素粒子現象論研究会2021 （大阪市立大学）

2021. 11. 8

Impacts of small-scale N-body simulations on DM annihilations constrained from 21cm line observations

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Phys. Rev. D104, 083547, arXiv 2103.14801

Contents:

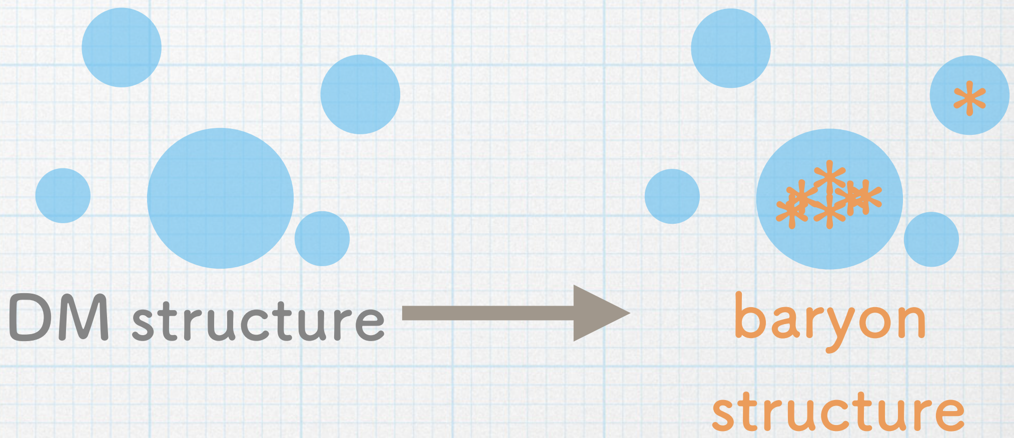
Introduction

indirect detection: various possibilities

DM Motivation & Candidate

DM=non-baryonic matter in the Universe of $\Omega_{\rm DM}h^2 \sim 0.12$

- **motivation**
  - structure formation
  - rotation curves
  - bullet cluster
  - …



- **candidate**
  - Weakly Interacting Massive Particle (WIMP)
  - Strongly (or self) Interacting Massive Particle (SIMP)
  - axion/axion-like particle (ALP)
  - primordial black hole (PBH)
  - …

Three pillars

- direct detection

$$\mathrm{DM} + \mathrm{SM} \longrightarrow \begin{cases} \mathrm{DM} + \mathrm{SM} \\ \mathrm{DM}' + \mathrm{SM}' \end{cases}$$

- collider experiments

$$\mathrm{SM} + \mathrm{SM} \longrightarrow \mathrm{SM}' + \cdots + \mathrm{DM} + \cdots$$

- indirect detection

$$\begin{cases} \mathrm{DM} \\ \mathrm{DM} + \mathrm{DM} \end{cases} \longrightarrow \mathrm{SM} + \cdots$$

Indirect: variations

A. looking for the DM annihilation/decay products

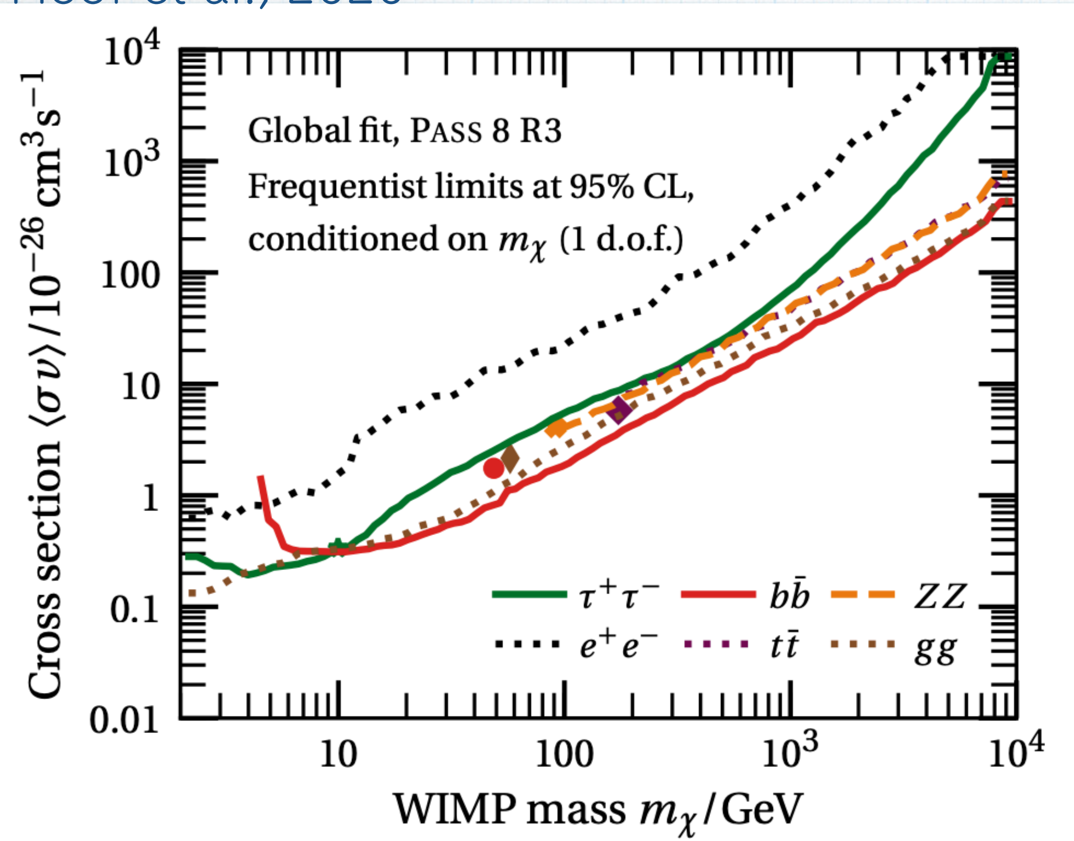
B. looking for the resultant modulations in the SM sector from DM interactions

need to select the strategy
for each DM model in case by case

Exs. (pattern A)

