Dark Advances at UCM

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MultiDark

Multimessenger Approach for Dark Matter Detection

Collaboration with F. Albareti, A. de la Cruz-Dombriz, V. Gammaldi, R. A. Lineros, S. J. Nuñez Jareño and A.L. Maroto

MIAPP Munich Institute for Astro- and Particle Physics

Outline

- Viviana Gammaldi
  - Indirect searches of heavy Dark Matter
- Santos J. Nuñez Jareño
  - Coherent Dark Matter
- Franco D. Albareti
  - Vacuum energy as Dark Matter

Indirect searches of heavy Dark Matter

Viviana Gammaldi
UCM& Multidark

Publications:

J.A.R. Cembranos , A. de la Cruz-Dombriz , V. Gammaldi, A.L. Maroto
Phys.Rev. D85 (2012) 043505
J.A.R. Cembranos, V. Gammaldi, A.L. Maroto
Phys.Rev. D86 (2012) 103506
J.A.R. Cembranos, V. Gammaldi, A.L. Maroto
JCAP 1304 (2013) 051
J.A.R. Cembranos , A. de la Cruz-Dombriz , V. Gammaldi , R.A. Lineros, A.L. Maroto
JHEP 1309 (2013) 077
J.A.R. Cembranos, V. Gammaldi, A.L. Maroto
Phys.Rev. D90 (2014) 4, 043004

Indirect searches of heavy Dark Matter

- Introduction
  - Gamma rays and Dark Matter
- Gamma ray fitting functions
  - HESS data from the Galactic Center
- Comparison of Monte Carlo event generators
  - PYTHIA 6.418 (Fortran)
  - HERWIG 6.5.10 (Fortran)
  - PYTHIA 8.165 (C++)
  - HERWIG 2.6.1 (C++)
- Conclusions

Indirect Searches: Cosmic rays

Cosmic-ray fluxes at the Earth from DM annihilating or decay in Galactic sources depend by the Standard Model (SM) secondary particle of interest.

Gamma rays:

$$\frac{d\Phi_\gamma}{dE} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \cdot \frac{dN_i^{(\gamma)}}{dE} \cdot \frac{\Delta\Omega \, \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

Neutrinos:

$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3} \sum_{a=1}^{2} \sum_{i}^{\text{channels}} P_{fp} \cdot \frac{\zeta_i^{(a,\nu_p)}}{a} \frac{dN_i^{(\nu_p)}}{dE} \cdot \frac{\Delta\Omega \, \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

Antiprotons:

$$\frac{\mathrm{d}\Phi_{\bar{p}}}{\mathrm{d}E_{\bar{p}}} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \frac{\mathrm{d}N_i^{(\bar{p})}}{\mathrm{d}E_{\bar{p}}} \cdot \frac{v_{\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{M}\right)^a R_{(a)}(E_{\bar{p}})$$

DM annihilation vs Decay

a=1 $\zeta^{(1)} = \Gamma$

a=2 $\zeta^{(2)} = \langle\sigma v\rangle$

They depend on the DM model.

For annihilation, it is standard to fix the value $\zeta^{(2)}$ around thermal one :

$$\langle \sigma v \rangle = 3 \cdot 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$$

The final flux has a different dependence with the DM mass and the density distribution in these cases.

simulated by Monte Carlo events

or HERWIG.

$$\frac{\zeta_i^{(a)}}{a} \cdot \frac{dN_i^{(\gamma)}}{dE} \cdot \frac{\Delta\Omega \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

nnels

$$\sum_i P_{fp} \cdot \frac{\zeta_i^{(a,\nu_p)}}{a} \frac{dN_i^{(\nu_p)}}{dE} \cdot \frac{\Delta\Omega \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

$$\frac{\zeta_i^{(a)}}{a} \frac{\mathrm{d}N_i^{(\bar{p})}}{\mathrm{d}E_{\bar{p}}} \cdot \frac{v_{\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{M}\right)^{a} R_{(a)}(E_{\bar{p}})$$

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$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3} \sum_{a=1}^{2} \sum_{i}^{\text{channels}} P_{fp} \cdot \frac{\zeta_i^{(a,\nu_p)}}{a} \frac{dN_i^{(\nu_p)}}{dE} \cdot \frac{\Delta\Omega \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

Antiprotons:

$$\frac{\mathrm{d}\Phi_{\bar{p}}}{\mathrm{d}E_{\bar{p}}} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \frac{\mathrm{d}N_i^{(\bar{p})}}{\mathrm{d}E_{\bar{p}}} \cdot \frac{v_{\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{M}\right)^a R_{(a)}(E_{\bar{p}})$$

DM density distribuion

Astrophysical factor encode the physics of DM distribution and particles propagation.

For gamma-rays and neutrinos:

$$\langle J_{(a)}\rangle = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} \mathrm{d}\Omega \int_0^{l_{max}(\Psi)} \rho^a[r(l)]dl(\Psi)$$

depends by the DM distribution and the devise angular resolution and effective area.

For antiprotons:

Is the solution of the diffusion equation that depends by the DM distribution and diffusion model.

$$\frac{\Delta\Omega \boxed{\langle J_{(a)}\rangle_{\Delta\Omega}}}{4\pi M^a}$$

$$\frac{dN_i^{(\nu_p)}}{dE}\cdot\frac{\Delta\Omega \boxed{\langle J_{(a)}\rangle_{\Delta\Omega}}}{4\pi M^a}$$

$$\left(\frac{\rho_\odot}{M}\right)^a \boxed{R_{(a)}(E_{\bar{p}})}$$

Indirect Searches: Cosmic rays

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Antiprotons:

$$\frac{\mathrm{d}\Phi_{\bar{p}}}{\mathrm{d}E_{\bar{p}}} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \frac{\mathrm{d}N_i^{(\bar{p})}}{\mathrm{d}E_{\bar{p}}} \cdot \frac{v_{\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{M}\right)^a R_{(a)}(E_{\bar{p}})$$

Indirect Searches: Simulations

Secondary particle fluxes are simulated by Monte Carlo events generator software such as PYTHIA or HERWIG.

Gamma-rays:

$$\frac{d\Phi_\gamma}{dE} = \sum_{a=1}^{2}\sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \cdot \boxed{\frac{dN_i^{(\gamma)}}{dE}} \cdot \frac{\Delta\Omega \left\langle J_{(a)} \right\rangle_{\Delta\Omega}}{4\pi M^a}$$

Neutrinos:

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Gamma Ray Fitting Functions

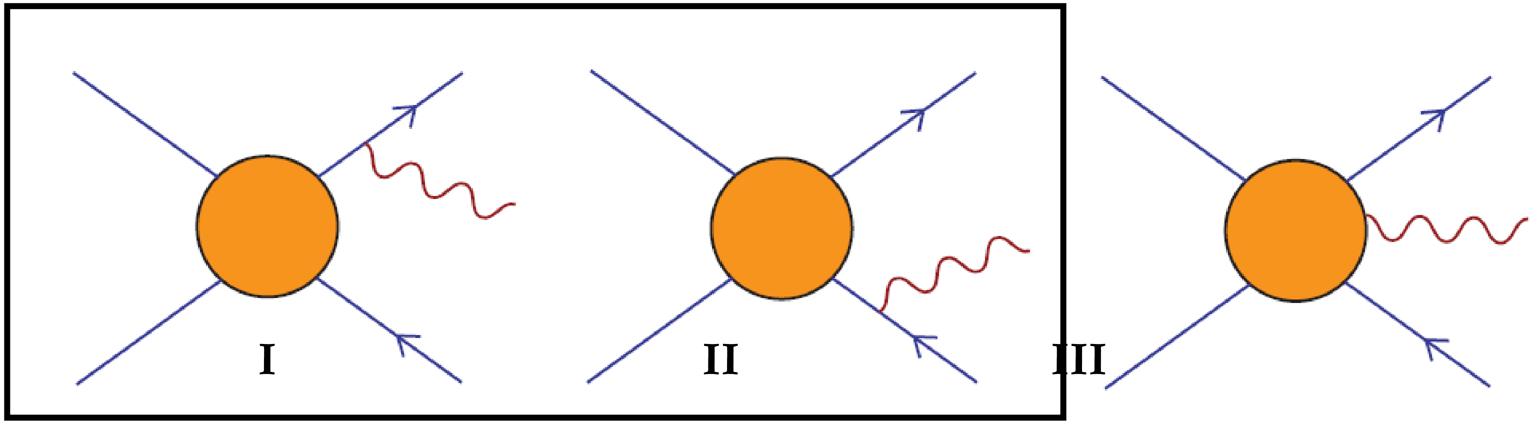
- Gamma-ray spectra do not depend on DM model or DM model except for small particular tuned regions of the parameter space:

- Fitting functions for particle-antiparticle channels.

JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

Internal Bremsstrahlung



Bringmann, Bergström and Edsjö **JHEP 0801:049,2008**.

✓ bremsstrahlung contributions **I** and **II** are included in the performed simulations.

✓ Model dependent contribution **III** is negligible except for very particular region of models with degenerate spectrum

Cannoni, Gómez, Sánchez-Conde, Prada & Panella **PRD 81 : 107303, 2010.**

Gamma Ray Fitting Functions

- Physical process to get gamma rays from WIMPs:

Firstly: Annihilation of WIMPs (mainly by pairs) in SM particles.

Secondly: Those unstable SM products decay and/or hadronize.

$$E_{\mathrm{CM}} = 2\,M \quad \text{Center of mass frame}$$

- Simulate E_{CM} ⇔ Simulate different WIMP masses.

- Package **PYTHIA 6.418** version was used.

- Variable $x \equiv E_\gamma/M$ in the interval [0, 1].

Energy bins:

$$[10^{-5},\ 10^{-3}]\ [10^{-3},\ 0.2]\ [0.2,\ 0.5]\ [0.5,\ 0.8]\ [0.8,\ 1.0]$$

Gamma Ray Fitting Functions

I. Leptons and quarks (except *top* quark)

$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1 \mathrm{exp}\left(-b_1 x^{n_1} - b_2 x^{n_2} - \frac{c_1}{x^{d_1}} + \frac{c_2}{x^{d_2}}\right) + q\, x^{1.5} \ln\left[p(1-x)\right] \frac{x^2 - 2x + 2}{x}$$

II. *W* and *Z* gauge bosons

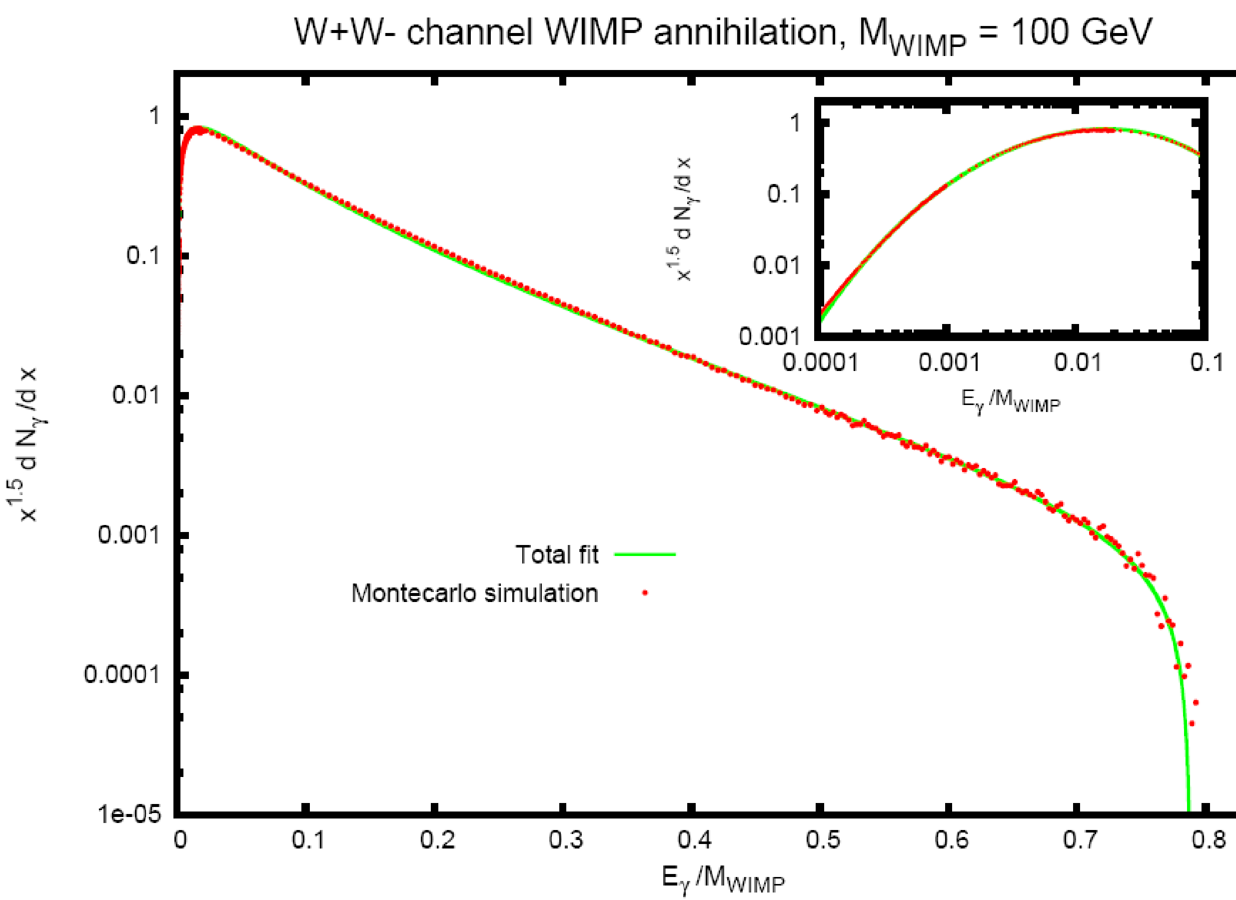
$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1 \exp\left(-b_1\, x^{n_1} - \frac{c_1}{x^{d_1}}\right)\left\{\frac{\ln[p(j-x)]}{\ln p}\right\}^q$$

$$x \equiv E_\gamma/M$$

III. Top quark

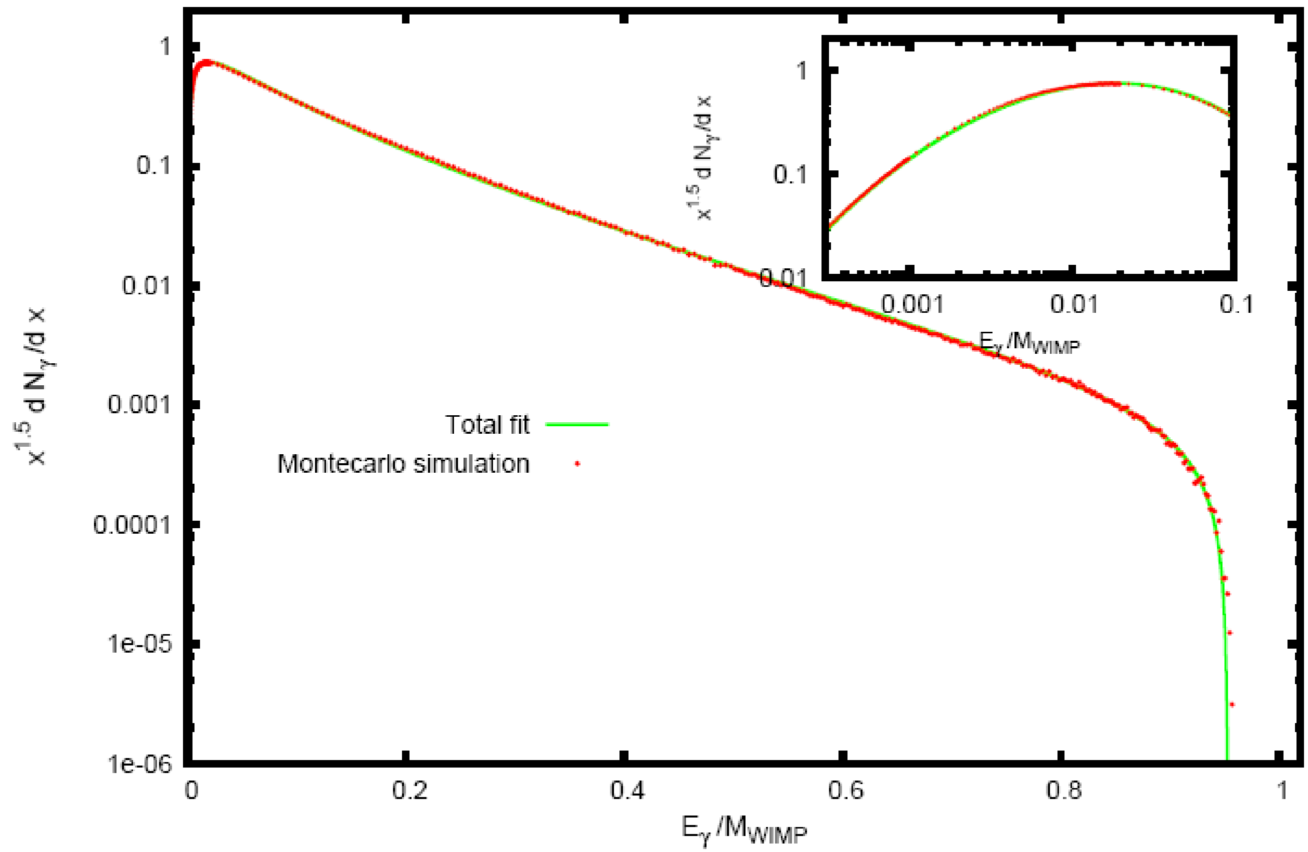
$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1 \exp\left(-b_1\, x^{n_1} - \frac{c_1}{x^{d_1}} - \frac{c_2}{x^{d_2}}\right)\left\{\frac{\ln[p(1-x^l)]}{\ln p}\right\}^q$$

