1915 – 2015

A few ideas and models on dark matter

Benjamin Koch

in collaboration with

Cristobal Armaza, Maximo Bañados, Marco Aurelio Diaz, Sebastian Garcia, Davi Rodriguez, Illia Sahpiro, and Sebastian Urrutia

bkoch@fis.puc.cl

[a] PUC, Chile

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Graz

Dez 2015

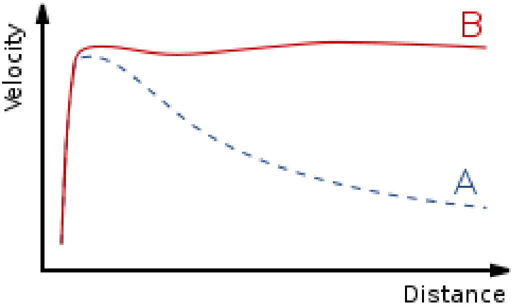
Outline

- Evidence
- Not- evidence
- Within gravity
- Particles
- Light particles high energy signals
- Conclusion?

DM Evidence

DM Evidence

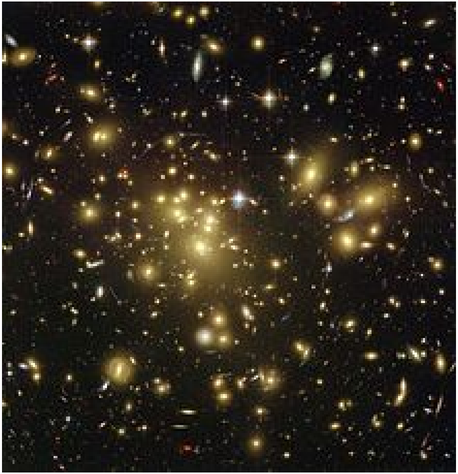
Galaxy rotation curves:



Stars outside are faster than visible mass inside would allow them to do

DM Evidence

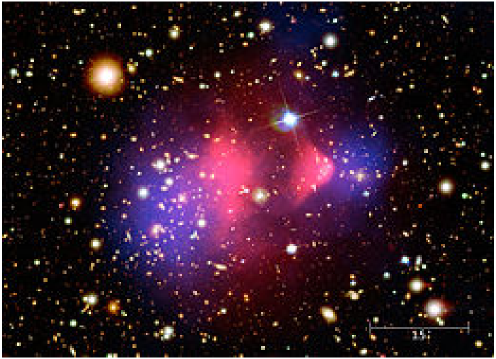
Gravitational lensing, clusters of galaxies:



Something dark and transparent and massive
between galaxy cluster and us (DM).

DM Evidence

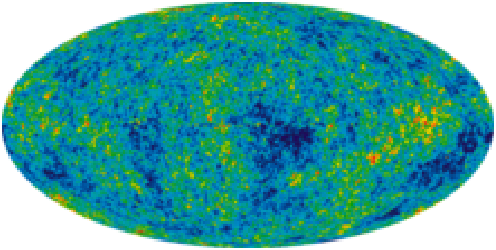
Gravitational lensing, collision of galaxies:



Something dark and transparent and massive in 2 galaxies.
But also tells the DM interacts weaker than interstellar gas.

DM Evidence

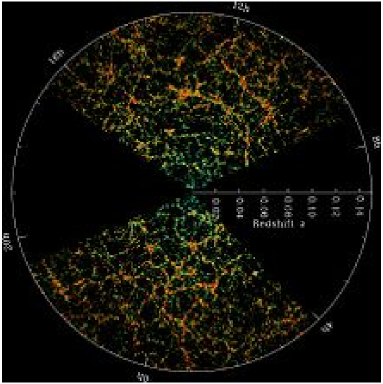
CMB fluctuations:



Escape from plasma → neutral matter in recombination.
Only can model power spectrum of perturbations if one assumes certain amount of dark energy and dark matter.

