

Dark Matter and the Transient Sky

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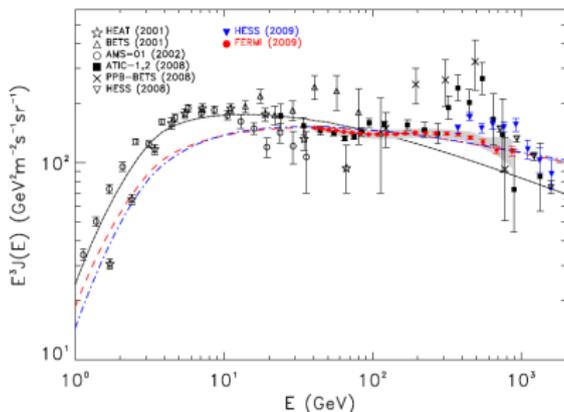
* Permanent Address.



Context

We have much evidence for dark matter from gravitational interactions, but to discover its nature we must probe its couplings to known matter.

There has much discussion of anomalies in the high-energy spectrum of cosmic-ray electrons and positrons.... [Grasso et al., arXiv:0905.0636]



N.B. models which yield $\chi\chi \rightarrow \gamma\gamma$ can be crossed to yield $\gamma\chi \rightarrow \gamma\chi$.

We use GRBs — “*the Transient Sky*” — to hunt for dark matter directly.

Prequel: On Dark Matter

Dark matter is established under the assumption that gravity is understood.

We do know most dark matter must be...

- stable or effectively so on Gyr time scales
- not “hot” – i.e., not relativistic at the time it decoupled from ordinary matter in the cooling early Universe
- have no substantial strong or electromagnetic charge

The Standard Model explains much, but it provides no suitable candidate.



Dark Matter is an Unknown Known?

It has been long thought that the dark-matter candidate, if produced as a thermal relic, ought to be a Weakly Interacting Massive Particle or WIMP.

[Jungman, Kamionkowski, Griest, Phys. Rept. 1996]

Such dark matter candidates can emerge naturally from models concocted to explain why the weak scale is $\mathcal{O}(100 \text{ GeV})$. Enter supersymmetry and the **neutralino**.

This seems to make the stability requirement challenging.

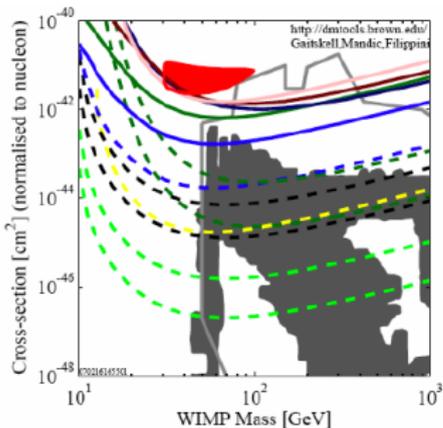
A single species of WIMP with mass $M_{\text{WIMP}} \sim \mathcal{O}(100) \text{ GeV}$ can reproduce the relic density!

This is the WIMP “miracle”.

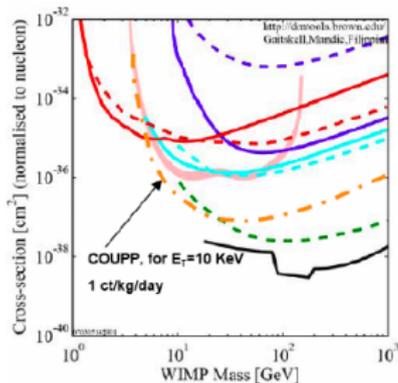
Such candidates can be established in scattering expts through the identification of anomalous nuclear recoils....

