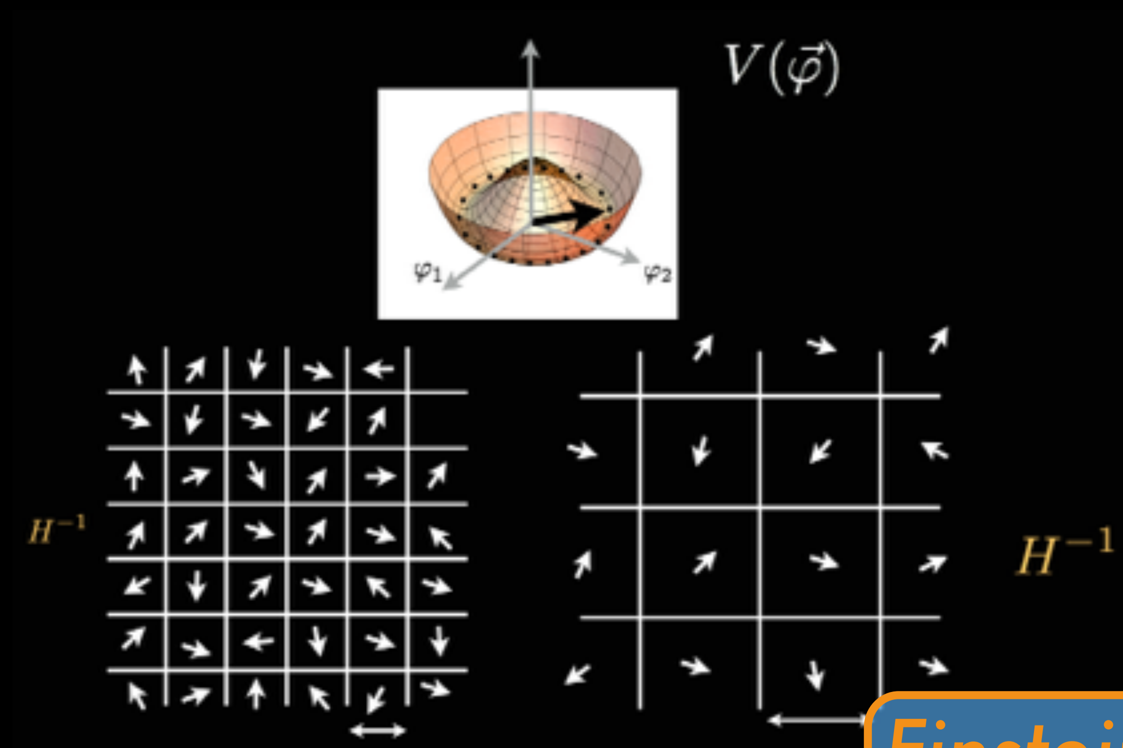


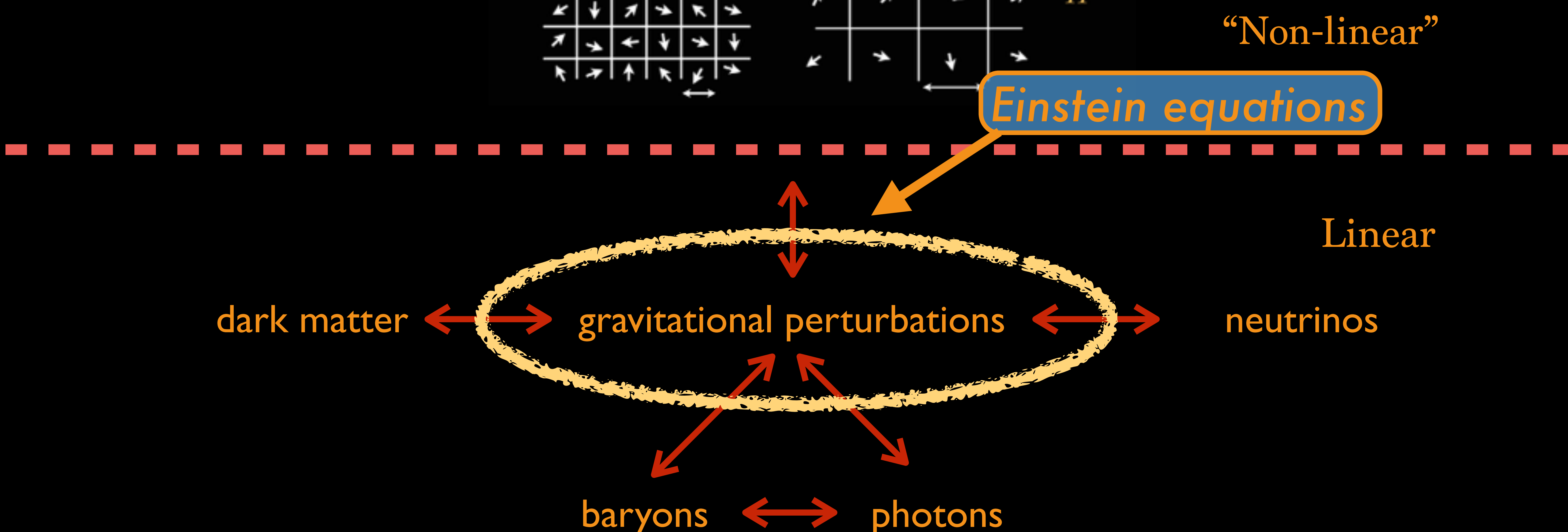
"Non-linear"

