Vector Boson as a Dark Matter

Amin Rezaei Akbarieh

IPM, 2012

(based on: Y.Farzan and A.R.A , accepted for publication in JCAP)

Outline

- Dark Matter

Evidence, …

- Our Model

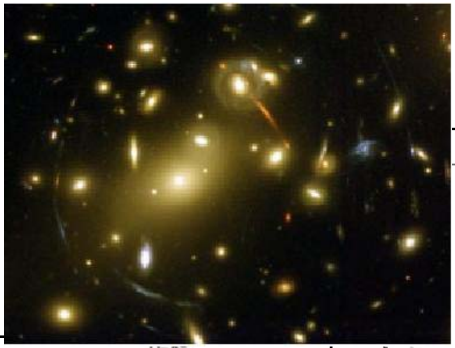
Different phases, Direct, Indirect,…

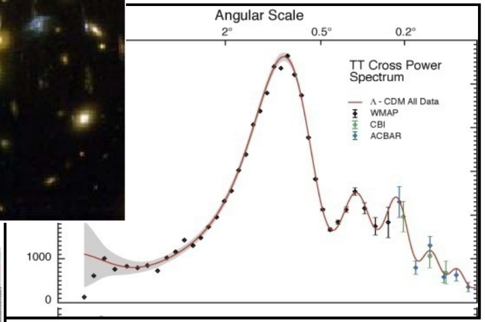
- Signature at the colliders.

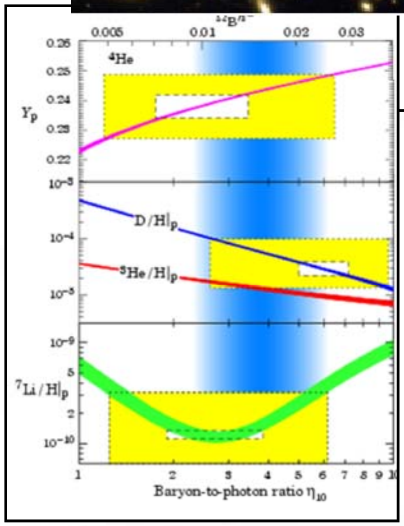
- Conclusion

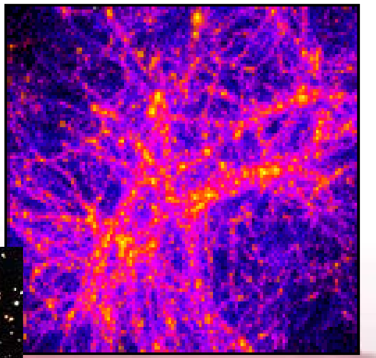
Evidence For Dark Matter

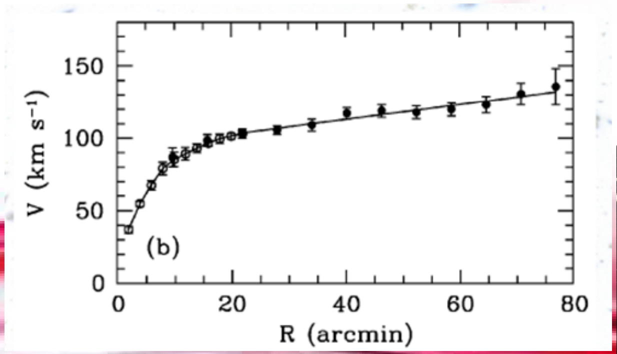
- Galactic rotation curves
- Gravitational lensing
- Light element abundances
- CMB anisotropies
- Large scale structure
- Etc…





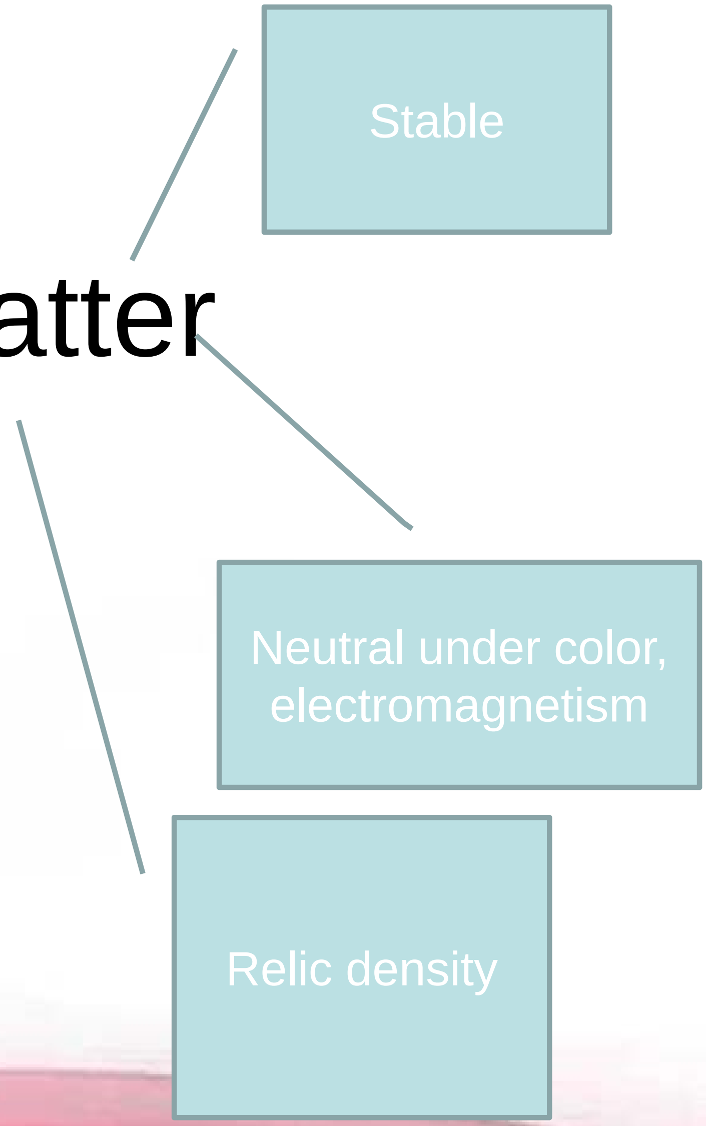






What is the nature of Dark Matter?