DM Evidence

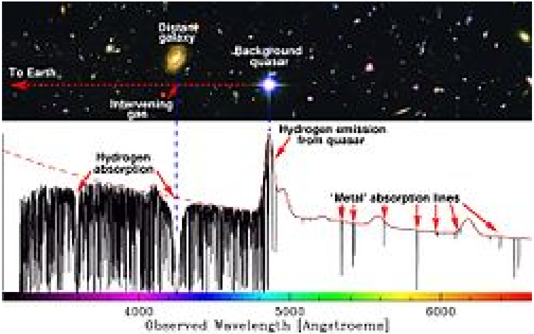
Barionic accoustig oscillations:



Remain from plasma → neutral matter in recombination.
Only can model power spectrum of densities if one assumes certain amount of dark energy and dark matter.

DM Evidence

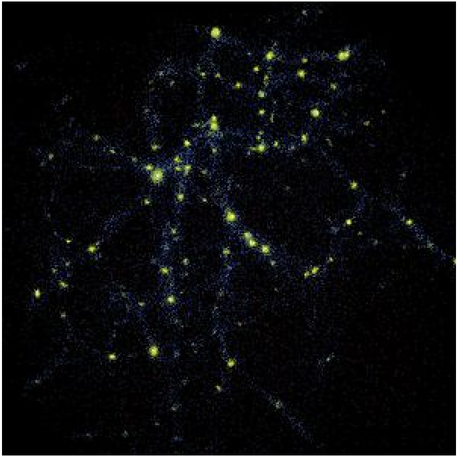
Lyman alpha forrest:



Model hydrogen absorption lines (without redshift 1216A).
Only works with dark energy and dark matter

DM Evidence

Structure formation:



Numerical simulation of structure needs also DM

DM Non-Evidence

DM Non-Evidence

DM Non-Evidence

Direct passive detection:

Many experiments, Xenon, Edelweiss, ...
Big detectors, low background, no signal

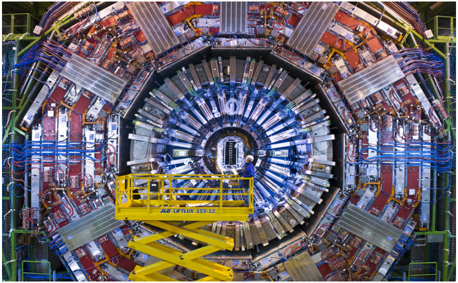
DM Non-Evidence

Direct passive detection:

Many more experiments
Bigger detectors, lower background ... no signal?

DM Non-Evidence

Produce and detect:



Several experiments, ATLAS, CMS, ...

No signal

DM Non-Evidence

Indirect passive detection:

Several experiments, Fermi-LAT, CTA ...

No signal

Difference

What is the difference?

The non-detections involve SM interactions only

The yes-detections involve SM interactions AND Gravity

- Newton $U = G\frac{Mm}{r}$
- Newton $F = G\frac{Mm}{r}$ & geodesics $\frac{d^2x^\mu}{dt^2} = \Gamma^\mu_{\alpha\beta}u^\alpha u^\beta$
- Universe evolution $H^2 = H_0^2(\Omega_M(1+z)^3 + \Omega_r(1+z)^2 + \Omega_\Lambda)$

Difference

What is the difference?

The non-detections involve SM interactions only

The yes-detections involve SM interactions AND Gravity

- Newton $U = G\frac{Mm}{r}$
- Newton $F = G\frac{Mm}{r}$ & geodesics $\frac{d^2x^\mu}{dt^2} = \Gamma^\mu_{\alpha\beta}u^\alpha u^\beta$
- Universe evolution $H^2 = H_0^2(\Omega_M(1+z)^3 + \Omega_r(1+z)^2 + \Omega_\Lambda)$

Difference

What is the difference?
The non-detections involve SM interactions only
The yes-detections involve SM interactions AND Gravity

