Introduction of Dark Matter (DM)

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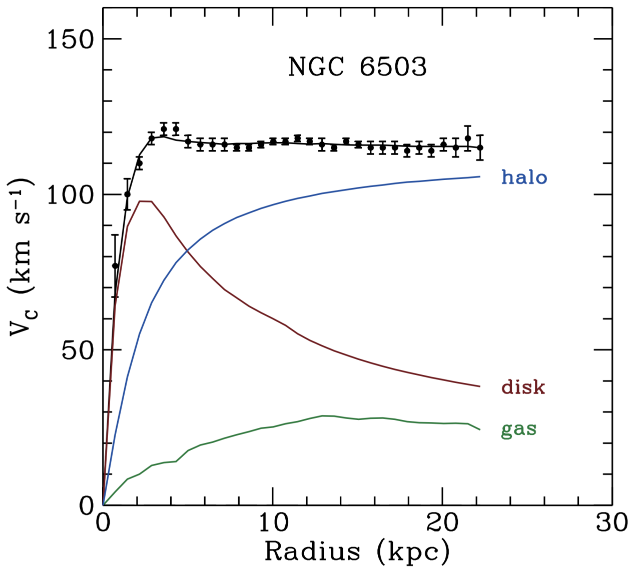
Outline

1. Why DM?
2. Particle-like DM vs. Wave-like DM
3. Two Popular Examples of DM Models
4. Some Ideas for DM Searches
5. Summary

Why DM?

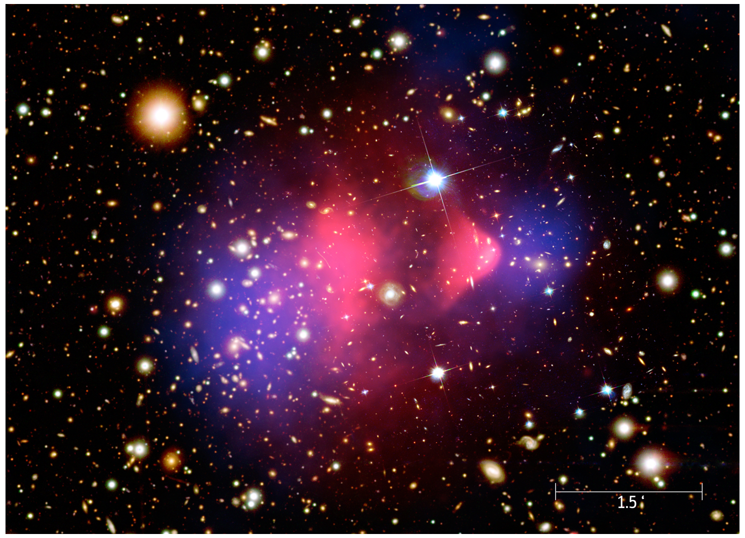
Evidences of DM: from galaxy scale to cosmological scale

Rotation curve



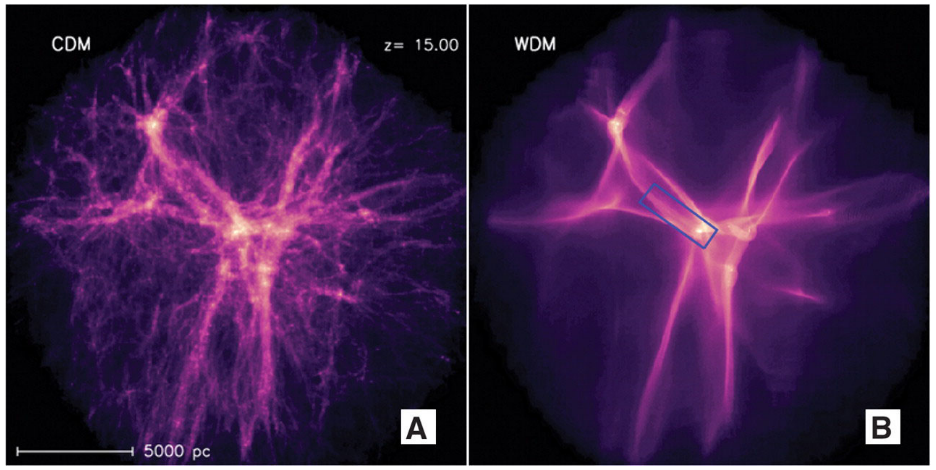
[Begeman, Broeils, Sandars ('91)]

Bullet clusters



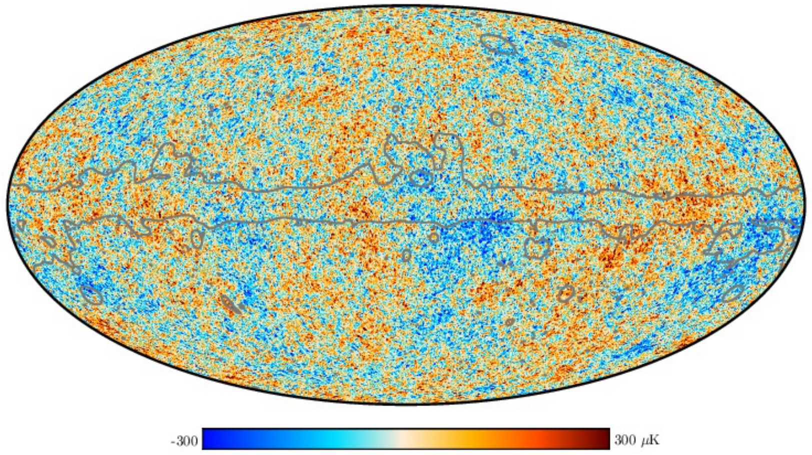
[ESA / Picture from Wikipedia]

Structure formation



[CDM vs. WDM (3keV): Geo, Theuns ('91)]

CMB angular power spectra



[Planck Collaboration ('18)]

DM properties

Weakly Interacting

➡ Charge neutral, non-colored, $\cdots$

Stable (or long-lived)

➡ Lifetime $\gg$ present cosmic age

Cold (i.e., non-relativistic, when $T \lesssim O(1)$ keV)

➡ $\rho_{\rm DM} \propto a^{-3}$, because $p_{\rm DM} \simeq 0$

Sizable energy density in the present universe

➡ $\Omega_{\rm DM} \simeq 0.3111 \pm 0.0056$
[Planck Collaboration ('18)]

Questions

What is DM?

and

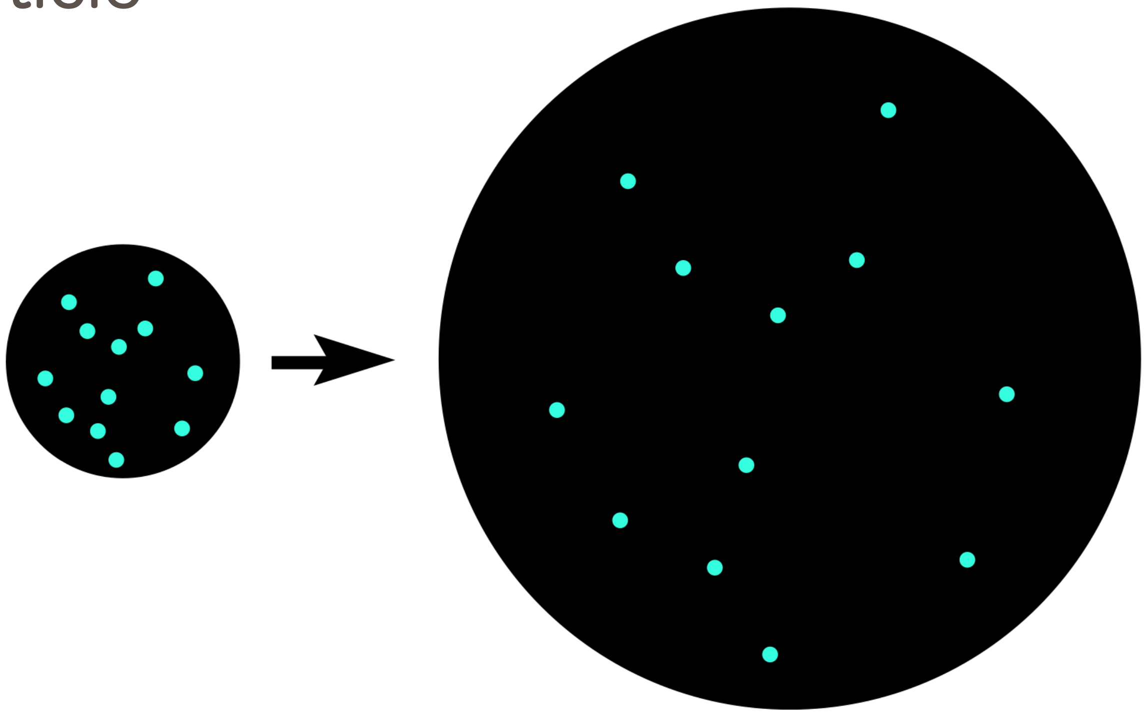
What is the BSM physics behind the DM?

