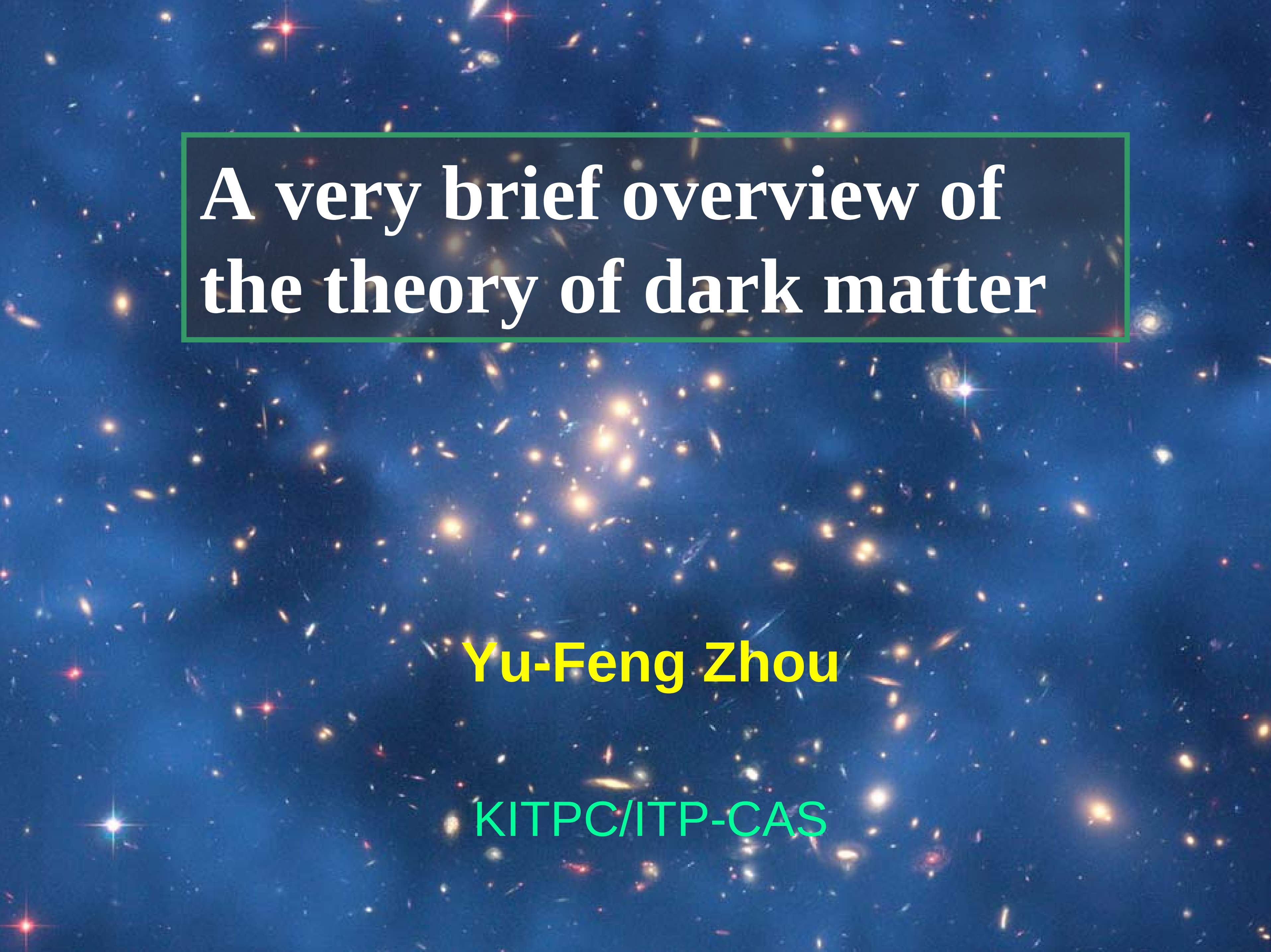


A very brief overview of the theory of dark matter

Yu-Feng Zhou

KITPC/ITP-CAS

Outline

- Introduction: evidences of DM from observations
- WIMPs as DM candidates
- Implications of the recent experimental results for the nature of DM
  - Decaying DM
  - Strongly interacting DM
  - Nonthermal DM, superWIMP
  - Others: WIMPless, multi-component DM, Asymmetric DM, Inelasstic DM etc.

Out of equilibrium: the origin of species

- Number density highly suppressed

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} \boxed{e^{-m/T}}$$

at low temperature $T = 2.7\mathrm{K}$

- Predict equal number of baryons and anti-baryons for T=40MeV

$$\boxed{\frac{n_b}{n_\gamma} = \frac{n_{\bar{b}}}{n_\gamma}} \simeq \left(\frac{m_N}{T}\right)^{3/2} \exp(-m_N/T) \simeq 10^{-18}$$

There will be little left in the Universe !