Linear



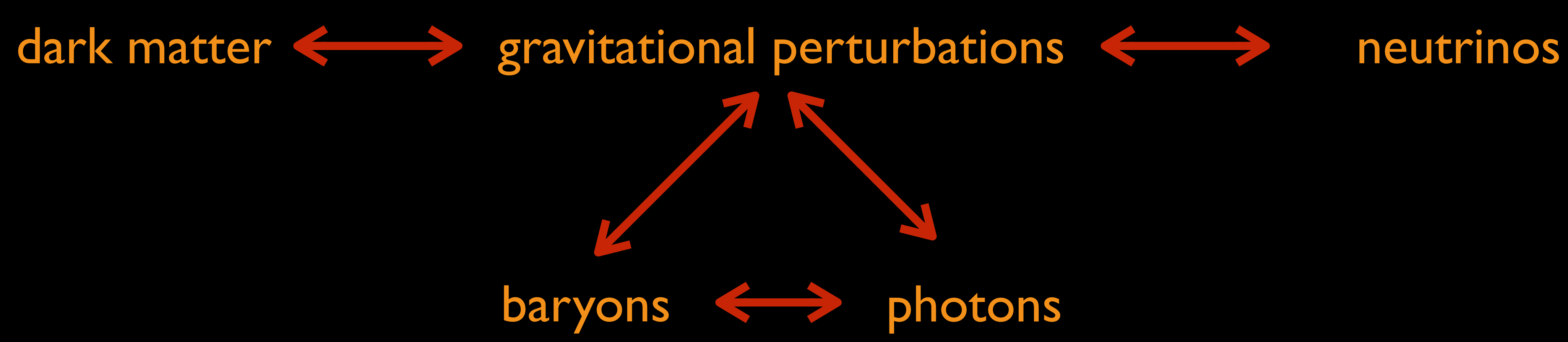
System to follow



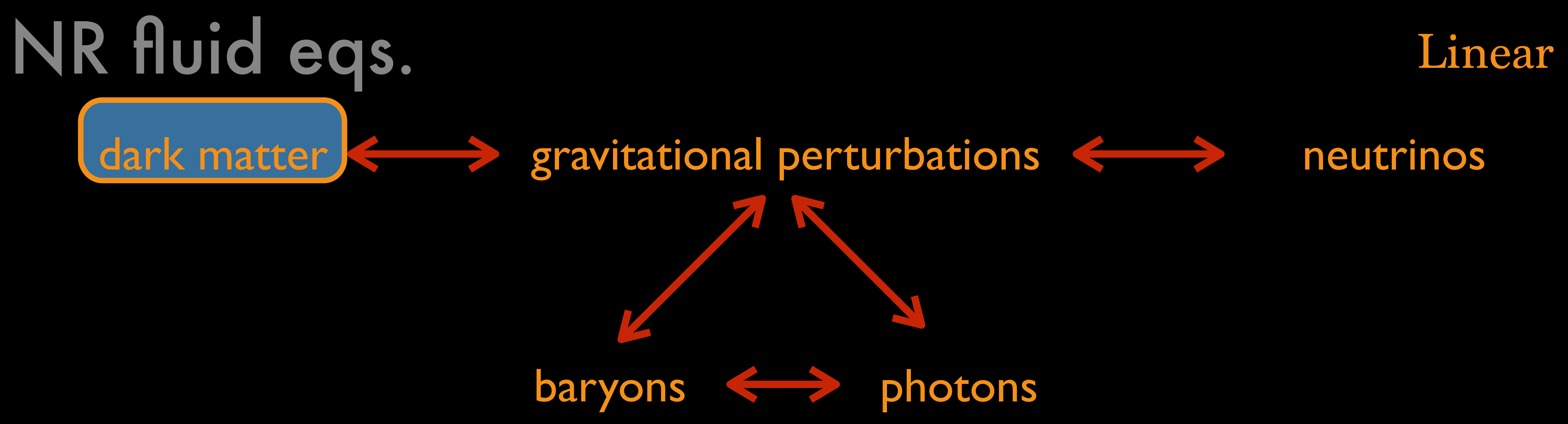


System to follow

Linear

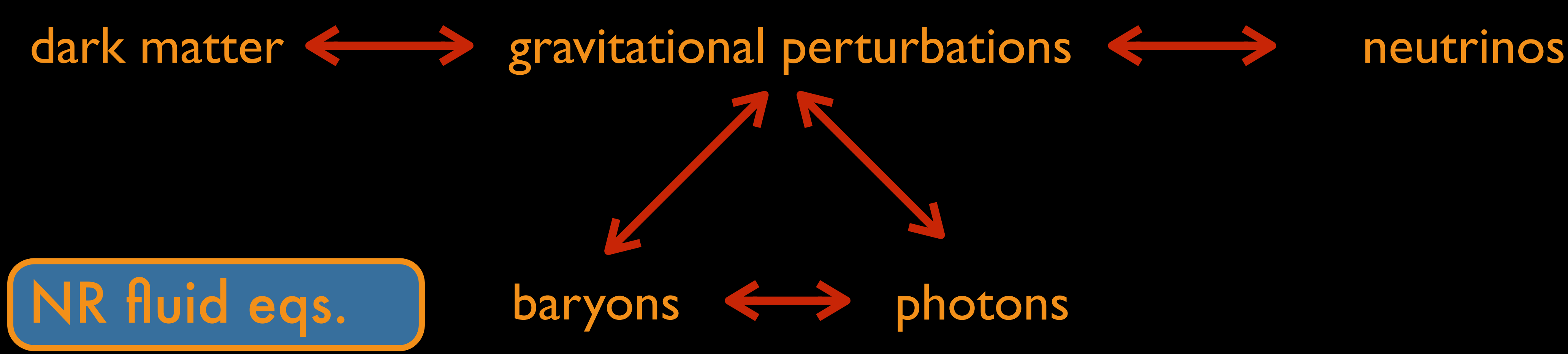


System to follow

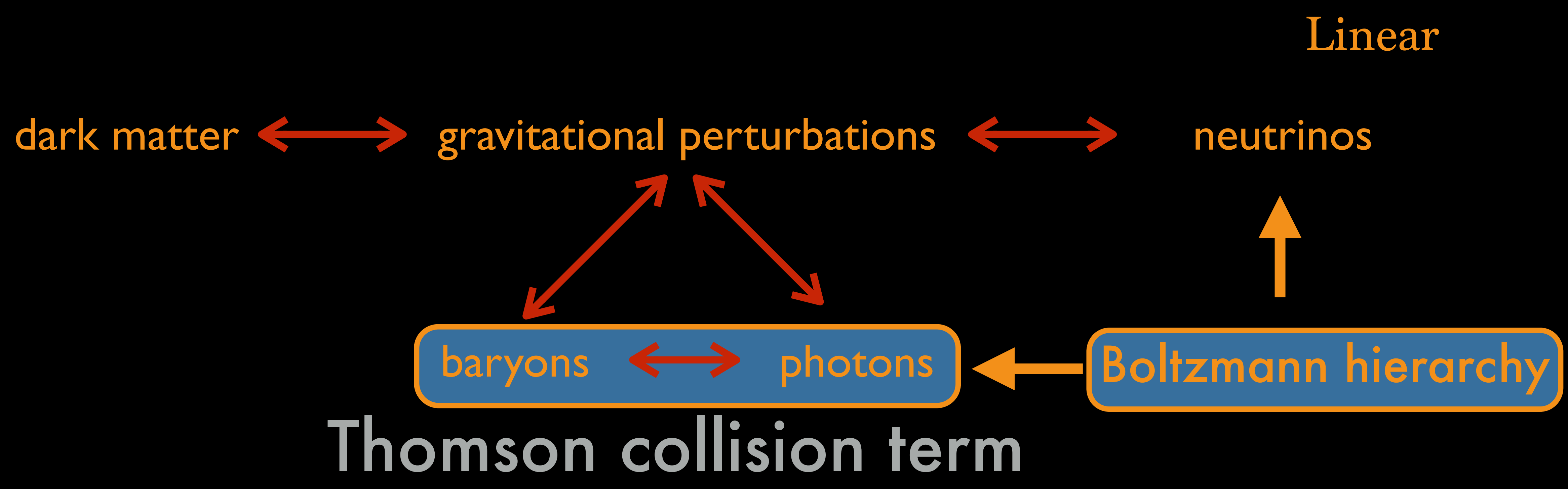


System to follow

Linear



System to follow

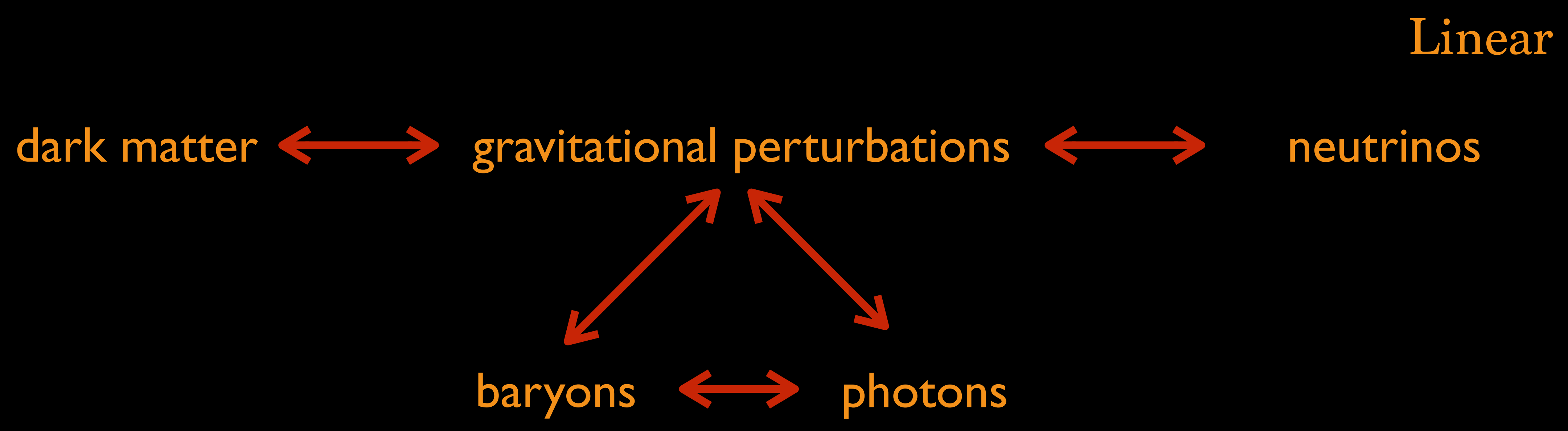


System to follow

as in Hu/White
astro-ph:9702120

