Two Extreme Examples of Dark Matter Mass:
150 TeV Dark Baryon and Fuzzy Axion

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Contents

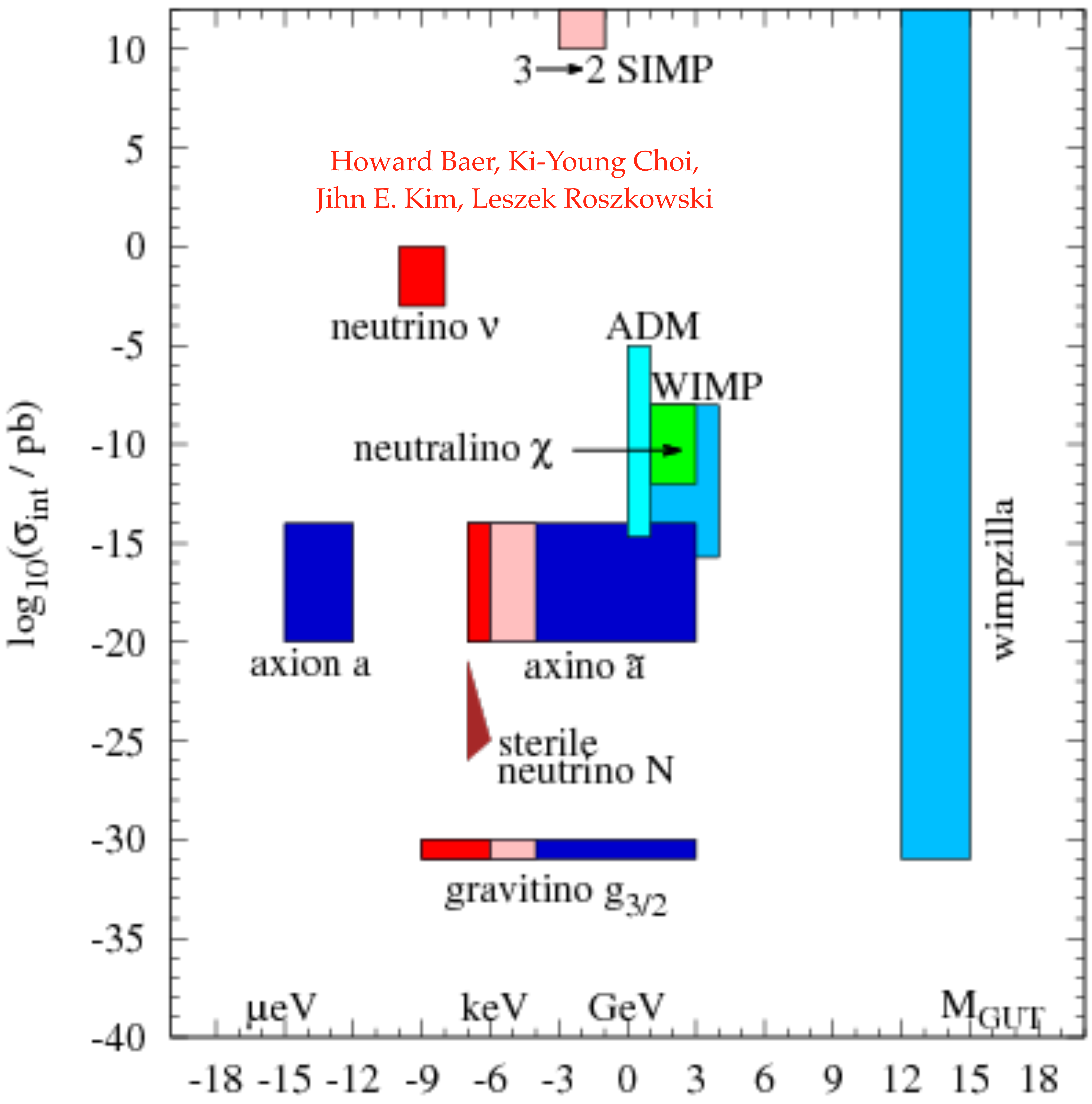
- Motivation of going beyond GeV to TeV WIMP

- 150 TeV dark baryon
  - Stability
  - detection

- 1e-22 eV Fuzzy axion
  - Quantum pressure.
  - N-body simulation

- Conclusion

There are so many DM models located at different mass scales.



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A few particle dark matter theories:

- axion
- sterile neutrino
- SUSY DM
    - neutralino in MSSM
    - Bino/Wino/Higgsino/Photino
    - sneutrino
    - gravitino
    - decaying gravitino
    - gravitino with large messenger mass
    - split SUSY DM
    - bound states for Sommerfeld enhancement
    - bino in E_6SSMwith massless inert singlets
    - neutralino from axion decay
    - NMSSM DM
    - mixed axion/neutralino
    - invisible photino
    - etc., etc. etc.
- Kaluza-Klein DM
- leptophilic DM
- leptophilic from non-abelian discrete symmetry
- asymmetric DM
- scalar singlet DM
- superGUT unified
- mirror DM

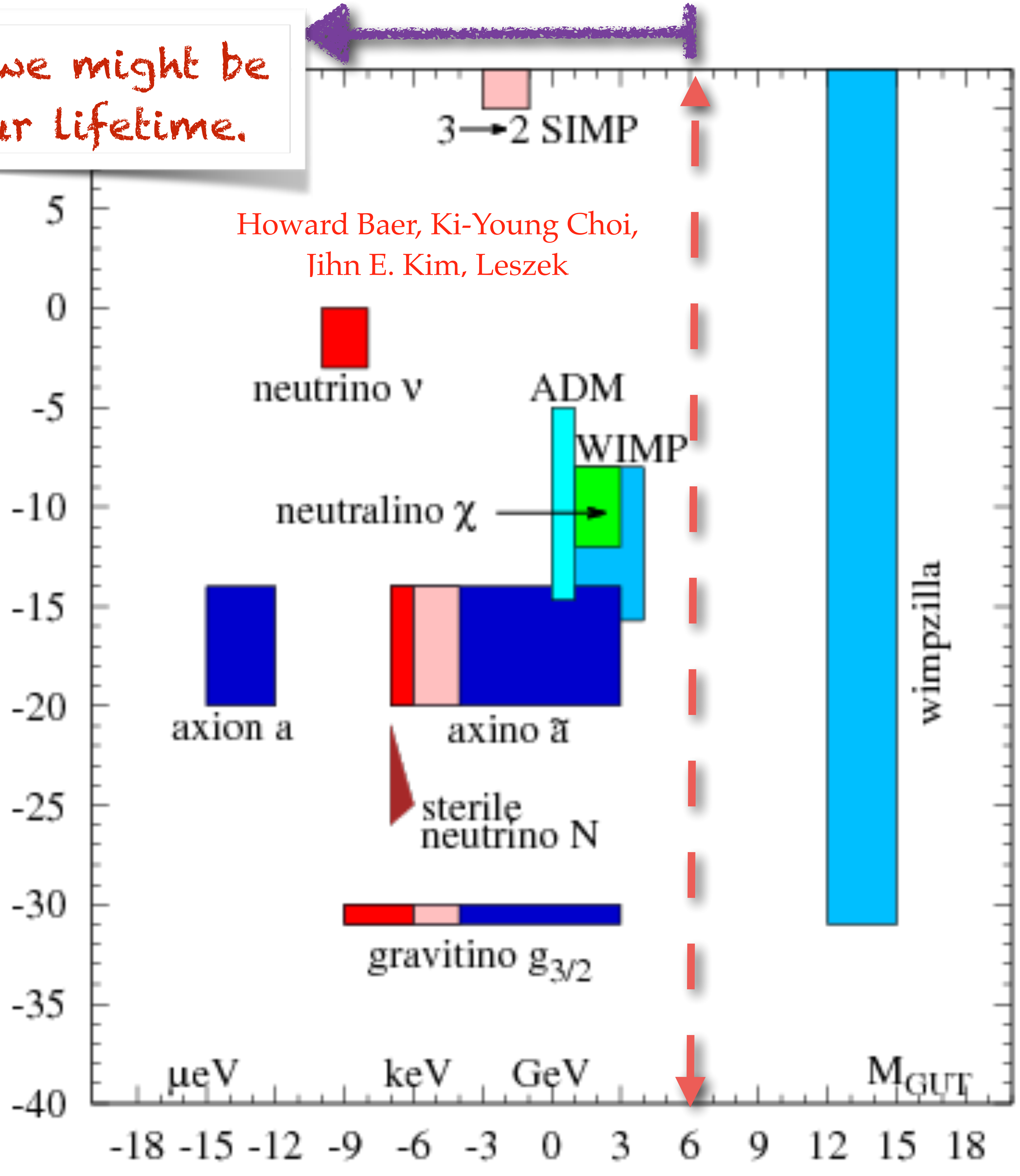
- non-thermal from decay of moduli
- resonance with momentum dependence
- helicity modification due to QED corrections
- dipole moment interacting DM
- dark instanton
- bosonic gas DM
- anti-baryonic
- ultra-light bosonic DM
- invisible photino
- T13 flavor symmetry decaying DM
- hydrodynamic vacuum DM
- dilatation anomaly DM
- bulk viscous unified DM
- ELKO field DM
- two singlet DM
- cosmic braneworld ultra-light DM
- superheavy quark clusters
- luxino
- non-canonical kinetic term DM
- branes filled with scalar fields
- real gauge singlet
- Higgs portal
- number theory DM
- asymmetric sneutrino
- modified Ricci model DM
- vacuum solitons
- complex singlet scalar
- D4 x Z2 flavor group DM
- non-minimal KK DM
- axion portal cascade
- light (MeV mass) DM

- two singlet DM
- self-interacting DM
- isospin violating DM
- inert Higgs
- skyrmion in littlest Higgs model
- techni-dilaton DM
- type-II seesaw mSUGRA DM
- vector DM
- goldsini
- WIMPless DM
- inert triplet DM
- vacuum solitons
- BEC from U(1) symmetry breaking
- eXciting DM (XDM)
- inelastic DM (iDM)
- flavor SU(3)Q triplet/singlet
- isospin violating
- axion-like repulsive DM
- D6 flavor symmetry
- warped Radion
- G2-MSSM
- gauged right-handed neutrino
- integration constant Horava DM
- tensor-four-scalar
- scalarons in R2 gravity
- secluded DM
- etc., etc., etc., etc., etc.