However, it is possible to reproduce the relic density with lighter particles with stronger (weak but not weak scale!) mutual interactions. [Feng and Kumar, PRL 2008]

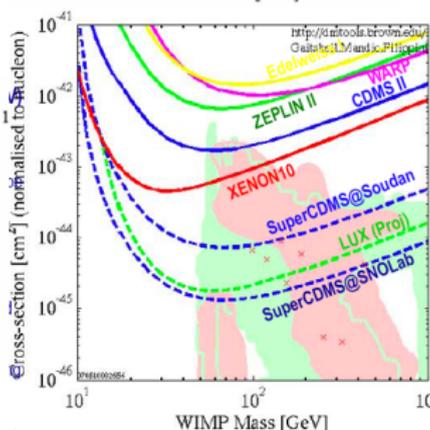
Direct Detection Limits on WIMPs



- DATA listed top to bottom on plot
- DAMA 2000 58kg kg-days NaI Ann Mod. 3sigma, w/o DAMA 1
- CRESST 2004 10.7 kg-day CaWO4
- Edelweiss 1 final limit, 62 kg-days Ge 2000+2002+2003 limit
- WARP 2 3L, 96.5 kg-days 55 keV threshold
- ZEPLIN II (Jan 2007) result
- CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
- XENON10 (10 kg) projected sensitivity
- CDMS Soudan 2007 projected
- SuperCDMS (Projected) 2-ST@Soudan
- XENON100 (100 kg) projected sensitivity
- LUX 300 kg LXe Projection
- SuperCDMS (Projected) 25kg (7-ST@Snolab)
- SuperCDMS (Projected) Phase B
- SuperCDMS (Projected) Phase C
- Baltz and Gondolo 2003
- Baltz and Gondolo, 2004, Markov Chain Monte Carlos
- 070216161501



- DATA listed top to bottom on plot
- CDMS Soudan 2004+2005 Si SD-proton
- CRESST 1 SD-proton (est.)
- CRESST 2001 spin days, 1.51 kg-days, 262g sapphire
- CDMS Soudan 2004+2005 Ge SD-proton
- PICASSO SD-proton (2005)
- SIMPLE SD-proton (2005)
- DAMA 2000 NaI SD-proton (est.)
- NALD spin days, projected limit, 12 p.e./keV with 100 kg-yrs exposure
- SuperK indirect SD-proton
- 070216161501



If Dark Matter is not a WIMP...

its relic density need not be fixed by thermal freezeout, and its stability need not be guaranteed by a discrete symmetry.

What mechanisms then are operative and how do we discover them?

Some possibilities...

- Its stability may be guaranteed by a hidden gauge symmetry.

E.g., dark matter can possess a hidden U(1) symmetry. If the gauge mediator is massless, dark matter can have a *millicharge*.

[B. Holdom, PLB 1986; Pospelov, Ritz, arXiv:0810.1502; Fox, Poppitz, arXiv:0811.0399 ...]

We can discover this from the appearance of dispersive effects in the speed of light \implies Enter GRBs.

- Its relic density may be related to Ω_B .

If so, dark matter ought be **asymmetric**.

[Nussinov, PLB 1985; Barr, Chivukula, Farhi, PLB 1990; Ellis et al., NPB 1992.

Ryttov and Sannino, arXiv:0809.0713 [hep-ph]; Kaplan, Luty, Zurek, arXiv:0901.4117 [hep-ph].]

In contradistinction to scattering experiments, we can discover an asymmetry thr. the gyromagnetic Faraday effect. [SG, PRL 2008, PRD 2009.]

