Gravitational Dark Matter

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- Dark Matter solution from gravity.
- Quantum gravity.
- UV modifications:
  - Effective Quantum Field Theory approach
  - Fourth Order Gravity

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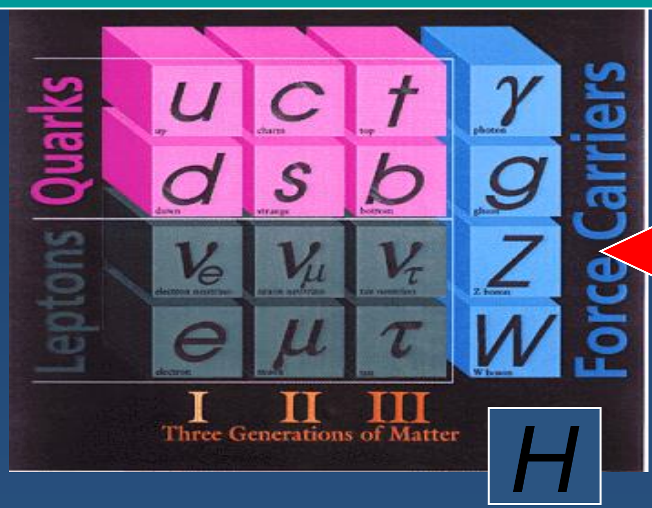
- New metric modes:
  - Abundance
  - Phenomenology and detection

Framework

Standard Model



M_{Pl}

Gravitational Sector

$h_{\mu\nu}$

?

SM scale:

$$\Lambda_{SM} \approx 100 \ GeV$$

Gravity scale:

$$10^{-3} eV \leq \Lambda_G \leq M_P$$

Quantum Gravity

- We do not know any consistent renormalizable Quantum field theory of gravity with a finite number of parameters (terms).
- The present theory of gravity is renormalizable if understood in the framework of quantum effective field theories.

J.F. Donoghue, **gr-qc/9405057**

- Gravity is not just Einstein equations.
  - What is the scale of quantum gravity?
  - Dark Energy/Dark Matter?
  - IR vs UV modifications

Quantum Gravity

- Einstein Gravity is not consistent at high energies:
  - Non-Unitarity
  - Non-renormalizable

$$C^2 = 2W = 2(R_{\alpha\beta}R^{\alpha\beta} - R^2/3)$$

$$\Gamma^{(2)}_{div} = \frac{1}{(4\pi)^2\varepsilon}\int d^4x\sqrt{-g}\left\{\alpha_a R^2 + \alpha_b C^2\right\}$$

- The present theory of gravity is renormalizable if treated in the framework of quantum effective field theories.

J.F. Donoghue, **gr-qc/9405057**

Fourth Derivative Gravity

- The action is renormalizable:

$$S\,(g_{\mu\nu}) = \int d^4x\sqrt{-g}\,\left\{-\,\Lambda^4 - \frac{M_P^2}{2}\,R + \frac{M_P^2}{12\,m_0^2}\,R^2 - \frac{M_P^2}{4\,m_2^2}\,C^2\right\} + \,(\text{surface terms})$$

$$C^2 = C_{\mu\nu\alpha\beta}{}^2 = 2W \;=\; 2(\,R_{\alpha\beta}\,R^{\alpha\beta} \;-\; R^2/3) + \,(\text{surface terms})$$

- The gauge fixing condition can be introduced within the standard Faddev-Popov prescription:

K.S. Stelle, **PRD16:953,1976**

K.S. Stelle, **Gen.Rel.Grav.9:353,1978**

$$\int [\delta h_{\mu\nu}]\,[\delta c_\tau]\,[\delta\bar{c}^\lambda]\;(\det C^{\mu\nu})^{-\frac{1}{2}}\;e^{iS(g_{\mu\nu})+iS_{\rm gf}+iS_{FP}}$$

Graviton Spectrum

- The propagator in the transverse or physical gauge is given by:

$$D_{\mu\nu\rho\sigma}(p) = \frac{i}{(2\,\pi)^4}\left\{\frac{\left[P^{(2)}_{\mu\nu\rho\sigma}(p) - 2\,P^{(0-s)}_{\mu\nu\rho\sigma}(p)\right]}{p^2} + \frac{2\,P^{(0-s)}_{\mu\nu\rho\sigma}(p)}{p^2 - m_0^2} - \frac{P^{(2)}_{\mu\nu\rho\sigma}(p)}{p^2 - m_2^2}\right\}$$

$$\begin{aligned} P^{(0-s)}_{\mu\nu\rho\sigma}(p) &= \frac{1}{3}\,\theta_{\mu\nu}\theta_{\rho\sigma} \\ P^{(2)}_{\mu\nu\rho\sigma}(p) &= \frac{1}{2}(\theta_{\mu\rho}\theta_{\nu\sigma} + \theta_{\mu\sigma}\theta_{\nu\rho}) - \frac{1}{3}\,\theta_{\mu\nu}\theta_{\rho\sigma} \end{aligned}$$

$$\begin{aligned} \theta_{\mu\nu} &= \eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \\ \omega_{\mu\nu} &= \frac{p_\mu p_\nu}{p^2} \end{aligned}$$

$$p^2 \longrightarrow p^2 + i\epsilon$$

- The same propagator can be written as:

$$D_{\mu\nu\rho\sigma}(p) = \frac{-i}{(2\,\pi)^4}\left\{\frac{m_2^2\,P^{(2)}_{\mu\nu\rho\sigma}(p)}{p^2(p^2 - m_2^2)} + \frac{2\,m_0^2\,P^{(0-s)}_{\mu\nu\rho\sigma}(p)}{p^2(p^2 - m_0^2)}\right\}$$

The Model

- The gravitational action is reduced to:

$$S(g_{\mu\nu}) = \int d^4x \sqrt{-g} \left\{ -\Lambda^4 - \frac{M_P^2}{2} R + \frac{M_P^2}{12\, m_0^2} R^2 + \ \dots \right\}$$

- The rest of terms in the QEFTG are necessary in order to renormalize the divergences coming from radiative corrections. However, their effects will be negligible for the rest of the discussion.

- Validity of the model?

