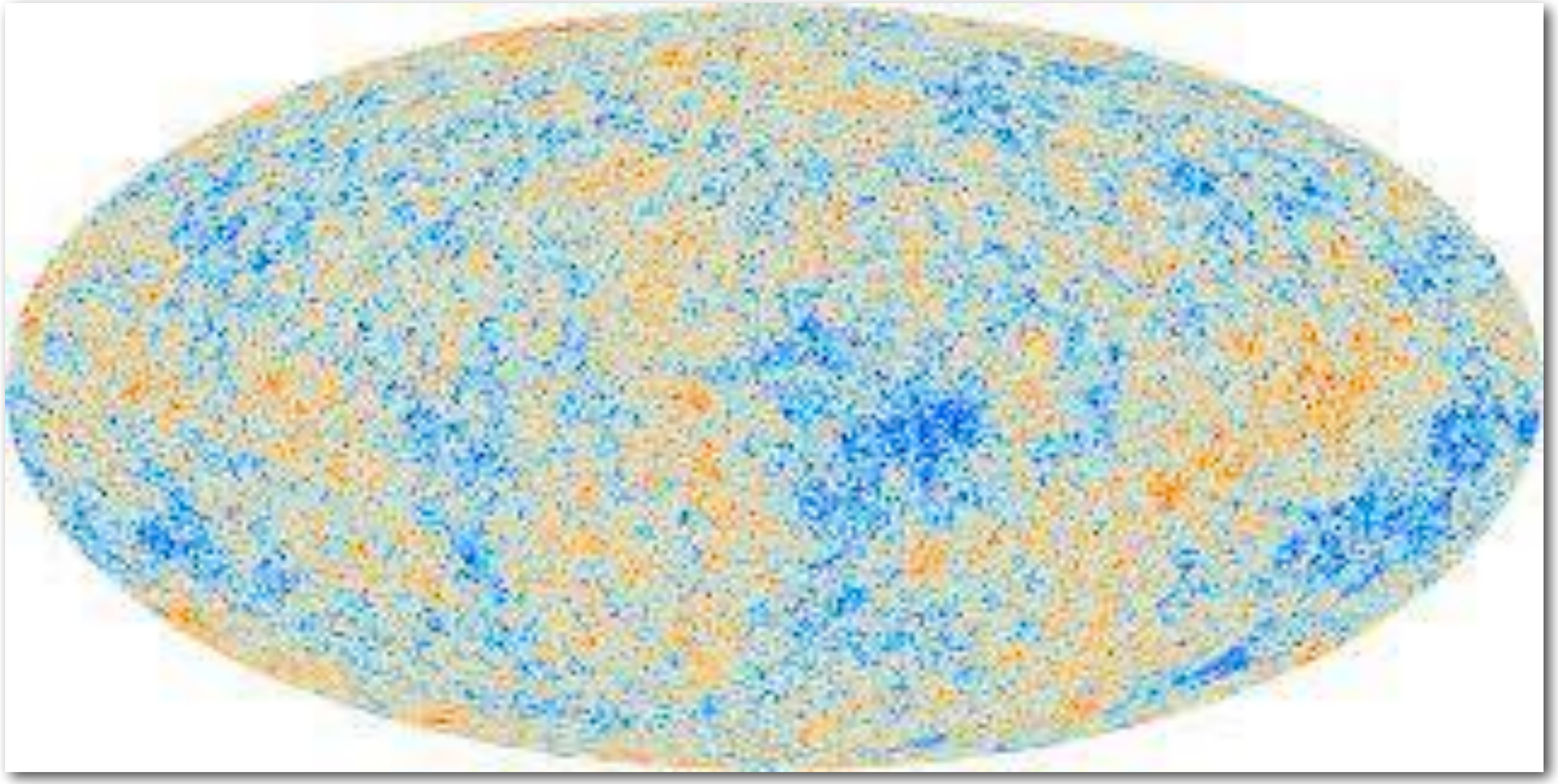
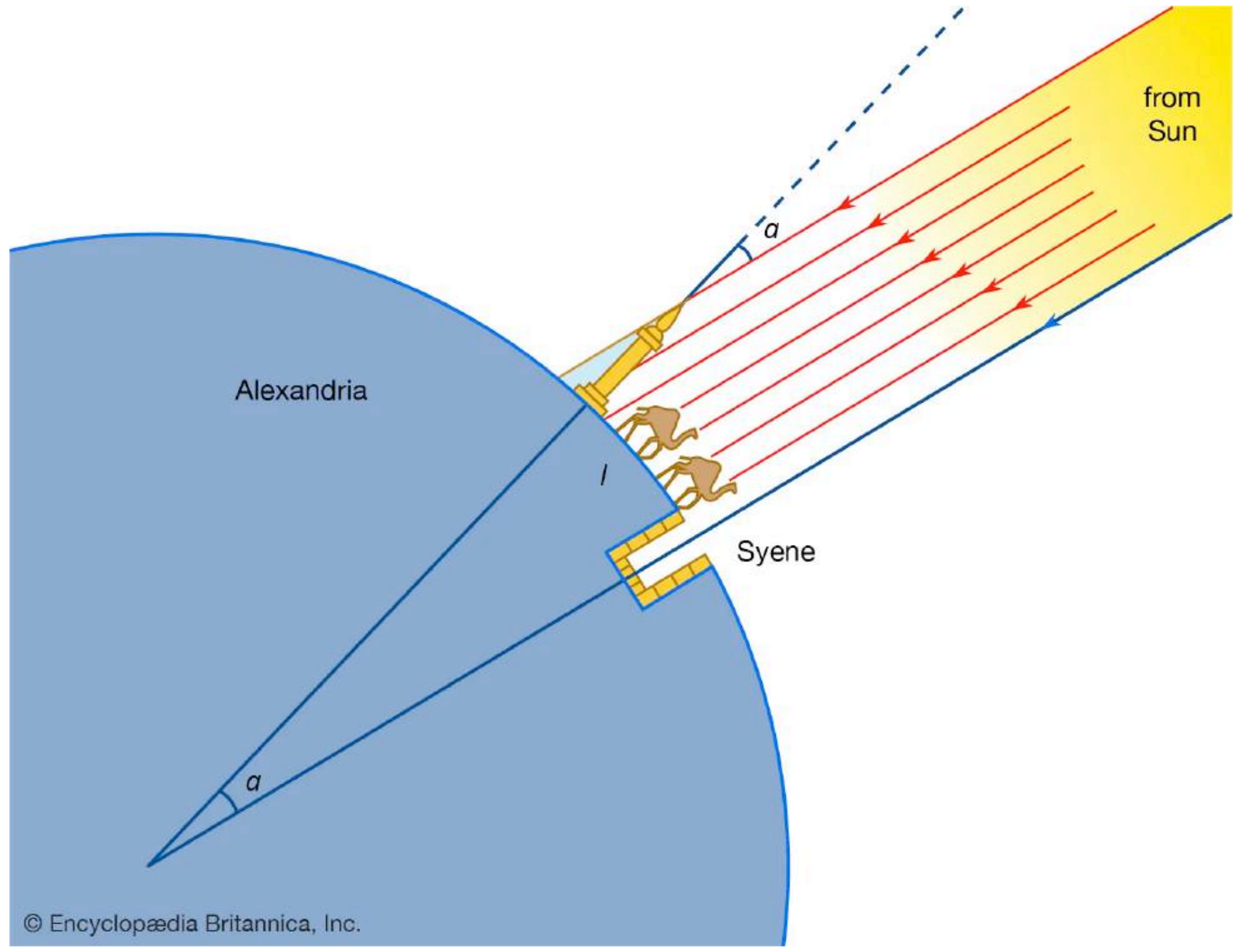
Is Planckian discreteness observable in cosmology?

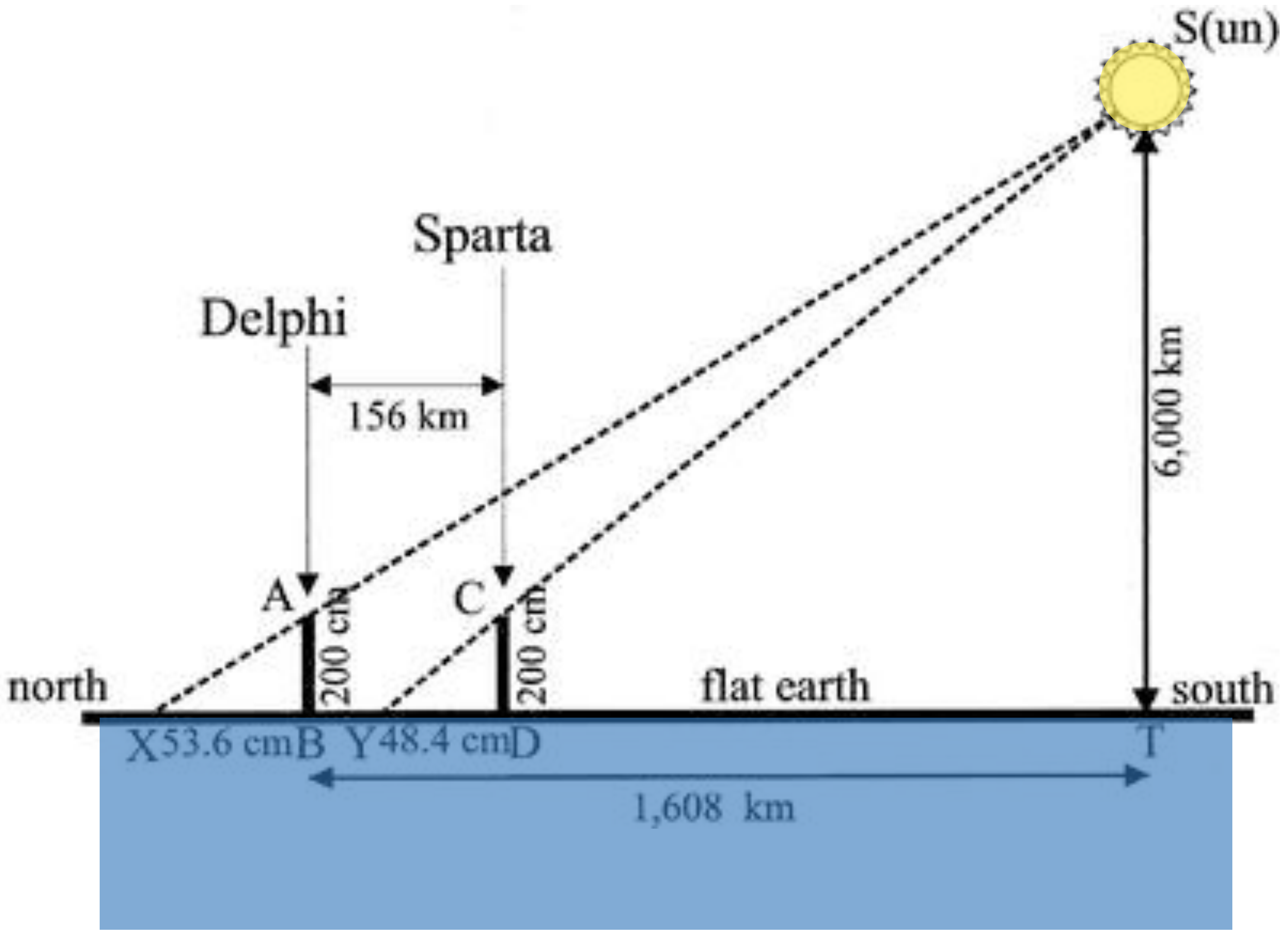


Alejandro Perez
FAU^2 workshop,
June 2024

Same data different theories



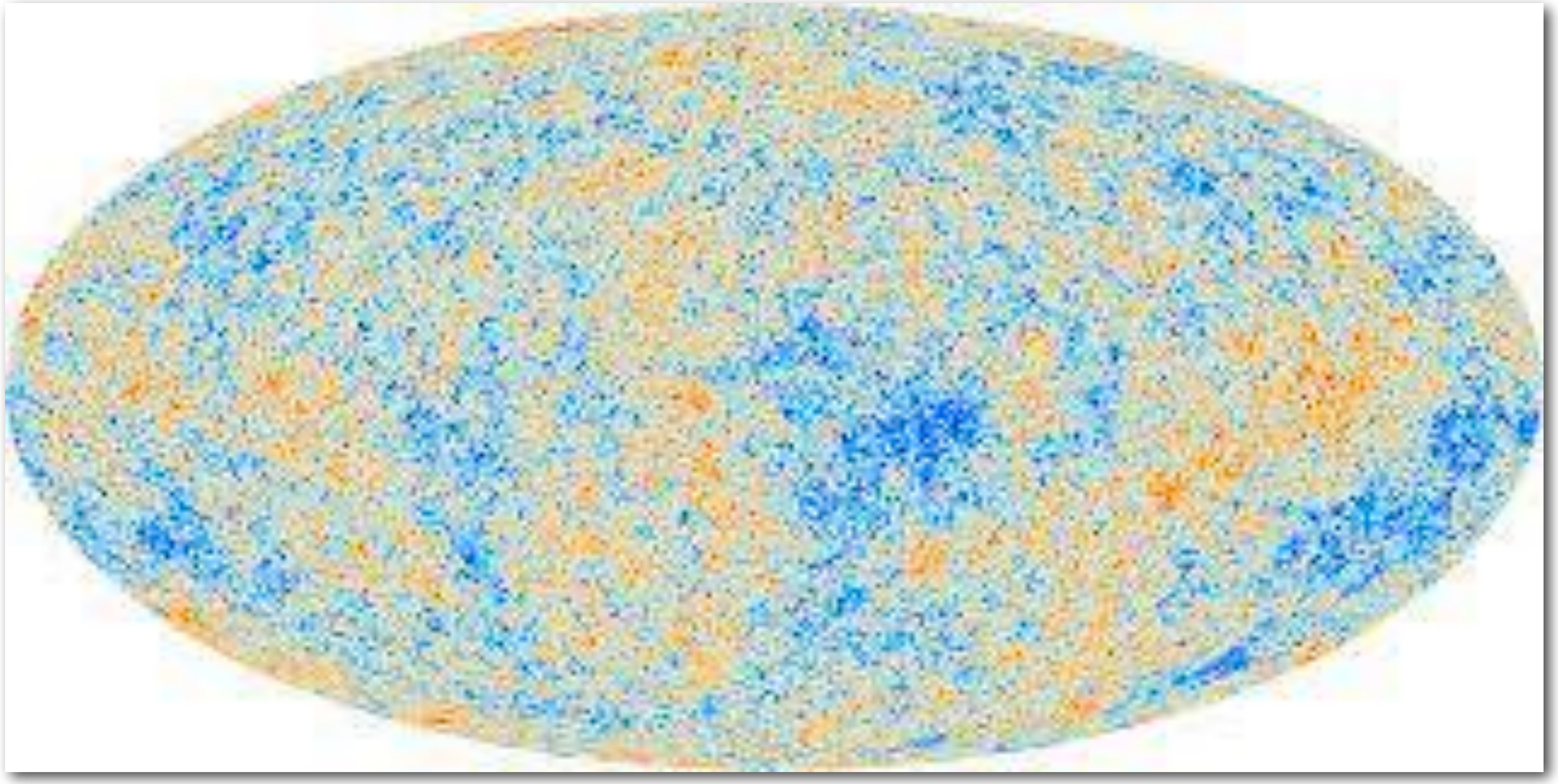
Eratosthenes, 240bc



(perhaps) Anaxagoras, 450bc

Couprie, D.L. (2018). Anaxagoras and the Measurement of the Sun and Moon. In: When the Earth Was Flat. Historical & Cultural Astronomy. Springer, Cham. https://doi.org/10.1007/978-3-319-97052-3_11

The data: structure in the cosmic microwave background (CMB)



We can have some confidence in the story of the evolution of the universe from the time of electron–positron annihilation to the present, as told in the previous three chapters. About earlier times, so far we can only speculate.

