Particle-physics Boost Factors

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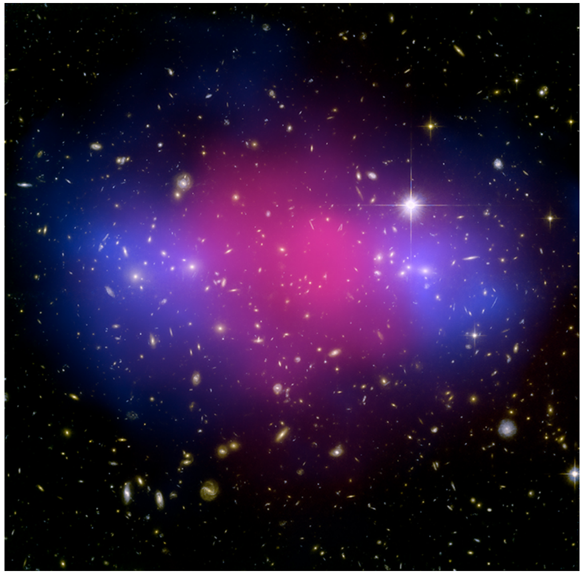
Contents of my talk

- Introduction of particle-physics boost factors
  - Non-thermal DM production
  - Breit-Wigner resonance mechanism
  - Sommerfeld mechanism
- Constraints on particle-physics boost factors
- Summary

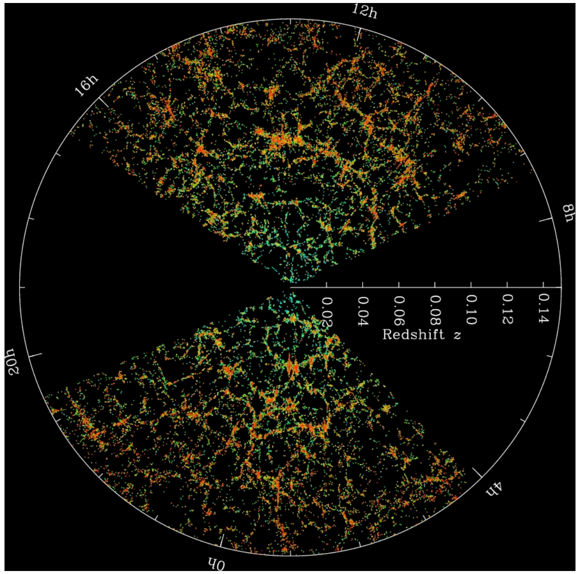
Introduction

A Clash of Clusters



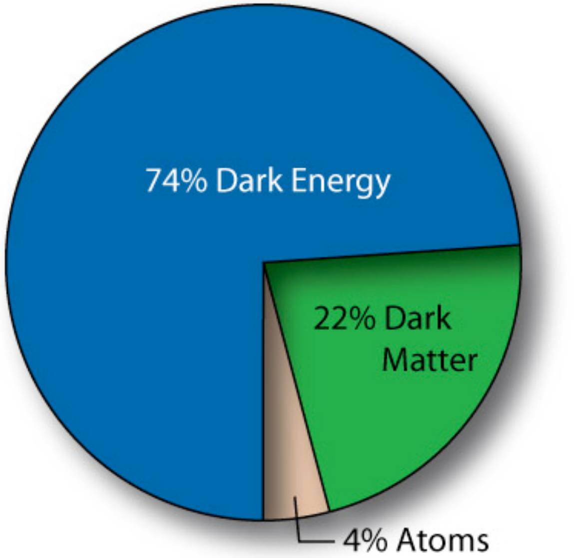
Credit: X-ray (NASA/CXC/Stanford/S.Allen); Optical/Lensing (NASA/STScI/UC Santa Barbara/M.Bradac)

SDSS Galaxy Map



Credit: M. Blanton and the Sloan Digital Sky Survey.

Content of the Universe



Credit: NASA / WMAP Science Team

- What is (cold) dark matter in the Universe ?
- How is the dark matter produced in the early universe ?

Thermal relic scenario

DM particle, χ, is weakly-interacting massive particle (WIMP), and it is in thermal equilibrium in the early universe.

Boltzmann eq. for DM number density $(Y \equiv n/s)$ as a function of $x(= M/T)$.

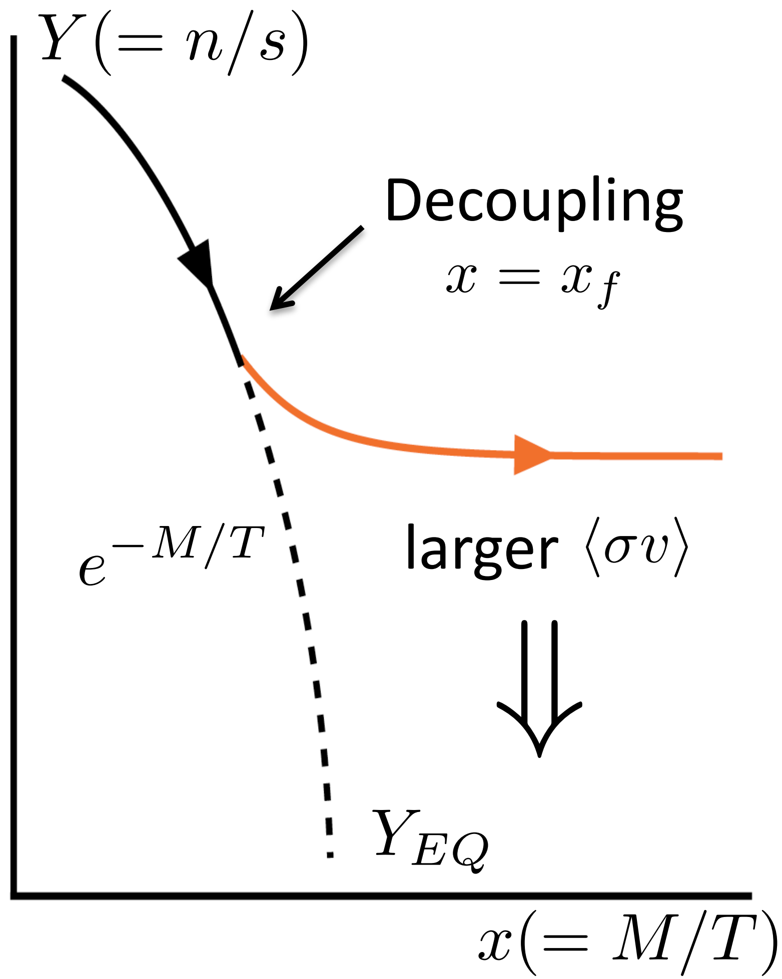
$$\frac{dY}{dx} = -\frac{s\langle\sigma v\rangle}{xH}(Y^2 - Y_{EQ}^2)$$

After $x_f \simeq 20$, DM is decoupled from thermal bath.

$$Y_\infty \propto x_f/\langle\sigma v\rangle$$

When S-wave process in the DM annihilation is dominant,

$$\Omega_{\rm DM} = 0.23\left(\frac{3\times 10^{-26}cm^3/s}{\langle\sigma v\rangle}\right)$$



Thermal relic scenario

DM particle, χ, is weakly-interacting massive particle (WIMP), and it is in thermal equilibrium in the early universe.