Dark Matter


Stable
Neutral under color, electromagnetism
Relic density

Spin

Mass

Portal

Production Mechanism

Dark Matter

Stable

Neutral under color, electromagnetism

Relic density

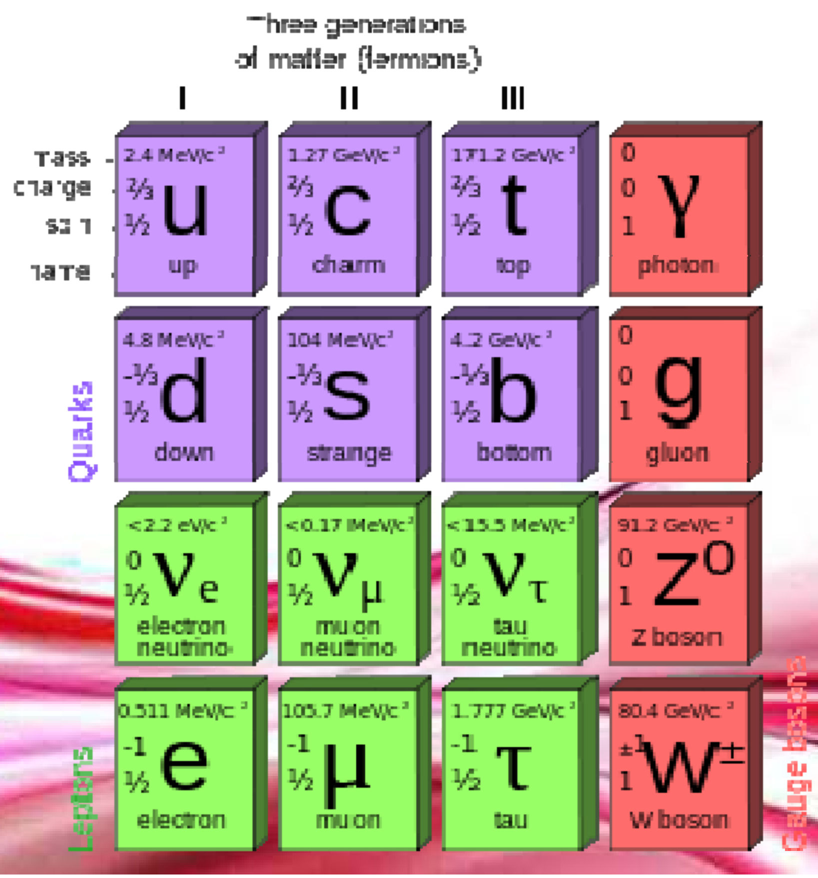
Dark Matter

Stable

Neutral under color, electromagnetism

Relic density

SM → Beyond the SM

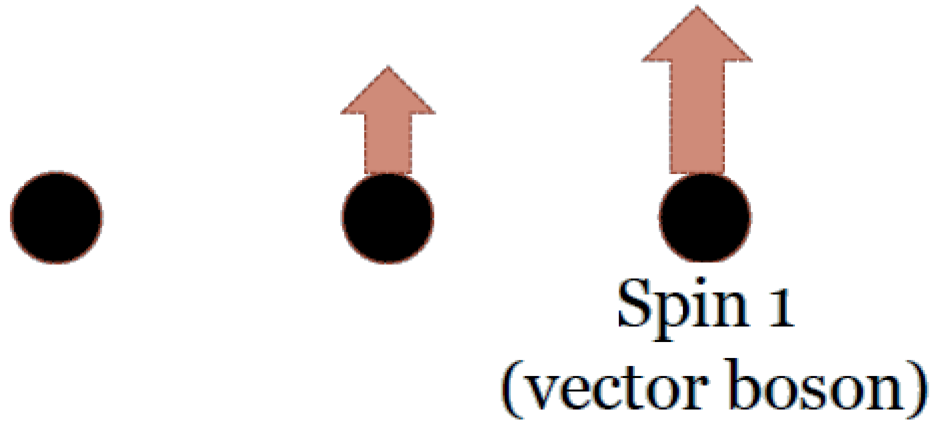


SPIN of dark matter?

Spin 0, 1 /2, are all extensively studied.

SPIN of dark matter?

Spin 0, 1 /2, are all extensively studied



VDM: A model for Vector Dark Matter.

Y.Farzan and A.R.A , accepted for publication in JCAP

Gauge group: $SU(3) \times SU(2) \times U(1)_Y \times U(1)_X$

Gauge Vector: V_μ

Scalar(s) to break the new gauge symmetry: Φ

SM→SM

Z_2 symmetry

$V_\mu \to -V_\mu$

$$\mathcal{L} = \mathcal{L}^{SM} + (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi^\dagger, \phi, H) - \frac{1}{4}V_{\mu\nu}V^{\mu\nu}$$

Minimal version of the Model

Scalar sector: $\Phi = (\phi_r + i\phi_i)/\sqrt{2}$

Covariant derivative: $D_\mu = \partial_\mu - i g_V V_\mu$

$$V = -\mu_\phi^2|\Phi|^2 - \mu^2|H|^2 + \lambda_\phi|\Phi|^4 + \lambda|H|^4 + \lambda_{H\phi}|\Phi|^2|H|^2$$

