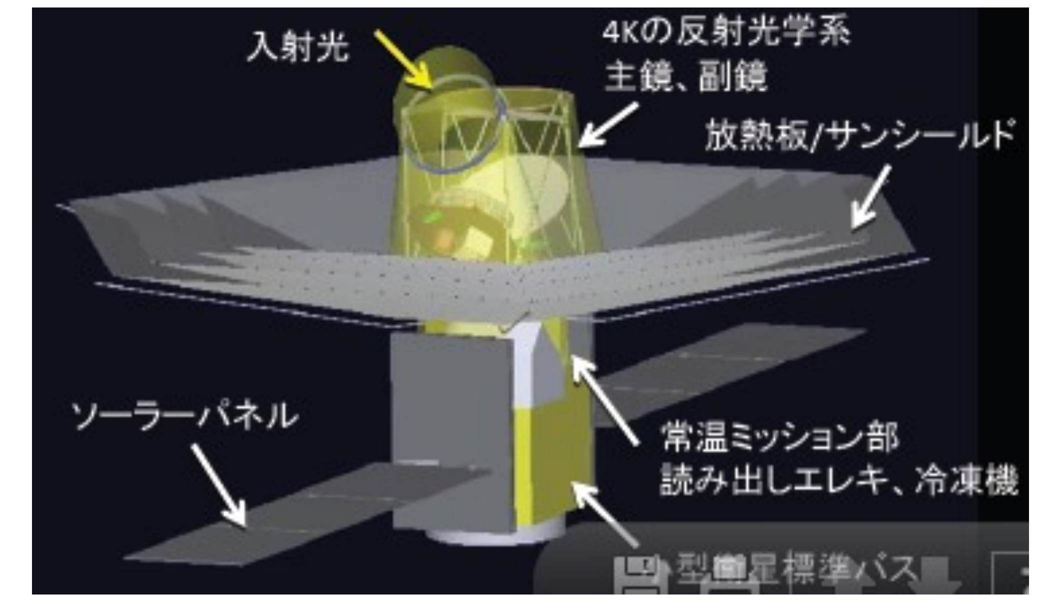
My next 10 years

Galaxy Survey: HETDEX

PI: Gary Hill
(UT Austin)

- Hobby-Eberly Telescope Dark Energy Experiment (HETDEX); **10-m** dish of HET
- High-z; and a huge volume
  - **z=1.9–3.5**; **10 Gpc^3 volume**
- First-ever **blind** emission-line galaxy survey
  - 0.8 million Lyman-alpha galaxies
- Starting in 2014, lasting for at least 3 years
- Detection of dark energy at z~2; neutrino mass
- Non-gaussianity, *including the galaxy bispectrum*

CMB Polarization: LiteBIRD



PI: Masashi Hazumi
(KEK)

- LiteBIRD; 30-cm mirror; a half degree beam
- **6 bands** within 50–320 GHz, excluding CO lines
  - TES bolometers or Kinetic Inductance Detectors (KIDs)
- We want to launch this in 2020, lasting for 2 years
- **Detection of r~10^{-3}**
  - The error budget includes noise and foreground. No need for delensing
- Constraint on the tensor tilt, if r is "big" enough (r~10^{-2})

So, my next 10 years will be...

- ...devoted to the continuation of what we have been doing over the last few decades
  - COBE -> WMAP -> Planck -> LiteBIRD
  - CfA -> 2dF/SDSS -> WiggleZ/BOSS -> HETDEX/others
- “Inertial motion” = a continuation from the past
- These are important steps forward in measurements; however, *do we really want to be in inertial motion forever?*

What Are the New Challenges For Early Universe Cosmologists?

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
"*New Challenges for Early Universe Cosmologists*,"
Lorentz Center Conference, August 9, 2013

New Challenges in the Post-Planck Era

- I heard many people saying "I was disappointed by the Planck results. Cosmology is boring now!"

- What are the challenges now? **Challenges are in our mind.** In my point of view, the post-Planck world provides new opportunities, because...

New Opportunities in the Post-Planck Era

- An important milestone has been achieved: n_s<1 is now discovered. And...

New Opportunities in the Post-Planck Era

GRUBER FOUNDATION

July 11, 2013

COSMOLOGY

2013 Gruber Cosmology Prize Citation

The Gruber Foundation proudly presents the 2013 Cosmology Prize to Viatcheslav Mukhanov and Alexei Starobinsky for their profound contribution to inflationary cosmology and the theory of inflationary perturbations of the metric. These developments changed our views on the origin of our universe and on the mechanism of formation of its structure.

Viatcheslav Mukhanov

Alexei Starobinsky

n_s~0.96 [Mukhanov & Chibisov 1981], now observed;
and the R^2 inflation [Starobinsky 1980], continues to fit the data rather well

- **But...**

New Opportunities in the Post-Planck Era

- **But...** these predictions were made a long time ago. Finally discovering $n_s<1$ is wonderful and remarkable, but what else can younger generations contribute to this field? Not much, really...

- Similarly:

New Opportunities in the Post-Planck Era

- **Similarly**: imagine that f_{NL} was discovered in the Planck data. That would be a remarkable achievement, revolutionizing the field of inflation.

- However, a lot of fundamental work have already been done on f_{NL}, and frankly there would not be too much left for younger generations to chew on, even if it was detected. Therefore...

New Opportunities in the Post-Planck Era

- **Therefore**... younger generations should be glad that the Planck data continue to support vanilla single-field inflation models because this means that all of us, junior or senior, **are back on the same starting line!**

You don't have to read too many papers on f_{NL}!

Advice from Hayashi

- Chushiro Hayashi:
  - “A good research area is the one that has the least references.”

Chushiro Hayashi

“ 林先生の部屋に伺ったところ，少し憤然として「最近の若い人はそういう考え方をするのですか！ referenceがたくさんあるということはその分野の研究が既にかなり進んでいて今から自分がやってもあんまり寄与できない．referenceがない分野こそ良いテーマなのだが…」と残念がられた．頭がガーンとした．” (Takashi Nakamura)

“Thinking outside the box”

- **Challenges are in our mind.** Yes, it is difficult to find something novel if we work on the subjects along the line of what has been done already.
- One of the challenges in our mind: worrying too much about the observability in a short time scale.
    - Just forget about the observability. *If the physics is beautiful, it is worth doing!*

Learning from the past

- Slava Mukhanov:
  - "I thought that it would take *1000 years* to detect the logarithmic dependence of the power spectrum."