Taken from Griest (2014).

Signals at	Experiments	DM Hints
Coillders	LHC, LEP, Tevatron, ...	None
Direct detection	XENON100, LUX, PandaX...	DAMA, CoGeNT, CRESST at low DM mass region.
Cosmic rays 1. Positrons 2. antiprotons 3. neutrinos	1. PAMELA, Fermi-LAT, AMS02... 2. PAMELA, AMS02 3. IceCube	1. High energy positron excess 2. 70 GeV excess 3. TeV-PeV neutrinos
Gamma rays	Fermi-LAT, ...	FERMI bubbles, GCE
X-ray	XMM-Newton	3.55 keV line

The mass region we might be able to see in our lifetime.



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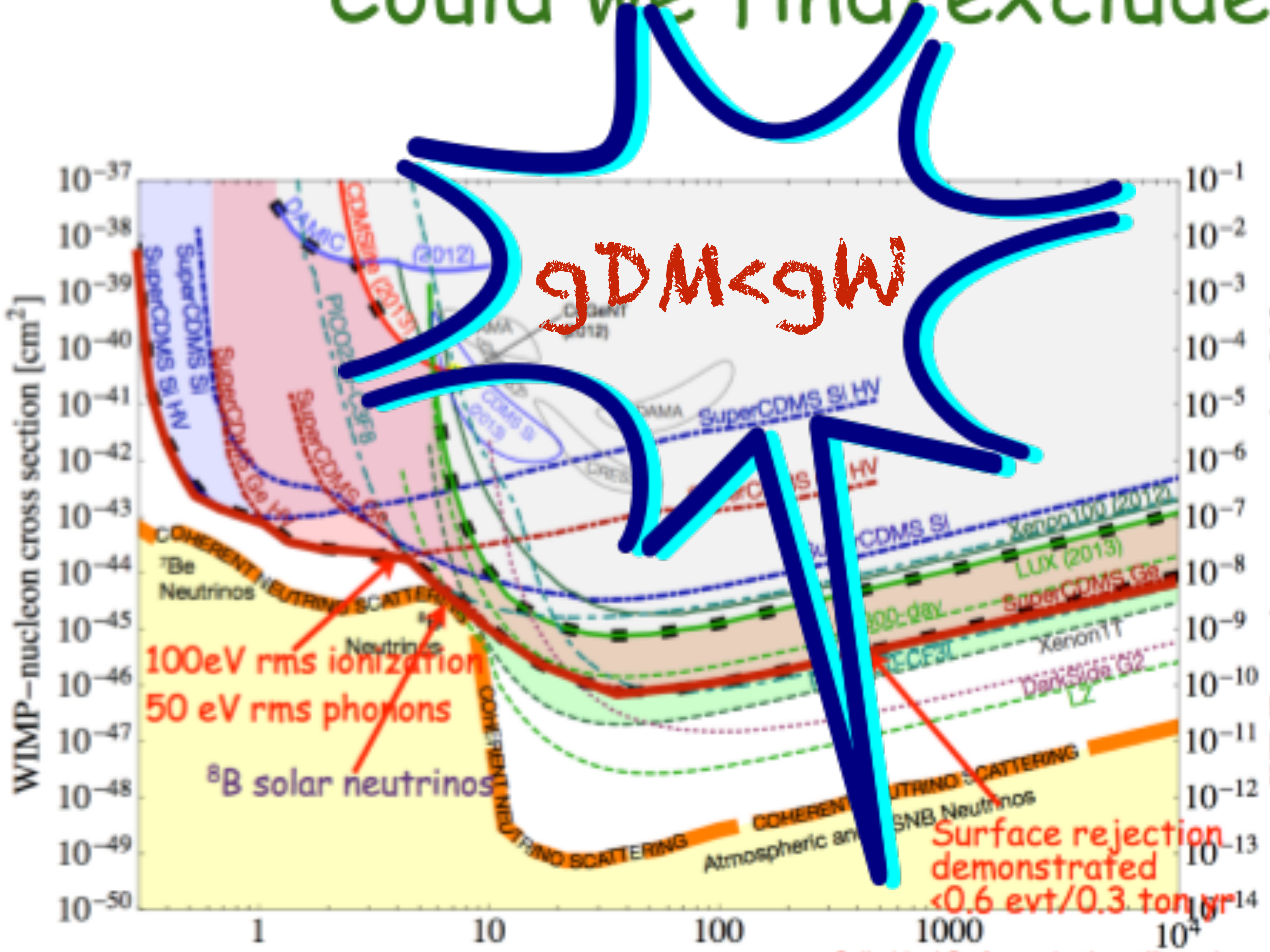
Summary

Could we find/exclude WIMP DM in 20 years?

