DARK MATTER MODELS

WESTFÄLISCHE
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European
Commission

Dark Matter Candidates

Among other well-motivated candidates:

1.- Supersymmetric (SUSY) models:

Lightest supersymmetric particle (LSP): Neutralinos, gravitinos, axinos, …

2.- Universal Extra Dimensions (UED):

Lightest KK mode (LKKM): B^1, G^1,…

3.- Brane-World Scenarios (WBS):

Branons,…

4.- CP Problem in QCD solution:

Axion, and coherent dark matter…

5.- Models for neutrino masses:

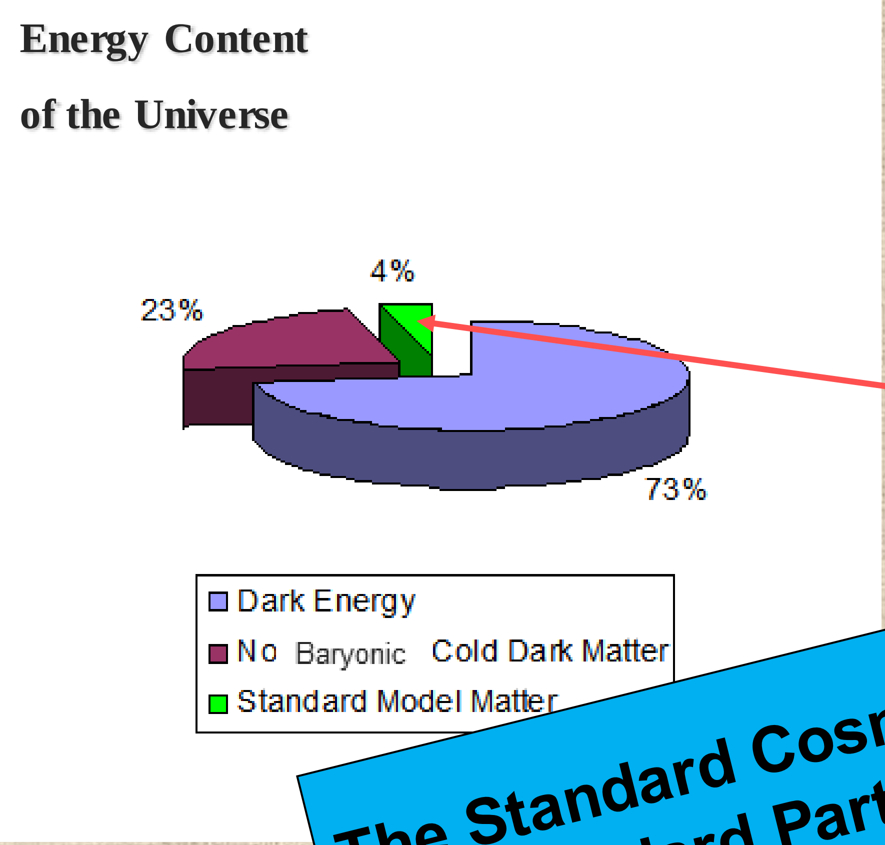
Sterile neutrinos,…

6.- UV completion of gravity:

R^2 Dark Matter,…

7.- …

Cosmological model



The Standard Cosmology wants non Standard Particles

Search of DM candidates beyond the SM.

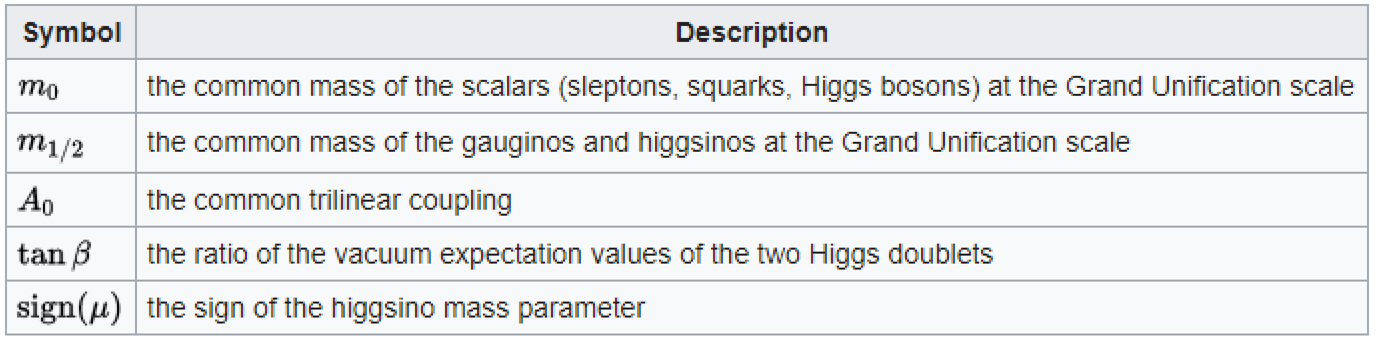
Dark Matter Properties

- **Thermal DM vs. Non-thermal DM**
  - **WIMPs: Weakly Interacting Massive Particles**
  - **SuperWIMPs: SuperWeakly Interacting Massive Particles**
- **Decaying DM vs. Stable DM**
  - **SuperWIMPs, axion-like particles, ...**
- **Interacting DM vs. Non-interacting DM**
  - **Motivated by small scale structure problems**
- **Cold DM vs. Hot DM**
  - **Warm DM also motivated by small scale structure problems**

Supersymmetry

Symmetry between fermionic and scalars, that introduces new degrees of freedom that can work as dark matter DM.

The minimal model is the cMSSM that depends on 6 free parameters: $\{ m_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}(\mu) , m_{3/2} \}$



Symbol	Description
m_0	the common mass of the scalars (sleptons, squarks, Higgs bosons) at the Grand Unification scale
$m_{1/2}$	the common mass of the gauginos and higgsinos at the Grand Unification scale
A_0	the common trilinear coupling
$\tan\beta$	the ratio of the vacuum expectation values of the two Higgs doublets
$\mathrm{sign}(\mu)$	the sign of the higgsino mass parameter

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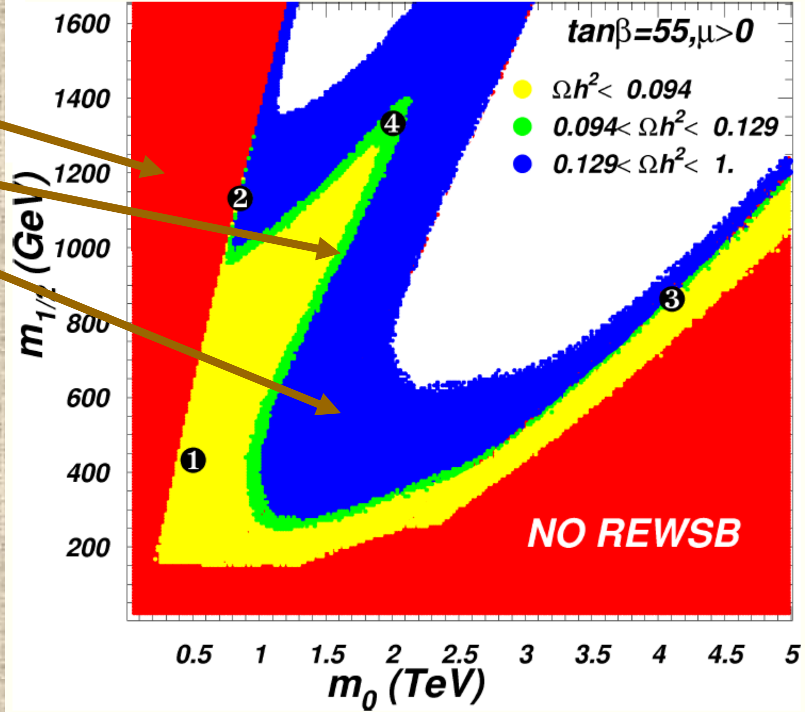
1.- WIMP scenario: Neutralino χ

1.a. $\tilde{\tau}$ LSP excluded

1.b. χ LSP favored

1.c. $\Omega_{LSP}h^2 > 0.13$ excluded



A. Belyaev, ALCPG, Snowmass (2005)

WIMP signatures:

a. Direct detection

b. Indirect detection

c. Production in colliders

d. Precision observables

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2.- SuperWIMP scenario: gravitino $g_{3/2}$

2.a. $\tilde{\tau}$ NLSP favored

2.b. χ NLSP disfavored

2.c. $\Omega_{NLSP}h^2 > 0.13$ favored

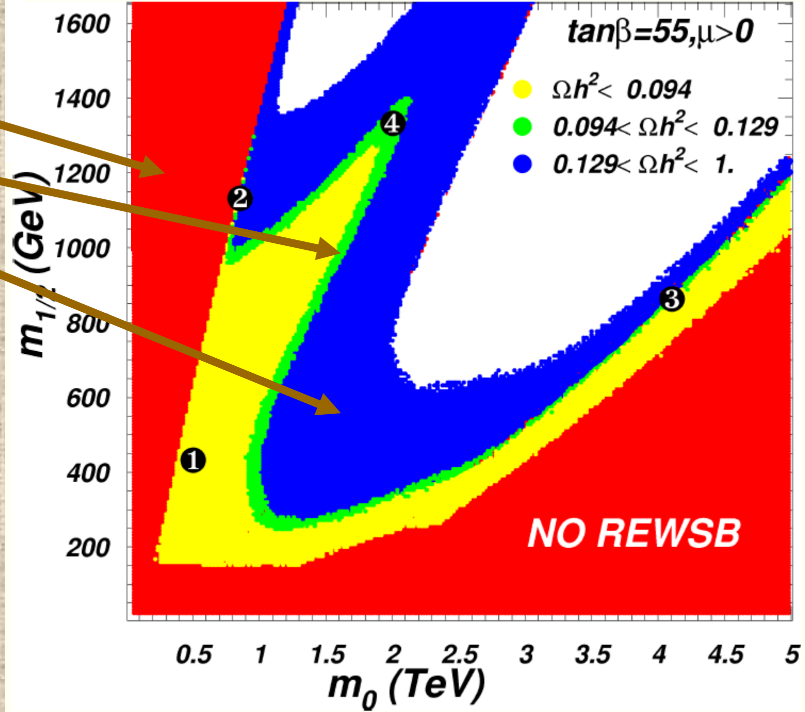
SuperWIMP signatures:

a. Indirect detection

b. Big Bang Nucleosynthesis

c. Microwave Background

d. Structure Formation



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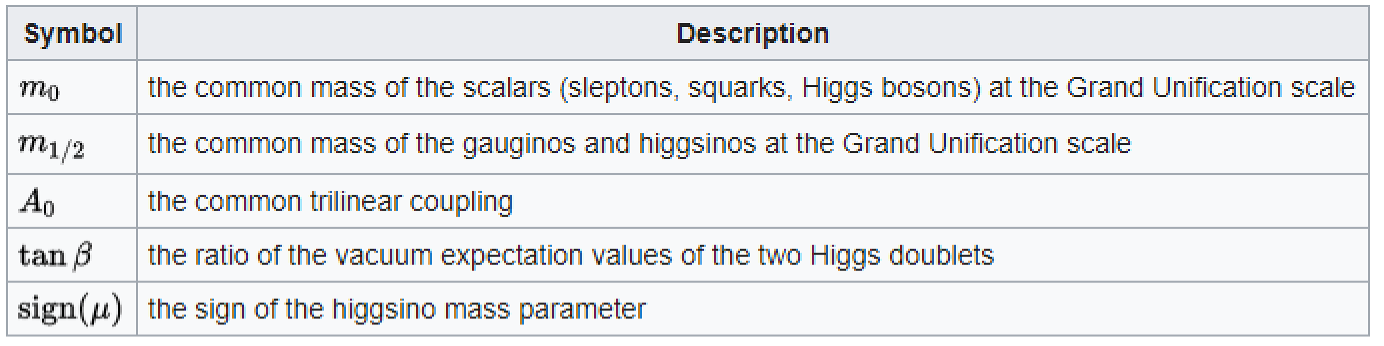

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Supersymmetry

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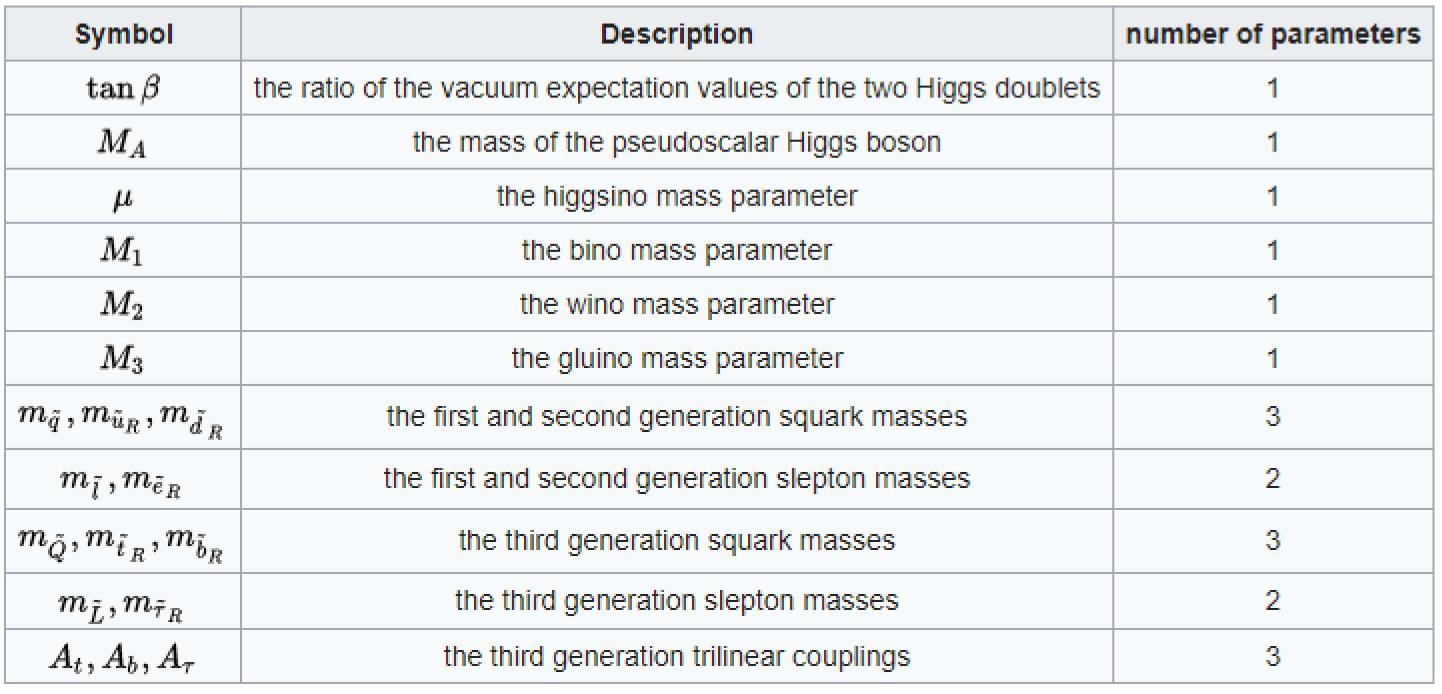
The pMSSM depends on 20 free parameters:



Symbol	Description	number of parameters
$\tan\beta$	the ratio of the vacuum expectation values of the two Higgs doublets	1
M_A	the mass of the pseudoscalar Higgs boson	1
μ	the higgsino mass parameter	1
M_1	the bino mass parameter	1
M_2	the wino mass parameter	1
M_3	the gluino mass parameter	1
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}$	the first and second generation squark masses	3
$m_{\tilde{l}}, m_{\tilde{e}_R}$	the first and second generation slepton masses	2
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}$	the third generation squark masses	3
$m_{\tilde{L}}, m_{\tilde{\tau}_R}$	the third generation slepton masses	2
A_t, A_b, A_τ	the third generation trilinear couplings	3

Djouadi, A.; Rosier-Lees…, arXiv:hep-ph/9901246

EXTRA DIMENSIONS

The main motivations for considering extra dimensions have a theoretical origin.

