暗物质间接探测与相关宇宙学

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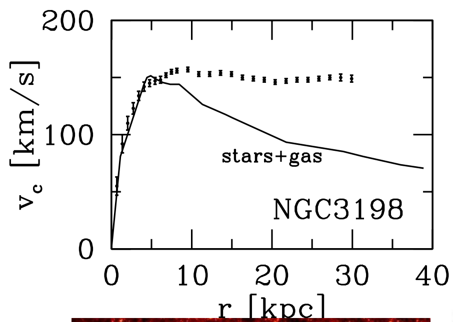
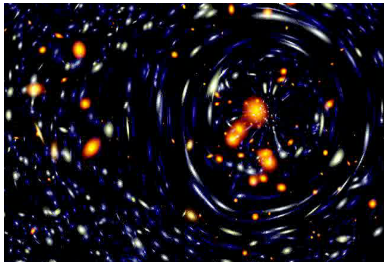
第十一届威海新物理研讨会

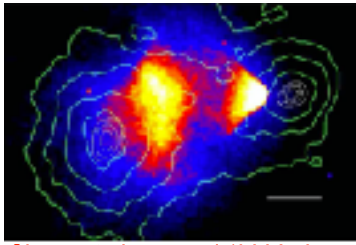
2022.7.31-8.7

暗物质的观测证据

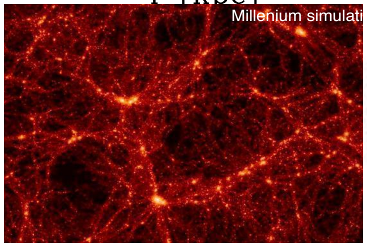
- 星系旋转曲线
- 引力透镜
- 大尺度结构
- 微波背景辐射
- 子弹星系团碰撞

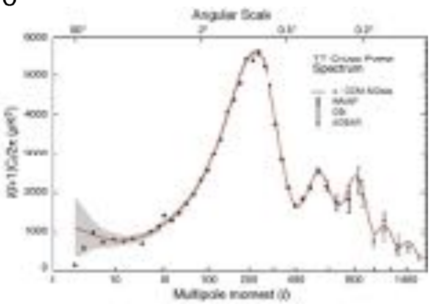


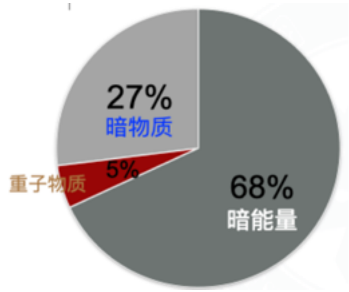




Clowe et al, astro-ph/0608407





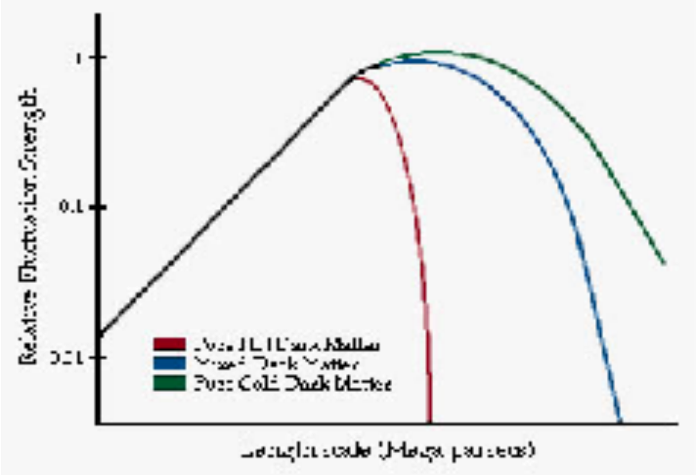


目前确切的证据都来自引力作用

冷暗物质: *WIMP*, *Axion*, …

温暗物质: *keV* 惰性中微子…

热暗物质: 中微子…



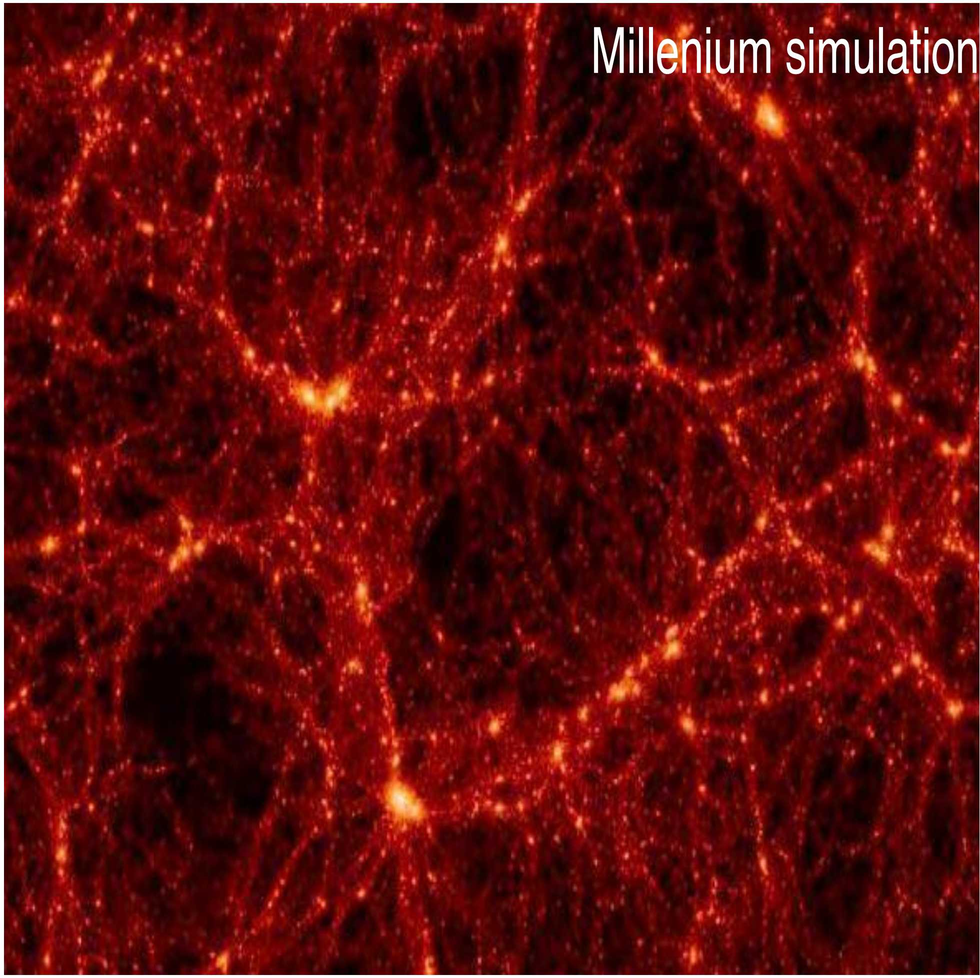
扰动的演化

- 背景（均匀+各项同性）> 没有结构
- 扰动（不均匀）> 结构

$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$$

$$\sigma^2(R) = \frac{1}{2\pi^2} \int W_R^2(k) P(k) k^2 dk,$$

- *P(k)* 物质功率谱



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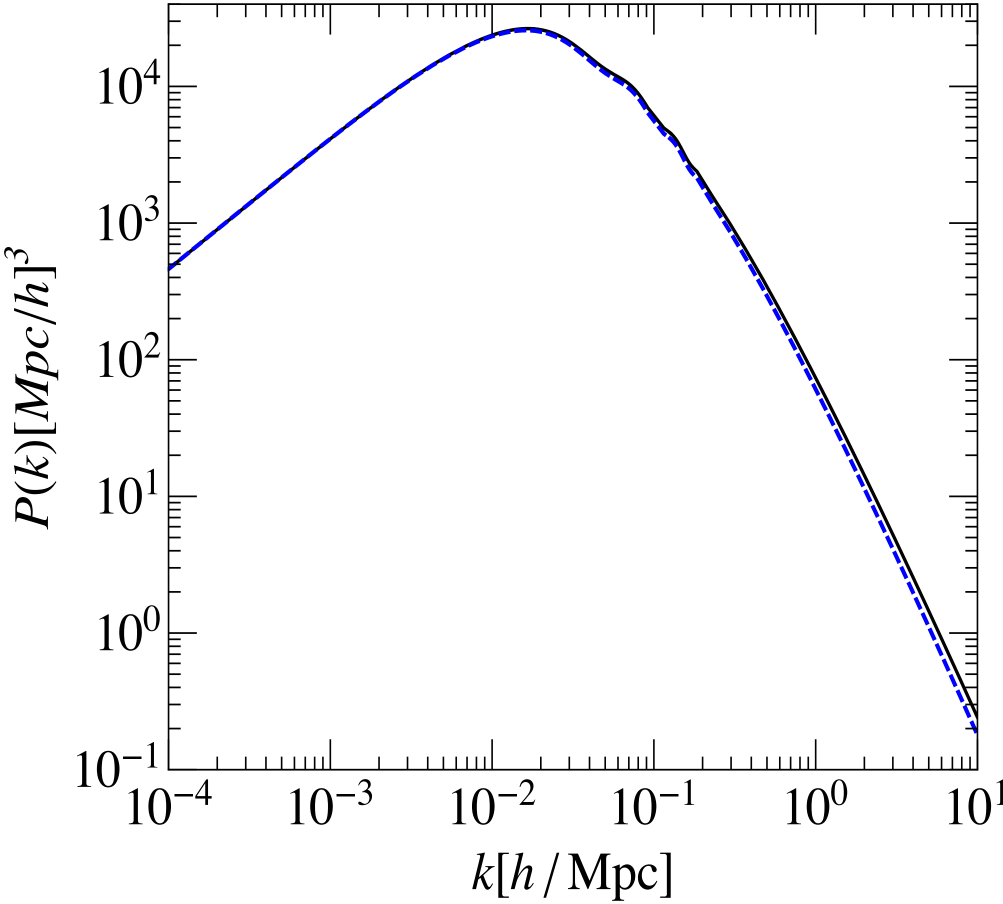
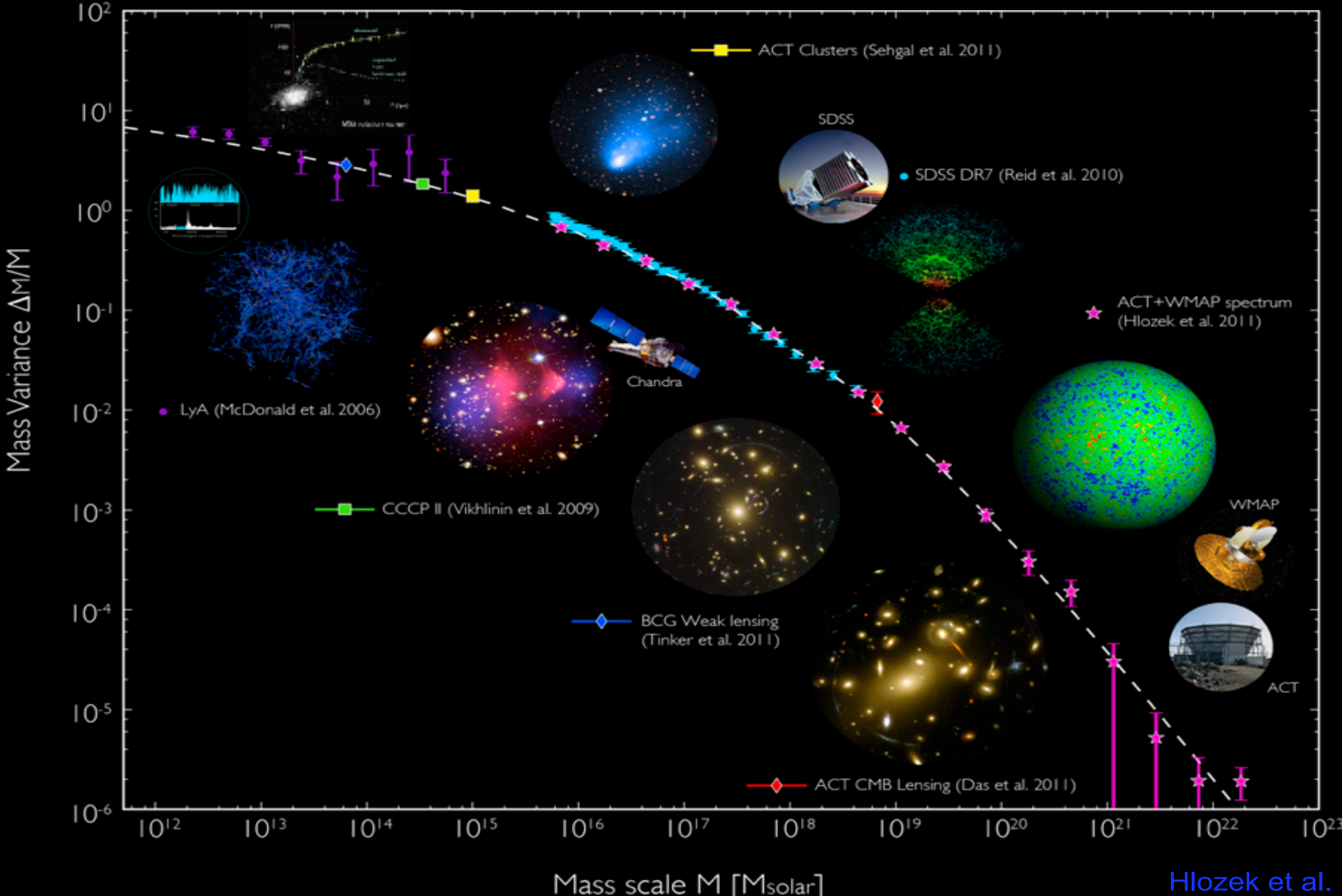


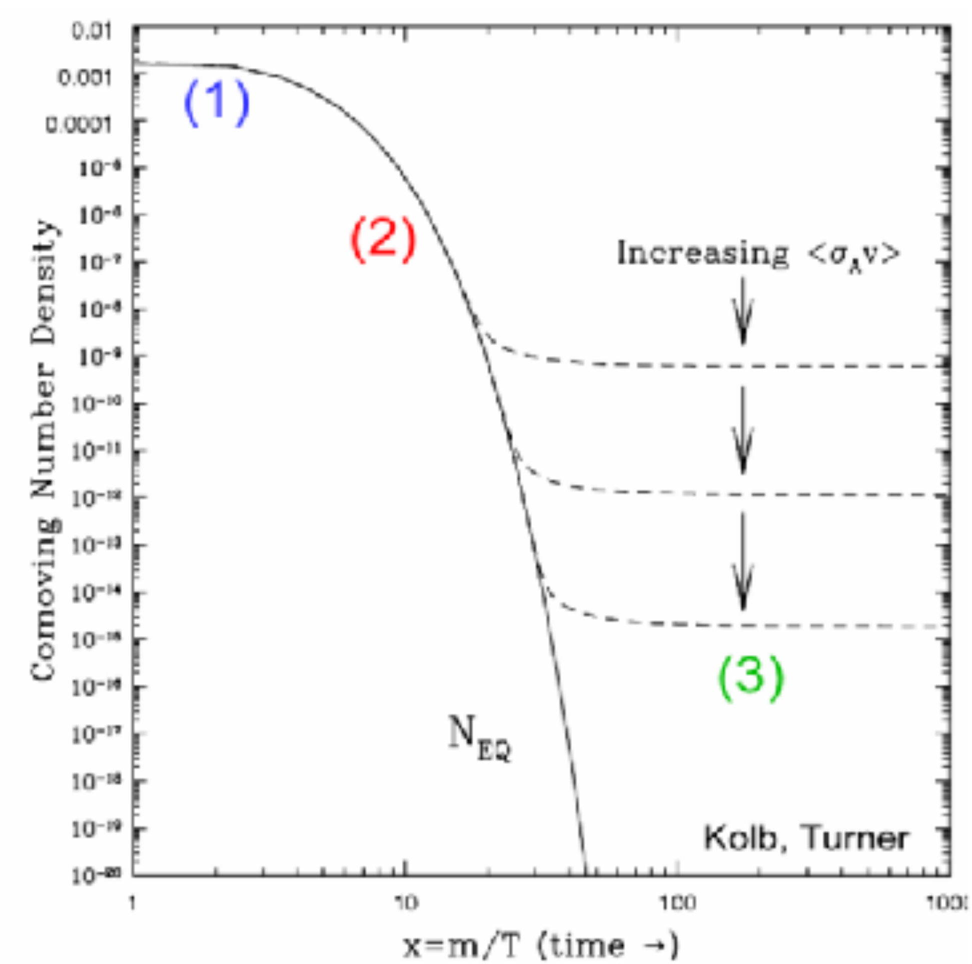
ΛCDM



Hlozek et al. 2012

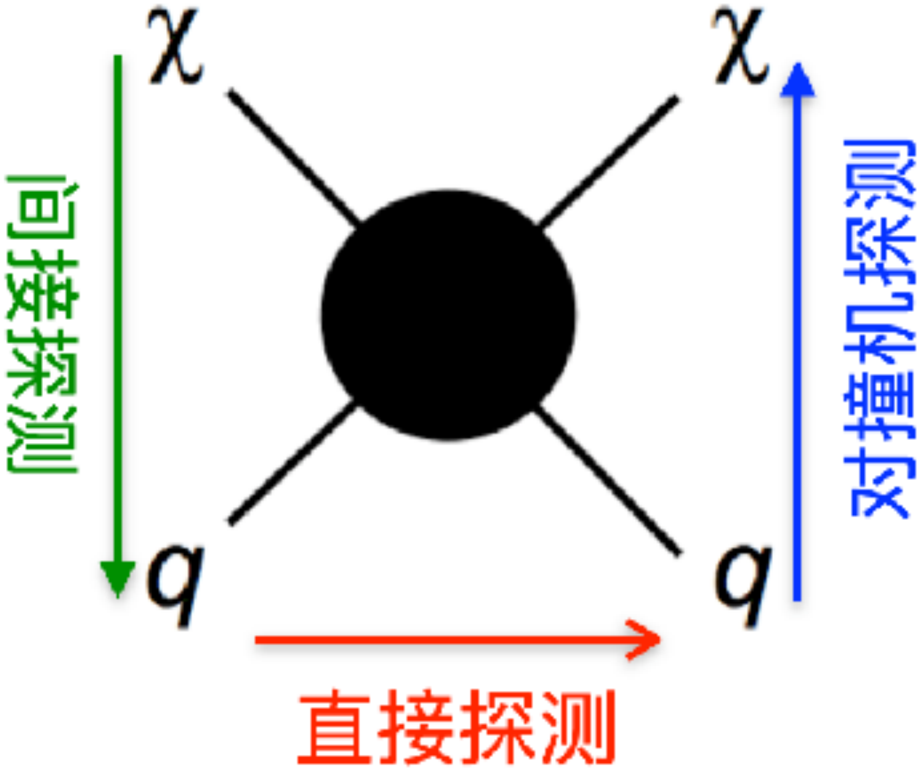
弱相互作用大质量粒子

- WIMP, 质量 10GeV～100TeV
- 耦合常数 ~ 0.5
- 剩余丰度 Ω~0.3
- 热历史
  - 热平衡 XX<>ff
  - 热平衡 XX >ff
  - 退耦
- 冷暗物质 (CDM)



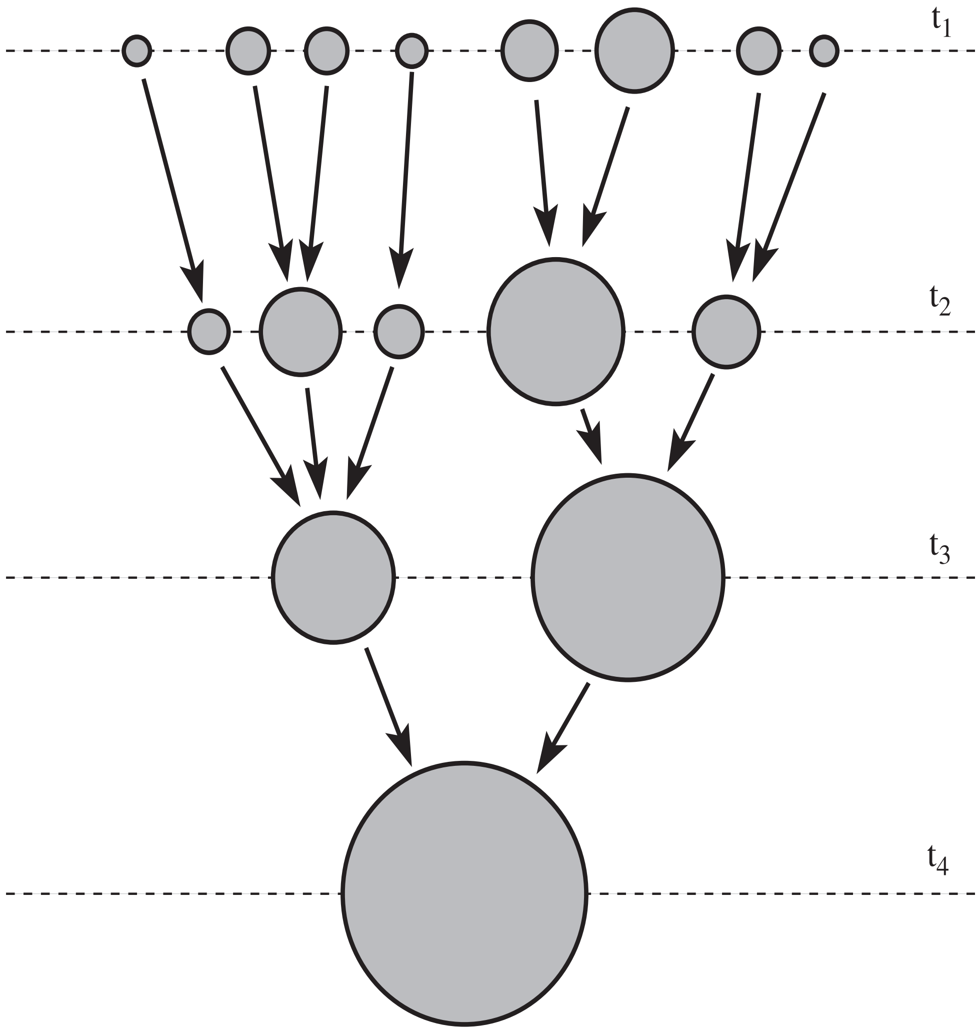
弱相互作用大质量粒子

- WIMP, 质量 10GeV～100TeV
- 耦合常数 ~ 0.5
- 剩余丰度 Ω~0.3
- 探测方式
  - 对撞机 qq > XXj
  - 直接 Xq > Xq
  - 间接 XX > qq
- 超出标准模型理论