Weinberg, Chapter 4, Inflation,
in *`Cosmology', Oxford (2008)*

The plan of the talk:

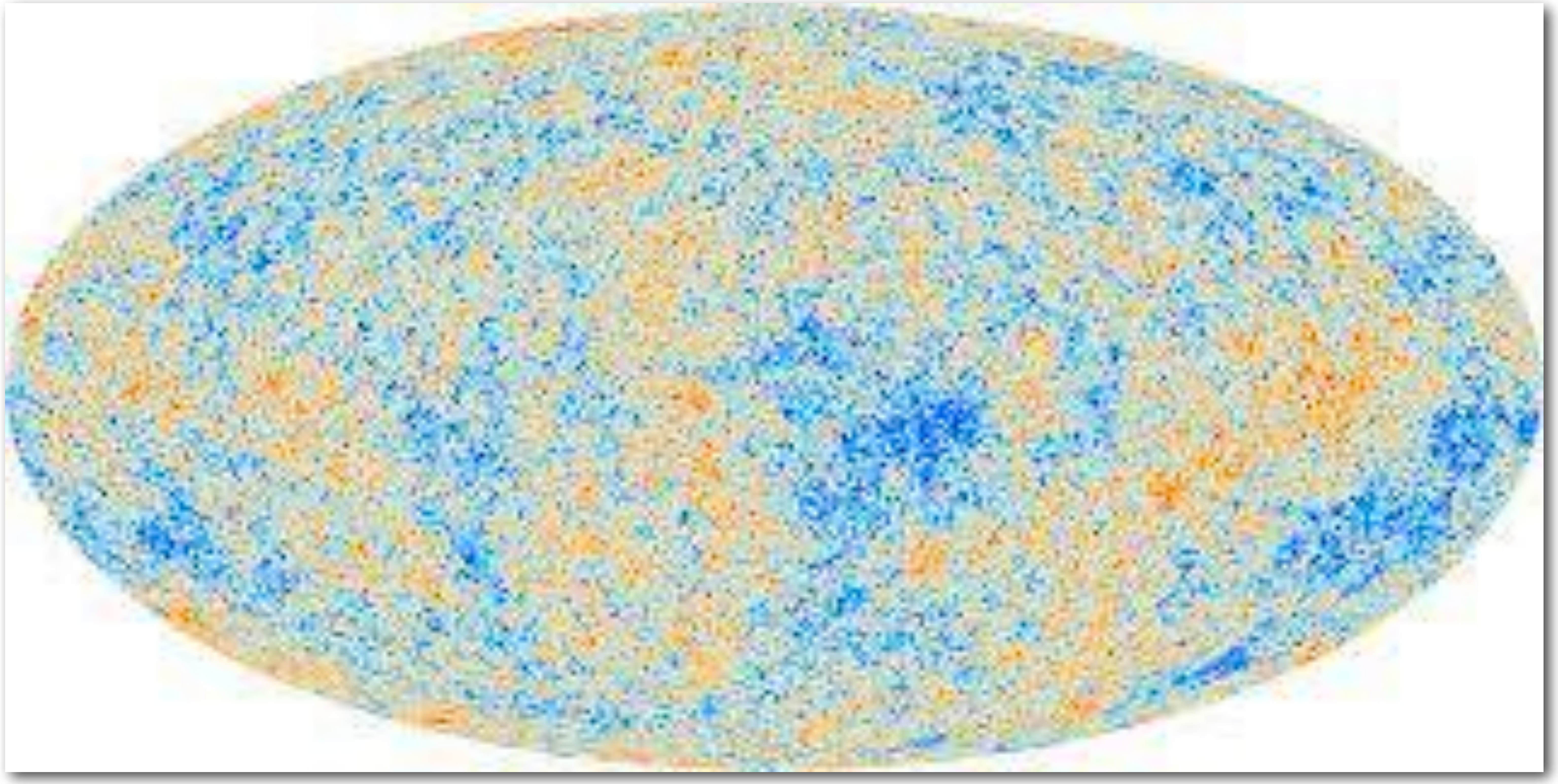
Introduction: a very brief account of the inflationary paradigm for the origin of structure in the CMB

Part I: I will present a different perspective based on quantum gravity inputs. The new version of the story is compatible with observations in the CMB but conceptually very different. At the very least it shows that there are more than one possibility (conceptually speaking)

Part II: The previous discussion opens an un-expected possibility: The big bang (reheating) could have been as hot as the Planck scale. With some extra hypothesis (motivated again by quantum gravity) a natural candidate of dark matter particle appears as a prediction.

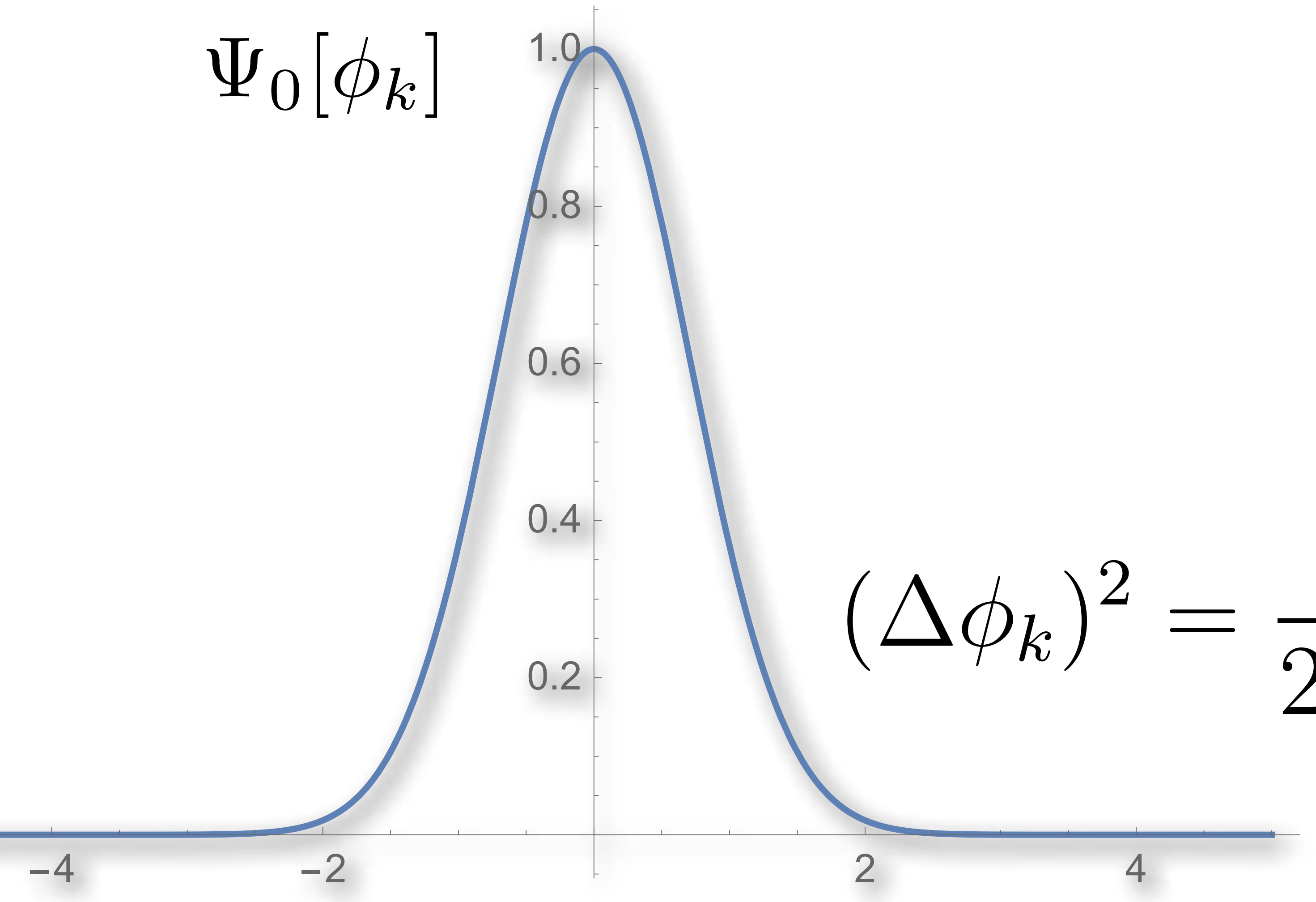
We propose a protocol for direct detection of such dark matter candidate.

The data: structure in the cosmic microwave background (CMB)



The standard inflationary theory of primordial inhomogeneities

… from Wald and Hollands 2002



$$(\Delta\phi_k)^2 = \frac{1}{2a^3(k/a)}$$

The Lagrangian for a single Fourier mode

$$L_k = \frac{a^3}{2}[|d\phi_k/dt|^2 - \frac{k^2}{a^2}|\phi_k|^2]$$

$$\frac{d^2\phi_k}{dt^2} + 3H\frac{d\phi_k}{dt} + \frac{k^2}{a^2}\phi_k = 0$$

When k/a<H
the friction term wins
and modes freeze!

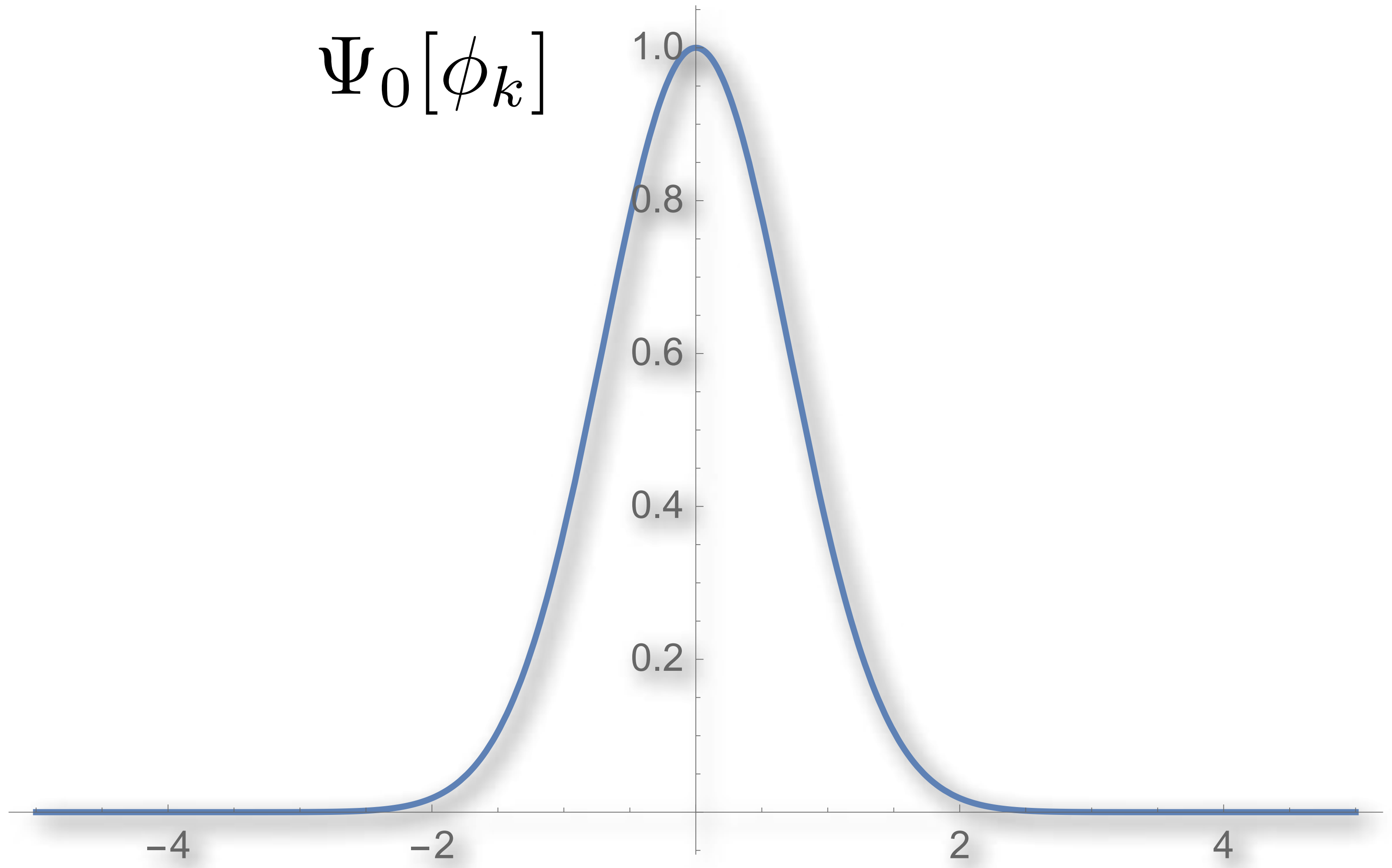
The fluctuations
of the scalar field modes
after horizon crossing are
scale invariant

