Particle Dark Matter
~Current status of theory & search~

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53rd Summer school on Astronomy & Astrophysics @Hongo, Tokyo August 3rd, 2023

Contents

- What is Dark Matter (DM)?
- DM candidates
- DM search directions

Part 1

- New direction of DM search (Neutron star as DM target)

Part 2

What is Dark Matter?

Dark Matter

cf. $M(r) = \int dr 4\pi r^2 \rho(r)$

Missing mass [Oort (1932)]

- Vertical stellar motion of solar neighborhood
  → Our universe (=visible component) lacks the mass → Missing mass problem

"Dark Matter" [Zwicky (1933)]

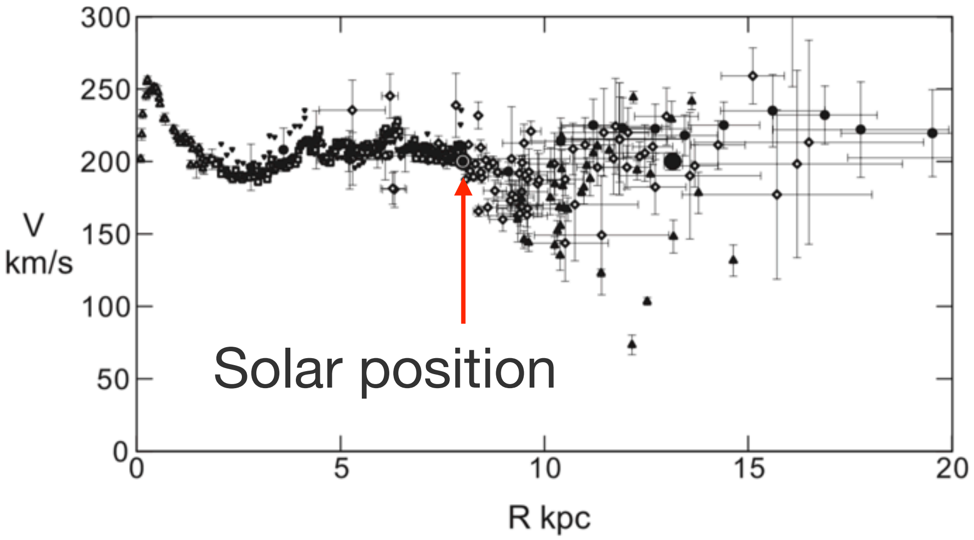
- Dynamical mass of Coma cluster is analyzed
- Virial theorem is applied
  $2(\text{Kinetic energy}) = (\text{Potential energy})$ @stable system

Rotational curve of galaxy [Rubin, et al. (1970)]

- Expectation: $v_c = \sqrt{\frac{GM_<}{r}}$, (Newtonian gravity)
- Observed: $v_c \sim (\text{constant})$

$$\frac{mv(r)^2}{r} = \frac{GmM(r)}{r^2}$$

→ $M(r) \sim r$
→ $\rho(r) \propto 1/r^2$
→ Invisible mass?



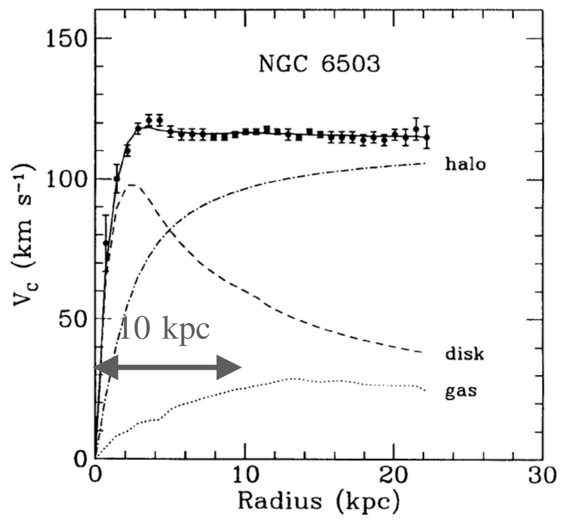
DM: Necessary condition

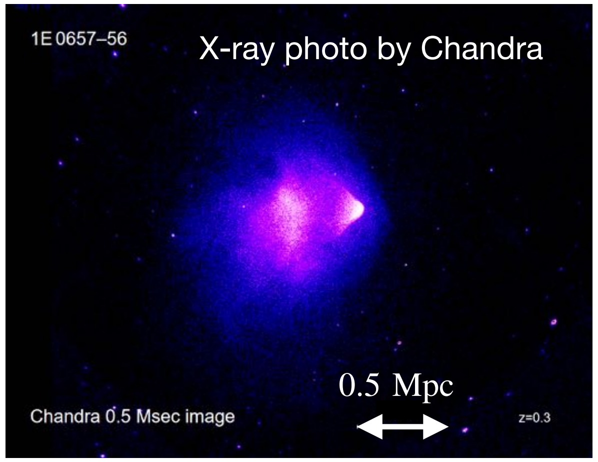
DM evidences (summary)

- Rotational curves of galaxy — Rubin et al. (1980)
- Bullet clusters — Markevich et al. (2002), Clowe et al. (2006)
- Gravitational lensing — Oguri et al. (2018)

Implication? → **Invisible(="Dark") unknown massive source**

※ Evidences are discovered independently in various scales
※ Required as necessary component in our universe (discussed later)





Qualitative feature of DM

- Electrically neutral
- Behave as matter @structure formation (~Massive)
- Stable /long-lived

Vast possibilities for DM candidates
But no suitable candidate in the Standard Model (SM)

(review) Standard Model Particles

Quarks

→ Exist as baryon/meson

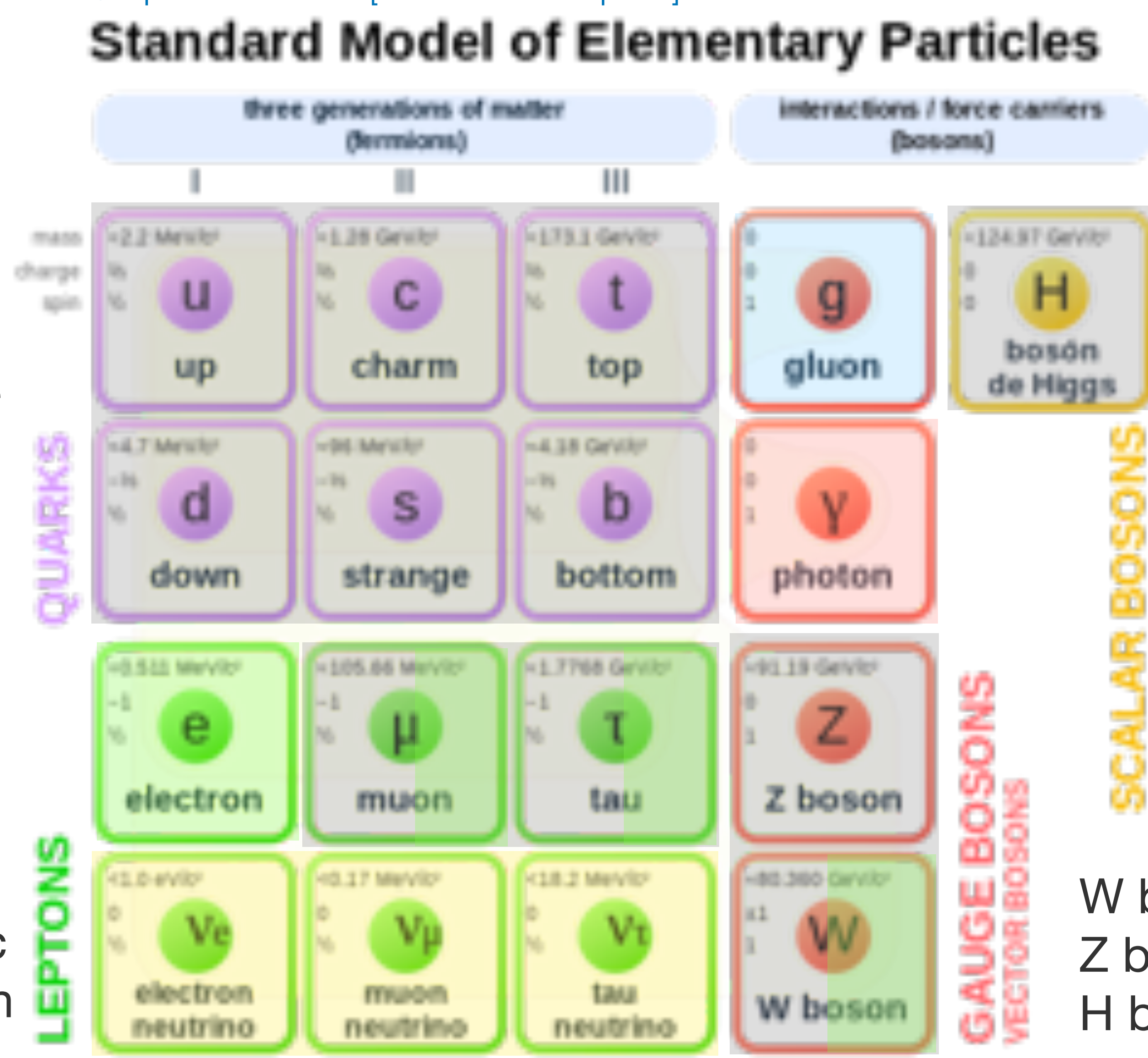
Proton : charged
Neutron : neutral but unstable
Pion : charged &/or unstable

Leptons

Electron : stable but charged

Neutrino?: neutral but relativistic
@ structure formation

SM particle contents [Picture from Wikipedia]



: unstable

: charged

: massless

: strong int.

W boson: charged & unstable
Z boson : neutral but unstable
H boson : neutral but unstable

If DM is an elementary particle, we need to update the SM table

What is the particle nature of DM?
(eg. DM mass, DM spin, DM interaction w/ SM particle, DM self-interaction, …)

DM density profile

$r_s = 24.42$ kpc,
$\rho_s = 0.184$ GeV cm^{-3}.

N-body simulation

- Realizing DM halo in computer fixing cosmological model (such as ΛCDM model)
- Global (~ 100 kpc) profile of DM halo can be predicted → vs observations

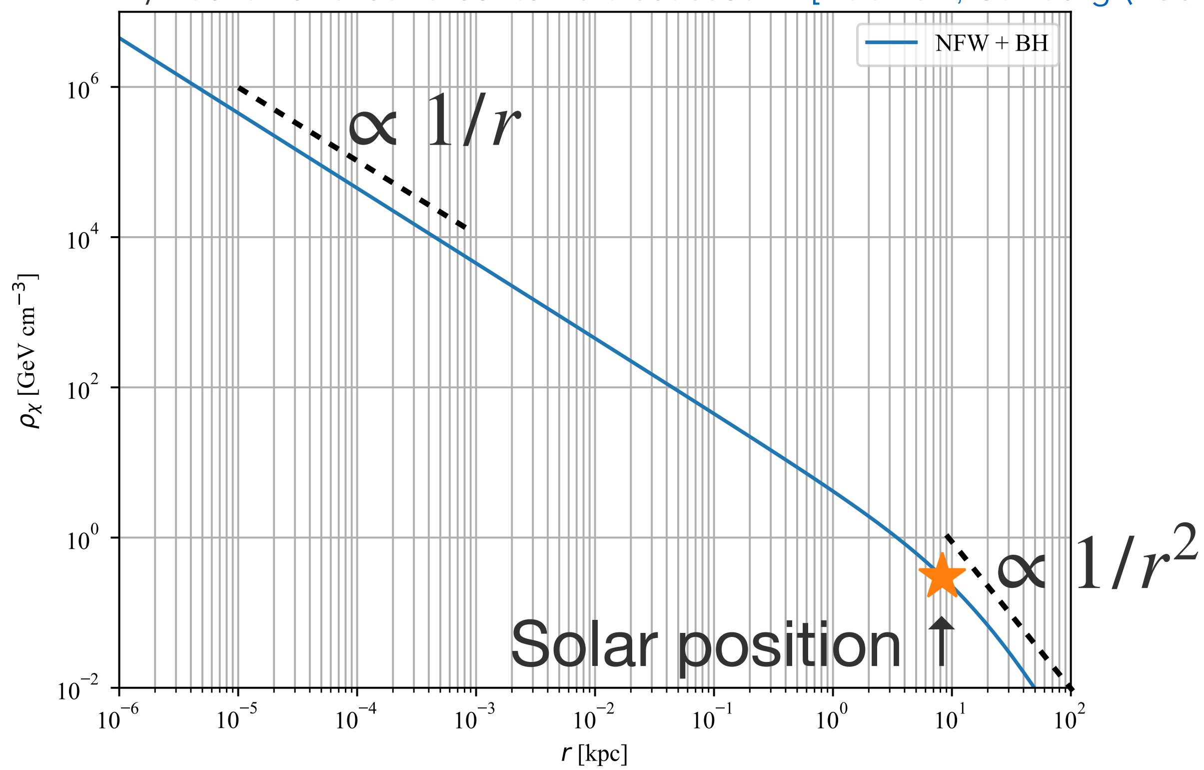
Navarro-Frenk-White profile

- N-body simulation of Cold DM profile
- Center part: shallower than $\sim r^{-1}$
- Near viral radius: steeper than $\sim r^{-2}$