Particle-like DM vs. Wave-like DM

Particle-like DM

DM can be a non-relativistic particle

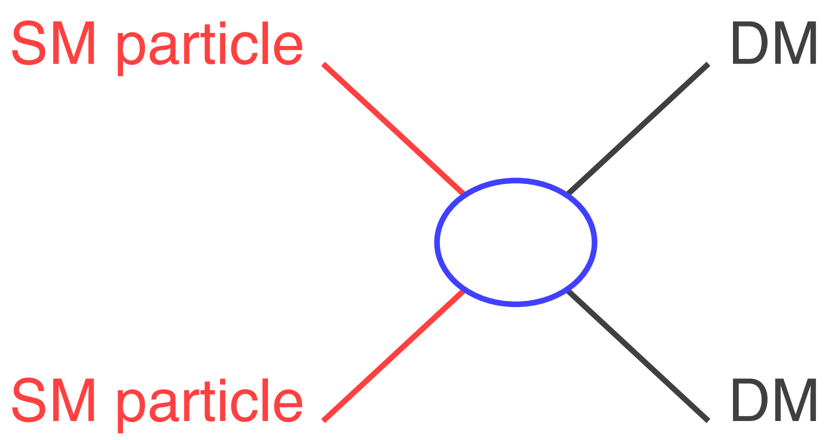
- $\rho_{\rm DM}(\vec{r}) \simeq m_{\rm DM} \sum_i \delta(\vec{r} - \vec{r}_i)$
- $\bar{v}_{\rm DM} \ll 1$

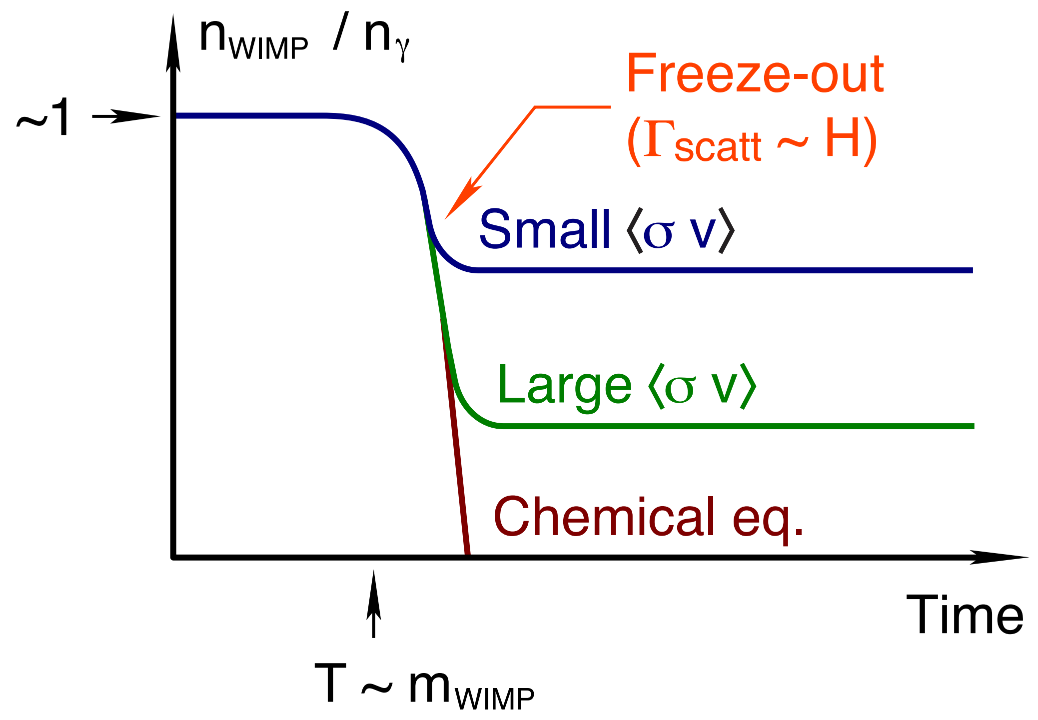


Weakly interacting massive particles (WIMPs) are examples

- Stability is often guaranteed by a symmetry
- Occupation number < 1

Thermal relic DM scenario





$$\Omega^{(\mathrm{thermal})}_{\mathrm{WIMP}} \simeq 0.2 \times \left(\frac{\langle \sigma v_{\mathrm{rel}} \rangle}{1\ \mathrm{pb}} \right)^{-1}$$

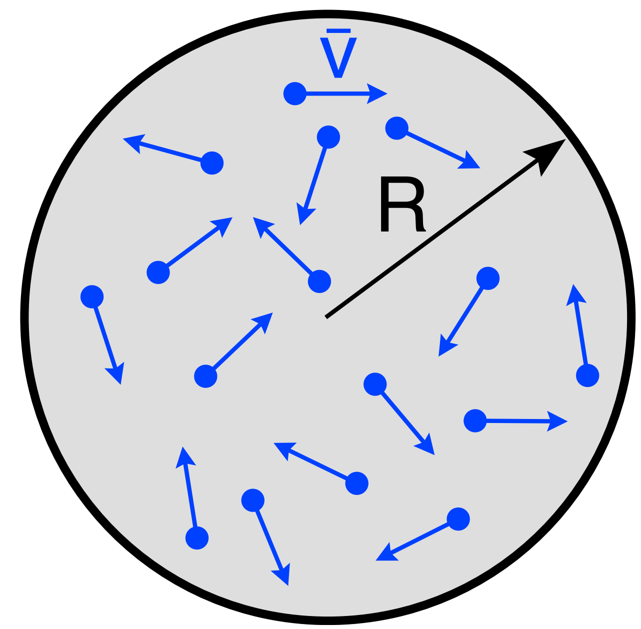
➡ $1\ \mathrm{pb} \sim \dfrac{4\pi\alpha^2}{(500\ \mathrm{GeV})^2}$: DM at EW scale?

➡ Unitarity bound: $m_{\mathrm{DM}} \lesssim 100\ \mathrm{TeV}$ for thermal relic DM

➡ Notice: Non-thermal production is also possible

Tremaine-Gunn bound for fermionic DM

For DM with velocity dispersion $\bar{v}$



- Virial mass: $M_{\rm virial} \sim \dfrac{R\bar{v}^2}{G_{\rm N}}$
- Phase-space volume: $\dfrac{1}{(2\pi\hbar)^3}\displaystyle\int d^3p d^3x \sim (m\bar{v})^3 R^3$

➡ $M_{\rm max} \sim m(m\bar{v})^3 R^3$ for fermionic DM

If DM is fermion: $M_{\rm virial} \lesssim M_{\rm max}$

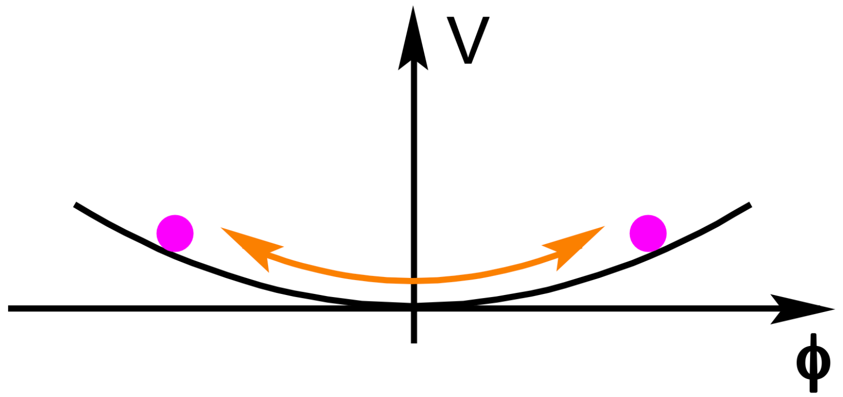
$$m \gtrsim \left(G_{\rm N} R^2 \bar{v}\right)^{-1/4} \sim 100\ {\rm eV} \times \left(\frac{R}{10\ {\rm kpc}}\right)^{-1/2} \left(\frac{\bar{v}}{100\ {\rm km/sec}}\right)^{-1/4}$$

➡ Fermionic DM must be heavier than ~ 100 eV (e.g., dSph)

➡ For $m \lesssim 100$ eV, occupation number is larger than ~ 1

Wave-like DM

$$\mathscr{L} \simeq \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2$$



➡ $\ddot{\phi} + \nabla^2 \phi - m^2 \phi = 0$

➡ $\phi \simeq \bar{\phi} \cos(mt + \alpha)$

Energy density: $\rho_\phi \simeq \frac{1}{2} m^2 \phi^2 + \frac{1}{2} \dot{\phi}^2 \simeq \frac{1}{2} m^2 \bar{\phi}^2$

Pressure: $p_\phi \simeq \frac{1}{2} m^2 \phi^2 - \frac{1}{2} \dot{\phi}^2 \;\Rightarrow\; \langle p_\phi \rangle_{\text{time}} \simeq 0$