Graviton Spectrum

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- The same propagator can be written as:

$$D_{\mu\nu\rho\sigma}(p) = \frac{-i}{(2\,\pi)^4}\left\{\frac{-P^{(2)}_{\mu\nu\rho\sigma}(p)}{p^2} + \frac{2\,m_0^2\,P^{(0-s)}_{\mu\nu\rho\sigma}(p)}{p^2(p^2 - m_0^2)}\right\}$$

Classical Dynamic

- The Einstein equations are modified:

$$\left[1 - \frac{1}{3\,m_s^2} R\right] R_{\mu\nu} - \frac{1}{2}\left[R - \frac{1}{6\,m_s^2} R^2\right] g_{\mu\nu} - \mathcal{I}_{\alpha\beta\mu\nu} \nabla^\alpha \nabla^\beta \left[\frac{1}{3\,m_s^2} R\right] = \frac{T_{\mu\nu}}{M_{\rm Pl}^2},$$

A. A. Starobinsky, **PLB91:99,1980**

$$\mathcal{I}_{\alpha\beta\mu\nu} \equiv (g_{\alpha\beta} g_{\mu\nu} - g_{\alpha\mu} g_{\beta\nu})$$

- Starobinsky and other authors studied this action and other extensions in the 80's in order to generate inflation.

Einstein Limit

- In any case, we will work always at curvatures $R << m_0^{\ 2}$, when the EEs are a good approximation.

- In fact, we can work in the so called Einstein frame, where the new scalar degree of freedom is explicitly separated from the metric tensor, which has associated the standard Einstein-Hilbert action.

Einstein Frame

- Trough a conformal transformation:

$$\tilde{g}_{\mu\nu} = \exp(\sqrt{2/3}\varphi/M_{\rm Pl})g_{\mu\nu}$$

the standard action for gravity is recover in addition to a standard action for the scalaron with the potential given by:

$$V_\varphi = \frac{3}{4} m_s^2 M_{\rm Pl}^2 \left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{\varphi}{M_{\rm Pl}}\right)\right]^2$$

$$\mathcal{L}_\varphi = -V_\varphi \simeq -\frac{m_s^2}{2}\varphi^2 + \frac{m_s^2}{M_{\rm Pl}\sqrt{6}}\varphi^3 - \frac{7\,m_s^2}{36\,M_{\rm Pl}^2}\varphi^4 + \ldots$$

Scalaron Couplings

- The scalaron is universally coupled to matter trough the trace of the energy momentum tensor:

$$\mathcal{L}_{\phi-T_{\mu\nu}} = \frac{-1}{M_{\rm Pl}\sqrt{6}}\,\phi\, T^{\mu}_{\mu}$$

- It means that at tree level, the coupling with SM particles are given by:

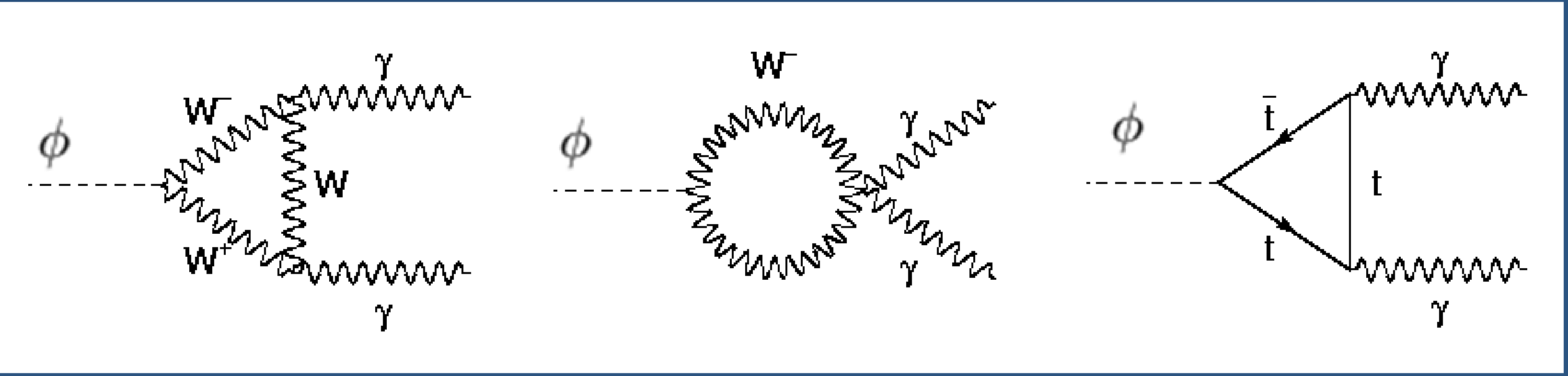
$$\mathcal{L}^{\rm tree\ level}_{\phi-SM} = \frac{-1}{M_{\rm Pl}\sqrt{6}}\,\phi\,\left\{2\,m_h^2 h^2 - \nabla_\mu h \nabla^\nu h + \sum_\psi m_\psi\,\bar\psi\psi - 2\,m_W^2\,W^+_\mu W^{-\mu} - m_Z^2\,Z_\mu Z^\mu\right\}$$

Radiative Scalaron Couplings

- On loop generates the coupling with photons and gluons:

$$\mathcal{L}^{\text{one loop}}_{\phi-SM} = \frac{-1}{M_{\rm Pl}\sqrt{6}}\,\phi\left\{\frac{\alpha_{EM}c_{EM}}{8\pi}F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s c_G}{8\pi}G^a_{\mu\nu}G^{\mu\nu}_a\right\}$$

- Contributions to the photon vertex:



Abundance

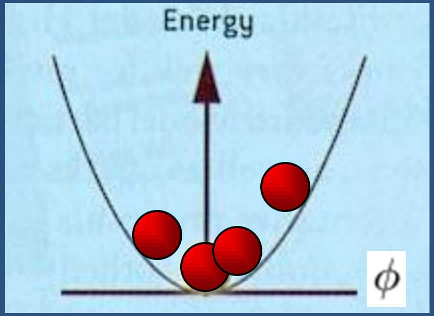
- Thermal abundance would require $T >> \sqrt{m_0 M_P}$
  - Beyond the validity of Einstein Equations.
- Misalignment mechanism
  - For $H(T) >> m_0$ → $\phi = \phi_1$

$$T_1 \simeq 15.5\,\mathrm{TeV}\left[\frac{m_s}{1\,\mathrm{eV}}\right]^{\frac{1}{2}}\left[\frac{100}{g_{e\,1}}\right]^{\frac{1}{4}}$$

  - For $3H(T) \leq m_0$ → ϕ oscillates around the minimum of its potential. These oscillations correspond to a zero-momentum condensate.

