大学共同利用機関法人
高エネルギー加速器研究機構

国立大学法人
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THE GRADUATE UNIVERSITY FOR ADVANCED STUDIES [SOKENDAI]

Dark matter in cosmology

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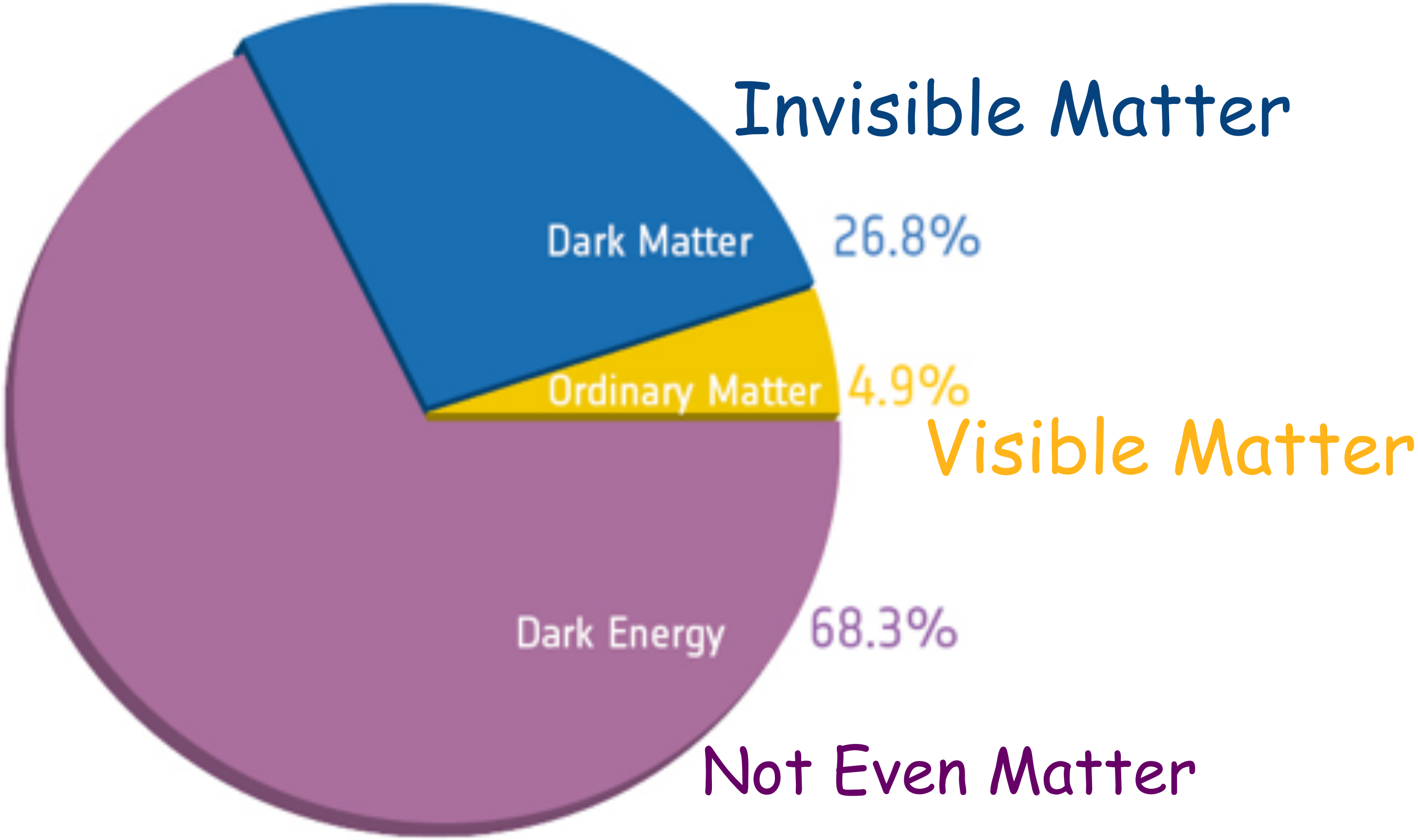
Introduction

Planck Satellite

$$\Omega_i \equiv \left.\frac{\rho_i}{\rho_c}\right|_0$$



Einstein's Cosmological Constant

Or unknown scalar field?

Friedmann equation

$$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

- Hubble parameter

$$H(t) = \dot{a} / a$$

a(t): scale factor

- Density parameter

$$\Omega_j(t) = \rho_j(t) / \rho_{cr}(t)$$

$$\rho = \rho_\Lambda + \rho_{CDM} + \rho_b + \rho_R$$

$$\rho_m = \rho_{CDM} + \rho_b$$

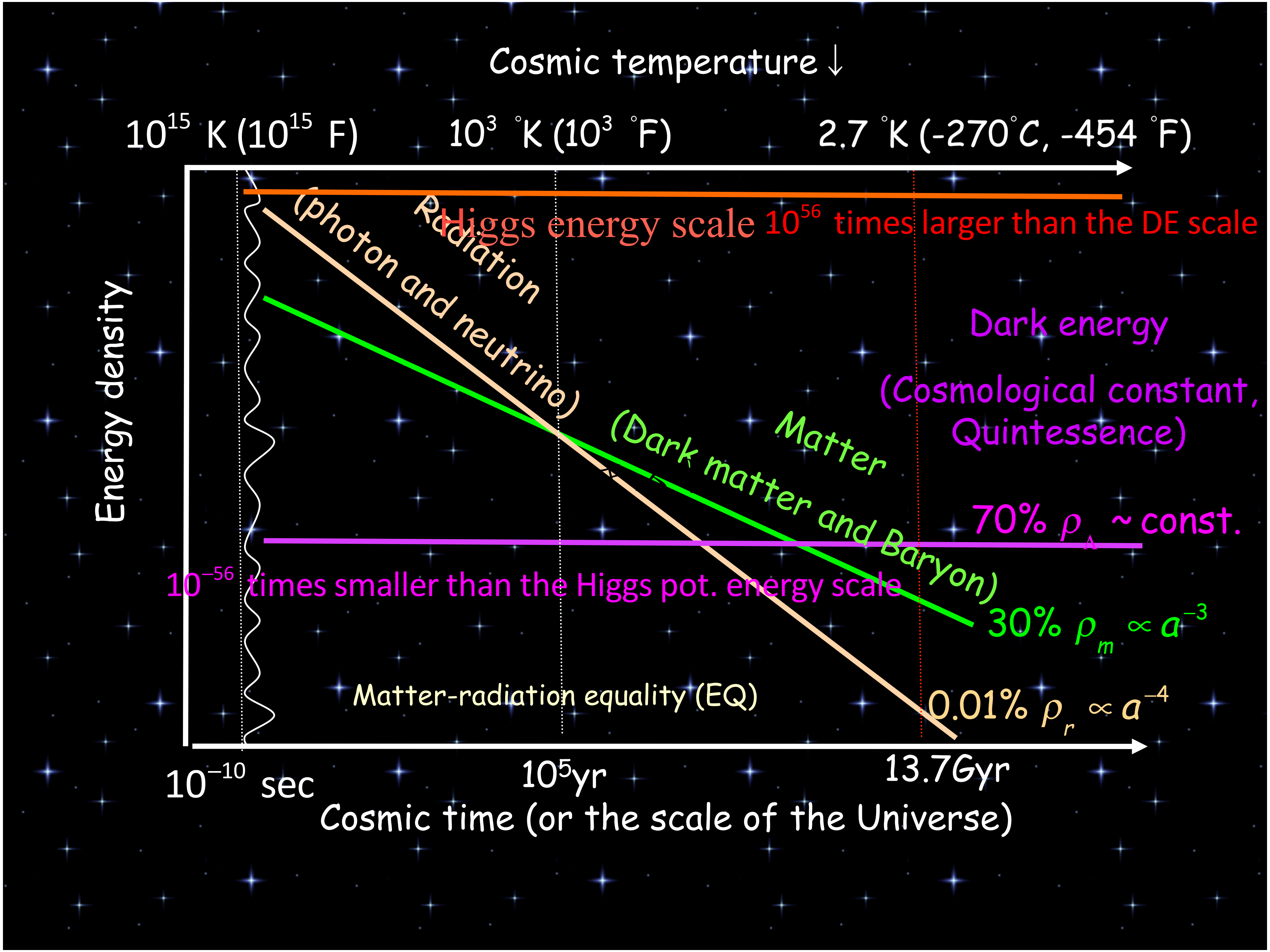
- Critical energy density

$$\rho_{cr}(t) = 3H(t)^2 / (8\pi G)$$

- Flat universe (K=0)

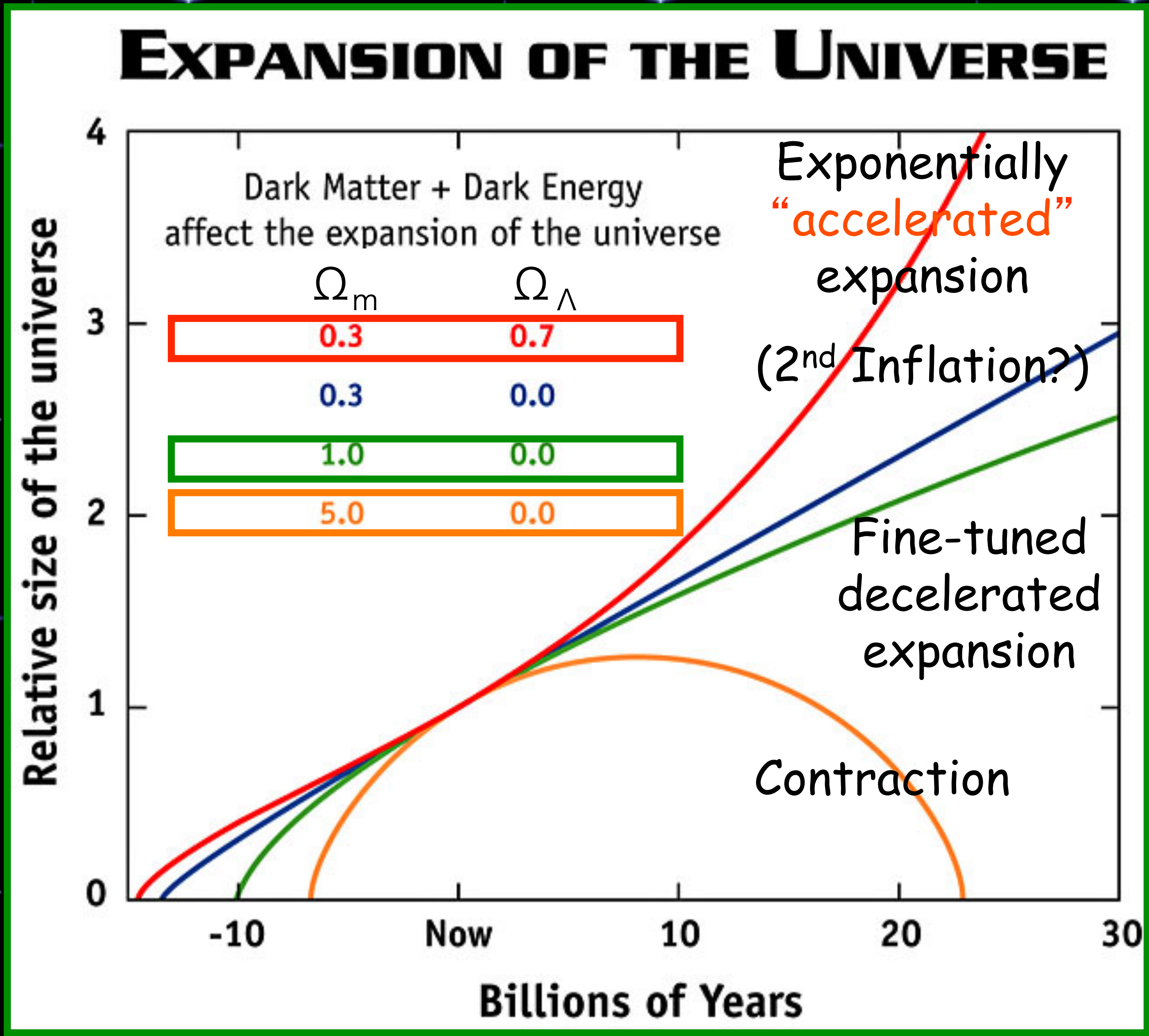
$$-\Omega_K(t) \equiv K / (aH)^2 = \Omega_\Lambda(t) + \Omega_m(t) + \cancel{\Omega_R(t)} - 1 = 0$$

$$\Omega_\Lambda(t_0) + \Omega_m(t_0) = 1$$



Cosmic temperature ↓
10^15 K (10^15 F)
10^3 °K (10^3 °F)
2.7 °K (-270°C, -454 °F)
Higgs energy scale 10^56 times larger than the DE scale
Radiation
(photon and neutrino)
Dark energy
(Cosmological constant, Quintessence)
Matter
(Dark matter and Baryon)
70% ρ_Λ ~ const.
10^−56 times smaller than the Higgs pot. energy scale
30% ρ_m ∝ a^−3
Energy density
Matter-radiation equality (EQ)
0.01% ρ_r ∝ a^−4
10^−10 sec
10^5yr
13.7Gyr
Cosmic time (or the scale of the Universe)

$$\Omega_i \equiv \left.\frac{\rho_i}{\rho_c}\right|_0$$



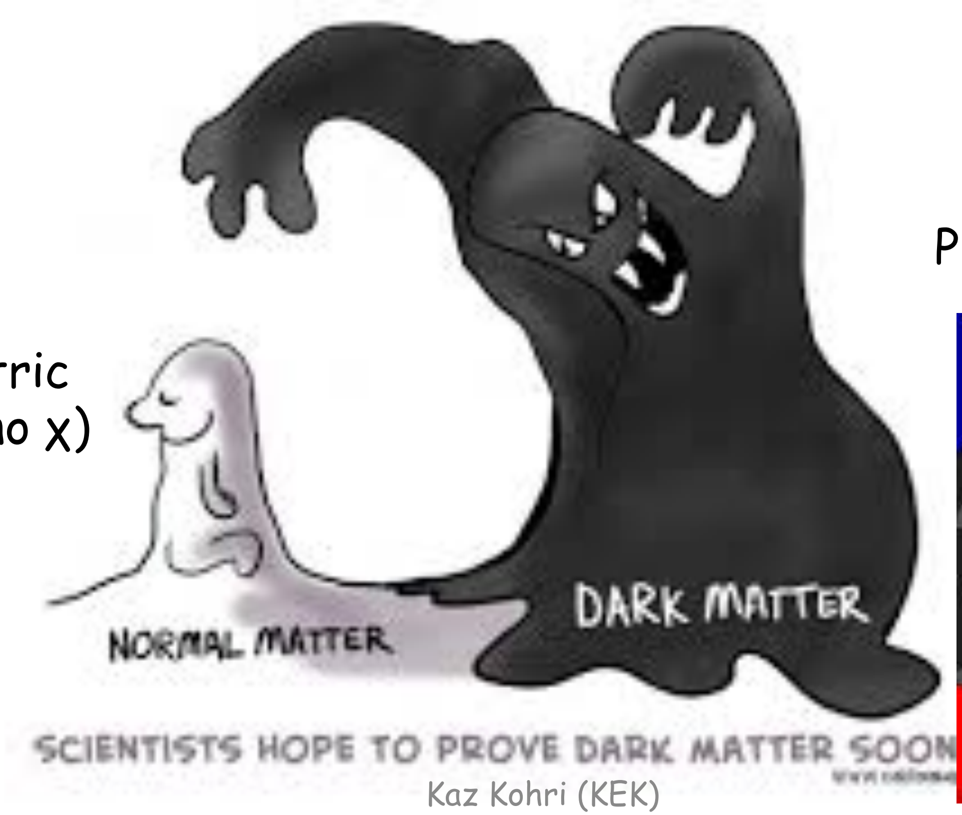
http://map.gsfc.nasa.gov/

DARK MATTER

- We cannot observe them
- We do not know who they are

axion

New supersymmetric particle (neutralino χ)



Primordial black holes

Sterile neutrino

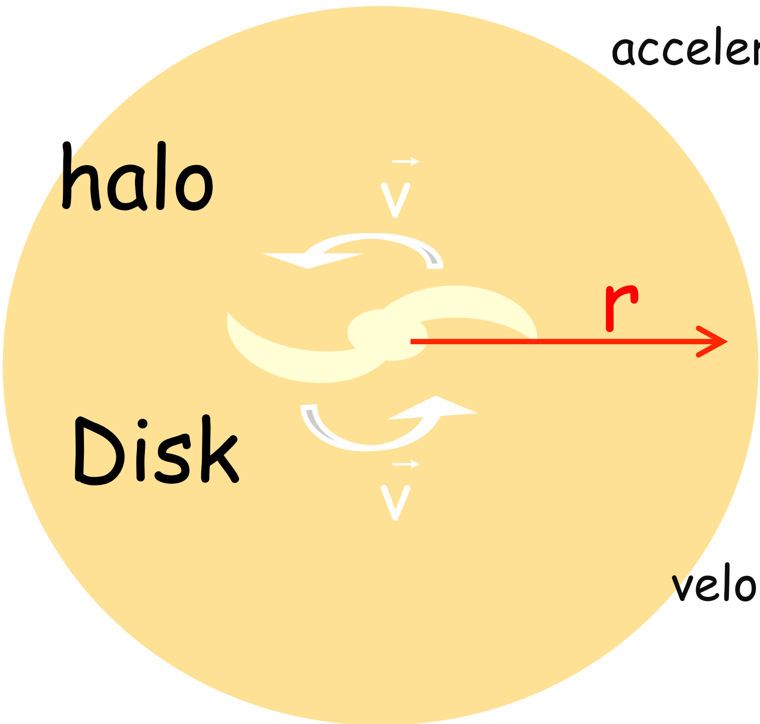
Properties of DM

- Completely obscured optically
- Gravitated toward the galaxy/clustes of galaxies
- 5 times more abundant than baryon (atoms)
- Decelerating the cosmic expansion

Clear Evidences?

