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Particle Physics at Crossroads

# Parity symmetry and WIMP

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# Role of symmetry for DM

- \* Predict the existence of DM

Peccei-Quinn symmetry  $\longrightarrow$  QCD axion

Supersymmetry + R-Parity  $\longrightarrow$  Lightest SUSY particle

- \* Constrain the properties of DM (sector)

Peccei-Quinn symmetry  $\longrightarrow$   $\frac{\alpha}{8\pi} \frac{a}{f_a} F\tilde{F}, \frac{\partial_\mu a}{f_a} \bar{e}\gamma^\mu\gamma^5 e$   
 $a \rightarrow a + \delta$

Supersymmetry

boson  $\longleftrightarrow$  fermion

$\longrightarrow$  Predictions on interactions  
Existence of colored particles

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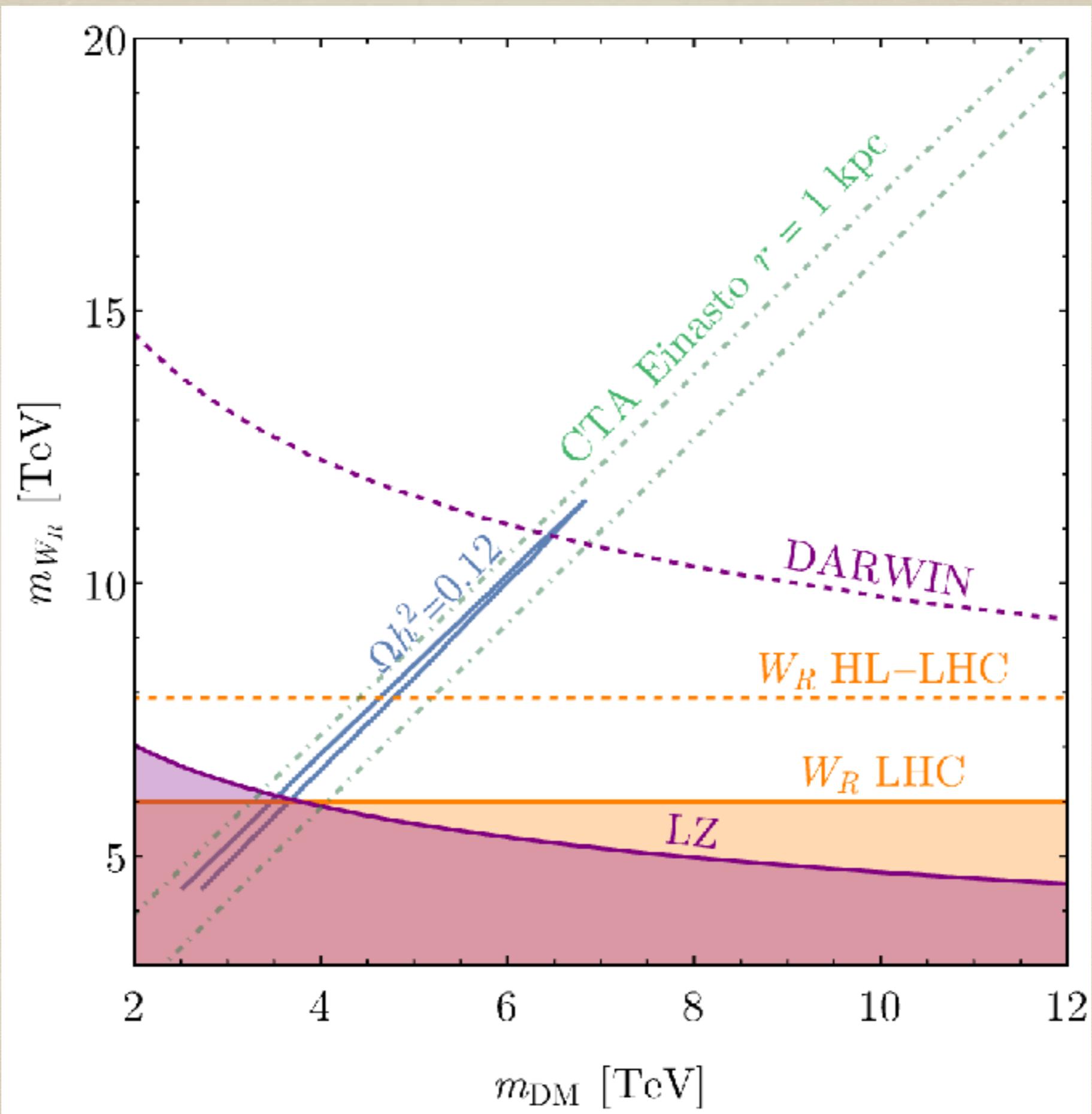
- \* **Constrain the properties of DM (sector)**

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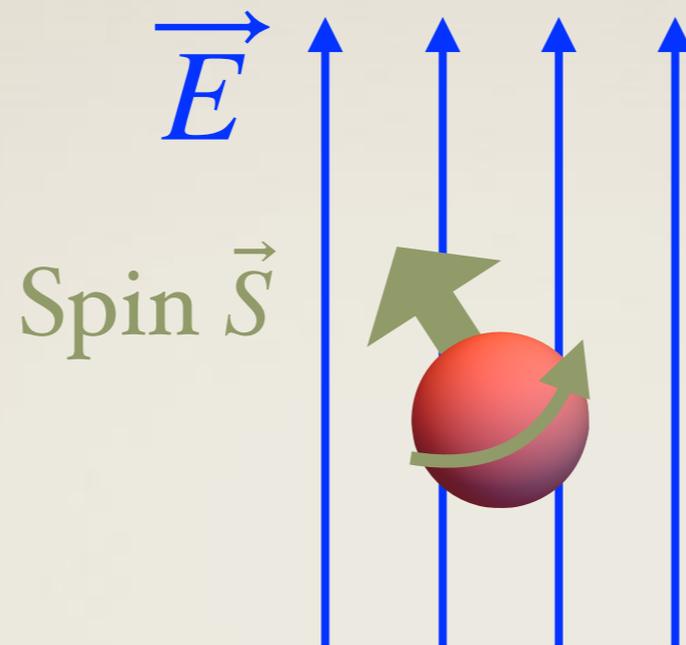
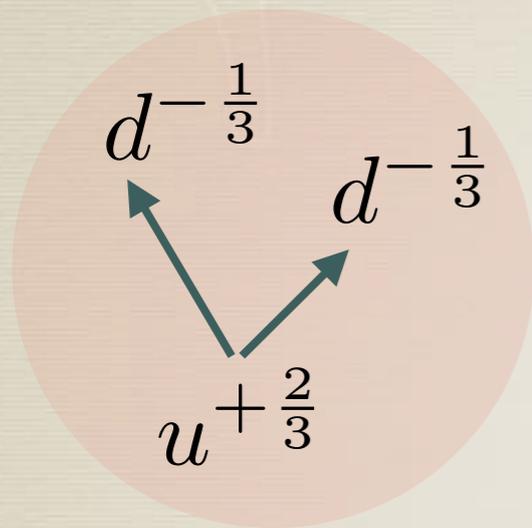


# Outline

Today, we focus on Parity symmetry  
and associated gauge symmetry

- \* The strong CP problem and Parity
- \* WIMP dark matter and Parity
- \* Outlook and summary

# Strong CP problem



$$H = d_n \vec{E} \cdot \vec{S}$$

$$d_n/e \sim 0.1 \text{ fm} \sim 10^{-14} \text{ cm} ?$$

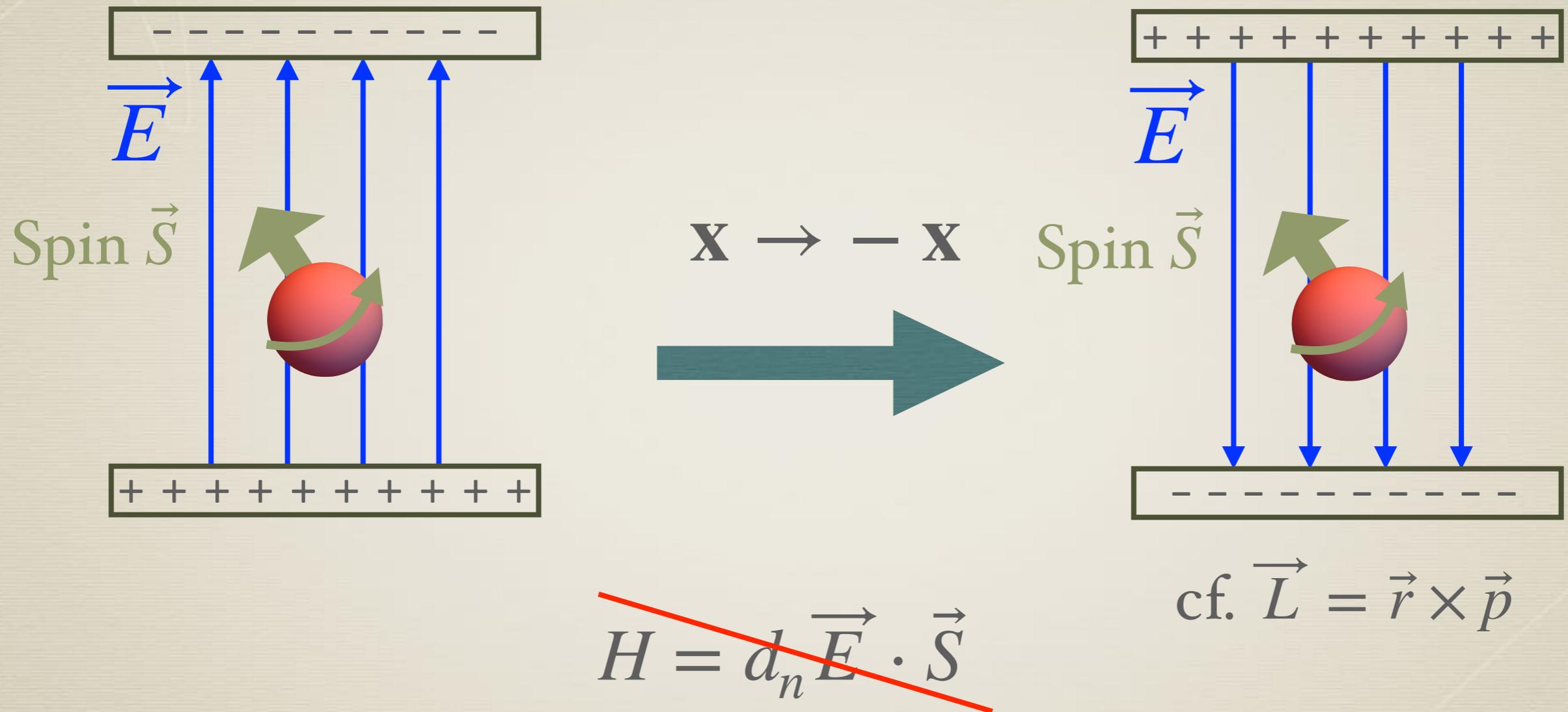
Experiments say that  $d_n/e < 2.9 \times 10^{-26} \text{ cm}$

Baker et.al (2006)

The strong interaction obeys the CP symmetry,  
which is violated in weak interaction

**Strong CP problem** 't Hooft (1976)

# Parity symmetry



# Parity symmetry

At the microscopic level,

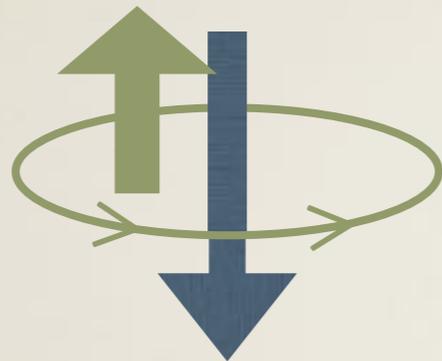


# Weak interaction

At the microscopic level,

Lee and Yang (1956)  
Wu (1956)

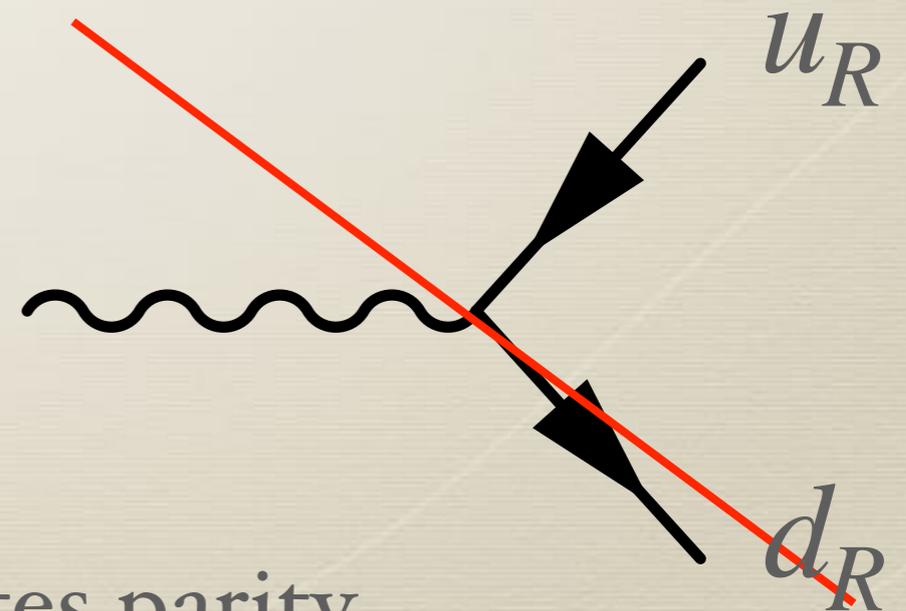
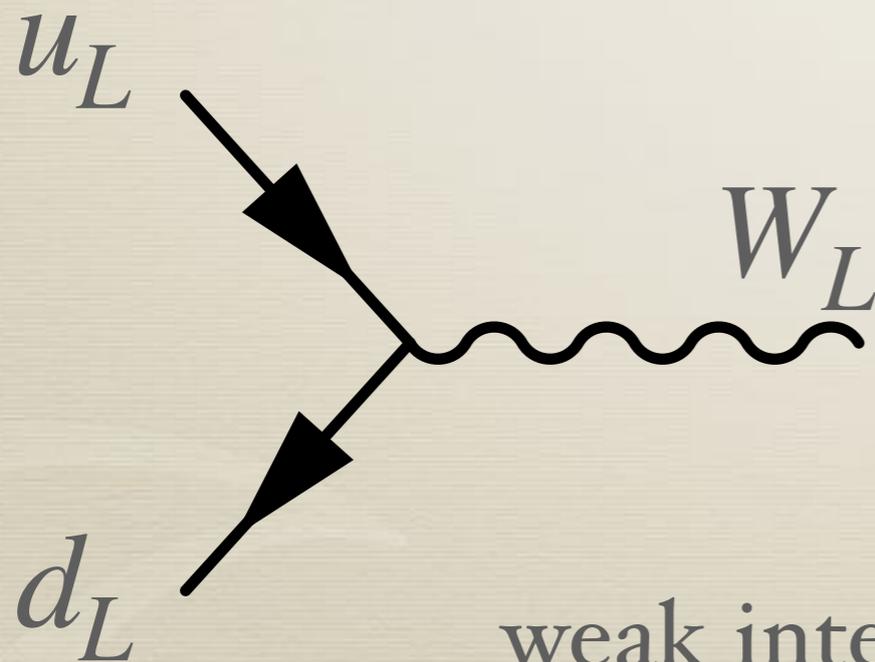
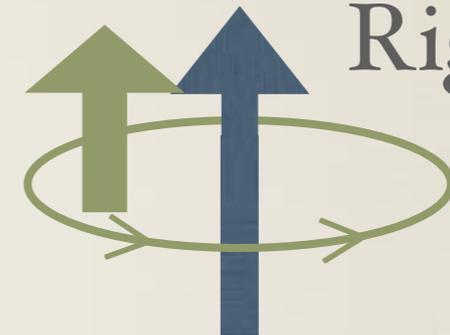
Left-handed