W+W- channel Fitting Function

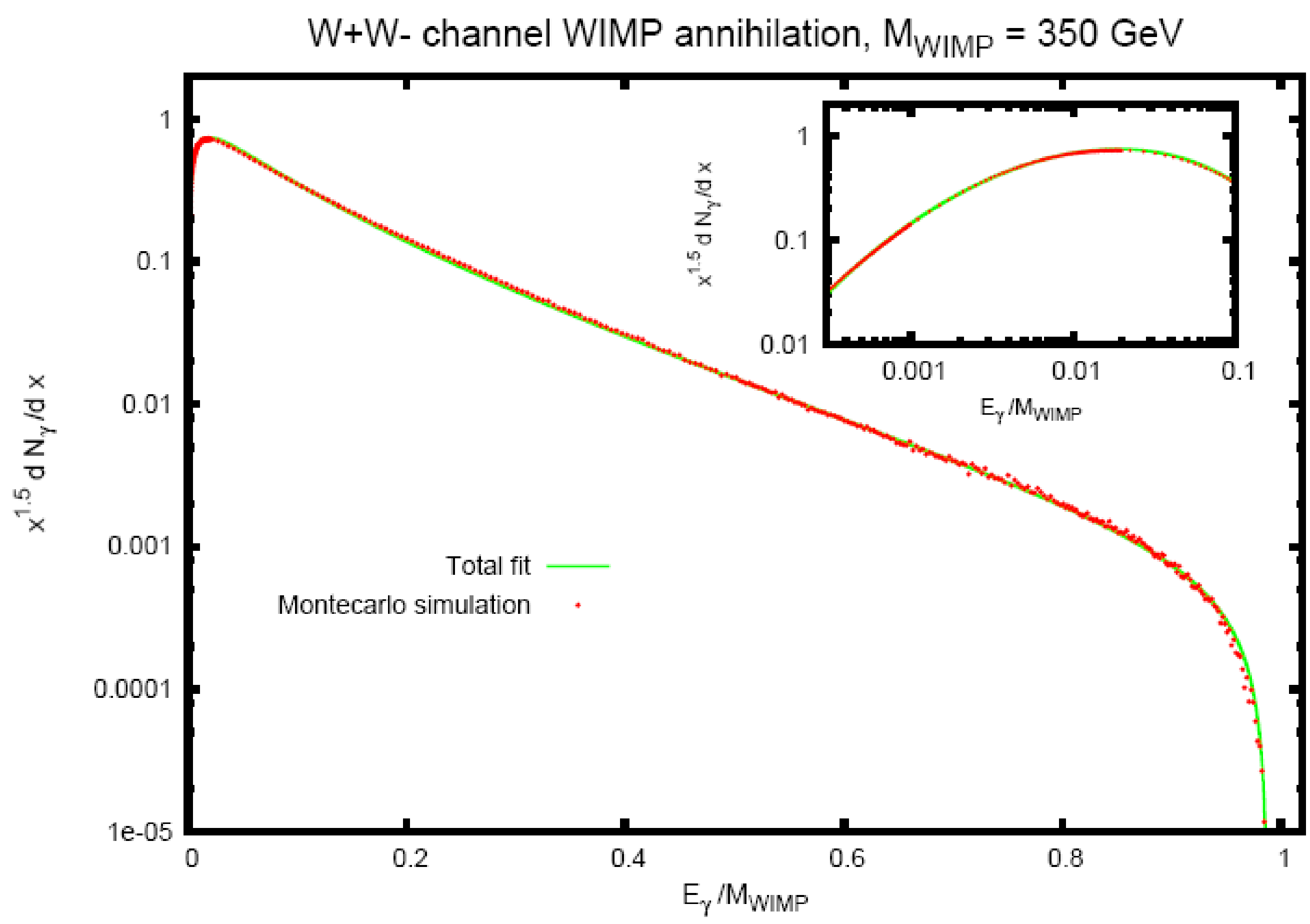


W+W- channel Fitting Function

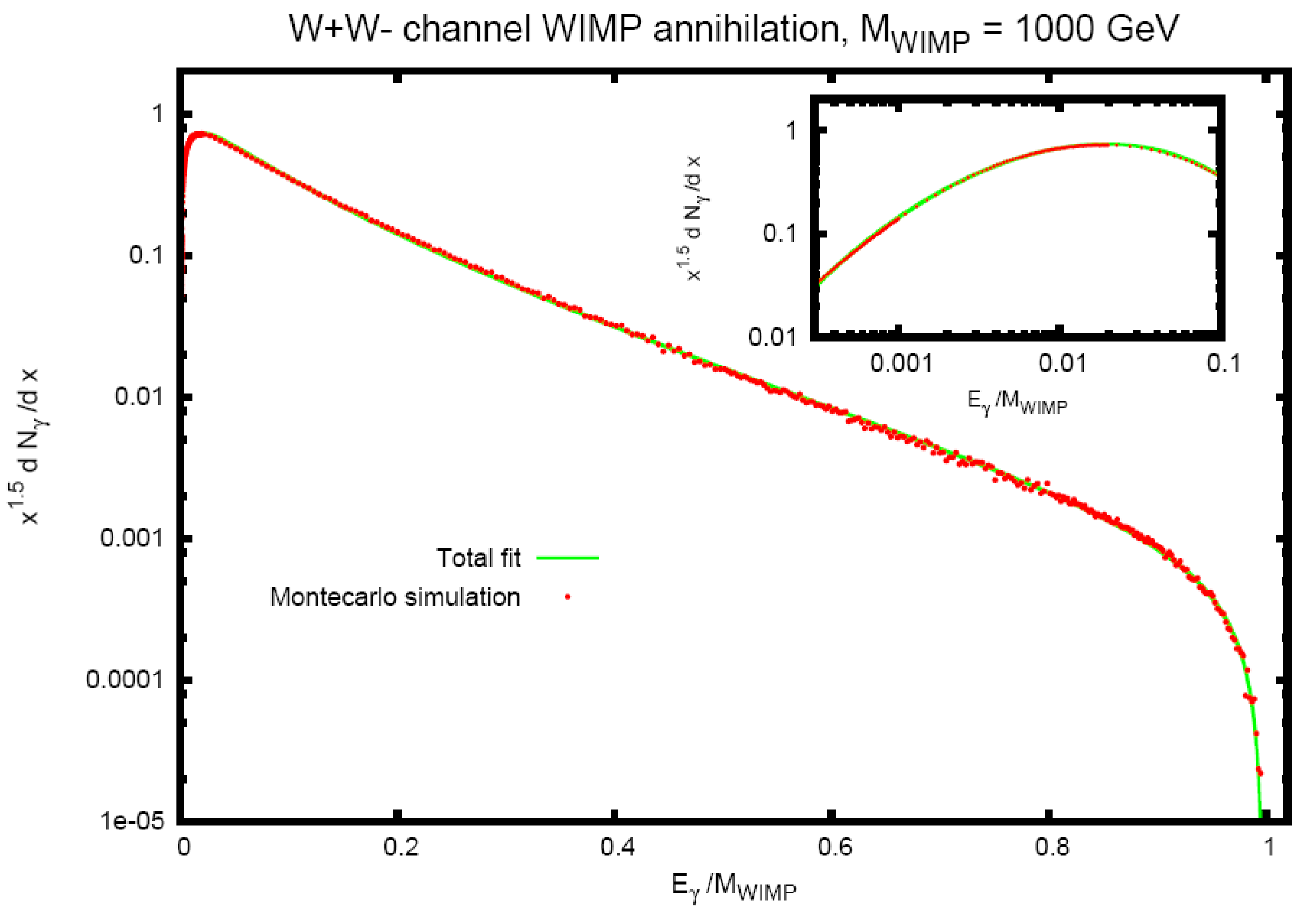
W+W- channel WIMP annihilation, M_{WIMP} = 200 GeV



W+W- channel Fitting Function



W+W- channel Fitting Function



Gamma Ray Fitting Functions

✓ MATHEMATICA **[AdICD et *al.*, 2010]**

MultiDark
Multimessenger Approach for Dark Matter Detection

http://teorica.fis.ucm.es/PaginaWeb/downloads.html

✓ ROOT-based **[D. Nieto et *al.*, 2011]**

DAMASCO (DArk Matter Analytical Spectral COde)

http://cta.gae.ucm.es/gae/damasco

MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

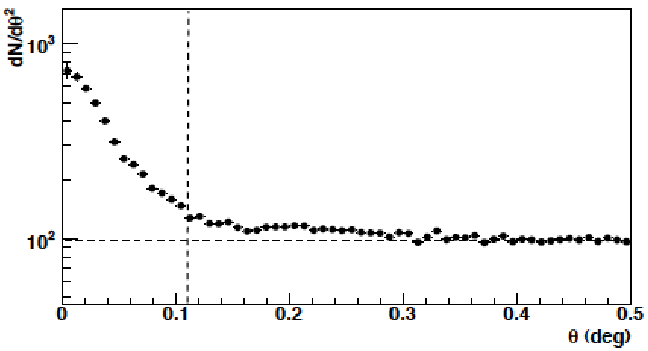
(PYTHIA 6.418, Fortran)

Application to HESS data

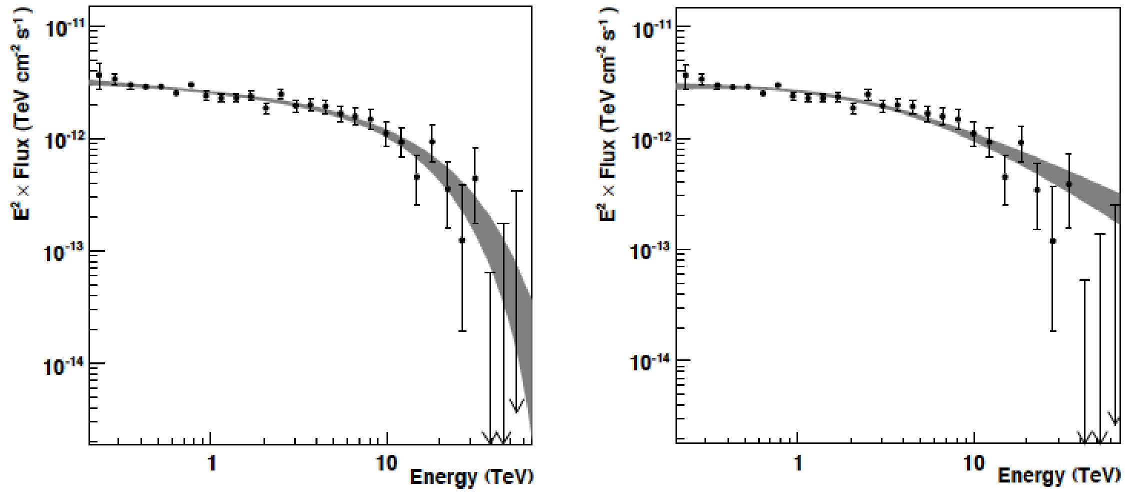
By HESS:

270 GeV-70 TeV

Θ < 0.1°



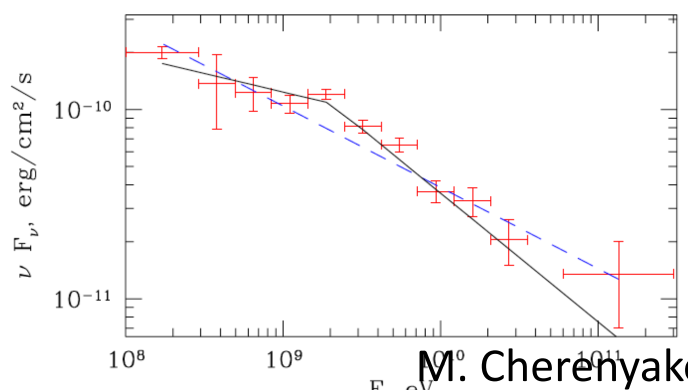
F. Aharonian et al. A&A 503, 817-825 (2009)



F. Prada et al. Phys. Rev. Lett. 95, 241301 (2004)

By Fermi-LAT:

100 MeV-300 GeV

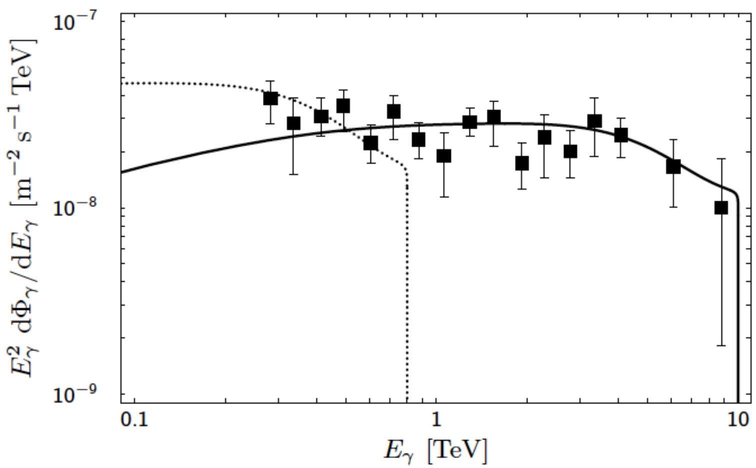


$$E > E_{br}$$
$$\chi^2/d.o.f. = 0.81$$
$$\Gamma = 2.68 \pm 0.05$$

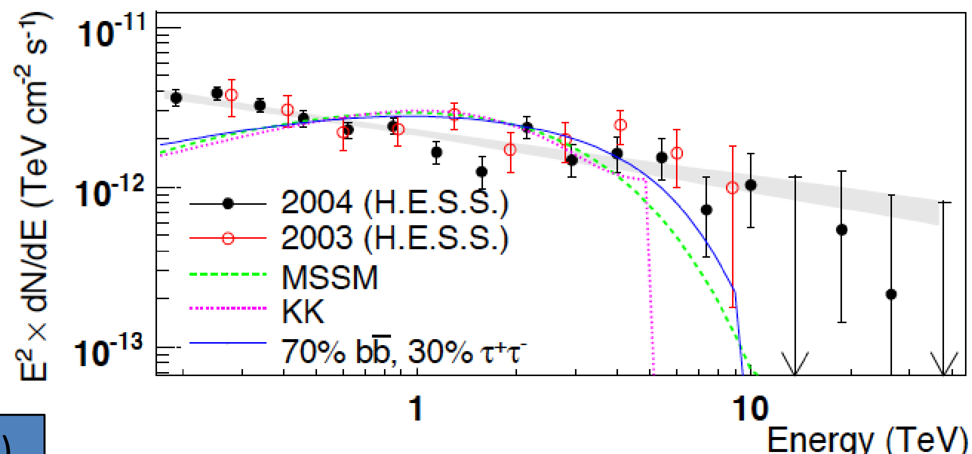
M. Cherenyakova et al. ApJ 726, 60 (2011)

Gamma Rays from the Galactic Center

Previous fits of DM signals are not able to be consistent with HESS observations without taking into account a background contribution.



L. Bergstöm et al. arXiv:astro-ph/0410359v2(2005)



F. Aharonian et al. arXiv: astrp-ph/0610509v2 (2006)

Galactic Center

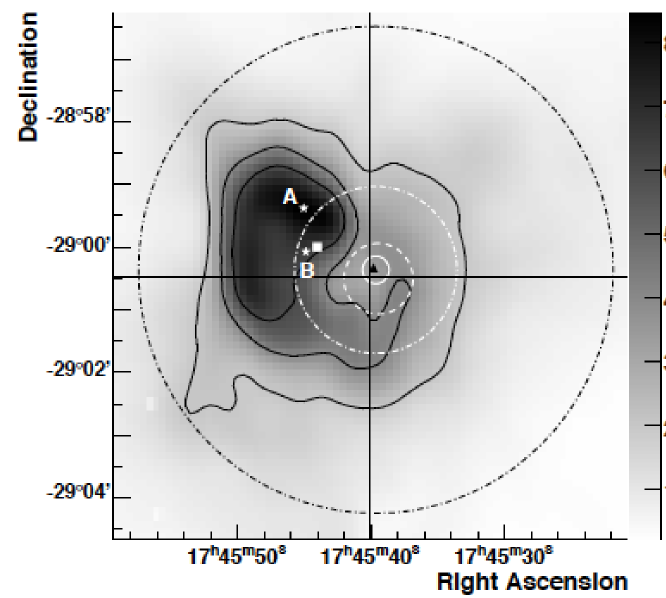
- Possible DM distribution close to the Earth but embedded in a very complex region due to the presence of multiplies sources.

- Multiplies sources observed (Radio flux, Sgr A* black hole, SNR Sgr A East, pulsar candidate, gamma emission).

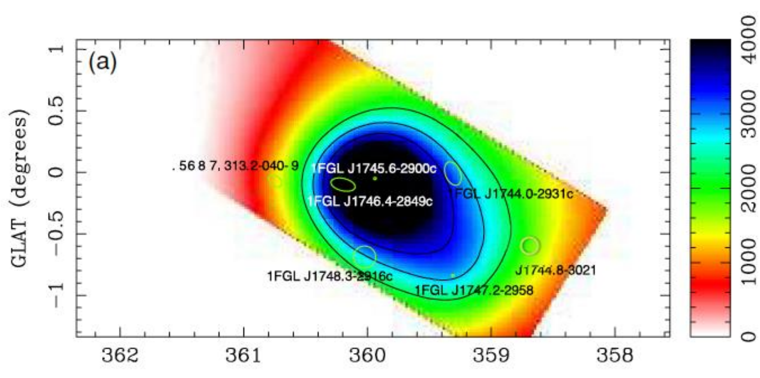
- Variability in Radio and X,

but not in gamma flux

HESS J1745-290



1FGL J1745.6-2900c



Gamma Rays from the Galactic Center

Background component: $$\frac{d\Phi_{Bg}}{dE} = B^2 \cdot \left(\frac{E}{\mathrm{GeV}}\right)^{-\Gamma}$$

$$\boxed{\frac{d\Phi_{Tot}}{dE} = \frac{d\Phi_{Bg}}{dE} + \frac{d\Phi_{DM}}{dE}}$$

4 free parameters:

$$B, \Gamma, A, M$$

DM contribution: $$\frac{\mathrm{d}\,\Phi_{\mathrm{DM}}}{\mathrm{d}\,E} = \sum_i \frac{\langle \sigma_i v \rangle}{2} \frac{\mathrm{d}\,N_i}{\mathrm{d}\,E} \times \frac{\overbrace{\Delta\Omega \, \langle J_{(2)} \rangle_{\Delta\Omega}}^{A}}{4\pi M^2}$$

Gamma Rays from the Galactic Center

Channel	M (TeV)	$A\,(10^{-7}\,\mathrm{cm}^{-1}\mathrm{s}^{-1/2})$	$B\,(10^{-4}\,\mathrm{GeV}^{-1/2}\mathrm{cm}^{-1}\mathrm{s}^{-1/2})$	Γ	$\chi^2/\,\mathrm{dof}$	$\Delta\chi^2$	b
e^+e^-	7.51 ± 0.11	8.12 ± 0.73	2.78 ± 0.79	2.55 ± 0.06	2.09	32.6	111 ± 20
$\mu^+\mu^-$	7.89 ± 0.21	21.2 ± 1.92	2.81 ± 0.53	2.55 ± 0.06	2.04	31.4	837 ± 158
$\tau^+\tau^-$	12.4 ± 1.3	7.78 ± 0.69	3.17 ± 0.62	2.59 ± 0.06	1.59	20.6	278 ± 76
$u\bar{u}$	27.9 ± 1.8	6.51 ± 0.46	9.52 ± 9.47	3.08 ± 0.35	0.78	1.2	987 ± 189
$d\bar{d}$	42.0 ± 4.4	4.88 ± 0.48	8.26 ± 7.86	3.03 ± 0.34	0.73	0.0	1257 ± 361
$s\bar{s}$	53.9 ± 6.2	4.85 ± 0.57	6.59 ± 5.43	2.92 ± 0.29	0.90	4.1	2045 ± 672
$c\bar{c}$	31.4 ± 6.0	6.90 ± 1.06	53.0 ± 157	3.70 ± 1.07	1.78	25.0	1404 ± 689
$b\bar{b}$	82.0 ± 12.8	3.69 ± 0.61	6.27 ± 6.07	2.88 ± 0.35	1.32	14.2	2739 ± 1246
$t\bar{t}$	87.7 ± 8.2	3.68 ± 0.34	6.07 ± 3.34	2.86 ± 0.19	0.88	3.6	3116 ± 820
W^+W^-	48.8 ± 4.3	4.98 ± 0.40	5.18 ± 2.23	2.80 ± 0.15	0.84	2.6	1767 ± 419
ZZ	54.5 ± 4.9	4.73 ± 0.40	5.38 ± 2.45	2.81 ± 0.16	0.85	2.9	1988 ± 491

$$A^2 = \frac{\langle\sigma v\rangle\,\Delta\Omega\,\langle J_{(2)}\rangle_{\Delta\Omega}}{8\pi M^2}$$

$$\langle\sigma v\rangle = 3\cdot 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$$

$$\Delta\Omega \simeq 10^{-5}$$

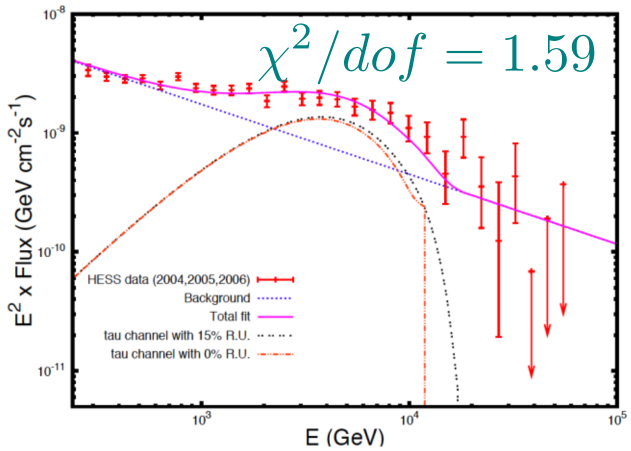
$$b \equiv \langle J_{(2)}\rangle / \langle J_{(2)}^{\mathrm{NFW}}\rangle$$

$$\langle J_{(2)}^{\mathrm{NFW}}\rangle \simeq 280\cdot 10^{23}\ \mathrm{GeV}^2\mathrm{cm}^{-5}$$