In the last years the most part of the development in theoretical physics required the introduction of extra dimensions (ED):

1.- Modern Kaluza-Klein (KK) Theories
2.- Supersymmetry (SUSY) and Supergravity (SUGRA)
3.- Superstrings
4.- M-Theory

Universal Extra Dimensions

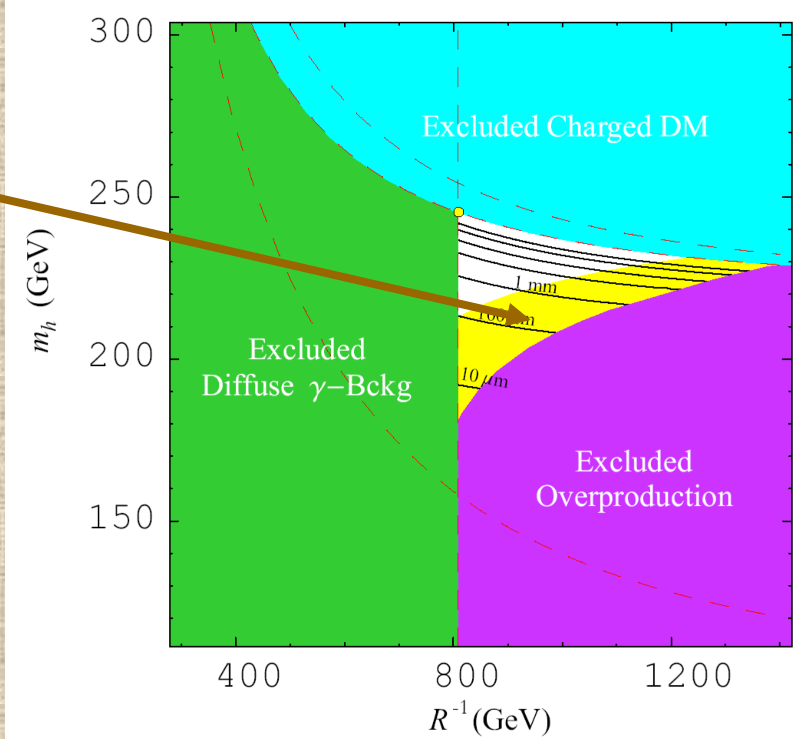
The existence of spatial extra dimensions is predicted by many theoretical ideas as the string models.

Particles that propagates in the extra dimensions introduces new degrees of freedom that can work as DM.

The minimal model introduces 1 new parameter: $\{ \mathrm{R}, m_{\mathrm{h}} \}$

1.- WIMP scenario:

KK-photon



Cembranos, Feng, Strigari (2006)

WIMP signatures:

a. Direct detection
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Universal Extra Dimensions

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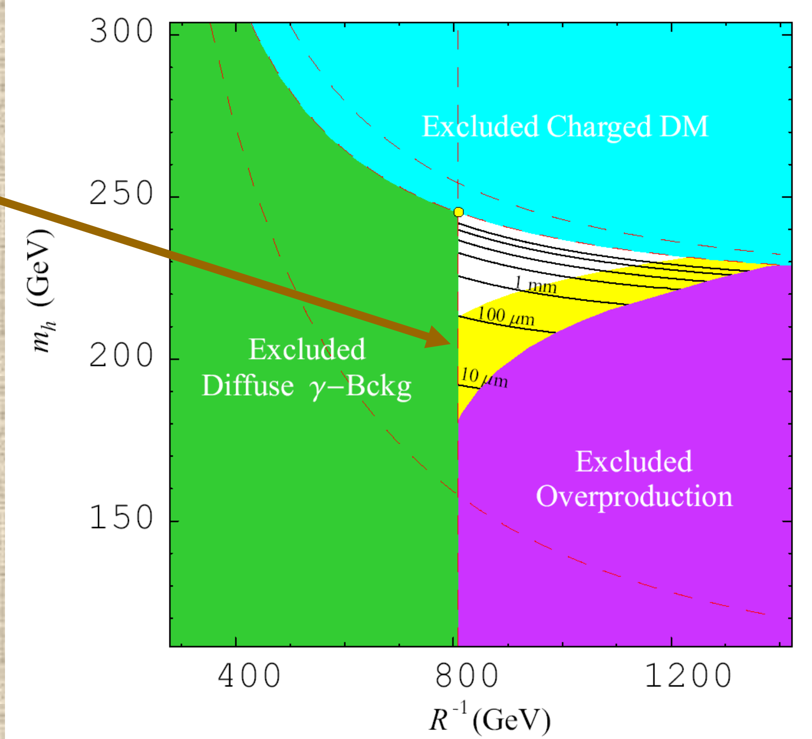
Minimal model 1 new parameter: $\{ R, m_h \}$

1.- SuperWIMP scenario:

KK-graviton



Cembranos, Feng, Strigari (2006)

SuperWIMP signatures:

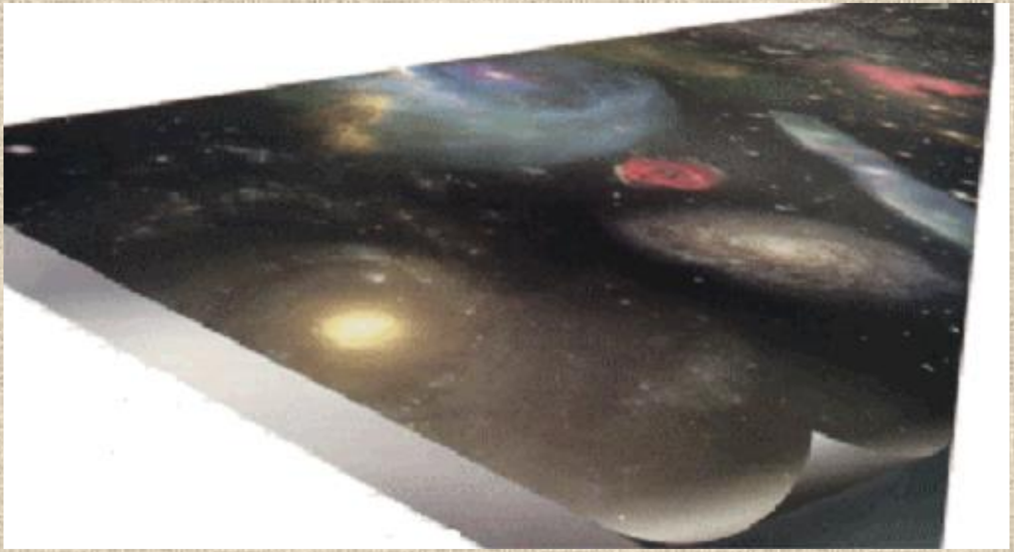
a. Indirect detection
b. Big Bang Nucleosynthesis
c. Microwave Background
d. Structure Formation

WWU MÜNSTER

BRANE WORLDS

The main idea is that our universe is restricted to a 3-brane embedded in a higher *D* dimensional space, with $D = 4+\delta$, being the δ extra dimensions compactified..

In this picture the Standard Model (SM) particles are confined to the 3-brane but gravitons can propagate along the whole bulk space.



BRANE FLUCTUATIONS

Rigid objects do not exist in relativistic theories.

Consequences of the brane oscillations:

1.- Branons: New fields which represent the position of the brane in the bulk space.

These fields are the (pseudo-)Goldstone bosons corresponding to the spontaneous symmetry breaking of the translation invariance produced by the presence of the brane.

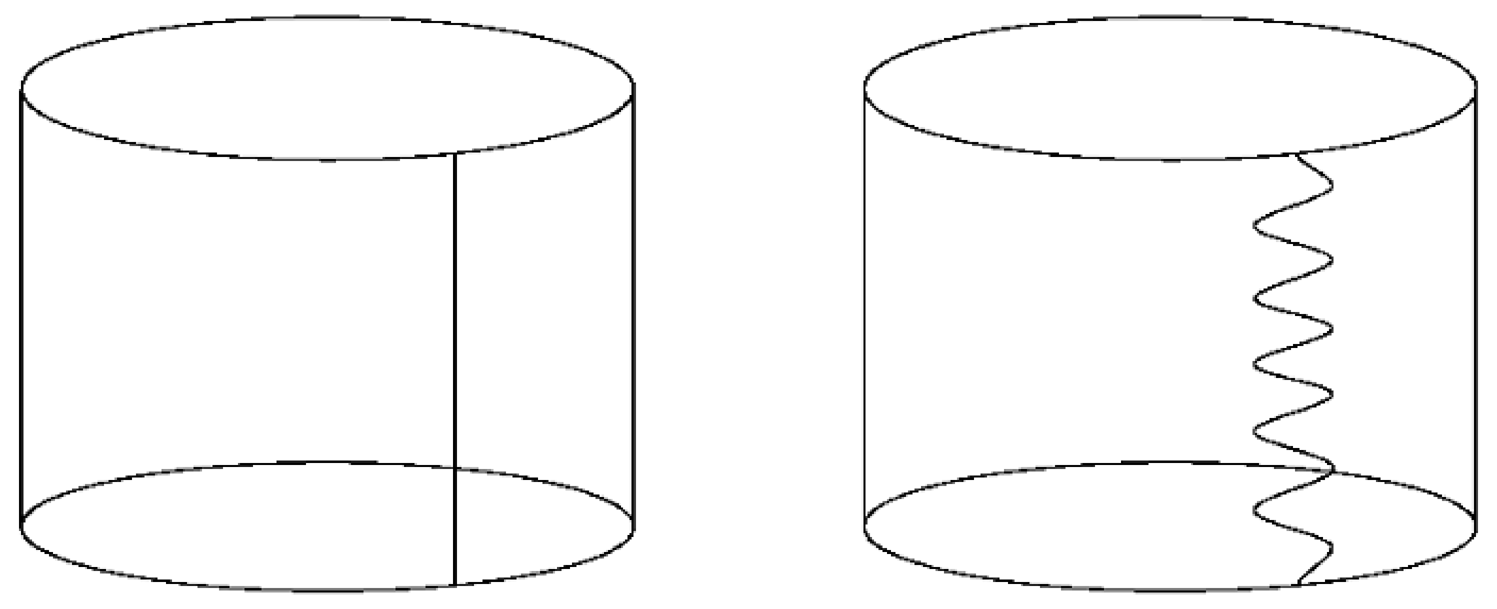
2.- KK coupling suppression : The recoil of the brane produces an effective coupling of the SM fields on the brane with the KK modes of the bulk fields given by :

$$g_n \equiv g \cdot e^{-\frac{1}{2}\left(\frac{n}{R}\right)^2 \frac{M_F^2}{f^4}}$$

(Bando, Kugo, Noguchi and Yoshioka)

LOWER DIMENSIONAL EXAMPLE

Brane with trivial topology. The ground state of the brane is represented on the left. On the right we plot an excited state.



DISFORMAL SCALAR FIELDS

Scalar field with coupling:

$$\bar{g}_{\mu\nu} = \mathcal{A}(\phi, (\partial\phi)^2)g_{\mu\nu} - \frac{\mathcal{B}(\phi, (\partial\phi)^2)}{m^4}\partial_\mu\phi\partial_\nu\phi$$

Bekenstein, PRD 48 (1993) 341

They arise in many different theories:

1. Brane-world models

Cembranos, Dobado, Maroto, PRL 90 (2003) 241301

Alcaraz, Cembranos, Dobado, Maroto, PRD 67 (2003) 075010

2. Massive gravity

Rham, Gabadadze, PRD 82 (2010) 04020, 1007.0443

Gabadadze, Rham, Tolley, PRL 231101 (2011) 1011.1232

SM INTERACTIONS

The interaction of the branons with the SM particles is given by:

$$\begin{aligned} S_B &= \int_{M_4} d^4x \sqrt{g}\left[-f^4 + \mathcal{L}_{SM}(g_{\mu\nu})\right] \\ &= \int_{M_4} d^4x \left[-f^4 + \mathcal{L}_{SM}(\eta_{\mu\nu}) + \frac{1}{2}\eta^{\mu\nu}\delta_{\alpha\beta}\partial_\mu\pi^\alpha\partial_\nu\pi^\beta - \frac{1}{2}M^2_{\alpha\beta}\pi^\alpha\pi^\beta \right. \\ &+ \left. \frac{1}{8f^4}\left(4\delta_{\alpha\beta}\partial_\mu\pi^\alpha\partial_\nu\pi^\beta - M^2_{\alpha\beta}\pi^\alpha\pi^\beta\eta_{\mu\nu}\right)T^{\mu\nu}_{SM}(\eta_{\mu\nu})\right] + \mathcal{O}(\pi^3). \end{aligned}$$

As in the case of the gravitons, the branons couple to the SM through:

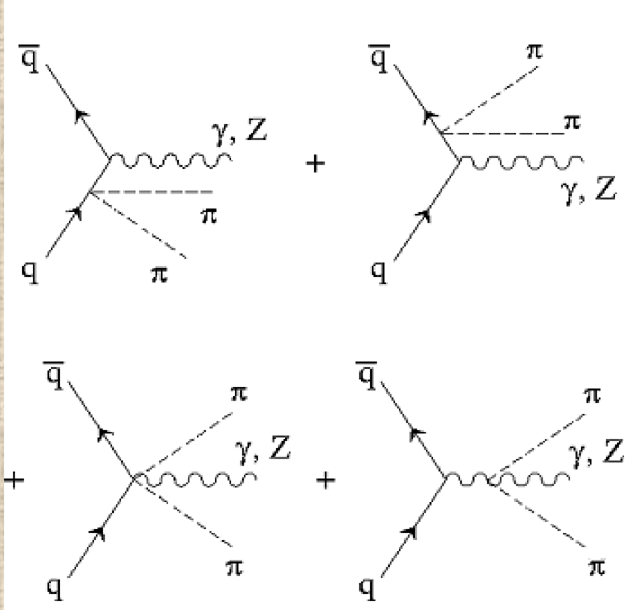
$$T^{\mu\nu}_{SM} = -\left(\tilde{g}^{\mu\nu}\mathcal{L}_{SM} + 2\frac{\delta\mathcal{L}_{SM}}{\delta\tilde{g}_{\mu\nu}}\right)\Bigg|_{\tilde{g}_{\mu\nu}=\eta_{\mu\nu}}$$

(Sundrum, Creminelli and Strumia)

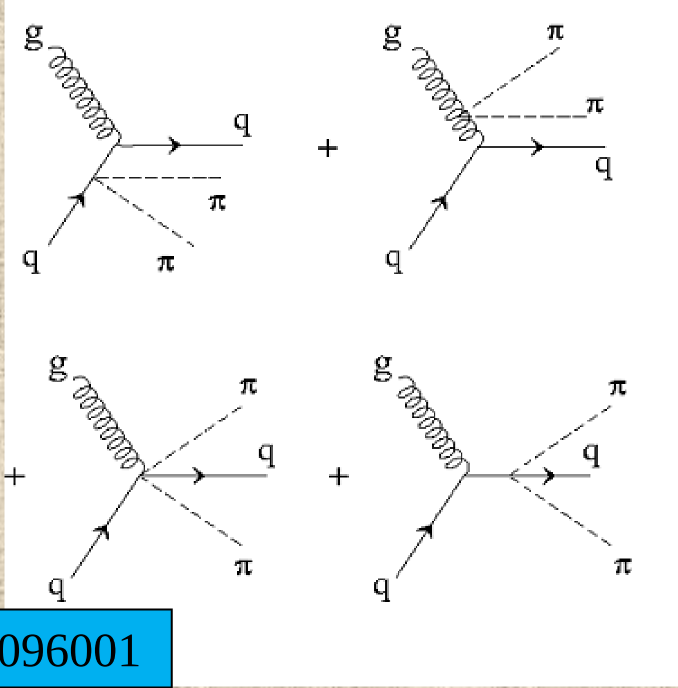
HADRONIC COLLIDERS

The main experimental signals come from the single photon channel (or electroweak boson) and the monojet production plus missing energy and transversal momentum.

One photon or Z production



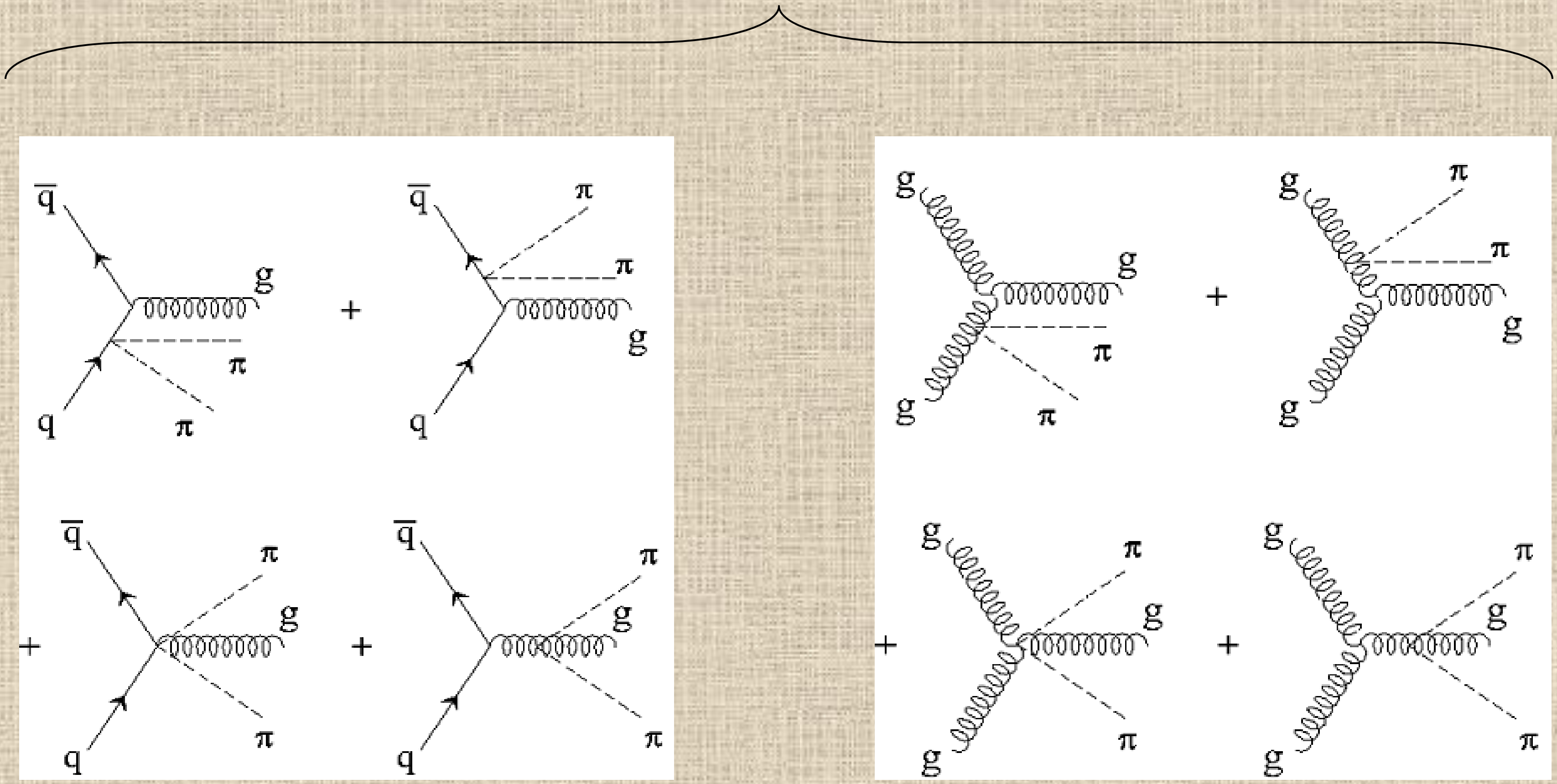
One quark production



Cembranos, Dobado, Maroto, PRD 70 (2004) 096001

GLUON PRODUCTION

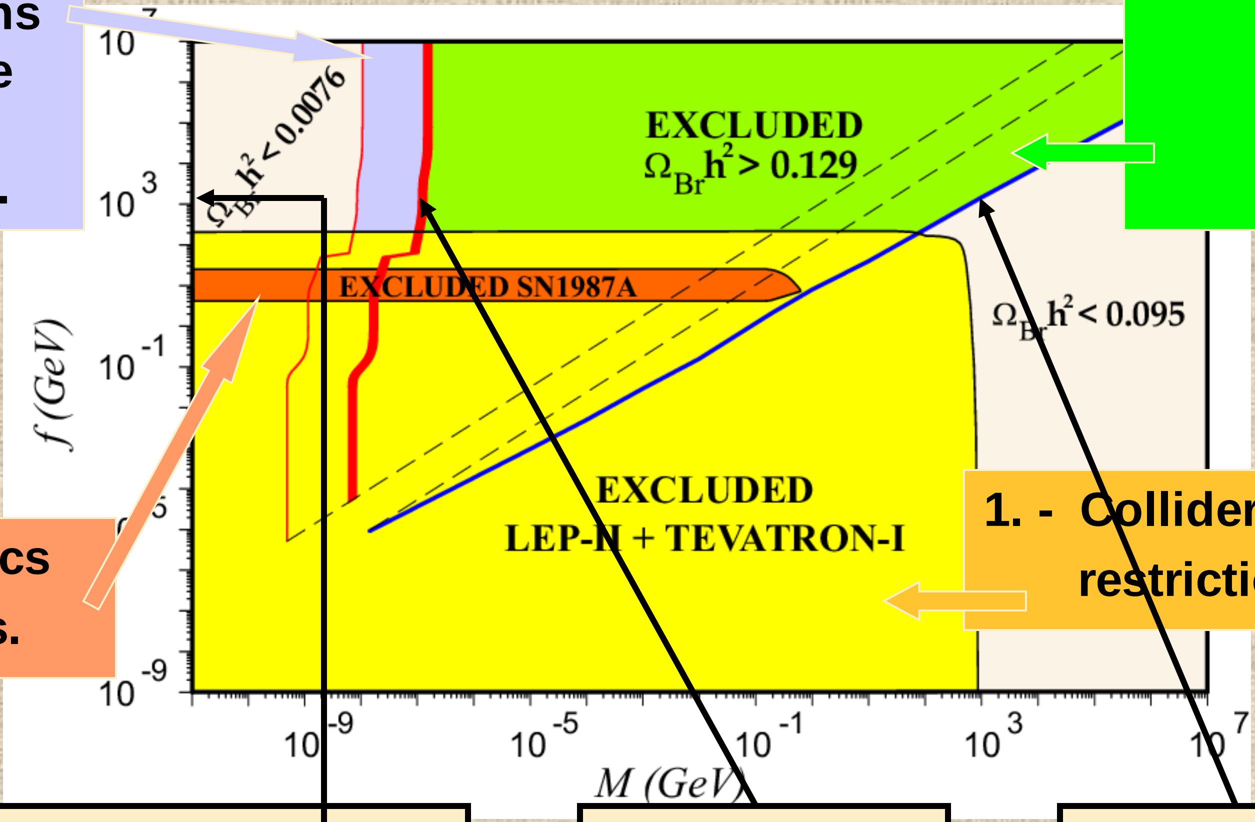
Gluon production



Cembranos, Dobado, Maroto, PRD 70 (2004) 096001

GENERAL SITUATION

General situation of the branon physics and its cosmological interest (N=1):



3. - Restrictions due to the power spectrum.

2.- Restrictions due to the total dark matter density.

1. - Collider restrictions.

4. - Astrophysics restrictions.

C.- Branons as Non Thermal Relic

B.- Branons as Warm DM

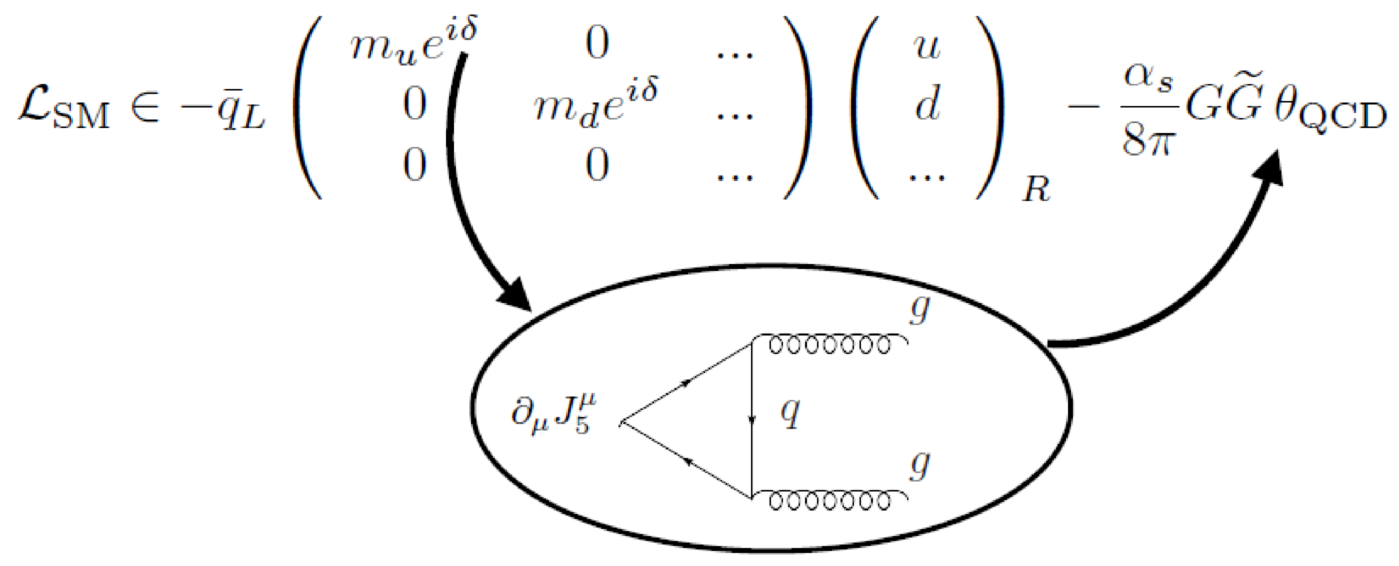
A.- Branons as WIMPs

Cembranos, Dobado, Maroto, PRL 90 (2003) 241301, PRD 68 (2003) 103505

Strong-CP Problem

- **In QCD, the CP violating phase is physical:**

$$\theta = \theta_{\rm QCD} + \delta$$



$$\mathcal{L}_{\rm SM} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta} & 0 & \dots \\ 0 & m_d e^{i\delta} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta_{\rm QCD}$$

Strong-CP Problem

- **In QCD, the CP violating phase is physical:**

$$\theta = \theta_{\rm QCD} + \delta$$

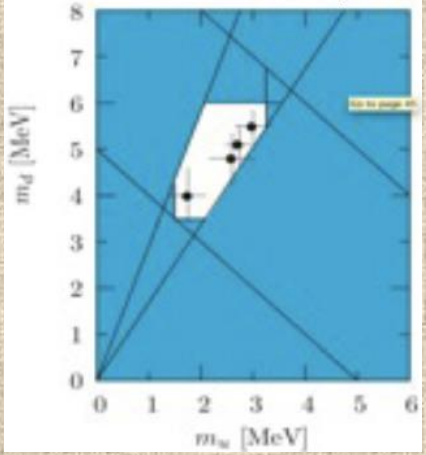
  - Electric Dipole Moment of the Neutron:

$$d_n \sim \theta \times \mathcal{O}(10^{-2})[e\,{\rm fm}]$$
$$d_n^{\rm exp} < 3 \times 10^{-13}[e\,{\rm fm}]$$

  - Strong CP problem: $\theta < 10^{-10}$

Strong-CP Problem

- **Solutions:**
  - The presence of a massless quark:



  - Introducing a new axial U(1) symmetry:
    - Spontaneusly broken → Nambu-Goldstone boson
    - The theta parameter becomes dynamical: $\theta \to a/f_a$ Axion
    - The new U(1) is explicitly broken by QCD radiative effects:

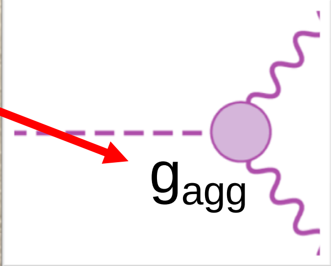
→ pseudo-Nambu-Goldstone boson

Strong-CP Problem

The QCD-axion is predicted by the Pecci-Quinn solution to the strong-CP problem. Many other theories beyond the SM predicts light pseudo-scalars very weakly coupled to SM particles.

$$m_a \simeq 0.6 \times 10^{-4}\ \text{eV} \left(\frac{10^{11}\ \text{GeV}}{f_a}\right).$$

The main phenomenology and signatures comes from the two photon coupling (Primakov effect):

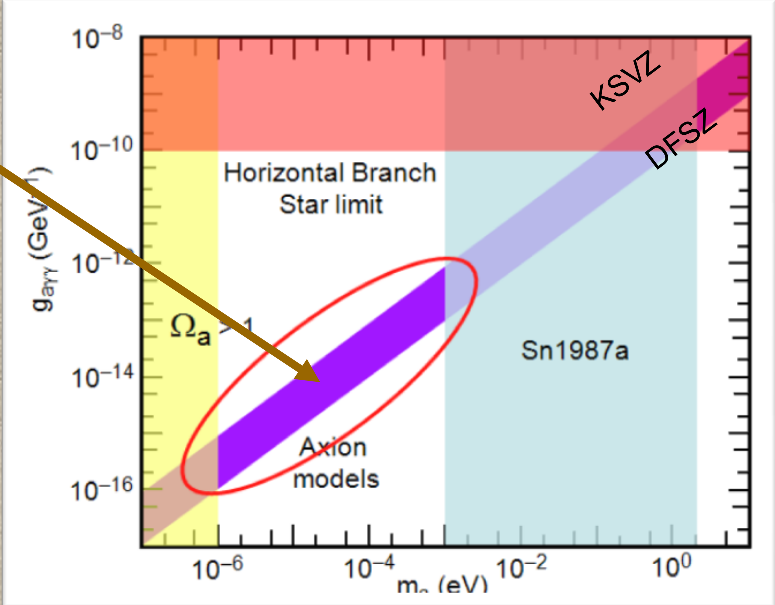


1.- SuperWIMP scenario:

Axions

SuperWIMP signatures:

- a. Indirect detection
- a.1. Axion solar flux
- b. Star and SN cooling
- c. Laser experiments

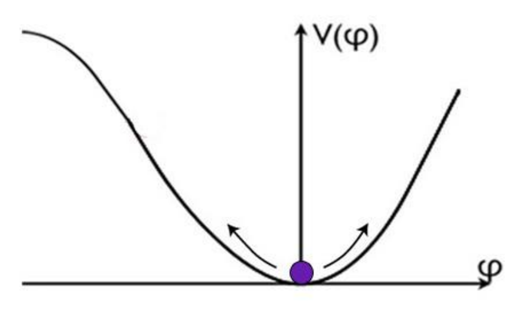


G. Carosi et al [ADMX] (2010)

Coherent Dark Matter

Scalar field DM

Homogeneous field (M. S. Turner, Phys. Rev. D 28 (1983) 6.)



$$V(\phi) = a\phi^n$$

$$\omega = \frac{n-2}{n+2}$$

Average eq. of state

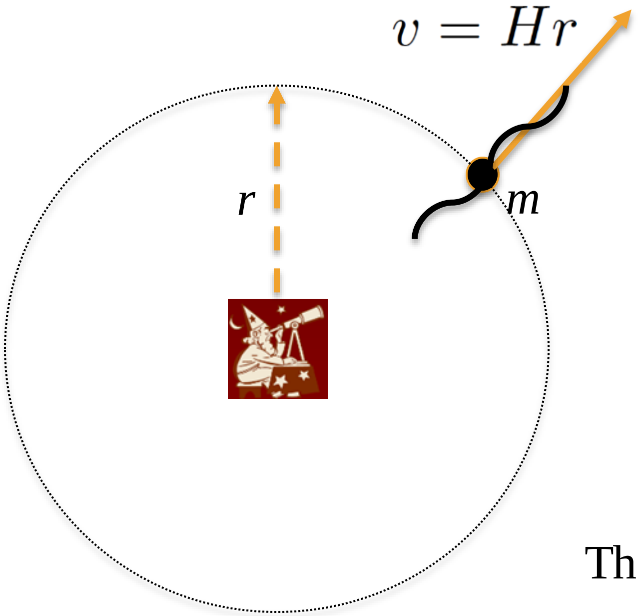
$$\begin{cases} n = 2 & \text{matter} \\ n = 4 & \text{radiation} \end{cases}$$

Coherent Dark Matter

Heuristic interpretation (Hu et al, PRL85, 1158 (2000), Hlozek et al, PRD 91 103512 (2015))

Consider a particle of mass *m* << 1 eV moving with the Hubble flow *H*

$\lambda_{\text{Compton}} >> d_{\text{inter part.}}$ DM described by a classical field



The corresponding de Broglie wavelength:

$$\lambda_{\text{dB}} = \frac{1}{mv} = \frac{1}{mHr}$$

Thus, the particle can be localized only in a sphere with radius:

$$r \geq \lambda_{\text{dB}} \Longrightarrow \boxed{r \geq \frac{1}{\sqrt{Hm}}}$$

That corresponds to a (physical) wavenumber k=π/r

$$k_\star = \pi\sqrt{mH}$$

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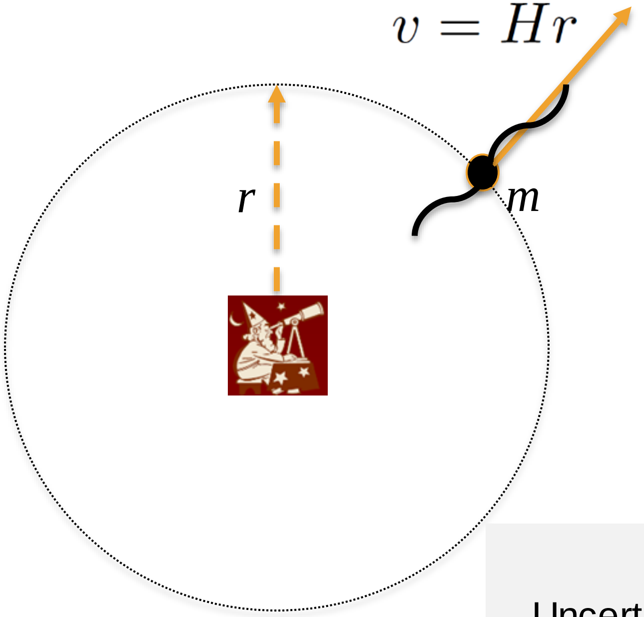


Thus, we have:

$k < \pi\sqrt{Hm}$	particle-like behaviour
$k > \pi\sqrt{Hm}$	wave-like behaviour

Jeans scale = de Broglie wavelength

Uncertainty principle modifies small-scale structure formation

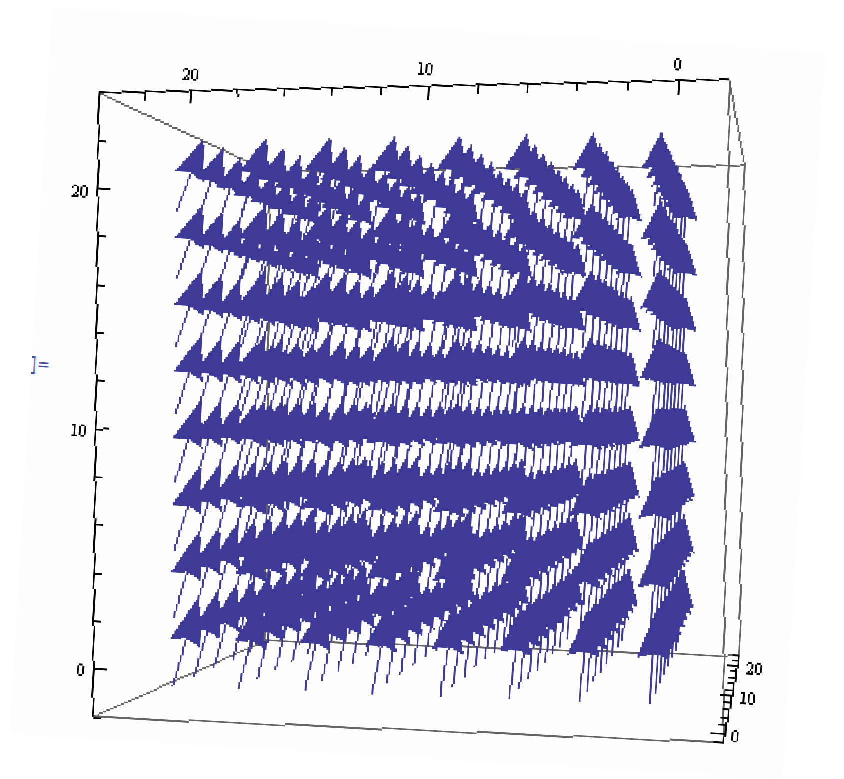
Theoretical frameworks for vector fields

New vector fields appear in many theoretical extensions of the Standard Model:

- **GUT** P. Langacker, Phys. Rep. 72 C, 185 (1981)
- **SUSY** S. Weinberg, Phys. Rev. D 26, 287 (1982); P. Fayet, Nucl. Phys. B 187, 184 (1981)
- **Fith force extensions** E. D. Carlson, Nucl. Phys. B 286, 378 (1987)
- **Paraphoton models** L. B. Okun, Sov. Phys. JETP 56, 502 (1982)
  [Zh. Eksp. Teor. Fiz. 83, 892 (1982)]
- **Superstring compactifications** J. Ellis et al., Nucl. Phys. B 276, 14 (1986)
  Goodsell, A. Ringwald, Fortsch. Phys. 58, 716 (2010)

The anisotropy problem

However, vector coherent oscillations are generally anisotropic. This fact can be in contradiction with the large isotropy of the universe as shown by the cosmic microwave background (CMB).



Isotropy theorem for Abelian vector fields

Abelian vector fields described by the action:

$$S = \int d^4x \sqrt{g} \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(A_\mu A^\mu) \right)$$

If the field evolves rapidly and A_i , $\dot{A}_i$ are bounded during its evolution:

1.- The energy momentum tensor is diagonal and isotropic in average.

JARC, Hallabrin, Maroto, Nunez Jareno, Phys. Rev. D86 (2012)

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Similar argument than for the Virial theorem in classical mechanics:

(for a FLRW background)⟹

$$0 = \frac{G_{ij}(T) - G_{ij}(0)}{T} = \left\langle 2V'(A^2)\frac{A_i A_j}{a^2} \right\rangle + \left\langle \frac{\dot{A}_i \dot{A}_j}{a^2} \right\rangle$$

$$G_{ij} = \frac{\dot{A}_i A_j}{a^2}, \quad i,j = 1,2,3$$

JARC, Hallabrin, Maroto, Nunez Jareno, Phys. Rev. D86 (2012)

Example I: SU(2) theory

The self-interaction for non-Abelian theories changes the average equation of state. For high energy densities or large coupling constants it will behave as radiation, in the opposite limit, the Abelian behavior is recovered.

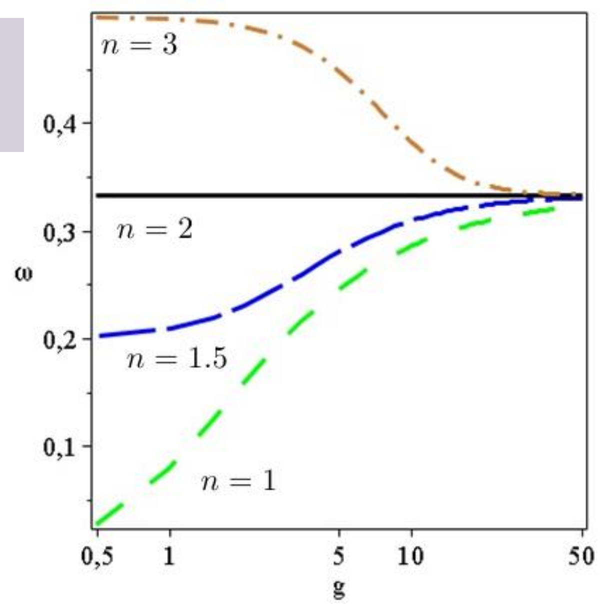
$$V = \frac{1}{2}(-M^2 A^a_\rho A^{a\,\rho})^n$$