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

[Navarro, Frenk, White (1996)]

1/r behavior around center is discussed in [Dubinski, Carlberg (1991)]



Variation of DM density profiles

Cusp vs Core

- Cusped profile

$$\rho_{\text{Einasto}}(r) \equiv \rho_s \exp\left[-\frac{2}{\alpha_s}\left(\left(\frac{r}{r_s}\right)^{\alpha_s} - 1\right)\right]$$

- Cored profile

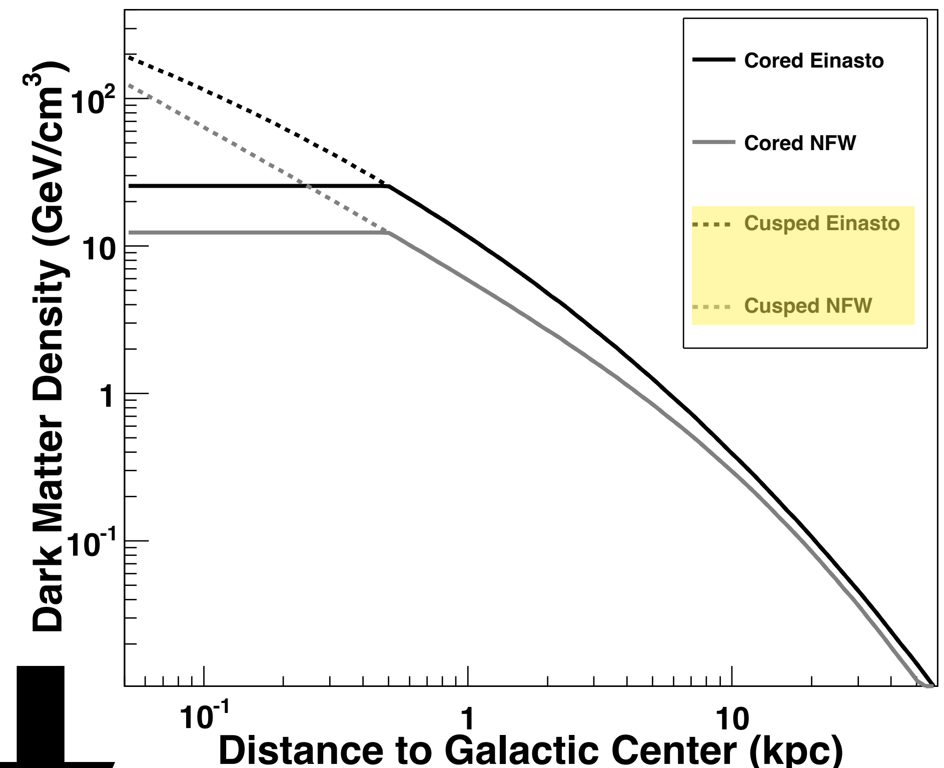
$$\rho(r) = \begin{cases} \rho_{\text{Einasto}}(r) & \text{for} \quad r > r_c, \\ \rho_{\text{Einasto}}(r_c) & \text{for} \quad r < r_c, \end{cases}$$

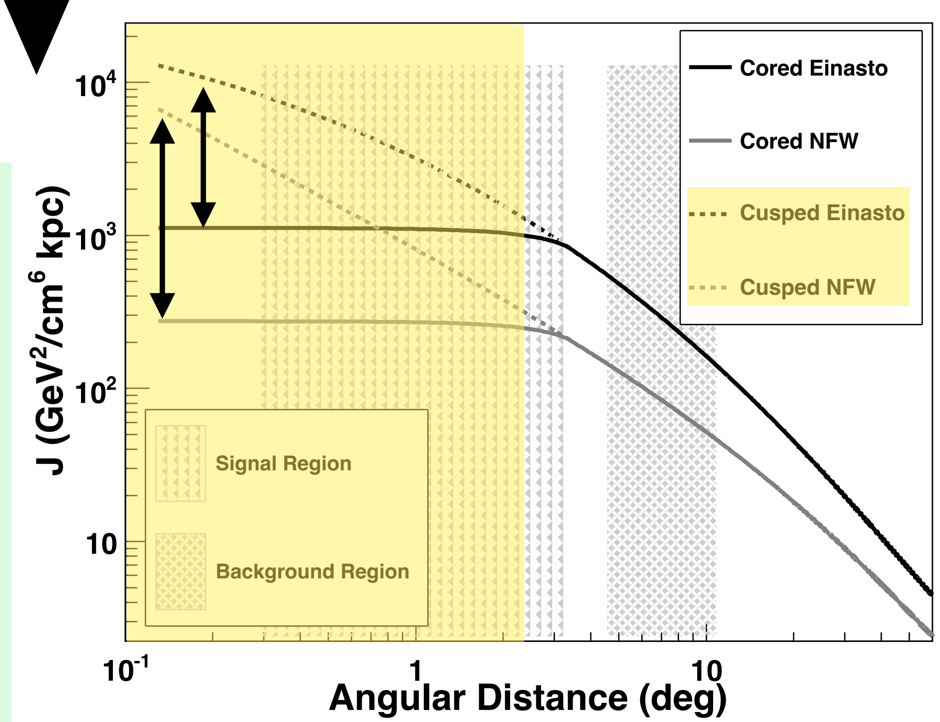
(r_c : core radius)

Profiles	Einasto	Einasto2
ρ_s [GeV cm^{-3}]	0.079	0.033
r_s [kpc]	20.0	28.4
α_s	0.17	0.17

Einasto: [Bertone, et al. (2009)]
Einasto2: [Cirelli, et al. (2011)]

[Abramowski, et al. [H.E.S.S] (2015)]





Cusped profile: Enhancement in flux for small angle
Numerical impact → several orders

→ Huge uncertainty from DM density profiles especially to probe DM in **indirect detection**

(∵ We need global DM density profile)

DM candidates

DM candidates (1/2)

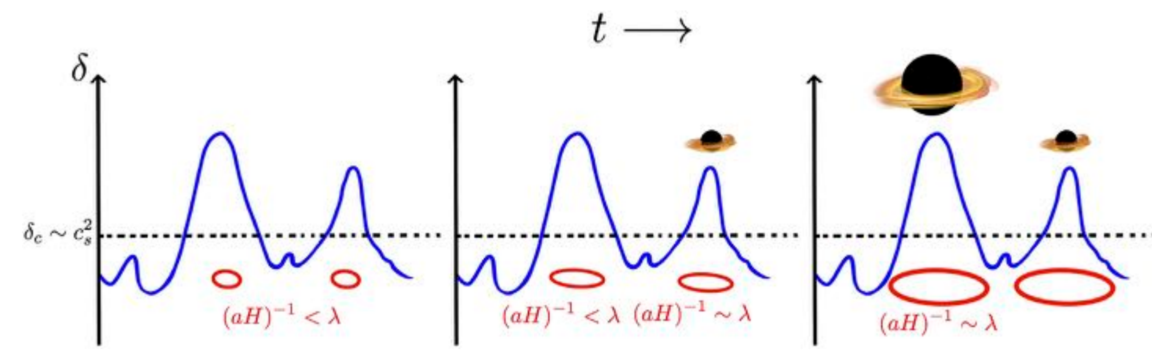
c_s : speed of sound

Primordial blackhole (PBH)

[Chapline (1975)] [Meszaros (1975)]

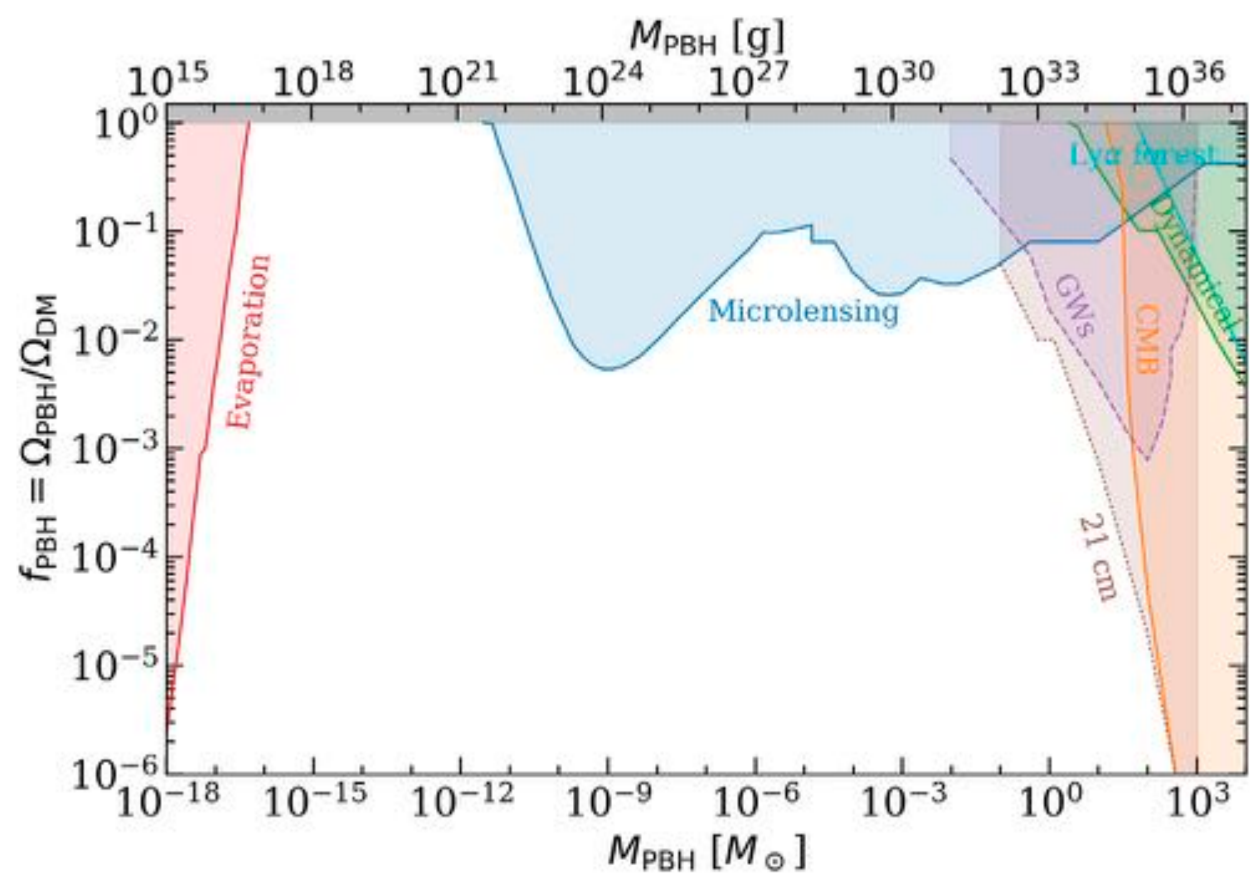
[Villanueva-Domingo, Mena, Palomares-Ruiz [review] (2021)]

- Compact object formed in early universe
- (density fluctuation)> (critical value) $\simeq c_s^2$
  → Corresponding region collapse
- (BH scale) ~Universe @collapse time
- BH mass can be flexible
  cf. (stelar BH mass) $\sim M_\odot$



Current status

- $M_{\rm BH} \lesssim 10^{-16}\ M_\odot$:
  PBH evaporates in current universe
- $M_{\rm BH} \in [10^{-16}, 10^{-12}] M_\odot$:
  100% DM is possible but some constraints are under debate
- $M_{\rm BH} \gtrsim 10^{-12} M_\odot$:
  constrained by Microlensing, CMB, etc



DM candidates (2/2)