暗物质晕的形成

- 广义相对论与标准宇宙学扰动理论
- 结构形成标准图像
- 暗物质晕等形成的等级结构
- 小尺度暗晕先形成
- 然后并合形成更大的暗物质晕



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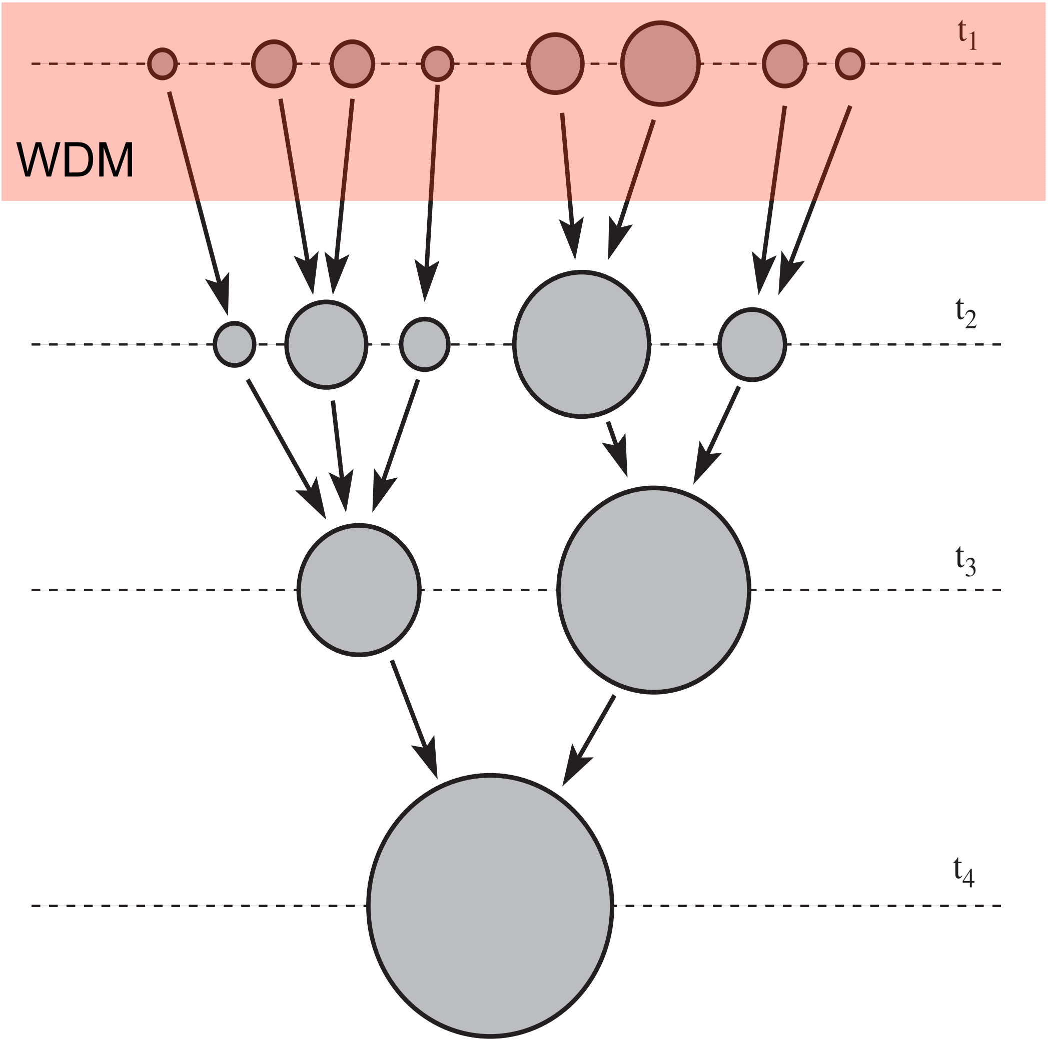

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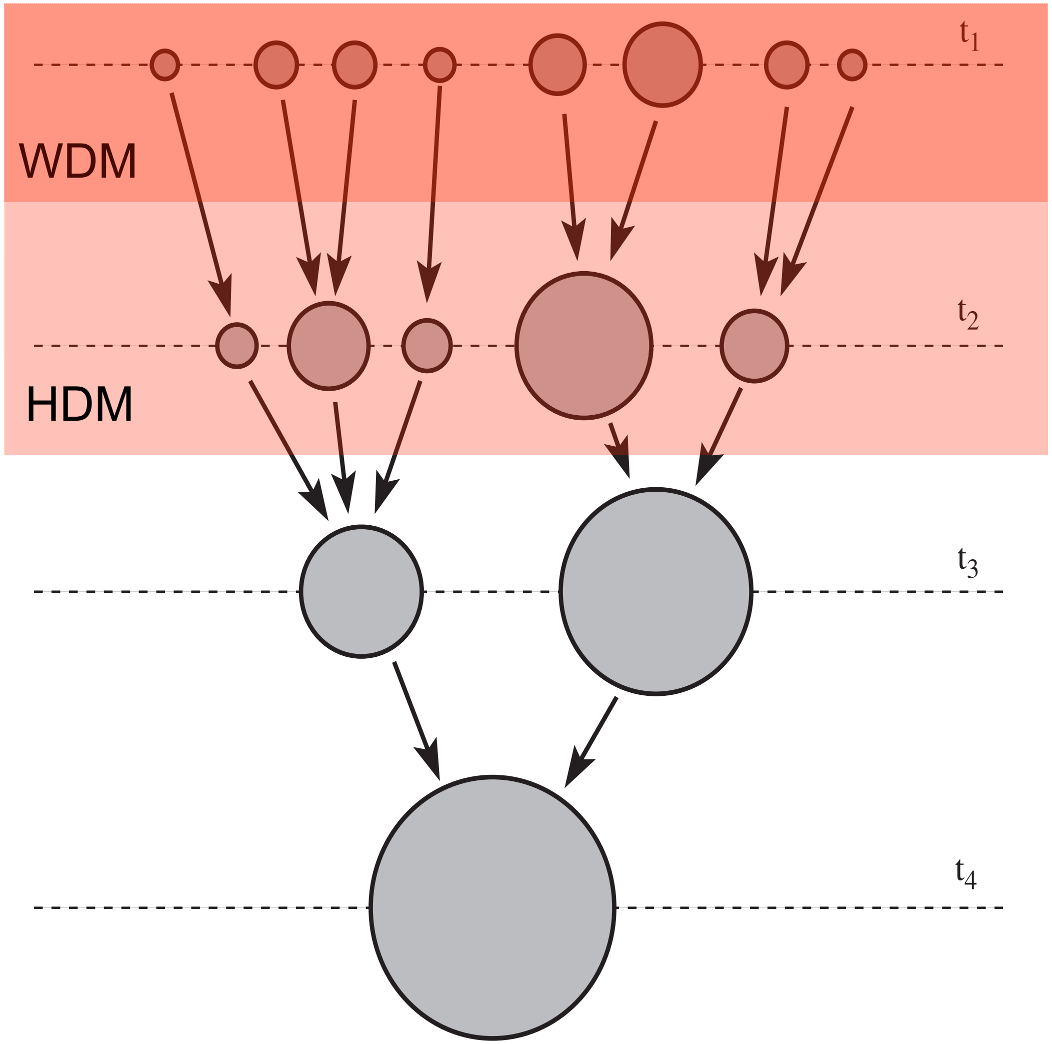


冷暗物质（WIMP）

- 在早期宇宙中一般处于热平衡
- 退耦时的温度 T ~ m/20, 速度 v ~ c/3，之后速度反比尺度因子a
- 当宇宙的温度降到keV时，暗物质粒子的速度很小，温度很低，所以称为冷暗物质
- 暗物质与普通物质的相互作用不影响结构形成
- 暗物质之间的相互作用可以忽略
- Collisionless DM

Cusp vs. Core

- 暗物质密度分布

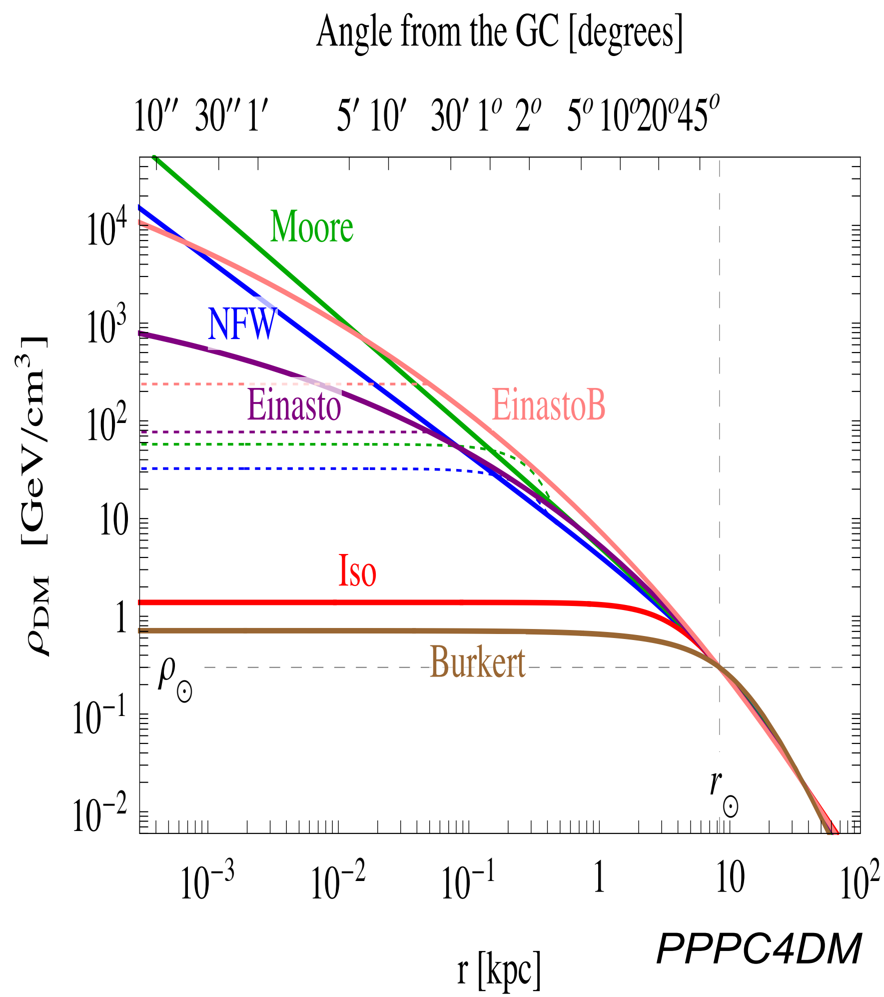
$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

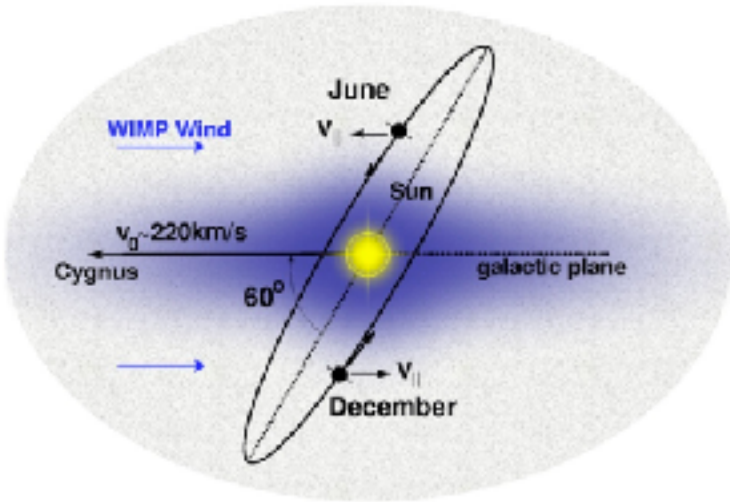
$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

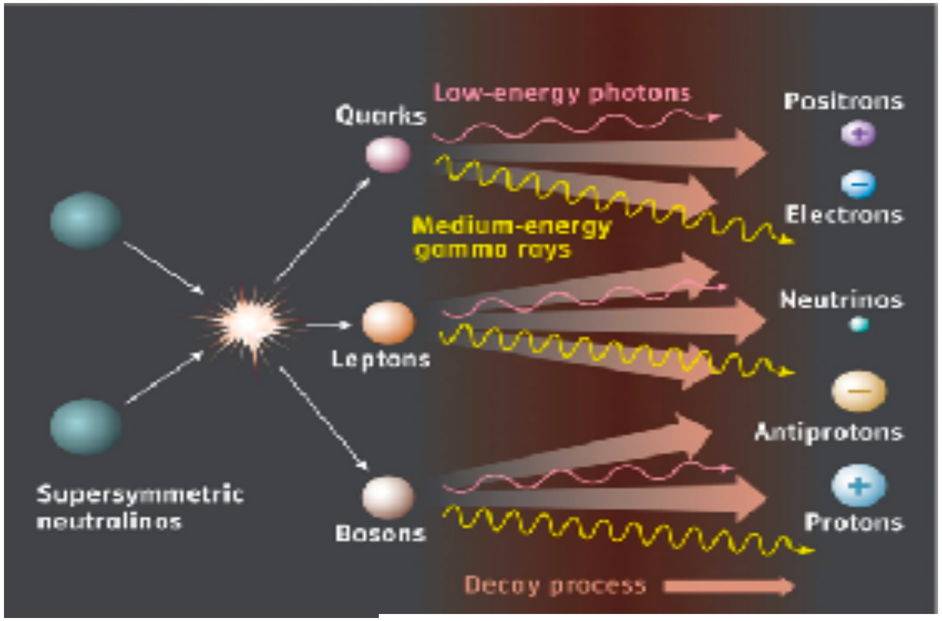


Cuspy profiles, such as NFW, are predicted by N-body simulation of CDM

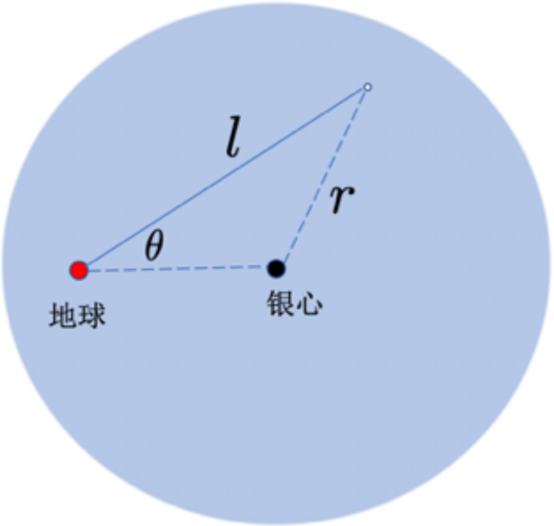
暗物质间接探测

- 暗物质湮灭





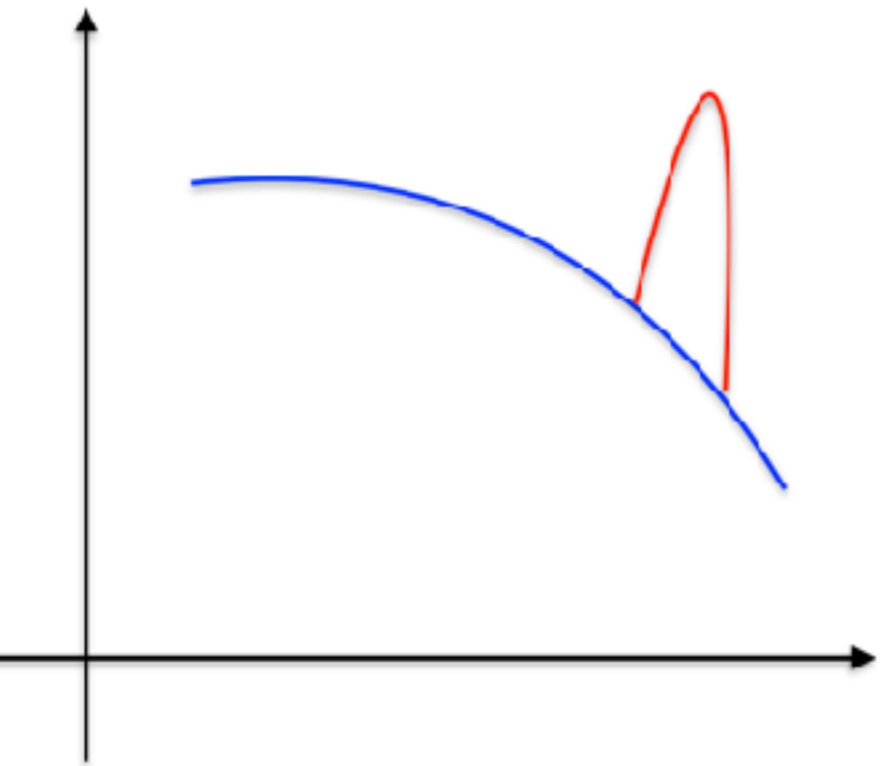
$$\Phi_\gamma(E_\gamma) \simeq \langle\sigma_A v\rangle \frac{dN_\gamma}{dE_\gamma}\int_{\text{line of sight}} \frac{\rho^2(r)}{m_\chi^2} dl(\theta)d\theta$$



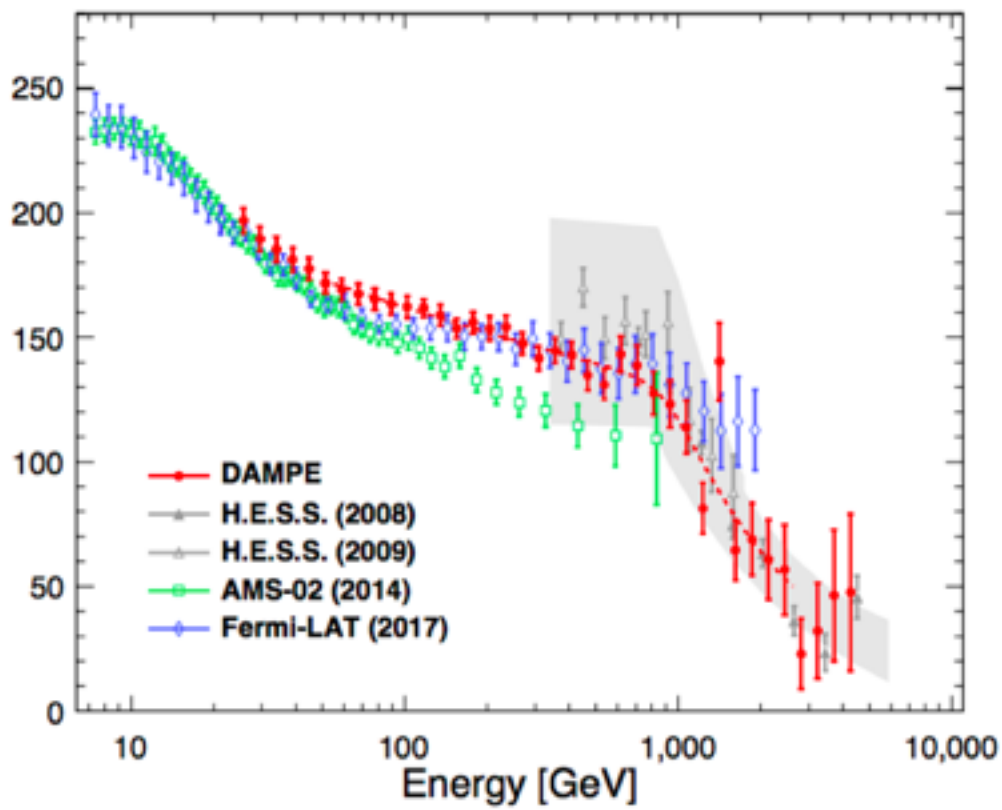
$$\rho(r) = \rho_0\,(r/r_s)^{-\gamma}\,[1+(r/r_s)]^{\gamma-3}$$ NFW profile

间接探测

- 暗物质湮灭的信号
- 连续谱上叠加特征谱



$$\text{flux} \propto \langle \sigma v \rangle$$



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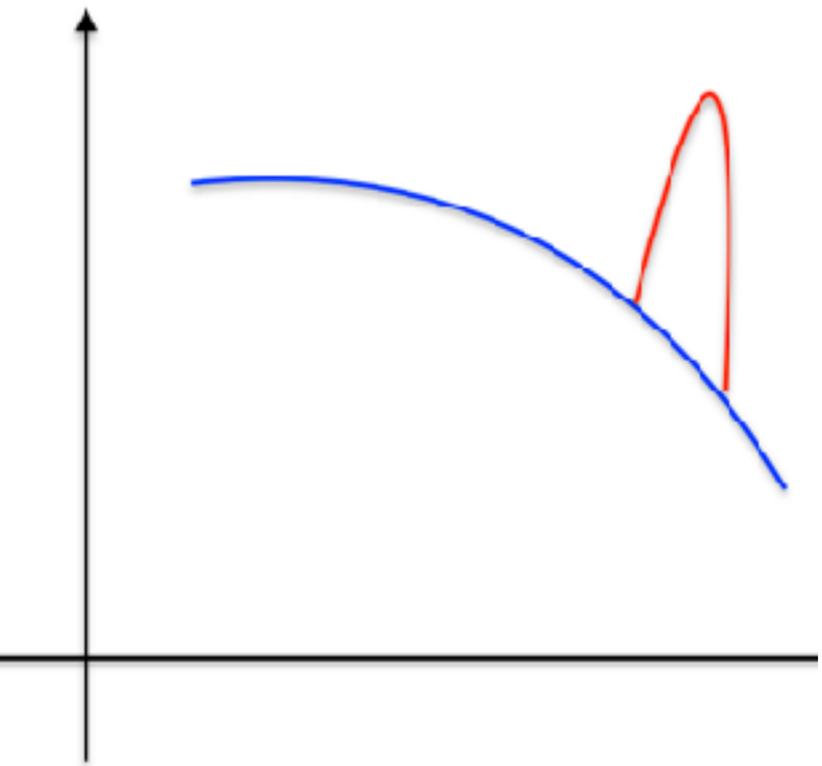
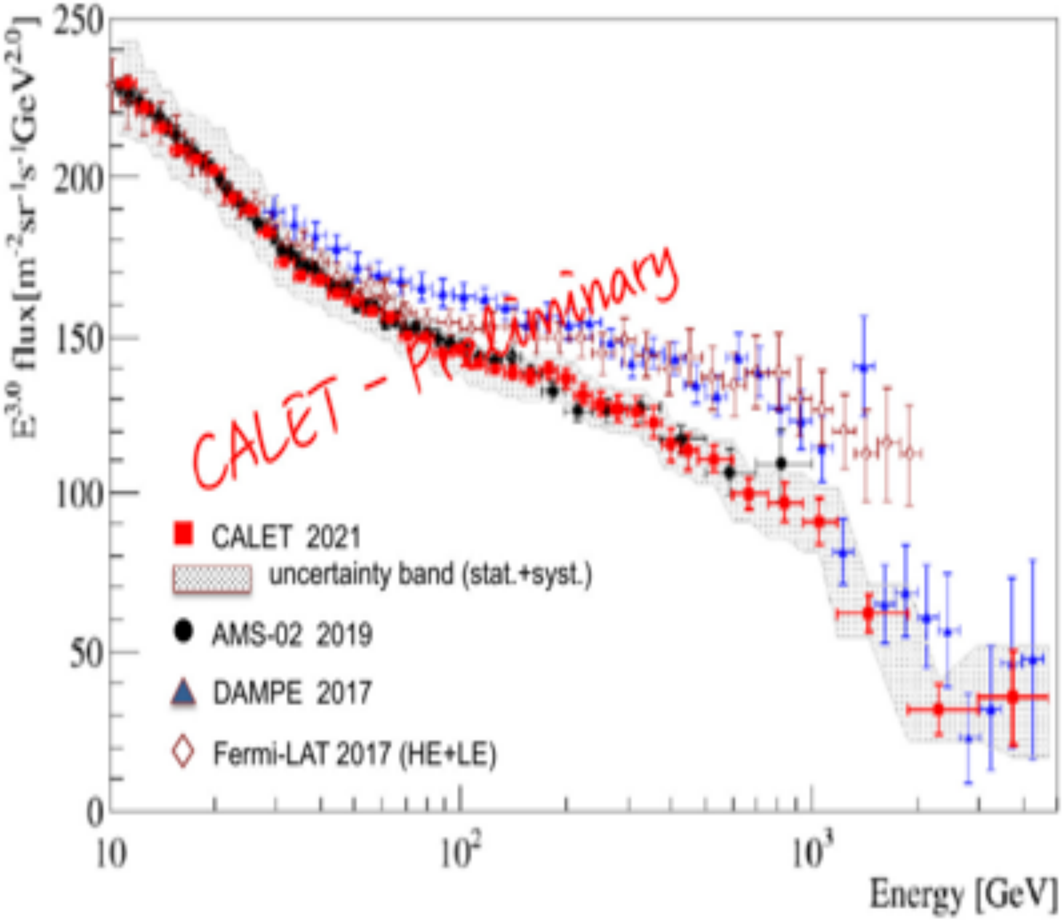
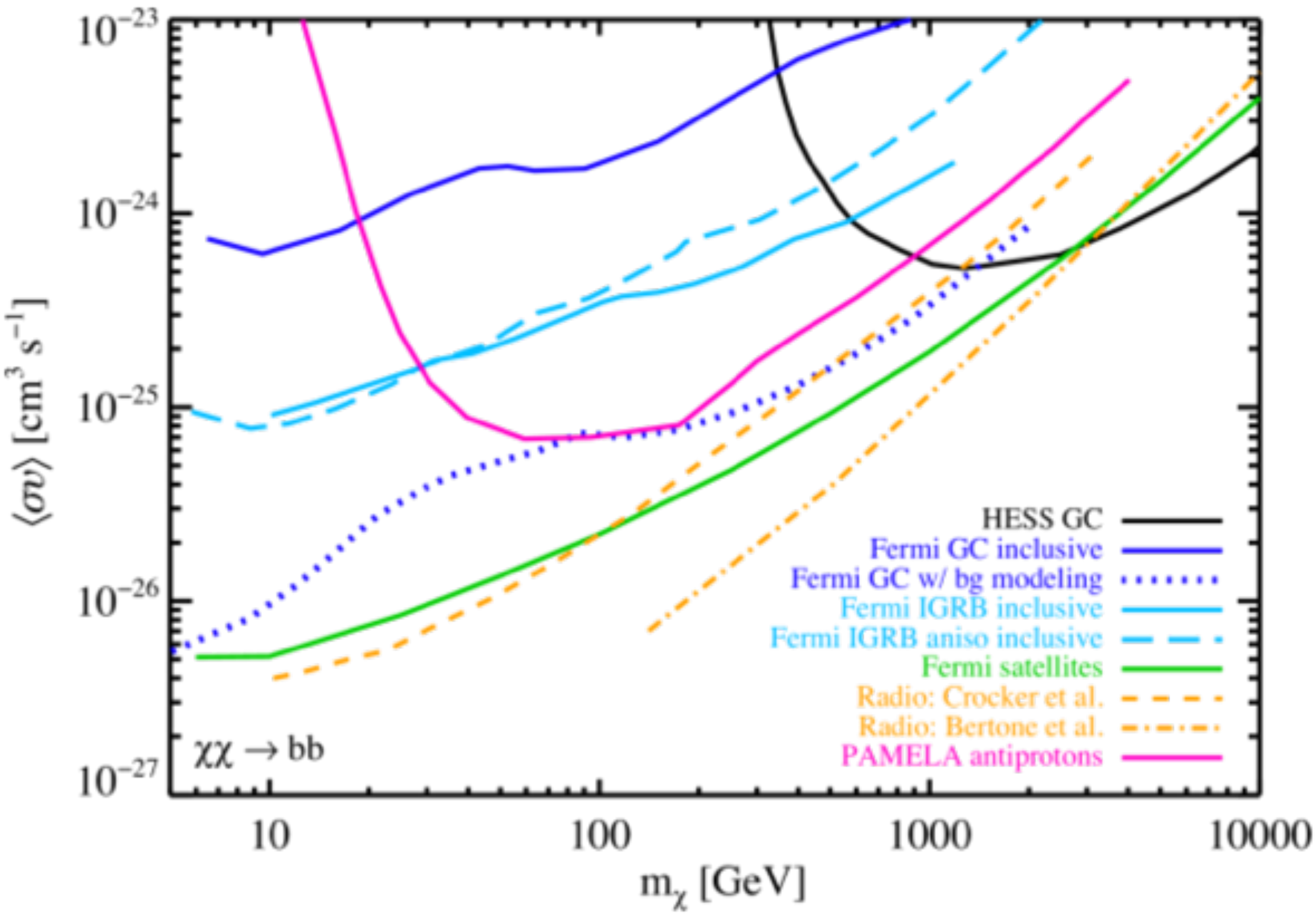