1) Rotation curves of spiral galaxies

Observing Doppler shift of 21 cm line of neutral hydrogen



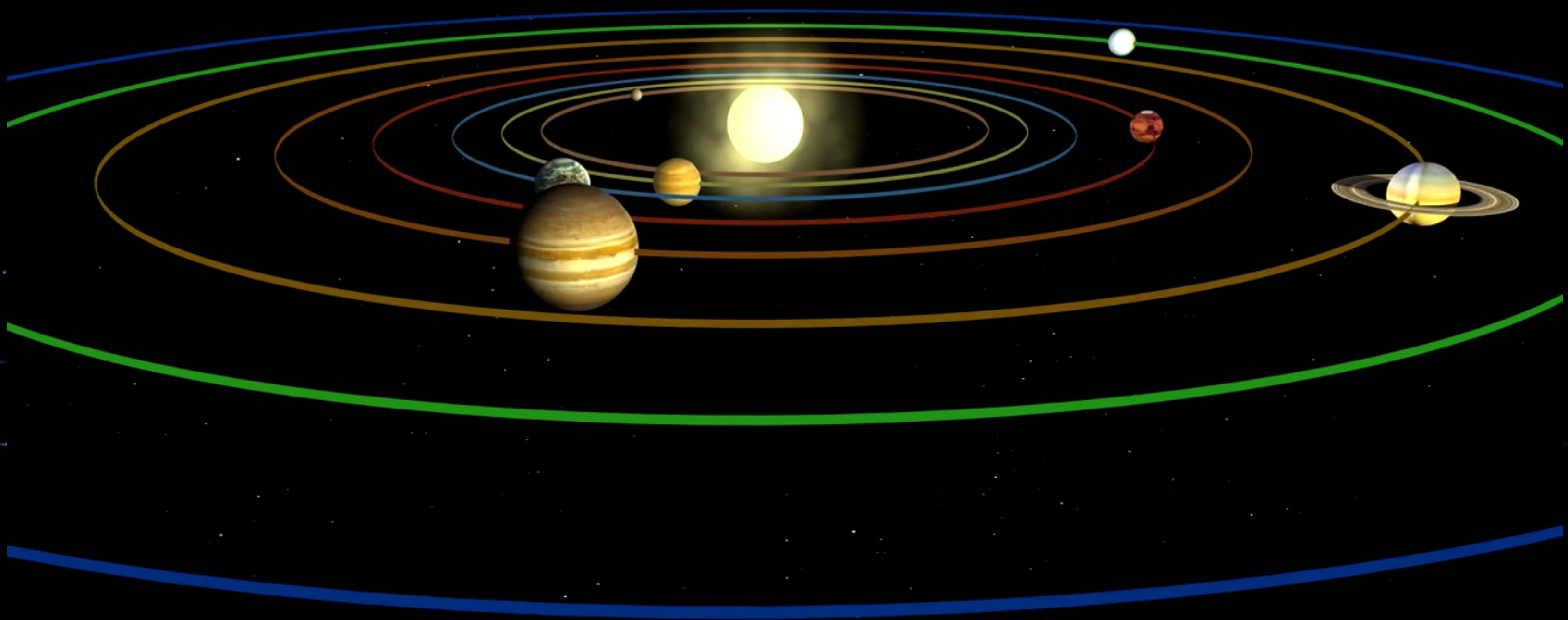
acceleration

$$a = \frac{v^2}{r} \sim G\frac{M}{r^2}$$

velocity

$$v \sim \sqrt{GM / r} \ ?$$

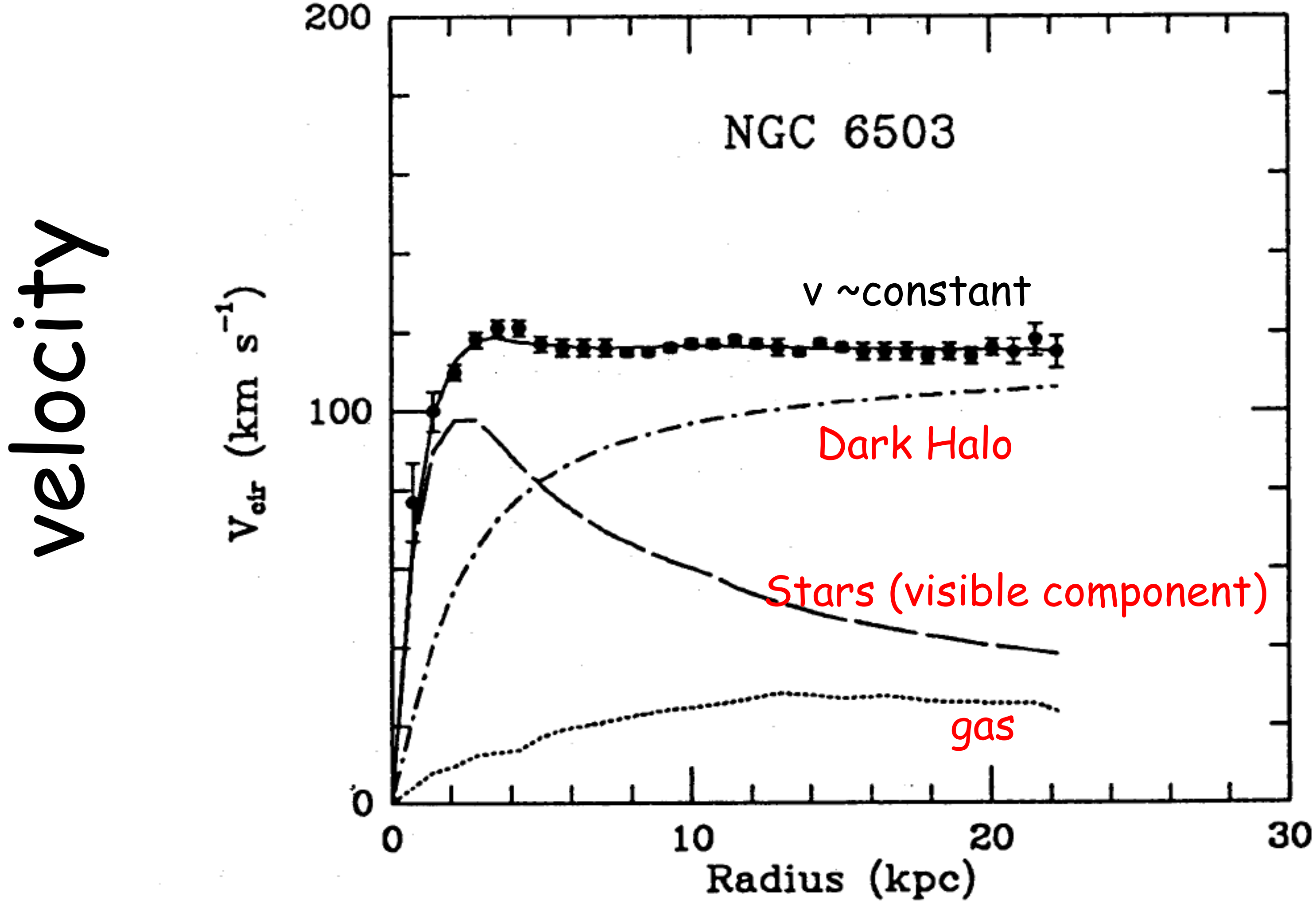
Rotating planets in solar system less dark-matter system



$$v \sim \sqrt{GM / r}$$

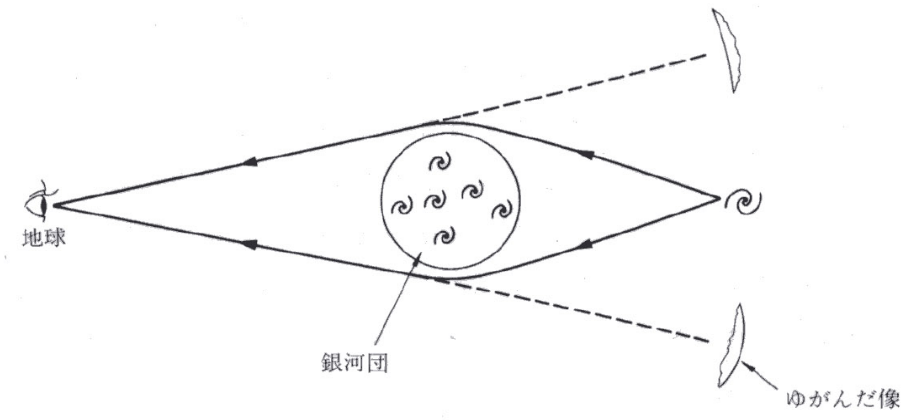
All of the Planets Orbit in a Counter-Clockwise Direction

Rotation curve



Begeman, Broils,Sandars etal (91)

2) Gravitational Lensing Effects



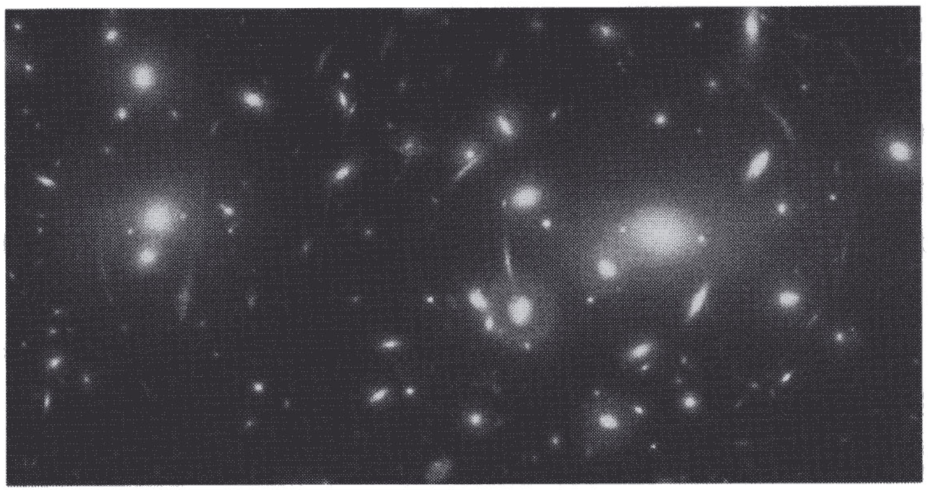
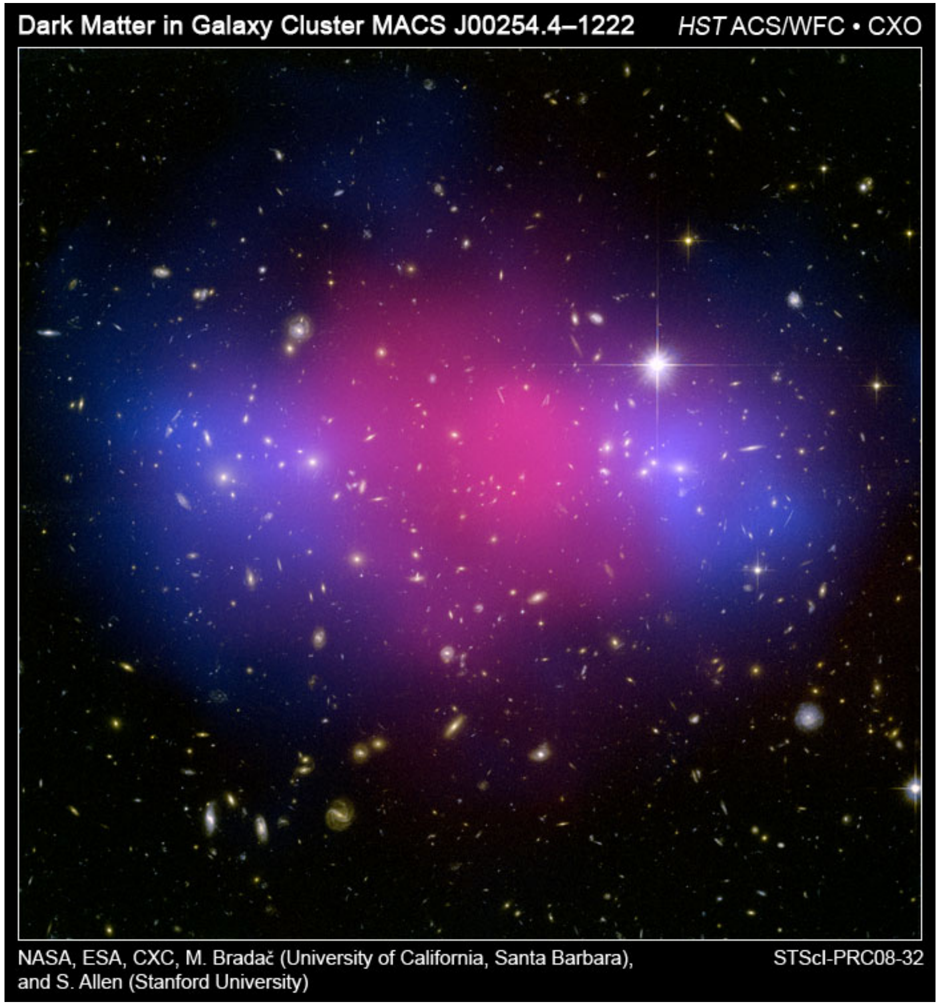


図2.11　銀河団アーベル2218による重力レンズ
〔NASA/宇宙望遠鏡科学研究所 提供〕

二間瀬敏史著 「なっとくする宇宙論」

Gravitational lensing in colliding cluster of galaxies



(2007)