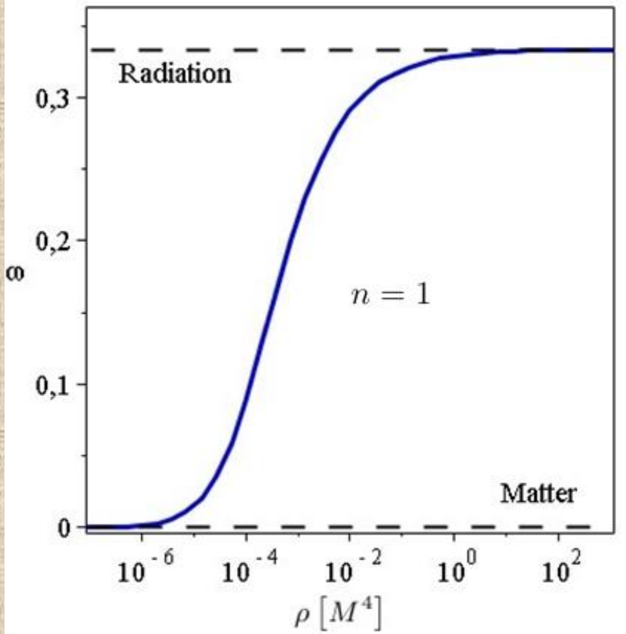
$$\boldsymbol{g \downarrow,\ \rho \downarrow}$$

$$\boldsymbol{\omega = \frac{n-1}{n+1}}$$

$$\boldsymbol{g \uparrow,\ \rho \uparrow}$$

$$\boldsymbol{\omega = \frac{1}{3}}$$





JARC, Maroto, Nunez Jareno, Phys. Rev. D87 (2013) 043523

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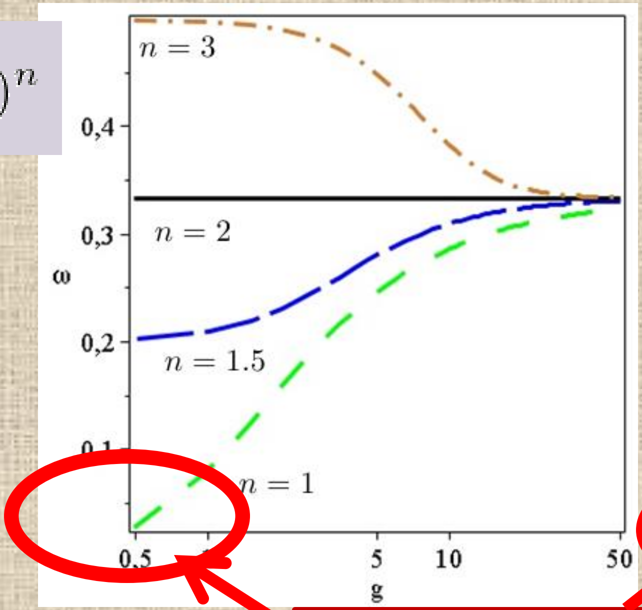
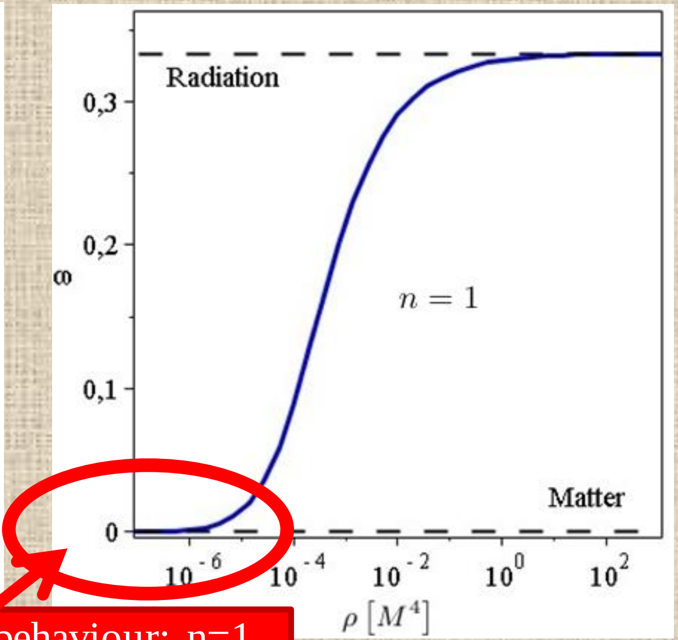




DARK MATTER behaviour: n=1

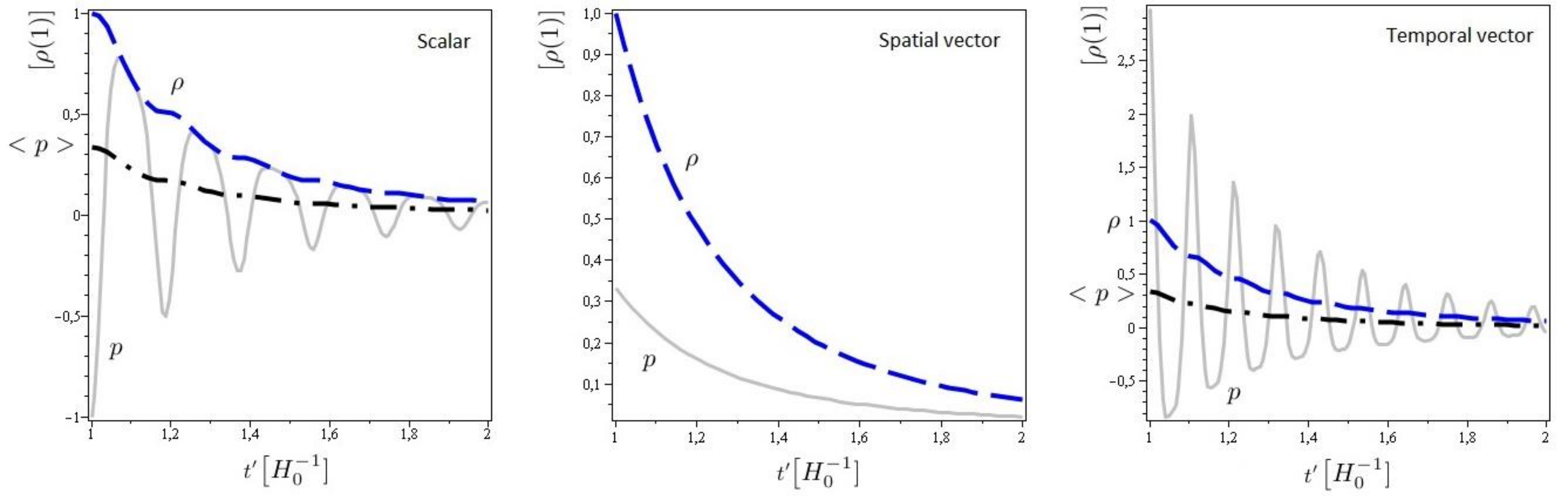
JARC, Maroto, Nunez Jareno, Phys. Rev. D87 (2013) 043523

Example II: n=2

For a power law potential, the equation of state of the average energy is the same for: scalar, Abelian vectors, spatial and temporal Non-Abelian vector components (by assuming a negligible self-interactions).

$$V = \frac{1}{2}(-M^2 A_\rho A^\rho)^n \longrightarrow \omega = \frac{n-1}{n+1}$$

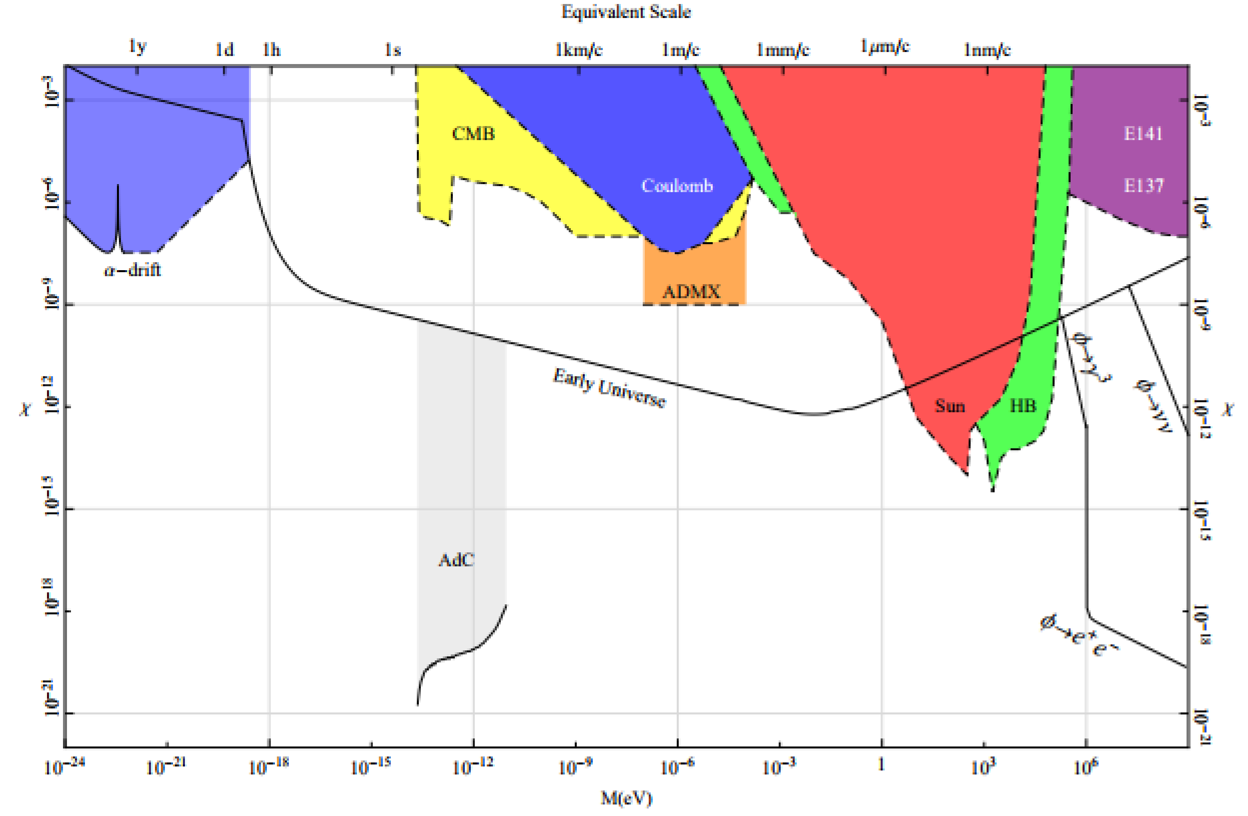
Although their evolutions are very different:



JARC, Maroto, Nunez Jareno, Phys. Rev. D87 (2013) 043523

Dark Photons

Parameter space



Nelson and Jakub Scholtz, arXiv:1105.2812v3 [hep-ph]

Isotropy theorem for higher-spin fields

Homogeneous field (J.A.R. Cembranos, A.L.M., S.J. Núñez Jareño, JCAP 1403 (2014) 042)

Homogeneous fields with non-zero spin break isotropy, but:

$$\mathcal{L} \equiv \mathcal{L}\left[\phi^A, \partial_\mu \phi^A\right]$$

ϕ_A and $\dot{\phi}_A$ bounded

$$\omega_A^{-1} \ll T \ll H^{-1}$$

For **rapidly oscillating fields**, virial theorem ensures diagonal and isotropic energy-momentum tensor in average

Power-law theories:

$$\mathcal{H} = \left(\lambda^{AB} g_{00} \Pi_A^0 \Pi_B^0\right)^{n_T} + \left(M_{AB}\phi^A\phi^B\right)^{n_V}$$

Average equation of state:

$$\omega = \frac{2\, n_V}{1 + \frac{n_V}{n_T}} - 1$$

Higher-spin DM

Example: **Spin 2 DM**

Spin 2. Massive gravitons as wave DM

(Cembranos, A.L.M., Núñez Jareño, JCAP 1403 (2014) 042)

Fierz-Pauli Lagrangian

$$\mathcal{L} = \frac{M_{Pl}^2}{8}\Big[\nabla_\alpha h^{\mu\nu}\nabla^\alpha h_{\mu\nu} - 2\nabla_\alpha h^\alpha_\mu \nabla_\beta h^{\mu\beta} + 2\nabla_\alpha h^\alpha_\mu \nabla^\mu h^\beta_\beta - \nabla_\alpha h^\mu_\mu \nabla^\alpha h^\nu_\nu - m_g^2\left(h_{\mu\nu}h^{\mu\nu} - \left(h^\mu_\mu\right)^2\right)\Big] .$$

Average equation of state:

$$\omega = \frac{2n_V}{1+\frac{n_V}{n_T}} - 1 = 0$$

Lectures on Dark Matter

Jose A. R. Cembranos

Higher-spin DM

Example: **Spin 2 DM**

Spin 2. Massive gravitons as wave DM
(Cembranos, A.L.M., Núñez Jareño, JCAP 1403 (2014) 042)

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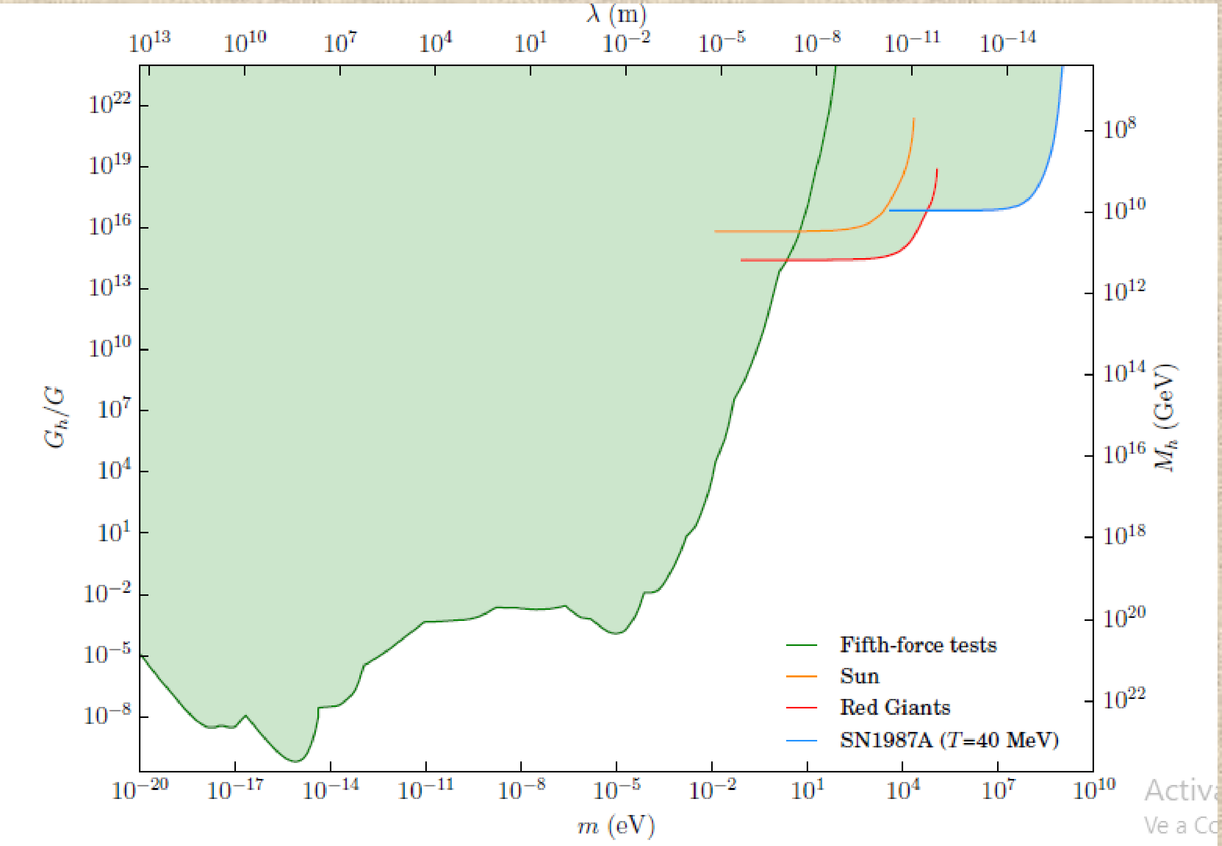
Condensate of massive graviton and dark matter, K. Aoki and K. Maeda, arXiv:1707.05003 [hep-th]

Oscillating spin-2 Dark Matter, L. Marzola, M. Raidal, and F. R. Urban, arXiv:1708.04253 [hep-ph]

Dark gravitons

Parameter space



Cembranos, Maroto, Villarrubia-Rojo, **JHEP 1709 (2017) 104**]

Neutrino Masses

Neutrino masses cannot be introduced in the Standard Model (SM) without the presence of new particles. These new particles will be typically very weakly coupled to the SM and natural DM candidates.

