# Short lecture: Observational constraints on Dark Matter models

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**Les Houches School - "Dark Universe"**
30/07/2025

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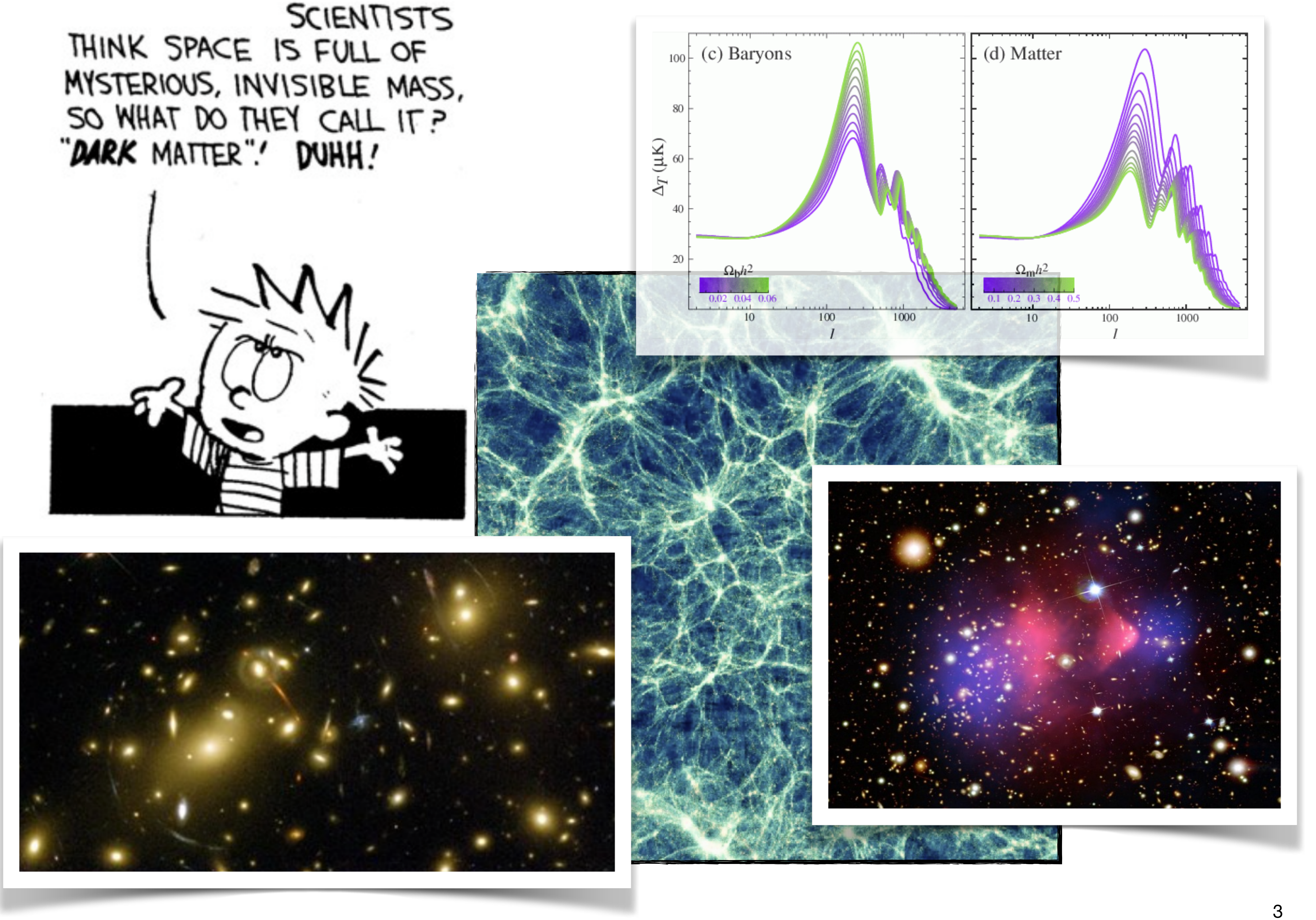
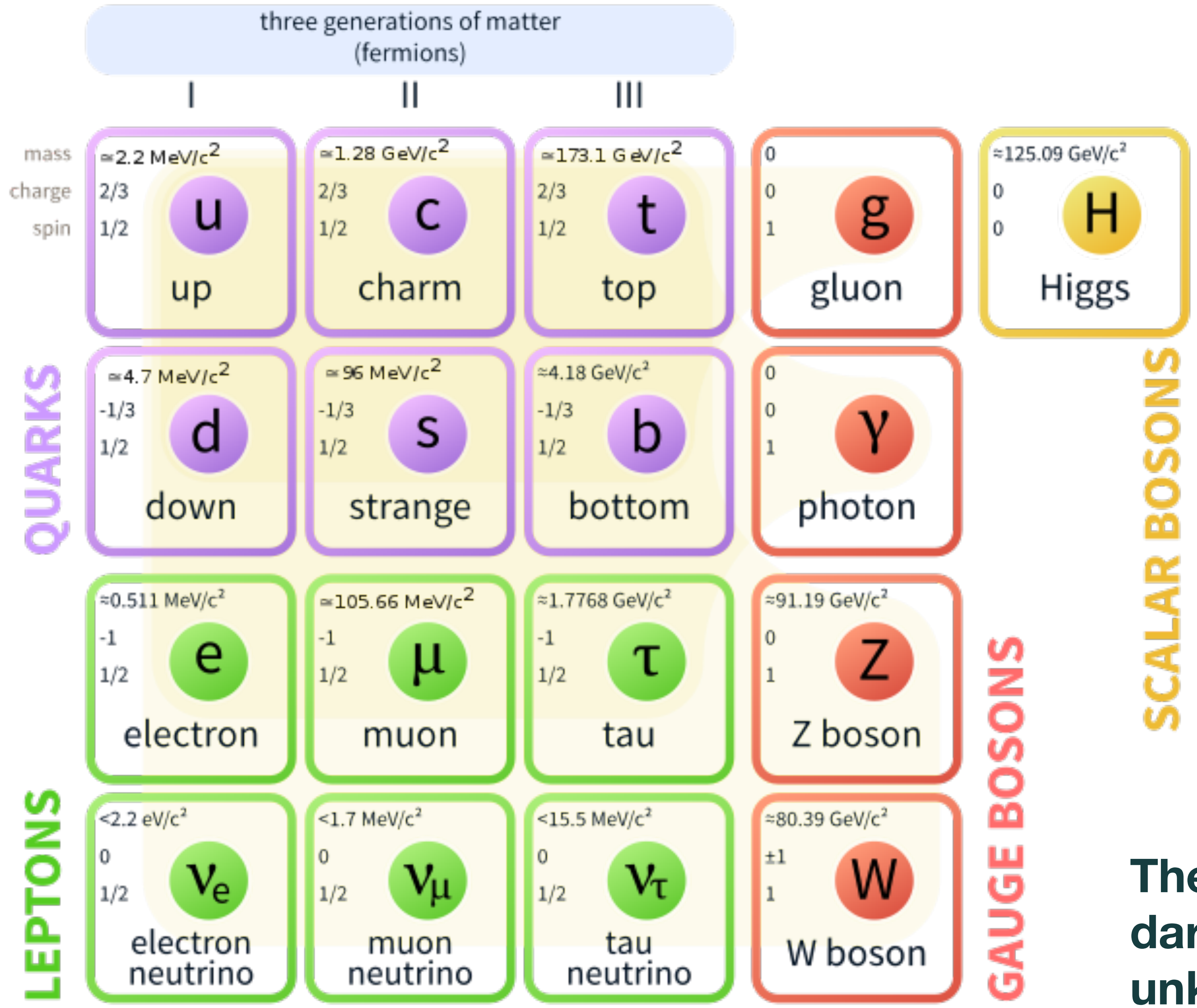
CEA Saclay

# Contents

- **Reminder: Dark Matter models**
- **Constraining WIMPs**
  - Direct and indirect detection
  - Also direct detection of QCD axions
- **Using the Lyman-$\alpha$ forest to constrain some DM scenarios**
  - **The Lyman-$\alpha$ forest**
  - Examples: WDM, FDM, PBH


SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH!
(c) Baryons
(d) Matter
$\Delta_T$ (μK)
100
80
60
40
20
$\Omega_b h^2$
0.02 0.04 0.06
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5
10
100
1000
$l$

# Standard Model of Elementary Particles

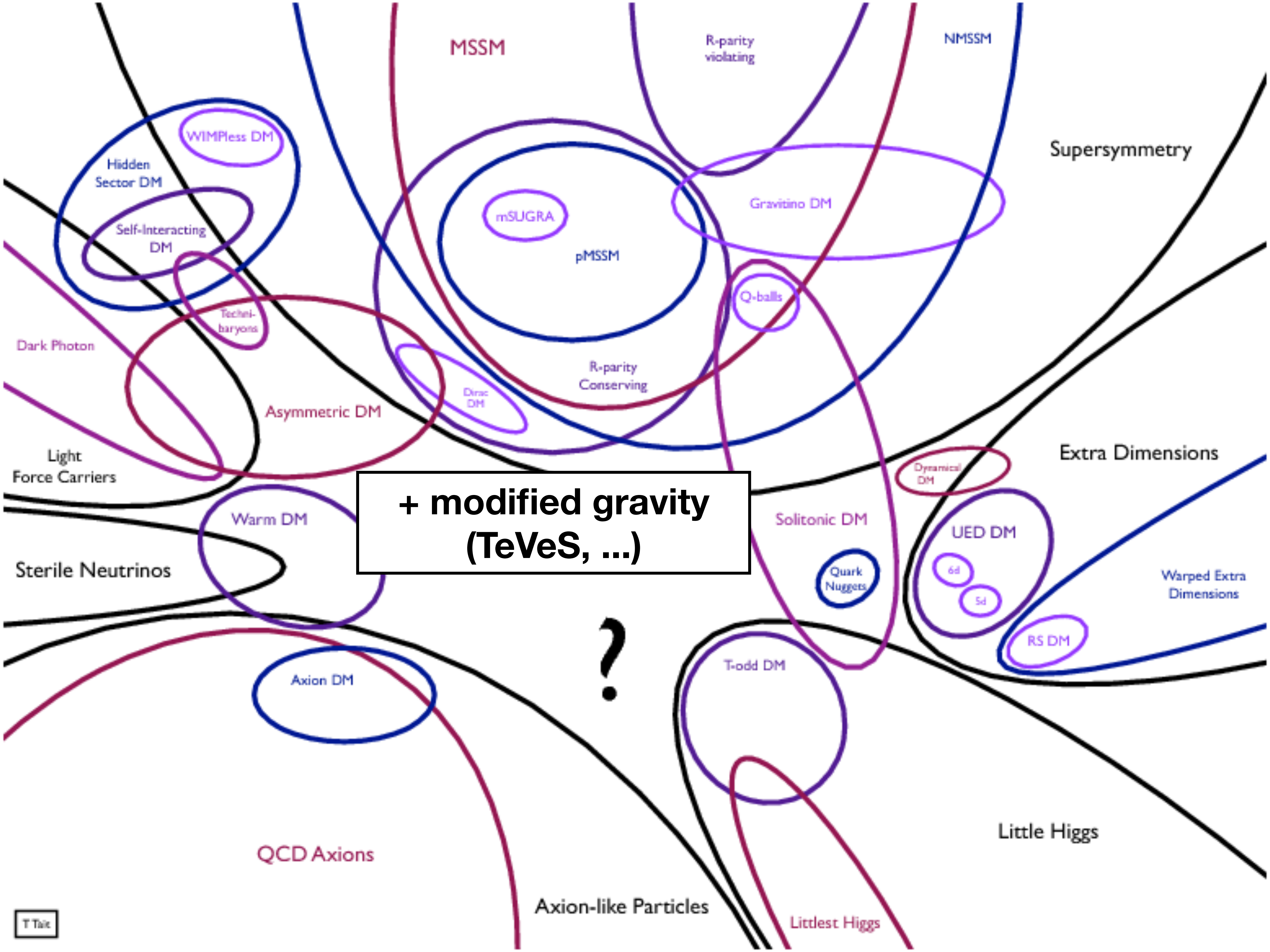


**Neutrinos ?**
No: too light ⇒ "hot" relic

(relativistic in the early Universe)

**QCD composite state?**

**The microphysical nature of dark matter is completely unknown**, as of 2025.



**+ modified gravity**
**(TeVeS, ...)**

# What can we say about the mass of dark matter ?

An example: **dwarf galaxy observations**

- Small galaxies (< kpc)
- Large amount of dark matter (velocities ~10-50 km/s)

a) Heisenberg uncertainty principle: de Broglie wavelength

$$\frac{\lambda}{10\,\mathrm{kpc}} \sim \left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)\left(\frac{10\,\mathrm{km/s}}{v}\right)$$

$\lambda_{\mathrm{dB}}$ cannot be larger than the galaxy size

**$m_{\mathrm{DM}} \gtrsim 10^{-22}$ eV**

# What can we say about the mass of dark matter ?

An example: **dwarf galaxy observations**
- Small galaxies (< kpc)
- Large amount of dark matter
  (velocities ~10-50 km/s)

b) If dark matter is a **fermion:**
Pauli exclusion principle
phase space volume / state: $\Delta x . \Delta p \sim h$
⇒ bound on number density

**$m_{DM} \gtrsim$ 200 eV** if a fermion [Alvey+ 2010.03572]

# What can we say about the mass of dark matter ?

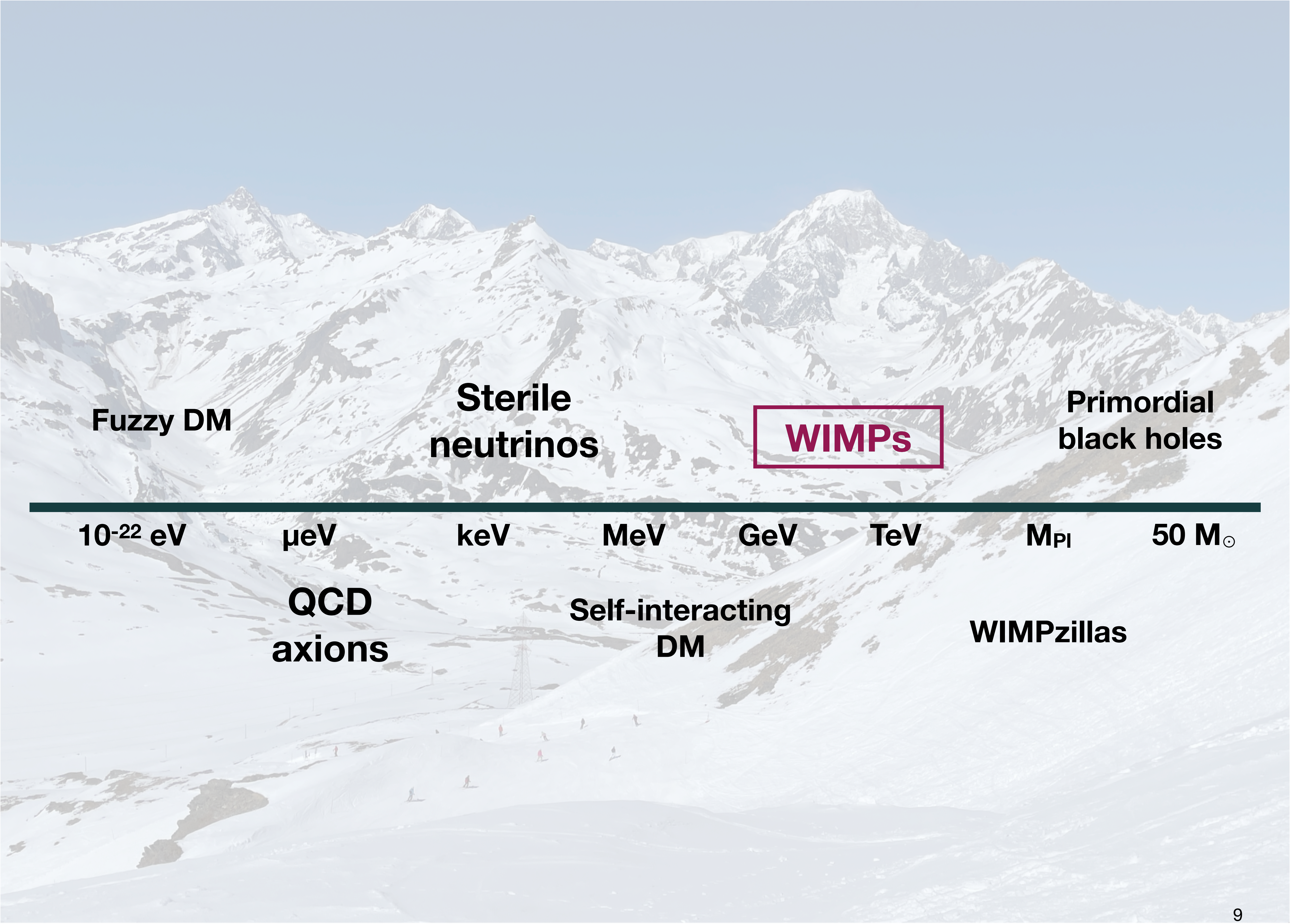
An example: **dwarf galaxy observations**

- Small galaxies (< kpc)
- Large amount of dark matter (velocities ~10-50 km/s)

c) If $m_{DM}$ is very large: "granular" structure of the halo
→ tidal forces disrupt the galaxy on short timescale

**$m_{DM} \lesssim$ 10-100 $M_\odot$**

(primordial black hole)



**Fuzzy DM**

**Sterile neutrinos**

**WIMPs**

**Primordial black holes**

**$10^{-22}$ eV** **μeV** **keV** **MeV** **GeV** **TeV** **$M_{Pl}$** **$50\ M_\odot$**

**QCD axions**

**Self-interacting DM**

**WIMPzillas**

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# The WIMP model

**Weakly Interacting Massive Particle**

Most explored scenario in the 90’s - 2010’s

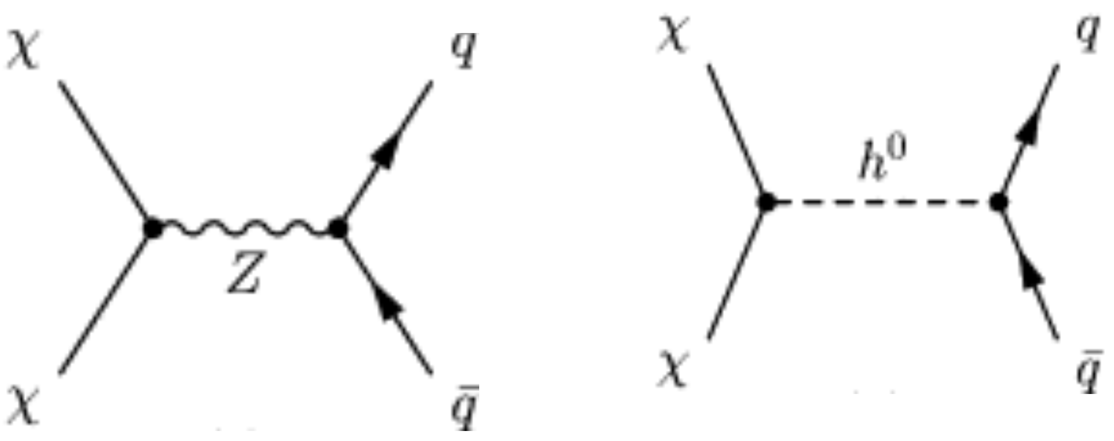
**Assume "new physics" at the scale of electroweak phenomena:**

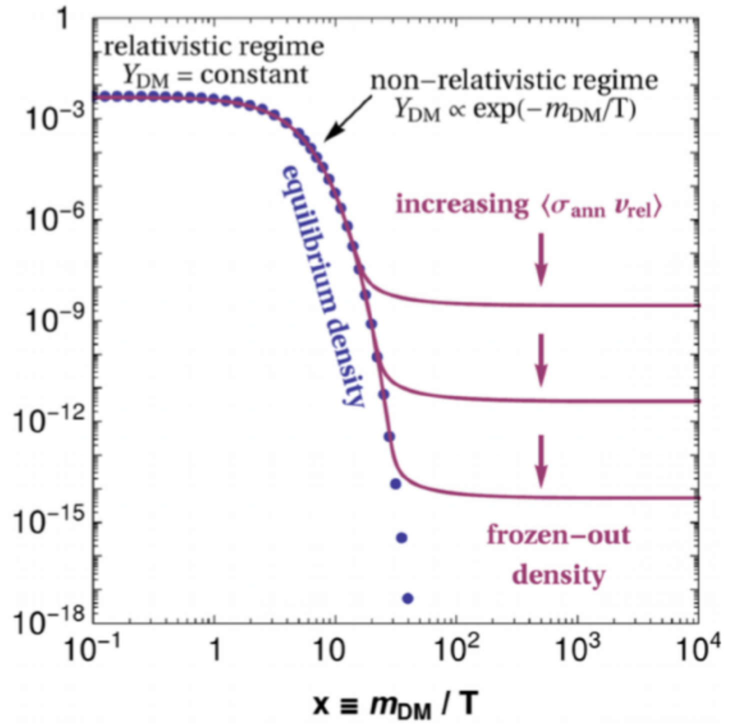
Solve the "hierarchy problem", with eg. supersymmetry or extra dimensions

A new, stable particle $\chi$ :

Mass ~ "weak scale" ~ 10 GeV - 1 TeV (W, Z, and Higgs masses ~ 100 GeV)

Interacts with Standard Model particles through "weak" couplings:



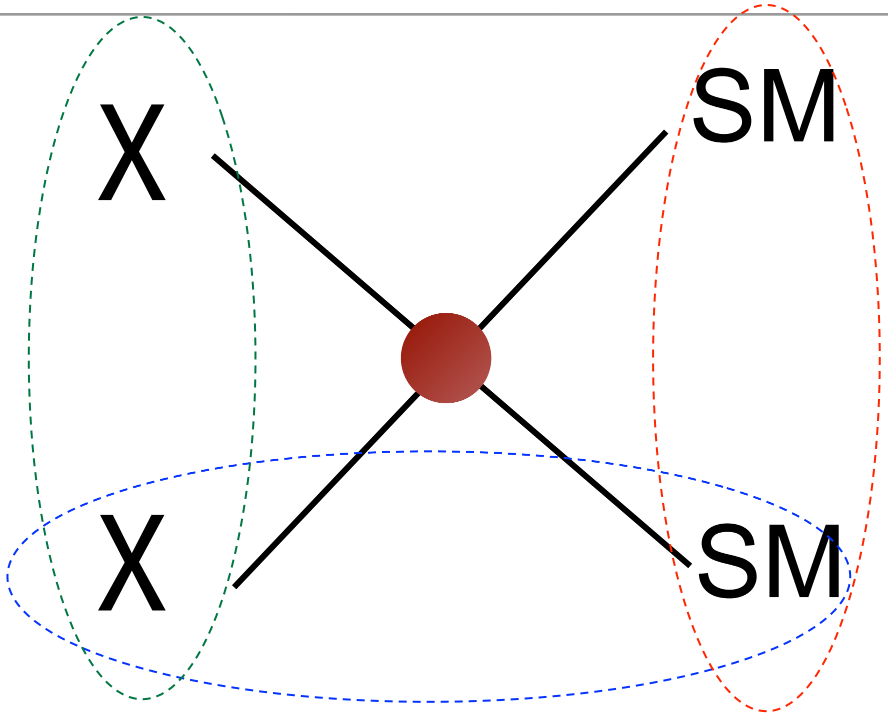


Thermal relic density from the primordial plasma:

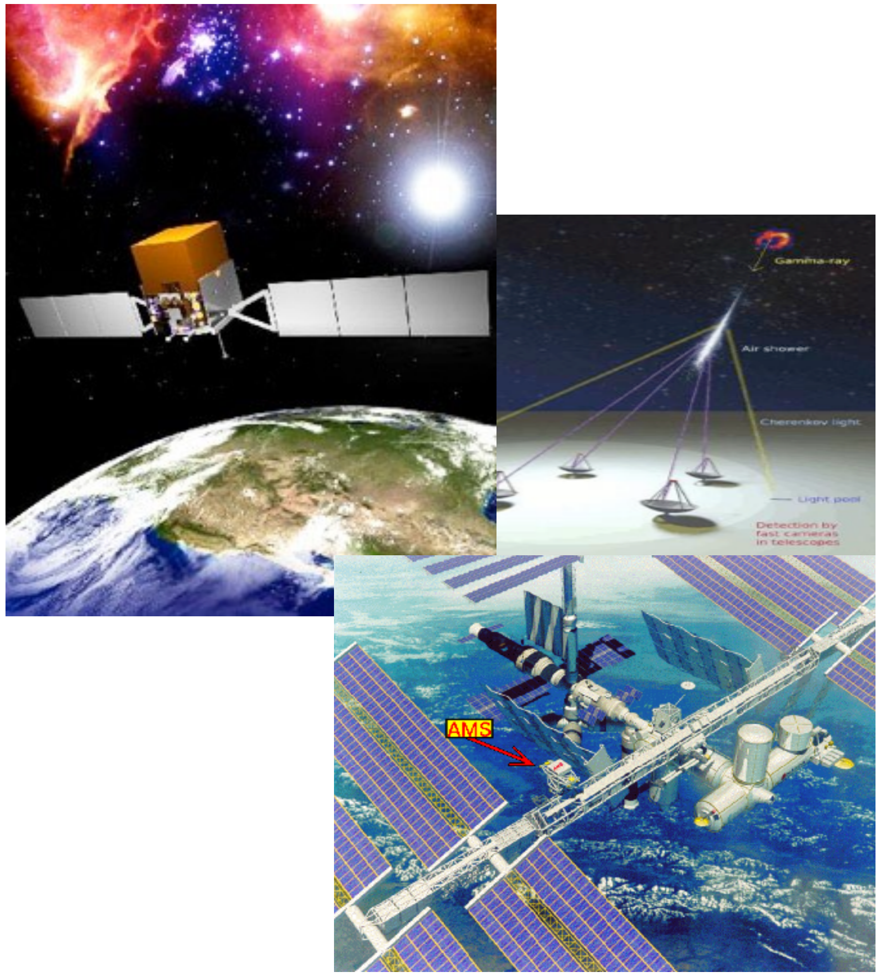
→ **Roughly matches the measured dark matter density**

