Testing Gravity 2017

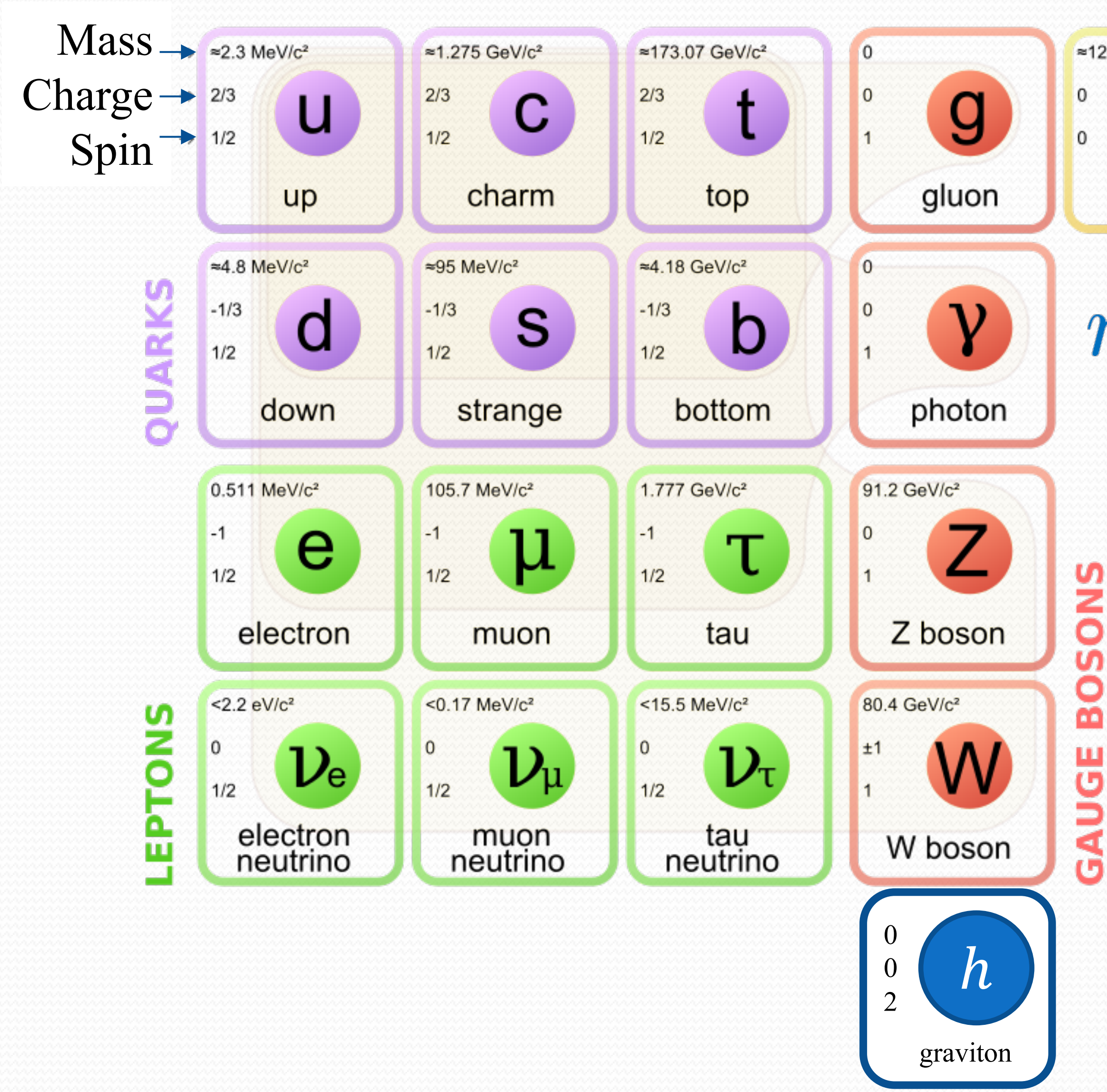
How Light is gravity?

Based on review with Tate Deskins, Andrew Tolley, Shuang-Yong Zhou, 1606.08462, RMP
see also Yagi & Stein, 1601.01413

Imperial College London

Claudia de Rham
27 Jan 2017

How light is gravity ???

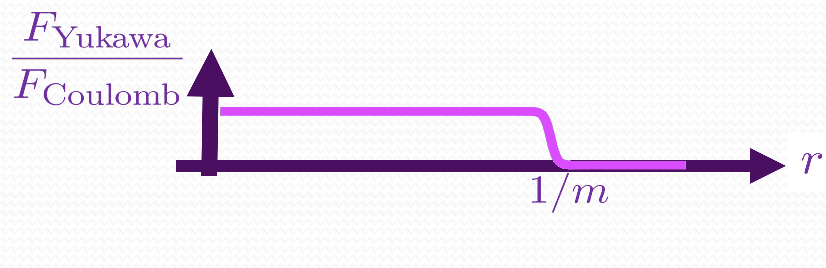


$$m_\gamma \lesssim 10^{-20}\mathrm{eV}$$

How light is gravity ???

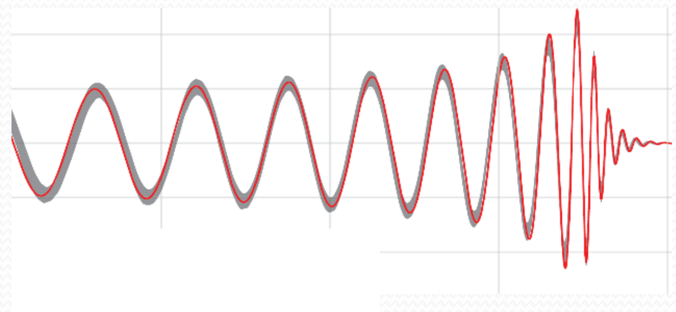
Yukawa

m_g (eV)	λ_g (km)	
10^{-23}	10^{12}	Solar System tests
10^{-32}	10^{21}	Weak lensing
10^{-29}	10^{19}	Bound clusters