Cold DM Abundance:

$$\Omega_\phi h^2 \simeq 0.86\left[\frac{m_s}{1\,\mathrm{eV}}\right]^{\frac{1}{2}}\left[\frac{\phi_1}{10^{12}\,\mathrm{GeV}}\right]^2\left[\frac{100\,g_{e\,1}^3}{(\gamma_{s1}\,g_{s1})^4}\right]^{\frac{1}{4}}$$



J. Cembranos, PRL102:141301 (2009)

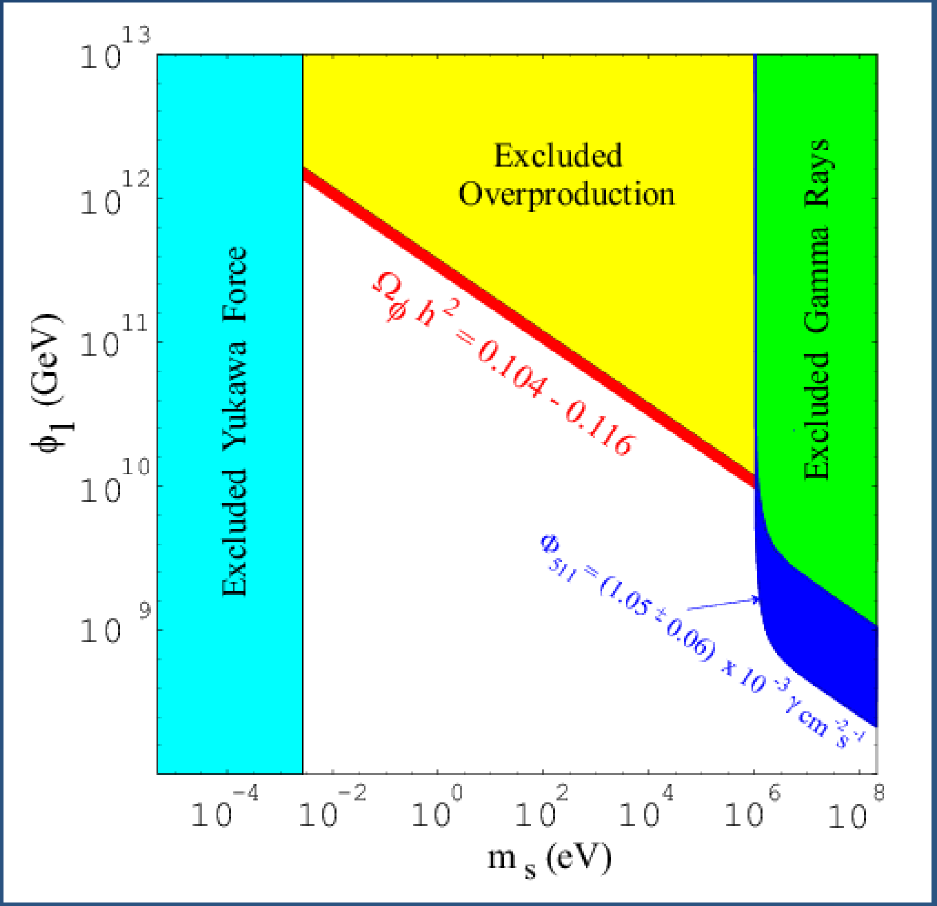
R2-gravity as Dark Matter

Parameter space of R2-gravity as DM:

- **R2 abundance inside the WMAP limits.**

Constraints:

- **Overproduction.**



New Force Constraints

The new scalar graviton generates a Yukawa new interaction among standard matter:

$$V_{ab} = -\alpha \frac{1}{8\pi M_{\rm Pl}^2} \frac{M_a M_b}{r} e^{-m_s r}$$

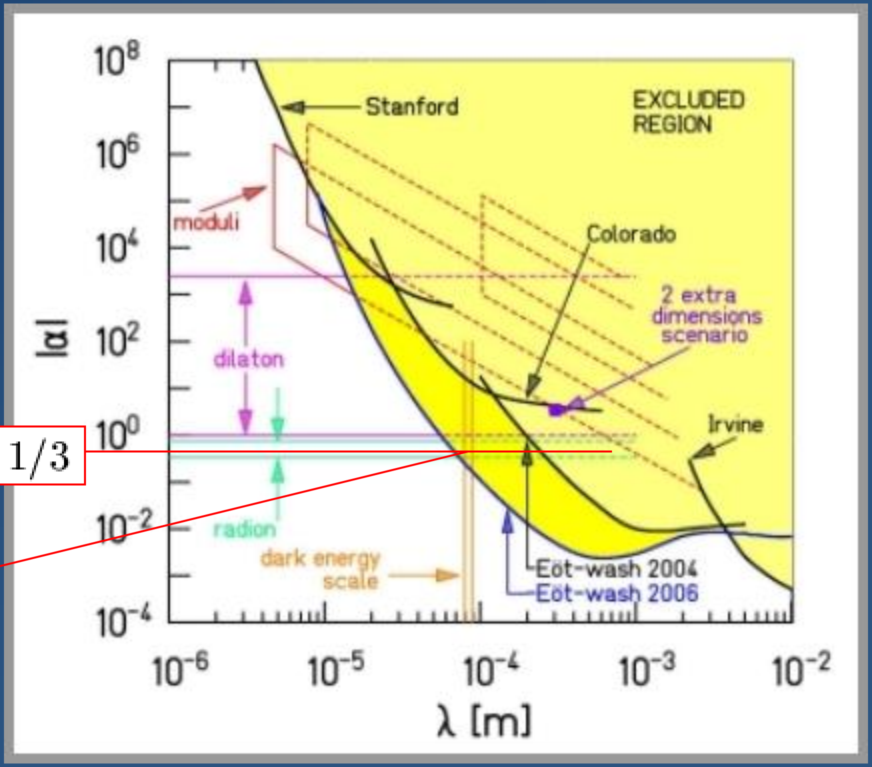
With $\alpha = 1/3$ **.**

The University of Washington Eöt-Wash group has tested the strength of gravity at distances down to 0.06 mm.

D. J. Kapner *et. al.*, **hep-ph/0611184**

Consistent with Newton's inverse-square law.