(WIMP miracle)

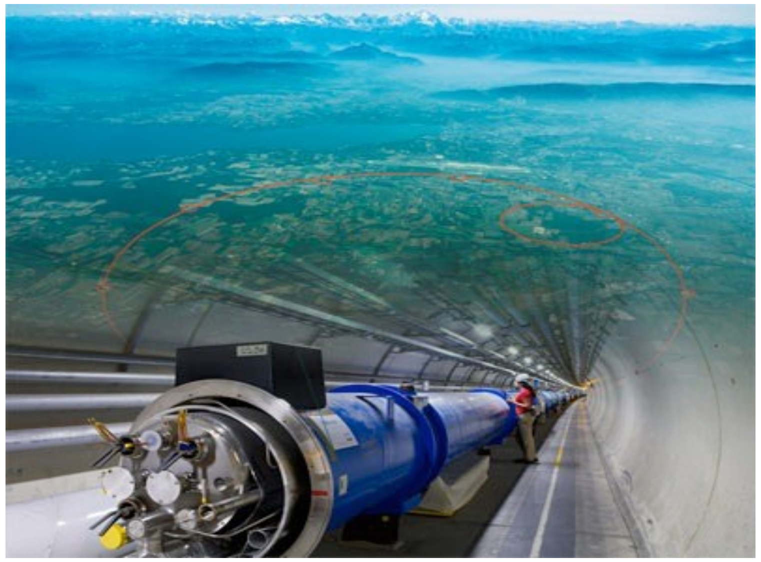
# WIMP scenarios are testable



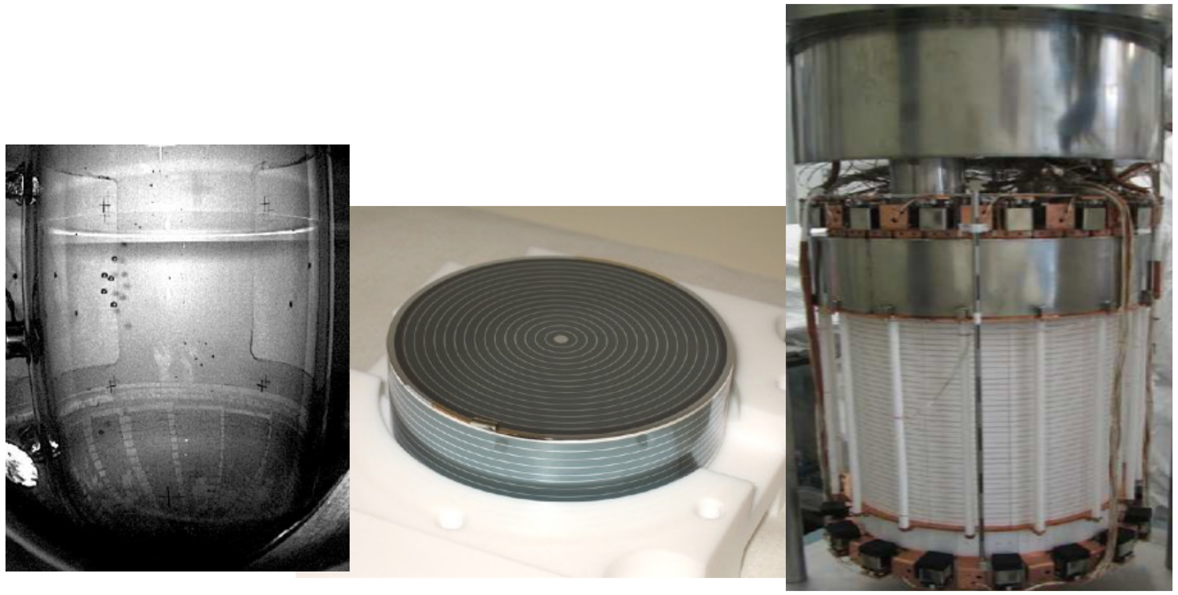
Indirect detection



Colliders



Direct detection

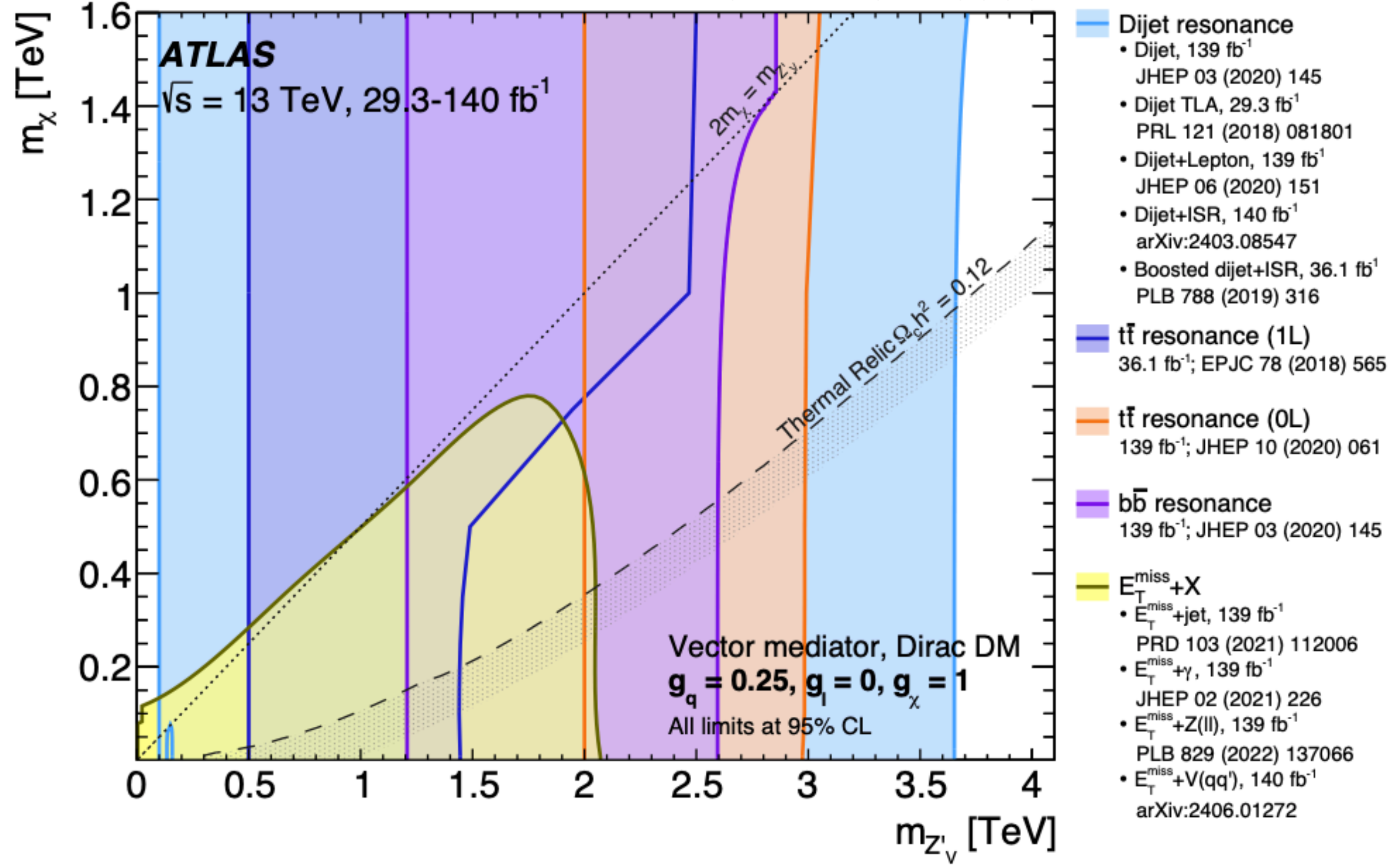


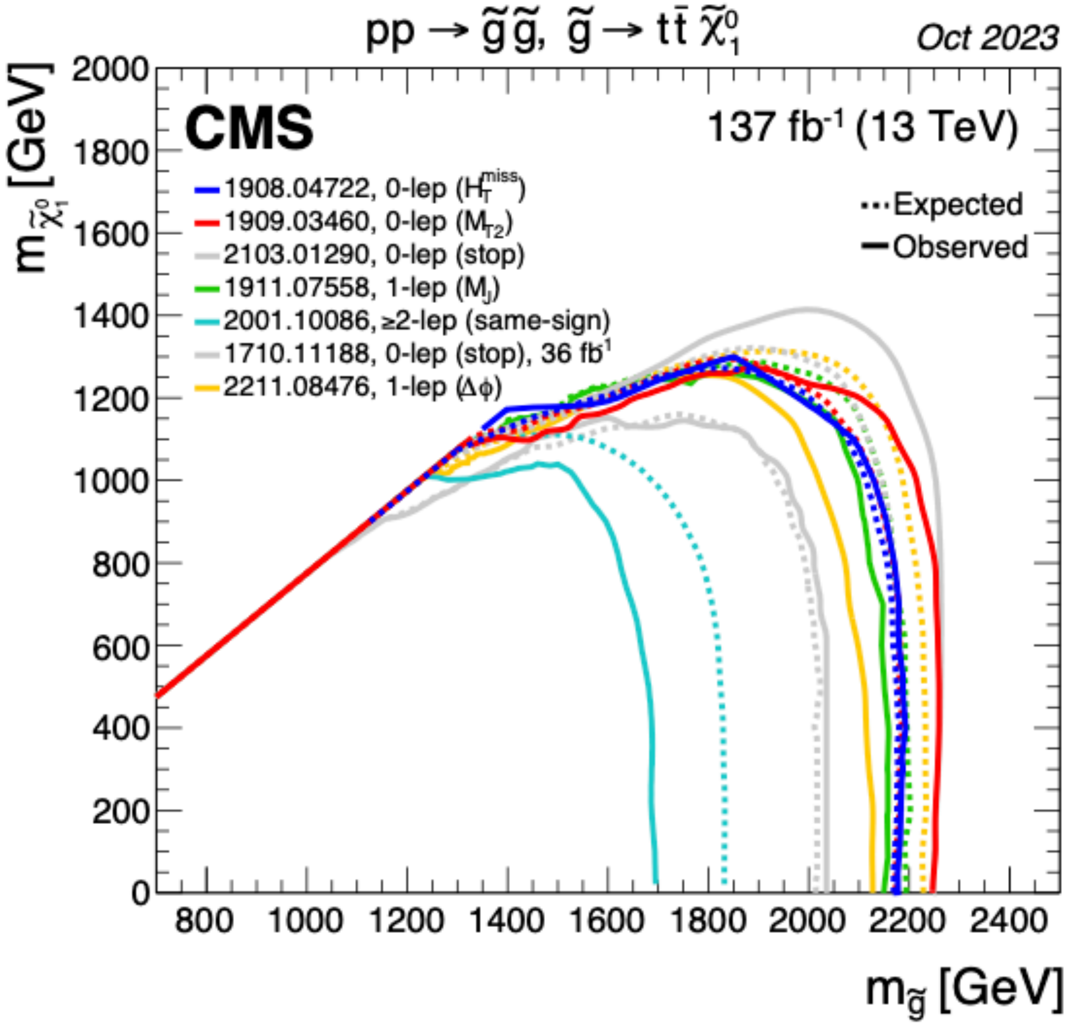
# No signs for new physics at LHC

"simplified model"

specific SUSY scenario

arxiv:2404.15930

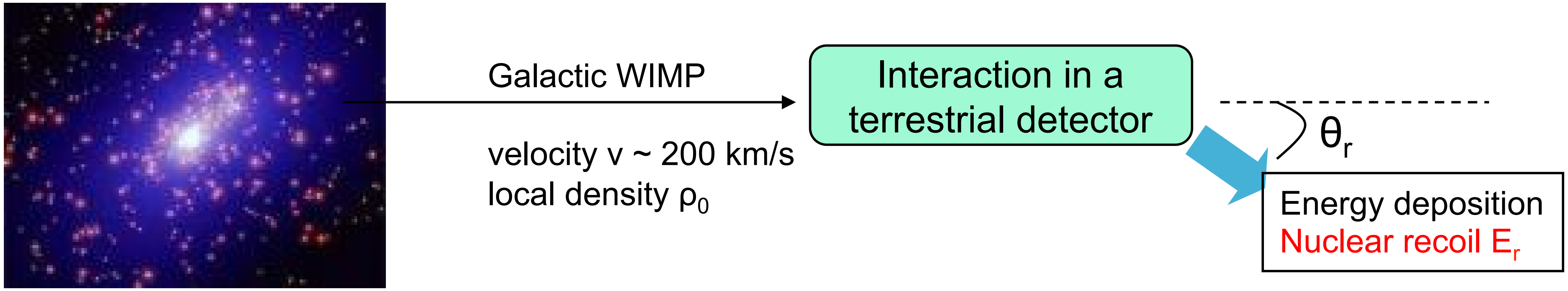




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Simplest SUSY scenarios
severely constrained

# Direct detection of WIMP dark matter



$$E_r = \left(\frac{m_\chi}{2}v^2\right)\times\frac{4m_N m_\chi}{\left(m_N+m_\chi\right)^2}\times\cos^2\vartheta_r$$ ~ 1 - 100 keV

Particle physics

Astrophysics (WIMP velocity distribution and local density)

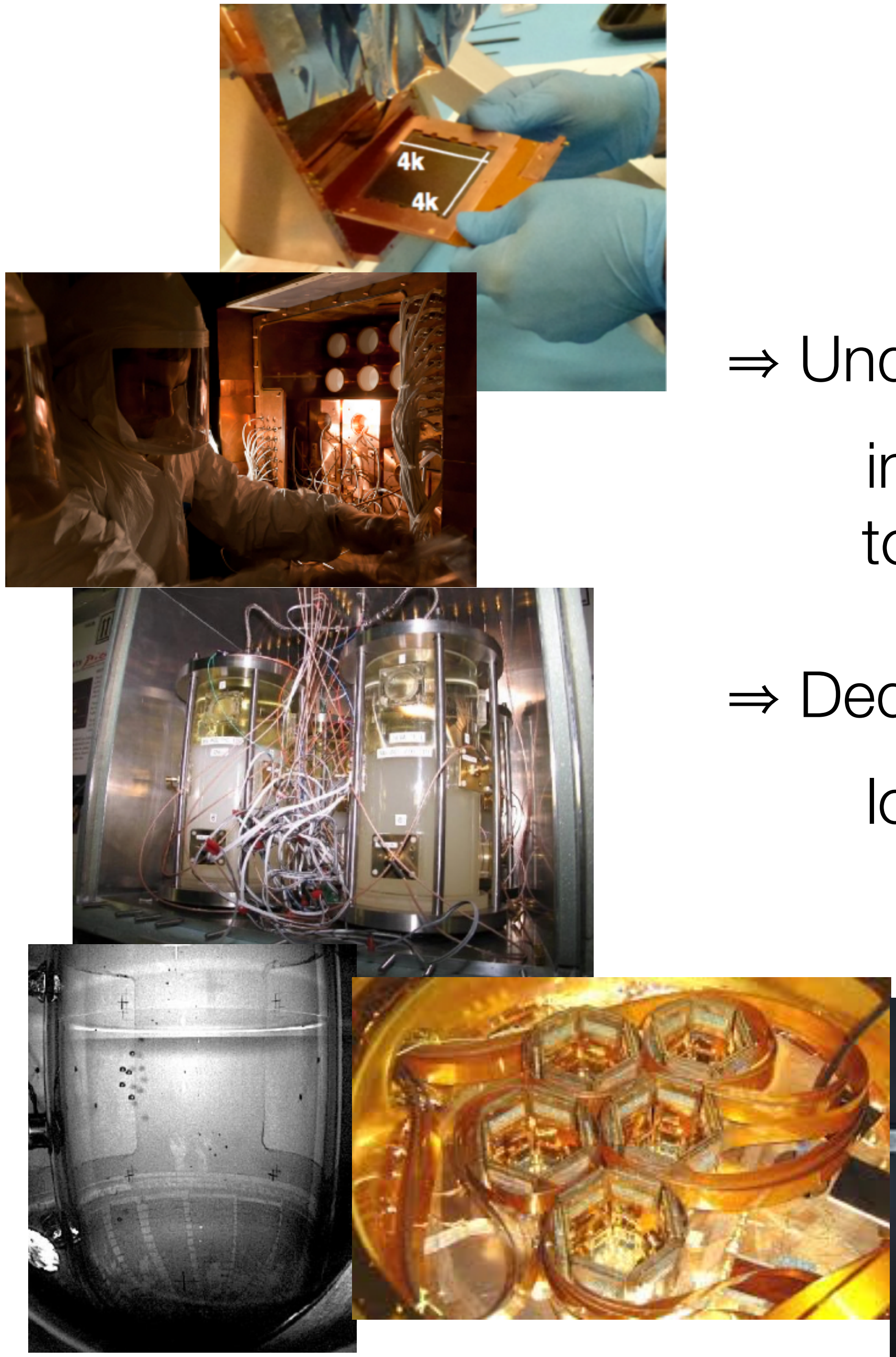
$$\boxed{\frac{dR}{dE_r} = \frac{\sigma_0\,\rho_0}{2\,m_\chi m_r^2}F^2(q)\int_{v_{\min}}^{\infty}dv\,\frac{f_1(v)}{v}}$$

Nuclear physics

~ 1 interaction / ton / day
for σ ~ 3x10$^{-32}$ cm$^2$

- Kinetics => search for **interactions with nuclei** (nuclear recoil NR)
- **Energy spectrum** ~ exponential
- **Scaling with M$_{\text{WIMP}}$** : low recoil energies at low M$_{\text{WIMP}}$

# WIMP direct detection: signals from underground



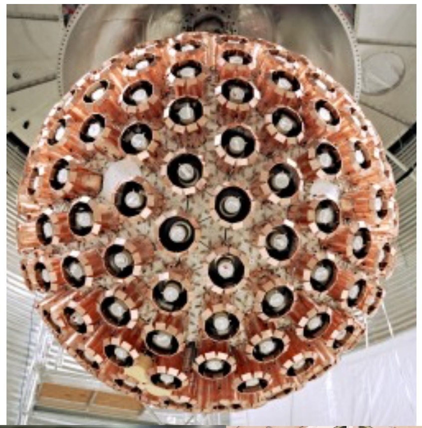
**- low energy detection threshold**
**- ultra-low radioactive background**

⇒ Underground shielded infrastructures:

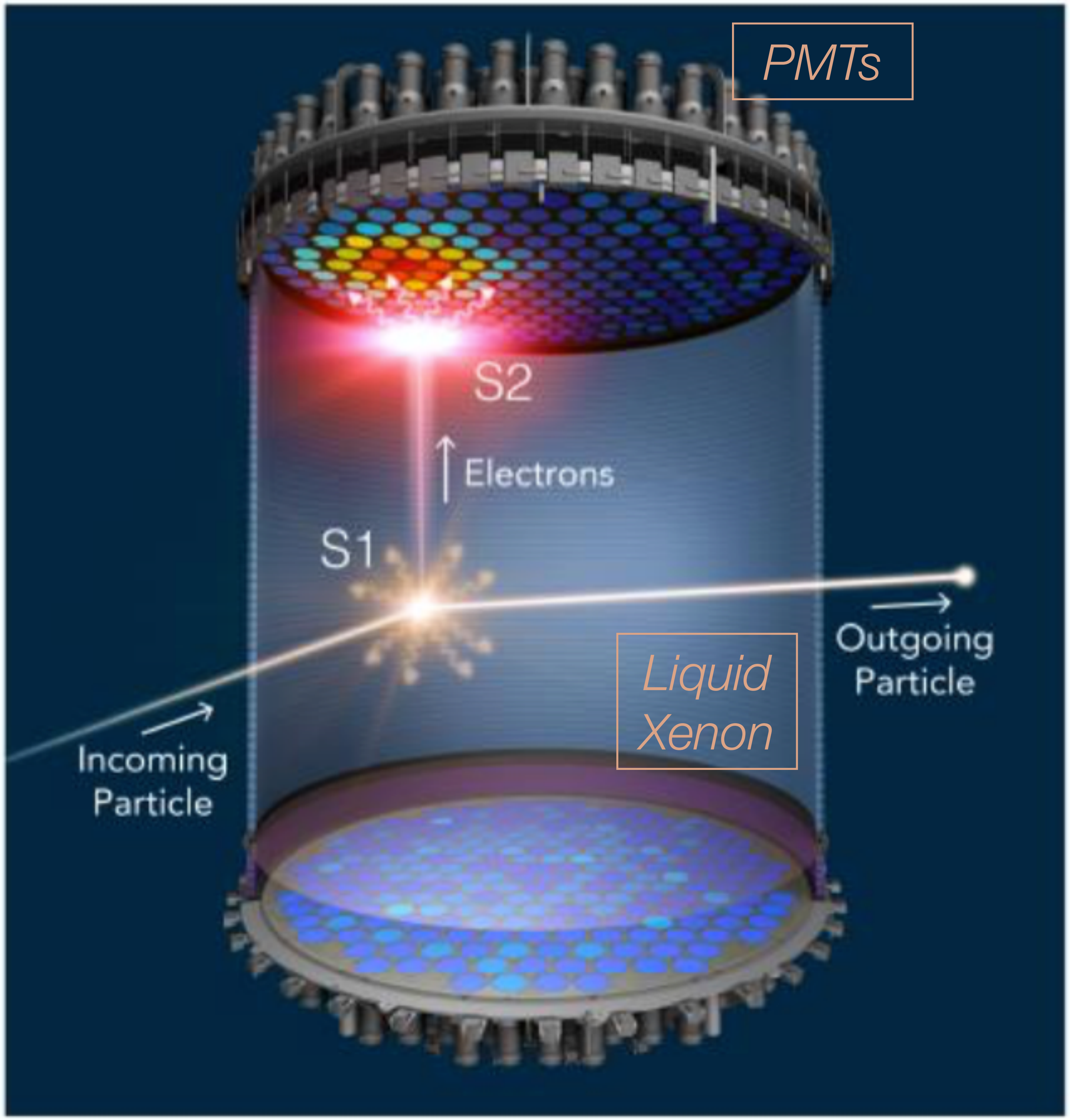
in tunnels, mines, ...
to protect against cosmic-rays

⇒ Dedicated detectors for recoil identification:

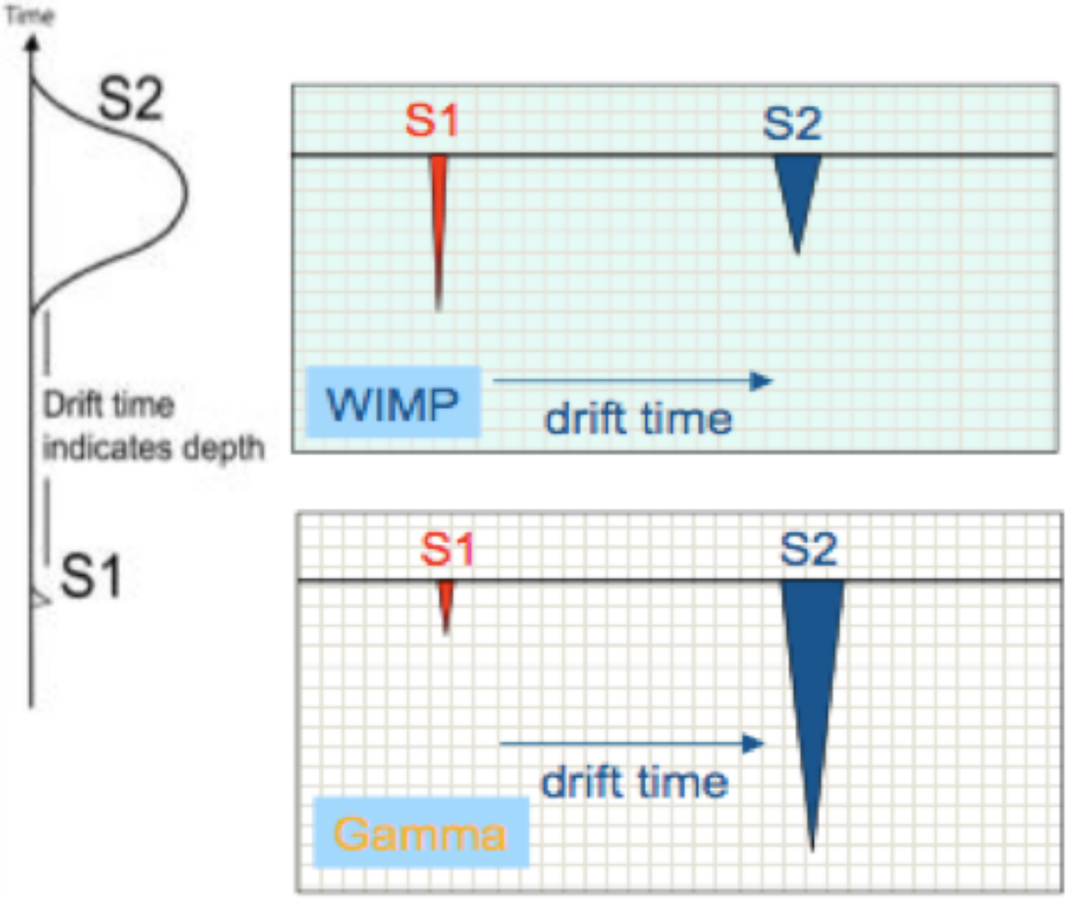
lots of technologies tested !