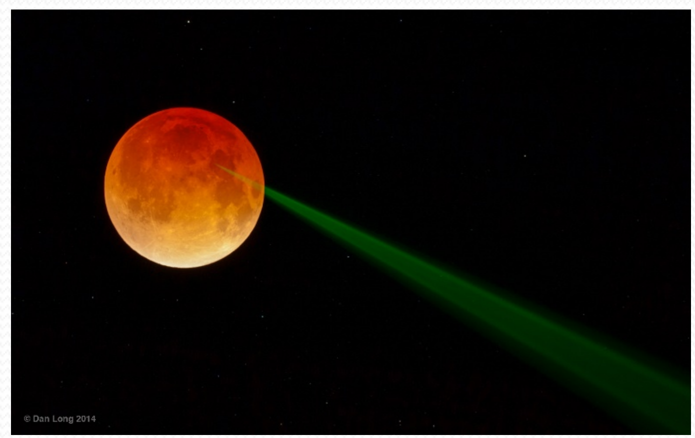
Dispersion Relation

m_g (eV)	λ_g (km)	
10^{-22}	10^{11}	aLIGO bound
10^{-20}	10^{9}	Pulsar timing
10^{-30}	10^{20}	B–mode's in CMB



Fifth Force

m_g (eV)	λ_g (km)	
10^{-32}	10^{22}	Lunar Laser Ranging
10^{-27}	10^{17}	Binary pulsar
10^{-32}	10^{22}	Structure formation



CdR, Deskins, Tolley, Zhou, 1606.08462

Yukawa Potential

In the weak field approximation, a graviton mass leads to a *Yukawa potential*

Solar system bounds: comparing the Kepler ratio $\frac{a^3}{T^2}$ between Earth and Mars,

$$m_g \lesssim 10^{-23}\mathrm{eV}$$

Talmadge et al., 1988

Cluster bounds: The core of clusters of a typical size 1-10Mpc are virialized

$$m_g \lesssim 10^{-29}\mathrm{eV}$$

Goldhaber and Nieto, 1974

Weak Lensing: power spectra of effective convergence gets corrected by $\frac{k^2}{k^2 + m_g^2}$

Assuming ΛCDM, $m_g \lesssim 10^{-32}\mathrm{eV}$

Choudhury et al., 2004

Yukawa Potential

Constraints coming from the departure to the Coulomb potential provide the best bounds *but*…:

1. In soft massive gravity, even though the potential is weaker than $1/r$ it is never Yukawa suppressed

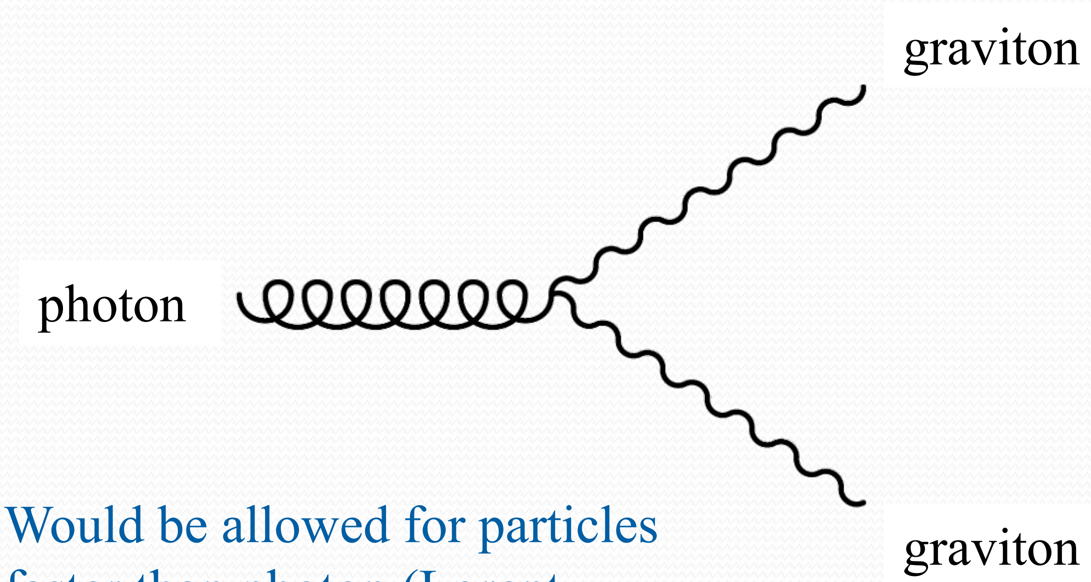
2. Many black hole solutions in massive gravity also have a non-Yukawa suppressed asymptotic form

3. The mass of the graviton is typically redressed by its environment

4. There may be departures from ΛCDM

Cherenkov Radiation

Particles traveling faster than GWs could decay into GWs



Forbidden process in
Lorentz invariant models
(if the photon is massless)

Would be allowed for particles
faster than photon (Lorentz
violating models)

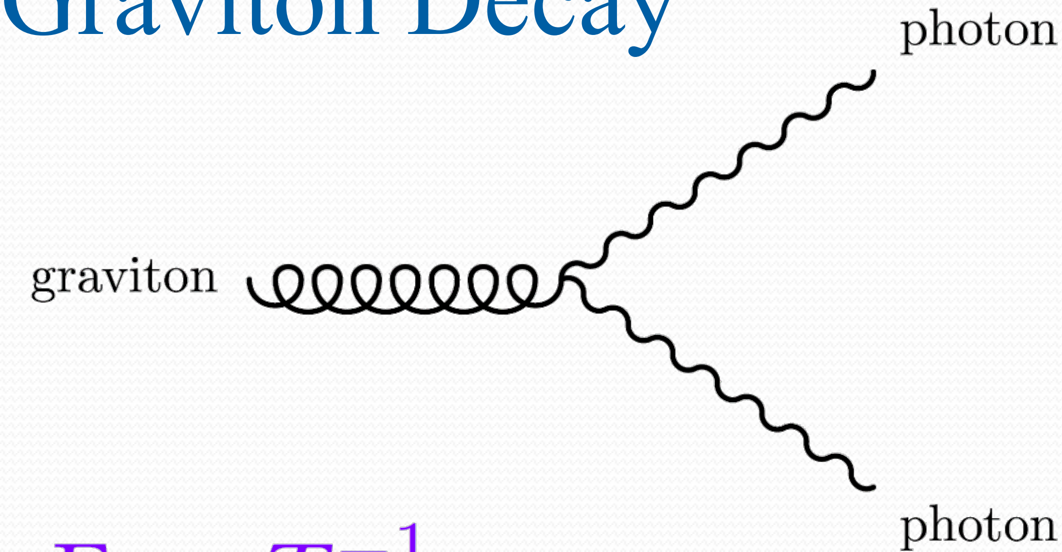
eg. Blas, Ivanov, Sawicki, Sibiryakov1602.04188

Can be used to put bounds on the difference of speeds
but those translate into very weak bounds on the graviton mass