- Dark matter with mass 100GeV-1TeV is consistent with thermal relic scenario,

$$\sigma v \sim \pi \frac{\alpha^2}{m^2} = \pi \frac{(1/127)^2}{(300\text{GeV})^2} = 3 \times 10^{-26} cm^3/s$$

- From the naturalness, new physics beyond the standard model in particle physics is expected to appear around 100 GeV -1TeV scale.

DM candidate:

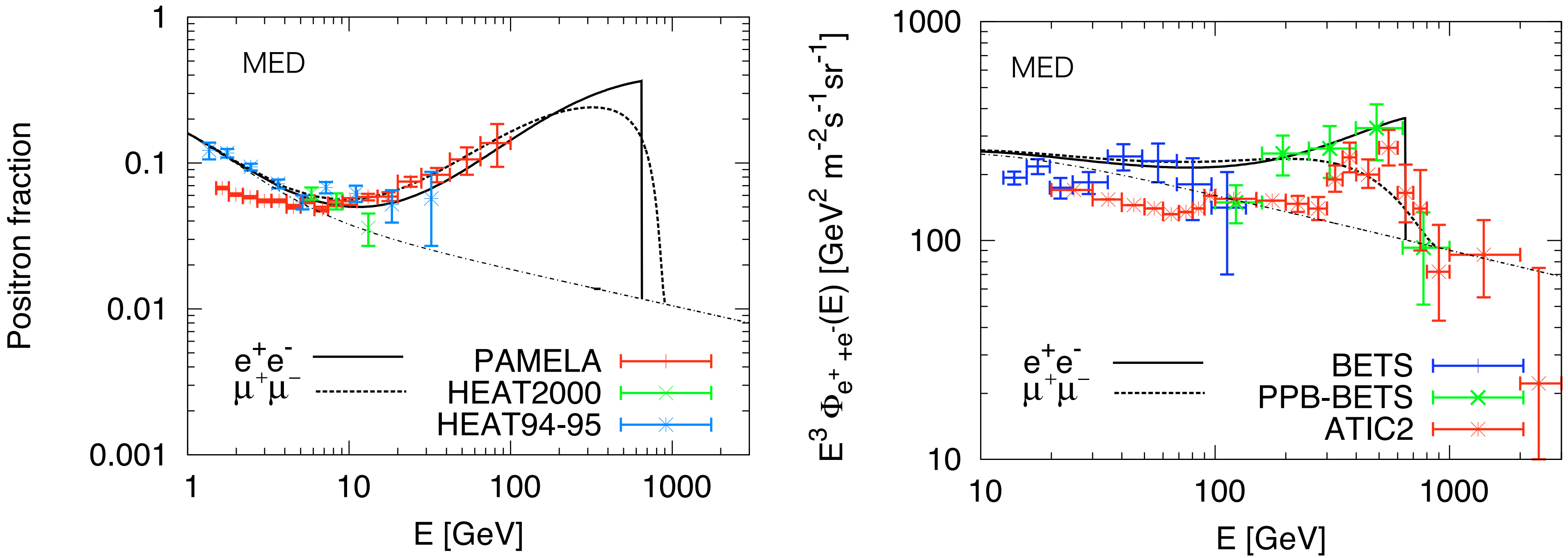
Neutralino in Supersymmetric standard model

Kaluza-Klein photon in Universal extra dimension

T-odd photon in Little Higgs model

Puzzle in cosmic rays physics

Anomalies in e+/e- fluxes measured by Pamela/ATIC might be signature of DM annihilation in our Galaxy.



$$\langle \sigma v \rangle = 5 \times 10^{-24} cm^3/s,\ \ M = 650\text{GeV}\ (\chi\chi \to e^+e^-)$$
$$\langle \sigma v \rangle = 1.5 \times 10^{-23} cm^3/s,\ \ M = 900\text{GeV}\ (\chi\chi \to \mu^+\mu^-)$$

However, effective cross section is 10^2-10^3 times larger than expected in thermal relic scenario.

Boost factors

Source term from DM annihilation in cosmic rays

$$Q(E, \vec{x}) = \frac{1}{2} n^2(\vec{x}) \langle \sigma v \rangle \frac{dN_{e^\pm}}{dE}$$

Astrophysical boost factors:

Clumpy structure in dark matter spatial distribution, $n(\vec{x})$

Particle-Physics boost factors:

- Non-thermal DM production
- Velocity-dependent annihilation cross section

typical velocity at thermal decoupling: $v \sim 0.3c$

in our galaxy: $v \sim 10^{-3}c$

➡ Breit-Wigner resonance mechanism
Sommerfeld mechanism

Non-thermal DM production

Heavy long-lived particles decay in the DM particles at $x_{nt}(\equiv M/T_{nt})$, below decoupling temperature from thermal bath, $x_f(= M/T_f)$.

$$\Omega_{\rm DM} \lesssim \Omega_{\rm DM}(\text{thermal}) \times \frac{x_{nt}}{x_f}$$

Boost Factors

$$\lesssim 0.2 \times \left(\frac{M}{200\text{GeV}}\right)\left(\frac{3\times 10^{-24}cm^3/s}{\langle\sigma v\rangle}\right)\left(\frac{100\text{MeV}}{T_{nt}}\right)\left(\frac{10}{g_\star(T_{nt})}\right)^{1/2}$$

Candidates: In some SUSY models, the long-lived gravitino/moduli produce efficiently Wino or Higgsino DM, whose annihilation cross section is larger as

$$\langle\sigma v\rangle \simeq 3\times 10^{-24}cm^3/s \times \left(\frac{M}{200(100)\text{GeV}}\right)^{-2}$$