But the observations give

$$\boxed{\frac{n_b}{n_\gamma} \gg \frac{n_{\bar{b}}}{n_\gamma} \simeq 10^{-10}}$$

- The conditions for baryogenesis

1. B violation
2. C and CP violation
3. Out of equilibrium

But how to generate ? no clear answer yet !

Andrei Sakharov

- Now we know that dark matter density is five times more, why ?

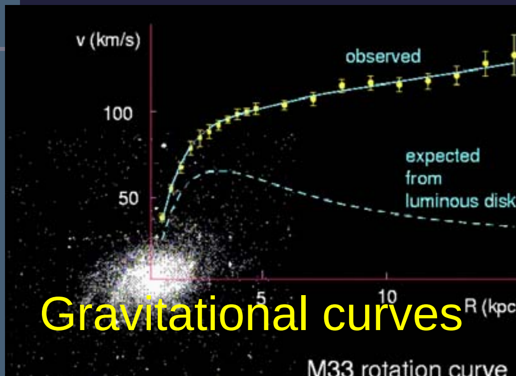
Early Indications of dark matter

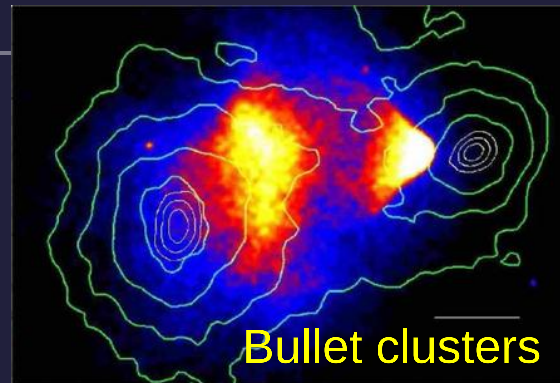
- 1933, Zwicky found a large mass-to-light ratio ~400 from velocity dispersion in the Coma cluster. The first indication of dark matter.
- 1936, Smith found unexpected high mass in the Virgo cluster.
- 1939, Babcock found that the outer region of Andromeda galaxy rotates with a high speed.
- 1959, Kahn and Woltjer inferred from the relative motion between M31 and our Galaxy that the Local Group is much heavier than expected.
- 1970, Rubin and Ford measured the rotational curve in M31 with unprecedented precision and distance (24kpc), clearly showed the existence of DM or deviation of Newton’s law of gravitation.