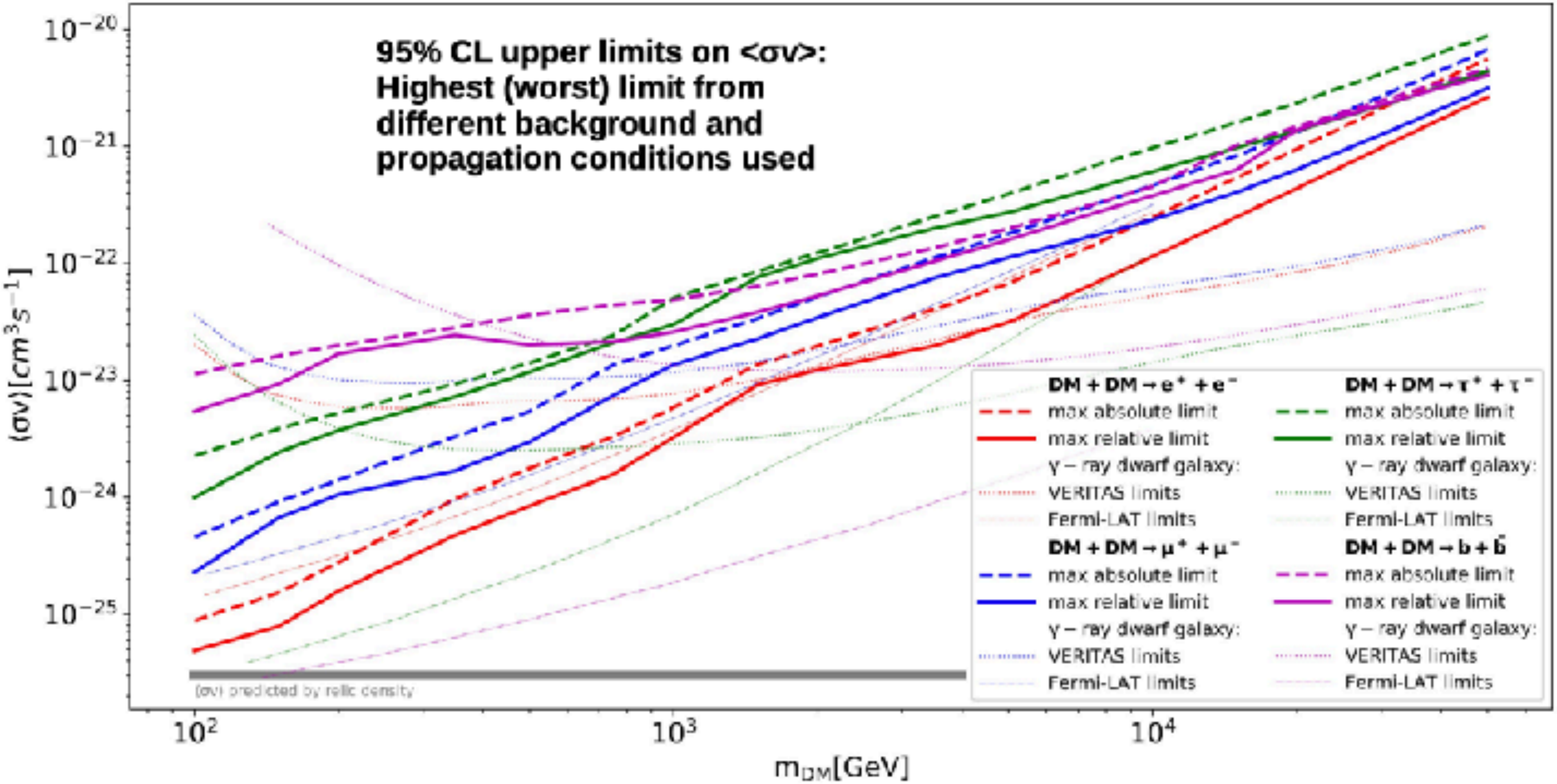
间接探测

- 各种观测对暗物质湮灭截面的限制



Fermi-LAT

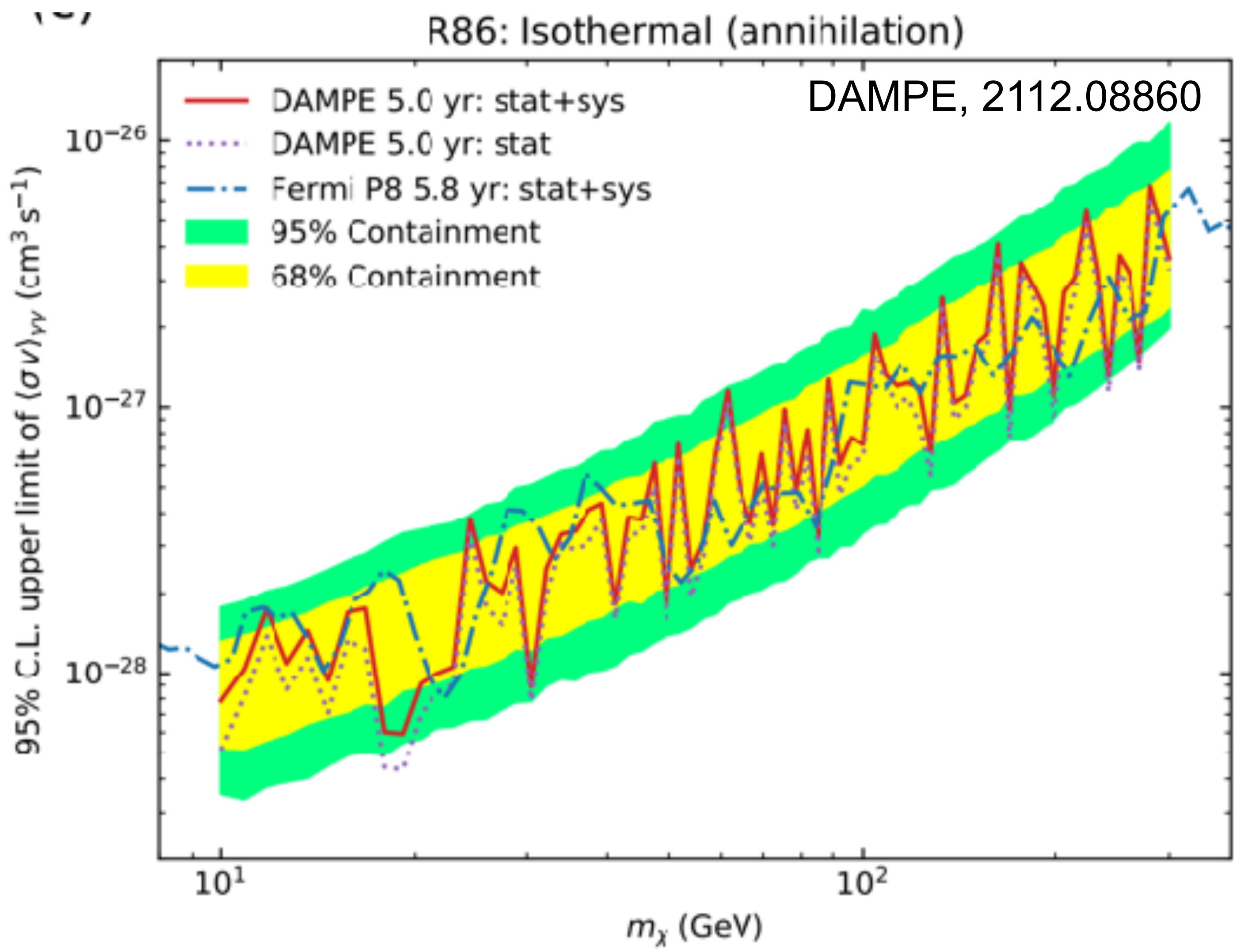
- Fermi-LAT对暗物质湮灭截面的限制



VERITAS limits: Phys. Rev. D, 95(8):082001, 2017 ; Fermi-LAT limits: Phys. Rev. Lett., 115(23):231301, 2015.