$$m_s \geq 2.7 \cdot 10^{-3}\text{eV} \qquad \text{at } 95\ \%\ \text{c.l.}$$



R2-gravity as Dark Matter

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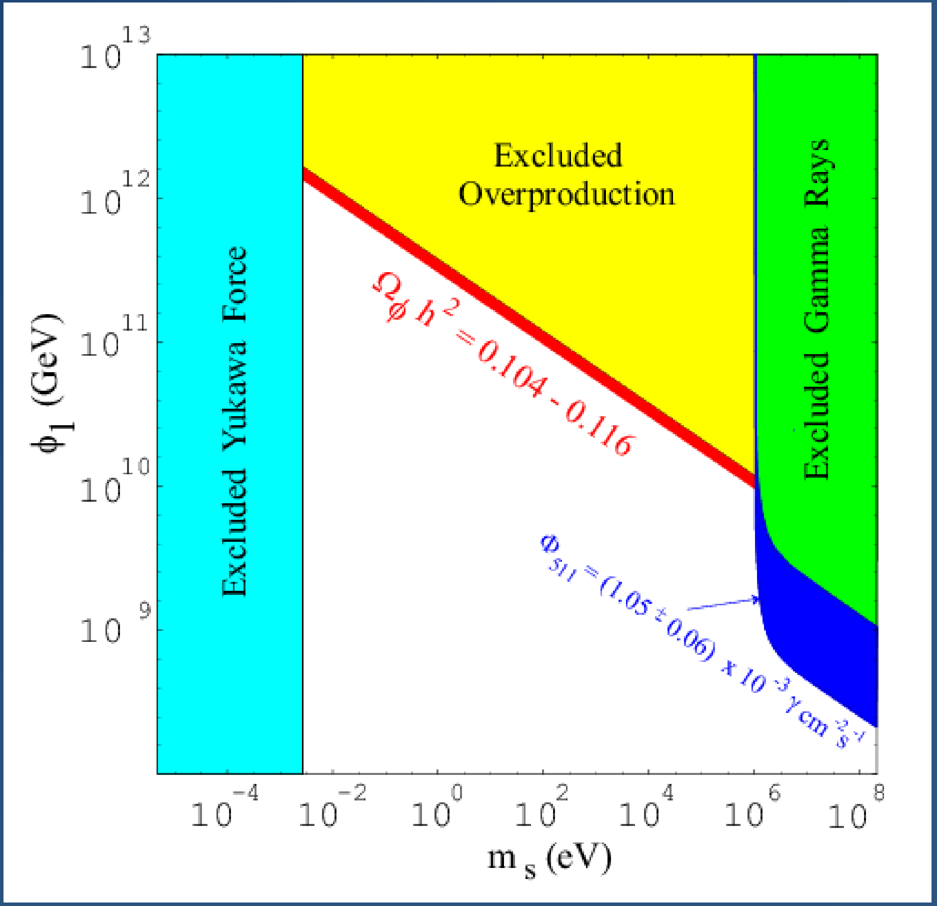


Electron-positron Decay

Depending on its abundance, the mass is constrained from above.

The e^+e^- **decay is the most constraining if the R2-gravity constitutes the total non-baryonic DM.**

The decay rate in a generic pair fermion-antifermion:

$$\Gamma_{\phi\to\psi\bar{\psi}} = \frac{N_c m_\psi^2 m_s}{48\pi M_{\rm Pl}^2}\left(1-\frac{4m_\psi^2}{m_s^2}\right)^{3/2}$$

In particular, for the e^+e^- **decay:**

$$\Gamma_{\phi\to e^+e^-} \simeq \left[2.14\times 10^{24}\, s.\, \frac{r_e^2}{(r_e^2-1)^{3/2}}\right]^{-1}$$

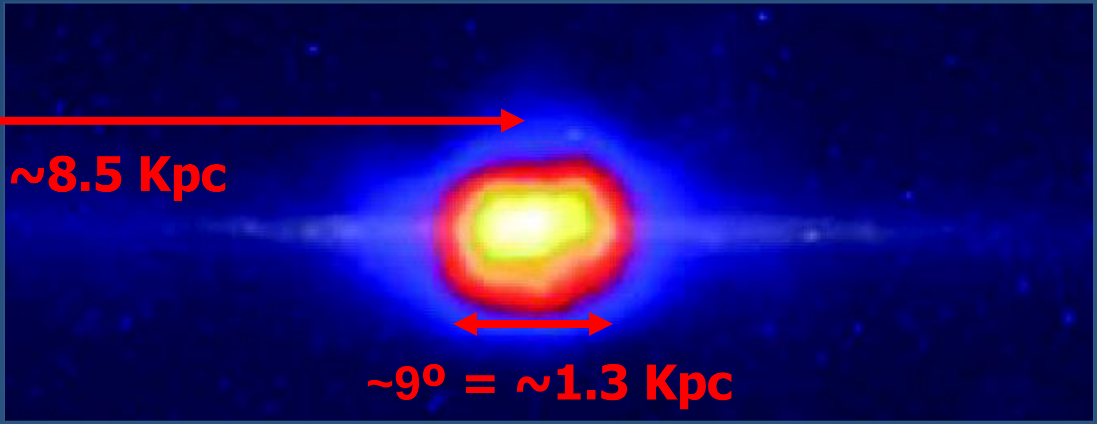
$$r_e = m_s/(2m_e)$$

511 keV γ from the GC

We have had observations of 511 photons coming form the center of the galaxy for the last 30 years with different instruments.

instrument	year	flux $[10^{-3}\ ph\ cm^{-2}\ s^{-1}]$	centroid $[keV]$	width (FWHM) $[keV]$	references
HEAO-3[a]	1979 – 1980	1.13 ± 0.13	510.92 ± 0.23	$1.6^{+0.9}_{-1.6}$	Mahoney et al. 1994
GRIS[b]	1988 *and* 1992	0.88 ± 0.07		2.5 ± 0.4	Leventhal et al. 1993
HEXAGONE[b]	1989	1.00 ± 0.24	511.33 ± 0.41	$2.90^{+1.10}_{-1.01}$	Smith et al. 1993
TGRS[c]	1995 – 1997	1.07 ± 0.05	510.98 ± 0.10	1.81 ± 0.54	Harris et al. 1998
SPI	2003	$0.99^{+0.47}_{-0.21}$	$511.06^{+0.17}_{-0.19}$	$2.95^{+0.45}_{-0.51}$	

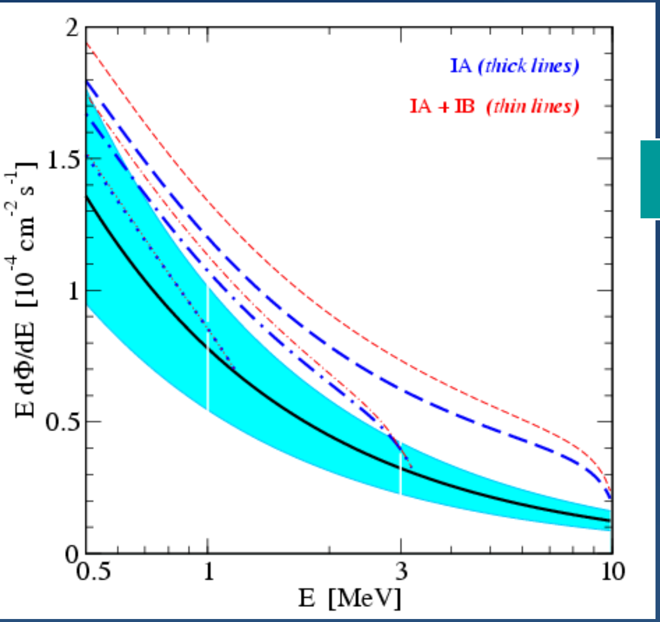
Pierre Jean *et al*, **astro-ph/0309484**



511 keV signal by SPectromètre Integral

511 keV γ line signal

The signal comes from $e^+e^- \to \gamma\gamma$, but it is difficult to find a source of 10^43 positrons per second inside the bulge with kinetic energies smaller than ~ 4 MeV as it is required.