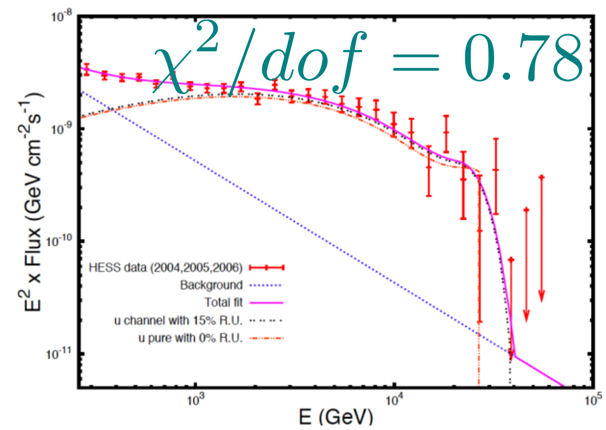
J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1204.0655v1], [Phy. Rev. D 85, 043505] ; [arXiv:1302.6871v2][astro-ph.CO], JCAP04 (2013) 051

Gamma Rays from the Galactic Center

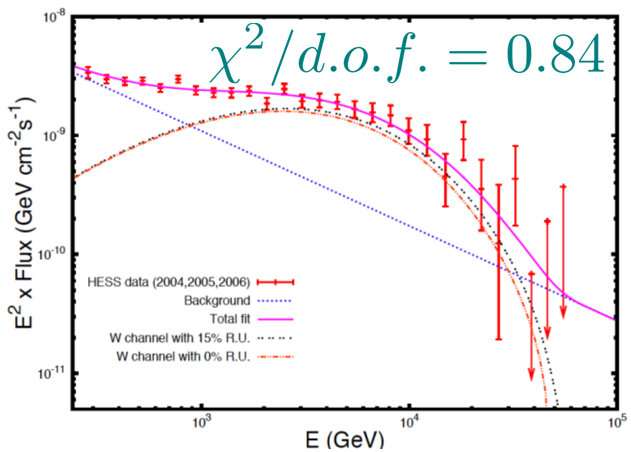
Lepton channel best fit: tau^+tau^-



Quark channel best fit: u-ubar



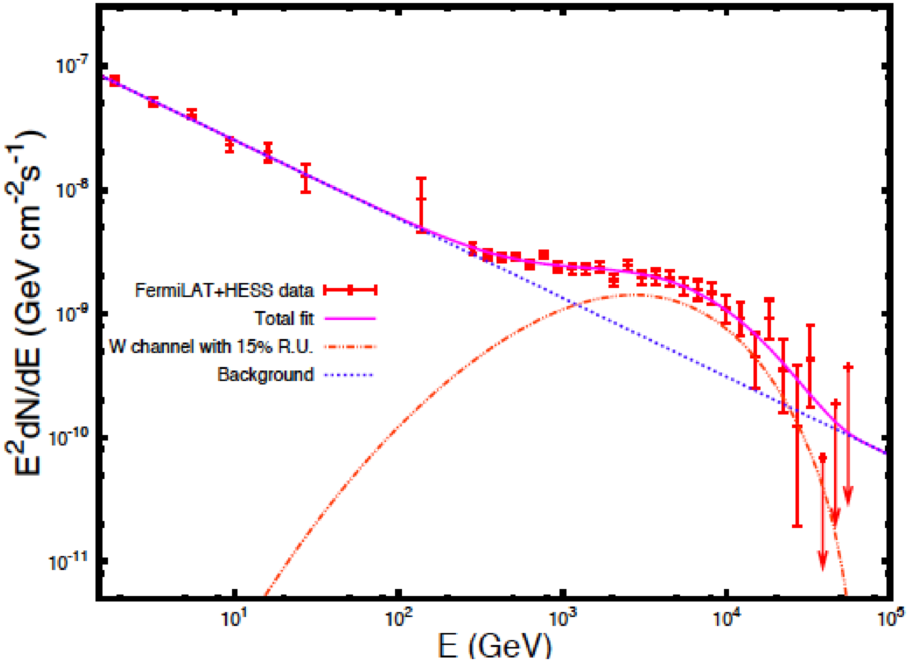
Boson channel best fit: W^+W^-



M_{DM}>10 TeV

J. A. R Cembranos, V. G., A. L. Maroto arXiv [1204.0655v1], PRD 86, 103506 (2012); [arXiv:1302.6871v2][astro-ph.CO], JCAP04 (2013) 051

Gamma Rays from the Galactic Center



M_{DM}>10 TeV

Bg. compatible with Fermi-LAT

(Fermi-LAT Data)	W^+W^-
M	51.7 ± 5.2
A	4.44 ± 0.34
B	3.29 ± 1.03
Γ	2.63 ± 0.02
$\chi^2/\,\mathrm{dof}$	0.75

J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1204.0655v1], PRD 86, 103506 (2012); [arXiv:1302.6871v2][astro-ph.CO], JCAP04 (2013) 051

Neutrinos from the Galactic Center

$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3}\sum_{a=1}^{2}\sum_{i}^{\text{channels}} P_{fp}\cdot\frac{\zeta_i^{(a,\nu_p)}}{a}\frac{dN_i^{(\nu_p)}}{dE}\cdot\frac{\Delta\Omega\,\langle J_{(a)}\rangle_{\Delta\Omega}}{4\pi M^a}$$

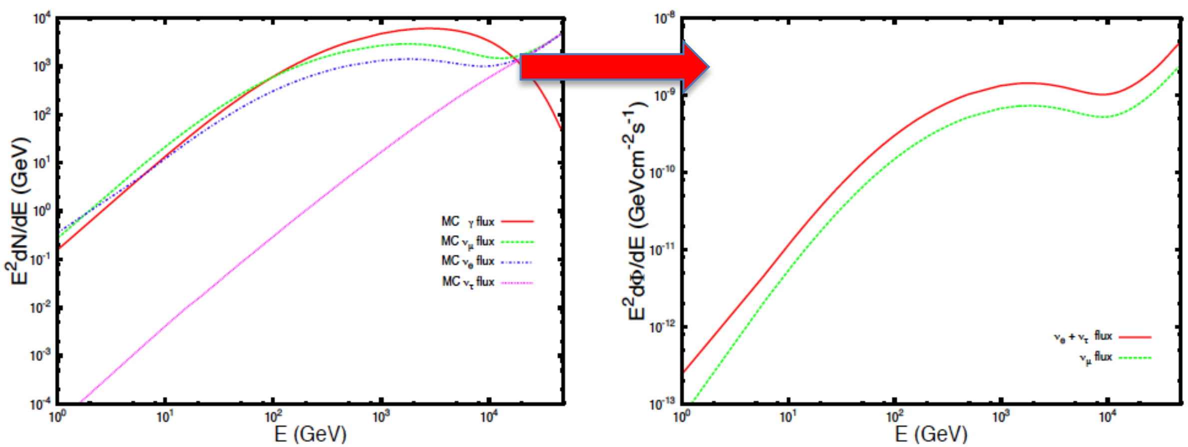
1. W^+W^- boson channel parameters from gamma-rays fit:

$M_{DM} \approx 50$ TeV

Neutrinos flux at the Earth needs to account for:

2. neutrino oscillation

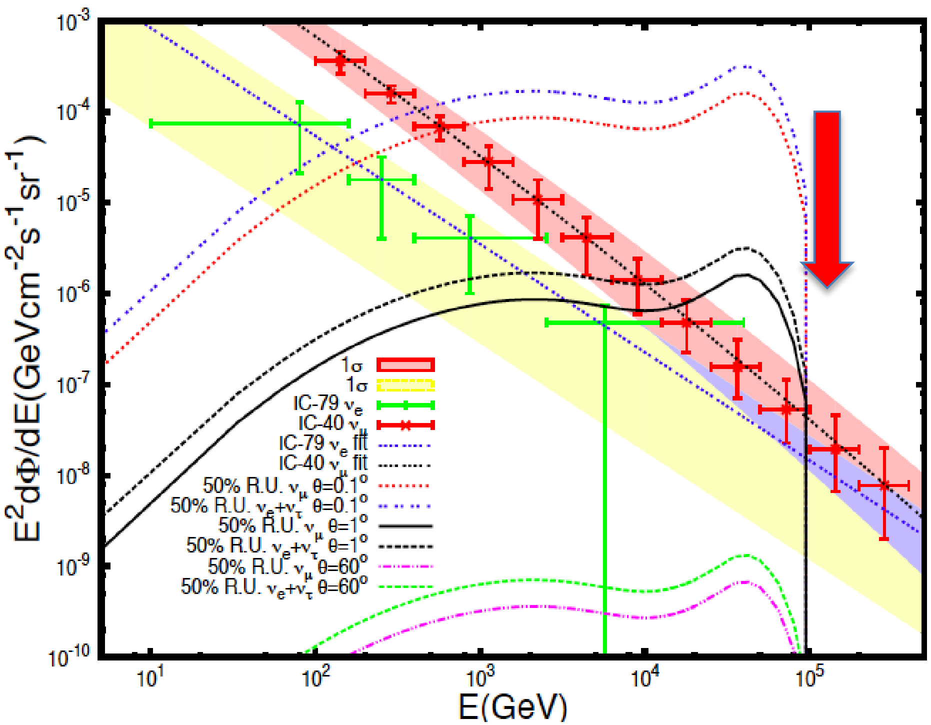
3. detector different (in)sensitivity to neutrinos flavors and antineutrinos



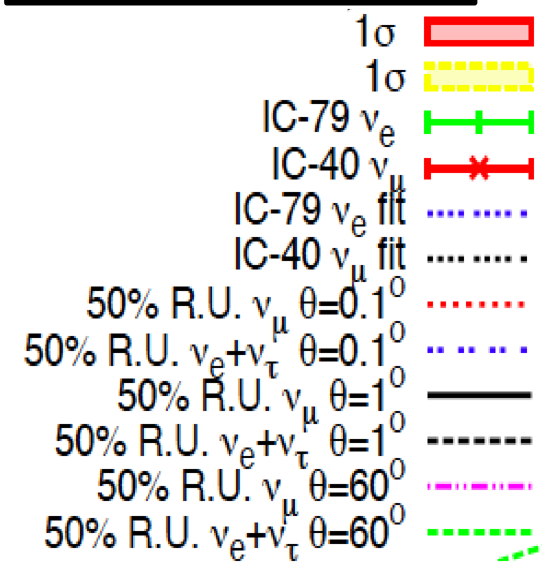
J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1403.6018], PRD; [arXiv:1404.2067]TAUP 2013 Proceedings

Neutrinos from the Galactic Center

$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3}\sum_{a=1}^{2}\sum_{i}^{\text{channels}} P_{fp}\cdot \frac{\zeta_i^{(a,\nu_p)}}{a}\,\frac{dN_i^{(\nu_p)}}{dE}\,\frac{\boxed{\Delta\Omega}\,\langle J_{(a)}\rangle_{\Delta\Omega}}{4\pi M^a}$$



$$\Delta\Omega = 2\pi(1-\cos\theta)$$



Neutrinos from the Galactic Center

Effective Area and Resolution Angle depend on:

- Energy range;
- Neutrino flavor and background;
- Position of the source with respect to the detector (Northern or Southern sky);
- Number of strings in the configuration of observation.

$$\chi_{\nu_i} = \frac{\Phi_{\nu_i}\sqrt{A_{\rm eff}\, t_{\rm exp}\, \Delta\Omega}}{\sqrt{\Phi_{\nu_i} + \Phi_{\nu_i}^{\rm Atm}}} = 5\,(3,\ 2)$$

$$N_{\nu_f}^{t_{exp}} = \int_{E_{\rm min}^{\nu}}^{\infty} dE_\nu\, \frac{d\Phi_{\nu_f}}{dE} \times A_{\rm eff}\, t_{\rm exp}$$

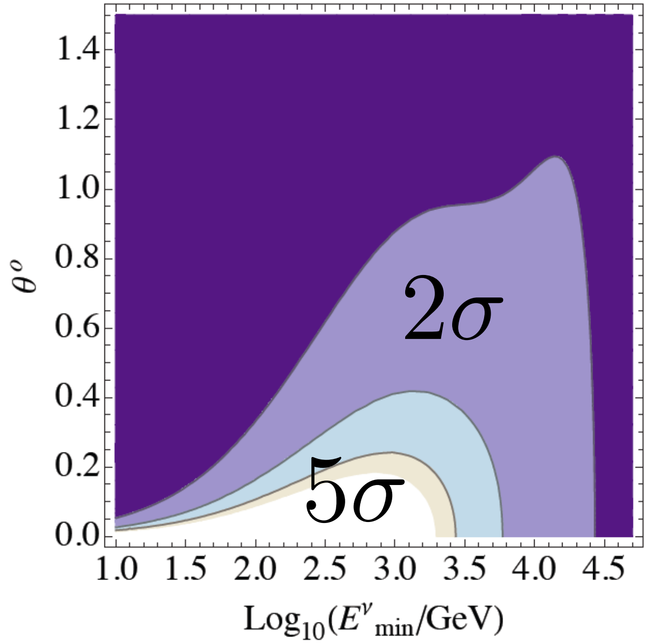
J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1403.6018], PRD; [arXiv:1404.2067]TAUP 2013 Proceedings

Neutrinos from the Galactic Center

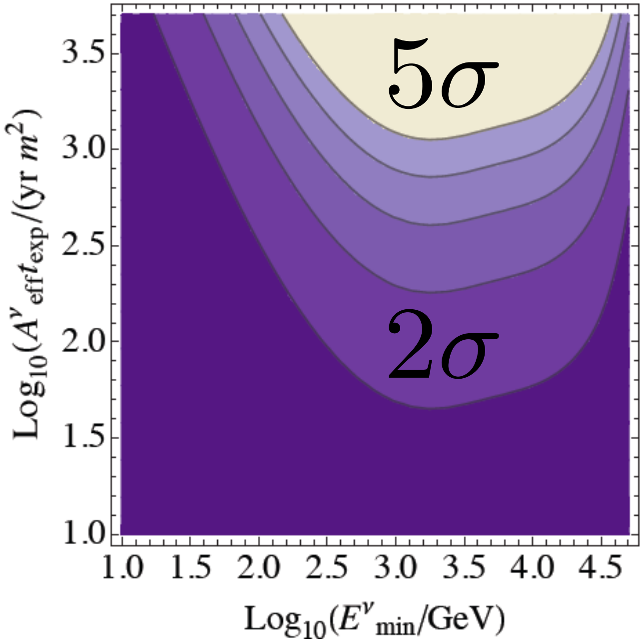
W^+W^- **channel**, with θ = 0.6º, E_{min}≈ 1 TeV and 5 years we need:

A_{eff} ≈ 40 m² to get ≈2σ signal; A_{eff} ≈ 200 m² to get a ≈5σ signal;

$Af = A_{\rm eff} \times t_{\rm exp} = 100\,{\rm m}^2\,{\rm yr}$



$\theta = 0.6°$

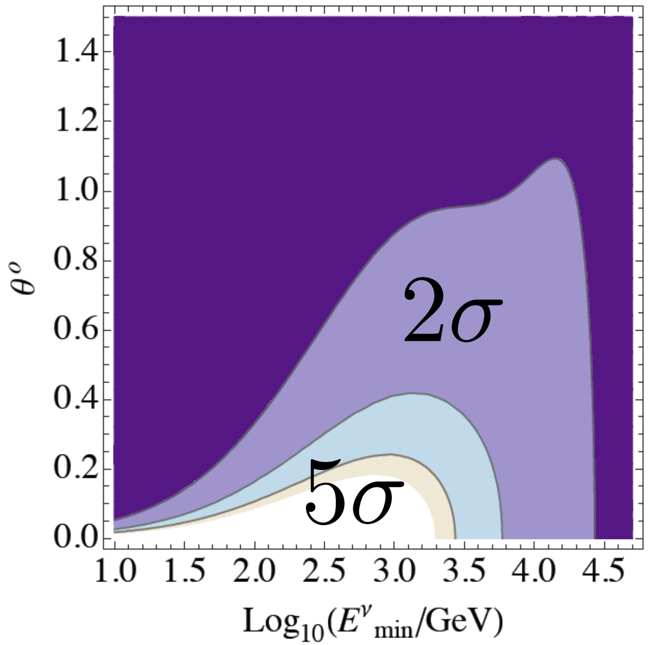


J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1403.6018], PRD; [arXiv:1404.2067]TAUP 2013 Proceedings

Neutrinos from the Galactic Center

W^+W^- **channel**, with $\theta = 0.6^o$, $E_{min} \approx 1$ TeV and 5 years we need:

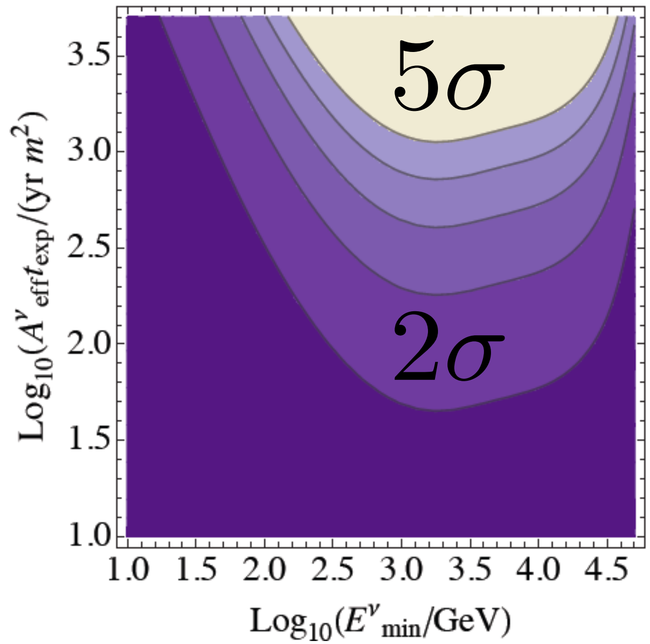
$A_{eff} \approx 40\ m^2$ to get ≈2σ signal; $A_{eff} \approx 200\ m^2$ to get a ≈5σ signal;