See Yasuho Yamashita and Jay Tasson's talks

Graviton Decay

If the graviton has a mass:



aLIGO direct detection: $\Gamma \ll T^{-1}_{\text{GW travel time}}$

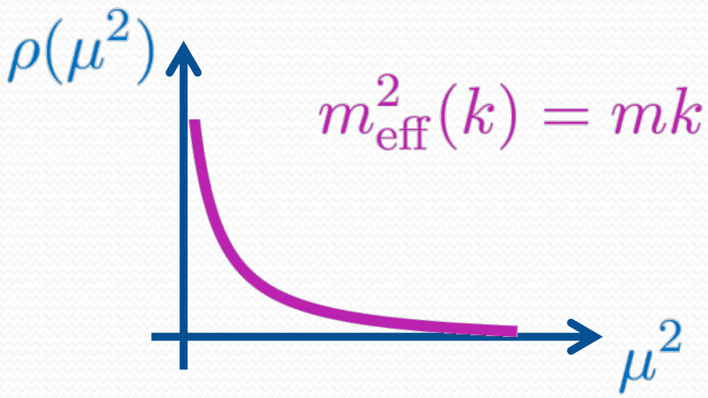
Very weak bound…

Constraints from cosmology: $\Gamma \ll H_{\text{today}}$

$$\mathrm{Im}[m_g^2] \ll H_{\text{today}} \sqrt{\mathrm{Re}[m_g^2]}$$

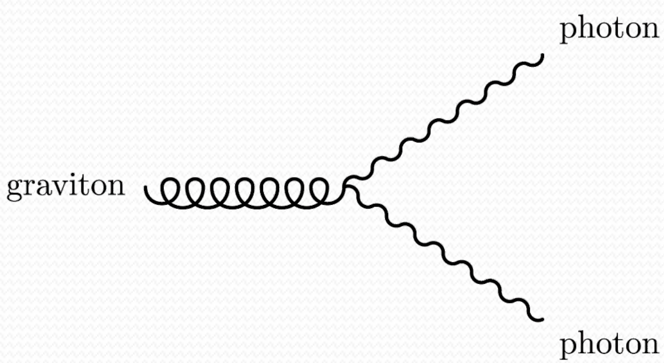
Graviton Decay

If the graviton is a resonance (eg. in DGP, Cascading Gravity,…)



The graviton already has a finite lifetime even without taking into account its possible decay into photons

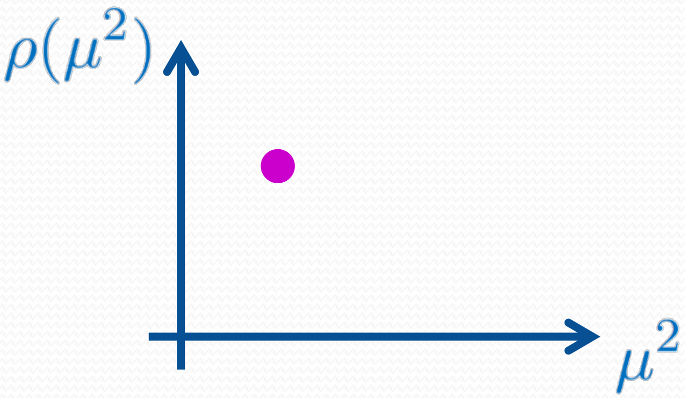
$$m \lesssim H_{\rm today}$$



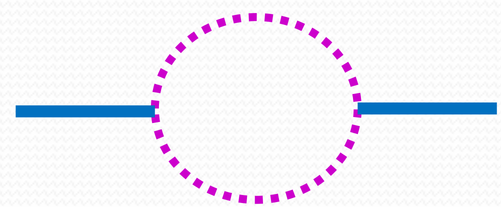
Graviton Decay

For a hard mass graviton

At tree-level, $\mathrm{Im}[m_g^2] = \Gamma = 0$



loop-effect on graviton self-energy

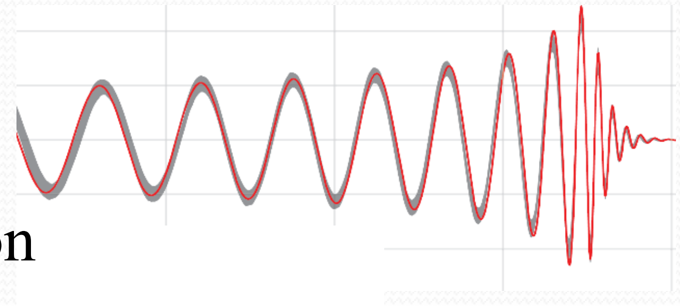


$$\Gamma \sim N \frac{m_g^3}{M_{\mathrm{Pl}}^2}$$

N: total number of light particles that may exist
(photon + axion, hidden sector not subject to SM constraints,…)

$$m_g \lesssim 10^7 \mathrm{eV} \times N^{-1/3}$$

Direct detection of GWs

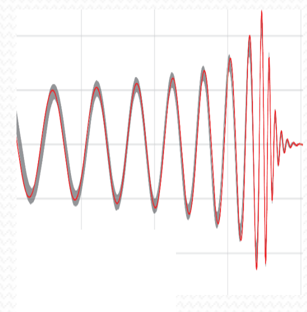


Constraints modifications of the dispersion relation

$$E^2 = \mathbf{k}^2 + m_g^2$$

Generic for the helicity-2 modes of any Lorentz invariant model of massive gravity (including DGP at the level of spectral representation)

GW signal would be more squeezed than in GR



matched filtering technique allows to determine the signal duration when emitted $\Delta\tau_e$ very accurately which can be compared with the signal duration when observed $\Delta\tau_a$.

$$\Delta t = \Delta\tau_a - \Delta\tau_e(1+z)$$

Will 1998

Direct detection of GWs

modifications of the dispersion relation put a bound on the graviton mass

$$m_g \lesssim 4 \times 10^{-22}\mathrm{eV} \left(f\Delta t \frac{f}{100\mathrm{Hz}} \frac{200\mathrm{Mpc}}{D} \right)^{1/2}$$

Phase distortion $f\Delta t$ can be measured up to $1/\rho$ (ρ: the signal to noise ratio)

For GW150914,

$$D \sim 400\mathrm{Mpc}, \;\; f \sim 100\mathrm{Hz}, \;\; \rho \sim 23 \quad \Rightarrow \quad m_g \lesssim 10^{-22}\mathrm{eV}$$

For GW151226, ρ is smaller and the BHs are lighter so f is larger $\longrightarrow$ not as competitive

