Is Planckian discreteness observable in cosmology?

Alejandro Perez FAU^2 workshop, June 2024

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

Eratosthenes, 240bc

(perhaps) Anaxagoras, 450bc

Same data different theories

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.

the past veinberg, Chapter 4, Inflation, before the period of radiation domination, during which the Robertson– 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 \mathbb{H} oscillator, with negligible damping. On the other hand, when the wavelength is when the wavelength is wellme standard initiationary theory of primordial innomogeneities The stenderd inflationary theory of primerdial inhomogeneities fluctuations at long wavelengths can be seen by considering the simple model of a free simple model of a free

well and will relate to will relate to will relate to will relate the control of the co ... from Wald and Hollands 2002 $\frac{m}{2}$ multipled states in a spatial field scalar field, $\frac{m}{2}$

of the scalar field modes $(\Delta \phi_k)^2|_{k=1} = \frac{H^2}{\sqrt{2}}$ the Hubble radius, the ground state with state with $\frac{1}{a}$ and $\frac{1}{a}$ will continue to $\frac{1}{a}$ and $\frac{1}{a}$ will continue to $\frac{1}{a}$ and $\frac{1}{a}$ and $\frac{1}{a}$ and $\frac{1}{a}$ and $\frac{1}{a}$ and $\frac{1}{a}$ and \frac α The fluctuations and the consequently, when the consequently, when the mode is the mode in the mode is after horizon crossing are $\left[\frac{(\Delta\phi_k)^2}{\frac{k}{a}H}\right]_{\frac{k}{a}=H} = \frac{1}{2k^3}$ scale invariant $\Delta_{\mathcal{M}}$ will remain constant with time. The constant with time $\Delta_{\mathcal{M}}$ is a constant with time. The constant with time $\Delta_{\mathcal{M}}$ IT SHOULD BE NOTED THE HULLUALIONS
Short has during a model of the scalar field modes 5 of the scalar field modes $(\Delta \phi_k)^2|_{k=H} = \frac{H}{2H^2}$ and nonizur crossing are
scale invariant much larger than the Hubble radius, the Hubble radius, the mode will be mode will be an overdamped oscillator;

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

 $\frac{a^2}{a^2}\phi_k = 0$ the friction term wins
and modes freeze! $\mathcal{H} = \mathcal{H} = \mathcal$ When k/a<H and modes freeze!

$$
\frac{d^2\phi_k}{dt^2} + 3H\frac{d\phi_k}{dt} + \frac{k^2}{a^2}\phi_k = 0 \quad \text{the friction term wins} \\ \text{and modes freeze!}
$$

The Lagrangian for a single external to the mode
 \blacksquare The Lagrangian for a single Fourier mode

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

after some form of *collapse of the wave function*

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

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

\ldots from vertice matrix \ldots from vertice matrix \ldots … 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.["]

The standard inflationary theory of primordia factor of (a/a0)², which is enormous for the modes of interest and thereby accounts for how The standard inflationary theory of primordial inhomogeneities

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

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 θ dionery theory of primordial inhomogeneities $\rm{unangular\,}$ and $\rm{or\,}$ or primormar innomogeneities

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 \blacksquare Planck scale, perhaps even too low for inflation to be natural at 1999.

 $\mathcal{F}_{\mathcal{A}}$ a.11 Constraints on single-field chaotic inflationary models with potentials \mathcal{A}

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

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

The scenario avoids the cosmological Schroedinger cat tension!

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

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]

QUANTUM GRAVITY DISCRETENESS BREAKS Cosmological symmetries AT THE PLANCK SCALE

AT LARGE SCALES THE SPACETIME IS HOMOGENEOUS AND ISOTROPIC

Discreteness and Lorentz invariance

Discreteness should

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

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.

 $R = 8\pi GT =$

Emerging semiclassical scalar field fluctuations at lower but close to fundamental scale *^k* the horizon crossing (HC) ame <u>annen sear</u>

The basic idea in a picture The basic idea in a picture T

 $\ddot{\delta}$ in $\ddot{\$ *k*2 $\frac{d}{dz} \delta \phi_{\vec{k}} = \xi_{\vec{k}}(t - t)$ HC *^k*)*,* (1.8)

granularity of the microscopic theory from which geometry & matter emerge *^k*)*mp*.