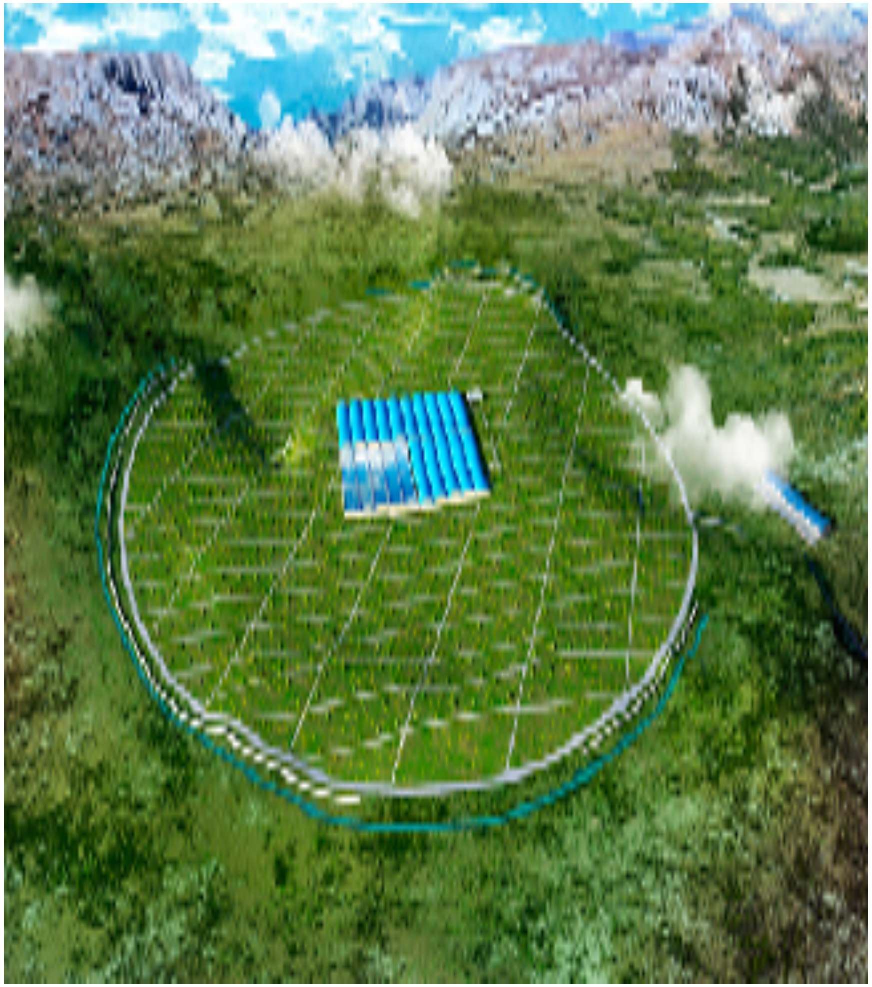
DAMPE

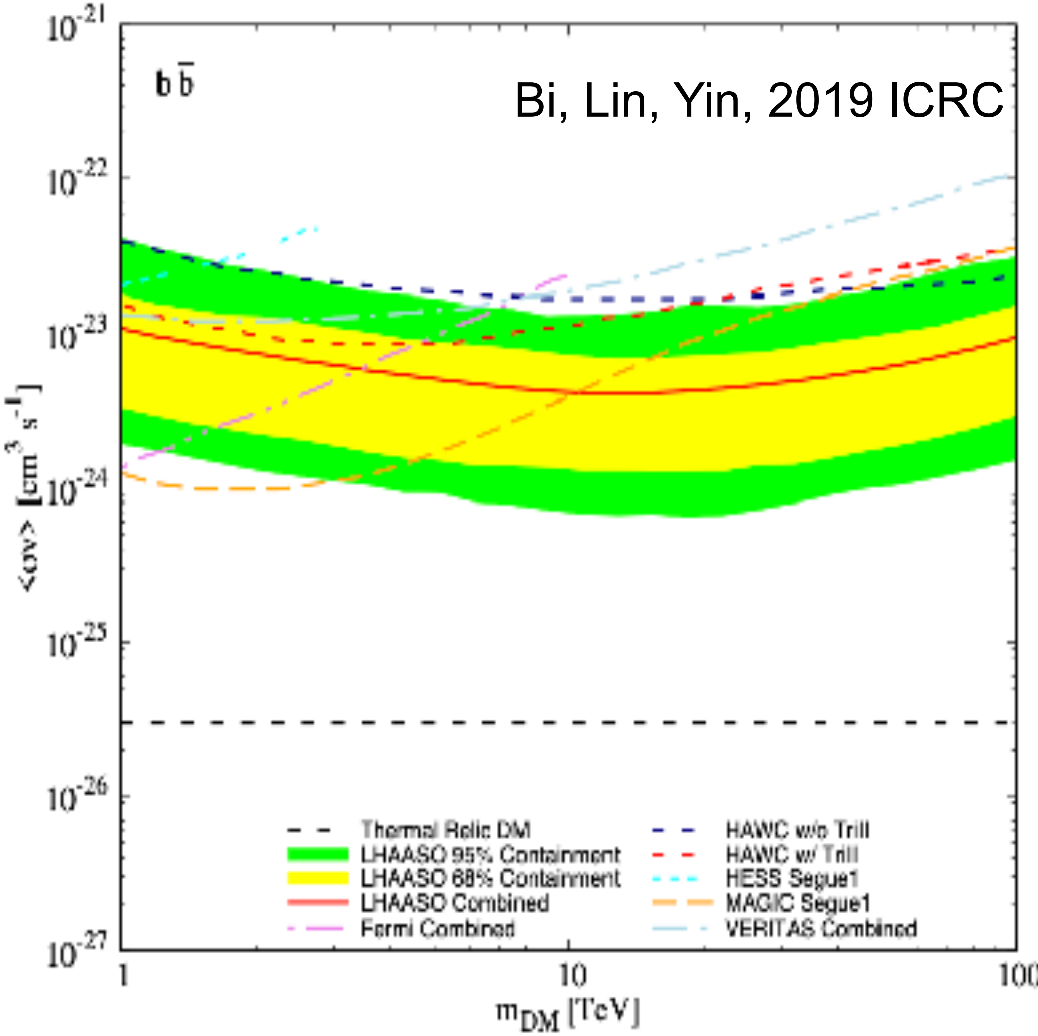
- DAMPE伽马射线对暗物质湮灭截面的限制



LHASSO

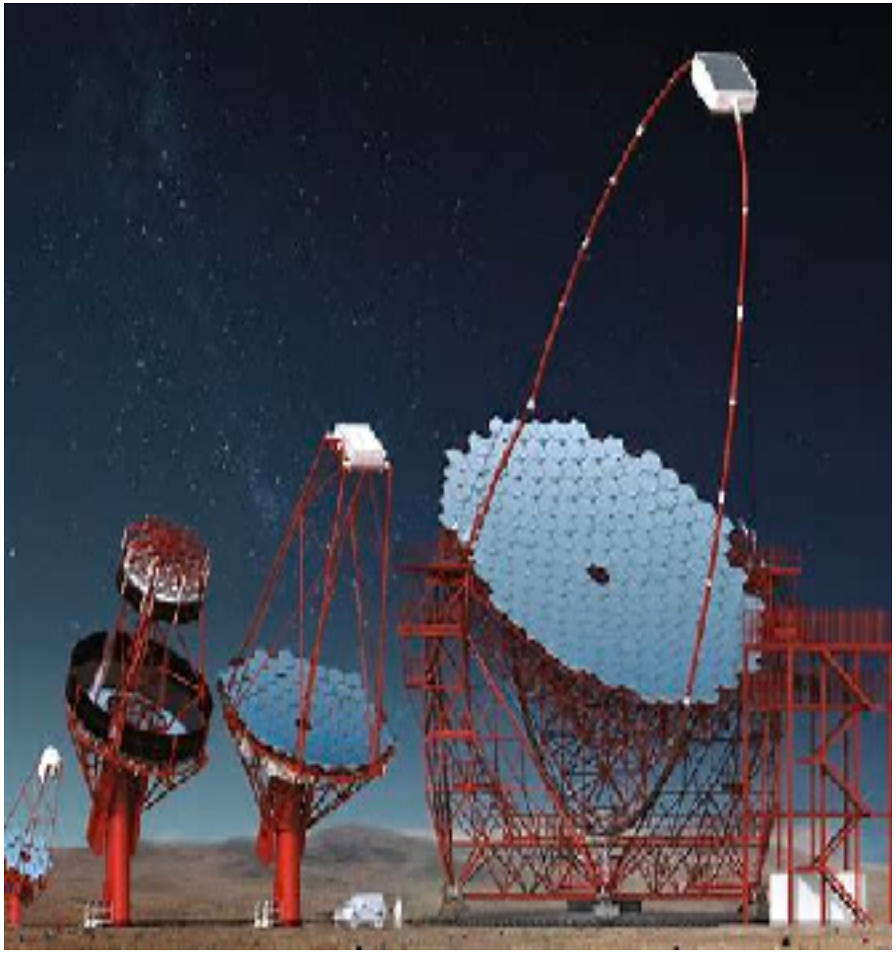
- LHAASO对暗物质湮灭截面的限制



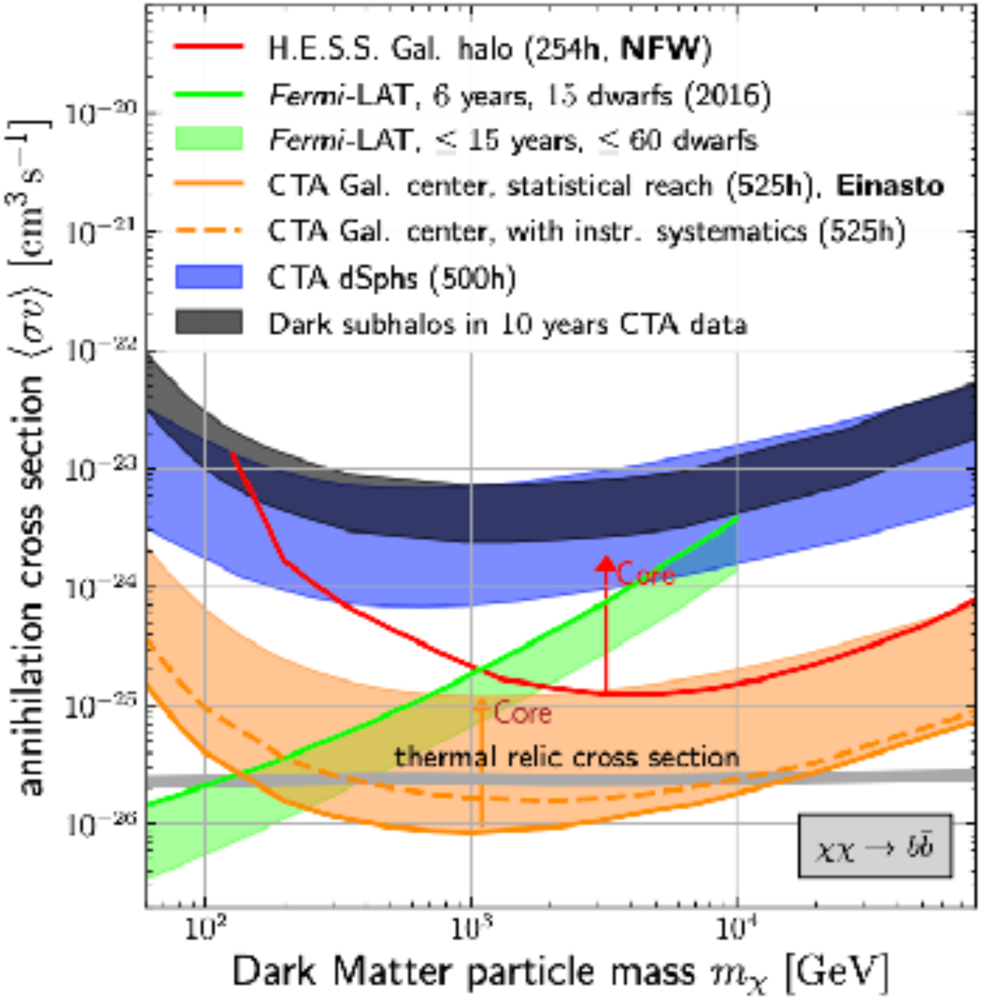


CTA

- CTA 灵敏度

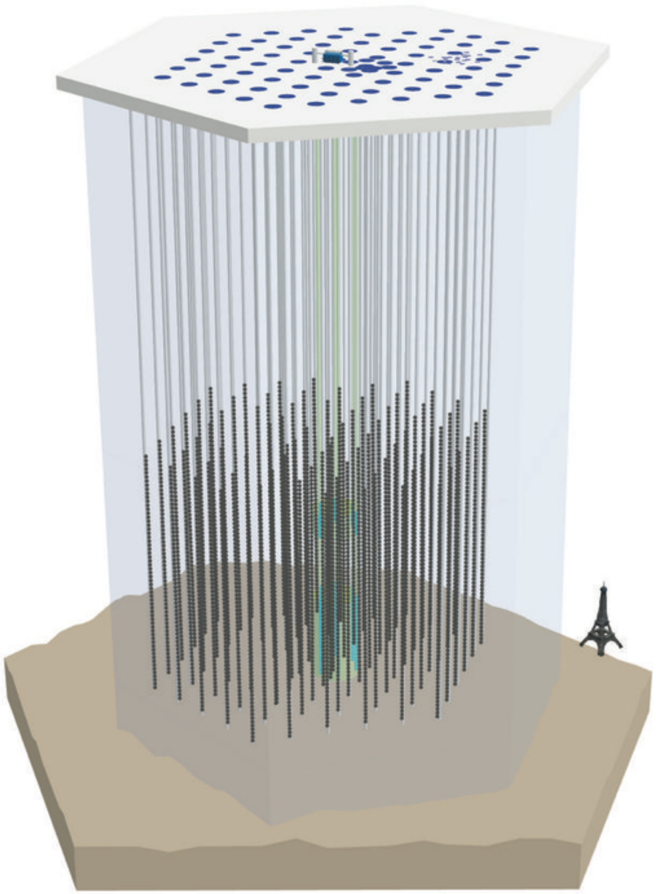


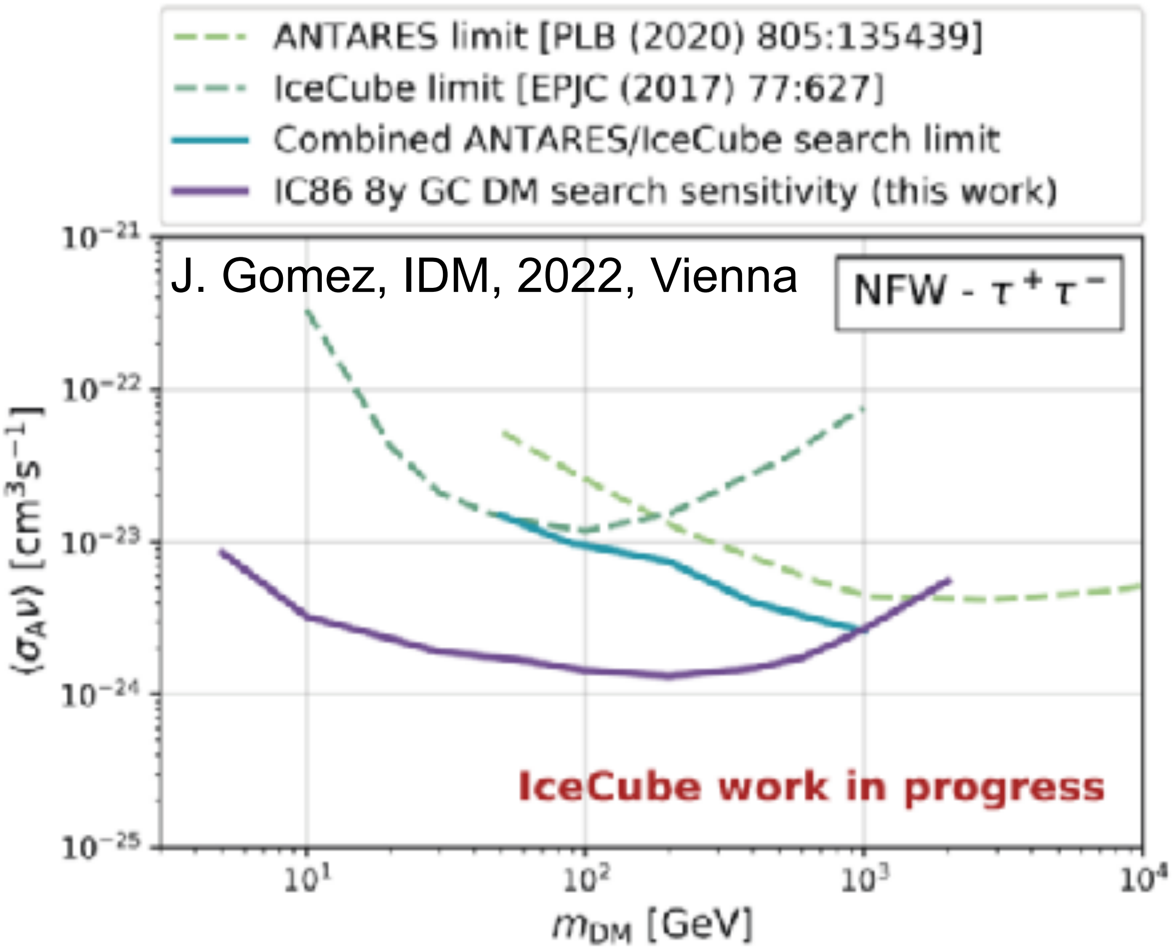
Spain, Chile



IceCube

- GC dark matter annihilation

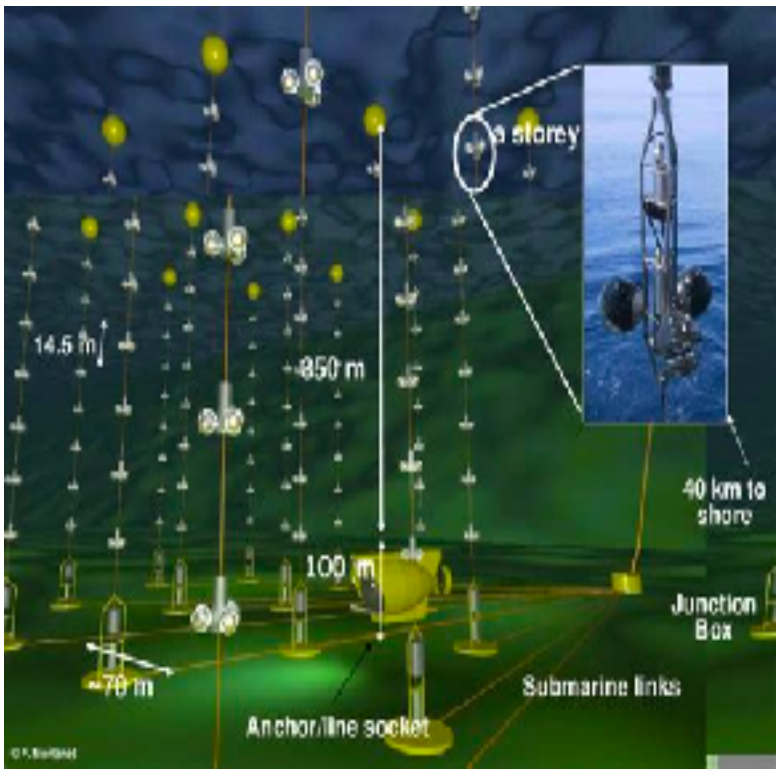




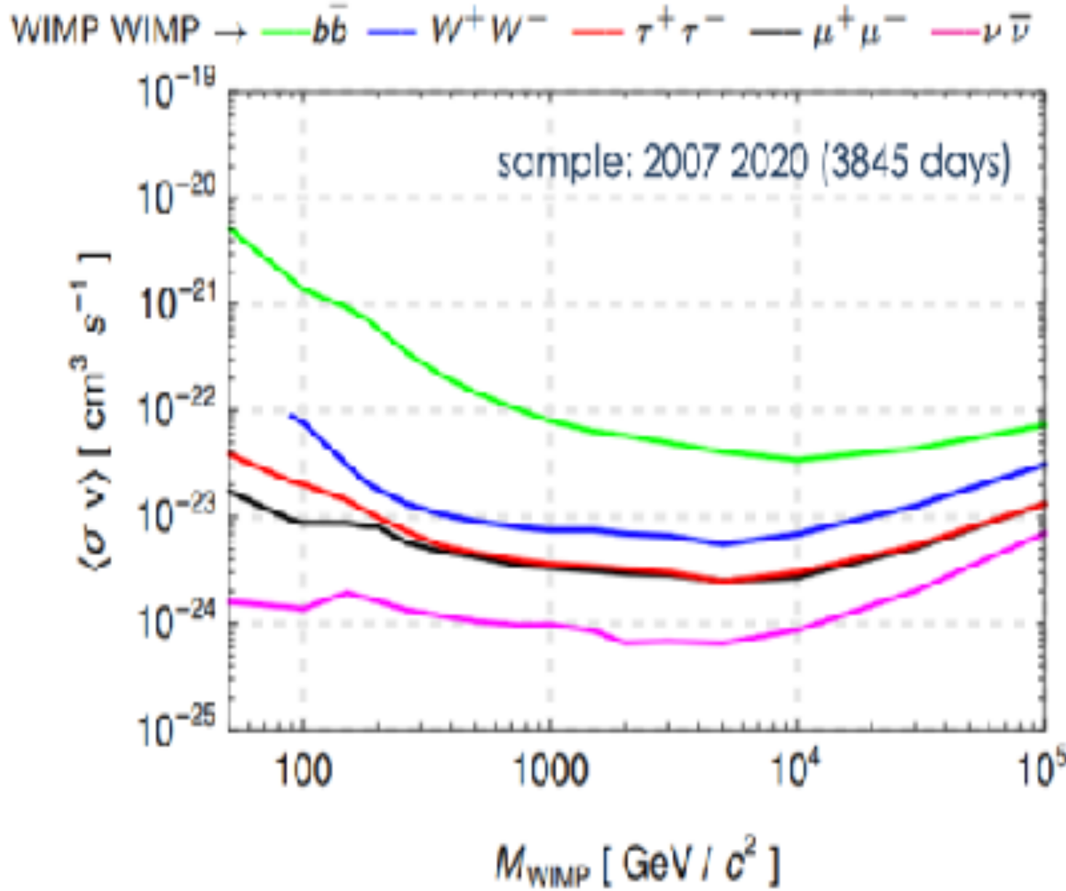
ANTARES

- Undersea experiment

Mediterranean Sea



ANTARES, Phys. Lett. B 805, 135439 (2020)



超出 Collisionless DM

- 理论动机
  - Atomic DM, Mirror DM, Composite DM…
  - Eventually, all DM is *interacting* in some way, the question is how strongly?
  - Self-Interacting DM $\frac{\sigma}{M_X} \sim \mathrm{cm}^2/\mathrm{g} \sim \mathrm{barn}/\mathrm{GeV}$
- 可能的观测对象
  - *CMB, LSS, BBN*
  - 其他天体物理效应,…
- 可以解决冷暗物质中的疑难
  - *Cusp-vs-Core, Too-big-to-fail, missing satellite? …*
  - H_0, σ_8? 3σ

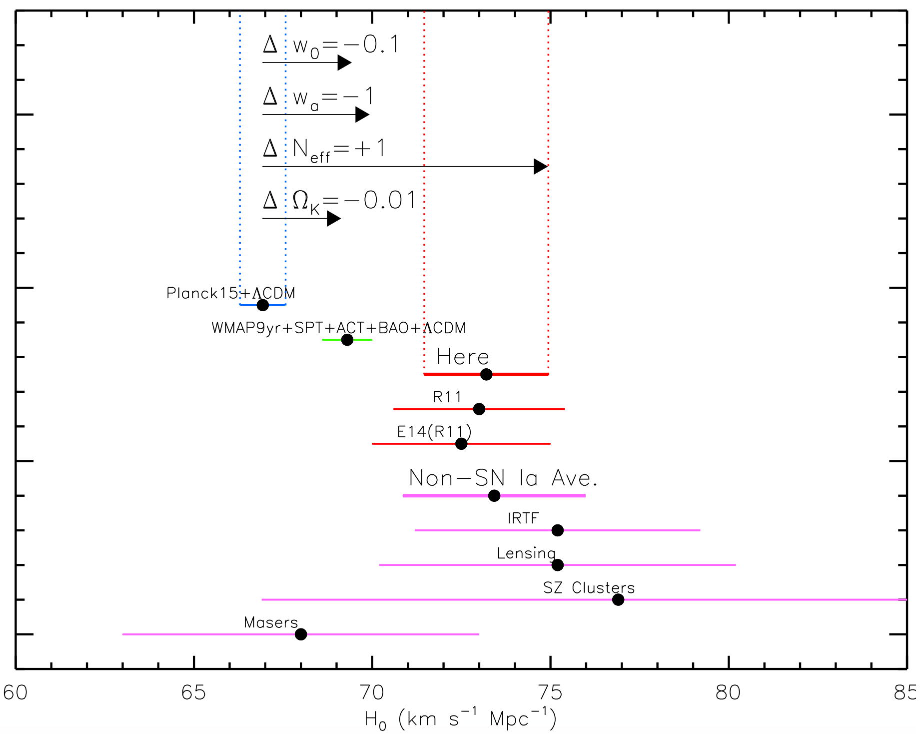
哈勃常数疑难

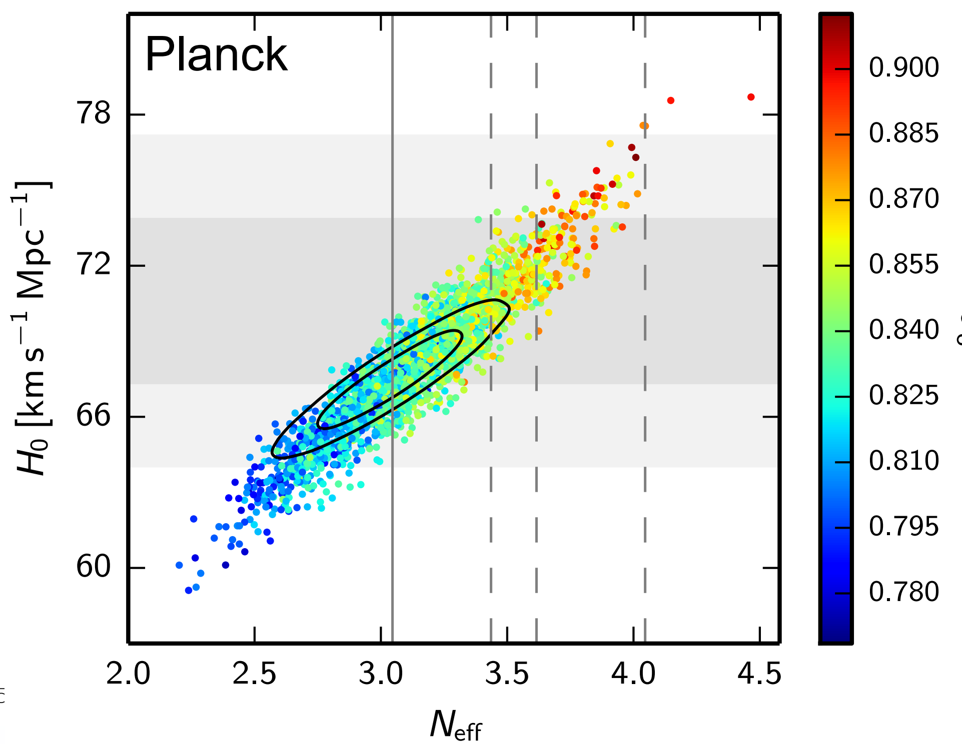
- Hubble Constant *H_0*

$$H \equiv \frac{1}{a}\frac{da}{dt} = \frac{\sqrt{\rho_r + \rho_m + \rho_\Lambda}}{M_p}$$

- Planck gives $67.8 \pm 0.9\ \mathrm{km\ s^{-1} Mpc^{-1}}$
- HST gives $73.24 \pm 1.74\ \mathrm{km\ s^{-1} Mpc^{-1}}$

RIESS ET AL.





σ8 疑难?

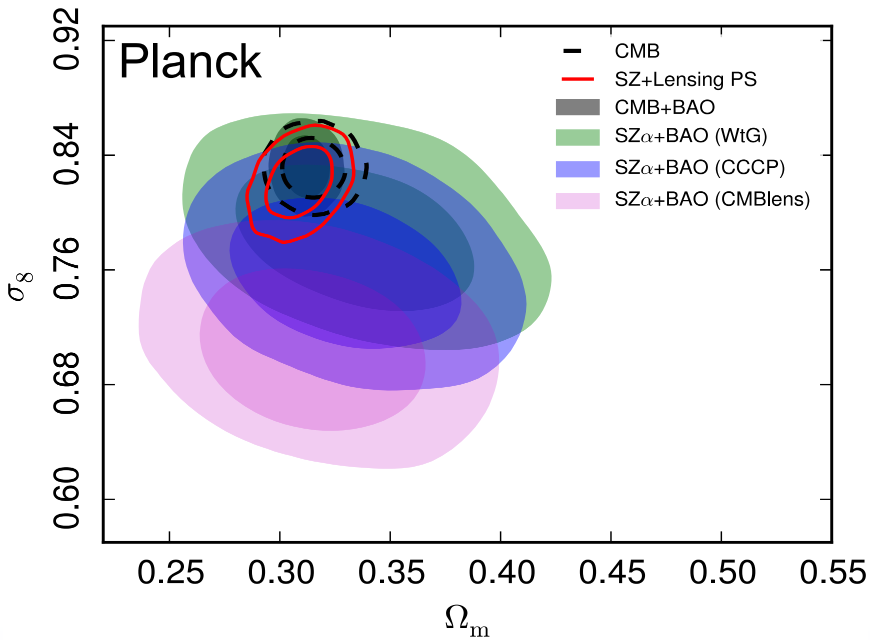
- Variance of perturbation field→collapsed objects

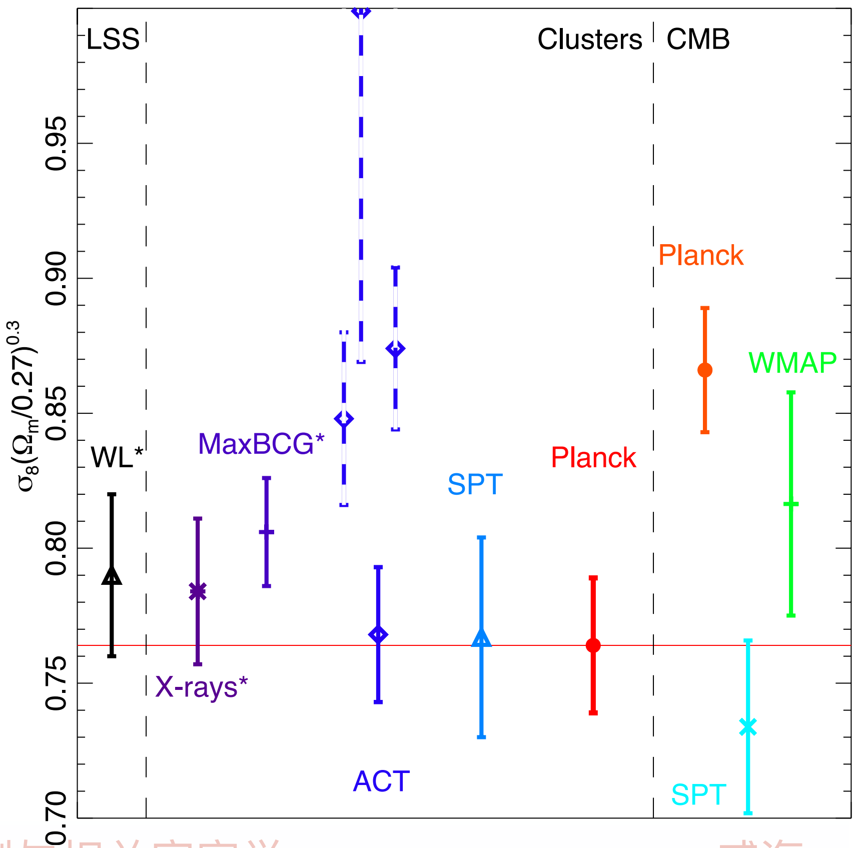
$$\sigma^2(R) = \frac{1}{2\pi^2}\int W_R^2(k)P(k)k^2dk,$$

- where the filter function $W_R(k) = \frac{3}{(kR)^3}\left[\sin(kR) - kR\cos(kR)\right],$

  $P(k)$ 物质功率谱

- $\sigma_8 \equiv \sigma(8h^{-1}\mathrm{Mpc})$





σ_8 疑难?