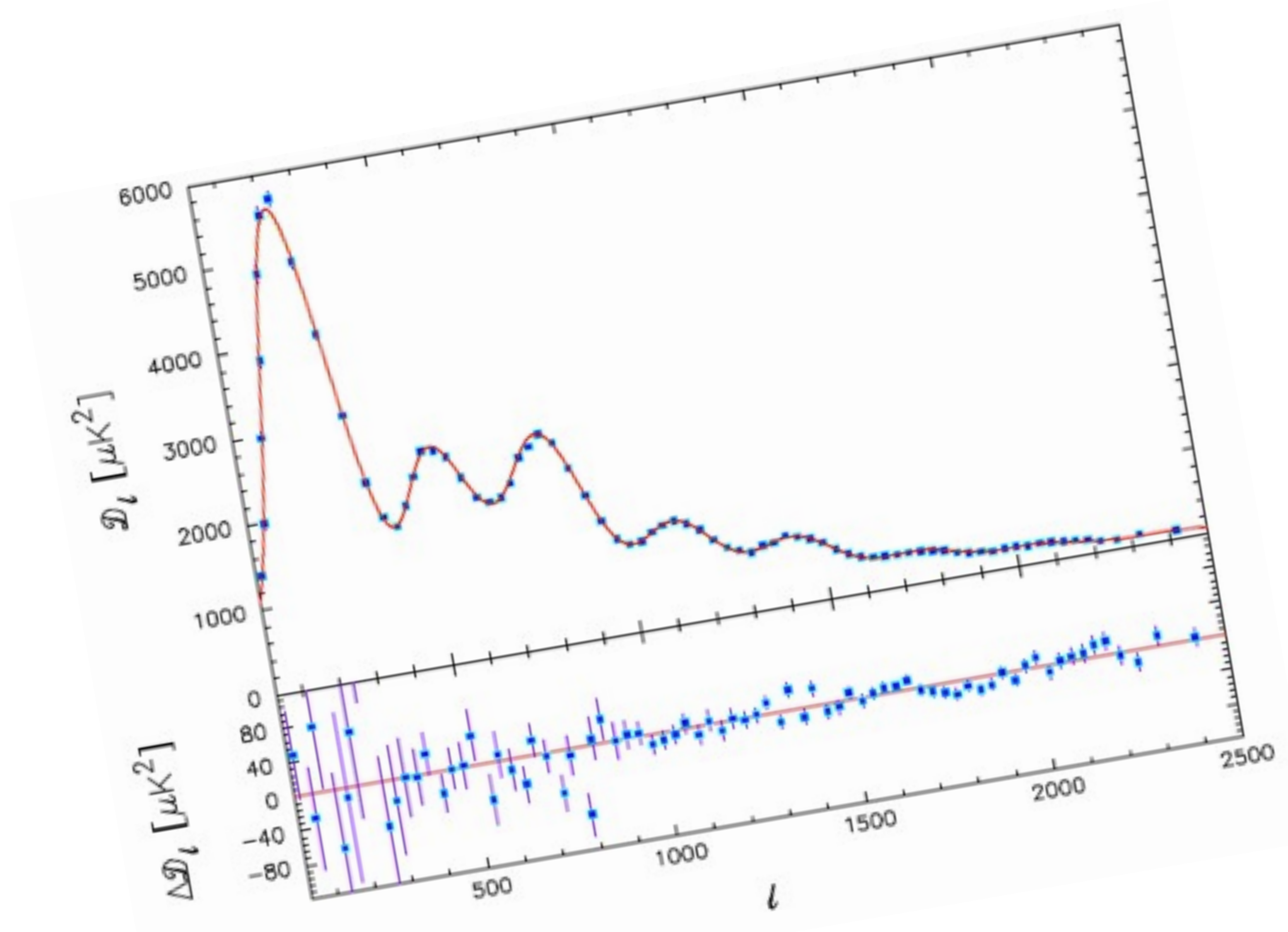
Viatcheslav Mukhanov

n_s=0.960±0.007

Learning from the past

- Rashid Sunyaev:
  - "I did not think that the acoustic oscillation would ever be observed."

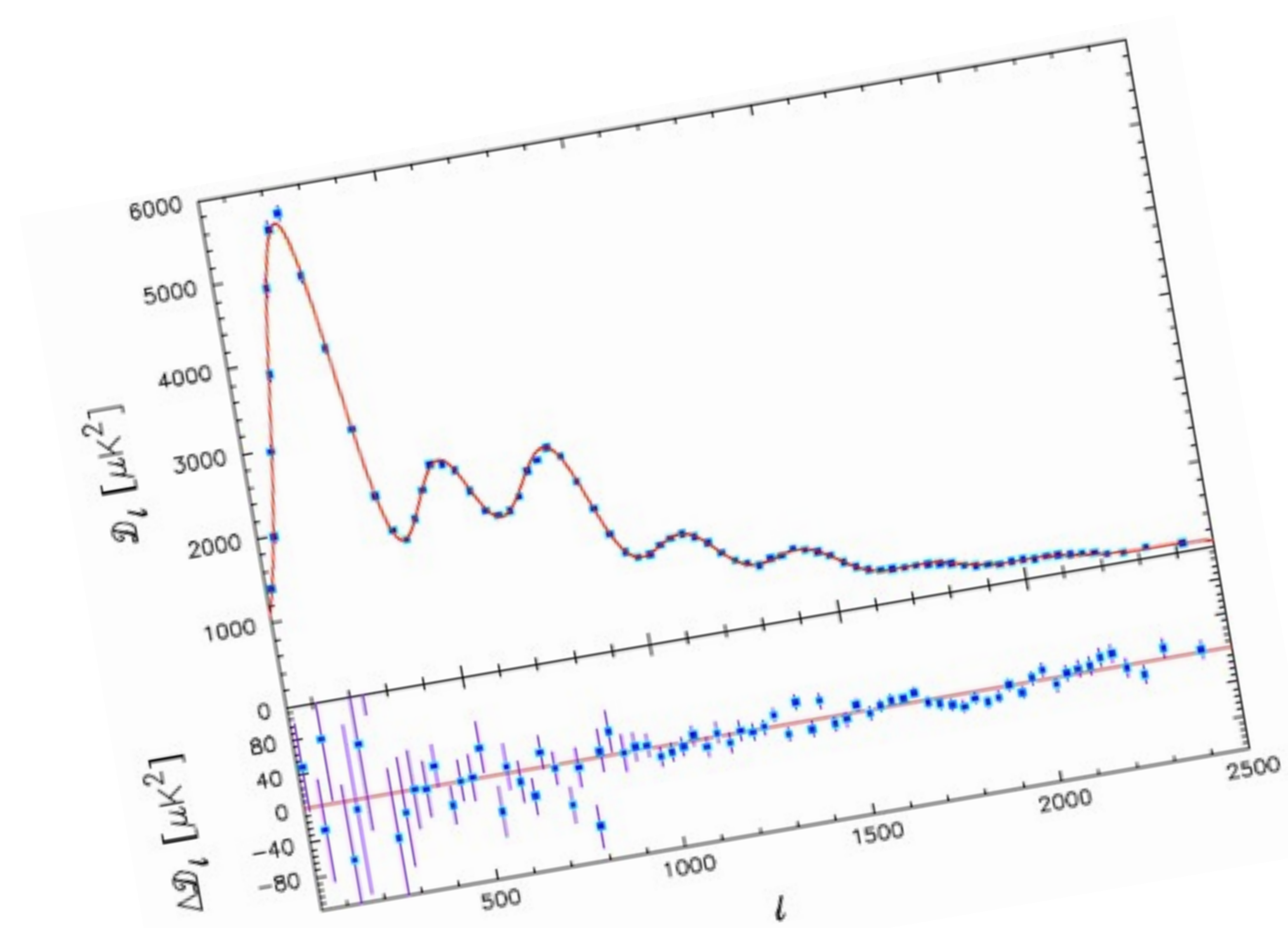
Rashid Sunyaev



Learning from the past

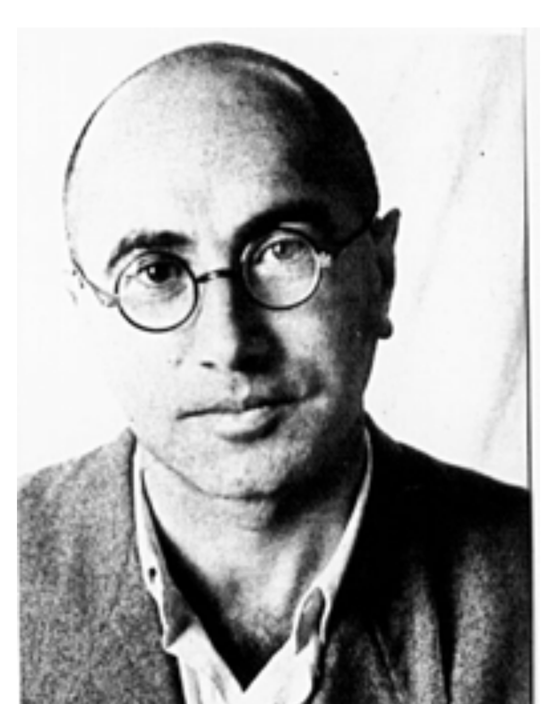
- Jim Peebles (Annu. Rev. Astro. Astrophys. 2012):
  - "I did not continue with (computation of CMB), in part because I had trouble imagining that such tiny disturbances to the CMB could be detected..."