Parity



Right-handed



weak interaction violates parity

# Spontaneously broken parity

Introduce a new gauge boson

Mohapatra and Senjanovic (1978), Beg and Tsao (1978)  
D'Agnolo and Hook (2015), Hall and KH (2018)  
Craig, Garcia Garcia, Koszegi, and McCune (2020)  
Hisano, Kitahara, Osamura and Yamada (2023)



and give a large mass to it  
by breaking  $SU(2)_R$  at high energy scale

Weak interaction violates parity,  
but strong interaction does not

# Spontaneously broken parity

Babu and Mohapatra (1989)



(\*For specialists : the Higgses have no physical phase degree of freedom and the higgs vev does not introduce CP phases)

# Fine-tuning?

We need  $\langle H_R \rangle \gg \langle H_L \rangle$  to make  $W_R$  heavy

$$V = \lambda \left( |H_L|^2 - v_R^2 \right)^2 + \lambda \left( |H_R|^2 - v_R^2 \right)^2 \quad : \text{parity symmetric}$$

$$+ \Delta m^2 \left( |H_L|^2 - |H_R|^2 \right) \quad : \text{spontaneous parity breaking in another sector} \\ \text{(e.g. pure Yang-Mills with } \theta = \pi \text{)}$$

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$$\frac{v_R^2}{\Lambda_{\text{cut}}^2} \times \frac{v_L^2}{v_R^2} = \frac{v_L^2}{\Lambda_{\text{cut}}^2}$$

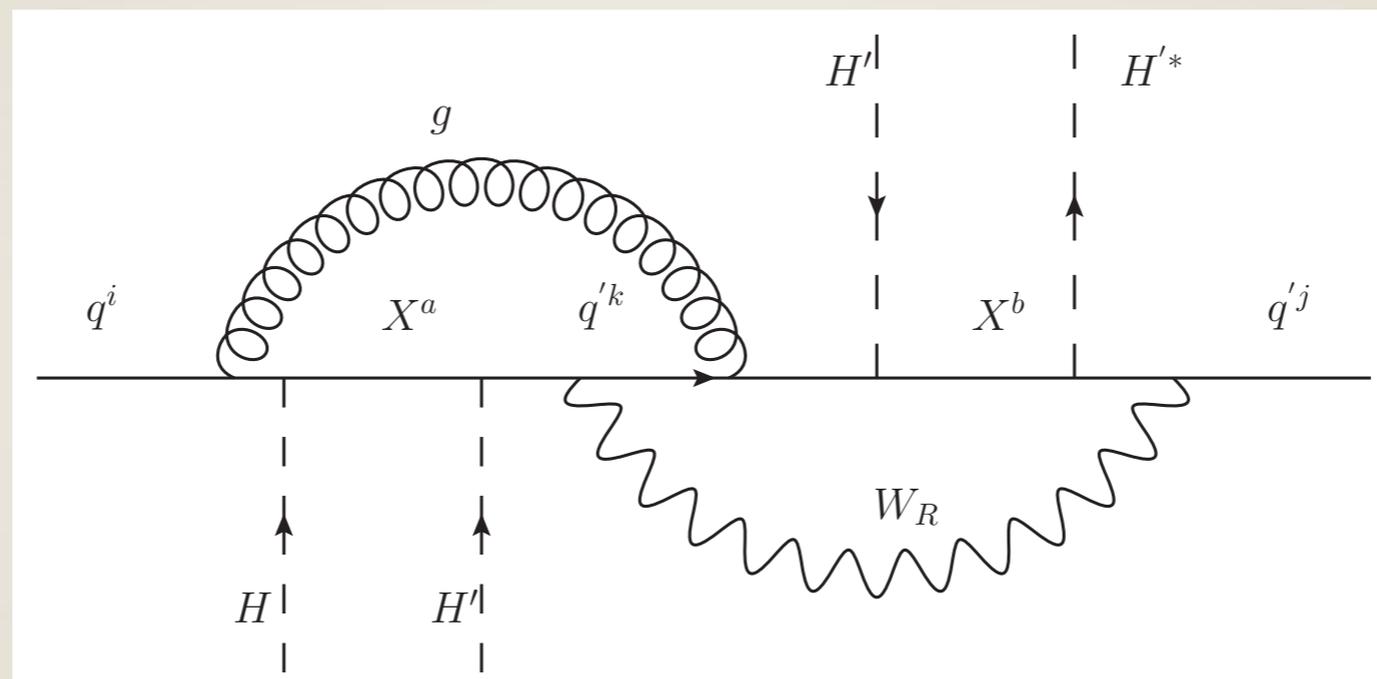
Despite the intermediate scale  $v_R$ ,

same as that of standard model

# Non-zero strong CP phase

Hall, KH (2018)

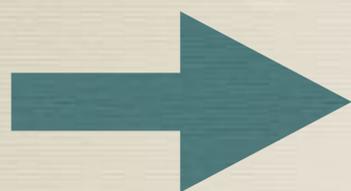
Hisano, Kitahara, Osamura and Yamada (2023)



$$\theta \sim 10^{-11} \times \text{flavor model dependent factor}$$

# Impacts of parity

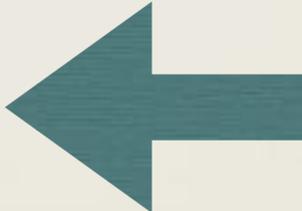
Parity  $\mathbf{x} \rightarrow -\mathbf{x}$  is a part of space-time symmetry



Parity constrains the interactions and masses of anything living in space time  
(like SUSY)

- \* Dark matter
- \* Matter-antimatter asymmetry of the universe
- \* Neutrino mass generation
- \* ...

# Outline

- \* The strong CP problem and Parity
- \* Dark matter and parity 
- \* Outlook and summary

# Open questions about DM

- \* Is it a particle or a macroscopic object (ex. black holes)?
- \* If a particle, what are its particle properties?  
spin, mass, interactions, ...
- \* How was  $\rho_{\text{DM}} \simeq 1 \text{ GeV}/\text{m}^3$  produced in the early universe?
- \* How can we detect dark matter?
- \* ...

# Dark matter by weak interaction

\* How was  $\rho_{\text{DM}} \simeq 1 \text{ GeV}/\text{m}^3$  produced in the early universe?

Electromagnetic

Strong

Weak

# Dark matter by weak interaction

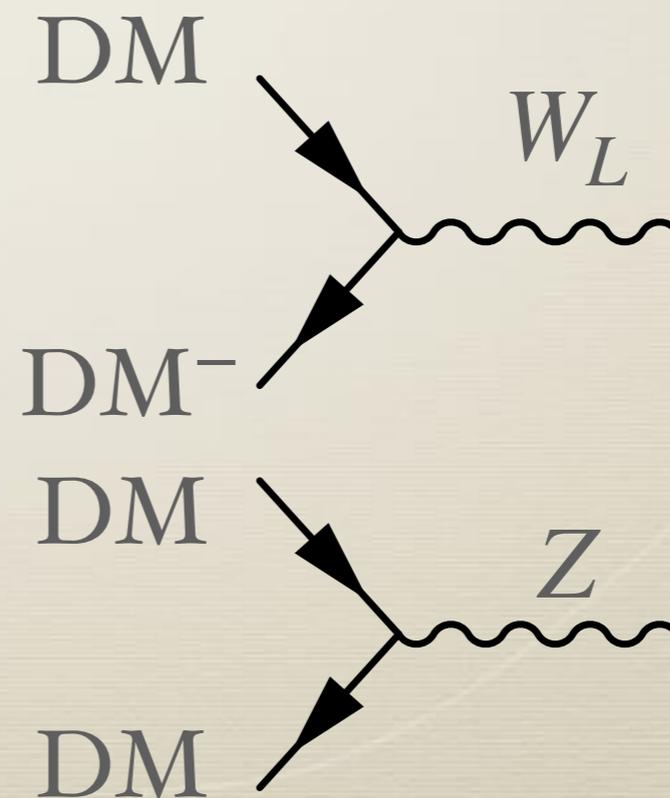
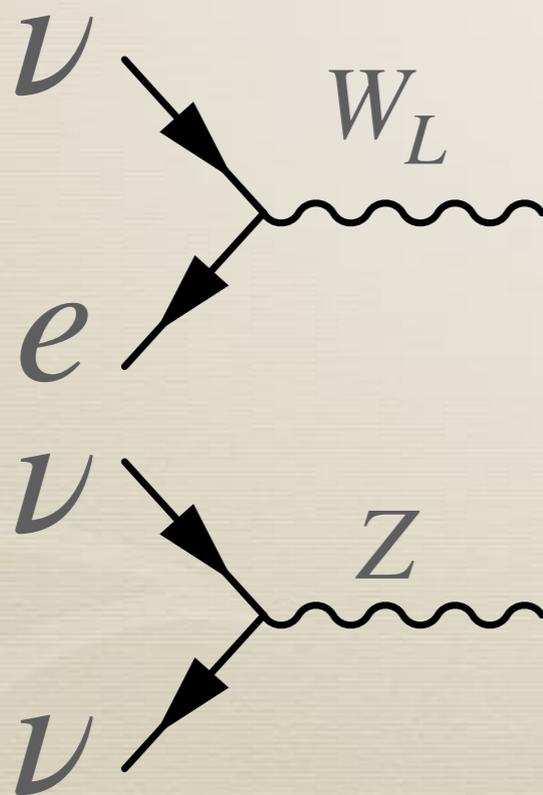
\* How was  $\rho_{\text{DM}} \simeq 1 \text{ GeV}/\text{m}^3$  produced in the early universe?

~~Electromagnetic~~

~~Strong~~

Weak

Indeed, a massive neutrino-like particle will not have electromagnetic or strong interactions

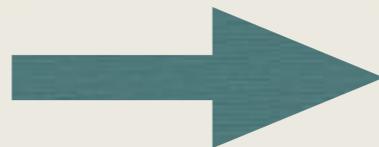


# Sharp prediction

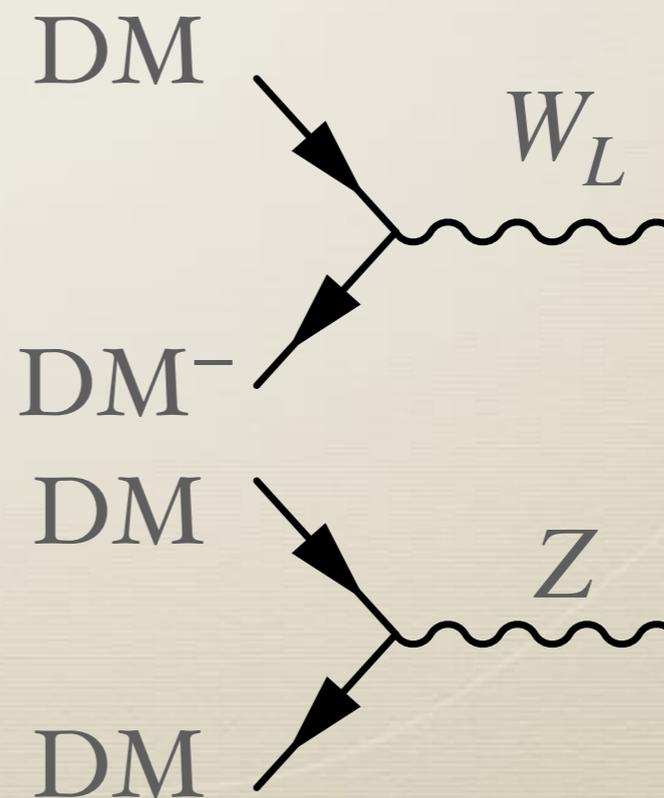
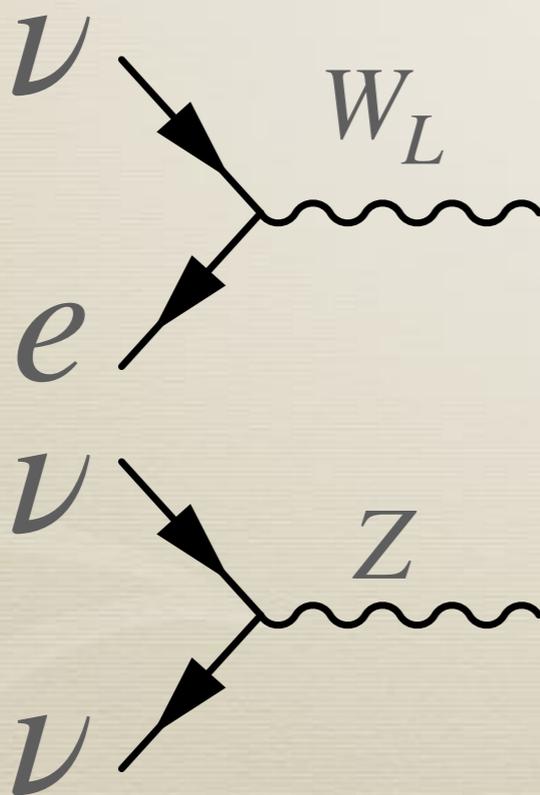
The strength of weak interaction is fixed  
The only free parameter is the DM mass  $m_{\text{DM}}$