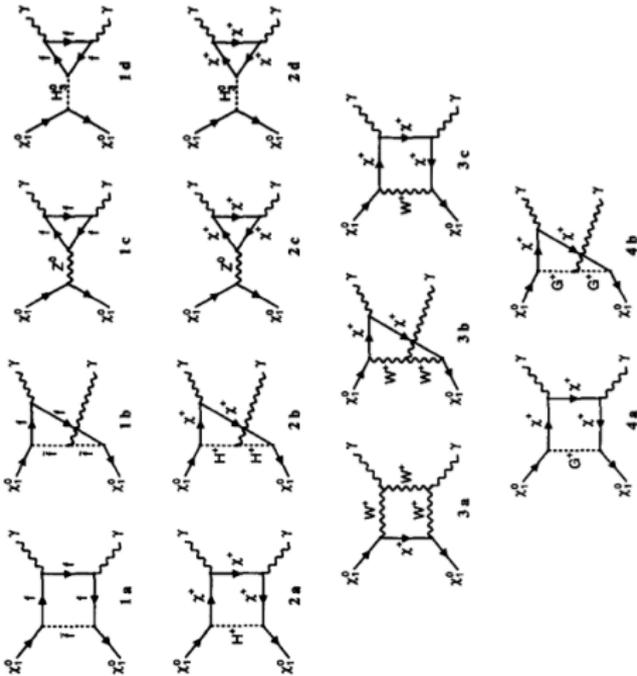
- On the frequency dependence of c , the speed of light
The best terrestrial limits are $|\delta c|/c \lesssim 1 \times 10^{-8}$. [J.L. Hall, review 1976]
Better limits require the use of astrophysical sources.
Note, e.g., from the Crab nebula $|\delta c|/c \lesssim 5 \times 10^{-17}$. [Warner and Nather, Nature 1969]
- On light–dark-matter scattering: an effective theory analysis for $\omega \ll \omega_{\text{th}}$
Enter a model-independent parametrization of the forward Compton amplitude.
The leading term as $\omega \rightarrow 0$ is set by the electric-charge-to-mass ratio of dark matter.
- cf. Dispersive effects in light propagation from Lorentz violation
- GRBs as a distant light source
- Use of GRB trigger with radio afterglow data to limit the millicharged dark matter hypothesis
Use statistical analysis to separate source from propagation effects.
- cf. Other millicharged dark matter limits
- Summary/Outlook

On Light-Dark-Matter Scattering

$\chi\chi \rightarrow \gamma\gamma$ has been calculated to one-loop-order in the MSSM.

[Bergström and Ullio, NPB 1997; Bern, Gondolo, Perelstein, PLB 1997]

Thus for $\gamma\chi \rightarrow \gamma\chi$ we have:



- These diagrams accrue imaginary parts at photon energies of $\omega \approx \omega_{\text{th}} = \mathcal{O}(200 \text{ GeV})$.
- The energy range of the Fermi GBM/LAT is 8 keV - 300 GeV, so that most of the energy range satisfies $\omega \ll \omega_{\text{th}}$ if dark matter is linked to new weak-scale physics.
- The forward Compton amplitude at these energies is real.

An Effective Theory Analysis: $\omega \ll \omega_{\text{th}}$

The index of refraction $n(\omega)$ is related to the forward Compton amplitude \mathcal{M} for $\gamma(k) + \chi(p)$ scattering via (for $|n - 1| \ll 1$)

$$n(\omega) = 1 + \frac{\rho}{4M^2\omega^2} \mathcal{M}_r(k, p \rightarrow k, p),$$

ρ is the dark-matter (DM) mass density and M is the DM particle mass.

$\mathcal{M}_r(k, p \rightarrow k, p)$ is evaluated in the dark-matter rest frame.

Under Lorentz symmetry and P , T , C we have

$$\mathcal{M}_r(k, p \rightarrow k, p) = f_1(\omega) \epsilon'^* \cdot \epsilon + i f_2(\omega) \mathcal{S} \cdot \epsilon'^* \times \epsilon,$$

[Gell-Mann, Goldberger, Thirring, Phys Rev 1954 (GGT); Goldberger, Phys Rev 1955]

ϵ (ϵ') is the photon polarization in its initial (final) state.

\mathcal{S} is the DM spin operator.

The photon is transverse: $\epsilon \cdot \hat{\mathbf{k}} = \epsilon' \cdot \hat{\mathbf{k}} = 0$.

$\mathcal{M}_r(k, p \rightarrow k, p)$ is implicitly a 2×2 matrix in the photon polarization.

Only its diagonal matrix elements describe dispersion \implies only f_1 matters.

A low-energy theorem fixes $f_1(0) = -2\epsilon^2 e^2$ for DM of charge ϵe .

[Thirring, Philos. Mag. 1950. $f_2(0)$ also known, see Brodsky and Primack, Ann Phys 1969.]