Planck2015, Sunyaev–Zeldovich cluster counts

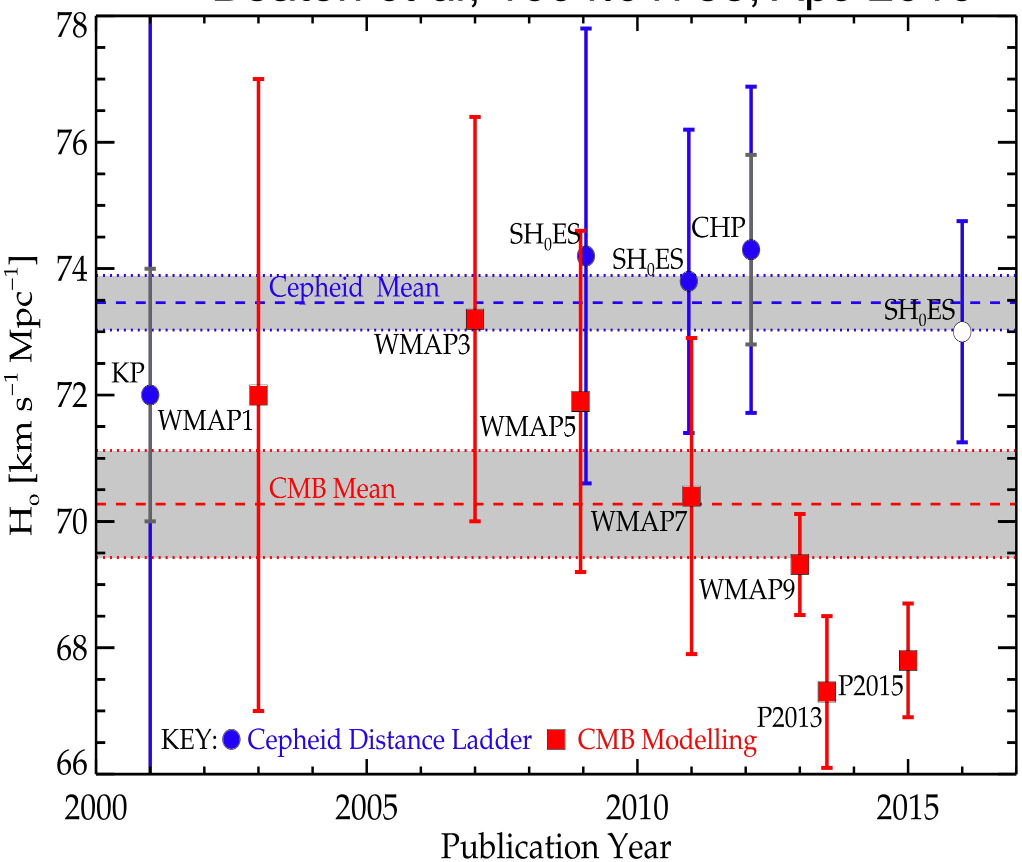
Data	$\sigma_8\left(\frac{\Omega_m}{0.31}\right)^{0.3}$	Ω_m	σ_8
WtG + BAO + BBN	0.806 ± 0.032	0.34 ± 0.03	0.78 ± 0.03
CCCP + BAO + BBN **[Baseline]**	0.774 ± 0.034	0.33 ± 0.03	0.76 ± 0.03
CMBlens + BAO + BBN	0.723 ± 0.038	0.32 ± 0.03	0.71 ± 0.03
CCCP + H_0 + BBN	0.772 ± 0.034	0.31 ± 0.04	0.78 ± 0.04

Planck2015, Primary CMB

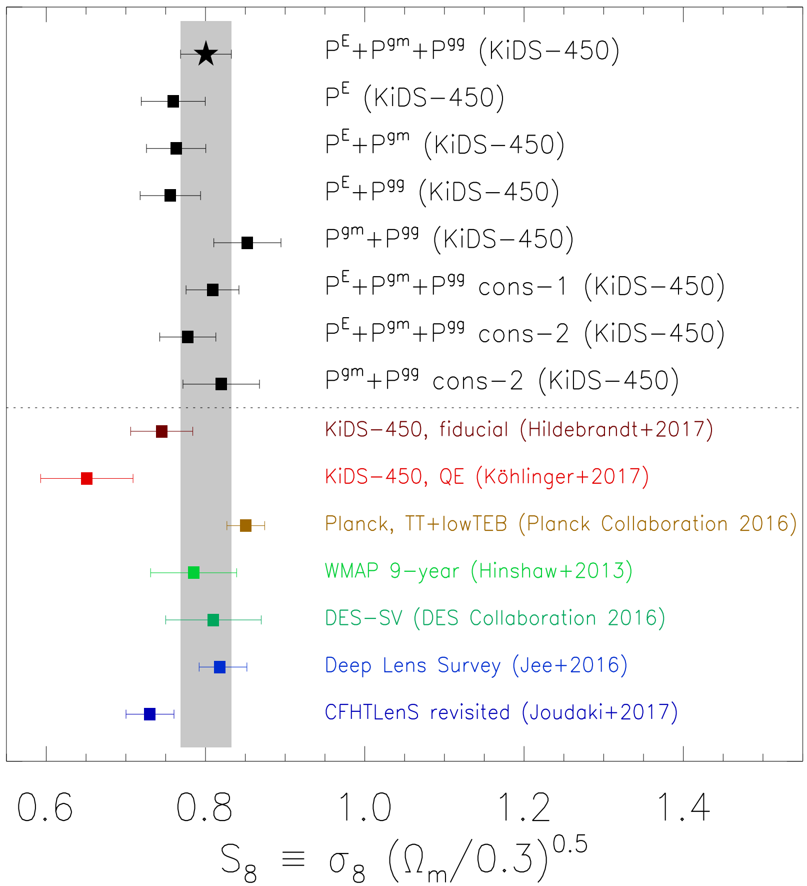
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012

系统误差还是新物理?

Beaton *et al*, 1604.01788, ApJ 2016



KiDS+GAMA, 1706.05004



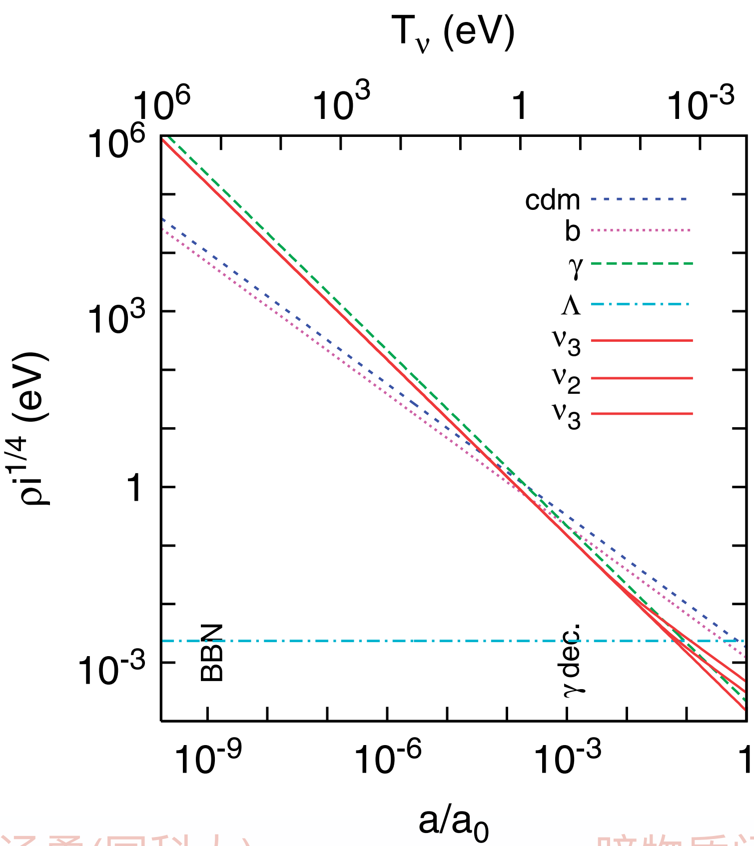
- 相互作用暗物质、衰变暗物质、暗辐射、早期暗能量、修改广义相对论,…

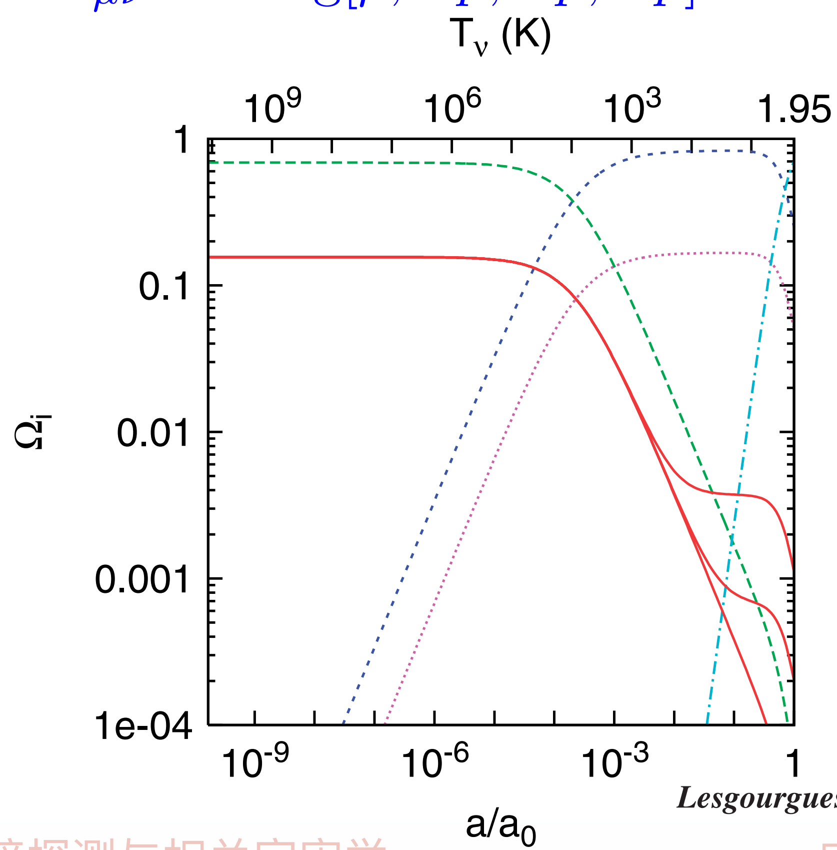
Cosmological History

- Einstein's equation

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- Homogeneous&isotropy $g_{\mu\nu} = \mathrm{Diag}[1, -a^2, -a^2, -a^2]$
  $T_{\mu\nu} = \mathrm{Diag}[\rho, -p, -p, -p]$





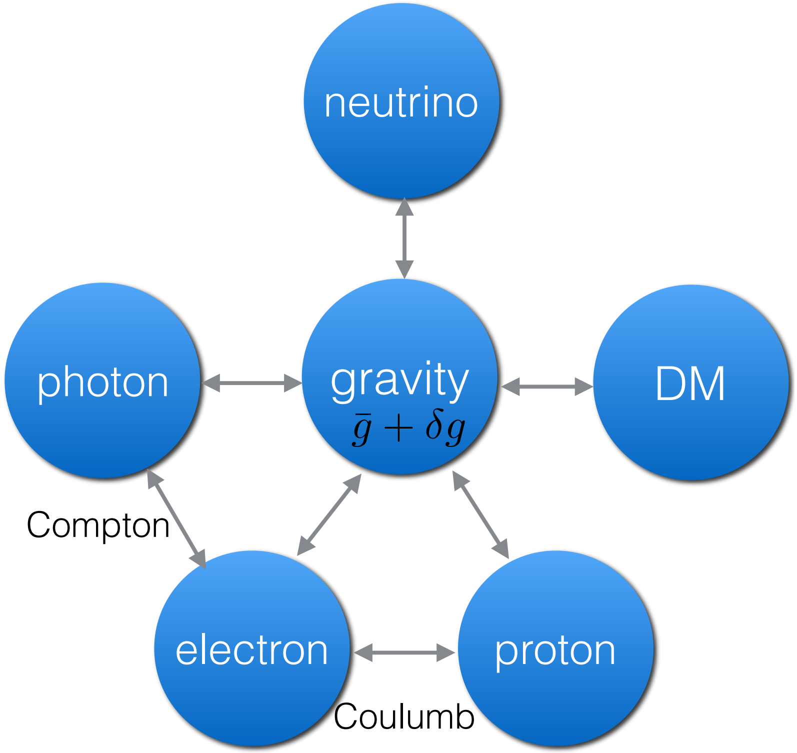
Lesgourgues, Pastor

Cosmological History

- Small perturbations (← Inflation)

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}, T_{\mu\nu} = \overline{T}_{\mu\nu} + \delta T_{\mu\nu},$$

- First-order perturbation of Boltzmann equation
  - anisotropy in CMB(δT)
  - matter power spectrum for LSS (δρ)
  - Primordial GW

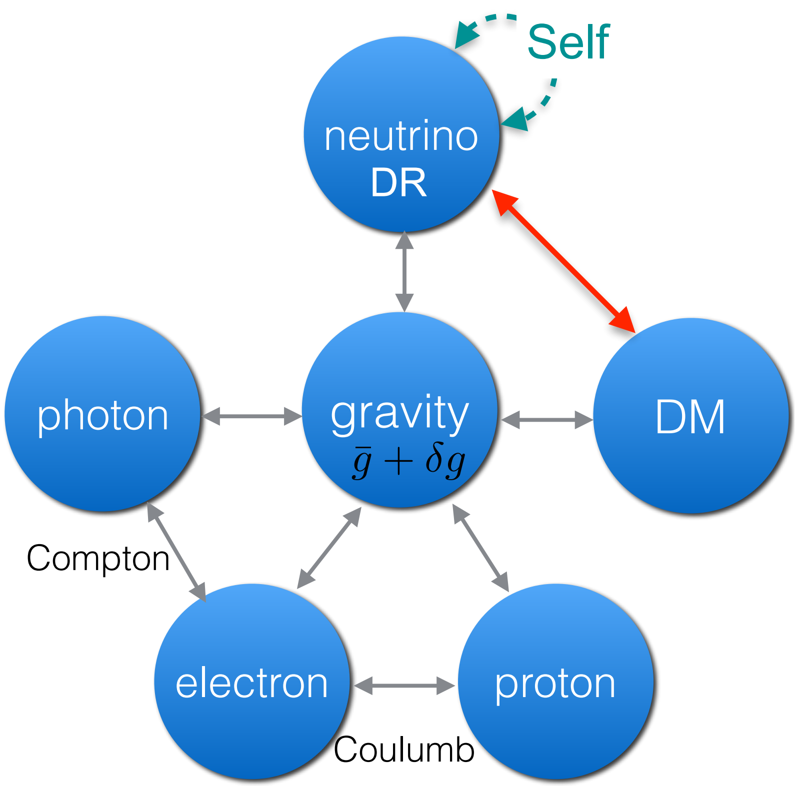


Modified Cosmological History

- Small perturbations (← Inflation)

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}, T_{\mu\nu} = \overline{T}_{\mu\nu} + \delta T_{\mu\nu},$$

- First-order perturbation of Boltzmann equation
  - anisotropy in CMB(δT)
  - matter power spectrum for LSS (δρ)
  - Primordial GW
- (Self-)Interaction sometimes also matters



Interacting Radiation

- free-streaming

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi} ,$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + k^2\psi ,$$

$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right] ,$$

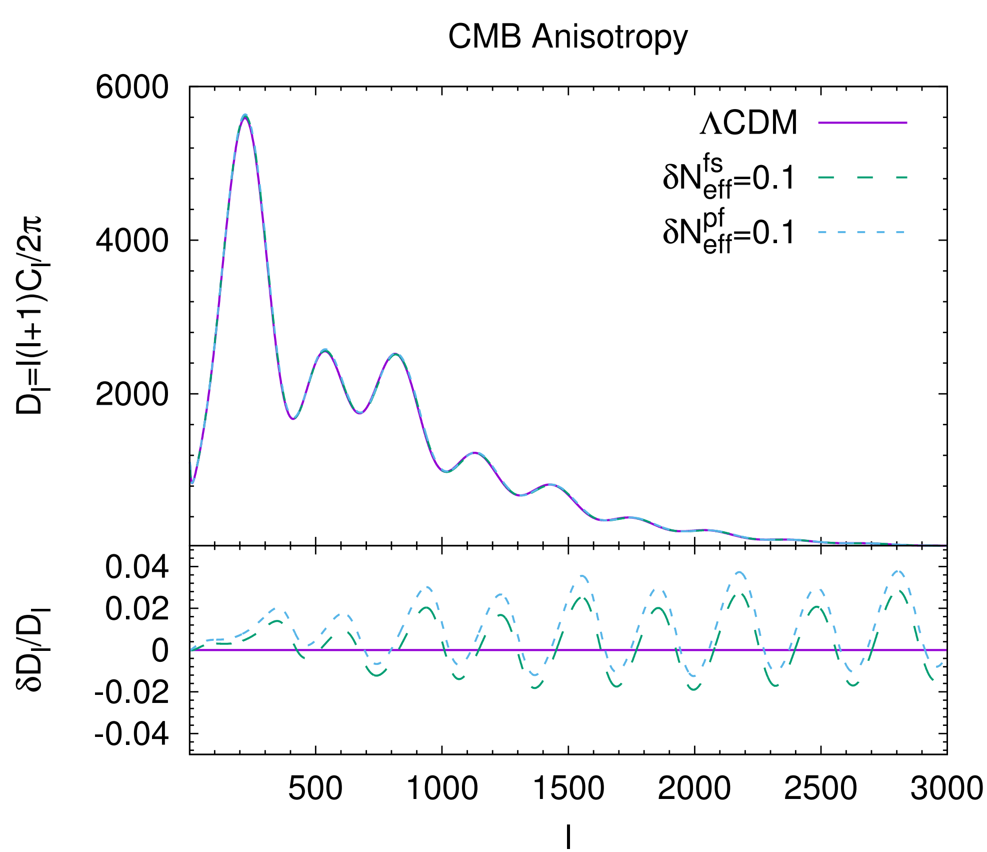
- perfect fluid $\Gamma \gg \mathcal{H}$

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi} ,$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + k^2\psi ,$$

$\sigma_\nu=0$

Y.Tang, arXiv:1603.00165(PLB)



Neutrinos as perfect fluid excluded, ***Audren* et al 1412.5948**

Diffusion Damping

- *Dark Matter* scatters with *radiation*, which induces new contributions in the cosmological perturbation equations,

Boehm, et al
Bringmann, et al
……

$$\dot{\delta}_\chi = -\theta_\chi + 3\dot{\Phi},$$

$$\dot{\theta}_\chi = k^2\Psi - \mathcal{H}\theta_\chi + S^{-1}\dot{\mu}\left(\theta_\psi - \theta_\chi\right),$$

$$\dot{\theta}_\psi = k^2\Psi + k^2\left(\frac{1}{4}\delta_\psi - \sigma_\psi\right) - \dot{\mu}\left(\theta_\psi - \theta_\chi\right),$$

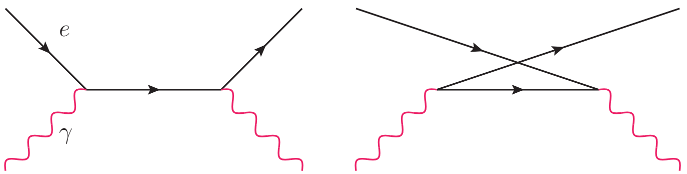
where dot means derivative over conformal time $d\tau \equiv dt/a$ (a is the scale factor), θ_ψ and θ_χ are velocity divergences of radiation ψ and DM χ's, k is the comoving wave number, Ψ is the gravitational potential, δ_ψ and σ_ψ are the density perturbation and the anisotropic stress potential of ψ, and $\mathcal{H} \equiv \dot{a}/a$ is the conformal Hubble parameter. Finally, the scattering rate and the density ratio are defined by $\dot{\mu} = a n_\chi \langle \sigma_{\chi\psi} c \rangle$ and $S = 3\rho_\chi/4\rho_\psi$, respectively.

Relation to Particle Physics

- The precise form of the scattering term, <σc>, is fully determined by the underlying microscopic or particle physics model, for example

IR behaviour

  - electron-photon, <σc>~$1/m^2$
    Thomson scattering



Relation to Particle Physics

- The precise form of the scattering term, $\langle \sigma c \rangle$, is fully determined by the underlying microscopic or particle physics model, for example

IR behaviour

  - electron-photon, $\langle \sigma c \rangle \sim 1/m^2$
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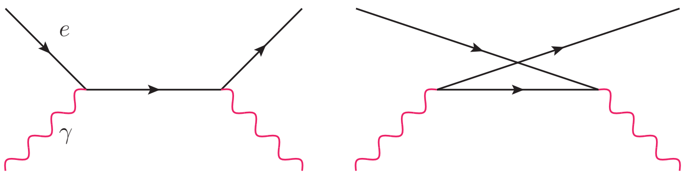
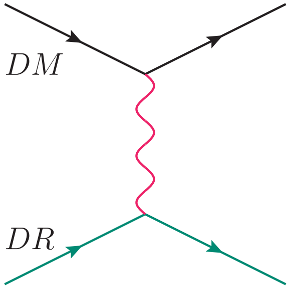


  - DM-radiation with massive mediator, $\langle \sigma c \rangle \sim T^2/m^4$



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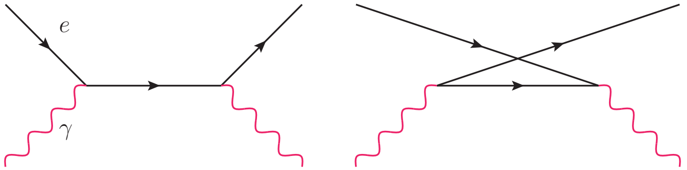

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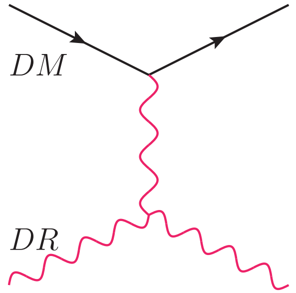

  - non-Abelian radiation, $\langle\sigma c\rangle \sim 1/T^2$
    Schmaltz et al(2015), 1507.04351,1505.03542

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- The precise form of the scattering term, $\langle\sigma c\rangle$, is fully determined by the underlying microscopic or particle physics model, for example

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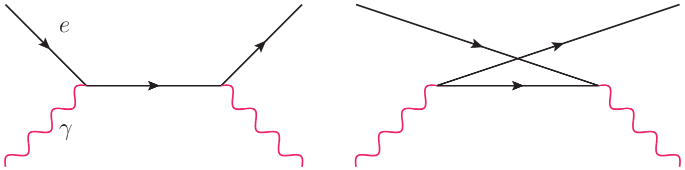

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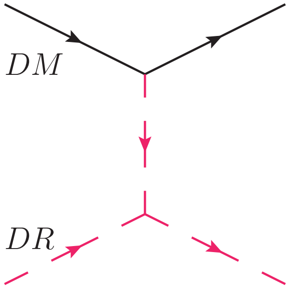

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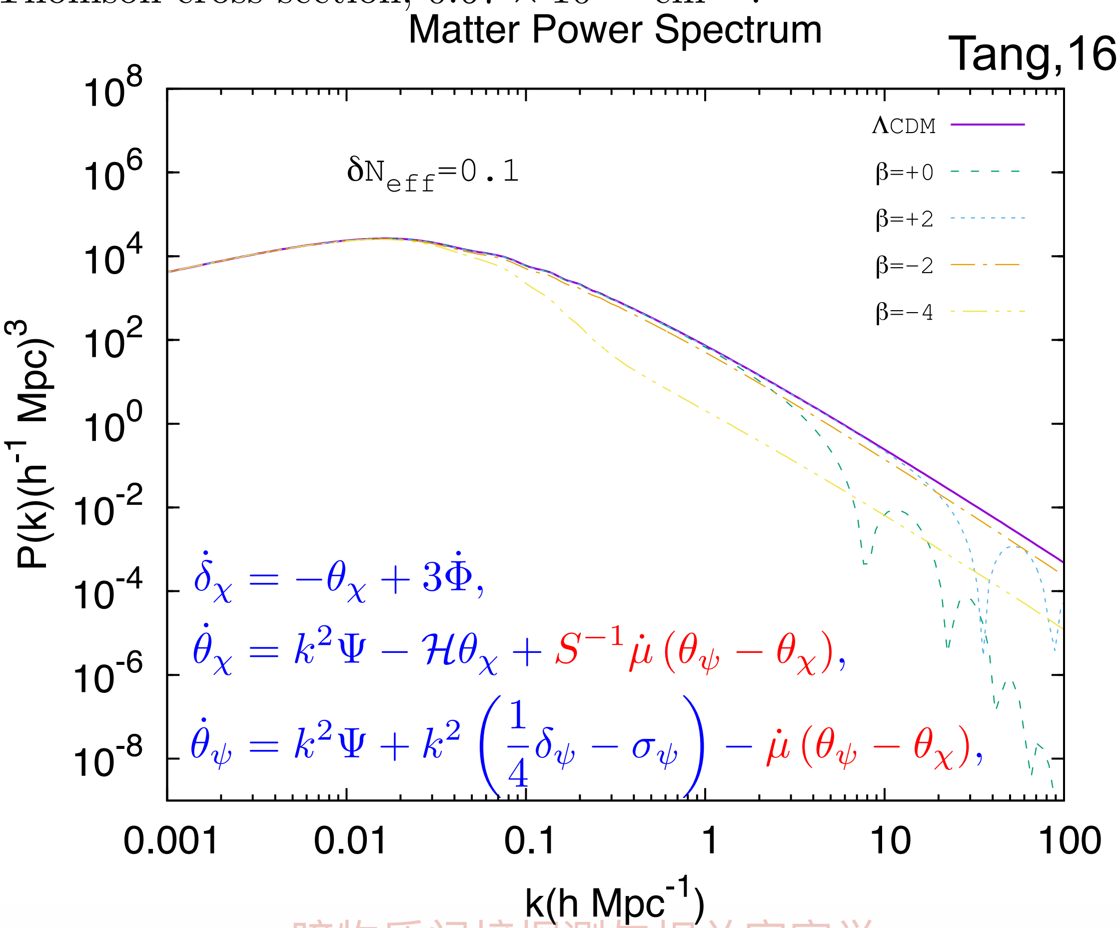
    Schmaltz et al(2015), 1507.04351,1505.03542
  - (pseudo-)scalar radiation, $\langle\sigma c\rangle \sim 1/T^2$, μ^2/T^4, T^2/m^4
    Tang,1603.00165

Effects on LSS

Parametrize the cross section ratio

$$u_0 \equiv \left[\frac{\sigma_{\chi\psi}}{\sigma_{\rm Th}}\right]\left[\frac{100{\rm GeV}}{m_\chi}\right], u_\beta(T) = u_0\left(\frac{T}{T_0}\right)^\beta,$$

where $\sigma_{\rm Th}$ is the Thomson cross section, $0.67\times10^{-24}{\rm cm}^{-2}$.