<u>Example:</u>

IC-79 ν_μ
Southern Sky at
≈ 30-100 TeV:

$A_{eff} \approx 5\text{-}20\ m^2$
θ ≥ 0.5º;

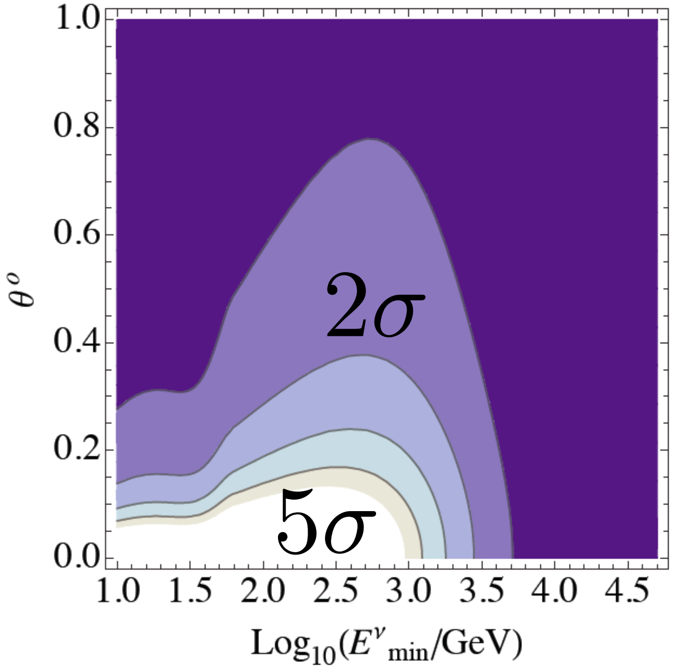


J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1403.6018], PRD; [arXiv:1404.2067]TAUP 2013 Proceedings

Neutrinos from the Galactic Center

uubar channel, with $\theta = 0.6^o$, $E_{min} \approx$ 1 TeV and 5 years we need:

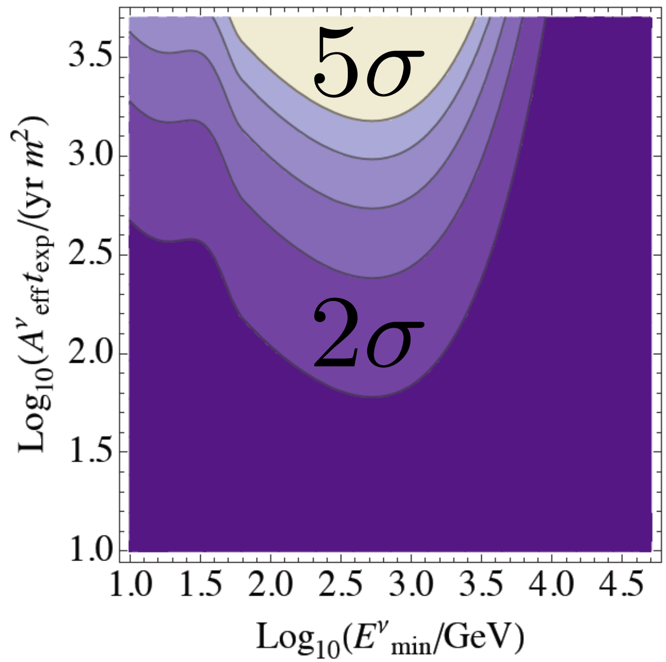
Aeff ≈ 63 m^2 to get ≈2σ signal; Aeff ≈ 400 m^2 to get a ≈5σ signal;



<u>Example:</u>

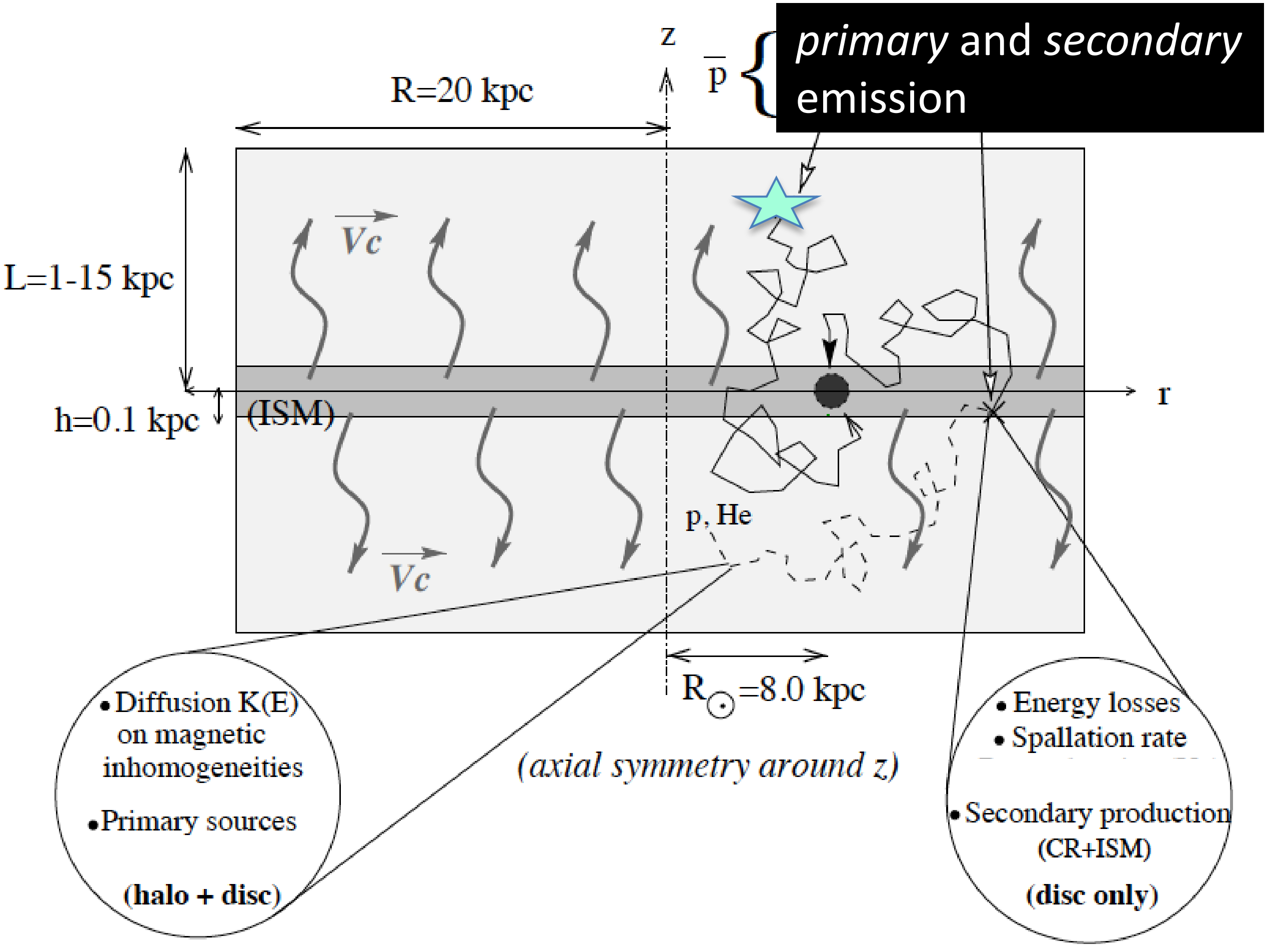
IC-79 ν_μ
Southern Sky at
≈ 30-100 TeV:

$A_{eff} \approx$ 5-20 m^2
$\theta \geq 0.5$º;



J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1403.6018], PRD; [arXiv:1404.2067]TAUP 2013 Proceedings

Antiprotons from the Galactic Center



- V_c convective velocity
- $K(E_{\bar{p}})$ pure diffusion term
- p-$\bar{p}$ annihilations (secondary) and ISM interactions (tertiary)
- $Q(E_{\bar{p}}, x, t)$ is the primary source

A&A 388, 676-687 (2002) Barrau et al. , arXiv:0112486v2

Antiprotons from the Galactic Center

$$\underbrace{\frac{\partial}{\partial t}\frac{dN_{\bar{p}}}{dE_{\bar{p}}}}_{\approx 0} - K(E_{\bar{p}}) \cdot \nabla^2 \frac{dN_{\bar{p}}}{dE_{\bar{p}}} + \frac{\partial}{\partial z}\left(sign(z) \frac{dN_{\bar{p}}}{dE_{\bar{p}}} V_c \right) = \boxed{\hat{Q}} - 2h\delta(z)\Gamma_{inel}\frac{dN_{\bar{p}}}{dE_{\bar{p}}}$$

The anti-proton differential flux at the Top of the Atmosphere (TOA) is the solution of the diffusion equation for steady state condition:

$$\frac{\mathrm{d}\Phi_{\bar{p}}}{\mathrm{d}E_{\bar{p}}} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta^{(a)}}{a} \frac{\mathrm{d}N_i^{(a,\bar{p})}}{\mathrm{d}E_{\bar{p}}} \cdot \frac{v_{\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{M}\right)^a \boxed{R_{(a)}(E_{\bar{p}})}$$

- $R(E_{\bar{p}})$ encodes all the astrophysics of spatial production and propagation ($\Pi(L)$ depends on the DM distribution):

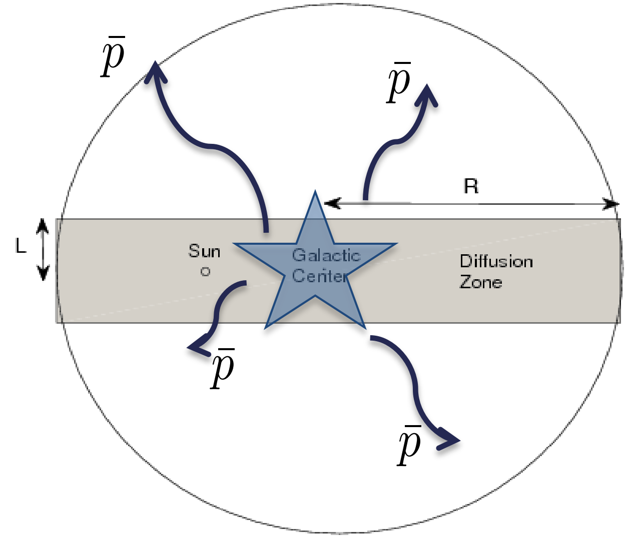
$$R(E_{\bar{p}}) = \sum_{m=1}^{\infty} J_0\left(\zeta_m \frac{r_\odot}{R}\right) \exp\left[-\frac{V_c L}{2K\left(E_{\bar{p}}\right)}\right] \frac{\Pi_m\left(L\right)}{A_m \sinh\left(S_m L/2\right)}$$

Antiprotons from the Galactic Center

The antiprotons spatial production and propagation is described by :

$$R^{\delta}(E_{\bar{p}}) = \frac{2}{R^2}\sum_{m=1}^{\infty}\frac{J_0\left(\zeta_1 \frac{r_\odot}{R}\right)}{A_m J_1^2(\zeta_m)} \times Const$$

$$A_m(E_{\bar{p}}) = 2h\Gamma_{inel} + V_c + K(E_{\bar{p}})\, S_m \coth\left[S_m L/2\right]$$



$$K(E_{\bar{p}}) = K_0 \beta (p/GeV)^{\delta}$$

Model	δ	K_0 [kpc^2/Myr]	V_c [km/s]	L [kpc]
MIN	0.85	0.0016	13.5	1
MED	0.70	0.0112	12	4
MAX	0.46	0.0765	5	15

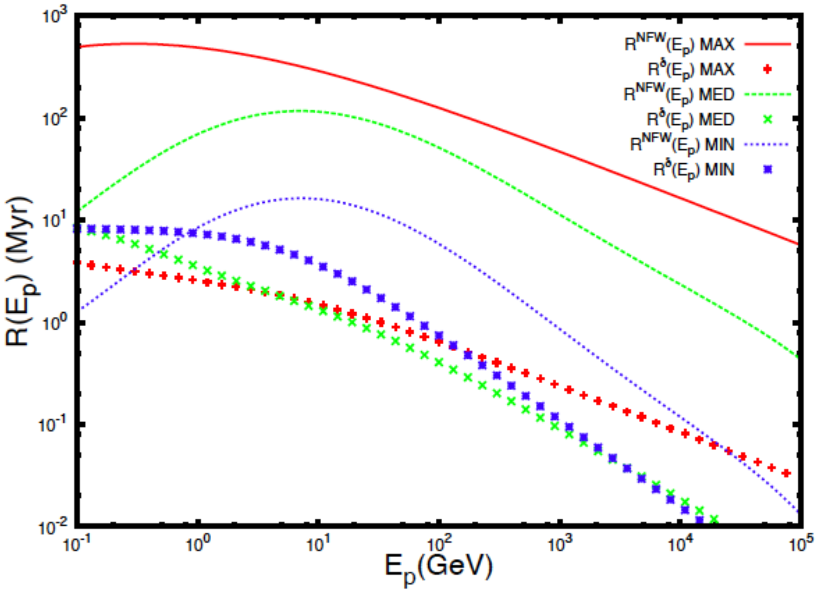
Where the new constant volume needs to be determined.

Antiprotons from the Galactic Center

To determine the new constant, we refer to the astrophysical factor for "not charged" particles:

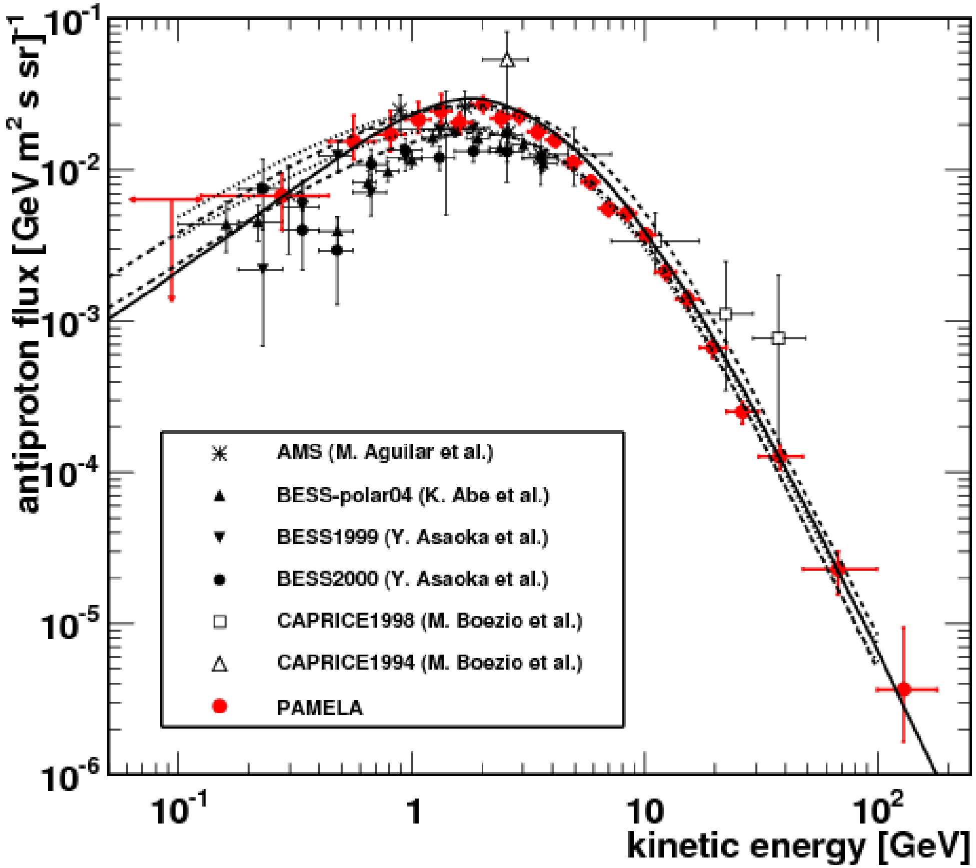
$$\langle J_a \rangle = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \mathrm{d}\Omega \int_0^{l_{max}(\Psi)} \rho^a[r(l)]dl(\Psi)$$

$$\left(\frac{\rho(r,0)}{\rho_\odot}\right)^2 \simeq C_2 \times \delta^{(3)}(\vec{r})$$



$$C_2 = Const \times 2\pi = \langle J \rangle_{\Delta\Omega}^{NFW} \Delta\Omega_{HESS} \left(\frac{D_\odot}{\rho_\odot}\right)^2 \approx \quad 2.13 \times 10^{60} m^3 \mathrm{sr}$$

Pamela Antiproton Data



- Compatible with antiproton *secondary* emission
- Any new primary source needs to be compatible with such antiproton flux.

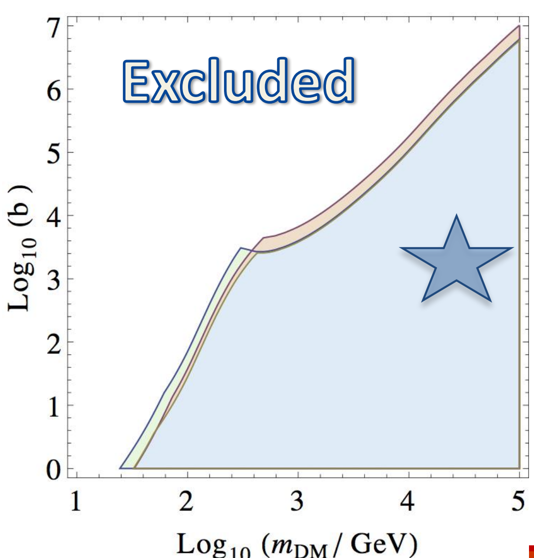
Phys. Rev. Lett. 105, 121101 – Adriani et al. arXiv:1007.0821v1

Antiprotons from the Galactic Center

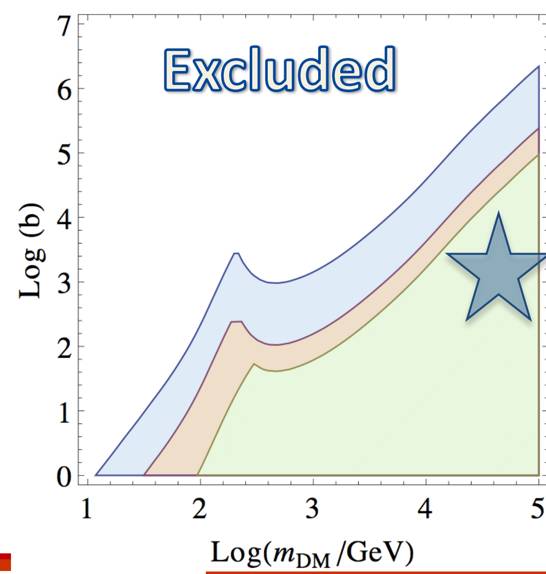
$$\frac{d\Phi_{\bar{p}}}{dE_{\bar{p}}} = \frac{v_{\bar{p}}}{4\pi}\frac{1}{2}\left(\frac{\rho_{\odot}}{m_{DM}}\right)^2 \sum_j \langle\sigma v\rangle_j \frac{dN^j_{\bar{p}}}{dE_{\bar{p}}}\left(b^j_{NFW} \times R^{NFW}(E_{\bar{p}}) + b^j_{\delta} \times C_1 \times R^{\delta}(E_{\bar{p}})\right).$$

MIN MED MAX

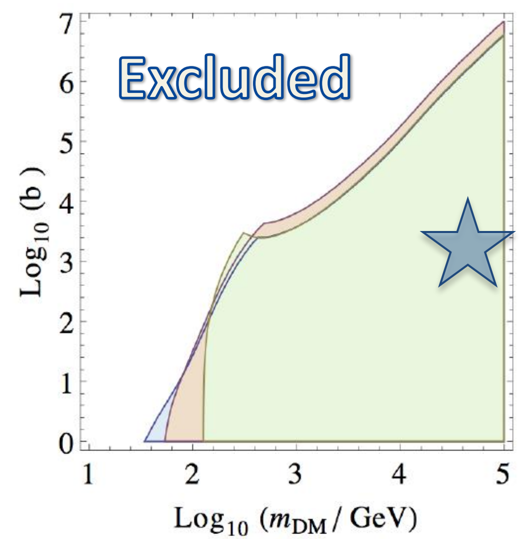
$b^W_{NFW}=0$



$b^W_{\delta}=0$



$b^W_{NFW}=1$



Antiprotons from the Galactic Center

- Gamma-ray HESS data from the J1745-290 point-like source in the GC is well fitted by heavy 50 TeV DM annihilating into W^+W^-

- Fermi-LAT gamma-rays data from the same region are compatible with a power-law background component.