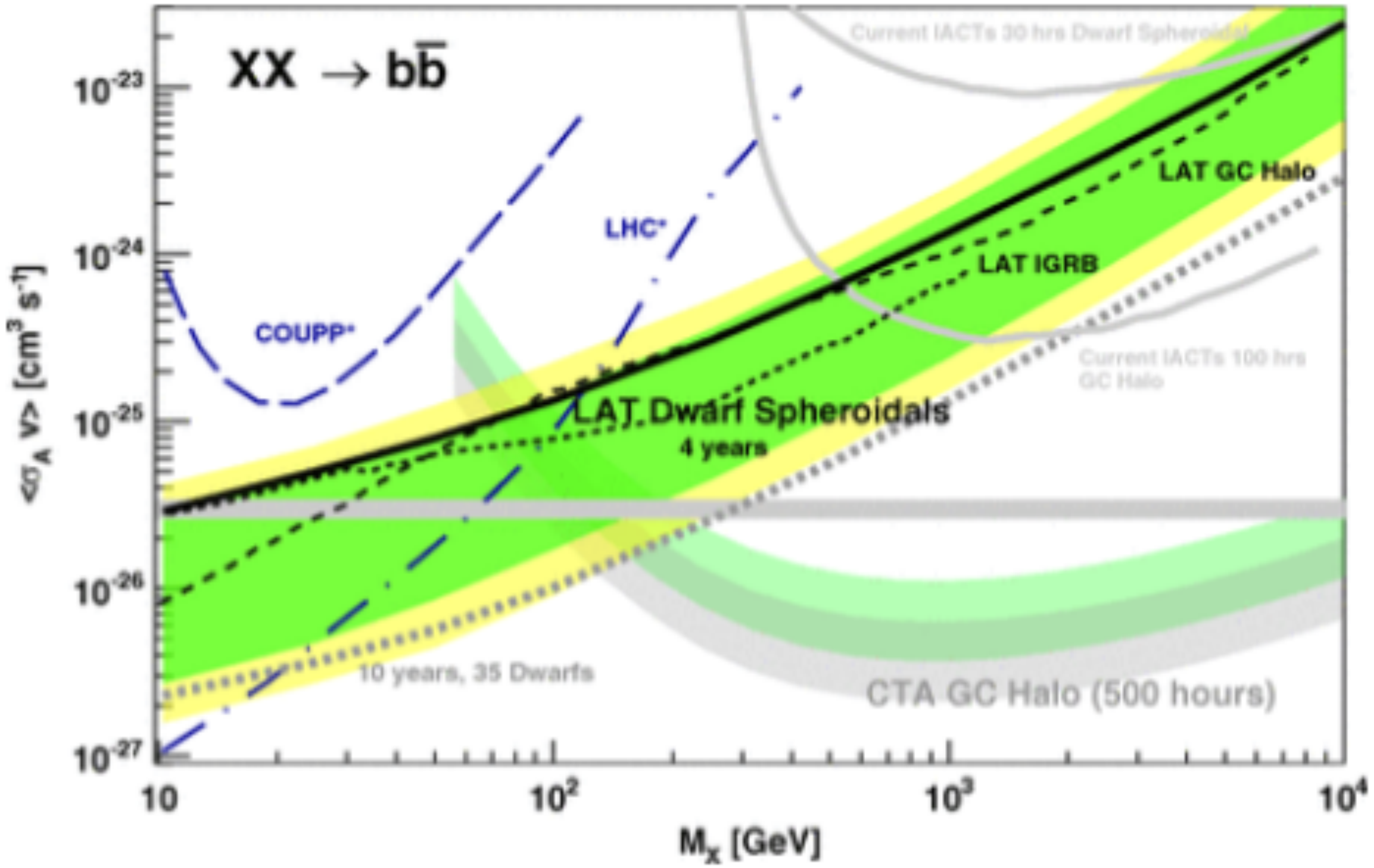


100eV rms ionization
50 eV rms phonons

^{8}B solar neutrinos

Surface rejection demonstrated <0.6 evt/0.3 ton yr

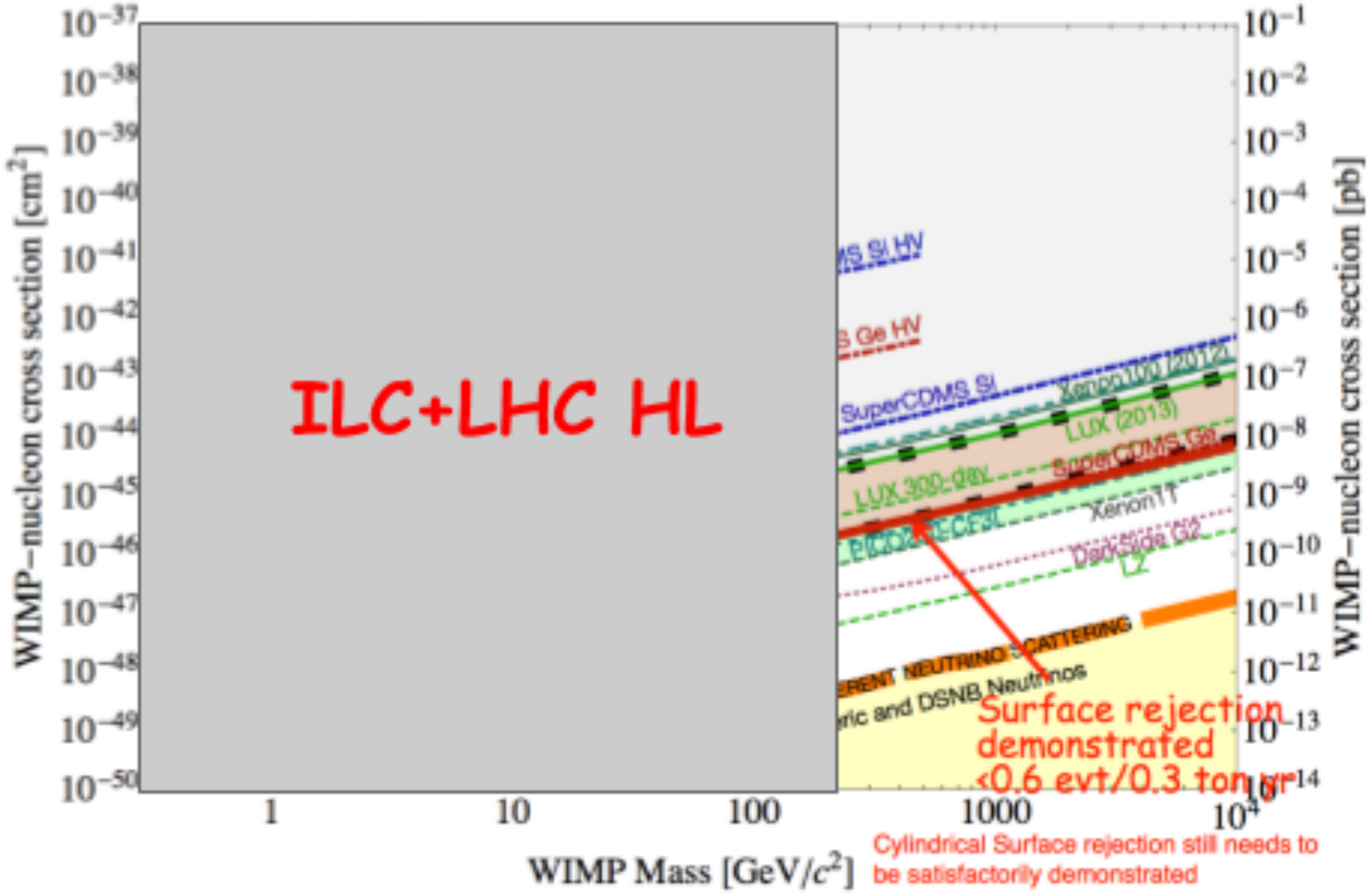
Cylindrical Surface rejection still needs to be satisfactorily demonstrated



The most popular model is WIMPs but it seems to be killed soon...

Summary

Could we find/exclude WIMP DM in 20 years?



ILC+LHC HL

Surface rejection demonstrated <0.6 evt/0.3 ton yr

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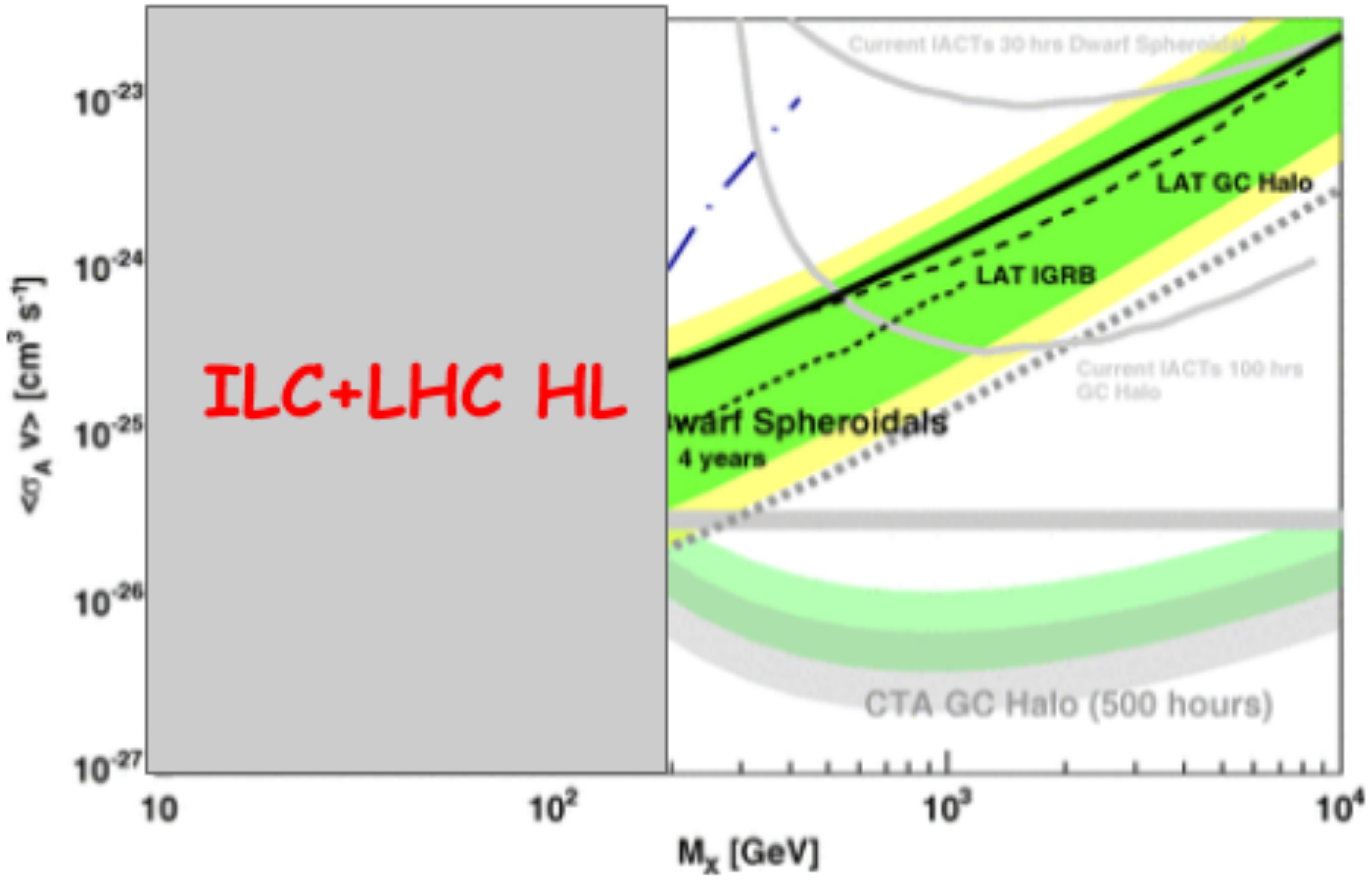
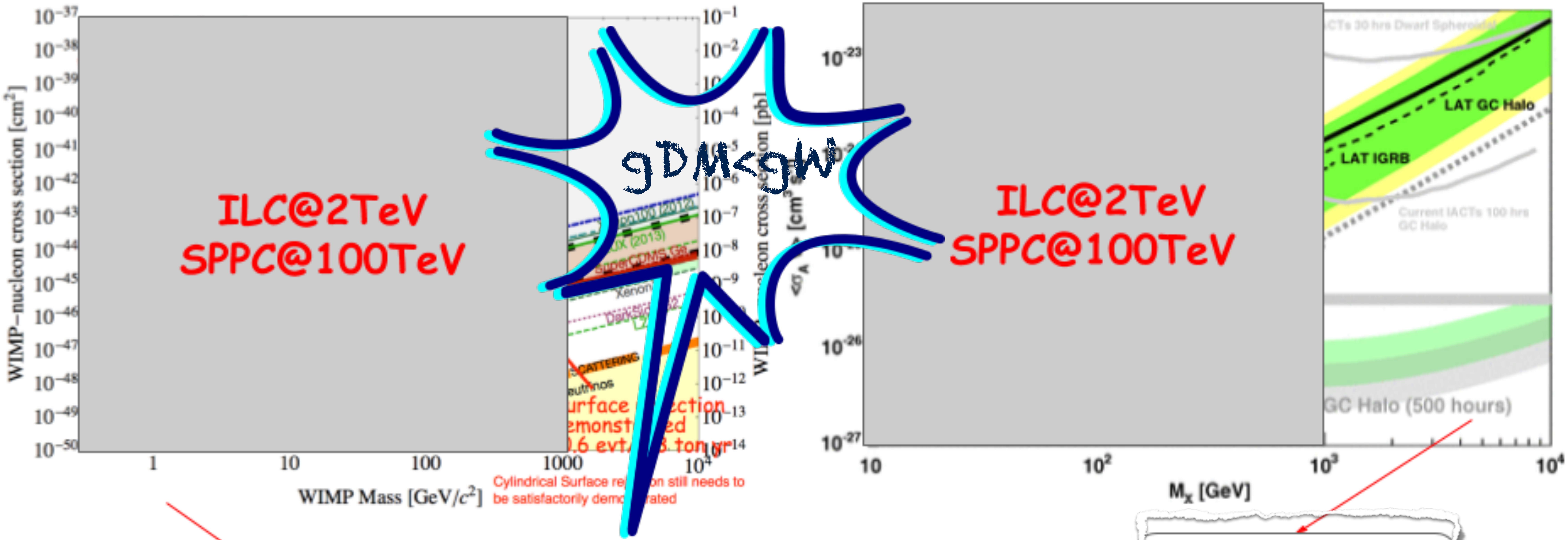


ILC+LHC HL

So, it is nature to see that the next generation of CDM searches are shifting their focuses to different mass regions.