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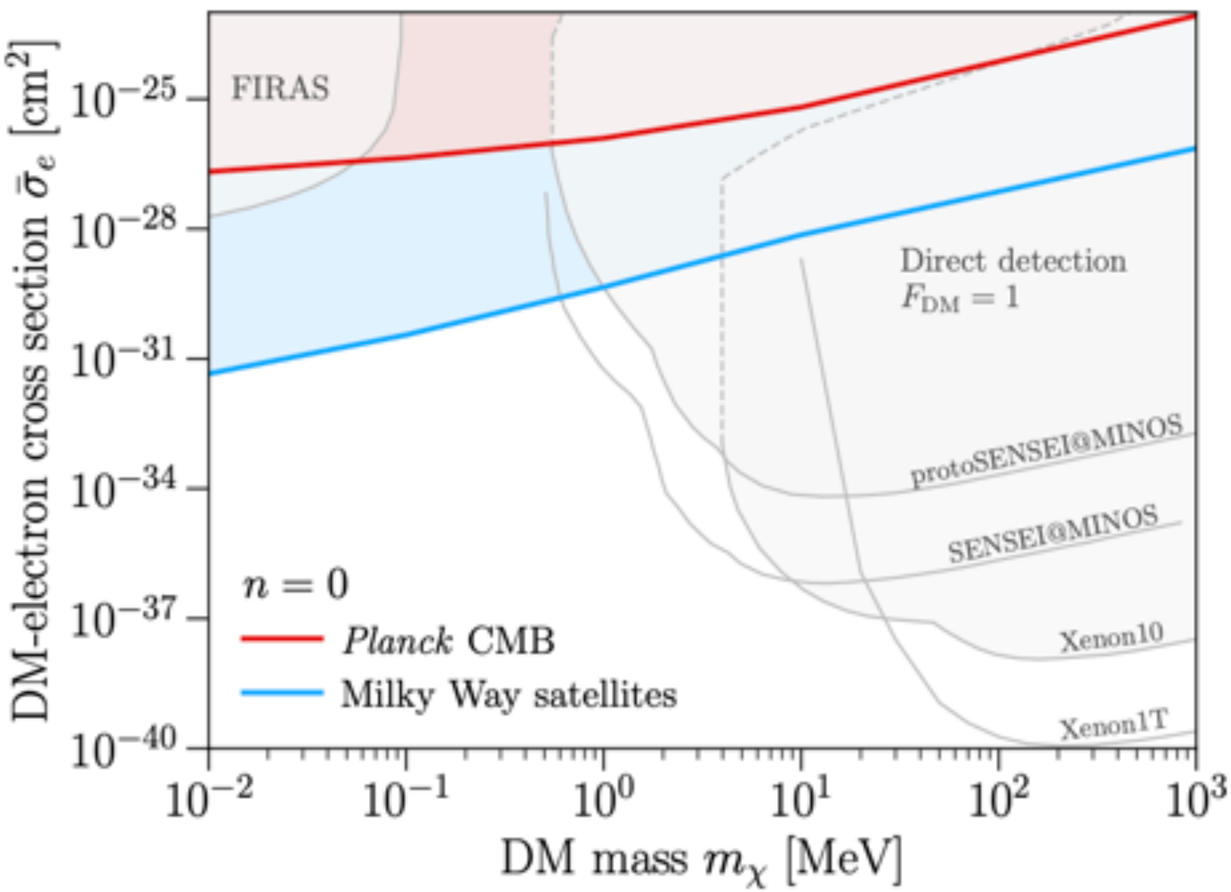
Recent Works

- 2107.12380, DM-electron

$$\sigma_{\rm MT} = \bar{\sigma}_e \frac{4}{4+n} \left(\frac{2\mu_{\chi e}}{\alpha m_e}\right)^n v^n$$



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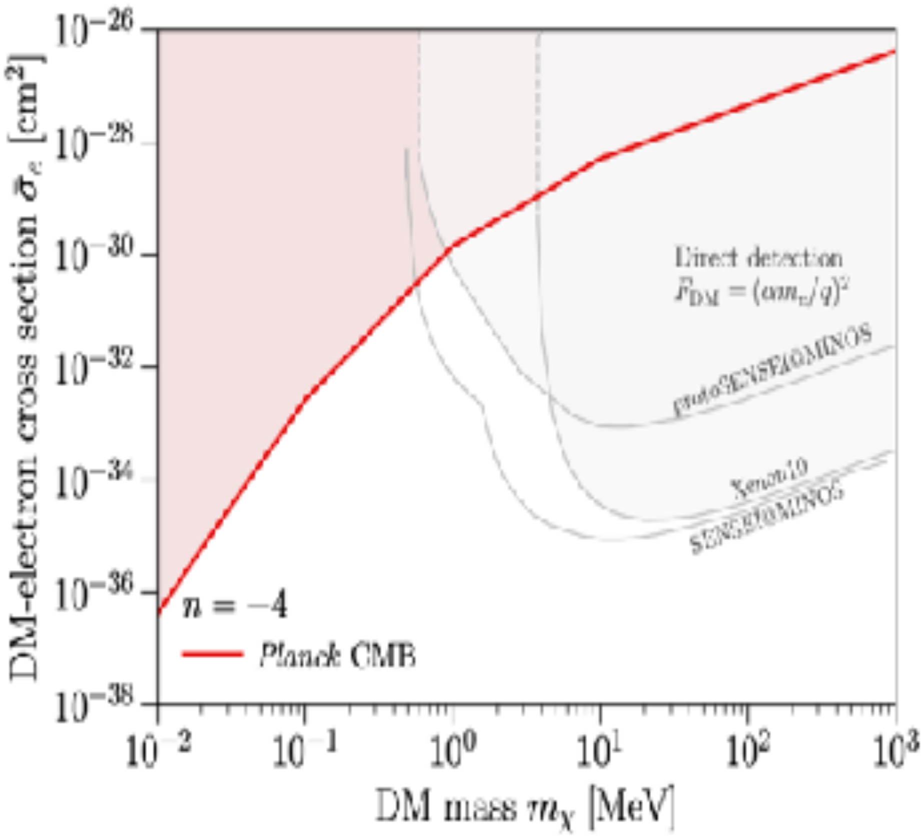
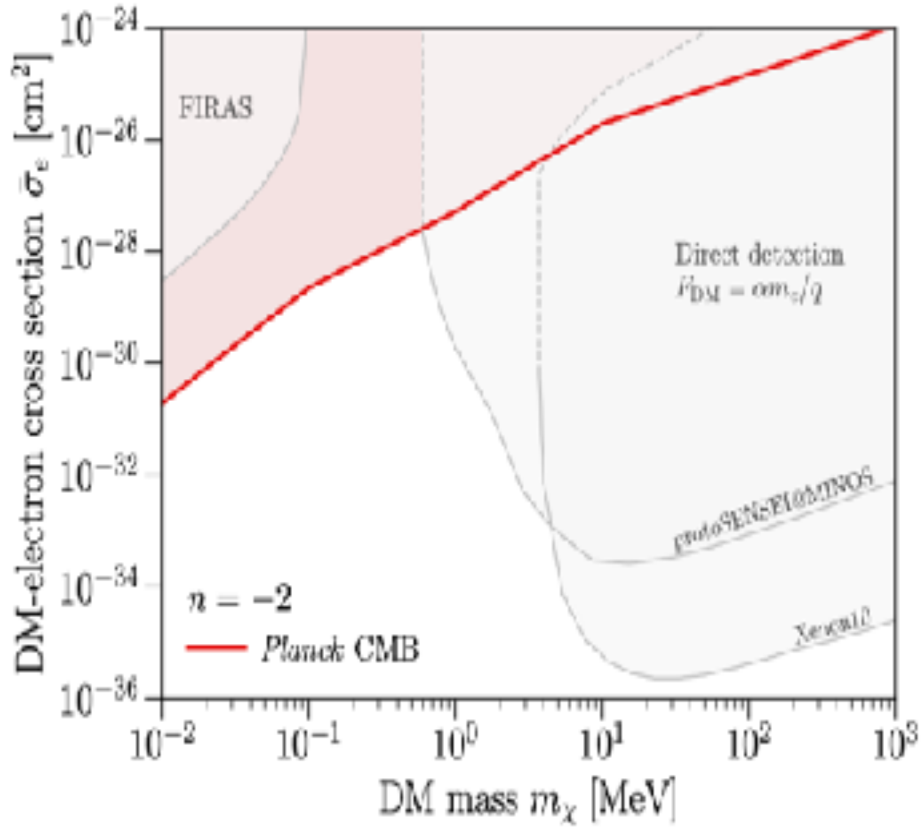
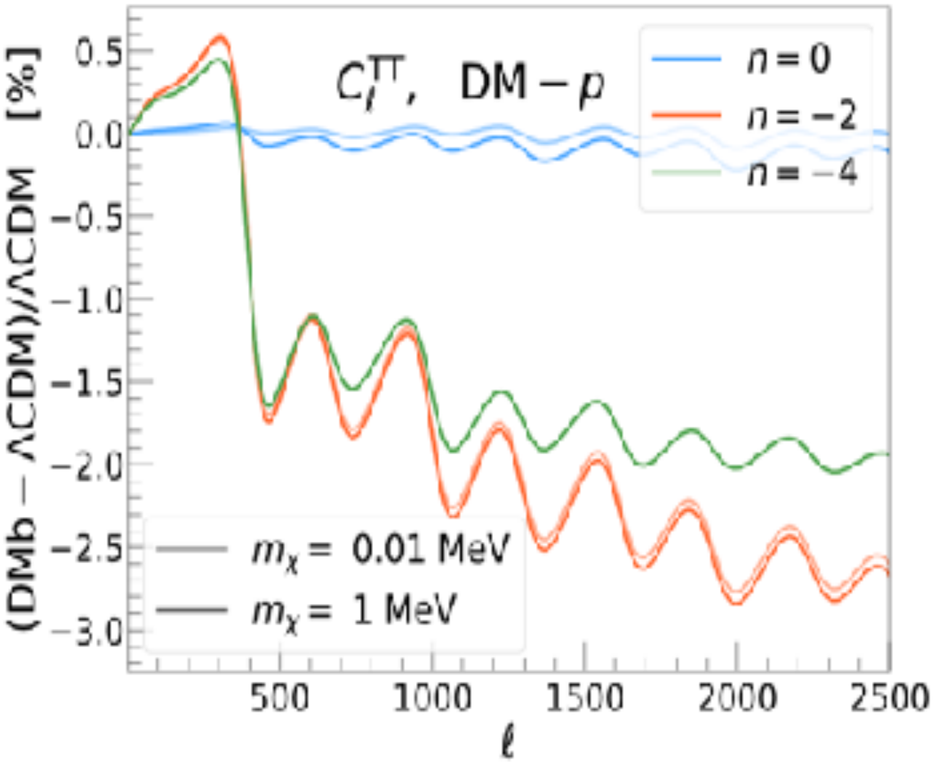


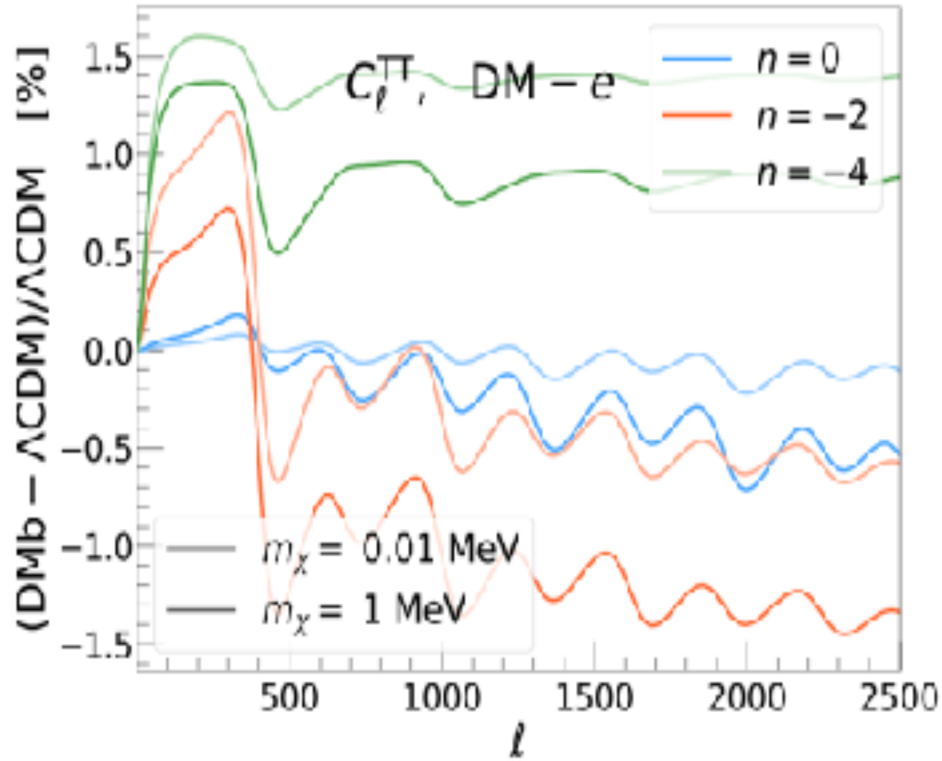


Recent Works

- 2107.12377, DM-proton

$$\sigma_{\rm T}^{\chi B} = \sigma_n^{\chi B} v_{\rm rel}^n$$





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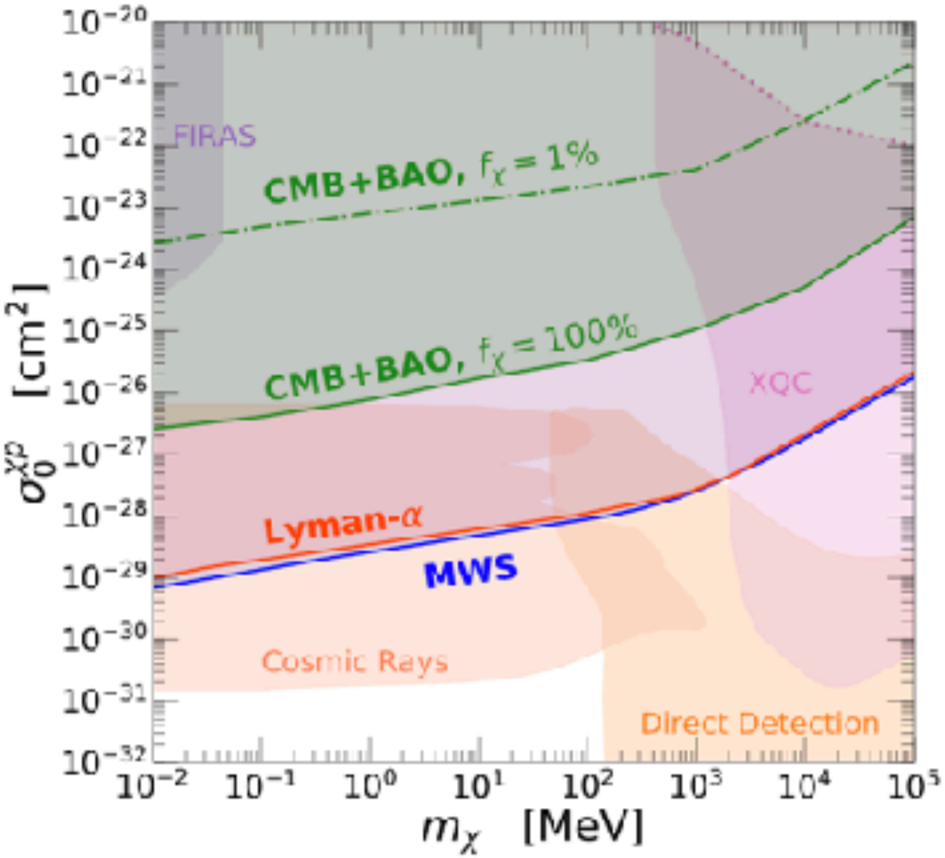
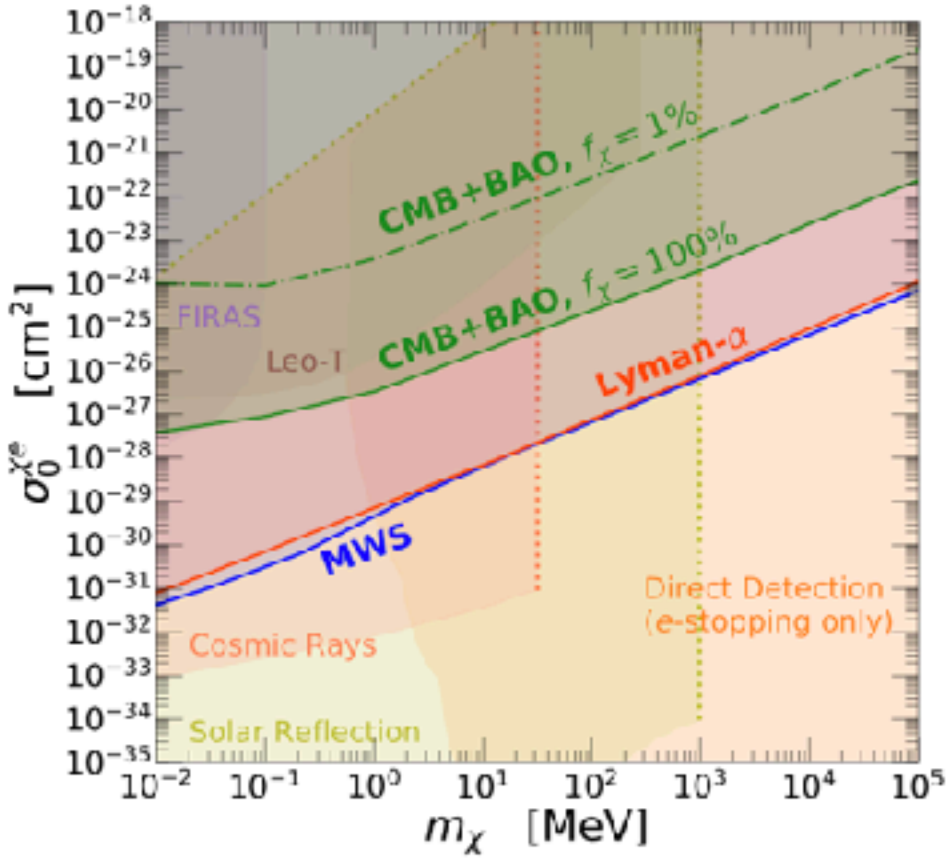




A Light Dark Photon

P.Ko, ***YT***, *1608.01083(PLB)*

- Lagrangian

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + D_\mu\Phi^\dagger D^\mu\Phi + \bar{\chi}\left(i\not{D} - m_\chi\right)\chi + \bar{\psi}i\not{D}\psi$$
$$- \left(y_\chi\Phi^\dagger\bar{\chi}^c\chi + y_\psi\Phi\bar{\psi}N + h.c.\right) - V(\Phi, H),$$

- DM χ (+1), dark radiation ψ (+2), scalar(+2)
- *U(1)* symmetry (*unbroken*), massless dark photon V_μ
- Φ is responsible for the DM relic density

$$\Omega h^2 \simeq 0.1 \times \left(\frac{y_\chi}{0.7}\right)^{-4}\left(\frac{m_\chi}{\mathrm{TeV}}\right)^2.$$

- Φ can decay into ψ and *N*.

Dark Radiation δN_{eff}

- Effective Number of Neutrinos, N_{eff}

$$\rho_R = \left[1 + N_{\text{eff}} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma,$$

$$\rho_\gamma \propto T_\gamma^4$$

- In SM cosmology, N_{eff} =3.046, neutrinos decouple around MeV, and then stream freely.
- Cosmological bounds

Joint CMB+BBN, 95% CL preferred ranges *Planck 2015, arXiv:1502.01589*

$$N_{\text{eff}} = \begin{cases} 3.11^{+0.59}_{-0.57} & \text{He+}\textit{Planck}\text{ TT+lowP,} \\ 3.14^{+0.44}_{-0.43} & \text{He+}\textit{Planck}\text{ TT+lowP+BAO,} \\ 2.99^{+0.39}_{-0.39} & \text{He+}\textit{Planck}\text{ TT,TE,EE+lowP,} \end{cases}$$

Constraint on New Physics

$$\left.\begin{aligned} N_{\text{eff}} &< 3.7 \\ m^{\text{eff}}_{\nu,\,\text{sterile}} &< 0.52\ \text{eV} \end{aligned}\right\} \quad 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+BAO.}$$

Dark Radiation δN$_{\rm eff}$

- Massless dark photon and fermion will contribute

$$\delta N_{\rm eff} = \left(\frac{8}{7}+2\right)\left[\frac{g_{*s}\left(T_\nu\right)}{g_{*s}\left(T^{\rm dec}\right)}\frac{g^D_{*s}\left(T^{\rm dec}\right)}{g^D_{*s}\left(T_D\right)}\right]^{\frac{4}{3}},$$

where T_ν is neutrino's temperature,

g_{*s} counts the effective number of dof for entropy density in SM,

g^D_{*s} denotes the effective number of dof being in kinetic equilibrium with V_μ.

For instance, when $T^{\rm dec} \gg m_t \simeq 173$GeV for $|\lambda_{\Phi H}| \sim 10^{-6}$, we can estimate $\delta N_{\rm eff}$ at the BBN epoch as

$$\delta N_{\rm eff} = \frac{22}{7}\left[\frac{43/4}{427/4}\frac{11}{9/2}\right]^{\frac{4}{3}} \simeq 0.53, \tag{1}$$

δN$_{\rm eff}$=0.4~1 for relaxing tension in Hubble constant

Numerical Results

We take the central values of six parameters of ΛCDM from `Planck`,

$\Omega_b h^2 = 0.02227,$	Baryon density today
$\Omega_c h^2 = 0.1184,$	CDM density today
$100\theta_{\rm MC} = 1.04106,$	$100 \times$ approximation to r_*/D_A
$\tau = 0.067,$	Thomson scattering optical depth
$\ln\left(10^{10} A_s\right) = 3.064,$	Log power of primordial curvature perturbations
$n_s = 0.9681,$	Scalar Spectrum power-law index

which gives $\sigma_8 = 0.817$ in vanilla ΛCDM cosmology.