Breit-Wigner resonance mechanism

The non-relativistic DM annihilation is enhanced due to resonance,

$$\sigma v \propto \frac{M_R^2 \Gamma_R^2}{(E_{CM}^2 - M_R^2)^2 + M_R^2 \Gamma_R^2}$$

when $M_R^2 = 4M^2(1-\delta) \quad (|\delta| \ll 1)$

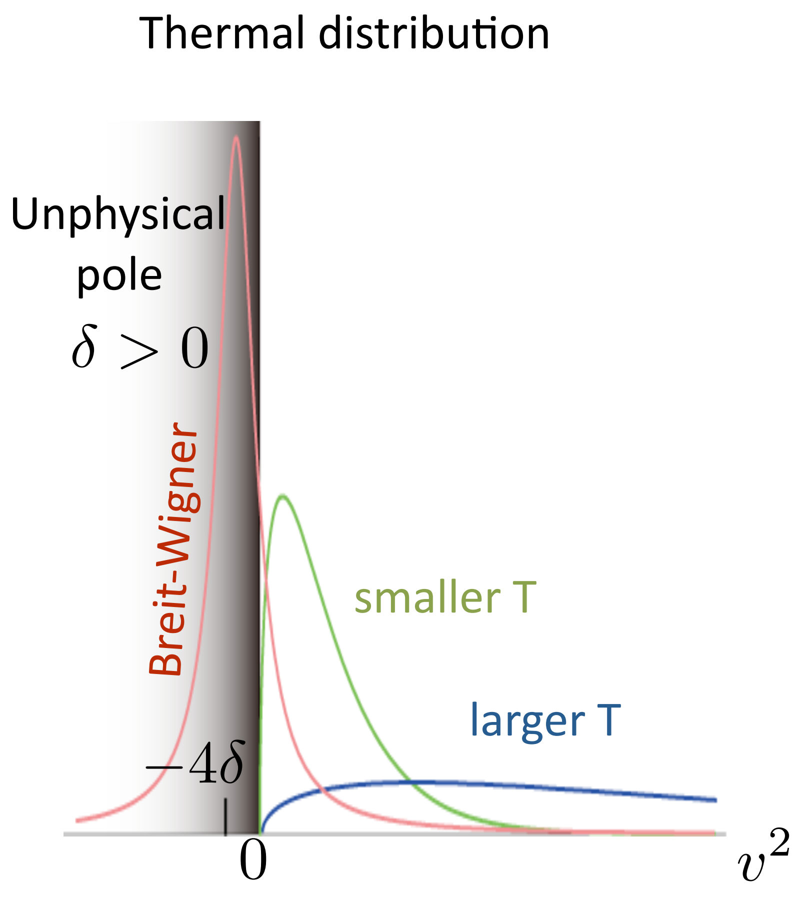
$$E_{CM}^2 \simeq 4M^2 + M^2 v^2 \quad (v^2 \ll 1)$$

If $\delta > 0$, the thermal-averaged cross section $\langle \sigma v \rangle$ becomes larger at lower temperature ($x \lesssim x_a (\equiv 1/\max[\delta, \gamma])$)

(Ibe, Murayama, Yanagida)

$$\langle \sigma v \rangle \simeq (x/x_a)^2 \times \langle \sigma v \rangle_{T=0}$$

Here, $x \equiv M/T$ and $\gamma \equiv \Gamma_R / M_R$.



Breit-Wigner resonance mechanism

Annihilation is maintained even after 'decoupling" ($x = x_f(\sim 1/20)$)

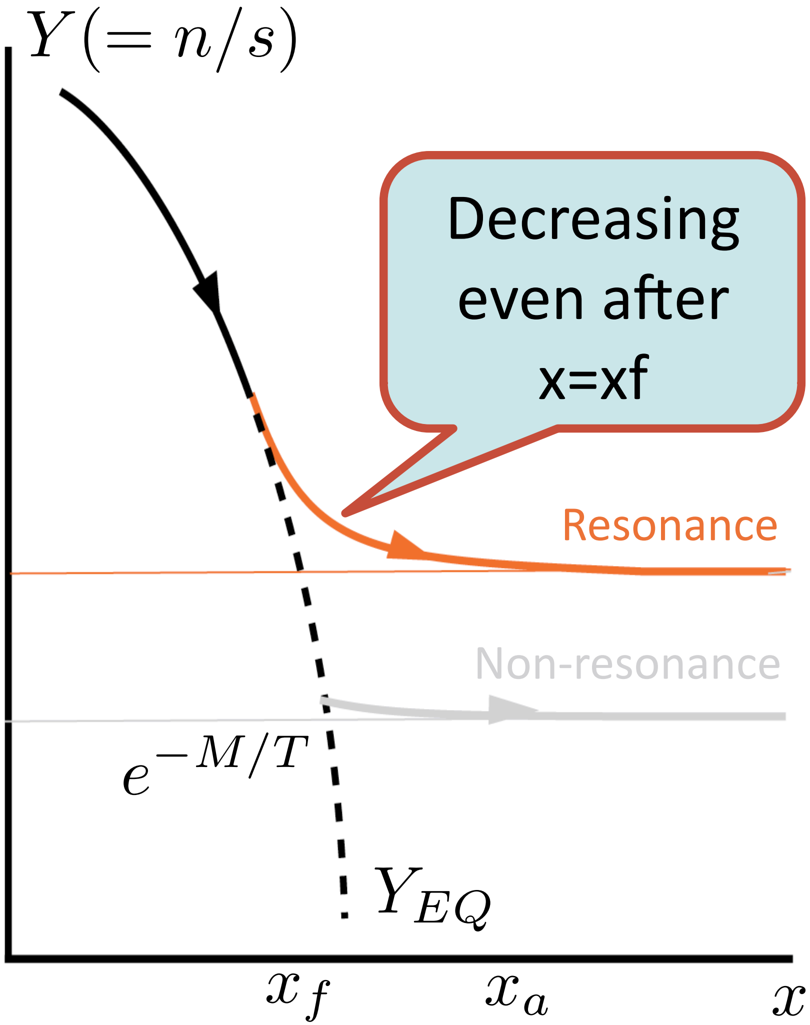
$$\frac{dY}{dx} = -\frac{s\langle\sigma v\rangle}{xH} \propto -Y^2$$

$$(x_f \lesssim x \lesssim x_a)$$

$$\Omega_{\rm DM} \simeq \Omega_{\rm DM}(\text{non-res}) \times \frac{x_a}{x_f}$$