Will 1998
Abbott et al., 2016

Direct detection of GWs

modifications of the dispersion relation put a bound on the graviton mass

$$m_g \lesssim 4 \times 10^{-22}\mathrm{eV}\left(f\Delta t \frac{f}{100\mathrm{Hz}}\frac{200\mathrm{Mpc}}{D}\right)^{1/2}$$

Phase distortion $f\Delta t$ can be measured up to $1/\rho$ (ρ: the signal to noise ratio)

For eLISA, could have

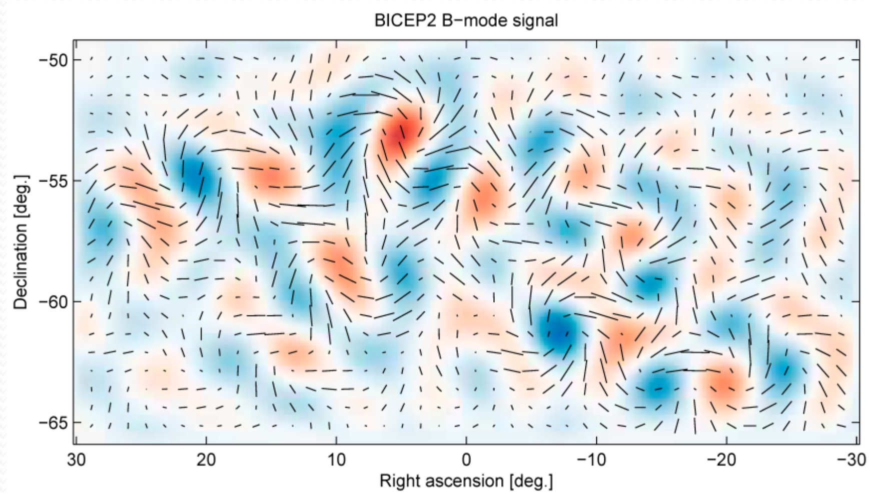
$\rho \sim 10^3$

$D \sim 3\mathrm{Gpc}$ $\Longrightarrow$ $m_g \lesssim 10^{-26}\mathrm{eV}$

$f \sim 10^{-3}\mathrm{Hz}$

Will 1998

Bounds from Primordial Gravitational Waves



if ever detected...

would imply the graviton is effectively massless at the time of recombination

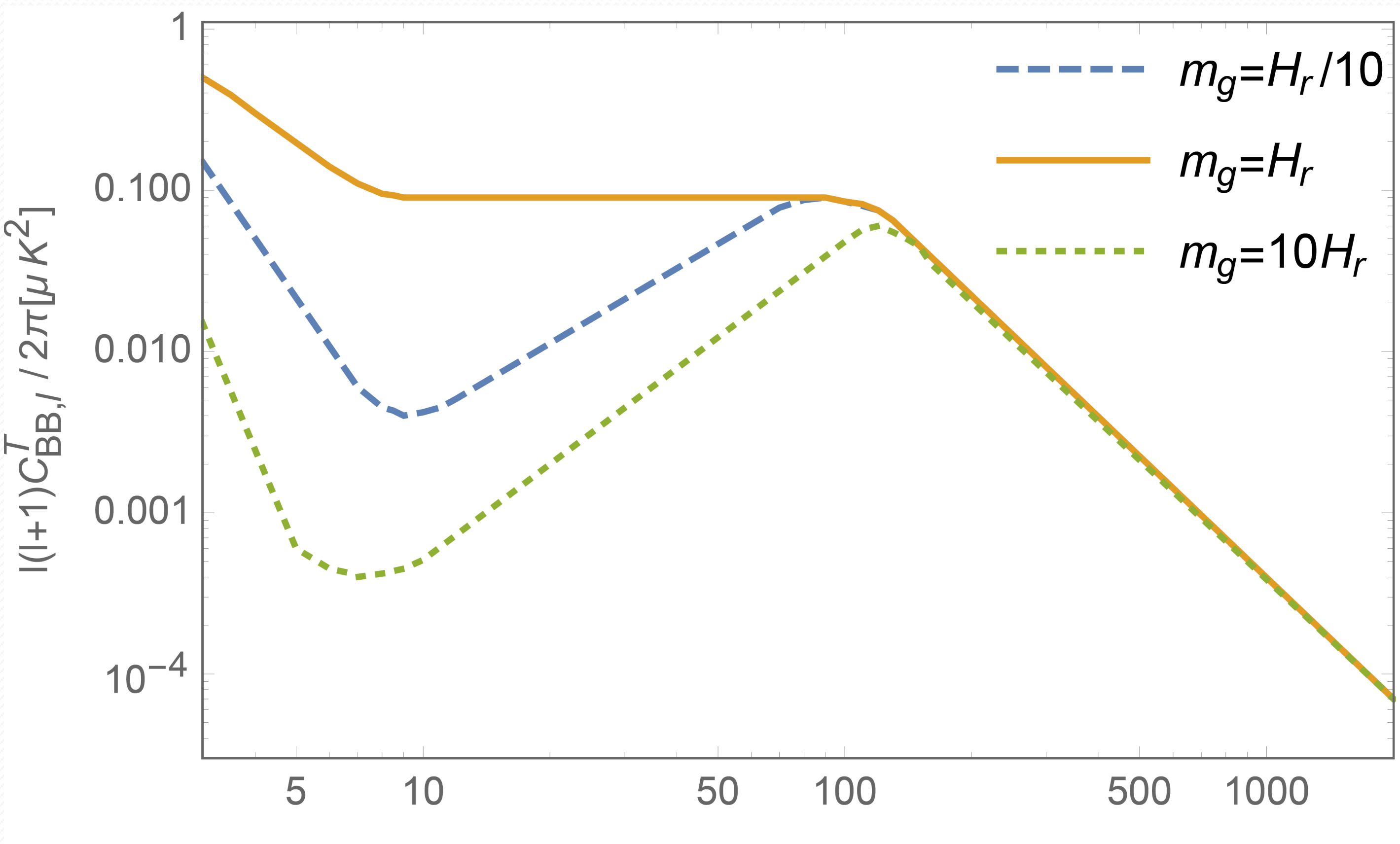
$$m_{\rm eff} \ll 10^{-29}{\rm eV}$$

Dubovsky, Flauger, Starobinsky & Tkachev, 2010 (for Lorentz-breaking MG)
Fasiello & Ribeiro, 2015, (for bi-gravity)
Lin&Ishak, 2016 (Testing gravity using tensor perturbations)