l=1,2 for photons
l=1-12 for neutrinos

CN gauge



System to follow

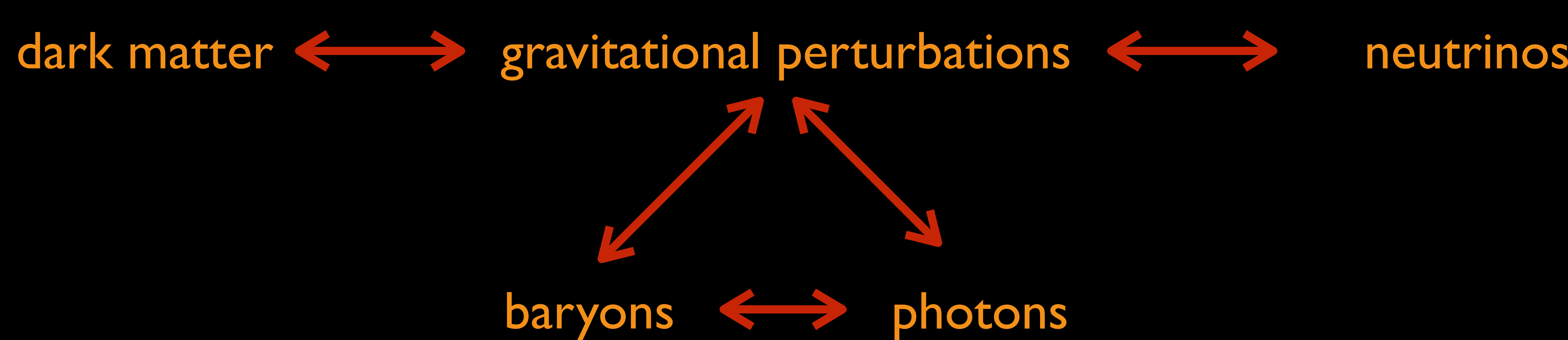
as in Hu/White
astro-ph:9702120

l=1,2 for photons
l=1-12 for neutrinos

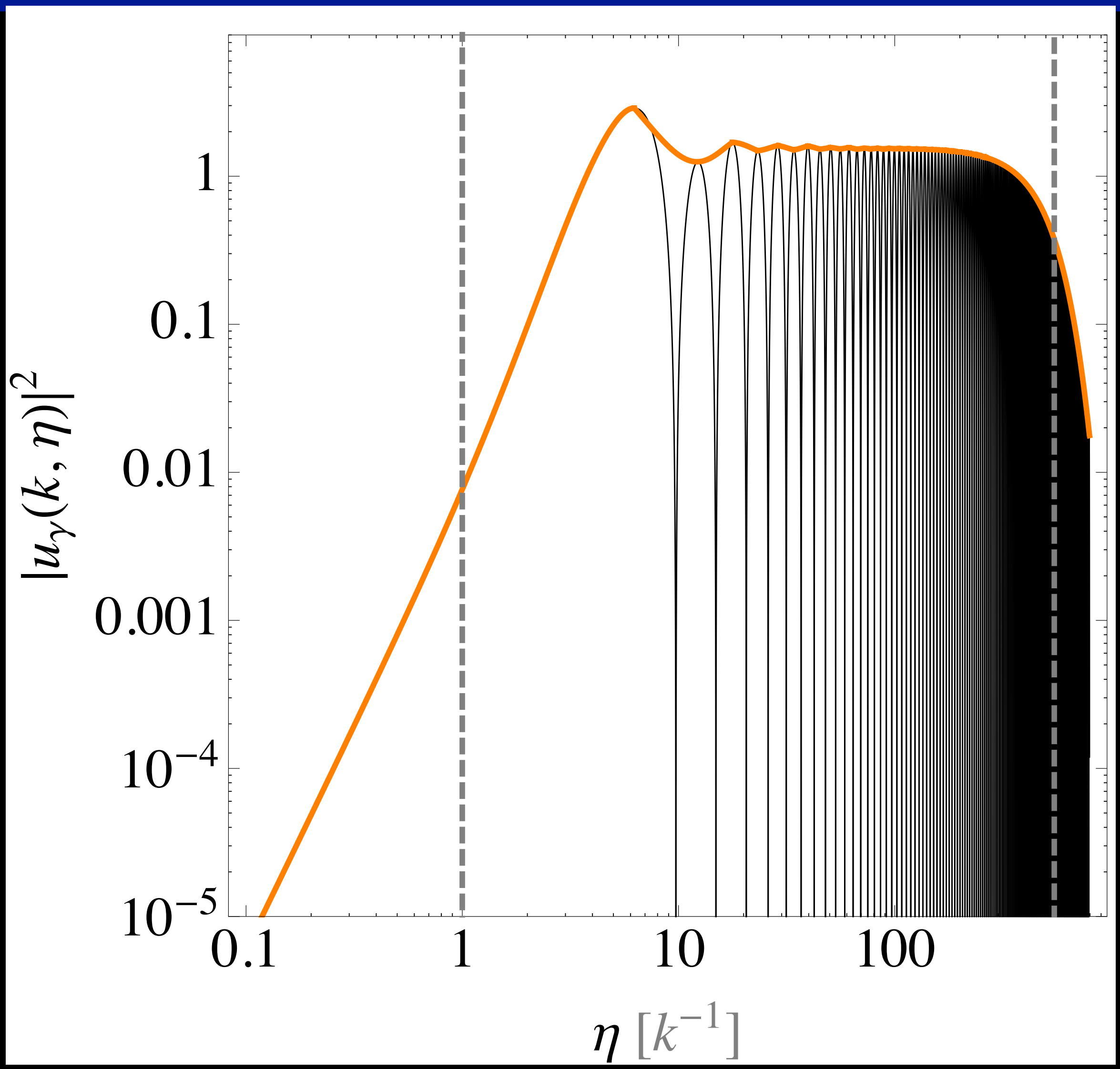
CN gauge

$$\epsilon \equiv \frac{k}{\dot{\tau}} \ll 1 \longrightarrow \begin{array}{c} k \ll k_{\rm mfp}, \\ \text{Can have } k \sim k_{\rm D} \end{array}$$