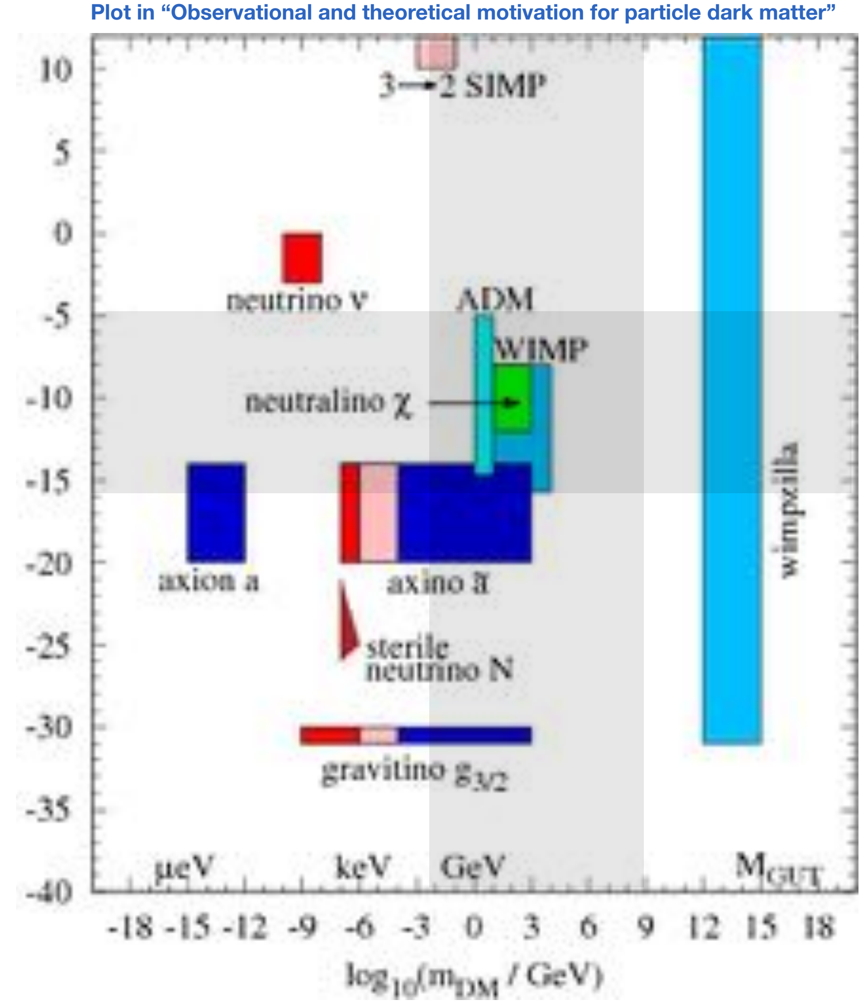
Particle DM

- Even if we focus on particle DM candidates, we have vast possibilities for DM
  → DM identification is ultimately a challenging task
- What kind of information do we need for DM identification?
  - DM mass
  - Coupling w/ SM particles

Concrete candidates

- **Weakly Interacting Massive Particle (WIMP)**
- Sterile neutrino
- Axion
- Feebly Interacting Massive Particle
- Strongly Interacting Massive Particles
- Self-interacting DM …

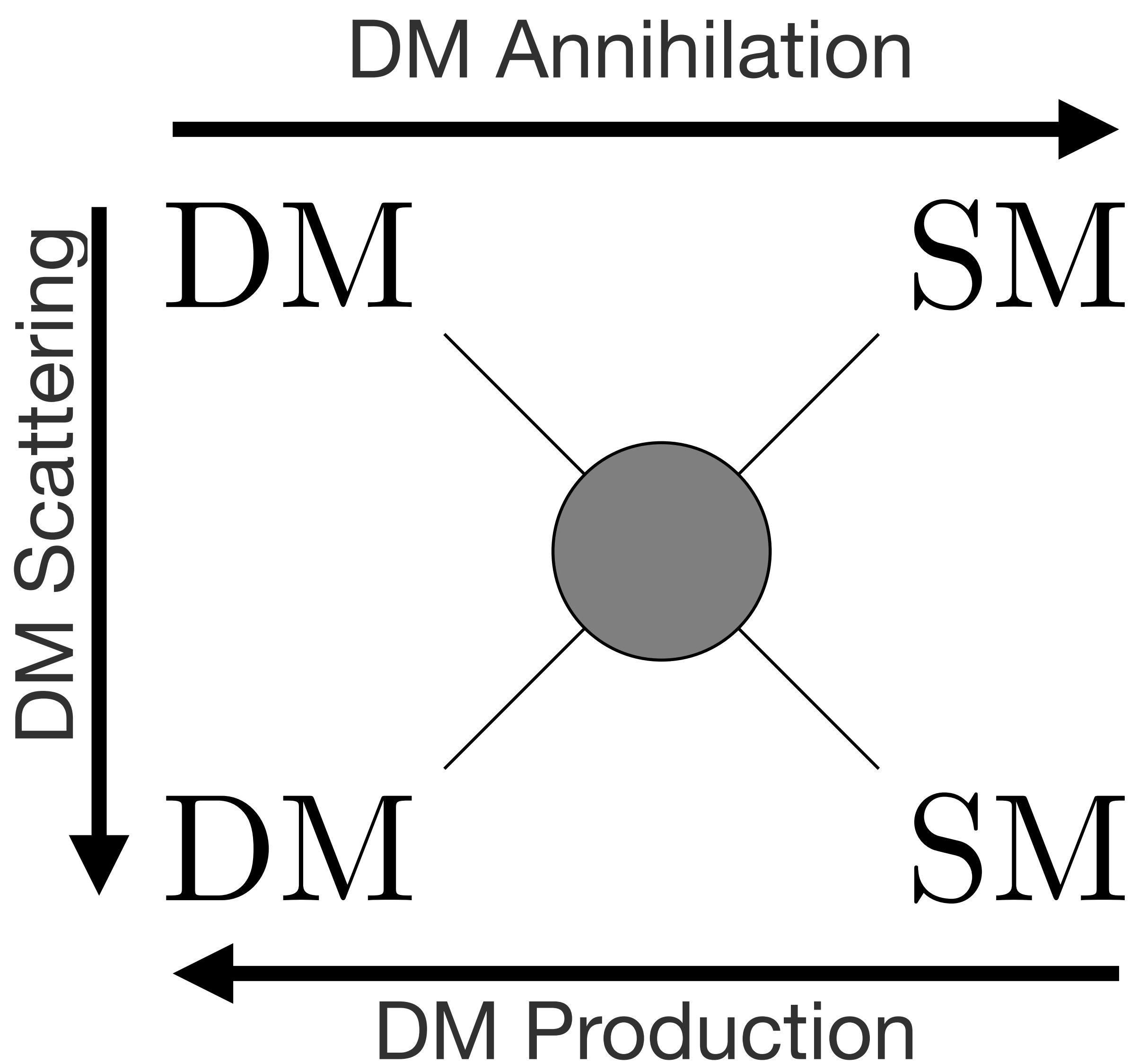
Plot in "Observational and theoretical motivation for particle dark matter"



Weakly Interacting Massive Particle

Assumption

DM is an unknown elementary particle that “weakly” interacts w/ SM particles



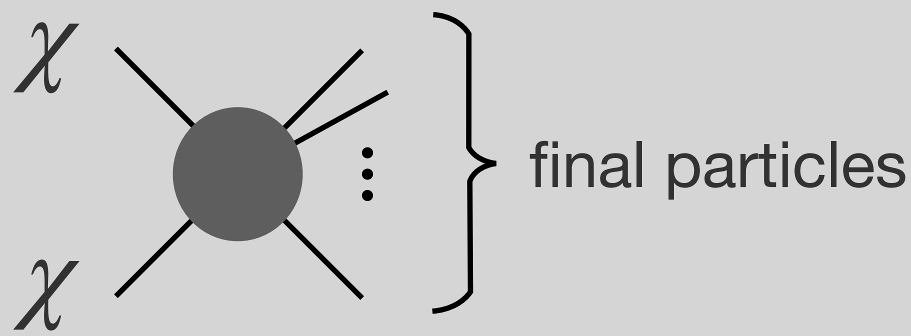
Features

- DM is thermalized in early universe
- WIMP candidate often appears if we extend the SM frame work
- We have various channels to test (& crosscheck) DM property

Let’s see what happen once we assume this hypothetical unknown particle in the expanding universe

Annihilation rate

DM pair annihilation:



$\mathscr{M}_{\chi\chi\to\mathrm{final}}$: Annihilation amplitude of DM

- related to probability of each process
- highly depends on individual model

Phase space $(\mathbf{x},\mathbf{p})$, internal d.o.f.

Definition:

$$\langle \sigma_{\mathrm{ann}} v \rangle = \sum_{\mathrm{final}} \frac{\int |\mathscr{M}_{\chi\chi\to\mathrm{final}}|^2 (f^{\chi}_{\mathrm{eq}})^2 d(\mathrm{phase\ space})}{\int (f^{\chi}_{\mathrm{eq}})^2 d(\mathrm{phase\ space})}$$

Adding all the possible modes

distribution function of DM @ equilibrium

$$f_{\mathrm{eq},i} = \frac{1}{e^{\frac{E_i}{T}} \pm 1} \sim e^{-\frac{E_i}{T}}$$

$\left[\begin{array}{l} E_i : \text{energy of particle} \\ T : \text{temperature} \end{array} \right]$

Boltzmann equation

Time evolution of DM number density

Change of DM # in time evolution of expanding universe

Change of DM # due to particle processes

$$\boxed{\frac{dn_\chi}{dt} + 3Hn_\chi} = \boxed{-\langle \sigma_{\rm ann} v \rangle (n_\chi^2 - n_{\chi,\rm eq}^2)}$$

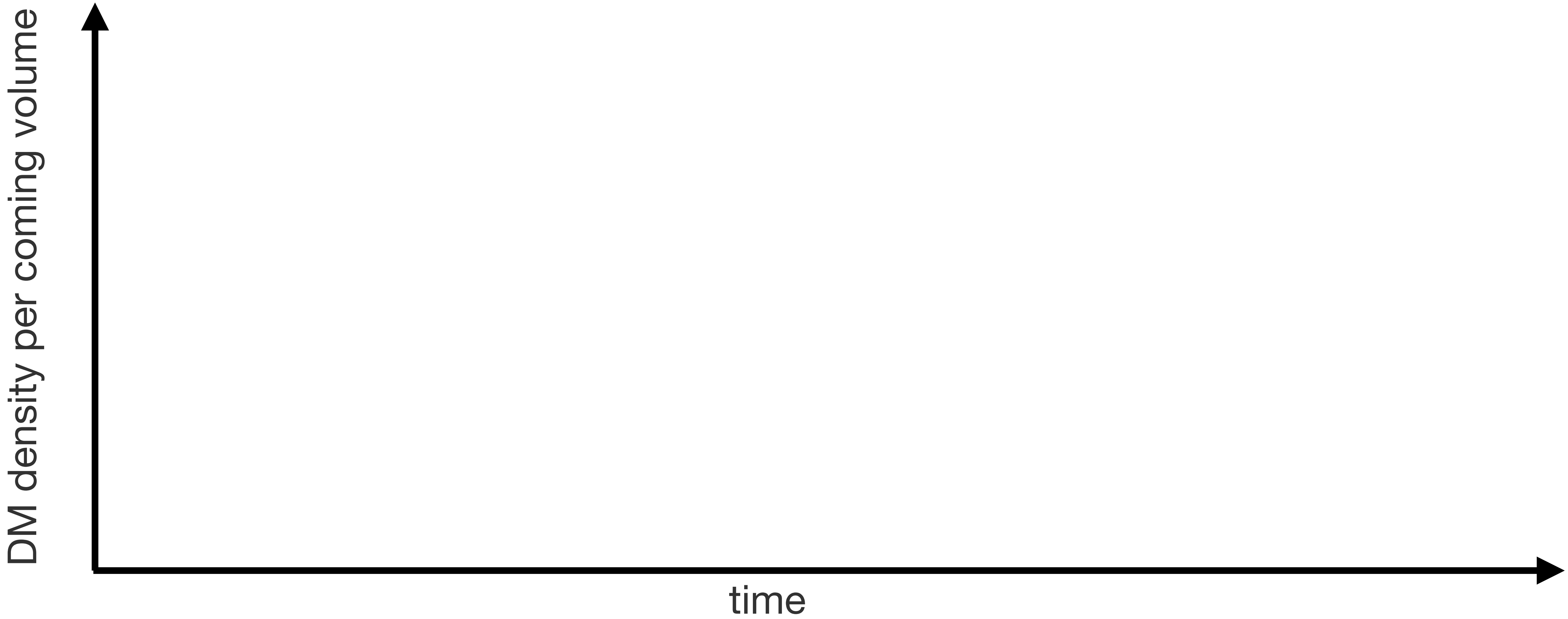
- Annihilation rate control process → $\propto \langle \sigma_{\rm ann} v \rangle$
- **Pair** annihilation process → $\propto (\text{DM \# density})^2$
- No change @equilibrium → $\propto (n_\chi^2 - n_{\chi,\rm eq}^2)$