With the same input as above, now take

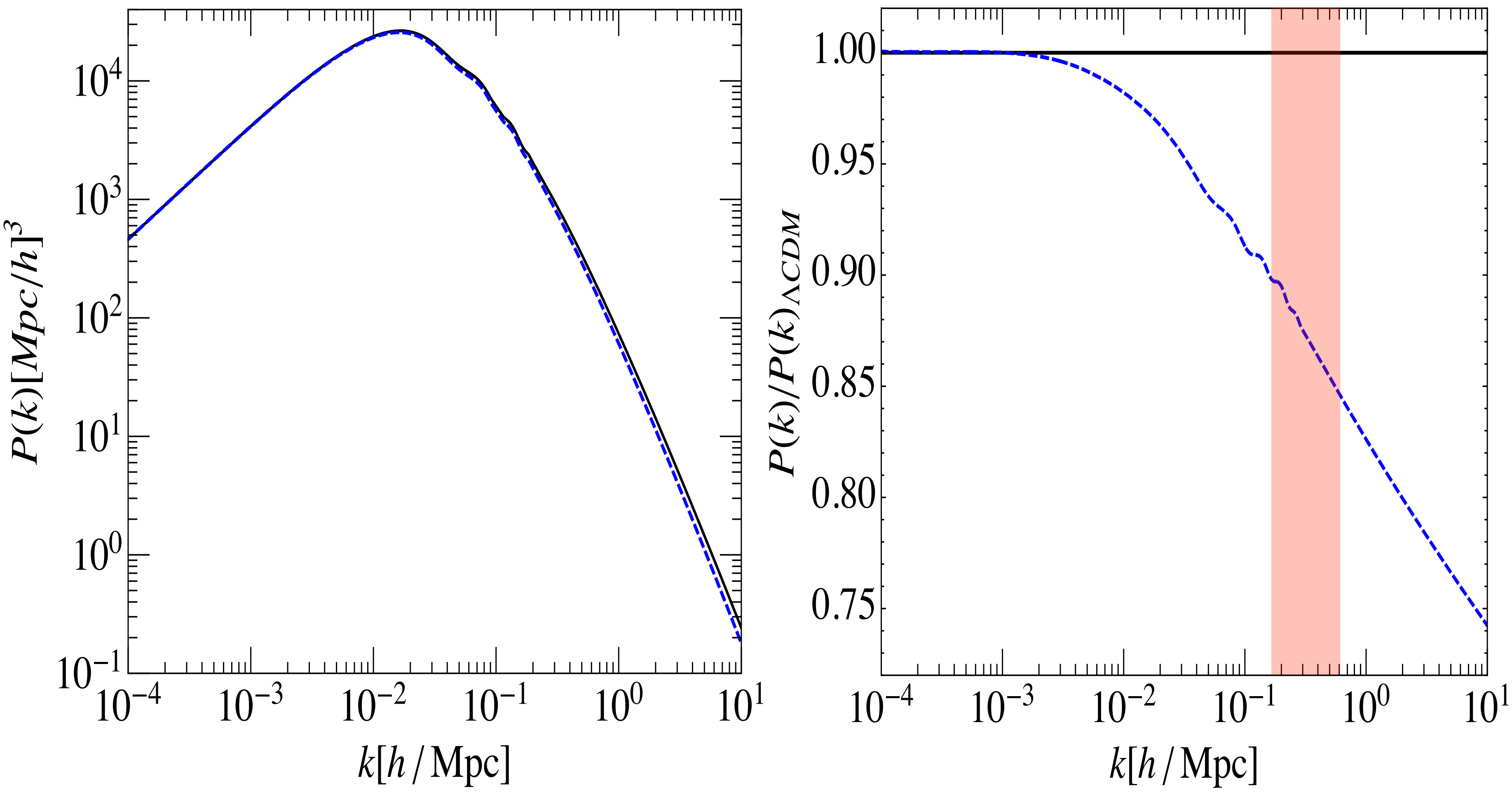
$$\delta N_{\rm eff} \simeq 0.53, m_\chi \simeq 100 \text{GeV and } g_X^2 \simeq 10^{-8}$$

in the interacting DM case, we have $\sigma_8 \simeq 0.744$.

Modified Boltzmann code ***CLASS*****(*Blas&Lesgourgues&Tram*)**

Matter Power Spectrum

DM-DR scattering causes diffuse damping at relevant scales, resolving σ_8 problem



Residual Non-Abelian DM&DR

P.Ko&**YT**, 1609.02307

- Consider *SU(N)* Yang-Mills gauge fields and a Dark Higgs field Φ

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \left(D_\mu\Phi\right)^\dagger\left(D^\mu\Phi\right) - \lambda_\phi\left(|\Phi|^2 - v_\phi^2/2\right)^2,$$

- Take *SU(3)* as an example,

$$A^a_\mu t^a = \frac{1}{2}\begin{pmatrix} A^3_\mu + \frac{1}{\sqrt{3}}A^8_\mu & A^1_\mu - iA^2_\mu & A^4_\mu - iA^5_\mu \\ A^1_\mu + iA^2_\mu & -A^3_\mu + \frac{1}{\sqrt{3}}A^8_\mu & A^6_\mu - iA^7_\mu \\ A^4_\mu + iA^5_\mu & A^6_\mu + iA^7_\mu & -\frac{2}{\sqrt{3}}A^8_\mu \end{pmatrix}.$$

- *SU(3)* → *SU(2)*

$$\langle\Phi\rangle = \begin{pmatrix} 0 & 0 & \frac{v_\phi}{\sqrt{2}} \end{pmatrix}^T, \Phi = \begin{pmatrix} 0 & 0 & \frac{v_\phi + \phi(x)}{\sqrt{2}} \end{pmatrix}^T,$$

The massive gauge bosons $A^{4,\cdots,8}$ as dark matter obtain masses,

$$m_{A^{4,5,6,7}} = \frac{1}{2}gv_\phi,\ m_{A^8} = \frac{1}{\sqrt{3}}gv_\phi,$$

and massless gauge bosons $A^{1,2,3}_\mu$. The physical scalar ϕ can couple to $A^{4,\cdots,8}_\mu$ at tree level and to $A^{1,2,3}$ at loop level.

$SU(N) \to SU(N-1)$

- *2N-1* massive gauge bosons: Dark Matter
- *(N-1)²-1* massless gauge bosons: Dark Radiation
- mass spectrum

$$m_{A^{(N-1)^2,\ldots,N^2-2}} = \frac{1}{2} g v_\phi, \; m_{A^{N^2-1}} = \frac{\sqrt{N-1}}{\sqrt{2N}} g v_\phi,$$

This can be proved by looking at the structure of f^{abc}. Divide the generators t^a into two subset,

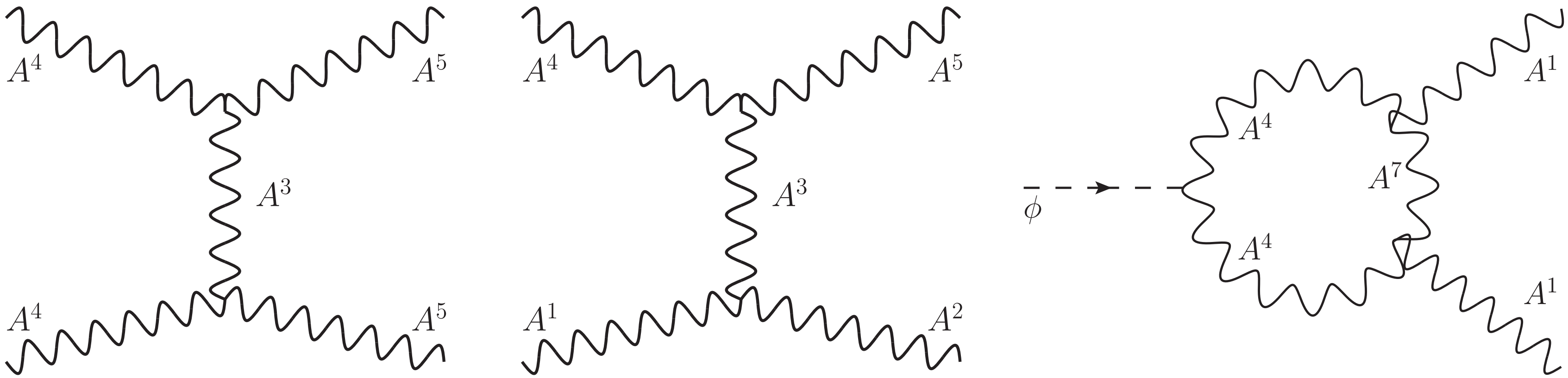
$$a \subset [1, 2, ..., (N-1)^2 - 1], a \subset [(N-1)^2, ..., N^2 - 1].$$

Since $[t^a, t^b] = i f^{abc} t^c$ for the first subset forms closed $SU(N-1)$ algebra, we have $f^{abc} = 0$ when only one of a, b and c is from the second subset. If one index is $N^2 - 1$, then other two must be among the second subset to give no vanishing f^{abc}, because t^{N^2-1} commutes with t^a from $SU(N-1)$.

Phenomenology

- Scattering and decay processes

Ko&Tang, 1609.02307



- Constraints

$$\delta N_{\text{eff}} = \frac{8}{7}\left[(N-1)^2 - 1\right] \times 0.055,$$

$$g^2 \lesssim \frac{T_\gamma}{T_A}\left(\frac{m_A}{M_P}\right)^{1/2} \sim 10^{-7},$$

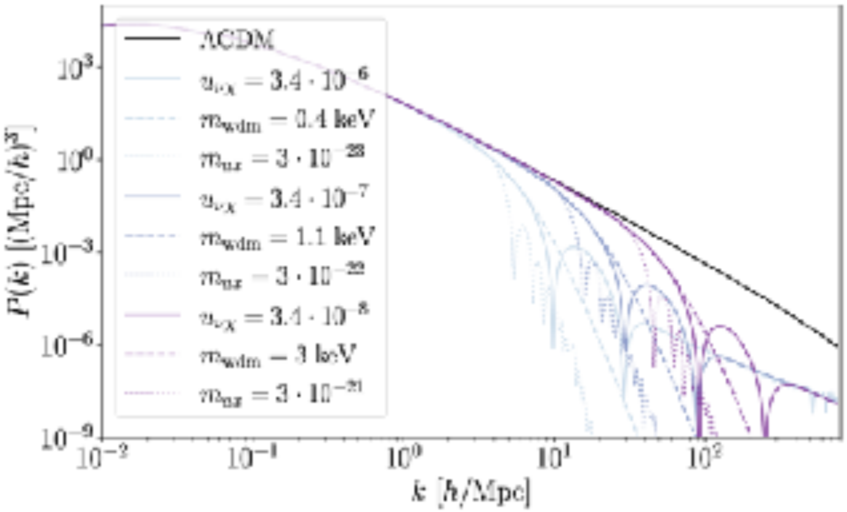
$$\frac{m_A}{T_{\text{reh}}} \sim \ln\left[\frac{\Omega_b M_P g^4}{\Omega_X m_p \eta}\right] \sim \mathcal{O}(30).$$

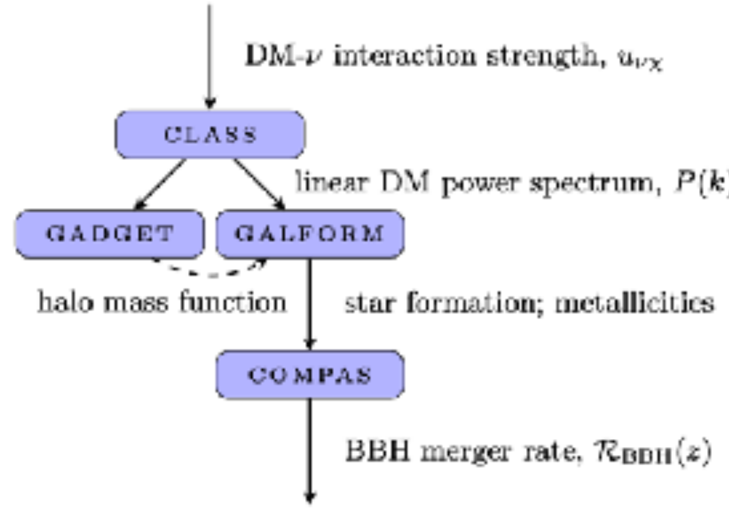
- ***N<6 if thermal***
- ***small coupling,***
- ***non-thermal production,***
- ***low reheating temperature***

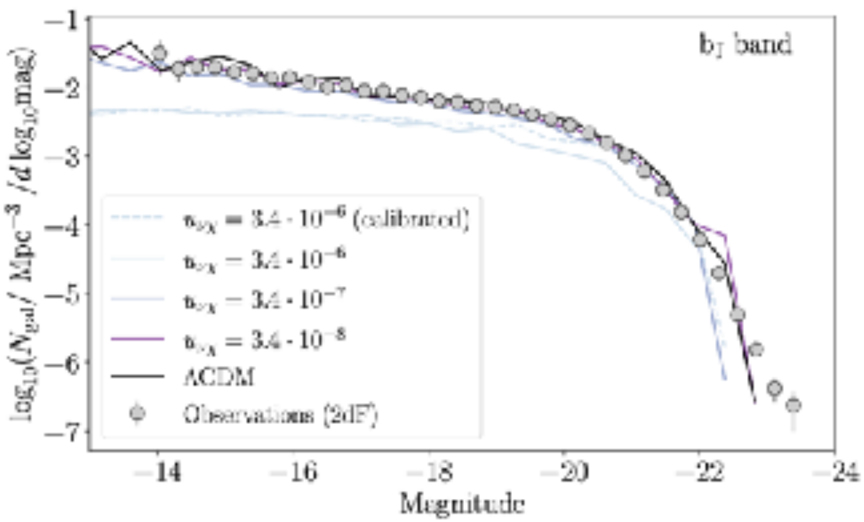
Schmaltz et al(2015) EW charged DM

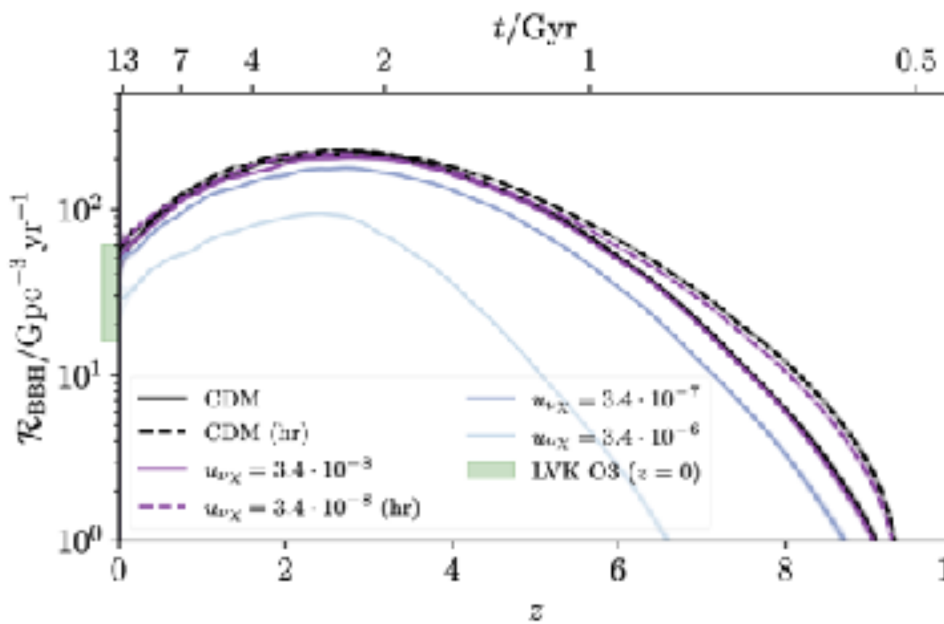
GW to probe small scale

- 2207.14126, Boehm&Wong *et al*



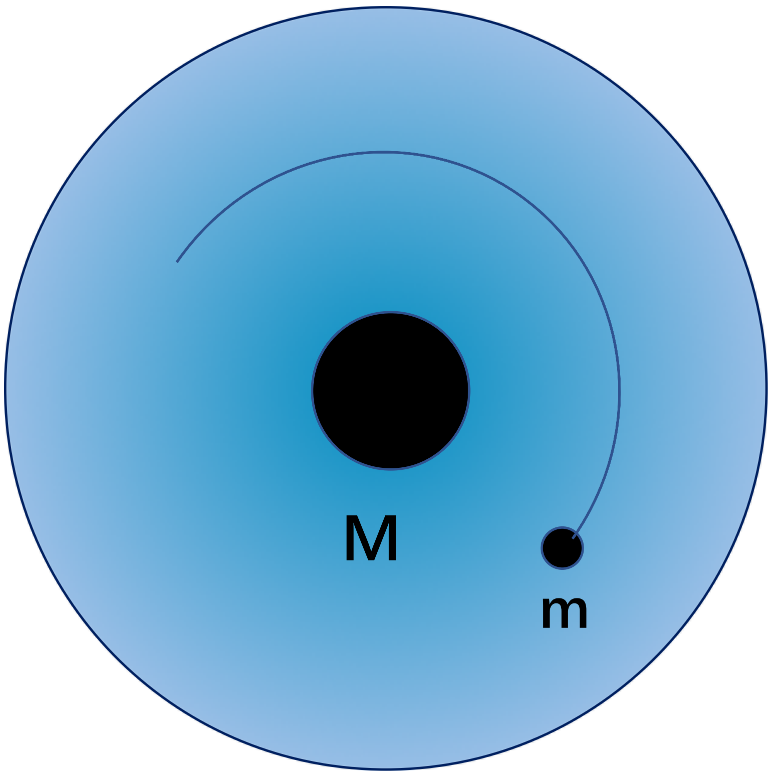


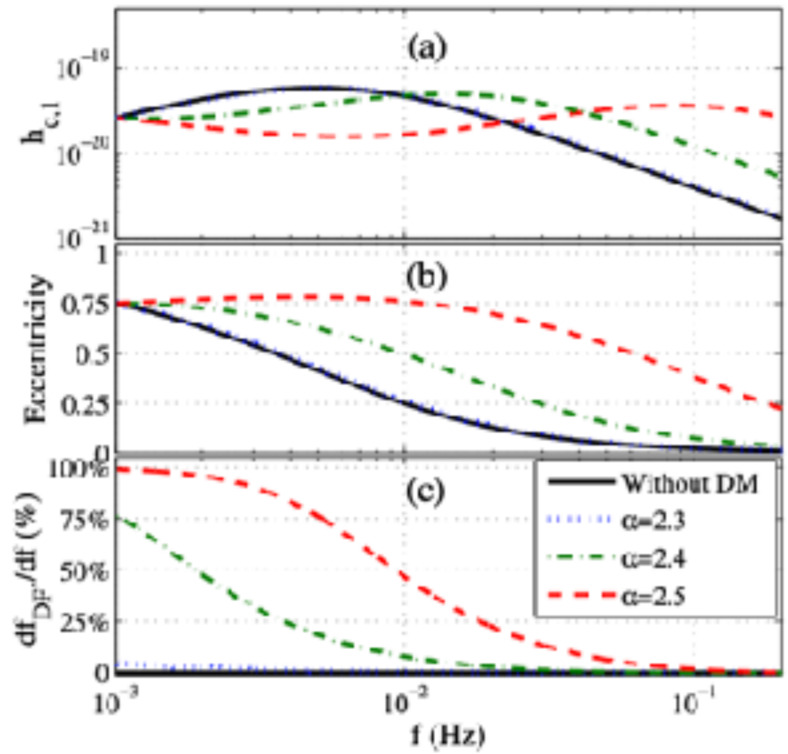




DM spike and GW

- Extreme mass ratio inspiral (EMRI)
- Dynamical friction from DM $$m\frac{d^2\mathbf{x}}{dt^2} = \mathbf{F}_\mathrm{G} + \mathbf{F}_\mathrm{DF}$$
- Gravitational wave $$h_{ij} \sim \frac{G}{d}\frac{d^2Q_{ij}}{dt^2},\ Q_{ij} \sim m\left(x_i x_j - \frac{1}{3}x^2\delta_{ij}\right)$$

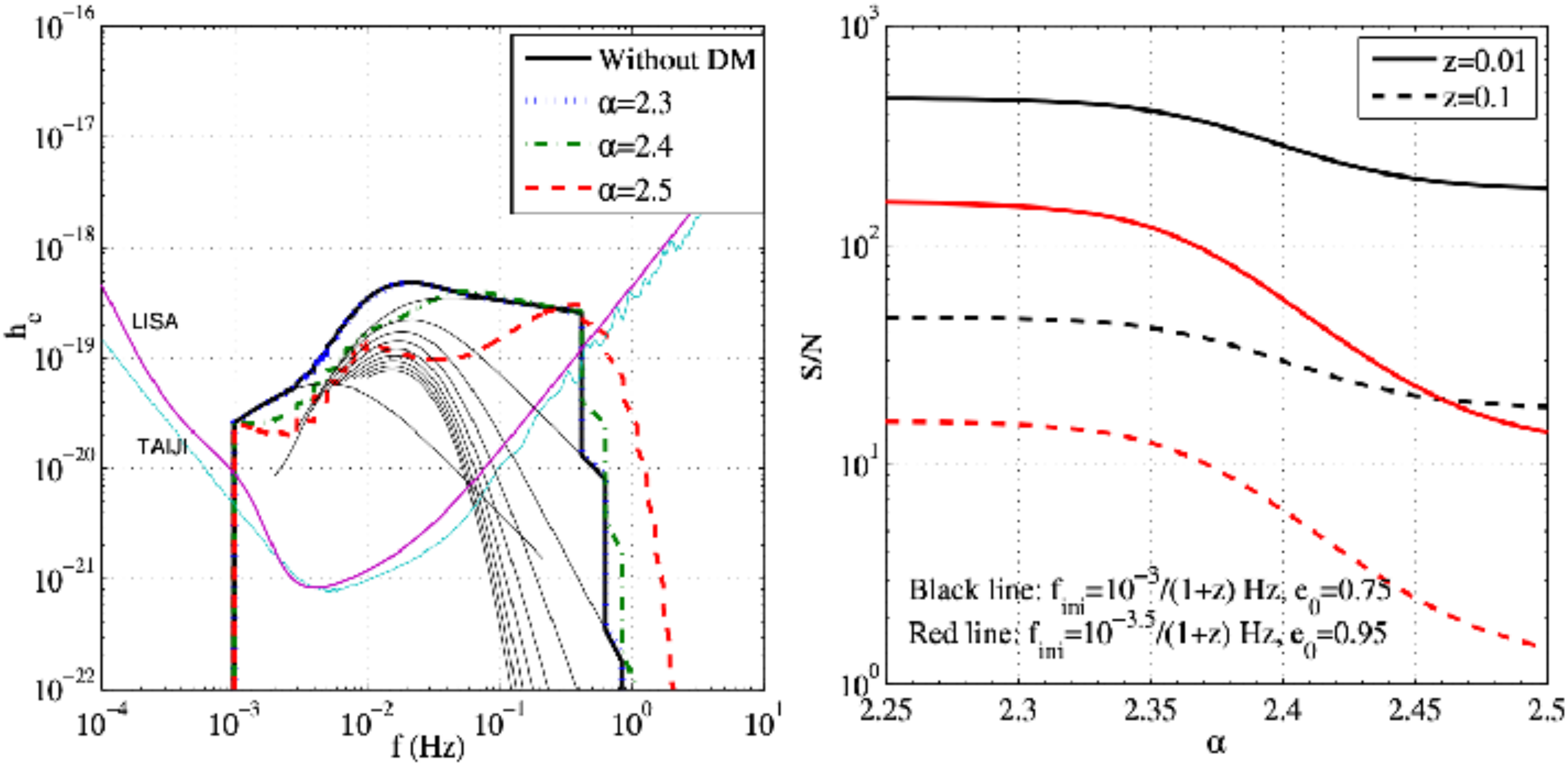




Li, Tang, Wu, 2112.14041(Science China)