Boost Factors

$$BF \sim \frac{\max[\delta,\gamma]^{-1}}{x_f}$$

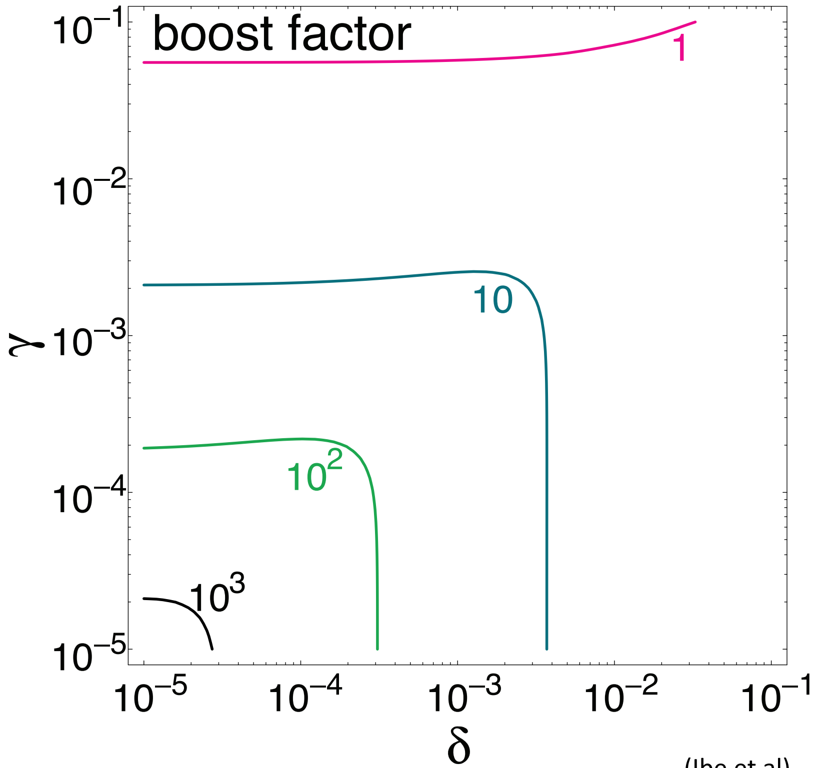


Breit-Wigner resonance mechanism

In order to get a large boost factor (~100 -1000), we need DM particle pair close to the resonance with narrow width.

1) How to produce unphysical resonance close to threshold?
2) How to suppress width?

Can we suppress annihilation after "decoupling"?



(Ibe et al)

$$M_R^2 = 4M^2(1-\delta)$$
$$\gamma \equiv \Gamma_R / M_R$$

Sommerfeld mechanism

Long-distance attractive forces modify wave function of the DM two-bodies state, and enhances the annihilation cross section.

Radial Shroedinger equation for S-wave wave function $\Psi(r)(=\psi(r)/r)$

$$\frac{1}{M}\psi''(r) - V(r)\psi(r) = -Mv^2\psi(r)$$

Annihilation cross section is enhanced (suppressed) by a factor

$$S \equiv |\psi(\infty)/\psi(0)|^2$$

(Here, boundary condition is $\psi'(\infty) = iMv\,\psi(\infty)$ [plane wave].)

When long-distance force is Coulomb-like ($V = -\alpha/r$)

$$S = \frac{\pi\alpha/v}{1 - e^{-\pi\alpha/v}}$$

→ Boost Factors $S \simeq \pi\alpha/v \; (v \ll \alpha)$ $\quad (Mv^2 \ll \alpha^2 M)$

Sommerfeld mechanism

Yukawa potential:

$$V(r) = -\frac{\alpha}{r} e^{-m_\phi r}$$

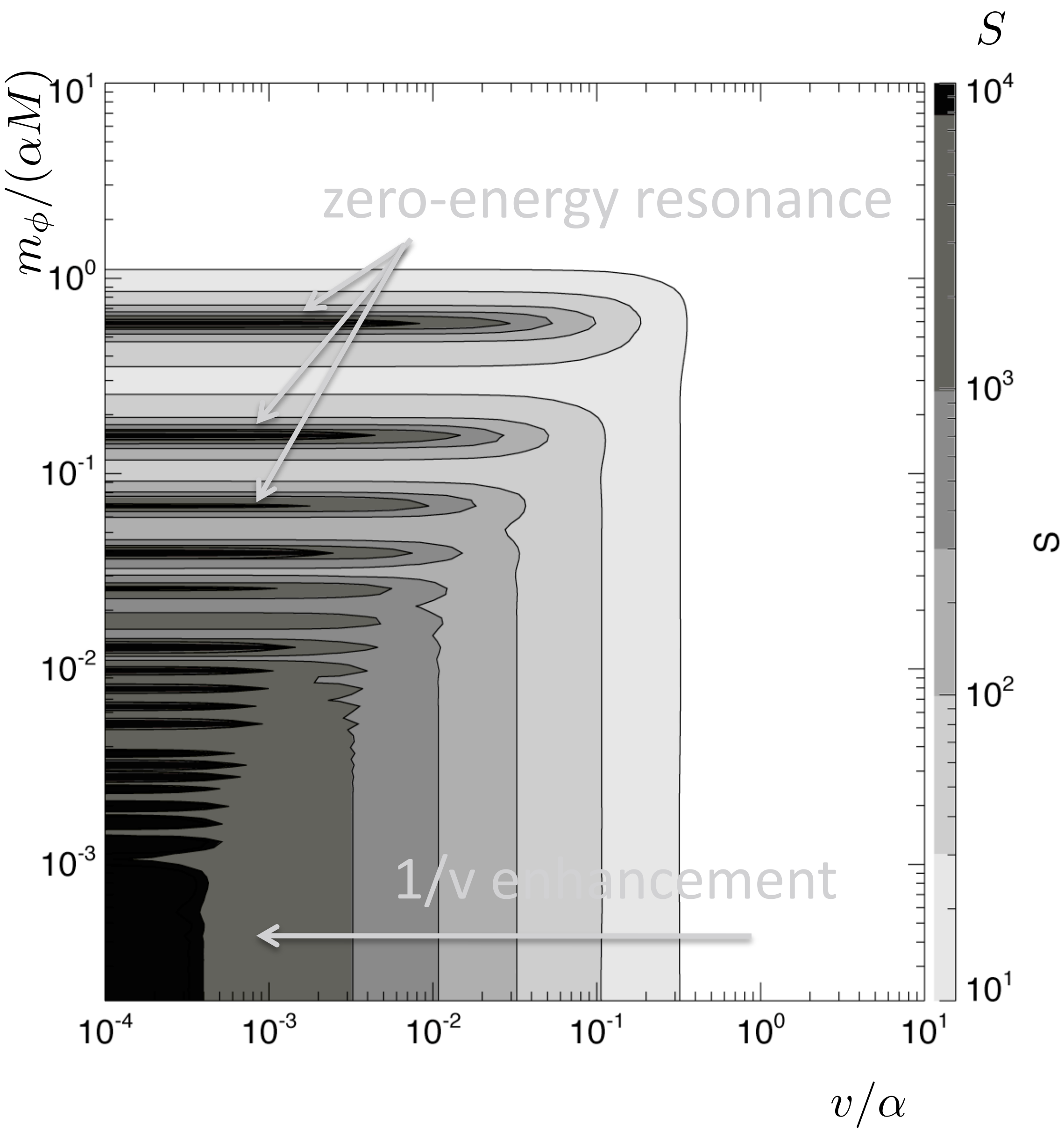
Origin:

massive particle exchange

1,electroweak gauge bosons

2,hidden gauge bosons

3, hidden scalar bosons



(Arkani-hamed et al)

1/v enhancement

Yukawa potential:

$$V(r) = -\frac{\alpha}{r} e^{-m_\phi r}$$

When $\alpha^2 M \gg M v^2 \gg \alpha m_\phi$, 1/v enhancement is induced.