Summary

Could we find/exclude WIMP DM in 20~30 years?



Too low coupling -> WIMPless
Non-thermal relic density scenario

Too low coupling
Too heavy mass
-> Composite DM

150 TeV dark baryon

- stability
- detection

The dark matter stability

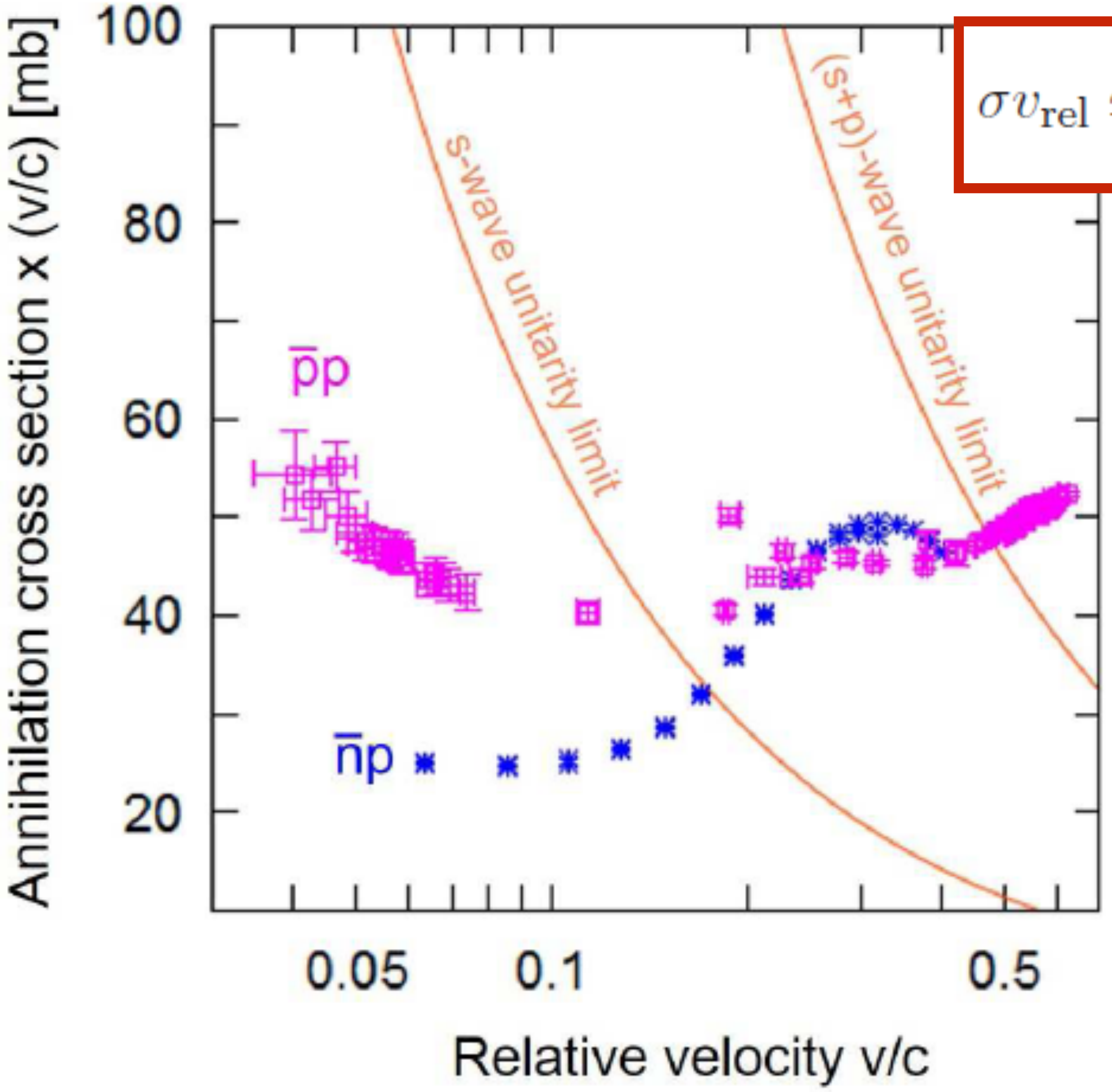
- Suppose the hidden strong gauge group is an SU(N) gauge group. Dark matter can be N dark quarks to form a dark baryon.
- The DM has an decay width with GUT scale suppressed.

$$\boxed{\Gamma \sim m_\chi^{3N-4}/\Lambda^{3N-5}}$$

- The minimal N is 3 and we except dimension-6 QQQL operator for N=3 case.

Dark matter annihilation and mass

$$\sigma v_{\rm rel}^{\tt DM}(m_\chi) = \sigma v_{\rm rel}^{\tt QCD} \times \left(\frac{1\ \mathrm{GeV}}{m_\chi}\right)^2$$



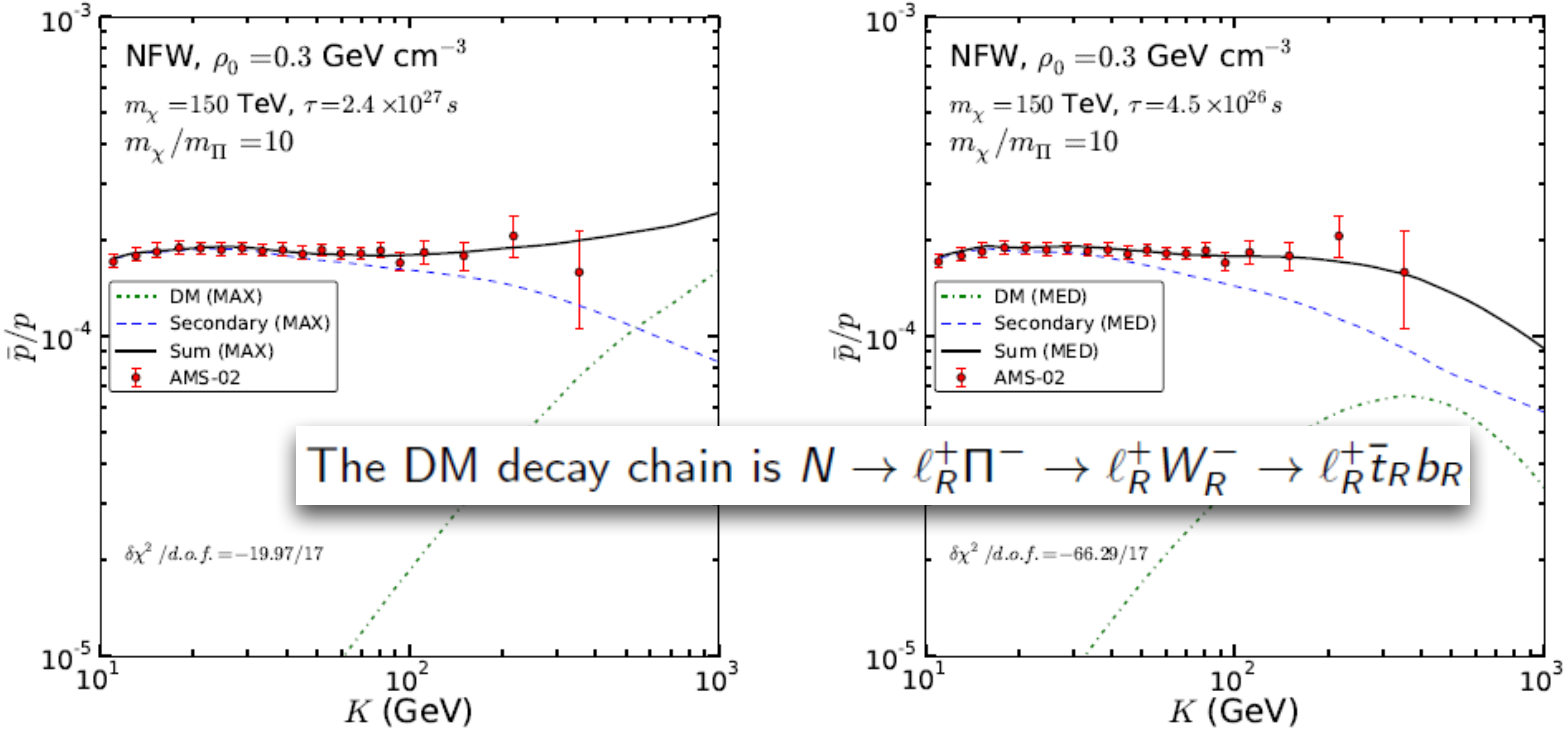
$$\sigma v_{\rm rel} \simeq \frac{4\pi(2\ell+1)}{m_B^2 v_{\rm rel}}.$$

- At thermal freeze out $v_{\rm rel} \sim 0.2c - 0.4c$, not only s wave but some higher partial wave contribute.
- For $\Omega_\chi h^2 = 0.12$ and Dirac fermion, s wave unitarity bound is 84 TeV of Griest and Kamionkowski (PRL 64, 615), with $v_{\rm rel} \simeq 0.45c$; or 130 TeV of Griest and Seckel (PRD 43, 3191), with $v_{\rm rel}$ averaged.
- Rescaling the annihilation cross section, from the QCD case with $m = 0.938$ GeV to the DM of $\sigma_a v_{\rm rel} = 3 \times 10^{-26}$ cm^{3}s^{-1}, we get

$$m_\chi \simeq 150\ \mathrm{TeV!}$$

- Dark matter annihilation cross section at the early universe are due to s and p wave contribution together.
- Dark matter mass~150 TeV.