Oscillating bosonic field can be CDM

・Axion (or ALP), hidden photon, ⋯

・For wave-like CDM, the potential should be parabolic

Fuzzy DM

If the DM mass is very light

- The de Broglie wavelength becomes astrophysical size

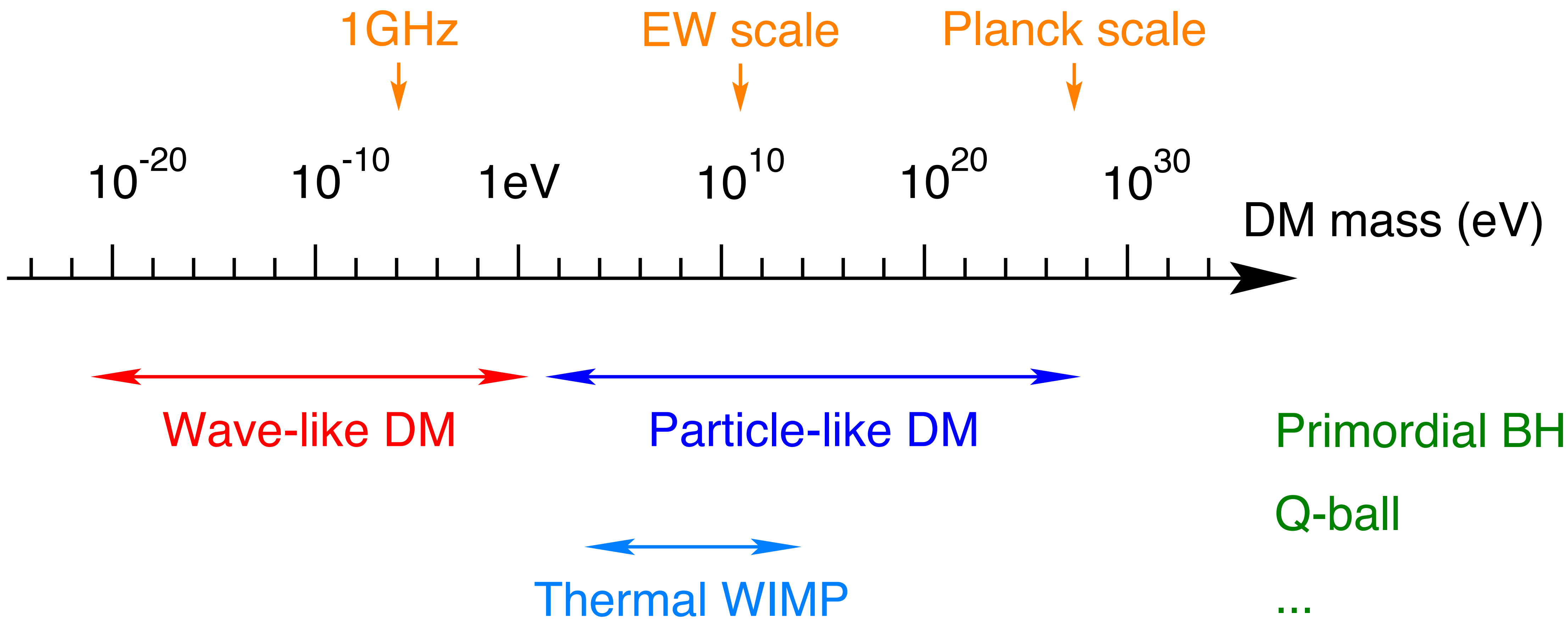
$$\frac{\lambda}{2\pi} = \frac{\hbar}{mv} \sim 2\ \mathrm{kpc} \times \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{-1} \left(\frac{v}{10\ \mathrm{km/sec}}\right)^{-1}$$

- Effects on cosmological density fluctuation may become sizable

DM cannot be too light
[For review, see, e.g., Ferreira 2005.03254]

- Ly-α: $m \gtrsim 10^{-21}\ \mathrm{eV}$
- CMB: $m \gtrsim 10^{-24}\ \mathrm{eV}$
- ...

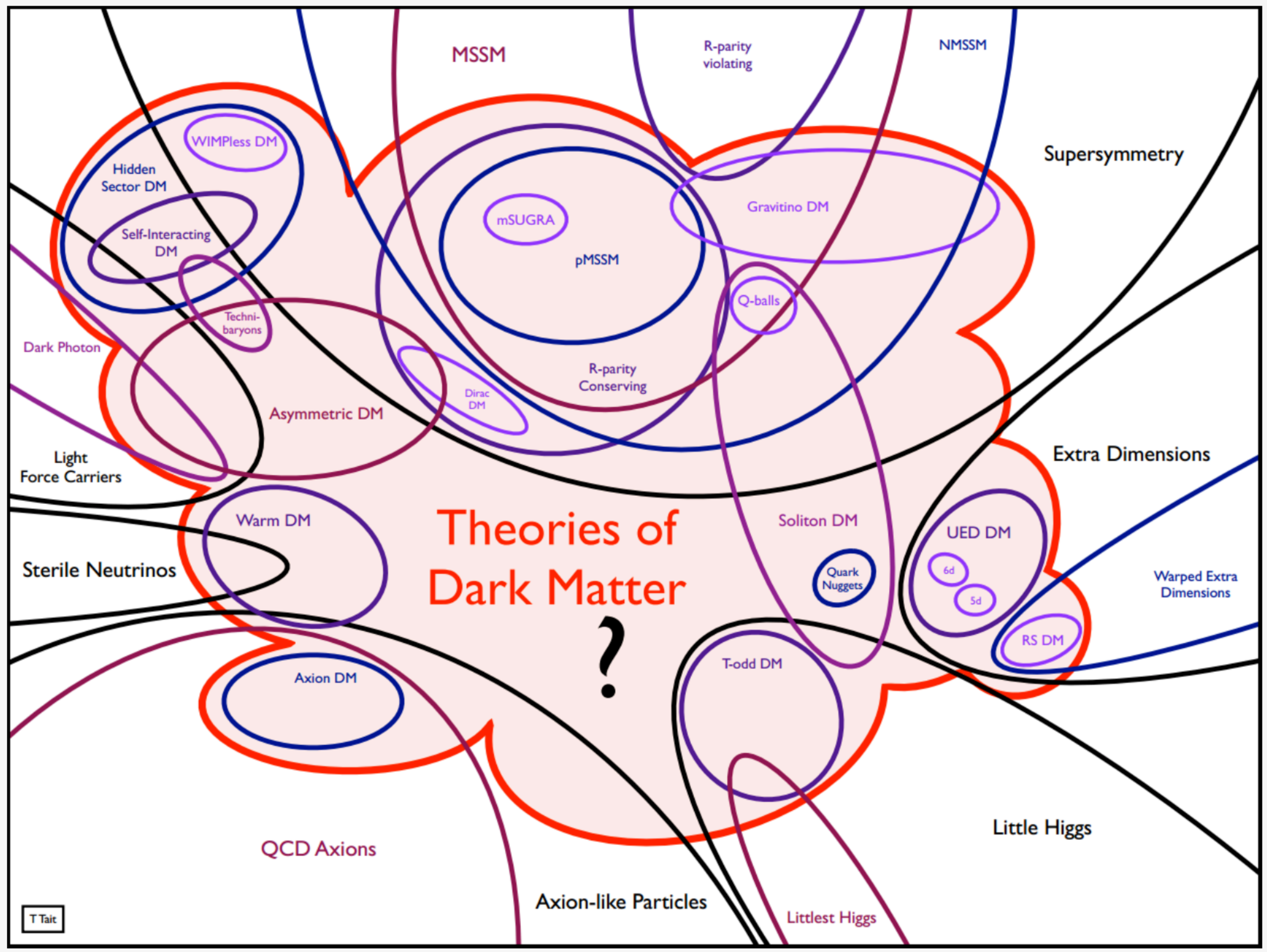
DM models



➡ The mass scale of the DM is unknown

➡ There are a variety of DM candidates

DM models



[Figure by T. Tait]

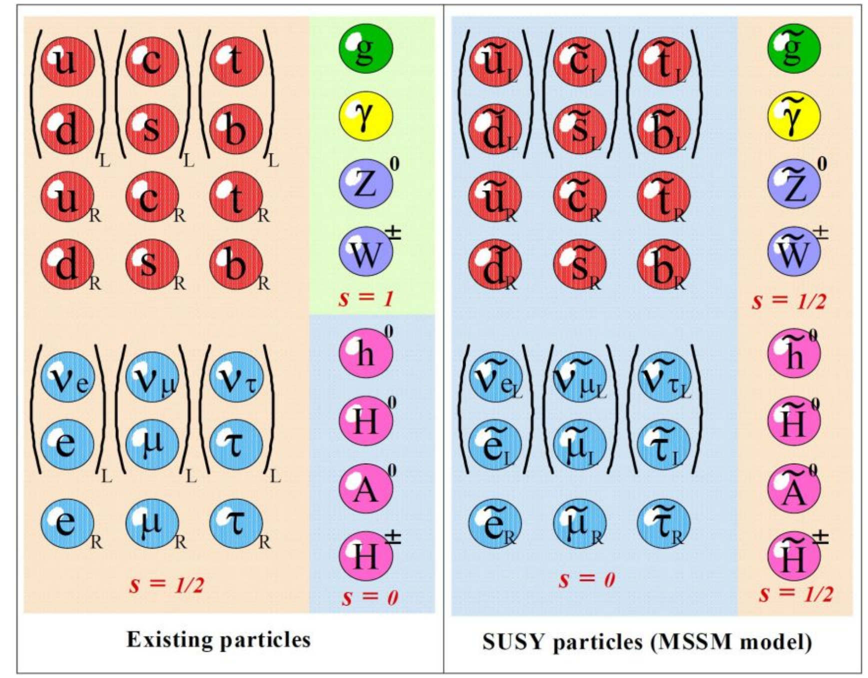
➡ Detection methods of DM highly depend on DM model, and we should try anything we can

Two Popular Examples

Example of particle-like DM: lightest neutralino

SUSY provides DM candidate

- Lightest superparticle (LSP)
- Stability of the LSP is guaranteed by R-parity



[from Particles and Friends]