J.F. Beacom and H. Yuksel , **astro-ph/0512411**

Proposed sources of positrons

1. Supernovas Type II, Ia and Ic
2. Wolf-Rayet Stars
3. Neutron stars, pulsars
4. Cosmic rays
5. Black holes
6. Dark Matter:
    6.1. Annihilating DM
    6.2. Decaying DM

511 keV γ from Decaying DM

Several authors have studied this signal within different decaying Dark Matter models:

1. Sterile neutrinos
2. Axinos
3. Moduli
4. WIMPs
5. Branons

C. Picciotto and M. Pospelov , hep-ph/0402178
D. Hooper and L.T. Wang, hep-ph/0402220
S. Kasuya and M. Kawasaki, astro-ph/0602296
M. Pospelov and A. Ritz, hep-ph/0703128
J. Cembranos and L. Strigari, 0801.0630[astro-ph]

To account for the signal, all of them find the conditions (supposing a total DM abundance):

M (or ΔM) ~ 1 MeV

τ ~ 10^26 sec / M (MeV)

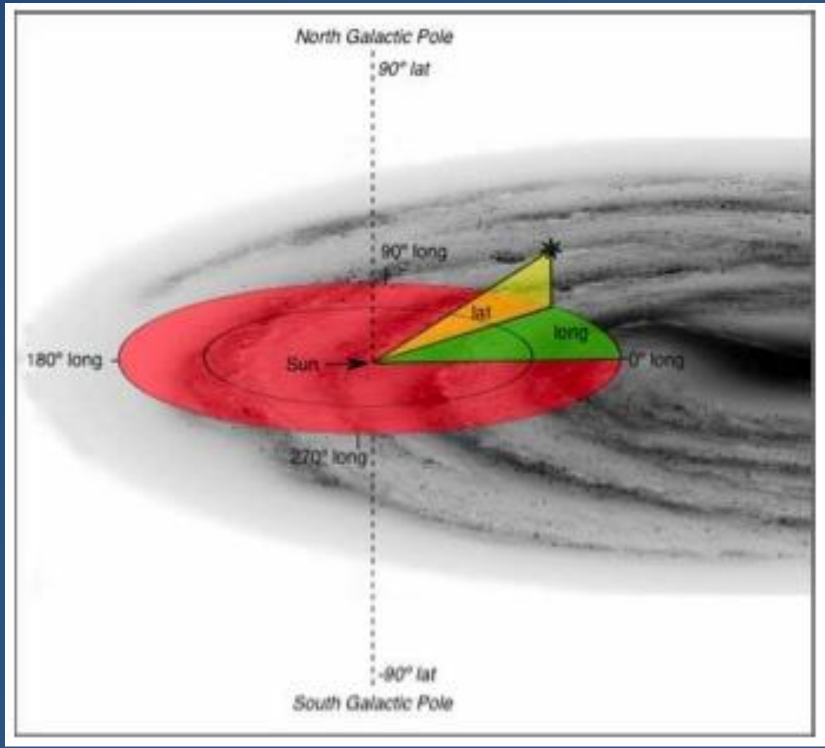
Decaying DM, source of 511 keV γ

Decaying DM could account for the 511 keV line with cuspy dark halos ($\gamma \geq 1.5$).

$$\rho_0 = 0.12 \text{ GeV cm}^{-3}, \; r_0 = 10 \text{ kpc}, \; \gamma = 1.5, \; \beta = 3, \; \alpha = 8$$

J. Cembranos and L. Strigari, PRD77:123519 (2008)

$$\rho(r) = \frac{\rho_0}{(r/r_0)^\gamma \left[1 + (r/r_0)^\alpha\right]^{(\beta-\gamma)/\alpha}}$$



The preferred life-time is dominated by high uncertainties in the halo profile and substructure:

$$\frac{\Omega_{\rm DDM} h^2 \, \Gamma_{\rm DDM}}{M_{\rm DDM}} \simeq \left[(0.2 - 4) \times 10^{27} \text{ s MeV}\right]^{-1}$$

J. Cembranos, PRL102:141301 (2009)

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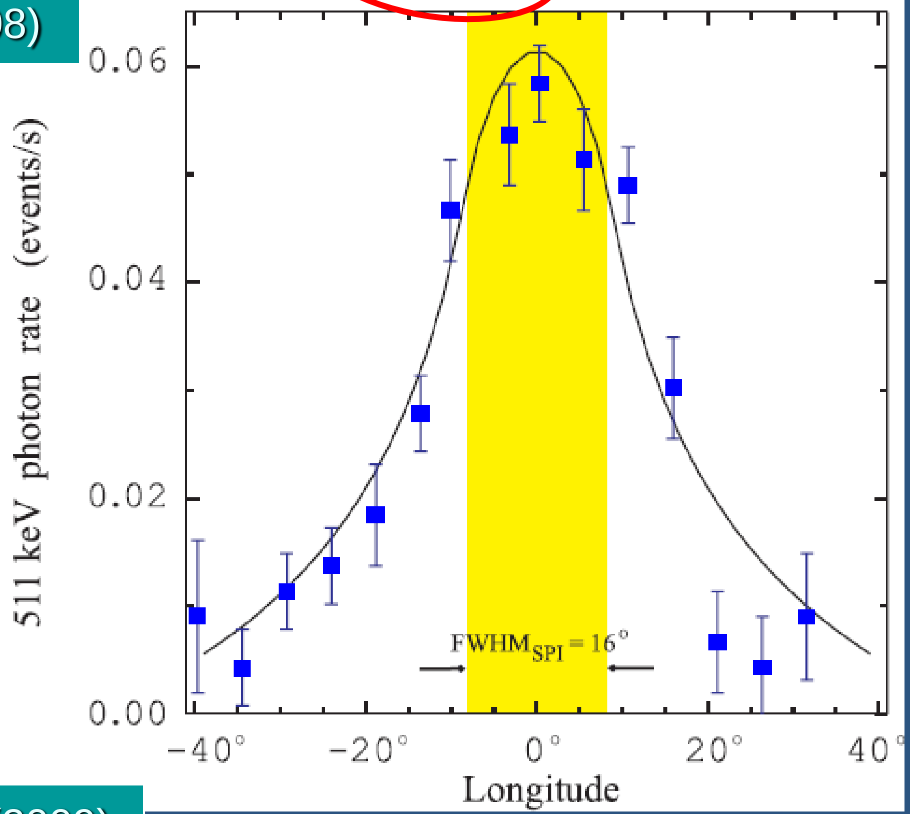