$$(\Delta\phi_k)^2\Big|_{\frac{k}{a}=H} = \frac{H^2}{2k^3}$$

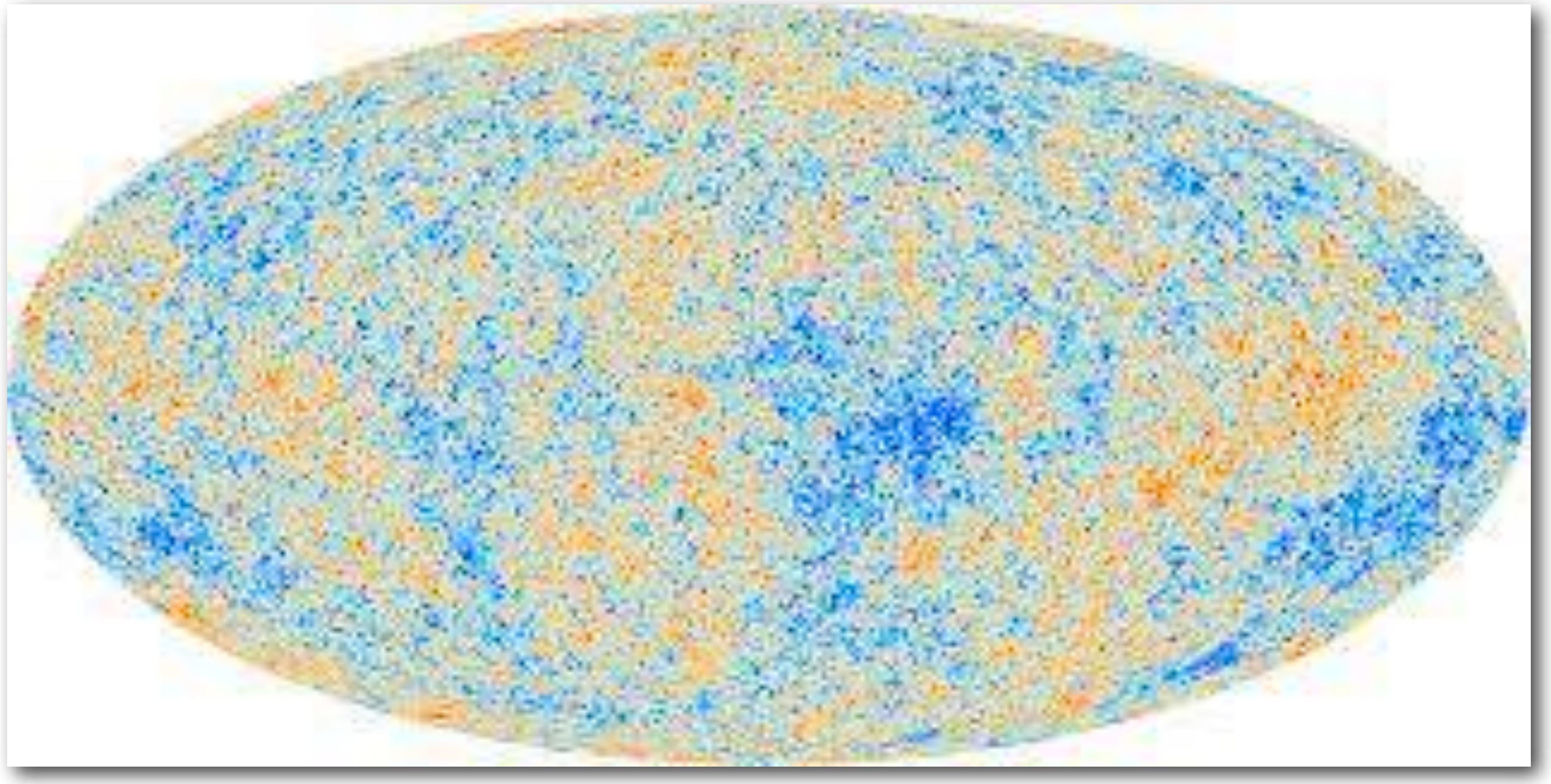
The standard inflationary theory of primordial inhomogeneities

… from Wald and Hollands 2002

“In order for the above initial fluctuation spectrum of ϕ_k to produce a corresponding initial fluctuation spectrum of the density perturbations, it is necessary that the scalar field also make a large, essentially classical contribution to the stress-energy of the universe.”



$$(\Delta\phi_k)^2\Big|_{\frac{k}{a}=H} = \frac{H^2}{2k^3}$$



Quantum fluctuations are transformed into density fluctuations by something like a measurement turning them into classical fluctuations after some form of *collapse of the wave function*

The expectation value of the energy-momentum tensor is homogeneous and isotropic in this state.

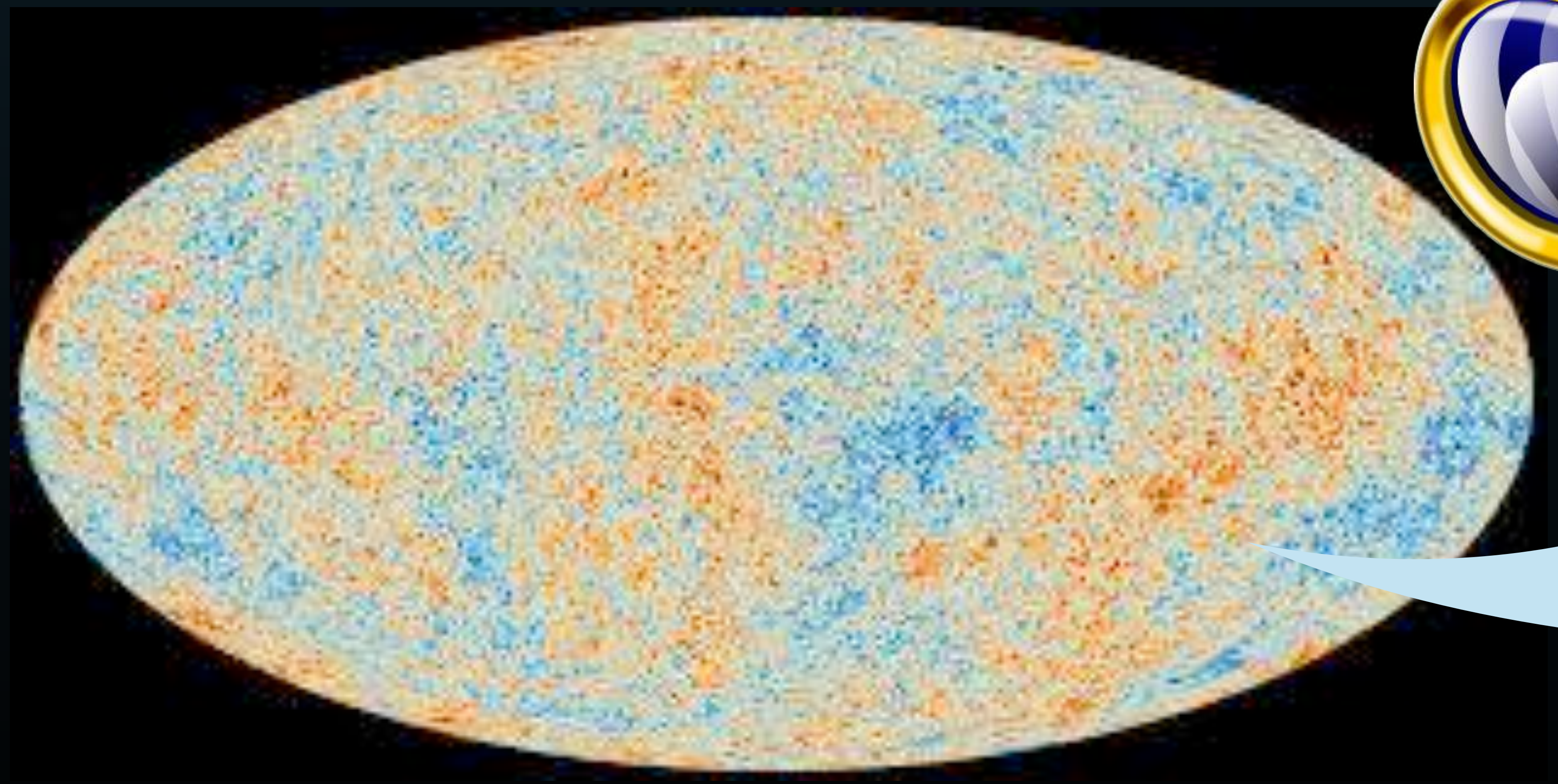
$$\langle 0|T_{ab}(t,\vec{x})|0\rangle = \langle 0|T_{ab}(t,\vec{x}+\vec{r})|0\rangle$$

The cosmological Schroedinger cat tension (the measurement problem in QM)

On the quantum origin of the seeds of cosmic structure

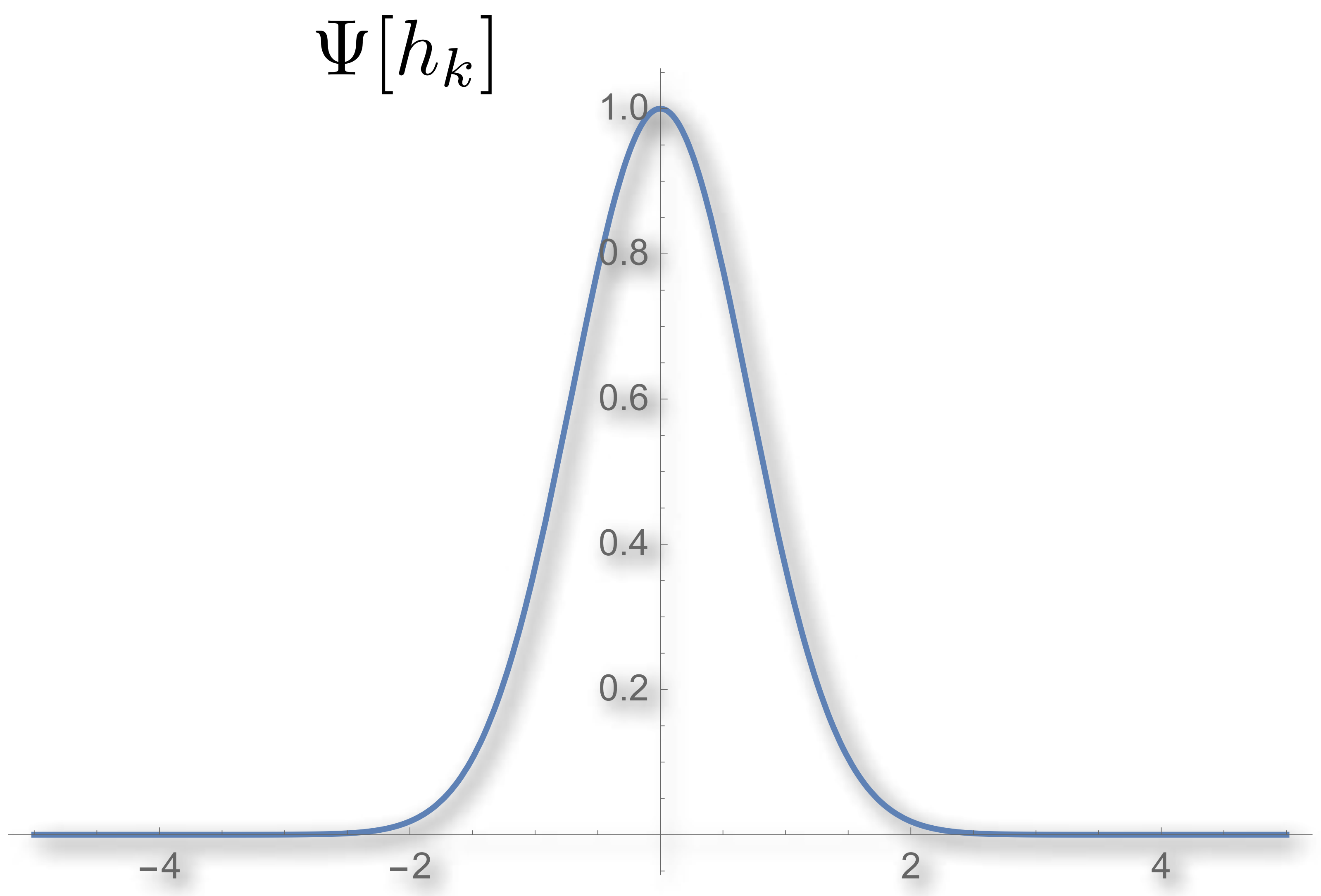
Alejandro Perez (Penn State U. and Marseille, CPT), Hanno Sahlmann (Penn State U.), Daniel Sudarsky (Penn State U. and Mexico U., ICN) (Aug, 2005)

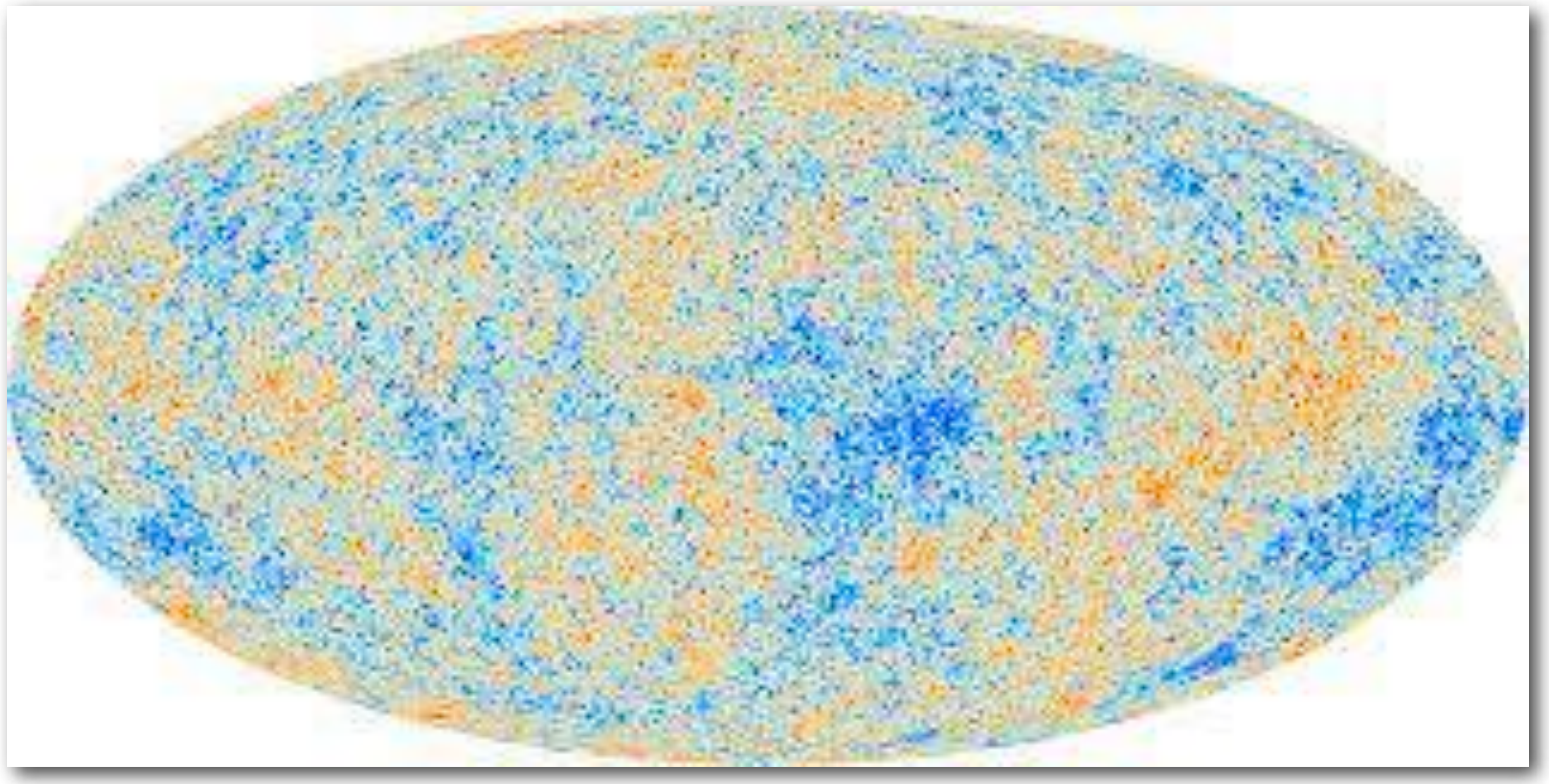
Published in: *Class.Quant.Grav.* 23 (2006) 2317-2354 • e-Print: gr-qc/0508100 [gr-qc]



