Massive Gravitons as Dark Matter

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KA and S. Mukohyama, arXiv: 1604.06704,
KA and K. Maeda, arXiv: 1707.05003,

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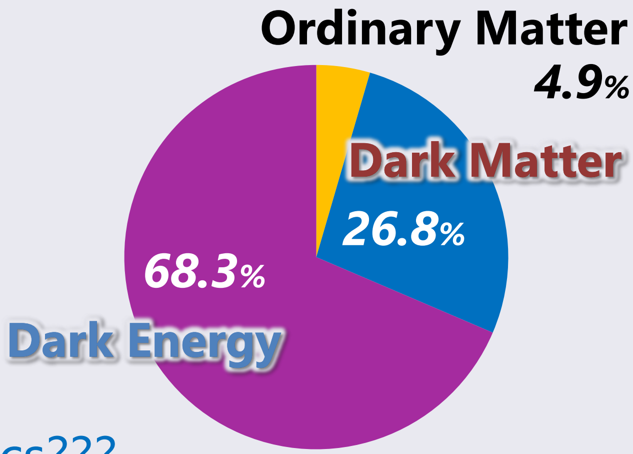
Introduction

What is dark matter??

We should need beyond standard physics!!

Beyond standard particle physics?

Beyond standard gravity?



DM candidates in beyond SM of particle physics???

→ WIMPs, Axion and other many candidates…

We haven't detected new particle (DM is more "dark"?)

DM with only gravitational interactions??? (DM from gravity sector?)

Interactions are definitely Planck suppressed.

Non-linear bigravity theory

Additional massive graviton? (the simplest: one massless + one massive)

(Hassan, and Rosen, 2011)

$$S = \frac{1}{2\kappa_g^2}\int d^4x\sqrt{-g}R(g) + \frac{1}{2\kappa_f^2}\int d^4x\sqrt{-f}\mathcal{R}(f) + S_{\mathrm{int}}(g,f)$$

The interaction terms are given by dRGT form (ghost-free).

de Rham, Gabadadze, and Tolley (2011)

What we want to calculate?

Gravitons propagating on background

$$g_{\mu\nu} = g_{\mu\nu}^{\mathrm{background}} + \delta g_{\mu\nu}^{\mathrm{perturbation}}$$

$$f_{\mu\nu} = f_{\mu\nu}^{\mathrm{background}} + \delta f_{\mu\nu}^{\mathrm{perturbation}}$$

Backreaction from gravitons

High frequency approximation

In general, there is no way to decompose
``background`` and ``perturbations`` if backreaction is included.

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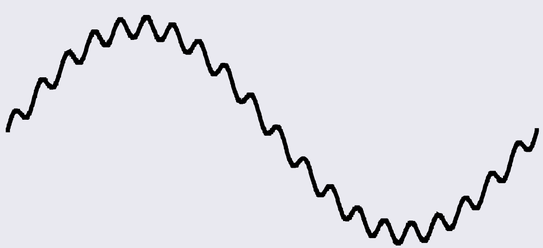
Backreaction from gravitons

However, they can be decomposed when perturbations are high-frequency.
(Isaacson, 1968)



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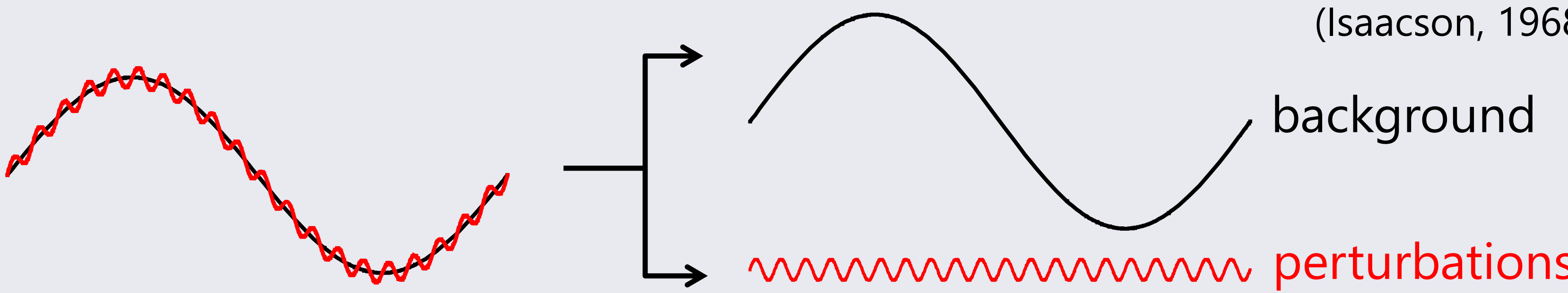