- Newton $U = G\frac{Mm}{r}$
- Newton $F = G\frac{Mm}{r}$ & geodesics $\frac{d^2x^\mu}{dt^2} = \Gamma^\mu_{\alpha\beta}u^\alpha u^\beta$
- Universe evolution $H^2 = H_0^2(\Omega_M(1+z)^3 + \Omega_r(1+z)^2 + \Omega_\Lambda)$

Within gravity

Within gravity

Maybe something wrong with Gravity
(remember evidence only from Newton and Hubble)

Ideas in this direction

- MOND
- Extra fields in EH action "Scalar-Tensor" ...
- Non-local operators $S = \int dx^4 R + R\frac{1}{\Box}R + \ldots$
- ...
- Our idea in this direction: "Scale dependence of gravitational couplings"*

*B.K. and Paola Rioseco, arXiv:1501.00904;

D. Rodrigues, B.K., O. Piattella, I. Shapiro, AIP Conf.Proc. 1647 (2015) 57-61; D. Rodrigues, P. Letelier, I. Shapiro, arXiv:1102.2188;

JCAP 1004 (2010) 020.

Within gravity

Maybe something wrong with Gravity
(remember evidence only from Newton and Hubble)

Ideas in this direction

- MOND
- Extra fields in EH action "Scalar-Tensor" ...
- Non-local operators $S = \int dx^4 R + R \frac{1}{\Box} R + \ldots$
- ...
- Our idea in this direction: "Scale dependence of gravitational couplings"*

*B.K. and Paola Rioseco, arXiv:1501.00904;

D. Rodrigues, B.K., O. Piattella, I. Shapiro, AIP Conf.Proc. 1647 (2015) 57-61; D. Rodrigues, P. Letelier, I. Shapiro, arXiv:1102.2188;

JCAP 1004 (2010) 020.

Within gravity

Scale dependence

Allow for “Scale dependence of gravitational couplings” modifies Einstein’s field equations.
De Sitter case:
eom $g_{\mu\nu}$:

$$G_{\mu\nu} = -g_{\mu\nu}\Lambda_k - \Delta t_{\mu\nu} \quad , \tag{1}$$

eom k:

$$R\nabla_\mu\left(\frac{1}{G_k}\right) - 2\nabla_\mu\left(\frac{\Lambda_k}{G_k}\right) = 0 \quad . \tag{2}$$

can be solved with “Schwarzschild Ansatz” generalized de Sitter solution:

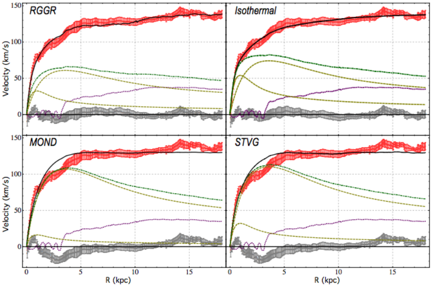
$$G(r) = \frac{G_0}{\epsilon r + 1} \quad (3)$$

$$f(r) = 1 + 3 G_0 M_0 \epsilon - \frac{2 G_0 M_0}{r} - (1 + 6\epsilon G_0 M_0)\epsilon r - \frac{\Lambda_0 r^2}{3} + r^2 \epsilon^2 (6\epsilon G_0 M_0 + 1) \ln\left(\frac{c_4(\epsilon r + 1)}{r}\right) \quad (4)$$

$$\Lambda(r) = \frac{-72\epsilon^2 r(\epsilon r + 1)\left(\epsilon r + \frac{1}{2}\right)\left(G_0 M_0 \epsilon + \frac{1}{6}\right)\ln\left(\frac{c_4(\epsilon r+1)}{r}\right) + 4r^3 \Lambda_0 \epsilon^2 + \left(12\epsilon^3 + 6\Lambda_0 \epsilon + 72\epsilon^4 G_0 M_0\right) r^2}{2r(\epsilon r + 1)^2} + \frac{\left(72\epsilon^3 G_0 M_0 + 11\epsilon^2 + 2\Lambda_0\right) r + 6\epsilon^2 G_0 M_0}{2r(\epsilon r + 1)^2} \quad . \quad (5)$$

Constants of integration: G_0, M_0, Λ_0, ϵ, c_4

Effect on rotation curves



Comparison with MOND, DM, ...
promising

Effect on lensing

... not so promising
Could be there but unlikely to explain it all

Try particles

Effect on lensing

... not so promising
Could be there but unlikely to explain it all

Try particles

Particles

Particles

Particles

New particles, new game:

Anything goes as long as...