# Dual-phase Xenon TPC



« S1 » = direct light, <u>scintillation</u>
« S2 » = light emitted when electrons are accelerated in the gas phase, <u>ionization</u>

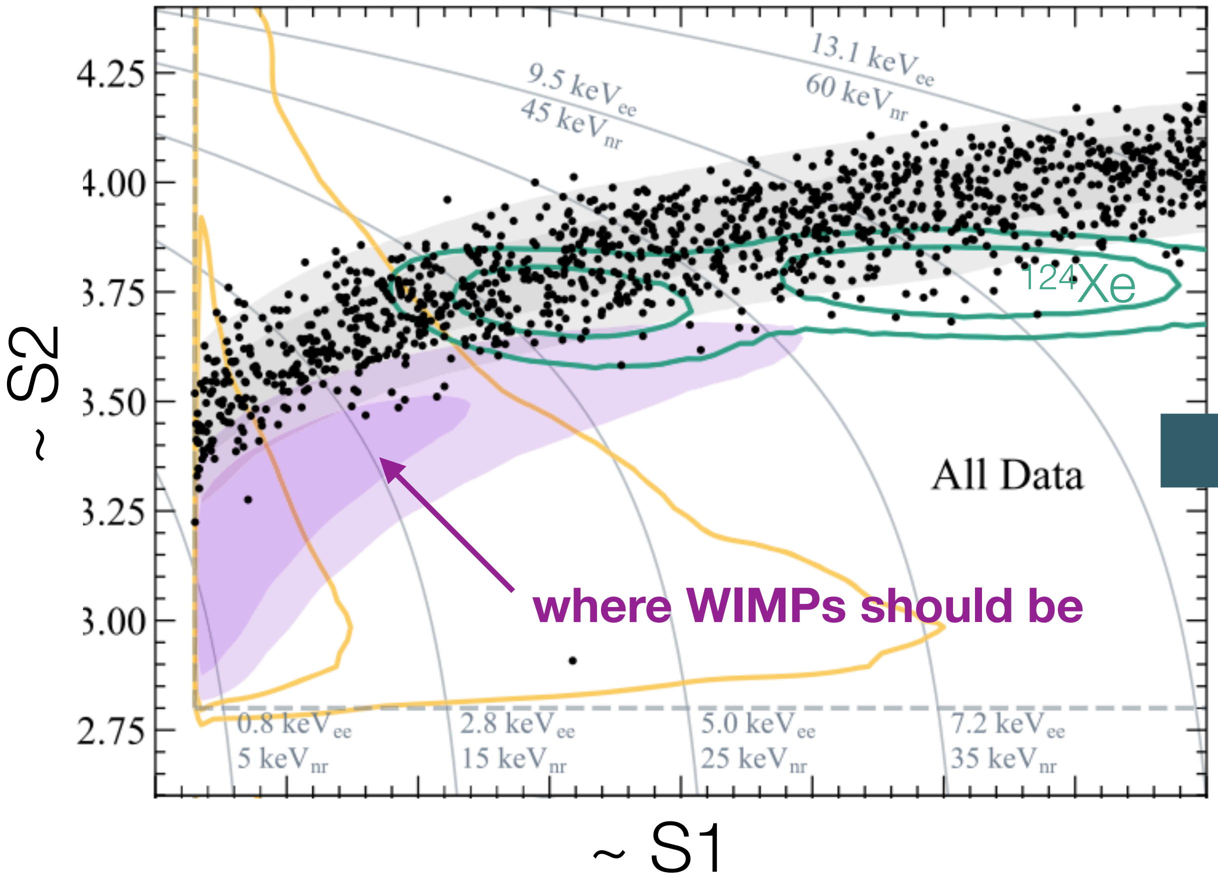


$(S2/S1)_{wimp} << (S2/S1)_{gamma}$

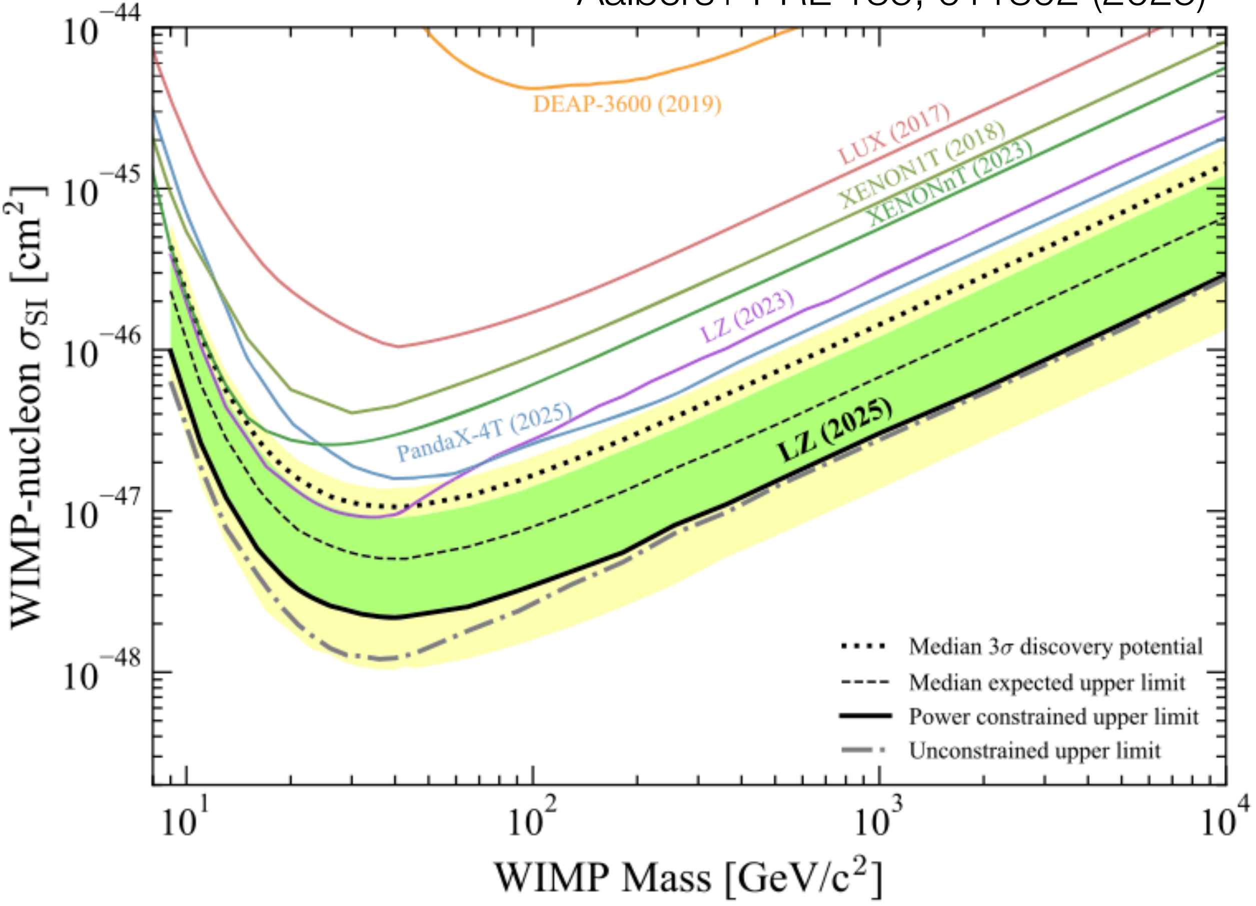
# Example result: Lux-Zeplin Experiment

4.2 tonne-years collected in 280 live days
Many interactions recorded but properties compatible with known radioactivity

**Upper bound on WIMP-nucleus interaction rate** (cross-section),
set from profile likelihood ratio test statistics



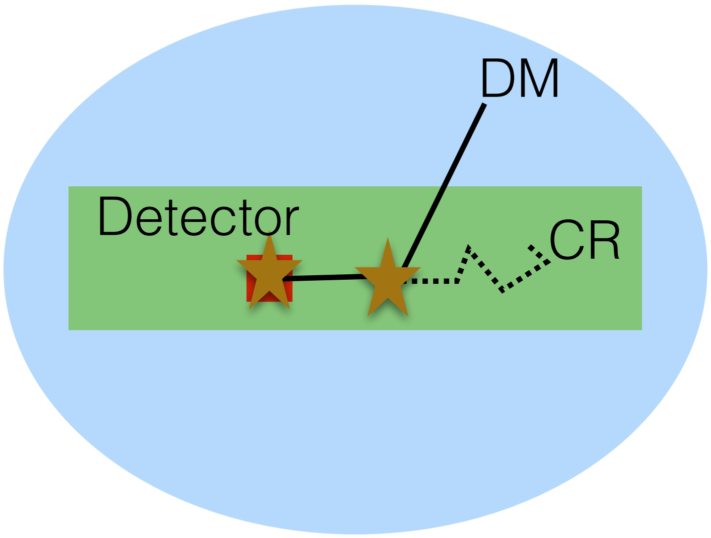
Aalbers+ PRL 135, 011802 (2025)



# Extending bounds towards lower mass

**thermal relic mass range ~ 100 keV (HDM, BBN..) - 100 TeV (unitarity)**

**DM - cosmic ray scattering**



=> secondary high energy DM flux: easier to detect !

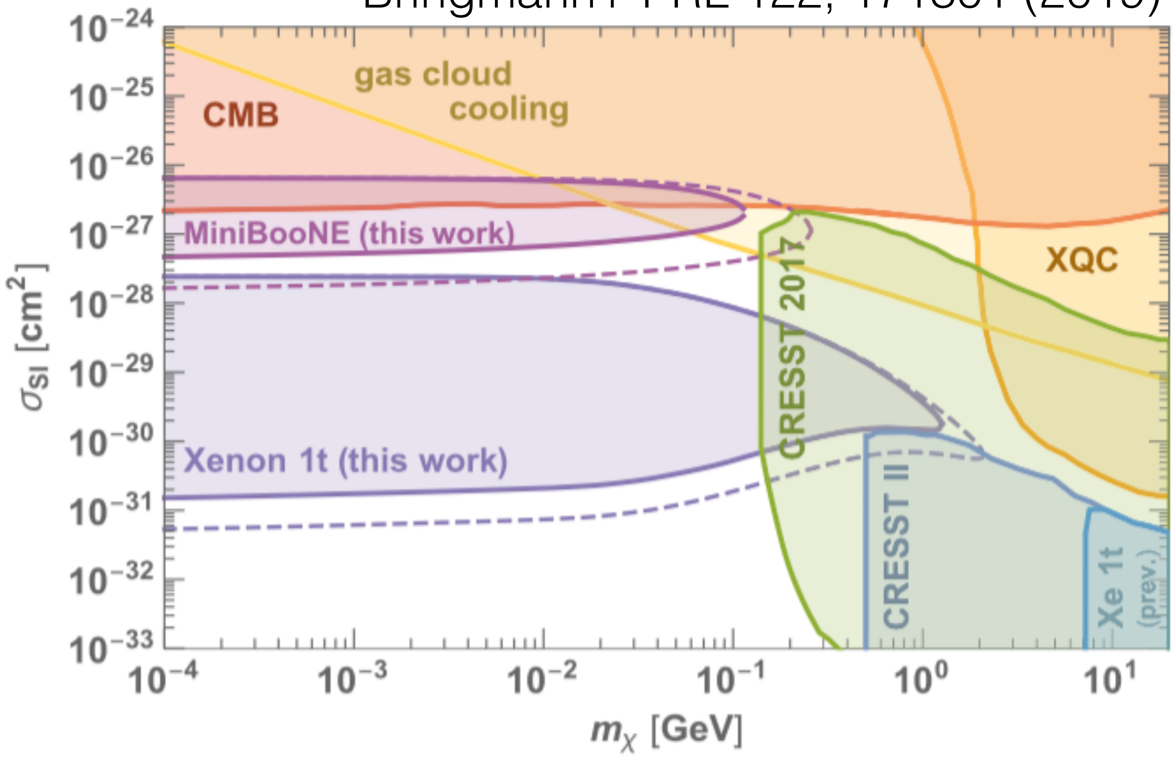
CR flux

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff}\frac{\rho_\chi^{\rm local}}{m_\chi} \times \sum_i \sigma^0_{\chi i} G_i^2(2m_\chi T_\chi)\int_{T_i^{\rm min}}^\infty dT_i \frac{d\Phi_i^{\rm LIS}/dT_i}{T_\chi^{\rm max}(T_i)}$$

size of CR halo

particle physics

Bringmann+ PRL 122, 171801 (2019)



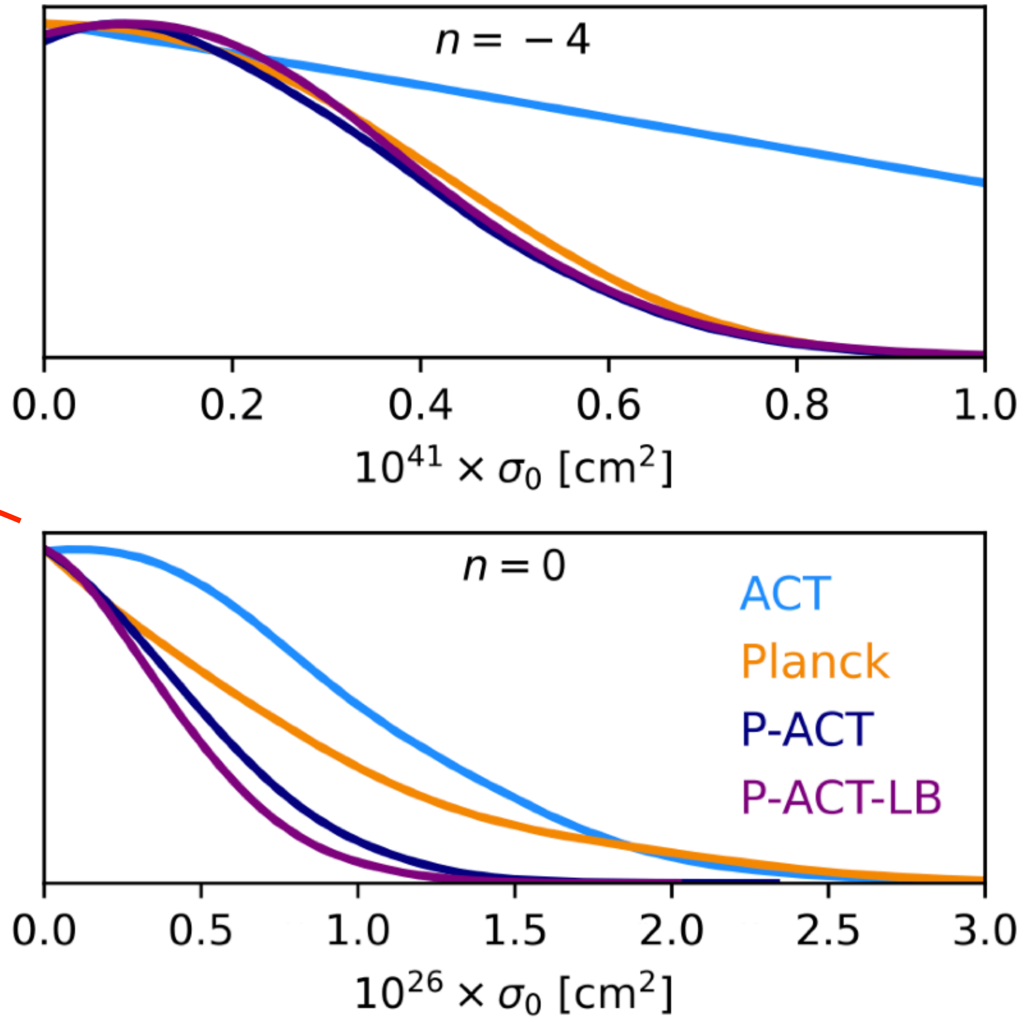
# Extending bounds towards lower mass: CMB

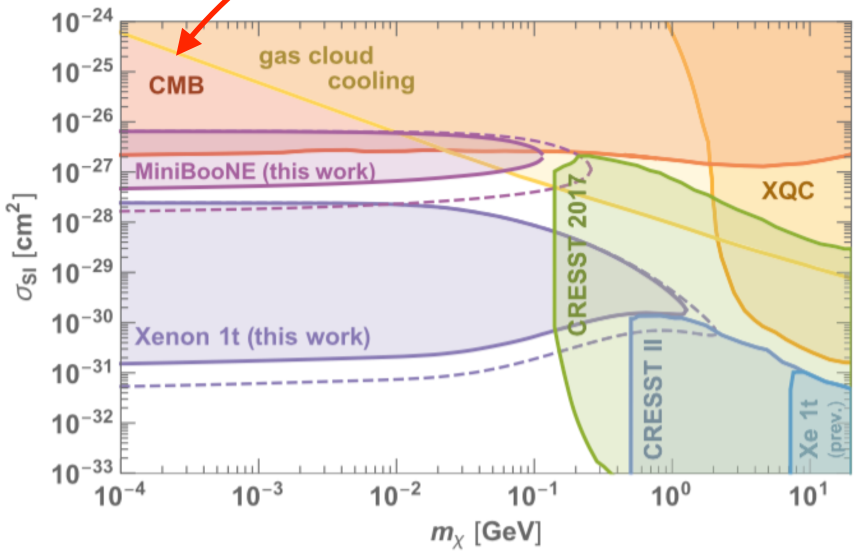
DM scattering with baryons ⇒ exchange heat + momentum

- CMB: collisional damping of small scales
- also IGM heating

$$\sigma = \sigma_0\, v^n$$

ACT DR6 2503.14454
$m_{DM}$ ~ 1 MeV





# WIMP indirect detection: signals from the sky

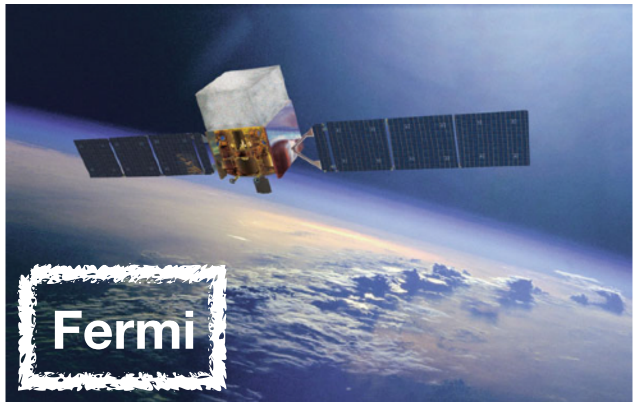
DM dense regions:

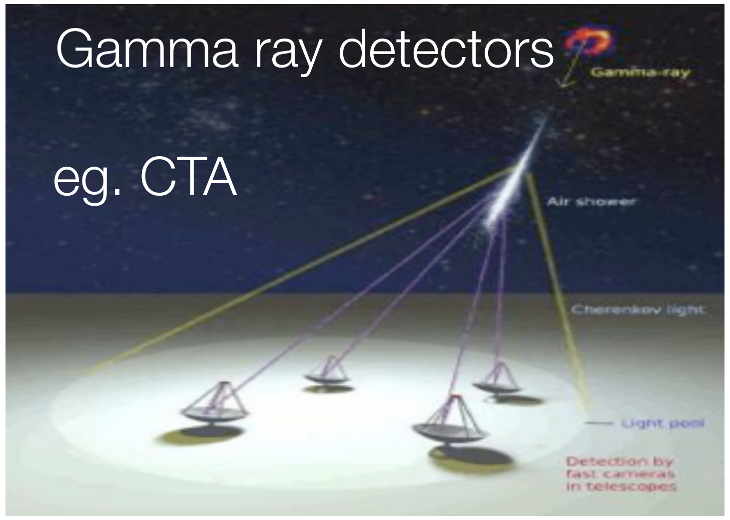
$$\chi\,\chi \to \underbrace{\gamma,\, p,\, e\ldots}_{}$$

high-energy particles E ~ mχ, detectables :

$$\Phi_i(\psi, E) = \sigma v \underbrace{\frac{dN_i}{dE}\,\frac{1}{4\pi m_{\rm DM}^2}}_{\text{particle physics}} \underbrace{\int_{\text{line of sight}} d\,s\rho^2\left(r(s,\psi)\right)}_{\text{astrophysics (DM halo)} \,\to\, \text{J-factor}}$$

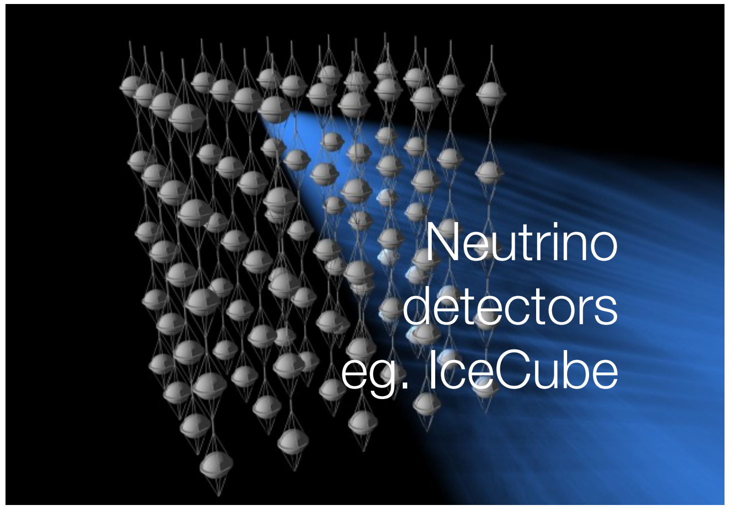
annihilation cross section



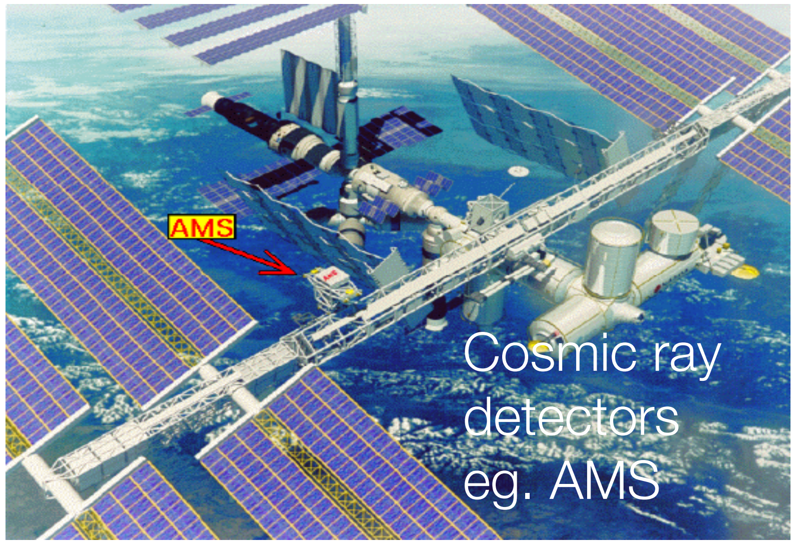


Gamma ray detectors

eg. CTA



Neutrino detectors
eg. IceCube



Cosmic ray detectors
eg. AMS

# Example: Fermi observations from dwarf galaxies

- Stack Fermi signal on 30 dwarfs with measured J-factors

$$J = \int d\Omega \int dl \rho^2$$

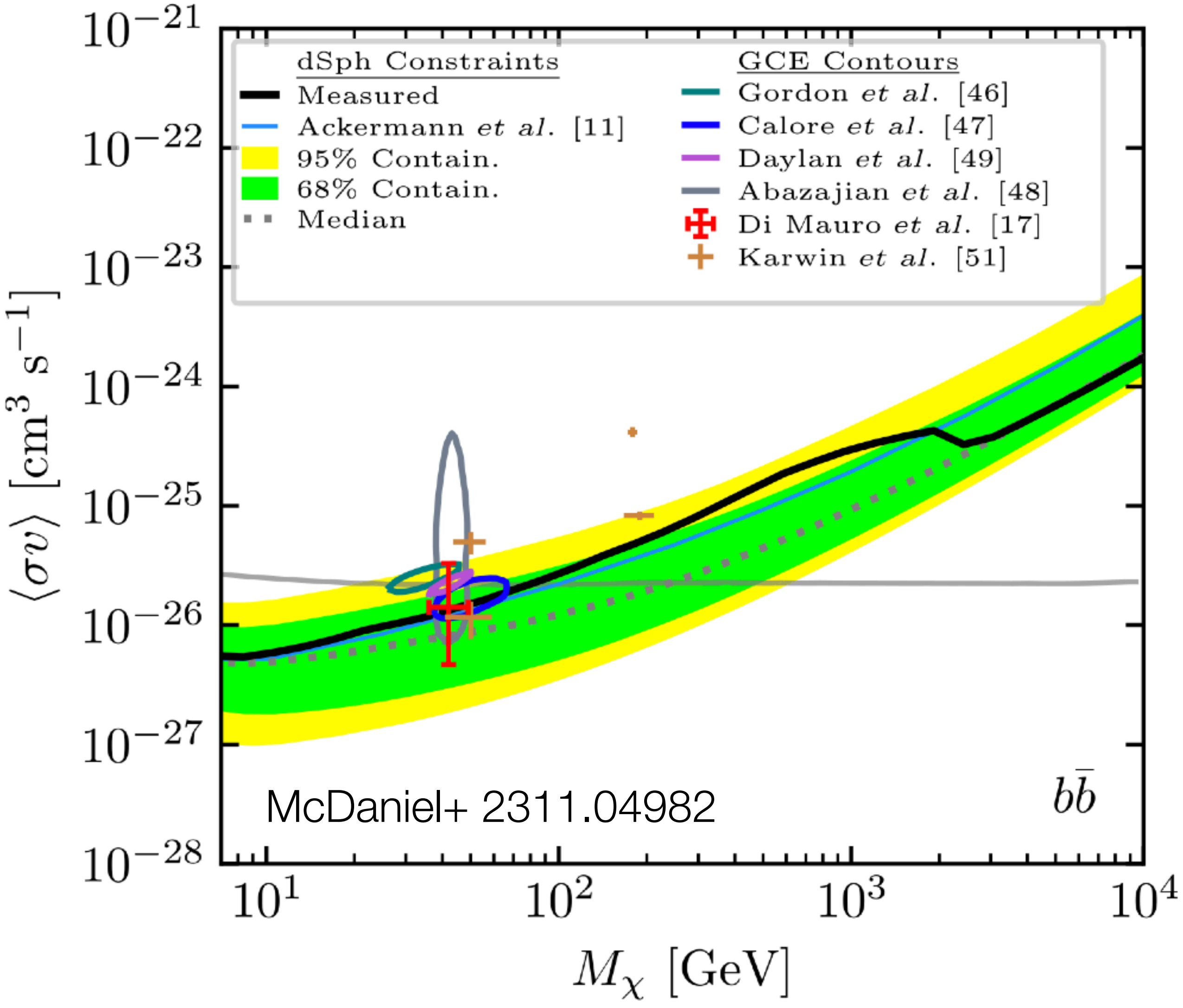
Fornax again!