It is saturated if $v \lesssim m_\phi / M$.

Pamela/ATIC anomalies are explained when

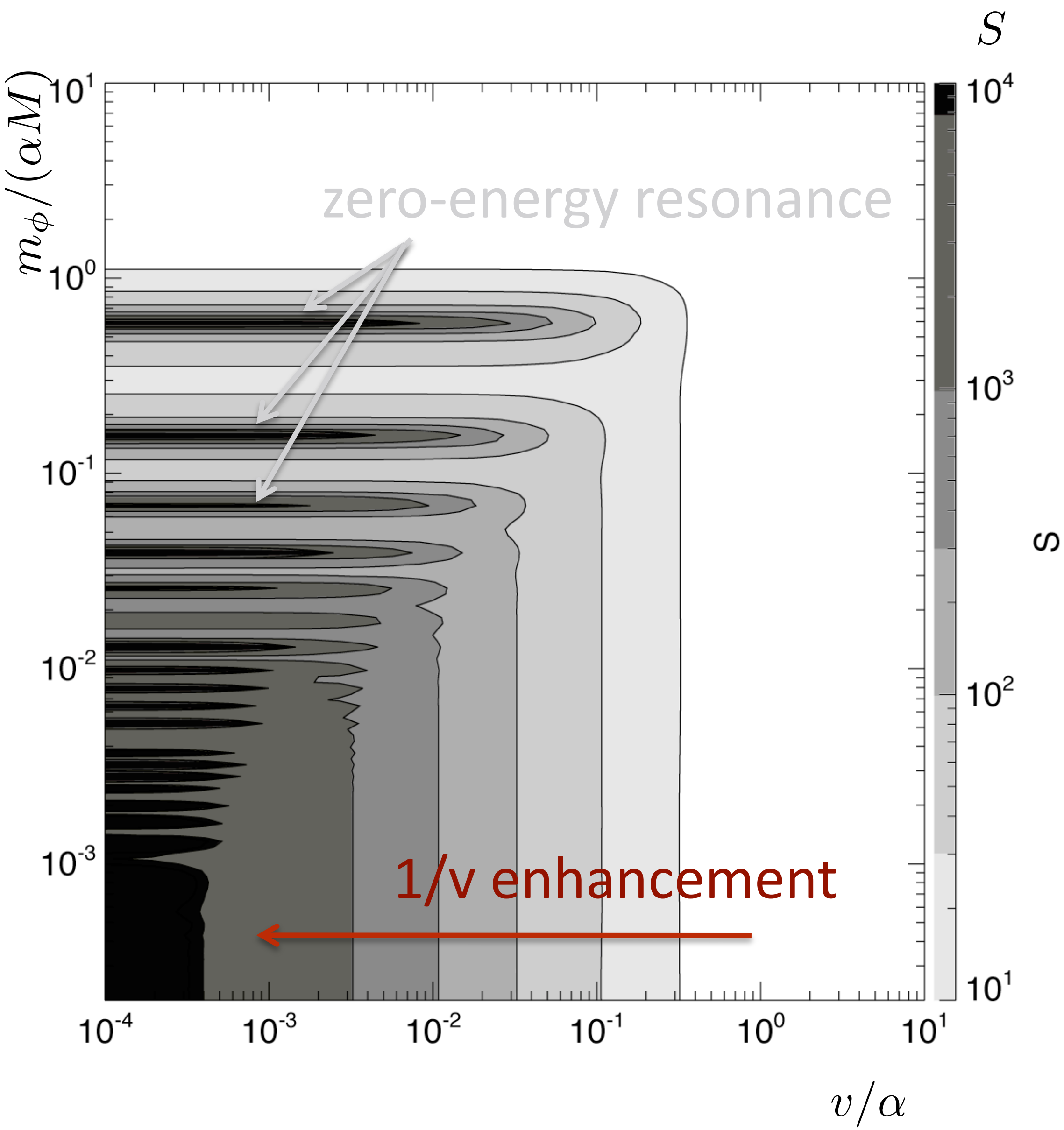
$$m_\phi \lesssim 1\text{GeV}$$

$$\alpha \sim 1/30$$

$$M \sim 1\text{TeV}$$

since $v \sim 10^{-3}$.

(Arkani-hamed et al, and also many papers)



(Arkani-hamed et al)