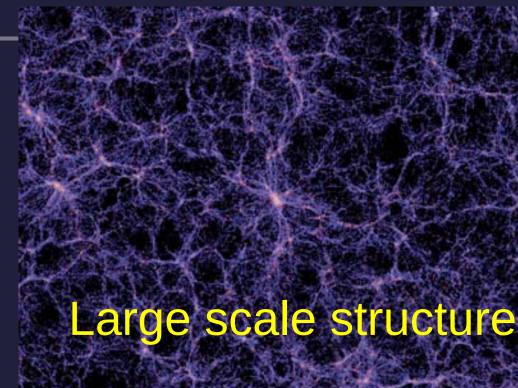
Fritz Zwicky

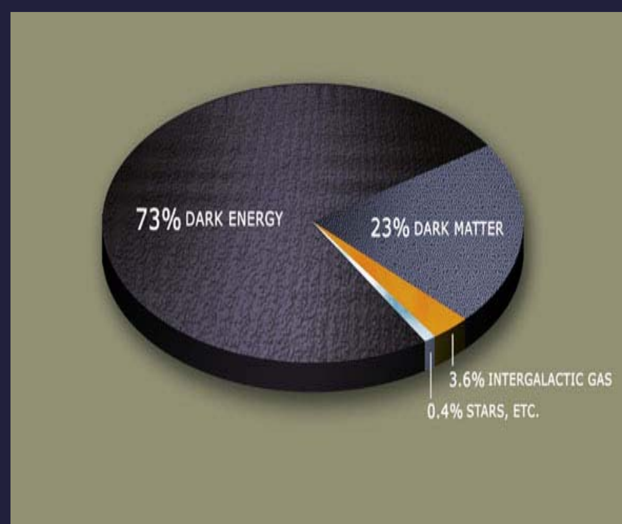
Vera Rubin

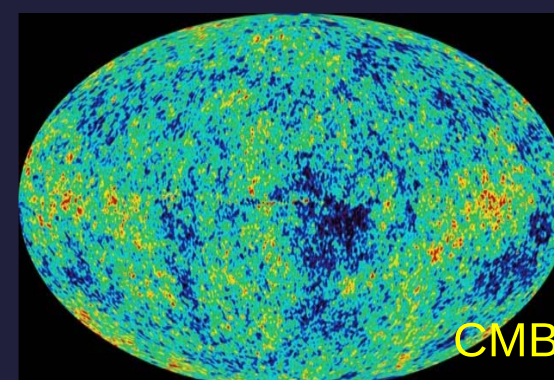
DM revealed from gravitational effects











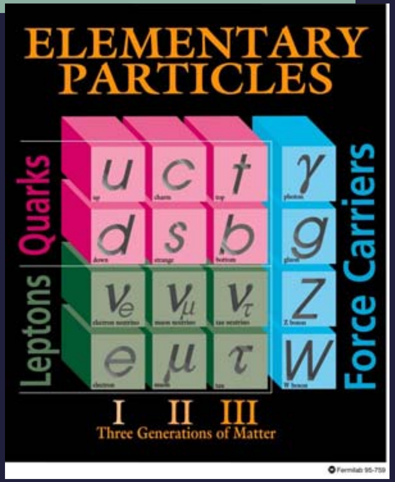
What we know about DM

- Massive: from gravitational interactions.
- Stable: lifetime longer than the age of the Universe
- Electro-magnetic and color neutral: dark, but can annihilate into photons
- Non-baryonic
  - MACHOs: disfavored by micro-lensing survey
  - MOND: disfavored by bullet clusters
  - D/H from BBN: $\Omega_b h^2 = 0.0229 \pm 0.0013$
  - CMB: $\Omega_b h^2 = 0.0226 \pm 0.00053, \; \Omega_m h^2 = 0.1334 \pm 0.005$
- Non-relativistic motion (from N-body simulations)
  - Cold DM substructure, halo core
  - Warm DM ?

A big challenge to the standard model of particle physics !

DM as a challenge to the standard model of particle physics (SM)

- The standard model (SM)
  - Particles:
    - Quarks: ~~u,d,c,s,t,b (charged)~~
    - Leptons: ~~electron (charged, stable),~~
    - ~~muon, tau (charged, unstable)~~
    - $\boxed{\text{neutrino (neutral, stable)}}$
    - Gauges bosons: ~~W, Z0 (neutral, unstable),~~
    - ~~gamma (neutral, massless)~~
    - (Higgs boson): ~~H0 (neutral, unstable)~~
  - Interactions : SU(3)xSU(2)xU(1)



Neutrino is not a viable DM candidate

- Abundance of a hot relic

$$\Omega_\nu h^2 = \sum_{i=1}^{3} \frac{m_i}{93\mathrm{eV}} \qquad \Omega_\nu h^2 < 0.07$$

$$m_\nu < 2.05\mathrm{eV}\ (95\%\mathrm{C.L.})$$

- CMB anisotropies: $\Omega_\nu h^2 < 0.0067\ (95\%\mathrm{C.L.})$
- Structure formation

neutrino erase fluctuations below ~40 Mpc, imply a top-down structure formation.

Neutrino cannot be the main part of DM,
We must go beyond the particle Standard Model !