- Actual generation of neutrino experiment is not able to exclude such DM hypothesis mainly due to detector angular resolution.

- PAMELA antiprotons data are compatible with a NFW heavy DM.

Reliability of Monte Carlo generators

- Indirect Dark Matter searches suffer from important uncertainties:

  - DM distribution:

    Baryonic effects

    Central density of DM halos

    Substructures

  - DM particle models:

    Model dependent analyses

    Not very constrained space of parameters.

- Monte Carlo event generators

  - Focus in collider physics

Outline: Monte Carlo Event Generators

- Introduction
- Comparison of Monte Carlo event generators
- Software:
  - PYTHIA 6.418 (Fortran)
  - HERWIG 6.5.10 (Fortran)
  - PYTHIA 8.165 (C++)
  - HERWIG 2.6.1 (C++)
- Conclusions

JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

Motivation

- Gamma-ray spectra do not depend on DM model or DM model except for small particular tuned regions of the parameter space:

- Fitting functions for particle-antiparticle channels.

JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

- Numerical functions for particle-antiparticle channels.

Cirelli et al., JACP 1103 (2011) arXiv :1012.4515

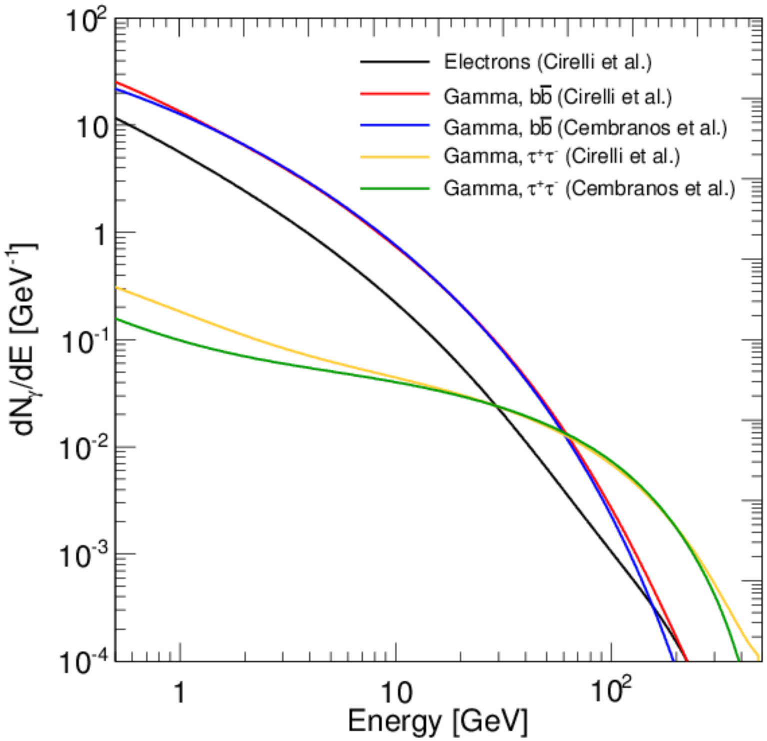
(PYTHIA 8.165 , C++)

Motivation

➤ Comparison

Miguel Angel Sanchez Conde and Mattia Fornasa, private communication (2012).

$$M_{DM} = 500 \text{ GeV}$$



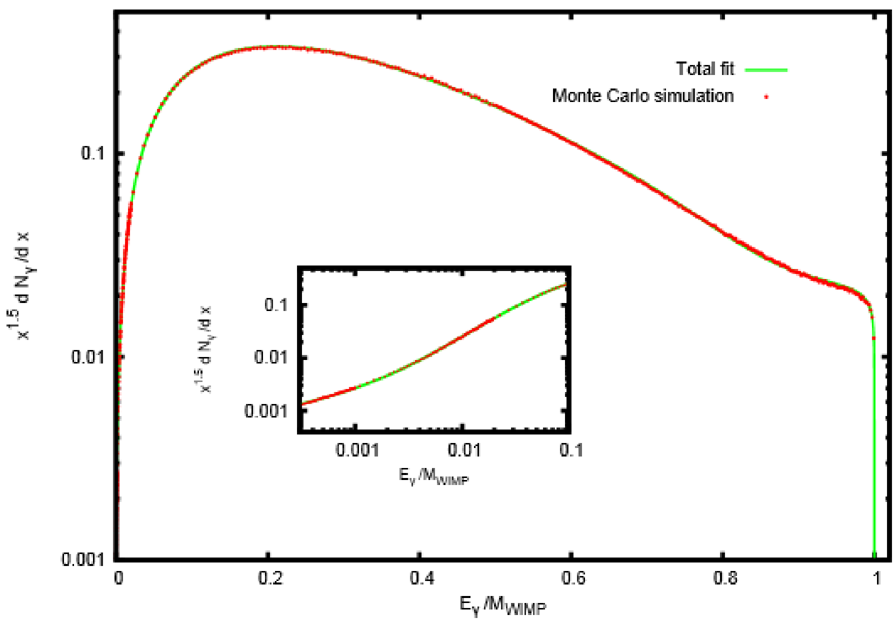
JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

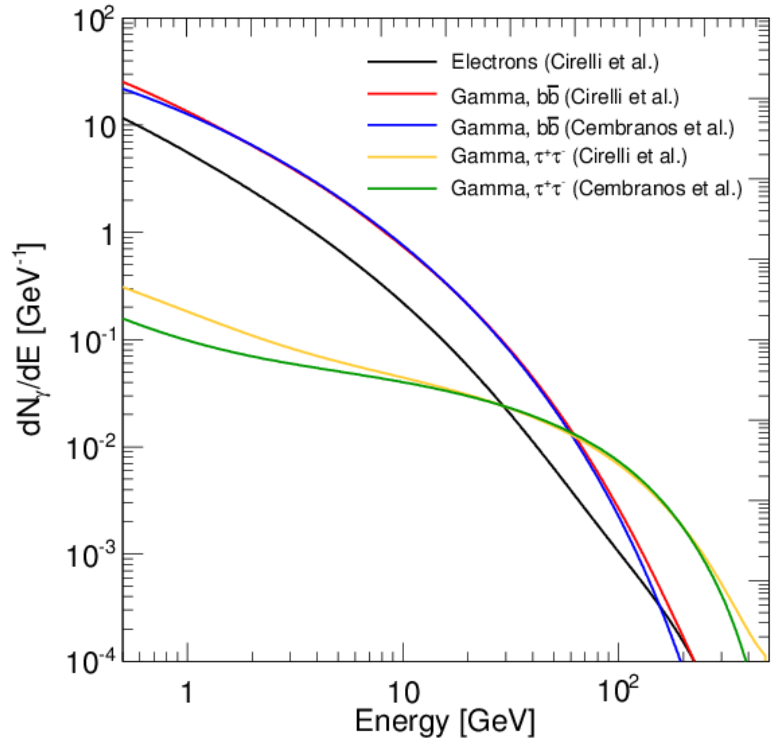
Cirelli et al., JACP 1103 (2011) arXiv :1012.4515

(PYTHIA 8.165 , C++)

Motivation



(c) Photon spectrum for $M = 1000\,\mathrm{GeV}$ for $\tau^+\tau^-$ channel.



JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

Cirelli et al., JACP 1103 (2011) arXiv :1012.4515

(PYTHIA 8.165 , C++)

Comparison analysis

- Comparison of Monte Carlo event generators:
  - PYTHIA 6.418 (Fortran)
  - HERWIG 6.5.10 (Fortran)
  - PYTHIA 8.165 (C++)
  - HERWIG 2.6.1 (C++)

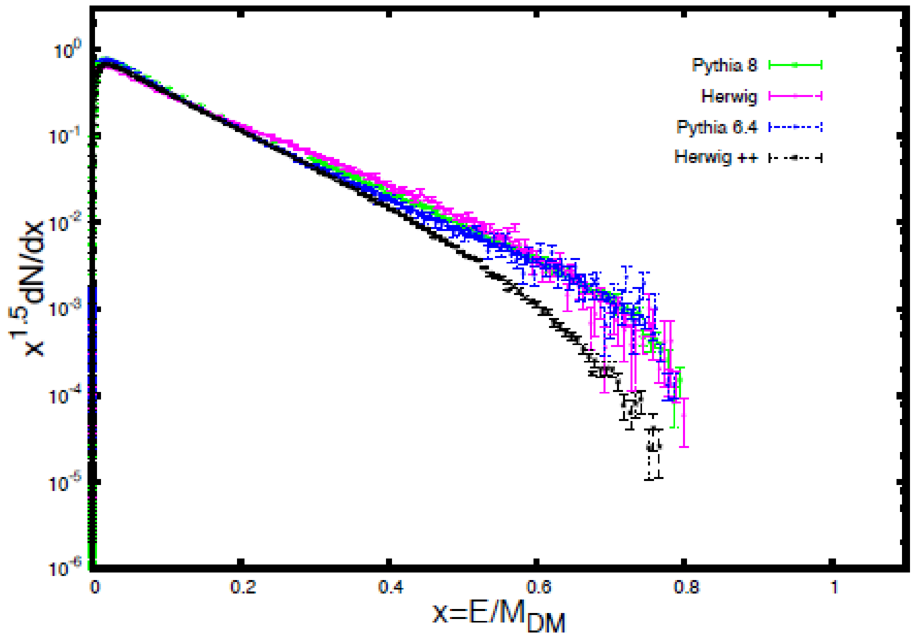
- DM Annihilating/decaying Channels:
  - W^+W^-
  - $\tau^+\tau^-$
  - $b\,\bar{b}$
  - $t\,\bar{t}$

- DM masses: $50\ \mathrm{GeV} < M_{DM} < 10\ \mathrm{TeV}$

JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

W^+W^- channel

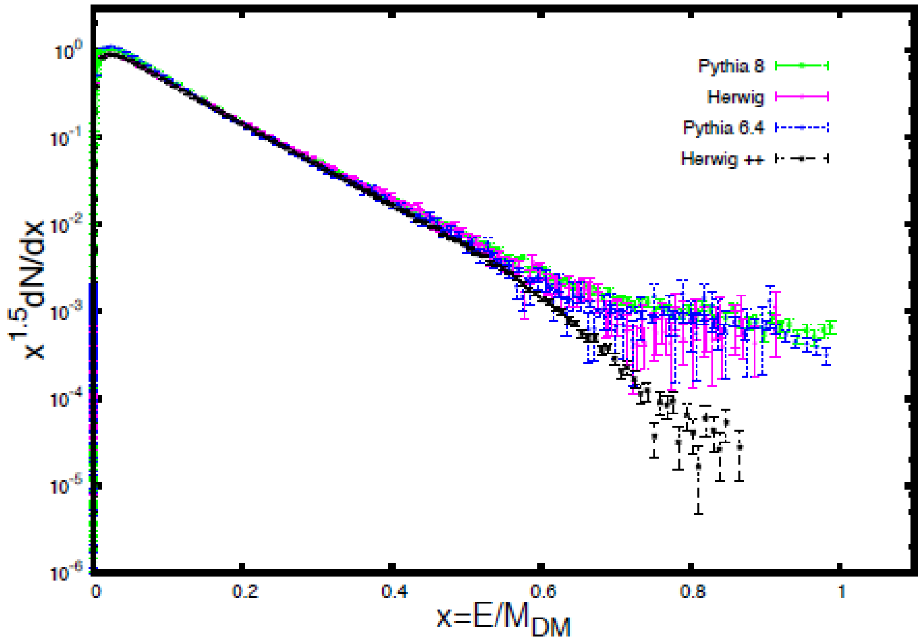
$M_{DM} = 100$ GeV



JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

$b\,\bar{b}$ channel

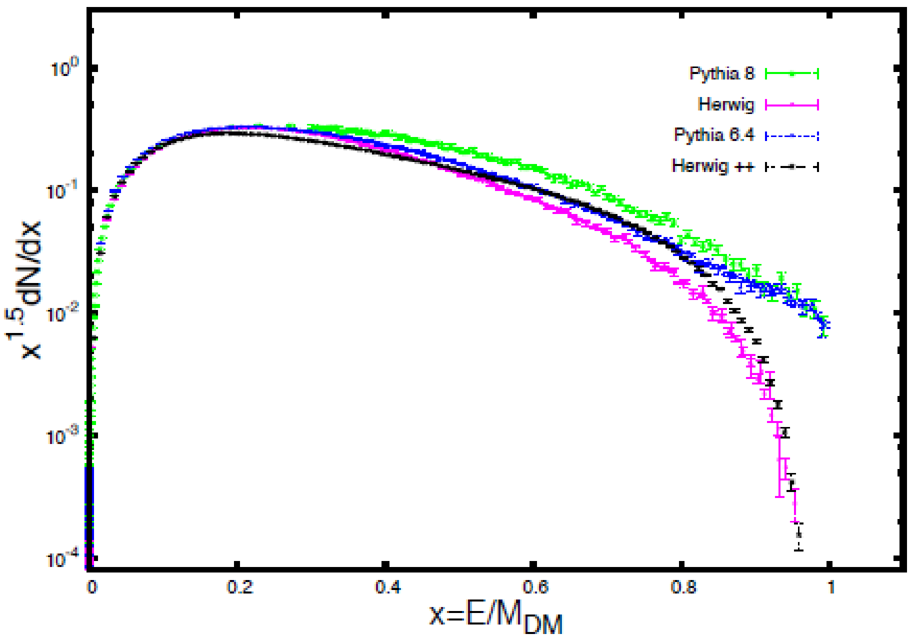
$M_{DM} = 100\ \mathrm{GeV}$



JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

$\tau^+\tau^-$ channel

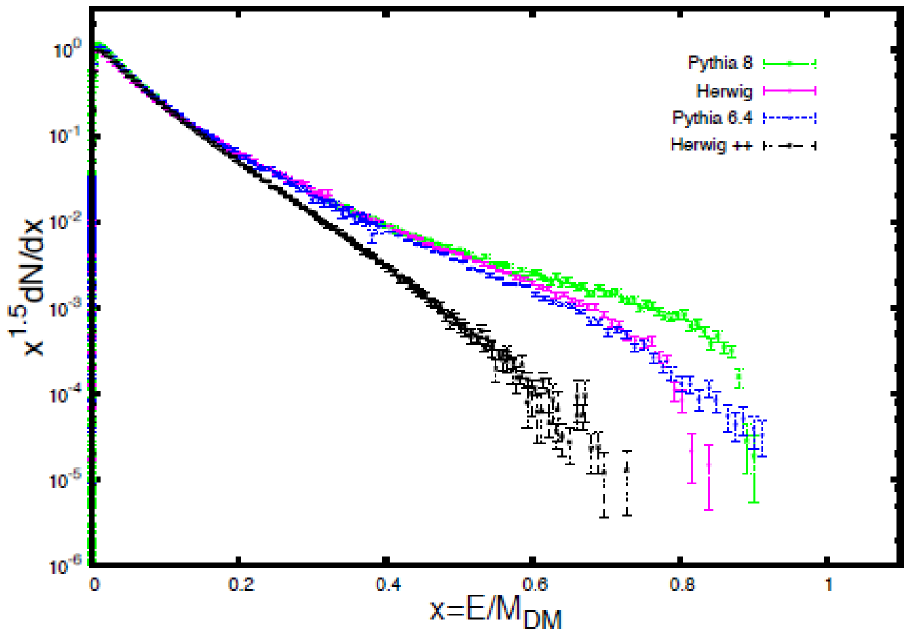
$$M_{DM} = 100 \text{ TeV}$$



JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

$t\,\bar{t}$ channel

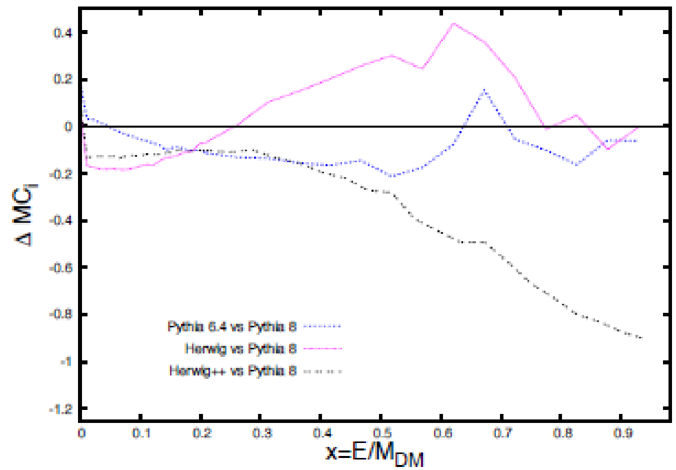
$M_{DM} = 500$ GeV



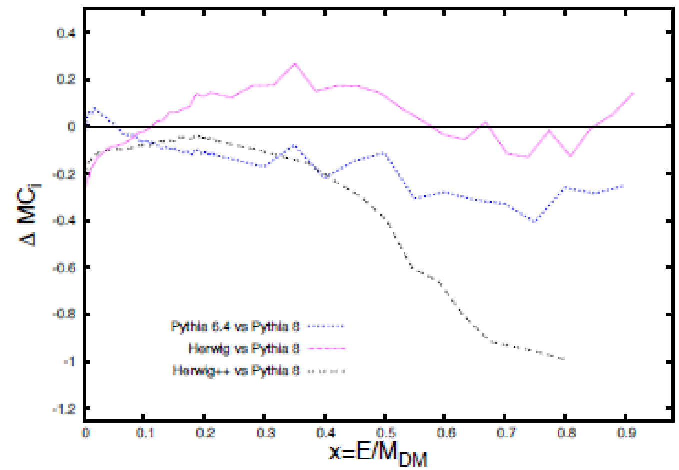
JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