An Effective Theory Analysis: $\omega \ll \omega_{\text{th}}$

Under analyticity and unitarity as well, we have [GGT, Goldberger, 1955]

$$\text{Re}f_1(\omega) - \text{Re}f_1(0) = \frac{4M\omega^2}{\pi} \int_0^\infty d\omega' \frac{\sigma(\omega')}{\omega'^2 - \omega^2},$$

The optical theorem is used to replace $\text{Im}f_1(\omega)$ with the unpolarized cross section σ . Expanding for $\omega \ll \omega_{\text{th}}$

$$n(\omega) = 1 + \frac{\rho}{4M^2\omega^2} (A_0 + A_2\omega^2 + \dots),$$

where $A_0 = \text{Re}f_1(0)$. Note $A_i > 0$.

The phase velocity $v_p = \omega/k = 1/\tilde{n}$ with $\tilde{n} \equiv \text{Re } n$.

However, the group velocity v_g controls dispersive effects:

$$v_g = d\omega/dk = (\tilde{n} + \omega(d\tilde{n}/d\omega))^{-1}.$$

Light emitted from a source at a distance l away possesses a frequency-dependent arrival time $t(\omega)$: $t(\omega) = l(\tilde{n} + \omega d\tilde{n}/d\omega)$, or

$$t(\omega) = l \left(1 + \frac{\rho}{4M^2} \left(\frac{-A_0}{\omega^2} + A_2 + 3A_4\omega^2 + \mathcal{O}(\omega^4) \right) \right).$$

We must take the cosmological expansion into account as well.

An Effective Theory Analysis: $\omega \ll \omega_{\text{th}}$

At red shift z the photon energy is blue shifted by a factor of $1 + z$ relative to its present-day value ω_0 : [Jacob and Piran, JCAP 2008]

$$t(\omega_0, z) = \int_0^z \frac{dz'}{H(z')} \left(1 + \frac{\rho_0(1+z')^3}{4M^2} \left(\frac{-A_0}{((1+z')\omega_0)^2} + A_2 + 3A_4(1+z')^2\omega_0^2 + \dots \right) \right)$$

with the Hubble rate $H(z') = H_0 \sqrt{(1+z')^3 \Omega_M + \Omega_\Lambda}$.

There is no “boost factor” here.

WMAP parameters characterize the matter density and light travel time.

We use the combined analysis of the WMAP five-year data and more in the Λ CDM model: [Komatsu et al, ApJ Suppl 2009]

- $H_0 = 70.5 \pm 1.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$
- $\Omega_M = 0.274 \pm 0.015$
- $\Omega_\Lambda = 0.726 \pm 0.015$ Note $\Omega_M + \Omega_\Lambda = 1$.

Various strategies must be employed to isolate the A_i .

Interpretation of the A_i :

- A_0 is fixed by the DM electric charge.

This term appears as $1/\omega^2$ and thus is best isolated with radio studies.

- A_2 is fixed by the DM polarizability.

This term incurs no frequency-dependent shift in the speed of light.

It is “dark” grey dust. It could impact the determination of Ω_Λ Since $A_2 > 0$, the longer arrival time mimics a larger distance scale.

Note precision of H_0 determination (and of w_Λ studies) is improving.

[Riess et al., arXiv:0905.0695]

- A_2 is fixed by a higher-order DM polarizability.

This term appears as ω^2 and is best constrained with optical or gamma-ray studies.

- ...

An Effective Theory Analysis: Terrestrial Tests

Over what range of ρ and M is our framework valid?

Our limits on dark-matter properties rely on the validity of

$$n(\omega) = 1 + \frac{\rho}{4M^2\omega^2} \mathcal{M}_r(k, \rho \rightarrow k, \rho),$$

which follows if $|n - 1| \ll 1$.

The interparticle spacing a is crudely $a \sim (\rho/M)^{-1/3} \equiv N^{-1/3}$.

No additional conditions emerge as scattering in the forward direction is always coherent; it is independent of the location of the scatterers.