Graviton $T^{\mu\nu}$ in Bigravity

Assuming $|\partial^2 \overset{(0)}{g}| \ll m^2$, we find the Einstein and Klein-Gordon equations

$$G^{\mu\nu}[\overset{(0)}{g}] \simeq \frac{1}{M_{\rm pl}^2}(\langle T^{\mu\nu}_{\rm gw}\rangle_{\rm low} + \langle T^{\mu\nu}_{G}\rangle_{\rm low})$$

$$\Box h_{\mu\nu} \simeq 0\,, \quad (\Box - m^2)\varphi_{\mu\nu} \simeq 0$$ + TT conditions

where $T^{\mu\nu}_{\rm gw} \sim (\partial h_{\mu\nu})^2\,, \quad T^{\mu\nu}_{G} \sim (\partial \varphi_{\mu\nu})^2 + m^2 \varphi_{\mu\nu}^2$

The metrics are given by

$$g_{\mu\nu} \simeq \overset{(0)}{g}_{\mu\nu} + \frac{h_{\mu\nu}}{M_{\rm pl}} + \frac{\varphi_{\mu\nu}}{M_G}\,, \quad f_{\mu\nu} \simeq \overset{(0)}{g}_{\mu\nu} + \frac{h_{\mu\nu}}{M_{\rm pl}} - \frac{\varphi_{\mu\nu}}{\alpha M_G}\,,$$

$(\alpha = M_{\rm pl}^2/M_G^2)$

Matter coupling?

Minimal way: $S^{[\rm m]} = S^{[\rm m]}(\psi, g) \;\to\; \frac{1}{2M_{\rm pl}} h_{\mu\nu} T^{\mu\nu}_{\rm m} + \frac{1}{2M_G}\varphi_{\mu\nu} T^{\mu\nu}_{\rm m}$

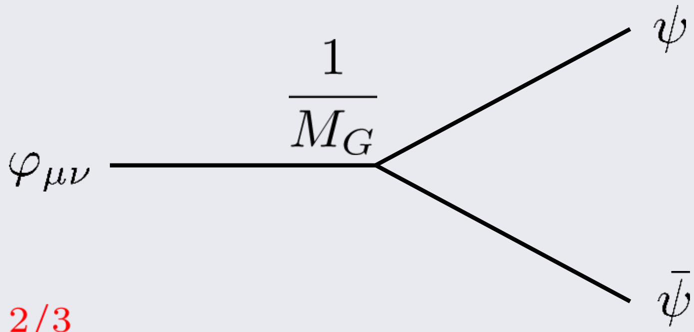
General bounds on massive graviton DM

We can obtain upper bound on graviton mass from the decay rate.

$$S_{\text{massive}} = \int d^4x \left[\text{kinetic} + \text{mass} + \frac{1}{2M_G} \varphi_{\mu\nu} T_{\text{m}}^{\mu\nu} \right]$$

Total decay rate of massive graviton has to be

$$\Gamma_G \sim 0.1 \frac{m^3}{M_G^2} \ll H_0$$



Upper bound on graviton mass: $m \lesssim 10 \left(\frac{M_G}{M_{\text{pl}}} \right)^{2/3} \text{MeV}$

Lower bound on graviton mass: $m \gtrsim 10^{-23}\ \text{eV}$

de Broglie wavelength < dwarf galaxy scale

Stochastic massive gravitons

KA and S. Mukohyama, arXiv: 1604.06704.

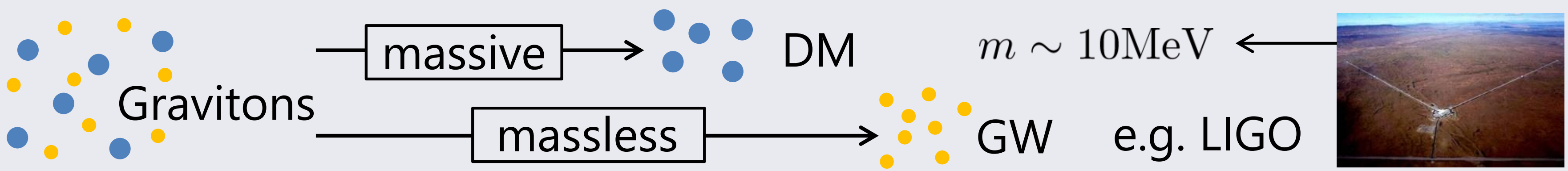
The low frequency projection $\langle \cdots \rangle_{\rm low}$ can be chosen as spacetime average.

$$\langle T_G^{\mu\nu} \rangle_{\rm low} \simeq \frac{1}{4} \langle \varphi^{\alpha\beta} \varphi_{\alpha\beta} \rangle_{\rm low} p^\mu p^\nu \; = \text{Dark matter}$$

$$(p^\mu p_\nu = -m^2)$$

How to generate massive gravitons?

$$\rightarrow \frac{1}{2M_{\rm pl}} h_{\mu\nu} T_{\rm m}^{\mu\nu} + \frac{1}{2M_G} \varphi_{\mu\nu} T_{\rm m}^{\mu\nu}$$



When GWs are generated, MGs (=DM) are also generated.