 $H\lesssim m_p$ $\left| \begin{array}{c} \end{array} \right|$ *^k*) (1.9)

we assume inflation is the cannot measure (interact with \sim 100 μ cannot select any canonic select any canonic select any cannot select any canno rest framewith rest framewith respect to which a fundamental value of $H\lesssim m_p$ work as a good rod and constant relational excitation to interact with the microscopic dynamical granularity. The microscopic dynamical granularity of the microscopic dynamical granularity. The microscopic dynamical granul *Y*e assume intlation is
driven by a Planckian cosmological constant as
ver flati itlation is
lanckian where the stock is shifted to the variable \sim

to the instant when the wavelength of the mode is Planckian, i.e., when *k* = *a*(*t*

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

Modelling the generation of inhomogeneities via a Example 18 Series Brownian diffusion: As mentioned, we assume that the primordial value of $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ state at the natural Planck value. In an approximation of \mathbf{D} **Modelling the generation of inhom** Modelling the generation of inhomogeneities via e process whose and are denoted a via the double-brane are denoted with the doublewith a meaning measures. The first moments of the state \mathbf{D} is the stochastic process in the stochastic process is the stochastic process in the stochastic process is the stochastic process in the stochastic process i

We assume that the stochastic process respects the symmetries of the FLRW background, hh*k*ii = 0*.* (5) *q*)*,* (6) where $P(\mathcal{P}(k) \geq 0)$ is the so-called power spectrum of the so-called power spectrum of the so-called power

 $\delta \phi_k \equiv \langle \psi | \delta \phi_k | \psi \rangle \neq 0, \quad k \leq m_p a$ ((0 φ_k)) = 0

The generation process is modelled via an homogeneous and isotropic $\langle\langle\delta\phi_k\delta\phi_q\rangle\rangle = P_{\delta\phi}(k)~\delta(\vec{k})$ **the stochastic process** which, in the absence of interactions, follow the standard semiclassical evolution equations ¨*^k* + 3*H*˙ *^k* + stochastic process

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

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

The generation process is modelled
via an homogeneous and isotropic
stochastic process
double-brakets
$$
\langle\langle\rangle\rangle
$$
 = ensemble average

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

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

Energy cost of the a Brownian diffusion: scalar field perturbations) is encoded in a non trivial energy momentum tensor violating FIRM SY COST OF THE G DI ON Energy cost of the a Brownian diff First consider the term *d* hh⇢(2)ii*/da* in the previous equation in view of (11). There are t uit a divwillah ulliusivil.

)²ii *^uau^b* hh(^r $\left(\frac{1}{2}, \frac{1}{2} \right)$ $\langle\!\langle\delta\phi(t,\vec{x})\delta\phi(t,\vec{x})\rangle\!\rangle$ $\bigg\langle \bigg\rangle \bigg\rangle$ $\langle \langle \delta \phi(t, \vec{x}) \delta \phi(t, \vec{x}) \rangle \rangle =$

$$
\langle\!\langle T_{ab}[\delta\phi]\rangle\!\rangle\;=\;\langle\!\langle \nabla_a\delta\phi\nabla_b\delta\phi\rangle\!\rangle-\frac{g_{ab}}{2}\,\langle\!\langle \nabla_\alpha\delta\phi\nabla^\alpha\delta\phi\rangle\!\rangle\approx\frac{\langle\!\langle(\nabla\delta\phi)^2\rangle\!\rangle}{2a^2}\;\;u_au_b-1
$$

² hhr↵r↵ii ⇡ hh(^r

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

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

hh*Tab*[]ii ⁼ hhr*a*r*b*ii *^gab*

$$
J \; = \; \gamma H^5
$$

is understood via the work per unit time necessary to produce the work per unit time necessary to produce the
In homogeneities work per unit time necessary to produce the inhomogeneities work per unit time to produce the

dW

dt

⁼ r*^a* hh*Tab*ii *^u^b*

*Hk*²

✓ *k*²

◆

i

 $P_{\delta\phi}$

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

The power spectrum of scalar perturbations can be translated into the (gauge into the (gauge into the (gauge i

INFLATIONARY ^{II} CONVEYOR BELT "

Whose solution is the scale invariant spectrum

Gravitational waves are suppressed q^2 = 0. However, the semiclassical Einstein's equations at second order \mathbf{J} equation for the GW, we have t
in the GW, we have the GW, we h *ij* —i.e. the graviational waves (GW)—do not contain matter sources, so **olavitational waves are suppressed** Γ ✓ *k*² *H*⁴

l

The quadratic dependence on suggests the strong suppression we evoke above. A precise