The gravitational waves spectrum

The relationship between the scalar field fluctuations and the scalar metric fluctuations depends on the details of inflation via the linearised Einstein equations



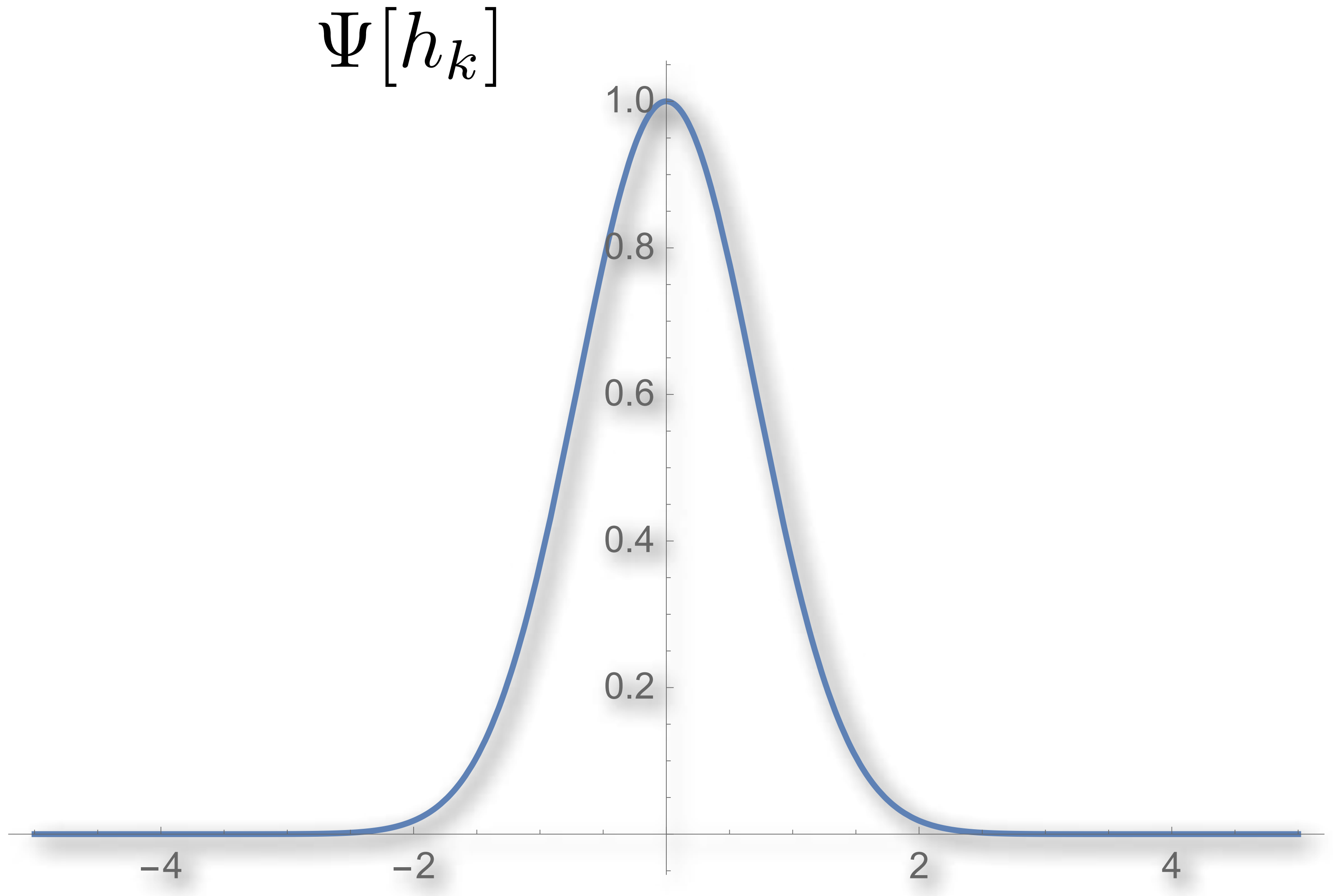


$$(\Delta h_k)^2\Big|_{\frac{k}{a}=H} = \frac{H^2}{m_p^2 k^3}$$

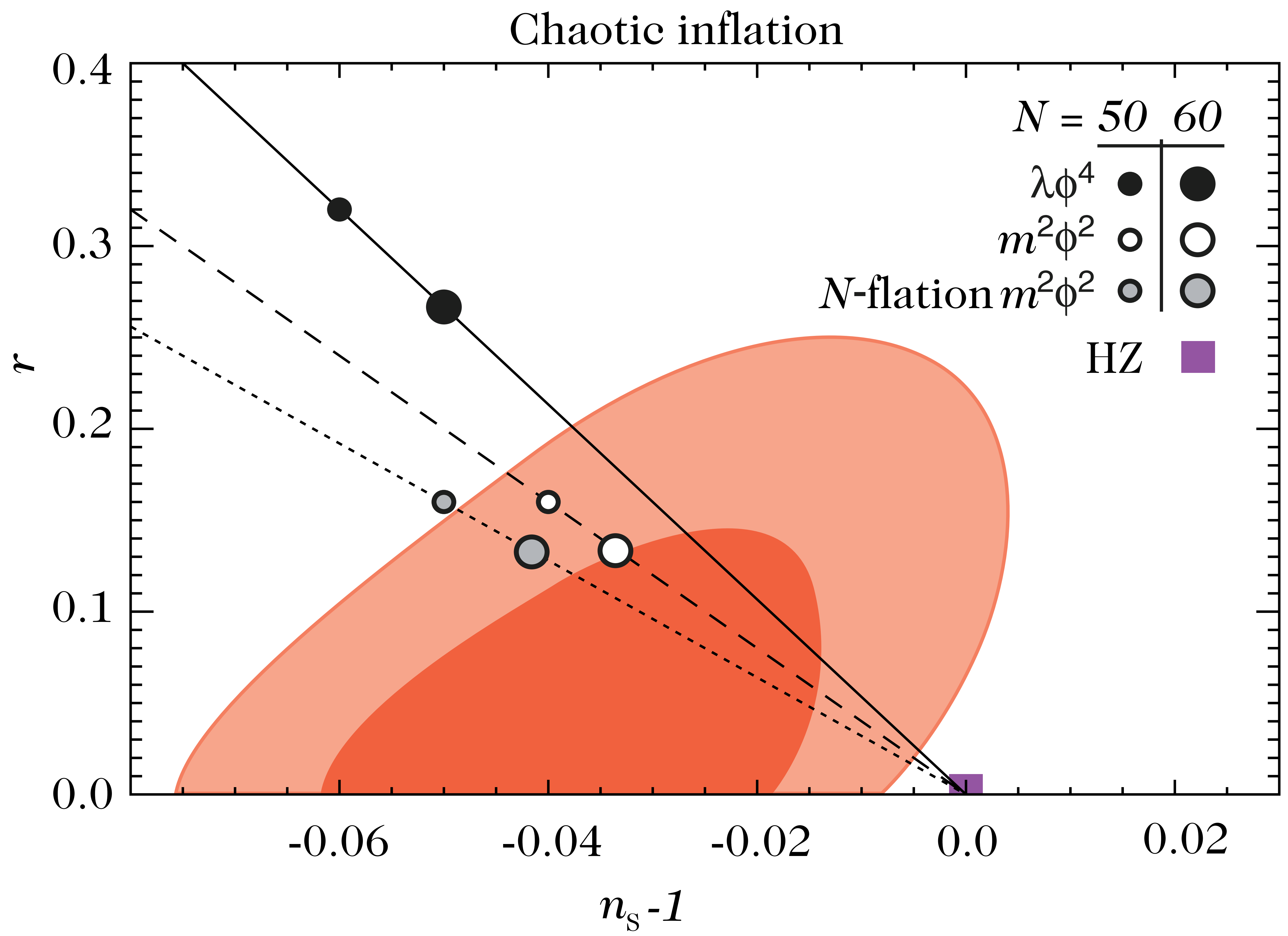
The gravitational wave spectrum depends only on the scale of inflation

The absence of traces of gravitational waves in the CMB implies (in the context of the standard theory of inflation) that the scale H must be much lower than the Planck scale, perhaps even too low for inflation to be natural

The standard inflationary theory of primordial inhomogeneities



$$(\Delta h_k)^2\Big|_{\frac{k}{a}=H} = \frac{H^2}{m_p^2 k^3}$$



The absence of traces of gravitational waves in the CMB implies (in the context of the standard theory of inflation) that the scale H must be much lower than the Planck scale, perhaps even too low for inflation to be natural

PART I:

Planckian discreteness as seeds for cosmic structure

Lautaro Amadei (Marseille, CPT), Alejandro Perez (Marseille, CPT) (Apr 18, 2021)

Published in: *Phys.Rev.D* 106 (2022) 6, 063528 • e-Print: 2104.08881 [gr-qc]

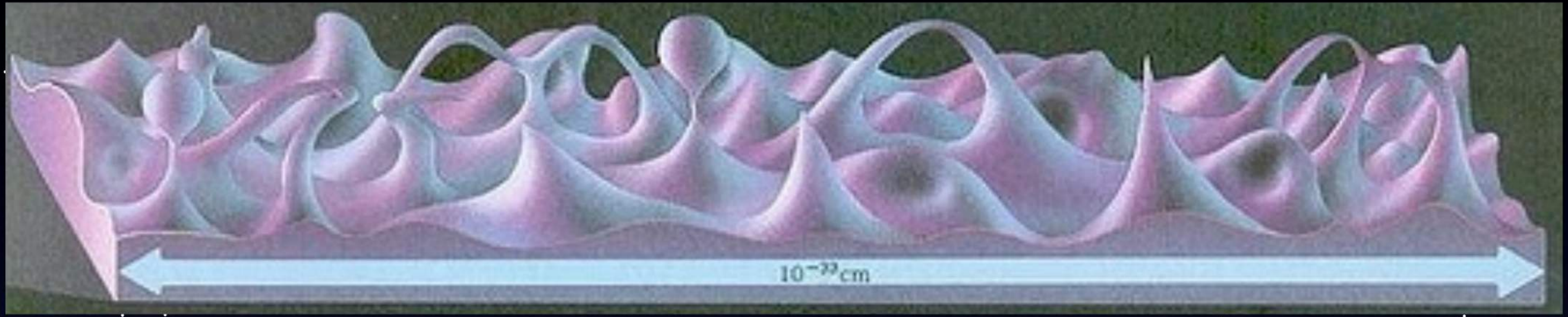
An alternative scenario: inhomogeneities would be born from the interaction of matter with the fundamental granularity.

$$\langle\psi|T_{ab}(t,\vec{x})|\psi\rangle \neq \langle\psi|T_{ab}(t,\vec{x}+\vec{r})|\psi\rangle$$

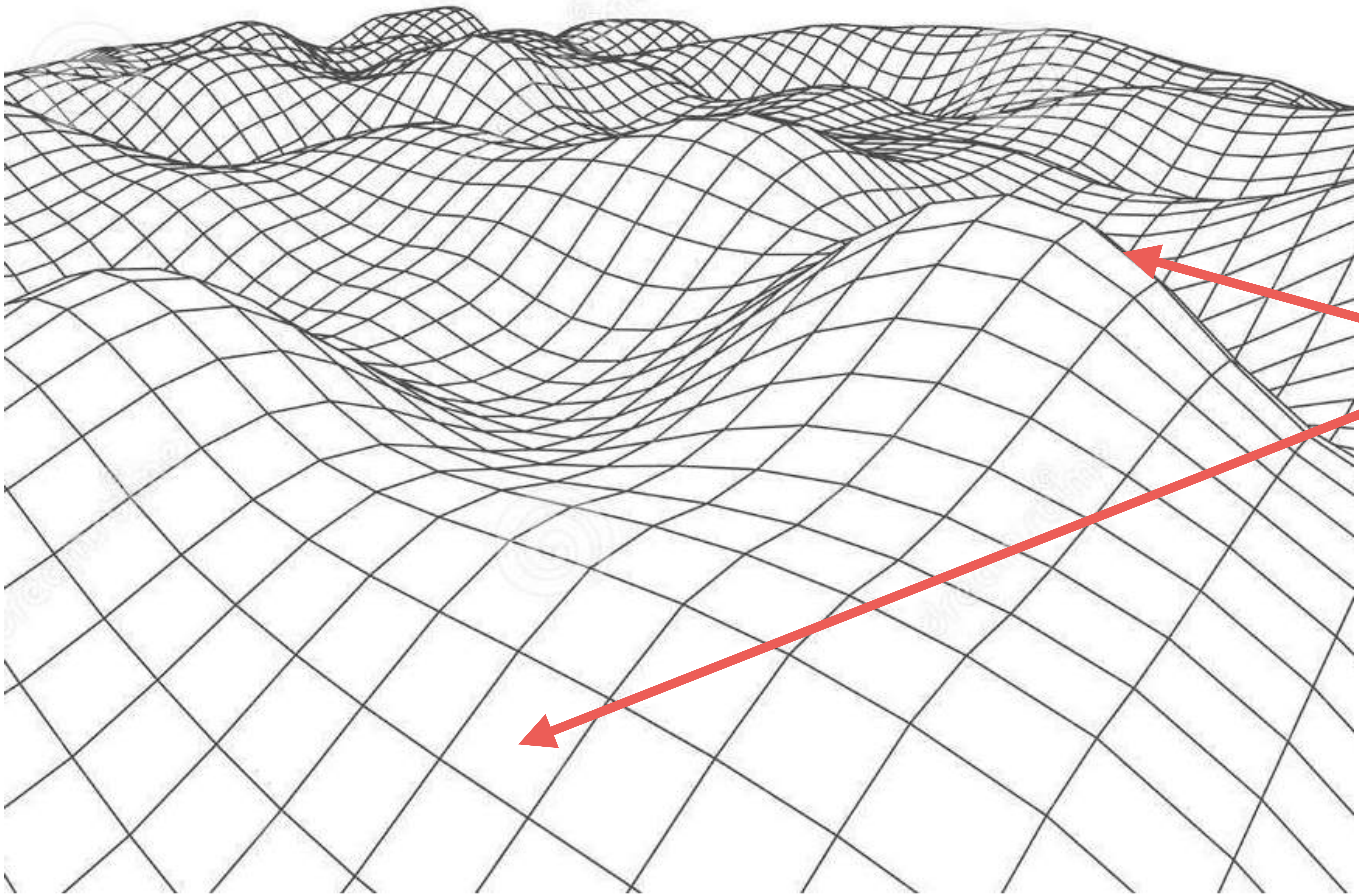
The scenario avoids the cosmological Schroedinger cat tension!