J. Cembranos, PRL102:141301 (2009)

R2-gravity as Dark Matter

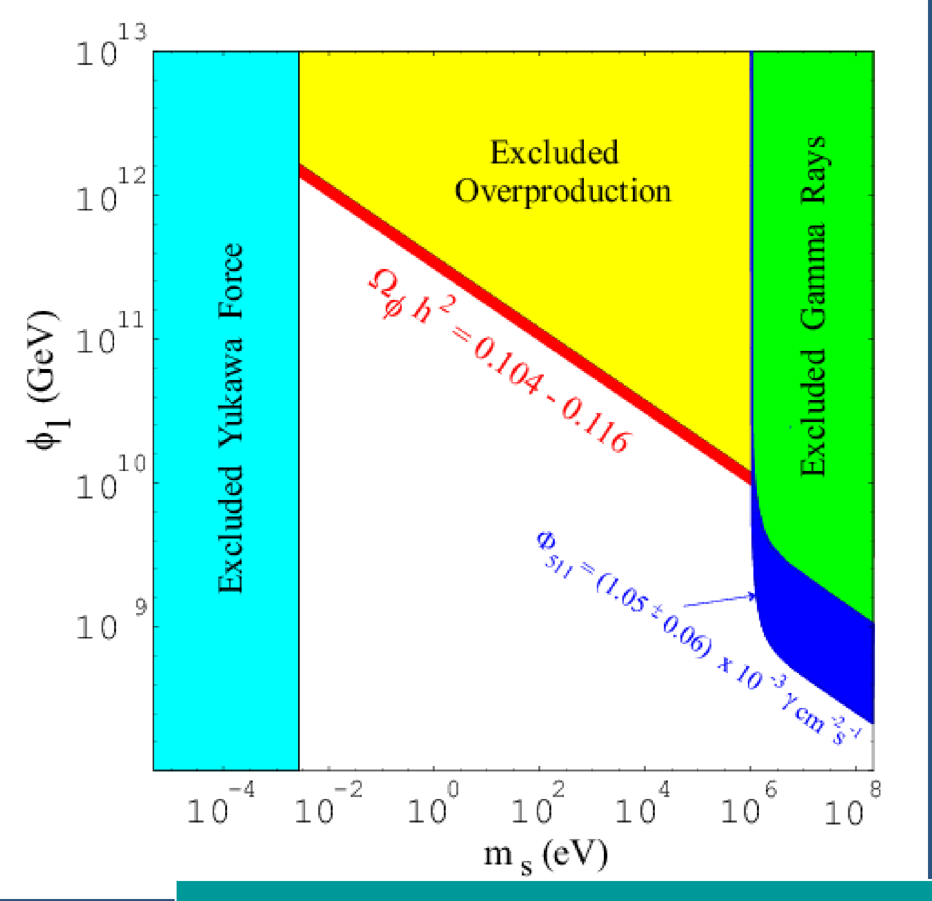
Parameter space for R2-gravity as DM:

- **Abundance inside the WMAP limits.**

Constraints:

- **Overproduction.**
- **Eöt-Wash experiments.**
- **Gamma rays.**

- **511 keV line from the GC (INTEGRAL data).**



J. Cembranos, PRL102:141301 (2009)

Conclusions

- New degrees of freedom in the gravitational sector are viable candidates for DM.
- We have studied R2-gravity, as a particular example.
- Other signatures:

1.- Observations of γ lines from the GC:

Potentially able to test the heavy part of the allowed spectrum.

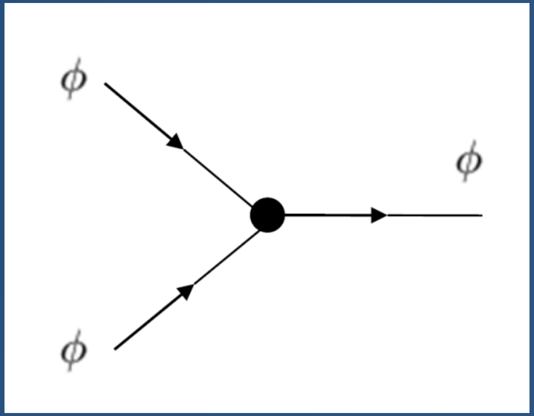
$$\Gamma_{\phi\to\gamma\gamma} = \frac{121\,\alpha_{EM}^2 m_s^3}{13824\,\pi^3 M_{\rm Pl}^2} \simeq \left[2.5\times10^{29}\,s.\,\left[\frac{1\,{\rm MeV}}{m_s}\right]^3\right]^{-1}$$