Jim Peebles

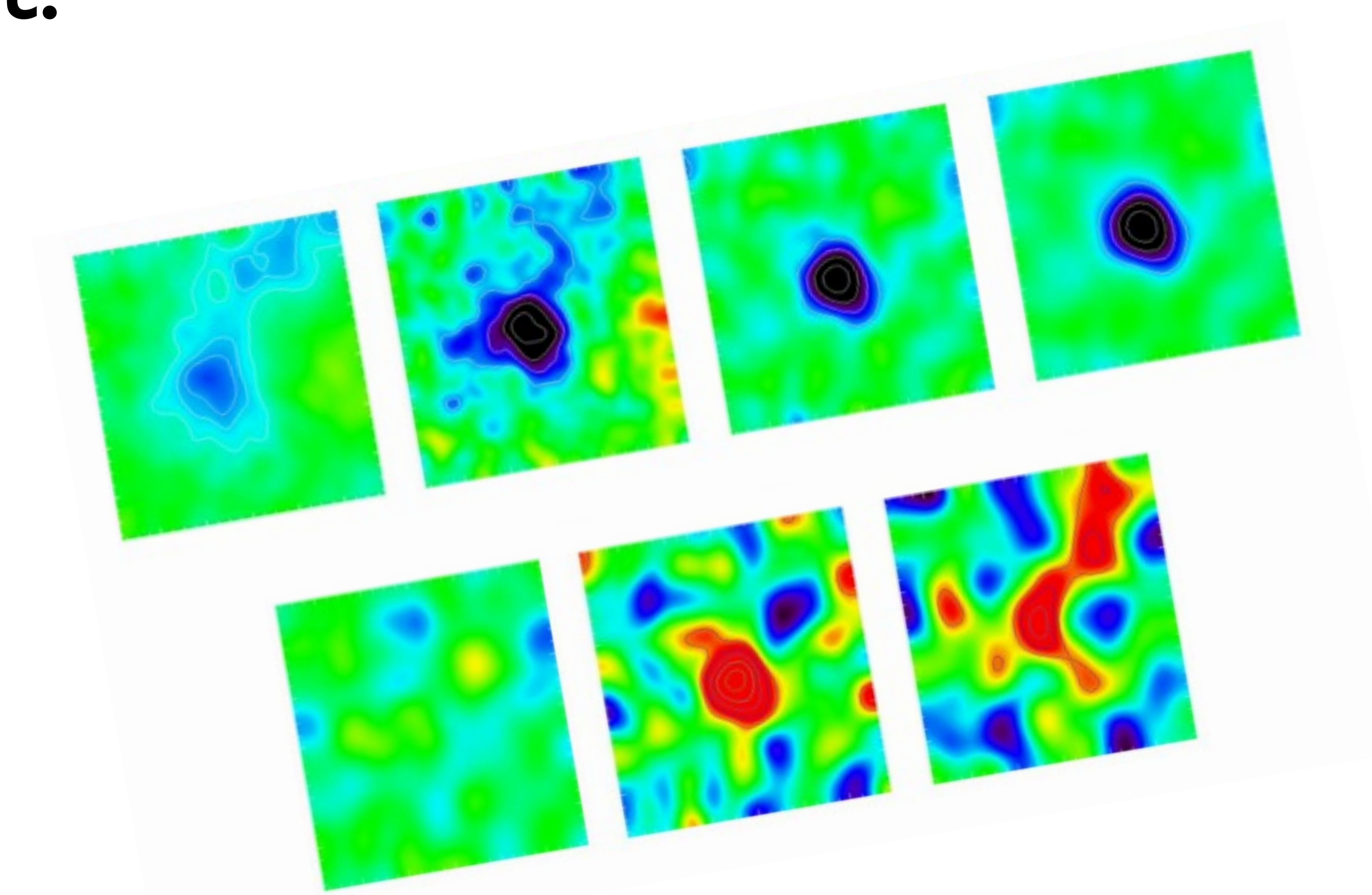


Learning from the past

- Yakov Zel'dovich:
  - "(Speaking to Sunyaev about the Sunyaev-Zel'dovich effect:) This is a small effect, but the physics is beautiful. Let's publish it."