DM and symmetries

Stability: symmetry + kinematics

- **Symmetries important for keeping particle stable**

  electron: U(1) em. symmetry, lightest charged particle

  proton: U(1) B-L symmetry, lightest baryon

  neutrino: Lorentz symmetry, lightest fermion

- **DM are often protected by symmetries**

Well-known examples

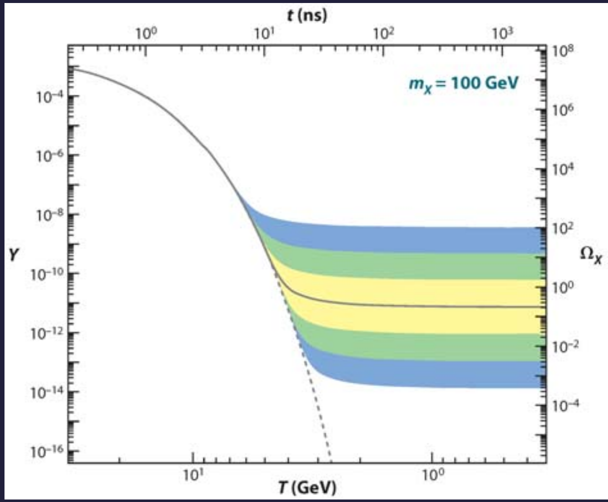
  SUSY: R-parity, LSP

  UED: KK-parity, LKP

  Little Higgs: T-parity

The WIMPs miracle

- Thermal freeze out: the origin of species



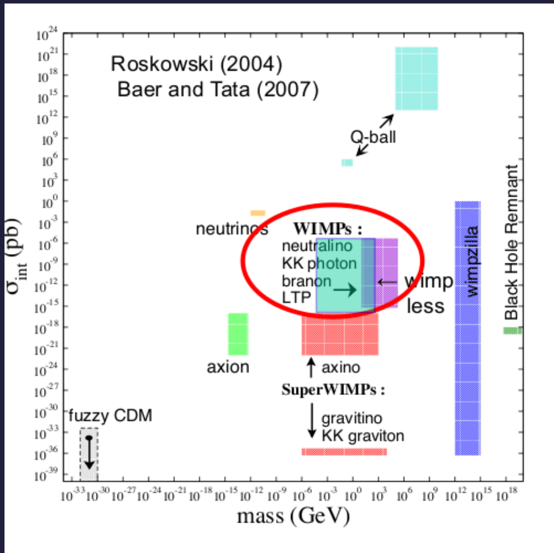
$$\frac{dY}{dx} = -\frac{<\sigma v> s}{Hx}(Y^2 - Y_{eq}^2)$$

$$\Omega h^2 \approx -\frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma v>}$$

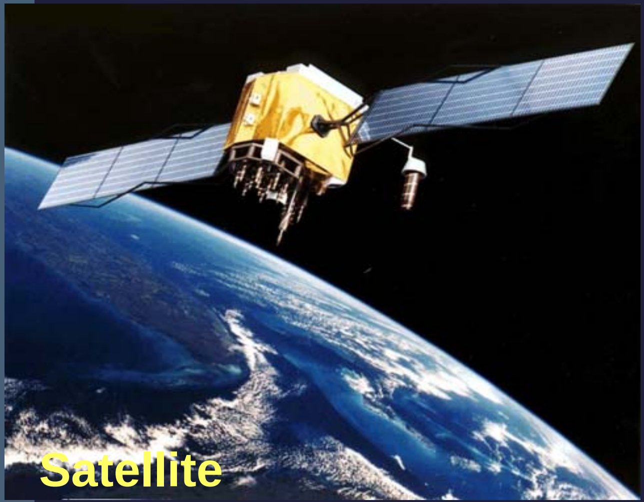
$$<\sigma v> \approx \frac{g^4}{m^2}$$

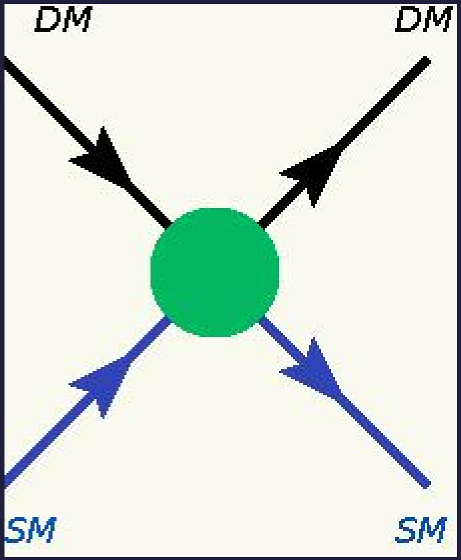
Weakly Interacting Massive Particles (WIMPs)

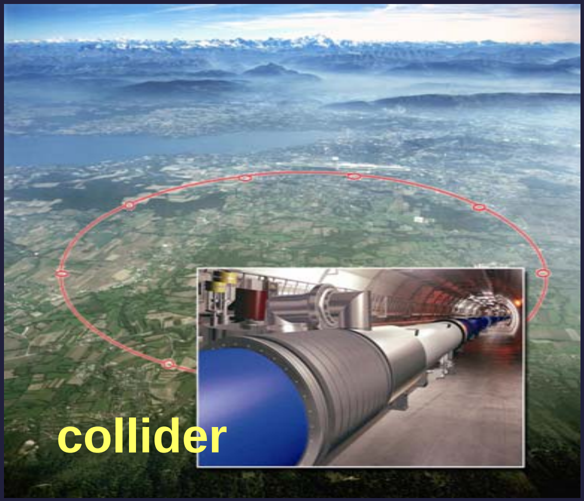
- Particle physics independently predicts WIMPs
- WIMPs have just the right relic density
- WIMPs are testable by the current exp.