Solve this equation → **prediction** on DM energy density observed today

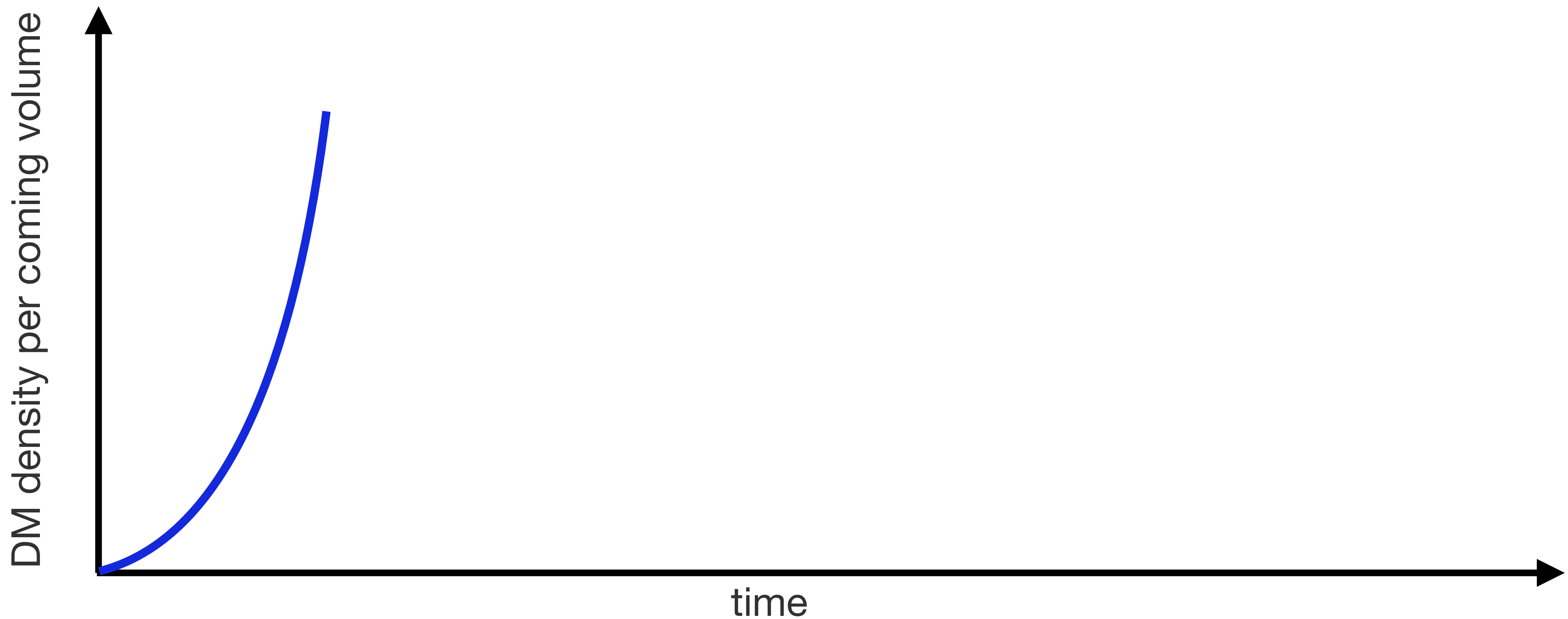
CMB observation → Observationally favored DM energy density

We can test this scenario by comparing theoretical prediction in light of observation

Thermal history

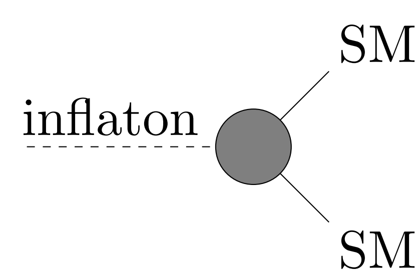


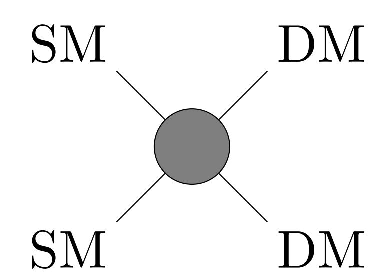
Thermal history



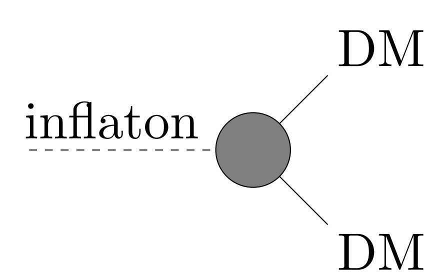
Production

eg1. DM production from SM particles
produced during reheating



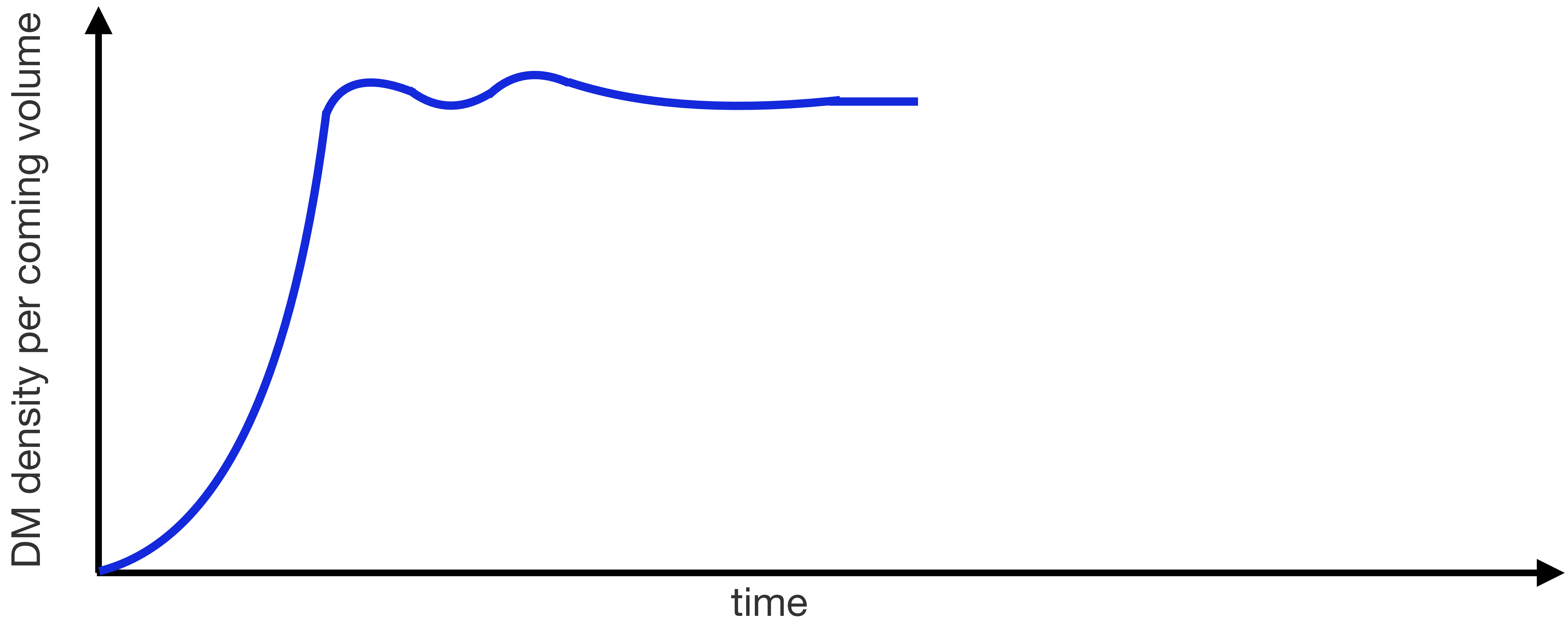


eg2. DM production directly from inflaton



※ Many possibilities for initial condition

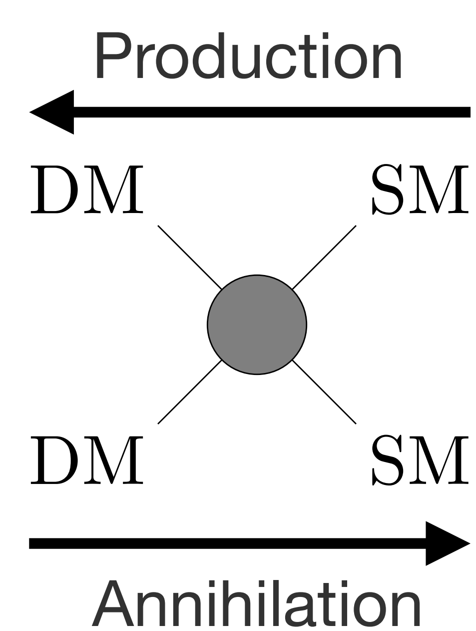
Thermal history



Equilibrium

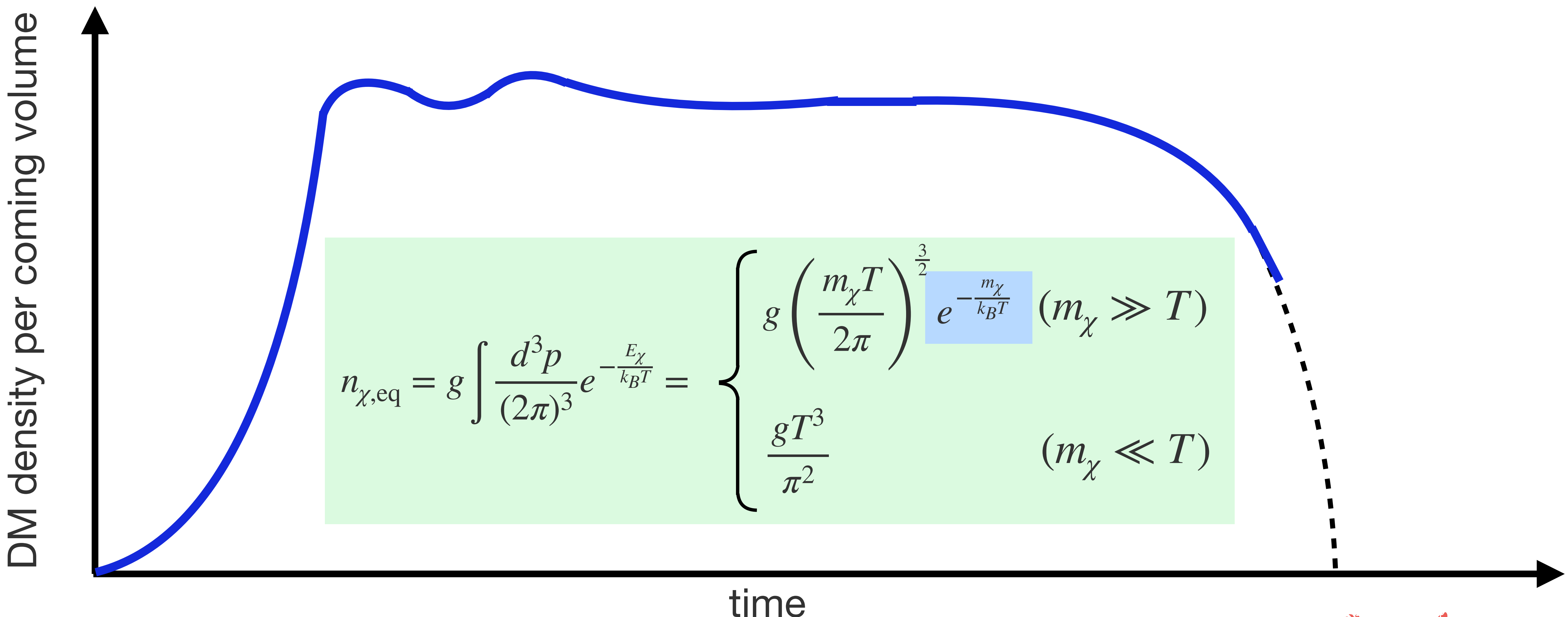
DM is in thermal equilibrium through the interaction w/ SM particles

→ Physics after equilibrium can “forget” about initial condition
We can derive general predictions independent of initial condition



Thermal history

g: internal d.o.f

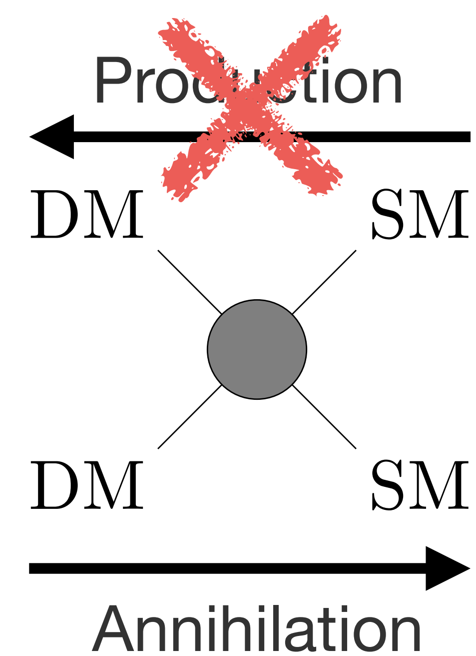


$$n_{\chi,\mathrm{eq}} = g\int \frac{d^3p}{(2\pi)^3} e^{-\frac{E_\chi}{k_B T}} = \begin{cases} g\left(\dfrac{m_\chi T}{2\pi}\right)^{\frac{3}{2}} e^{-\frac{m_\chi}{k_B T}} & (m_\chi \gg T) \\ \dfrac{gT^3}{\pi^2} & (m_\chi \ll T) \end{cases}$$