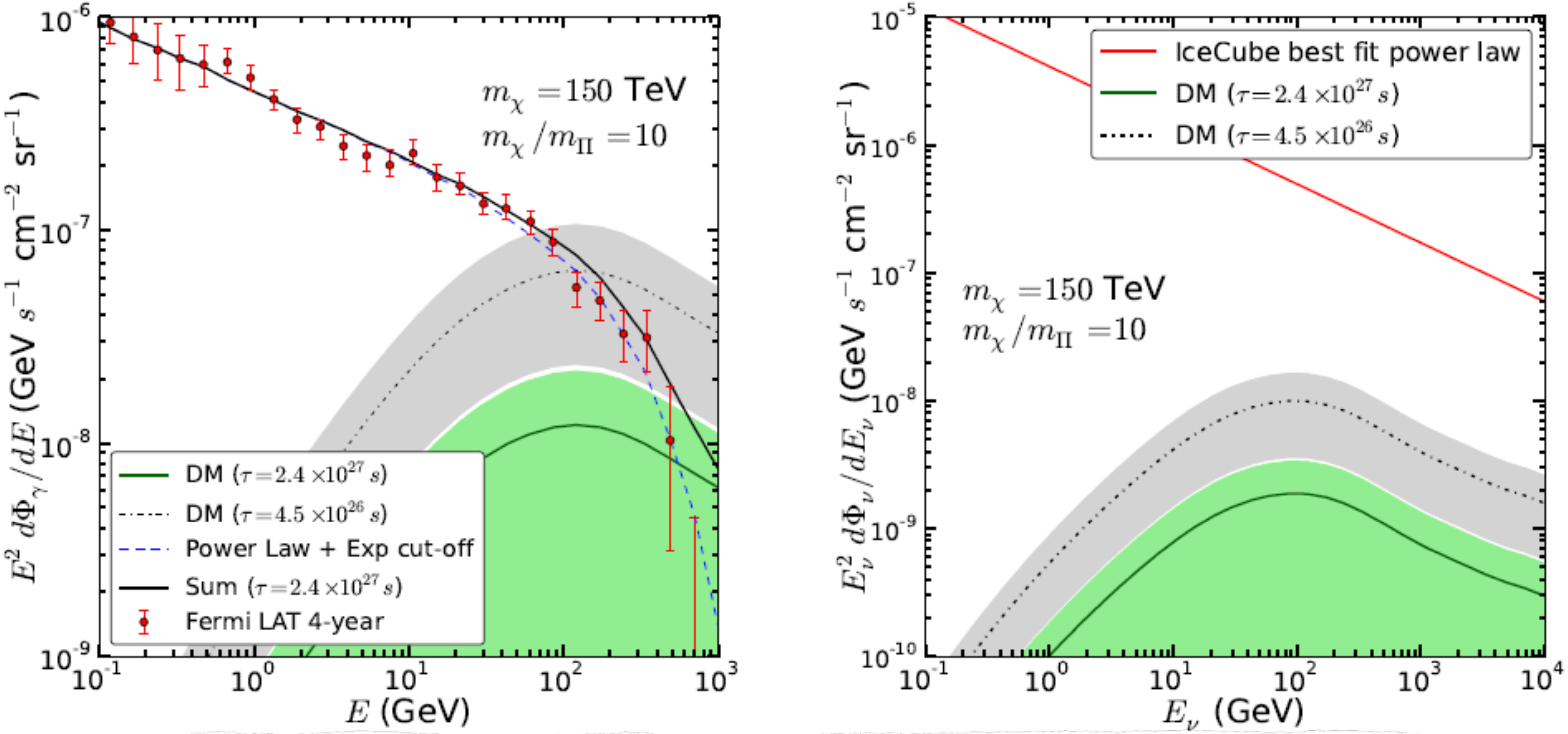
AMS02 Proton and antiproton ratio measurement



The DM decay chain is $N \to \ell_R^+ \Pi^- \to \ell_R^+ W_R^- \to \ell_R^+ \bar{t}_R b_R$

AMS02 antiproton data shows a slightly excess which indicates a decaying composite with mass 150 TeV and decay time ~O(1e27) sec.

Extragalactic Gamma Ray and Neutrino

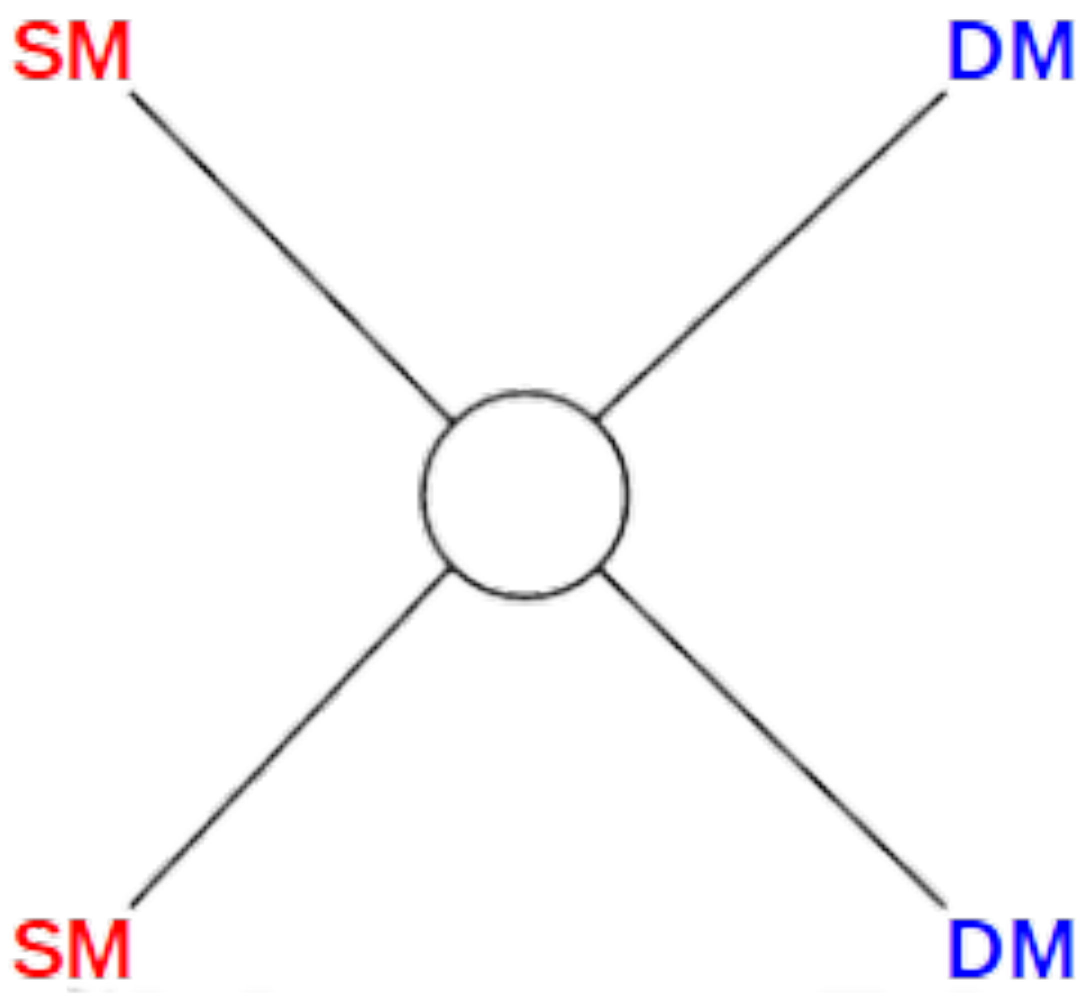


The decay time O(1e27) s is is marginal to these two experiments !!!