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

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

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

 \blacksquare No restrictions from lack of observation of GW $A_{\rm eff}$ the inflationary phase, the e $A_{\rm eff}$ of the e $A_{\rm eff}$ of the order of the order of the order of the order of the P calculation of the scale $H!$ $N_{\rm e}$ prospections from look of shearwation of $C_{\rm M}$ rection interaction interaction of the scale H! No restrictions from lack of observation of GW

^Ph(*k*) ' ² *^H*⁴ precise analysis shows [20] that the tensor power spectrum is scale invariant with Primordial gravitational waves from Planckian discreteness scale invariance (as the one of the proposition) and the evolution of the evolution of the evolution of the Hub-G. Bengochea, G. Leon, AP (in preparation)

 $P_h(k)$

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

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) on the number of e-folds. Figure 8.11 illustrates the position of one of these models in rdial innomogeneities in a scalar held with a vel $(1, r)$ to tender ratio (as required from absentation alai-lo-leiisol Ta

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

- **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

PART II:

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!*

mp

^p*g^s* (*mp/mpbh*)

⌘ *nv < H,* (15) equilibrium. Planckian discreteness as seeds for cosmic structure $Planckian$ discretene D Planckian discreteness as seeds for cosmic structure

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

a **final matrix of interaction**, and *participal in the speed of interaction*, and *v* the speed for and **Planckian discreteness as seeds for cosmic structure
Lautaro Amadei (Marseille, CPT), Alejandro Perez (Marseille, CPT) (Apr 18, 2021)** *p* (Marseille, CPT), Alejandro Perez (Marseille, CPT) (Aproved to the Perez (Marseille, CPT) (Aproved to the Perez of the Perez (Marseille, CPT) (Aproved to the Perez of the Perez of the Perez of the Perez of the Perez of

Dark matter as Planck relics without too exotic hypotheses

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)** lora Moulin
1

 $\Gamma \equiv n \sigma v < H$ Published in: *Phys.Rev.D* 100 (2019) 12, 123505 • e-Print: 1906.0 $e\pi\sigma v < H$ Published in: *Phys.Rev.D* 100 (2019) 12, 123505 \cdot e-Print: 1906.09930 [hep-ph]

p*g^s*

pbh

^H ⇡ ^p*g^s*

*T*3

p

pbh

Lautaro Amadei (Marseille, CPT), Alejandro Perez (Marseille, l ne gravitational miracle and published in: Phys.Rev.D 106 (2022) 6, 063
Dark matter as Planck relics without too The gravitational miracle Equation and the Fublished in: Phys. Rev. D *m*₁² *m*₁₄⁴ *gsT*³*m*² The gravitational miracle

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

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

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

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

D

This implies that the density of D and $\mathcal{D}_\mathcal{A}$ is the density of $D_\mathcal{A}$ and $\mathcal{D}_\mathcal{A}$ is the density of $D_\mathcal{A}$

 $\frac{1}{\sqrt{2}}$ *^F* ⌘ ⇢*DM*(*TD*) $\frac{11}{100}$ to 2000, the mass n of DM ranges from 1.0 n of the n *mpbh T T^D* these BHs behave like a pressure-less fluid decaying as 1*/a*³ or equivalently as *T*³. T_{SUSY} from $100 + 2000$ the measure we use F_{SUSY} from 10 m to 11 m 1 *T T^D* these BHs behave like a pressure-less fluid decaying as 1*/a*³ or equivalently as *T*³. ⇢*DM*(*T*) = ⇢*DM*(*TD*) *n*, t ⇡ ⇢(*TD*)*^F ^T*³ \overline{b} ⇡ ^p*g^s* from 1. exp $p = 11$ As g_s ranges from 100 to 2000, the mass m_{pbh} ranges from 1.8 m_p to 1.1 m_p | {z } *T*3 *T*3 $\frac{10}{2}$ *T*3 $\frac{1}{200}$ \overline{a} $\frac{1}{2}$ *m*² *p* 0110 $\frac{1}{2}$ n_{pbh} 1 *m*³ *pbh* ² ◆ rom 1.8 m_p *As* q_s *ranges from T*3 *T*3 *D n* to 2000, the T₁ *D* $mass\ n$ *T*3 ι_{pb} *p m*² ra *pbh* es f m 1.8 m_p *m*³ m_p *p* $1.1~m_p!$ As g_s ranges from 100 to 2000, the mass m_{pbh} ranges from 1.8 m_p to 1.1 $m_p!$. As g_s ranges from 100 to 2000, the mass m_{pbh} ranges from 1.8 m_p to 1.1 $m_p!$