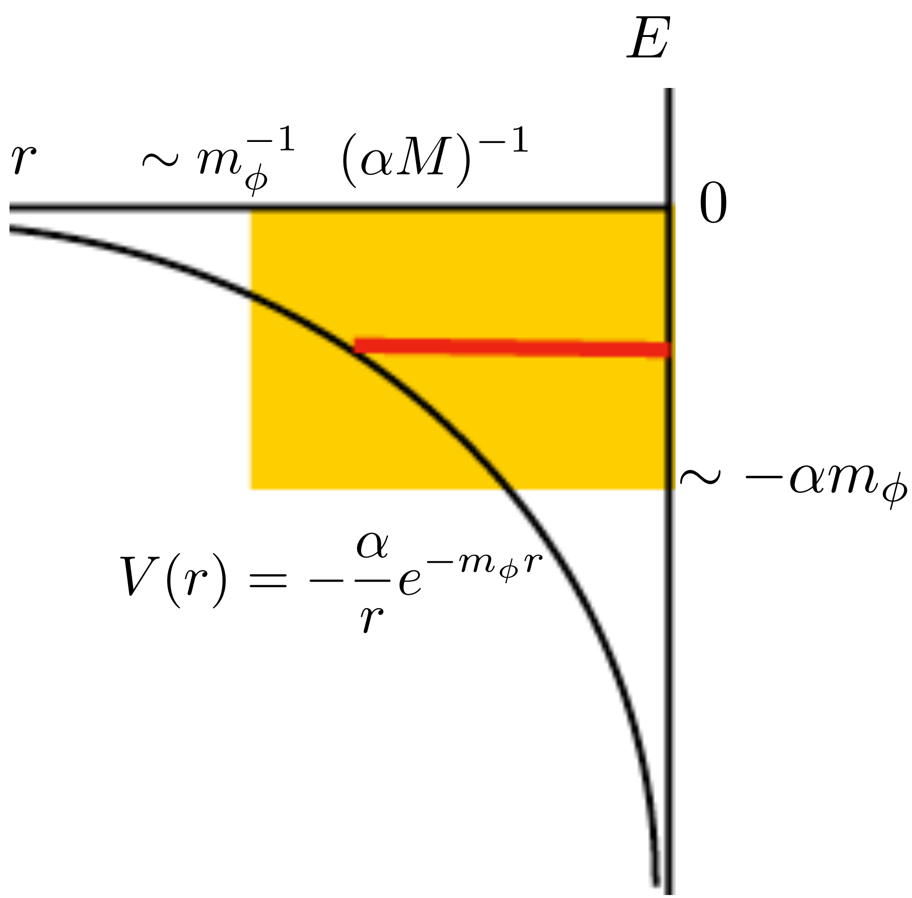
Zero-energy resonance

When $\alpha M \gtrsim m_\phi$, bound state(s) appear in the two-body DM particle system, and if $\alpha m_\phi \gg M v^2$, cross section is enhanced by the resonance.

When the binding energy is close to zero (zero-energy resonance), the cross section is further enhanced as

$$\sigma v \propto 1/v^2$$

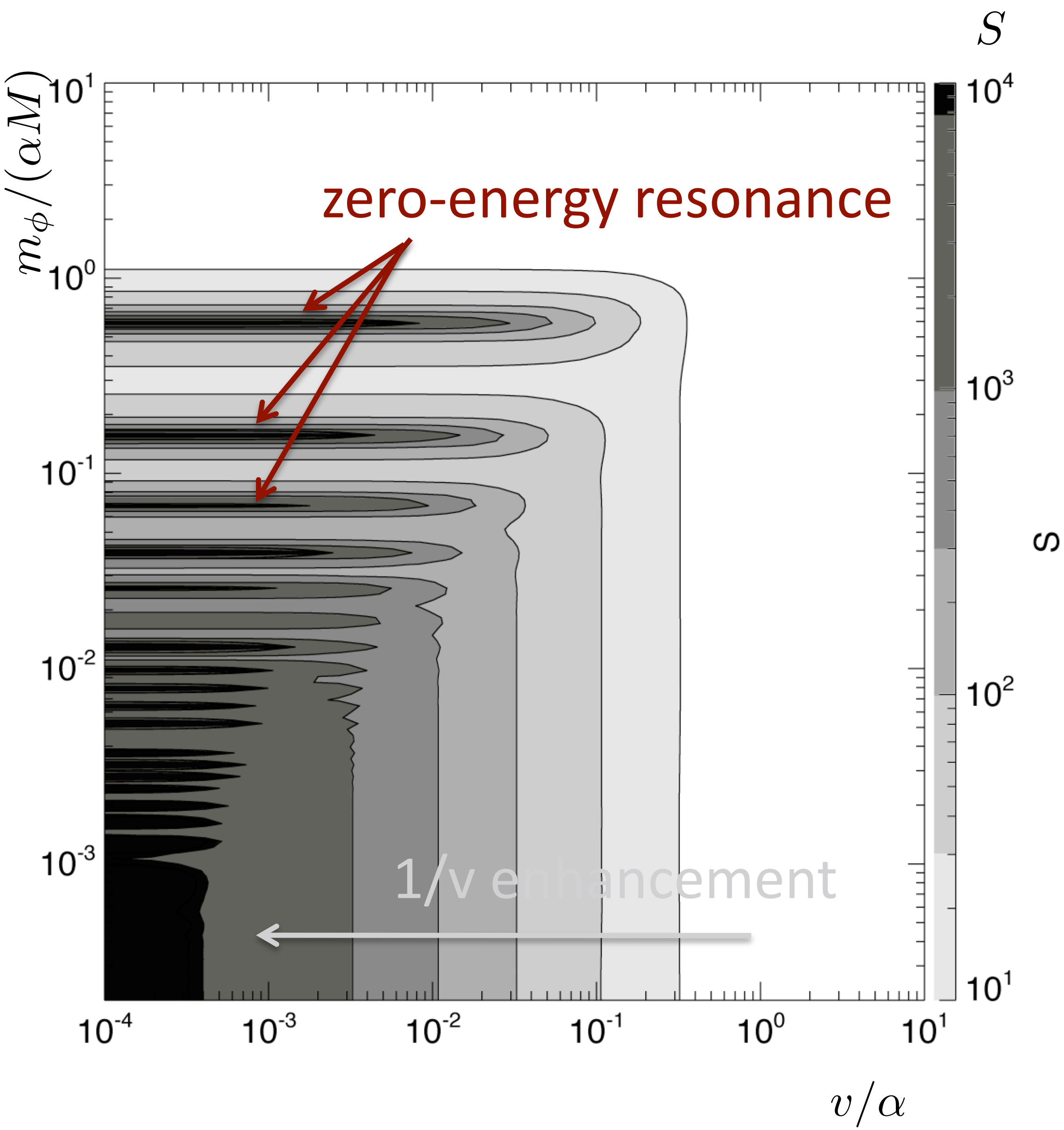
(JH, Matsumoto, Nojiri)



Zero-energy resonance

Pamela/ATIC anomalies are explained when

$$m_\phi \lesssim 100\text{GeV}$$
$$\alpha \sim 1/30$$
$$M \sim 1\text{TeV}$$



(Arkani-hamed et al)

Sommerfeld mechanism

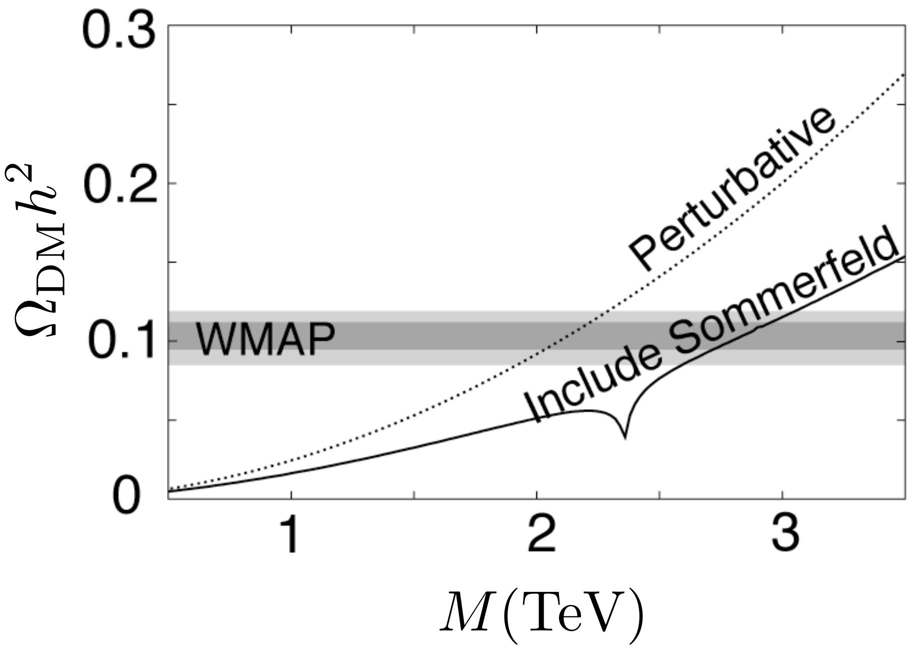
Annihilation after "decoupling" is suppressed compared with Breit-Wigner resonance mechanism.