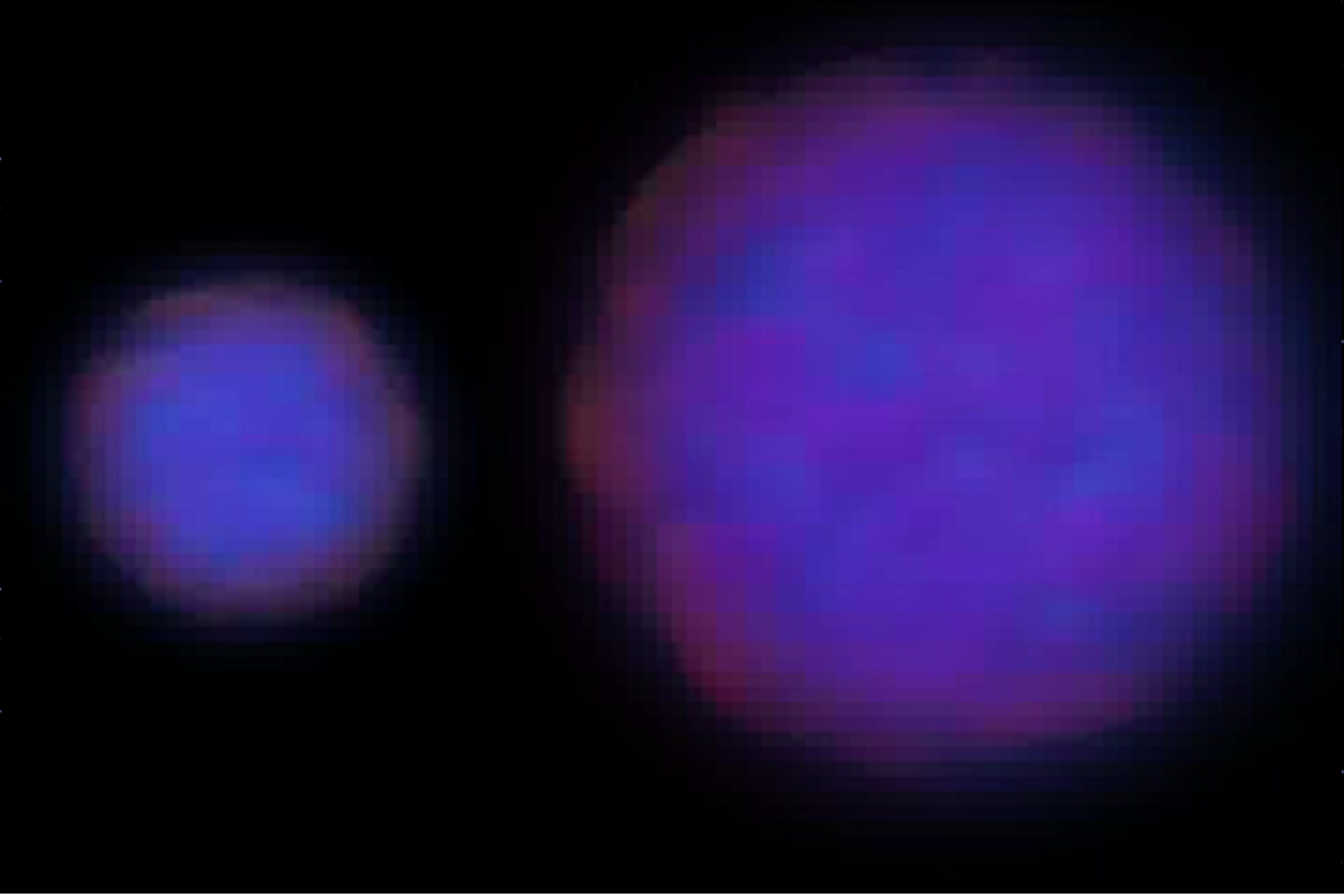
- Red: Baryon observed by X-ray produced by brems of thermal electron

- Blue: DM observed by gravitational lens

$$\frac{\sigma}{m} < \frac{\text{barn (b)}}{\text{GeV}} \sim \frac{\text{cm}^2}{\text{g}}$$

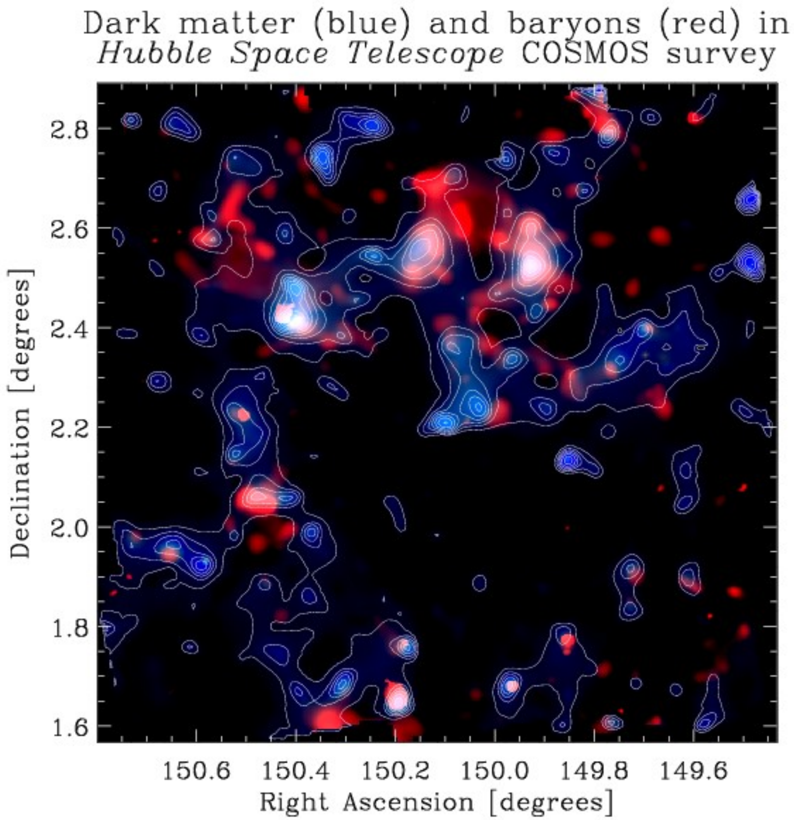
Baryon σ/m ~ 4b/GeV is excluded

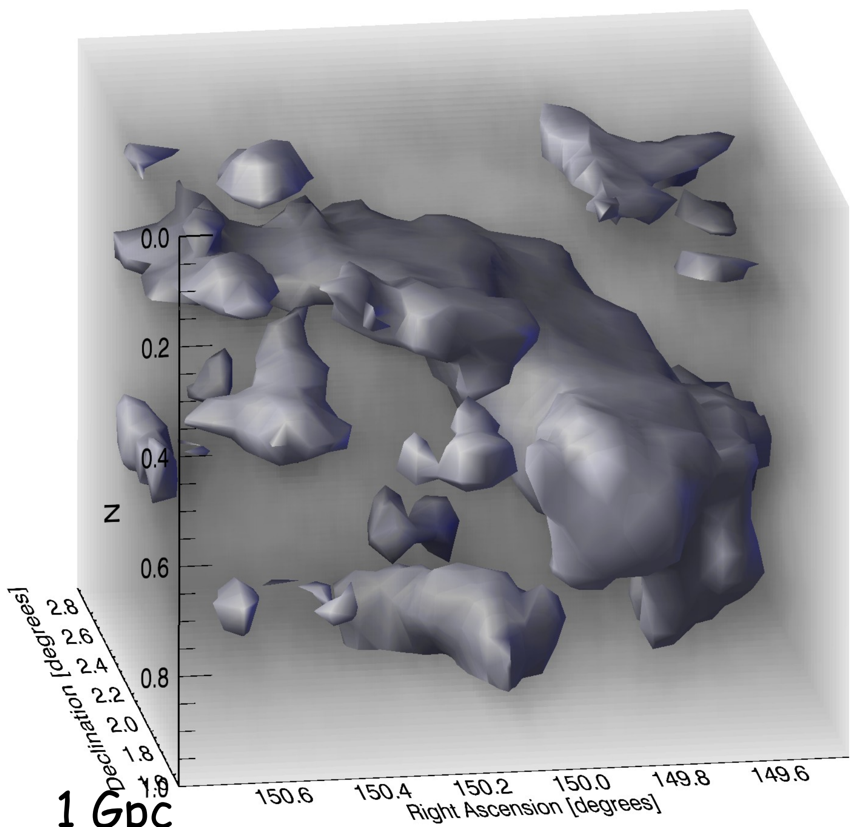
Bullet Cluster



Gravitational Lens Effect

- Cosmos Evolution Survey（コスモスプロジェクト）
- 2 square degree, 500 thousand galaxies, 0.05 arcsec





1 Gpc

Richard Massey et al (07)

http://cosmos.phys.sci.ehime-u.ac.jp/~tani/Cosmos/PressRelease/

3) Structure formation

Cold Dark Matter (CDM) has an essential role for formation of Large Scale Structure (LSS), i.e, galaxies and clusters of galaxies

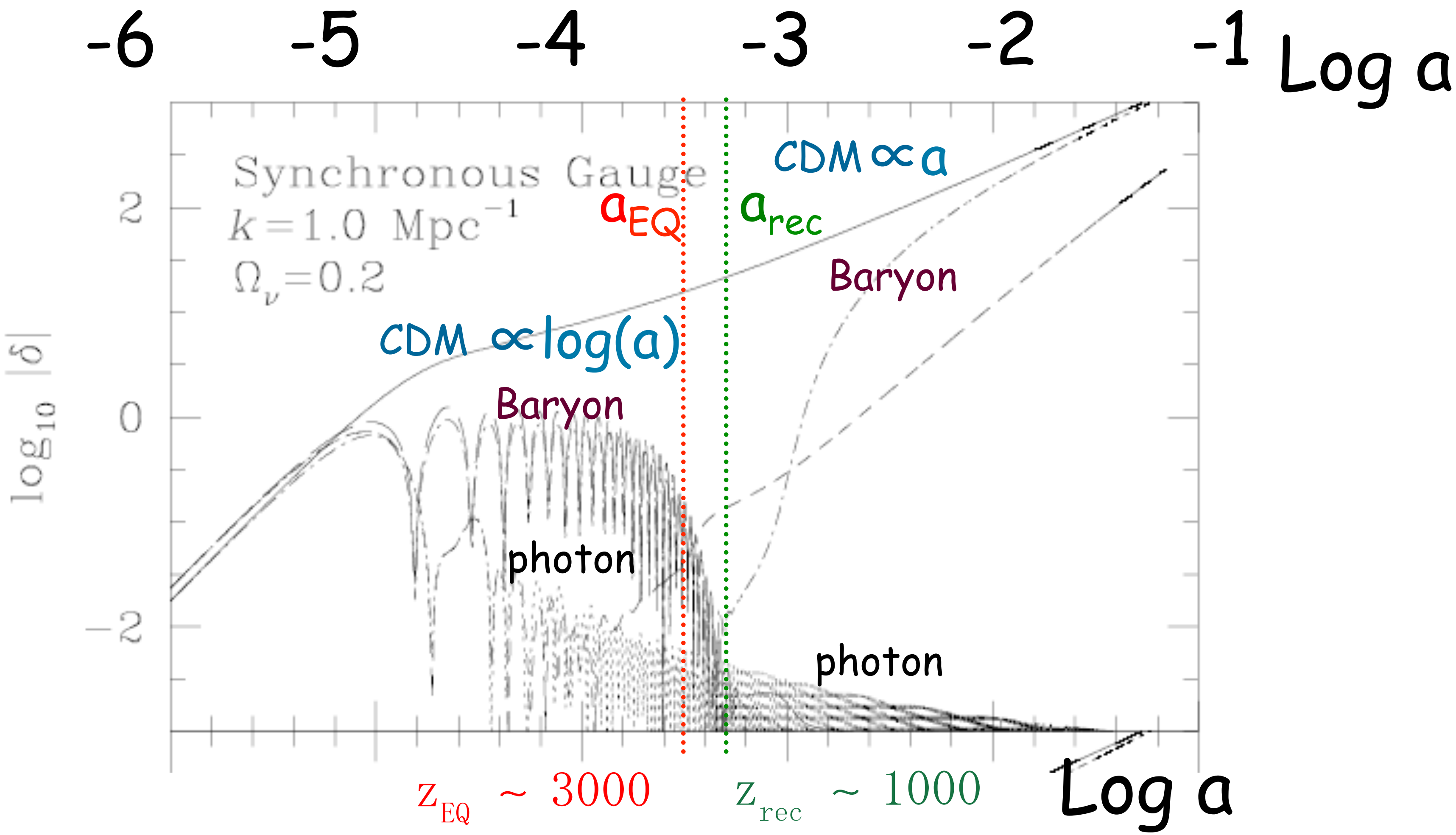
- Only pure fluctuation of baryon is too small to produce LSS because of oscillation and Silk damping
- CDM fluctuation evolves after matter-radiation equality epoch, which is ahead of baryon fluctuation

$$\delta \propto a(t)$$

- Baryon fluctuation catches up with CDM fluctuation after recombination

Time-evolution of CDM fluctuation

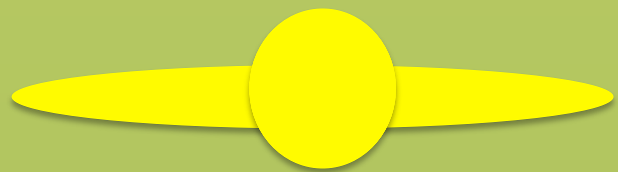
Horizon reentry before matter-radiation equality epoch



Ma and Bertschinger (95)

Time-evolution of the DM fluctuation to produce a galaxy

First, dark matter halo was produced in the early universe

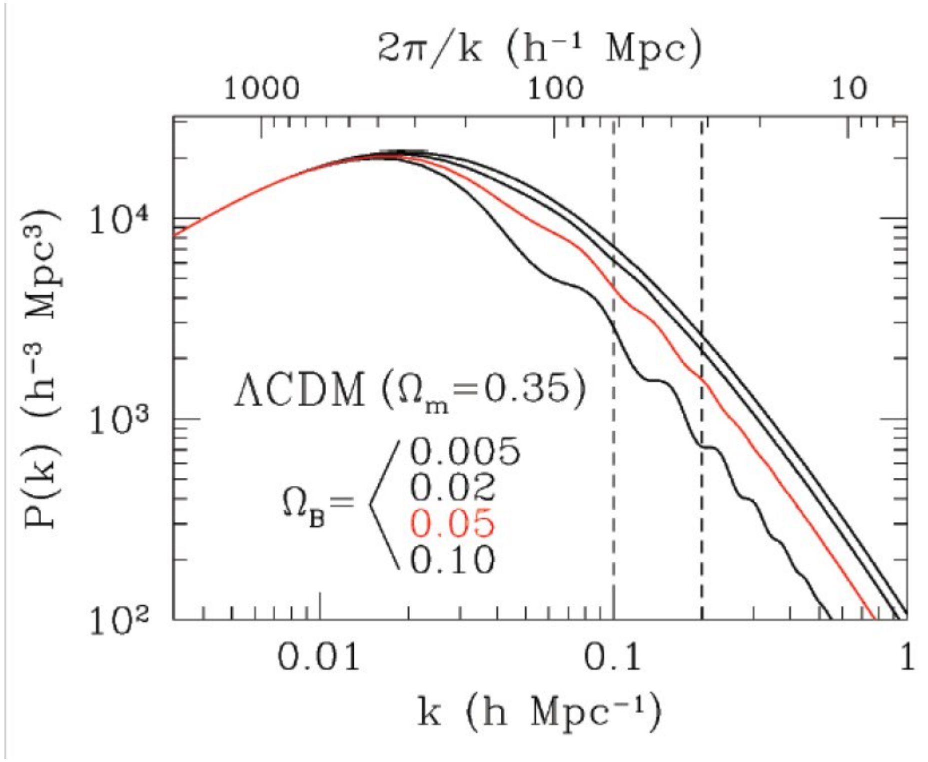


Then a galaxy (made by baryons) is produced inside the CDM halo due to the gravity of dark matter

We see $\frac{\rho_{DM}}{\rho_{baryon}} \sim 5$

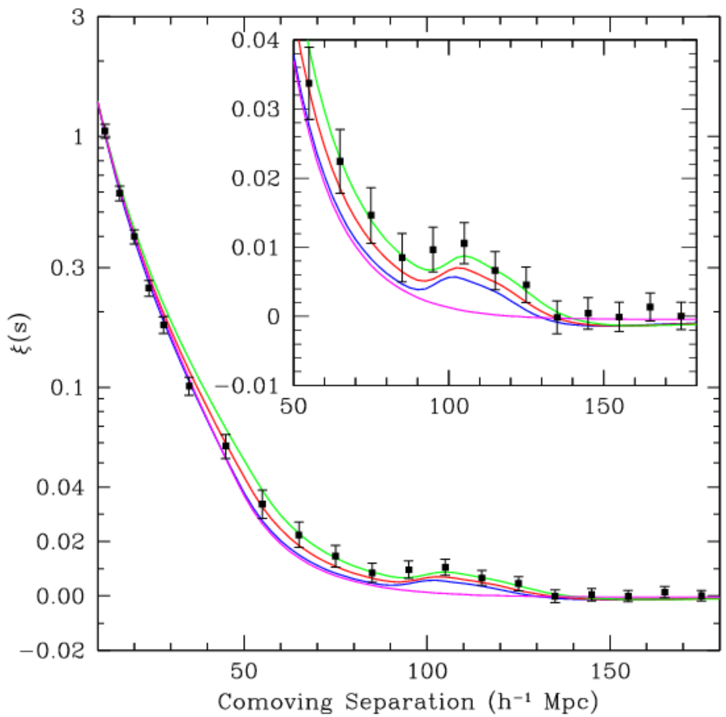
Baryon Acoustic Oscillation (BAO)