Lightest neutralino is often assumed to be the LSP (and DM)

- $\chi_1^0 = U_{1,1}\tilde{B} + U_{1,2}\tilde{W}^0 + U_{1,3}\tilde{H}_u^0 + U_{1,4}\tilde{H}_d^0$
- $\Omega_{\rm LSP}^{\rm (thermal)} = \Omega_{\rm c}$ is possible in some parameter region

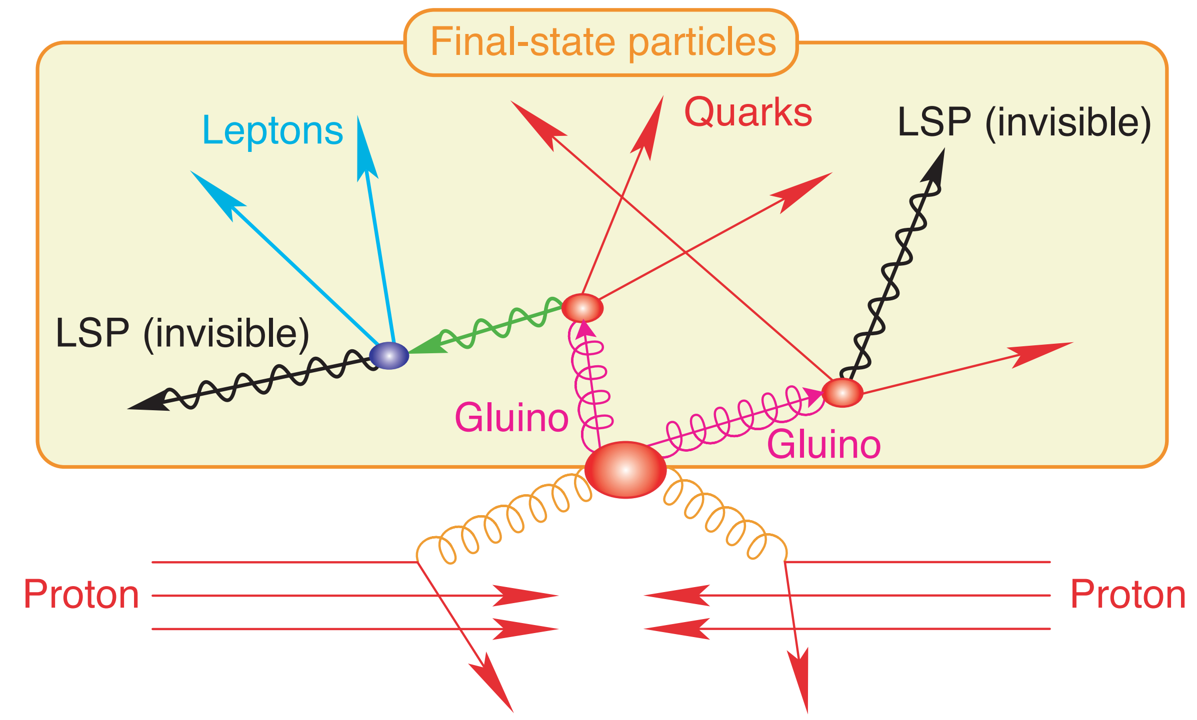
➡ $m_{\chi_0^1} \simeq 2.7\ \mathrm{TeV}$ for Wino DM / $m_{\chi_0^1} \simeq 1.0\ \mathrm{TeV}$ for Higgsino DM

[Hisano, Matsumoto, Nagai, Saito, Senami ('06); Cirelli, Strumia, Tambrini ('07)]

LSP search at the LHC

SUSY events are (usually) characterized by:

- High p_T jets
- Large MET



We may also consider:

- Disappearing track search
- Displaced vertex search
- Indirect search, relying on SUSY loop effects
- ...

Example of wave-like DM: axion (and ALPs)

Axion: Pseudo-NG boson in association with Peccei-Quinn symmetry

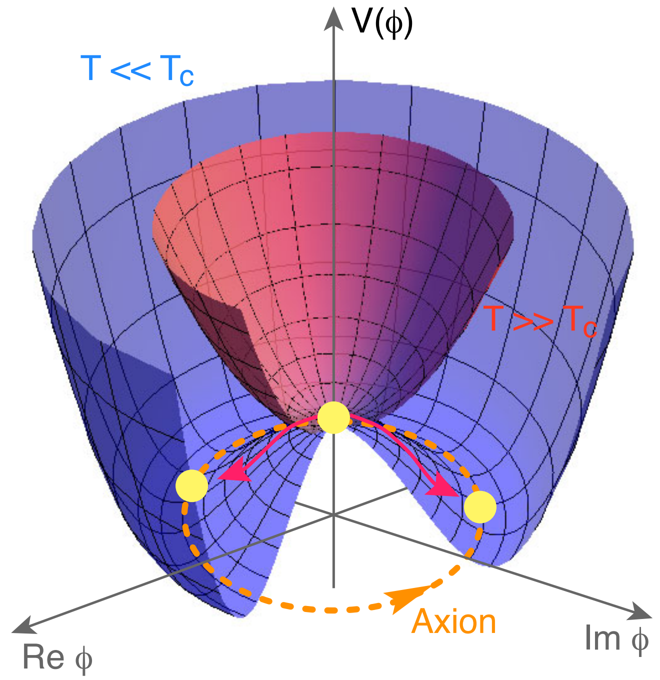
- Axion acquires its mass from QCD anomaly

$$m_a \simeq 5.7\ \mathrm{meV} \times \left(\frac{f_a}{10^9\ \mathrm{GeV}}\right)^{-1}$$ with f_a = axion decay constant

- Axion can be DM, if it was initially misaligned

$$\Omega_a h^2 \simeq 0.18 \times \theta_{\rm i}^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19}$$

[Turner ('86)]



Potential of PQ scalar

[Kawasaki, Nakayama ('13)]

- Axion interacts with SM particles

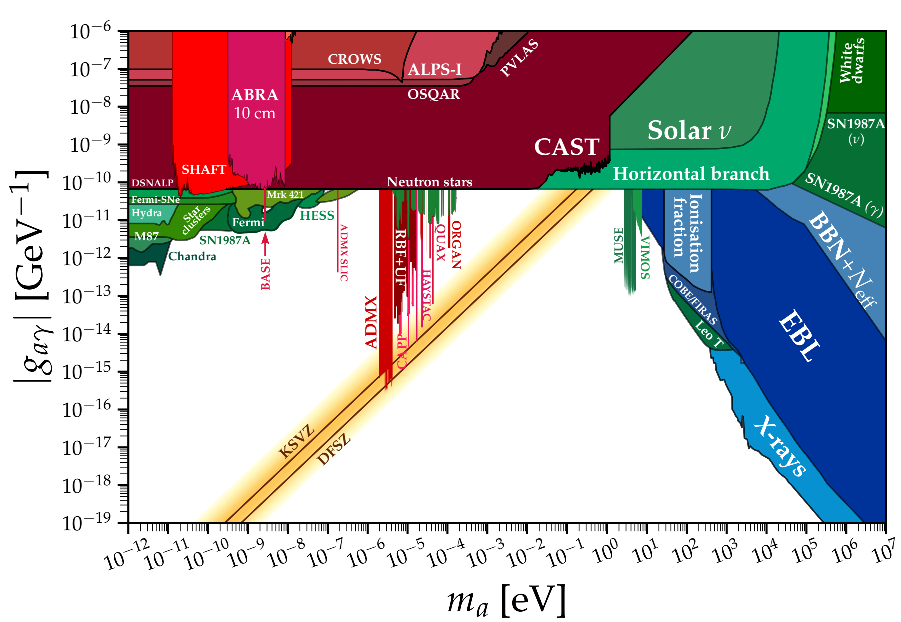
$$\mathscr{L}_{\rm int} \ni g_{a\gamma\gamma} a \vec{E}\vec{B} + \sum_{N=p,n} \frac{g_{aNN}}{2m_N} \bar{N}\gamma^\mu\gamma_5 N \partial_\mu a,$$ with $g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi}\frac{1}{f_a}$ and $g_{aNN} \sim \frac{m_N}{f_a}$

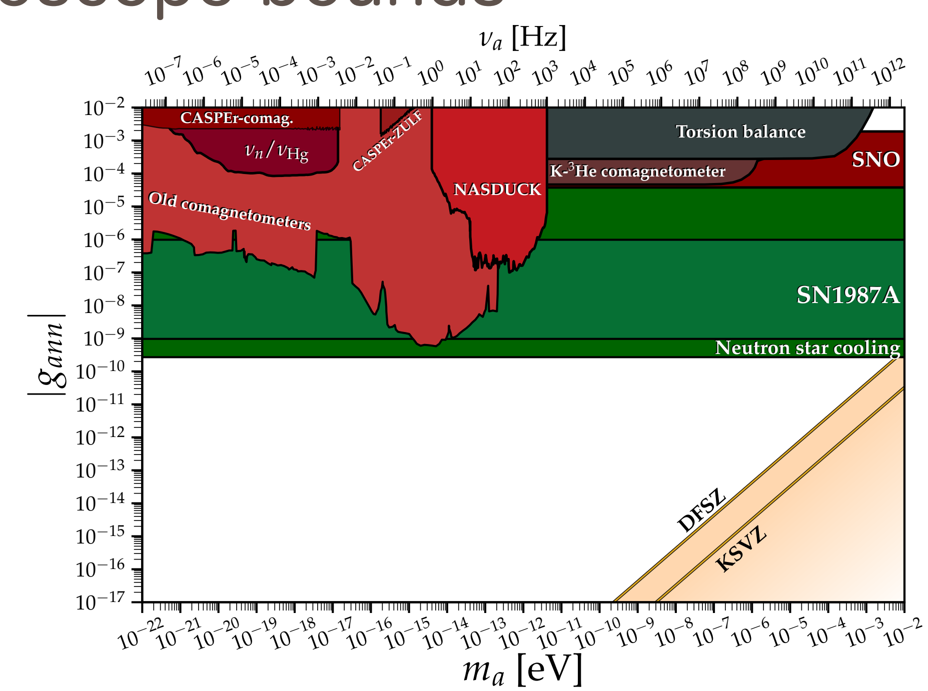
Axion / Axion-like particles (ALPs)