- No signal: ϕ <~ $10^{-9}$ cm$^{-2}$ s$^{-1}$
  ⇒ bound on ⟨σv⟩ (profile likelihood)

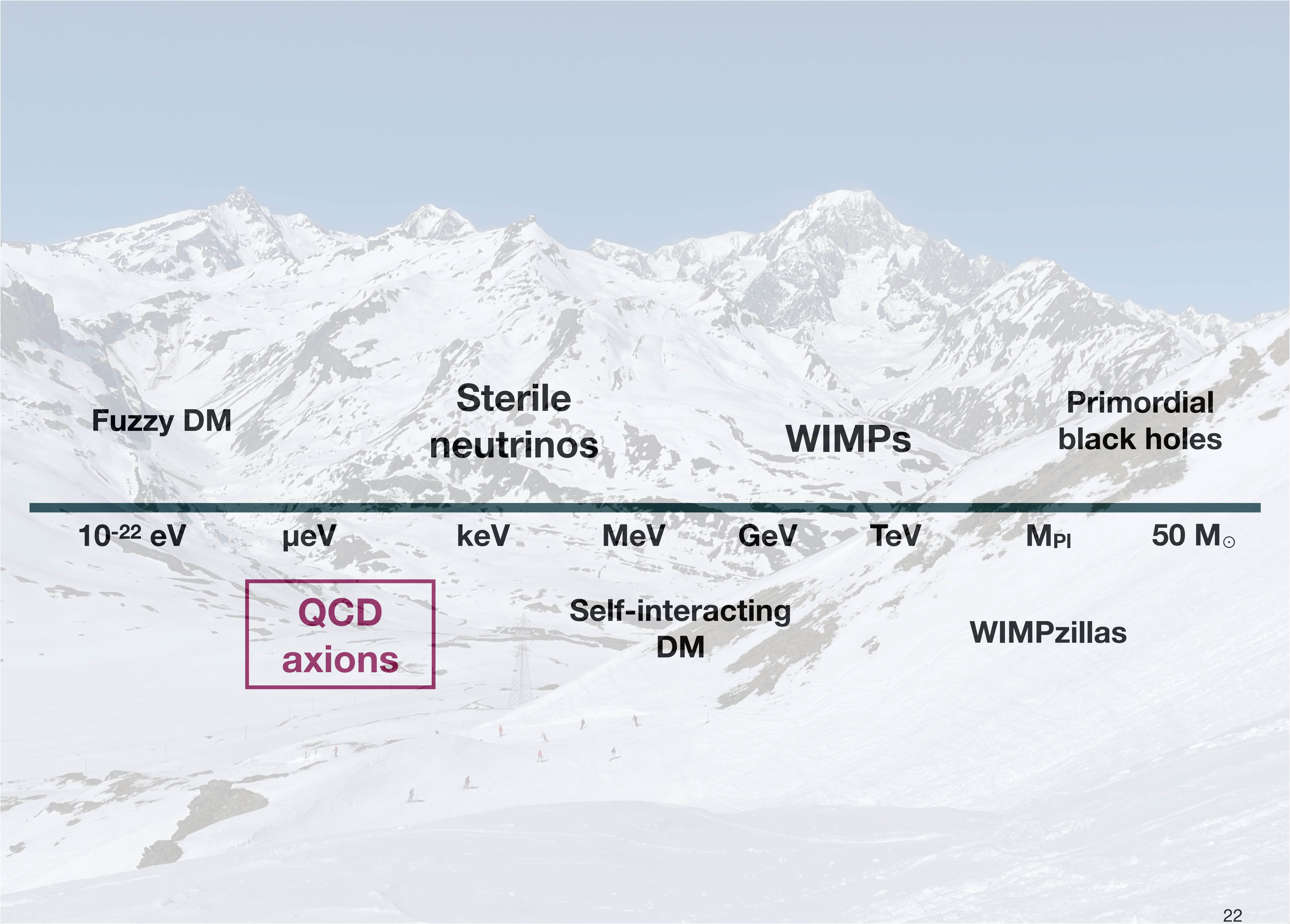
- Compare result with thermal relic prediction: **constrain thermal relics up to ~ 100 GeV**

**Similar bound from CMB**
alter ionization history (broaden width of last-scattering surface):

$$f_{\rm eff} \frac{\langle \sigma v \rangle}{m_{\rm DM}} \lesssim 4 \times 10^{-28}\ {\rm cm^3/s/GeV}$$



McDaniel+ 2311.04982



Fuzzy DM

Sterile neutrinos

WIMPs

Primordial black holes

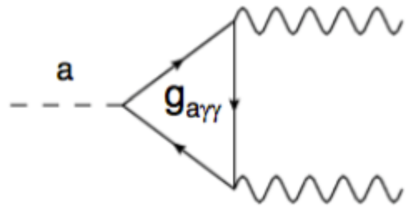
$10^{-22}$ eV    μeV    keV    MeV    GeV    TeV    $M_{Pl}$    $50\ M_\odot$

**QCD axions**

Self-interacting DM

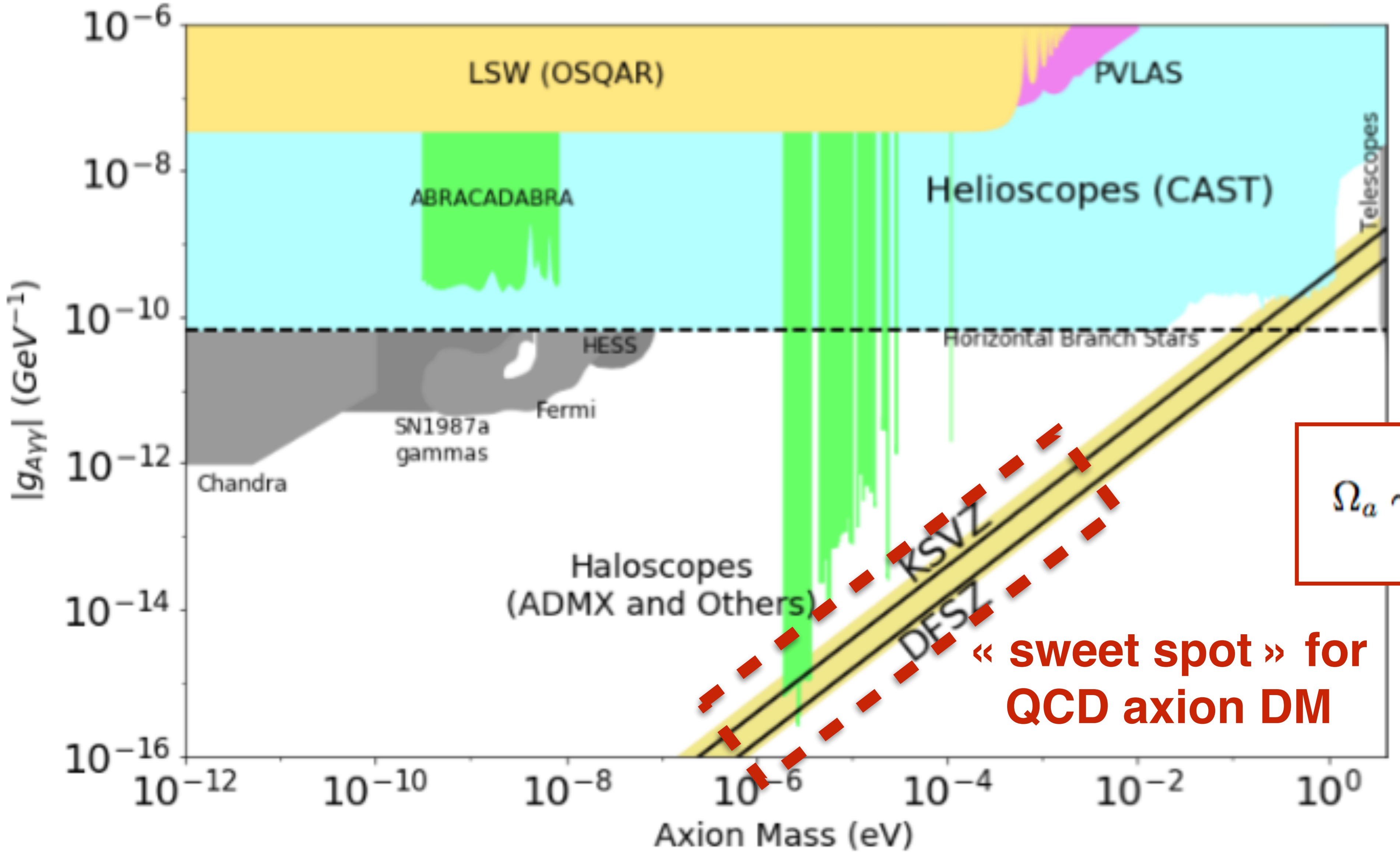
WIMPzillas

# QCD axions coupling to photons



Effective coupling ~ $g_{a\gamma\gamma}$ . a . (E . B)

**for QCD axion**: $g_{a\gamma\gamma} \sim 1/f_a \sim m_a$



**« sweet spot » for QCD axion DM**

$$\boxed{\Omega_a \sim 0.36 \left(\frac{10\ \mu\mathrm{eV}}{m_a}\right)^{1.184}}$$

(misalignment mechanism)

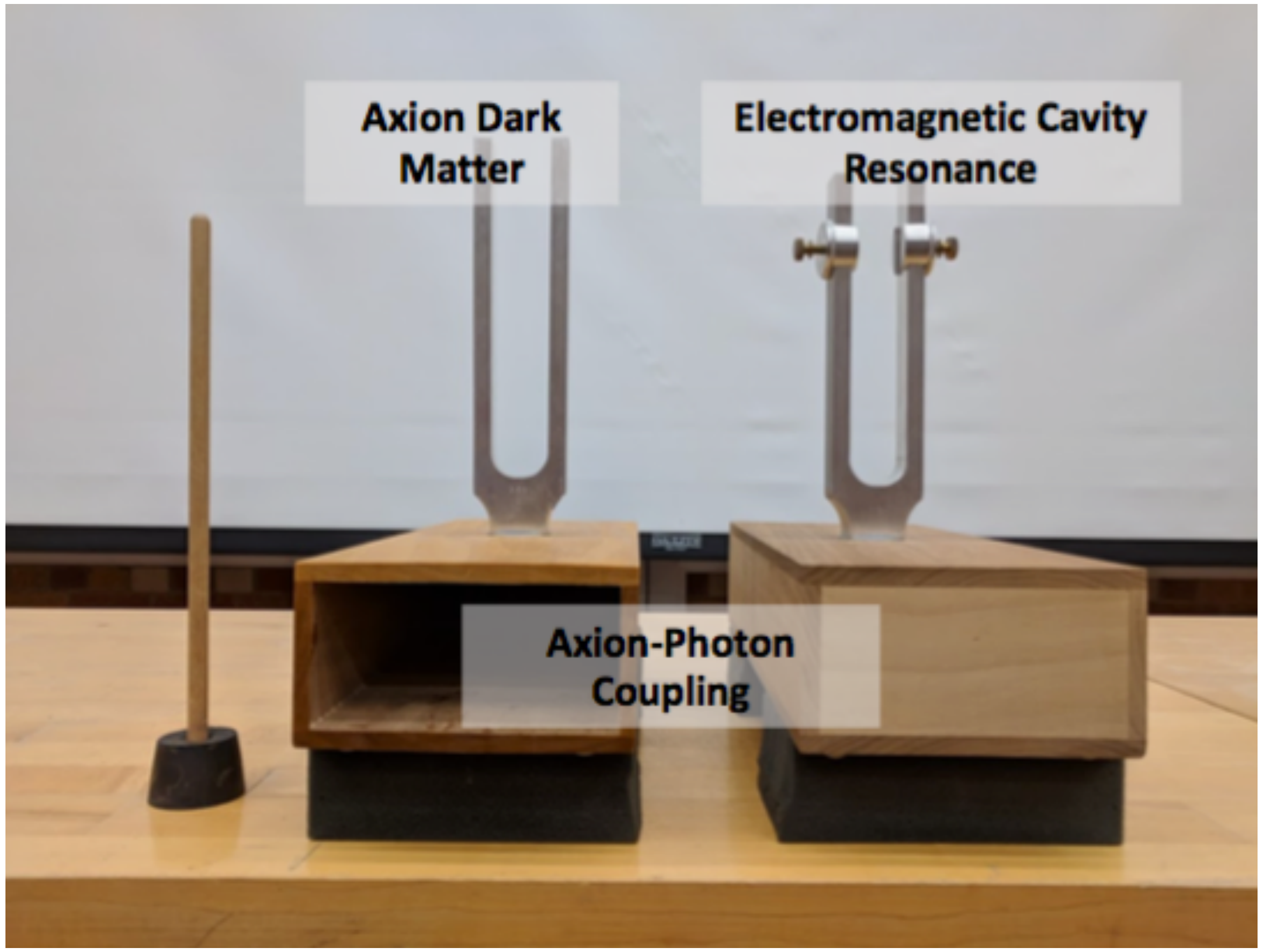
# Axion direct detection: « haloscopes »

**$g_{a\gamma\gamma}$ . a . (E . B)**

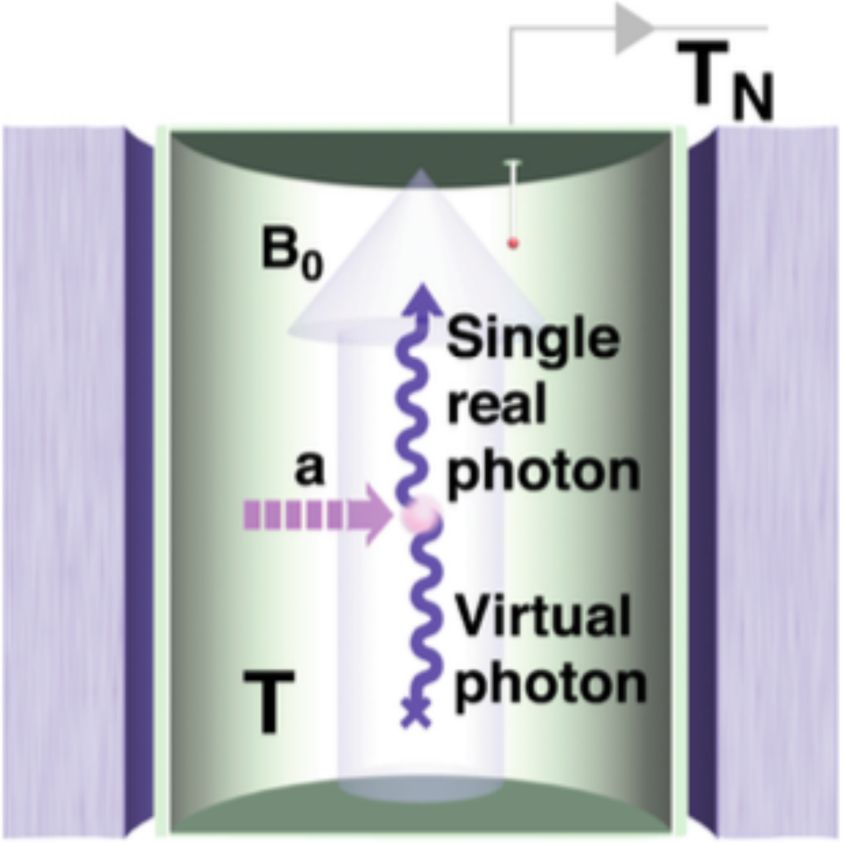
a : axion from DM halo, oscillates @ $\omega = m_a$

B : magnet (static)

resonant cavity ==> detect E @ $\omega = m_a$



field

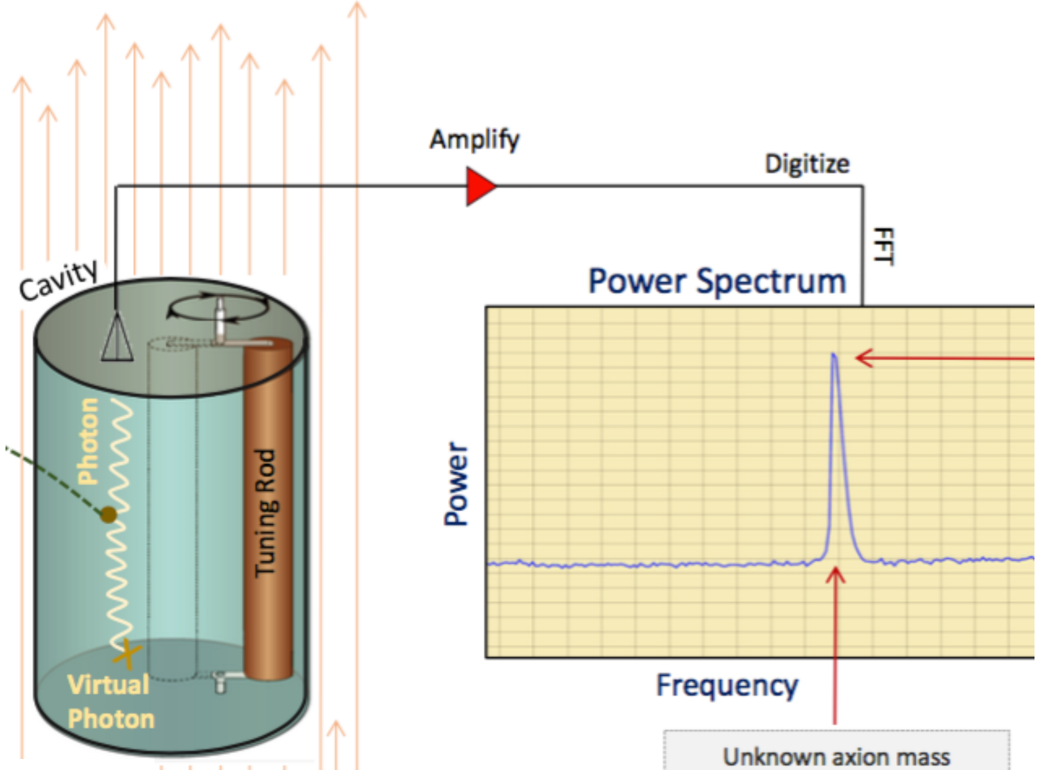


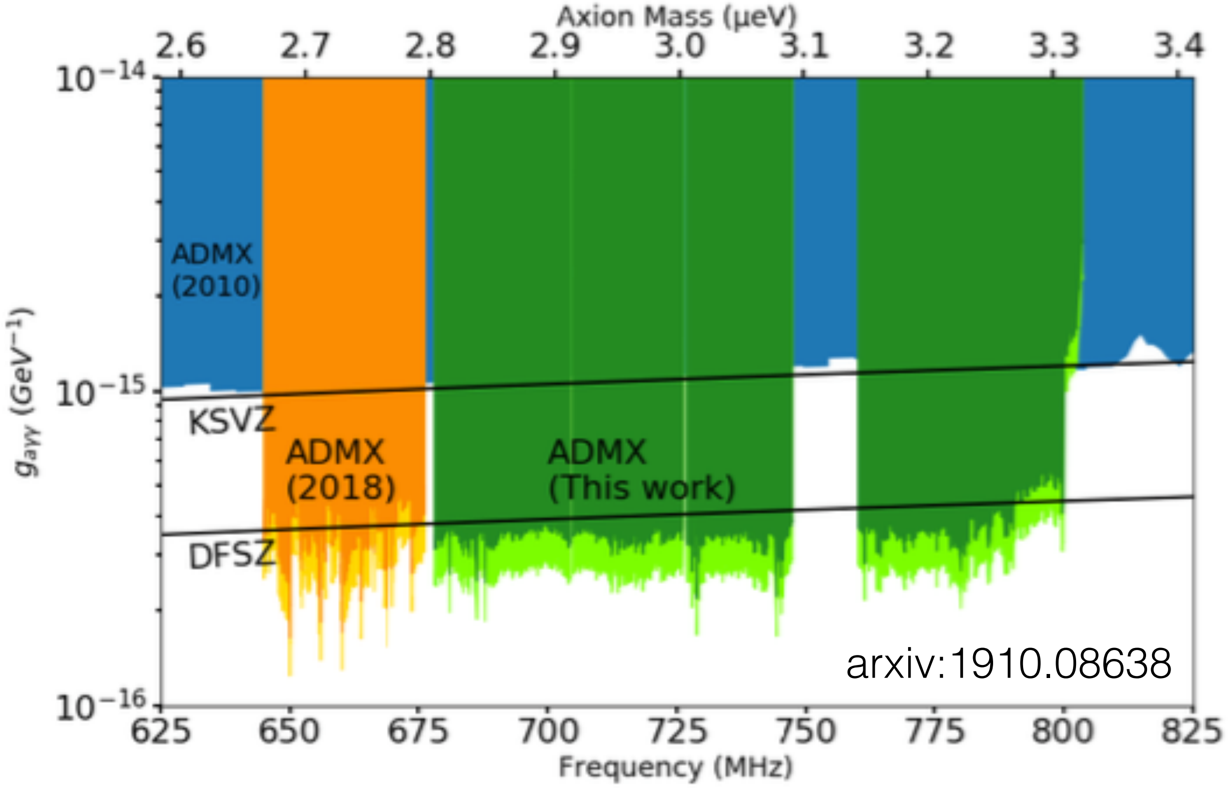
particle

# Example result: ADMX experiment

- millikelvin cryogenics
- ultralow noise quantum amplifiers

$$\frac{S}{N} = \frac{P_{\text{axion}}}{k_B T_{\text{sys}}} \sqrt{\frac{t}{b}}$$





arxiv:1910.08638

narrow QCD axion mass range excluded

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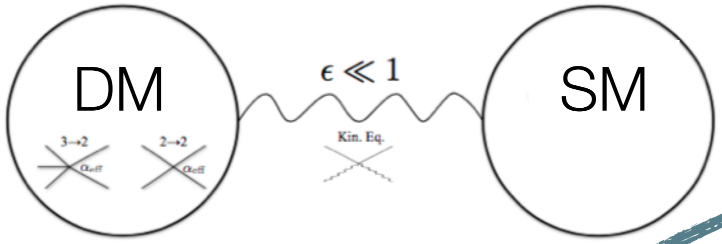
# DM solutions to the « small-scale issues »

**Strongly-Interacting DM (SIDM)**

σ/m ~ 0.1-1 cm2/g
best solve cusp-core

eg. sub-GeV thermal relic
with 3➝2 annihilation

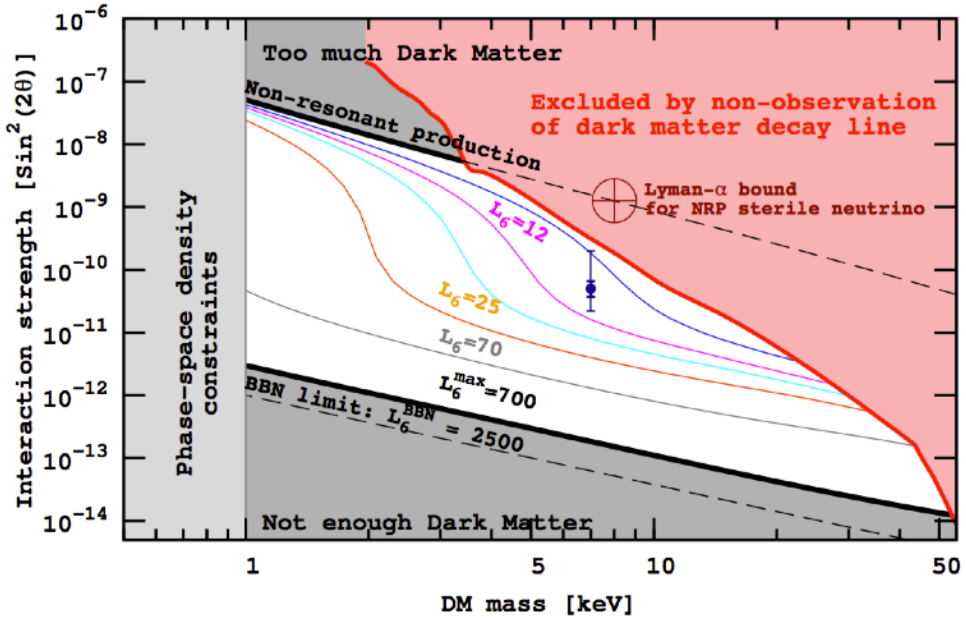


**Warm Dark Matter (WDM)**

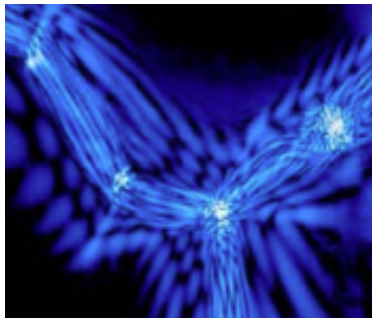
free-streaming
best solve missing satellites

eg. sterile neutrino

3.5 keV line signal ?