Matter power spectrum in k-space



http://www.aip.de/groups/cosmology/

2-point corr. func. in real space

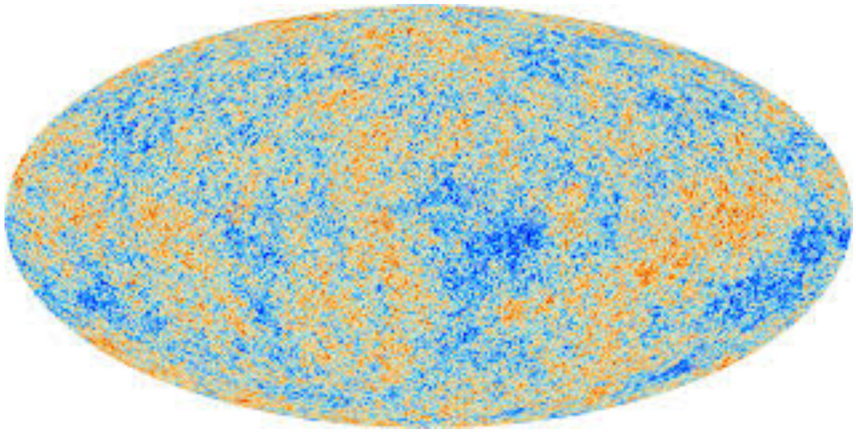


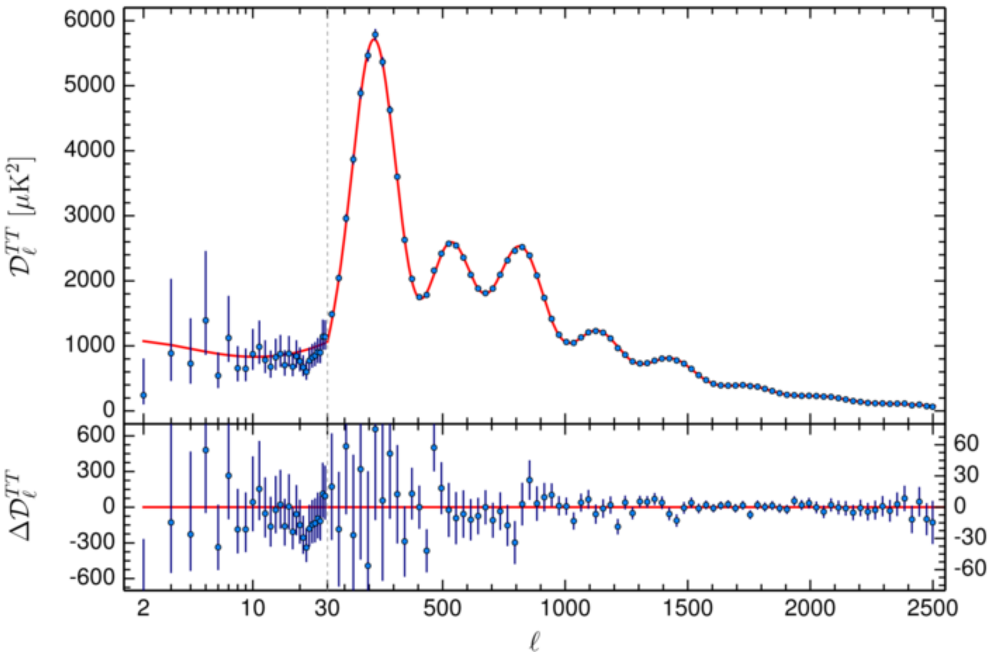
Bassett and Hlozek, arXiv:0910.5224 [astro-ph.CO]

CMB observations

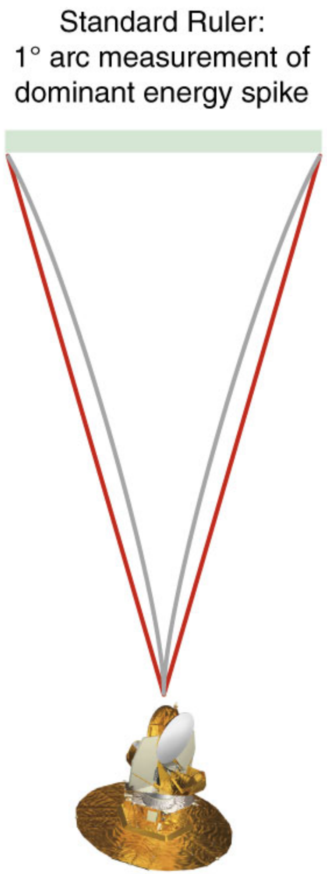
Temperature fluctuation

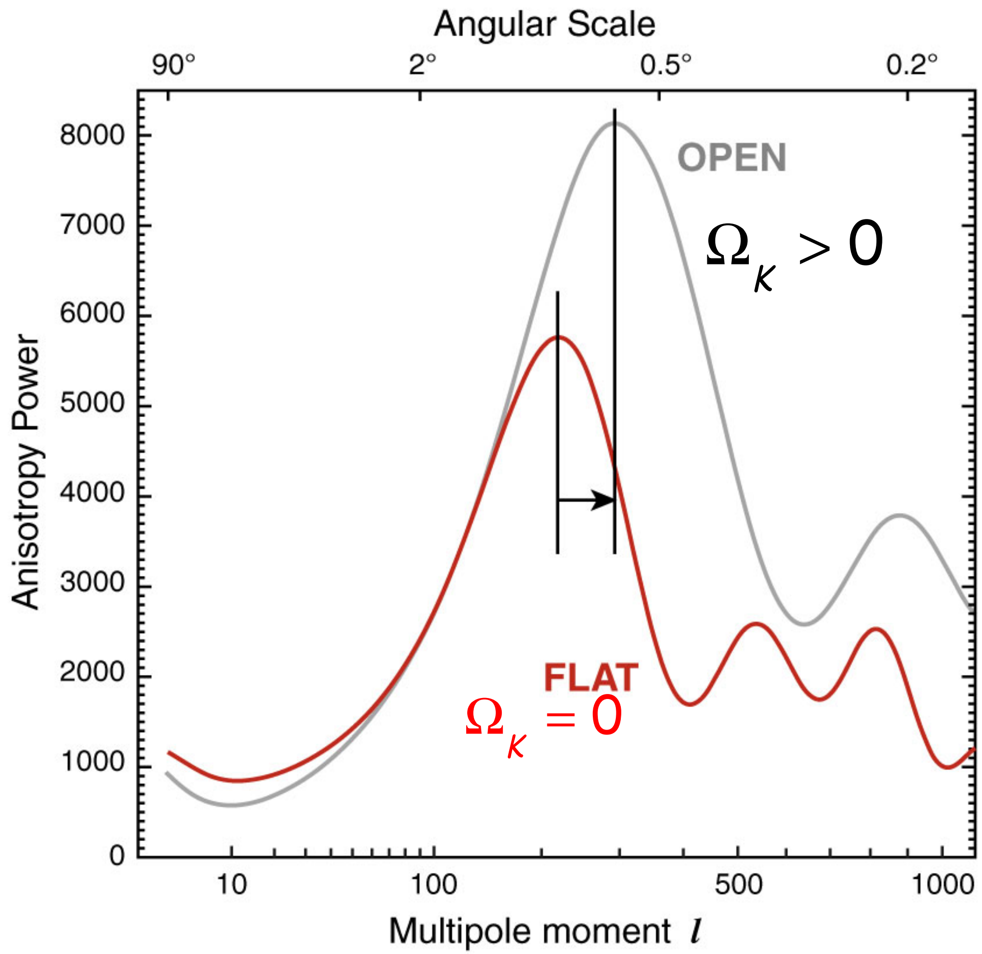
Planck 2015 results. XIII, 1502.01589v3





Is the universe open or flat?

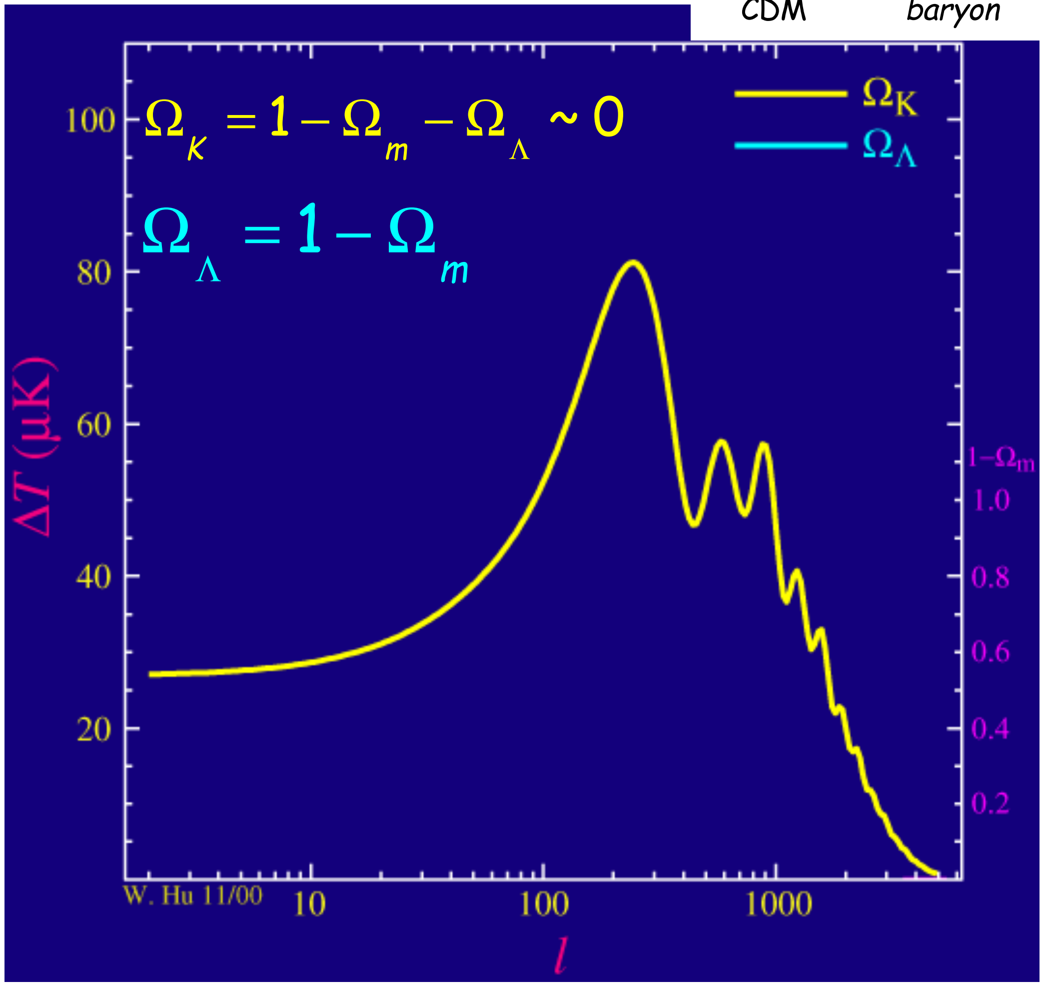




https://map.gsfc.nasa.gov/mission/sgoals_parameters_geom.html

Flat with cosmological constant $\Omega_K \sim 0$

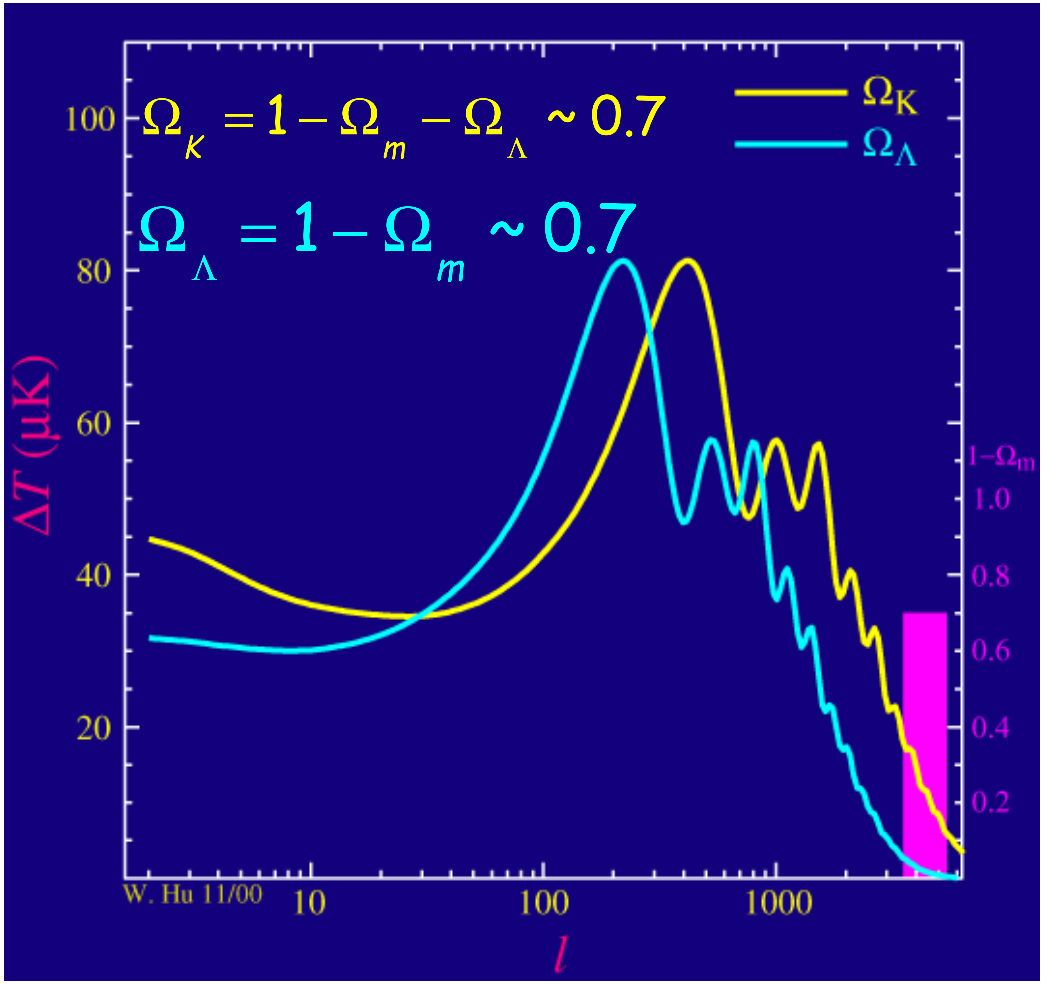
$$\Omega_{CDM} + \Omega_{baryon} + \Omega_{\Lambda} = 1 - \Omega_K = 1$$