Annihilation

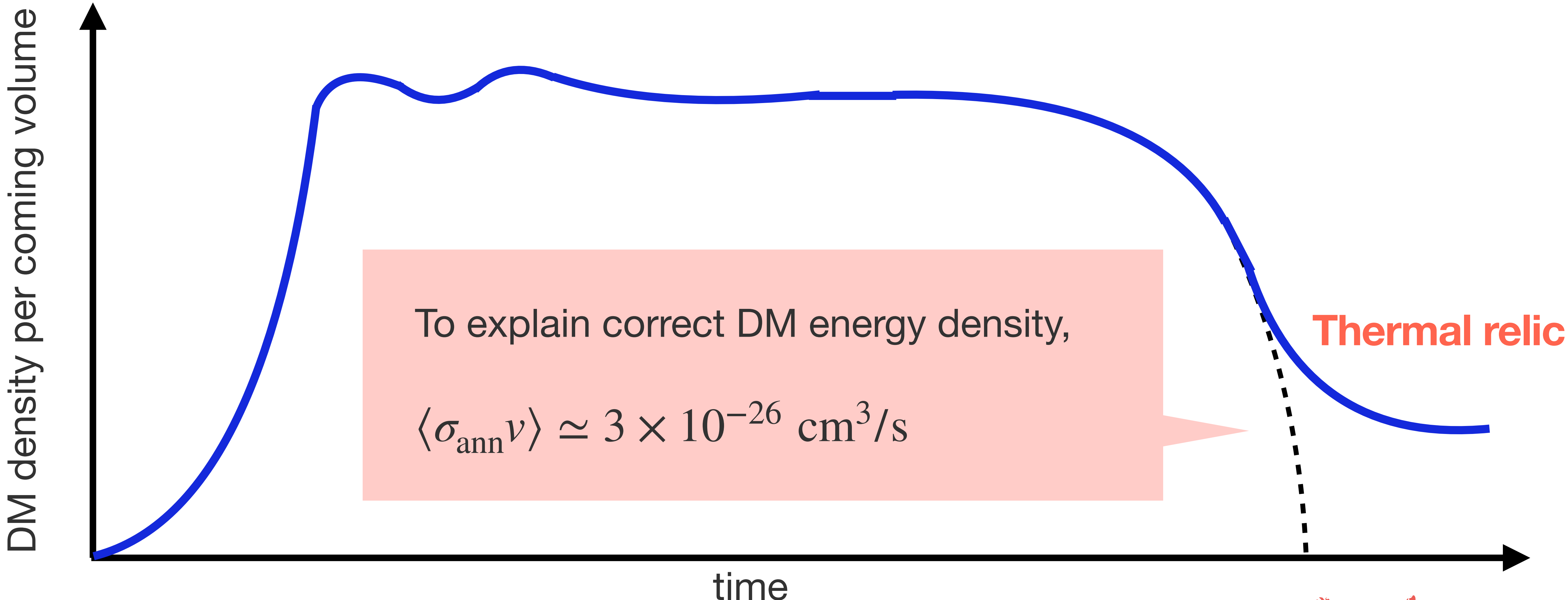
During cosmic expansion, temperature keep decreasing

→ Thermal bath can no longer produce DM pair
→ DM # density decrease exponentially



Thermal history

H: Hubble constant

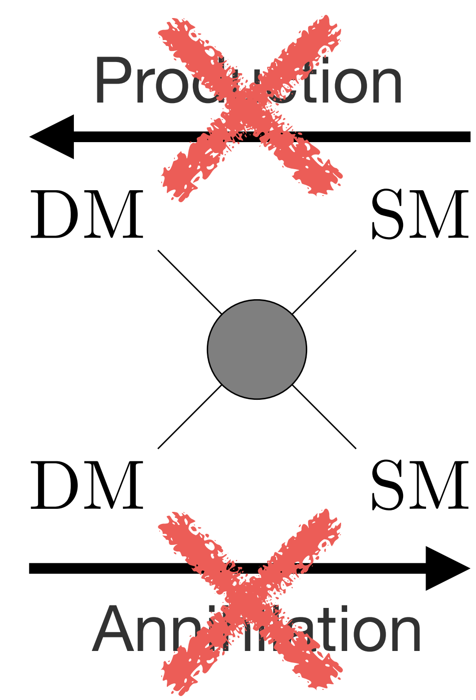


Freeze-out

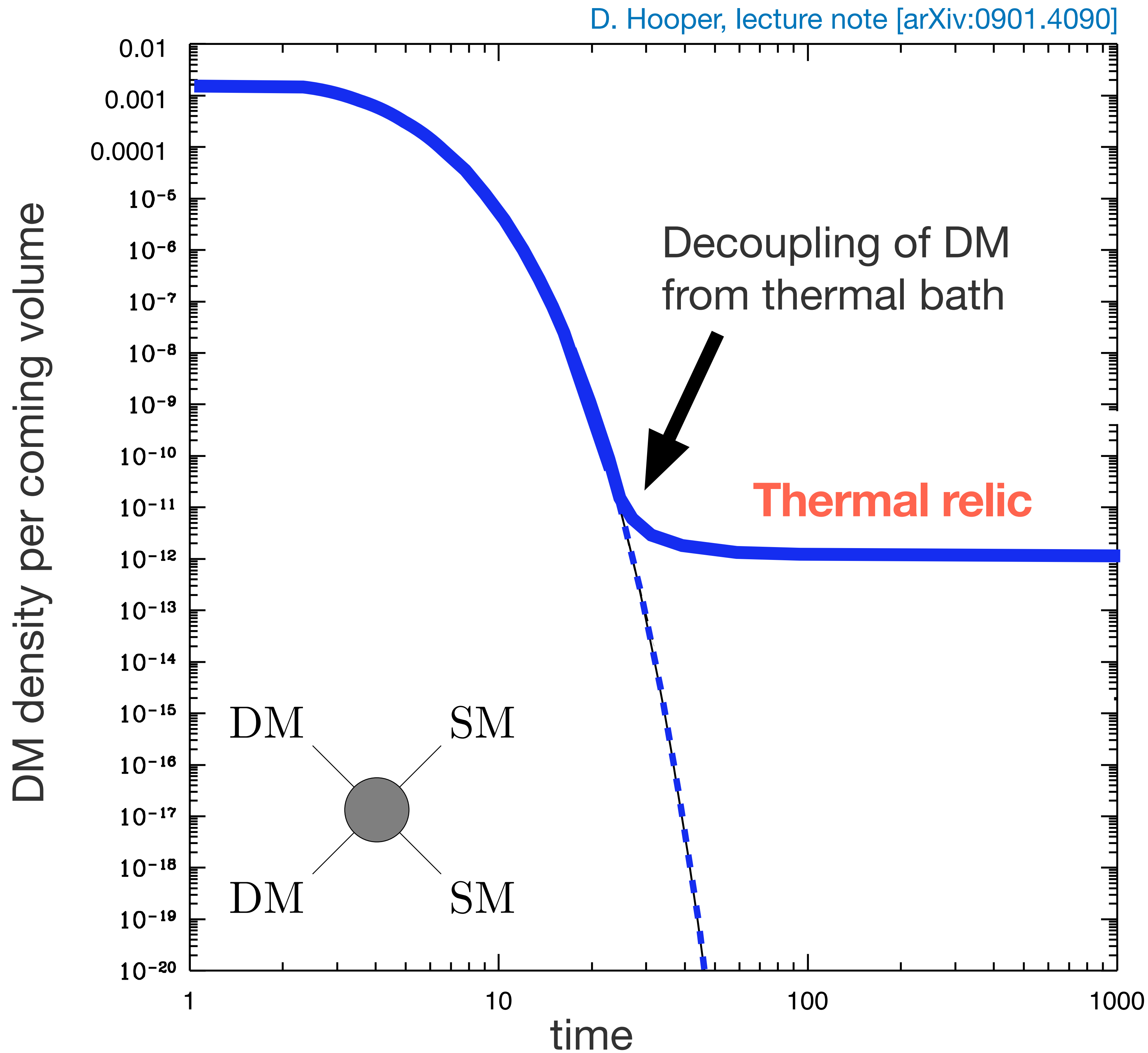
DM cannot meet with annihilation partner due to expansion

(cosmic age) vs (typical scale of DM annihilation)

$$1/H \overset{!}{\simeq} 1/(n_{\chi,{\rm eq}}\langle \sigma_{\rm ann} v \rangle)$$



WIMP Scenario

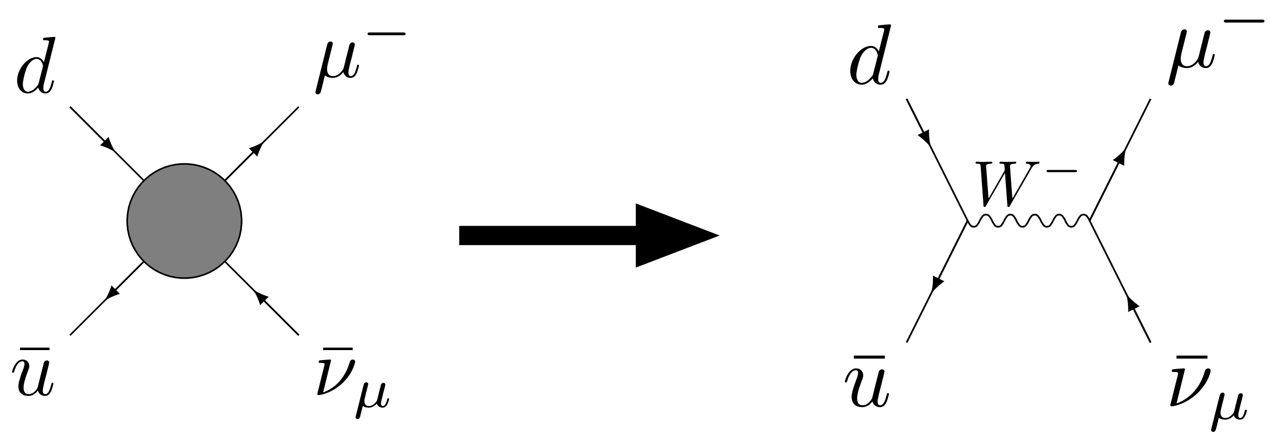


Implication of WIMP scenario

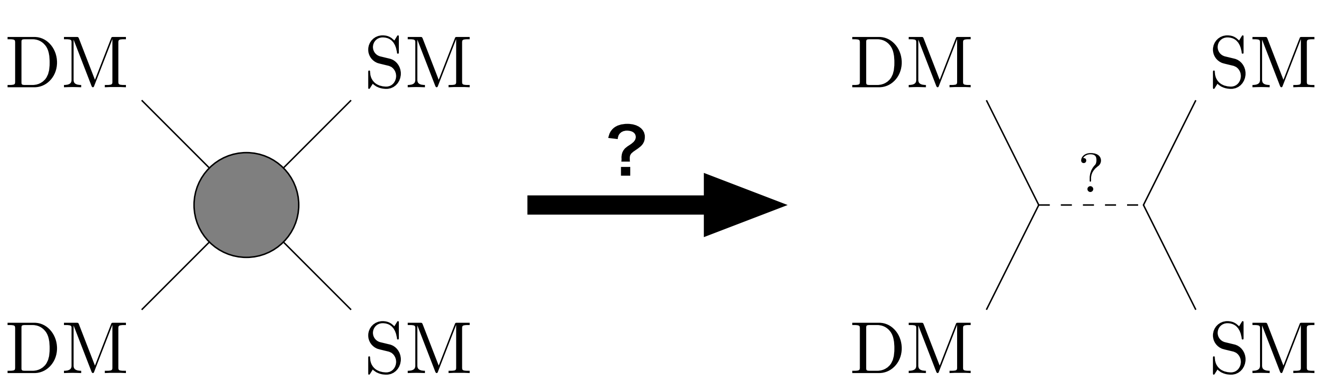
$c = 3 \times 10^{8}\ \mathrm{m/s}$
$1\ \mathrm{b} = 10^{-24}\ \mathrm{cm}^2$

$\langle \sigma_{\mathrm{ann}} v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} = 1\ \mathrm{pb} \cdot c$ = Typical cross section for weak process

What happen in weak process? (eg. Decay of charged pion)



Electroweak boson
(W boson, $m_W = 80.4\ \mathrm{GeV}$)
mediates interaction



Mediator in electroweak scale?

- Higgs boson?
- Z boson?
- new particles?