We may also consider axion-like particles (ALPs)

- m_a, $g_{a\gamma\gamma}$ and g_{aNN} are treated as free parameters
- ALPs may show up in, e.g., string phenomenology

Cosmological, astrophysical, and haloscope bounds



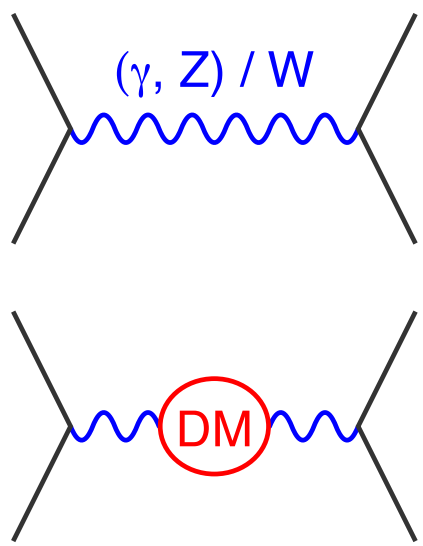


[PDG 2023]

➡ Collider search of axion / ALP DM may be challenging

Some Ideas for DM Search

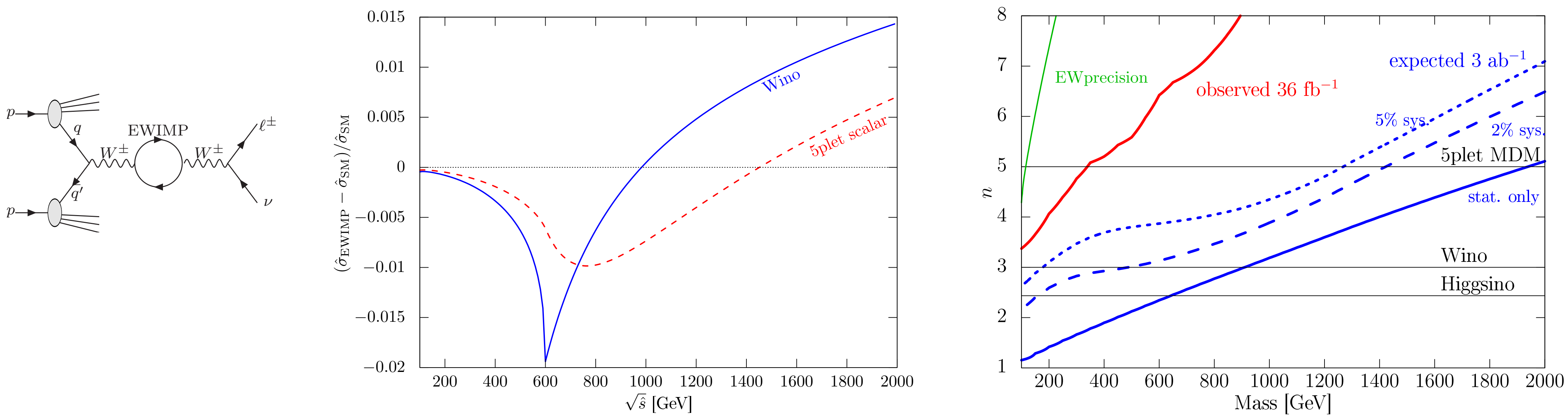
“Indirect” DM detection at colliders



- DM particle / mediator may affect the vacuum polarization
- Such an effect can be detected by precisely measuring cross sections
  [Alves et al. ('14); Harigaya et al. ('15); ...]

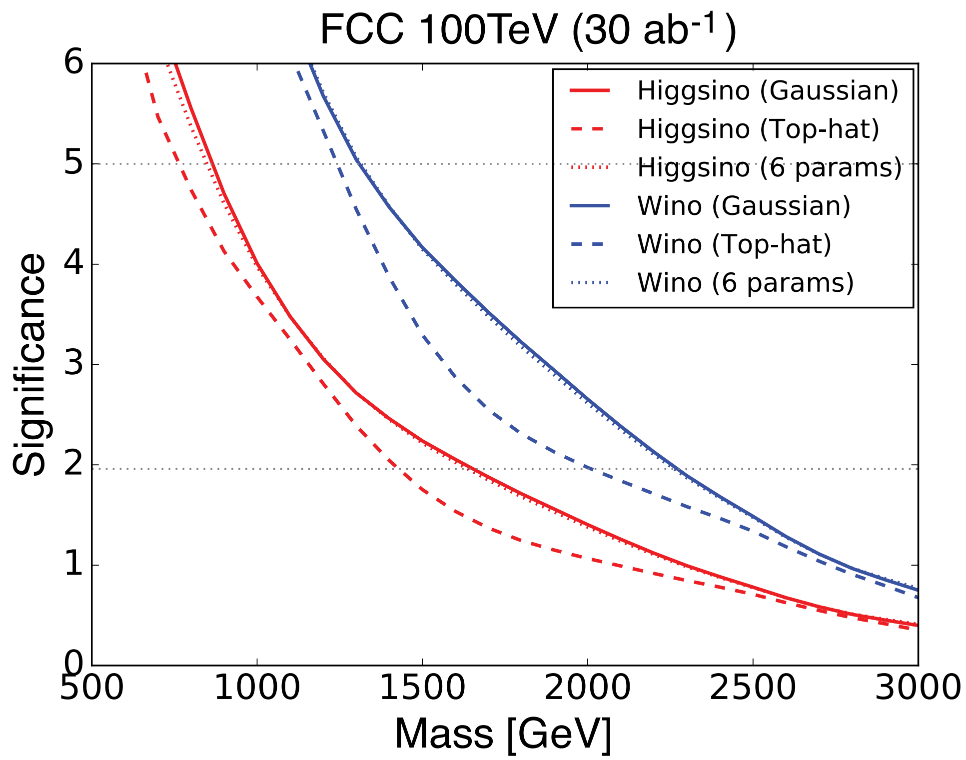
Mono-lepton events with high M_T at HL-LHC

[Matsumoto, Shirai, Takeuchi ('18)]



Indirect DM searches at very high energy colliders

FCC

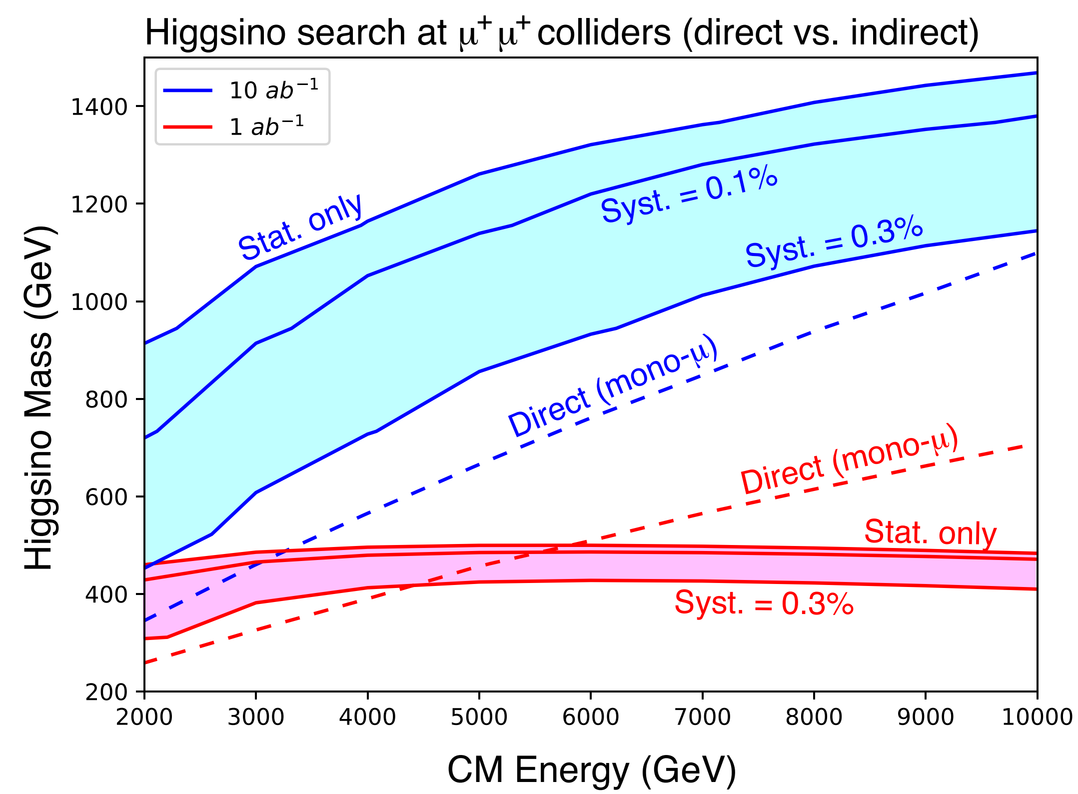


[Abe, Chigusa, Ema, TM ('19)]

$\mu^+\mu^+$ collider (μTristan, ...)