Laboratory studies in dilute atomic systems (BEC condensate) do confirm the persistence of the index of refraction at low densities

$N \sim 10^{14} \text{cm}^{-3} \Rightarrow P \sim 10^{-3} \text{mbar} \Rightarrow$ “high” vacuum conditions!

though the parameters of these studies satisfy $\omega < (\rho/M)^{1/3}$.

[Campbell et al., PRL 2005]

Any failure as $\rho/M \rightarrow 0$ has not been established.

Searches for Lorentz Violation

Searches for frequency-dependent time lags from GRB data have also been used to set limits on Lorentz violation.

[Amelino-Camelia et al., Nature 1998]

Such tests have suggested/searched for dispersive effects which $\sim \omega$.

[Amelino-Camelia et al., Nature 1998; Ellis et al. ApJ 2000]

However, transmission experiments cannot offer true tests of T .

In such cases matter effects and Lorentz violation in vacuo can be confused.

[Kostelecky and Mewes, review arXiv:0809.2846]

We have seen, however, for $\omega < \omega_{\text{th}}$ for scattering in which the dark matter is at rest no term in ω appears.

The z dependence of the two scenarios is also different.

We will employ, however, the statistical analysis these studies suggest to separate propagation and GRB source effects.

[Ellis et al. ApJ 2000, ..., Jacob and Piran JCAP 2008]

Gamma-Ray Bursts (GRBs) are very bright objects which appear at cosmological distance.

Fermi expects to discover 200 per year.

GRBs possess properties (spectral peak photon energy, minimum rise time, ...) which correlate with their luminosity. Thus they can be used to probe the Hubble diagram to larger z and study the properties of dark energy.

A study of 69 GRBs extends the Hubble diagram to $z > 6$ and is consistent with the usual concordance model.

[Schaefer, ApJ 2007]

We need not employ the GRBs as “standard candles”.

We pick GRBs for which z is measured.

To determine A_0 we also require observations in the radio.

Our selection criteria: We demand that

- the energy of the GRB be compatible with the energy range of the Fermi GBM. [excludes GRB 080109A and GRB 020903A]
- the radio flux detection be in the right location, be new, and be significantly non-zero (3σ). [excludes GRB 030277A, GRB 980425A, and GRB 011130A]

We find 53 GRBs in all to consider and include all detected radio frequencies of 75 GHz or less in our fit.

Our observable is $\tau = t(\omega_0^{\text{low}}, z) - t(\omega_0^{\text{high}}, z)$. We let $\omega \equiv \omega_0^{\text{low}}$ henceforth. Thus we fit

$$\frac{\tau}{1+z} = \tilde{A}_0 \frac{K(z)}{\nu^2} + \delta((1+z)\nu)$$

Note the frequency $\nu \equiv \omega/2\pi$ and $K(z) \equiv (1+z)^{-1} \int_0^z dz' (1+z')H(z')^{-1}$.

Recall $4\pi^2 \tilde{A}_0 = -A_0 \rho_0 / 4M^2 = 2\pi \alpha \varepsilon^2 \rho_0 / M^2$
and $\rho_0 \simeq 1.19 \times 10^{-6} \text{ GeV/cm}^3$ [WMAP 5-yr]

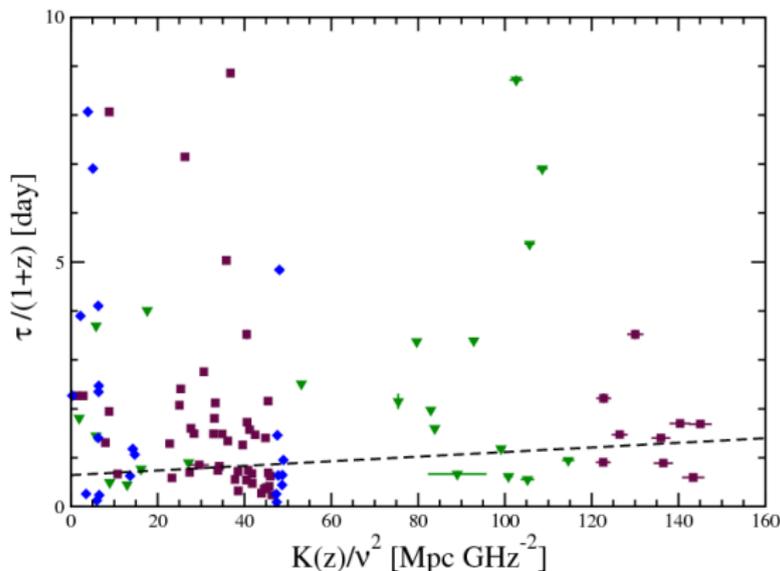
The function $\delta((1+z)\nu)$ allows for a frequency-dependent time lag for emission from the GRB in the GRB rest frame.