D

p

pbh

p

*T*2

✓

◆

 $\sim \sqrt{g_s} m_p$ $H \approx \sqrt{g_s}$ T^2 *m^p* \overline{r} *pbh* $\frac{1}{q_s-1}$ \sum_{p}

*m^p m*⁴

p

 $\rho \propto g_s T^4$ $\rho \propto g_s T^4$ $\rho \propto g_s T^4$

a careful treatment shows that the central claim, that follows, remains correct in order of magnitude.

⁶ ⇥ ¹⁰³*m^p* ⇡ ⁶ *^T*GUT to 10²*mp*, i.e. scales not extraordinarily higher than usual precluding possible

How to detect such (purely gravitationally) interacting particles How to detect such (purely gravitationally) interacting Newtonian two-body problem is exactly solvable using $\overline{ }$ $\overline{}$ rticles 2*r*²

v

M

that *M m* implying that the center of mass coincides

with the position of of the DM particle *M*. The action

di↵erence is invariant under Galilean transformations.

In spherical coordinates—and ignoring the constant

term in the Lagrangian—the action (A4) becomes

dt (A5)

Detecting Gra
Alejandro Perez Detecting Gravitationally Interacting Dark Matter with Quantum Interference

Marios Christode
e-Print: 2309.08 Alejandro Perez (Marseille, CPT), Carlo Rovelli (Marseille, CPT and Western Ontario U. and Perimeter Inst. Theor. Phys.), Marios Christodoulou (Vienna U.) (Sep 15, 2023) $\begin{array}{c} \n\text{gr-qcl} \\
\text{gr-qcl}\n\end{array}$

L = *mr*²˙ = constant*,* (A6)

 $\bm \sigma$

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

where r_0 is the point of closest approach

Krnjaic (Fermilab), Jacob M. Taylor (Joint Quantum Inst., College Park and NIST, Wash., D.C.)
Phys.Rev.D 102 (2020) 7, 072003 • e-Print: <u>1903.00492</u> • DOI: <u>10.1103/PhysRevD.102.072003</u> Daniel Carney (Joint Quantum 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),

*r*⁰ = *^mpv*² (A14) For *d* `*^p* one has Classical detection seems very hard

What about quantum mechanically relative (using interferometry) configurations as a configuration of the configurations as a configuration of the configurations of the configur N and involves the integrated New- N erence of the integrated New- N erence of the integrated Newwhat about quantum mechanically Newton constant. The integration of each term is log- \overline{a} about quantum mechanically which only involves the division of the division of the integrated New-Alerence of the integrated

How to detect such (purely gravitationally) interacting particles How to detect such (purely gravitationally) interacting relative paradigm phases between the two superiors of the two superiors of the two superiors of the two superiors

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Detecting Gra
Alejandro Perez

Marios Christode
e-Print: 2309.08

 \mathbb{R}^n The correct approximation gives The correct opproximation given the correct approximation gracs. The correct approximation gives:

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

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

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

GmM

 \overline{M}

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]

 $\overline{\mathbf{M}}$ \overline{p} α *r*ticle $\sin n \approx 10^{-3}c$ Assuming that $M \approx m$. $\sim 10^{-3}$ mag $\sim 10^{-3}$ or the using the solution α mode in \sim 10 μ m γ one would be $\mathcal{L}_{\mathcal{S}}$ and $\mathcal{L}_{\mathcal{I}}$ is $\mathcal{I}_{\mathcal{I}}$ (recall the gravitational miracle) means that putting in superposition a mass $m \approx 10^{-3} m_p$ one would reach $\Delta \phi \approx \epsilon/d$. The velocity of DM particles is $v \approx 10^{-7}$ 3 *c*. Assuming that *M* \approx 3m_p one would reach $\Delta\phi$ \approx $\epsilon/d.$