[Hamada et al. 2201.06664]

- Cooling of μ^+ is possible with current technology



[Fukuda, TM, Niki, Wei, in preparation]

- Precise understanding of the SM cross sections is necessary
- The reach is insensitiver to the decay lengths of the EWIMPs

Possible relation with flavor physics

Flavor U(1) may have QCD anomaly

➡ PQ U(1) symmetry may be embedded into flavor symmetry

[Ema, Hamaguchi, TM, Nakayama ('16); Calibbi, Goertz, Redigolo, Ziegler, Zupan ('16)]

$$\mathscr{L} = \lambda_{ij}^{d} \left(\frac{\phi}{M}\right)^{n_{ij}^{d}} \bar{Q}_i H d_{Rj} + \lambda_{ij}^{u} \left(\frac{\phi}{M}\right)^{n_{ij}^{u}} \bar{Q}_i \tilde{H} u_{Rj} + \cdots$$

$$\phi = v_\phi + \frac{1}{\sqrt{2}}(s + ia) \quad \text{with} \quad a = \text{"Flaxion"}$$

For example:

$$n^u = \begin{pmatrix} 8 & 4 & 3 \\ 7 & 3 & 2 \\ 5 & 1 & 0 \end{pmatrix}, \quad n^d = \begin{pmatrix} 7 & 6 & 6 \\ 6 & 5 & 5 \\ 4 & 3 & 3 \end{pmatrix}, \quad \lambda_{ij}^{u,d} \sim O(1), \quad \frac{v_\phi}{M} \sim 0.2$$

Flavor violating interaction of flaxion

Flaxion has flavor-violating interactions

$$\mathscr{L} \ni \sum_f \sum_{i,j} \left[m_{ij}^f \left(1 + \frac{h}{\sqrt{2} v_{\rm EW}} \right) \bar{f}_i f_j + i \frac{m_{ij}^f n_{ij}^f}{\sqrt{2} v_\phi} a \bar{f}_i \gamma_5 f_j \right]$$

Interesting process: $K^+ \to \pi^+ a$

$$\mathrm{Br}(K^+ \to \pi^+ a) \sim 1 \times 10^{-11} \times \left(\frac{10^{10}\,\mathrm{GeV}}{f_a} \right)^2 \times \mathcal{O}(1)$$

$$\mathrm{Br}(K^+ \to \pi^+ a) \lesssim 5 \times 10^{-11}$$

[NA62 Collaboration, 2103.15389]

NA62 Collaboration will improve the sensitivity

Other flavor violating processes may be also interesting

Hidden photon DM detection using qubits

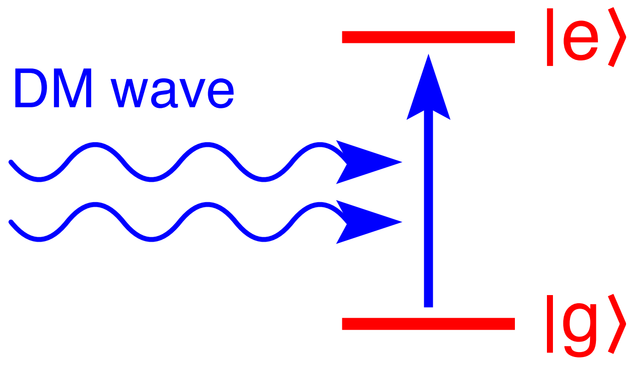
Quantum computers may be also used for DM detection

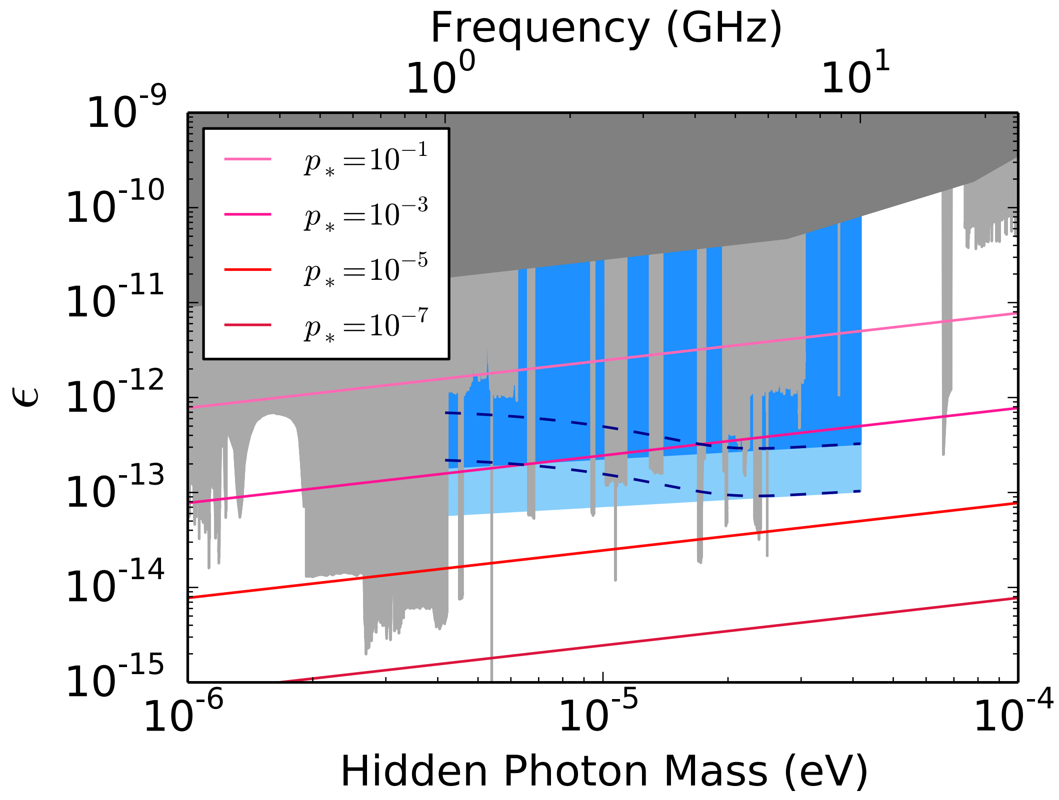
➡ Wave-like DM may excite qubits (in quantum computers)

[Chen, Fukuda, Inada, TM, Nitta, Sichanugrist ('22)]