The most motivated models are called ‘see-saw’ and most part of them introduces sterile neutrinos.

1.- SuperWIMP scenario:

Sterile neutrinos

SuperWIMP signatures:

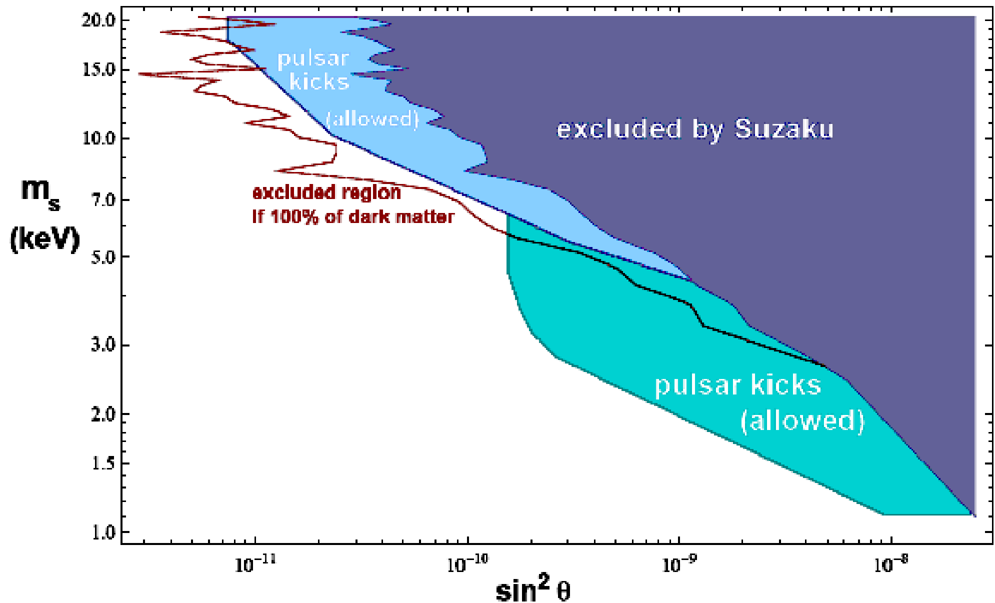
a. Indirect detection

a.1. Suzaku X-rays

(Ursa Minor)

b. Structure formation

c. Pulsar Kicks



Loewenstein, Biermann, Kusenko (2009)

UV modified gravity

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

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

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

- 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:

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

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

- 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**

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

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:

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

- 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

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

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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**

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

- 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:

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

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

WWU MÜNSTER

Scalaron Couplings

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

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

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

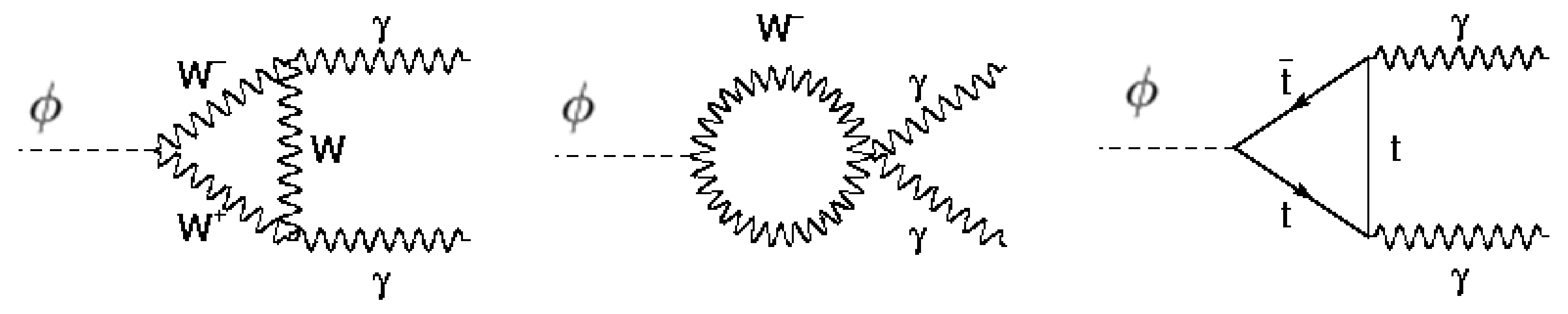
$$\begin{aligned}\mathcal{L}^{\mathrm{tree\ level}}_{\phi-SM} = \frac{-1}{M_{\mathrm{Pl}}\sqrt{6}}\,\phi\,\Big\{&2\,m_h^2 h^2 - \nabla_\mu h \nabla^\nu h \\ &+ \sum_\psi m_\psi\,\bar{\psi}\psi\, - 2\,m_W^2\,W^+_\mu W^{-\mu} - m_Z^2\,Z_\mu Z^\mu\Big\}\end{aligned}$$

Radiative Scalaron Couplings

- On loop generates the coupling with photons and gluons:

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

- Contributions to the photon vertex:



Lectures on Dark Matter

Jose A. R. Cembranos

Abundance

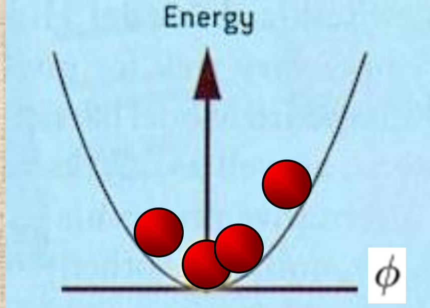
- Thermal abundance would require $T >> \sqrt{m_0 M_P}$
  - Beyond the validity of Einstein Equations.
- Misalignment mechanism

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

  - For $H(T) >> m_0$ → $\phi = \phi_1$
  - For $3H(T) \le m_0$ → 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)

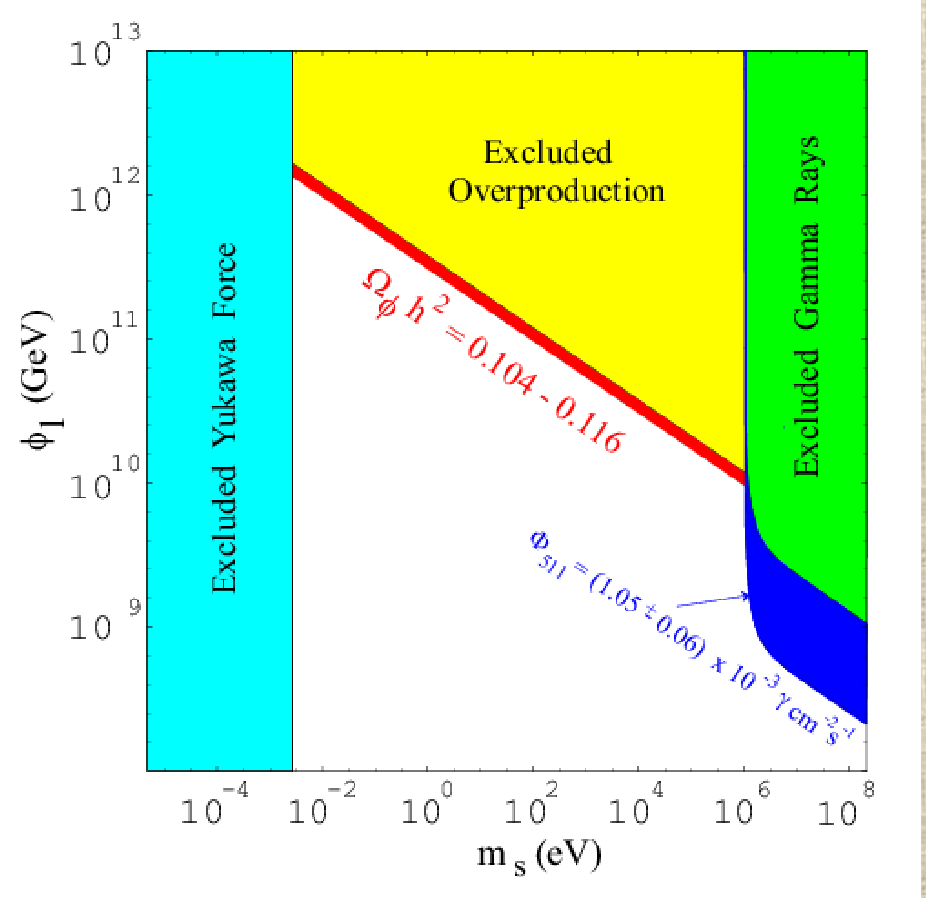
R2-gravity as Dark Matter

Parameter space of R2-gravity as DM:

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

Constraints:

🟨 **Overproduction.**



New Force Constraints

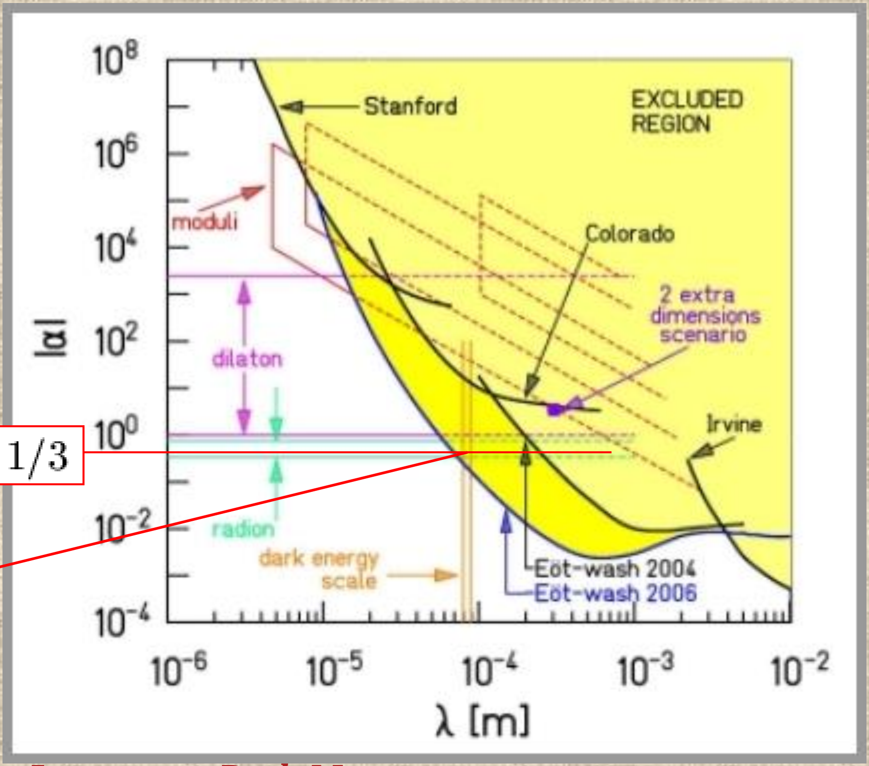
The new scalar graviton generates a Yukawa new interaction among standard matter:

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

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**



$\alpha = 1/3$

Consistent with Newton's inverse-square law.

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

R2-gravity as Dark Matter

Parameter space of R2-gravity as DM:

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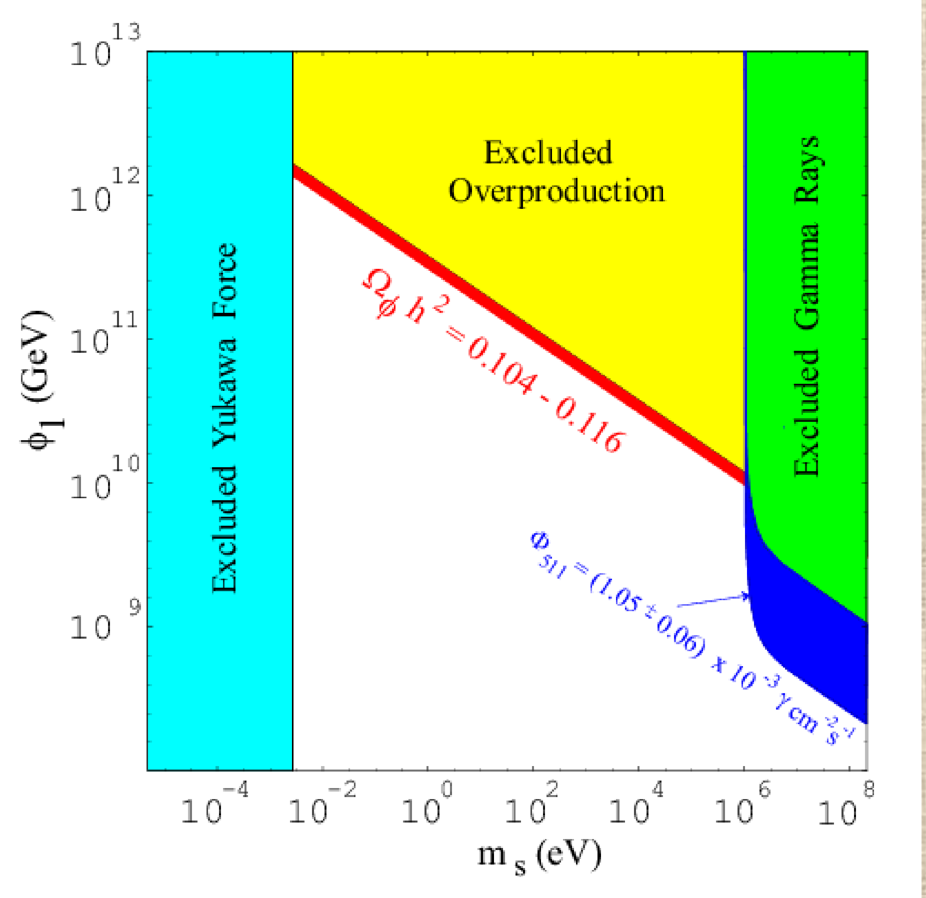
Constraints:

- 🟨 **Overproduction.**
- 🟥 **Eöt-Wash experiments.**



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:

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

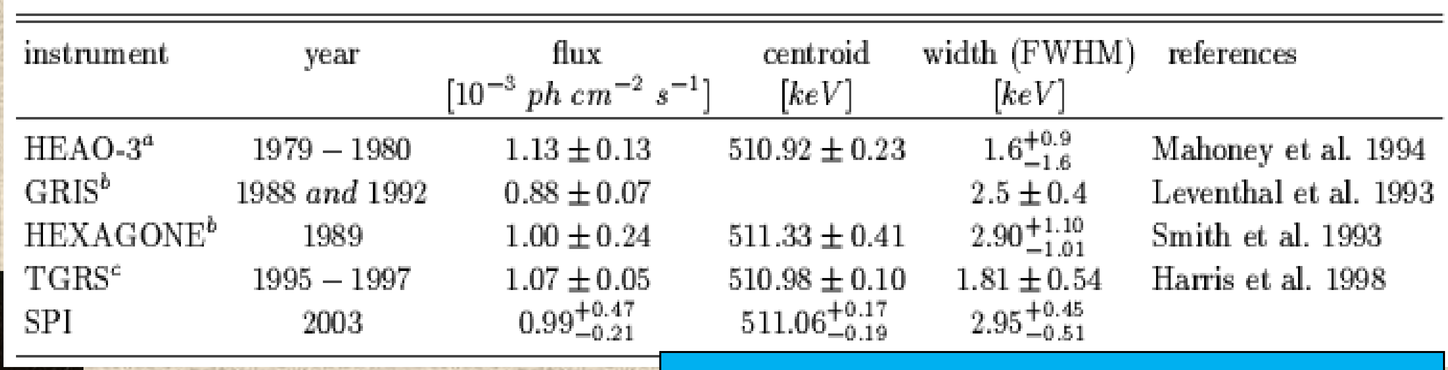
In particular, for the e^+e^- decay:

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

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

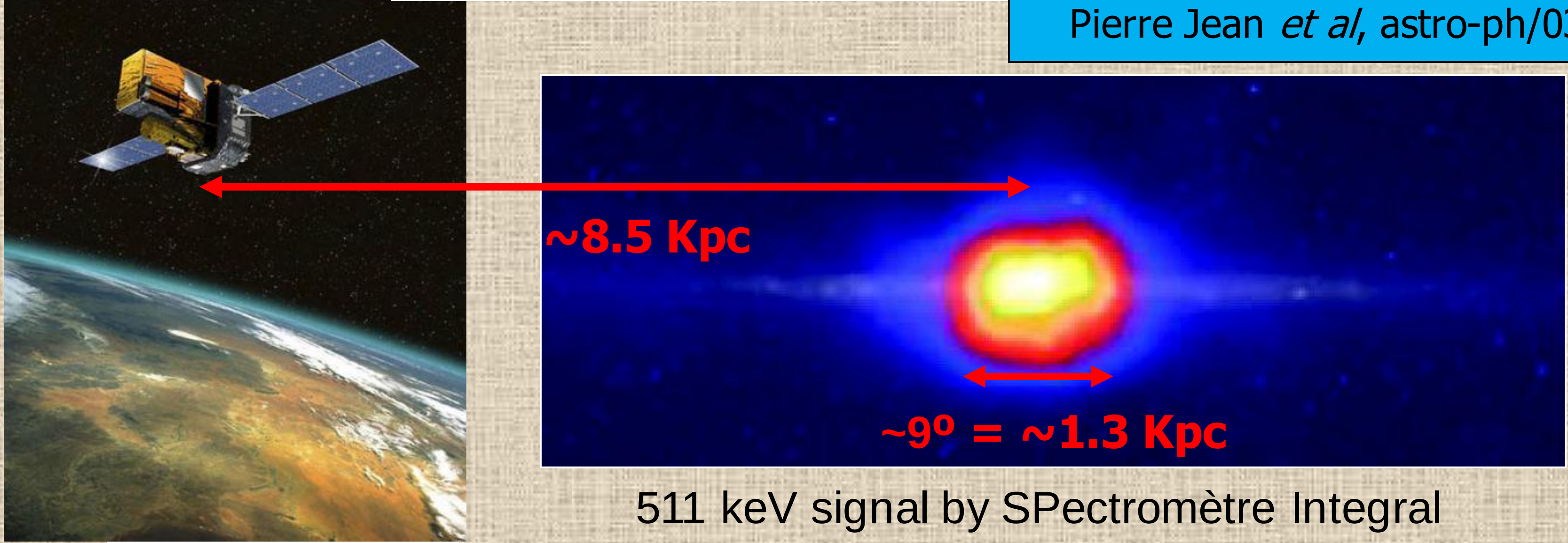
511 keV photons from the GC

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

R2-gravity as Dark Matter

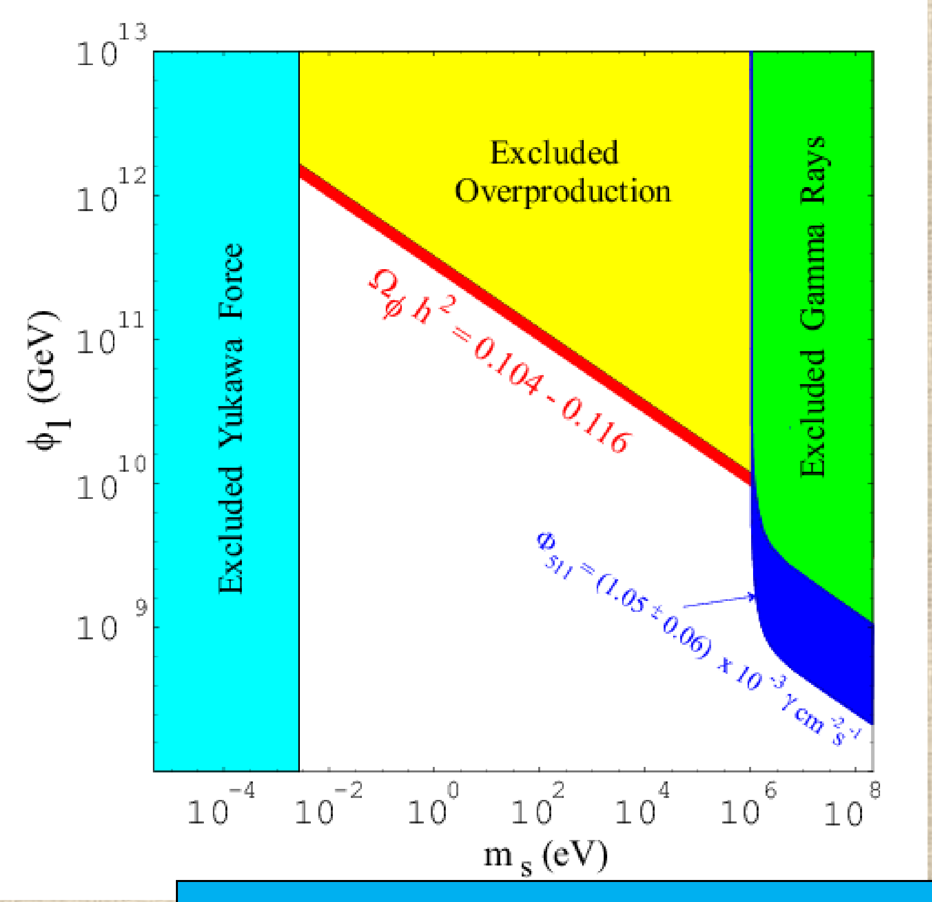
Parameter space for R2-gravity as DM:

🟥 **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

1.- We have discussed about DM candidates motivated by:

1.a. Supersymmetry: neutralinos, gravitinos.

1.b. Univ. Extra dimensions: KK-photon, KK-graviton.

1.c. Brane Worlds: Branons.

1.c. Neutrino masses: Sterile neutrinos.

1.d. Strong-CP problem: Axions.

1.e. UV modified Gravity: R2-scalar.

2.- They define different strategies for detection:

2.a. Cosmic rays

2.b. Direct detection

2.c. Structure formation

2.d.Eöt-Wash experiments

2.e. Primordial Abundances

2.f. Pulsar dynamic

2.g. Microwave background

2.h. Star and SN cooling

DIRECT RESULTS

The appropriate quantity to compare with the experimental results is not the elastic branon-nucleus cross section σ, but the differential cross section per nucleon at zero momentum transfer: σ_n.

$$\frac{d\sigma}{d|q|^2} = \frac{\sigma_n A^2 F^2(|q|)}{4v^2\mu^2}$$

$F(|q|)$ is a nuclear form factor
normalization $F(0) = 1$

A is the mass
number of the nucleus

$\mu = Mm/(M+m)$

$m \simeq 939$ MeV

v is the relative velocity

For the branon case:

$$\sigma_n = \frac{9M^2m^2\mu^2}{64\pi f^8}$$

Cembranos, Dobado, Maroto, PRL 90 (2003) 241301

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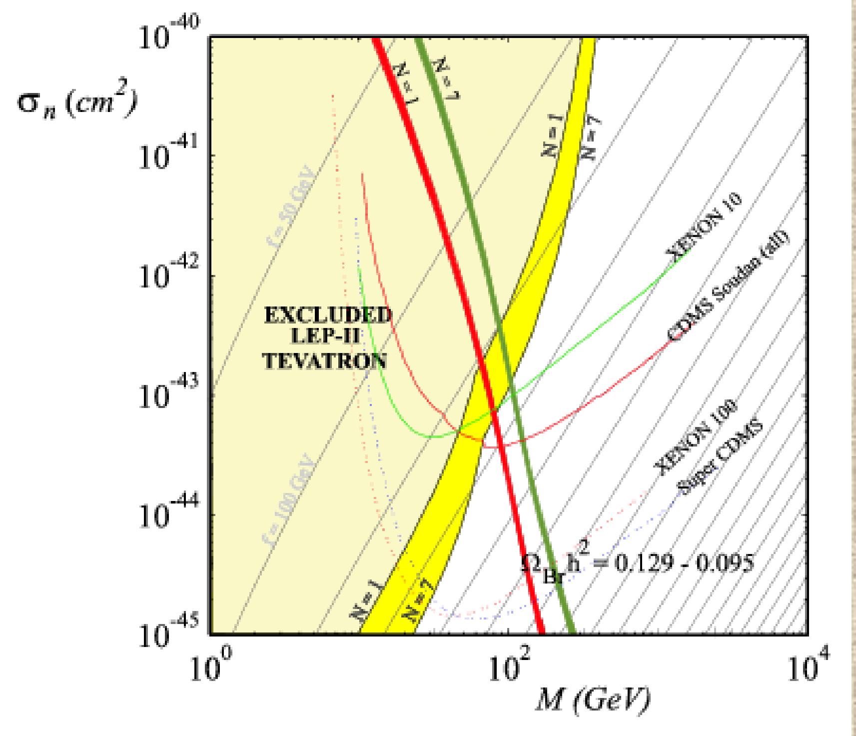

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Cembranos, Dobado, Maroto,
PRL 90 (2003) 241301

Cembranos, Díaz-Cruz, Prado,
PRD 84 (2011) 083522

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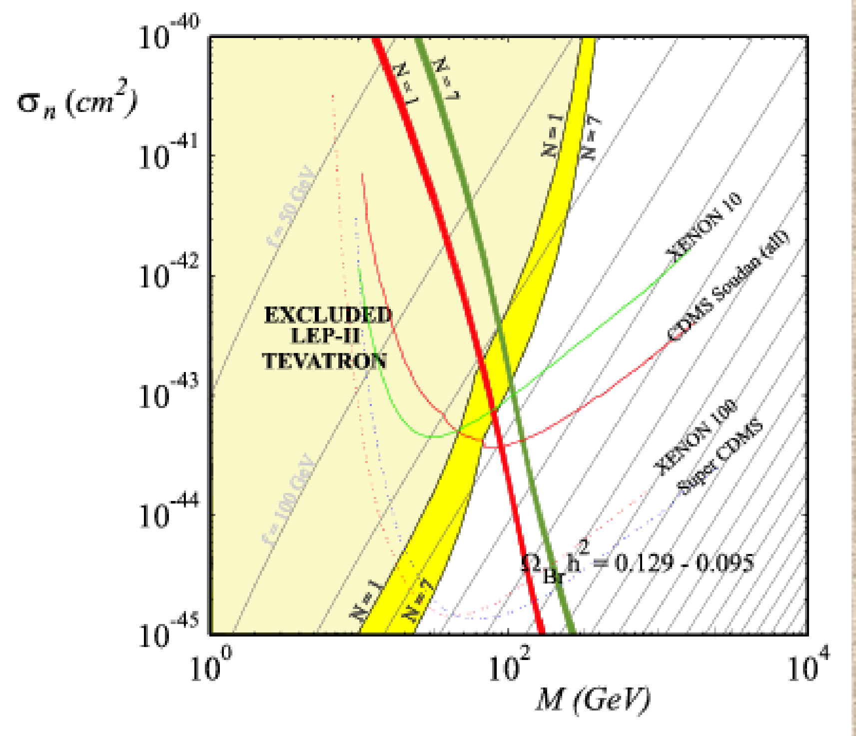
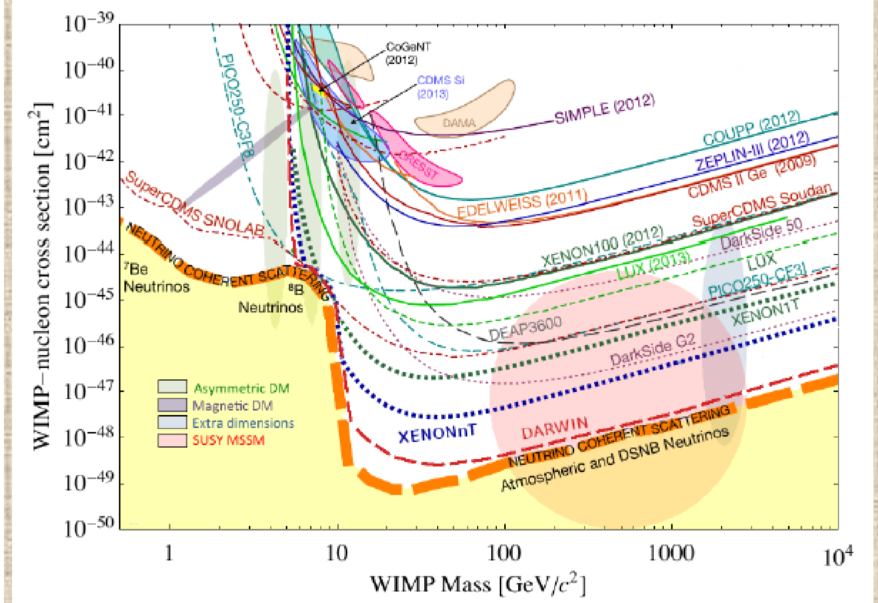
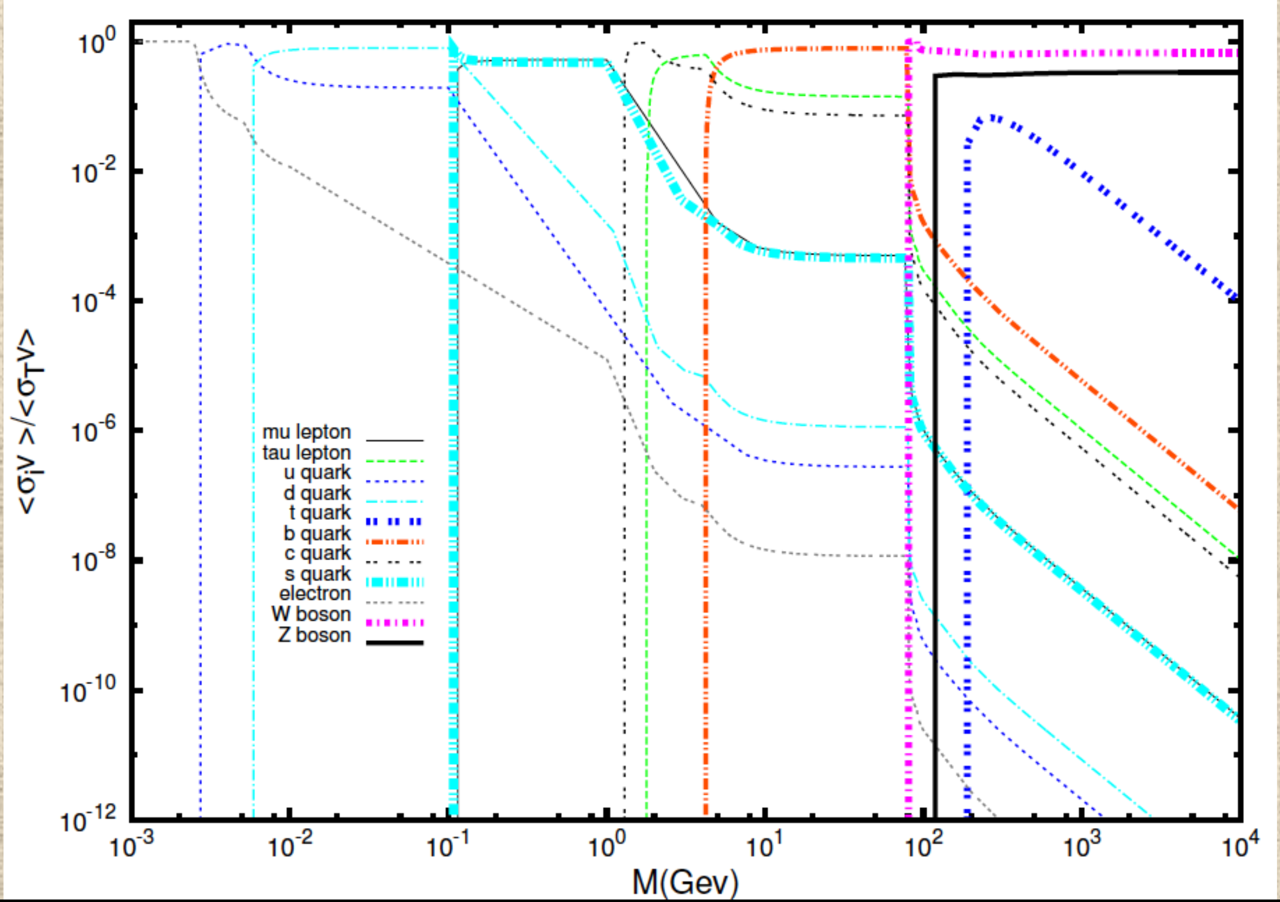