J. Cembranos, PRL102:141301 (2009)

Back-up Slides

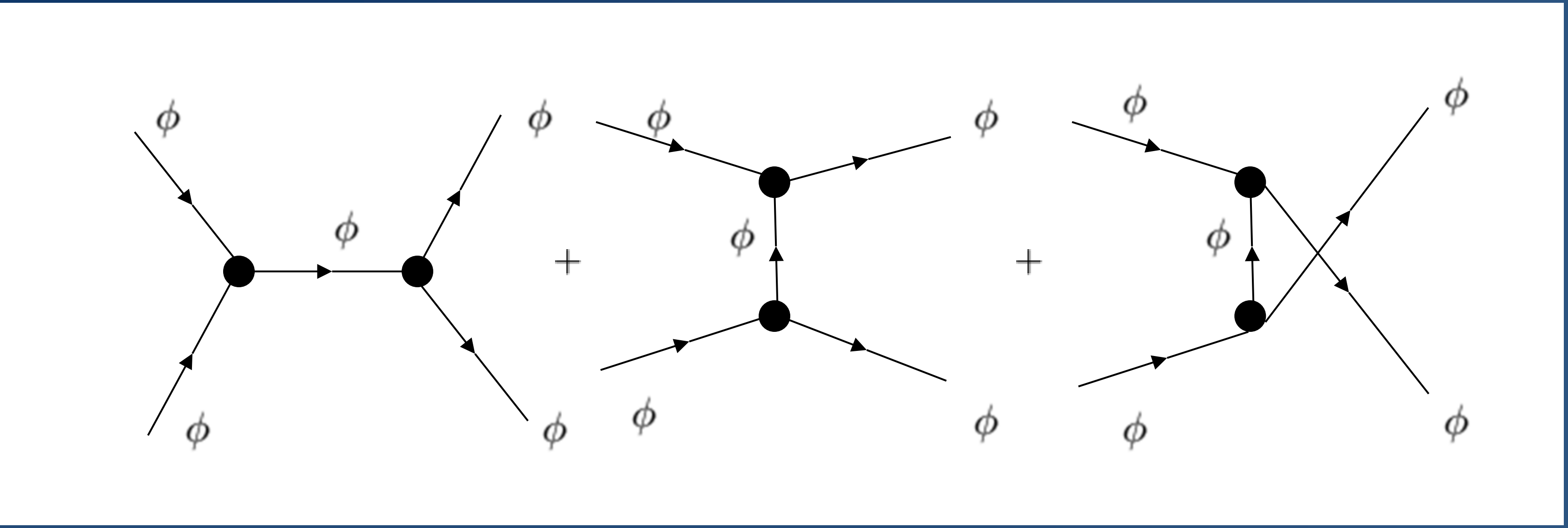
The Model

- The self-couplings of the gravitational degrees of freedom are given by a series in:
  - The number of fields suppressed by M_p
  - The number of derivatives suppressed by m_0
- The interesting case is $m_0 << M_P$. The leading order at high energies would be given by the interaction with highest number of derivatives (4) and lower number of fields (3).



$$V_{4,3}(P) \approx v_1 \left(\frac{P^4}{m_0{}^2 M_P} \right) + v_2 \left(\frac{P^2}{M_P} \right)$$

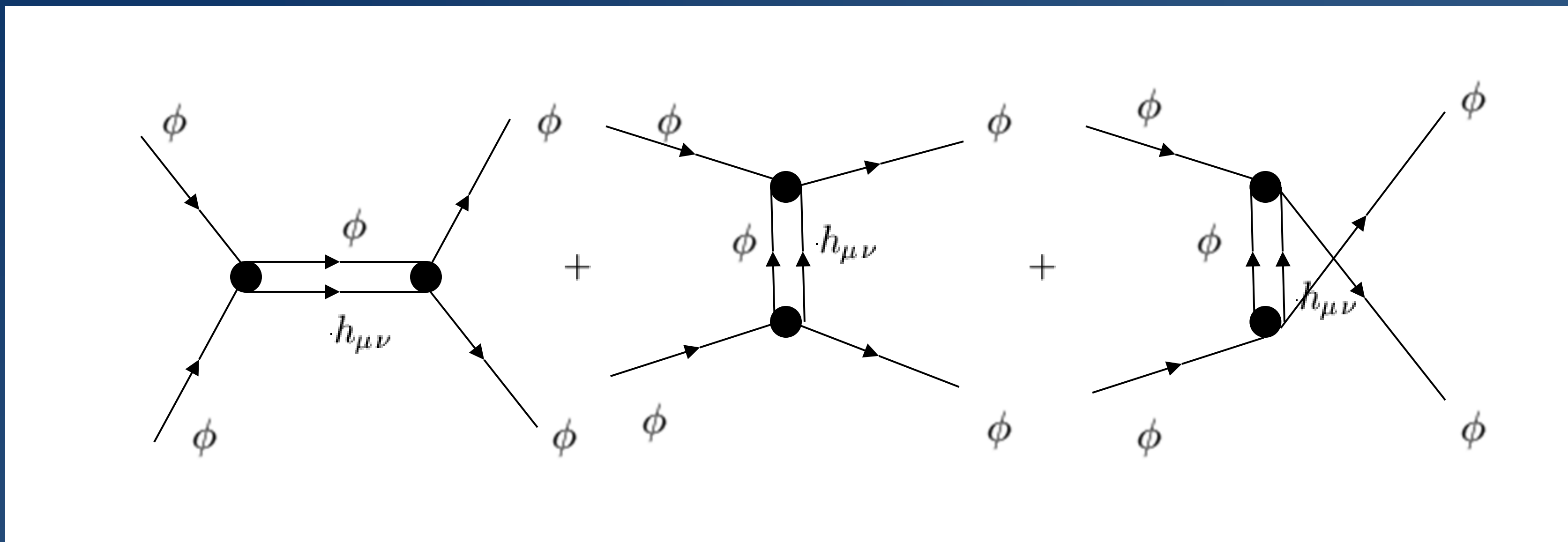
Four Scalar Amplitude



- The leading order at high energies:

$$A_{\{4,0,V_{4,3}\}}(P) \approx a\left(\frac{P^6}{m_0{}^4 M_P{}^2}\right) + b\left(\frac{P^4}{m_0{}^2 M_P{}^2}\right) + c\left(\frac{P^2}{M_P{}^2}\right) + \ldots$$

Four Scalar Amplitude



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$$A_{\{4,0,V_{4,3}\}}(P) \approx \cancel{a\left(\frac{P^6}{m_0^{4} M_P^{2}}\right)} + b\left(\frac{P^4}{m_0^{2} M_P^{2}}\right) + c\left(\frac{P^2}{M_P^{2}}\right) + \ldots$$

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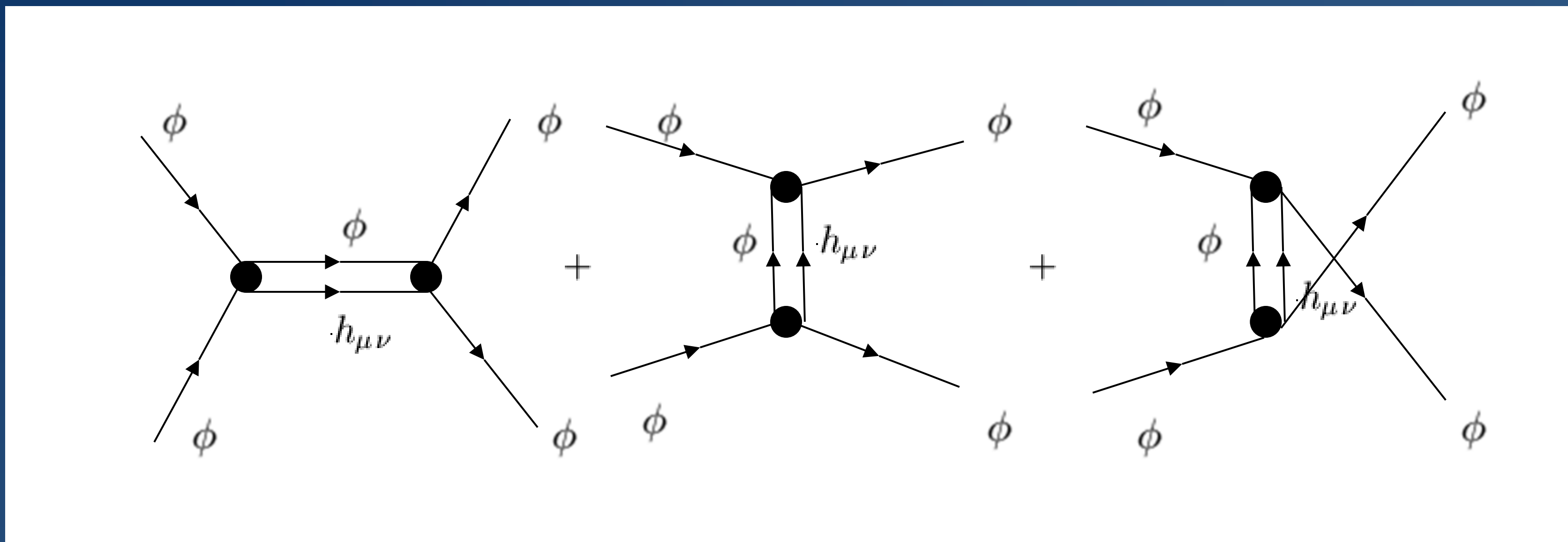
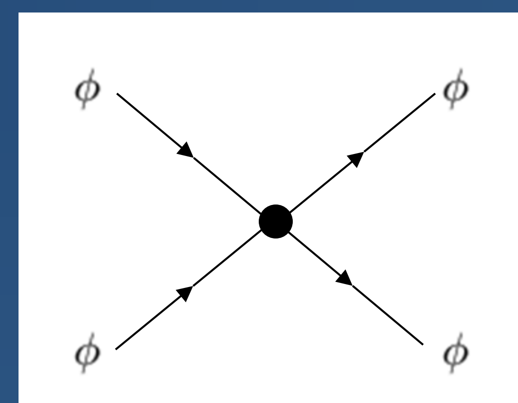