Deviations

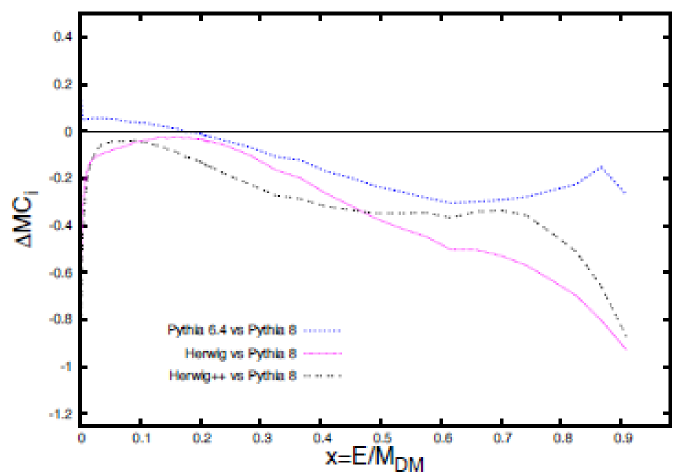
$$\Delta MC_i = \frac{MC_i - \text{PYTHIA 8}}{\text{PYTHIA 8}},$$



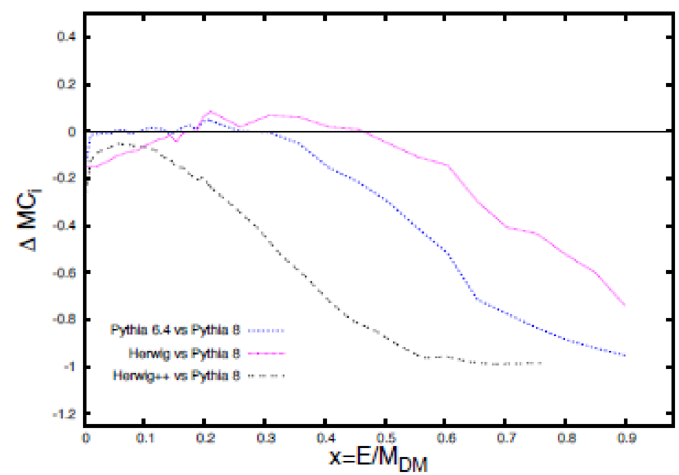
(a) W^+W^- channel



(b) $b\bar{b}$ channel



(c) $\tau^+\tau^-$ channel



(d) $t\bar{t}$ channel

$M_{DM} = 1\ \text{TeV}$

MIA

Photon multiplicities

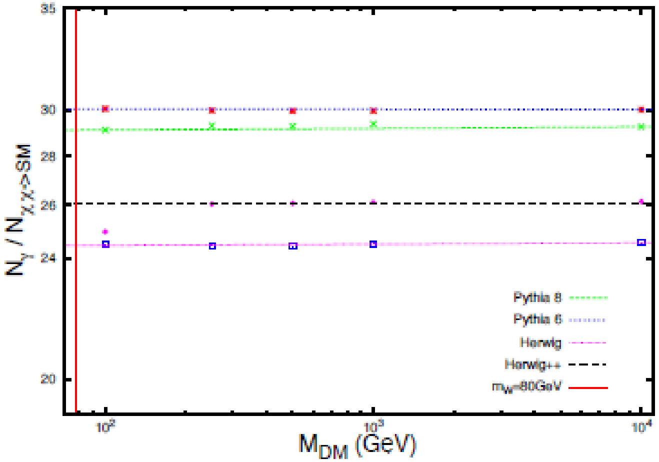
The total amount of photons is well fitted by a power law of the DM mass, *M*:

$$\frac{N_\gamma}{N_{\chi\chi\to SM}} \simeq a \cdot \left(\frac{M}{1\,\mathrm{GeV}}\right)^b ,$$

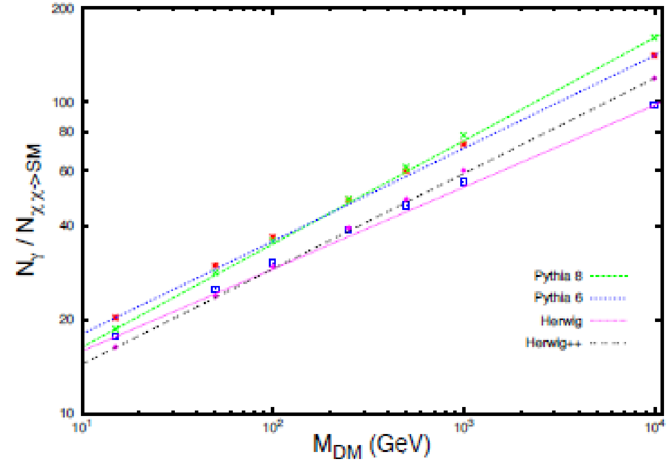
Software/PYTHIA 8	W^+W^-	$b\bar{b}$	$\tau^+\tau^-$	$t\bar{t}$
PYTHIA 6.4	$A = 1.04$ $B = 0$	$A = 1.18$ $B = -0.033$	$A = 0.96$ $B = 0.020$	$A = 1.49$ $B = -0.077$
HERWIG	$A = 0.84$ $B = 0$	$A = 1.13$ $B = -0.068$	$A = 1.00$ $B = -0.029$	$A = 1.02$ $B = -0.038$
HERWIG++	$A = 0.90$ $B = 0$	$A = 0.93$ $B = -0.025$	$A = 0.96$ $B = -0.039$	$A = 0.93$ $B = -0.031$

PYTHIA 8	$a = 28.9$ $b = 0.001$	$a = 7.62$ $b = 0.331$	$a = 2.29$ $b = 0.042$	$a = 14.1$ $b = 0.276$

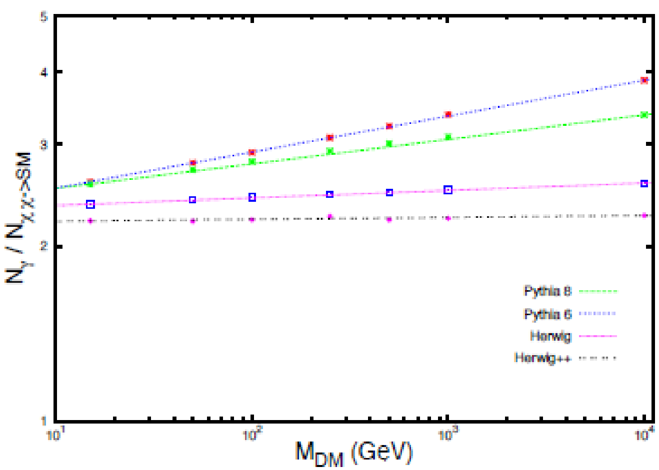
Photon multiplicities



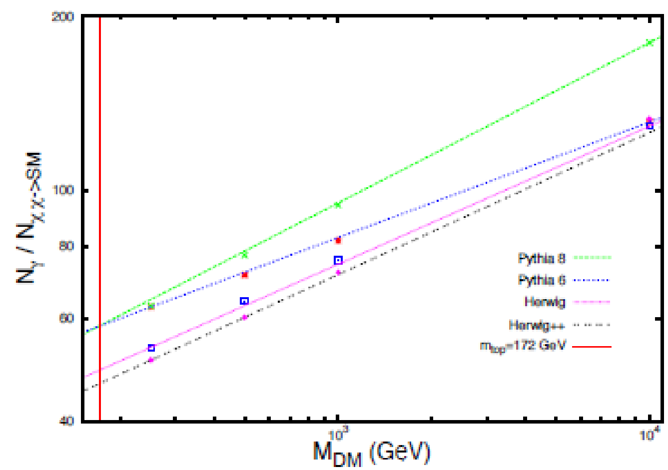
(a) W^+W^- channel.



(b) $b\bar{b}$ channel



(c) $\tau^+\tau^-$ channel



(d) $t\bar{t}$ channel

Conclusions

- Further implementation is needed in HERWIG++.
- For the other Monte Carlo event generators, the gamma-ray spectra simulated show also important differences.
- Relative deviations can only be bounded by 40-50% for hadronic and electro-weak channels.
- Situation is even worse for leptonic and top-antitop channels.
- On the other hand, situation improves a little for the total number of photons.

Maximum differences: factor 2.

JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

Coherent Dark Matter

Santos J. Nuñez Jareño
UCM& Multidark

Publications:

J.A.R. Cembranos, C. Hallabrin, A.L. Maroto, S.J. Núñez Jareño
Phys.Rev. D86 (2012) 021301
J.A.R. Cembranos, A.L. Maroto, S.J. Núñez Jareño
Phys.Rev. D87 (2013) 4, 043523
J.A.R. Cembranos, A.L. Maroto, S. J. Núñez Jareño
JCAP 1403 (2014) 042

Coherent Dark Matter

- Introduction
  - Coherent vector fields in cosmology
- Isotropy theorem for
  - Vector fields
  - General spin
- Conclusions

Coherent vector fields in cosmology

Coherent scalar fields are the standard candidates for solving cosmological unresolved questions as:

- Inflation: Inflaton.
- Dark matter: Axion and axion-like particles.
- Dark energy: quintessence, scalar-tensor theories of gravity,...

Simalar results can be provided by any bosonic field. Vector fields, and new vectors are maybe the best motivated theoretically.

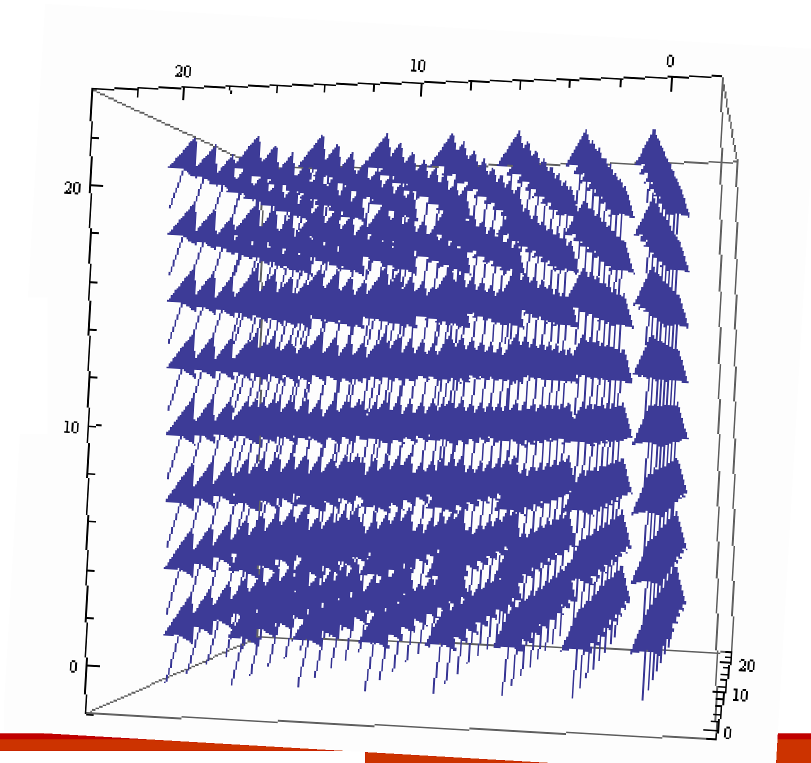
Theoretical frameworks

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

- **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); M. 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).



The anisotropy problem

There are different solutions in the literature:

- Using the scalar degree of freedom $\mathbf{A_0}$.

Beltran Jimenez, Maroto, Phys. Rev. D78, 063005 (2008)

Beltran Jimenez, Maroto, JCAP 0903, 016 (2009)

- **Particular solutions**: Triads of orthogonal vectors.

H.H. Soleng, Astron. Atrophys. 237, 1 (1990)

Bento, Bertolami, Moniz, Mourao, Sa, Class. Quant. Grav. 10, 285 (1993)

- Large number, N, of **randomly oriented fields**. Reducing anisotropy in $\sqrt{N}$.

Golovnev,, Mukhanov, Vanchurin, JCAP 0806, 009 (2008)

- **Average isotropy** for a linear polarized Abelian vector coherent oscillation with potential $A_\mu A^\mu$.

Dimopoulos, Phys. Rev. D 74, 083502 (2006)

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Isotropy theorem for Abelian vector fields

Abelian vector fields described by the action:

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

If the **field evolves rapidly** and $\boldsymbol{A_i}$ **,** $\boldsymbol{\dot{A}_i}$ **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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1.- **The energy momentum tensor is diagonal and isotropic in average.**

Similar argument than for the Virial theorem in classical mechanics:

(for a FLRW background) $\Longrightarrow$

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

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

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

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Abelian vector fields described by the action:

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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.**

2.- **Under power law potentials, the equation of state parameter is constant:**

$$V = \lambda (A_\mu A^\mu)^n \quad \longrightarrow \quad \omega = \frac{\langle p \rangle}{\langle \rho \rangle} = \frac{n-1}{n+1}$$

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

Isotropy theorem for Yang-Mills theories

Yang-Mills theories associated with semi-simple groups described by the action:

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

If the **field evolves rapidly** and $\boldsymbol{A^a{}_i}$ **,** $\boldsymbol{\dot{A}^a{}_i}$ **are bounded** during its evolution,

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

2.- **Without potential, the equation of state parameter is w = 1/3 , i.e. it behaves as radiation.**

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

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.

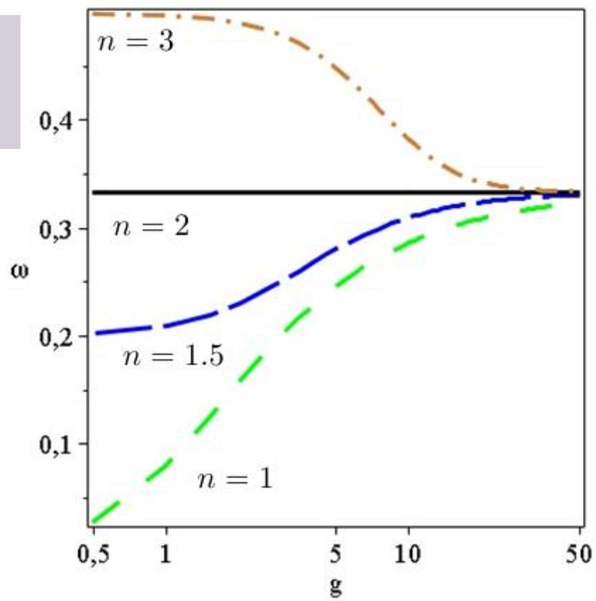
$$V = \frac{1}{2}(-M^2 A^a_\rho A^{a\,\rho})^n$$

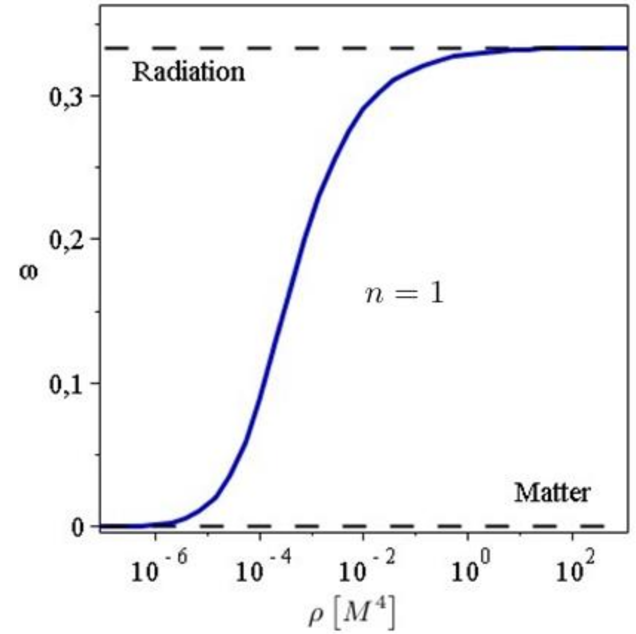
$g\downarrow,\ \rho\downarrow$

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

$g\uparrow,\ \rho\uparrow$

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





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

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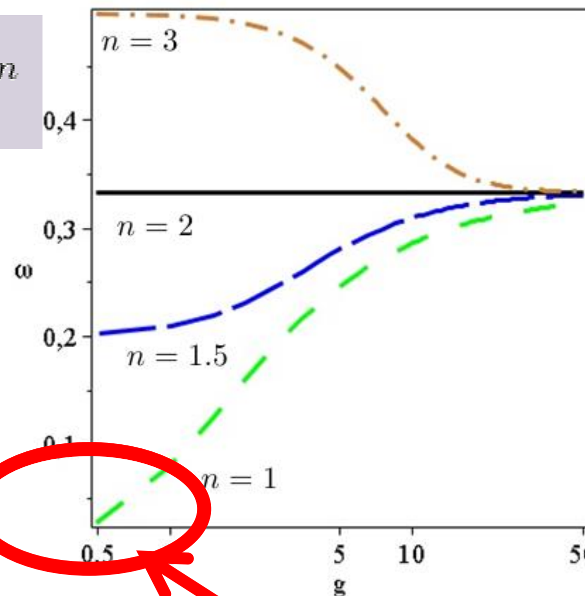
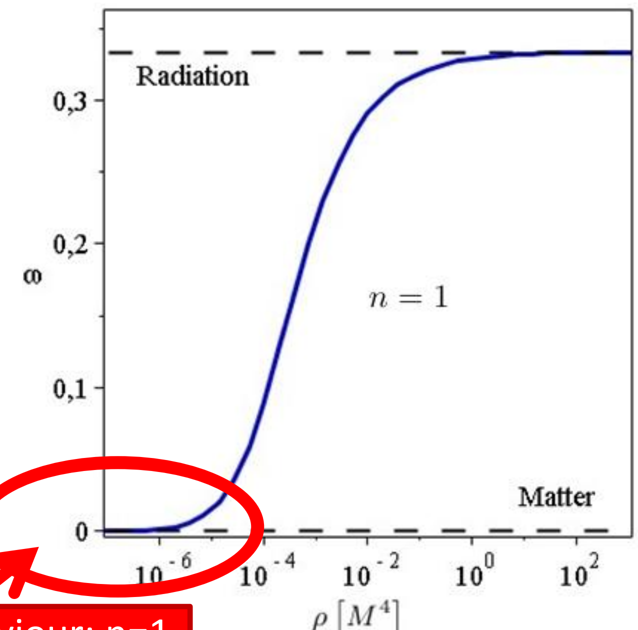




DARK MATTER behaviour: n=1

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

Gauge fixing term

The previous results can be extended to actions completed with the gauge fixing term:

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\ \mu\nu} + \frac{\xi}{2}(\nabla_\rho A^{a\ \rho})^2 - V(M_{ab}A^a_\rho A^{b\rho})$$

The result is the same, if the **field evolves rapidly** and $A^a{}_i$, $\dot{A}^a{}_i$ **are bounded** during its evolution,

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

2.- **Without potential, the equation of state parameter is w = 1/3 , i.e. it behaves as radiation.**