Freeze-out mechanism

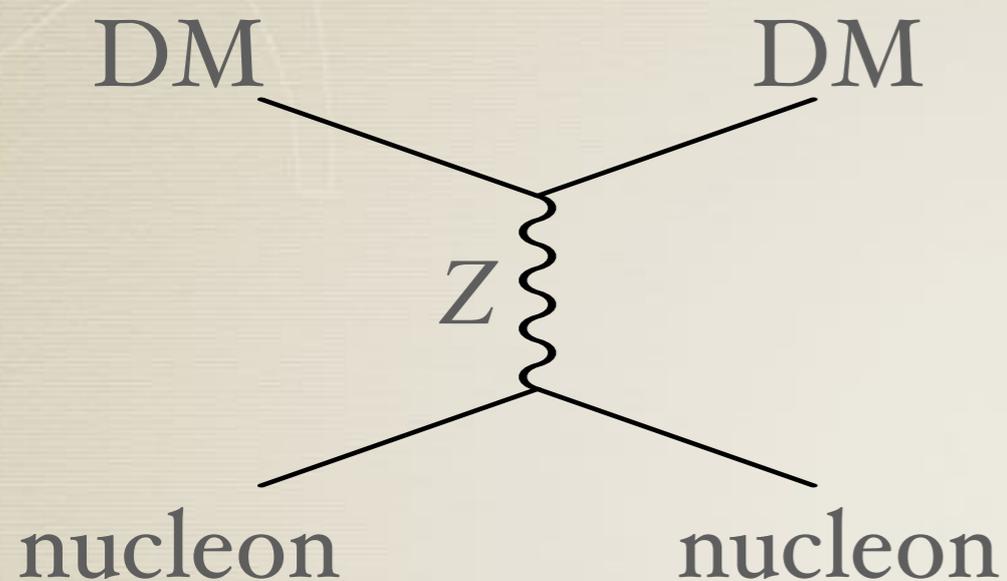
$$\rho_{\text{DM}} \simeq 1 \text{ GeV}/\text{m}^3$$



$$m_{\text{DM}} \simeq 1 \text{ TeV}$$

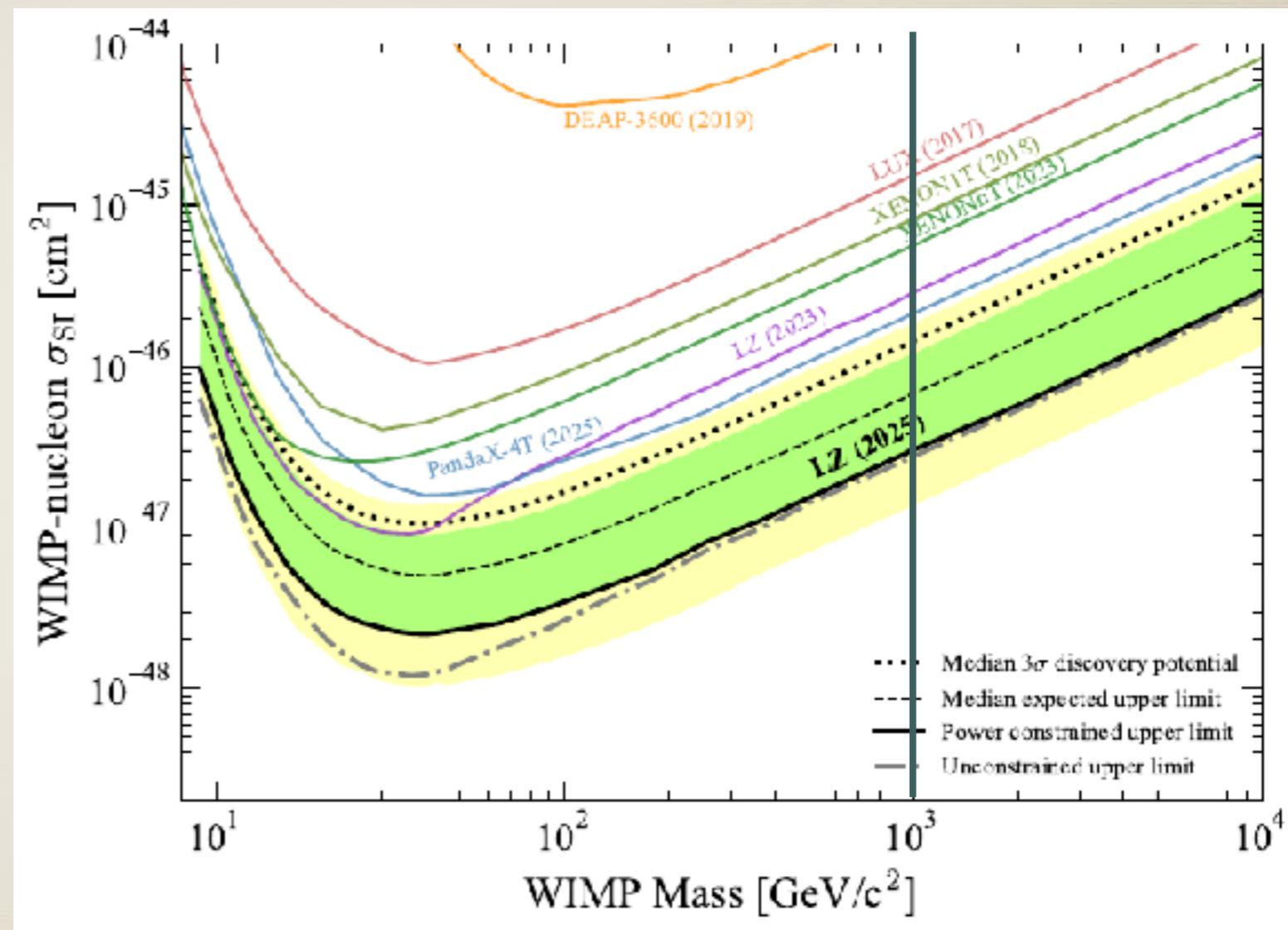


# Direct detection



Cross section

$$\sigma \sim 10^{-38} \text{cm}^2$$

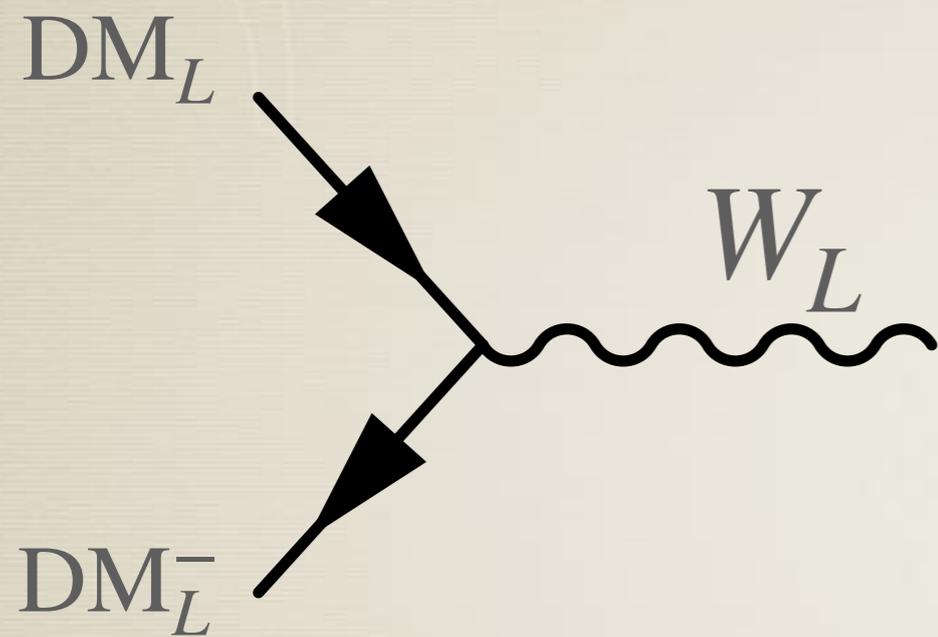


The minimal model is excluded

(Way out: add a singlet with a Majorana mass, mix it with DM, ...)

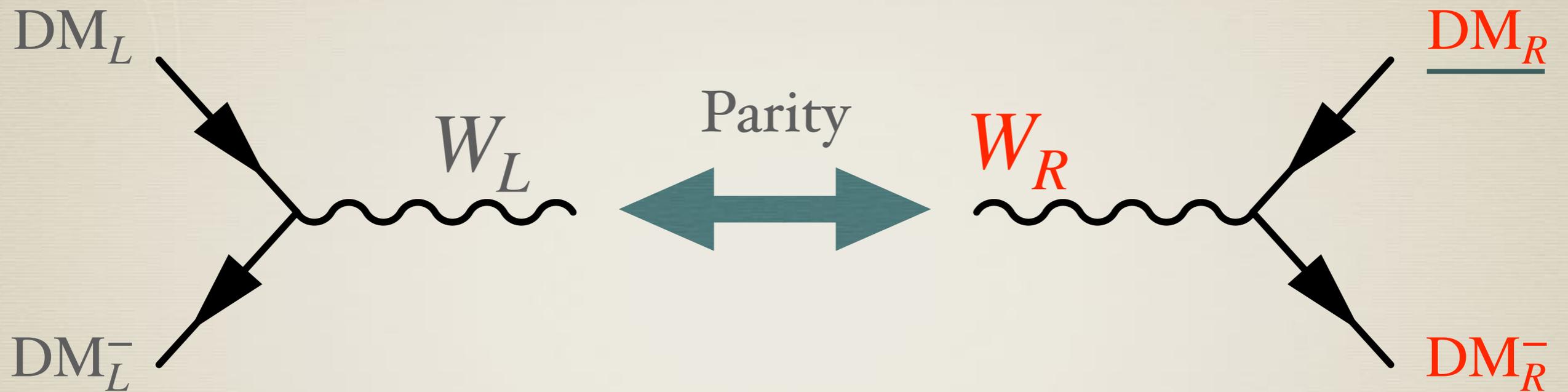
# Parity and dark matter

Baldwin, KH and Wang (2025)



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Baldwin, KH and Wang (2025)