PLANCKIAN DISCRETENESS INDUCING INHOMOGENEITIES

QUANTUM GRAVITY DISCRETENESS BREAKS cosmological symmetries AT THE PLANCK SCALE



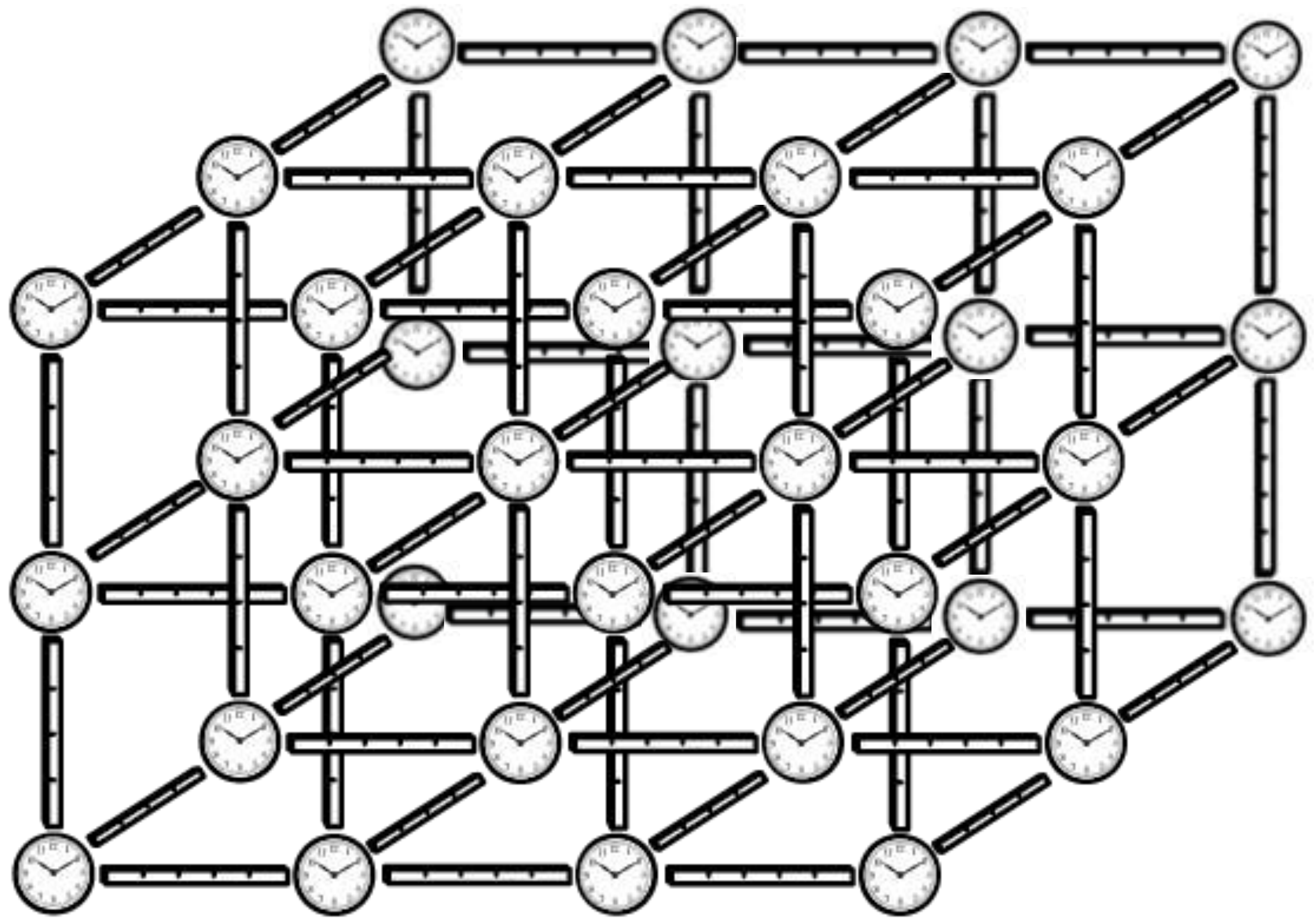
Discreteness and Lorentz invariance



Collins, AP, Sudarsky, Urrutia, Vusetich; *Phys. Rev. Letters.* 93 (2004).

Discreteness should manifest itself in regions of non trivial curvature

To probe **Planck scale** we need a **breaking of scale invariance (need a ruler!)**



Scale-invariance-breaking degrees of freedom are those where the phenomenology of granularity should primarily manifest.

The basic idea in a picture

$$\delta\phi_k \equiv \langle\psi|\widehat{\delta\phi_k}|\psi\rangle \neq 0, \quad k \leq m_p a$$

$$\delta\ddot{\phi}_{\vec{k}} + 3H\delta\dot{\phi}_{\vec{k}} + \frac{k^2}{a^2}\delta\phi_{\vec{k}} = \xi_{\vec{k}}(t - t_k^{\mathrm{HC}})$$

Emerging semiclassical scalar field fluctuations at lower but close to fundamental scale

granularity of the microscopic theory from which geometry & matter emerge

We assume inflation is driven by a Planckian cosmological constant

$$H \lesssim m_p$$

Modelling the generation of inhomogeneities via a Brownian diffusion:

$$\delta\phi_k \equiv \langle\psi|\widehat{\delta\phi_k}|\psi\rangle \neq 0, \quad k \leq m_p a$$

The generation process is modelled via an homogeneous and isotropic **stochastic process**

double-brakets $\langle\!\langle\rangle\!\rangle$ $\equiv$ ensemble average

$$\langle\!\langle\delta\phi_k\rangle\!\rangle = 0$$

$$\langle\!\langle\delta\phi_k\delta\phi_q\rangle\!\rangle = P_{\delta\phi}(k)\ \delta(\vec{k}+\vec{q})$$

$$\langle\!\langle\delta\phi(t,\vec{x})\delta\phi(t,\vec{x})\rangle\!\rangle = \frac{1}{(2\pi)^3}\int_{\mu}^{a(t)m_p} dk^3 P_{\delta\phi}(k)$$

Energy cost of the a Brownian diffusion:

$$\langle\langle \delta\phi(t,\vec{x})\delta\phi(t,\vec{x})\rangle\rangle = \frac{1}{(2\pi)^3}\int_{\mu}^{a(t)m_p} dk^3 P_{\delta\phi}(k)$$

$$\langle\langle T_{ab}[\delta\phi]\rangle\rangle = \langle\langle \nabla_a\delta\phi\nabla_b\delta\phi\rangle\rangle - \frac{g_{ab}}{2}\langle\langle \nabla_\alpha\delta\phi\nabla^\alpha\delta\phi\rangle\rangle \approx \underbrace{\frac{\langle\langle(\vec{\nabla}\delta\phi)^2\rangle\rangle}{2a^2}}_{\equiv\rho^{(2)}} u_a u_b - \underbrace{\frac{\langle\langle(\vec{\nabla}\delta\phi)^2\rangle\rangle}{6a^2}}_{\equiv P^{(2)}} h_{ab}$$

$$\frac{dW}{dt} = -\nabla^a \langle\langle T_{ab}\rangle\rangle u^b$$

$$\frac{dW}{dt}[P_{\delta\phi}] \equiv \frac{d}{dt}\rho^{(2)} + 3H\left(\rho^{(2)} + P^{(2)}\right) = \frac{d}{dt}\rho^{(2)} + 2H\rho^{(2)} = J.$$

$$J = \gamma H^5$$

Scale invariant power spectrum!

$$P_{\delta\phi}(k) = 2\gamma\frac{H^2}{k^3}$$

$\gamma \equiv$ is a diffusion parameter

INFLATIONARY "CONVEYOR BELT"

$$J = \gamma H^5$$

$$P_{\delta\phi}(k) = 2\gamma \frac{H^2}{k^3}$$

Gravitational waves are suppressed

$$\ddot{h}_{ij}^{(2)} - \frac{\nabla^2 h_{ij}^{(2)}}{a^2} + 3\frac{\dot{a}}{a}\dot{h}_{ij}^{(2)} = \frac{\{32\pi G \partial_i \delta\phi \partial_j \delta\phi\}^{TT}}{a^2}$$

$$P_{\delta\phi}(k) = 2\gamma \frac{H^2}{k^3}$$

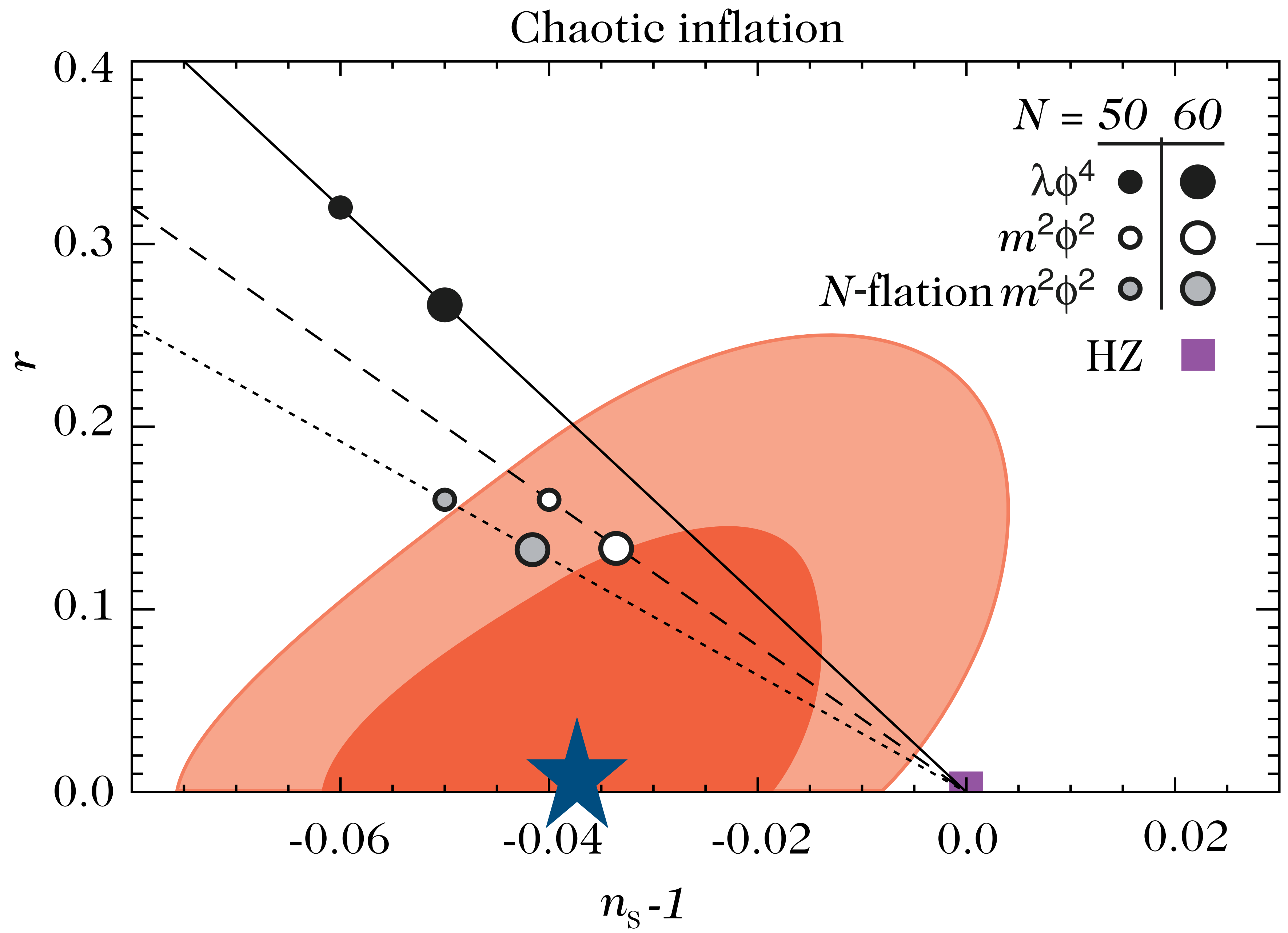
Primordial gravitational waves from Planckian discreteness

G. Bengochea, G. Leon, AP (in preparation)

$$P_h(k) \simeq \gamma^2 \frac{H^4}{m_p^4 k^3}$$

No restrictions from lack of observation of GW on the scale H!

An alternative mechanism for the production of a scale invariant power spectrum of primordial inhomogeneities in a scalar field with a very small scalar-to-tensor ratio (as required from observations)



Planckian discreteness as seeds for cosmic structure

Lautaro Amadei (Marseille, CPT), Alejandro Perez (Marseille, CPT) (Apr 18, 2021)

Published in: *Phys.Rev.D* 106 (2022) 6, 063528 • e-Print: 2104.08881 [gr-qc]

There is no quantum to classical transition
and reheating can have a temperature close to the Planck scale

$$\langle\psi|T_{ab}(t,\vec{x})|\psi\rangle \neq \langle\psi|T_{ab}(t,\vec{x}+\vec{r})|\psi\rangle$$

PART II:

The gravitational miracle: a natural dark matter candidate follows from the assumption that H can be close to the Planck scale.

Dark matter as stable Planckian primordial black holes and how to detect them

Particle physics dark matter candidates

WIMPS: particles that arise naturally if supersymmetry exists. Their abundance would be just about the right one in the context of cosmology (*the WIMP-miracle*).

However, all searches have led to negative results and consensus is growing in thinking that this option is being ruled out by observations.

AXION field: expected to exist on theoretical grounds as it would provide the means to resolve the so-called *strong CP problem*. Neutrons have no (so far undetected) electric dipole moment (the theta parameter of QCD is very small).

Under active search observationally.

A quantum gravity dark matter candidate

Planck mass particle interacting gravitationally only: such would be the *darkest* of possibilities. It is natural to expect that such a particle would be part of the spectrum of physics emerging from *quantum gravity*.

As a mental image we could think of them as Planckian black holes.

Such tiny BHs are usually ruled out as DM candidates because they would be highly unstable due to Hawking radiation. BUT Hawking calculation is only valid for macroscopic BHs.

Arguments and models in loop quantum gravity suggest that black holes stop Hawking radiating close to the Planck scale (they become effectively extremal due to quantum effects).