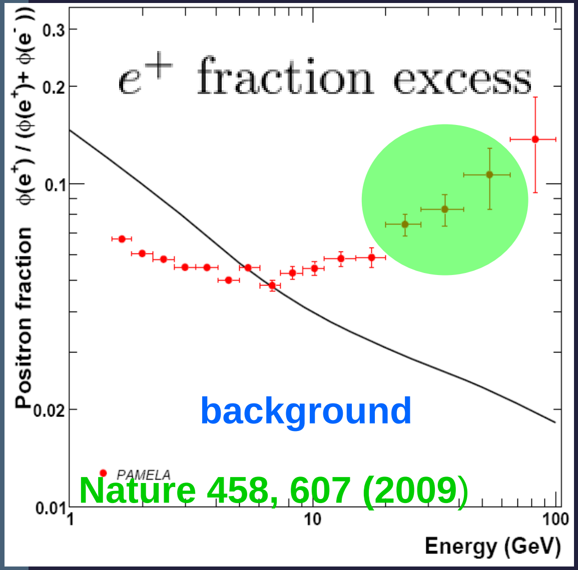
Search for non-gravitational effects ?

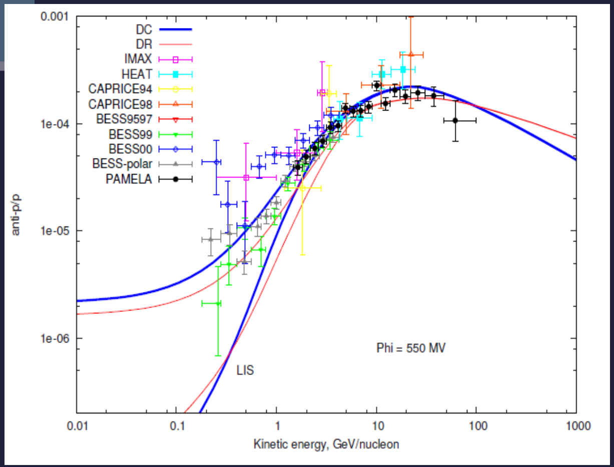






Hint of DM ? Positron fraction





PAMELA

if interpreted as DM signal

- Large annihilation cross section **now**, boost factor problem.
  - *Sommerfeld enhancement ?*
  - *Resonance enhancement ?*
  - *Non-thermal DM ?*
  - *DM may slightly decay ?*
- Mainly annihilation/decay into leptons, not quarks
  - *Light final states <1GeV ?*
  - *Leptophilic interaction ?*