To provide a context, consider the ε/M which would result if the time lag associated with the radio afterglow of one GRB were a propagation effect. Choosing the GRB with the largest value of $K(z)/\nu^2$, we have a time lag of $\tau/(1+z) = 2.700 \pm 0.006$ day associated with GRB 980703A at $z = 0.967 \pm 0.001$ measured at a frequency of $\nu = 1.43$ GHz.

Setting $\delta = 0$ and noting that $K(z)/\nu^2 = 1170 \pm 10 \text{ Mpc GHz}^{-2}$ measured time lag τ fixes $\varepsilon/M \simeq 9 \times 10^{-6} \text{ eV}^{-1}$.

Turning to our data sample of 53 GRBs we make a least-squares fit to determine \tilde{A}_0 and $\delta((1+z)\nu)$. We require $\tilde{A}_0 > 0$.

In the GRB rest frame: 4.0 – 12 GHz (\blacktriangledown , green), 12 – 30 GHz (\blacksquare , maroon), and 30 – 75 GHz (\blacklozenge , blue).



We fit to the points with frequencies of 4.0 – 75 GHz in the GRB rest frame, with a scale factor in the uncertainty in $\tau/(1+z)$ of 450 yields $\chi^2/\text{ndf} = 1.13$, with $\tilde{A}_0 = 0.0010 \pm 0.0019 \text{ day GHz}^2 \text{ Mpc}^{-1}$ and $\delta = 0.65 \pm 0.10 \text{ day}$. Thus $\tilde{A}_0 < 0.005 \text{ day GHz}^2 \text{ Mpc}^{-1}$ at 95% CL, and we determine

$$|\epsilon|/M < 1 \times 10^{-5} \text{ eV}^{-1}$$

at 95% CL.

cf. laser experiment constraint on millicharged particle production:

$$|\epsilon| < 3 - 4 \times 10^{-7} \text{ for } M \leq 0.05 \text{ eV.}$$

[Ahlers et al., PRD 2008]

Our scale factor is very large! This may stem, in part, from the circumburst environment, and, more generally, from time delay effects which arise from neither source effects nor propagation effects across the expanse of space.

[Note Frail et al., ApJ 2006 for discussion of GRB 050904A.]

We have studied the dependence of our fit results on the selected frequency window, as well as the stability of our fits to the significance of the radio afterglow observation, to evolution effects in z , and to the more poorly determined red shifts and radio afterglows and find no significant changes.

How much would our limits have to improve before dispersive effects from ordinary charged matter would become apparent?

Only contributions to \tilde{A}_0 from free electrons can be appreciable.

We estimate the cosmological free electron energy density ρ_e to be no larger than $\rho_e = (M_e/M_p)\rho_{\text{cr}}\Omega_b \approx 0.130 \text{ eV/cm}^3$.

Replacing $\rho_0 \rightarrow \rho_e$ and $\varepsilon/M \rightarrow 1/M_e$ in \tilde{A}_0 we find that our limit would have to improve by $\mathcal{O}(2 \times 10^{-3})$ before the contribution from free electrons could be apparent.

How much can our limits improve?

Systematic measurements at longer wavelengths would be extremely helpful.

Note, e.g., future 21 cm studies...