Bounds from Primordial Gravitational Waves

Modification to the tensor mode evolution

$$\mathcal{D}_q''(\tau) + 2\frac{a'}{a}\mathcal{D}_q'(\tau) + \left(q^2 + a^2 m_g^2\right)\mathcal{D}_q(\tau) = J_q(\tau)$$



Dubovsky, Flauger, Starobinsky & Tkachev, 2010 (for Lorentz-breaking MG)
Fasiello & Ribeiro, 2015, (for bi-gravity)

Lin&Ishak, 2016

Indirect Gravitational Wave Detection

Pulsar Timing Arrays could in principle detect ηHZ GWs

would put a bound $m_g \lesssim f \sim 10^{-23}\mathrm{eV}$

Lee et al., 2010

Binary Pulsar Radiation

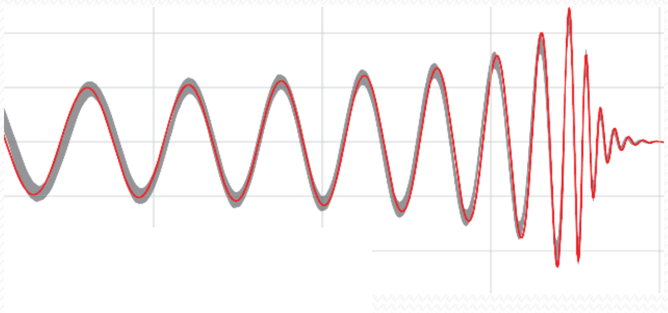
expect a correction of order m^2/f^2 to the power emitted by the tensor modes

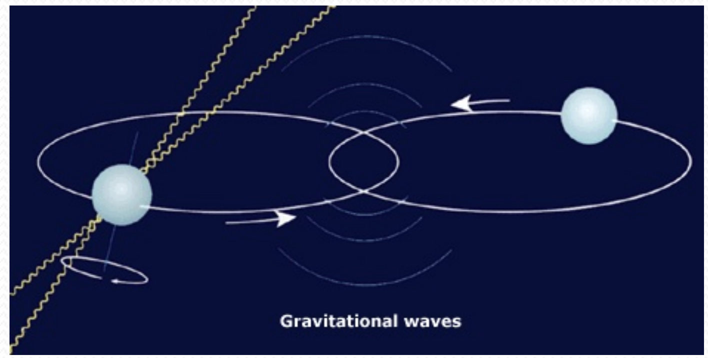
$$m_g \lesssim \frac{10^{-1}}{(\text{few hours})} \sim 10^{-20}\mathrm{eV}$$

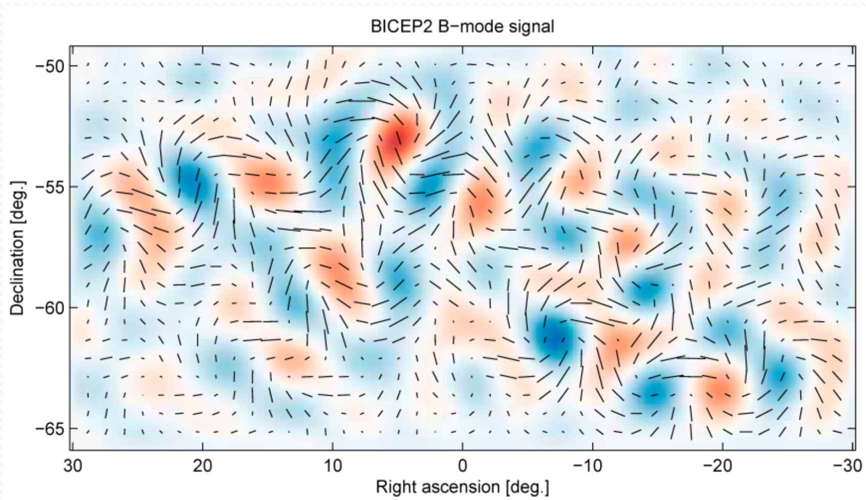
Finn and Sutton, 2002

Dispersion Relation

m_g (eV)	λ_g (km)	
10^{-22}	10^{11}	aLIGO bound
10^{-20}	10^{9}	Pulsar timing
10^{-30}	10^{20}	B–mode's in CMB

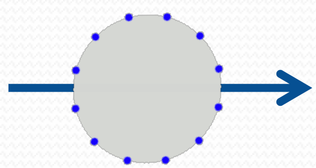


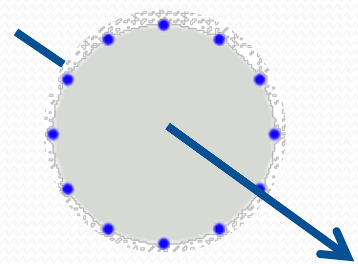




Scalar and Vector modes of the graviton

In a Lorentz invariant theory, a massive graviton also carries a helicity-0 and 2 helicity-1 modes.





Helicity-0 mode propagates an additional gravitational force that can be very well tested (particularly in the Solar System)

Behaves a Galileon scalar in some limit and is screened via a Vainshtein mechanism

Vainshtein mechanism

- Well understood for Static & Spherically Symmetric configurations $e.g. \quad T = -M_{\oplus}\,\delta^{(3)}(r)$
- Force mediated by the scalar mode $\phi'(r)$