http://background.uchicago.edu/~whu/animbut/anim3.html

Wayne Hu's HP

Open universe $\Omega_K > 0$



http://background.uchicago.edu/~whu/animbut/anim3.html

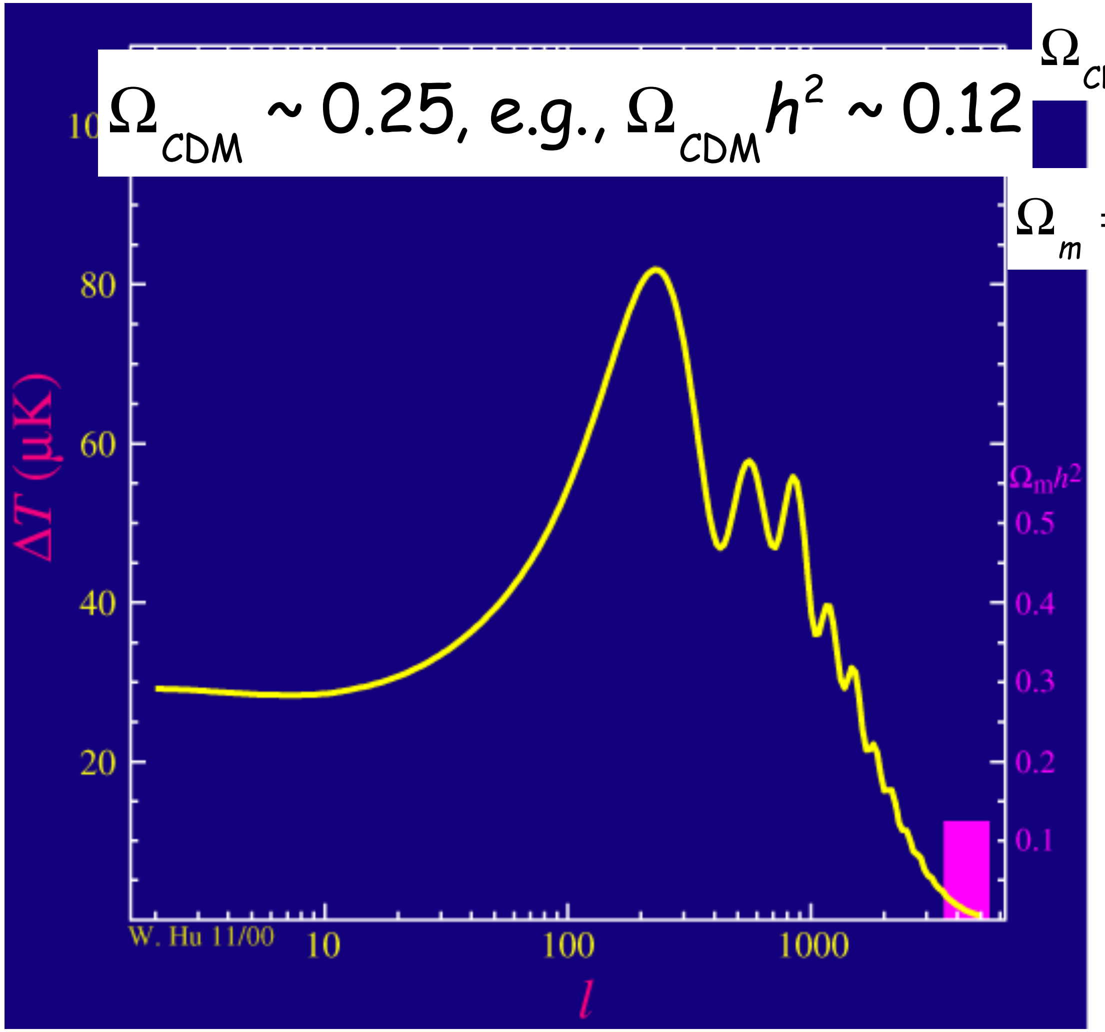
Wayne Hu's HP

Flat with cosmological constant

$$\Omega_{CDM} + \Omega_b + \Omega_\Lambda = 1$$

$$\Omega_{CDM} \sim 0.25,\ \text{e.g.,}\ \Omega_{CDM} h^2 \sim 0.12$$

$$\Omega_m = \Omega_{CDM} + \Omega_b \sim 0.3$$



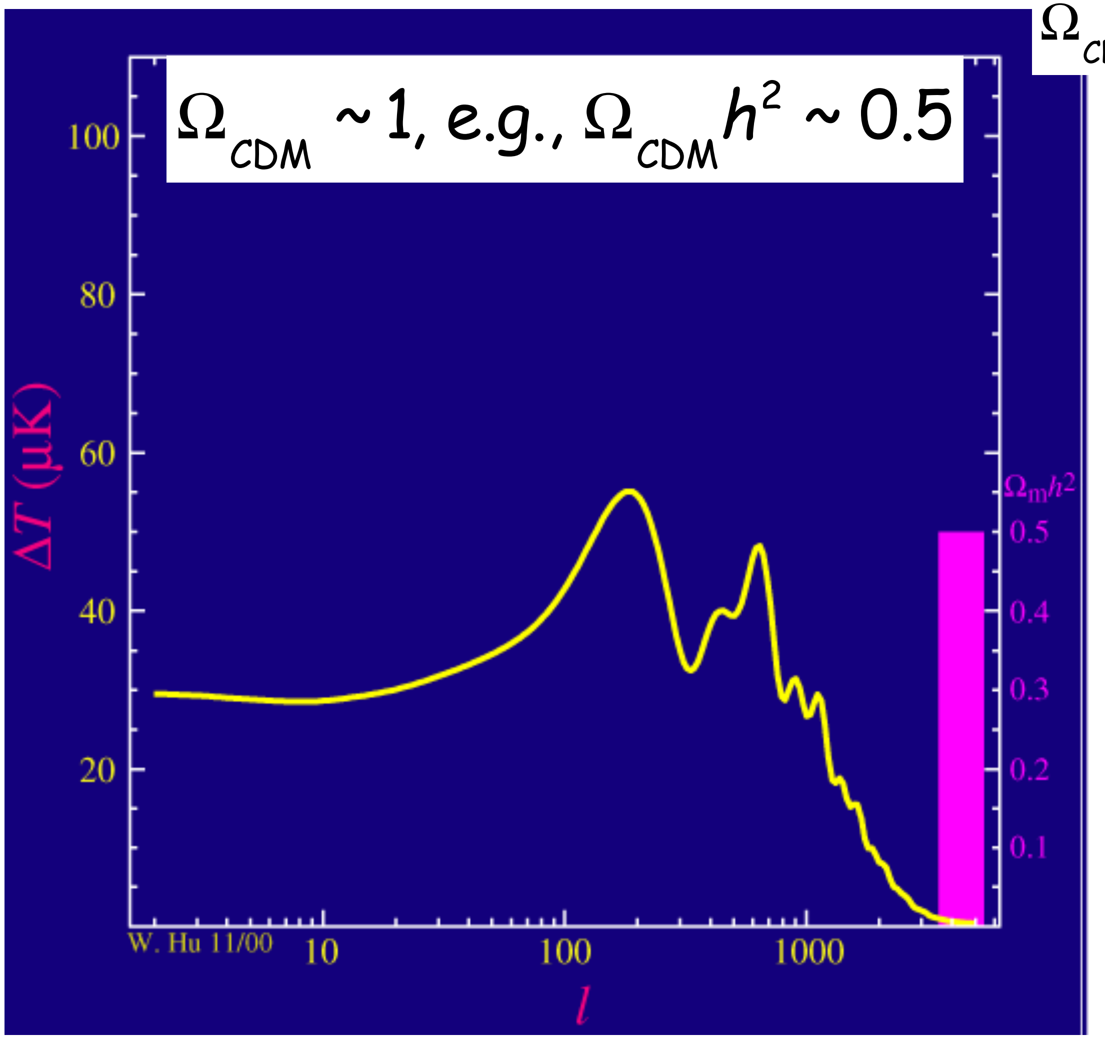
http://background.uchicago.edu/~whu/animbut/anim3.html

Wayne Hu's HP

Flat, but 100% dark matter

$$\Omega_{CDM} + \Omega_b + \Omega_\Lambda = 1$$

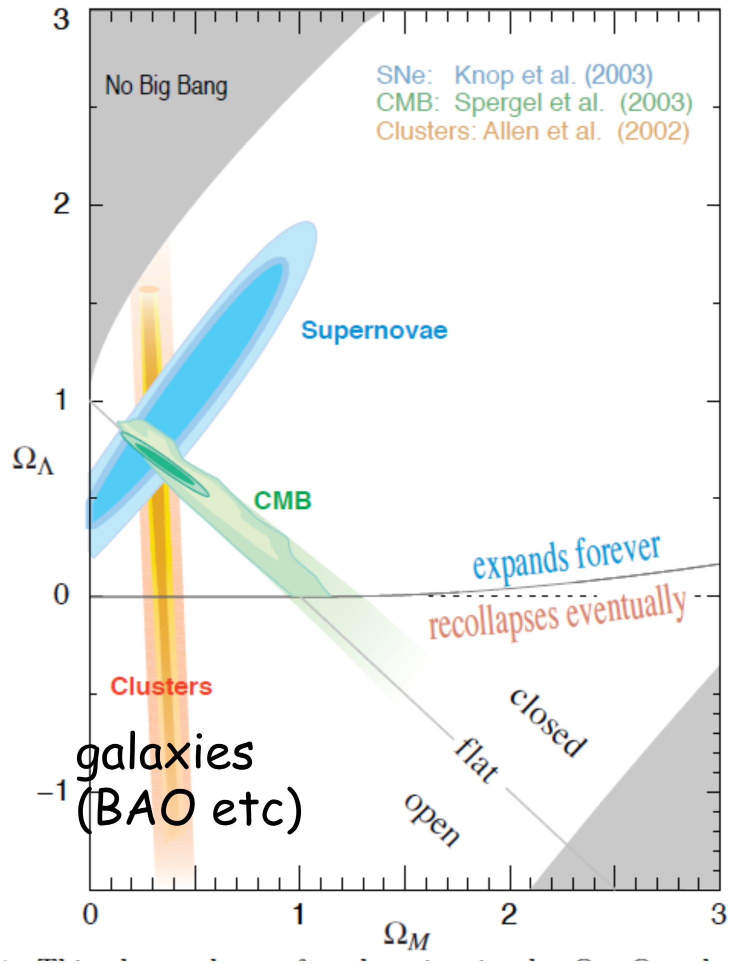
$$\Omega_m = \Omega_{CDM} + \Omega_b$$



http://background.uchicago.edu/~whu/animbut/anim3.html

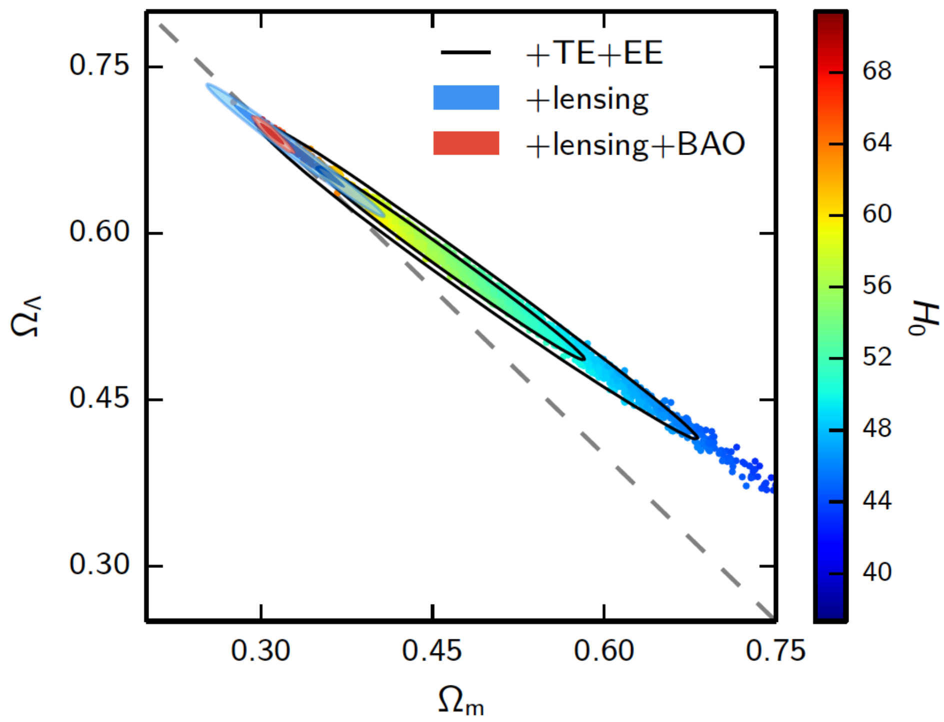
Wayne Hu's HP

Combined Figure



Lahav-Liddle PDG (2009)

+ Lensing potential reconstruction
+ Baryon Acoustic Oscillation (BAO)



Planck 2015 results. XIII, 1502.01589v3

Candidates for dark matter

- Weekly Interacting Massive Particle (WIMP) [Lightest SUSY Particle (LSP) neutralino χ, right-handed sneutrino $\tilde{\nu}_R$, …]
- Axion a
- Right-handed (sterile) neutrino $\nu_R (\nu_s)$
- SuperWIMP [gravitino ψ_μ, axino $\tilde{a}$, …]
- Primordial black hole (PBH)
- …

Weakly-interacting massive particle (WIMP)

- Value of the annihilation cross section is close to the Weak one
- Relic density coincides the observed value (WIMP miracle) if $\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$
- Supersymmetric partners can be the dark matter

neutralino ⇔ photon, Z-boson, Higgs

right-handed scalar neutino ⇔ Right-handed neutrino

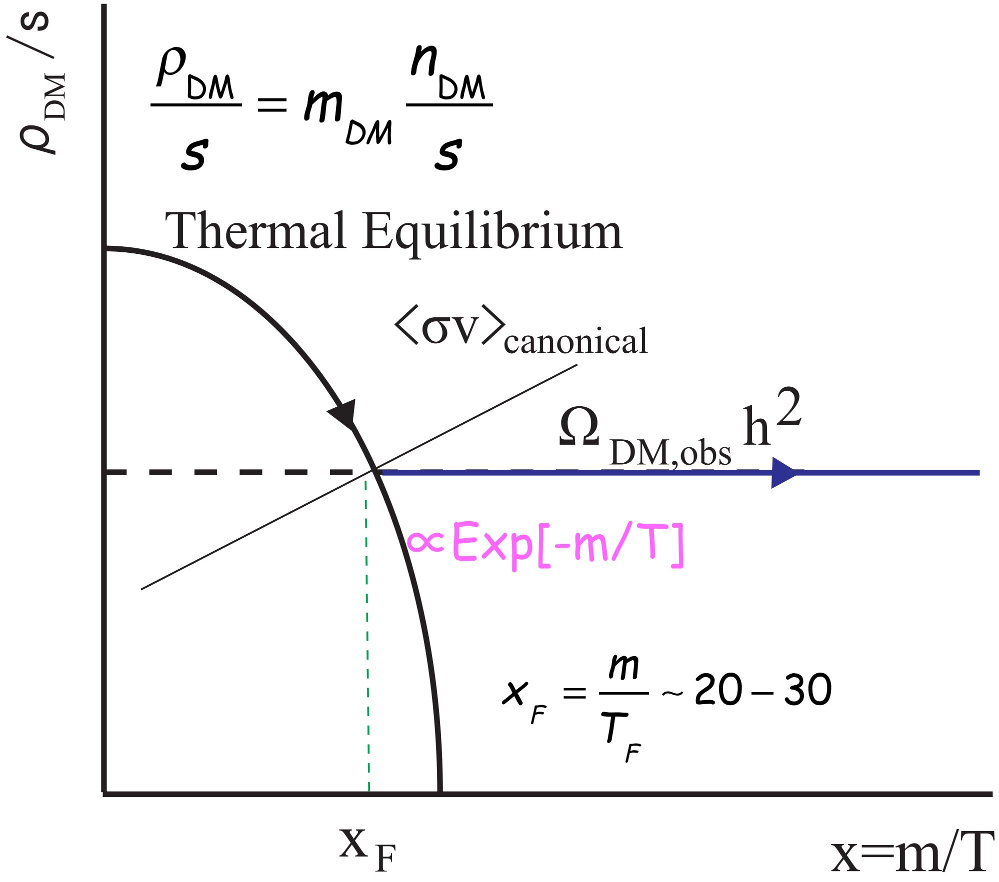
Thermal freeze out of WIMP

Boltzmann equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle[(n_\chi)^2 - (n_\chi^{eq})^2]$$

$$n_\chi \sim \left.\frac{3H}{\langle\sigma v\rangle}\right|_{\text{frezeout}}$$

$$\Omega_\chi \sim 0.25\left(\frac{\langle\sigma v\rangle}{\left(0.1/\text{TeV}\right)^2}\right)^{-1}$$



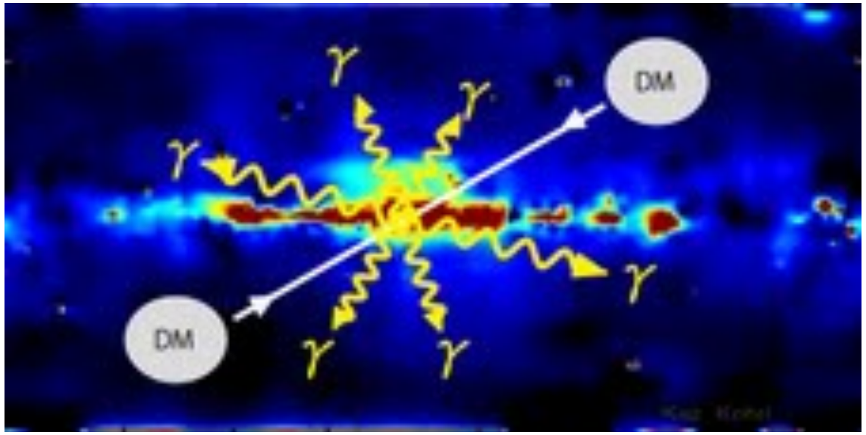
$\Omega_\chi\ h^2$ does not depend on m_χ

Predicting TeV Physics!!!