Hidden photon DM may be detected with transmon qubits

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu$$

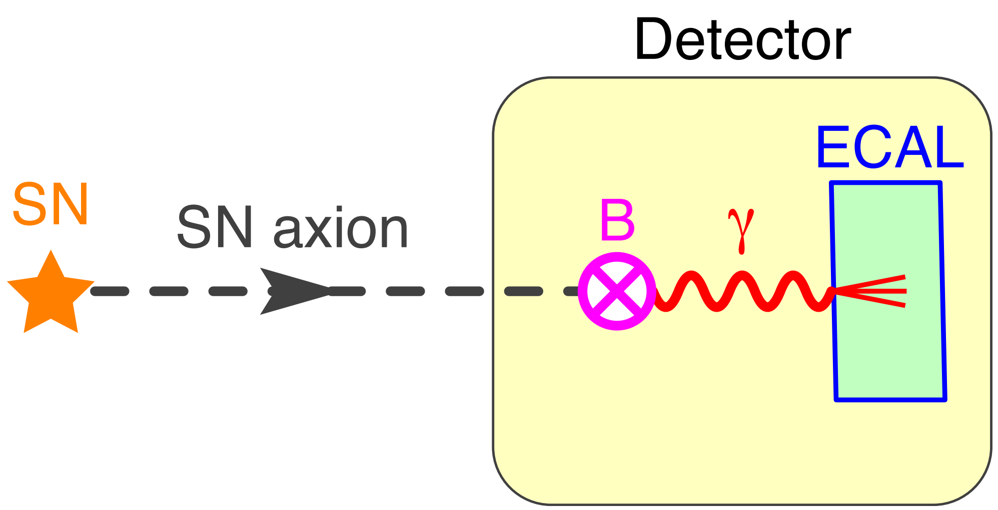


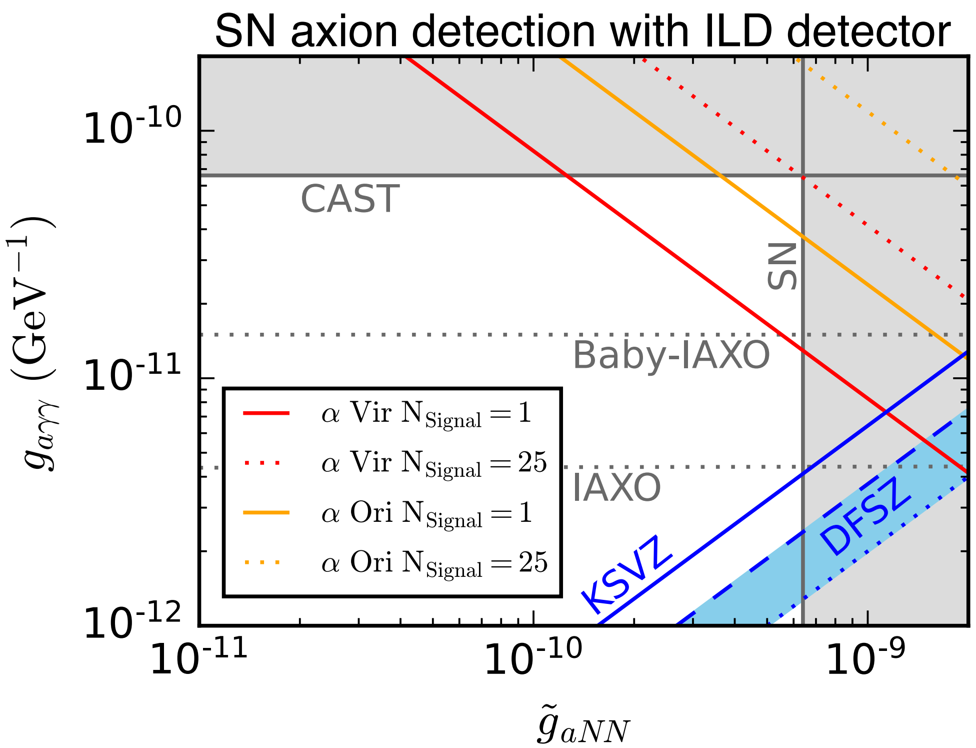


Detection of axions from a nearby SN

If a new SN occurs nearby the Earth:

- Collider detectors can be used to detect axions from the SN
  [Asai, Kanazawa, TM, Sichanugrist ('22); see also Ge et al. ('20)]
- We may rely on pre-SN alert system, based on SN neutrinos





[Asai, Kanazawa, TM, Sichanugrist ('22)]

- We should stop the beam and prepare for the SN axion, once the SN alert comes out

Summary

Summary

There should exist DM, but it has not been detected yet

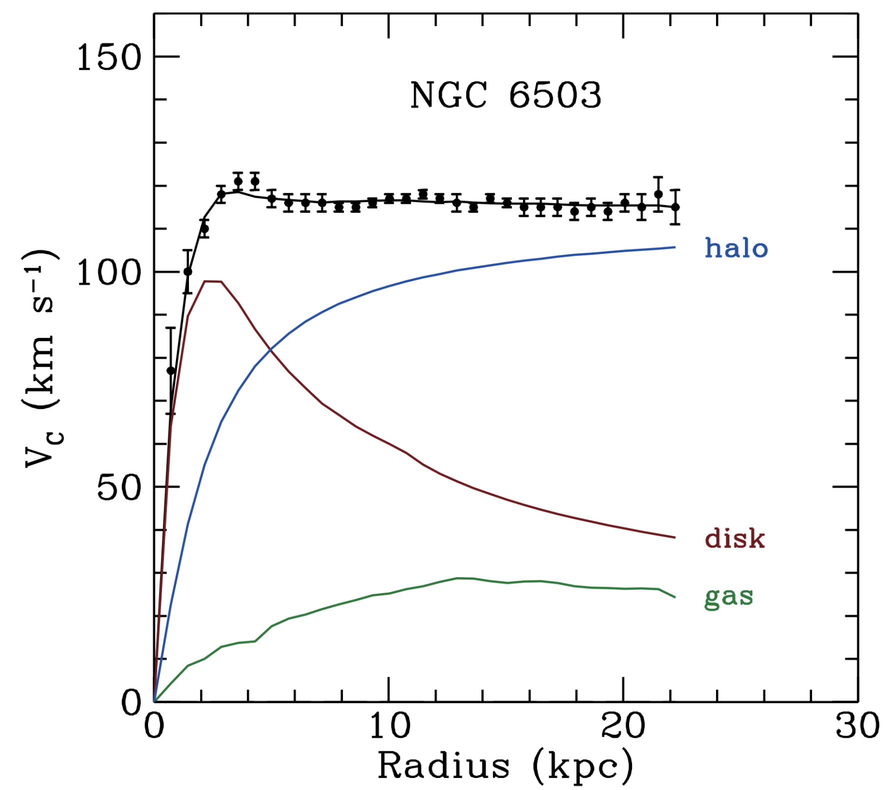
➡ We should keep on trying to find DM

➡ New ideas for the discovery are necessary

➡ We should try all possible detection methods (colliders, direct, and indirect searches)

Backups

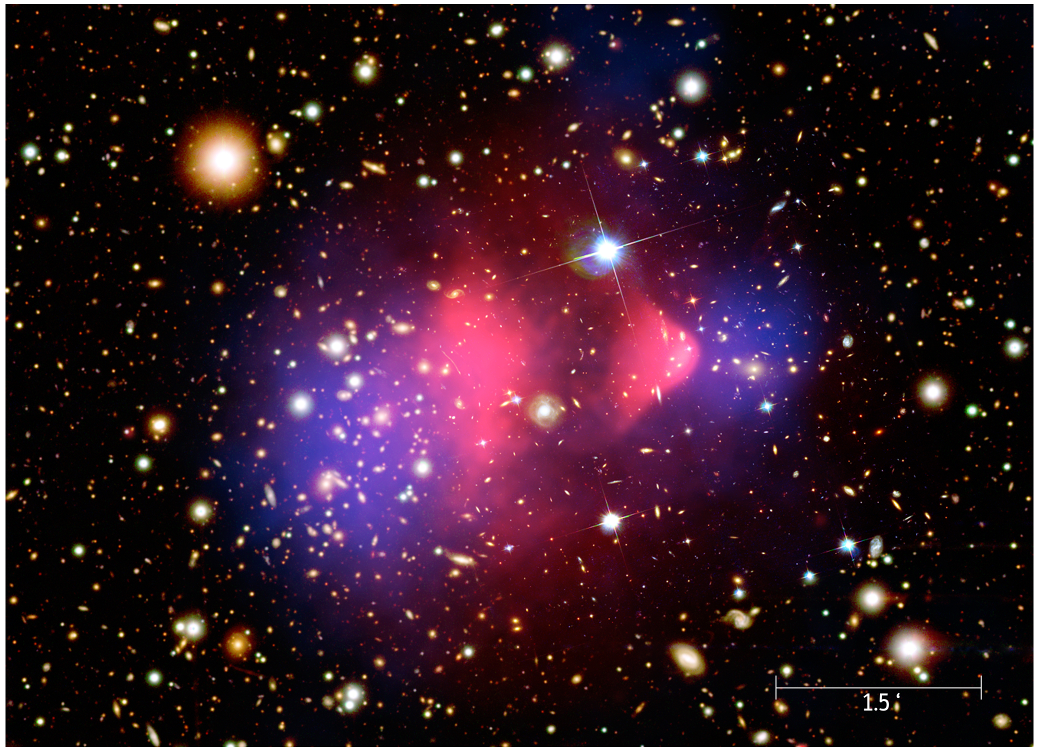
Why DM (1): Rotation curve



[Begeman, Broeils, Sandars ('91)]

- Visible objects are not enough to explain the rotation curve
- DM is necessary
- Galaxy size > $(m_{\rm DM} v_{\rm DM})^{-1}$ (see the discussion later)

Why DM (2): Bullet clusters



[ESA / Picture from Wikipedia]