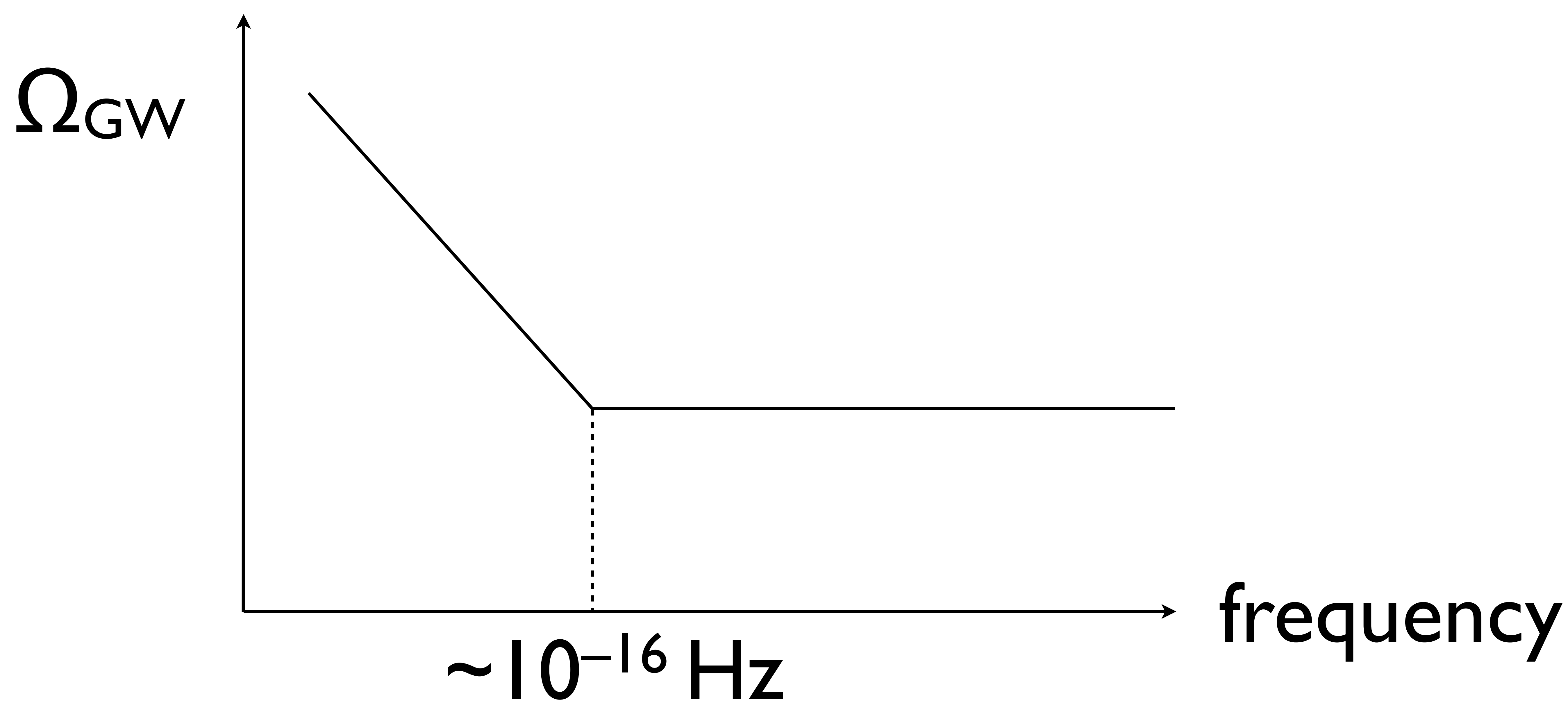


Yakov Zel'dovich

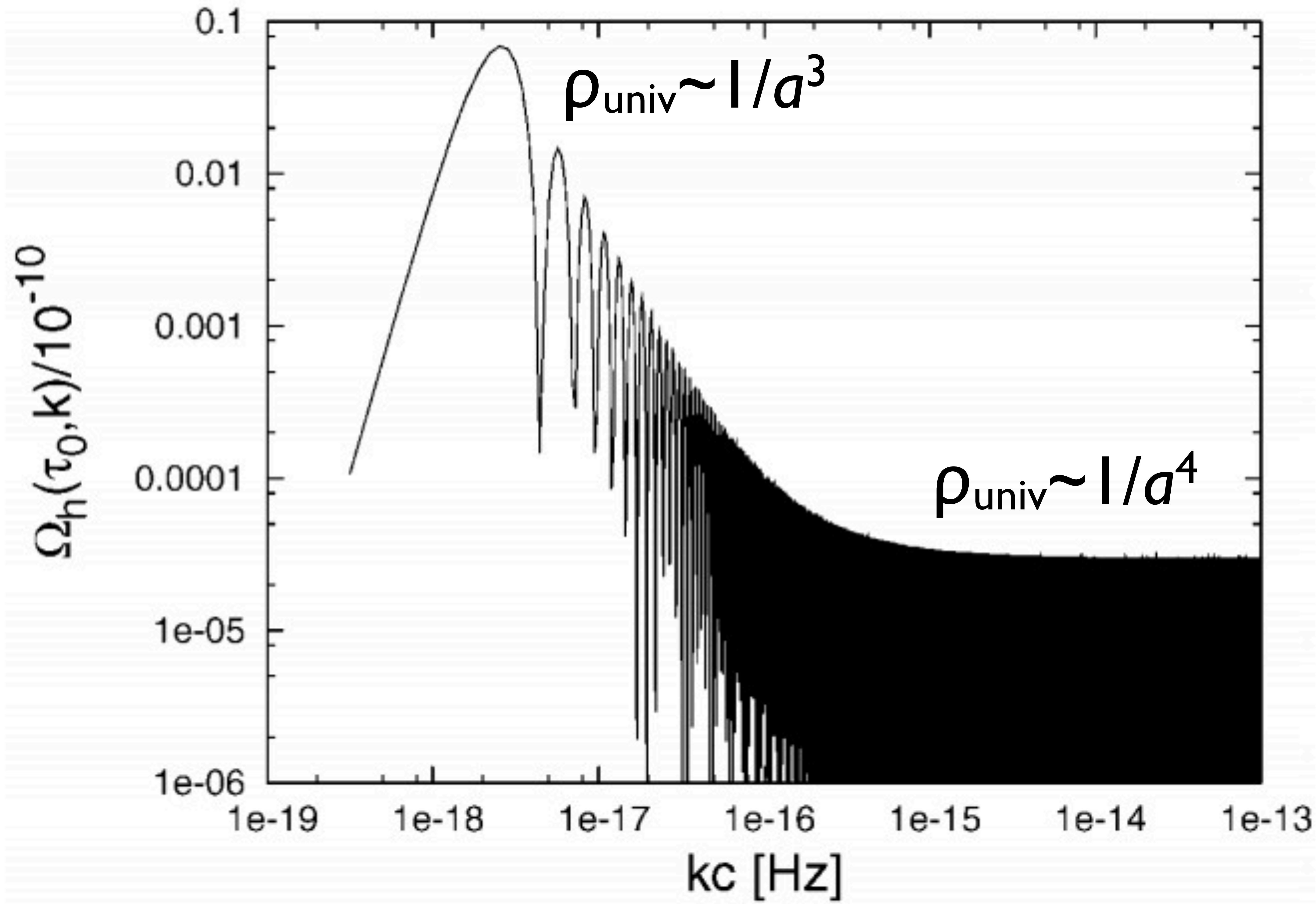


An Example

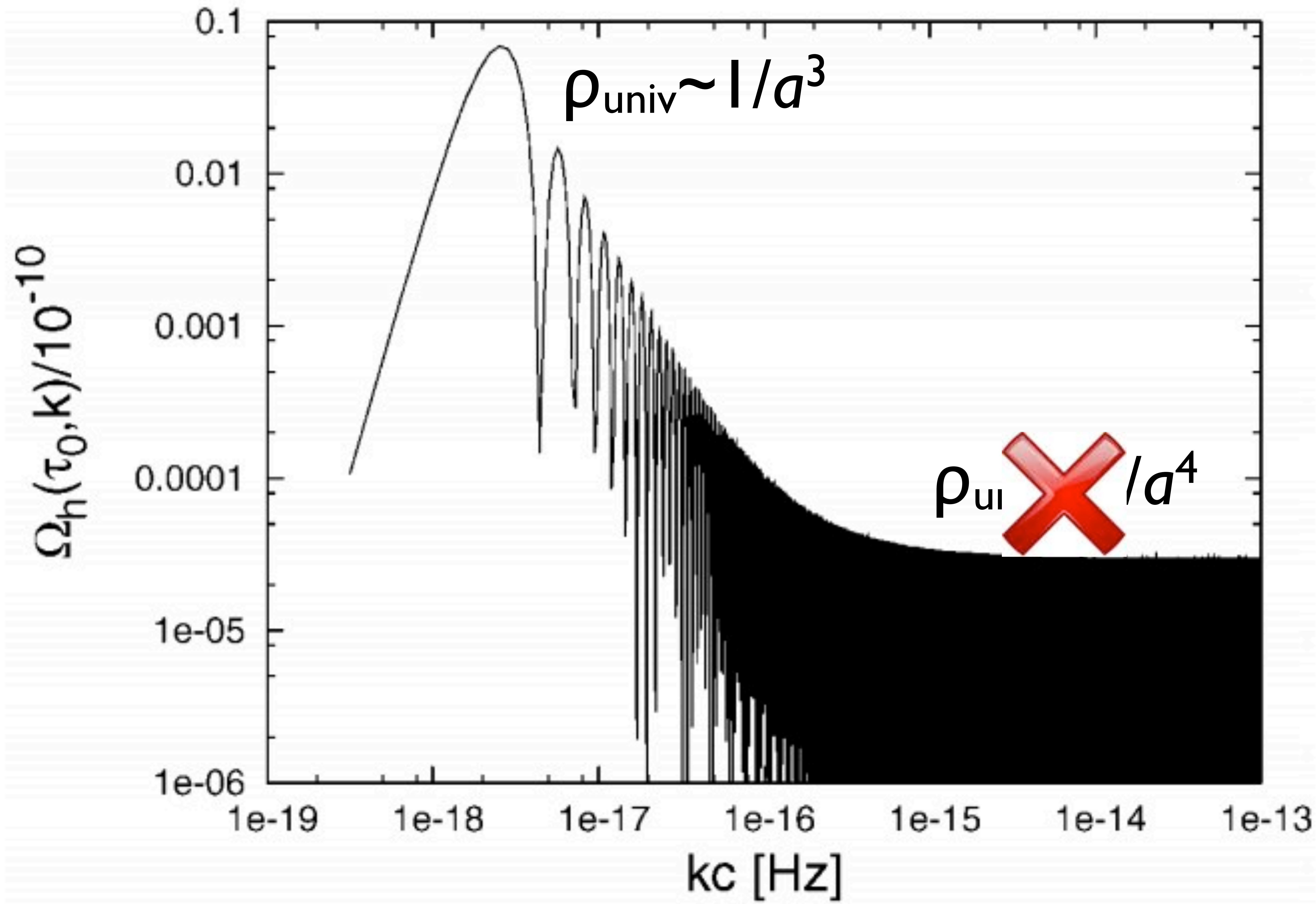
- The energy density spectrum of primordial gravitational waves. It is usually said that it goes as 1/(frequency)^2 in the low-frequency region and is constant in the high-frequency region.