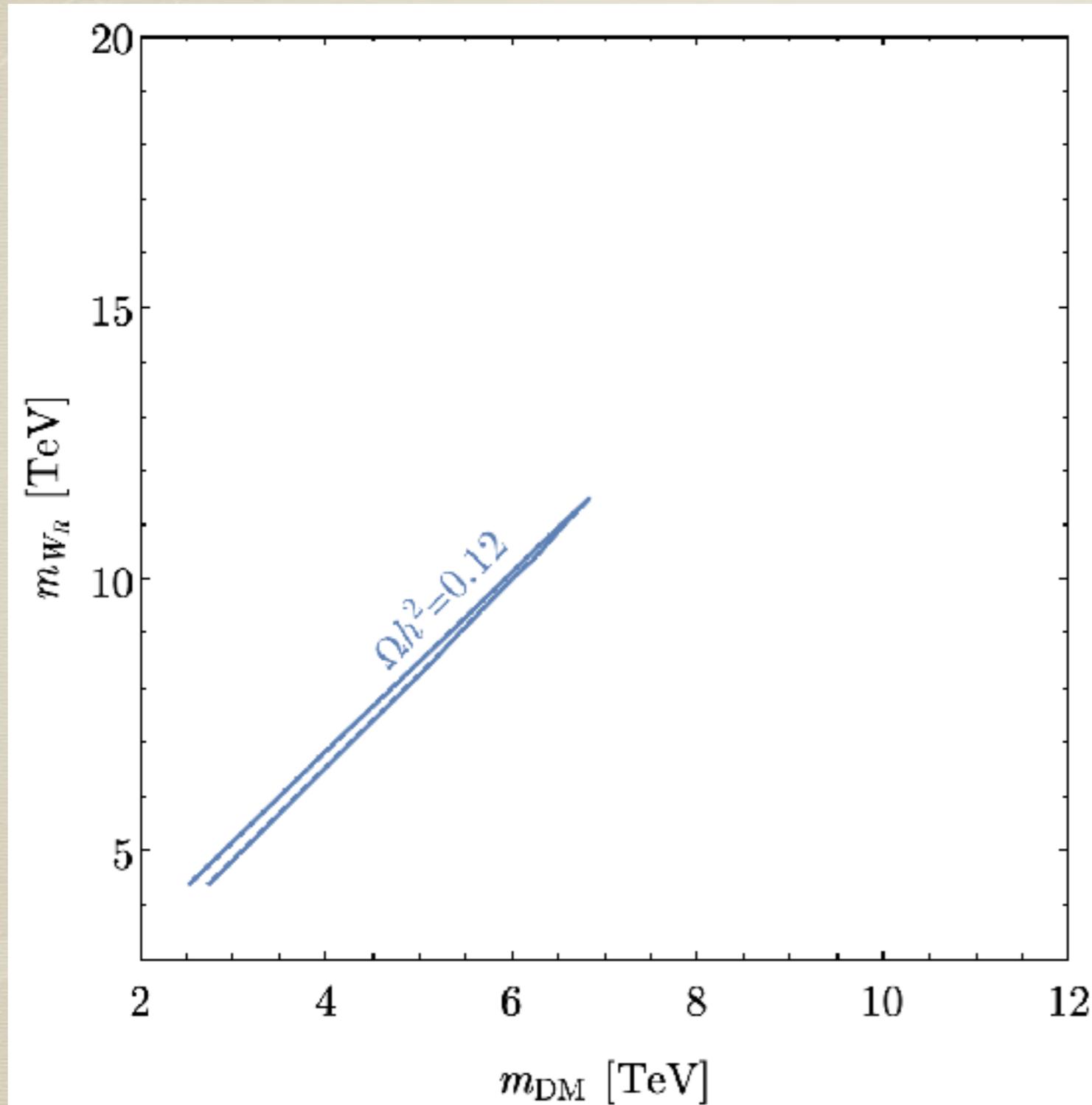


One can show that  $DM_R$  is the lightest and other states can decay into it

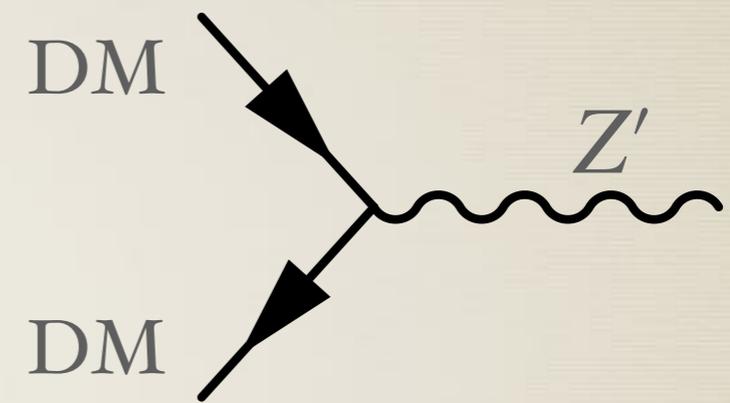
$$DM_R \equiv DM$$

Only two free parameters  $m_{DM}$  and  $m_{W_R}$  owing to Parity

# Dark matter abundance



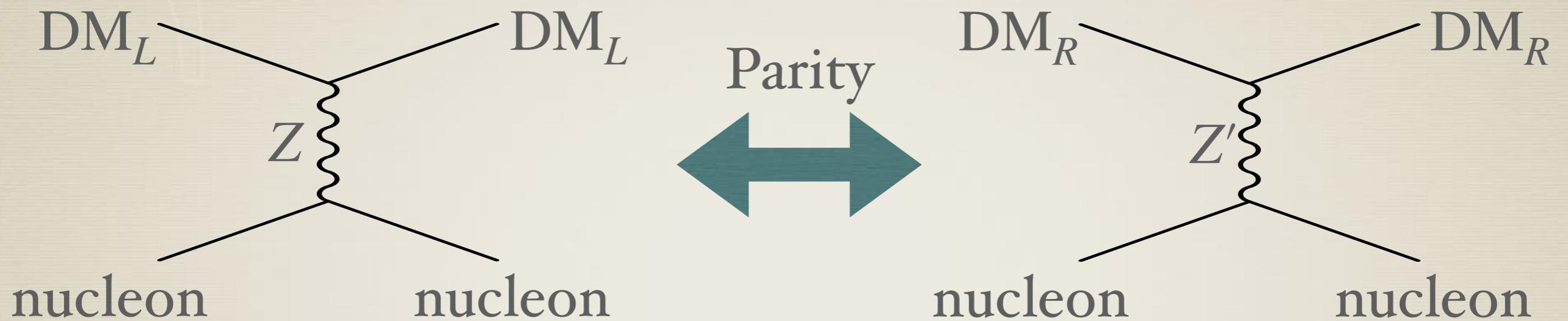
Baldwin, KH and Wang (2025)



Resonance at  $2m_{\text{DM}} \sim m_{Z'}$

Upper bound on a new symmetry breaking scale!

# Direct detection

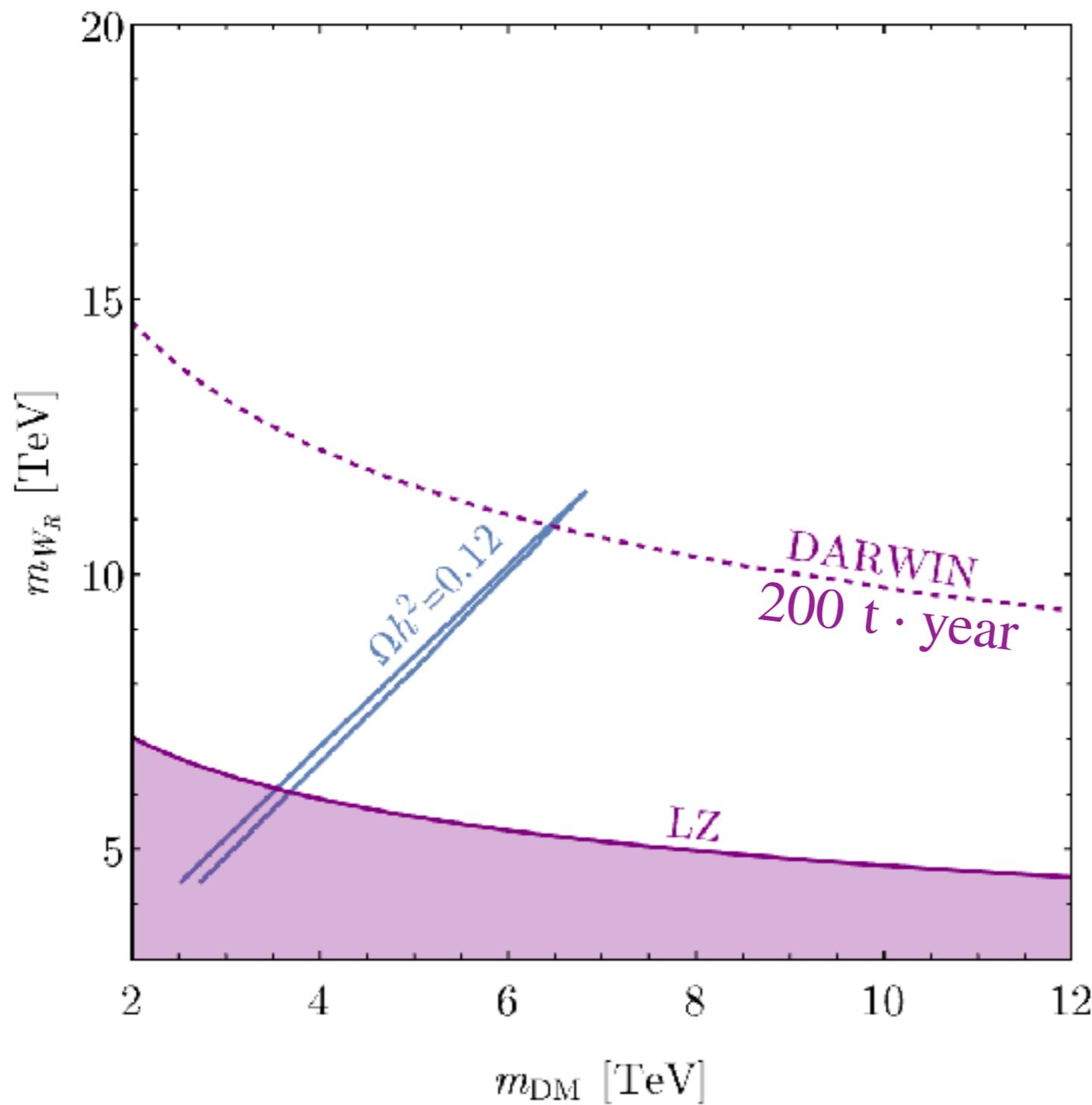


$$m_{Z'} \sim m_{W_R} \frac{m_Z}{m_{W_L}}$$

$$\sigma \propto \frac{1}{m_{W_R}^4}$$

# Direct detection

Baldwin, KH and Wang (2025)