Pink: Intense X-ray

⇒ Scattering of ordinary matters

Blue: Gravitational lensing

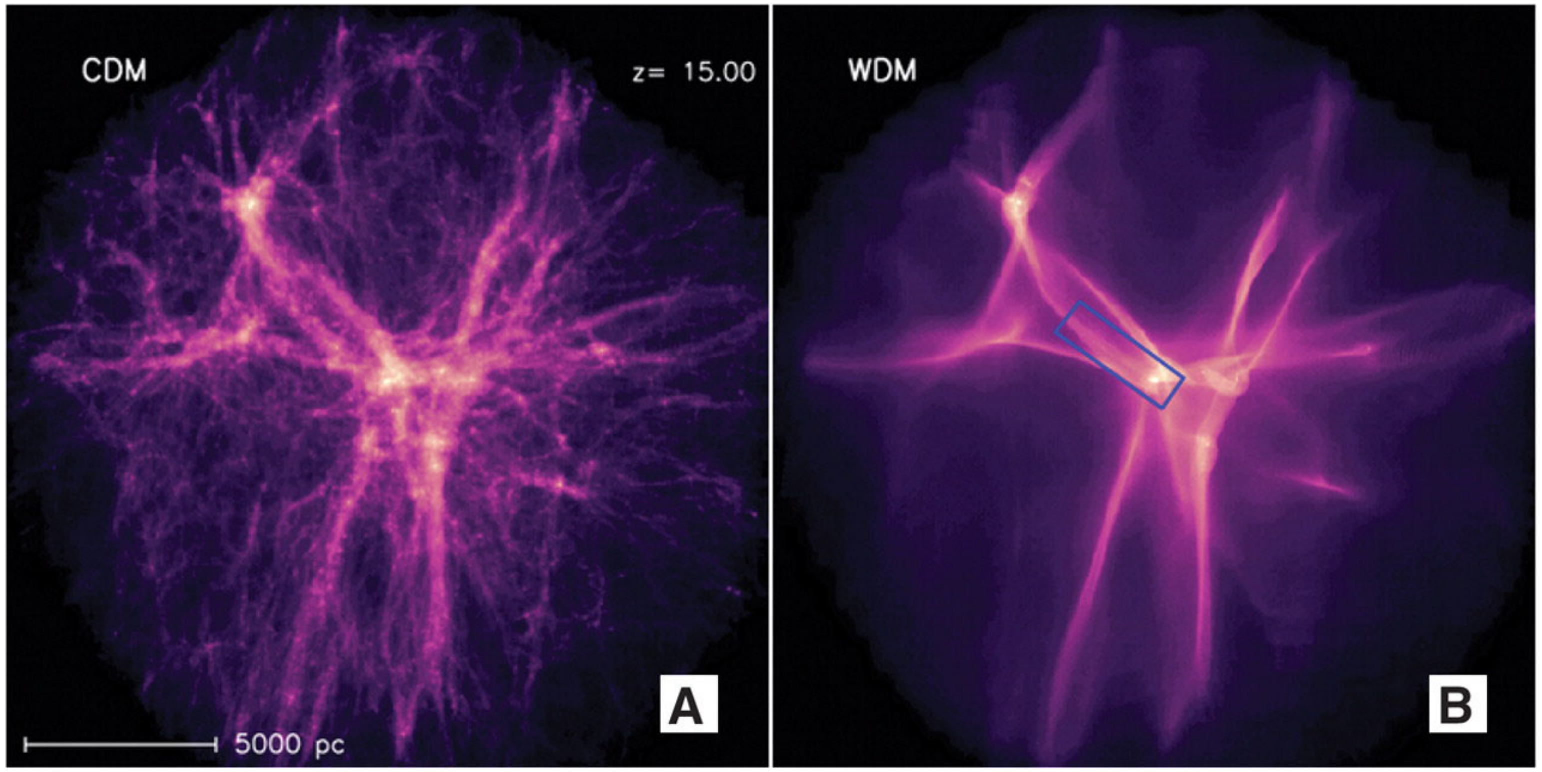
⇒ Due to DM energy density

DM interaction cross section: $\frac{\sigma_{\mathrm{DM-DM}}}{m_{\mathrm{DM}}} \lesssim \frac{1\ \mathrm{cm}^2}{\mathrm{g}}$

[Clowe, Gonzalez, Markevitch ('04); Markevitch et al. ('04); Randall et al. ('08); Harvey et al. ('15); Robertson, Massey, Eke ('17)]

⇒ If $\sigma_{\mathrm{DM-DM}} \sim \Lambda^{-2}$ and $m_{\mathrm{DM}} \sim \Lambda$, then $\Lambda \gtrsim 100\ \mathrm{MeV}$

Why DM (3): Structure formation



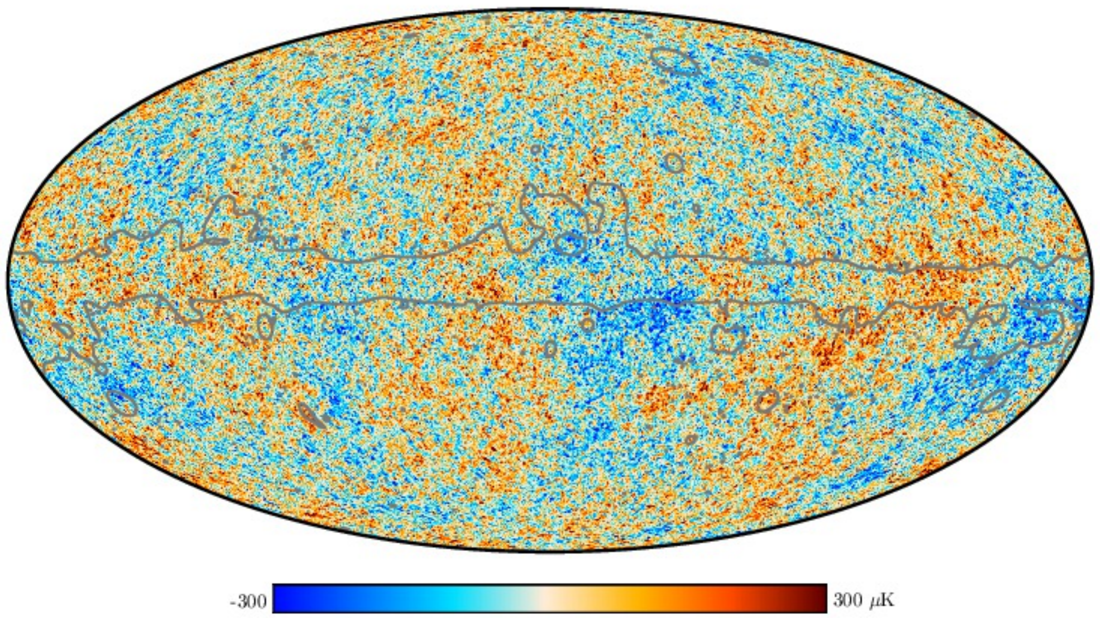
[CDM vs. WDM (3keV): Geo, Theuns ('91)]

DM is needed for structure formation

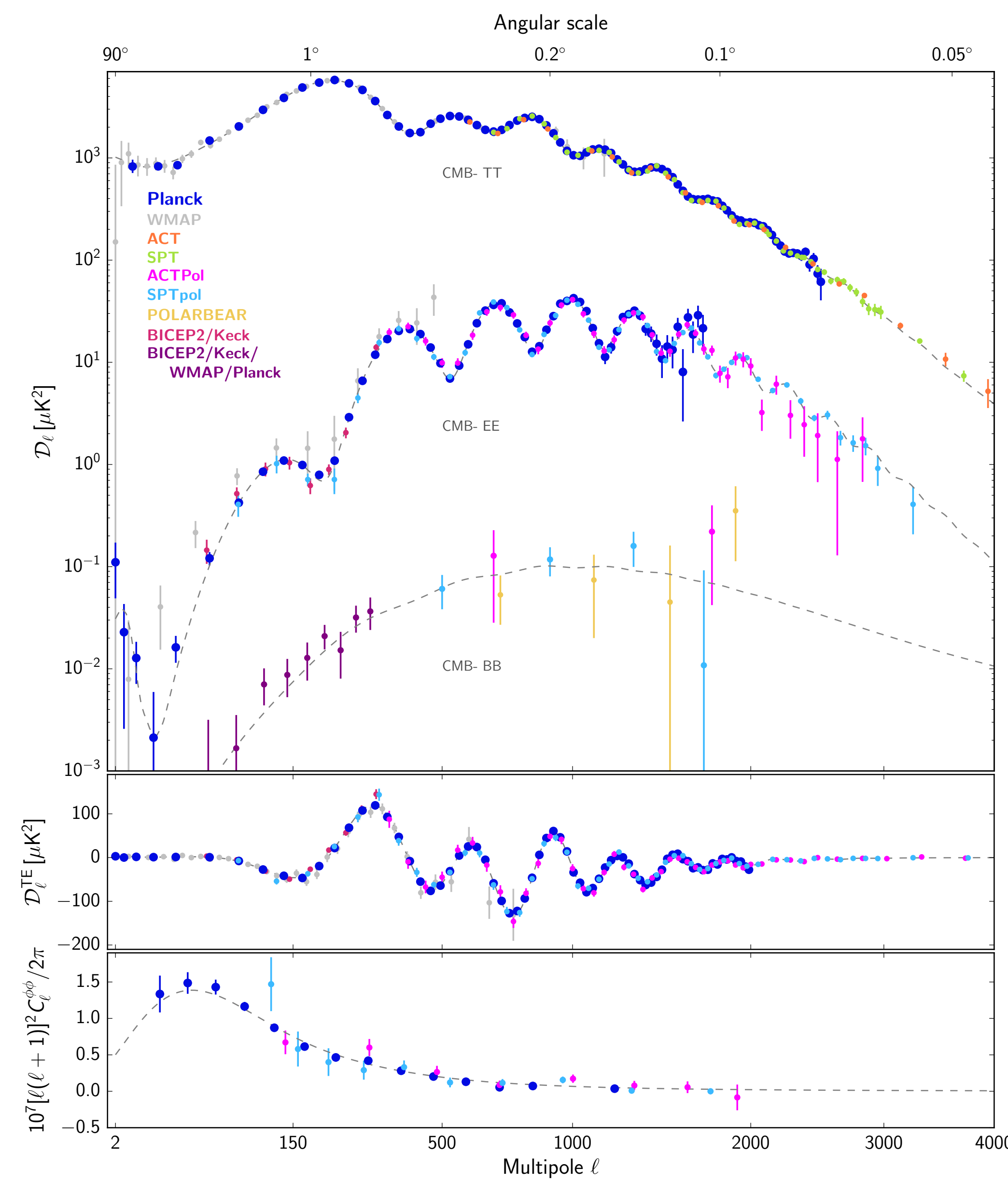
➡ Pressure of the DM should be negligible at $T \sim O(1)$ keV

➡ For thermal-WIMP DM: $m_{\rm DM} \gtrsim O(1)$ keV

Why DM (4): CMB observations



[Planck Collaboration ('18)]



Ω_{DM} from the CMB map: $\Omega_{DM} \simeq 0.3111 \pm 0.0056$