Massive gravitons from preheating

Supposing massive gravitons are relativistic at the production,
the present abundance of MG (=DM) is

$$\Omega_G \sim \frac{M_{\rm pl}^2}{M_G^2}\frac{m}{2\pi f}\Omega_{\rm gw}$$

f is the present frequency of GW

We focus on GW to be sensitive in the LIGO range.

e.g. $\rho_*^{1/4} \sim 10^8\,{\rm GeV} \Rightarrow f \sim 40\,{\rm Hz}\,,\ h^2\Omega_{\rm gw} \sim 10^{-9}$

(reheating energy scale)

Dufaux et al. JCAP 0903, 001 (2009)

A set of consistent parameters is

$$m \sim 10\ {\rm MeV}\,, \quad M_G \sim 10^6 M_{\rm pl}$$

Stochastic MG is indeed a candidate of DM!!

originated from preheating

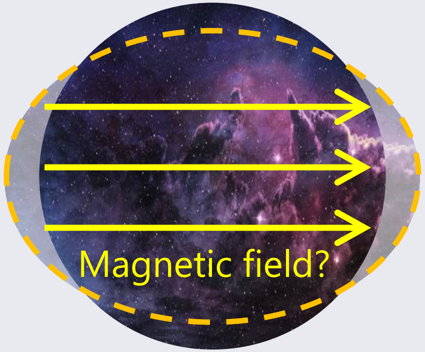
Coherent massive gravitons

KA and K. Maeda, arXiv: 1707.05003.

Previous: source is a stochastic field
→ high-momentum gravitons.

Next: source is a coherent field
→ low-momentum gravitons.

stochastic



coherent

Indeed, we have already known the coherent field in the universe!

Blazar observations implies

$$10^{-15}\,\mathrm{G} < B_0 \;(< 10^{-9}\,\mathrm{G})$$

over the coherent scale ~ Mpc

Taylor et al, 1101.0932.

Primordial magnetic field gives anisotropy of the universe = coherent MGs

Coherent gravitons from magnetic field

Anisotropy of the universe = coherent (zero-momentum) gravitons

We assume the configuration

$$\varphi_{\mu\nu}(t,\mathbf{x}) = \bar{\varphi}_{\mu\nu}(t) + \delta\varphi_{\mu\nu}(t,\mathbf{x})\,, \quad \delta\varphi_{\mu\nu} \ll \bar{\varphi}_{\mu\nu}$$

MG is dominated by the zero momentum mode

= "condensate" of massive gravitons

$\langle \cdots \rangle_{\rm low}$ can be chosen as a time average over one coherent oscillation.

→ $\langle T_G^{\mu\nu}(t,\mathbf{x}) \rangle_{\rm low}$ is given by a form of pressureless perfect fluid.

The amplitude must be $|\varphi_{\mu\nu}/M_G| \sim 10^{-29} \left(\frac{10^{-4}{\rm eV}}{m} \right) \left(\frac{M_{\rm pl}}{M_G} \right)$

For example, $B_0 \sim 10^{-12} - 10^{-10}{\rm G} \Rightarrow m \sim 10^{7} - 10^{-4}{\rm eV}, M_G = M_{\rm pl}$

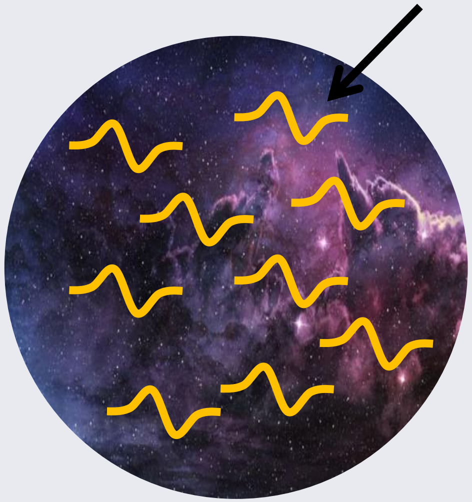
Summary

Massive graviton is a candidate of dark matter!!

GWs or the magnetic field can carry information about DM (=MG).

Direct detection of graviton mass → consistency relation

Spacetime “fluctuation” is DM



Spacetime “deformation” is DM