Detection

- GW waveform changed, and S/N modified

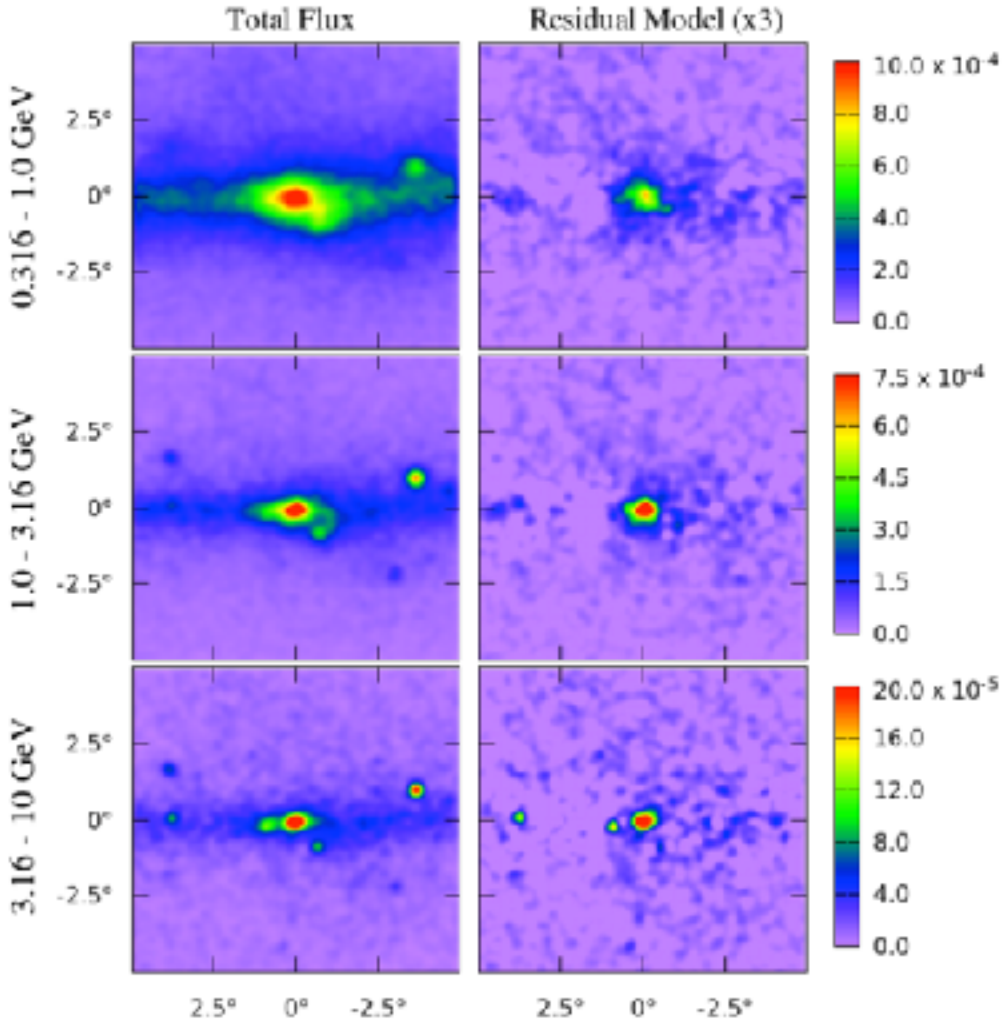


Li, Tang, Wu, 2112.14041(Science China)

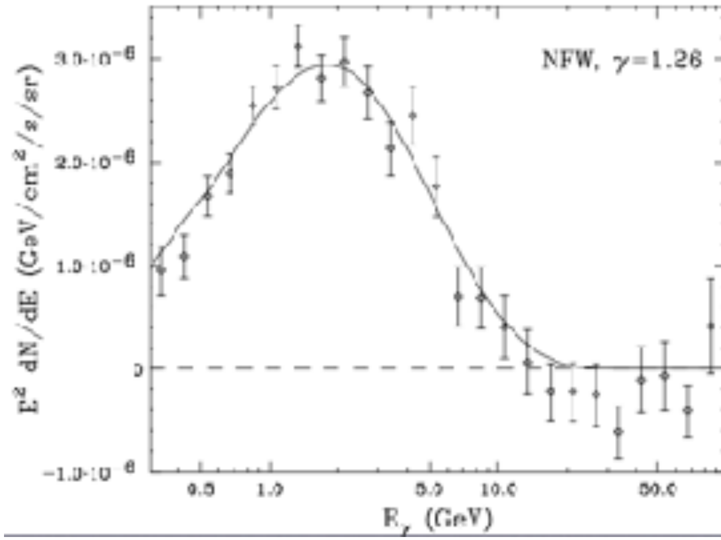
Thank you！

Discussions

- Gamma-ray excess in the galactic center



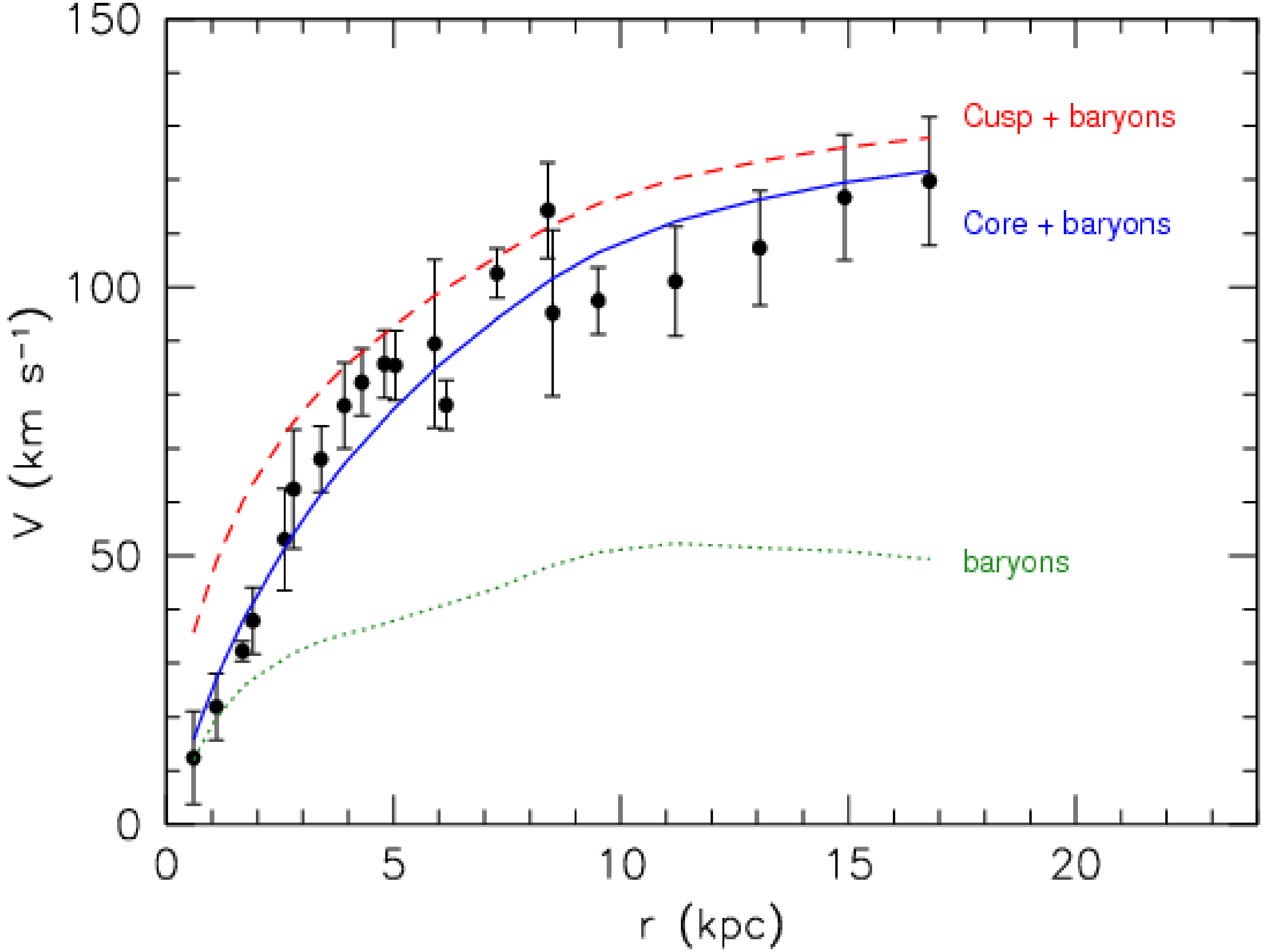
Daylan, Hooper, Slatyer et al, 2015



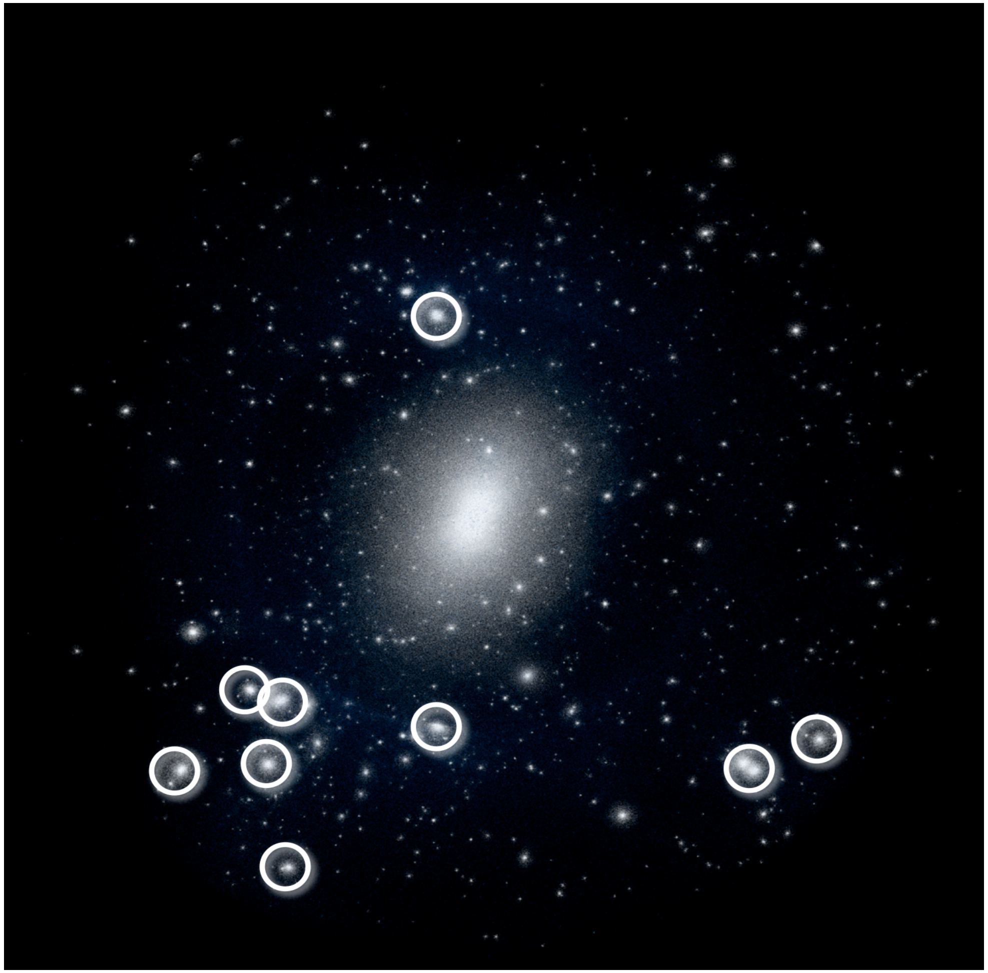
1. Dark matter?
2. Millisecond pulsar?

Cusp vs. Core

- 观测支持Core

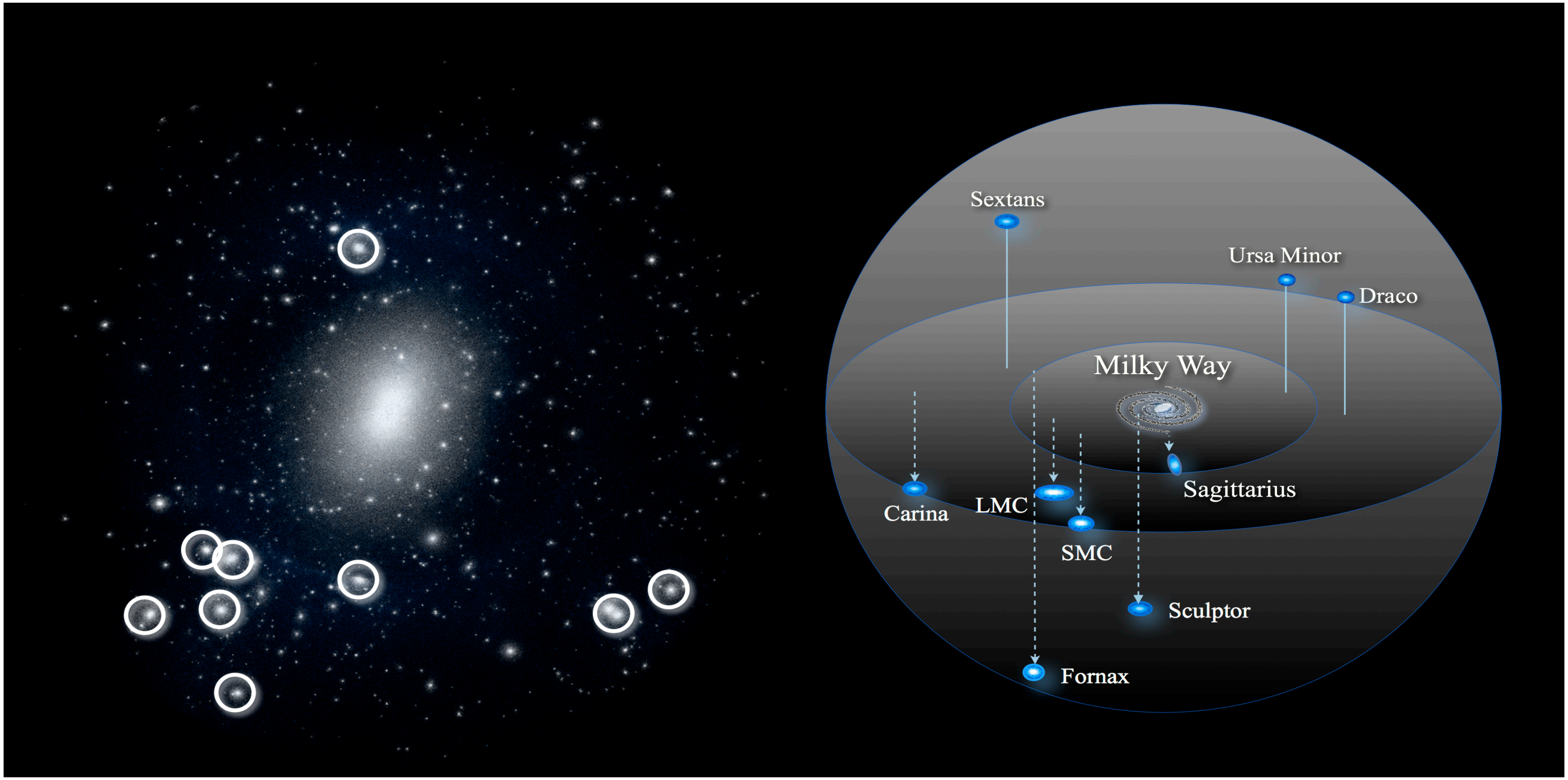


Missing satellite problem



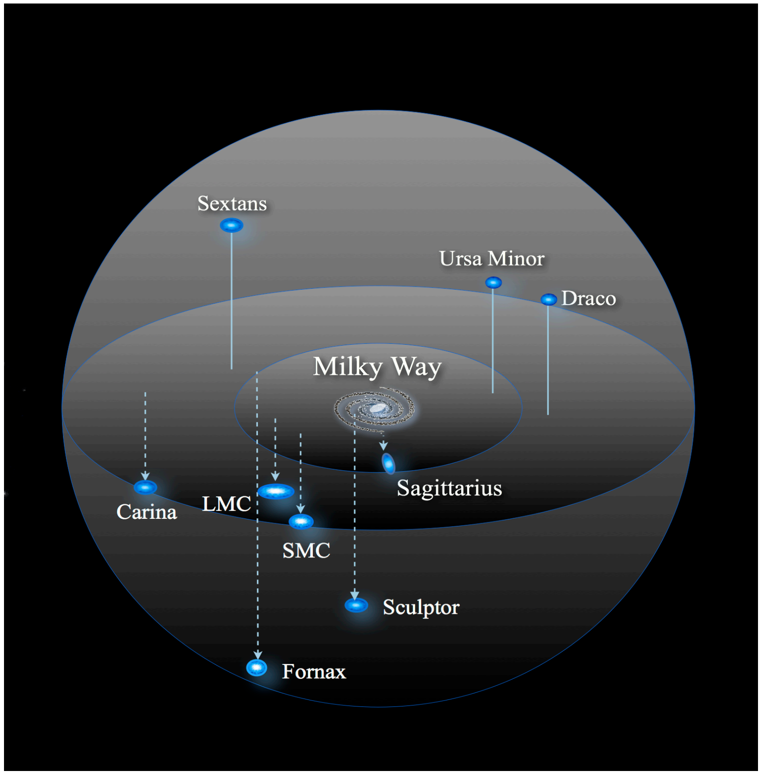
- Projected dark matter distribution of a simulated CDM halo.
- The numerous small subhalos far exceed the number of known Milky Way satellites.
- Circles mark the nine most massive subhalos.

Too-big-to-fail

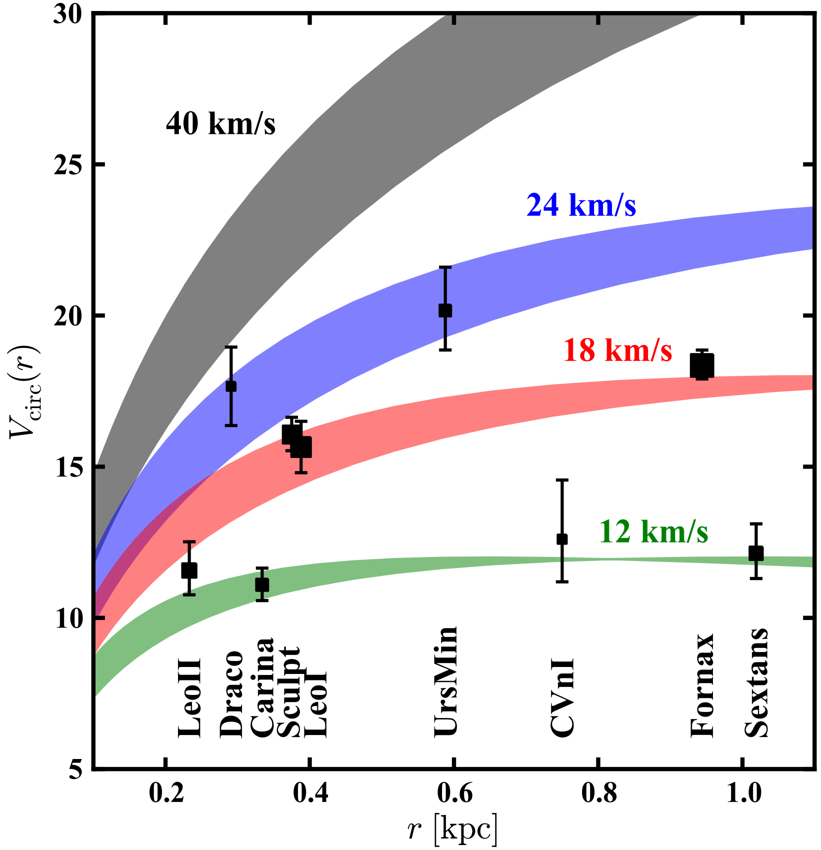


The central densities of the subhalos in the left panel are too high to host the dwarf satellites in the right panel, predicting stellar velocity dispersions higher than observed.

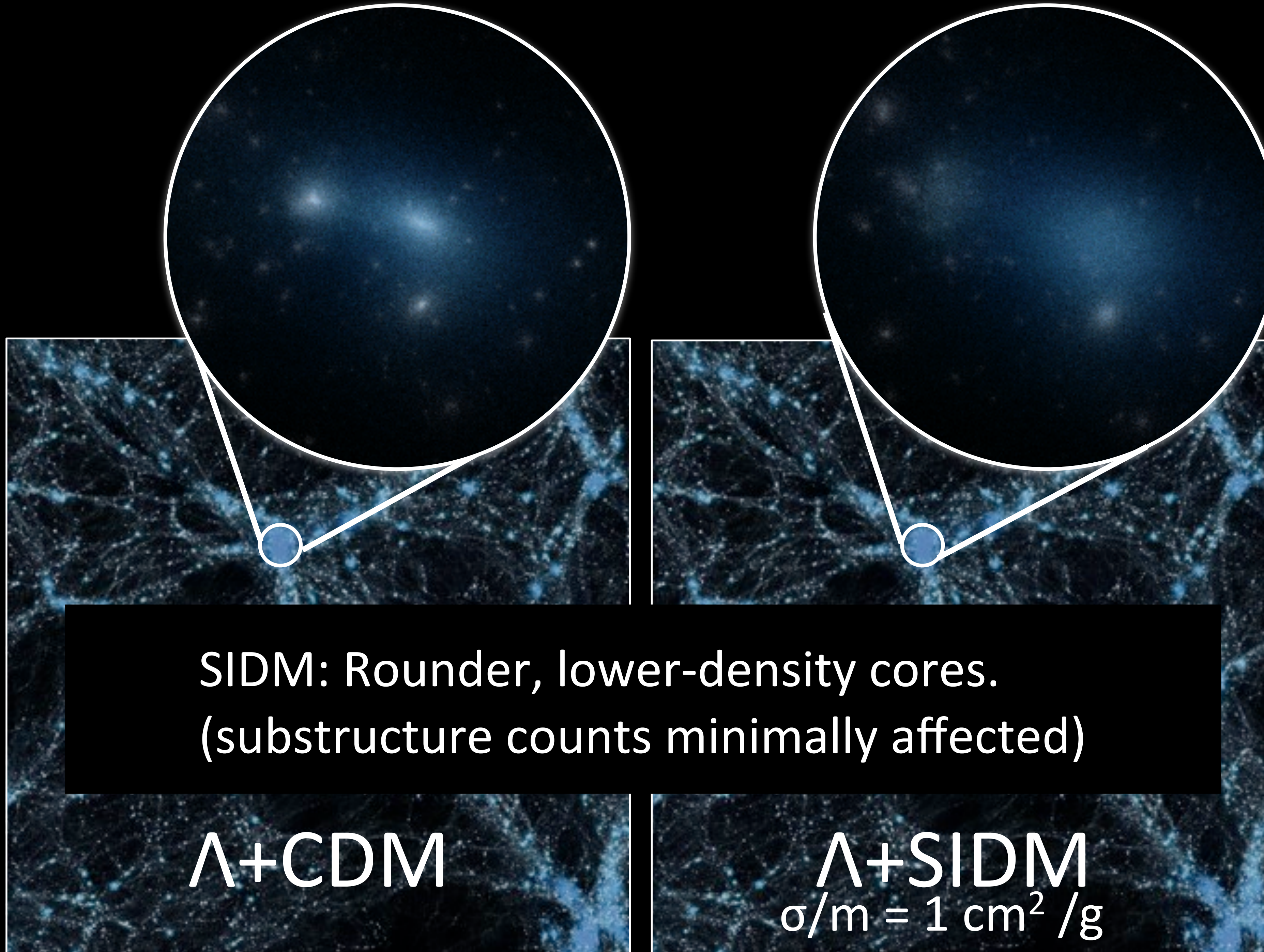
Too-big-to-fail



Bullock et al,1111.2048



- Right Panel: Observed circular velocity of the nine bright dSphs, along with rotation curves corresponding to NFW subhalo.


SIDM: Rounder, lower-density cores.
(substructure counts minimally affected)
Λ+CDM
Λ+SIDM
σ/m = 1 cm2 /g