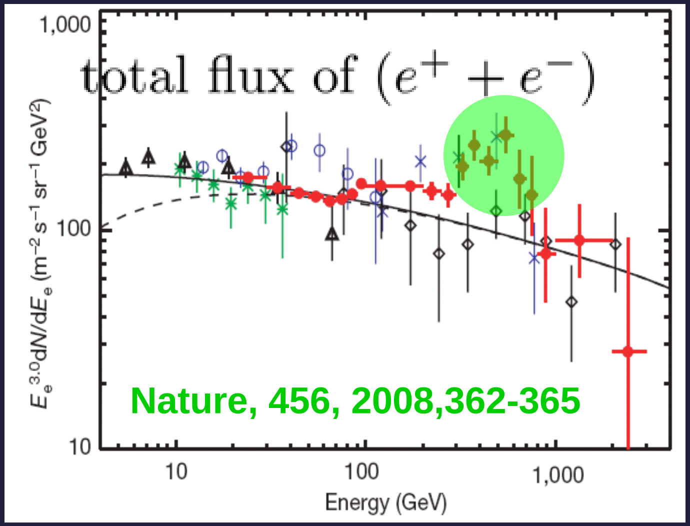
Hint of DM? electrons plus positrons

ATIC/PPB-BETS

Excess in the total flux

peak at ~600 GeV

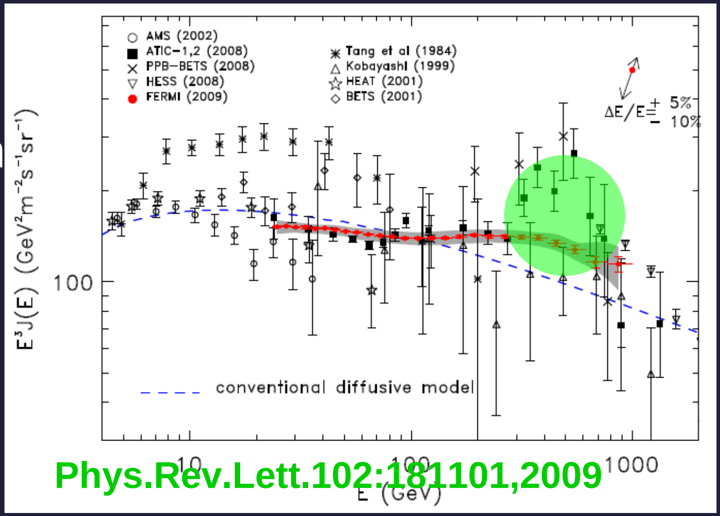
rapid drop below 800GeV



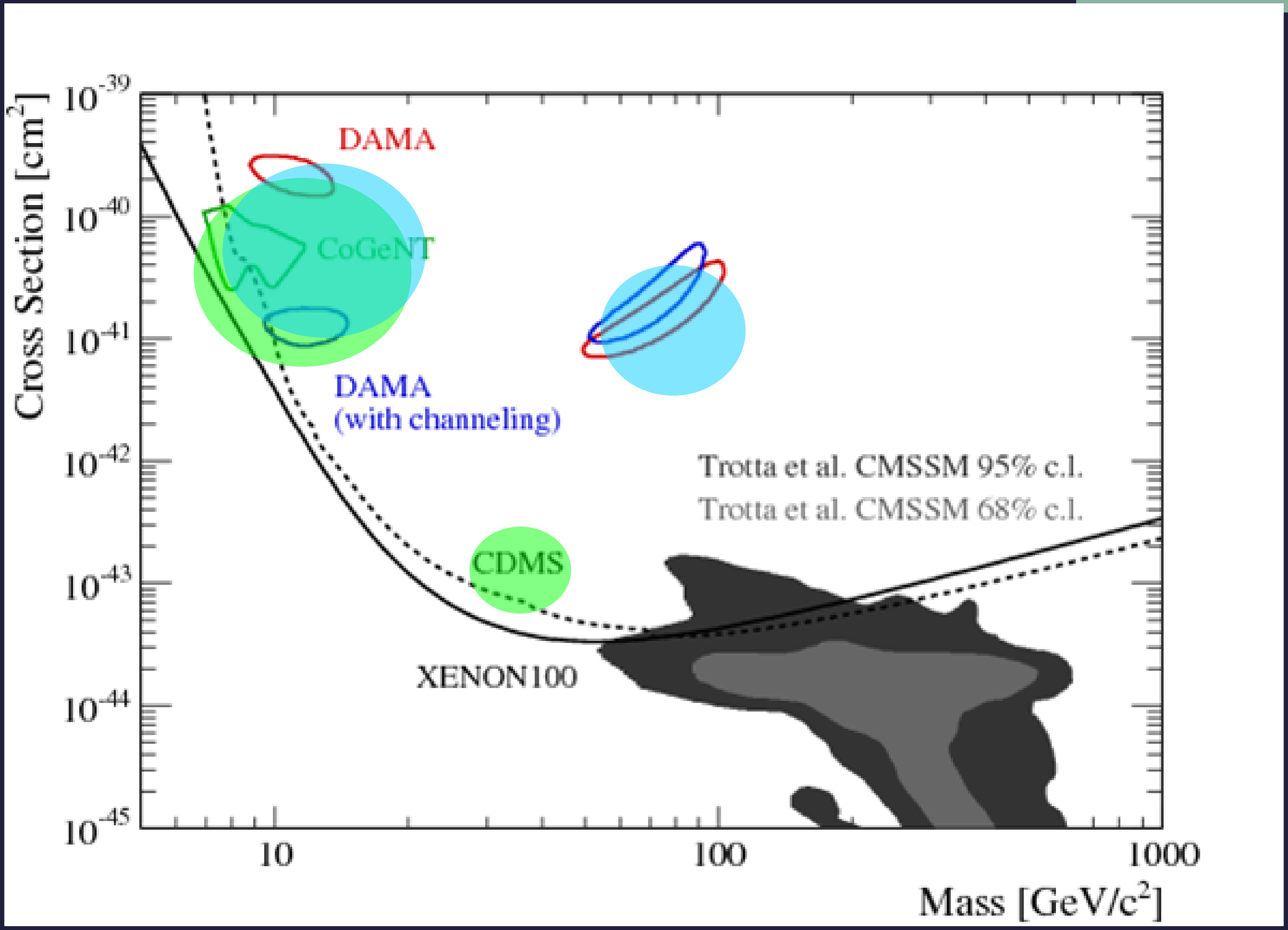
Fermi LAT

Spectrum harder than

expected background with power index around ~3.



Direct searches



Implications of the recent measurements ?

DM may not be the standard WIMP…

Decaying DM ?