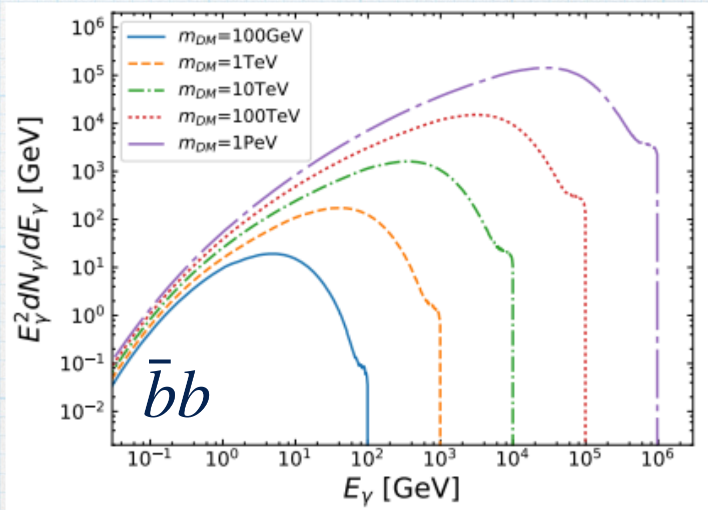
WIMP annihilation signal search

Hoof et al., 2020



DM + DM

-> SM+SM-> γ+ ⋯

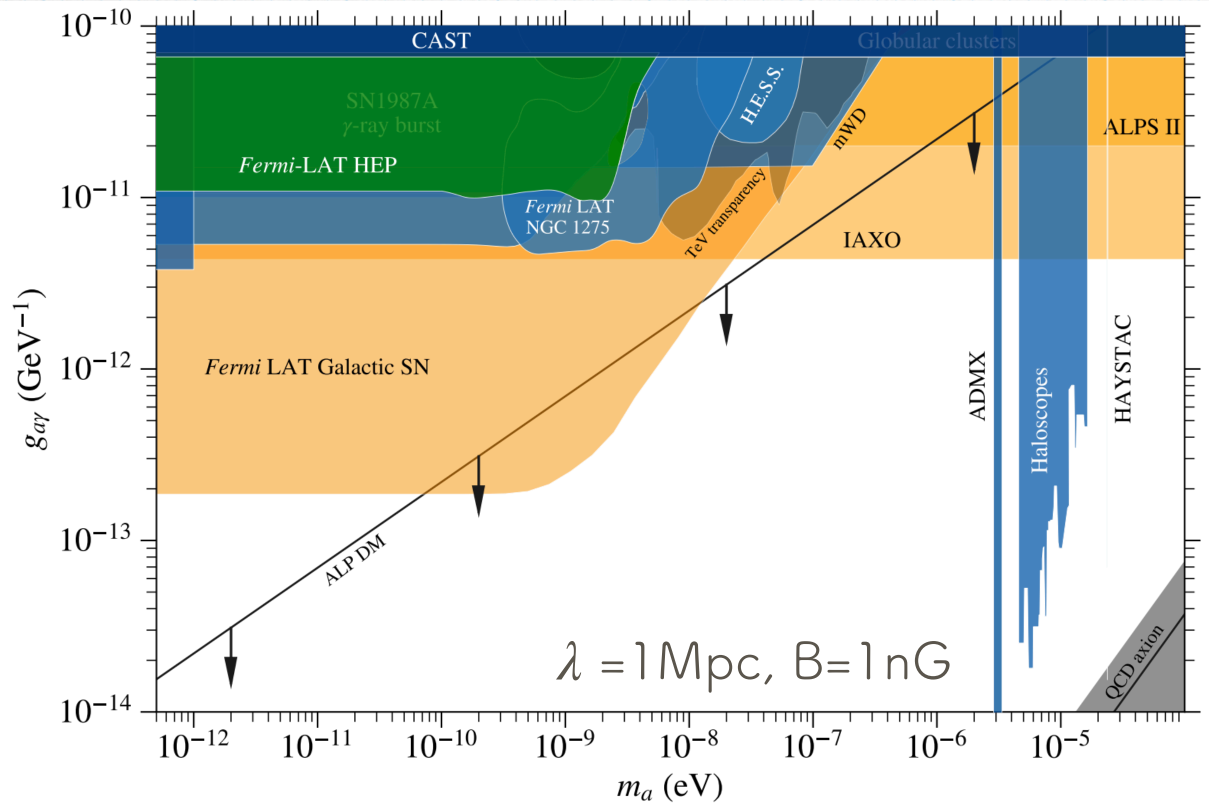


γ flux UL ↔ annihilation cross-section UL

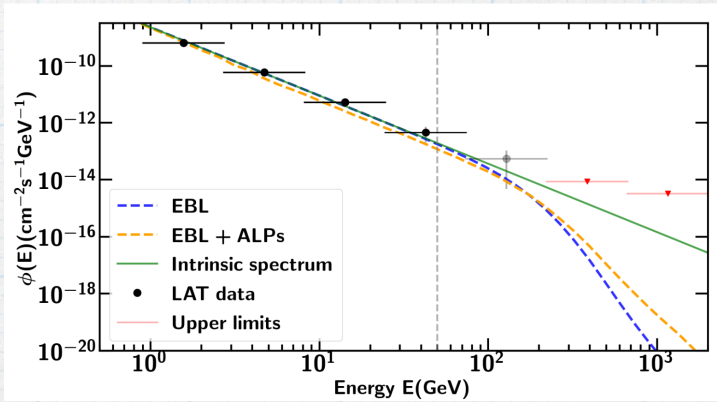
Exs. (pattern B)

ALP - photon conversion signal search

Buehler et al., 2020



γ -> DM -> γ



spectral distortion UL

↔ coupling strength UL

WIMP

a featured candidate

WIMP

- feel the gravity (massive)
- the mass

  $m_{\rm DM} \sim \mathcal{O}(100\ \text{MeV}) - \mathcal{O}(100\text{TeV})$
- achieve the relic abundance