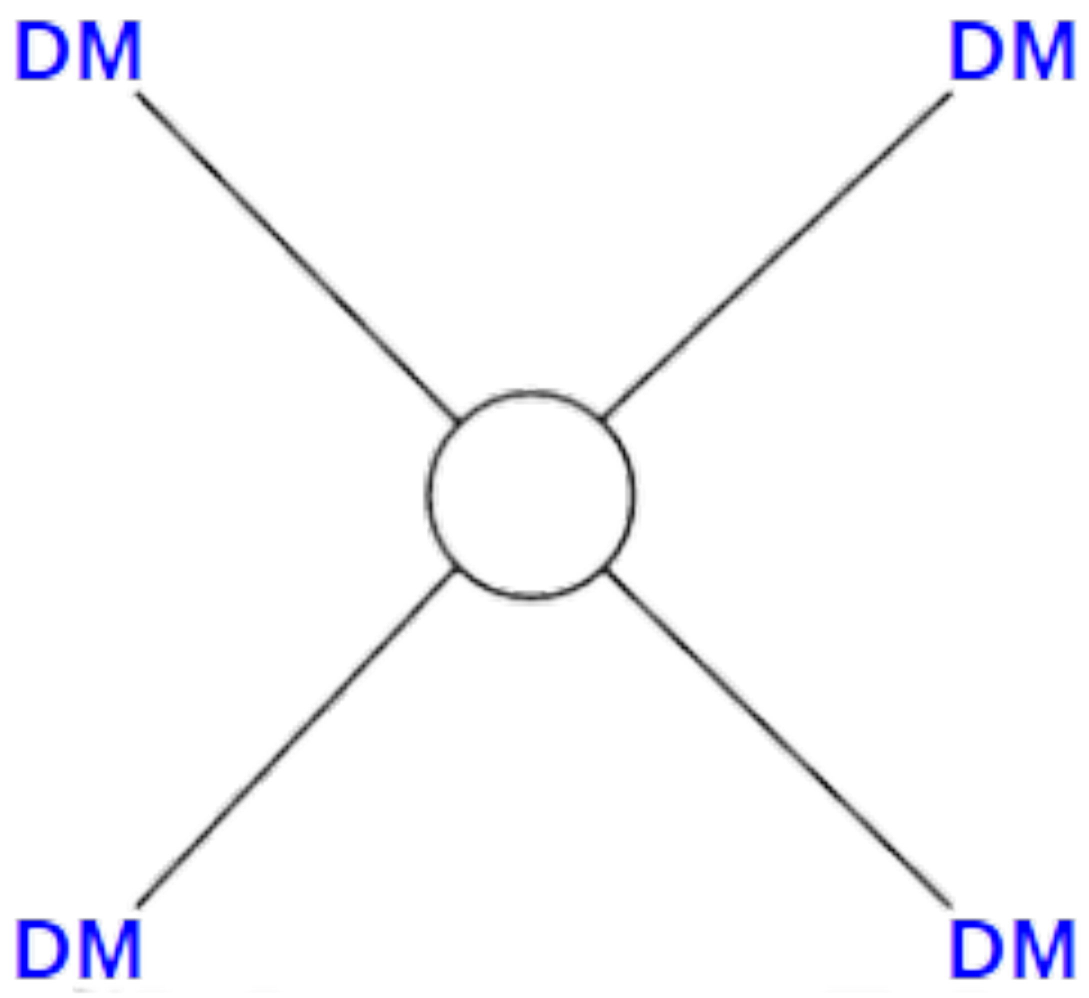
1e-22 eV Fuzzy axion

- Quantum pressure.
- N-body simulation

The strategy of DM hunting



- SM SM > DM DM. Measurement of the missing energy at the colliders
- SM DM > SM DM. Measurement of the recoil energy of SM particles.
- DM DM > SM SM Measurement of the flux of SM particles.
- DM DM > DM DM. Astrophysical structure



● Dark Matter is EXPECTED to have weak interaction between SM and DM but it is not necessary to be.

● However, if it has no weak interaction between DM and SM, method 1-3 are useless and we are not able to determine the DM mass.

Lambda Cold Dark Matter
small-scale crisis

The CDM model through detailed N -body simulations, though successfully explains the observations in large scale, fails to account for the observations in relatively smaller scales,
known as "small-scale crisis":
(i) the missing satellites problem,
(ii) the cusp-core problem, and
(iii) the too-big-to-fail problem.
In order to alleviate the problems, a new mechanism of velocity boost is needed for the DM momentum exchanges beyond the collisionless picture of the CDM.

> Heating and feedback certainly reduce the stellar luminosity of the satellite galaxies associated with sub-halos, but whether plausible parametrizations for these processes can match the observations over the full range of halo and sub-halo masses remains an open question.
> ~L. Hui, J. Ostriker, S. Tremaine, and E. Witten

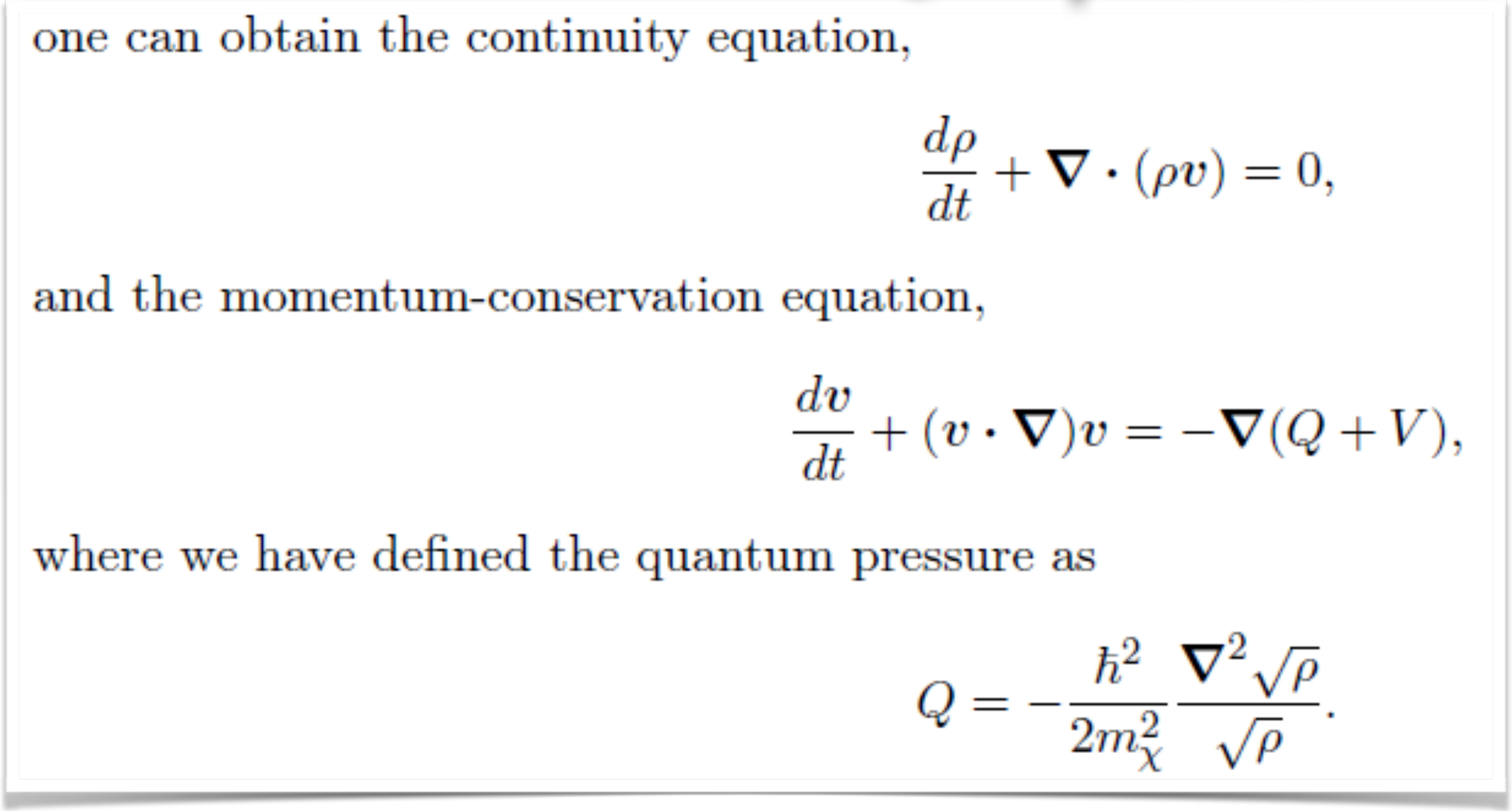
Quantum pressure from Schrödinger-Poisson equations

$$i\hbar\frac{d\Psi}{dt} = -\frac{\hbar^2}{2m_\chi}\nabla^2\Psi + m_\chi V\Psi,$$

$$\nabla^2 V = 4\pi G m_\chi|\Psi|^2.$$

$$\Psi = \sqrt{\frac{\rho}{m_\chi}}\exp(\frac{iS}{\hbar})$$

The Madelung equations



one can obtain the continuity equation,

$$\frac{d\rho}{dt} + \nabla\cdot(\rho v) = 0,$$

and the momentum-conservation equation,

$$\frac{dv}{dt} + (v\cdot\nabla)v = -\nabla(Q+V),$$

where we have defined the quantum pressure as

$$Q = -\frac{\hbar^2}{2m_\chi^2}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}.$$

A singularity of QP appearing at density zero.

Quantum pressure from Schrödinger-Poisson equations

$$\rho(\boldsymbol{r}) = \sum_j \sum_i m_i \delta(\boldsymbol{r} - \boldsymbol{r}_j),$$

$$\delta(\boldsymbol{r} - \boldsymbol{r}_i) = \frac{1}{2\sqrt{2}\lambda^3 \pi^{3/2}} \exp(-\frac{2|\boldsymbol{r} - \boldsymbol{r}_i|^2}{\lambda^2}),$$