$$\sigma \propto \frac{1}{m_{W_R}^4}$$

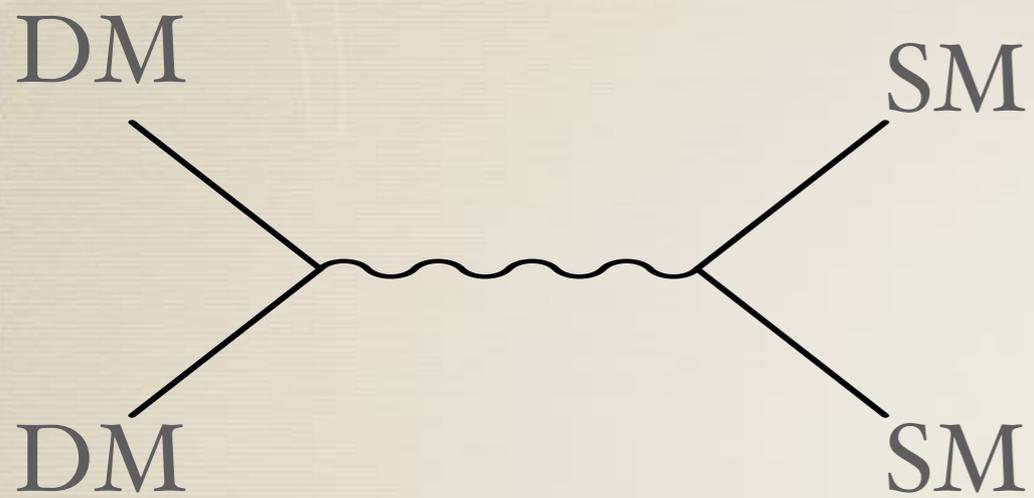
Future experiment



Current constraint

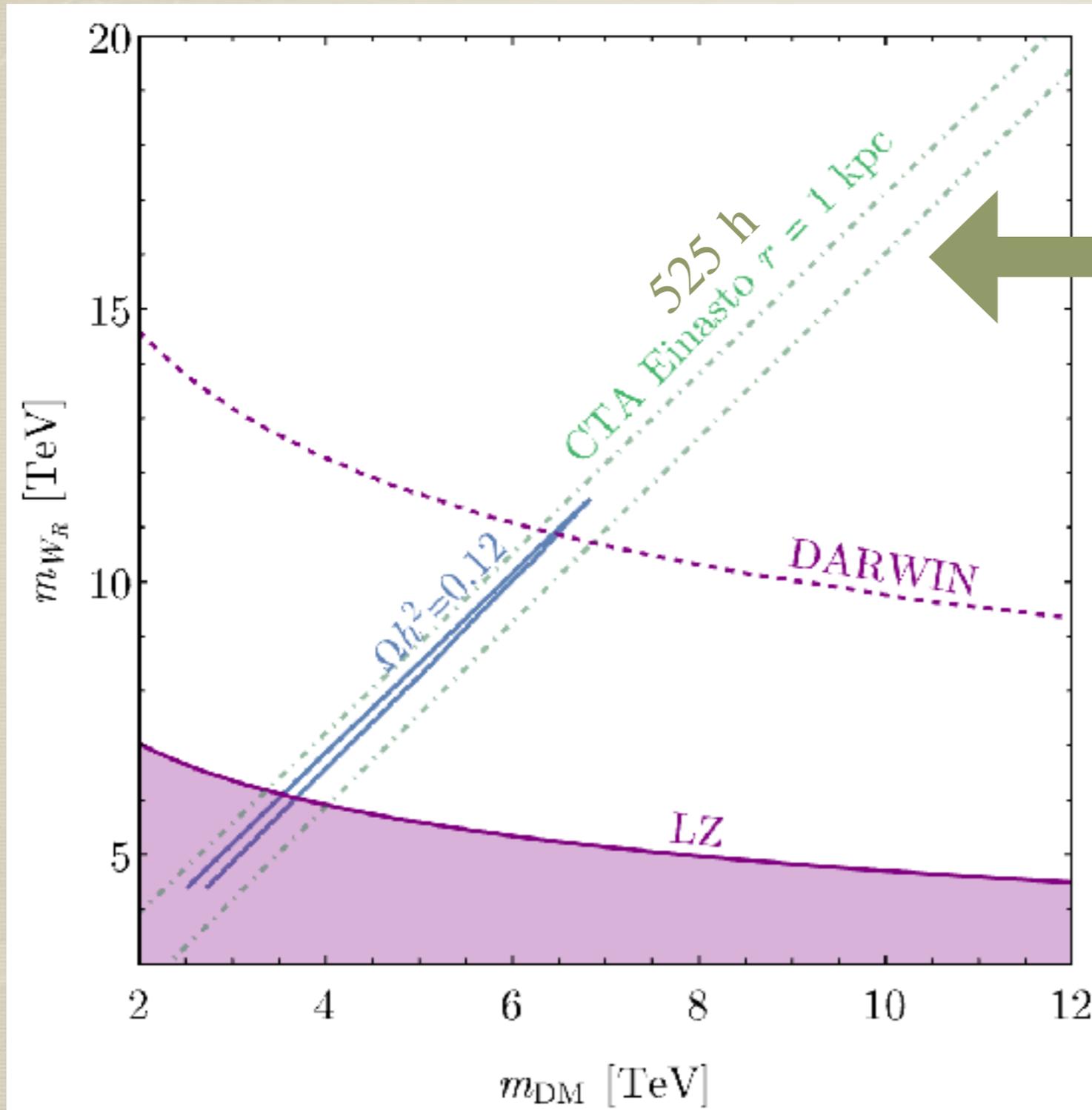


# Indirect detection

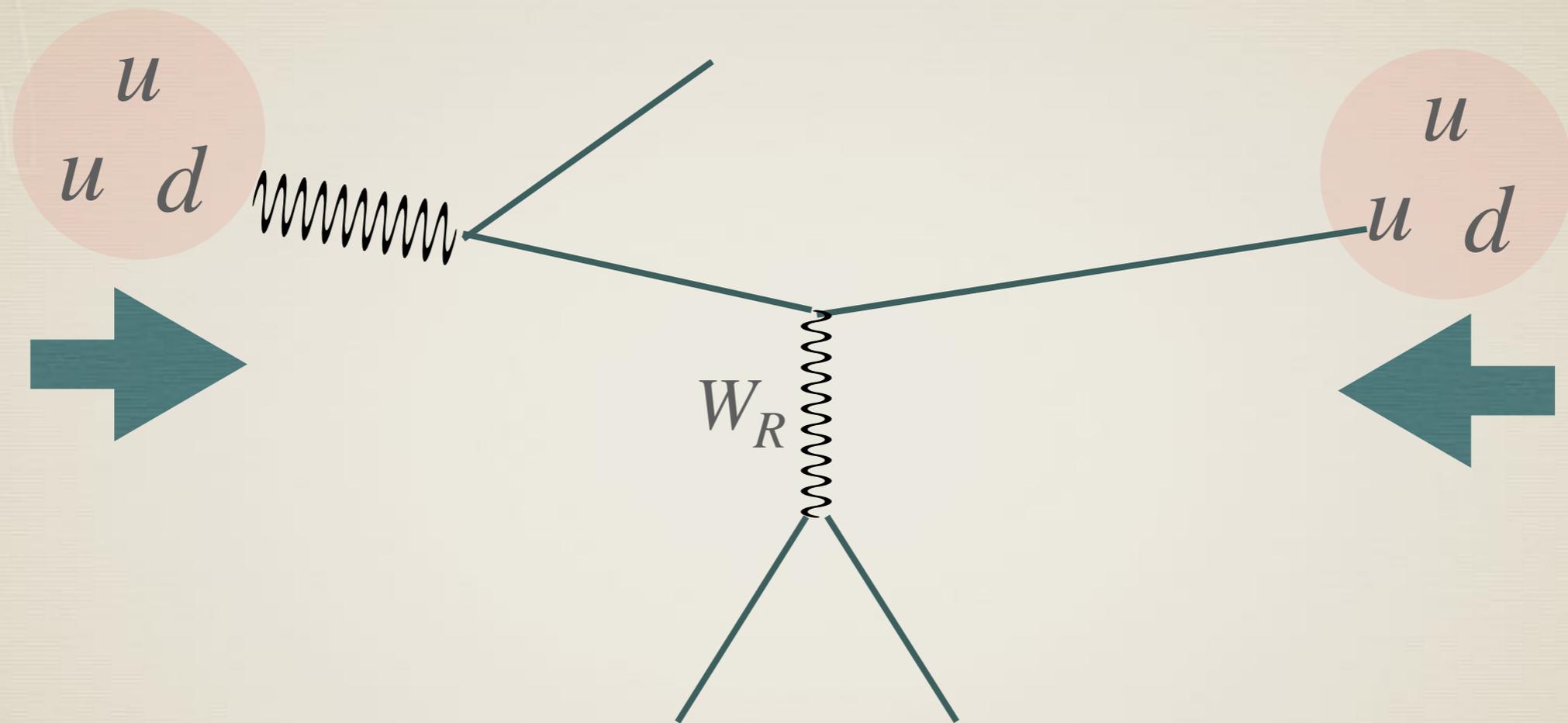


# Indirect detection

Baldwin, KH and Wang (2025)

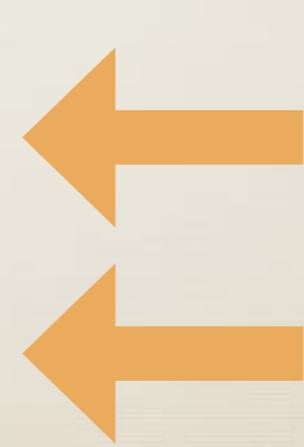
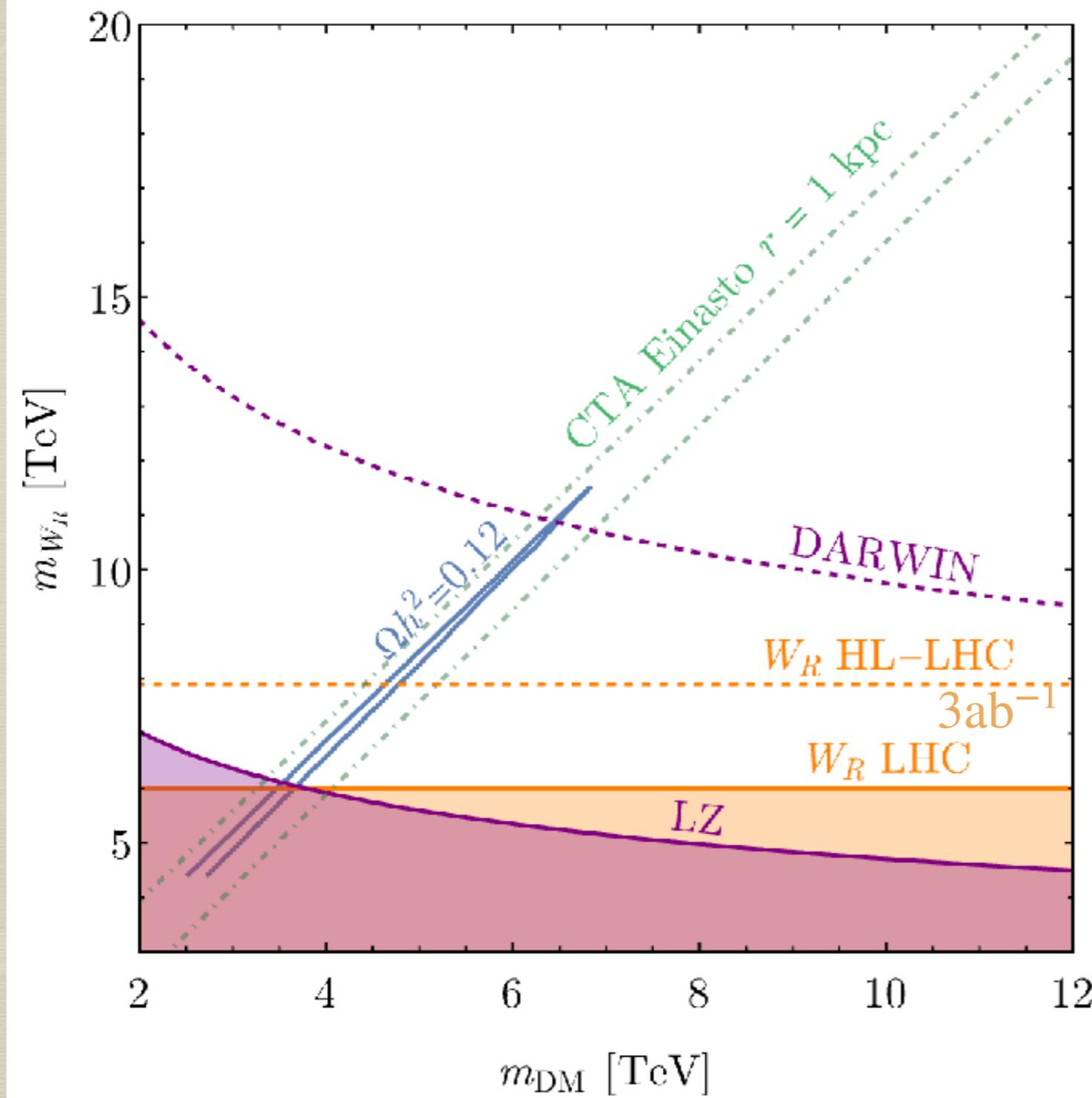


# Large Hadron Collider



# Large Hadron Collider

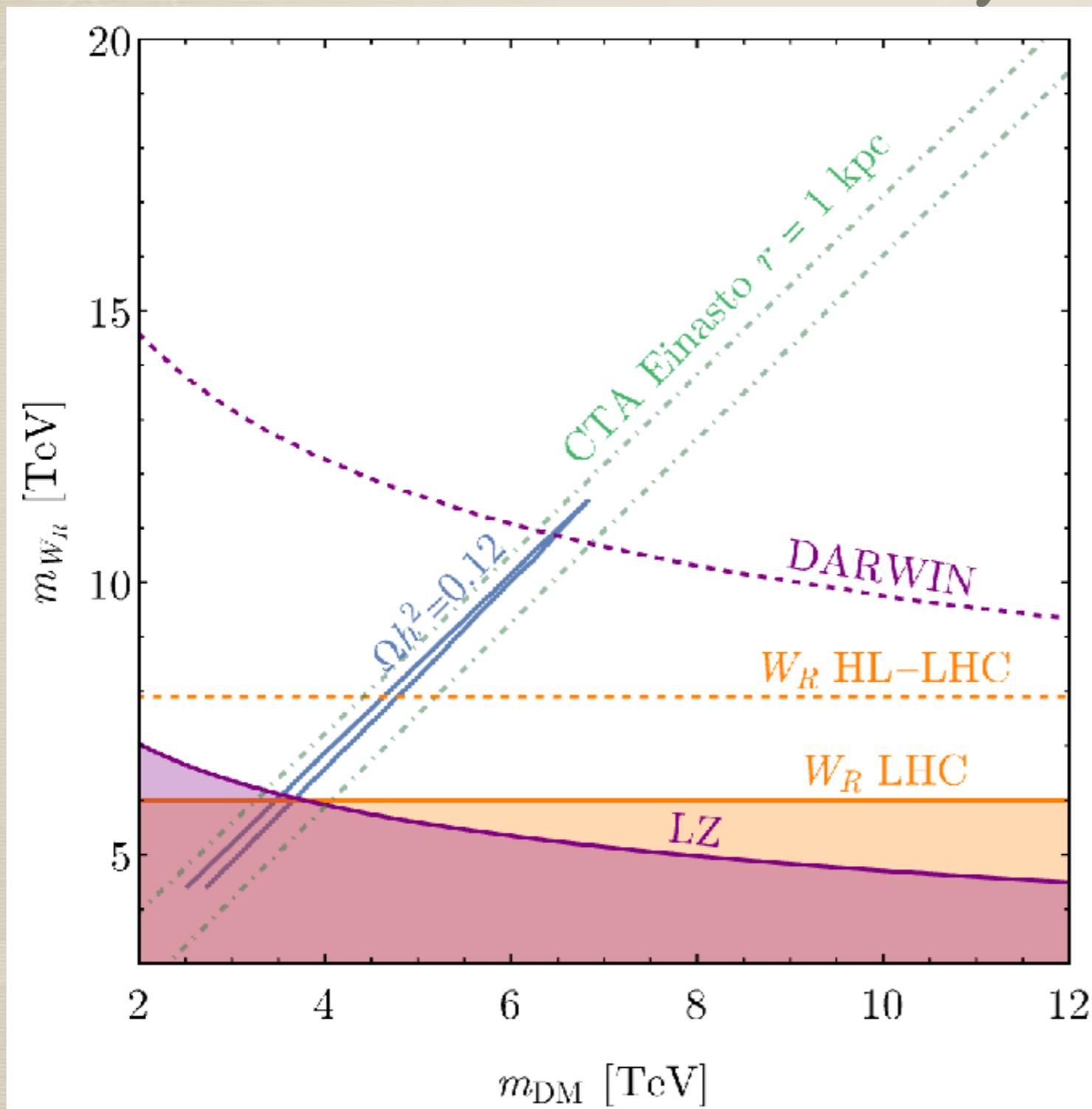
Baldwin, KH and Wang (2025)



Future upgrade

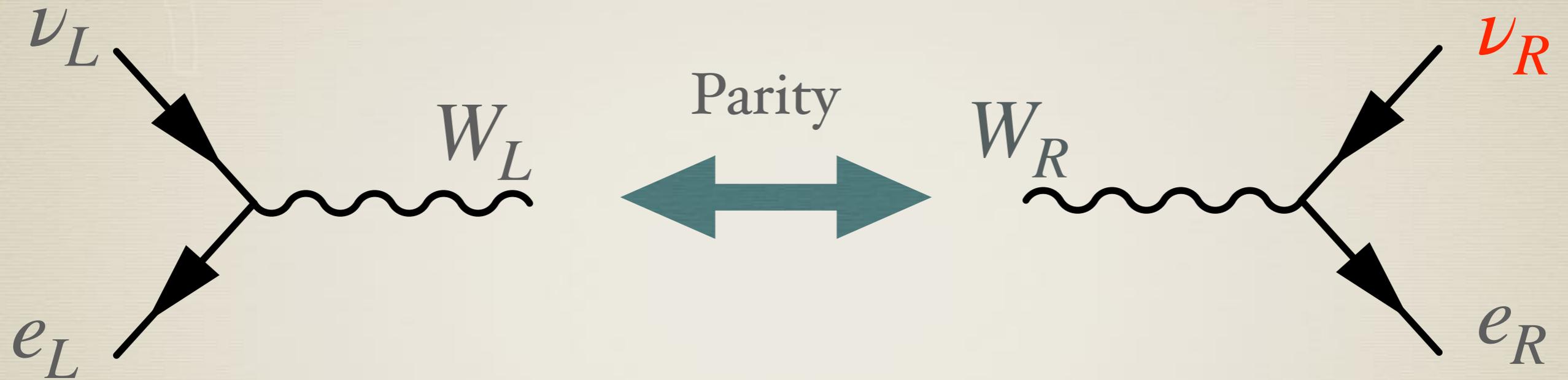
Current constraint

# Power of symmetry



- \* Only two parameters
- \* Strong upper bound on the new-physics scale
- \* Correlated signals

# Neutrino mass and $\mu$ TRISTAN



In a class of neutrino mass models,

- \* Large lepton number violation w/o neutrino masses
- \*  $\mu^+ \mu^+ \rightarrow W_L^+ W_R^{+(*)}$  can be sizable.  $\mu$ TRISTAN?