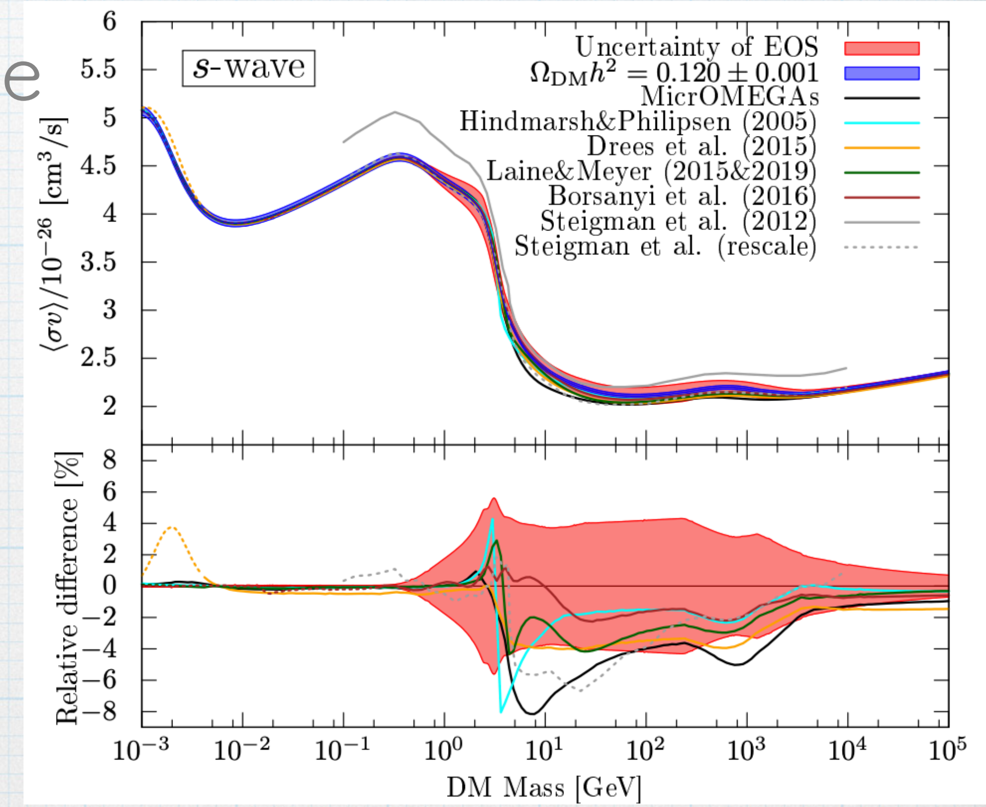
  $\Omega_{\rm DM}h^2 \sim 0.12$ via the

  freeze-out mechanism
- the annihilation

  cross-section

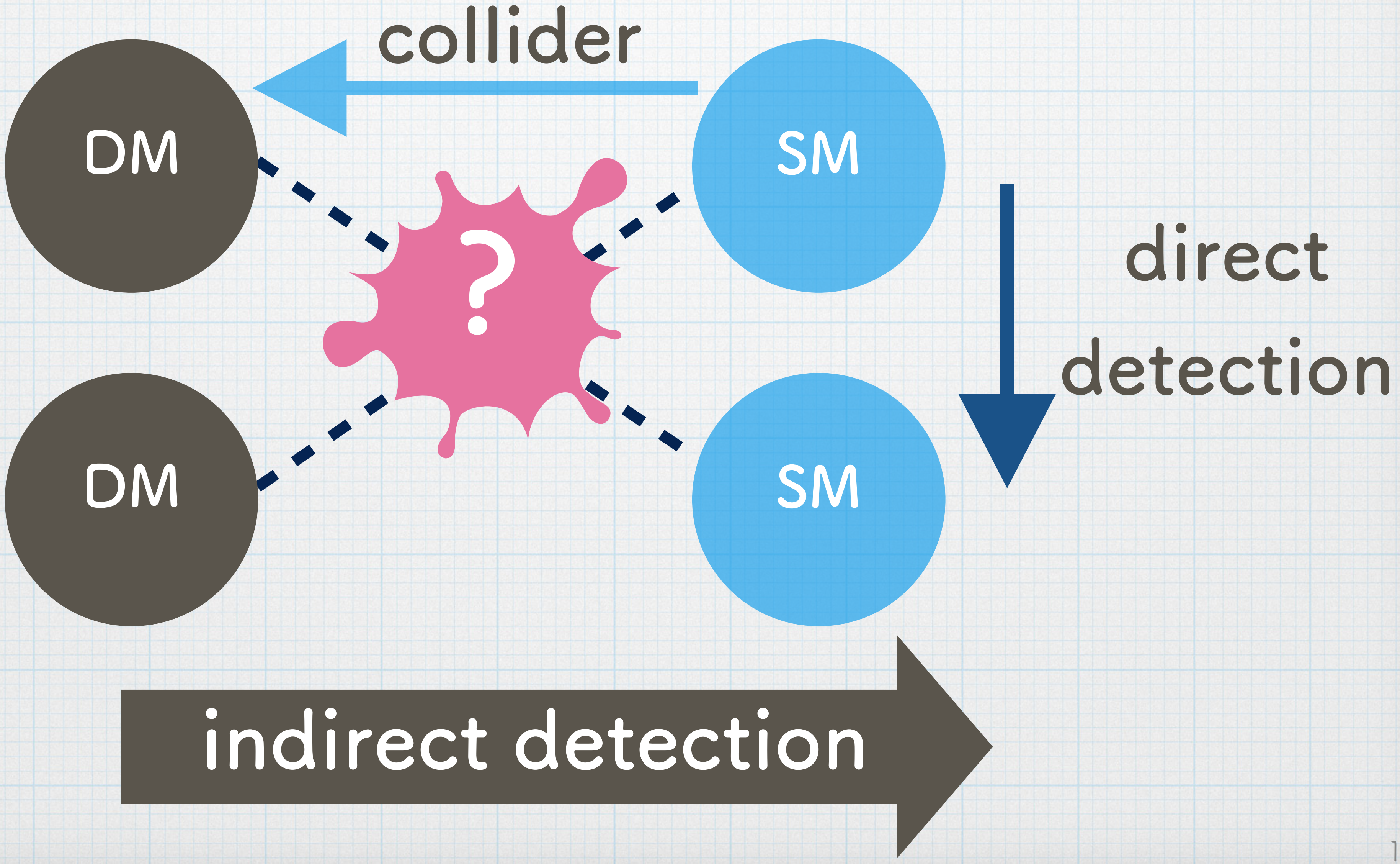
  $\langle \sigma v \rangle \sim \mathcal{O}(10^{-26}\text{cm}^3 s^{-1})$