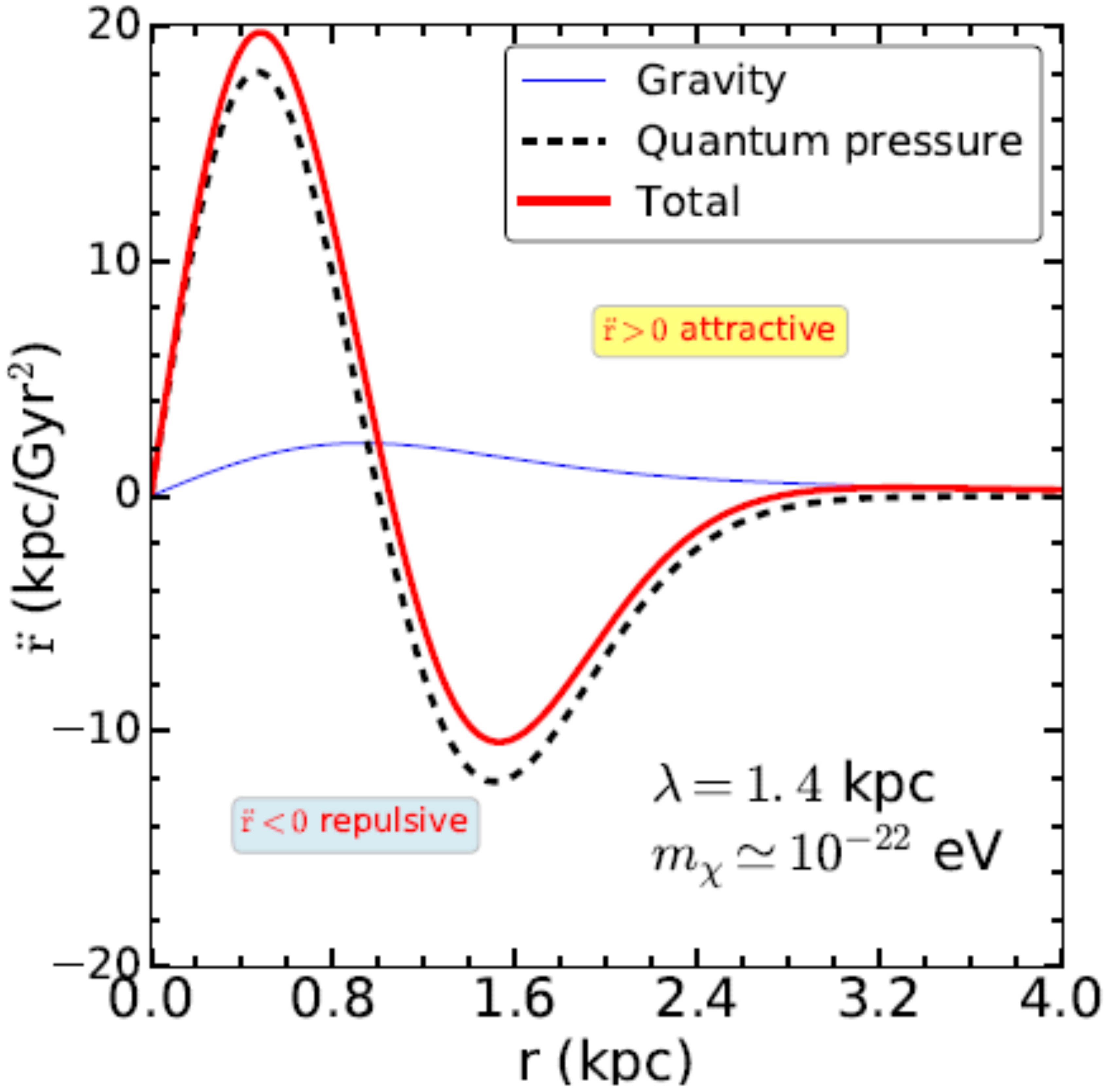
$$\frac{\lambda}{2\pi} = \frac{\hbar}{mv} = 1.92\,\mathrm{kpc}\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)\left(\frac{10\,\mathrm{km\ s^{-1}}}{v}\right)$$

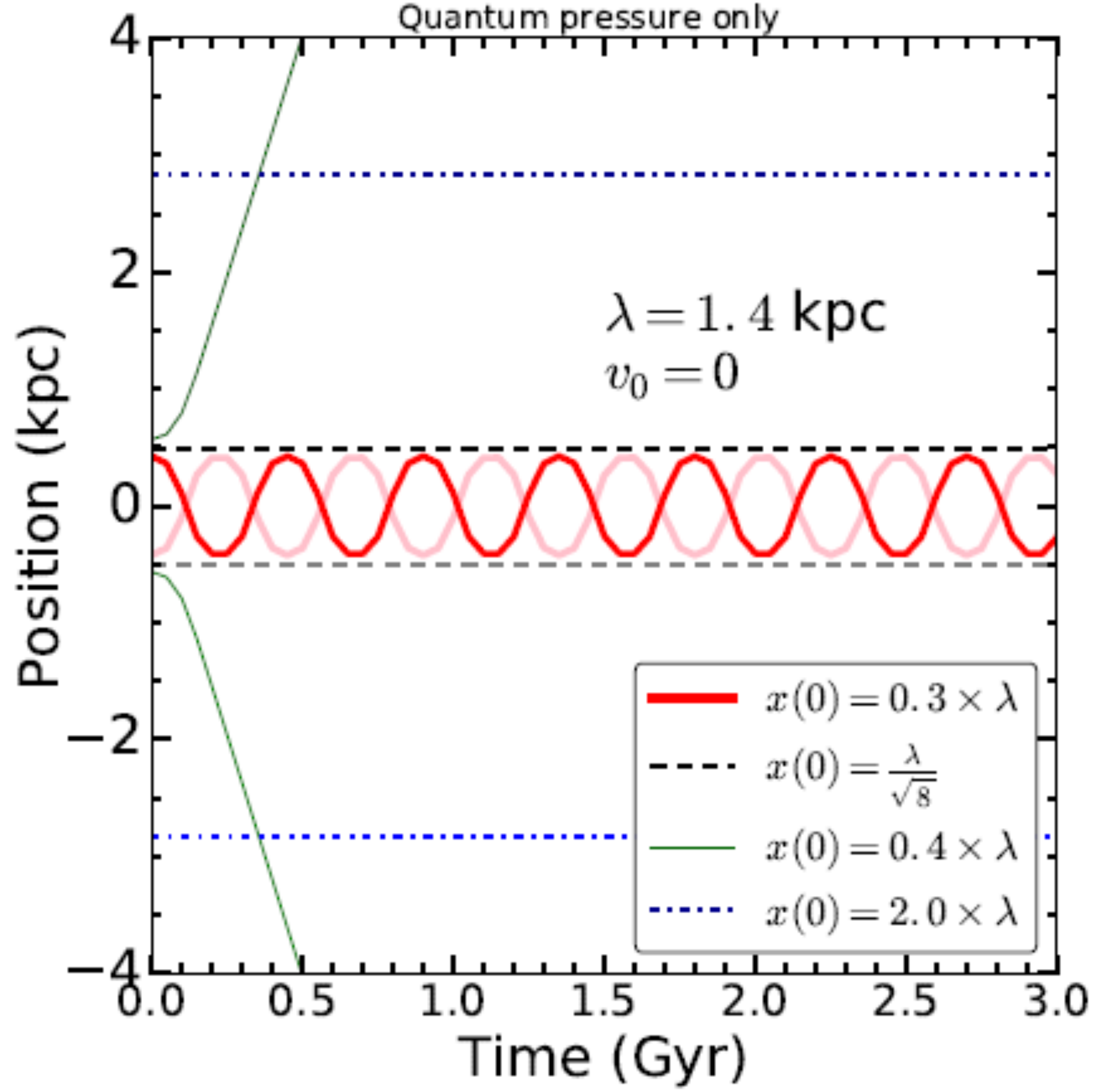
We are still happy because the Quantum pressure is function of Particle DM mass which can be used in the BSM Lagrangian. Particle physics is still useful but extend.

$$\boxed{\ddot{\boldsymbol{r}} = \frac{4M\hbar^2}{M_0 m_\chi^2 \lambda^4} \sum_j \exp\left[-\frac{2|\boldsymbol{r} - \boldsymbol{r}_j|^2}{\lambda^2}\right](1 - \frac{2|\boldsymbol{r} - \boldsymbol{r}_j|^2}{\lambda^2})(\boldsymbol{r}_j - \boldsymbol{r}).}$$

Quantum pressure in the N-body simulation

$$\ddot{\boldsymbol{r}} = \frac{4M\hbar^2}{M_0 m_\chi^2 \lambda^4} \sum_j \exp\left[-\frac{2|\boldsymbol{r}-\boldsymbol{r_j}|^2}{\lambda^2}\right] \left(1 - \frac{2|\boldsymbol{r}-\boldsymbol{r_j}|^2}{\lambda^2}\right)(\boldsymbol{r_j}-\boldsymbol{r}).$$

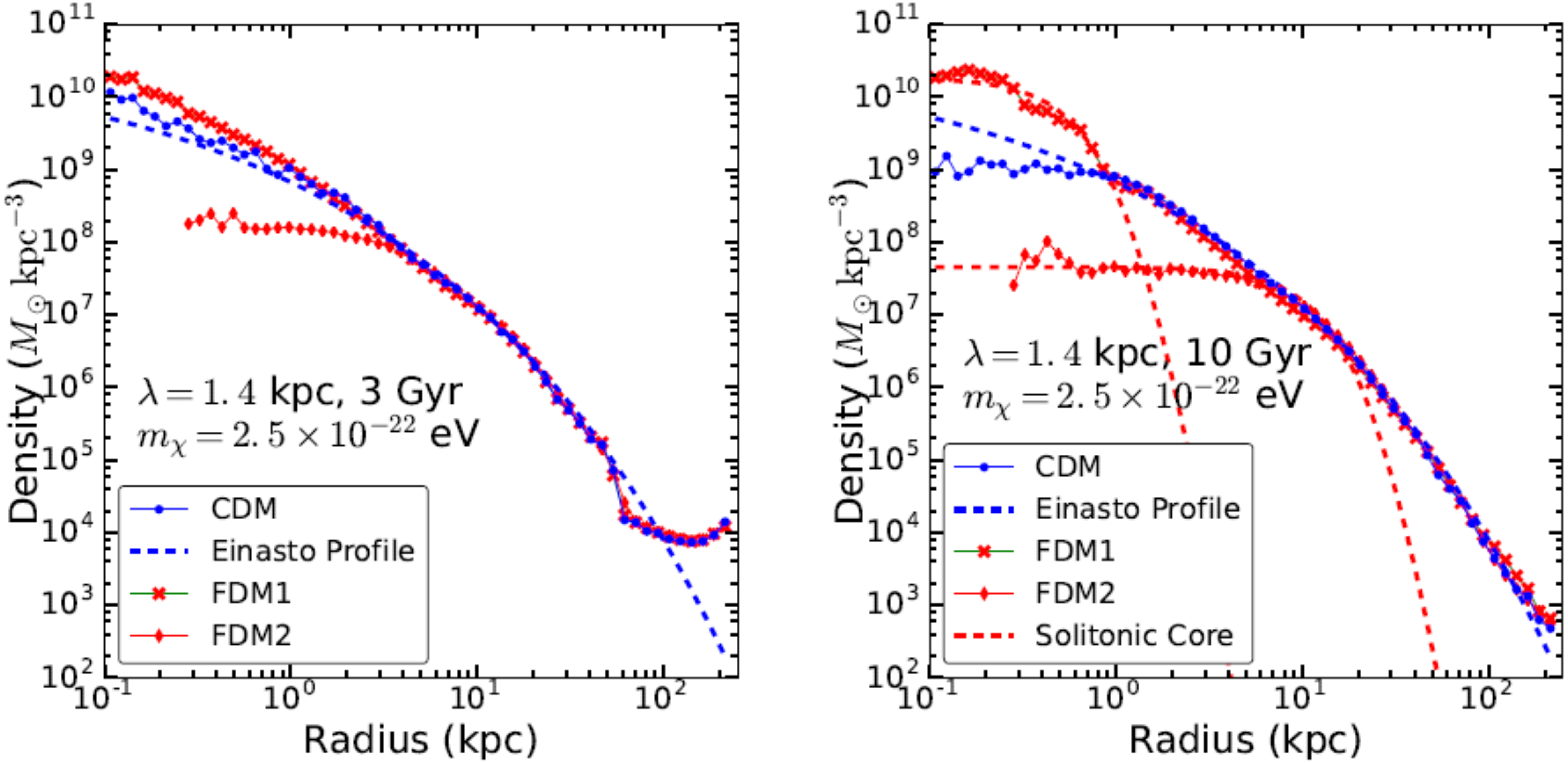




The quantum pressure as a short-range interaction in the exponentially decay term.