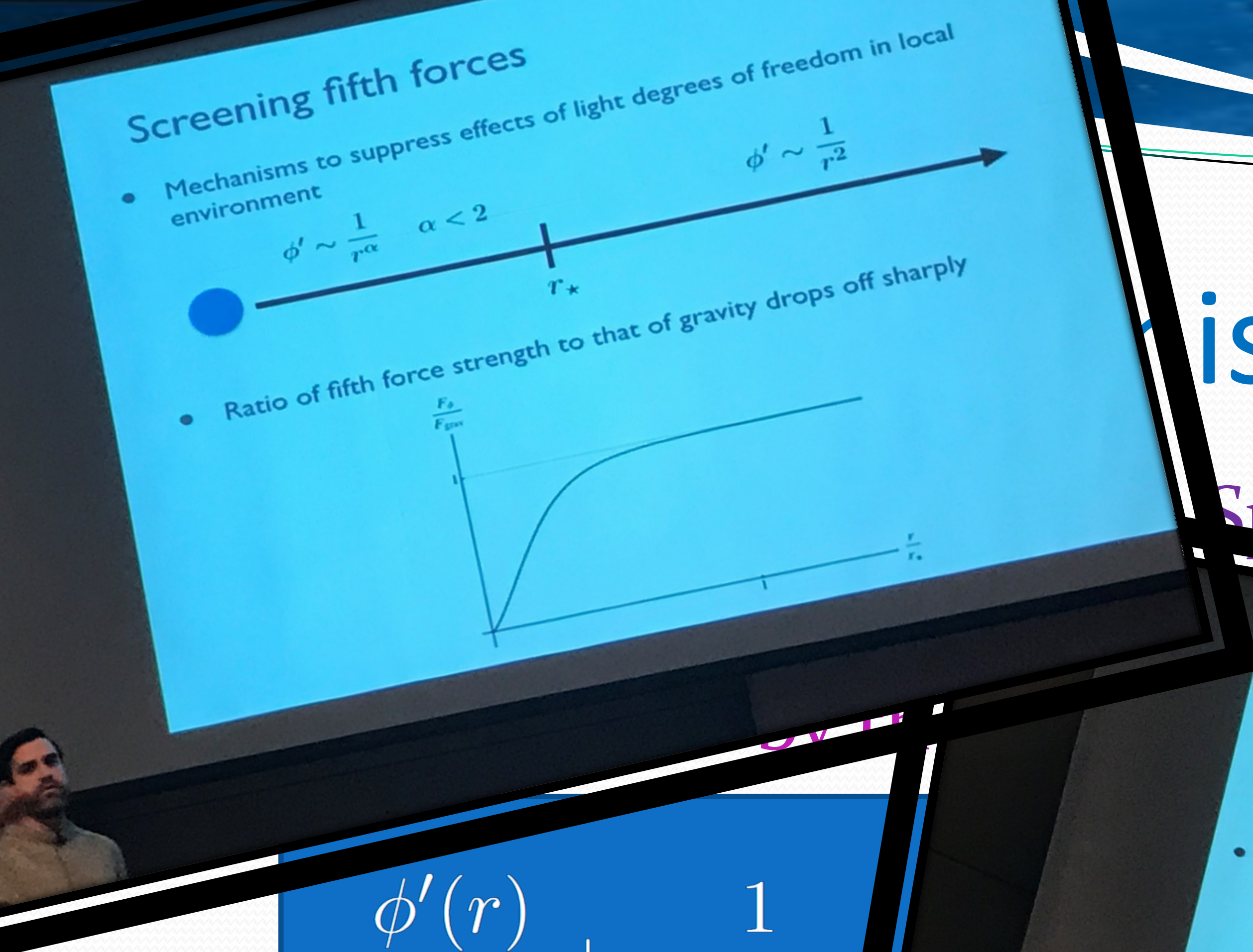
$$\boxed{\frac{\phi'(r)}{r} + \frac{1}{M_{\rm Pl} m^2}\left(\frac{\phi'(r)}{r}\right)^2 = \frac{M_{\oplus}}{4\pi M_{\rm Pl} r^3}}$$