Saikawa & Shirai, 2020



No signatures yet

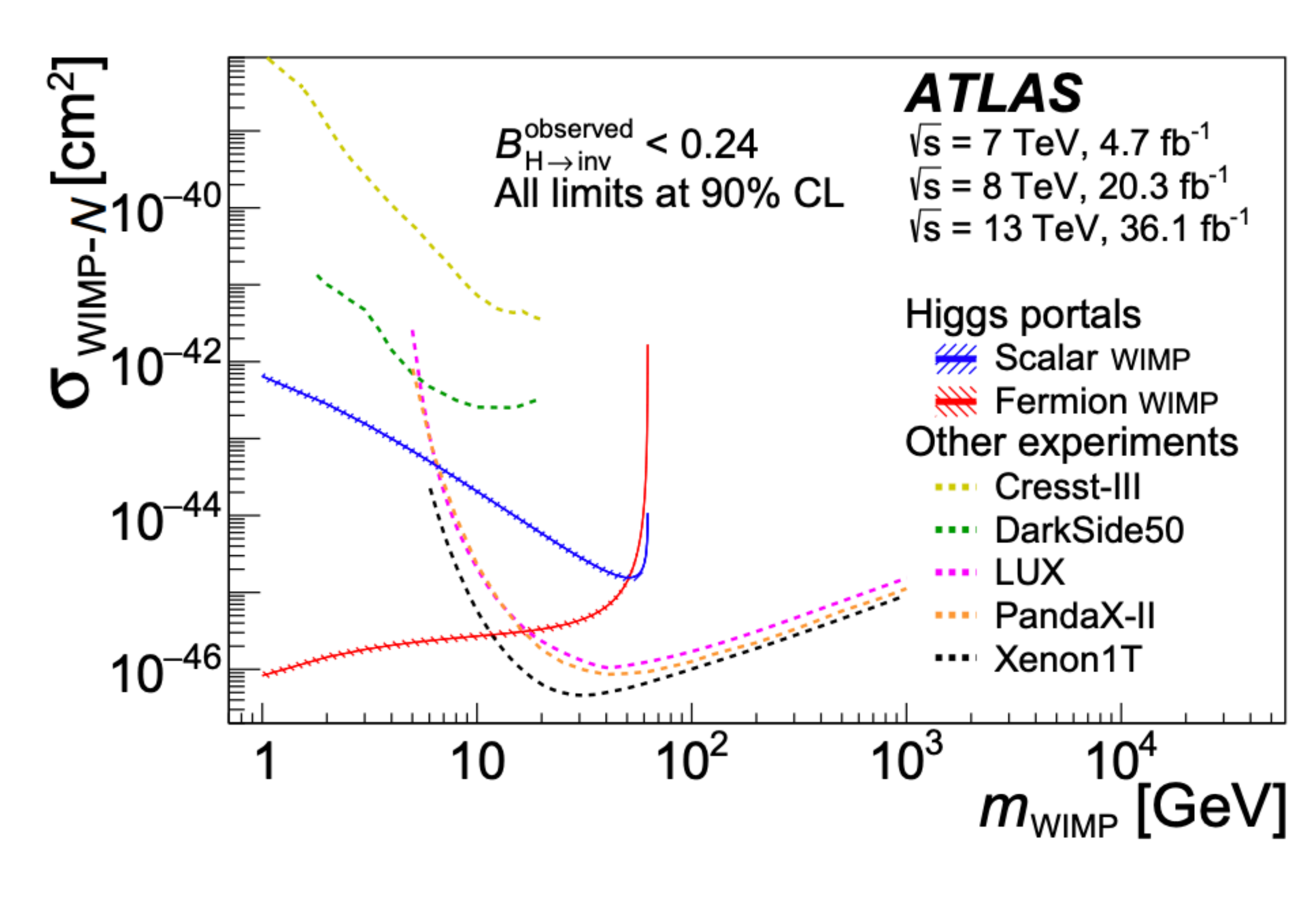
accessibility to WIMP



cf. collider & direct

WIMP annihilation signal search

Lorenz, 2019



Indirect WIMP search

DM + DM → something in the SM

somewhere in the Universe

final products $\gamma, e^{\pm}, p, \bar{p}, \nu, \ldots$

- pattern A : γ, ν, c.r signatures @$z \lesssim 10$
- pattern B:

  distortion of 21cm signatures @$z \gtrsim 15$

Strategy

indirect search for WIMP at high z

WIMP annihilation @$z \gtrsim 15$

DM sector

- the abundance is fixed
- small-scale halo structures

SM sector

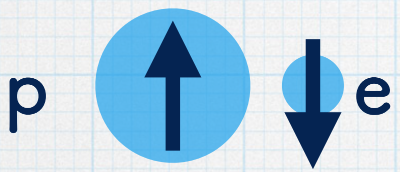
- almost neutral
- few astrophysical sources for ionizations

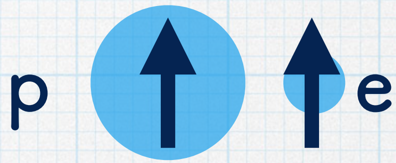
WIMP annihilation → energy injection / particle injection → IGM heating -> excitation

observable: T_{21} profile

ground state H (n_0)

excited state H (n_1)





ΔE = 5.9 μeV

λ = 21cm, ν = 1.4GHz

spin temperature $\dfrac{n_1}{n_0} = 3\exp\left[-\dfrac{\Delta E}{T_s}\right]$

↓ radiative transfer equations (τ: optical depth)

$$\delta T = \frac{T_s - T_\gamma}{1+z}\tau \sim 23m\mathrm{K}\left(1 - \frac{T_\gamma(z)}{T_s(z)}\right)\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2}\sqrt{\frac{1+z}{10}}x_{\mathrm{HI}}$$

matter temperature T_m

$T_s \simeq T_s(T_m, T_\gamma)$

w/o heating $T_m/T_\gamma \propto (1+z)$

after the cosmic dawn $T_s \gtrsim T_m$

Extra radiation make the increments from T_s

To do list:

- quantify the effects of energy injection from annihilating DM
- quantify the small-scale halo clustering

task1 : heating of IGM

2 effects: ionization fraction & gas temperature

- **ionization fraction (x_e) evolution:**

$$\frac{dx_e}{dt} = -C\left[\alpha_H(T_m)x_e^2 n_{\rm H} - \beta_H(T_\gamma)(1-x_e)e^{-E_\alpha/T_\gamma}\right] + \frac{dE_{\rm inj}}{dVdt}\frac{1}{n_{\rm H}}\left[\frac{f_{\rm ion}(t)}{E_0} + \frac{(1-C)f_{\rm exc}(t)}{(3E_0)/4}\right]$$

- **gas temperature (T_m) evolution**

$$\frac{dT_m}{dt} = -2H(t)T_m + \frac{8\sigma_T a_r T_\gamma^4}{3m_e}\frac{x_e}{1+f_{\rm He}+x_e}\left(T_\gamma - T_m\right) + \frac{dE_{\rm inj}}{dVdt}\frac{1}{n_{\rm H}}\left[\frac{2f_{\rm heat}(t)}{3(1+x_e+f_{\rm He})}\right]$$

from $z \gtrsim 1000$ to $z \sim 10$

task1 : heating of IGM

2 effects: ionization fraction & gas temperature

- **ionization fraction (x_e) evolution:**

$$\frac{dx_e}{dt} = -C\left[\alpha_H(T_m)x_e^2 n_{\rm H} - \beta_H(T_\gamma)(1-x_e)e^{-E_\alpha/T_\gamma}\right] + \frac{dE_{\rm inj}}{dVdt}\frac{1}{n_{\rm H}}\left[\frac{f_{\rm ion}(t)}{E_0} + \frac{(1-C)f_{\rm exc}(t)}{(3E_0)/4}\right]$$

- **gas temperature (T_m) evolution**

$$\frac{dT_m}{dt} = -2H(t)T_m + \frac{8\sigma_T a_r T_\gamma^4}{3m_e}\frac{x_e}{1+f_{\rm He}+x_e}\left(T_\gamma - T_m\right) + \frac{dE_{\rm inj}}{dVdt}\frac{1}{n_{\rm H}}\left[\frac{2f_{\rm heat}(t)}{3(1+x_e+f_{\rm He})}\right]$$

energy injection by WIMP annihilation

task2: density fluctuations

from $dE_{\rm inj}/dVdt$ part

$$\frac{dE_{\rm inj}}{dVdt} = \bar{\rho}^2_{\rm DM} B(z) \frac{< \sigma v >}{m_{\rm DM}}$$

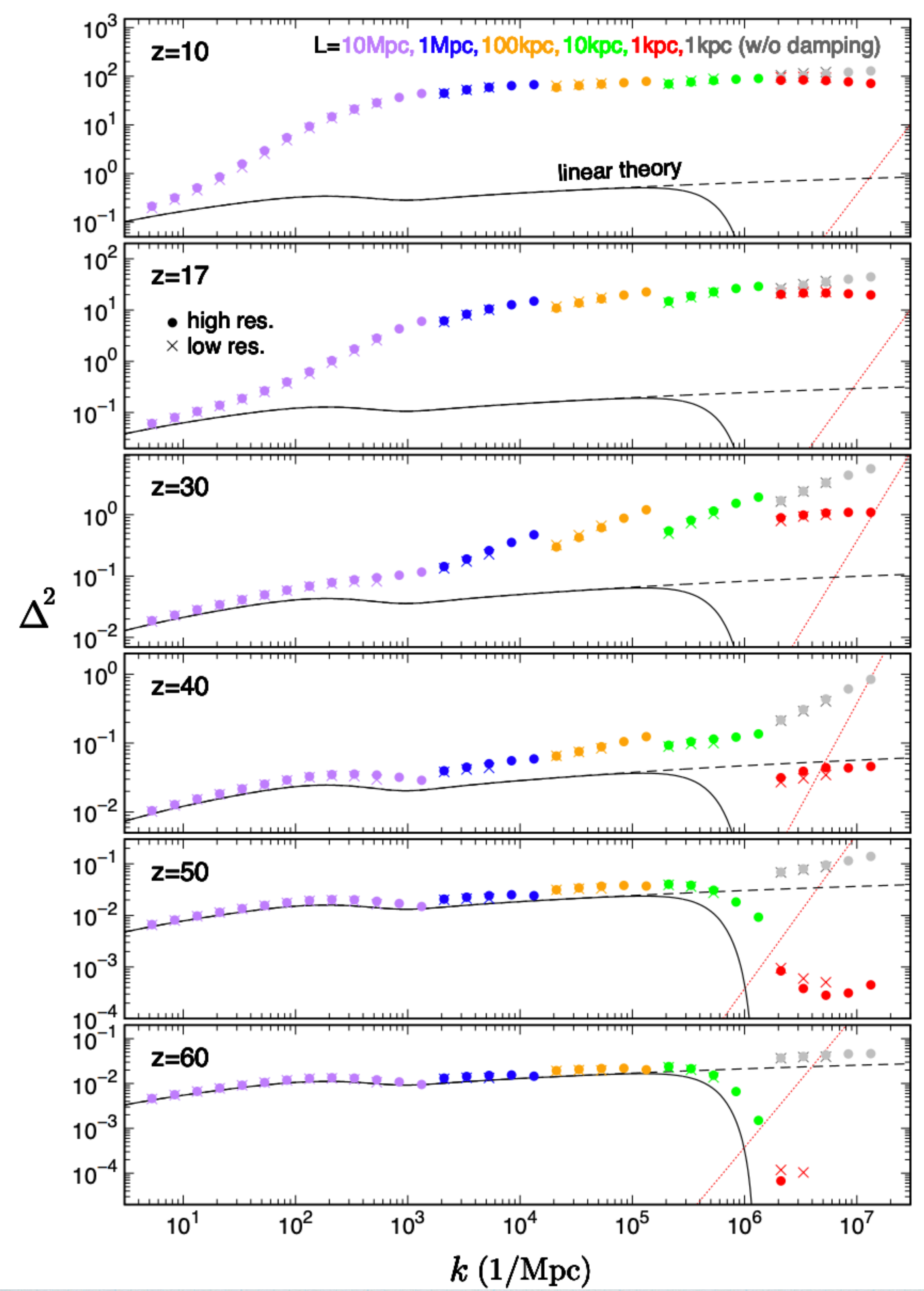
$$\sim 10^{-21} \left(\frac{B(z)}{10^2}\right) \left(\frac{1+z}{18}\right)^6 \left(\frac{< \sigma v >}{\rm canonical}\right) \left(\frac{m_{\rm DM}}{10^2 {\rm GeV}}\right)^{-1} \left(\frac{\Omega_m h^2}{0.12}\right)^2$$