Linear



Seeds drive baryon-photon plasma sound waves



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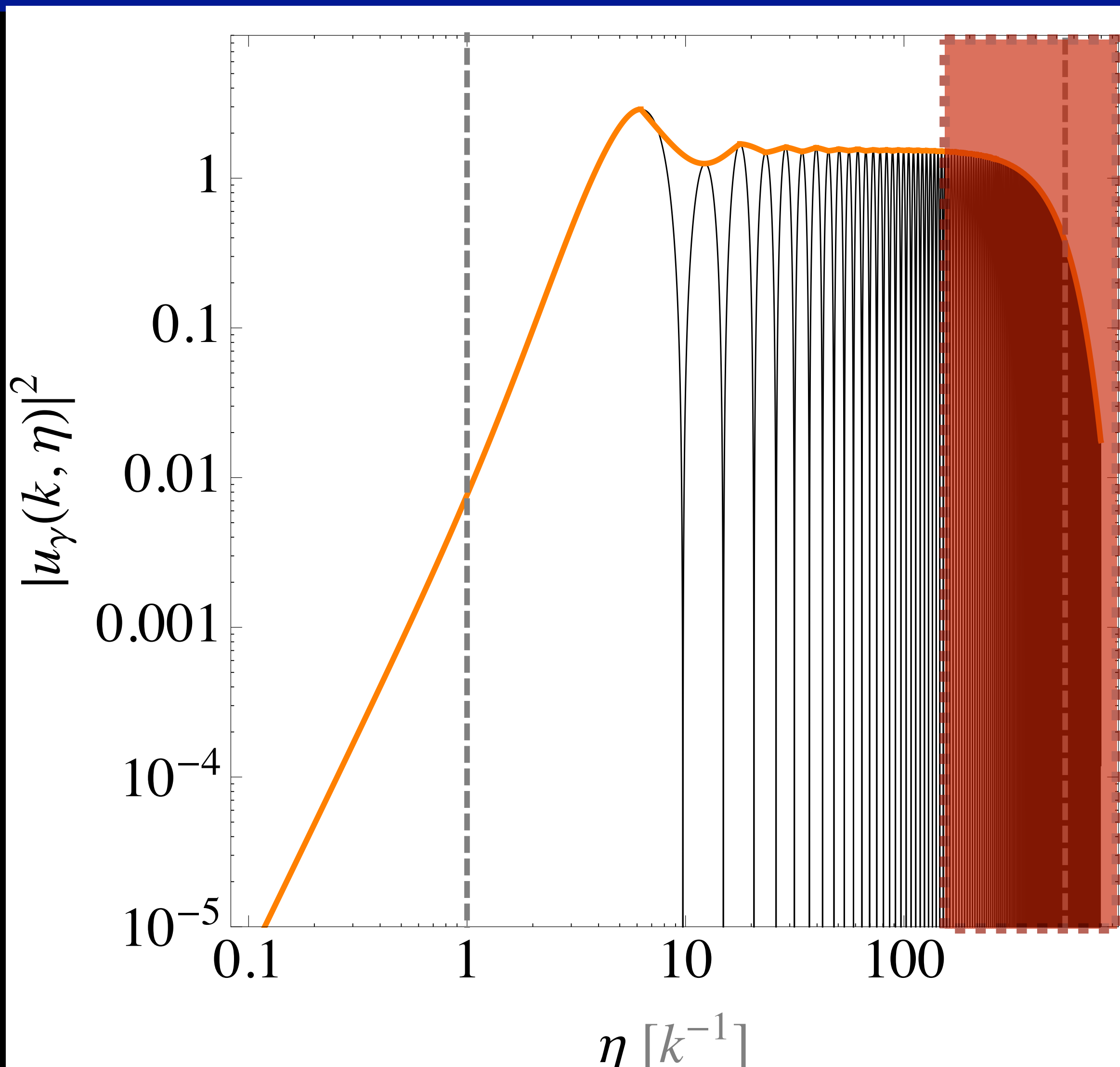
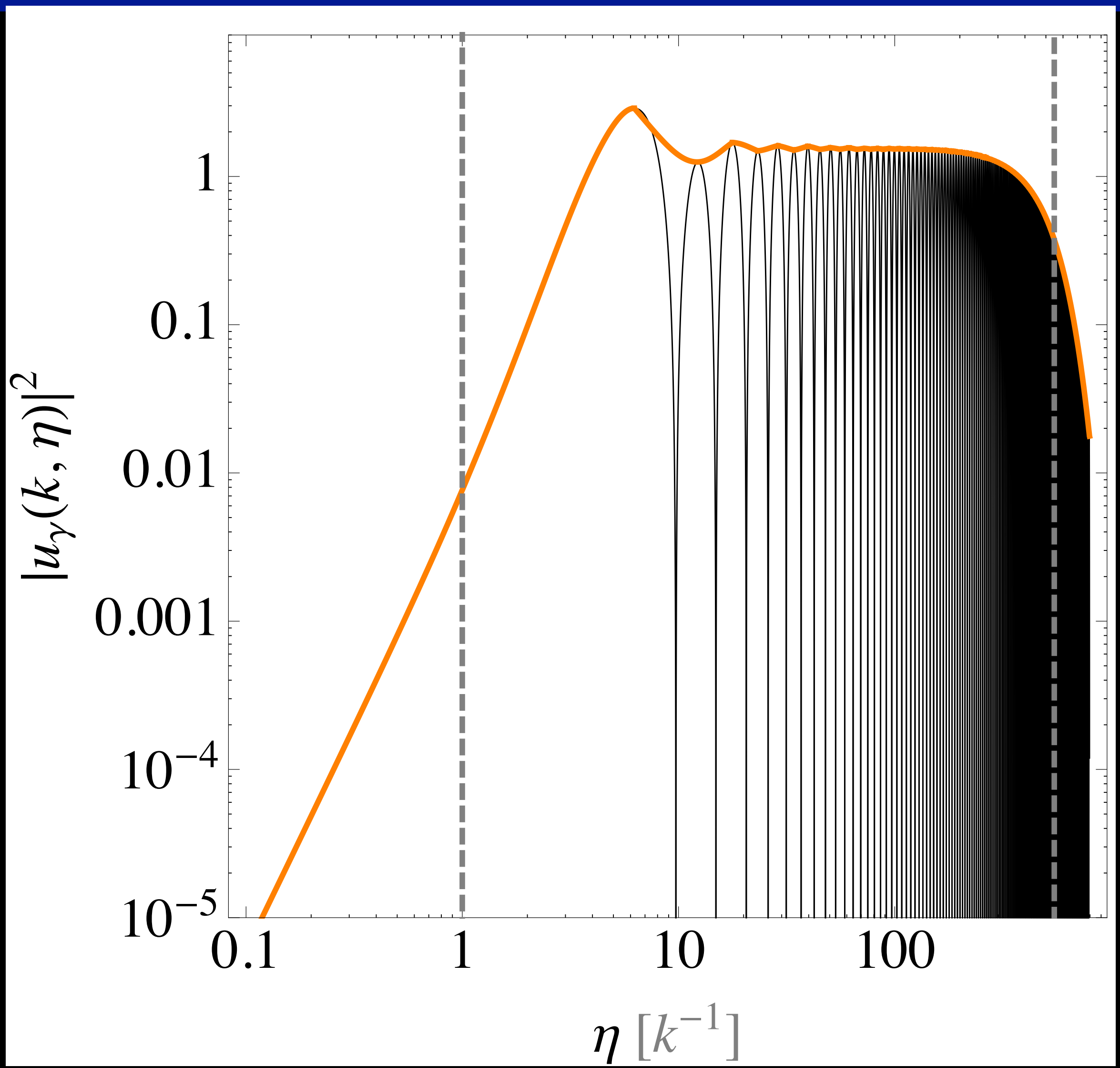


$$\delta_\gamma \sim \frac{1}{\sqrt{N}} \frac{v^2}{m_{\rm pl}^2} e^{-k^2/k_D^2}$$