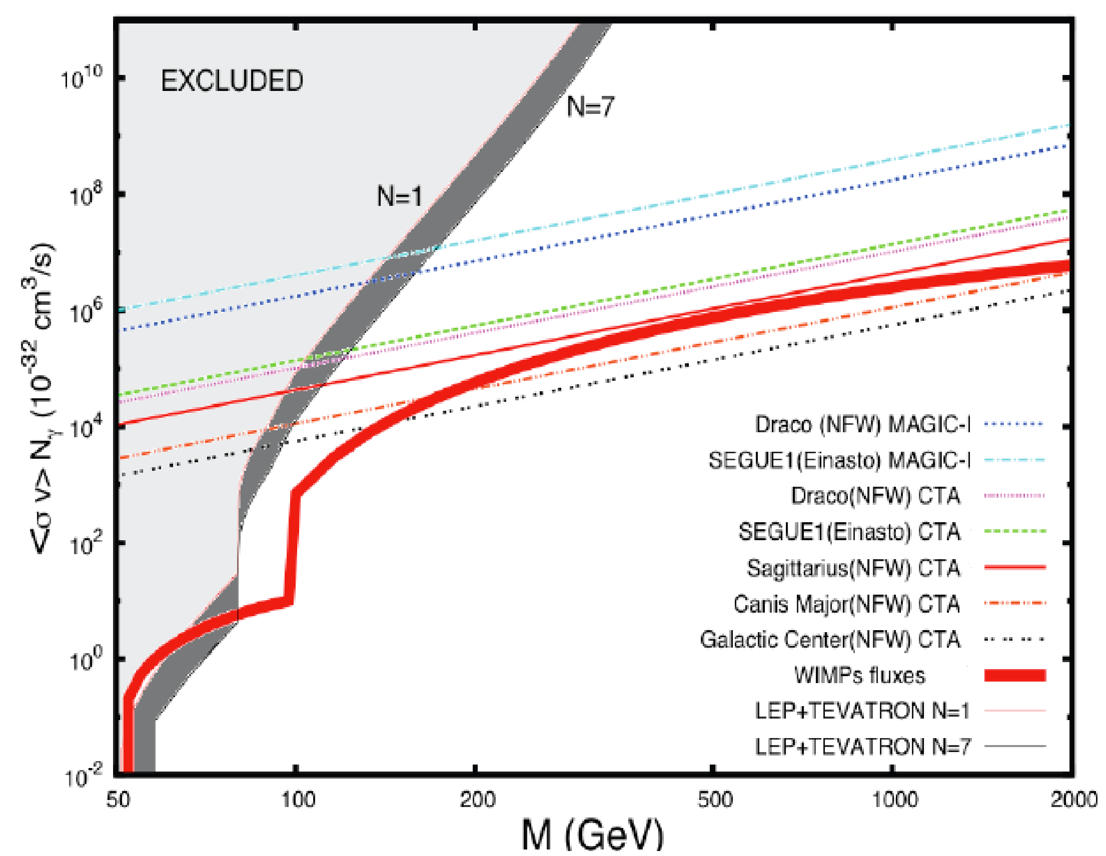
Cembranos, Dobado, Maroto,
PRL 90 (2003) 241301

Branon Branching Ratio



Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

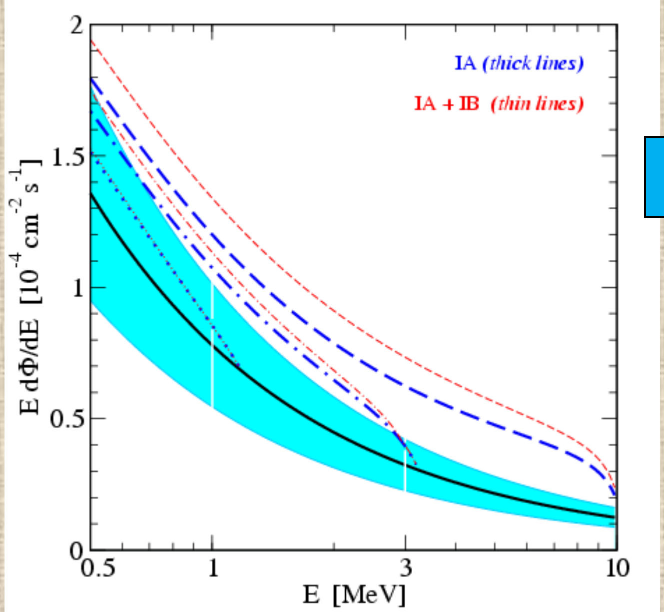
Exclusion limits for ACTs E>50GeV



Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

511 keV photons from the GC

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 photons from DDM

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

$\tau \sim$ 10^26 sec / M (MeV)

511 keV photons from the GC

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

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

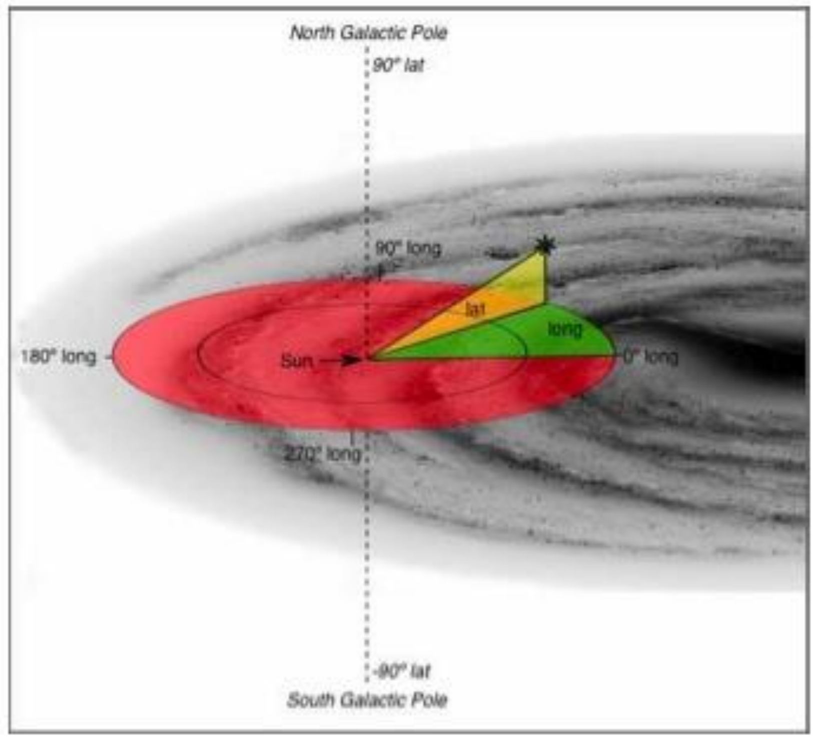
J. Cembranos and L. Strigari, PRD77:123519 (2008)

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

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 and L. Strigari, PRD77:123519 (2008)

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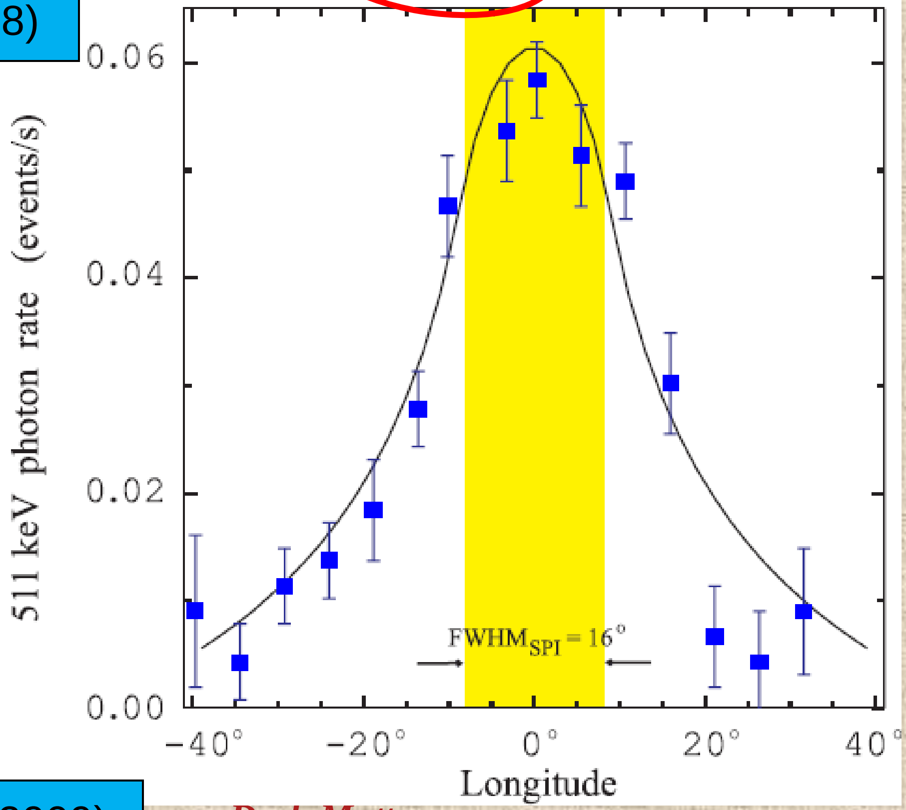


J. Cembranos, PRL102:141301 (2009)

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.

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

J. Cembranos, PRL102:141301 (2009)

UV modified gravity

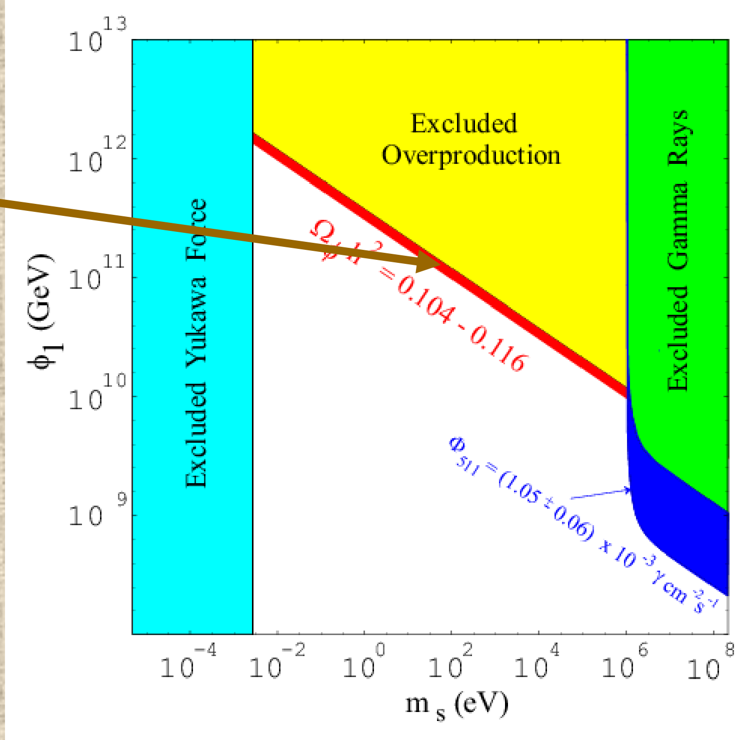
Einstein gravity is not consistent at high energies:
non-unitarity and non-renormalizable.

The UV modification of general relativity at high enery introduces new degrees of freedom that can work as DM.

The minimal realization is R2-gravity: 1 new parameter.

1.- SuperWIMP scenario:

R2-scalar



J. Cembranos, PRL102:141301 (2009)

SuperWIMP signatures:

a. Indirect detection

a.1. gamma rays

a.1.1. 511 line

b. Eöt-Wash experiments