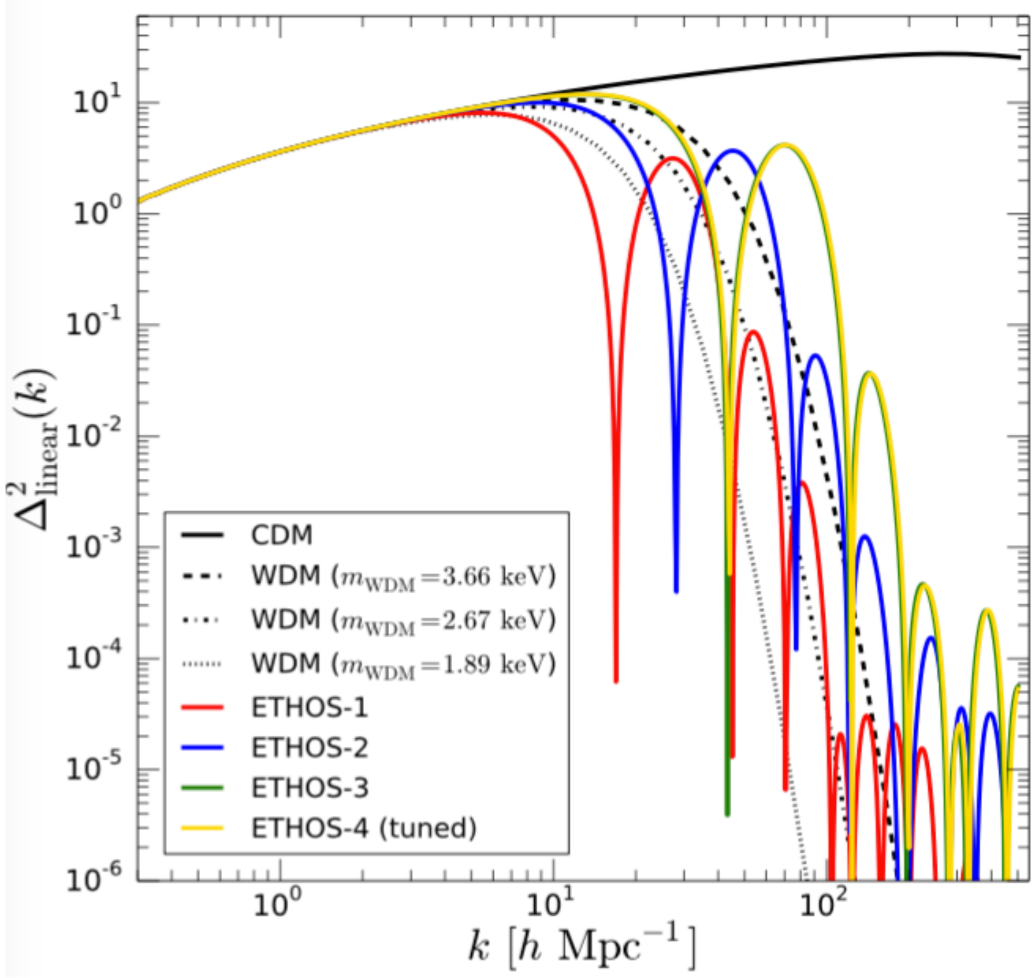


**Fuzzy Dark Matter (FDM)**



m~$10^{-22}$ eV
de Broglie
wavelength

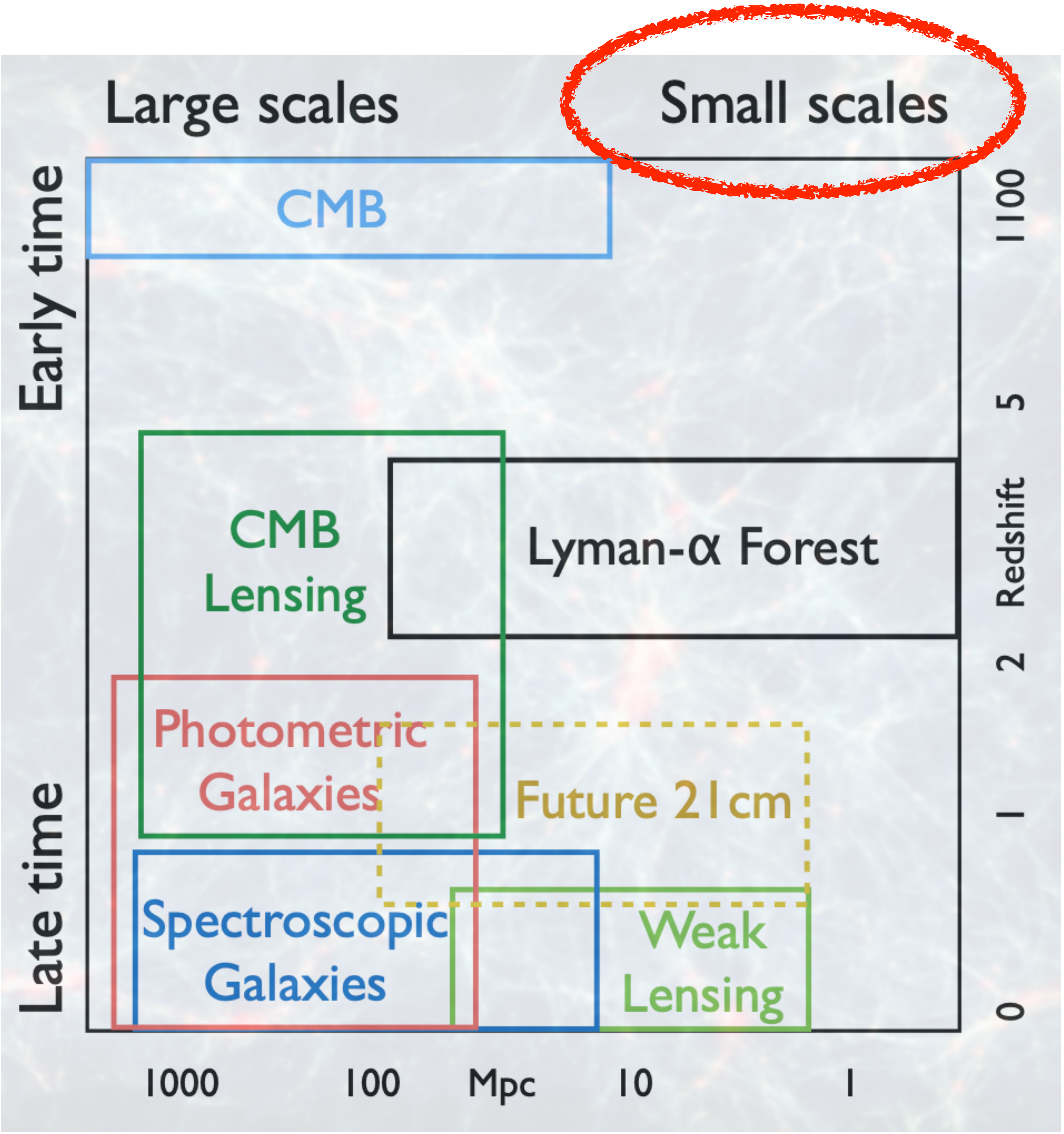
# These models predict a suppression of the small scale, linear matter power spectrum



*Vogelsberger+ 2015*

Need LSS probes sensitive to:

- large wavenumbers k
- **linear** matter fluctuations



# The Lyman-$\alpha$ forest

**Resonant absorption of light by neutral hydrogen in the intergalactic medium**

- background source: usually quasars (bright)
- $\lambda_{\text{rest}}$ = 1215 Å ⇒ redshifted absorption in optical waves for z ~ 2 - 5

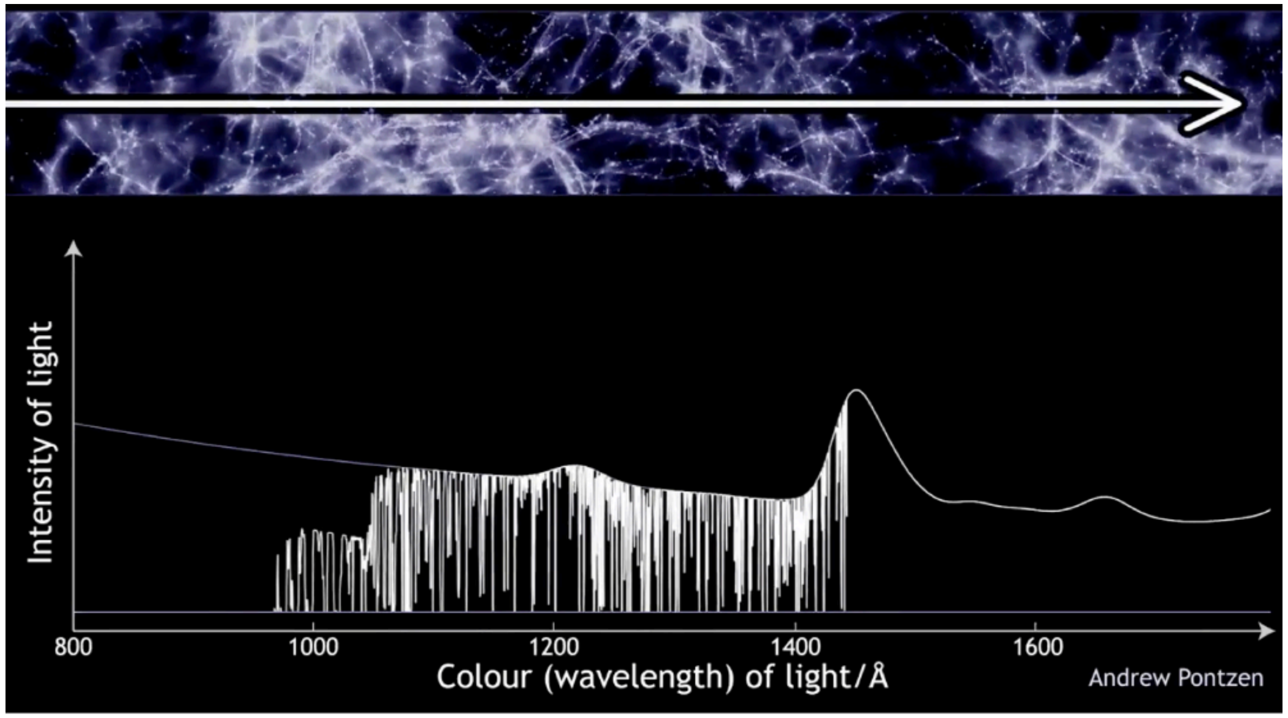
# The Lyman-$\alpha$ forest

$$F(\lambda) = e^{-\tau_{\mathrm{IGM}}(z)} \in [0,1]$$

$$\tau_{\mathrm{IGM}}(z_{\mathrm{a}}) \approx 2[1+\delta(z_{\mathrm{a}})]^2 \boxed{\frac{\alpha_{\mathrm{rec}}(T)}{\Gamma}} \left(\frac{1+z_{\mathrm{a}}}{4}\right)^{4.5}$$

$$\boxed{\left(\Gamma_{e,\mathrm{H\,I}} n_e + \Gamma_{\gamma,\mathrm{H\,I}}\right) n_{\mathrm{H\,I}} = \alpha_{\mathrm{r,H\,II}} n_e n_{\mathrm{H\,II}}}$$

HI fraction ~ $10^{-5}$



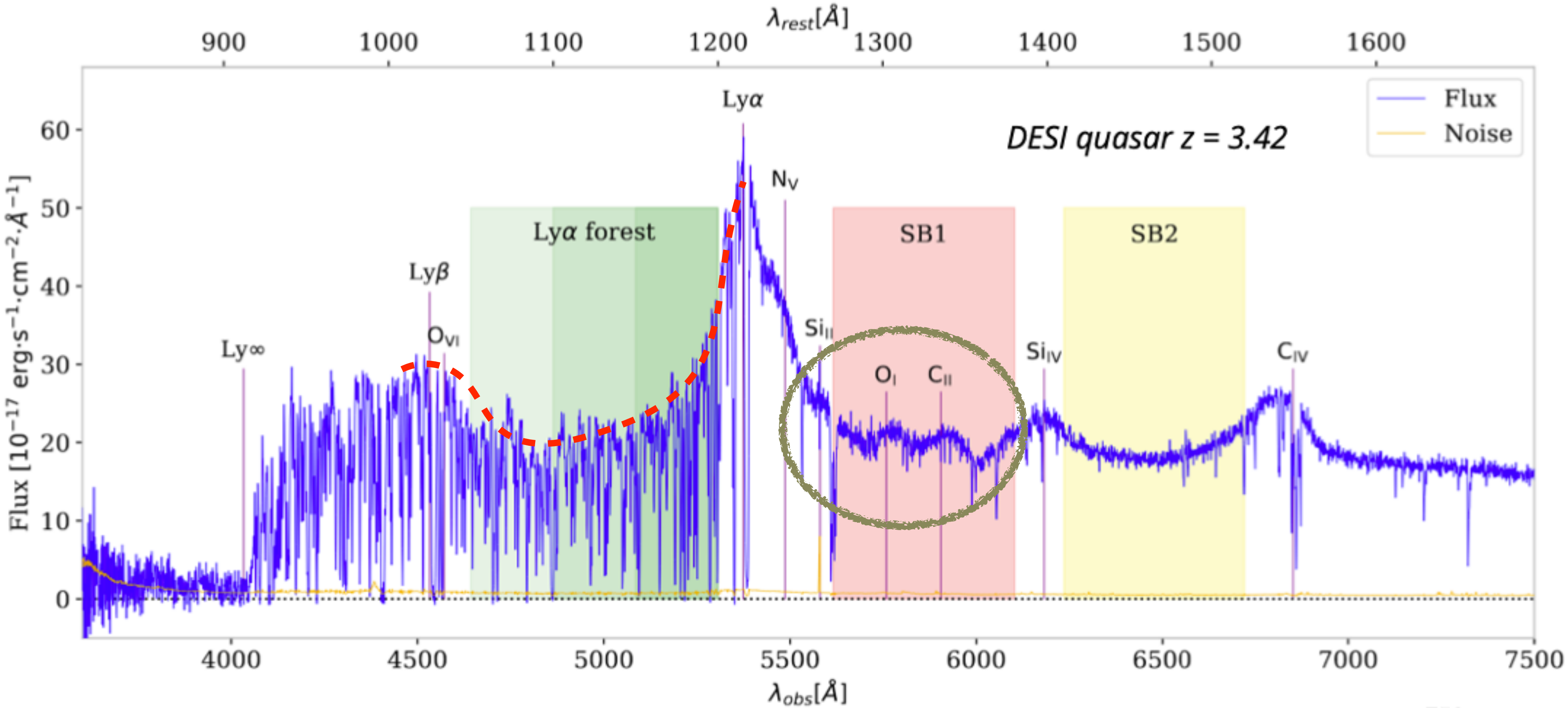
$\tau$ ~ 1 for HI in the IGM @ z ~ 2 - 4

⇒ sensitive to mild density fluctuations

(close to linear)

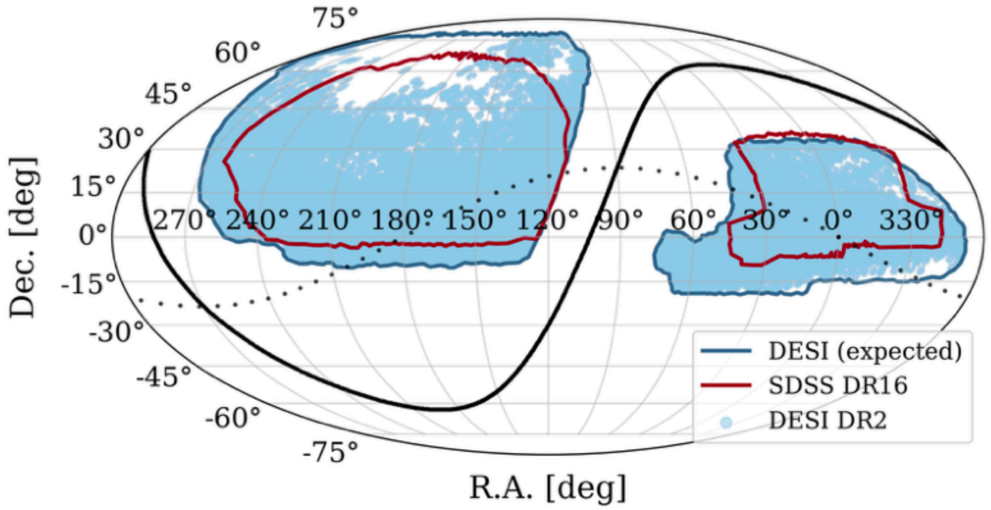
**Tracer of matter density fluctuations at z > 2**

# DESI Lyman-$\alpha$ forest sample



Real-life complications:

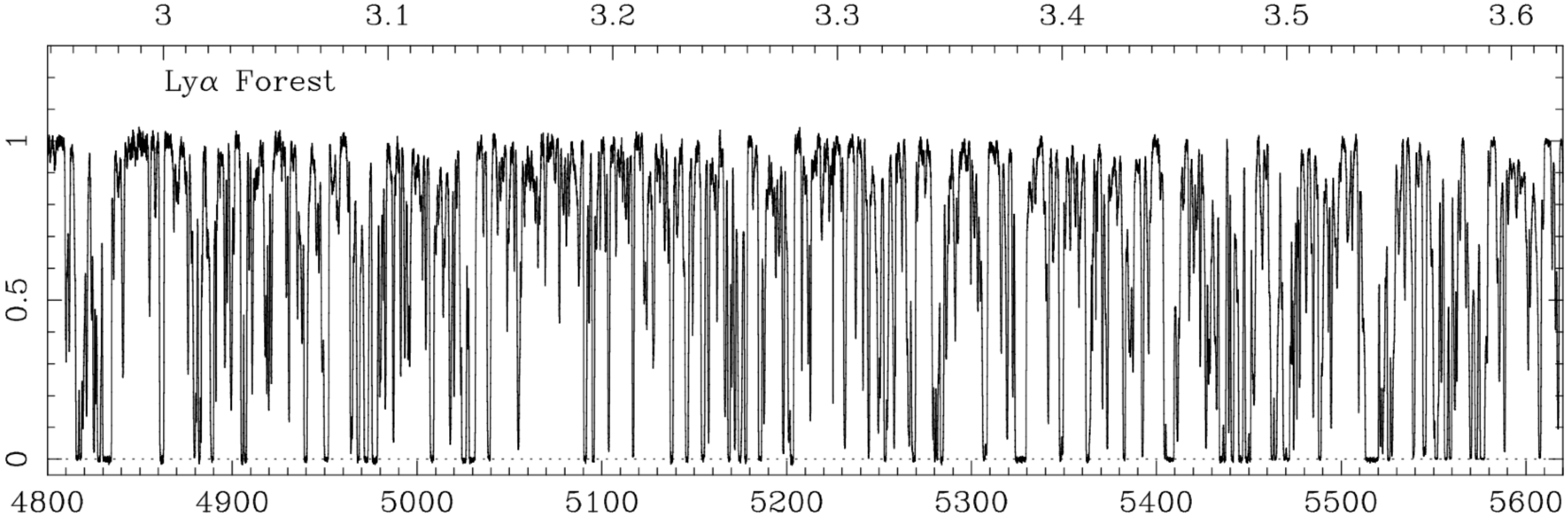
- metals
- quasar's continuum
- strong absorbers (circumgalactic medium)



DESI DR2 sample:
820,000 Ly$\alpha$ spectra ($z_{QSO}$>2.1) @ $z_{eff}$ = 2.33

# High-resolution Ly$\alpha$ forest samples

astro-ph/9511035
Keck/HIRES



**Small sample:**
KODIAQ (Keck/HIRES) ~ 300
SQUAD (VLT/UVES) ~ 460
XQ-100 (VLT/XSHOOTER) ~ 100

- High SNR
- High-resolution: ~ sub-Mpc scale

# Computing the Ly$\alpha$ forest signal

**Non-linear gravitational evolution + hydrodynamics :**

cosmo-hydro simulation (GADGET, NYX, Ramses..)