Z_2 symmetry

$Z_2^{(A)}: \; V_\mu \to -V_\mu \,, \;\; \Phi \to \Phi^*$

$Z_2^{(B)}: \; V_\mu \to -V_\mu \,, \;\; \Phi \to -\Phi^*,$

Unitary gauge

$$\Phi = \frac{\phi_r + v'}{\sqrt{2}} \text{ and } H = \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$$

$$V_\mu \to -V_\mu \;, \quad \phi_i \to -\phi_i$$

Goldstone boson absorbed as longitudinal component

Protecting the stability of the vector boson.

$$\frac{1}{2}[\phi_r \ h]\begin{bmatrix} 2\lambda_\phi v'^2 & \lambda_{H\phi} v v' \\ \lambda_{H\phi} v v' & 2\lambda v^2 \end{bmatrix}\begin{bmatrix} \phi_r \\ h \end{bmatrix}.$$

$$V_\mu \to -V_\mu, \quad \phi_r \to -\phi_r,$$

The new scalar can decay

Extended Model

Vector boson: V_μ

A pair of scalars: $\Phi = (\phi_1 \; \phi_2)$

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \to U \cdot \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\alpha & i\sin\alpha \\ i\sin\alpha & \cos\alpha \end{pmatrix} .$$

$$\frac{(\phi_1 + \phi_2)}{\sqrt{2}} \to e^{i\alpha} \frac{(\phi_1 + \phi_2)}{\sqrt{2}}$$

$$\frac{(\phi_1 - \phi_2)}{\sqrt{2}} \to e^{-i\alpha} \frac{(\phi_1 - \phi_2)}{\sqrt{2}}$$

Extended Model

$$Z_2^{(A)} : \Phi \to \sigma_3 \Phi \text{ and } V_\mu \to -V_\mu \ .$$

$$\Phi^\dagger \Phi = \phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2$$

$$\Phi^{Tr} \sigma_3 \Phi = \phi_1^2 - \phi_2^2$$

Z2 even

$$\Phi^\dagger \sigma_1 \Phi = \phi_2^\dagger \phi_1 + \phi_1^\dagger \phi_2 \ .$$

Z2 odd

Extended Model

$$V(\phi_1,\phi_2,H) = -\frac{\mu_H^2}{2}h^2 + \frac{\lambda_H}{4}h^4 - \mu^2(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2) + \lambda(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2)^2$$

$$+\frac{\lambda_1}{2}h^2(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2) + \xi'(\phi_1^\dagger\phi_2 + \phi_2^\dagger\phi_1)^2$$

$$+[\xi(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2)(\phi_1^2 - \phi_2^2) - \mu'^2(\phi_1^2 - \phi_2^2) + \lambda'(\phi_1^2 - \phi_2^2)^2 + \frac{\lambda_2}{2}h^2(\phi_1^2 - \phi_2^2) + h.c]$$

Imposing $Z_2^{(A)}$ → Accidental $Z_2^{(B)}$

$$Z_2^{(B)} : \Phi \to \sigma_3\Phi \text{ and } V_\mu \to -V_\mu\ .$$

Extended Model

- Symmetry of the model $U(1)_X \times Z_2 \times Z_2$

- Stability of Potential

$$\lambda, \lambda_H, \lambda_{H\phi}, \xi' > 0 \quad \lambda + 2\lambda' > 2|\xi|, \text{ and } \lambda_{H\phi} > 2|\lambda'_{H\phi}|$$

Some conservative assumption

For simplicity, we take all the couplings to be real.

- Spontaneous symmetry breaking

We can in general use the global $U(1)_X$ symmetry to absorb the imaginary component of $\langle\phi_2\rangle$ and write Φ^T in terms of real components as

$$\Phi^T = (\frac{v_r + \phi_r + iv_i + i\phi_i}{\sqrt{2}} \ \frac{v' + \phi'_r + i\phi'_i}{\sqrt{2}})$$

- The mass of the gauge boson

$$g_V\sqrt{v_r^2 + v_i^2 + v'^2}.$$

The new vector boson is a **DARK MATTER** candidate if

$$g_V^2(v_r^2 + v_i^2) < m_{\phi'}^2$$

Goldstone boson

The interesting point is that for a significant part of the parameter space, the minimum lies at $v' = 0$ and $v_r^2 + v_i^2 \neq 0$.

$$G \equiv \frac{-v_i \phi'_r + v_r \phi'_i}{\sqrt{v_i^2 + v_r^2}}$$

The mode perpendicular to the Goldstone boson

$$\phi' \equiv \frac{v_r \phi'_r + v_i \phi'_i}{\sqrt{v_i^2 + v_r^2}}.$$

By making a local $U(1)_X$ transformation, G can be absorbed and ϕ_2 will be of form $\phi' e^{i\beta}$ where $\beta = \arctan(v_i/v_r)$.

The interaction terms between the gauge boson and scalars are

$$\frac{g_V^2}{2} V_\mu V^\mu [(\phi_i^2 + \phi_r^2 + \phi'^2) + 2(\phi_i v_i + \phi_r v_r)] +$$

$$g_V V^\mu \left[-\sin\beta(\phi_r \partial_\mu \phi' - \phi' \partial_\mu \phi_r) + \cos\beta(\phi_i \partial_\mu \phi' - \phi' \partial_\mu \phi_i) \right].$$

Where

$$\beta = \arctan(v_i / v_r)$$

Different phases

$$\Phi^T = \left(\frac{v_r + \phi_r + iv_i + i\phi_i}{\sqrt{2}} \ \frac{v' + \phi'_r + i\phi'_i}{\sqrt{2}}\right)$$

- Phase I $\quad v' = 0,\ v_i, v_r \neq 0;$
- Phase II $\quad v' = v_r = 0 \text{ and } v_i \neq 0;$
- Phase III $\quad v' = v_i = 0 \text{ and } v_r \neq 0;$

Phase I

$$\begin{pmatrix} \phi_r \\ \phi_i \\ h \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{pmatrix}$$

$v' = 0,\ v_i, v_r \neq 0;$ ⟹ **Spontaneous CP-violation**

Small mixing ⟹ $a_{31}, a_{32}, a_{13}, a_{23} \ll 1.$

$$m_{\delta_3} \simeq m_h$$

We assume that the mixings between the SM Higgs and the new scalars are small.