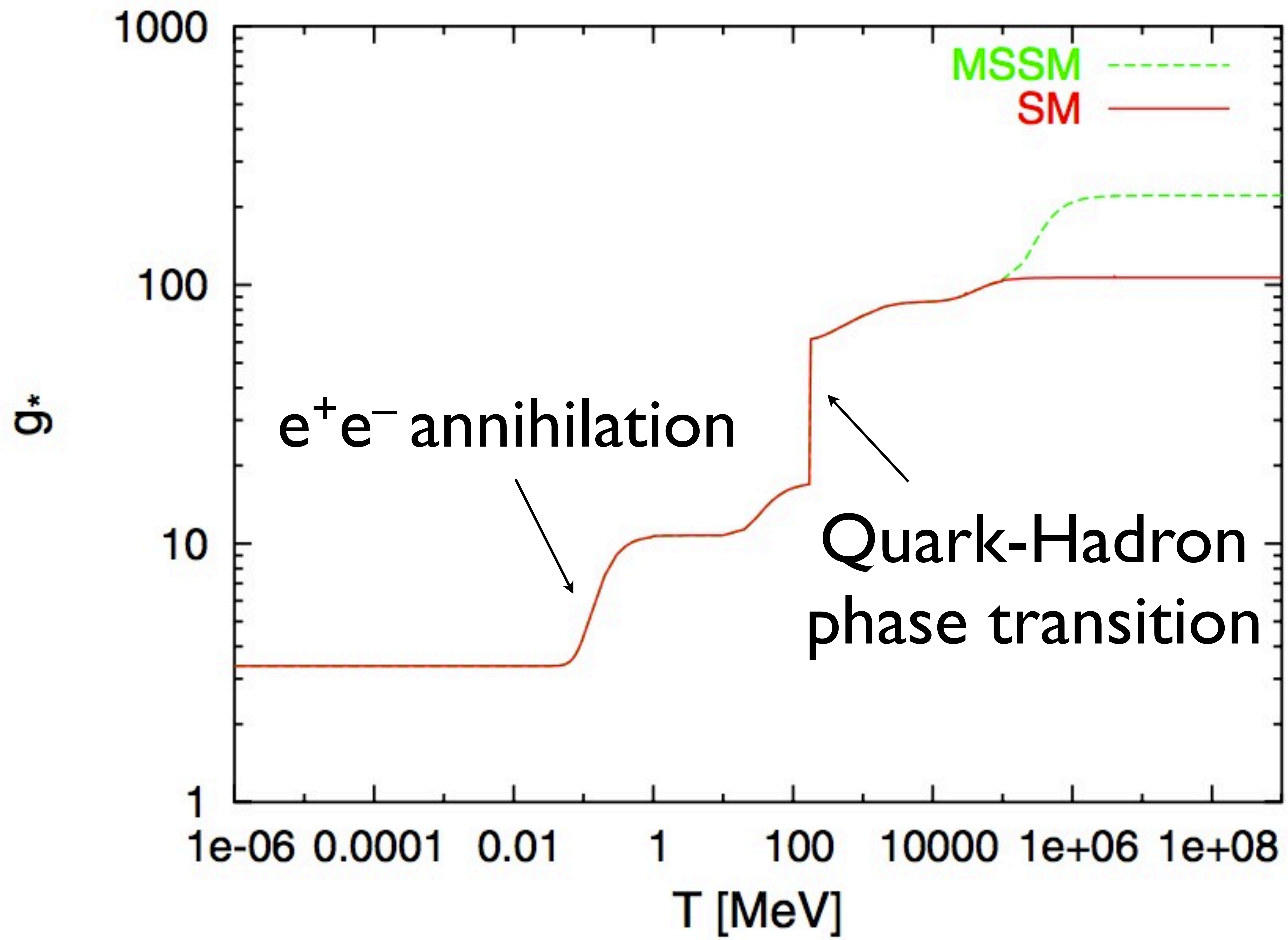
Previous Lore



Previous Lore



Jumps in the number of radiation species



Watanabe & Komatsu (2006)