Seeds drive baryon-photon plasma sound waves

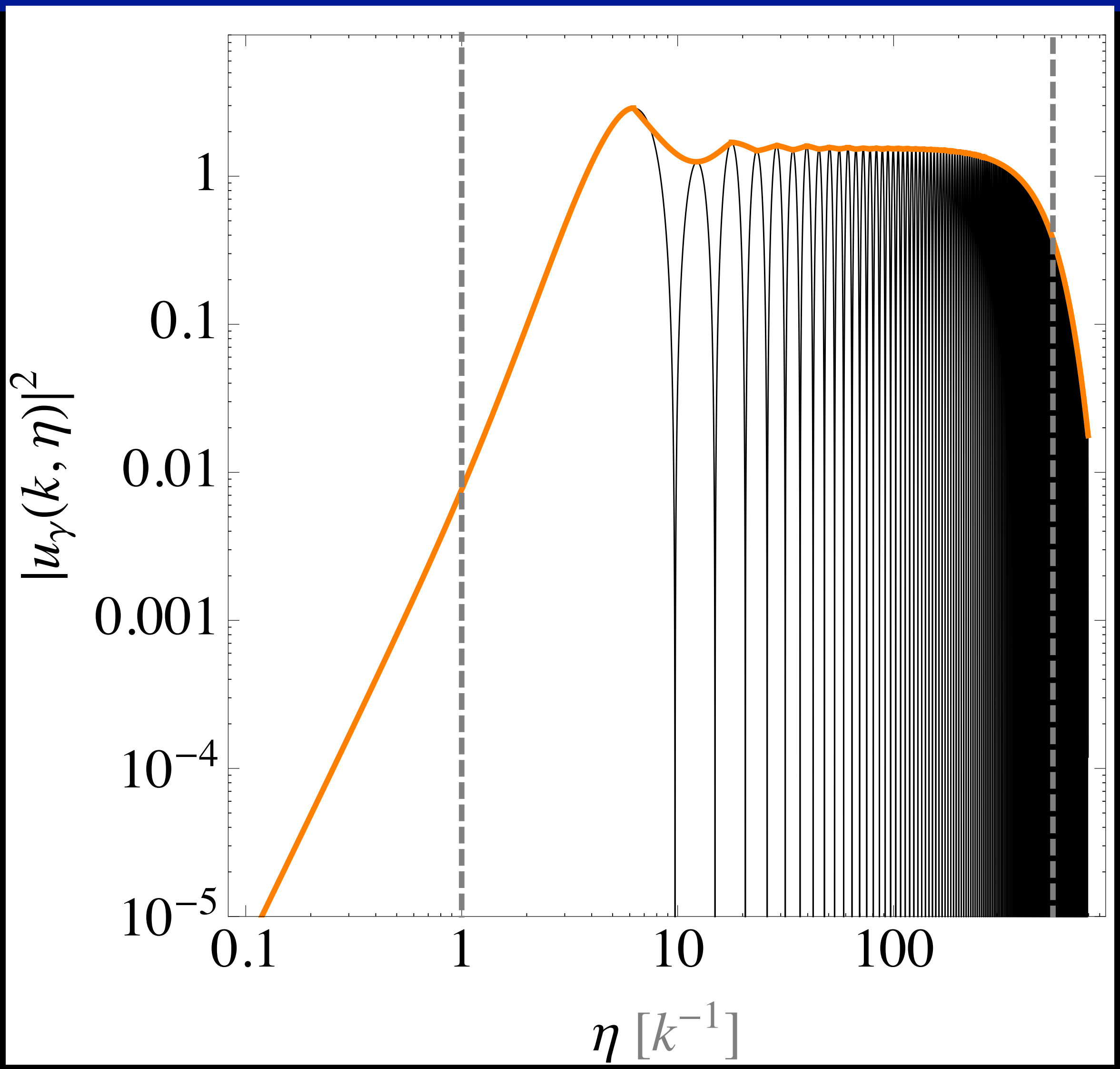


$$\mu \simeq 12 \times \frac{1}{N}\left(\frac{v}{m_{\rm pl}}\right)^4$$

Saturating Planck constraints

$$\mu \sim 3 \times 10^{-9}$$

Seeds drive baryon-photon plasma sound waves



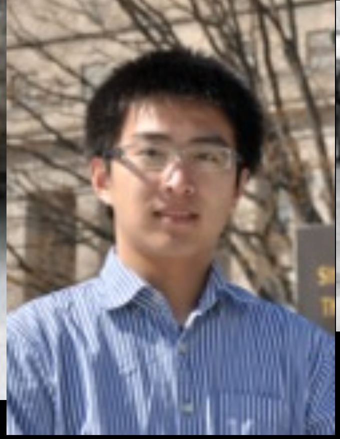
$$\mu \simeq 12 \times \frac{1}{N}\left(\frac{v}{m_{\rm pl}}\right)^4$$

Saturating Planck constraints

$$\mu \sim 3 \times 10^{-9}$$

$$T_{\mu\nu} \propto (\delta\phi)^2$$

Scalars, vectors, tensors excited
Here, only scalars......

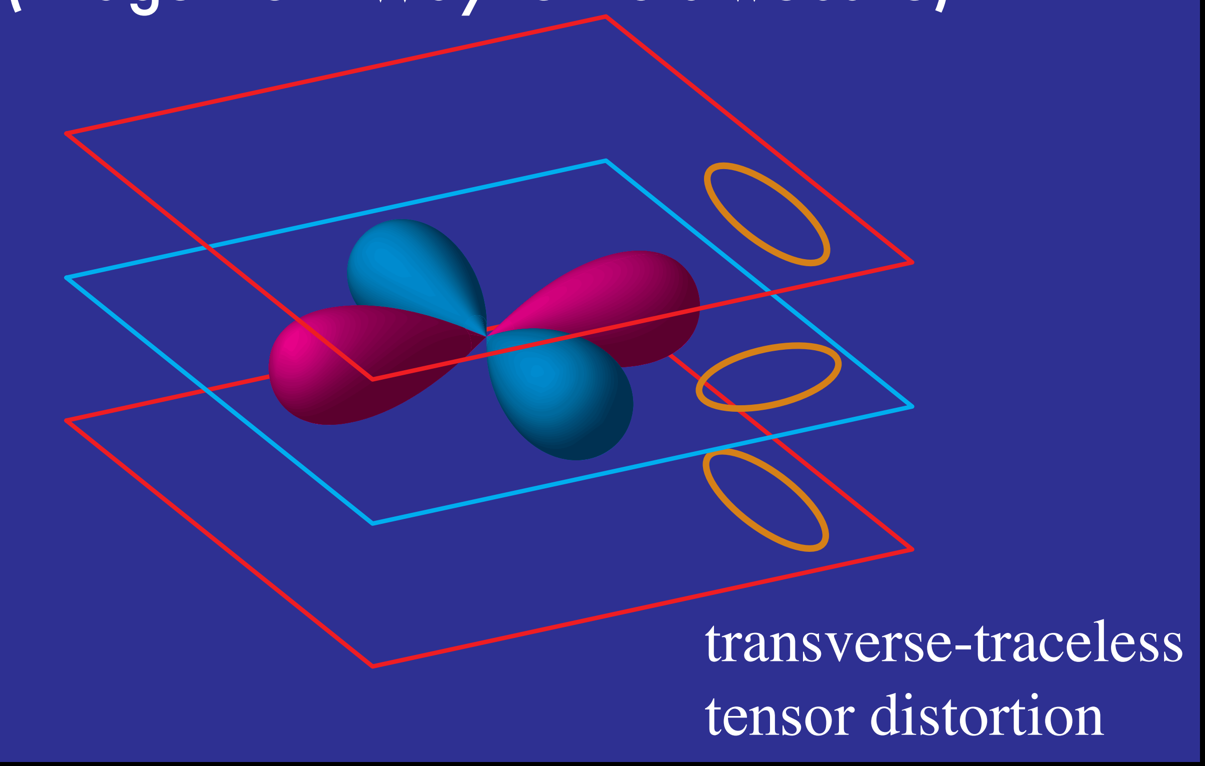
Spectral distortions from gravitational waves