Phase II

$v' = v_r = 0$ and $v_i \neq 0$;

$$a_{12} = a_{13} = a_{21} = a_{31} = 0.$$

In this case only ϕ_i mixes with h.

CP will be preserved.

A new Z2 symmetry $\phi_r \to -\phi_r$

Another component of Dark Matter

Equivalence of phases II and III

It is straightforward to verify that the phases II and III are equivalent provided that we substitute

$$(\mu^2, \lambda_H, \lambda, \xi', \lambda', \lambda_{H\phi}, \mu'^2, \lambda'_{H\phi}, \xi) \to (\mu^2, \lambda_H, \lambda, \xi', \lambda', \lambda_{H\phi}, -\mu'^2, -\lambda'_{H\phi}, -\xi)$$

and

$$\phi'_i \leftrightarrow \phi'_r \ .$$

Annihilation modes in the minimal model

The scalar field, ϕ_r, can be either lighter or heavier than V_μ. If it is heavier, the main annihilation mode for the V pair will be through s-channel scalar exchange. Taking the $\phi_r - h$ mixing small, we find

$$\langle \sigma(V + V \to \text{final}) v_{rel} \rangle = \frac{64}{3} g_V^4 [\frac{\lambda_{H\phi} v v'}{(m_h^2 - 4m_V^2)(m_{\phi_r}^2 - 4m_V^2)}]^2 F$$

with

$$F \equiv \lim_{m_{h^*} \to 2m_V} (\frac{\Gamma(h^* \to final)}{m_{h^*}}).$$

Annihilation modes in the minimal model

For $m_b < m_{DM} < m_W, m_{\phi_r}$,

the main annihilation mode will be to a $b\bar{b}$ pair which is constrained by bounds on the antiproton flux from PAMELA

For $m_W < m_V < m_{\phi_r}$

the main annihilation mode is to the W^+W^- pair.
If $m_Z < m_V$, the dark matter can also annihilate to a Z pair.

The bounds from the antiproton and gamma ray fluxes are strong.

Annihilation modes in the minimal model

For $m_W < m_V < m_{\phi_r}$

the main annihilation mode is to the W^+W^- pair.

If $m_Z < m_V$, the dark matter can also annihilate to a Z pair.

The bounds from the antiproton and gamma ray fluxes are strong.

The present bound from PAMELA on antiproton flux as well as the gamma ray bound from Fermi-LAT lie above 1 pb.

the forthcoming AMS02 experiment may be able to probe this scenario.

Annihilation modes in the extended model

- In case that δ_i are all heavier than V, the model can be considered as a Higgs portal model within which

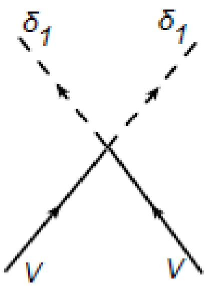
$$\langle\sigma(V+V\to \text{final})v_{rel}\rangle = \frac{64}{3}g_V^4[\sum_{j=1}^{3}\frac{a_{3j}(a_{1j}v_r + a_{2j}v_i)}{m_{\delta_j}^2 - 4m_V^2}]^2 F$$

with

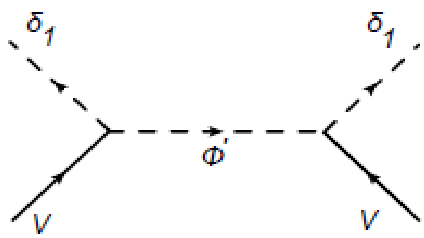
$$F \equiv \lim_{m_{h^*}\to 2m_V}(\frac{\Gamma(h^*\to final)}{m_{h^*}}).$$

Annihilation modes in the extended model

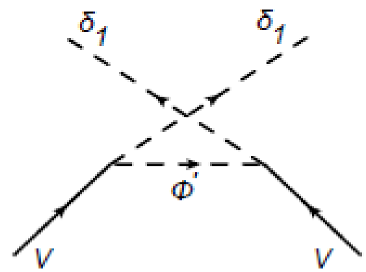
- In case that $m_{\delta_1} < m_{DM}$



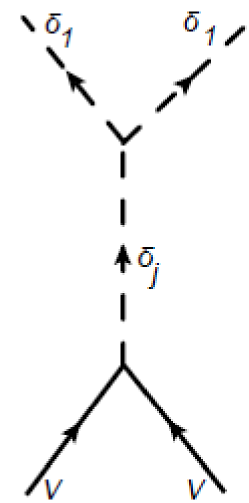
1-a

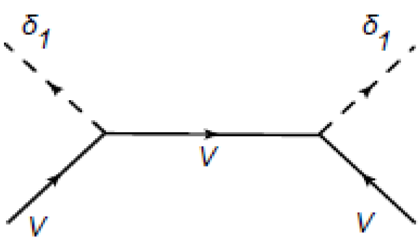


1-b

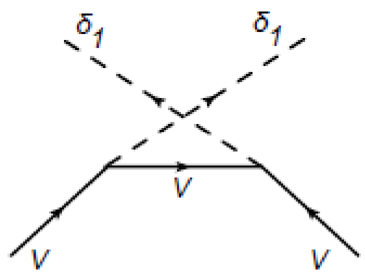


1-c





1-d



1-e

Interesting scenario

$$\sigma(V + V \rightarrow \text{anything}) = 1\ pb$$

$$\sigma(\delta_1 + \delta_1 \rightarrow h^* \rightarrow \text{final}) \gg 1\ pb.$$

Parameters of model. An example for phase II with $m_{\delta_1} < m_V$.