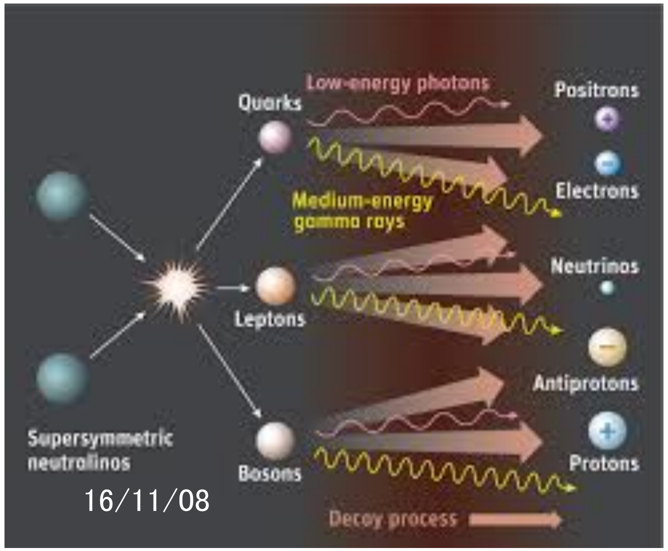
$$\langle\sigma v\rangle = 3\times10^{-26}cm^3/s$$

Indirect detection of DM

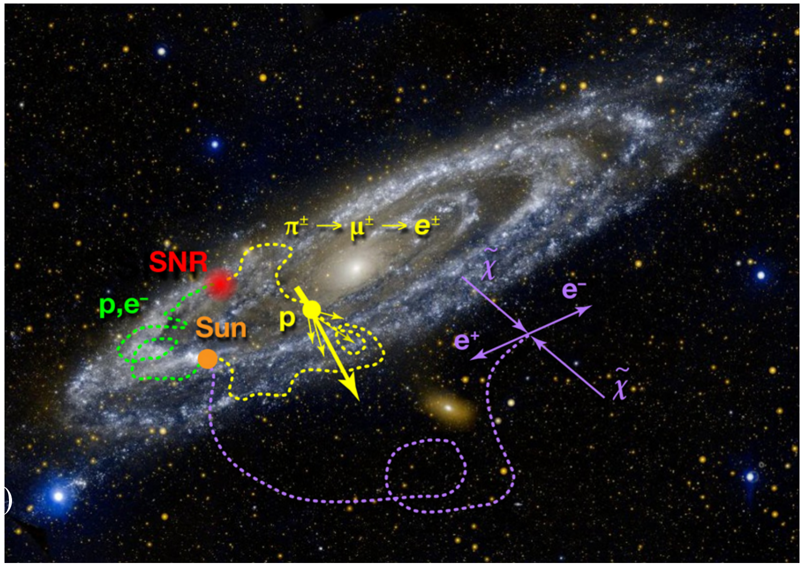
Annihilation or Decay?



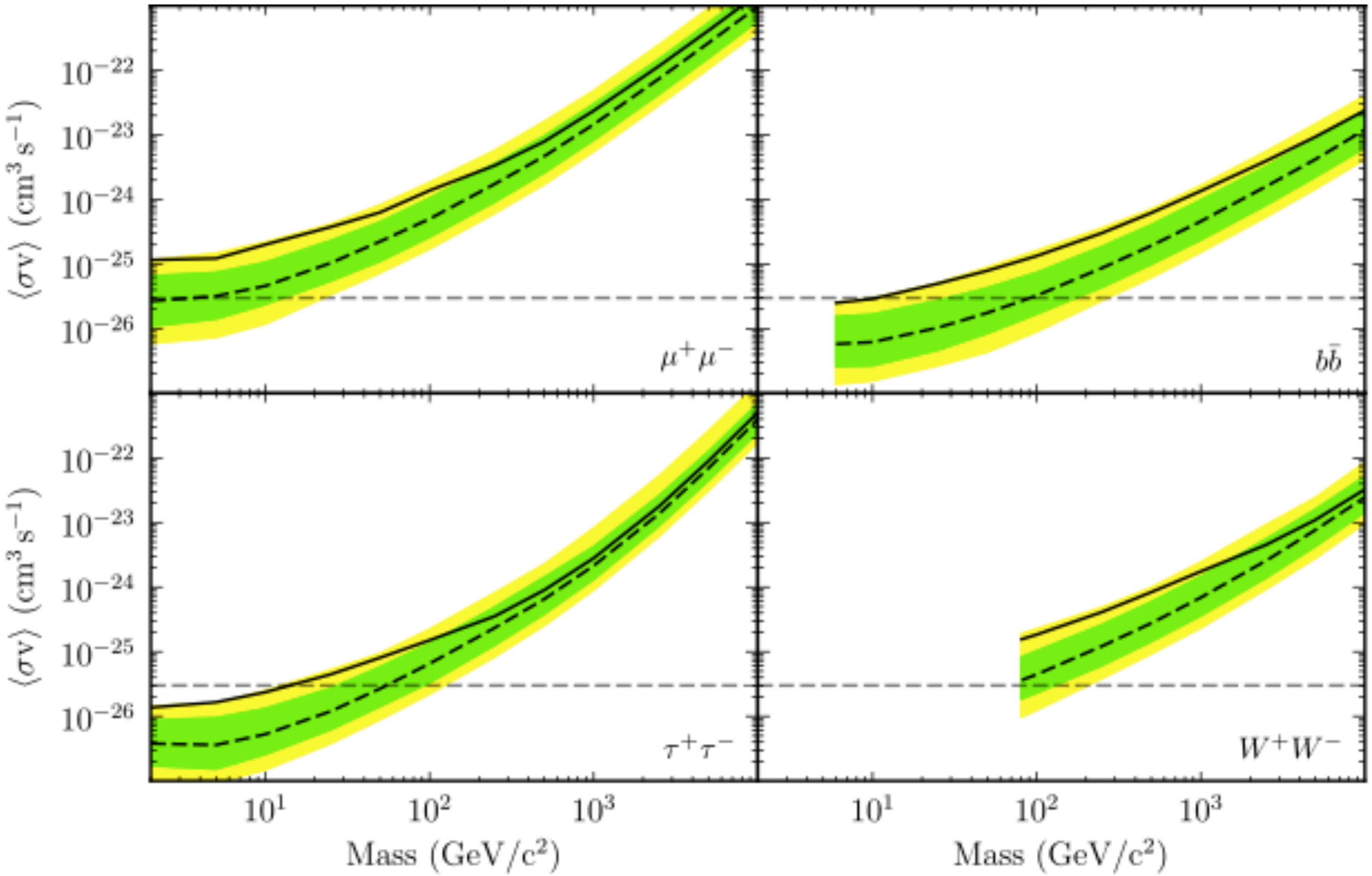
Daughter particles



Propagations of charged particles



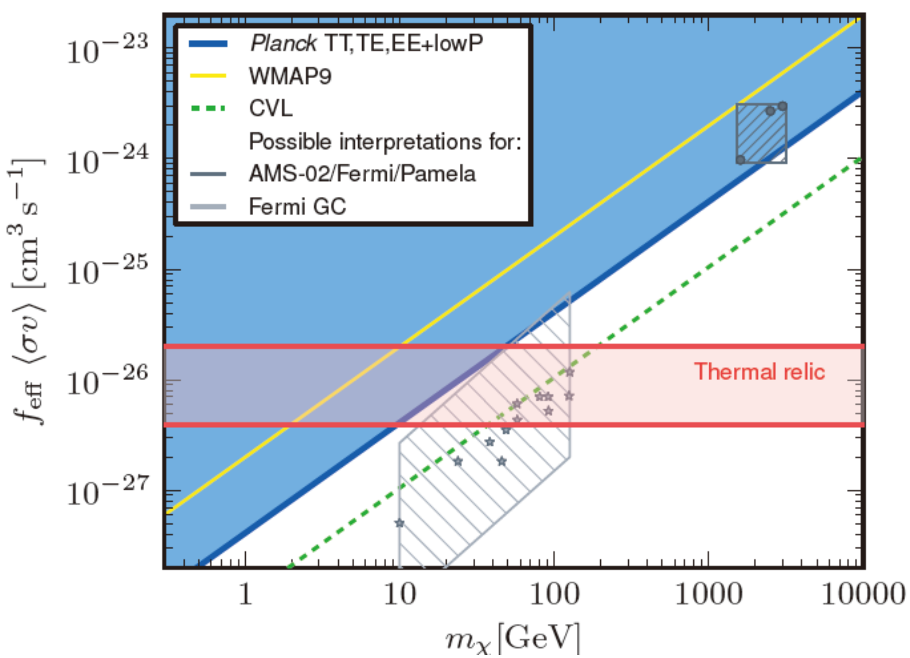
Gamma-ray by Fermi



Constraints from Dwarf steroidals by Fermi collaboration

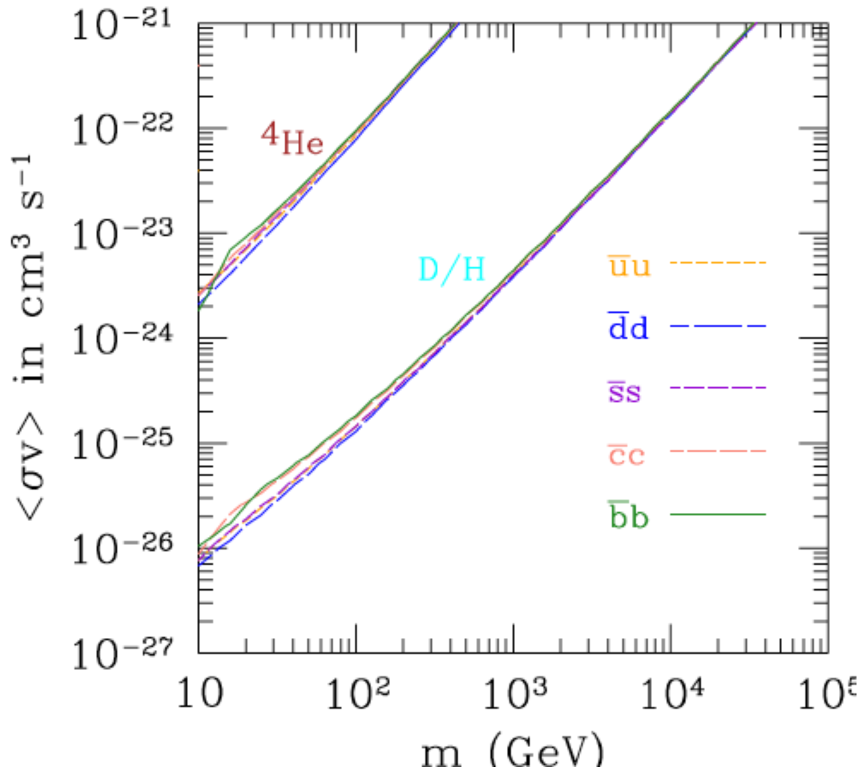
Cosmological bounds on annihilating dark matter

For electromagnetic modes from CMB
In order not to delay recombination



Planck 2015 results. XIII. Cosmological parameters

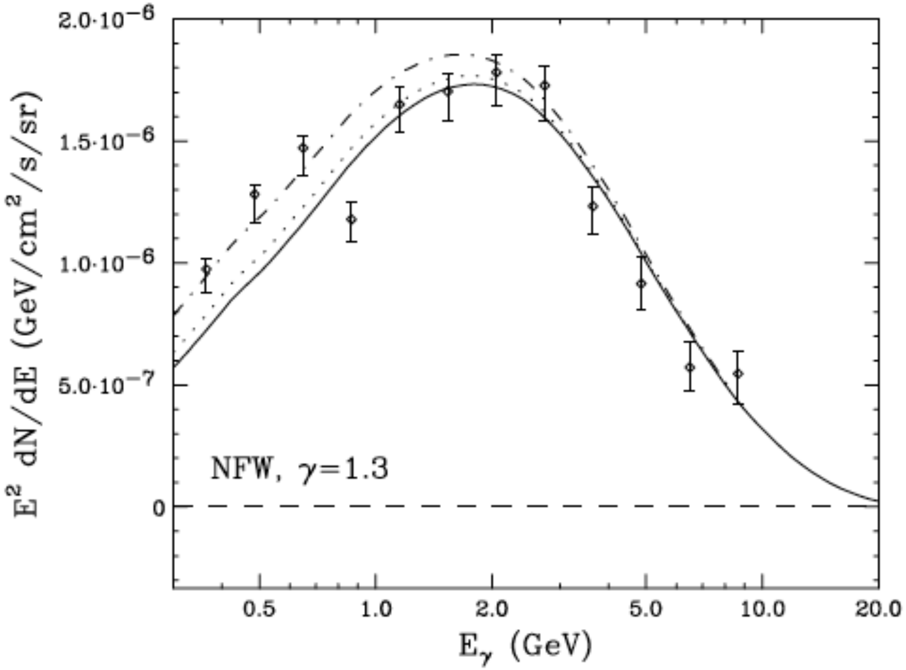
For b-bbar modes from BBN
In order not to produce more D

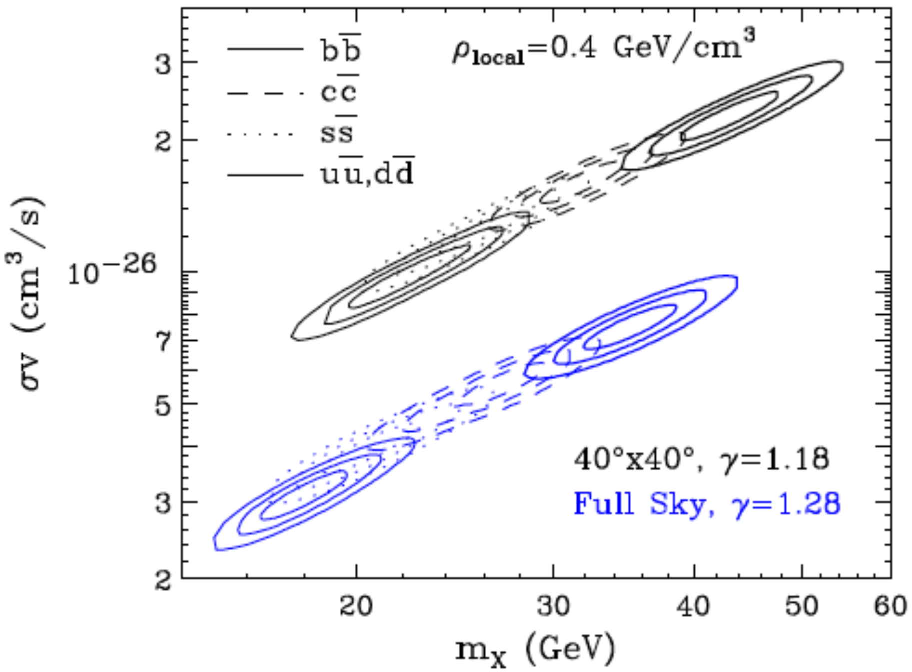


Kawasaki, Kohri, Moroi (2015)