Particles

New particles, new game:

Anything goes as long as...

- Right masses (not too light, rotation curves; not too heavy abundance and observability)
- right couplings (abundance, stability)
- right "non-couplings" collider and indirect detection constraints
- ...
- Our contribution in this direction, Higgs sector*, Susy-gravitino sector**

*M.A. Diaz, B.K., S. Urrutia-Quiroga arXiv:1511.04429

**M.A. Diaz, S. Garcia, B.K., Phys.Rev. D84 (2011) 055007

Simple SM extension: Inert Higgs Doublet Model (IDM) by N. G. Deshpande y E. Ma en 1978

- In addition to the usual SM Higgs doublet (Φ_S) one introduces an additional doublet (Φ_D)
- Discrete symmetry $\mathbb{Z}_2$ such that

$$\begin{array}{ccc} \Phi_S & \mapsto & \Phi_S \\ \Phi_D & \mapsto & -\Phi_D \\ SM & \mapsto & SM \end{array}$$

- Thus Φ_D has no tree level couplings to SM fermions
- Phenomenology compatible with SM

IDM potential:

$$V = {\mu_1}^2\mathbf{A} + {\mu_2}^2\mathbf{B} + \lambda_1\mathbf{A}^2 + \lambda_2\mathbf{B}^2 + \lambda_3\mathbf{AB} + \lambda_4\mathbf{CD} + \frac{\lambda_5}{2}\left(\mathbf{C}^2 + \mathbf{D}^2\right)$$

where $\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$ are given by

$$\mathbf{A} = {\Phi_S}^\dagger\Phi_S,\ \mathbf{B} = {\Phi_D}^\dagger\Phi_D,\ \mathbf{C} = \mathbf{D}^\dagger = {\Phi_S}^\dagger\Phi_D$$

- Only Φ_S acquires VEV since want to perserve $\mathbb{Z}_2$ symmetry
- **Degrees of freedom:**
  8 (two doublets) − 3 (Goldstone) = 5 (Physical scalars)
- **Parameters:**
  7 (potential) − 2 (M_Z, M_H) = 5 (free parameters)

Particles

Higgs

Physical content:

- Φ_S : *h*, *SM–like*, with Yukawa couplings
- Φ_D : $H, A, D^{\pm}$, inert scalars with interior couplings and couplings to EW gauge bosons through kinetic term
- $\mathbb{Z}_2$ symmetry
  - $\rightarrow$ Lightest inert scalar stabel
  - $\rightarrow$ DM candidate
- Parameters:

$$M_H,\ M_A,\ M_D \quad \text{y} \quad \lambda_2,\ \lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$$

Restrictions:

1. Positive potential, minimum, perturbativity and unitarity, inert vacuum
2. Several electroweak precision tests
3. Width of electroweak gauge bosons Z and W
4. DM candidate has to be H (neutral)
5. LHC restrictions: $\mathrm{Br}(h \to \text{invisible}) < 0{,}43$

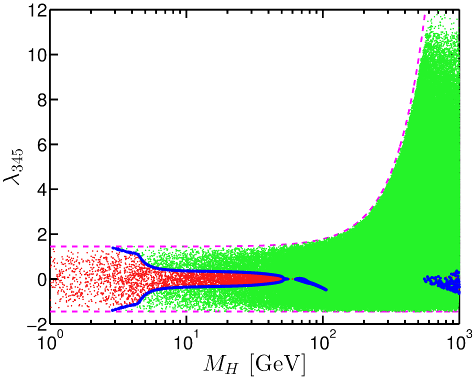
Now scan within those restrictions

Parameter scan and DM density:

- Random scan over previously mentioned parameters within restrictions
- Mass range $1\,\text{GeV} \leq M_{H,A,D} \leq 1\,\text{TeV}$
- Check *relic density* (WMAP, Planck) $\Omega_{DM}\, h^2 = 0{,}1181 \pm 0{,}0012$
- Cosmological parameters obtained with `micrOMEGAs`
- Tolerance in relic density $\pm 3\sigma$

Color coding	
● (green)	Relic density too low $< \rho_{DM} \pm 3\sigma$
● (blue)	Relic density within $\pm 3\sigma$
● (red)	Relic density too high $> \rho_{DM} \pm 3\sigma$

Results scan:
Projection to (M_H, λ_{345}) plane

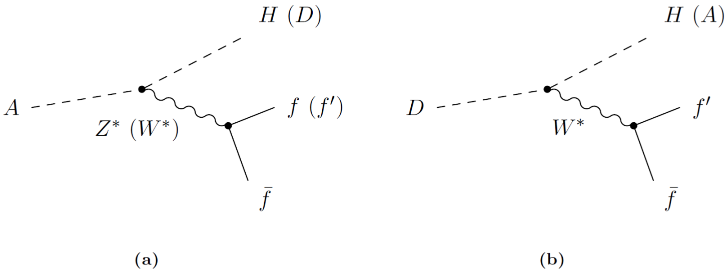


Note: Upper line from inert vacuum, lower line from vacuum stability condition

Particles

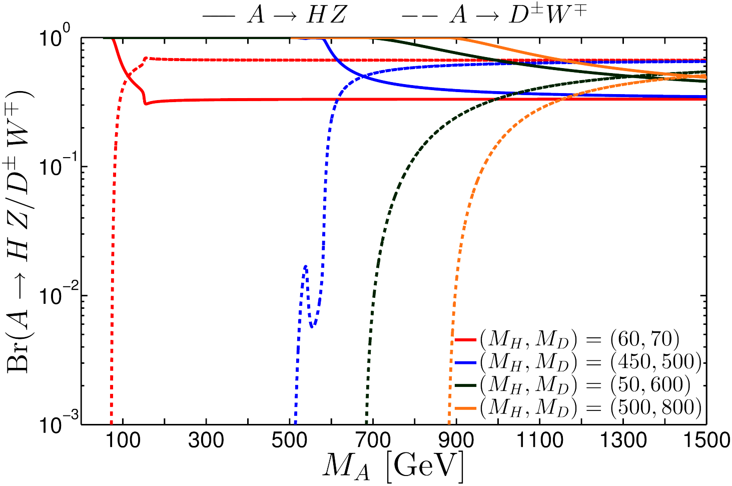
Higgs

For collider signals also study BR inert decays:



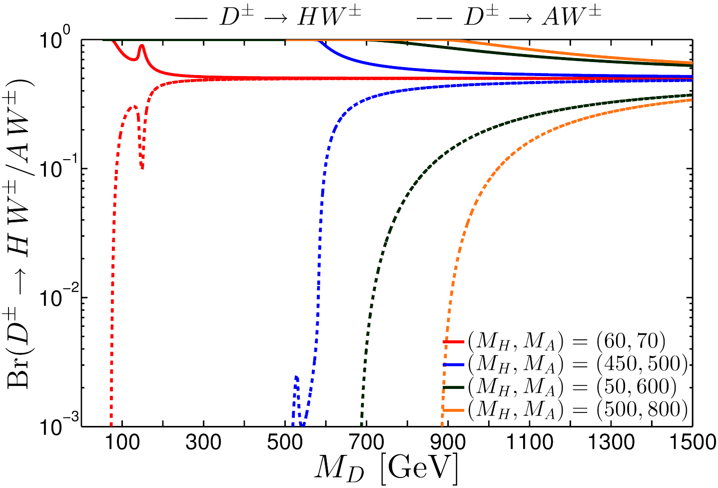
- Only depend on inert scalar masses + SM (No λ...)
- Take scalar masses on-shell