ξ	λ'	ξ'	λ	μ (GeV)	μ' (GeV)	g_V^2	$\lambda_{H\phi}$	$\lambda'_{H\phi}$
0.5	0.11	0.4	0.93	405	140	0.017	0.1	0.1

v_i	v_r	m_{δ_1}	m_{δ_2}	$m_{\phi'}$	m_V
795	0	100	500	1000	120

Direct detection

- Minimal version:

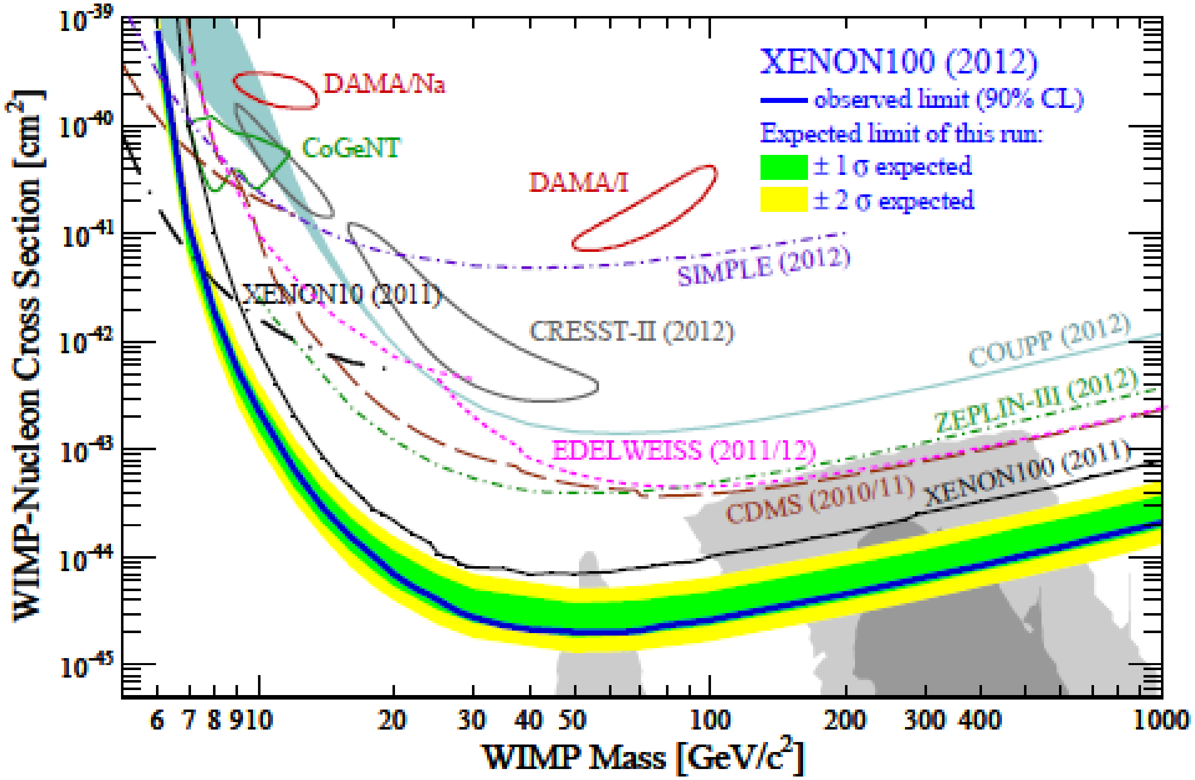
$$\sigma_N \equiv \sigma_{SI}(V + \mathrm{N} \to V + \mathrm{N}) = \frac{g_V^4 M_r^2 m_N^2}{\pi m_V^2 v_H^2}[\frac{\lambda_{H\phi} v v'^2}{m_h^2 m_{\phi_r}^2}]^2 f^2$$

- Extended model

$$\sigma_N \equiv \sigma_{SI}(V + \mathrm{N} \to V + \mathrm{N}) = \frac{g_V^4 M_r^2 m_N^2}{\pi m_V^2 v_H^2}[(\sum_{j=1}^{3} \frac{a_{3j}(a_{1j} v_r + a_{2j} v_i)}{m_{\delta_j}^2})]^2 f^2$$

Phase I with $2m_W < m_{\delta_1} < m_V$

$$\sigma_N \sim 10^{-46} \lambda_{H\phi}^2 (f/0.3)^2 \text{ cm}^2 \qquad m_V \sim \text{few } 100 \text{ GeV}$$



E. Aprile et al. [XENON100 Collaboration], arXiv:1207.5988 [astro-ph.CO].

signature at the high energy colliders

δ_i can be in principle produced with a cross section that is suppressed by $|a_{3i}|^2$ relative to the SM Higgs of mass m_{δ_i}.

For $m_{\delta_i} > 2m_W$

SM-like Higgs decaying to W^+W^- but with a production rate suppressed by a factor of $a_{3i}^2 \sim 0.1$.

The LHC should be able to put a bound on $|a_{3i}|^2$ for this range.

Another Discovery Channel

If $\lambda_{H\phi}$ and $\lambda'_{H\phi}$ are relatively large and some of the new neutral scalar particles are lighter than $m_h/2$, the Higgs should have sizeable invisible decay modes.

For $\lambda'_{H\phi} \ll \lambda_{H\phi}$

⇓

The invisible decay rate of the Higgs $\sim \lambda^2_{H\phi} v^2_H / (64\pi m_h)$

the bound from the LHC

rules out $\lambda_{H\phi} > 0.01$ for $m_{\delta_{1,2}} < m_h/2 \simeq 63$ GeV.