Galactic-center gamma-ray excesses and dark matter annihilation

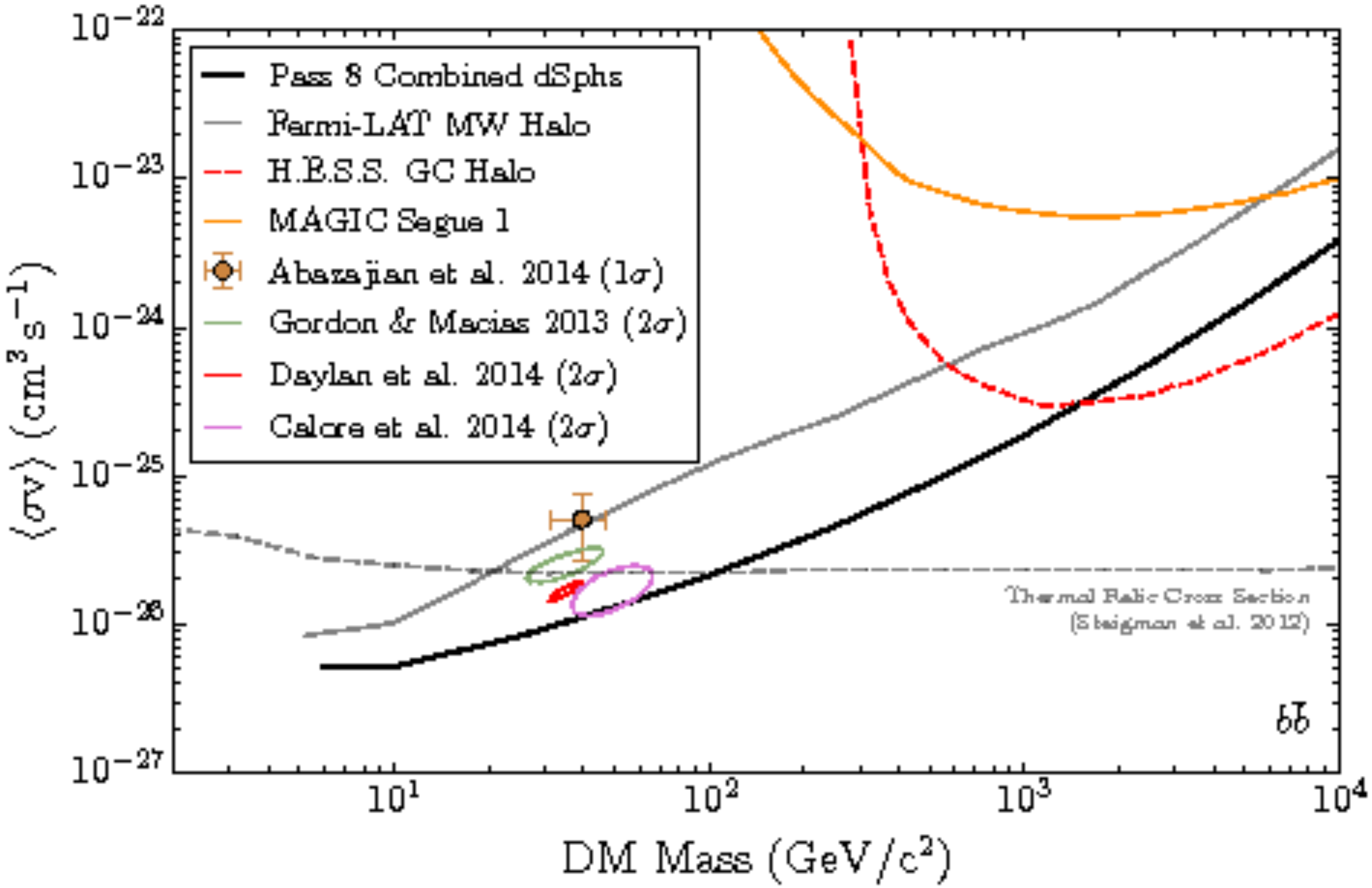
Daylan et al, 2014





Constraints by Fermi gamma-ray sattelite

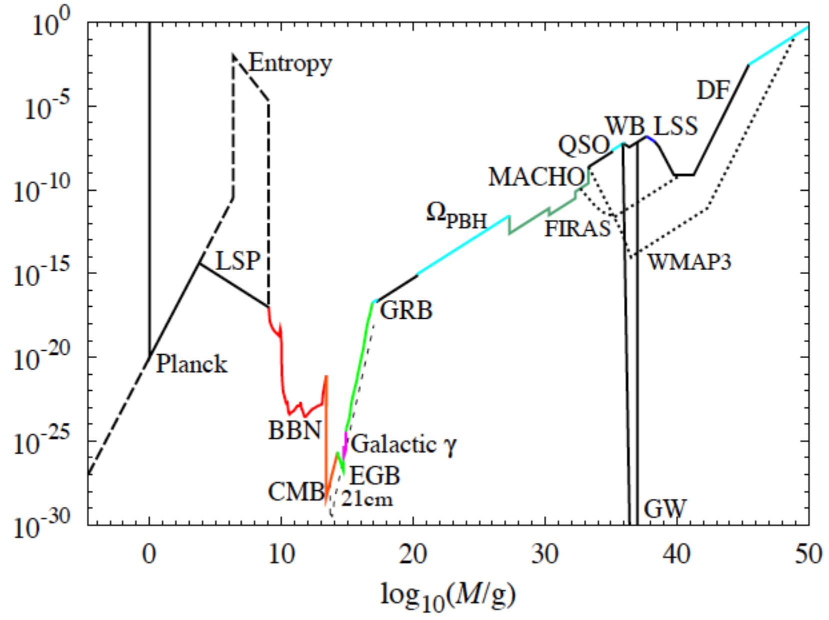
Fermi-LAT Collaboration (Ackermann, M. et al.) Phys.Rev.Lett. 115 (2015)



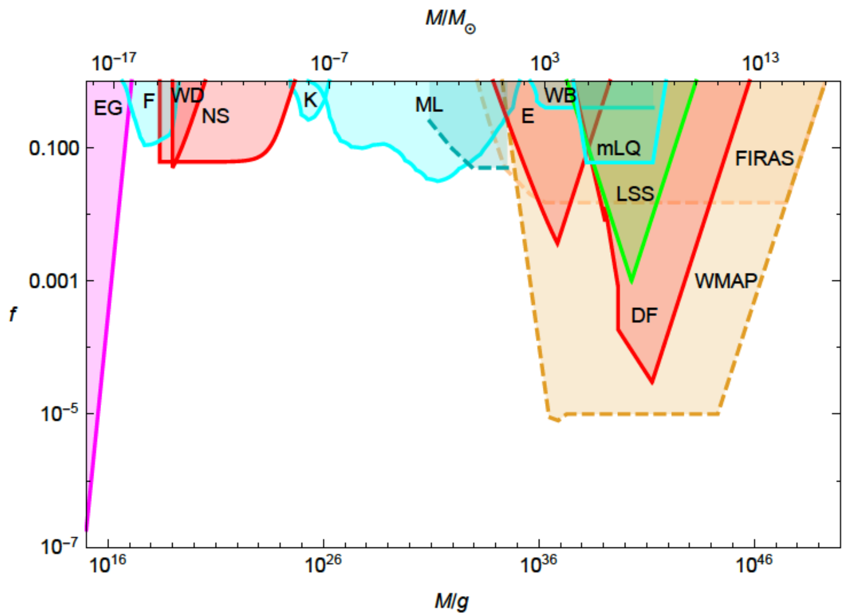
Primordial Black Hole dark matter

Horizon mass with the density fluctuation of the order O(1) can collapse to a PBH

Mass fraction at the formation



Fraction to dark matter density



PBH cannot become 100% DM?

Carr, Kohri, Sendouda, Yokoyama (2009)

Carr, Kunel, Sandstad (2016)

Positron and antiproton by AMS-02 or future CALET

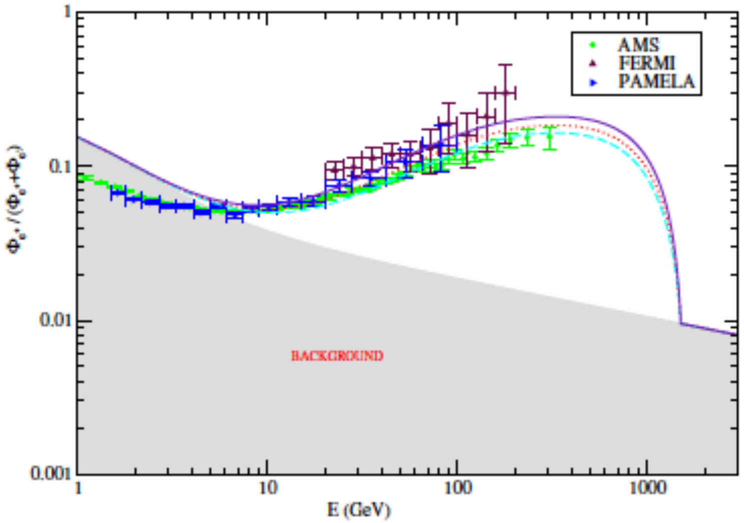


FIG. 2: Positron flux ratio in "med" model for $\tau_{DM} = 1.6 \times 10^{26}$s (solid-indigo) , $\tau_{DM} = 2.0 \times 10^{26}$s (dotted-red) and $\tau_{DM} = 2.4 \times 10^{26}$s (dashed-cyan).

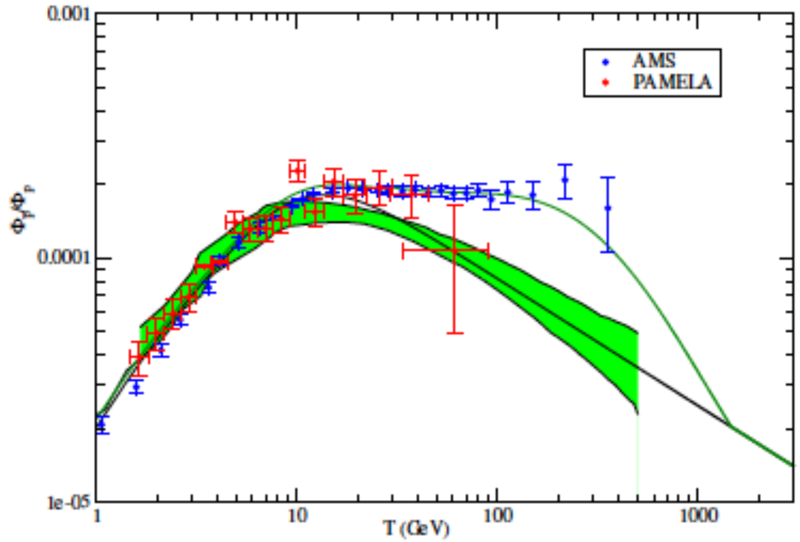


FIG. 6: Antiproton to proton flux ratio in "med" model for $\tau_{DM} = 2.5 \times 10^{27}$s.

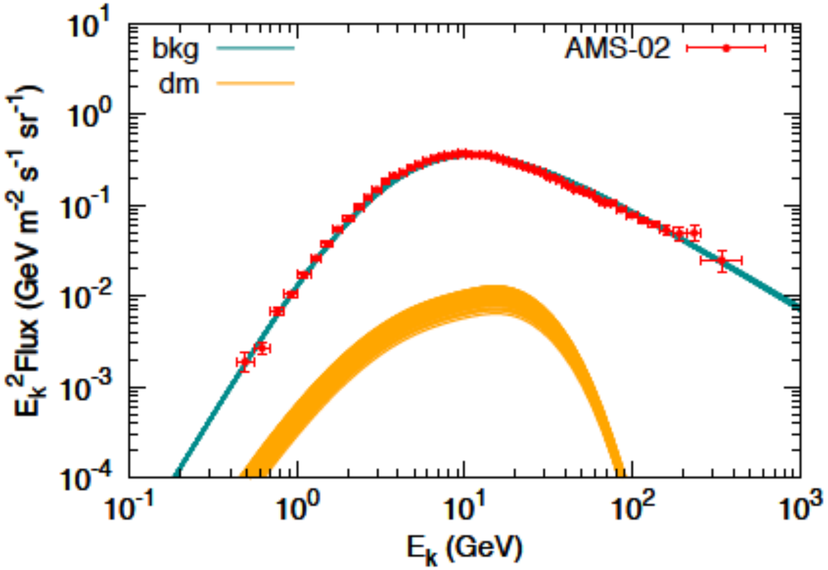
Kohri et al, in preparation

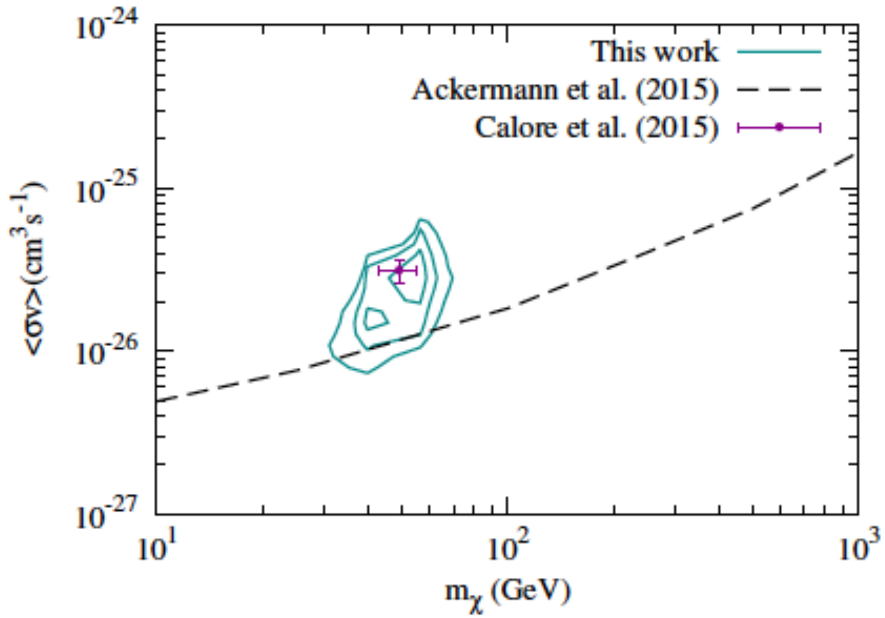
But still large uncertainties in the propagation models

Antiproton excesses and annihilating dark matter

Qui et al, arXiv:1610.03840 [astro-ph.HE]