Results inert decays (no λ dependence):



Crossover

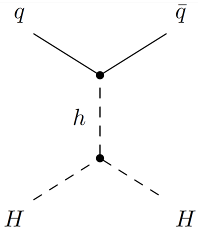
Results inert decays (no λ dependence):



No crossover, decay to DM H always larger

Results direct detection:

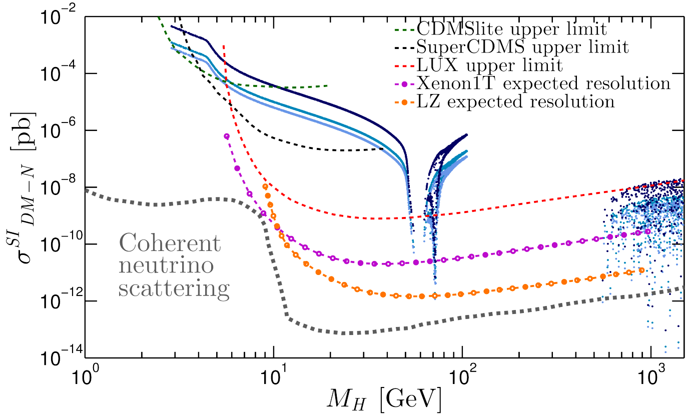
- Scattering DM–nucleon en el IDM ("Higgs portal")



$$\sigma^{SI}{}_{DM-N} = \frac{\lambda_{345}{}^2}{(4\pi M_h{}^4)} \frac{M_N{}^4 f_N{}^2}{(M_H + M_N)^2}$$

- f_N comes from QCD take conservative small values
- Tree level calculation
- Compare to upper limits from recent experiments

Results direct detection (only take right DM density):



Drop when $m_H = 2m_h$ (efficient h production), model will be largely testable

Light particles high energy signals

DM particles and "high energy" signals

- Collider production (just saw example)
- Annihilation work in progress
- Decay studied example*
- Acceleration of light DM particles**

*M. Diaz, S. Garcia, B.K. Phys.Rev. D84 (2011) 055007 **C. Armaza, M. Banados, B.K. arXiv:1510.01223

- Black holes can in principle produce $E_{CM} \to \infty$, but one neds
- Extremely rotating black hole
- Collision at the horizon
- Angular momentum l: critical

$\Rightarrow$ Unlikely, hard to observe

Light particles high energy signals

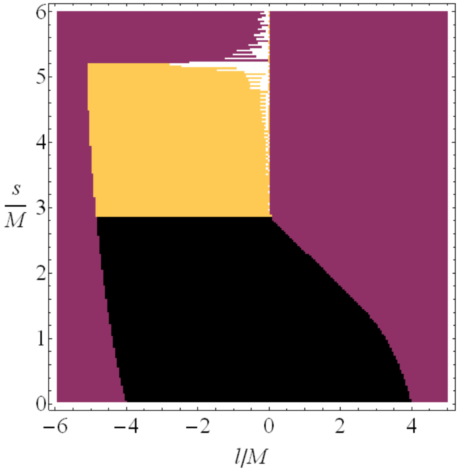
Idea:
Let the particle rotate and the black hole be spherical

- Can one produce $E_{CM} \to \infty$?
  If yes:
- Has the collision to be at the horizon?
- Has the angular momentum l: to be critical?
- Is there a notion of extremely rotating particle?

$\Rightarrow$ Solve Papapetru equations (geodesics modified by spin) and see ...

Light particles high energy signals

Result-1:



E_{CM} divergent for yellow region

That was the good news,

what are the bad news?

- For solar mass object and spin 1/2 need $m_{DM} \approx 10^{-15}$ eV
- Papapetru equations allow for solutions withsuperluminal regime???

Take home message

DM is still mysterious,
but the good thing is that
a lot of observational evidence coming up!

Thank you

Thank you !