Let's see the N-body Movie...

Solitonic Core - two solutions



- There are two solutions, FDM1 and FDM2.
- Both solutions develop solitonic core.

One is smaller (0.3 Kpc) but other one is as larger as 10 Kpc.

Conclusion (I)

- We have proposed a new scenario of baryonic DM based on a strong hidden SU(3) gauge group, which also connects to the visible sector through the SU(2)R×U(1)B-L gauge group.

- We find that theoretical estimation and fitting to recent AMS-02 antiproton data are both consistent with a decay life time of a few 1e27 seconds. Although being heavy, our DM model has a perspective of detection in the near future.

Conclusion (II)

- We have proposed to use a Gaussian kernel function to discretize the quantum pressure term in order to be used in PP method for N -body simulations.
- We found two stable solutions for FDM which can be interesting in the future cosmology simulation.

The End

Thank you for your attention
and Happy New Year.

A Simple and Promising baryonic DM Candidate

- DM candidate must be absolutely stable, or sufficiently long lived.

  The dark baryon is protected by the accidental dark baryon number in the hidden strong sector, even if decay operator is allowed, like proton decay in GUT.

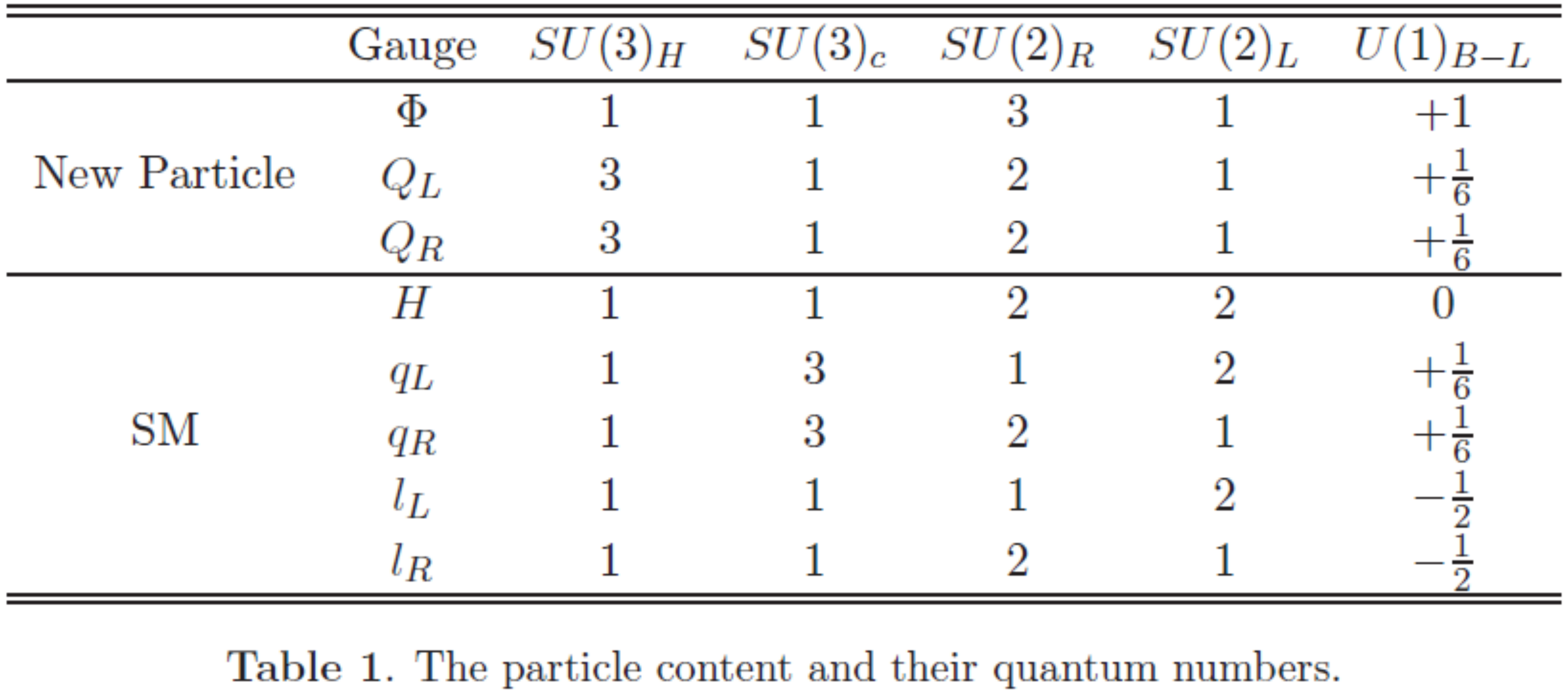
- Correct relic abundance is produced.

  the dark baryon is a thermal relic, its mass is determined by tuning the annihilation cross section to achieve the correct relic abundance.

  The constituent dark quark is charged under (part of) the SM gauge group, which guarantees a simple thermal history. This setup also opens interesting dark matter phenomenology.

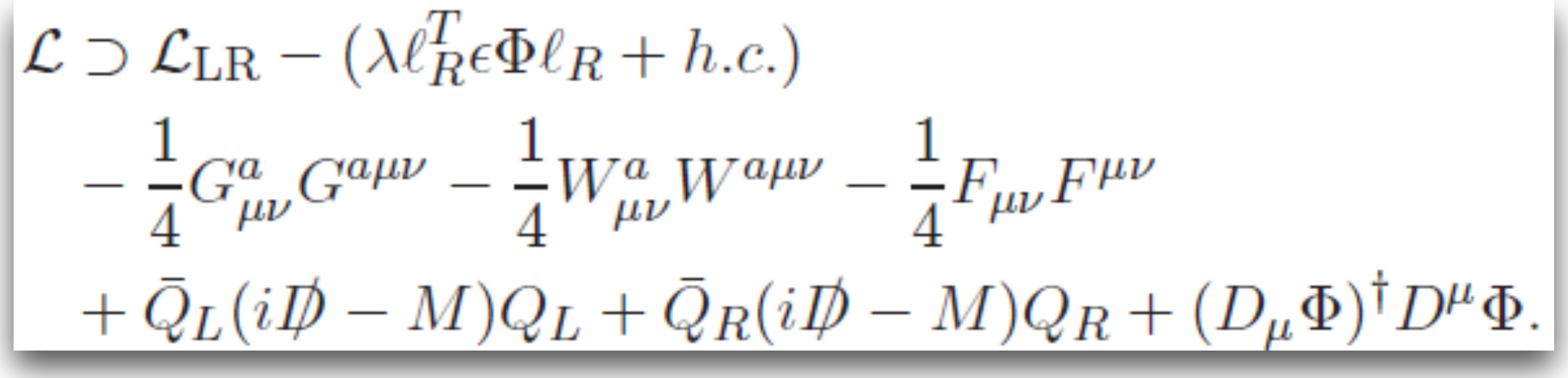
- May be able to explain AMS02 antiproton excess?

The Benchmark $SU(3)_{\rm hid} \times SU(2)_R \times U(1)_{B-L}$ Dark Matter Model



	Gauge	$SU(3)_H$	$SU(3)_c$	$SU(2)_R$	$SU(2)_L$	$U(1)_{B-L}$
New Particle	Φ	1	1	3	1	$+1$
	Q_L	3	1	2	1	$+\frac{1}{6}$
	Q_R	3	1	2	1	$+\frac{1}{6}$
SM	H	1	1	2	2	0
	q_L	1	3	1	2	$+\frac{1}{6}$
	q_R	1	3	2	1	$+\frac{1}{6}$
	l_L	1	1	1	2	$-\frac{1}{2}$
	l_R	1	1	2	1	$-\frac{1}{2}$

Table 1. The particle content and their quantum numbers.



$$\mathcal{L} \supset \mathcal{L}_{\rm LR} - (\lambda \ell_R^T \epsilon \Phi \ell_R + h.c.) - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{Q}_L (i\not{D} - M) Q_L + \bar{Q}_R (i\not{D} - M) Q_R + (D_\mu \Phi)^\dagger D^\mu \Phi.$$

The DM decay chain is $N \to \ell_R^+ \Pi^- \to \ell_R^+ W_R^- \to \ell_R^+ \bar{t}_R b_R$

The charged component of the dark pion should decay through a virtual W_R which is exactly like the QCD pion decay through a virtual SM W, and chirality flipping mechanism makes the t_R+b_R channel the dominant one.