Conclusions

- Model based on $U(1)_X \times Z_2 \times Z_2$
- Vector gauge boson as DM
- Minimal and extended version
- Extended version: spontaneous CP violation/multiple DM candidate
- SM-like Higgs with suppressed production rate

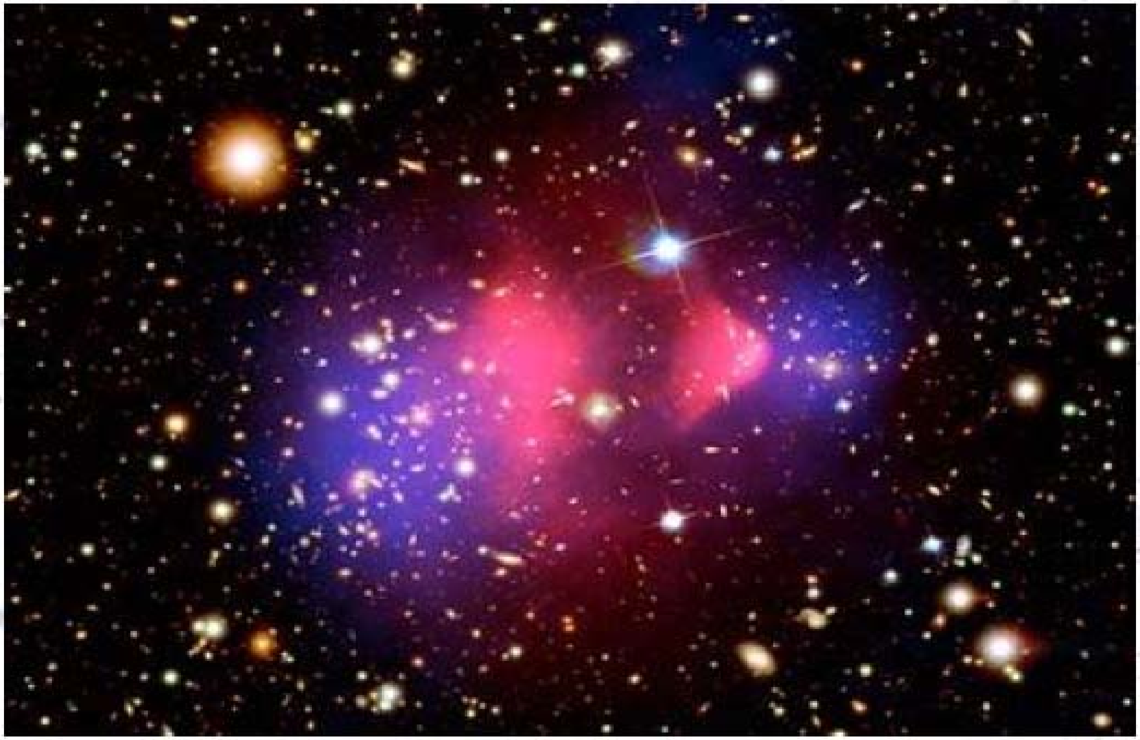
Thanks For Your Attention

Backup Slides

Evidences for Dark Matter

Dark matter in galaxy clusters...

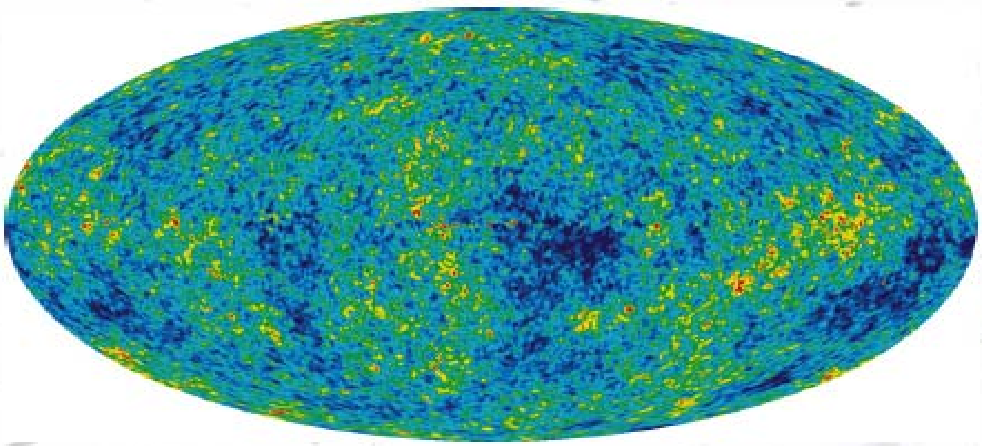
as can be seen for example in the Bullet Cluster through gravitational lensing