[eV/s/cm^3]

boost factor

$$B \equiv 1 + \langle \delta^2(\mathbf{x}, z) \rangle = 1 + \int_0^\infty \frac{dk}{k^2} \Delta^2(k, z)$$

non-linear evolution of small-scale fluctuation starts at $z \lesssim 30$



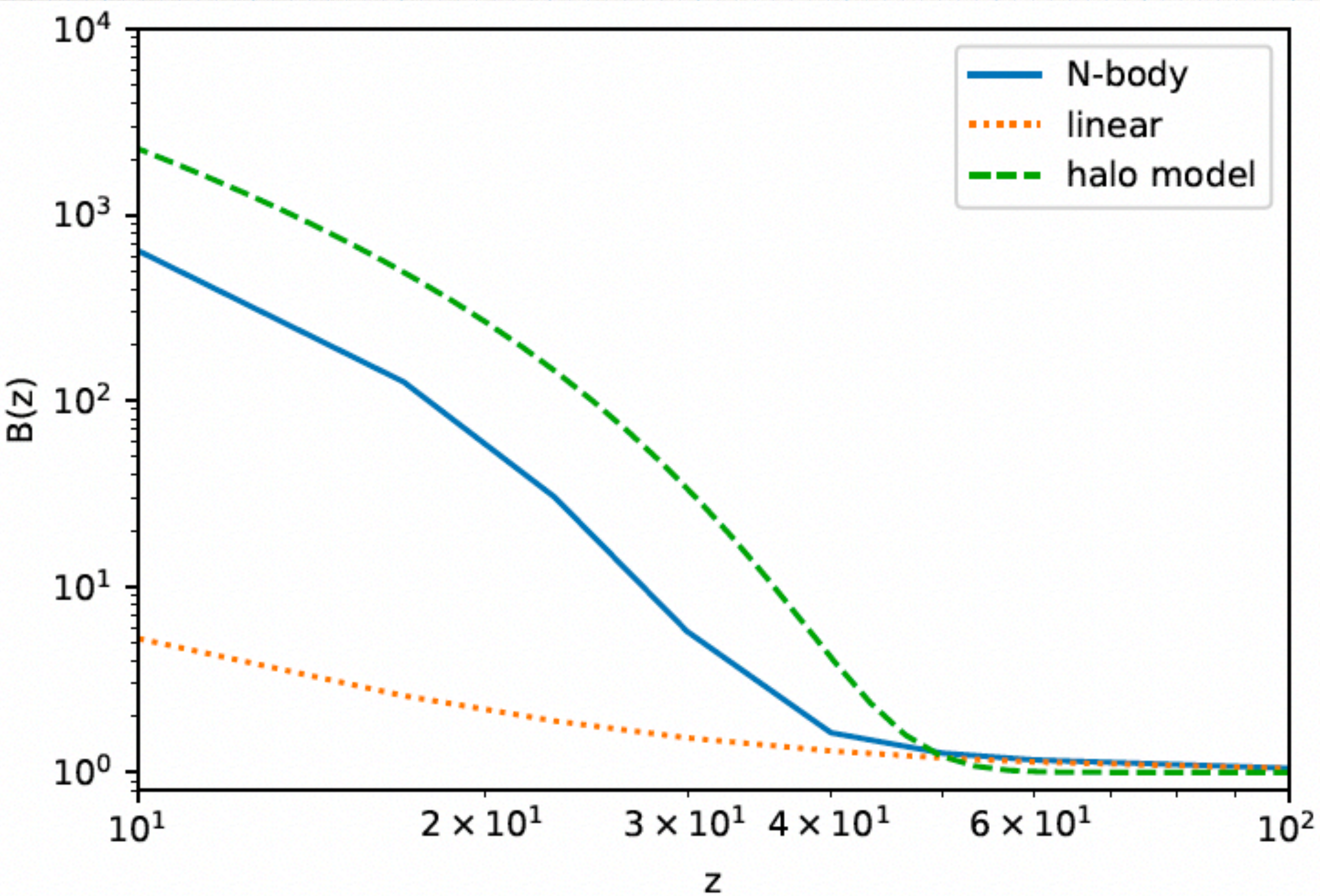
non-linear clustering

- difficulty in analytical evaluation
- deviations from the linear-theory prediction starts from $z \gtrsim 40$