J.Chluba, L.Dai, DG, M. Amin, M. Kamionkowski

arXiv: 1407.3653

Tensors source quadrupoles: superimpose blackbodies!

(image from Wayne Hu's website)



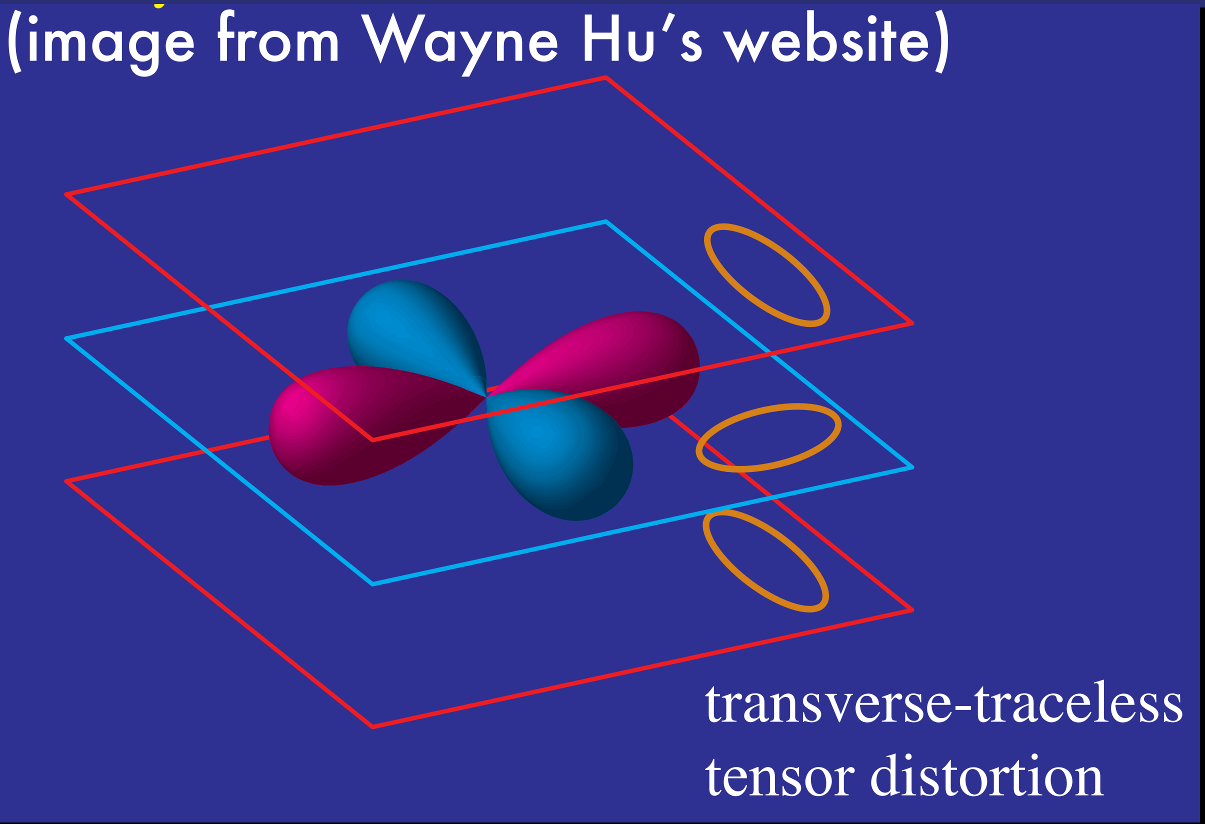
✳l=2 anisotropy appears from GW, *NO* diffusion needed

$$\partial_\eta \Theta_2^{(2)} = -\frac{9}{10}\dot{\tau}\Theta_2^{(2)} - \dot{h}$$

✳ Electron sees average spectrum – not BB

✳Rescatters into homogeneous component (spectral distortion)

Tensors source quadrupoles: superimpose blackbodies!



ϵ-expansion (tight-coupling) not always valid

✳l=2 anisotropy appears from GW, *NO* diffusion needed

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✳ Electron sees average spectrum -- not BB

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Physics of tensor driving in baryon-photon plasma

- ✳No pressure support (no compression)
- ✳Thomson scattering isotropizes radiation
- ✳Baryons don't cary shear – no Hubble damping

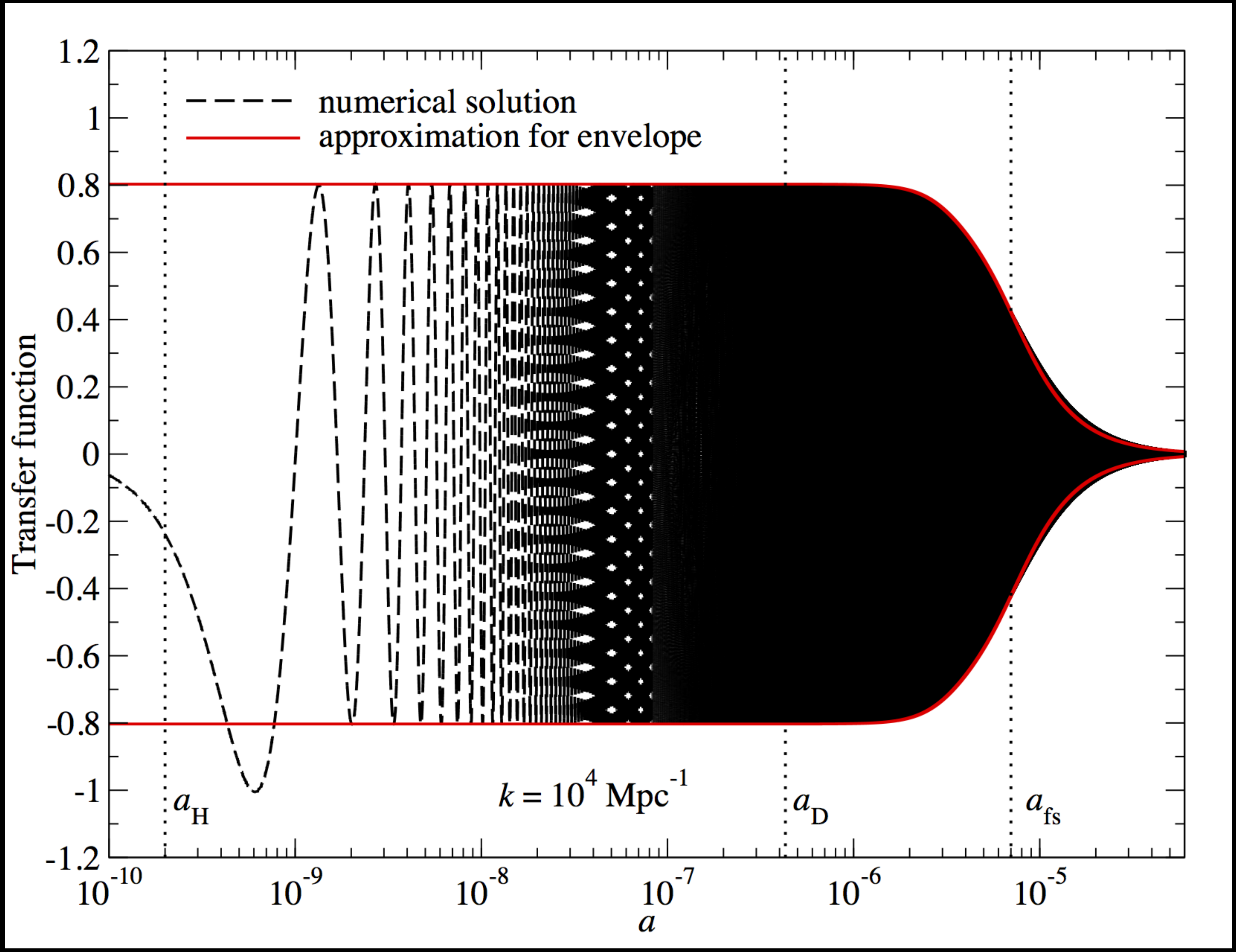
$$\partial_\eta \Theta_2^{(2)} = -\frac{9}{10}\dot{\tau}\Theta_2^{(2)} - \dot{h}$$