$\langle \sigma v \rangle \propto v^{-1}$ (1/v enhancement)

$\langle \sigma v \rangle \propto v^{-2}$ (zero-energy resonance)

$\langle \sigma v \rangle \propto v^{-4}$ (Breit-Wigner resonance)

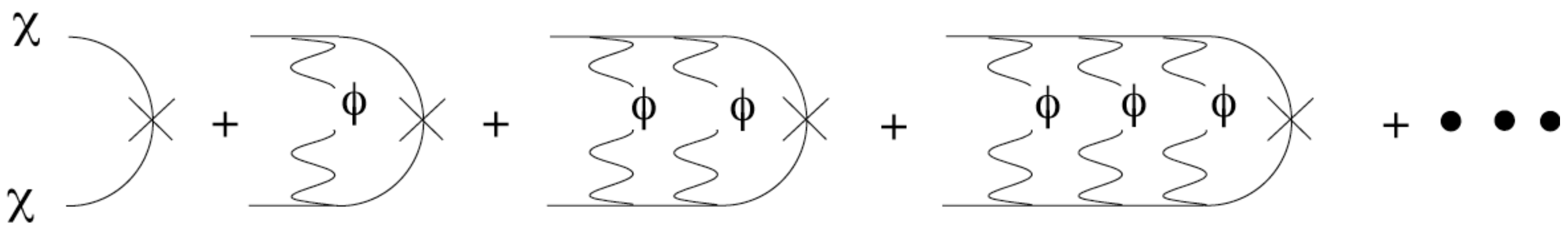
Thermal relic abundance of SU(2) triplet fermion DM



(JH, Matsumoto, Nagai, Saito, Senami)

Sommerfeld mechanism

Enhancement comes from ladder-diagrams in perturbative expansion.



$$\sim A_0$$

$$\sim A_0 \left(\frac{\alpha}{v}\right) \qquad \sim A_0 \left(\frac{\alpha}{v}\right)^2 \qquad \sim A_0 \left(\frac{\alpha}{v}\right)^3 \qquad (m_\phi \to 0)$$

$$\sim A_0 \left(\frac{\alpha M}{m_\phi}\right) \qquad \sim A_0 \left(\frac{\alpha M}{m_\phi}\right)^2 \qquad \sim A_0 \left(\frac{\alpha M}{m_\phi}\right)^3 \qquad (v \to 0)$$

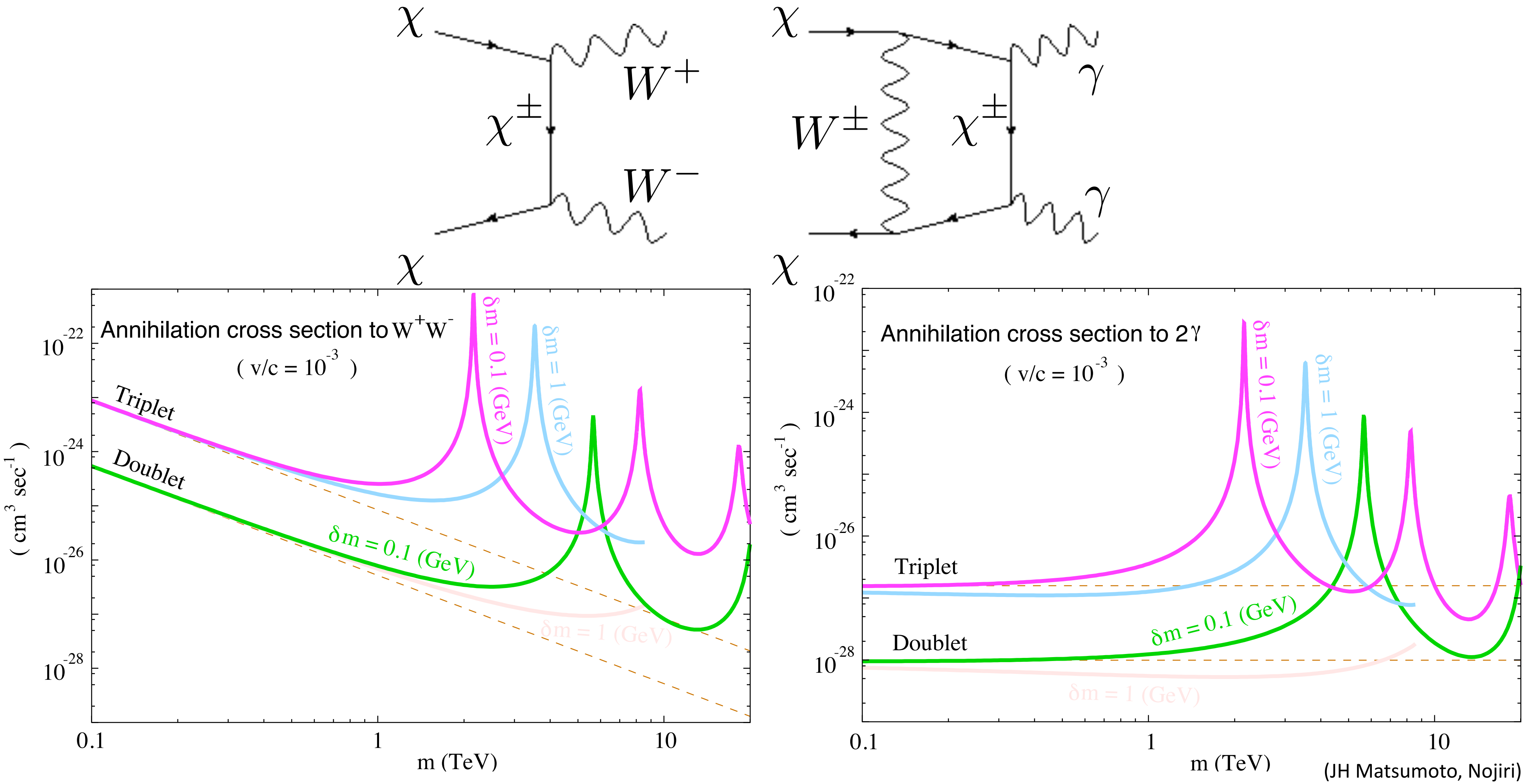
Enhancement factor for the l-th partial wave cross section is

$$S \simeq \frac{2\pi}{(l!)^2} \left(\frac{\alpha}{v}\right)^{2l+1} \quad (m_\phi \to 0)$$