- gaz from SPH or grid method
- includes explicit model for gaz thermodynamics (heating rates)
- * Do NOT model galaxy formation! *

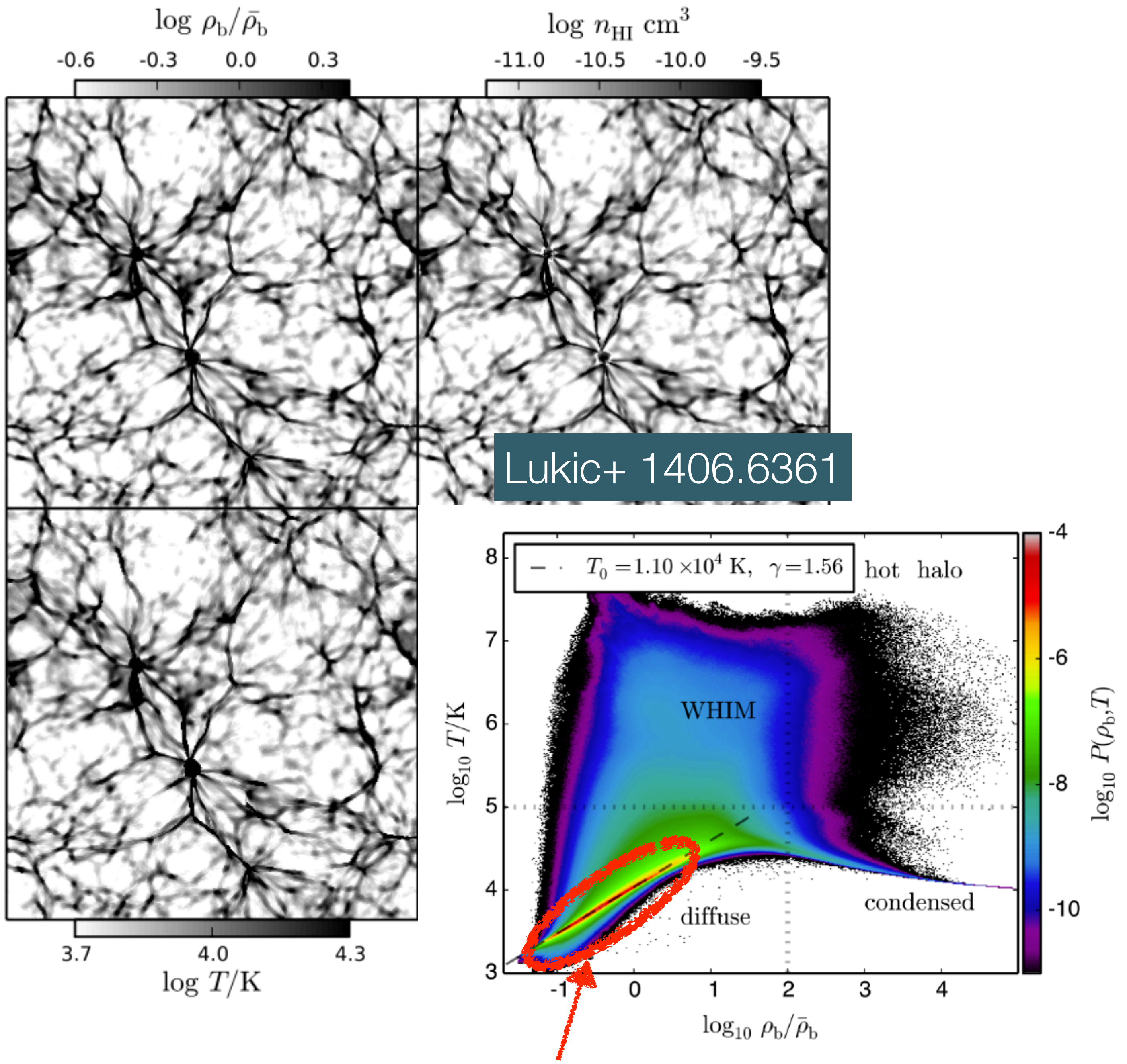
**Model Lya forest:**

Draw « lines of sight » in box, compute absorption

**Parameters**: cosmology,

IGM thernal parameters:

{T0, $\gamma$, mean Ly$\alpha$ flux (~ UV heating) }(z)



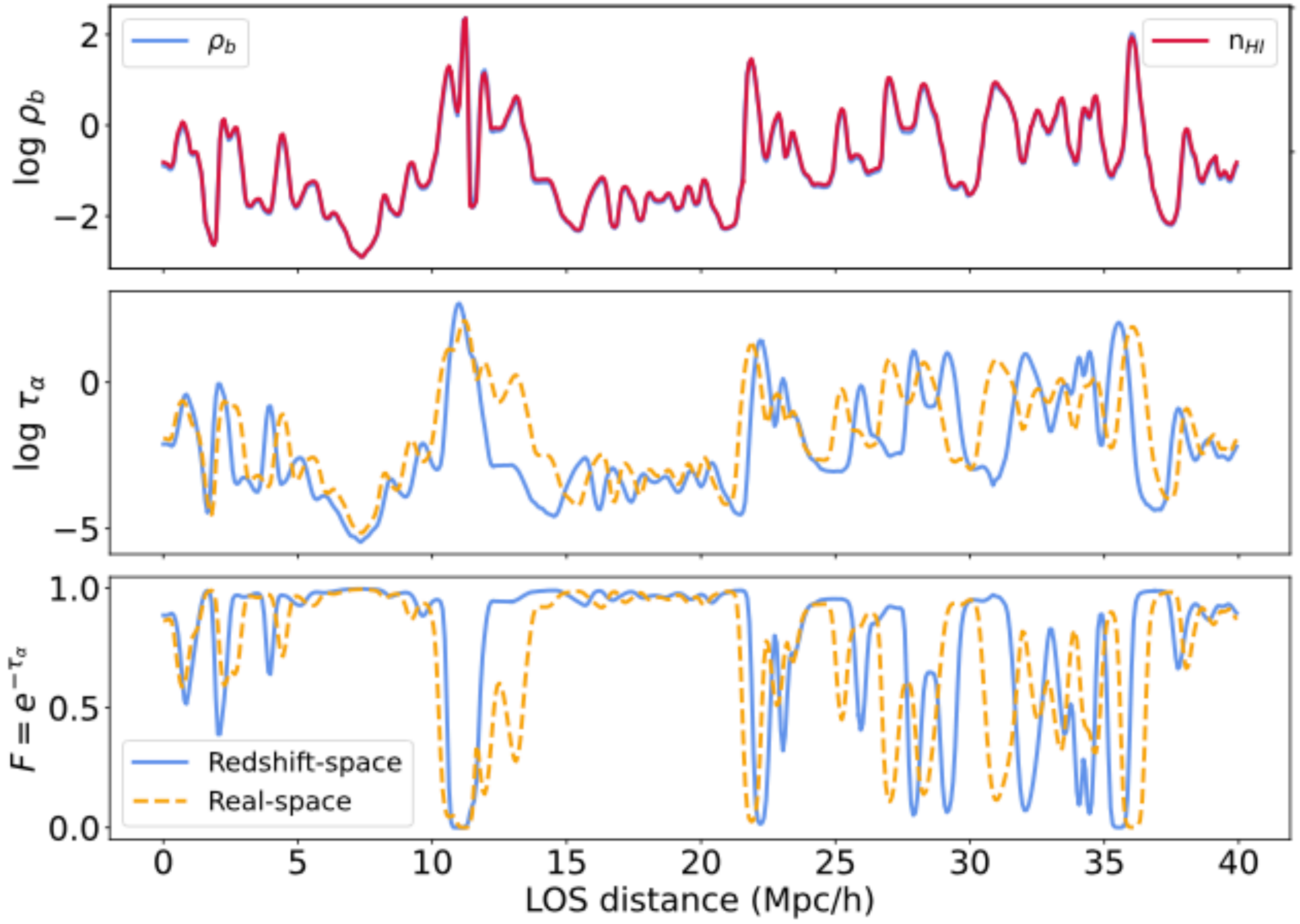
Lukic+ 1406.6361

$$T = T_0(1+\delta_b)^{\gamma-1}$$

# Computing the Ly$\alpha$ forest signal

**- Model Lya forest:**

Draw « lines of sight » in box, compute absorption

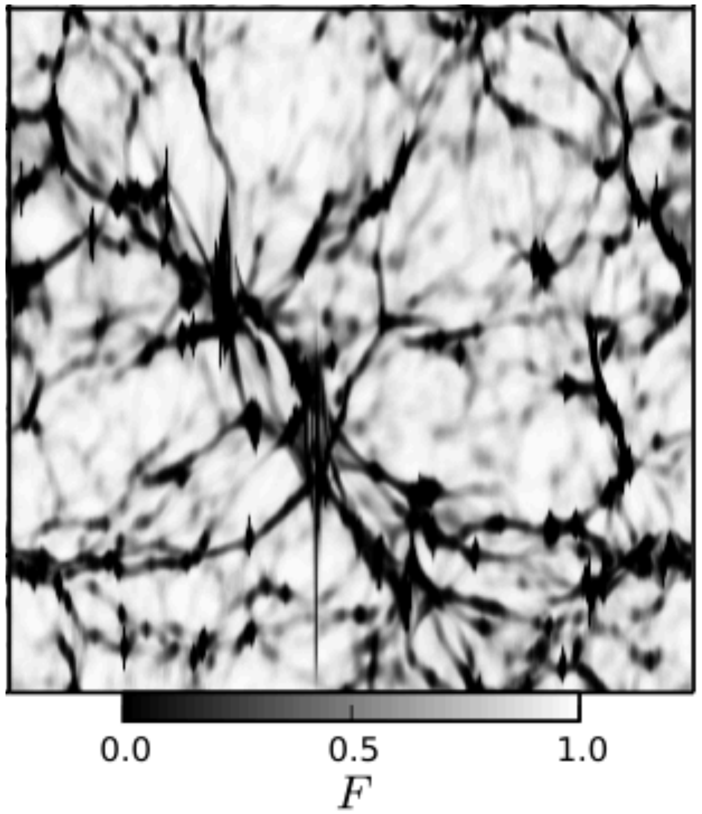


⇒ 3D field (anisotropic):

$$\delta_F = \frac{F}{\overline{F}} - 1$$

$\delta_F$ is the Lya "density contrast"

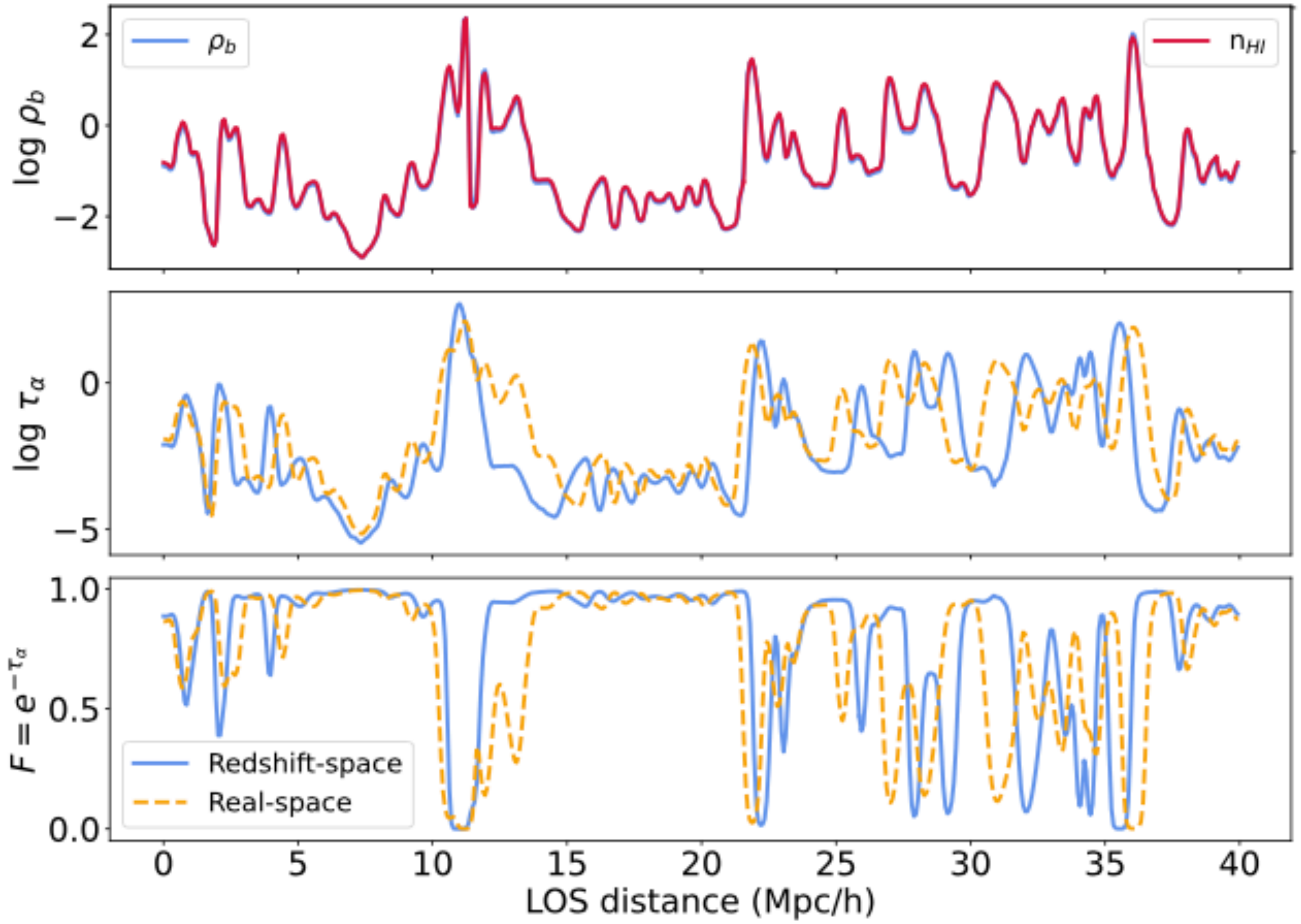
A 3D cosmological field



# Computing the Ly$\alpha$ forest signal

**- Model Lya forest:**

Draw « lines of sight » in box, compute absorption



⇒ 3D field (anisotropic):

$$\delta_F = \frac{F}{\overline{F}} - 1$$

$\delta_F$ is the Lya "density contrast"

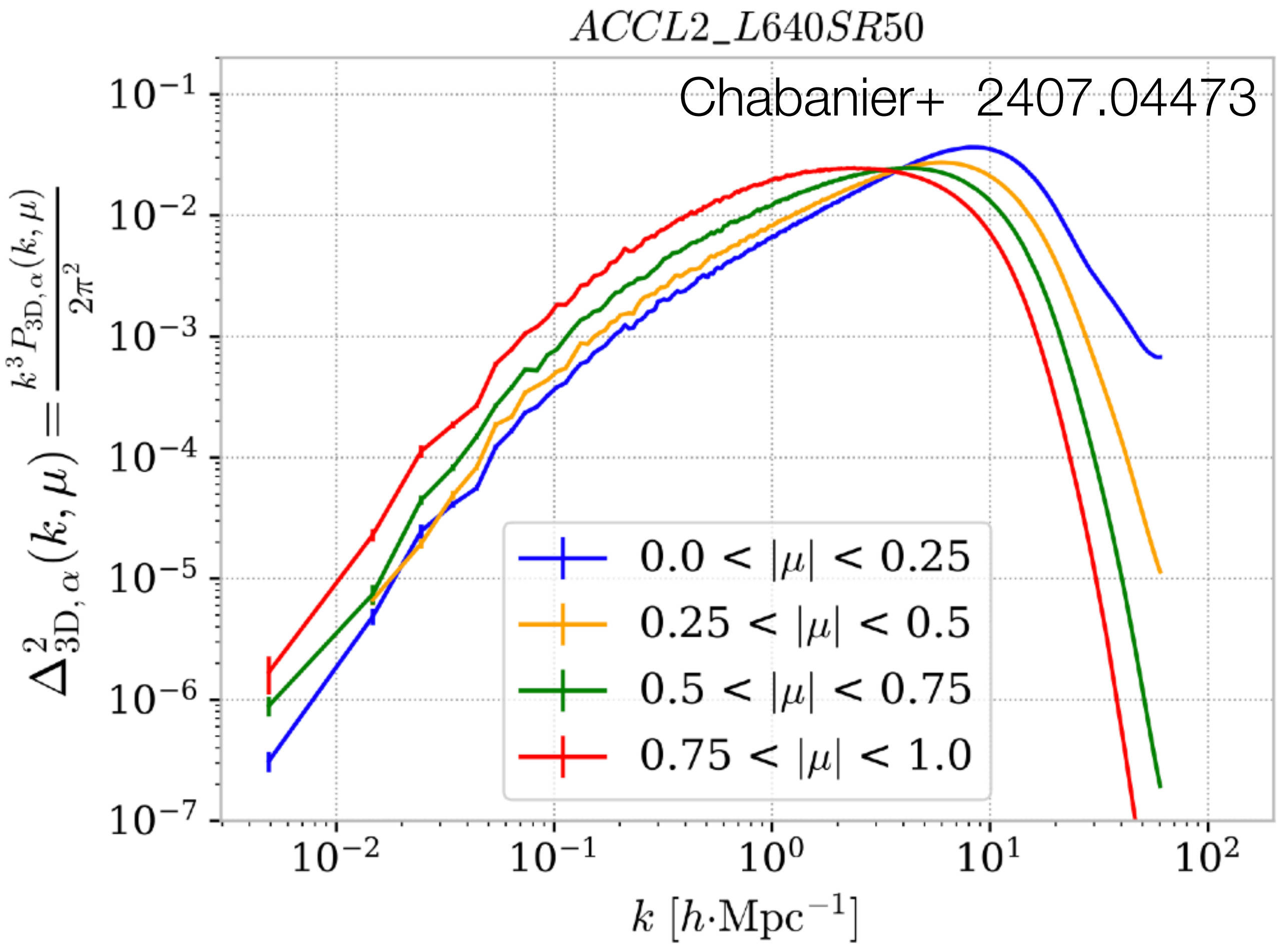
A 3D cosmological field

Compute its correlation function and (3D) power spectrum

$$\xi(r_\parallel, r_\perp) = \langle \delta_F(\vec{x}) \delta_F(\vec{x} + \vec{r}) \rangle$$

$$P_{3D}(k_\parallel, k_\perp) = \langle \, |\tilde{\delta}_F(k_\parallel, k_\perp)|^2 \, \rangle$$

# The Ly$\alpha$ 3D power spectrum



Chabanier+ 2407.04473

A biased LSS tracer, like galaxies:

$$P(k,\mu) \sim \boxed{b^2(1+\beta\mu^2)^2} P_{\rm lin}(k) \boxed{F_{\rm NL}(k,\mu)}$$

**linear bias + RSD**

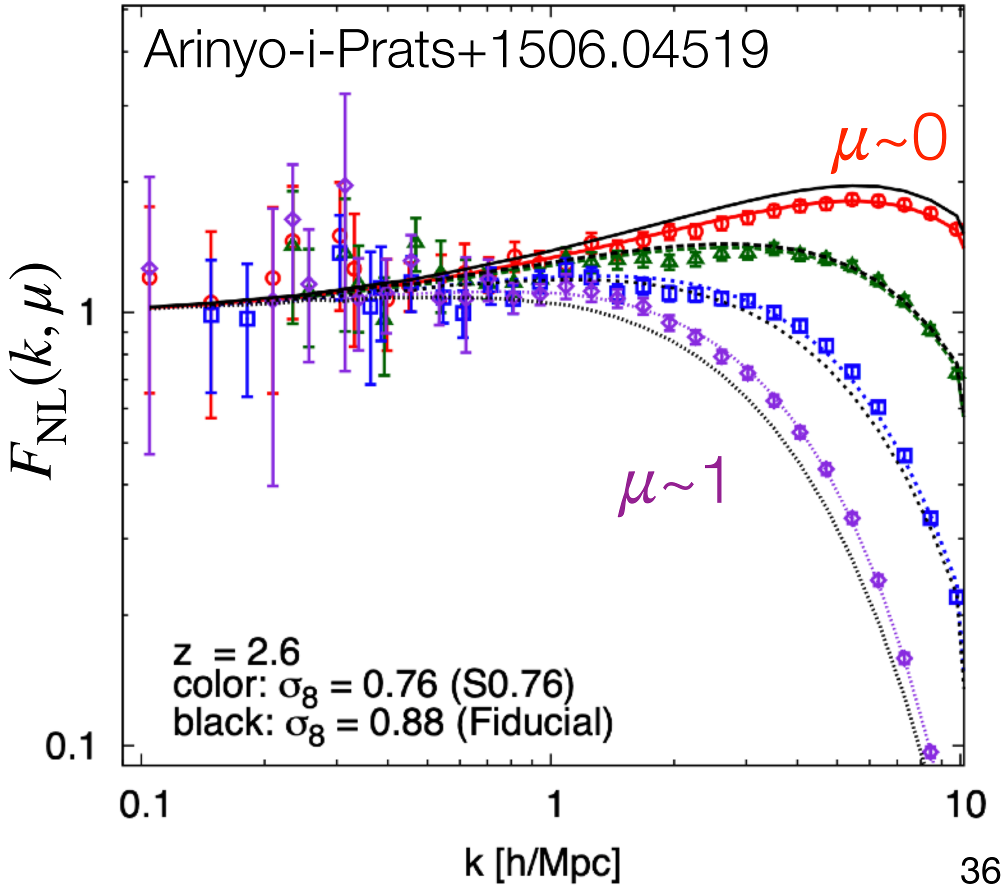
**NL effects**

simulations / EFT expansion

**NL effects are relatively small even @ k ~ 1 Mpc**

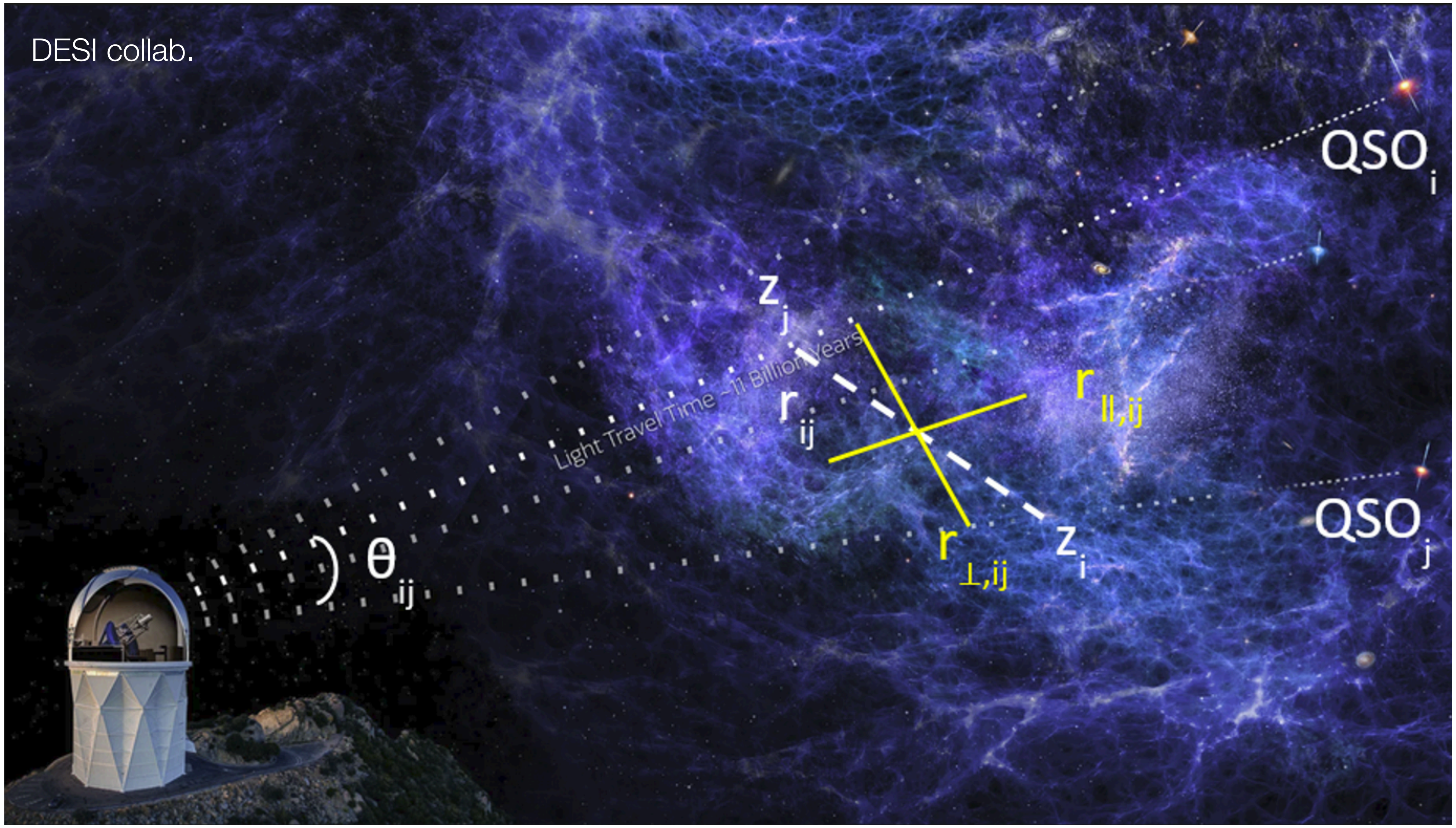
Main physical effects:

- Non-linear gravitational growth
- Thermal line broadening
- Jeans smoothing of the gas