DM annihilation scenario

- For standard thermal relic $\langle \sigma v \rangle_F \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

too small to account for PAMELA and Fermi data (boost factor needed)

- Annihilation rates strongly depend on halo profile
- Constrained by diffuse gamma rays

DM decay scenario

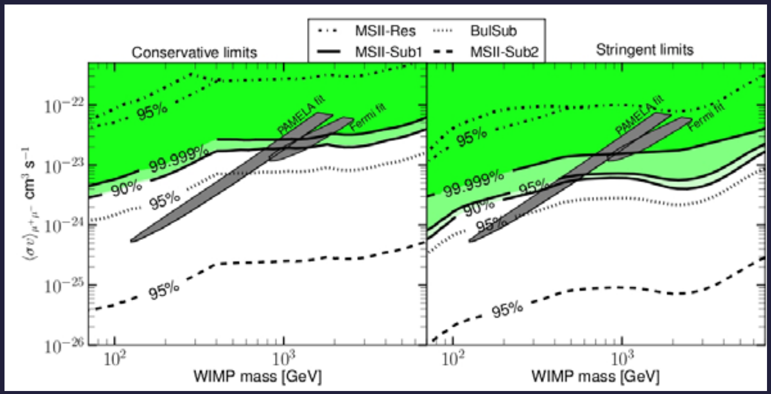
- No contradiction with relic density
- Extremely long lifetime required

$\tau \sim 10^{26}\mathrm{s} \gg \text{age of the Universe}$

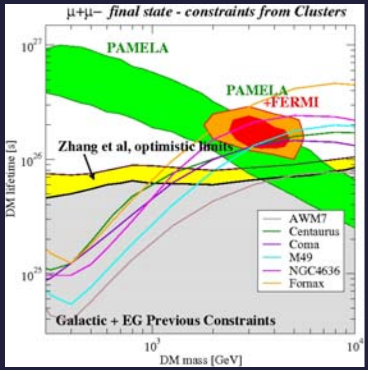
- Imply small symmetry breaking induced by high scale (GUT scale) physics

$$\mathcal{L} = \frac{1}{\Lambda} \bar{\psi} \chi \bar{\psi} \psi$$

- Less sensitive to the halo profile
- Weaker constraints



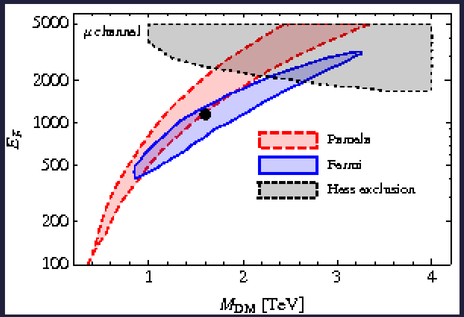
Abdo, et.al, arXiv:1002.4415



Dugger et.al, arXiv:1009.5988

Strong interacting DM ?

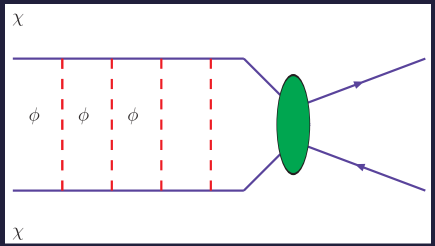
- DM annihilation interaction is weak at the time of freeze-out, but strong now.



Explanation

- Local cumps ? (unlikely)
- Temperature-dependent cross section ?
  - Strong: Sommerfeld enhancement
  - Weak: Resonance enhancement

- The Sommefeld effect



$$S_k = \left| \frac{\pi/\epsilon_v}{(1 - e^{-(\pi/\epsilon_v)})} \right| \to \frac{\pi\alpha}{v}$$

Call for long-range force !

Various constraints

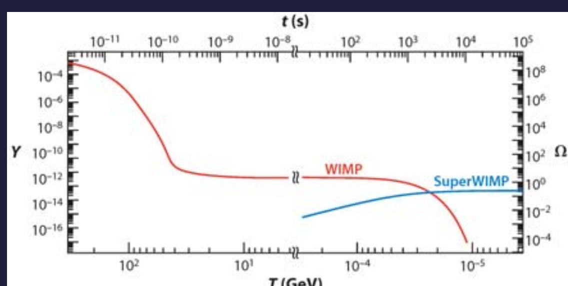
- CMB distortion
- Subhalo
- Proto-halo
- Galactic-center
- Halo shape

Nonthermal DM ?

- Thermal: decouple from thermal equilibrium
- Nonthermal: never reached thermal equilibrium (super weak)

Nonthermal generation of DM

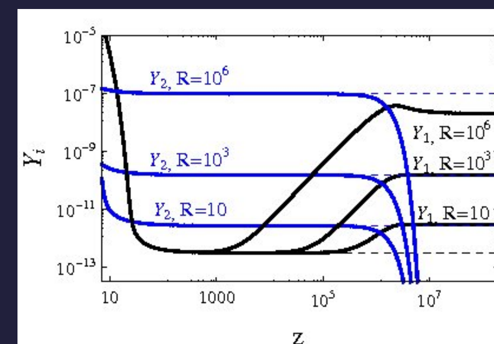
- by gravitational interaction
- by decay of unstable particles