Correct spectrum in the Standard Model

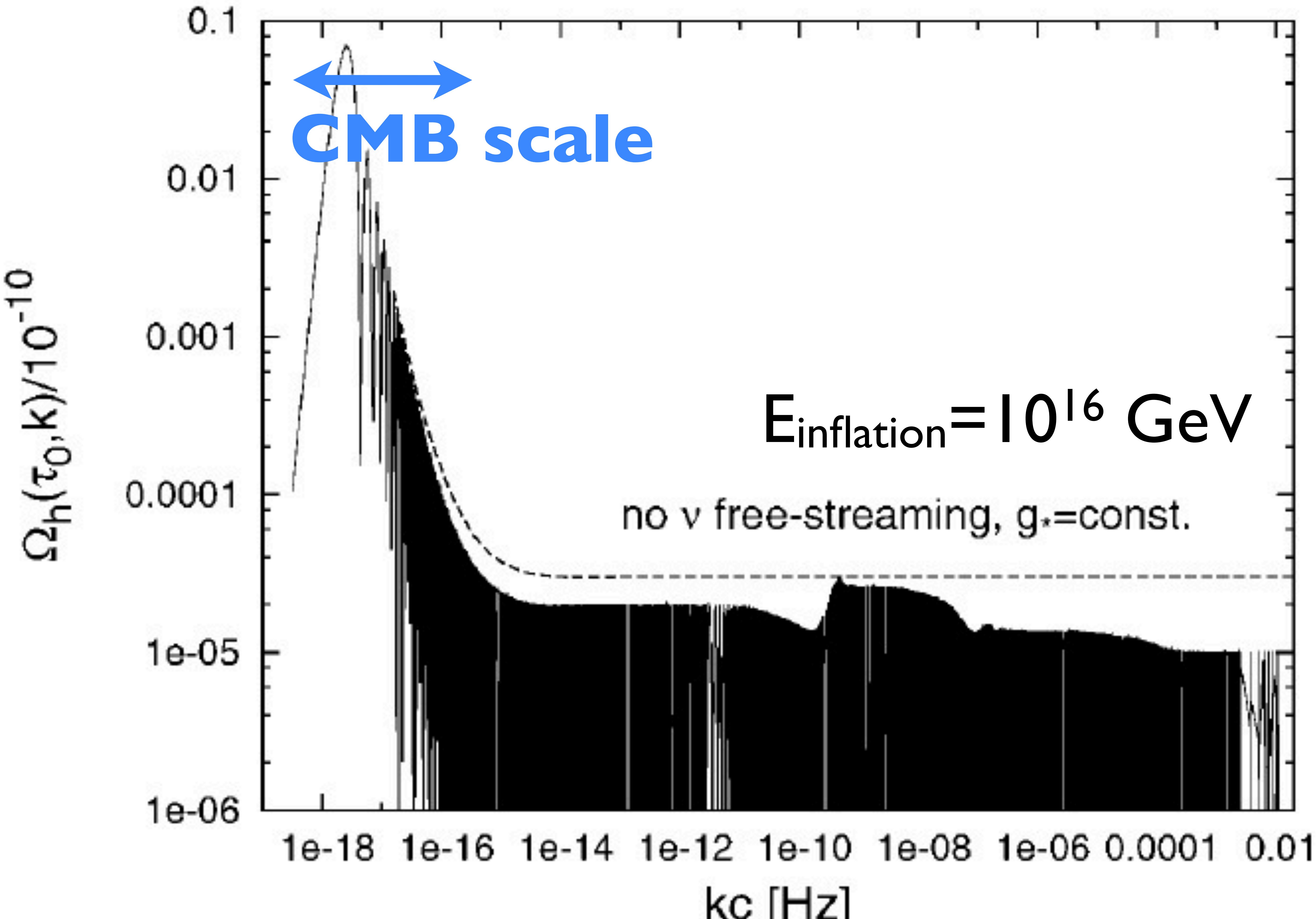
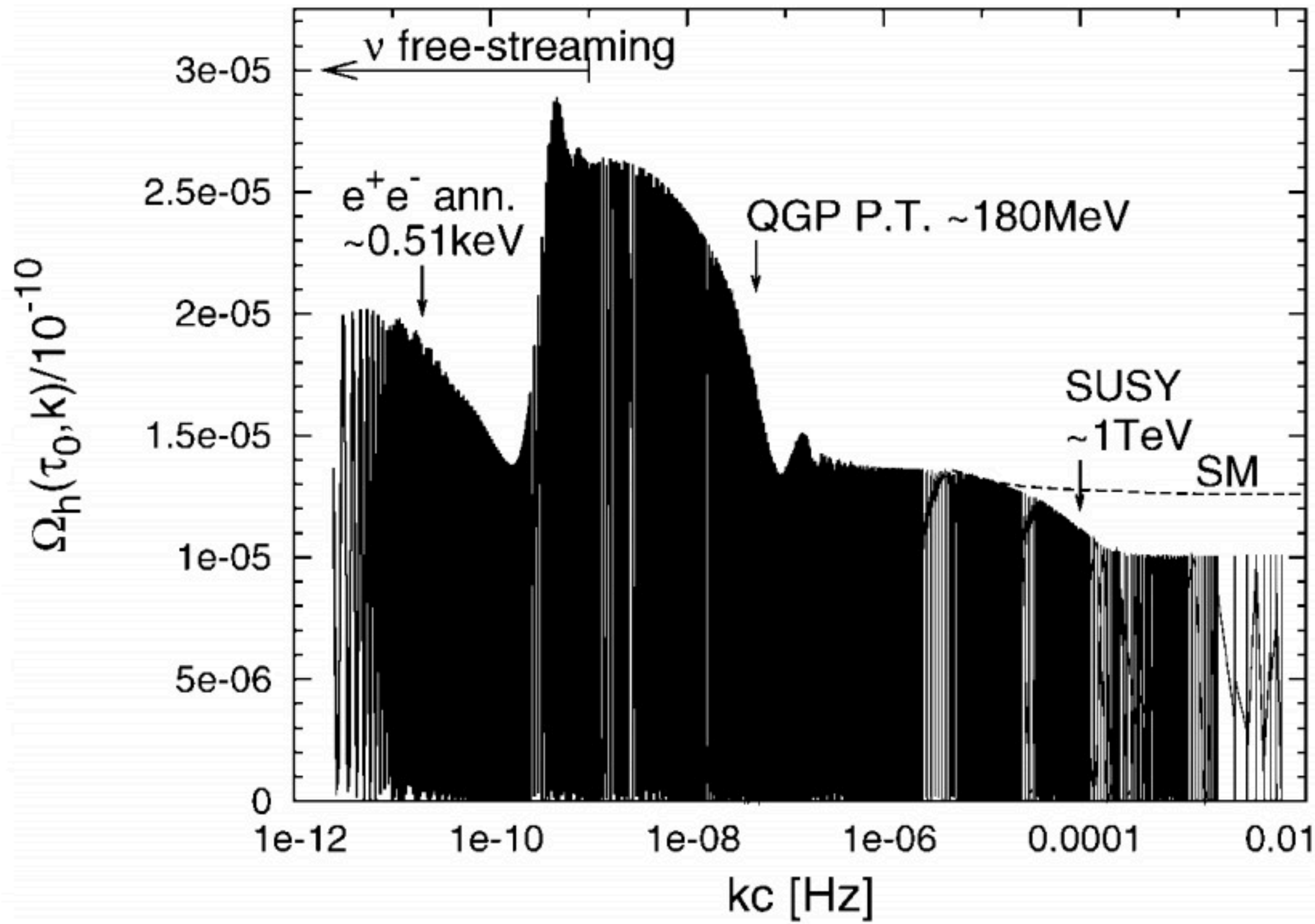


TABLE I. Particles in the SM and their mass and helicity states.

Particle	Rest mass [MeV]	The number of helicity states: g_i
γ	0	2
ν, $\bar{\nu}$	0	6
e^+, e^-	0.51	4
μ^+, μ^-	106	4
π^+, π^-	135	2
π^0	140	1
gluons	0	16
u, $\bar{u}$	5	12
d, $\bar{d}$	9	12
s, $\bar{s}$	115	12
c, $\bar{c}$	1.3×10^3	12
τ^+, τ^-	1.8×10^3	4
b, $\bar{b}$	4.4×10^3	12
W^+, W^-	80×10^3	6
Z	91×10^3	3
H	114×10^3	1
t, $\bar{t}$	174×10^3	12
SUSY particles	$\sim 1 \times 10^6$	~ 110

Watanabe & Komatsu (2006)



Yes, people do ask:

- "Is this effect ever measurable?"

- And my answer is always: "*I do not care*."
  - The lesson we have learned from CMB experiments is that, if experimentalists are convinced that it is worth measuring, they will get there much sooner than you'd think!
  - Theorist's job is to find something which may be small, but is *worth measuring*.

A Good Working Hypothesis

- B-mode polarization will be found at the level of $r \sim 10^{-3}$ or greater by, e.g., LiteBIRD (a Japan-led polarization satellite mission).
- The scale-invariance of gravitational waves also measured at, say, 10% level. Inflation is proven.
- The challenge: *then what?*

Some Challenging Questions

- How inflation happened?
  - How inflation started; how inflation ended?
  - What is inflaton?

- Do fluctuations really have the quantum origin?

How inflation happened?

- What can we measure to say anything at all about the origin of inflation?

- The necessary working hypothesis: the number of e-folds is the minimum value required to solve the horizon problem (or the flatness problem for open inflation).

How inflation happened?

