

Dark Matter in the Universe

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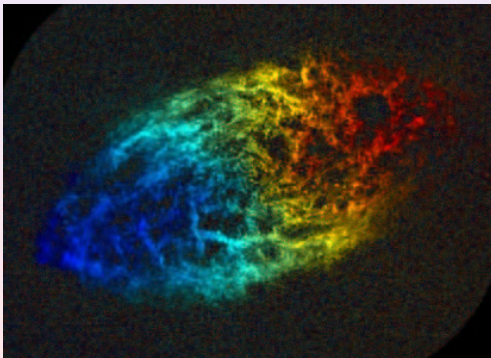
Prehistory:

- Zwicky 1933: estimates mass of Coma cluster with virial theorem, $\langle E_{kin} \rangle = -\frac{1}{2} \langle E_{grav} \rangle$
- ⇒ virial mass a factor 10 larger than luminous mass.
- Rubin, Ford 1970: rotation curves of galaxies are flat



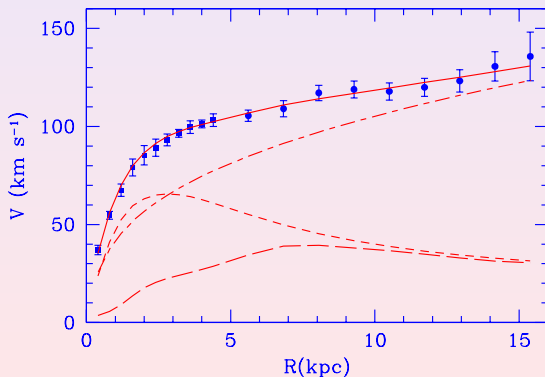
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The standard lore:

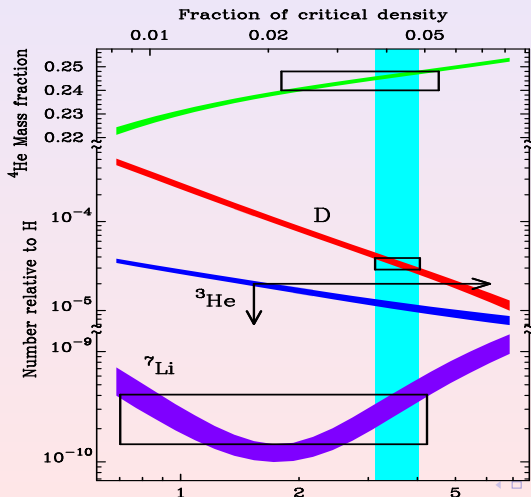
- inflation suggests $\Omega \equiv \rho/\rho_{\text{cr}} = 1$

$$H^2 \equiv \frac{8\pi}{3}G\rho - \frac{k}{R^2} + \frac{\Lambda}{3}$$

with $\rho_{\text{cr}} = 3H_0^2/(8\pi G)$

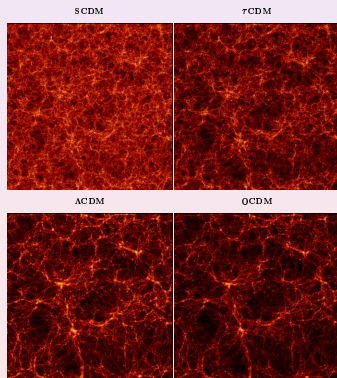
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- inflation suggests $\Omega \equiv \rho/\rho_{\text{cr}} = 1$
- BBN constrains baryon content, $\Omega_b h^2 = 0.019 \pm 0.001$



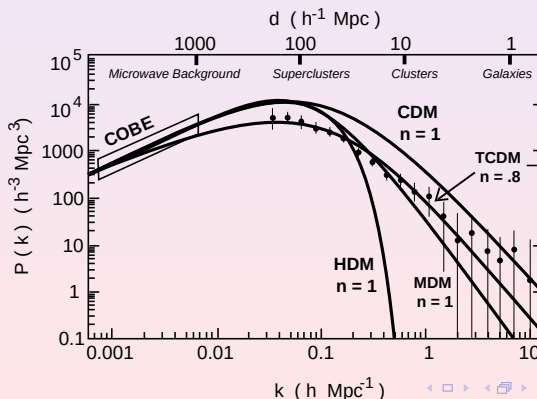
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- **Large-scale structure** requires that DM is
 - dissipation-less
 - “cold”, i.e. non-relativistic already for $z \gg z_{\text{dec}}$



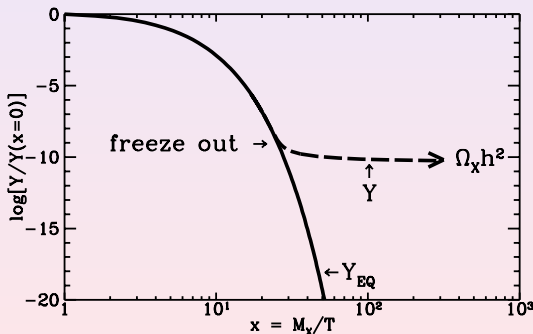
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The standard lore:

- inflation suggests $\Omega = 1$
- BBN constrains baryon content, $\Omega_b h^2 = 0.019 \pm 0.001$
- LSS requires that DM is dissipation-less and “cold”
- **thermal production** of CDM,



$$\Omega_X h^2 \sim \frac{3 \times 10^{-27} \text{cm}^3/\text{s}}{\langle \sigma v \rangle}$$

suggests **weakly interacting DM particle with mass $m \sim m_Z$**

The standard candidate: Neutralino

- SM: no baryogenesis, dark matter, structure formation
- SUSY as a well-motivated extension of the SM
- gauge coupling unification and hierarchy problem as evidence for low-scale SUSY
- R parity $R = (-1)^{3B+L+2s}$ reduces proton decay problem of SUSY GUTs

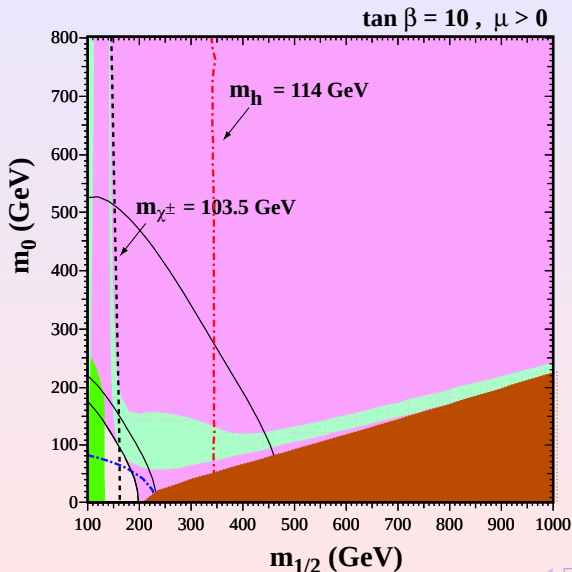
⇒ LSP is stable

⇒ **neutralino**

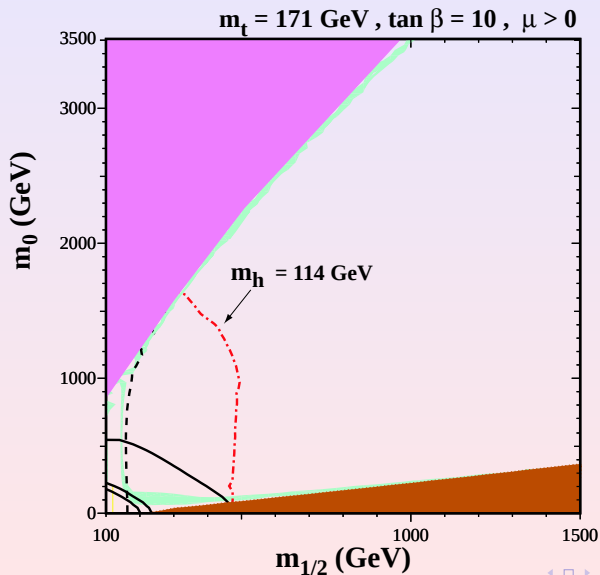
$$\chi = Z_{11}\tilde{B} + Z_{12}\tilde{W} + Z_{13}\tilde{H}_1 + Z_{14}\tilde{H}_2$$

possible **WIMP** candidate

Status of neutralino DM after LEP II:



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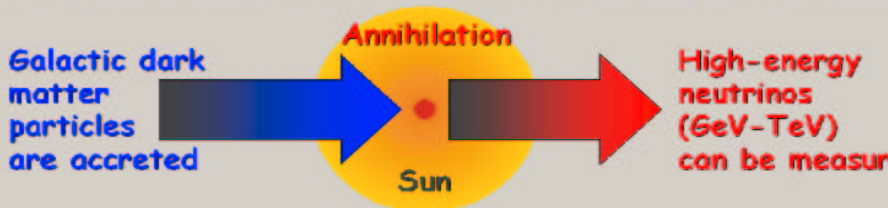


Status of neutralino DM after LEPII:

- after LEP: “same” fine-tuning even in SUSY required
- final word: LHC
- N.B.: **gravitino** is a good **LSP** (no reheating problem)

Neutralino as LSP: direct vs indirect detection

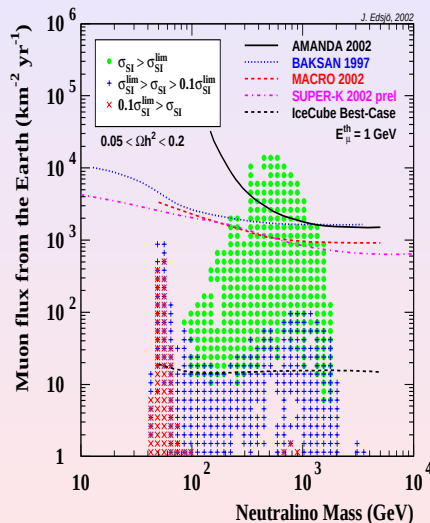
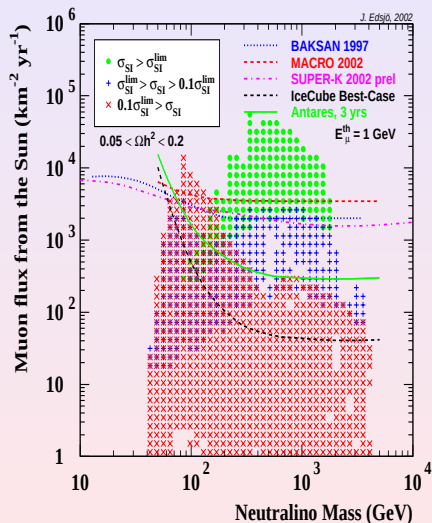
Indirect Method (Neutrino Telescopes)