Kitano, KH, Takai (2025)

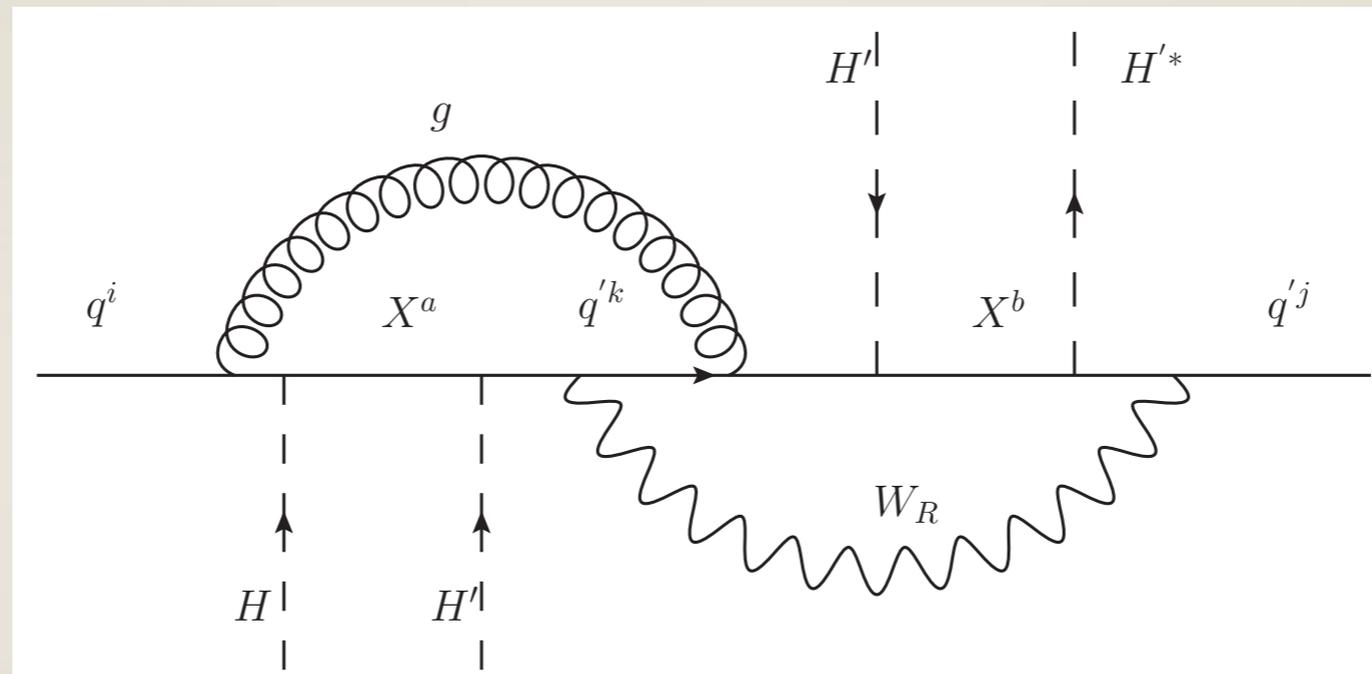
# Summary

- \* Symmetry can play a powerful role in DM physics
- \* The strong CP problem can be solved by parity symmetry and new gauge symmetry
- \* Models of WIMP DM are impacted by the new symmetry
- \* Collider (LHC), DM direct detection (DARWIN, ...), and indirect detection (CTA, ...), can probe the parameter space, with correlation among the signals

Backup

# Non-zero CPV

Hall, KH (2018)

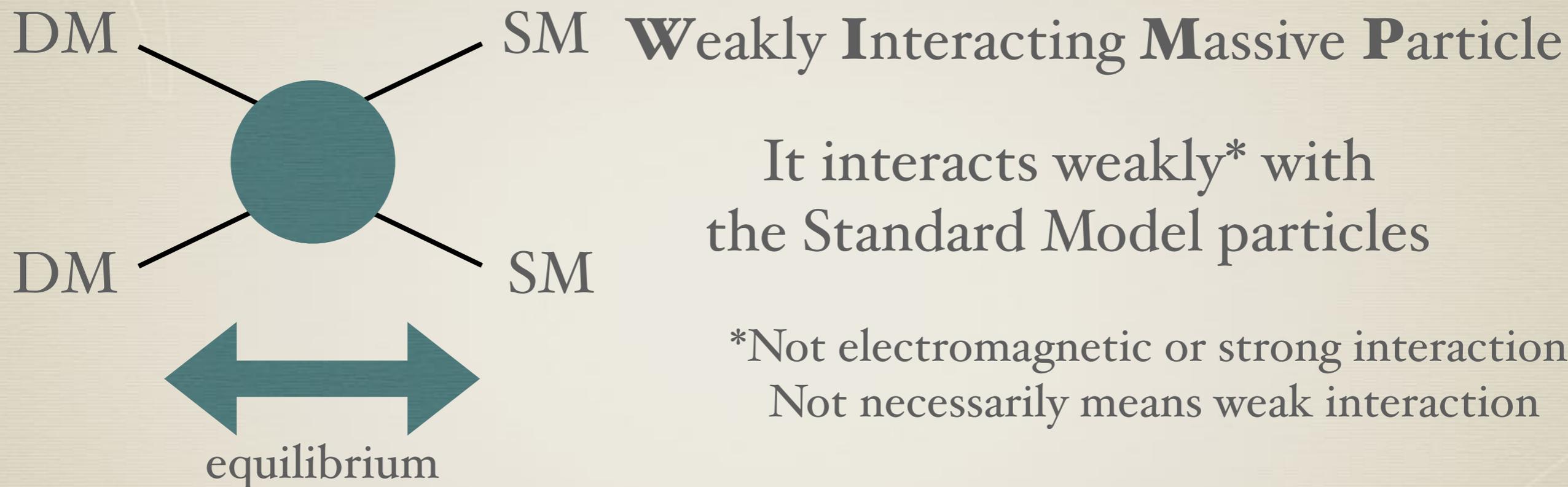


$$\delta\theta \sim 10^{-11} \frac{\theta_{23}^u \theta_{23}^d}{V_{cb}^2}$$

Suppressed by loop factors, flavor mixing

# WIMP DM

Lee and Weinberg (1977)



It interacts weakly\* with the Standard Model particles

\*Not electromagnetic or strong interaction.  
Not necessarily means weak interaction

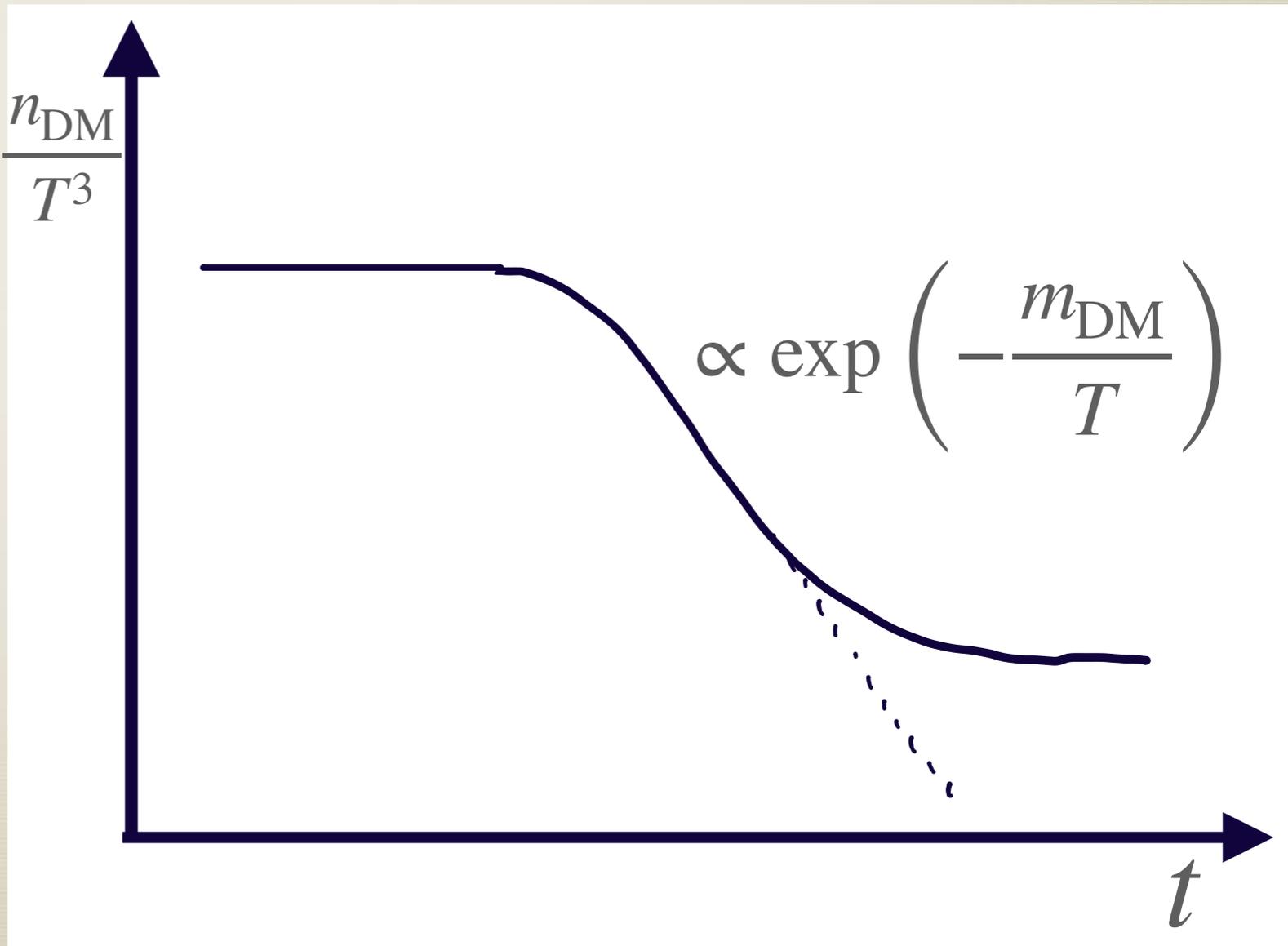
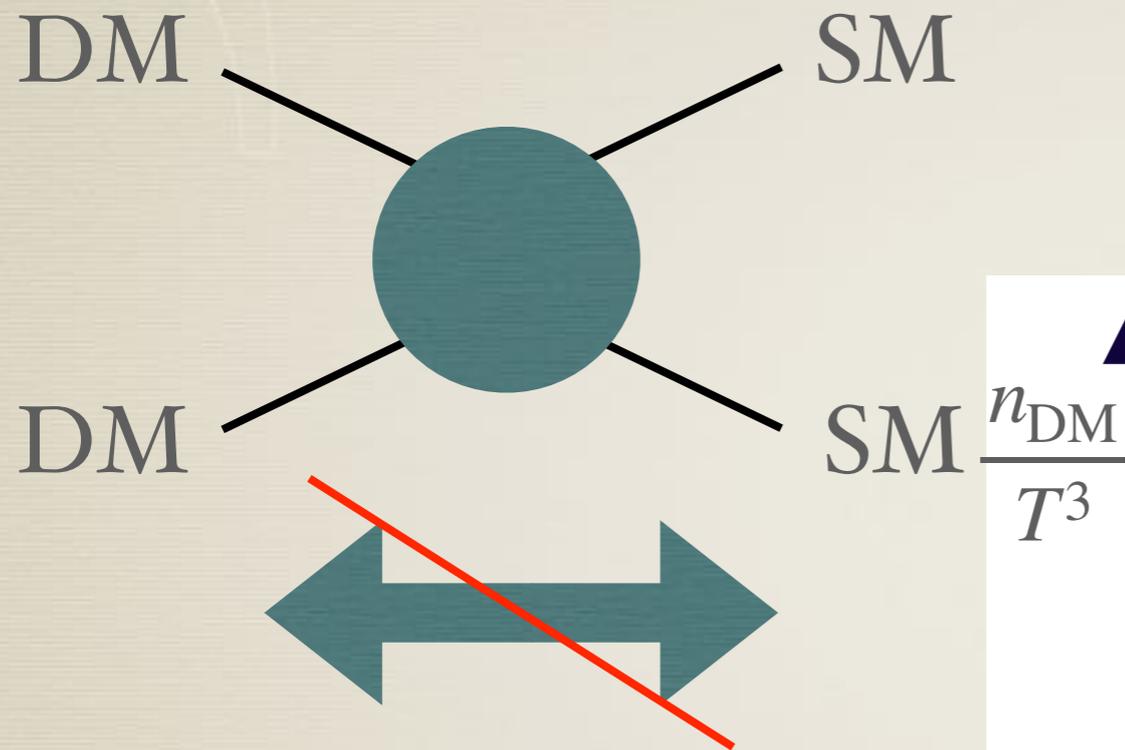
Weak, but strong enough for the DM abundance to reach a thermal equilibrium value

Number density  $n_{\text{DM}} \sim T^3$  for  $T \gg m_{\text{DM}}$

# WIMP DM

Lee and Weinberg (1977)

As the temperature decreases,

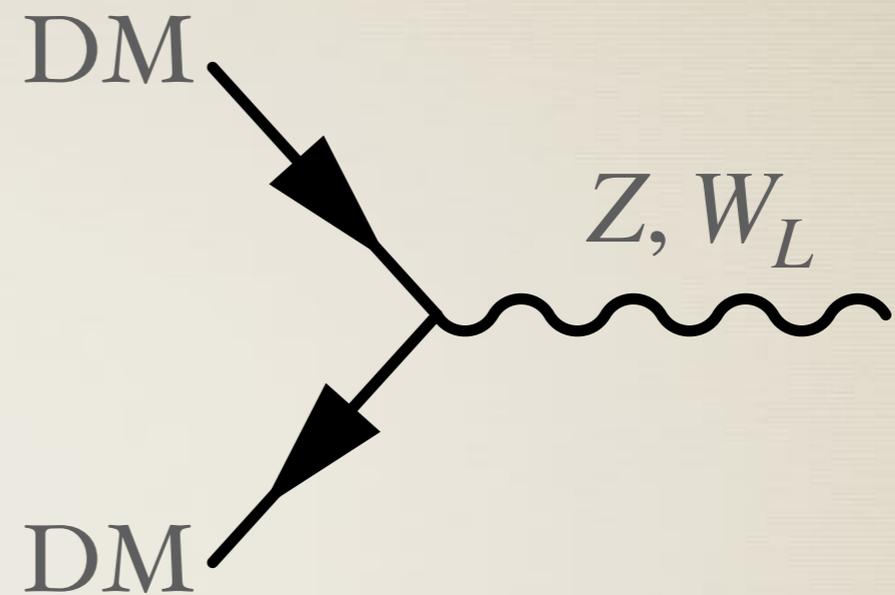


$$\frac{\rho_{\text{DM}}}{\rho_{\text{obs}}} \simeq \frac{10^{-26} \text{cm}^3/\text{s}}{\sigma v}$$