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

M \overline{M} TVL $\overline{\mathbf{a}}$ *n* \overline{M} M

the interaction of the interaction of the electrons with the electrons with the DM particle gives with the DM
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Detecting Gravitationally Interacting Dark Matter with Quantum Interference *S*
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Marios Christodoulou (Vienna U.) (Sep 15, 2023)
A-Print: 2209.08228 [cr. co] **ecting Gravitationally Interacting Dark Matter wit**
ndro Perez (Marseille, CPT), Carlo Rovelli (Marseille, CPT and
<mark>ps Christodoulou (Vienna U.</mark>) (Sep 15, 2023) **1 Quantum Interference**
I Western Ontario U. and Perimeter Inst. Theo Marios Christodoulou (Vienna U.) (Sep 15, 2023) seille, CPT and Western Ontario U. and Per \sim 3 μ and μ *.* (4) $\frac{1}{2}$ $\frac{$

 $b = Print: 2309.08238$ [gr-qc]

 $\overline{I} = I \sin(\Lambda t)$ $I = I_c \sin(\Delta \phi_e)$ material \mathcal{I} . Present technology allows for the integra- $I = I_c \sin(\Delta \phi_e)$ $\frac{1}{40}$ rise to the current across the junction of the
The junction of the junction o *I* = *I^c* sin(*e*)*,* (8)

and (at low temperatures) the density of superconducted by the density of superconducted b

 $\Delta \phi \approx 10^{-19} \epsilon/d$ $\Delta \varphi_e \approx 10^{-19} \epsilon/d$ $\Delta\phi_e~\approx~10^{-19}\epsilon/d$ 10²²*m^p* (the electron mass), ✏ is the insulator width

 \overline{v} τ ^{*i*} (*form*) τ ^{*e*} (*form*) τ ^{*i*} (*form*) τ ^{*i*} (*form*) τ ^{*i*} (*form*) τ $I \sim (\epsilon/d)s^{-1} \hspace{5mm} v$ In an idealized aligned configuration of about 10⁸ junc- $I \sim (\epsilon/d)s^{-1}$ *v* and $\left(\frac{c}{\alpha}\right)$ the density of superconducted superco $\mathbf{I} \sim (\mathbf{c}/\mathbf{u})$ *b*
c

The collective state of the electrons ng Josephson
mechanilistic response of previous pr crucial types is the process and provide the single provident intervals and provide the meet of a statistical reconstruction of the phase The collective state of the electrons a statistical reconstruction of the phase. It is easy to
see that the phase shift due to the interaction of the see that the phase shift due to the interaction of the electrons with the DM particle gives rise to the current. across the junction across the *I* \overline{c} The collective state of the electrons translates the probabilistic response of previous protocol into a directly measurable signal, circumventing the need of electrons with the DM particle gives rise to the current the interaction of the integration of the DM particle gives $\frac{1}{2}$ across the junction ! $robab$ which only involves the division of the division of the integrated New $t \hbox{ is } t \h$ cuve state of the efectrons transfates the probabilistic response of previous protocol into a across the junction The collective state of the electrons translates the

rise to the current across the junction of the
The junction of the junction o

Imnroved protocol using *^v* log(1 + ✏*/d*) ⇡ ² *S* = *dt* \bf{v} ed protocol using Joseph $\overline{}$ \mathbf{v} in the direction of the integrated New- \mathbf{v} $\overline{\mathbf{S}}$ $\overline{}$ rot **Figure 12 Follocal using Josephson**
 Find the Solutions p(*d* + ✏)² + (*vt*)² **junctions**

[11] Fein, Y.Y., Geyer, P., Zwick, P. et al. "Quantum superpo-

 $I \approx 10^{-11} (\epsilon/d)$ A with the DM particle. This optimal configuration is used for T $\tau = 10^{-11}$ $I\approx 10^{-11}(\epsilon/d)$ A 10⁷✏*/ds*¹ (electrons per second) with a single DM event (*^I* ⇡ ¹⁰¹¹(✏*/d*)A).

 $I_T~\approx~e kT/\hbar~\approx 10^{-7}T/$ 10⁷*T /*(1K)A would require *T <* 10¹mK in the setting $I_T \approx e kT/l$ $\frac{1}{1}$ \sim $\frac{1}{1}$ 7π /(1,75) \pm $I_T \approx e kT/\hbar \approx 10^{-7} T / (1 \text{K}) \text{A}$ of this letter. Much lower temperatures have been at-

\blacksquare \blacksquare

M t_{V} the DM particle would induce a current of the order of

where *^e* ⇡ ¹⁰¹⁹✏*/d* is given by (4) with *^m^e* ⇡

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 $10^{\text{A}}6$

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]

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!