…

DM search directions

Focusing on WIMP DM

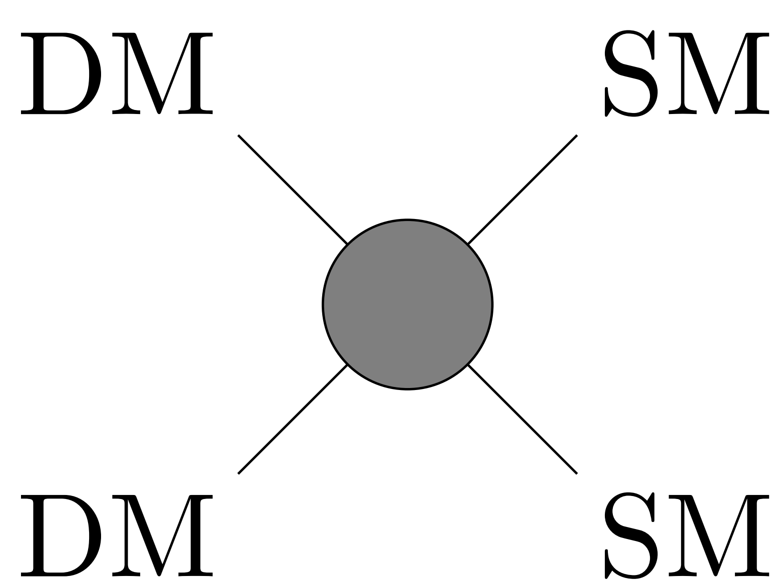
How to probe WIMP DM?

DM pair production

Collider experiment

DM scattering w/ SM particle

Direct detection

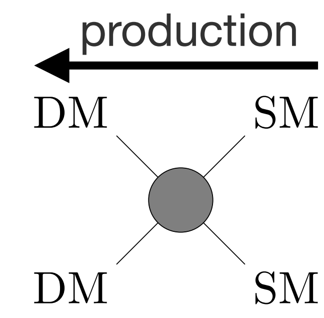


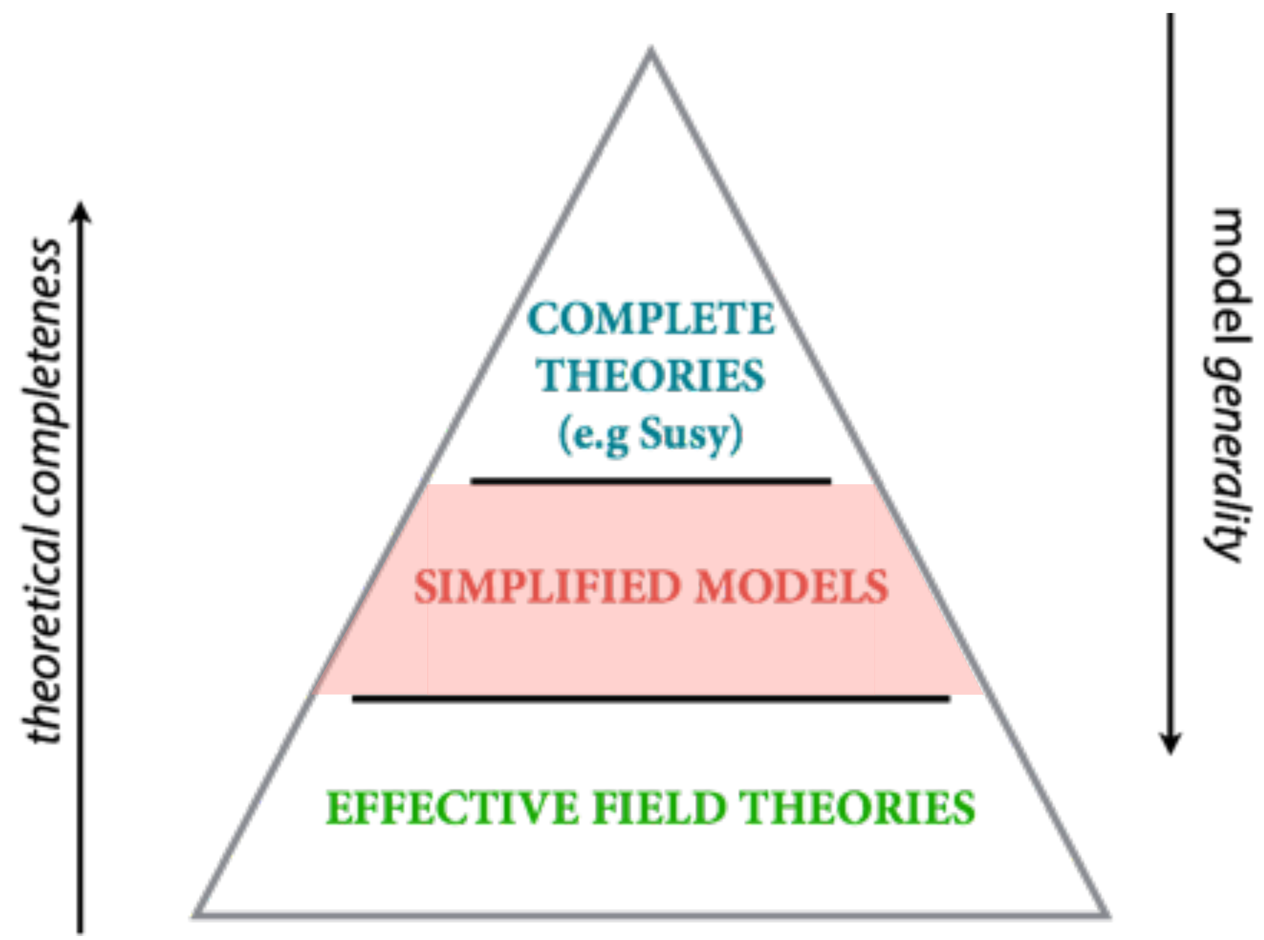
DM pair annihilation

Indirect detection

[Slide of P. Pani's talk @TAUP2019]

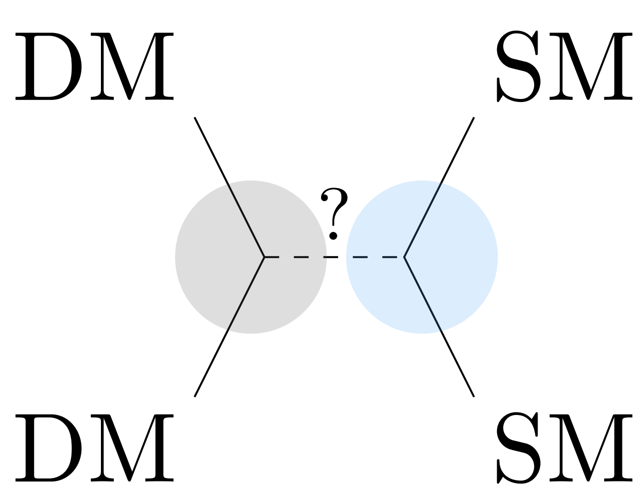
Collider search (overview)