Takahashi & Kohri, 2021

boost factor

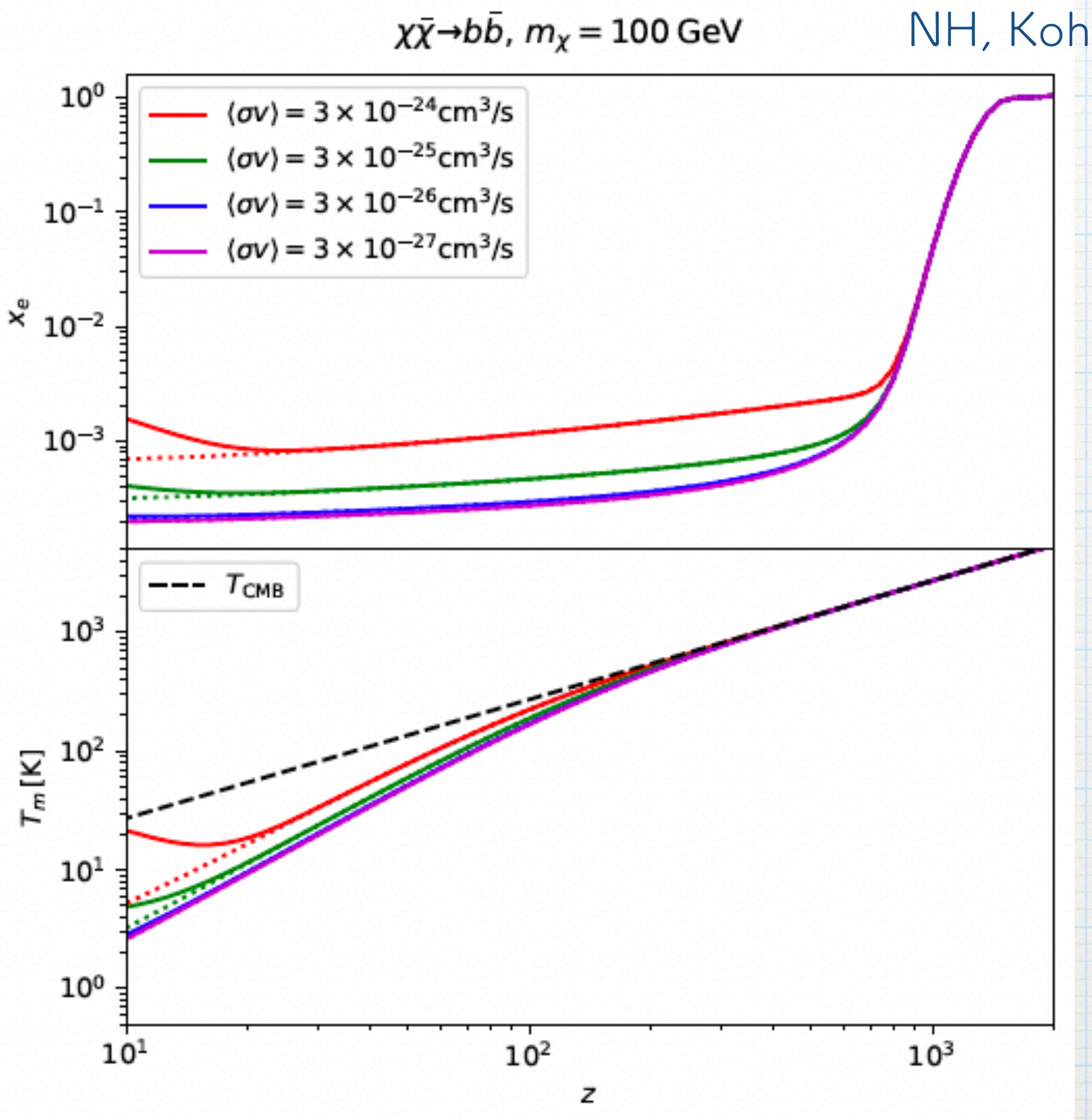
NH, Kohri, Sekiguchi, Takahashi, 2021



- halo model approach ->overestimate
- linear theory ->underestimate

See also Takahashi & Kohri, 2021

x_e & T_m evolutions



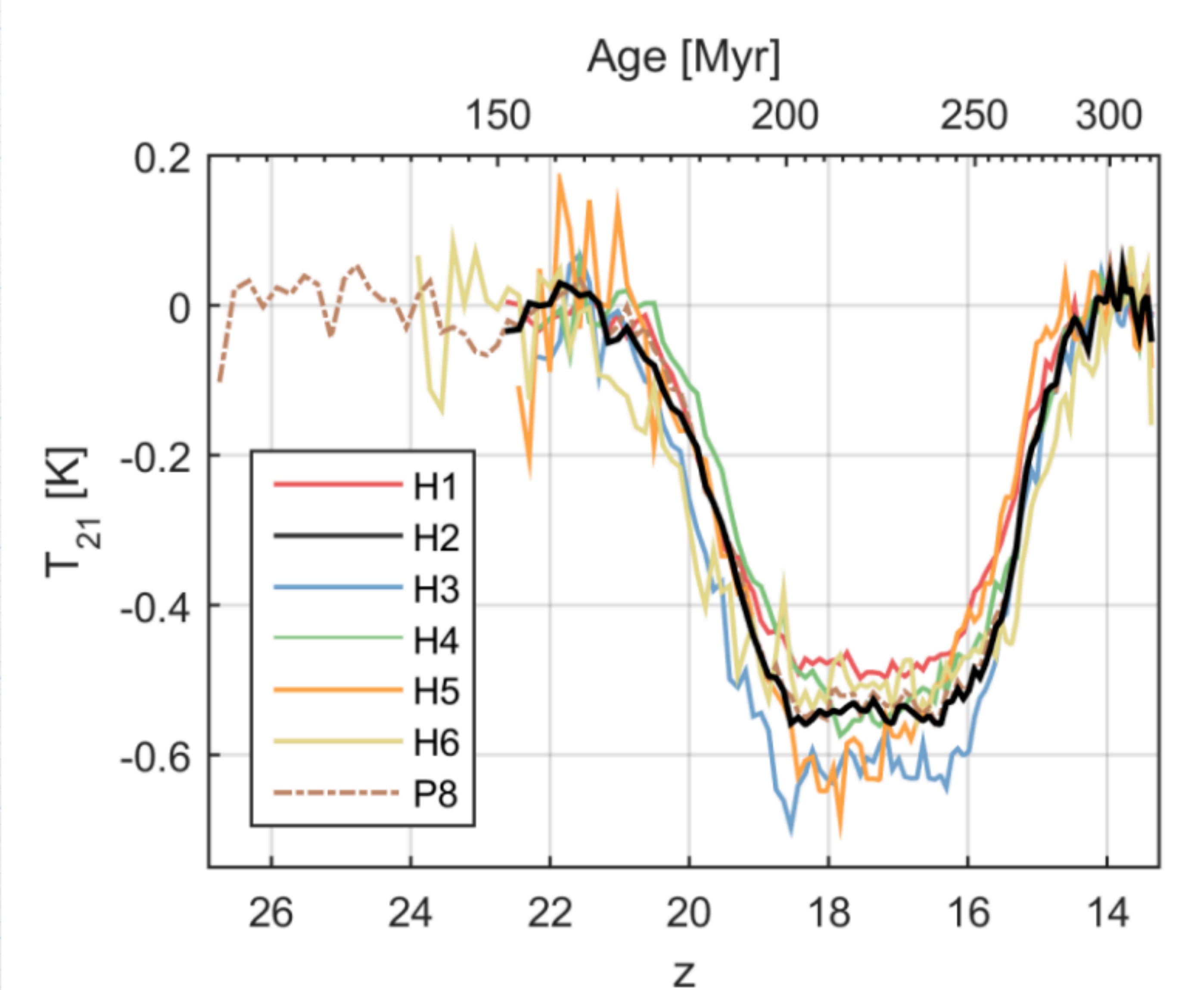
NH, Kohri, Sekiguchi, Takahashi, 2021

DM annihilation effects become apparent at non-linear regime

Requirement:
DM heating should satisfy the observation of 21cm absorption signal

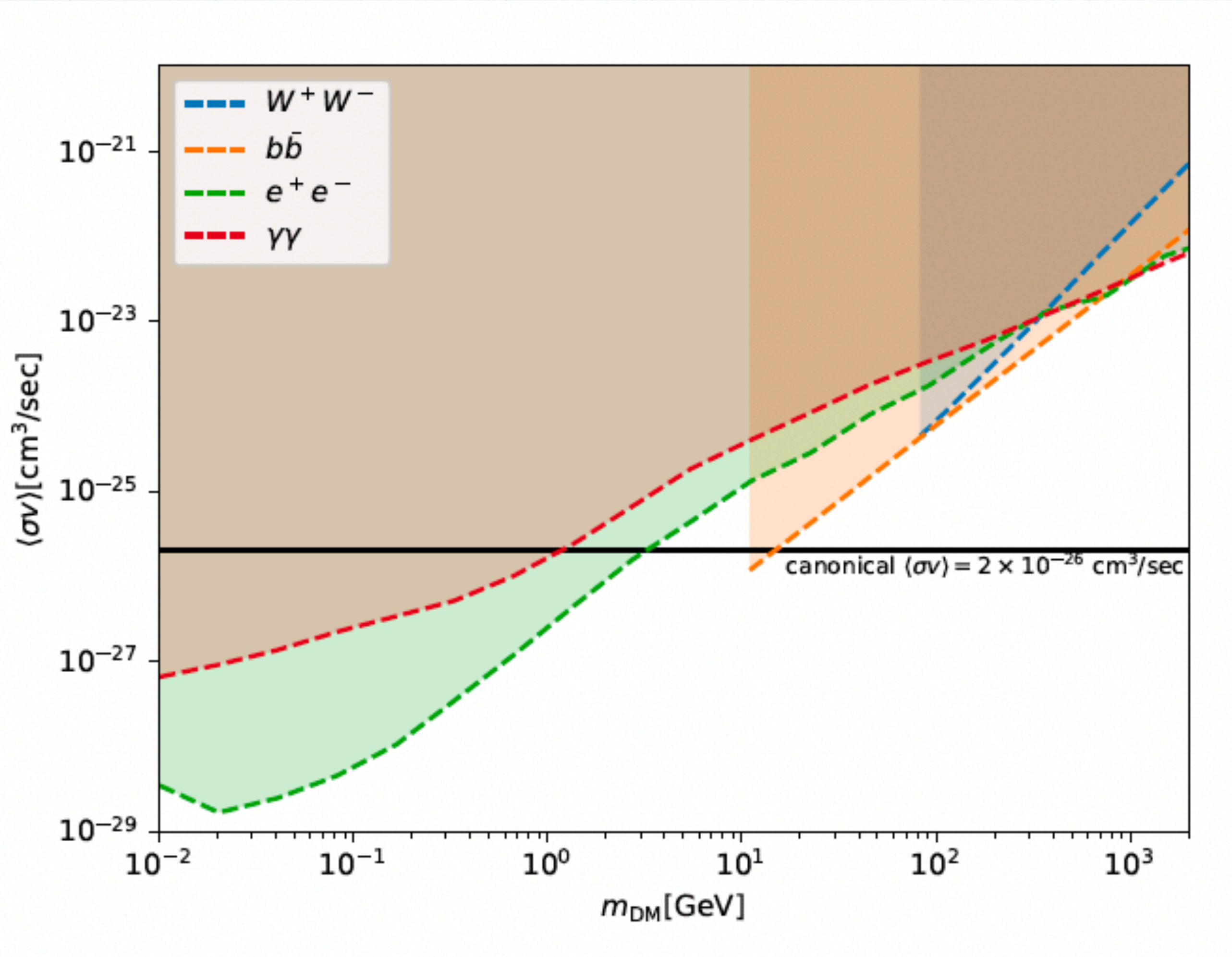
21cm observation: EDGES

Bowman et al., 2018



constraints on $\langle \sigma v \rangle$

NH, Kohri, Sekiguchi, Takahashi, 2021



DM annihilation effects become apparent at non-linear regime

Summary

Summary:

- Various strategies are taken in indirect searches of dark matter. One must choose and/or combine suitable ones.
- For WIMP, both of the search for annihilation products and the distortion signatures could be probes.
- WIMP annihilation around the decoupling epoch should modifies the 21cm signals, where non-linear clustering of DM could not be neglected.
- We can constrain WIMP annihilation cross-section below to the canonical value at $m \lesssim \mathcal{O}(10)$ GeV with 21cm observations.

References:

- Hiroshima, Kohri, Sekiguchi, Takahashi, 2021, Phys. Rev. D 104, 083547, arXiv 2103.14810
- D'Amico et al., 2018, Phys. Rev. Lett 121, 011103, arXiv 1803.03629
- Takahashi & Kohri, 2021, arXiv 2107.00897
- Bowman et al., 2018, Nature 555, 67, arXiv 1810.05912
- Hoof et al., 2020, JCAP 02(2020) 012, arXiv 1812.06986
- Buehler et al., 2020, JCAP 09(2020) 027, arXiv 2004.09396
- Lorenz, 2019, Mod. Phys. Lett. A 34(2019) 30, 1930005, arXiv 1908.09672