Arinyo-i-Prats+1506.04519

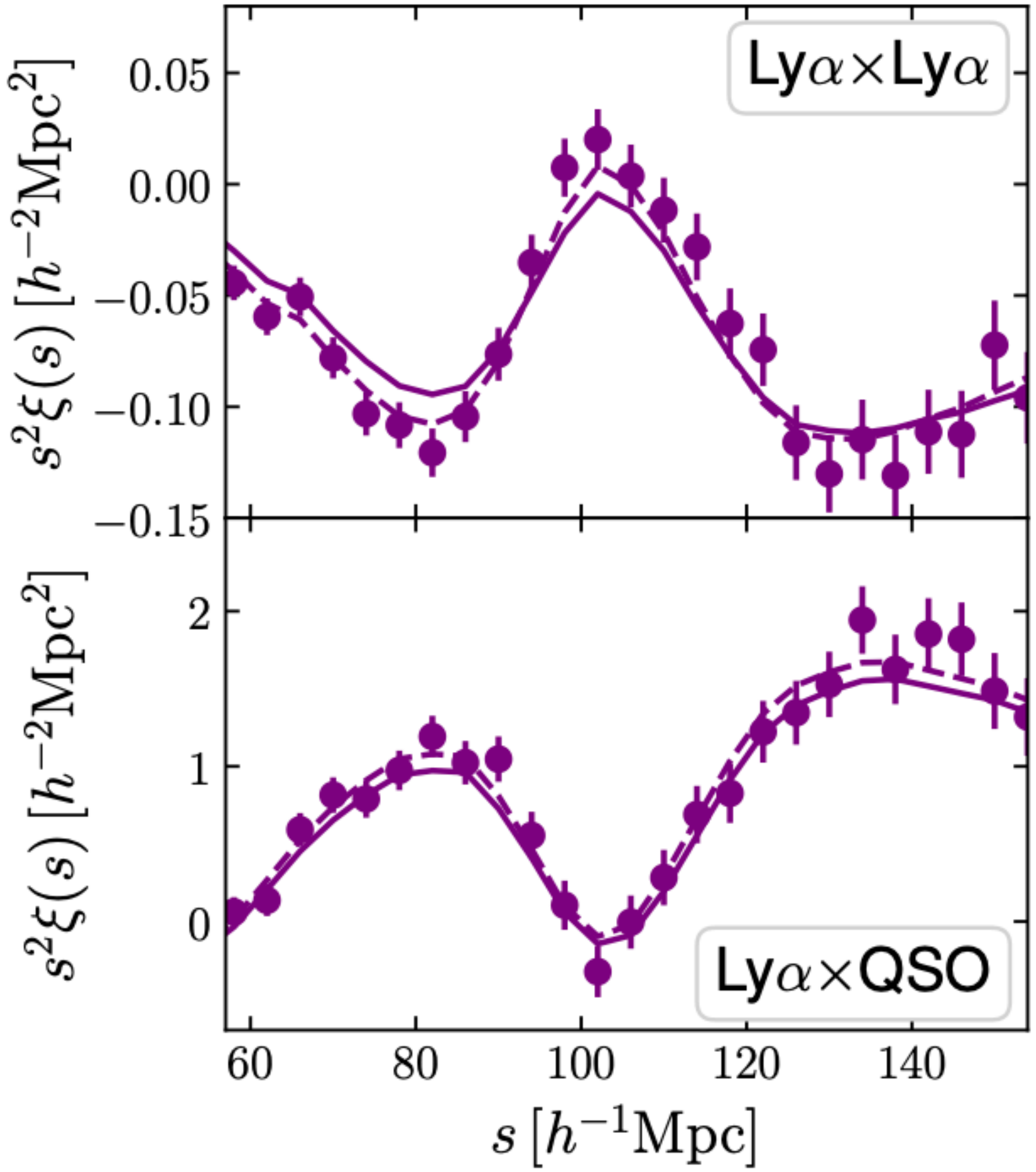
# Measuring Ly$\alpha$ correlations: large scales



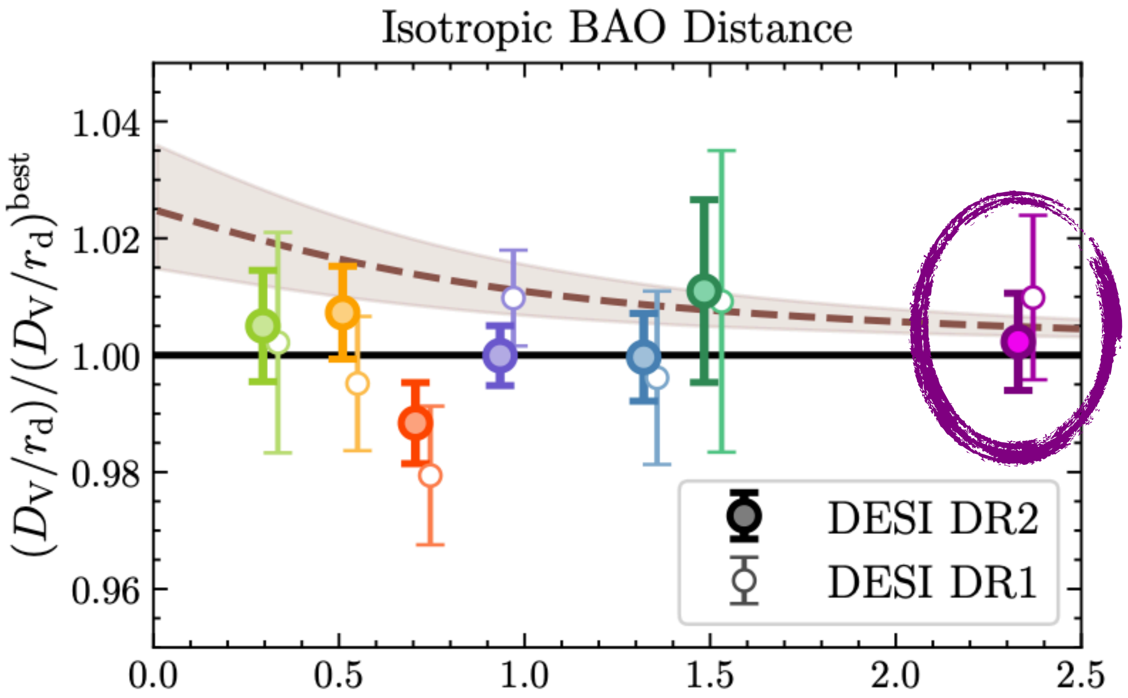
$$\xi(r_\parallel, r_\perp) = \langle \delta_F(\vec{x}) \delta_F(\vec{x} + \vec{r}) \rangle$$

**3D correlations:**
BAO,
Alcock-Paczynski from large scales
Linear growth of structures

# Measuring Ly$\alpha$ correlations: large scales



arxiv:2503.14739



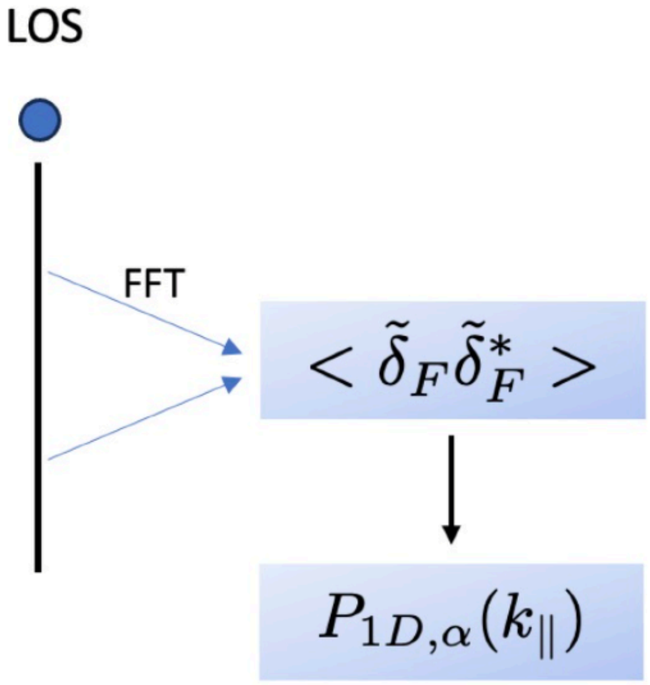
DESI DR2:

**0.7% (stat+syst) precision on isotropic BAO @ z=2.3**

$$\xi(r_{\parallel}, r_{\perp}) = \langle \delta_F(\vec{x})\delta_F(\vec{x}+\vec{r})\rangle$$

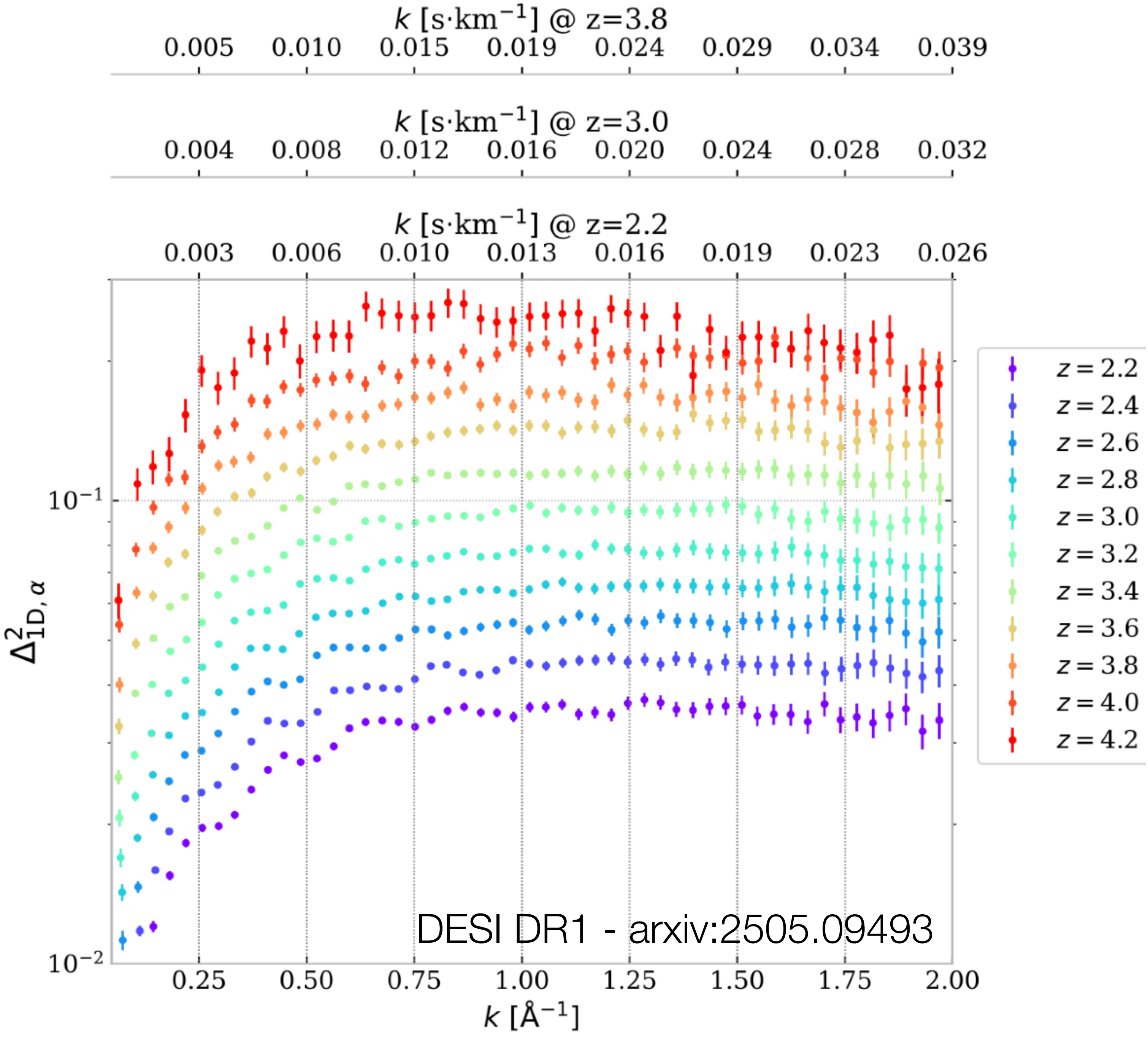
# Small scale Lyα correlations: P1D

LOS separation >> wavelength separation



$$P_{1D}(k_\parallel) = \int \frac{d^2 k_\perp}{(2\pi)^2} P_{3D}(k_\perp, k_\parallel)$$

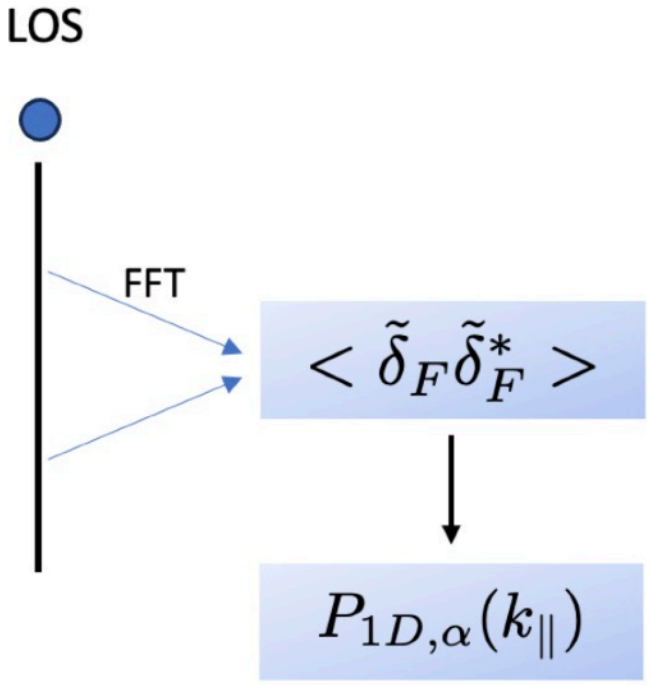
- "Historical" LSS probe, can be measured even with a few spectra
- Up to k ~ few Mpc$^{-1}$
- Now %-level precision



DESI DR1 - arxiv:2505.09493

# Small scale Ly$\alpha$ correlations: P1D

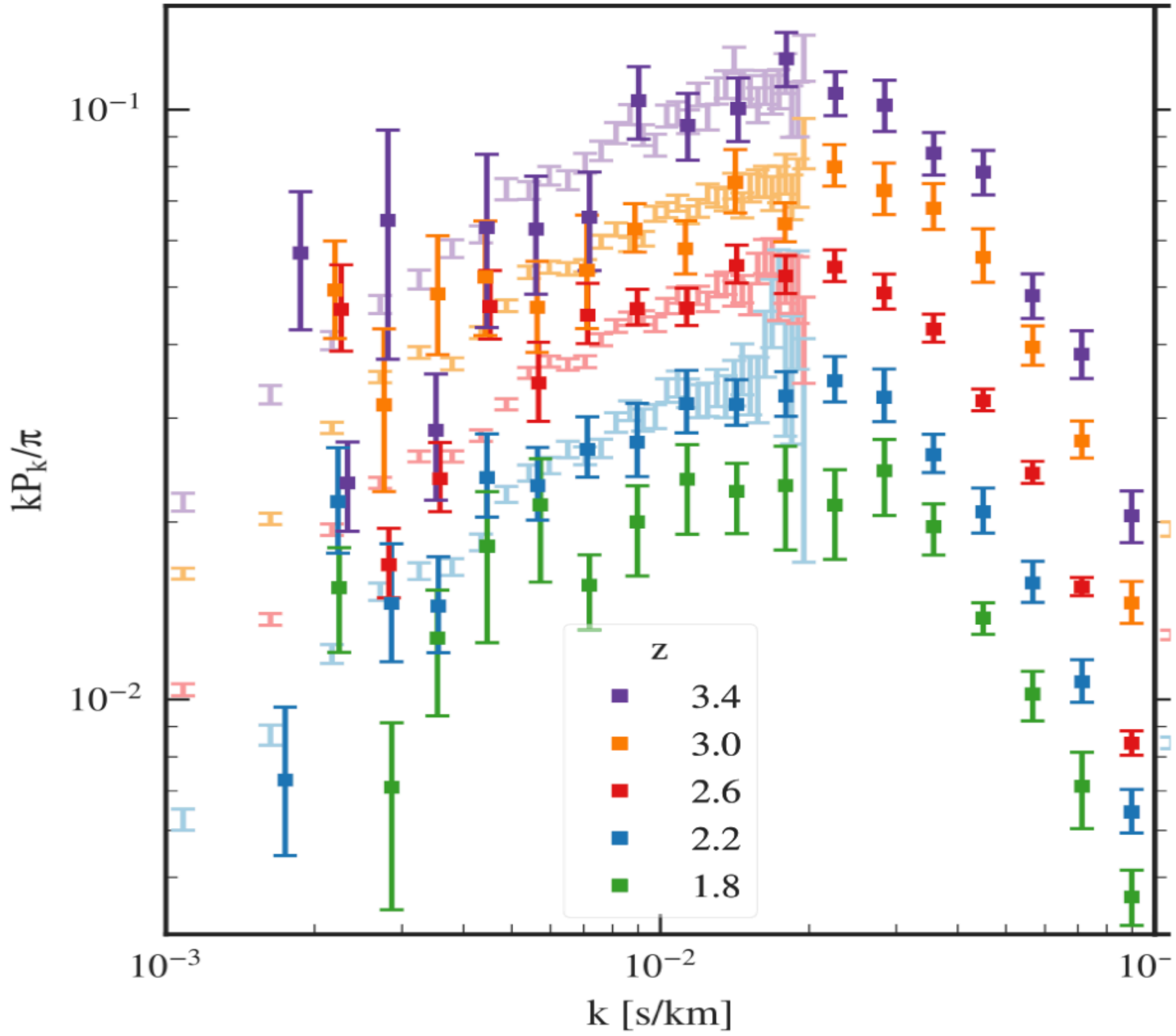
LOS separation >> wavelength separation



$$P_{1D}(k_\parallel) = \int \frac{d^2 k_\perp}{(2\pi)^2} P_{3D}(k_\perp, k_\parallel)$$

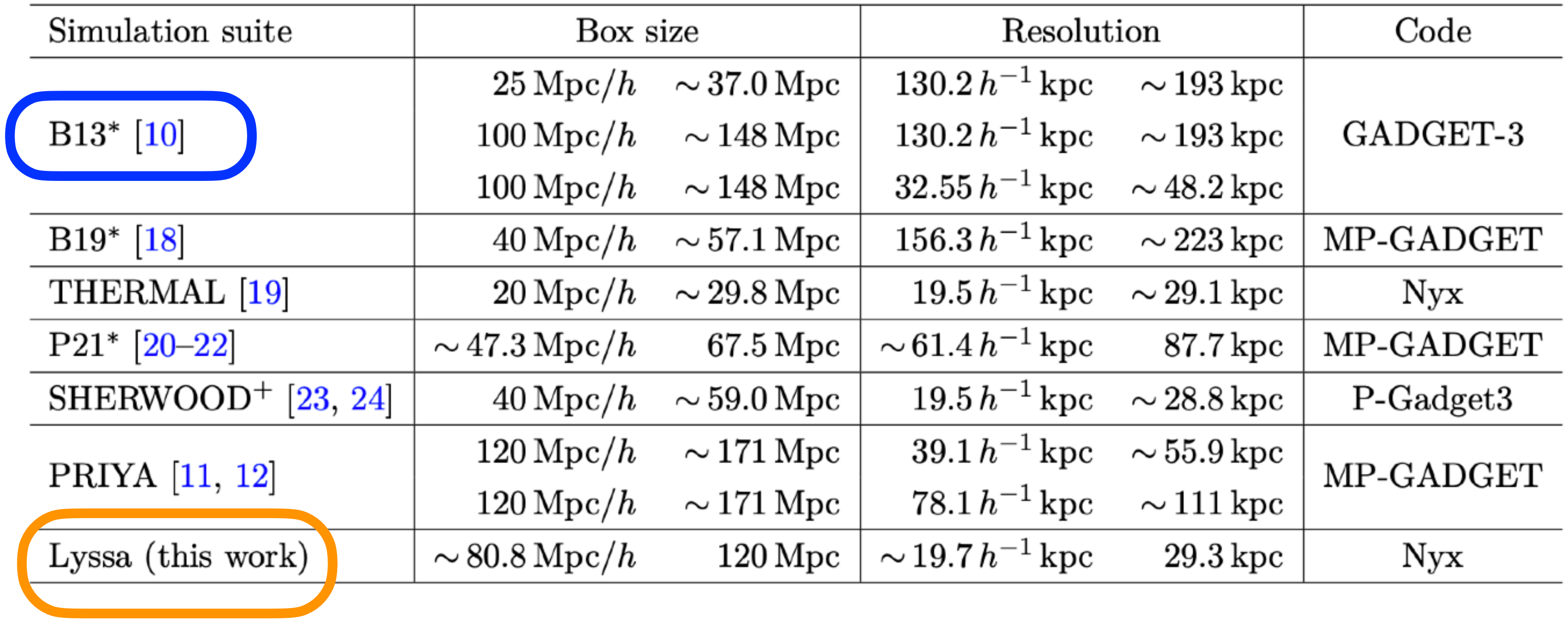
- "Historical" LSS probe, can be measured even with a few spectra
- Up to k ~ few Mpc$^{-1}$
- Now %-level precision

From high resolution data
eg. Walther+ 2018

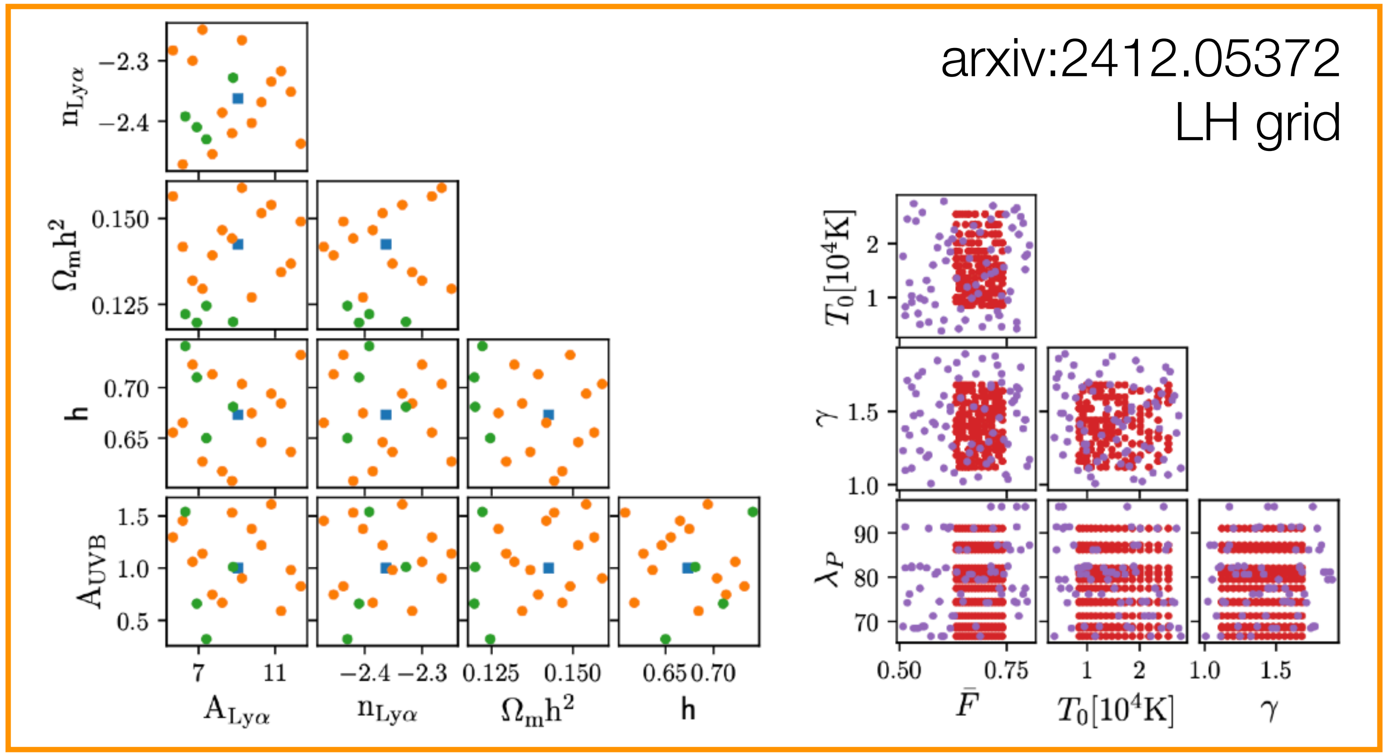


# Fitting P1D data with a model

- Predict P1D from a finite set of simulations
- Interpolation scheme (Taylor expansion; Kriging; emulator..)
- Include other nuisance parameters