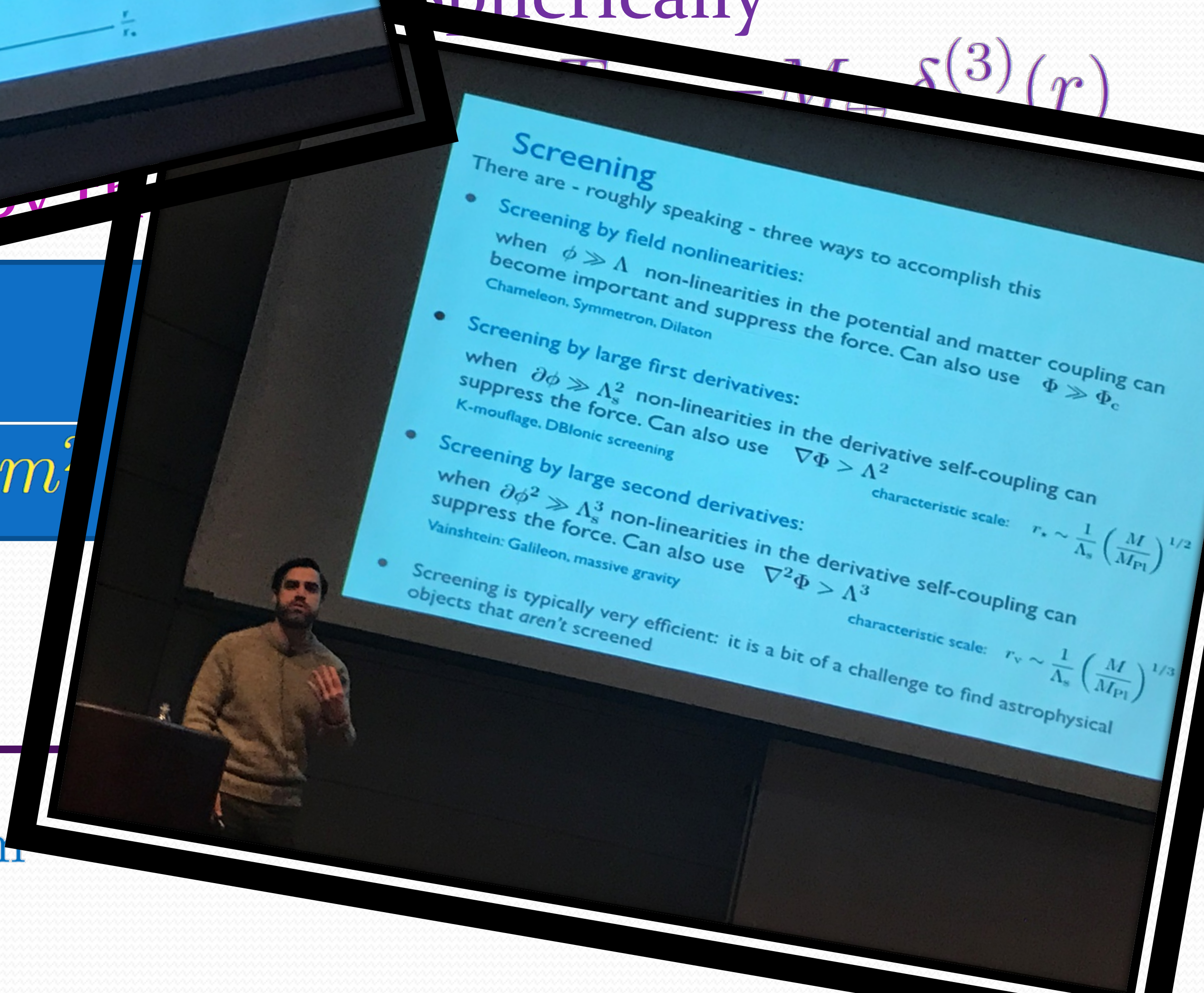
ism

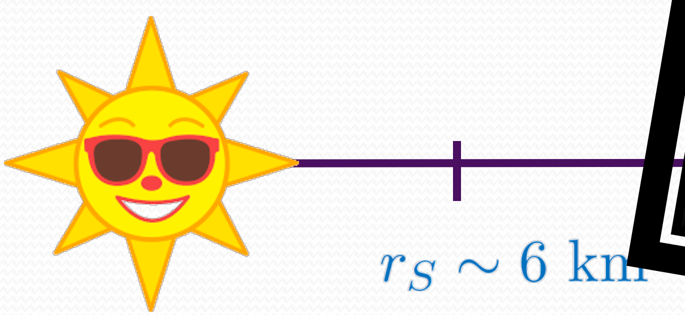
Spherically

$\delta^{(3)}(r)$

$$\frac{\phi'(r)}{r} + \frac{1}{M_{\rm Pl} m^2}$$







$r_S \sim 6$ km

Vainshtein mechanism

- Well understood for Static & Spherically Symmetric configurations $e.g. \quad T = -M_\oplus \, \delta^{(3)}(r)$
- Force mediated by the scalar mode $\phi'(r)$

$$\frac{\phi'(r)}{r} + \frac{1}{M_{\rm Pl} m^2} \left(\frac{\phi'(r)}{r} \right)^2 = \frac{M_\oplus}{4\pi M_{\rm Pl} r^3}$$

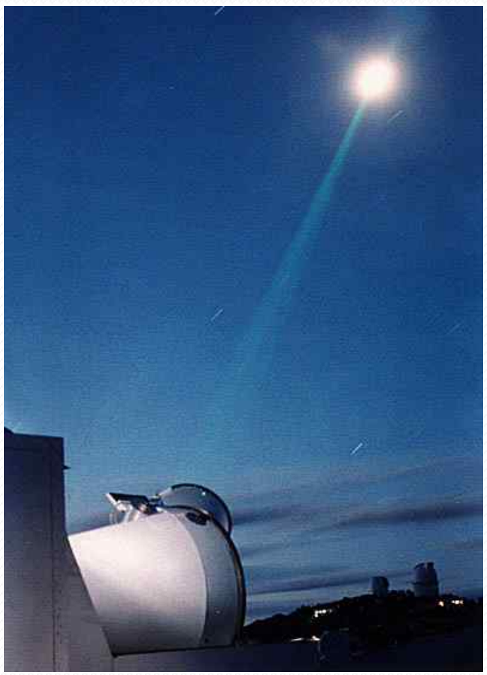
Vainshtein radius:

$$r_*^3 = \frac{1}{M_{\rm Pl} m^2} \frac{M_\oplus}{M_{\rm Pl}}$$

$$\text{for} \quad r \gg r_* \,, \quad \phi'(r) \sim \frac{M_\oplus}{M_{\rm Pl}} \frac{1}{r^2}$$

$$\text{for} \quad r \ll r_* \,, \quad \phi'(r) \sim \frac{M_\oplus}{M_{\rm Pl}} \frac{1}{r_*^{3/2} \sqrt{r}}$$

Lunar Laser Ranging bounds



For DGP, (cubic Galileon)

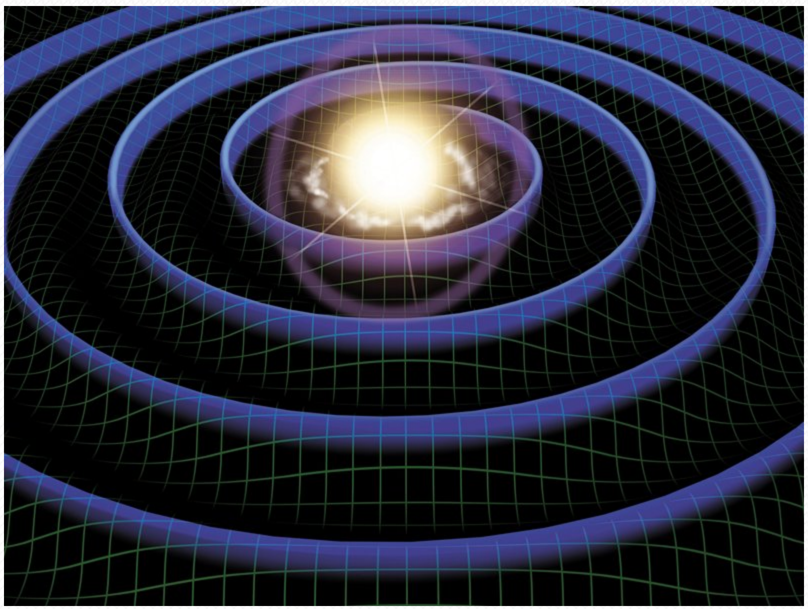
$$m_g < \delta\phi \left(\frac{r_{S,\oplus}}{a^3}\right)^{1/2} \qquad m_g \lesssim 10^{-32}\mathrm{eV}$$

For hard mass graviton, (~ quartic Galileon)

$$m_g < \delta\phi^{3/4} \left(\frac{r_{S,\oplus}}{a^3}\right)^{1/2} \qquad m_g \lesssim 10^{-30}\mathrm{eV}$$

Radiation into the scalar mode of the graviton

The existence of a scalar mode means new channels of radiation



Monopole & dipole exist but are suppressed by conservation of energy & momentum.