Measure redshifted 21 cm H line $0.5 < z < 2$ (about 500 MHz to 1000 MHz)

[J. Marriner, FCPA retreat, April 2009]

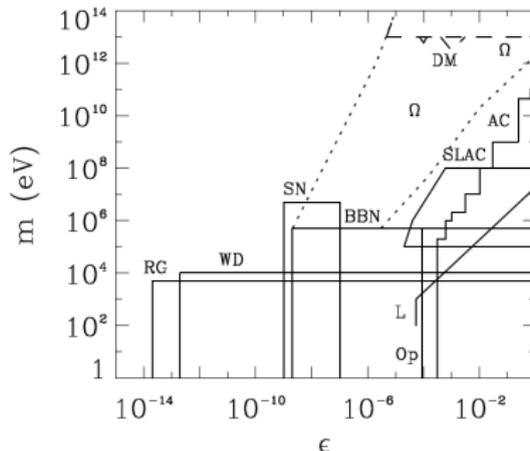
Our limits are set with observations at frequencies no lower than $\approx 5 \text{ GHz}$.

One can expect linear improvement in our limit on ε/M as ν decreases.

Other Millicharged Limits

These can be quite severe, though they are all indirect constraints. **There are constraints on the millicharge per se.**

[Davidson, Hannestad, and Raffelt, review, JHEP 2000.]



There are models in which the dynamics which give rise to millicharged matter are not operative at stellar temperatures.

[Masso Redondo, PRL 2006]

There are also constraints on long-range DM self-interactions.

These constrain the fine-structure constant in the dark sector and emerge from the manner in which numerical simulations of galactic structure confront observation.

Thus we have known for some time that dark matter does not have $|\varepsilon| = 1$.

[Gradwohl and Frieman, ApJ 1992]

More severe constraints appear to arise from studies of small scale structure!! [Feng et al., arXiv:0905.3039]

Summary and Outlook

The preponderance of matter is unknown, and we can probe its nature via its interactions with light.

The discovery of a non-zero millicharge would signal that dark matter is stable by dint of an internal $U(1)$ symmetry.

The discovery of dispersive effects in the speed of light in propagation from distant GRBs, more generally, would signal the presence of dark matter.

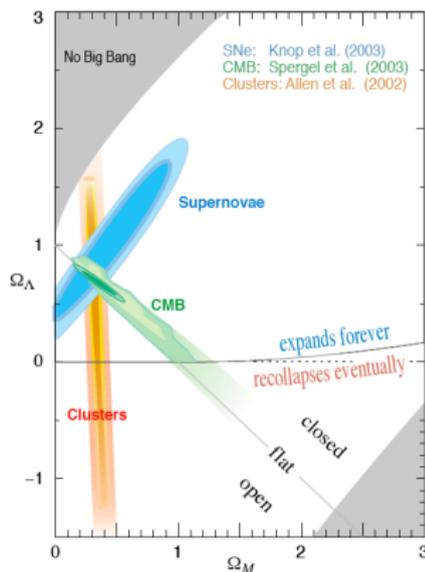
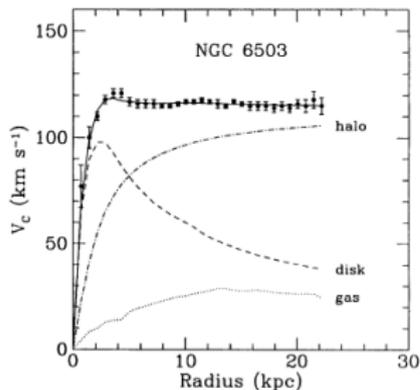
Studies of dispersive effects at optical energies and beyond can constrain "wimless" models and more....

Backup Slides

Observational Evidence for Dark Matter

Dark matter is established under the assumption that gravity is understood.

Note **galactic rotation curves** [V. Rubin et al., astro-ph/9904050] and a **cosmic “concordance”** [PDG, RPP, 2006.]



Today $\Omega_\Lambda \approx 0.73$, $\Omega_M \approx 0.27$, but $\Omega_{\text{baryon}} \approx 0.05$.
Most of the matter is unknown!