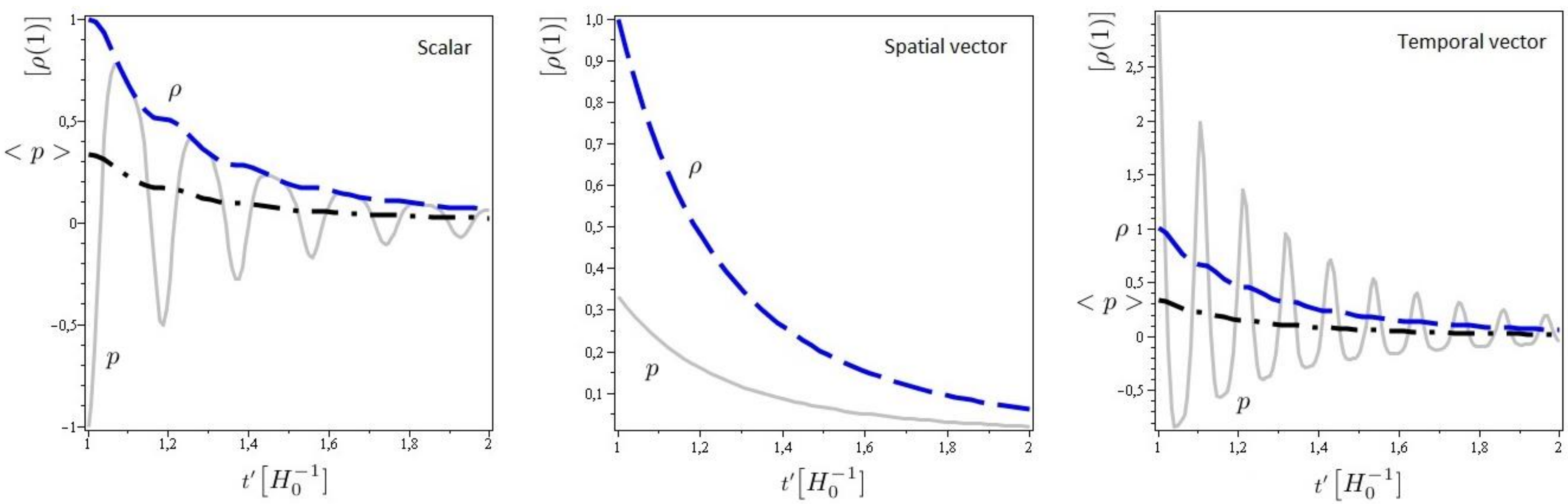
JARC, Maroto, Nunez Jareno, Phys. Rev. D87 (2013) 043523

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

Belinfante-Rosenfeld EMT

In order to obtain the spin independent result, let us briefly review the Belinfante-Rosenfeld approach in Minkowski space-time. Consider a Lagrangian density,

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

Under an infinitesimal translation $x^\mu \rightarrow x^\mu + \delta a^\mu(x)$

$$0 = \delta \int d^4x \mathcal{L} = -\int d^4x \; \delta a_\nu \partial_\mu \Theta^{\mu\nu} \longrightarrow \partial_\mu \Theta^{\mu\nu} = 0$$

Which is nothing but the Noether current associated to the symmetry under space-time translations, **the canonical energy-momentum tensor**,

$$\boxed{\Theta^{\mu\nu} = -\eta^{\mu\nu}\mathcal{L} + \frac{\partial \mathcal{L}}{\partial\left(\partial_\mu \phi^A\right)}\partial^\nu \phi^A}$$

Belinfante-Rosenfeld EMT

$$\boxed{\Theta^{\mu\nu} = -\eta^{\mu\nu}\mathcal{L} + \frac{\partial \mathcal{L}}{\partial\left(\partial_\mu \phi^A\right)}\partial^\nu \phi^A}$$

This tensor is no unique, we can always add a new piece with the form

$$\partial_\rho \tilde{\Theta}^{\rho\mu\nu}$$

antisymmetric in the first two indices. We are interested in a symmetric energy-momentum tensor, the required to appear in the right-side of Einstein equations,

$$\boxed{T^{\mu\nu} = \Theta^{\mu\nu} - \frac{1}{2}\partial_\rho\left(S^{\rho\mu\nu} + S^{\mu\nu\rho} - S^{\nu\rho\mu}\right)}$$

where $S^{\mu\nu\rho} = \Pi^\mu_A \Sigma^{\nu\rho}\phi^A$, with $\Sigma^{\nu\rho}$ the antisymmetric Lorentz group generator and $\Pi^\mu_A = \dfrac{\partial \mathcal{L}}{\partial\left(\partial_\mu \phi^A\right)}$ the generalized momentum associated with ϕ^A

Isotropy theorem in a FLRW background

The Belinfante-Rosenfeld energy-momentum tensor can be written in a curved space-time in a straightforward way by using minimal coupling, simply changing ordinary derivatives by covariant ones

$$\boxed{T^{\mu\nu} = \Theta^{\mu\nu} + \nabla_\rho \tilde{\Theta}^{\rho\mu\nu} = \Theta^{\mu\nu} - \frac{1}{2}\nabla_\rho \left(S^{\rho\mu\nu} + S^{\mu\nu\rho} - S^{\nu\rho\mu}\right)}$$

As a firts step, let us consider a Friedmann-Lemaître-Robertson-Walker metric and a homogeneous field. The responsible of the anisotropies is the non-canonical piece of the EMT.

$$\nabla_\rho \tilde{\Theta}^{\rho\mu\nu} = \partial_0 \tilde{\Theta}^{0\mu\nu} + \left(\Gamma^\rho_{\delta\rho}\tilde{\Theta}^{\delta\mu\nu} + \Gamma^\mu_{\delta\rho}\tilde{\Theta}^{\rho\delta\nu} + \Gamma^\nu_{\delta\rho}\tilde{\Theta}^{\rho\mu\delta}\right)$$

If the field oscillates with a frequency much higher than the expansion rate, we can neglect the scale factor derivatives.

Isotropy theorem in a FLRW background

Thus, if we average over periods $\omega^{-1} \gg \mathcal{T} \gg H$

$$\left\langle \nabla_\rho \tilde{\Theta}^{\rho\mu\nu} \right\rangle = \frac{1}{\mathcal{T}} \int_t^{t+\mathcal{T}} dt' \partial_0 \tilde{\Theta}^{0\mu\nu}(t') = \frac{\tilde{\Theta}^{0\mu\nu}(t+\mathcal{T}) - \tilde{\Theta}^{0\mu\nu}(t)}{\mathcal{T}}$$

$$\frac{\left\langle \nabla_\rho \tilde{\Theta}^{\rho\mu\nu} \right\rangle}{\langle T^{00} \rangle} \sim \mathcal{O}\left(\frac{\omega^{-1}}{\mathcal{T}} \right)$$

For sufficiently large $\mathcal{T}$, if the field and its conjugate momentum are bounded, this term vanishes.

The average energy momentum can be written as

$$\langle T^{00} \rangle = \langle \Pi^0_A \partial_0 \phi^A - \mathcal{L} \rangle \qquad \langle T^{jj} \rangle = \langle -g^{jj} \mathcal{L} \rangle$$

$$\langle T^{0j} \rangle = T^{0j} = 0 \qquad \langle T^{jk} \rangle = 0 \,;\, k \neq j$$

Isotropy theorem in a FLRW background

Moreover, using these results we can also express the average equation of state in this suggestive form

$$\boxed{\omega = \frac{\langle p \rangle}{\langle \rho \rangle} = \frac{\langle \mathcal{L} \rangle}{\langle \Pi^0_A \partial_0 \phi^A - \mathcal{L} \rangle} = \frac{\langle \mathcal{L} \rangle}{\langle \mathcal{H} \rangle}}$$

For theories with the form $\mathcal{H} = \left(\lambda^{AB} g_{00} \Pi^0_A \Pi^0_B\right)^{n_T} + \left(M_{AB}\phi^A \phi^B\right)^{n_V}$

$$\langle \partial_0 \left(\Pi^0_A \phi^A\right) \rangle = 0$$

$$\langle T \rangle = \frac{n_V}{n_T} \langle V \rangle$$

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

$$n_T = 1$$

$$\boxed{\omega = \frac{n_V - 1}{n_V + 1}}$$

Spin 2: Fierz-Pauli Lagrangian

As an example we will apply the previous results to the Fierz-Pauli theory of massive gravity on a curve space-time background given by the Lagrangian:

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

The momentum results,

$$\Pi^0_{\mu\nu} = \frac{M_{Pl}^2}{4}\Big[\nabla^0 h_{\mu\nu} - 2\delta^0_{(\mu}\nabla_\alpha h^\alpha_{\nu)} + \delta^0_{(\mu}\nabla_{\nu)} h^\alpha_\alpha + g_{\mu\nu}\nabla_\alpha h^{\alpha 0} - g_{\mu\nu}\nabla^0 h^\alpha_\alpha\Big]$$

Spin 2: Fierz-Pauli Lagrangian

Using the virial equation,

$$\left\langle \Pi^0_{\mu\nu} \frac{\partial \mathcal{H}}{\partial \Pi^0_{\mu\nu}} + \frac{\partial \mathcal{L}}{\partial h^{\mu\nu}}\, h^{\mu\nu} \right\rangle = \left\langle \Pi^0_{\mu\nu} \nabla_0 h^{\mu\nu} + \frac{\partial \mathcal{L}}{\partial h^{\mu\nu}}\, h^{\mu\nu} \right\rangle = \langle 2T - 2V \rangle = 0$$

And, thus

$$\boxed{\omega = \frac{\langle \mathcal{L} \rangle}{\langle \mathcal{H} \rangle} = \frac{\langle T - V \rangle}{\langle T + V \rangle} = 0}$$

Isotropy theorem in a general background

Let us extend this result to a more general space-time geometry by considering an inertial observer located at the origin and write the metic around it using Riemann normal coordinates:

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + \frac{1}{3} R_{\mu\alpha\nu\beta} x^\alpha x^\beta + \dots$$

If the following conditions hold,

1. The Lagrangian depends only on the fields and their gradients.
2. The field evolves rapidly, $|R^\gamma_{\lambda\mu\nu}| \ll (\omega_A)^2$, and $|\partial_j S^{\mu\nu\rho}| \ll |\partial_0 S^{\mu\nu\rho}|$, for $j = 1, 2, 3$;
3. ϕ^A and Π^0_A, remains bounded in the evolution.

The energy-momentum tensor takes in average the perfect fluid form for any locally inertial observer.

Conclusions

- We have obtain the average EMT of a homogeneous spin-arbitrary field in a FRWL universe. It results isotropic and diagonal if the fields are bounded and oscillate rapidly.
- As a matter of fact, by using the virial theorem a sugestive expression for the behaviour of the equation of state was given, as well as a simplification for power-law hamiltonians.
- To illustrate this, we shown a spin 2 Fierz-Pauli theory.
- Finally, the isotropy theorem for arbitrary-spin cosmological fields under a general background metric was enounced.

Perturbations

Scalar	$\Psi_k \sim$ constant $\varpi = 0$ $\delta\rho \sim a^{-3}$ $C_{eff}^2 = 0 + O(\varepsilon_m)$		$\Psi_k \sim$ constant $\varpi = 0$ $\delta\rho \sim a^{-3}$ $C_{eff}^2 = 0 + O(\varepsilon_m)$	$\Psi_k \sim$ decay & oscillate $\varpi = 0$ $\delta\rho \sim$ decay & oscillate $C_{eff}^2 = k^2/4\, m^2 a^2$	**Cut-off**
Vector	$\Psi_k \sim$ constant $\varpi = 1$ $\delta\rho \sim O(H^2 \varepsilon_m A \delta A)$ $C_{eff}^2 = 0 + O(\varepsilon_m)$	$\Psi_k \sim$ constant $\varpi = 0 + O(\varepsilon_m)$ $\delta\rho \sim a^{-3}$ $C_{eff}^2 = 0 + O(\varepsilon_m)$	$\Psi_k \sim$ constant $\varpi = 0 + O(\varepsilon_k)$ $\delta\rho \sim a^{-2}$ $C_{eff}^2 = 0 + O(\varepsilon_m)$	$\Psi_k \sim$ decay & oscillate $\varpi = 0 + O(\varepsilon_m/\varepsilon_k)$ $\delta\rho \sim$ decay & oscillate $C_{eff}^2 = O(\varepsilon_k\, \varepsilon_m)$	**Cut-off**
k^2	0 — $H^3/m\,a$	$H^3/m\,a$ — H^2	H^2 — $H\,m\,a$	$H\,m\,a$ — $m^2 a^2$	$m^2 a^2$ →

Preliminary results

Vacuum dark matter

Franco D. Albareti
UAM& Multidark

Publications:

F.D. Albareti , J.A.R. Cembranos, A.L. Maroto
Phys.Rev. D90 (2014) 12, 123509
F.D. Albareti , J.A.R. Cembranos, A.L. Maroto
Int. J. Mod. Phys. D (2014) 1442019

Vacuum dark matter

- **Vacuum energy as dark matter**
  - **Introduction**
  - **Renormalization schemes**
  - **Scalar field in flat RW backgrounds**
  - **The speed of sound of vacuum energy**

Objective

- ***Compute*** **the vacuum energy-momentum tensor in a de Sitter spacetime (renormlization scheme)**
- ***Analyze*** **its UV and IR behavior in terms of the equation of state parameter w : dust, radiation, cosmological constant…**
- ***Extend*** **interesting results to arbitrary flat RW geometries**

F.D. Albareti, J. A. R. Cembranos and A.L. Maroto,
arXiv:**1404.5946** [gr-qc] **Phys.Rev. D90 (2014) 12, 123509**;
and Int. J. Mod. Phys. D (2014) 1442019

Introduction

Quantum vacuum

- **QCD vacuum: Non-vanishing of gluon and quark condensates**
- **EW vacuum: Non-vanishing expectation value of the Higgs field.**
- **Vacuum energy**

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Regularization and renormalization

Flat space-time

Introduction

Quantum vacuum

Regularization and renormalization

Flat space-time	Curved space-time
↓	↓
Constant parameters	Non-trivial space-time dependence
↓	↓
Fixed experimentally	Constrained by observations

Renormalization schemes

- **Energy-momentum tensor (of a *massive scalar field*)**

$$\langle 0|T_{\mu\nu}|0\rangle_{\rm ren} = \langle 0|T_{\mu\nu}|0\rangle_{\rm bare} + \langle 0|T_{\mu\nu}|0\rangle_{\rm count}$$

- **Minimal requirements**
  - **Covariant and conserved** $\langle 0|T_{\mu\nu}|0\rangle_{\rm ren}$
  - $\rho_{\rm ren} \lesssim \rho_c$ **critical density**
- **Different ways**
  - **Three momentum cutoff**
  - **Dimensional regularization**

Comoving three momentum cutoff

- **Symmetries OK in flat RW geometries.**
- **Covariant scheme**
- **Energy-momentum tensor is conserved**
- **Limit on the frequency modes for the vacuum energy (*not the range of validity of the theory*)**

S.D.H. Hsu, Phys. Lett. B **594** (2004) 13;
M. Li, Phys. Lett. B **603** (2004) 1.

Scalar field in flat RW geometries

$$ds^2 = a^2(\eta)(\mathrm{d}\eta^2 - \mathrm{d}\mathbf{x}^2)$$

- **Expand in plane waves**

$$\phi(\mathbf{x},\eta) = \int \mathrm{d}^3\mathbf{k}\, \left(a_{\mathbf{k}}\, \phi_k(\eta)\, e^{i\,\mathbf{k}\,\mathbf{x}} + a^\dagger_{\mathbf{k}}\, \phi^*_k(\eta)\, e^{-i\,\mathbf{k}\,\mathbf{x}}\right)$$

- **Solve the KG equation for the temporal modes**

$$\Box\,\phi + m^2\,\phi = 0$$

- **Quantize**

$$[a_{\mathbf{p}}, a^\dagger_{\mathbf{q}}] = \delta^{(3)}(\mathbf{p} - \mathbf{q})$$

Scalar field in flat RW geometries

$$ds^2 = a^2(\eta)(d\eta^2 - d\mathbf{x}^2)$$

- **Compute the energy-momentum tensor**
- **Renormalize**

$$\rho_{\text{ren}} = \frac{2\pi}{a^2}\int_0^{\boxed{\Lambda_R}} dk\, k^2 \left(|\phi_k'|^2 + k^2|\phi_k|^2 + m^2a^2|\phi_k|^2\right)$$

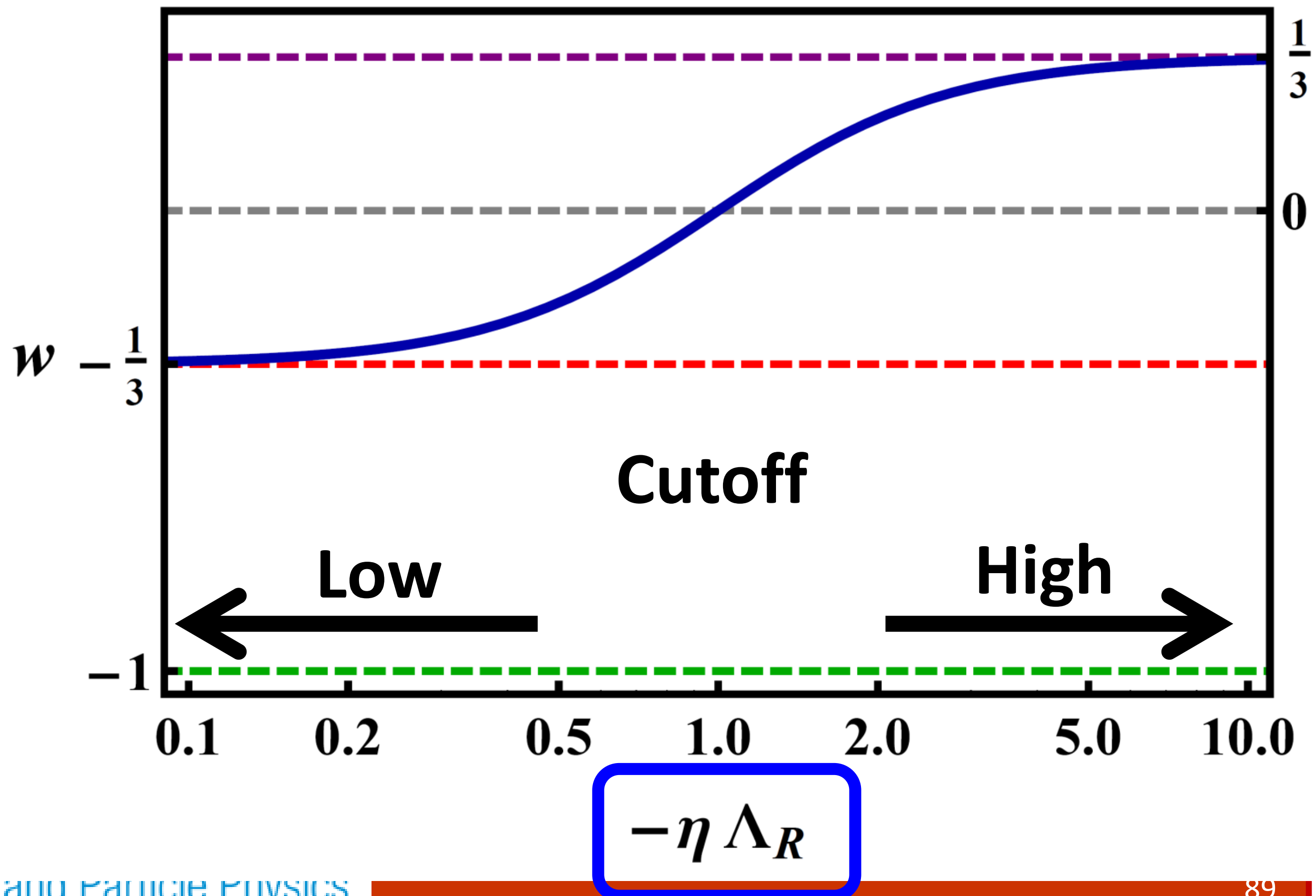
$$p_{\text{ren}} = \frac{2\pi}{a^2}\int_0^{\boxed{\Lambda_R}} dk\, k^2 \left(|\phi_k'|^2 - \frac{k^2}{3}|\phi_k|^2 - m^2a^2|\phi_k|^2\right)$$