(Iengo)

Sommerfeld mechanism by electroweak interaction

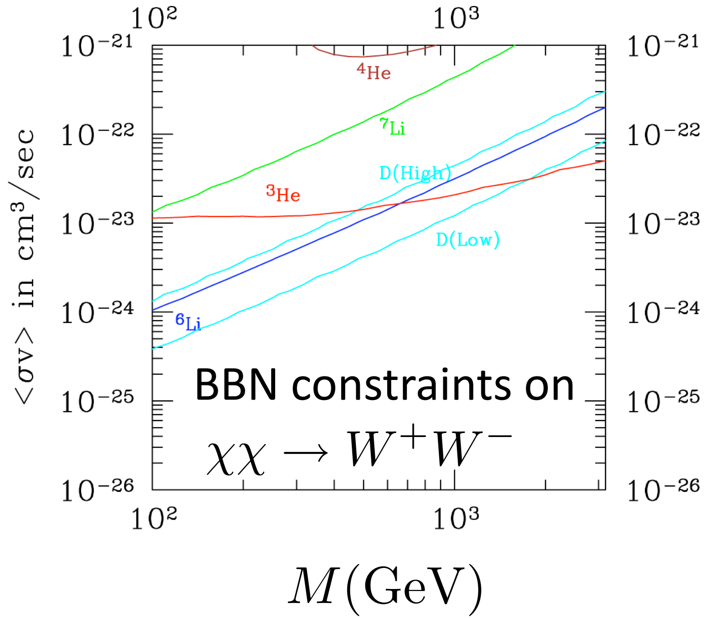
The DM particle is neutral so that annihilation into two photons is one-loop process. However, the cross section becomes comparable to that into W boson pairs due to the Sommerfeld mechanism.

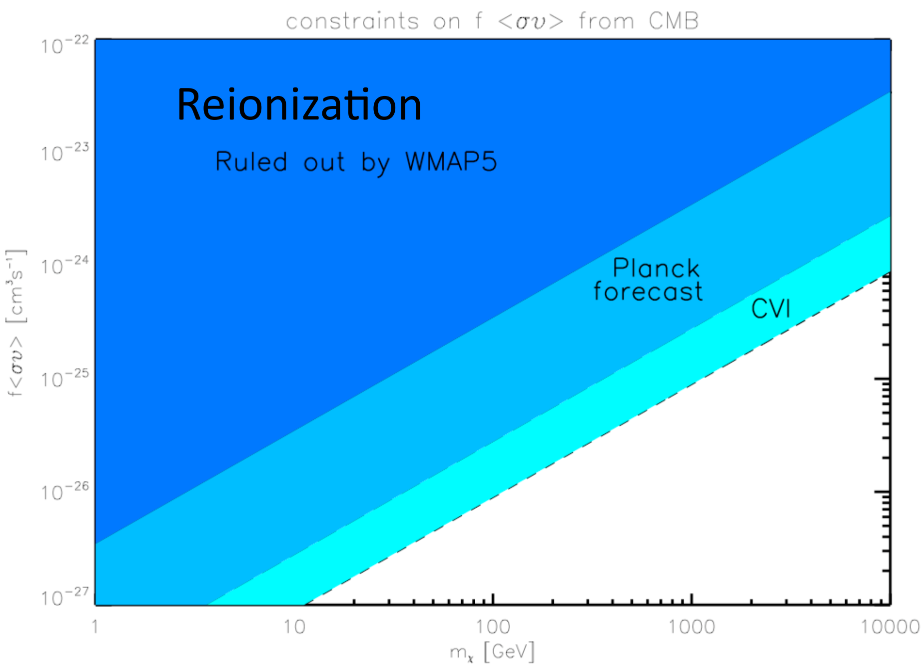


(JH Matsumoto, Nojiri)

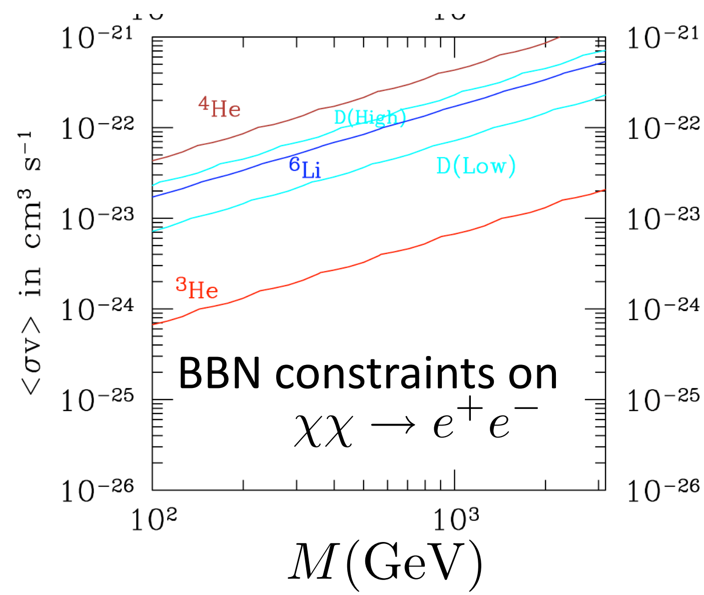
Constraints on particle-physics boost factors

EM/hadronic injections to thermal bath/CMB are constrained from Big-Bang Nucleosynthesis (BBN) and Reionization. Constraints look marginal to the Pamela/ATIC anomalies.





(Gallia,Ioccoc, Bertone, Melchiorri)



(JH, Kawasaki, Kohri, Moroi, Nakayama)

Summary of my Talk

In this talk, I review particle-physics boost factors. It may be needed to explain the recent observed anomalies in cosmic rays by DM annihilation. The representative mechanisms for particle-physics boost factor are

- Non-thermal DM production
- Breit-Wigner resonance mechanism
- Sommerfeld mechanism

Now many challenges to construct realistic models are devoted.

In order to check mechanisms for particle-physics boost factor, we have to check various consistencies among cosmic ray observations, BBN, and reionization history.