J.L.Feng 2004

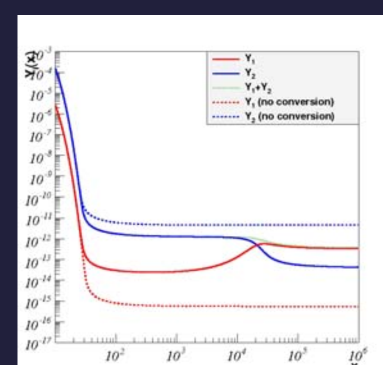
  - Late decay make affect BBN, CMB
  - DM may get warm
- by transitions from other particles

- Thermal DM density enhanced by late decay of unstable states



Zupan, etal, 2009

- Thermal DM density enhanced by other DMs



Liu, Wu, YFZ 2011

Other possibilities

- WIMP vs. WIMPless

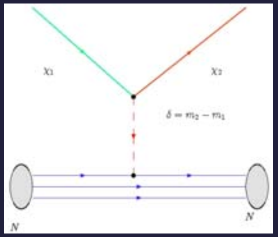
only the ratio matters

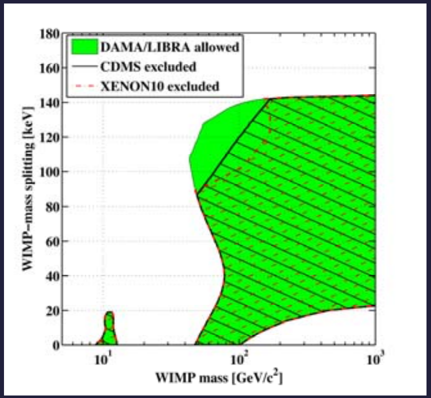
$$\Omega_X \approx \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

In GMSB models
$10^{-3} < g_X < 3,$
$10\mathrm{MeV} < m_X < 10\mathrm{TeV}$

- One component vs. multi-component DM
  - Multi-DM is natural: Neutrinos already part of the whole DM.
  - One heavy (TeV) and one light (GeV) DM can count for both indirect and direct candidate signals

- Symmetric vs. Asymmetric DM
  - In analogy to the baryon asymmetric Universe.
  - Common origin of both dark and visible matter
- Elastic vs. Inelastic DM
  - DM inelastic scattering changes the kinematics of collision
  - DAMA results can be made consistent with other experiments





Remarks & summary

- We are in an exiting era in DM search with the recent results from PMALA, ATIC, Fermi, HESS, CDMS-02, Xenon-100, GoGeNT, etc.
- The current experimental results open (re-open) many new possibilities of the nature of DM, such as: decaying DM, strong interacting DM, non-thermal DM, WIMPless, multi-component DM, asymmetric DM, inelastic DM etc.
- We are going to enter a more exiting era with the next generation DM detection exp. e.g. AMS-02, superCDMS, Xenon-1T, and CJPL (CDEX, PandaX, DarkSide)

7th International Workshop on
the Dark Side of the Universe
Sept. 26-30, 2011, KITPC/ITP-CAS, Beijing
in association with the KITPC program
"dark matter and new physics", Sept. 21-Nov. 6, 2011
"String phenomenology and cosmology", Sept. 6-Nov. 11, 2011
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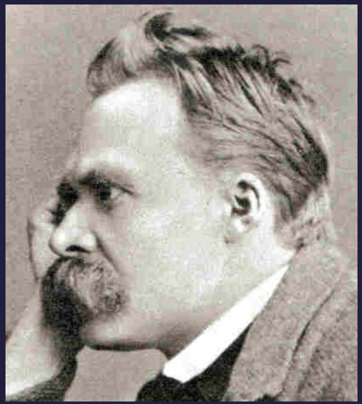
Thanks !

Modern Cosmology

from metaphysics to physics

Why is there something rather than nothing ?



Firedrich Nietzsche

Martin Heidegger

Jean-Paul Sartre

Nuclear Physics B 373 (1992) 453–478
North-Holland

NUCLEAR
PHYSICS B

Why there is something rather than nothing: Matter from weak interactions

A.E. Nelson [*,**] and D.B. Kaplan [**,+,++]

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Accepted for publication 29 October 1991

We show how the baryon number of the universe may be created by anomalous weak interactions during a first-order weak phase transition, in both conventional two-Higgs doublet models and in the supersymmetric standard model. The process we analyze involves non-equilibrium charge transport during the phase transition. Given current estimates of anomalous baryon violation rates, the models we examine are capable of producing a baryon-to-entropy ratio as large as $\rho_B/s \simeq 10^{-6}$ for maximal CP violation and optimal phase transition characteristic – many orders of magnitude larger than found with previously proposed mechanisms. Thus the observed value $\rho_B/s \simeq 10^{-10}$ can be easily explained by weak interaction physics in a manner that may eventually be experimentally verifiable.