De Sitter background

- **Exact analytical results**

  (Bessel functions)

- **Massless**



Scalar field in flat RW geometries

- **Exact analytical results**

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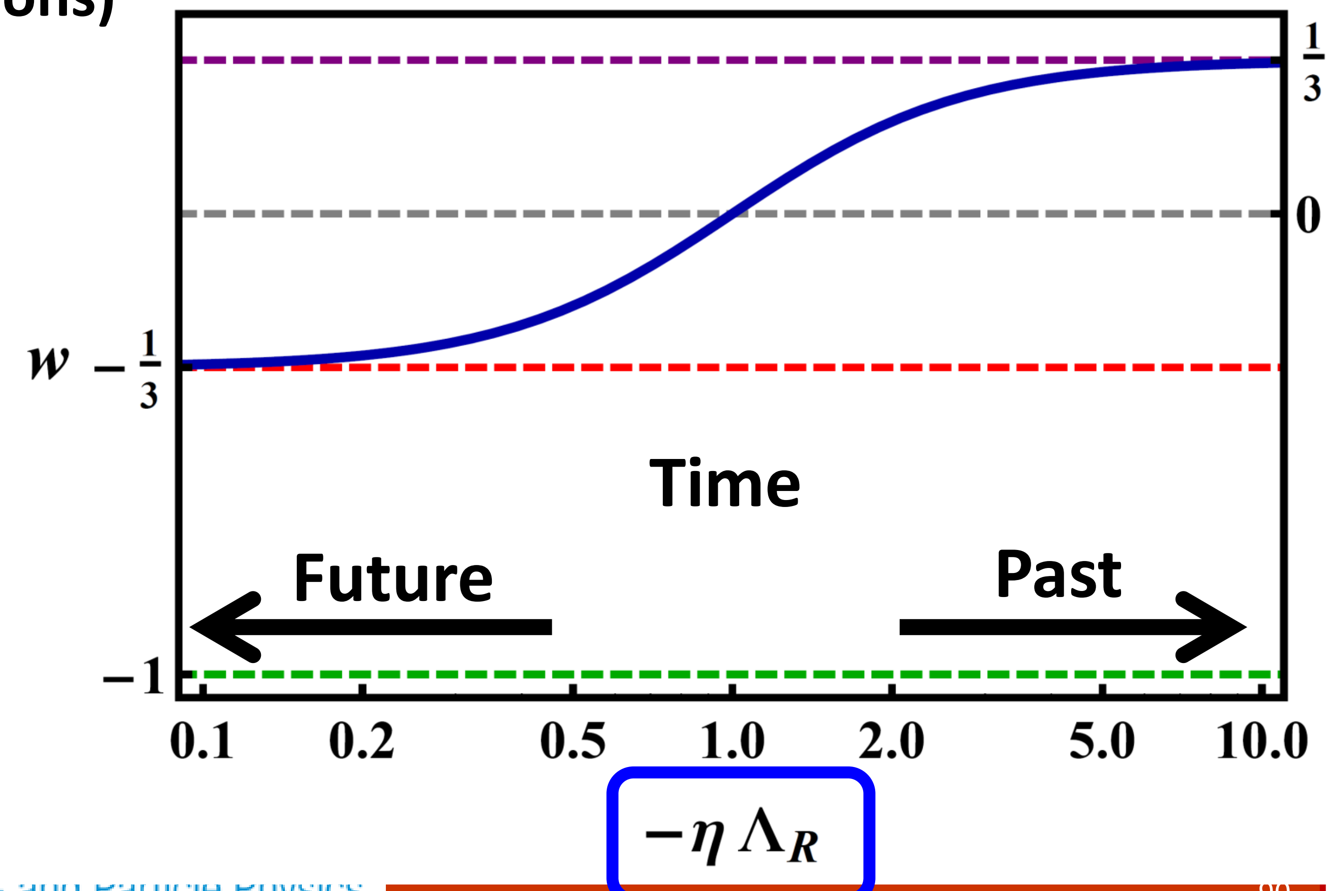

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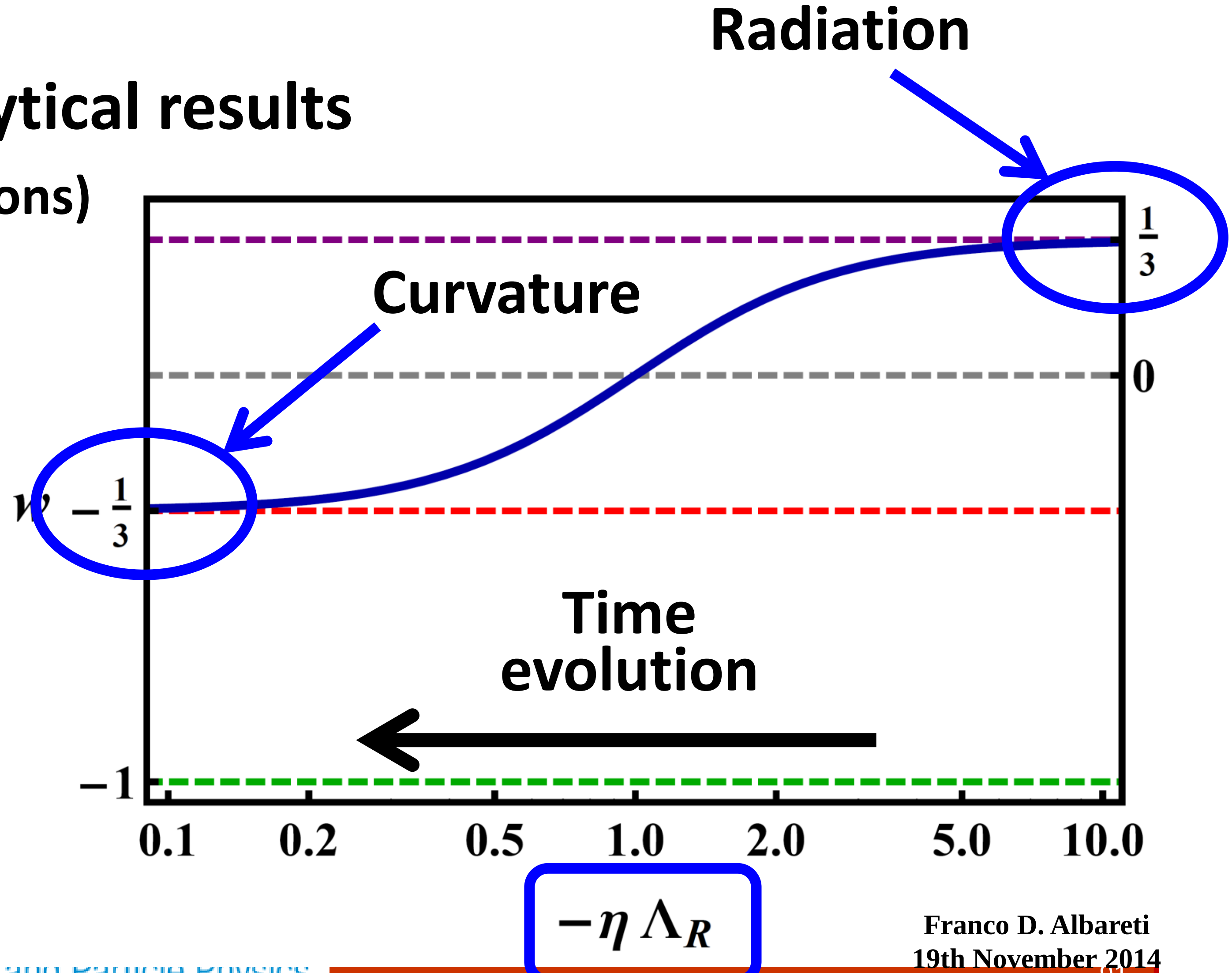

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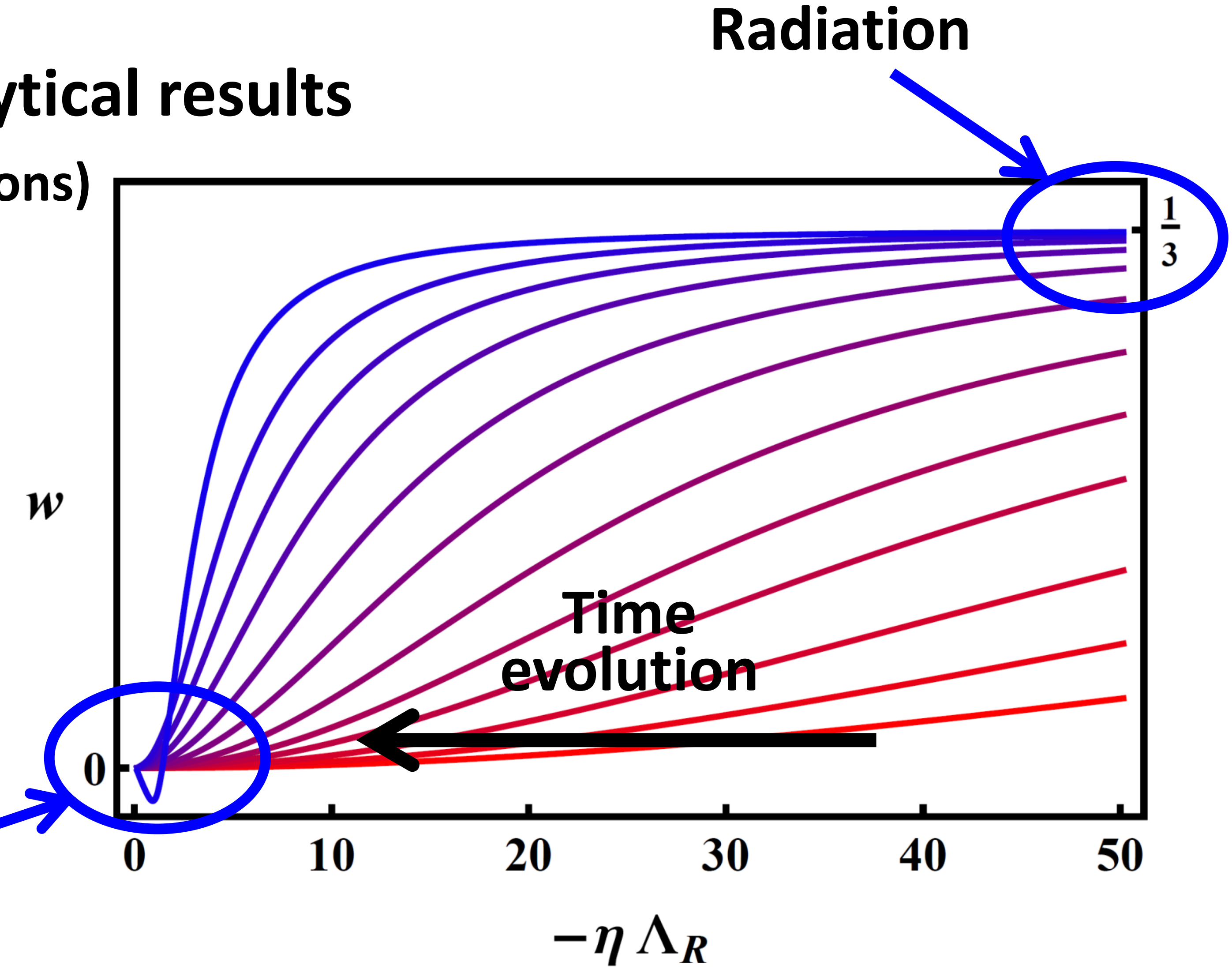


Scalar field in flat RW geometries

- **UV regime** $\boxed{\Lambda_R \gg m a}$

$$\rho^{UV}_{\mathrm{dS,ren}} \simeq \frac{H^4}{8\pi^2}\int_0^{\Lambda_R} \mathrm{d}k \left(\underbrace{2\,k^3\,\eta^4}_{\text{Radiation}} + \underbrace{\left(1+m_H^2\right) k\,\eta^2}_{\text{Curvature}} - \underbrace{\frac{m_H^2\left(m_H^2-2\right)}{4\,k}}_{\text{Cosmological constant}} \right)$$

No *dust* contribution in the UV

Scalar field in flat RW geometries

- **IR regime** $\boxed{\Lambda_R \ll ma}$

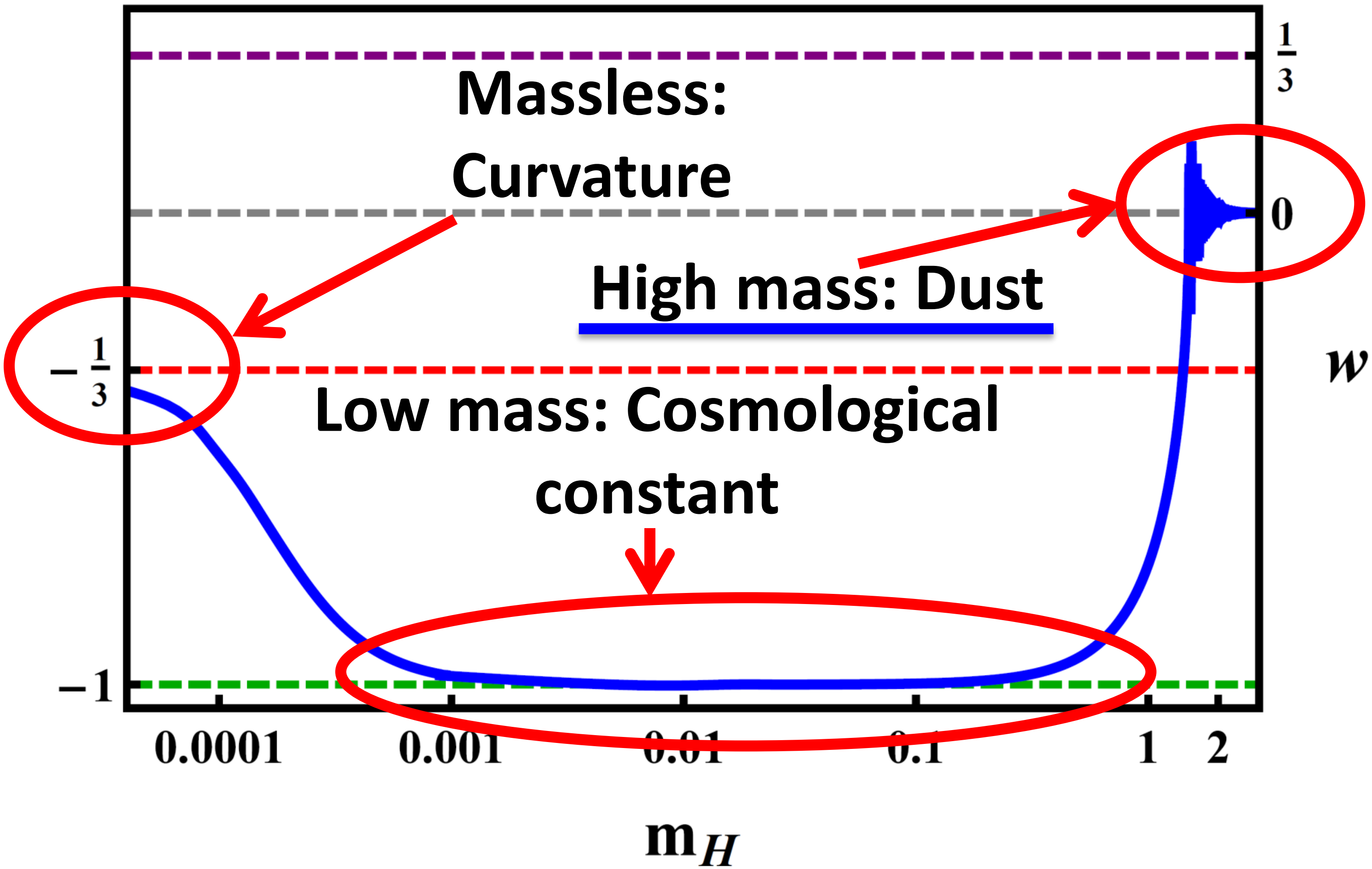
$$\rho^{IR}_{\mathrm{dS,ren}} \simeq \frac{H^4}{4\pi^2}\int_0^{\Lambda_R} \mathrm{d}k\, \underbrace{m_H k^2 \eta^3}_{\text{Dust}}$$

Scalar field in flat RW geometries

- **Mass dependence (at late times)**

Time fixed

Cutoff fixed



Arbitrary flat RW background

We assume

- **IR regime** $\boxed{\Lambda_R \ll ma}$
- **Massive fields** $\boxed{m \gg H}$

WKB method

$$\rho_{\text{ren}} = \frac{1}{8\pi^2}\int_0^{\Lambda_R} \mathrm{d}k\, k^2 \left(\frac{2m}{a^3} + \frac{9H^2}{4ma^3} + \frac{k^2}{ma^5}\right)$$

Arbitrary flat RW background

We assume

- **IR regime** $\boxed{\Lambda_R \ll ma}$
- **Massive fields** $\boxed{m \gg H}$

$\Big\}$ ***WKB method***

$$\rho_{\rm ren} = \frac{1}{8\pi^2}\int_0^{\Lambda_R} \mathrm{d}k\, k^2 \left(\frac{2m}{a^3} + \frac{9H^2}{4ma^3} + \frac{k^2}{ma^5}\right)$$

Arbitrary flat RW background

Cutoff constrained by observations (dark matter)

$$\rho_{\rm ren} = \frac{1}{12\pi^2}\frac{m}{a^3}\Lambda_R^3$$

$$\boxed{\Lambda_R \lesssim 8.96 \times 10^{-4}\, T_0 \left(\frac{m}{125\,\mathrm{GeV}}\right)^{-1/3}}$$

T_0 **Current CMB temperature**

Conclusions

1. Low k modes contribute as dust.

In general, they provide a subdominant contribution.

2. Small cutoff → **Generic prediction of holographic and non-holographic *entropy bounds* on the number of physical quantum states for any gravitating system**

A. G. Cohen et al., Phys. Rev. Lett. **82** (1999) 4971;
G. Abreu et al., Phys. Rev. Lett. **105** (2010) 041302.