- The leading order at high energies:

$$A_{\{4,0,V_{4,3}\}}(P) \approx a\left(\frac{P^6}{m\ldots M\ldots^{2}}\right) + b\left(\frac{P^4}{m\ldots M\ldots^{2}}\right) + c\left(\frac{P^2}{M_P^{\;2}}\right) + \ldots$$



Oscillating Expansion

- For long times, $m_0 t \gg 1$:

Scalar mode evolution

$$\phi(t) = \phi_0 \frac{\sin(m_0 t)}{\hat{a}^{3/2}(t)}$$

Relation between scale factors:

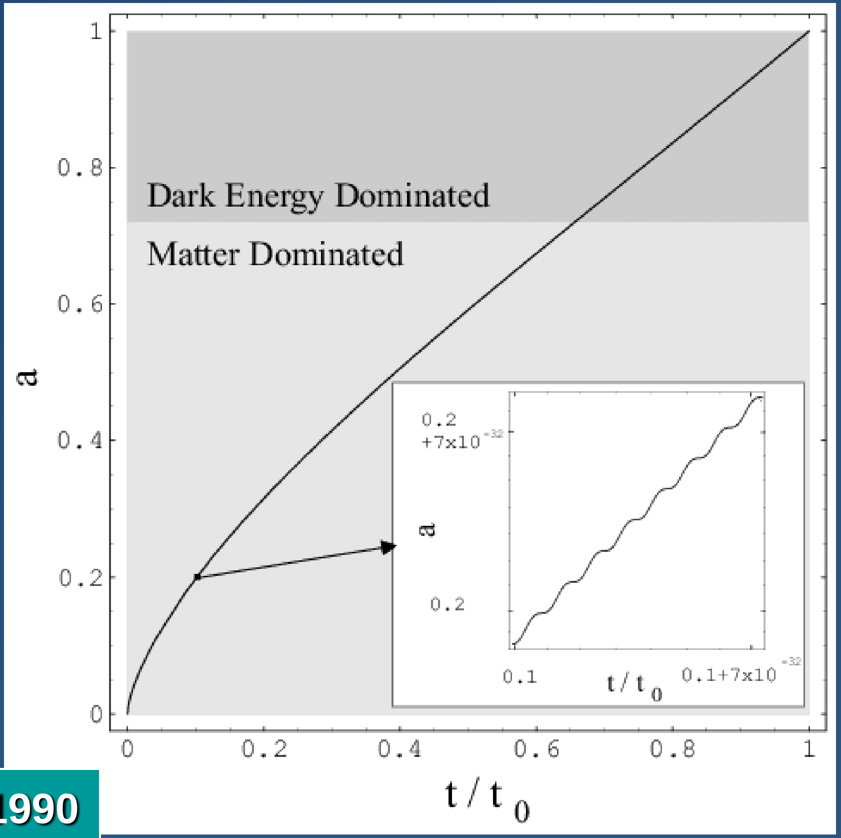
$$a(t) = \hat{a}(t)\left[1 + \frac{\phi(t)}{\sqrt{6} M_{\rm Pl}} + \dots\right] \qquad t = \hat{t}$$

Relation between Hubble rates:

$$H(t) = \hat{H}(t) + \frac{m_0 \phi_0}{\sqrt{6} M_{\rm Pl}} \frac{\cos(m_0 t)}{\hat{a}^{3/2}(t)} + \dots$$

$$H(t) = \sqrt{\frac{m_0^2 \phi_0^2}{6 M_{\rm Pl}^2 \hat{a}^3(t)} + H_0^2 \Omega(t)} + \frac{m_0 \phi_0}{\sqrt{6} M_{\rm Pl}} \frac{\cos(m_0 t)}{\hat{a}^{3/2}(t)} + \dots$$

$$\Omega(t) = \Omega_R \hat{a}^{-4}(t) + \Omega_M \hat{a}^{-3}(t) + \Omega_\kappa \hat{a}^{-2}(t) + \Omega_\Lambda + \dots$$



A. Vilenkin, **PRD32:2511,1985**

S. Kalara, N. Kaloper, K. Olive, **Nuc.Phys.B341:252,1990**

Other Signatures

- If $m_s < 2m_e$, the only observable decay channel is in two photons.
- It is loop suppressed:

$$\Gamma_{\phi\to\gamma\gamma} = \frac{\alpha_{EM}^2 m_s^3}{1536\pi^3 M_{\rm Pl}^2}\left|N_c e_i^2 F_i\right|^2$$

$$\left|N_c e_i^2 F_i\right| = 11/3 \quad \Longrightarrow \quad \Gamma_{\phi\to\gamma\gamma} = \frac{121\,\alpha_{EM}^2 m_s^3}{13824\,\pi^3 M_{\rm Pl}^2} \simeq \left[2.5\times 10^{29}\,s.\left[\frac{1\,{\rm MeV}}{m_s}\right]^3\right]^{-1}$$

1.- Observations of γ lines from the GC:

Potentially able to test heavy part of the spectrum.

2.- Modifications in the CMB through injection of energy in baryons

WMAP is able to test life-times around 10^25 s.

PLANCK wont improve enough to be sensitive to R2-gravity.