$$\Theta_2^2(k) \sim \begin{cases} \epsilon h & \text{if } k \ll \dot{\tau} \\ ih & \text{if } k \gg \dot{\tau} \end{cases}$$

- ✳Driven, critically damped oscillator
- ✳Diffusion/free-streaming populate higher multipole moments
    - ✳more anisotropy, additional 'heating' sources
    - ✳damped by powers of ϵ

Mode evolution

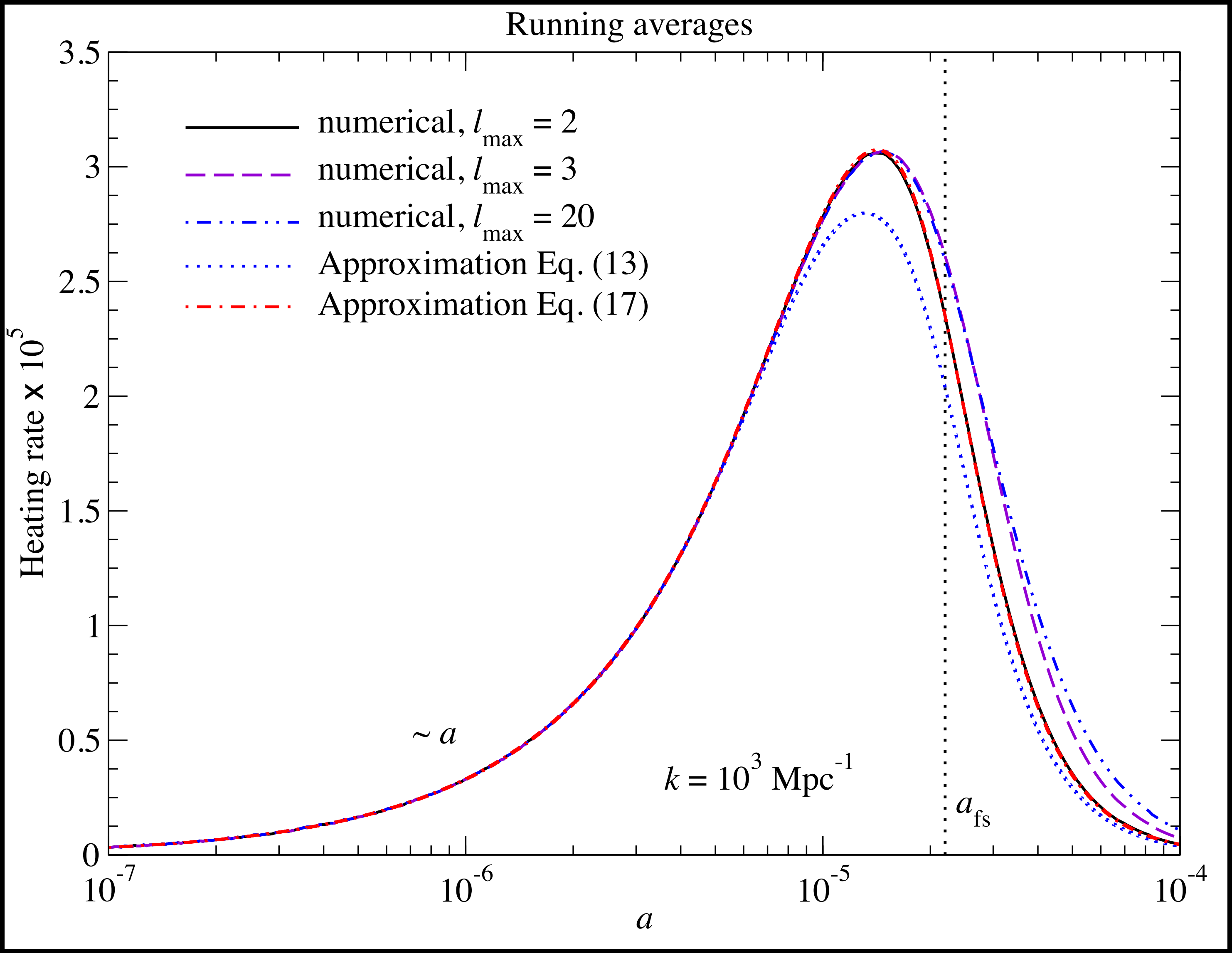
Θ_{22}



- ✳Ev'ln eqns in Hu/White

- ✳Tensor evolves as $h \propto \dfrac{\sin k\eta}{k\eta}$ + neutrino damping terms