$\sigma$  : cross-section

# Known interaction?

Like SM particles,



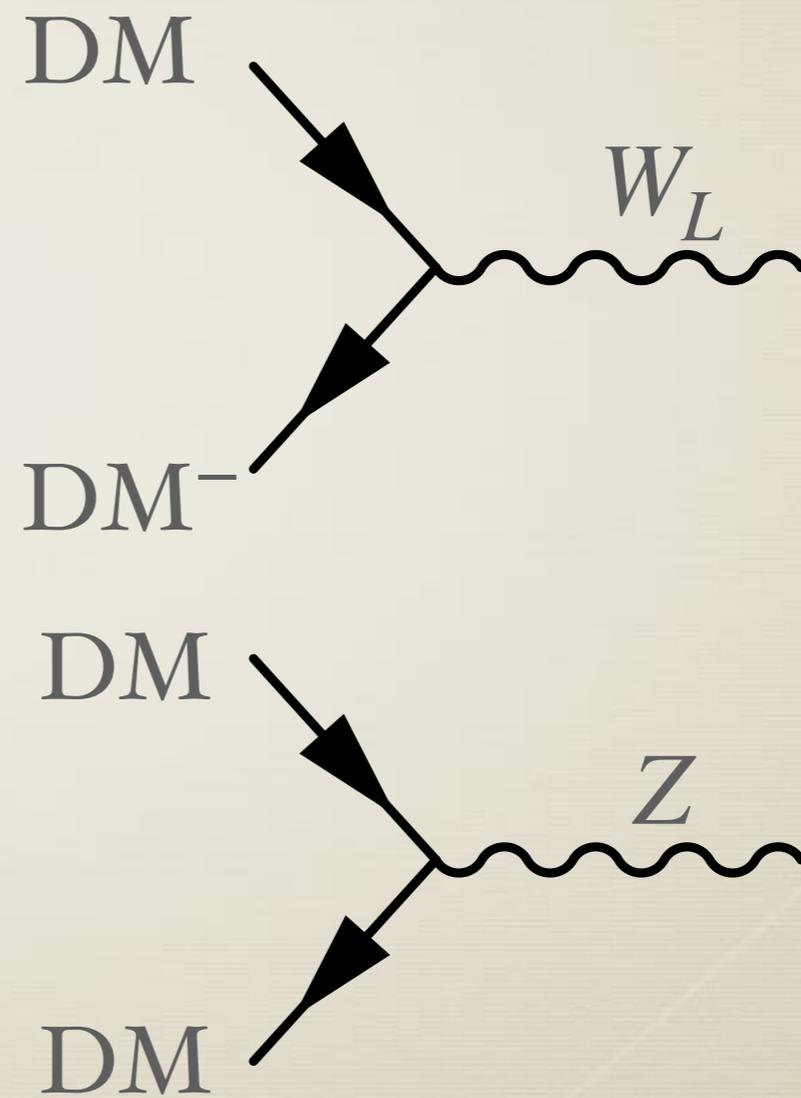
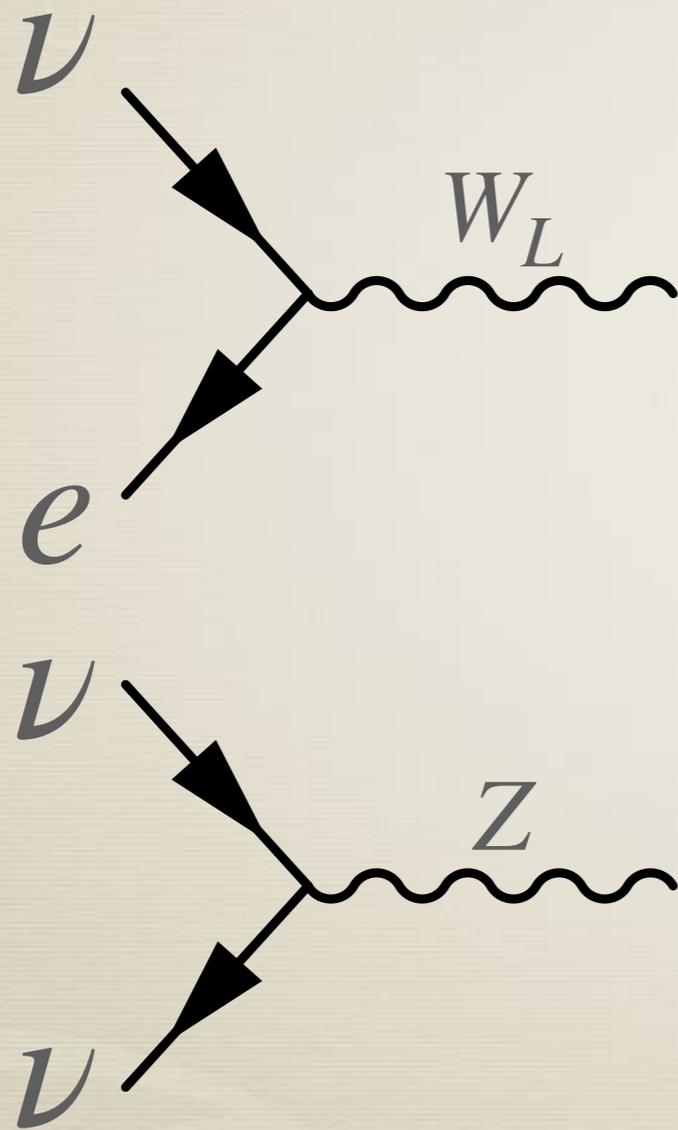
Gauge symmetry predicts the interaction strength.

After fixing the gauge charge of DM,  
the only free parameter is the DM mass  $m_{\text{DM}}$

$$\frac{\rho_{\text{DM}}}{\rho_{\text{obs}}} \simeq \frac{10^{-26} \text{cm}^3/\text{s}}{\sigma v(m_{\text{DM}})} \quad \Rightarrow \quad m_{\text{DM}} = O(1 - 10) \text{ TeV}$$

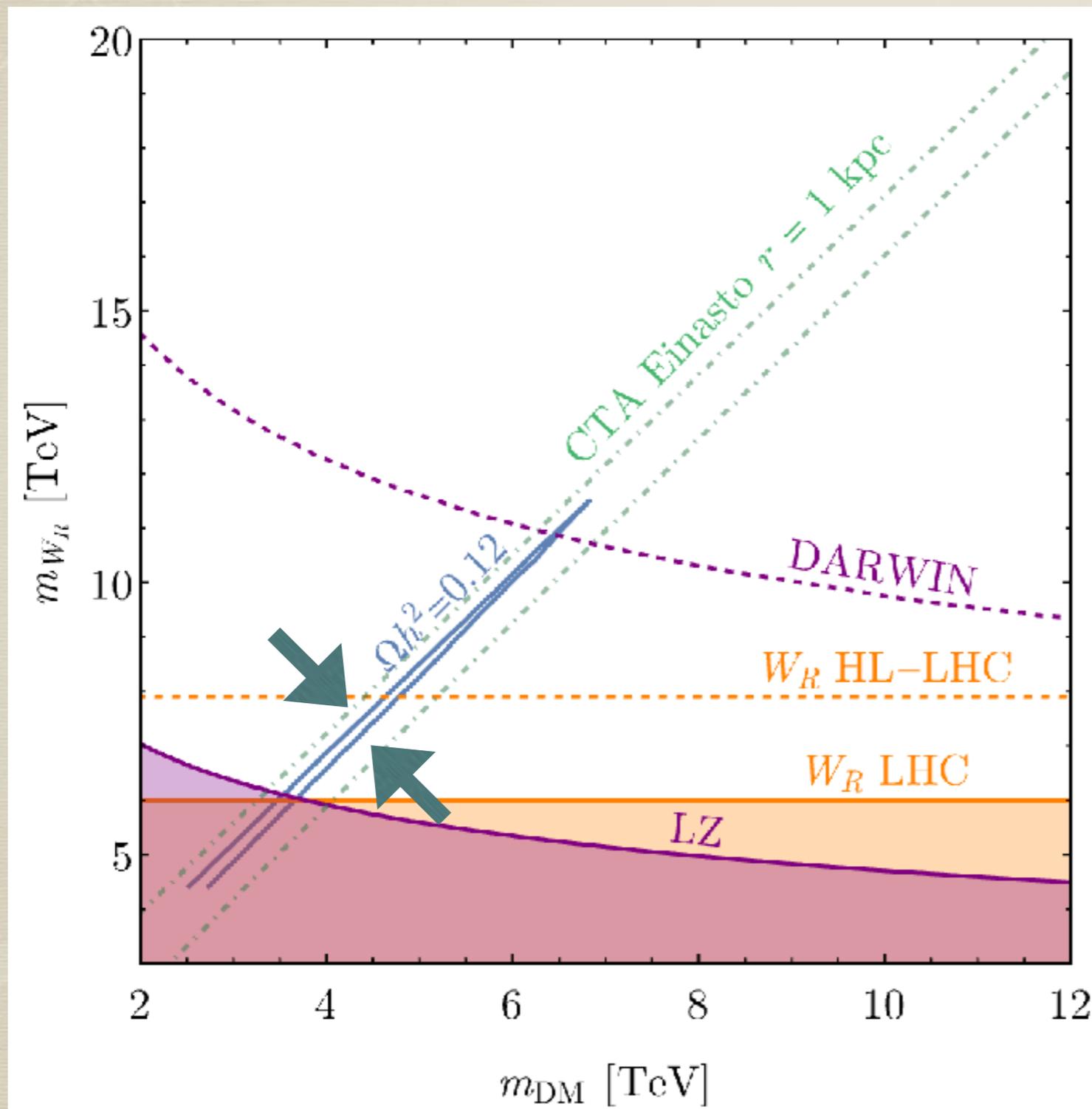
# Neutrino-like?

Neutrino does not have electromagnetic or strong interactions



$$m_{DM} \simeq 1 \text{ TeV}$$

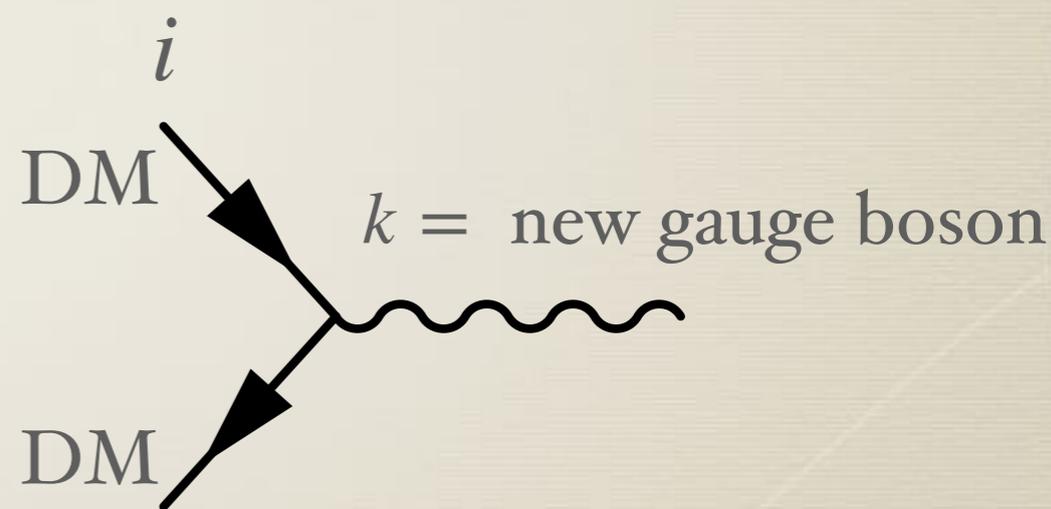
# Abundance of DM



Baldwin, KH and Wang (2025)

$$\langle f|i \rangle \propto \sum_k \frac{1}{E_i - E_k}$$

$k$  : intermediate state

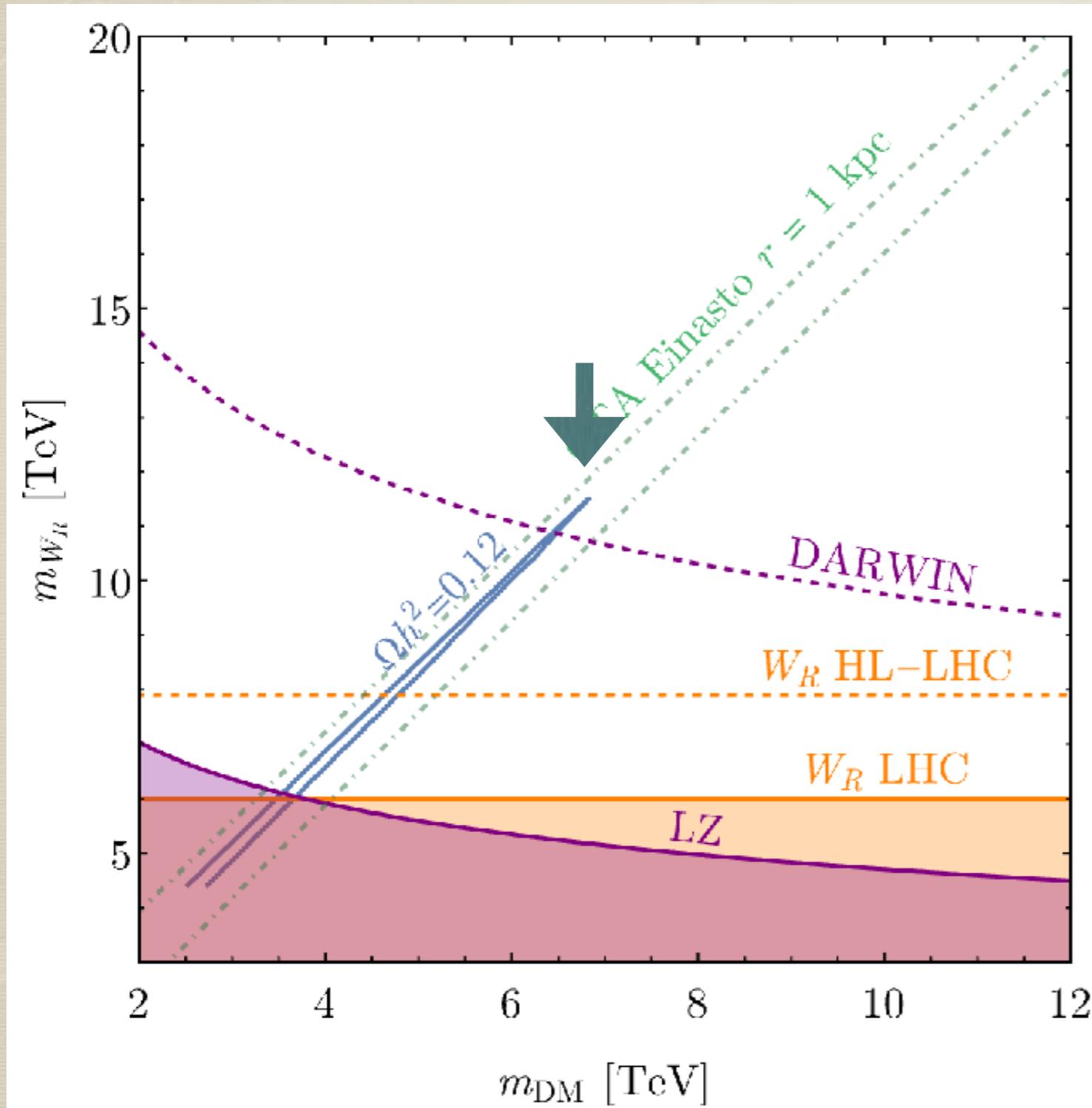


Resonance at  $2m_{\text{DM}} \sim m_{W_R}$

(To be precise,  $2m_{\text{DM}} = m_{Z'}$ )