And most strikingly, as I argue now, their abundance would be just right if the big bang is hot enough: ***the gravitational miracle!***

Planckian discreteness as seeds for cosmic structure

Lautaro Amadei (Marseille, CPT), Alejandro Perez (Marseille, CPT) (Apr 18, 2021)

Published in: *Phys.Rev.D* 106 (2022) 6, 063528 • e-Print: 2104.08881 [gr-qc]

Dark matter as Planck relics without too exotic hypotheses

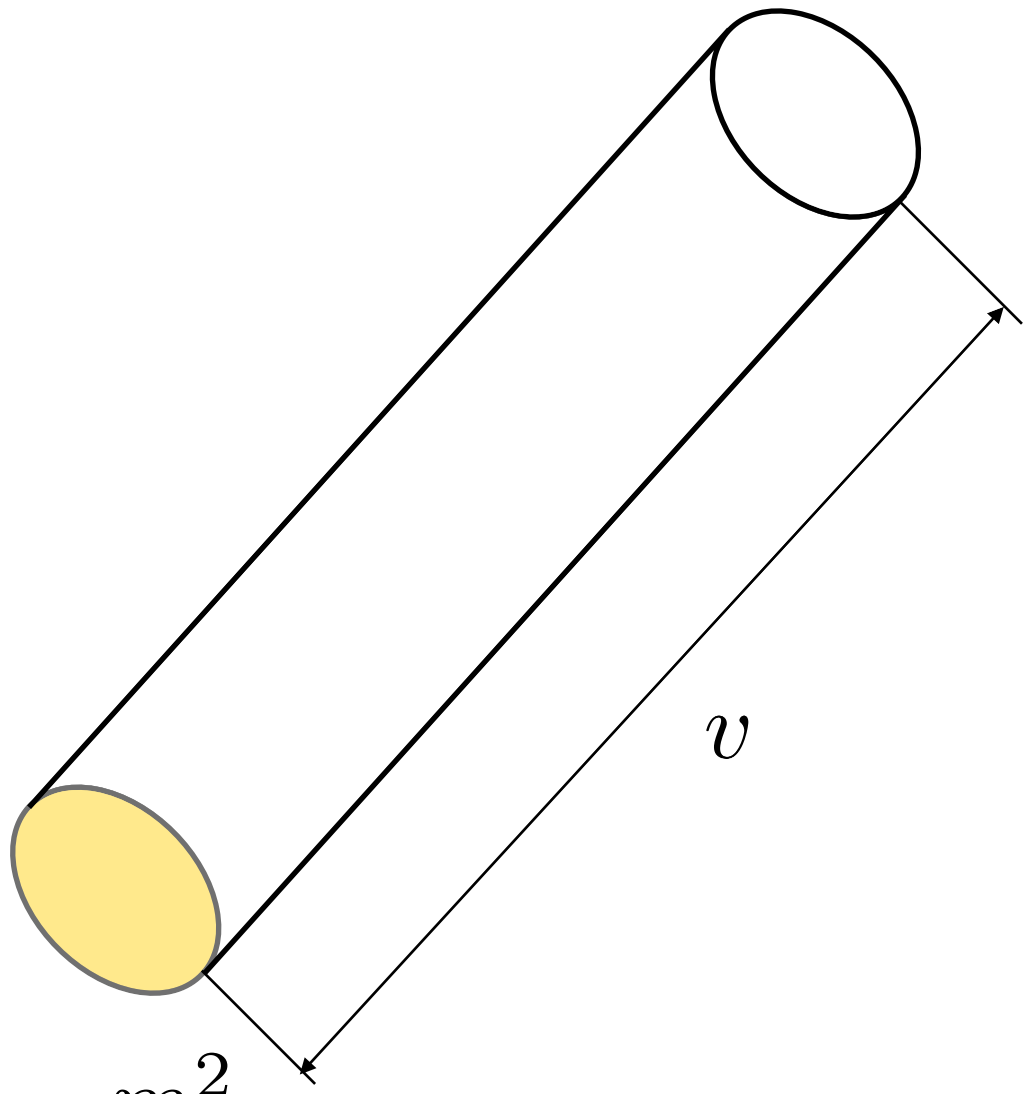
Aurélien Barrau (LPSC, Grenoble), Killian Martineau (LPSC, Grenoble), Flora Moulin (LPSC, Grenoble), Ngono (LPSC, Grenoble) (Jun 24, 2019)

Published in: *Phys.Rev.D* 100 (2019) 12, 123505 • e-Print: 1906.09930 [hep-ph]

The gravitational miracle

$$\Gamma \equiv n\sigma v < H$$

$$n \approx g_s T^3 \qquad \rho \propto g_s T^4$$



$$\sigma \approx \frac{m_{pbh}^2}{m_p^4}$$

$$\Gamma \approx \frac{g_s T^3 m_{pbh}^2}{m_p^4} \qquad H \approx \sqrt{g_s}\frac{T^2}{m_p}$$

$$T_D = \frac{m_p}{\sqrt{g_s}}\left(\frac{m_p}{m_{pbh}}\right)^2 \lesssim m_p$$

$$F \equiv \frac{\rho_{DM}(T_D)}{\rho(T_D)} \approx \exp\left(-\frac{m_{pbh}}{T_D}\right) \approx \exp\left(-\sqrt{g_s}\frac{m_{pbh}^3}{m_p^3}\right)$$

$$\rho_{DM}(T) = \rho_{DM}(T_D)\frac{T^3}{T_D^3} \approx \rho(T_D)F\frac{T^3}{T_D^3} \approx \underbrace{\sqrt{g_s}\frac{T^3}{m_p^3}\frac{m_p^2}{m_{pbh}^2}\exp\left(-\sqrt{g_s}\frac{m_{pbh}^3}{m_p^3}\right)}_{\text{Need this factor order } 10^{-120} \text{ at } T=T_{\text{today}}} m_p^4$$

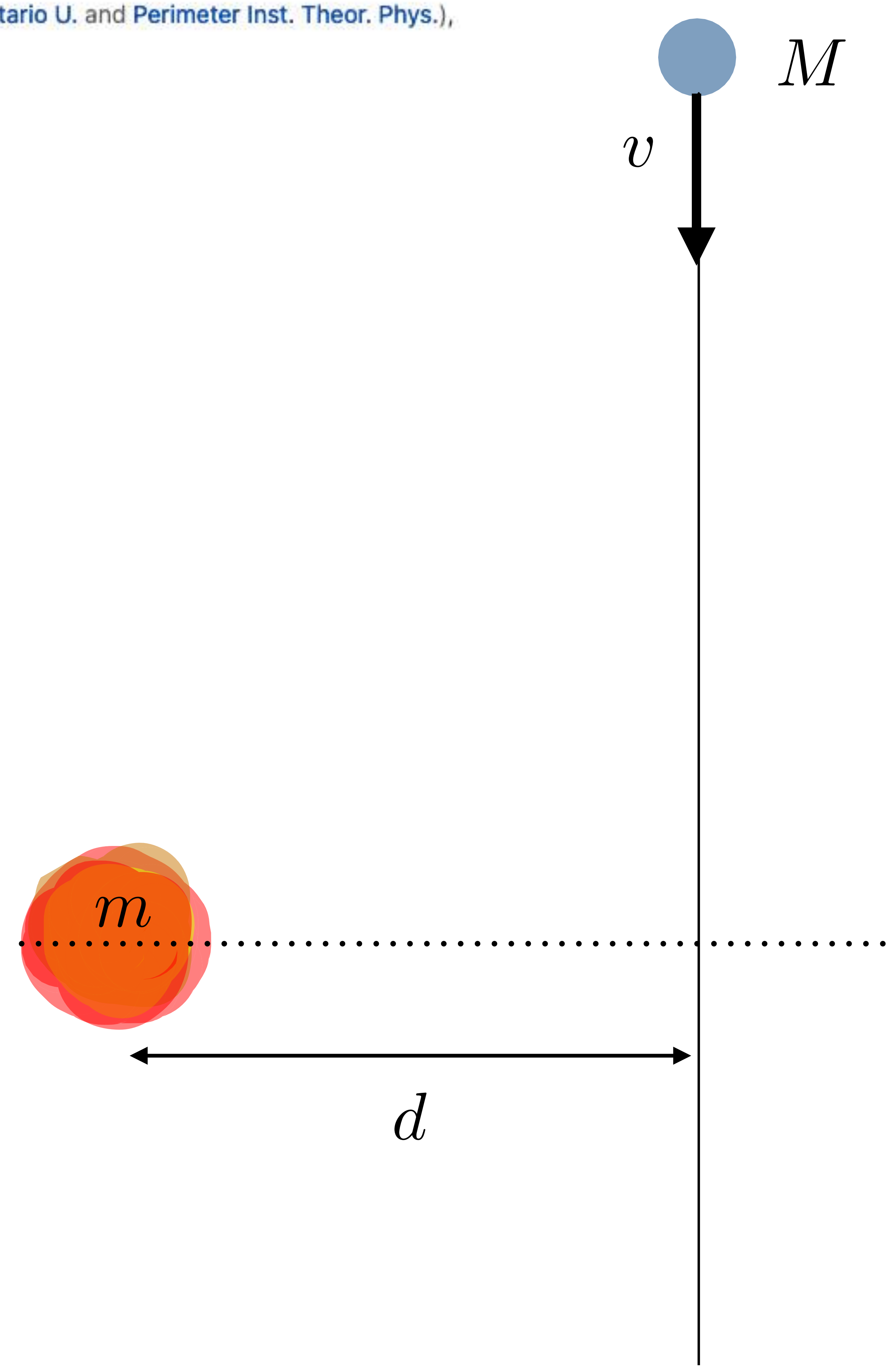
As g_s ranges from 100 to 2000, the mass m_{pbh} ranges from 1.8 m_p to 1.1 m_p!

How to detect such (purely gravitationally) interacting particles

Detecting Gravitationally Interacting Dark Matter with Quantum Interference

Alejandro Perez (Marseille, CPT), Carlo Rovelli (Marseille, CPT and Western Ontario U. and Perimeter Inst. Theor. Phys.), Marios Christodoulou (Vienna U.) (Sep 15, 2023)

e-Print: 2309.08238 [gr-qc]



Classical detection seems very hard

$$r_0 = d - \frac{c^2}{v^2}\frac{M}{m_p}\ell_p$$

where r_0 is the point of closest approach

Proposal for gravitational direct detection of dark matter

Daniel Carney (Joint Quantum Inst., College Park and NIST, Wash., D.C. and Fermilab), Sohitri Ghosh (Joint Quantum Inst., College Park), Gordan Krnjaic (Fermilab), Jacob M. Taylor (Joint Quantum Inst., College Park and NIST, Wash., D.C.)

Phys.Rev.D 102 (2020) 7, 072003 • e-Print: 1903.00492 • DOI: 10.1103/PhysRevD.102.072003

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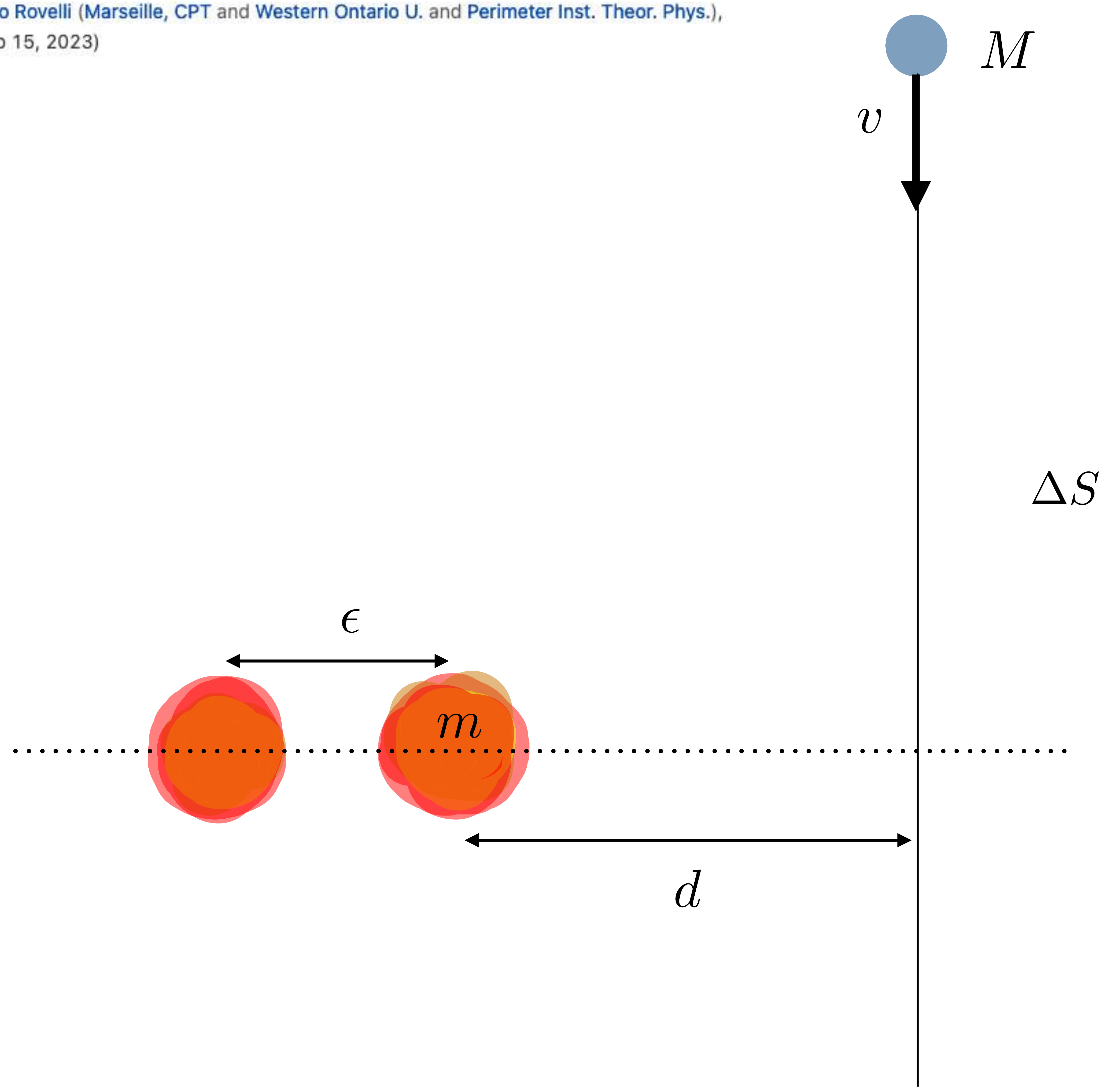

What about quantum mechanically (using interferometry)

$$\Delta S = \int dt \left(\frac{GmM}{\sqrt{d^2 + (vt)^2}} - \frac{GmM}{\sqrt{(d+\epsilon)^2 + (vt)^2}} \right)$$

$$\Delta S = 2\frac{GmM}{v} \log(1 + \epsilon/d) \approx 2\frac{GmM}{v}\frac{\epsilon}{d}$$

The correct approximation gives:

$$\Delta\phi = \frac{\Delta S}{\hbar} \approx 3\frac{mM}{m_p^2}\frac{c}{v}\frac{\epsilon}{d}$$