- What can we measure to say anything at all about the origin of inflation? **A few candidates:**
  - Curvature
  - Pre-inflationary relics (e.g., bubble collision)
  - Coupling of modes in the pre-inflationary phase (e.g., super-curvature modes in open inflation) to the observable modes
  - Non-Bunch-Davies initial state from quantum tunneling [B_ζ-> $e^{-\pi k_S}/(k_L^4 k_S^2)$; *Sugimura&Komatsu, to appear*]

Quantum Fluctuations

- The fundamental prediction of inflation is that fluctuations originated from quantum fluctuations.
- How can we test this?

Quantum or Classical?

$$\phi(\mathbf{x},\tau) = \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}} \left[\hat{a}_{\mathbf{k}}\varphi_k(\tau)e^{i\mathbf{k}\cdot\mathbf{x}} + \hat{a}^\dagger_{\mathbf{k}}\varphi^*_k(\tau)e^{-i\mathbf{k}\cdot\mathbf{x}}\right]$$

$$\begin{aligned}\phi(\mathbf{x},\tau) \;\approx\; & \int_{k<aH} d^3\mathbf{k}\left(\hat{a}_{\mathbf{k}} - \hat{a}^\dagger_{-\mathbf{k}}\right)\varphi_{k\ll aH}(\tau)e^{i\mathbf{k}\cdot\mathbf{x}} && \longrightarrow \phi_{\rm CL} \\ & + a^{-1}(\tau)\int_{k>aH}\frac{d^3\mathbf{k}}{(2\pi)^{3/2}\sqrt{2k}}\left(\hat{a}_{\mathbf{k}}e^{i\mathbf{k}\cdot\mathbf{x}-ik\tau} + \hat{a}^\dagger_{\mathbf{k}}e^{-i\mathbf{k}\cdot\mathbf{x}+ik\tau}\right) && \longrightarrow \phi_{\rm QM}\end{aligned}$$

$$[\phi_{\rm CL}(\mathbf{x},\tau), \pi_{\rm CL}(\mathbf{x}',\tau)] = 0$$

The large-scale modes commute!

conjugate momentum

$$[\phi_{\rm QM}(\mathbf{x},\tau), \pi_{\rm QM}(\mathbf{x}',\tau)] = i\int_{k>aH}\frac{d^3\mathbf{k}}{(2\pi)^3}e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')} = i\delta^{(3)}(\mathbf{x}-\mathbf{x}')$$

Quantum or Classical?

- Super-horizon modes become "classical" (in a sense of a vanishing commutation relation).
- However, when they re-enter the horizon, they become quantum again.
- We know that scalar perturbations did not become quantum again; so some decoherence must have happened to scalar perturbations.
- But, how about gravitational waves?

Grishchuk & Sidorov (1989;1990)

Squeezed State from Inflation

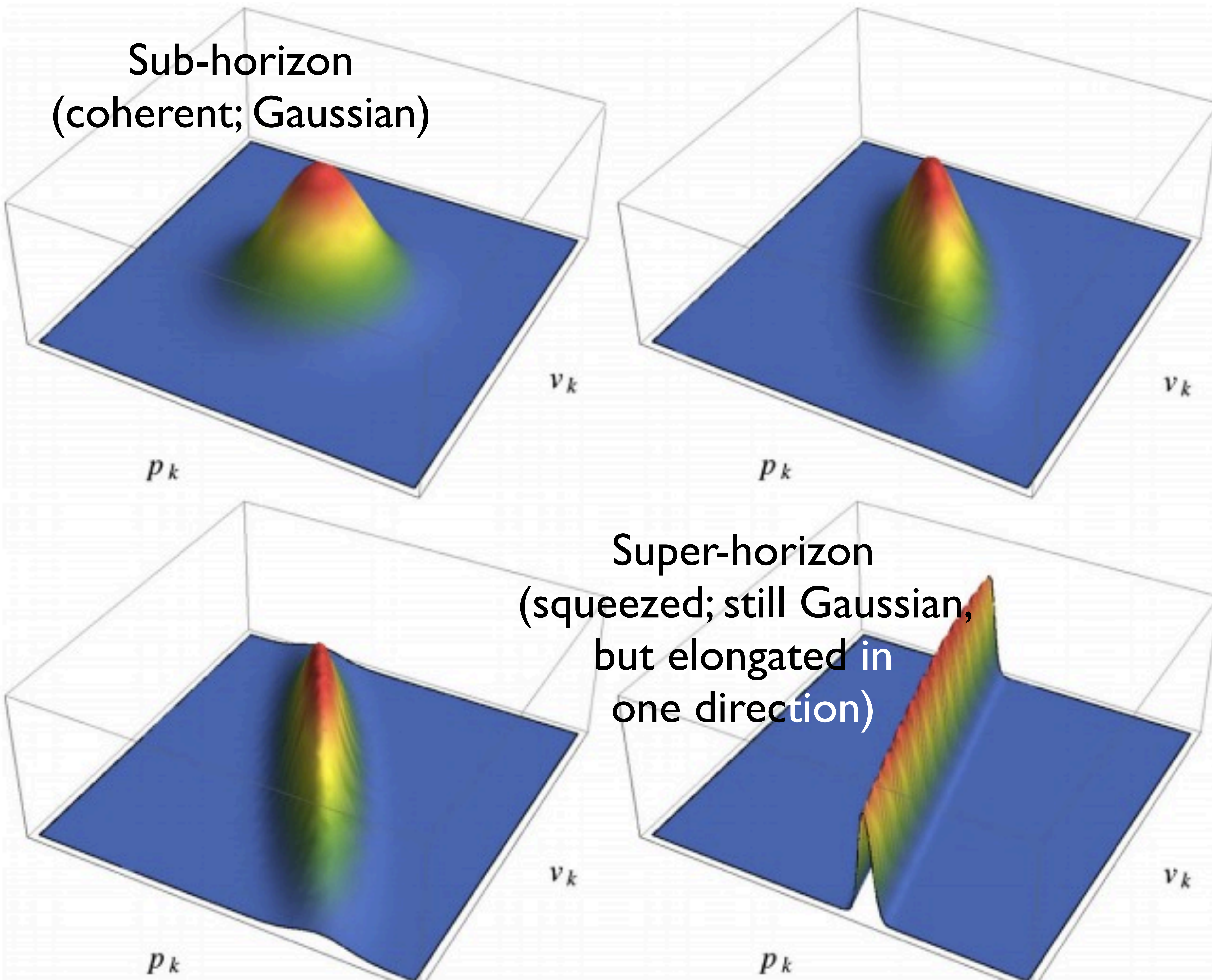


Figure from Martin, Vennin & Peter (2012)

- Inflation predicts that, on super-horizon scales, the variance in the field value (v_k) is much greater than the variance in the conjugate momentum (p_k).
- The area in v_k-p_k remains the same: no violation of Heisenberg's uncertainty principle (of course).