Heating rate

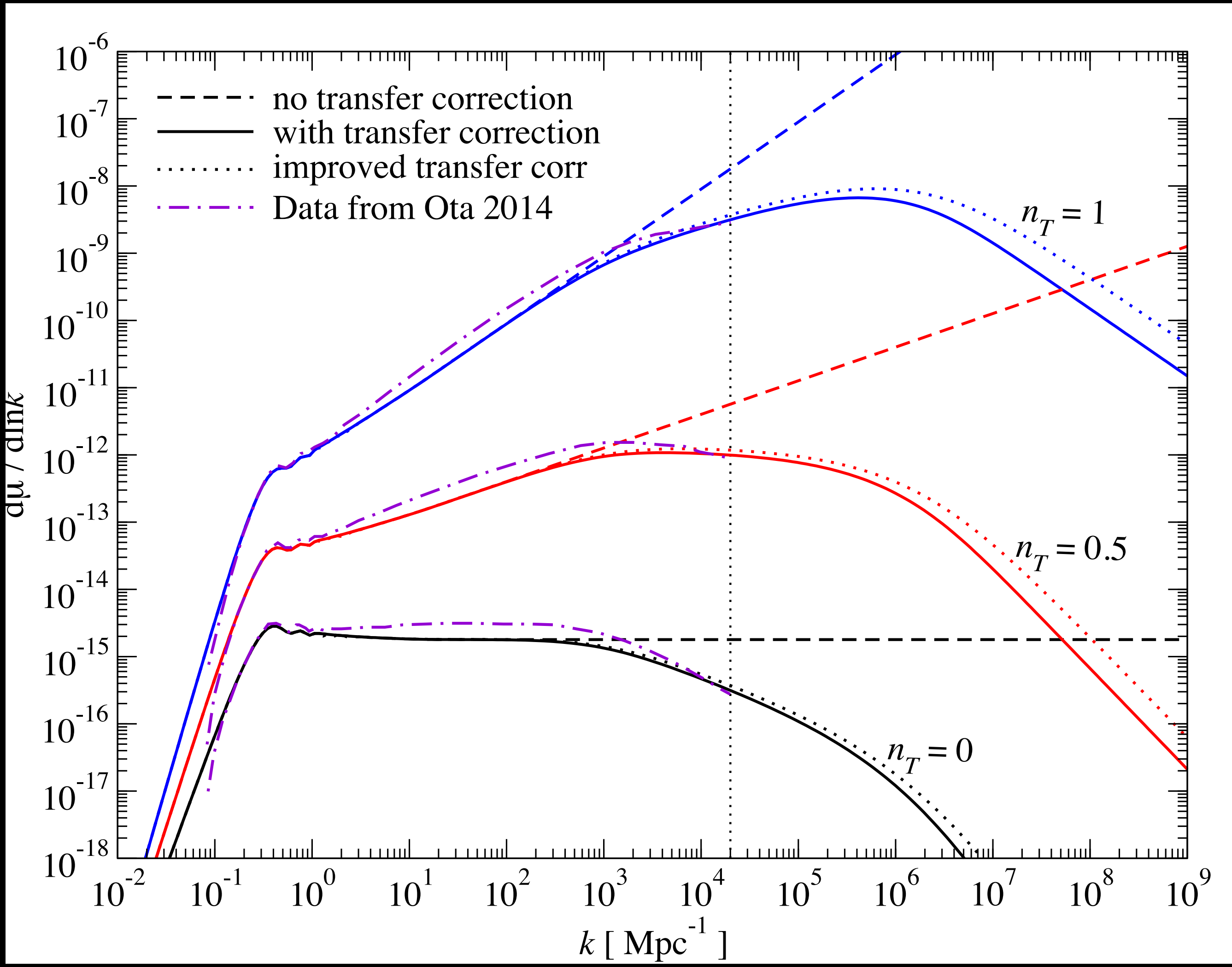


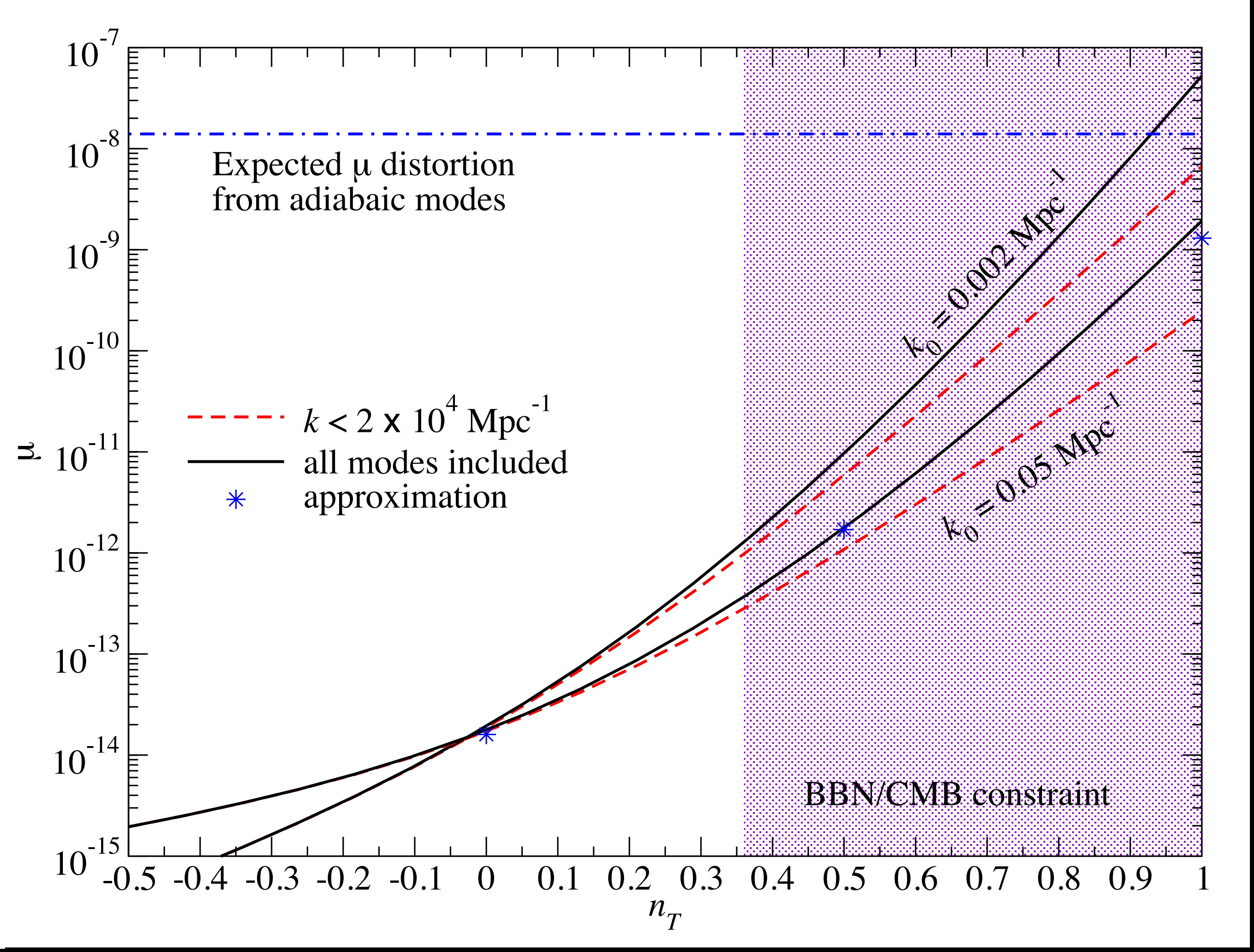
✳GW damped by photons as well, energy ⟶ γ anisotropy

✳Small change in GW amplitude, but main source of distortion

Distortion

✴Heating rate per log(k)





✴Stronger signal for blue spectra

✴Broader (but smaller) kernel compared to adiabatic modes

✴Detection would be formidable in range not probed by BBN

Punch-line and next steps

- SD are a powerful probe of NID/NIV mode: all spectra
- SDs are a nice probe of BI/CI mode: blue spectra
- SDs can test anisotropy constraints to scaling-seed models
- Blue tensors can yield detectable SDs
- Future work
    - Vector-sourced SDs
    - Amplitude of vector/tensor SDs from scaling seeds

Curvaton

- Tested correlated isocurvature with amplitudes allowed by Planck CMB local-type non-G constraints

- All 18 scenarios allowed by *Planck* limits are ~2 orders of magnitude away from PIXIE detectability

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- Tested correlated isocurvature with amplitudes allowed by Planck CMB local-type non-G constraints

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Simple curvaton models are not a promising target for SD experiments!