Cuocco et al, arXiv: 1610.03071v1

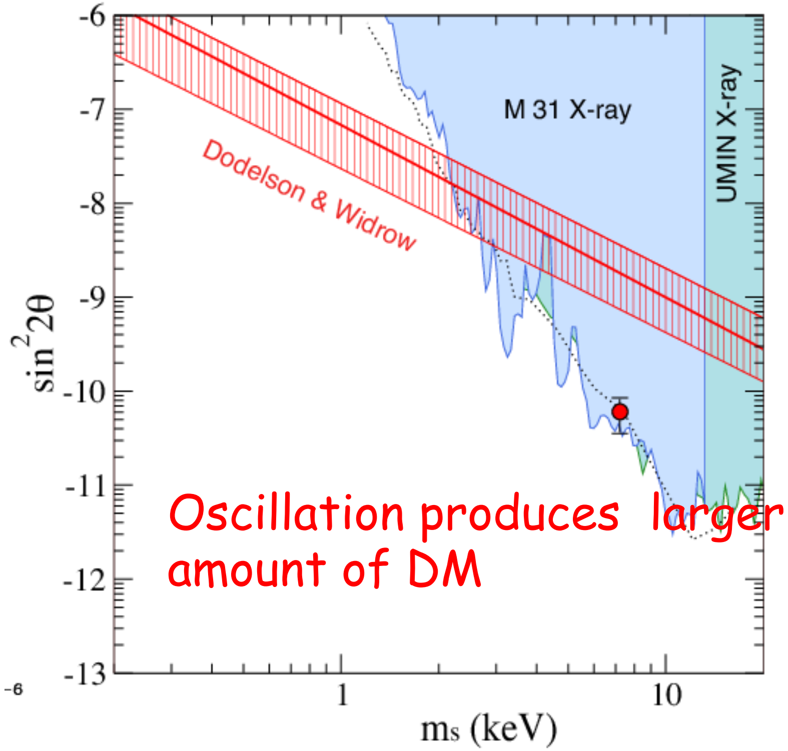




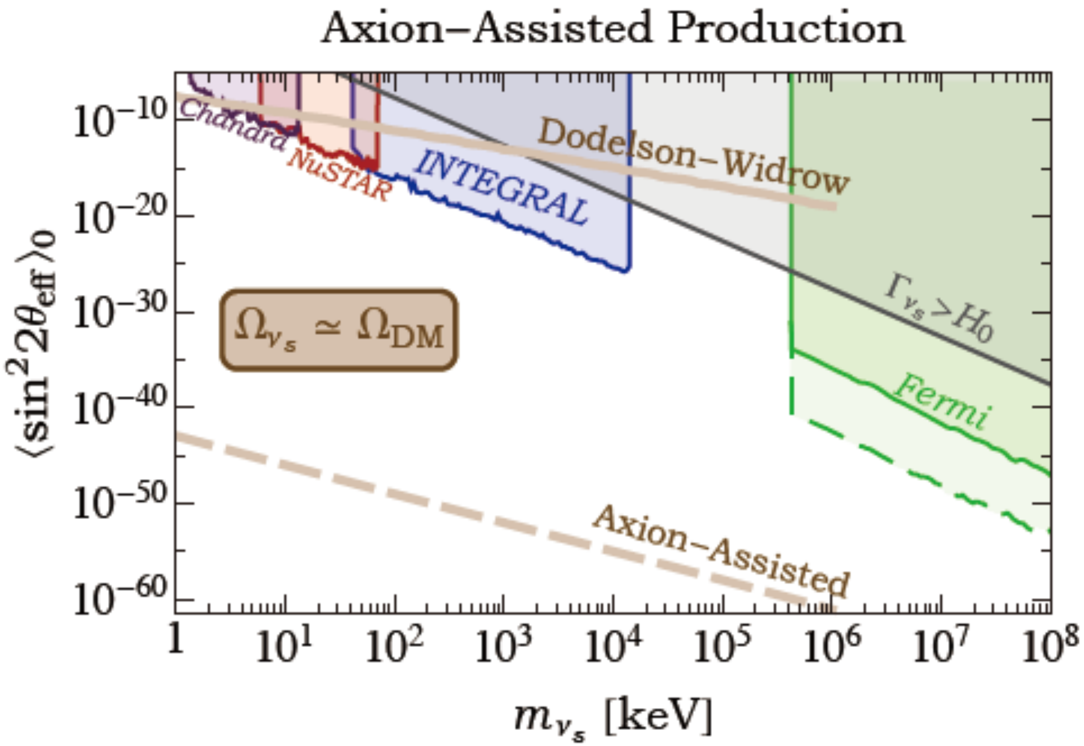
keV sterile neutrino DM

Relic abundance decoupled before the QCD phase transition (T_{dec} >> 100 MeV)

$$\Omega_{\nu_s} \sim 0.3\,(m_{\nu_s}/\mathrm{keV})$$



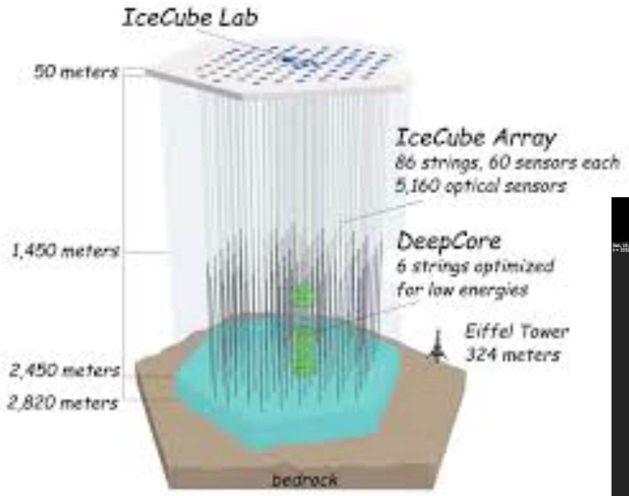
Oscillation produces larger amount of DM

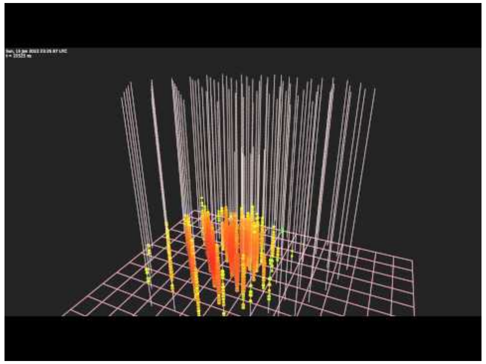


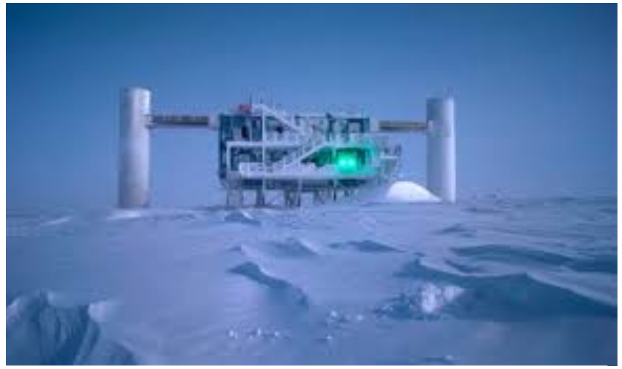
Klasen, Michael et al. arXiv:1507.03800 [hep-ph]

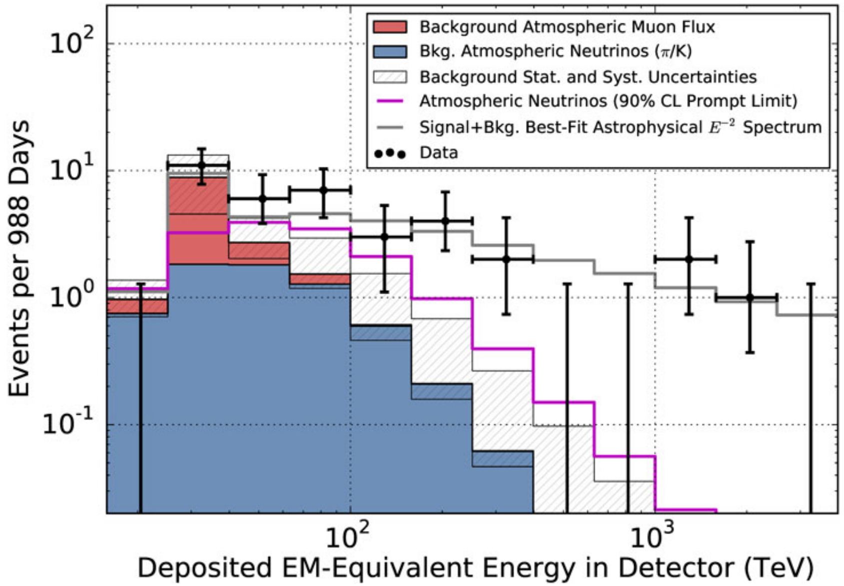
Berlin and Hooper, 2016

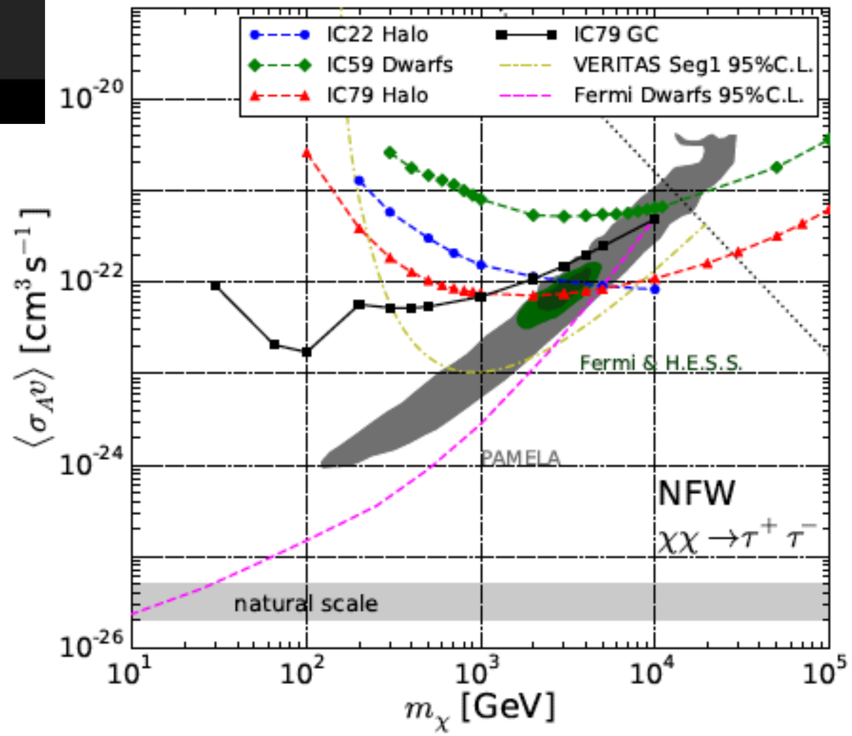
PeV neutrinos by IceCube









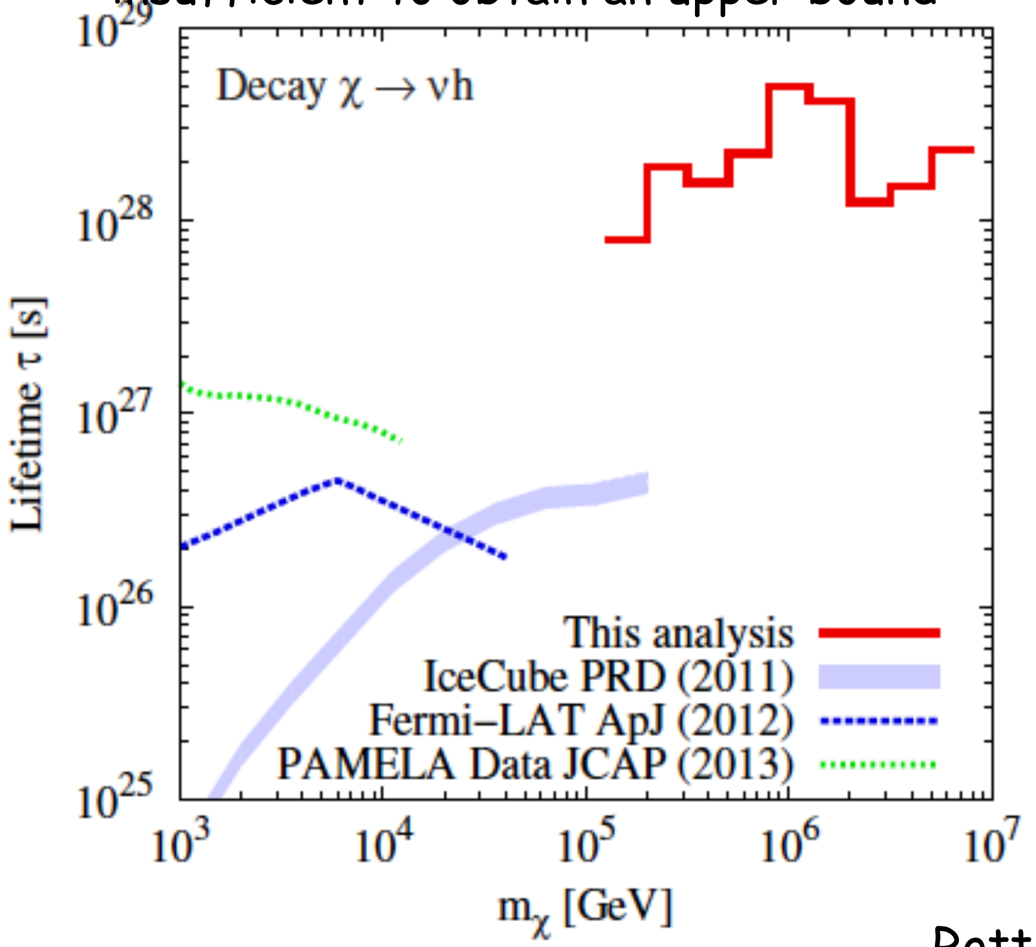


IceCube collaboration
M. G. Aartsen et al, 2014

IceCube collaboration
M. G. Aartsen et al, 2015

Lower bounds on lifetime for decaying DM

To be consistent with the flux, but statistically insufficient to obtain an upper bound



Rott, Kohri, Park ,2015

Summary

- (Cold) dark matter (CDM) exists in the Universe with the energy fraction of 27%, or 5 times larger than baryon (atoms)
- There are many candidates of CDM such as WIMP, axion, PBH, sterile neutrino, …
- Our next step is to detect it with high confidence levels and reveal its nature

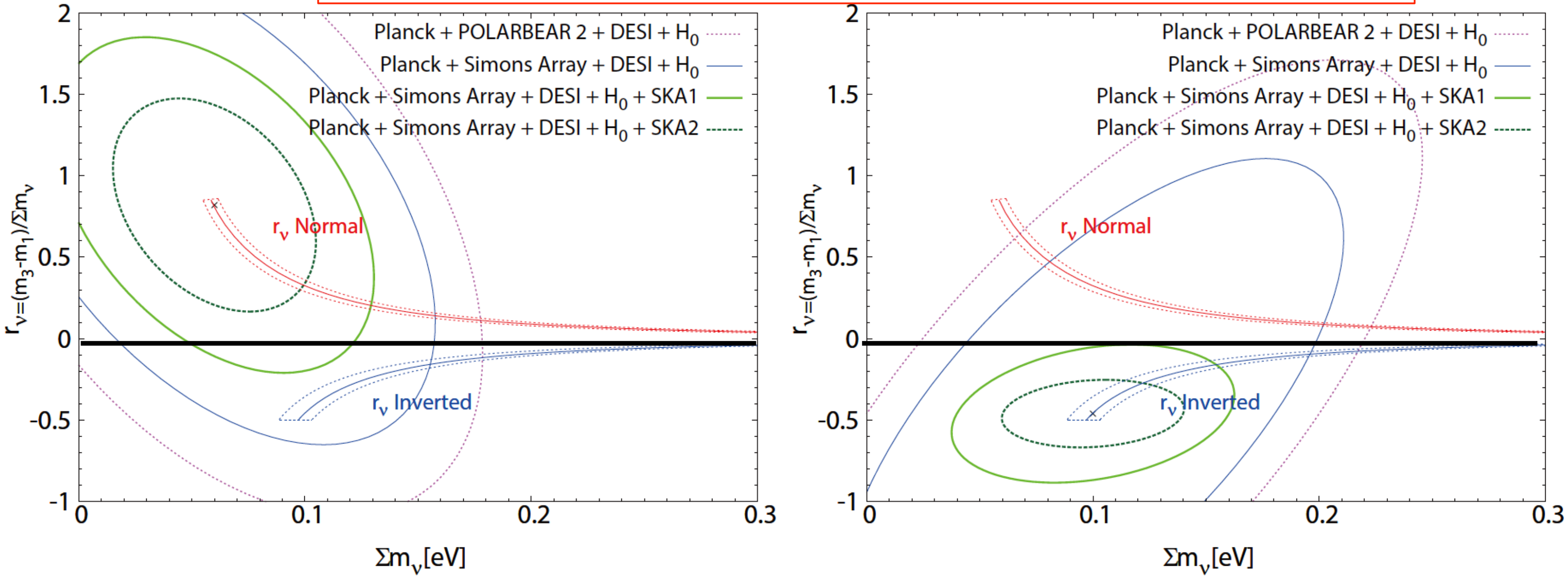
To answer Sergey Petcov ‘s question

Future constraints on neutrino hierarchy by 21cm, CMB and BAO

Oyama, Kohri, Hazumi (2015)

- Hierarchy parameter

$$r_\nu \equiv \frac{m_3 - m_1}{\Sigma m_i} = \begin{cases} > 0 & \text{normal hierarchy} \\ < 0 & \text{inverted hierarchy} \end{cases}$$



Future constraints on neutrino mass by 21cm, CMB, and BAO

Oyama, Kohri, Hazumi (2015)