Squeezing on Super-horizon Scales

- Solution for the field (de Sitter): $v_k \sim (2k^3)^{-1/2}(1+ik\eta)e^{-ik\eta}$
- Conjugate momentum: $p_k = v_k' \sim (2k^3)^{-1/2}k^2\eta e^{-ik\eta}$
- The ratio of the variances:
  - $k^2|v_k|^2/|p_k|^2 = |1+ik\eta|^2/(k\eta)^2$
  - -> 1 for $k\eta \to \infty$ [coherent state]
  - -> k^{-2} for $k\eta \to 0$ [squeezed]

Squeezed State and Tests of Gaussianity

- *The squeezed quantum state is statistically indistinguishable from an ensemble of classical fluctuations*
  - Coherent state: localized in v_k and p_k, the trajectory of the packet obeying the classical equation of motion
  - Inflationary squeezed state: not localized in v_k, equivalent to having many classical trajectories
- Therefore, tests of Gaussianity treating cosmological fluctuations as an ensemble of classical fluctuations do offer a test of the squeezed state

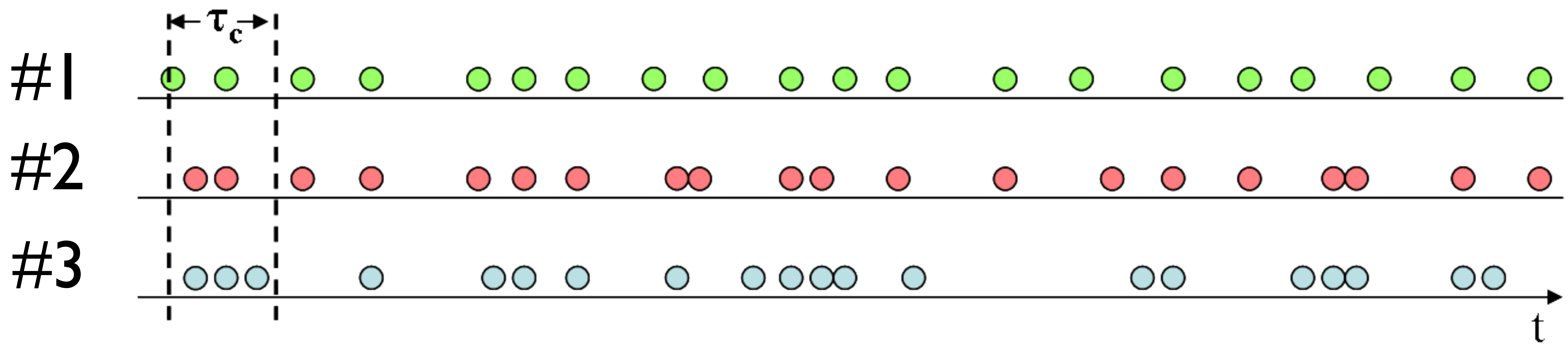
Question

- While testing the squeezed state is not necessarily a test of quantum fluctuations, can we test this more directly than Gaussianity tests?
- It is not clear to me how much more information we learn about inflation by testing the squeezed state more directly, but let me proceed.

Testing Squeezed State

- Primordial gravitational waves should be in a squeezed state (Grishchuk & Sidorov 1989;1990).

If we can see individual gravitons, they look like #3:



Photon detections as a function of time for a) antibunched, b) random, and c) bunched light

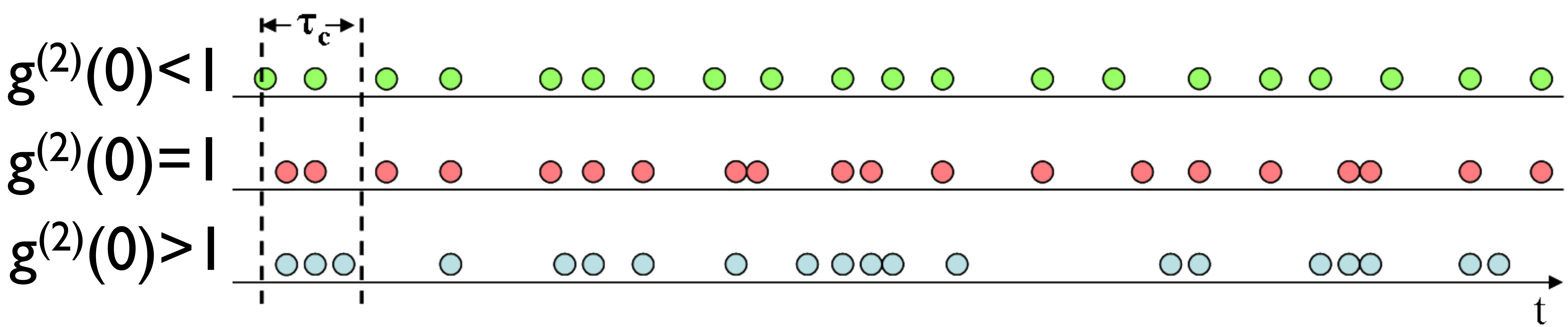
#1: anti-bunched; sub-Poisson; $\langle n^2\rangle - \langle n\rangle^2$ smaller than $\langle n\rangle$

#2: un-bunched; Poisson; $\langle n^2\rangle - \langle n\rangle^2$ equal to $\langle n\rangle$ ⟶ coherent state

#3: bunched; super-Poisson; $\langle n^2\rangle - \langle n\rangle^2$ larger than $\langle n\rangle$

Hanbury Brown-Twiss (HBT) Interferometry

- Imagine that we measure + or x modes of gravitational waves. Then measure the following ratio called the "*second-order coherence*":
- $g^{(2)}(\tau)=\langle h(t)h(t+\tau)h^*(t)h^*(t+\tau)\rangle/(\langle h(t)h^*(t)\rangle\langle h(t+\tau)h^*(t+\tau)\rangle)$



Photon detections as a function of time for a) antibunched, b) random, and c) bunched light

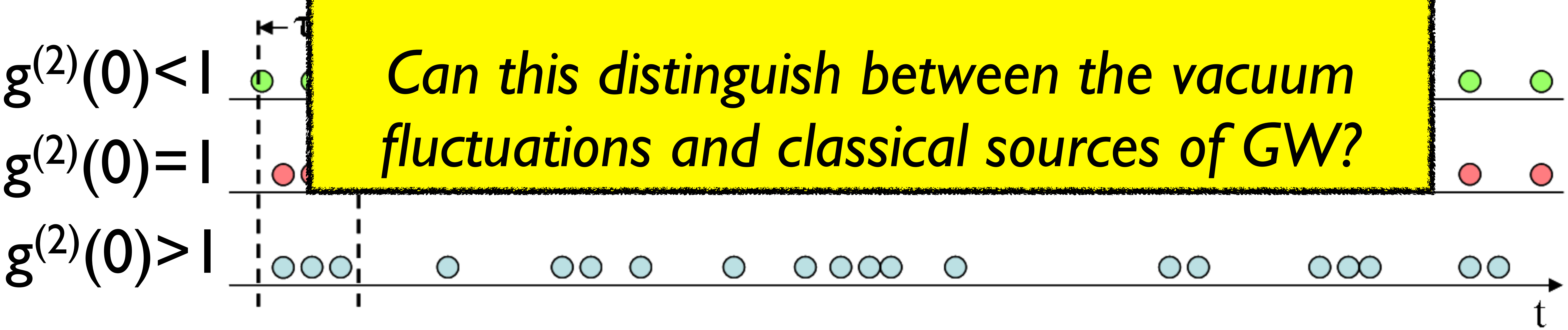
Hanbury Brown-Twiss (HBT) Interferometry

- Imagine nal waves. Then m *order coherenc*
- $g^{(2)}(\tau)=<$ $h^*(t+\tau)>)$

Inflation predicts $g^{(2)}(0)\approx 3$!
(Grishchuk&Sidorov 1989)

cf: chaotic light (light emitted by uncorrelated sources) gives $g^{(2)}(0)=2$

Can this distinguish between the vacuum fluctuations and classical sources of GW?



Photon detections as a function of time for a) antibunched, b) random, and c) bunched light

Summary

- New challenges = New opportunities. We are back on the same starting line.
- Learning from the past: Do not pay attention to the observability. *If it is worth measuring it, we will get there.*
- Challenging, but potentially testable, questions:
  - How inflation happened? Testing quantum tunneling models (assuming $N \sim N_{minimum}$)
  - Are fluctuations quantum? HBT interferometry of Gravitational waves to find a squeezed state?