Quadrupole emitted by helicity-0 mode is suppressed by Vainshtein mechanism
(best understood in a Galileon approximation)

Work with Furqan Dar, Tate Deskins,
John Tom Giblin & Andrew Tolley

Contours of $\dot{\phi}^2$

For the cubic Galileon:
Power still in the quadrupole as in GR
Corrections to GR are very suppressed

Galileon Quadrupole emission

$$P_{\text{Quadrupole}} \sim \frac{(\Omega_P \bar{r})^3}{(\Omega_P r_\star)^{3/2}} \frac{\mathcal{M}^2}{M_{\text{Pl}}^2} \Omega_P^2 \qquad r_*^3 = \frac{1}{M_{\text{Pl}} m^2} \frac{M_{\text{Binary}}}{M_{\text{Pl}}}$$

For the Hulse-Taylor Pulsar $\quad m_g \lesssim 10^{-27} \text{eV}$

- For the Cubic Galileon, higher multipoles are suppressed by additional powers of velocity

Galileon Quadrupole emission

$$P_{\text{Quadrupole}} \sim \frac{(\Omega_P \bar{r})^3}{(\Omega_P r_\star)^{3/2}} \frac{\mathcal{M}^2}{M_{\text{Pl}}^2} \Omega_P^2 \qquad r_*^3 = \frac{1}{M_{\text{Pl}} m^2} \frac{M_{\text{Binary}}}{M_{\text{Pl}}}$$

For the Hulse-Taylor Pulsar $\quad m_g \lesssim 10^{-27}\text{eV}$

- For the Cubic Galileon, higher multipoles are suppressed by additional powers of velocity
- Massive gravity and stable self-accelerating models always include *at least* a *quartic Galileon*
- In the Quartic Galileon, the angular direction is *not screened as much* as the others $\longrightarrow$ many multipoles contribute to the power with the same magnitude…

$\longrightarrow$ Multipole expansion breaks down

Effective metric

- In the Cubic Galileon, the Effective metric for perturbations had of the same behavior along all directions

$$S_{\mathrm{Gal}} = \int \mathrm{d}^4x \left(-\frac{1}{2}(\partial\pi)^2 + \frac{1}{\Lambda^3}(\partial\pi)^2\Box\pi + \frac{1}{M_{\mathrm{Pl}}}\pi T \right)$$

$$\pi = \pi_0(r) + \phi$$

With $Z_{\mu\nu} \sim \left(\frac{\pi_0'}{\Lambda^3 r}\right)\eta_{\mu\nu}$

$$\downarrow$$

$$S_{\mathrm{Gal}} = \int \mathrm{d}^4x \left(-\frac{1}{2}Z^{\mu\nu}(\pi_0)\partial_\mu\phi\partial_\nu\phi + \frac{1}{M_{\mathrm{Pl}}}\phi\delta T \right)$$

Effective metric

- In the Quartic Galileon, the Effective metric for perturbations is *different* along different directions

$$Z_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu \sim \left(\frac{\pi_0'}{\Lambda^3 r}\right)^2 \left(-\mathrm{d}t^2 + \mathrm{d}r^2 + r_\star^2 \mathrm{d}\Omega^2\right)$$

Need to expand about
a different background…
or work numerically

Work in progress…

"looks bigger on the inside !"

Multipoles are no longer suppressed by more power of velocity

Summary

A graviton mass could have a wealth of cosmological implications

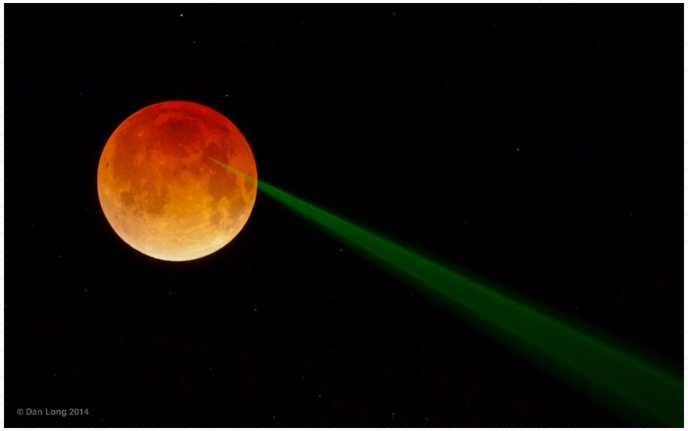
Dark energy, Degravitation, Inflation, Pre Big-Bang, bounces, (dark matter ?) …

The constraints on the graviton mass are already stronger than that on the photon.

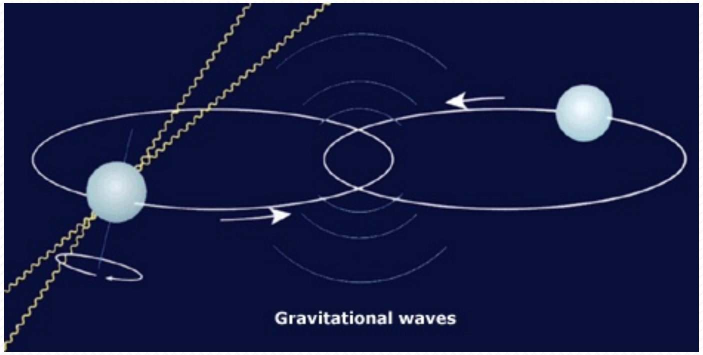
Very stringent bounds on a Yukawa-like type of behavior

Aside from those, direct detection with eLISA, primordial GWs detection could constraint the graviton on a very fundamental level.

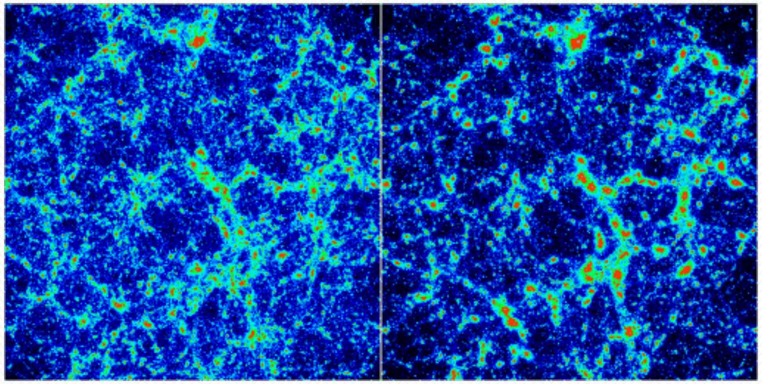
Summary



In a Lorentz invariant theory, the massive graviton also carry additional helicities (behaves as a Galileon) which impose strong bounds.



A better understanding of heliclity-o mode raditation is essential in further constraining these models.



How light is gravity ???

Yukawa

m_g (eV)	λ_g (km)	
10^{-23}	10^{12}	Solar System tests
10^{-32}	10^{21}	Weak lensing
10^{-29}	10^{19}	Bound clusters

Dispersion Relation

m_g (eV)	λ_g (km)	
10^{-22}	10^{11}	aLIGO bound
10^{-20}	10^{9}	Pulsar timing
10^{-30}	10^{20}	B–mode's in CMB

Fifth Force

m_g (eV)	λ_g (km)	
10^{-32}	10^{22}	Lunar Laser Ranging
10^{-27}	10^{17}	Binary pulsar
10^{-32}	10^{22}	Structure formation