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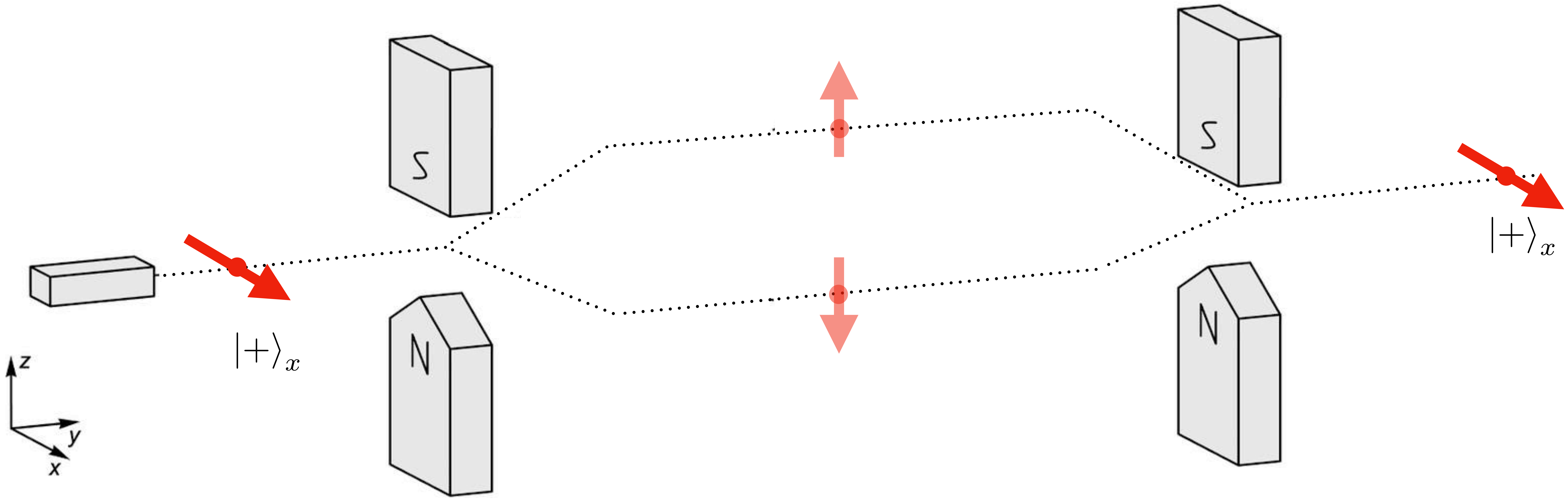
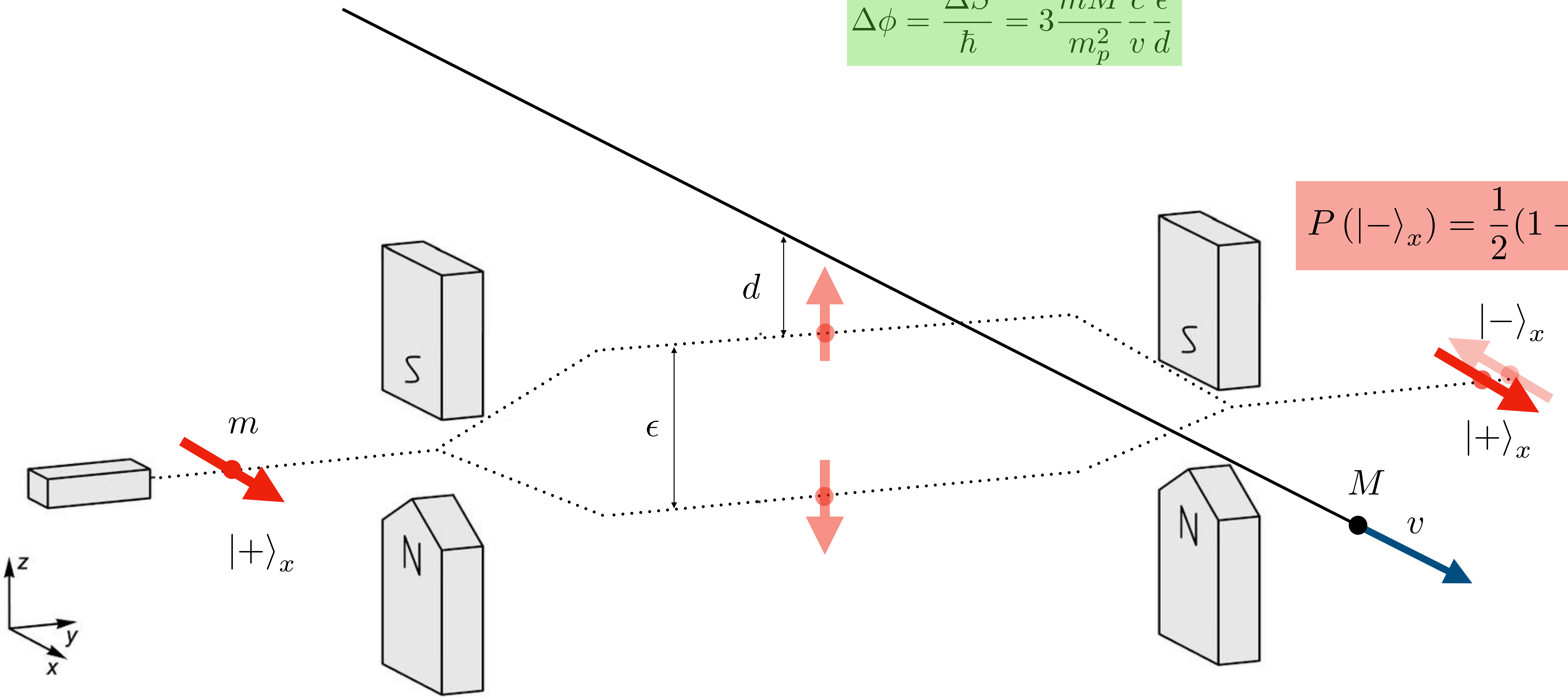


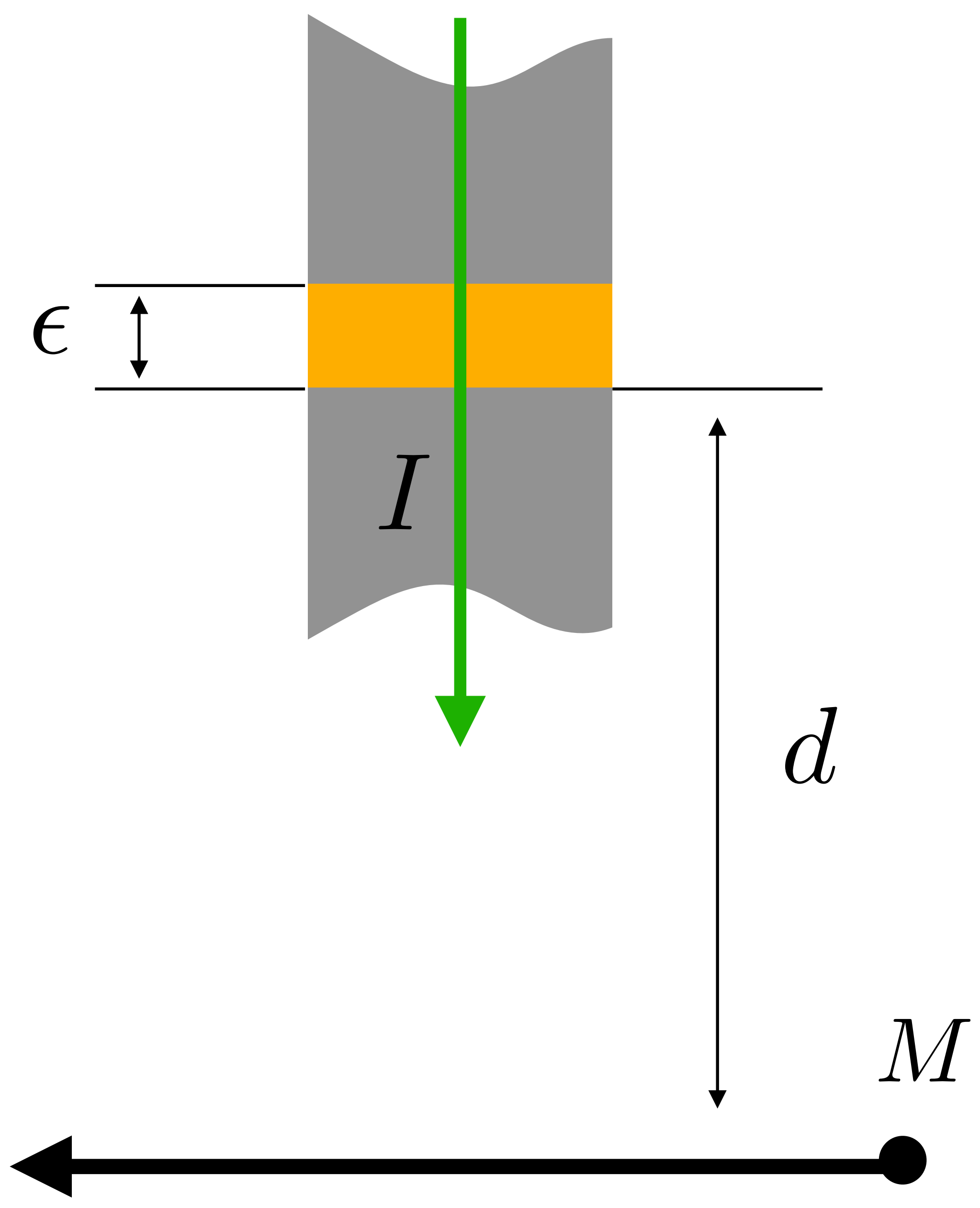
$$\Delta\phi = \frac{\Delta S}{\hbar} = 3\frac{mM}{m_p^2}\frac{c}{v}\frac{\epsilon}{d}$$



$$P\left(|-\rangle_x\right) = \frac{1}{2}(1-\cos(\Delta\phi))$$

The velocity of DM particles is $v \approx 10^{-3}c$. Assuming that $M \approx m_p$ (recall the gravitational miracle) means that putting in superposition a mass $m \approx 10^{-3} m_p$ one would reach $\Delta\phi \approx \epsilon/d$.

Improved protocol using Josephson junctions



The collective state of the electrons translates the probabilistic response of previous protocol into a directly measurable signal, circumventing the need of a statistical reconstruction of the phase. It is easy to see that the phase shift due to the interaction of the electrons with the DM particle gives rise to the current across the junction

$$I = I_c \sin(\Delta\phi_e)$$

$$\Delta\phi_e \approx 10^{-19}\epsilon/d$$

$$I \sim (\epsilon/d)s^{-1}$$

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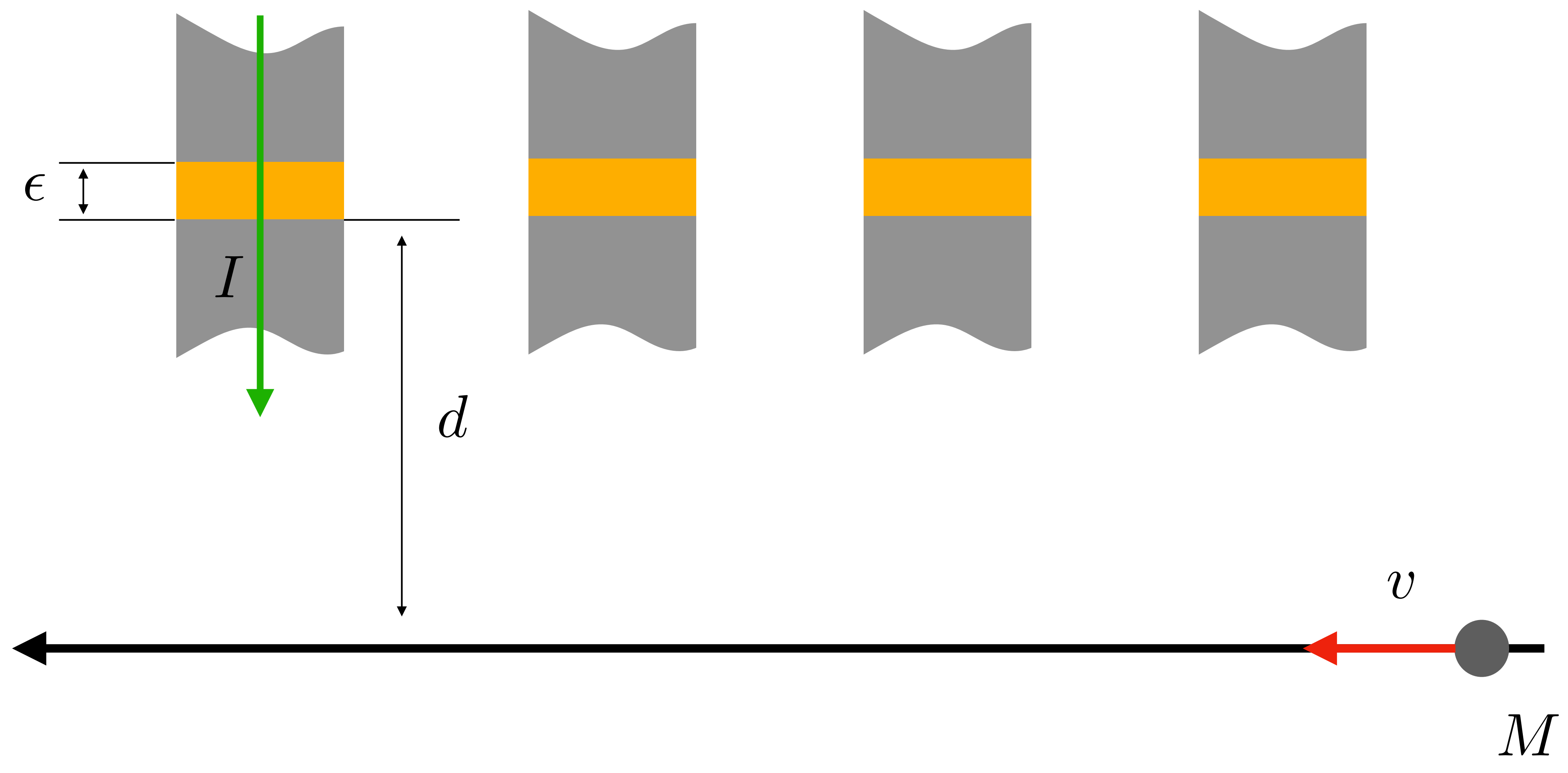
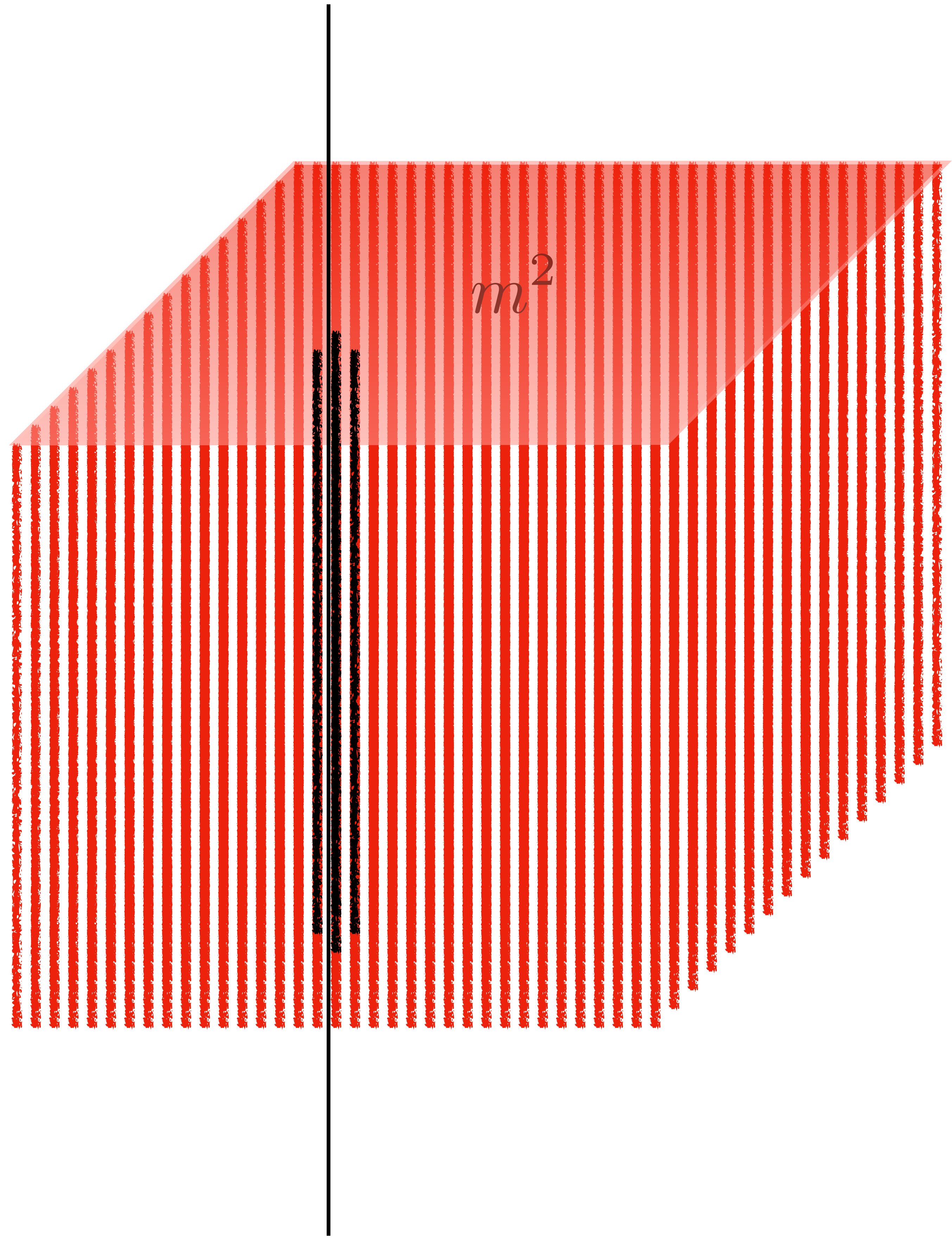