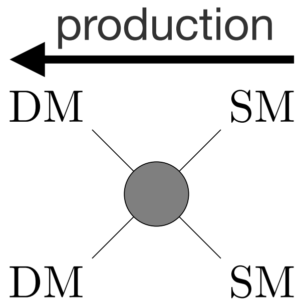
Parameter for analysis

- DM-SM particle interaction
- DM mass



- Mediator-SM particle interaction
- Mediator mass
- Mediator's decay width

DM search @LHC

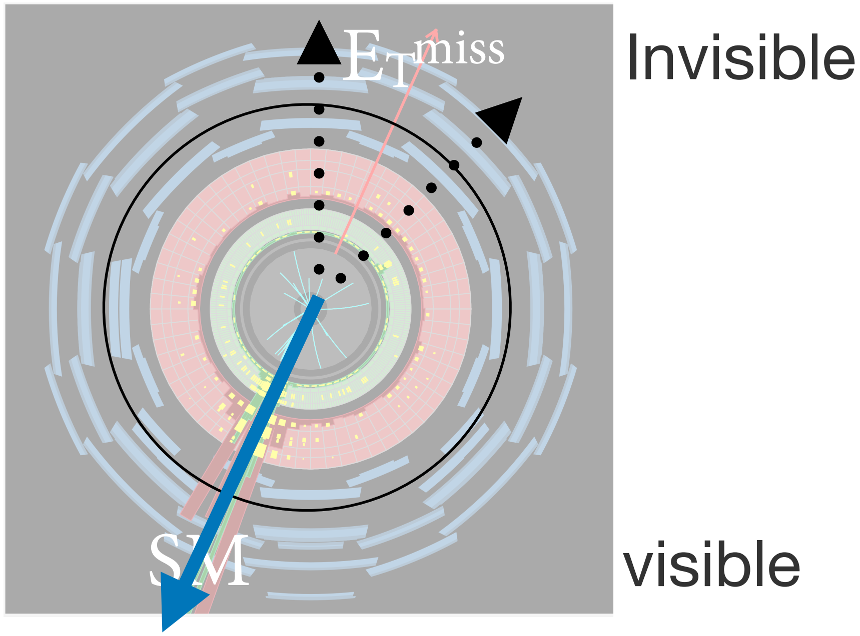


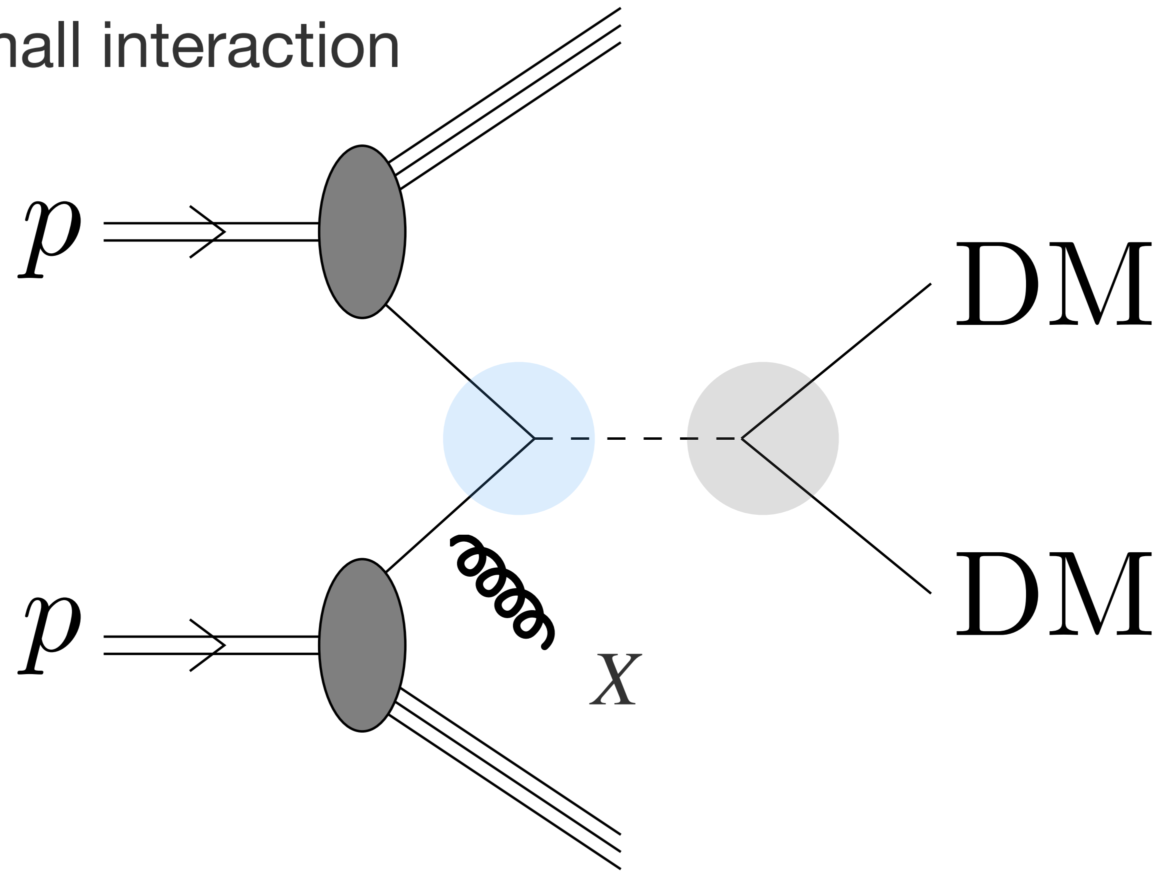
Typical event: Large missing E_T

$pp \to$ **missing** $+ X$

$X =$ gluon, photon, …

DM passes through the detector due to small interaction w/ the SM particles

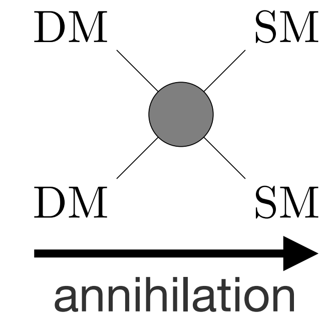




What we observe: Large missing transverse momentum $E_T^{\rm miss}$

We need X so that we can read out transverse momentum for reconstruction

Indirect detection

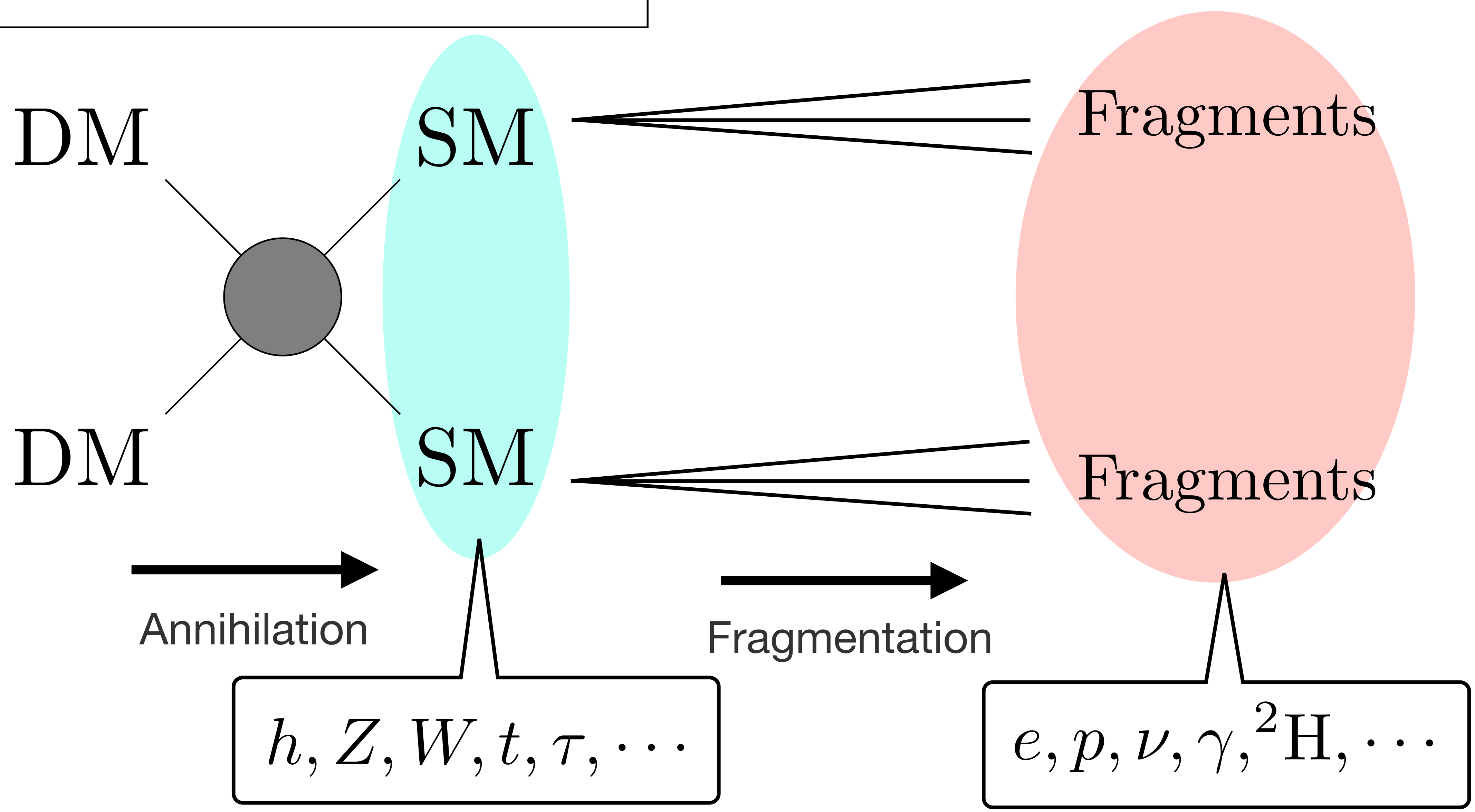


Implication of WIMP scenario

$\langle \sigma_{\rm ann} v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

→ Possibility to probe DM through annihilation

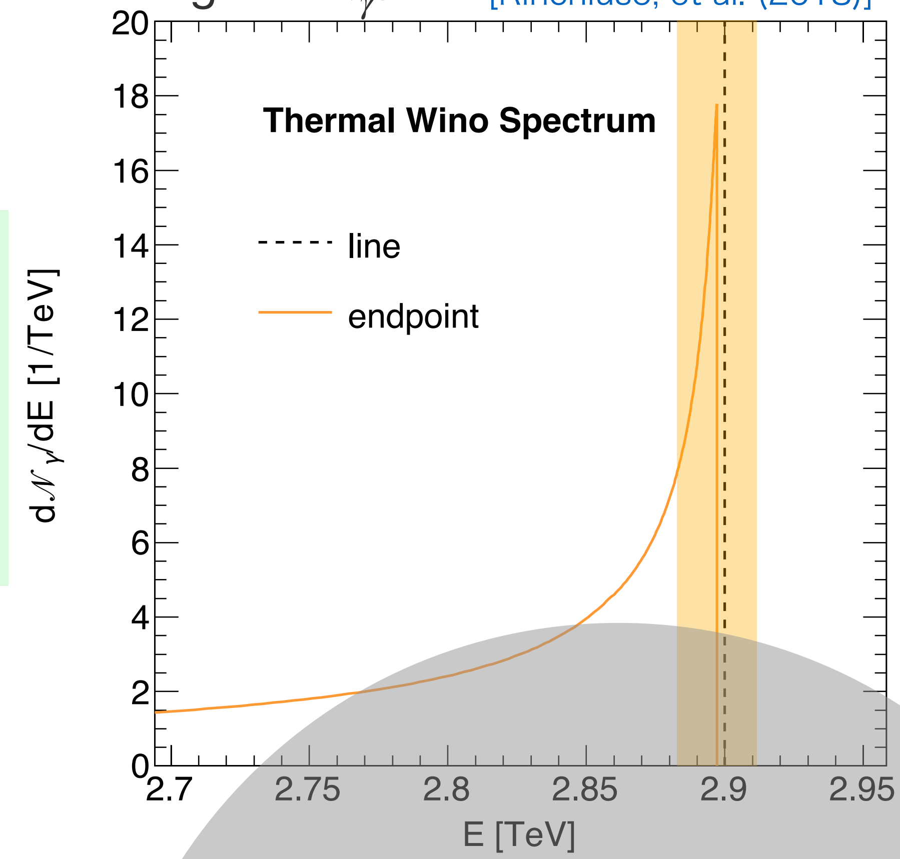
→ Direct test of WIMP scenario



What we observe: Fragment (stable particles) from DM annihilation

Photon flux from DM annihilation

eg. of dN_γ/dE [Rinchiuso, et al. (2018)]



Differential # of photon (eg. $\chi\chi \to \gamma\gamma$)

$$dN_\gamma = \frac{dN_\gamma}{dE} \frac{(\sigma_{\chi\chi\to\gamma\gamma} v)}{2!} \left(\frac{\rho_\chi}{m_\chi}\right)^2 dtdEdV \frac{dA}{4\pi\ell^2}$$

- **Energy spectrum of photon**

  $\frac{dN_\gamma}{dE} = 2\delta(E - m_\chi)$ for $\chi\chi \to \gamma\gamma$

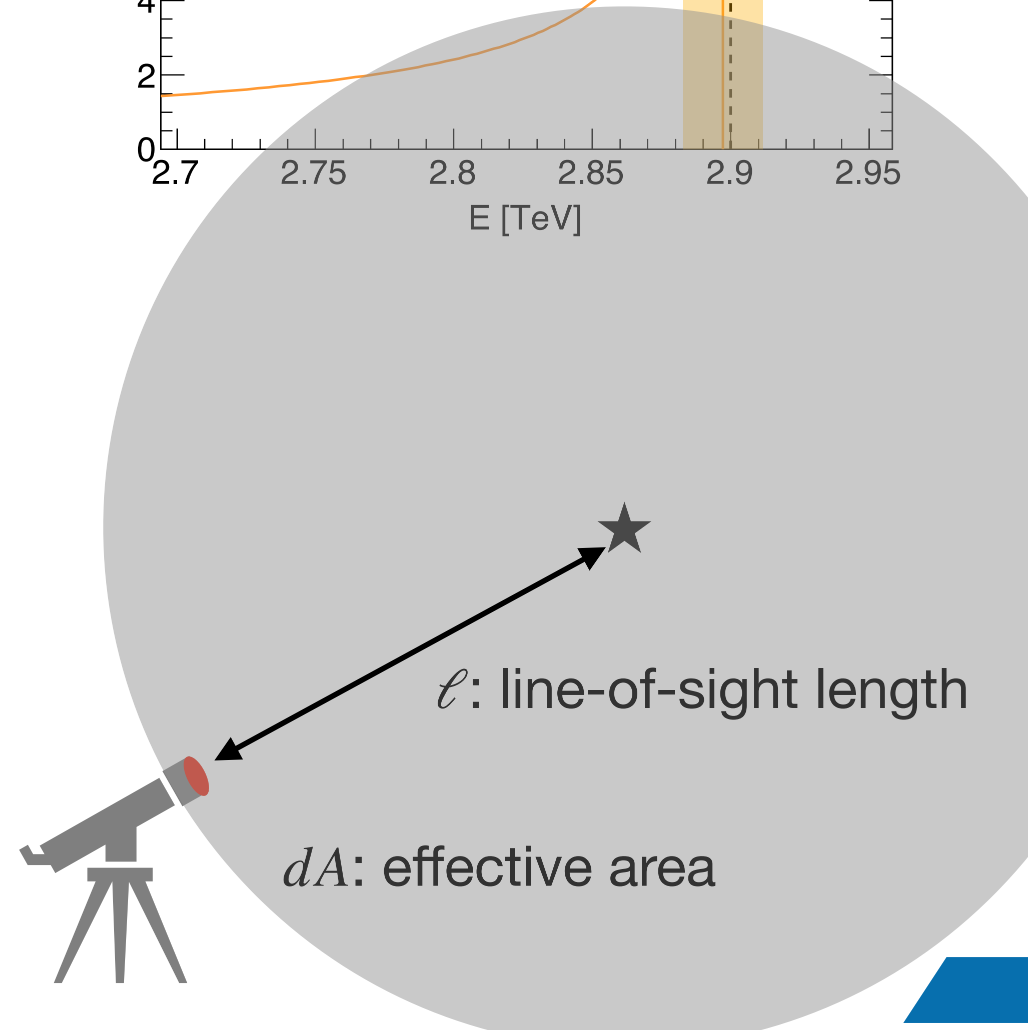
  → Forming line-like (monochromatic) spectrum

- **Rate of annihilation**

  probability for $\chi\chi \to \gamma\gamma$ to occur within $[E, E + dE]$

- **Ratio of observable photons**

  (Effective area for observation) / (Full emotion area)



Flux formula

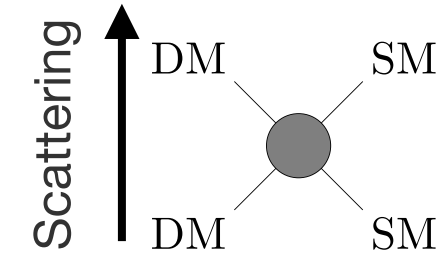
$$\frac{d\Phi_\gamma}{dE} = \frac{dN_\gamma}{dtdEdA} = \frac{1}{4\pi}\frac{(\sigma_{\chi\chi\to\gamma\gamma}v)}{2!m_\chi^2}\frac{dN_\gamma}{dE}\int\frac{\rho_\chi^2}{\ell^2}dV$$

- **Particle physics**
  - **DM mass**
  - **Annihilation cross section** ➡ cf. $(\sigma_{\rm ann}v) \simeq 3\times10^{-26}\ {\rm cm^3/s}$ for WIMP scenario
  - **Energy spectrum**