# Abundance of DM

Baldwin, KH and Wang (2025)

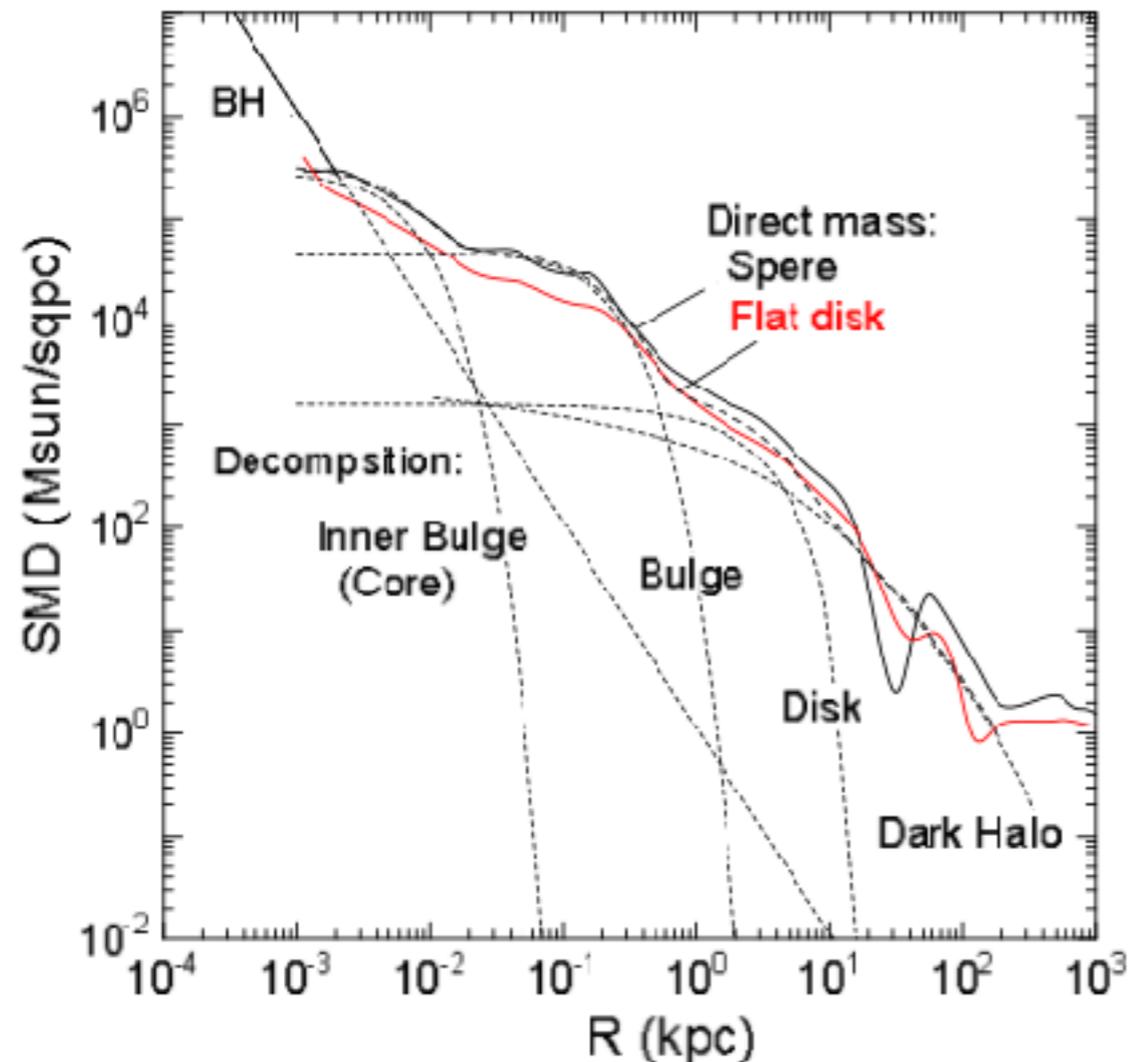


$$\sigma v \propto (\text{length scale})^2$$

$$\propto \frac{1}{(\text{mass scale})^2}$$

# Uncertainty: DM profile

$$N_{\text{sig}} \propto n_{\text{DM}}^2 \sigma v \propto \rho_{\text{DM}}^2 \sigma v$$



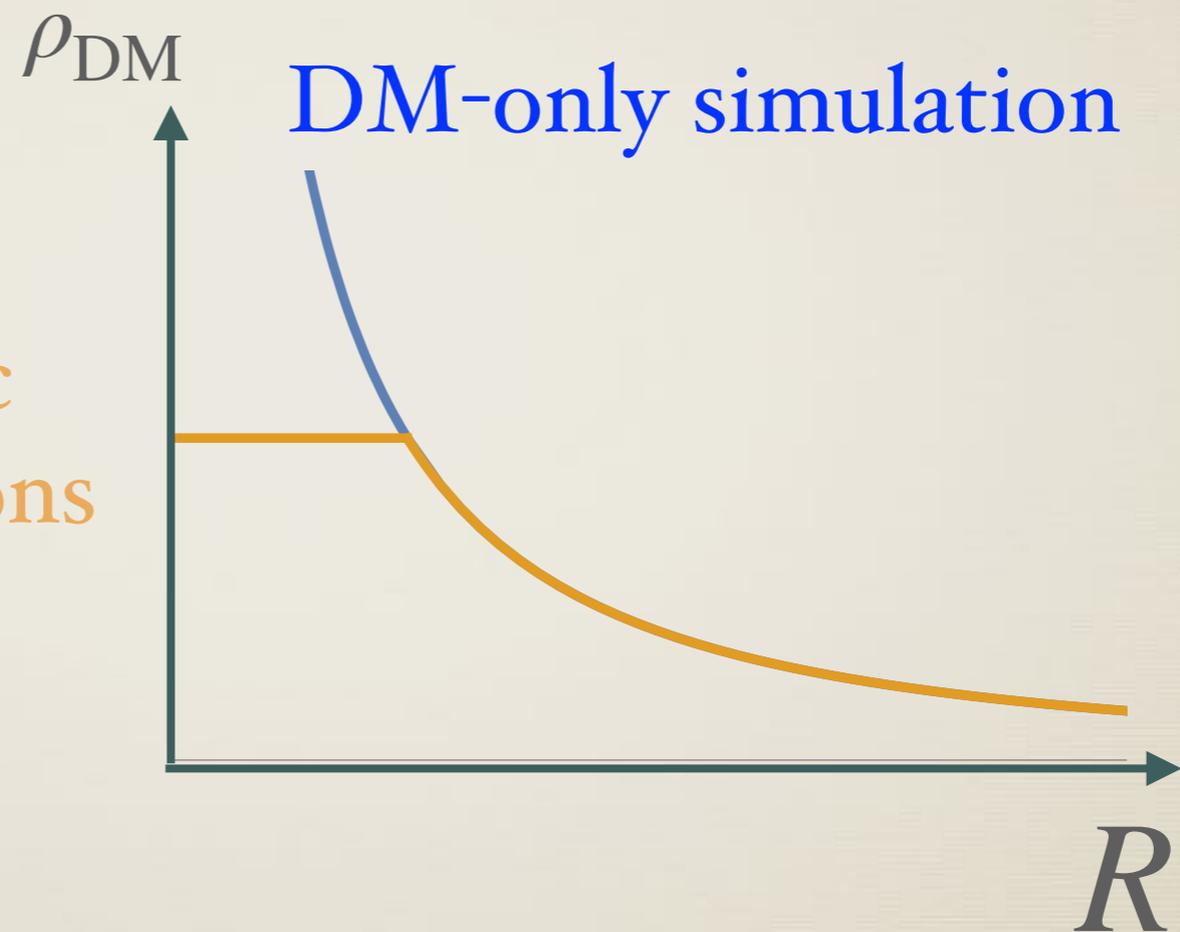
The center of the galaxy is denser and gives a larger signal  
But we cannot measure the DM density around the center because baryon dominates



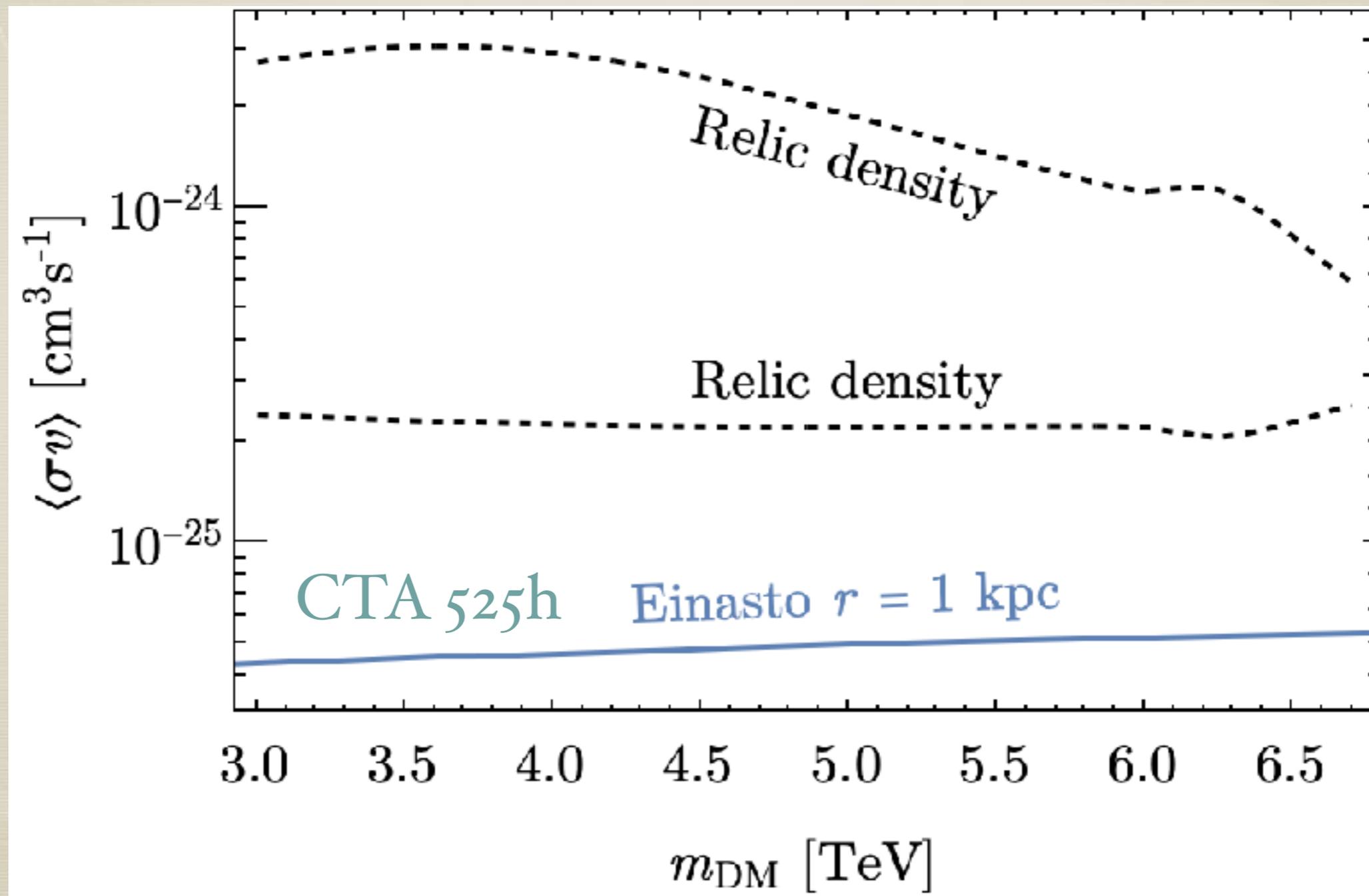
Rely on simulation  
and astrophysical theory

# Uncertainty: DM profile

Flattened at  $r < 1$  kpc  
by feedback from baryons



# Cherenkov Telescope Array



Maybe CTA can detect DM?

# Neutrino mass and $\mu$ TRISTAN

$$\sqrt{s} = 10 \text{ TeV}$$

$$\sqrt{s} = 30 \text{ TeV}$$