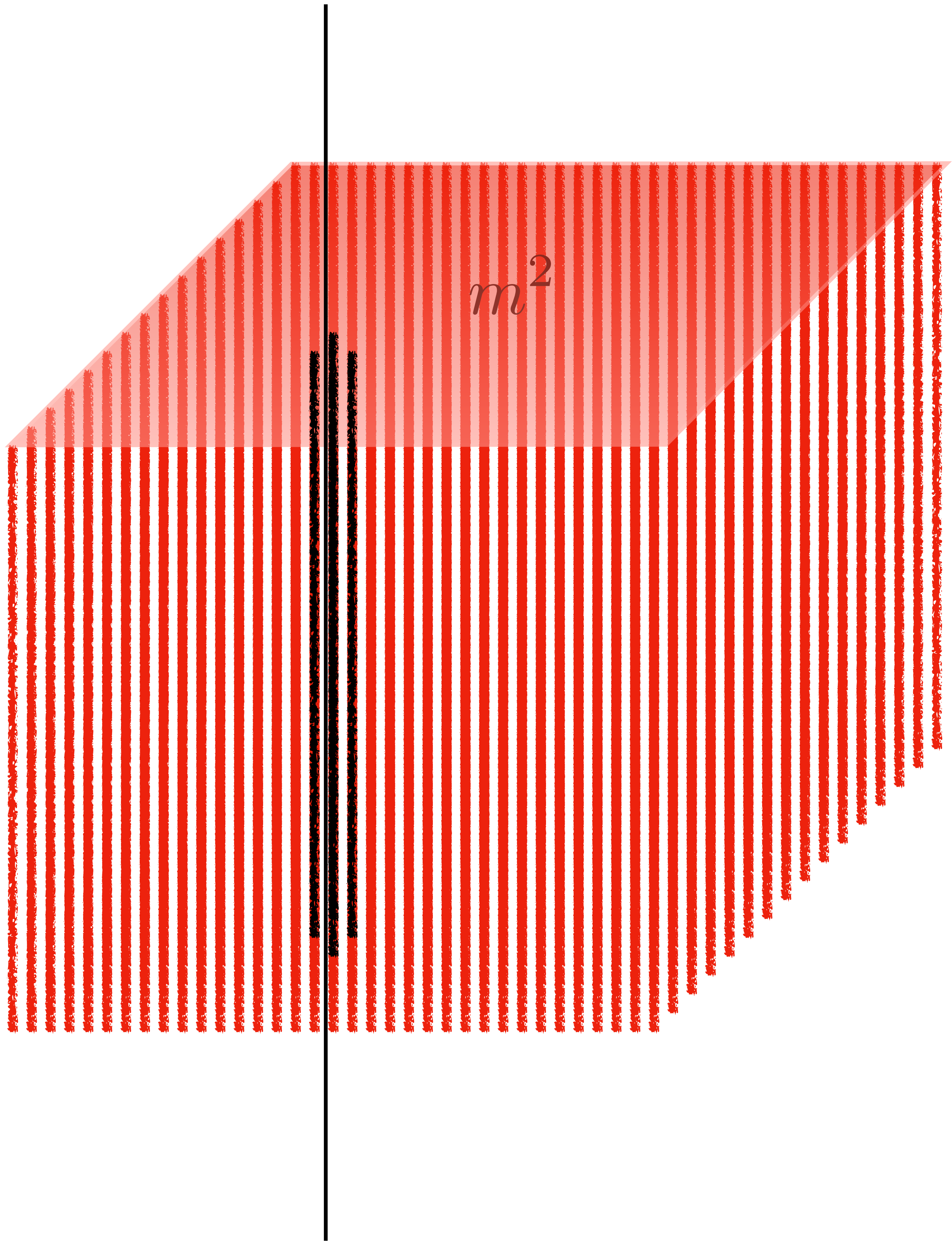
$$I \approx 10^{-11}(\epsilon/d)\mathrm{A}$$

$$I_T \approx ekT/\hbar \approx 10^{-7}T/(1\mathrm{K})\mathrm{A}$$

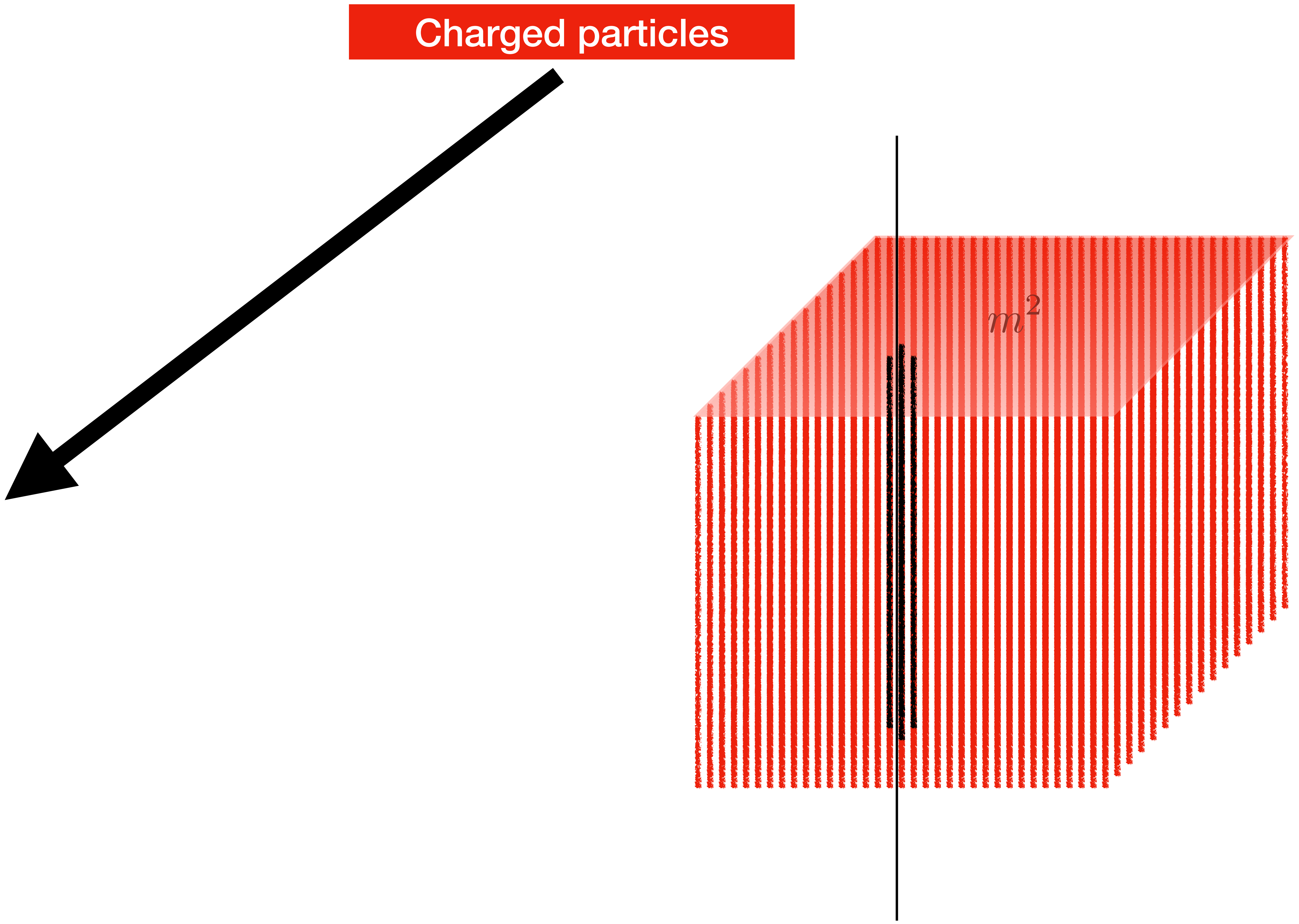


Other noise sources

Gravitational perturbations



Other noise sources

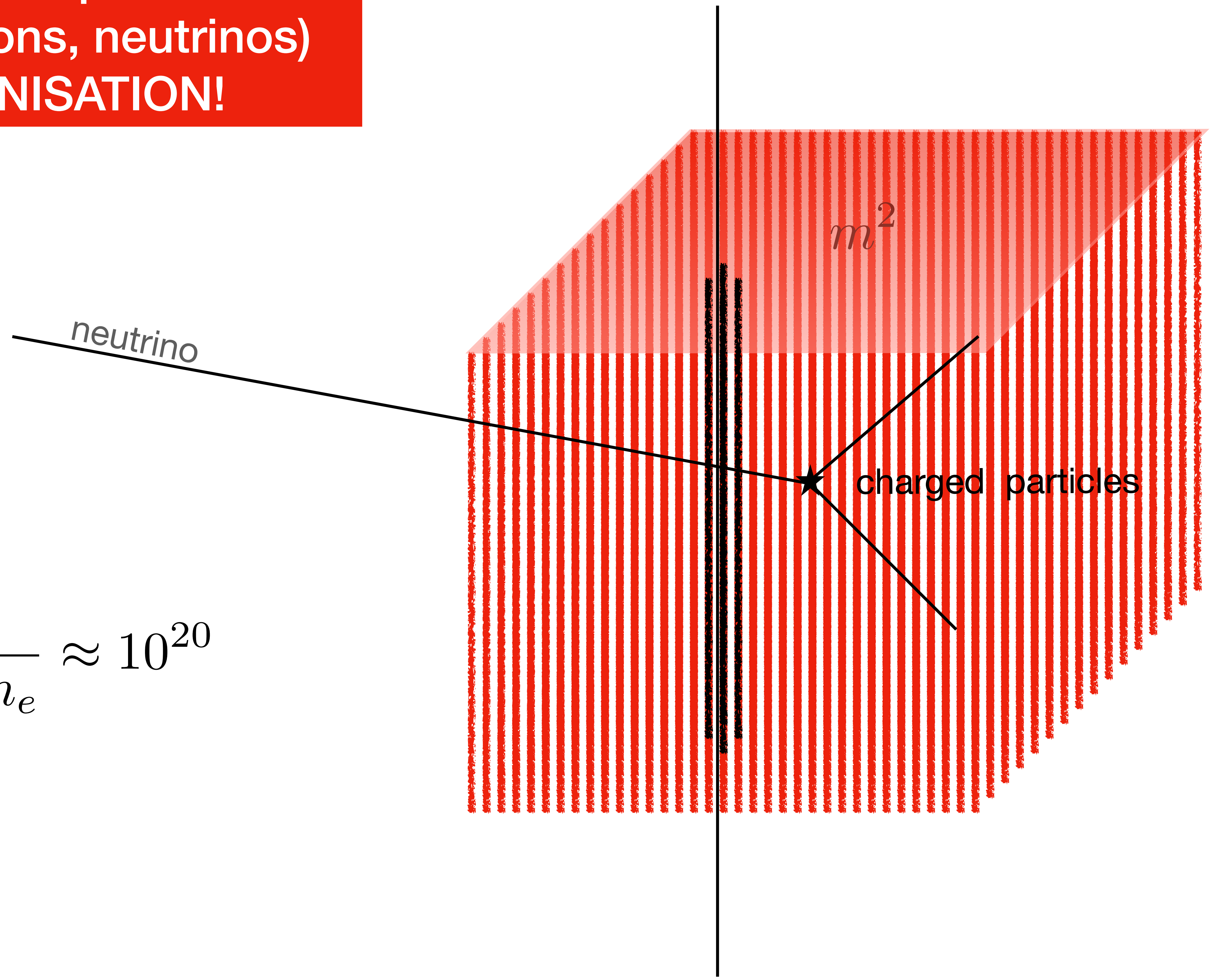


Other noise sources

Using WIMP detector knowledge: Assuming that it takes one hour to reset the system, the probability that a DM particle crosses the detector and is missed due to such noise source is less than one event in 10^6.

Projected WIMP sensitivity of the XENONnT dark matter experiment
XENON Collaboration • E. Aprile (Columbia U.) et al. (Jul 17, 2020)
Published in: *JCAP* 11 (2020) 031 • e-Print: 2007.08796 [physics.ins-det]

Neutral particles (neutrons, neutrinos) IONISATION!



$$\frac{e^2}{m_p m_e} \approx 10^{20}$$

Conclusion:

I introduced an alternative paradigm of structure formation where inhomogeneities in the CMB are the traces of inhomogeneities present at the Planck scale percolating to low energies during an inflationary era.

Consistency requires the inflationary scale to be close to the Planck scale (the natural quantum gravity scale), and most naturally, a reheating temperature that is about the Planck scale too.

The previous is not in conflict with the lack of observation of GW effects in the CMB (GW production is small within the picture).

If the big bang initial temperature is about the Planck scale, and if Planckian black holes are stable (as predicted by arguments in quantum gravity) then thermal production leaves a remnant DM density of such black holes that is of the correct order of magnitude to explain DM today (*the gravitational miracle*).

This would be the hardest of DM candidates to be directly detected. Quantum interferometry in the context of macroscopic quantum devices as Josephson junctions suggest that this could be possible in the not too far future.

This would provide an unprecedented observational handle into the structure of quantum gravity.

Thank you very much!