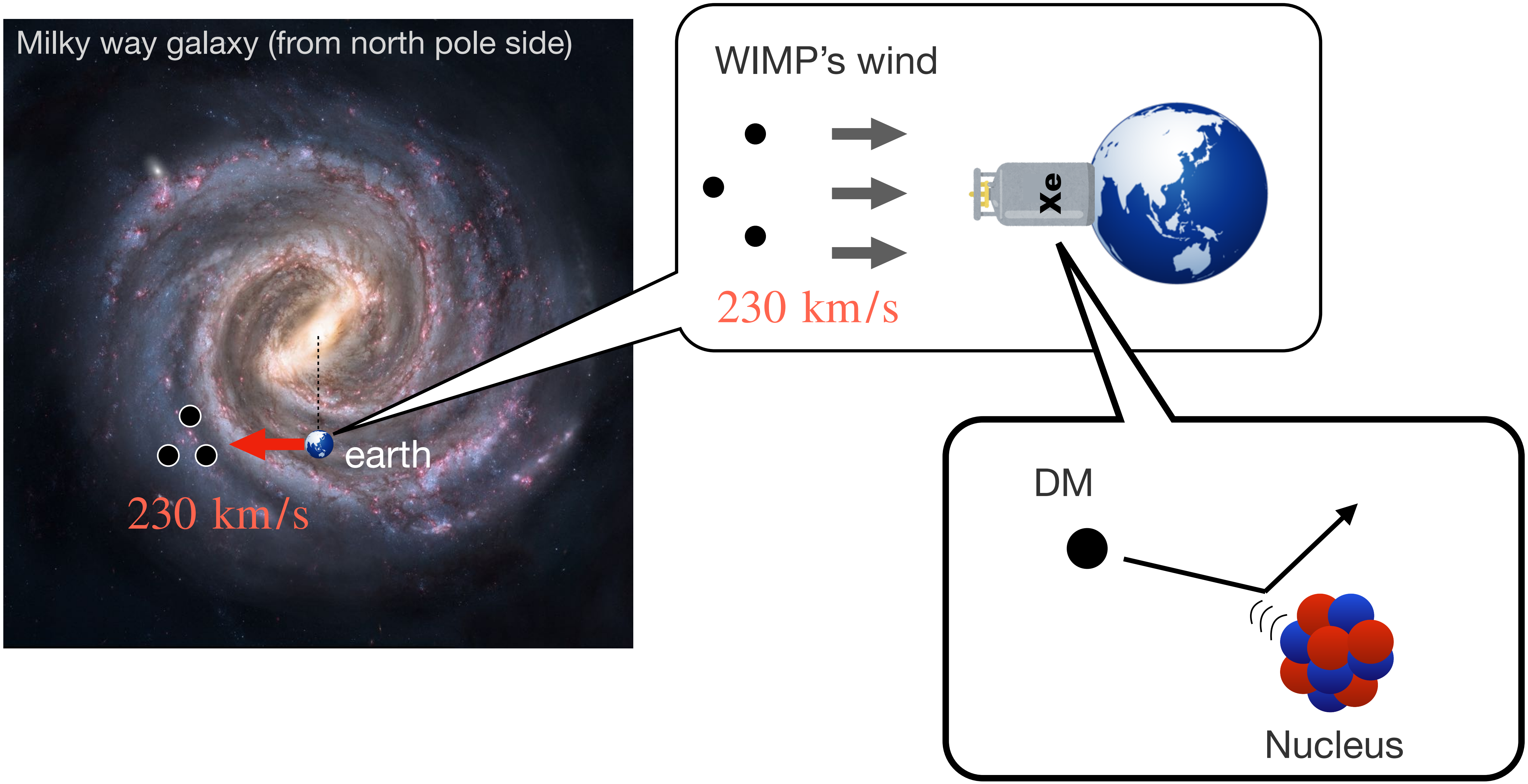
- **Astrophysics**
  - **DM density profile** ➡ Source of uncertainty to test prediction
  - **Region of integral** → Characterized by J-factor (see backup slide)

We can directly test WIMP scenario by probing annihilation process

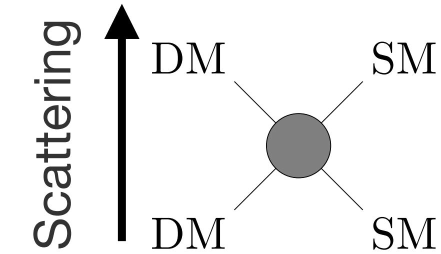
Direct detection (idea)



Sketch of direct detection



Direct detection (event rate)



Astrophysics

- DM density profile
- velocity distribution

$$\frac{dR}{dE_R} = \frac{1}{m_T}\frac{\rho_{\rm DM}}{m_{\rm DM}}\int_{v_{\rm min}}^{v_{\rm esc}} d^3\vec{v}\, v f(\vec{v},\vec{v}_E)\frac{d\sigma_{\rm scat}}{dE_R}(v,E_R)$$

Particle physics

Depending on particle nature of DM

- DM mass
- DM-nucleon cross section

Naive dimensional analysis
for DM w/ electroweak charge

$$v_{\rm min} = \sqrt{\frac{m_T E_{\rm th}}{2\mu^2}}$$

$v_{\rm esc}$: Escape velocity of DM

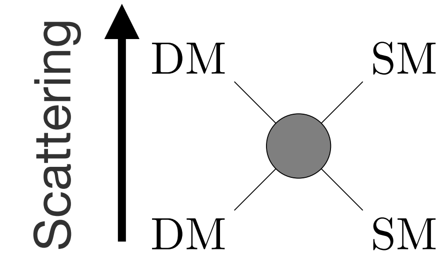
$$\mu \equiv \frac{m_N m_{\rm DM}}{m_N + m_{\rm DM}} \sim m_N$$: Reduced mass

$(N = n, p)$

$$G_F \sim 10^{-5}\ {\rm GeV}^{-2}$$

$$\sigma_{\rm scat} \sim \frac{1}{32\pi}G_F^2\mu^2 \sim 4\times 10^{-4}\ {\rm pb} \sim \underline{4\times 10^{-40}\ {\rm cm}^2}$$

Neutrino background



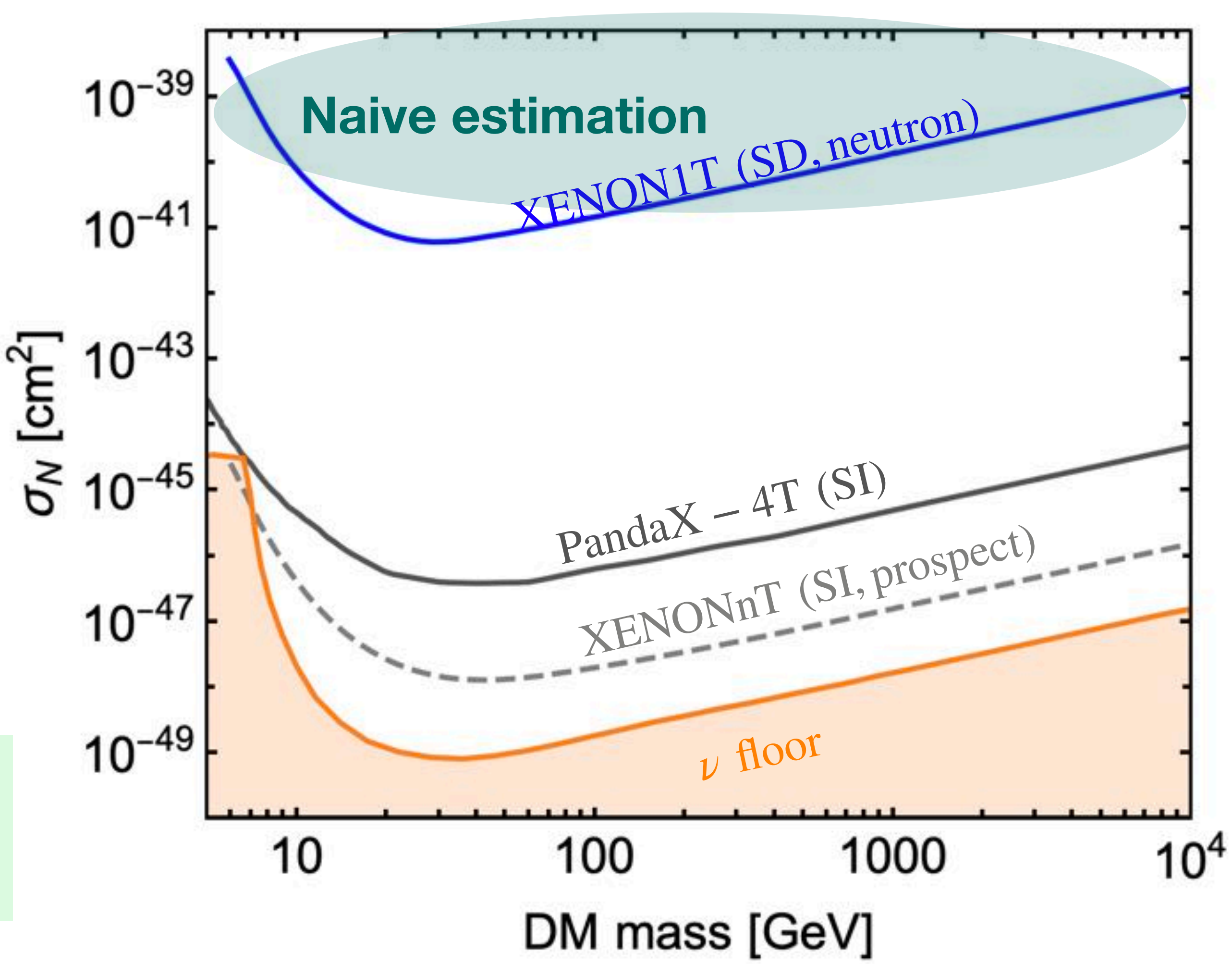
Pros & Cons

- Underground experiment can control background well
- Less uncertainty from DM profile (we only need local info. on density & velocity dist.)
- Serious background due to **neutrino scattering effects**

White region:
We can probe DM-nucleon scattering

Gray dashed curve:
Prospect of next generation exp.

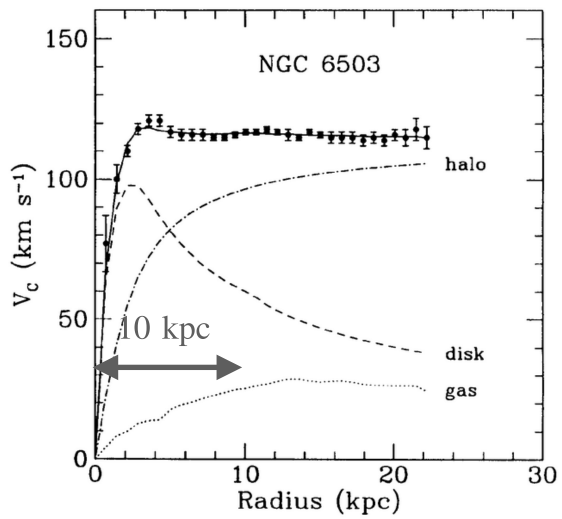
Orange region:
Coherent neutrino scattering is expected
→ We may not probe DM in this region



How to probe DM-nucleon scattering in this neutrino background region?

(→ next slide)

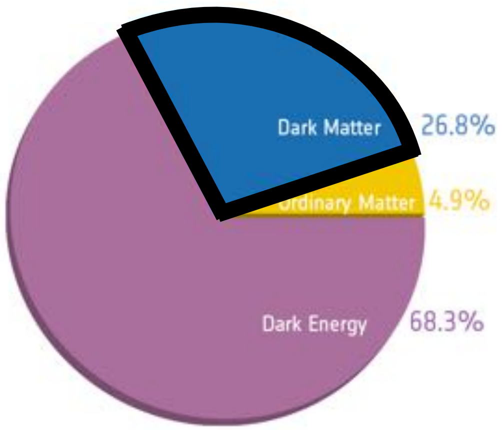
Summary: Part 1



DM in our universe

- Dark unknown gravitational source are independently implied
- Necessary component to provide density fluctuation in early universe

DM candidates

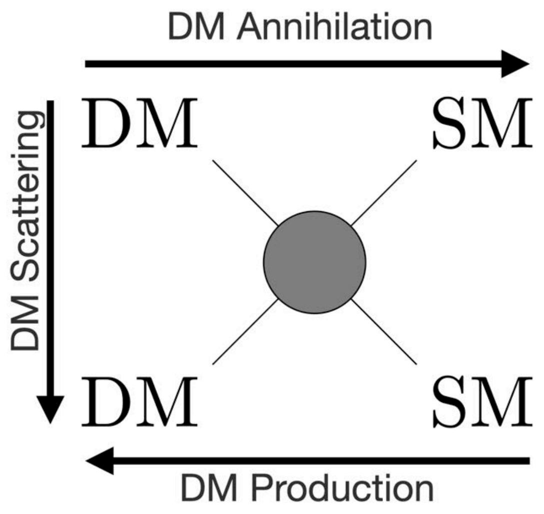


https://sci.esa.int/web/planck/-/51557-planck-new-cosmic-recipe

- Compact object: eg. Primordial blackhole
- Particle candidate: eg. Weakly Interacting Massive particle (WIMP)

Exp./Astrophys. information is indispensable for DM identification

WIMP DM search



- Collider search: Direct production by injecting energy
- Indirect detection: Direct test of WIMP scenario
- Direct detection: Background is well-controled but neutrino w/ BG

Developing new direction to probe DM is mandatory!