Direct Method (Laboratory Experiments)



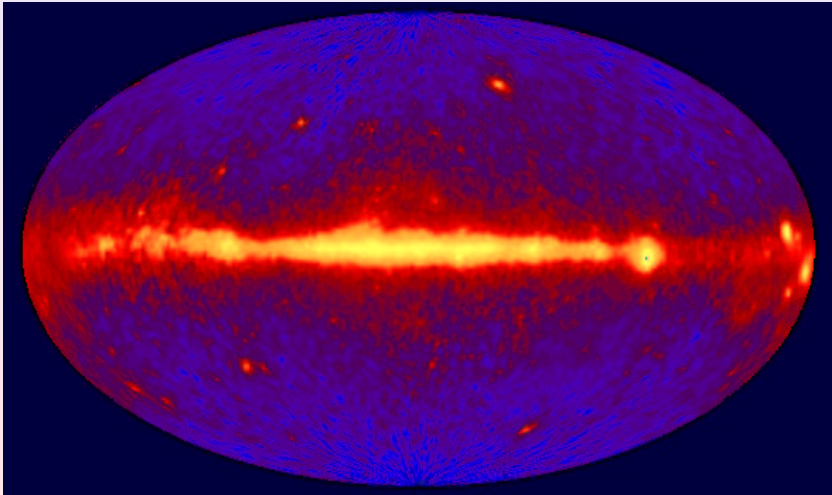
Muon flux from $\chi\chi$ annihilations (Sun vs. Earth):



Indirect detection claims:

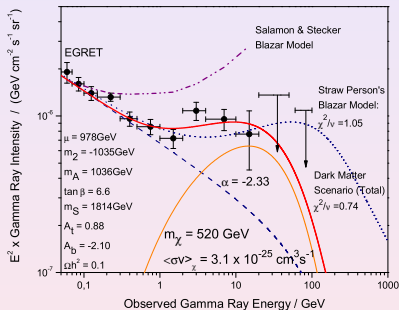
[Elsässer, Mannheim '04]

- Signal from $\chi\chi$ annihilations in the diffuse extragalactic photon background:



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- Signal from $\chi\chi$ annihilations in the diffuse extragalactic photon background:



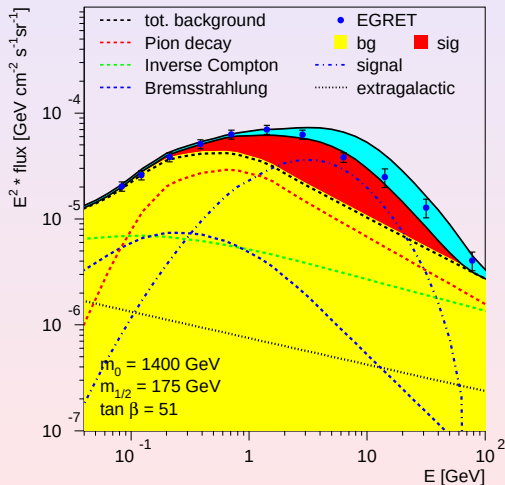
problems:

- modeling of background
- should lead to Galactic signal
- assumes γ absorption, not development of el.-mag. cascade

Indirect detection claims:

[de Boer et al. '03-06]

- Signal from $\chi\chi$ annihilations in the Galactic photon flux:

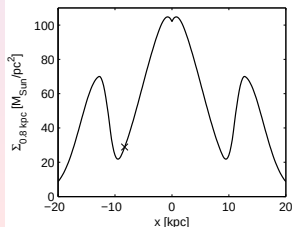
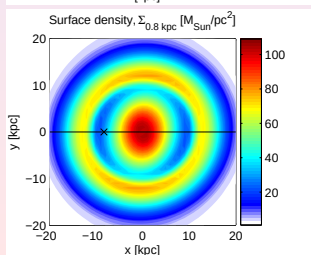
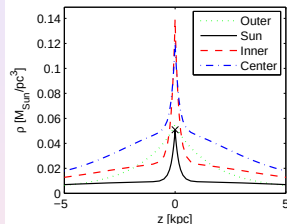
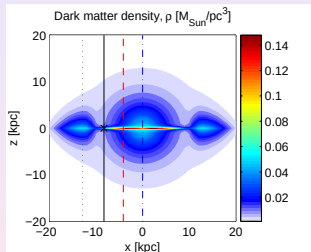


Indirect detection claims:

[de Boer et al. '03-06]

problems:

- DM distribution inconsistent with dissipationless



Indirect detection claims:

[de Boer et al. '03–06]

problems:

- DM distribution inconsistent with dissipationless
- anti-proton flux too large [Bergström, Edsjö, Gustafsson, Salati '06]
- boost factor very large
- assumes perfect modelling of astrophysical backgrounds
- if global CR parameters are allowed to deviate from local ones, **good fit without DM**

Summary of (other) detection claims:

- HESS high-energy excess from GC
- annual modulation signal of Dama
- discovery needs convincing signature:
 - 2γ line
 - directional signal (HE ν from Sun)
 - different DM signals fit together
 - cross-check by accelerator

Non-thermal DM: Axions

- Strong CP problem:

$$\mathcal{L} = -\frac{\alpha_s}{8\pi} \underbrace{(\theta - \arg \det M_q)}_{\bar{\theta} < 10^{-9}} G\tilde{G}$$

- interpretate $\bar{\theta}$ as field $\bar{\theta} \rightarrow a/f_a$, introduce potential such that $a \rightarrow 0$

⇒ axions couple to gluons and mix with pions

$$\mathcal{L} = -\frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G}$$

- axions are “like” pions, thus

$$m_a = m_\pi \frac{f_\pi}{f_a} \sim 0.6 \text{eV} \frac{10^7 \text{GeV}}{f_a}$$

i.e. light axions decouple

Non-thermal DM: Axions

- coupling to photons

$$\mathcal{L} = -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}, \quad g_{a\gamma} = \frac{\alpha}{2\pi f_a}C_\gamma$$

- Primakoff effect:



Cosmological Production of Axions

- light axions, $m_a \lesssim 1$ eV, were **never in thermal equilibrium**,
- possible **CDM** candidate

two production mechanisms:

- misalignment mechanism: axion mass is switched on at the **QCD phase transition**, $T \approx 200$ MeV. If axion field wasn't at minimum, **coherent oscillations** will be **excited**,

$$\Omega_a h^2 \approx 2 \times 4^{\pm 1} (\mu\text{eV}/m_a)^{1.2} \theta_i^2$$

- **axionic strings** form during the PQ phase transition and **emit axions** later on.

Stellar evolution limits:

- virial theorem:

$$\langle E_{kin} \rangle = -\frac{1}{2} \langle E_{grav} \rangle$$

$\Rightarrow$ star has negative specific heat

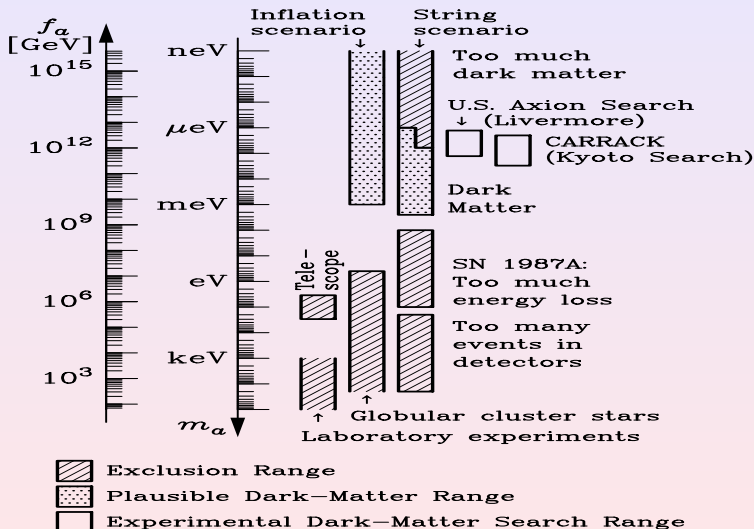
contraction $\Rightarrow$ heating & heating $\Rightarrow$ expansion

- self-regulated nuclear burning via interplay of thermal pressure and gravitation
- novel energy loss leaves stellar structure nearly unchanged, but leads to heating and thus to increased consumption of nuclear fuel
- reduction of stellar lifetime:

$$\frac{\delta\tau}{\tau} \sim \frac{L_a}{L_\gamma} \lesssim 1$$

$\Rightarrow$ upper limit on $g_{a\gamma}$, m_a ; lower limit on f_a

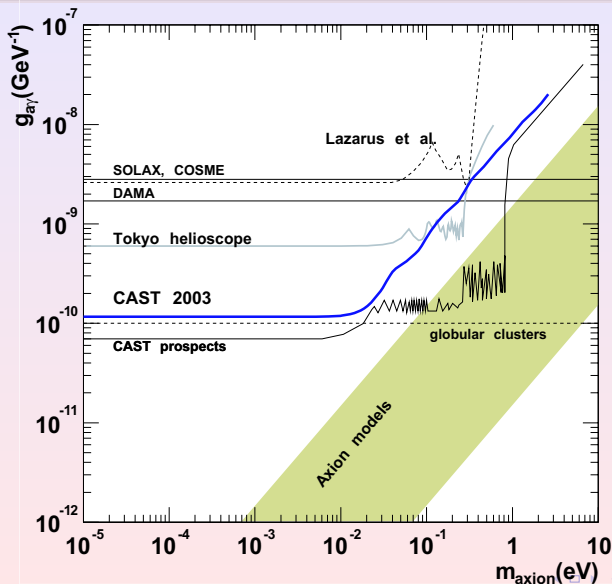
Summary of (old) axion limits:



Detection of Axions



Detection of Axions

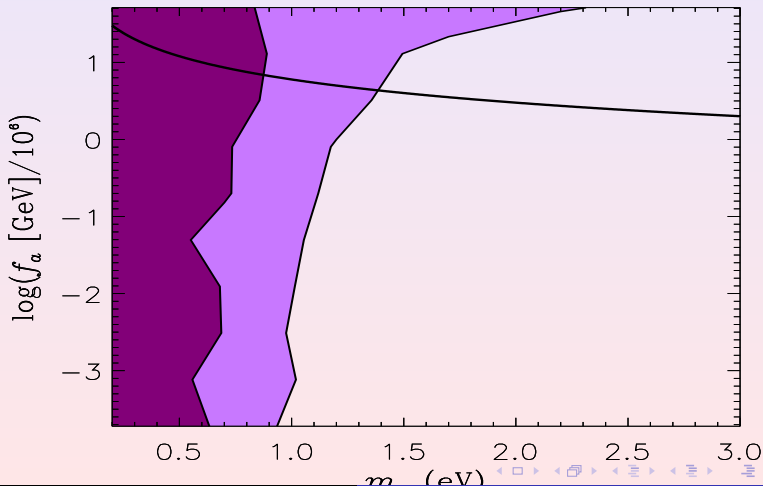


Axion limits II:

- cosmology and CAST sensitivity overlap now,

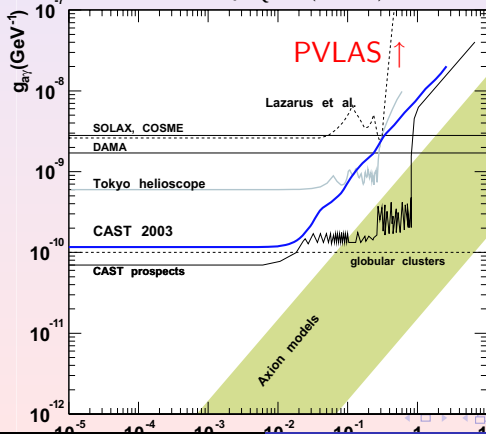
[Hannestad, Raffelt,

Mirizzi '05]



Axion limits II:

- cosmology and CAST sensitivity overlap now, [Hannestad, Raffelt, Mirizzi '05]
- global symmetries broken by gravity: power/exp. suppressed?
- **PVLAS**: $m_{a-7} \sim 1$ meV and $f_{PQ} = (2-6) \times 10^5$ GeV



Axion limits II:

- cosmology and CAST sensitivity overlap now, [Hannestad, Raffelt, Mirizzi '05]
- global symmetries broken by gravity: power/exp. suppressed?
- PVLAS: $m_a \sim 1$ meV and $f_{\text{PQ}} = (2 - 6) \times 10^5$ GeV
- new light vector particle ($\partial_\mu a \rightarrow B_\mu$) [Antoniadis, Boyarsky, Ruchayskiy '06]

Gravitational creation of superheavy matter

- Small fluctuations of field Φ obey

$$\ddot{\phi}_k + [k^2 + m_{\text{eff}}^2(\tau)] \phi_k = 0$$

- If m_{eff} is time dependent, vacuum fluctuations will be transformed into real particles.
 $\Rightarrow$ expansion of Universe leads to particle production

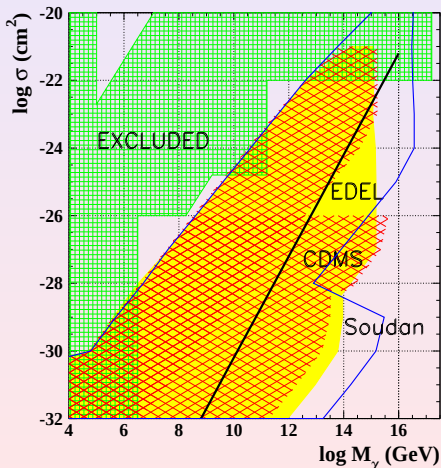
- In inflationary cosmology

$$\Omega_X h^2 = \left(\frac{M_X}{10^{12} \text{GeV}} \right)^2 \frac{T_{RH}}{10^9 \text{GeV}}$$

independent of details of particle physics, for any $M_X \lesssim H_I$

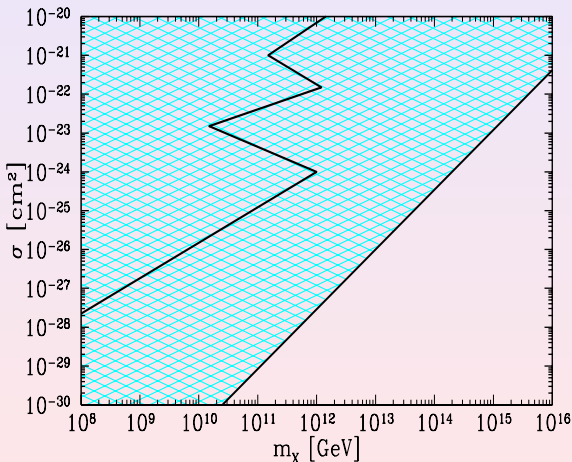
Detection of superheavy matter:

- **direct detection:** density $1/M_X$, recoil energy is constant
 $\Rightarrow$ large $\sigma_{\chi N}$ required



Detection of superheavy matter:

- **indirect detection** via neutrinos from the Sun:
detectable rate in ICECUBE $\Rightarrow \langle \sigma v \rangle \sim 10^{-26} \text{ cm}^2$



Lifetime of superheavy matter:

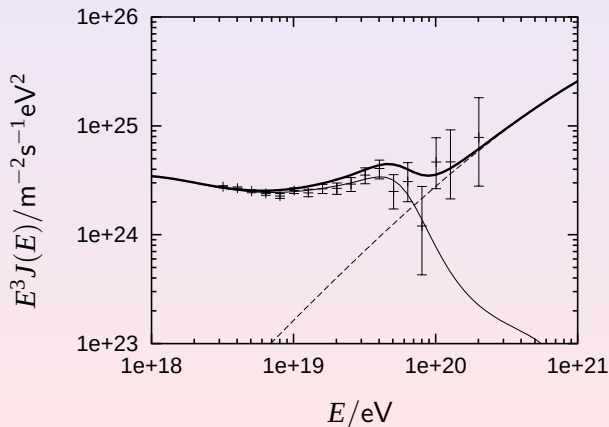
- for SHDM, even gravitational interactions $d = 5$ result in cosmological short lifetimes, $\tau_X \ll t_0$.

three possibilities:

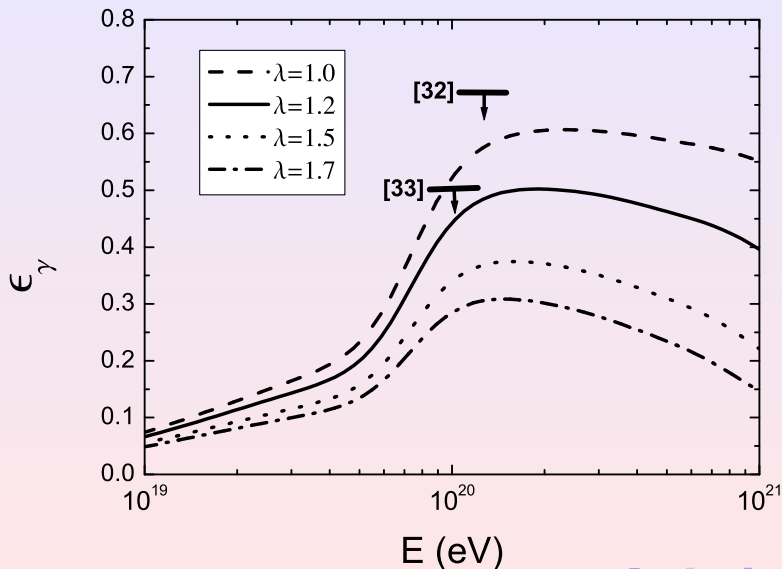
- (global) symmetry,
perhaps broken by wormhole effects, $\tau_X \propto \exp(S)$ or by
instanton effects, $\tau_X \propto \exp(4\pi^2/g^2)$
- discrete symmetries forbid operators with $d < 9$
- crypton, i.e. fractionally charged and confined particle of
superstring theories

Connection SHDM and UHECRs:

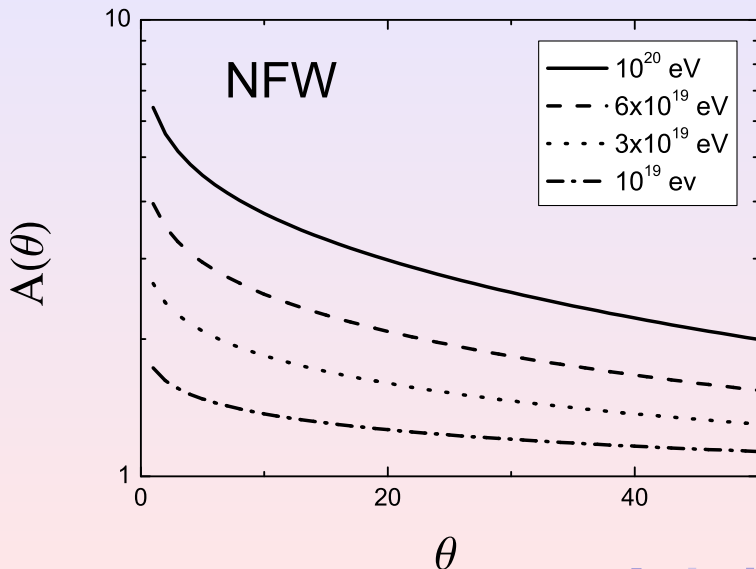
- UHECR above the GZK cutoff via photon, nucleon secondaries



Detection/exclusion of superheavy matter:



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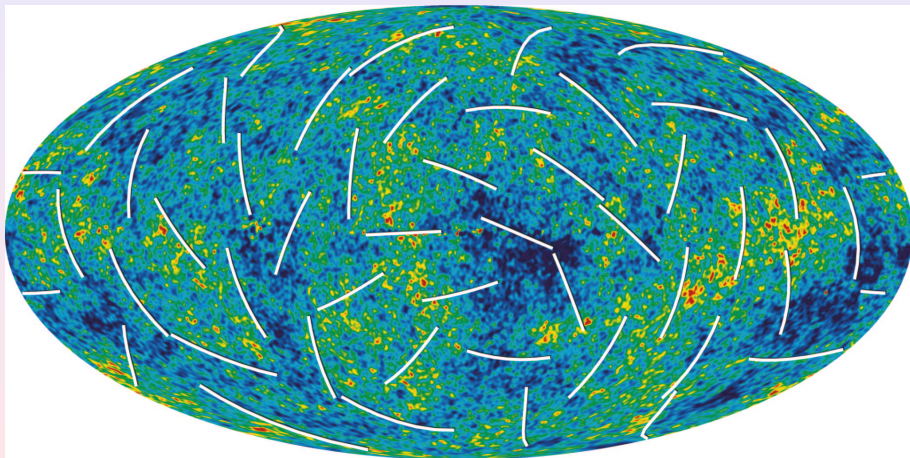


Summary superheavy dark matter:

- if stable, example of a well-motivated, undetectable DM particle
- **meta-stable** as explanation for UHECRs: close to be **excluded**

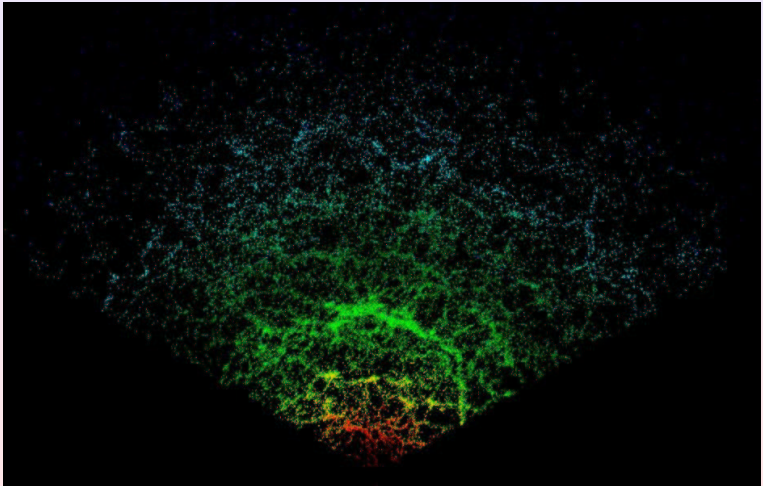
Concordance model

- CMB anisotropies:



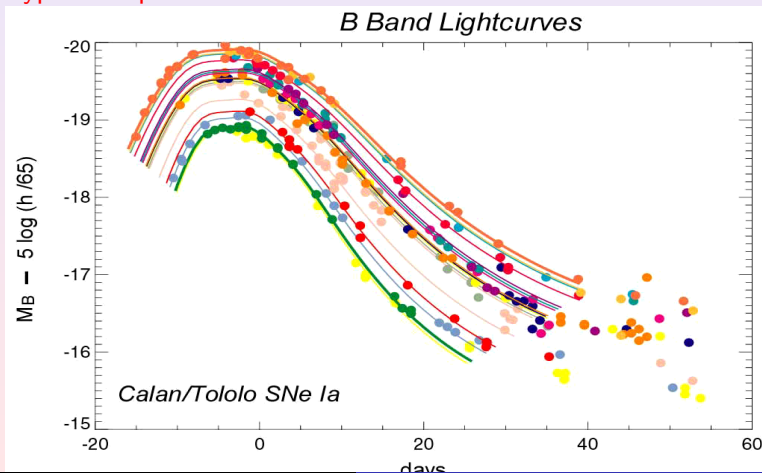
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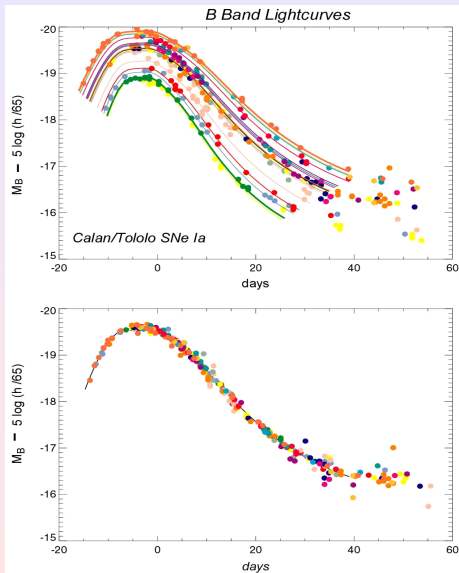


Concordance model

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- Type Ia Supernovae:

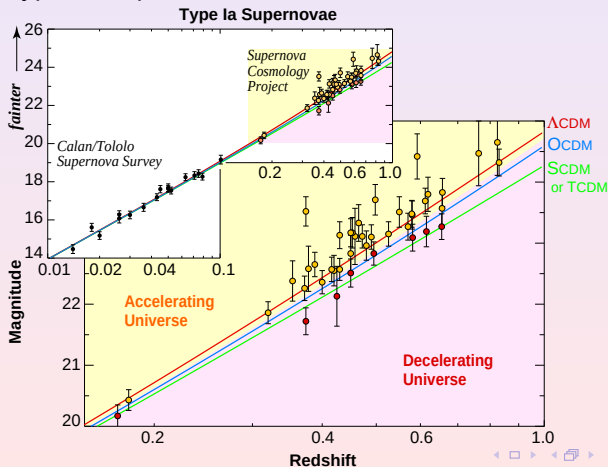


Concordance model



Concordance model

- CMB anisotropies
- Galaxy surveys
- Type Ia Supernovae:



Concordance model

Observations as probe of different redshifts:

- BBN ($z \sim 10^{10}$)
- CMBR ($z \sim 10^3$)
- SNe Ia ($0.3 < z < 2.5$)
- LSS ($z \lesssim 10$)

⇒ agreement leads to “concordance model” of cosmology with

- $\Omega_\Lambda \sim 0.7$
- $\Omega_m \sim 0.3$

Is modifying gravity an alternative?

- most evidence for DM from motions of luminous matter in gravitational fields
- Milgrom '84: modify Newton's law for accelerations
 $a < a_0 = 10^{-8} \text{ cm/s}^2$ ($a_0 \sim cH_0$)
- explains rotation curves of galaxies, Tully-Fisher relation
- rel. generalization exists (TeVeS):
two metrics related through

$$g_{\mu\nu} = e^{-2\phi}(\tilde{g}_{\mu\nu} + A_\mu A_\nu) - e^{2\phi} A_\mu A_\nu$$

with additional scalar

$$S_s = -\frac{1}{16\pi G} \int d^4x \sqrt{-\tilde{g}} [\mu (\tilde{g}^{\mu\nu} - A^\mu A^\nu) \phi_{,\mu} \phi_{,\nu} + V(\mu)]$$

and vector

$$S_v = -\frac{1}{32\pi G} \int d^4x \sqrt{-\tilde{g}} \left[K F^{\alpha\beta} F_{\alpha\beta} - 2\lambda (A^\mu A_\mu + 1) \right]$$

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- rel. generalization exists (TeVeS):
- fails in cluster of galaxies
- CMB and LSS?

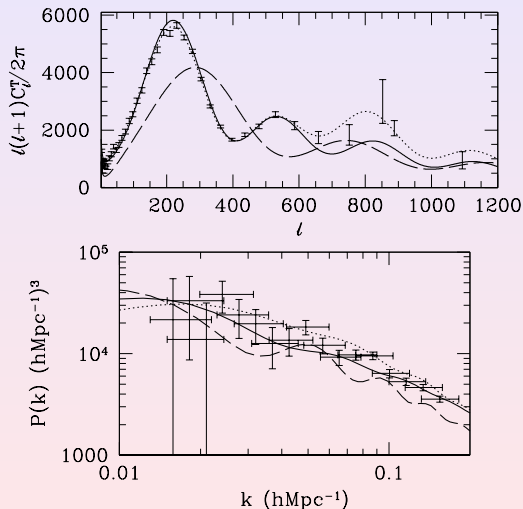
Power spectrum in MOND:

- CDM crucial for relative size of CMB peaks:
 - $n = 1, 3, 5, \dots$ peak baryons and CDM in phase
 - $n = 2, 4, \dots$ peak baryons and CDM out of phase

⇒ odd-numbered peaks enhanced
- Silk damping suppresses power on small scales
- enough degeneracy so that MOND **can mimic this?**

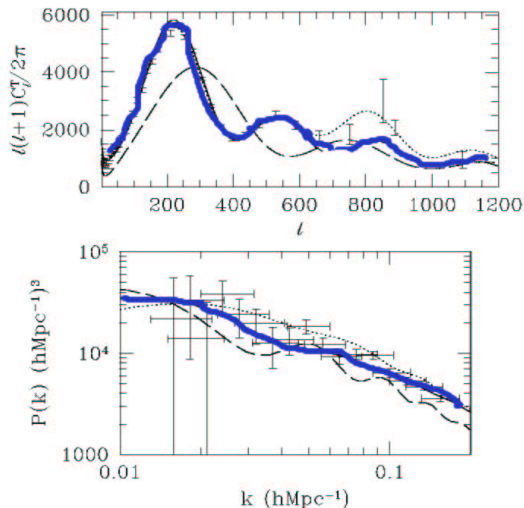
Power spectrum in MOND:

[Skordis, Mota, Ferreira, Boehm '05]

MOND with $\Omega_\Lambda = 0.78$ and $\Omega_\nu = 0.17$

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Power spectrum in MOND:

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TeVS:

- worse fit to data
- fails in cluster
- requires still $\Lambda \neq 0$
- esthetically a disaster

Summary

- Cosmology probes only generic properties of DM: abundance, cold, dissipation-less
- various candidates with these properties: neutralino, gravitino, axion, axino, SHDM, ...
- only a combination of accelerator, direct and/or indirect searches can identify the DM particle
- even in the best-case scenario (SUSY at LHC), confirmation of LSP as DM by (in-) direct searches necessary
- **dark energy/ Λ theoretical challenge** – alternatives to “concordance model”?