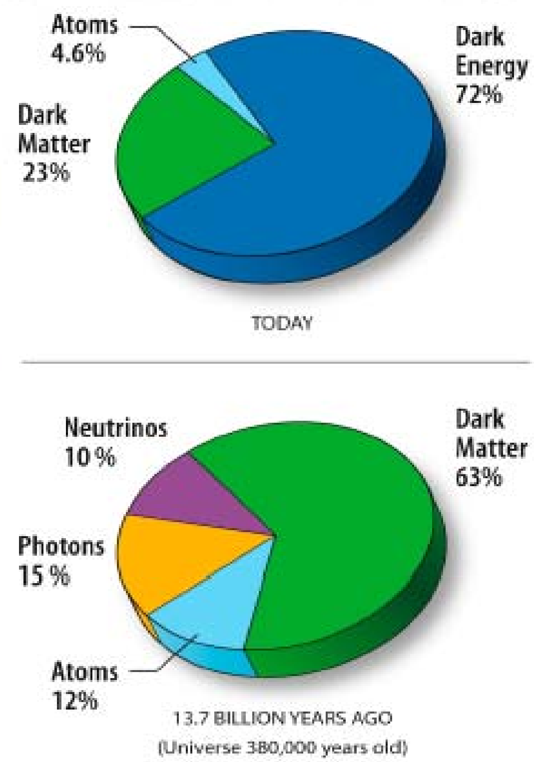


Evidences for Dark Matter

Dark matter from cosmological evolution…

e.g. as measured by WMAP

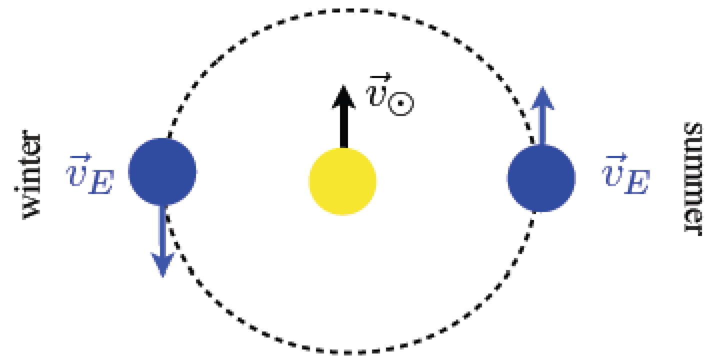




DAMA

NaI Annual Modulation Experiment running for 13 years

Galactic Dark Matter



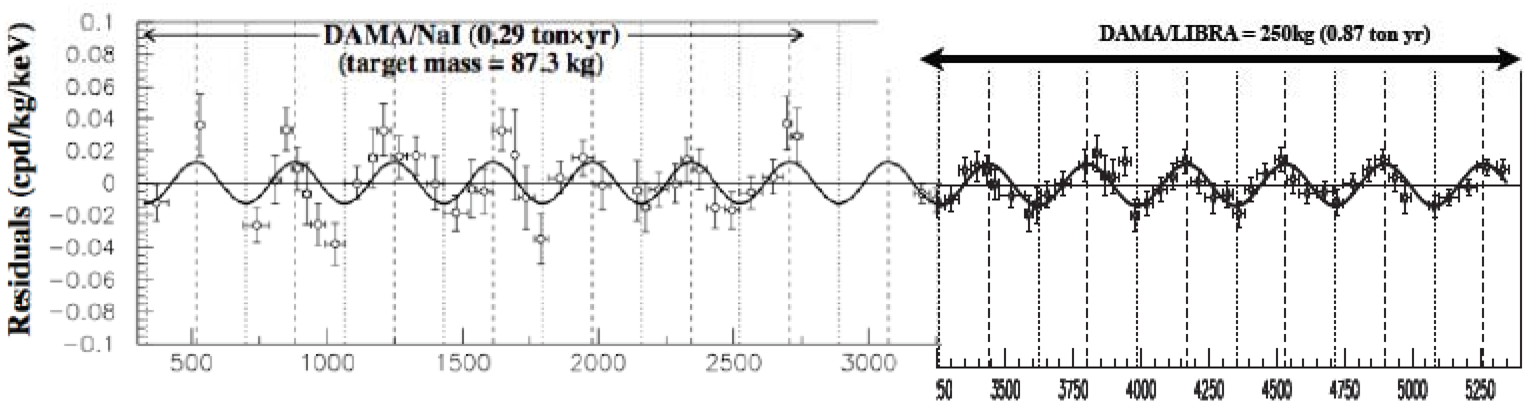
$v \leq v_{\rm esc} + |\vec{v}_E - \vec{v}_\odot|$ $v \leq v_{\rm esc} + |\vec{v}_E + \vec{v}_\odot|$

Annual modulation in WIMP signal

$$\Phi_{\rm dm} = n_{\rm dm}\, v$$

$$A_{\rm mod} = R_{\rm Sum} - R_{\rm Win}$$

Modulation amplitude ~2.5% for elastic scattering



Fermi Gamma Ray Space Telescope

Two Instruments:

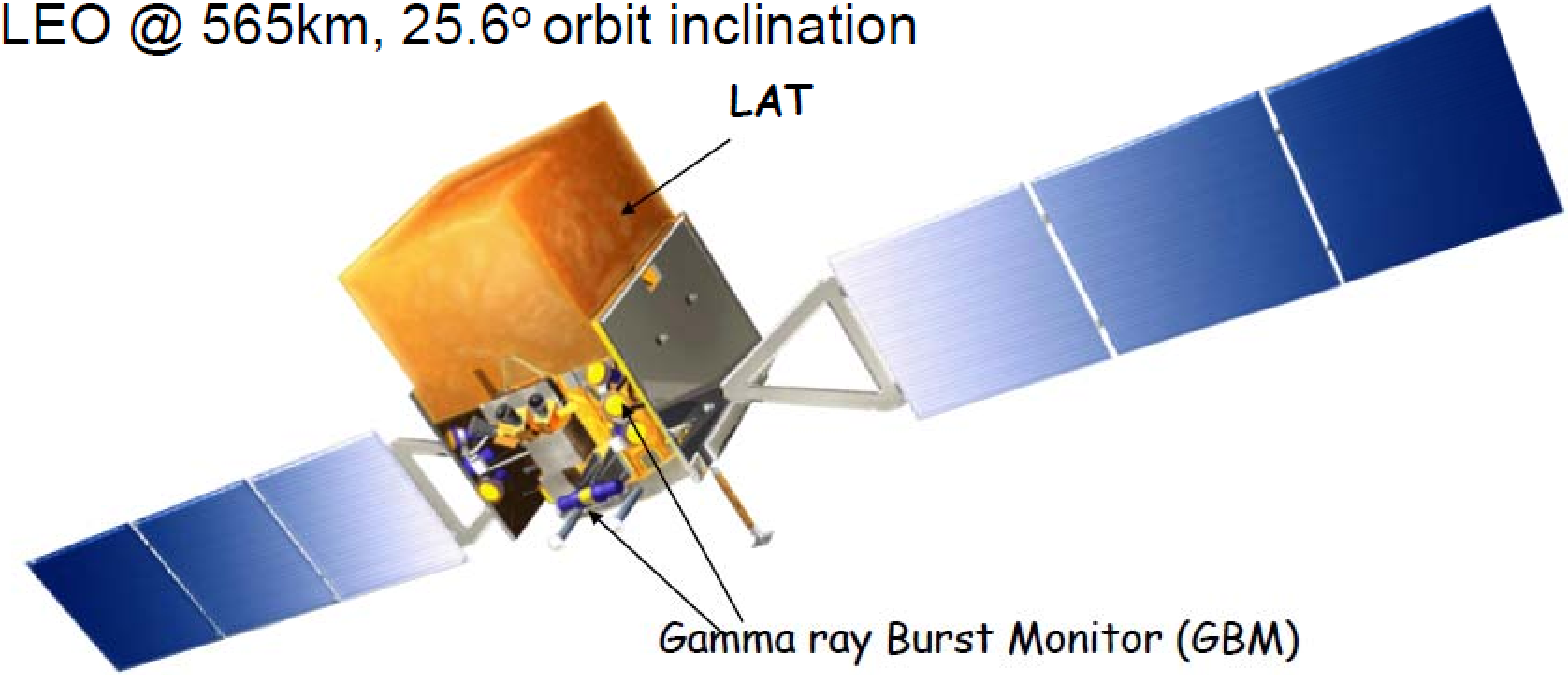
LAT: 20 MeV →300 GeV

GBM: 10 keV →30 MeV

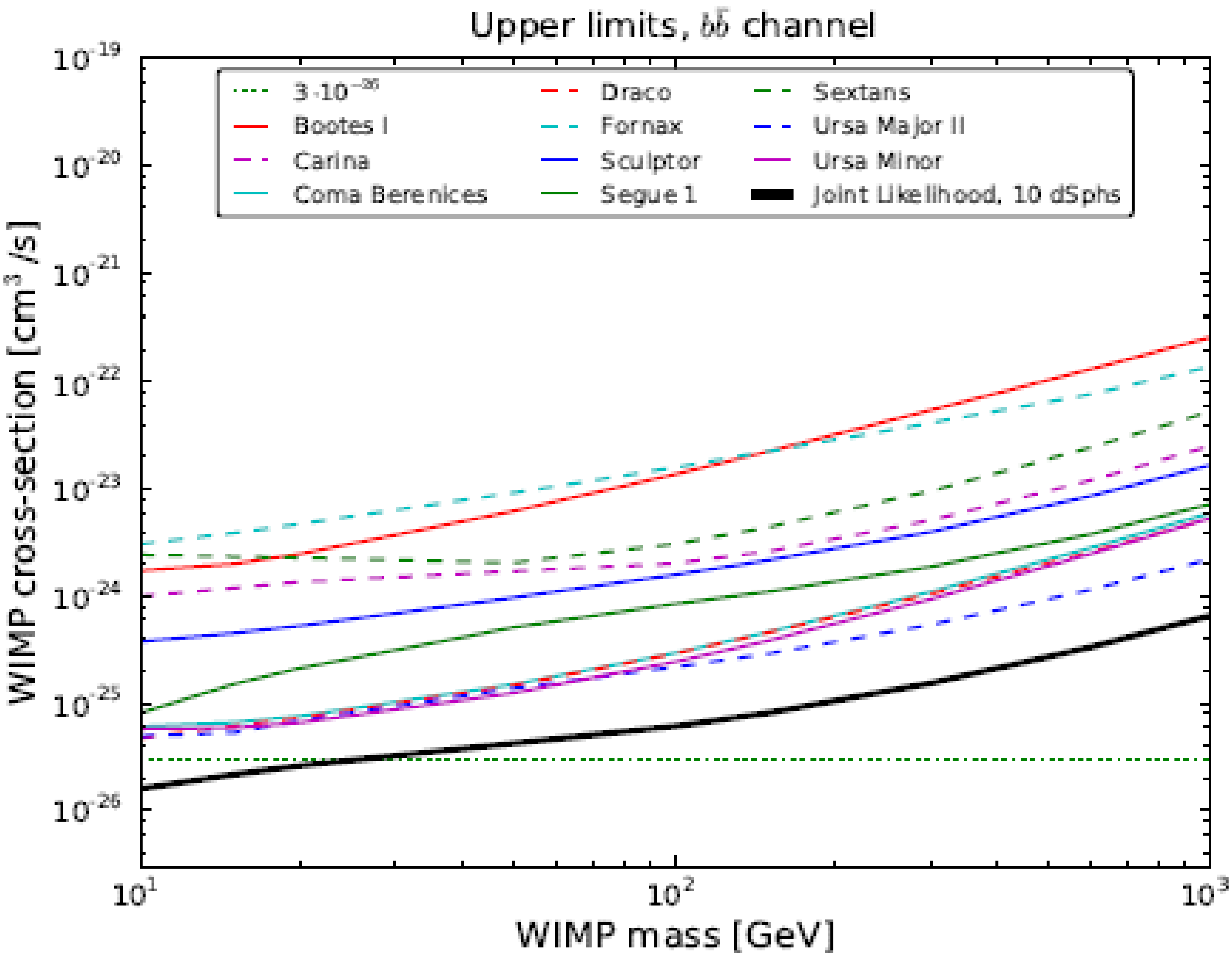
Launch: June 11, 2008

5-year mission (10-year goal)

LEO @ 565km, 25.6° orbit inclination



spacecraft partner:
General Dynamics



M. Ackermann et al. [Fermi-LAT Collaboration], Phys. Rev. Lett. 107 (2011) 241302 [arXiv:1108.3546 [astro-ph.HE]].