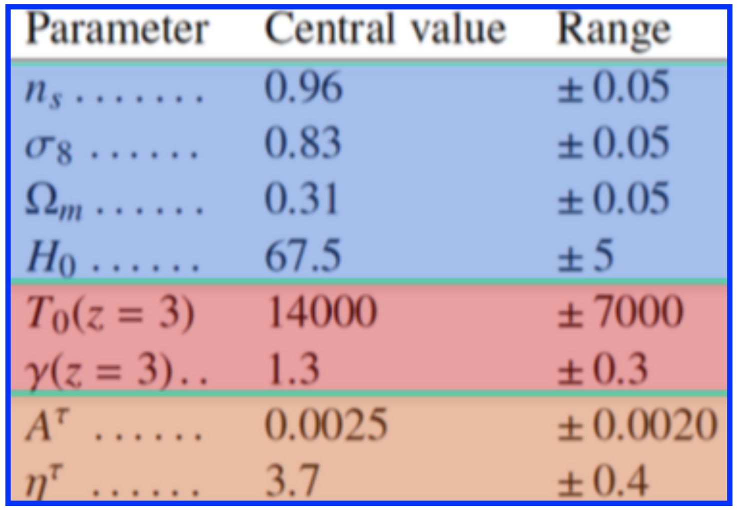


| Simulation suite | Box size | | Resolution | | Code |
|---|---|---|---|---|---|
| B13* [10] | 25 Mpc/$h$ | ~37.0 Mpc | 130.2 $h^{-1}$ kpc | ~193 kpc | GADGET-3 |
| | 100 Mpc/$h$ | ~148 Mpc | 130.2 $h^{-1}$ kpc | ~193 kpc | |
| | 100 Mpc/$h$ | ~148 Mpc | 32.55 $h^{-1}$ kpc | ~48.2 kpc | |
| B19* [18] | 40 Mpc/$h$ | ~57.1 Mpc | 156.3 $h^{-1}$ kpc | ~223 kpc | MP-GADGET |
| THERMAL [19] | 20 Mpc/$h$ | ~29.8 Mpc | 19.5 $h^{-1}$ kpc | ~29.1 kpc | Nyx |
| P21* [20–22] | ~47.3 Mpc/$h$ | 67.5 Mpc | ~61.4 $h^{-1}$ kpc | 87.7 kpc | MP-GADGET |
| SHERWOOD$^+$ [23, 24] | 40 Mpc/$h$ | ~59.0 Mpc | 19.5 $h^{-1}$ kpc | ~28.8 kpc | P-Gadget3 |
| PRIYA [11, 12] | 120 Mpc/$h$ | ~171 Mpc | 39.1 $h^{-1}$ kpc | ~55.9 kpc | MP-GADGET |
| | 120 Mpc/$h$ | ~171 Mpc | 78.1 $h^{-1}$ kpc | ~111 kpc | |
| Lyssa (this work) | ~80.8 Mpc/$h$ | 120 Mpc | ~19.7 $h^{-1}$ kpc | 29.3 kpc | Nyx |



arxiv:2412.05372
LH grid

Borde+ 2013
"Taylor" grid



| Parameter | Central value | Range |
|---|---|---|
| $n_s$ ....... | 0.96 | ±0.05 |
| $\sigma_8$ ...... | 0.83 | ±0.05 |
| $\Omega_m$ ...... | 0.31 | ±0.05 |
| $H_0$ ...... | 67.5 | ±5 |
| $T_0(z=3)$ | 14000 | ±7000 |
| $\gamma(z=3)$.. | 1.3 | ±0.3 |
| $A^\tau$ ...... | 0.0025 | ±0.0020 |
| $\eta^\tau$ ...... | 3.7 | ±0.4 |

# "Nuisance" parameters: an example

**AGN feedback**

heating and mass redistribution in the IGM

Need dedicated high-resolution simulations

Currently implemented as a nuisance parameter for inference

Specific redshift evolution

**Others:**

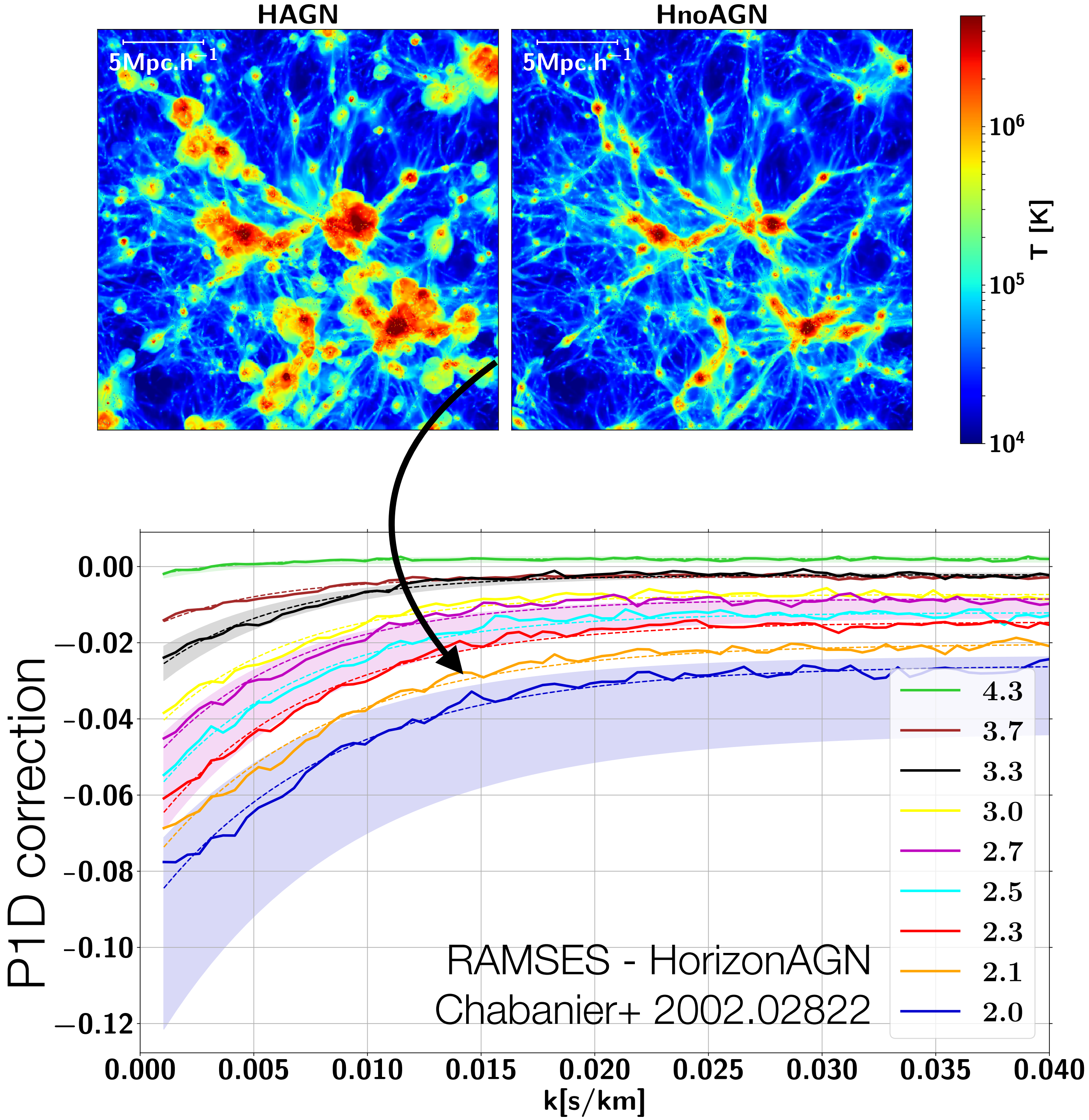
Strong absorbers

Metals

Inhomogeneous UV background

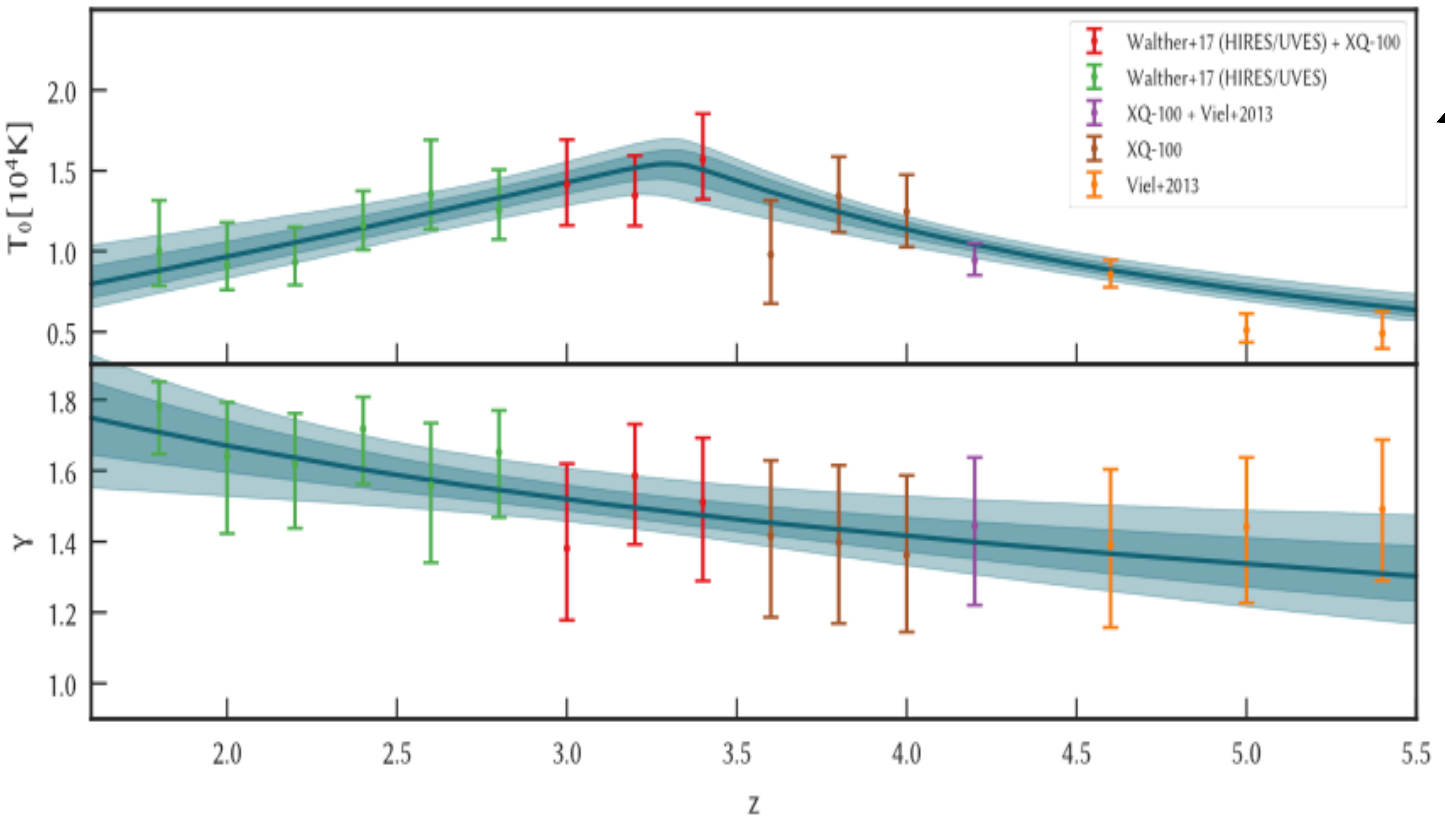
Effect of late reionization

…

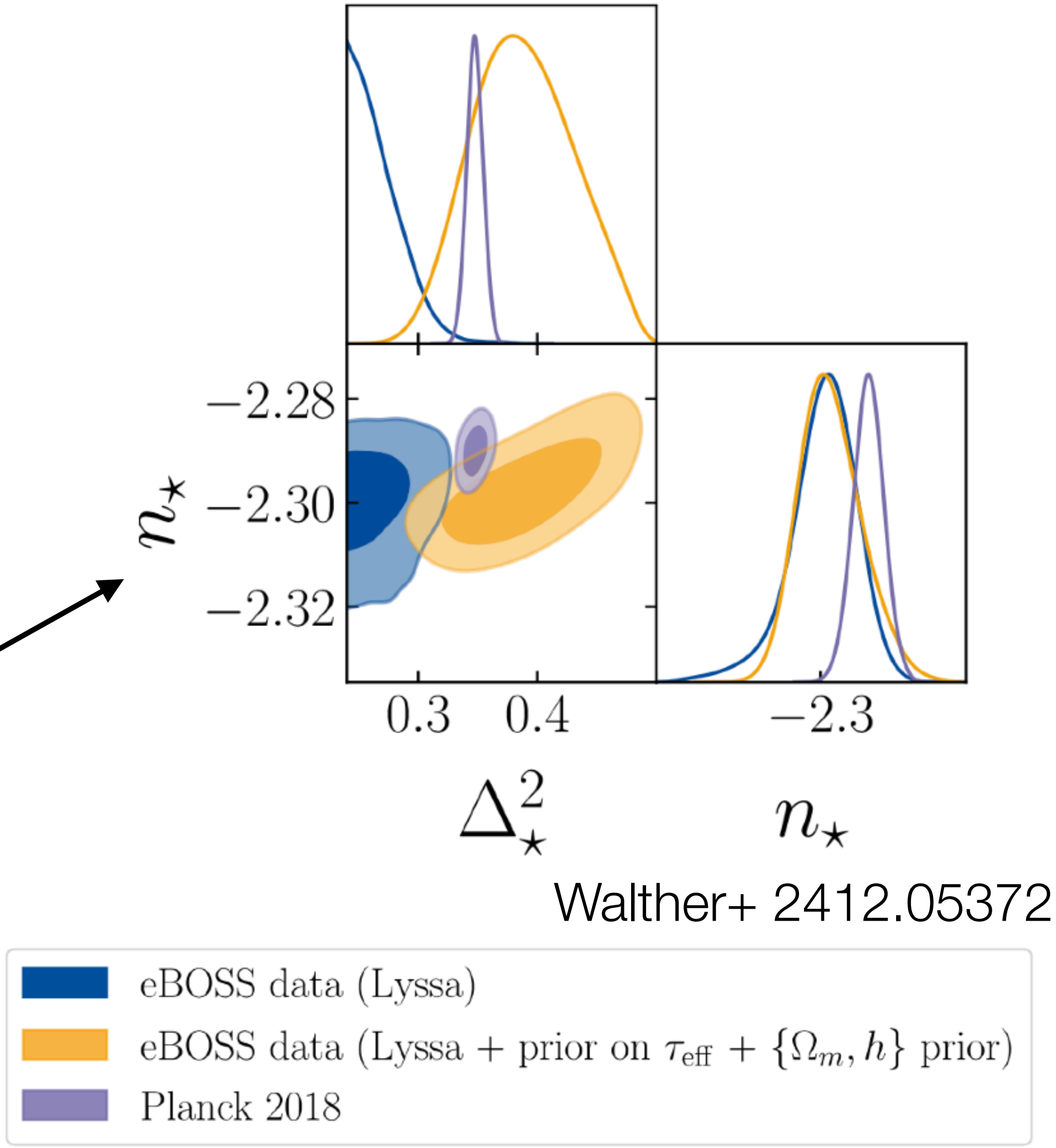


RAMSES - HorizonAGN
Chabanier+ 2002.02822

# Lyman-alpha P1D example fits



**IGM thermal properties**
mostly from high-k data



Walther+ 2412.05372

- 🟦 eBOSS data (Lyssa)
- 🟧 eBOSS data (Lyssa + prior on $\tau_{\rm eff}$ + $\{\Omega_m, h\}$ prior)
- 🟪 Planck 2018

**Cosmology**
- **from low-k data:**

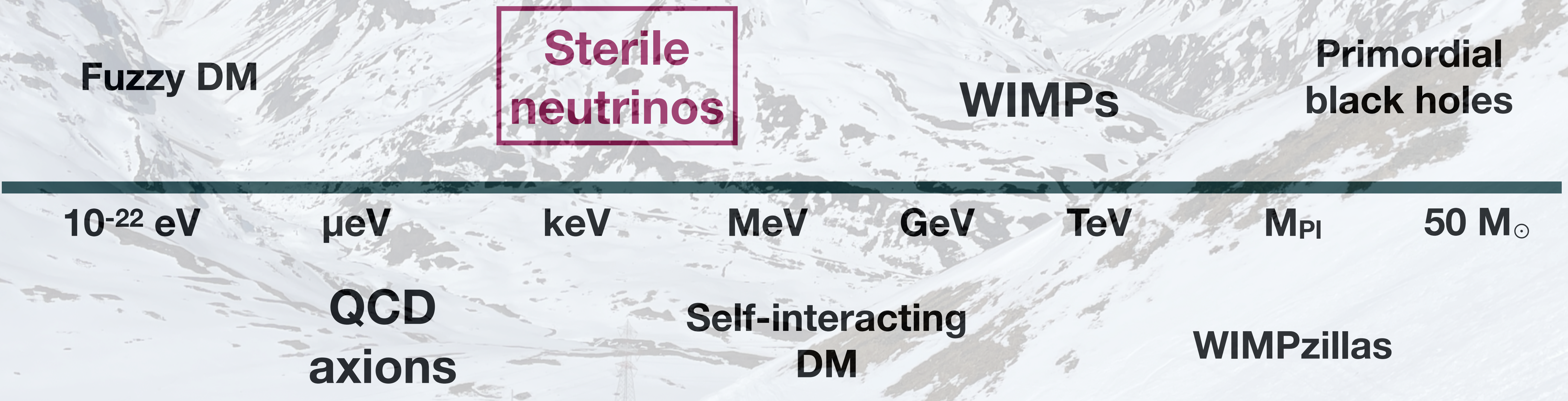
(amplitude, slope) of $P_{\rm matter,linear}$
@ z ~ 3, k ~ 1 $\rm Mpc^{-1}$
Difficult!

- **from high-k data:**

DM physics!

# Contents

- **Reminder: Dark Matter models**
- **Constraining WIMPs**
  - Direct and indirect detection
  - Also direct detection of QCD axions
- **Using the Lyman-$\alpha$ forest to constrain some DM scenarios**
  - **The Lyman-$\alpha$ forest**
  - **Examples: WDM, FDM, PBH**



Fuzzy DM

**Sterile neutrinos**

WIMPs

Primordial black holes

$10^{-22}$ eV

μeV

keV

MeV

GeV

TeV

$M_{Pl}$

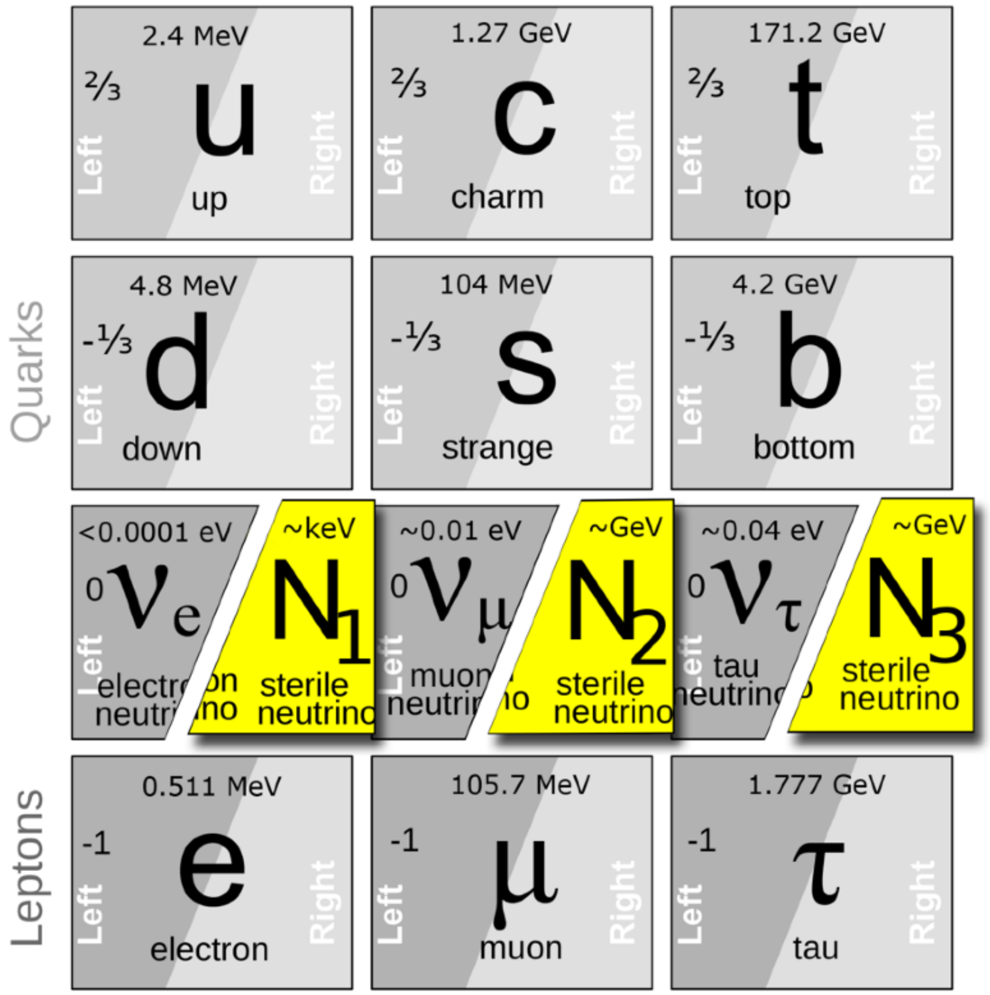
$50\ M_{\odot}$

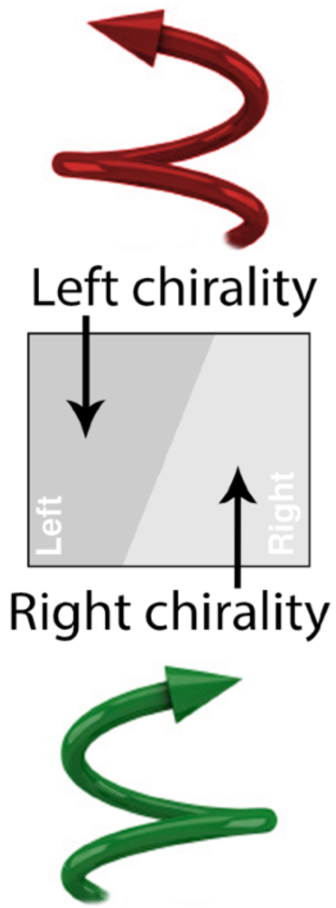
QCD axions

Self-interacting DM

WIMPzillas

# Sterile neutrinos





**Right-handed counterparts of standard model neutrinos**

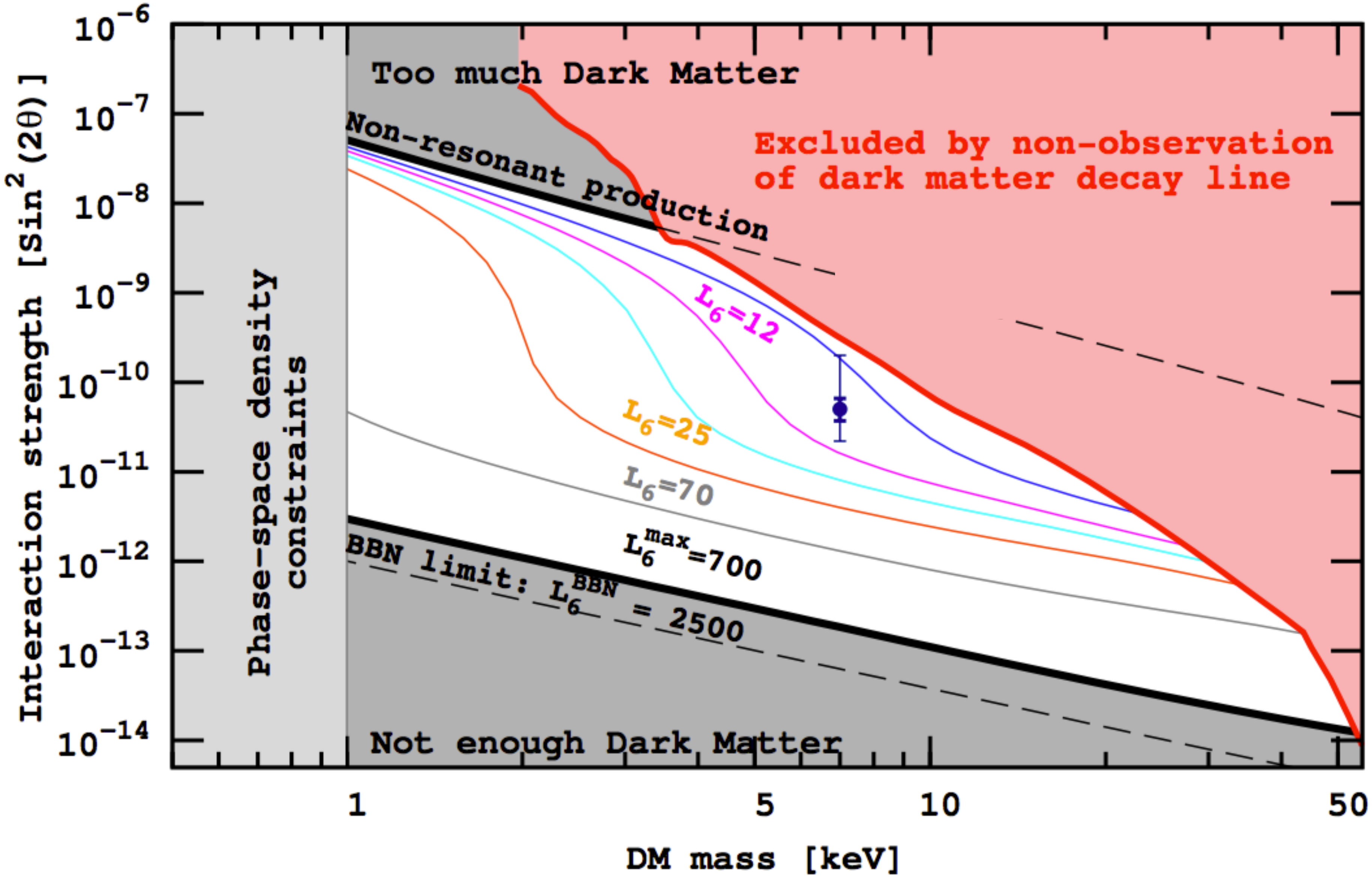
- No direct coupling to standard model gauge fields ("sterile")

- Quantum mixing with active neutrinos: coupling with standard model particles parametrised by "mixing angles" $\theta$

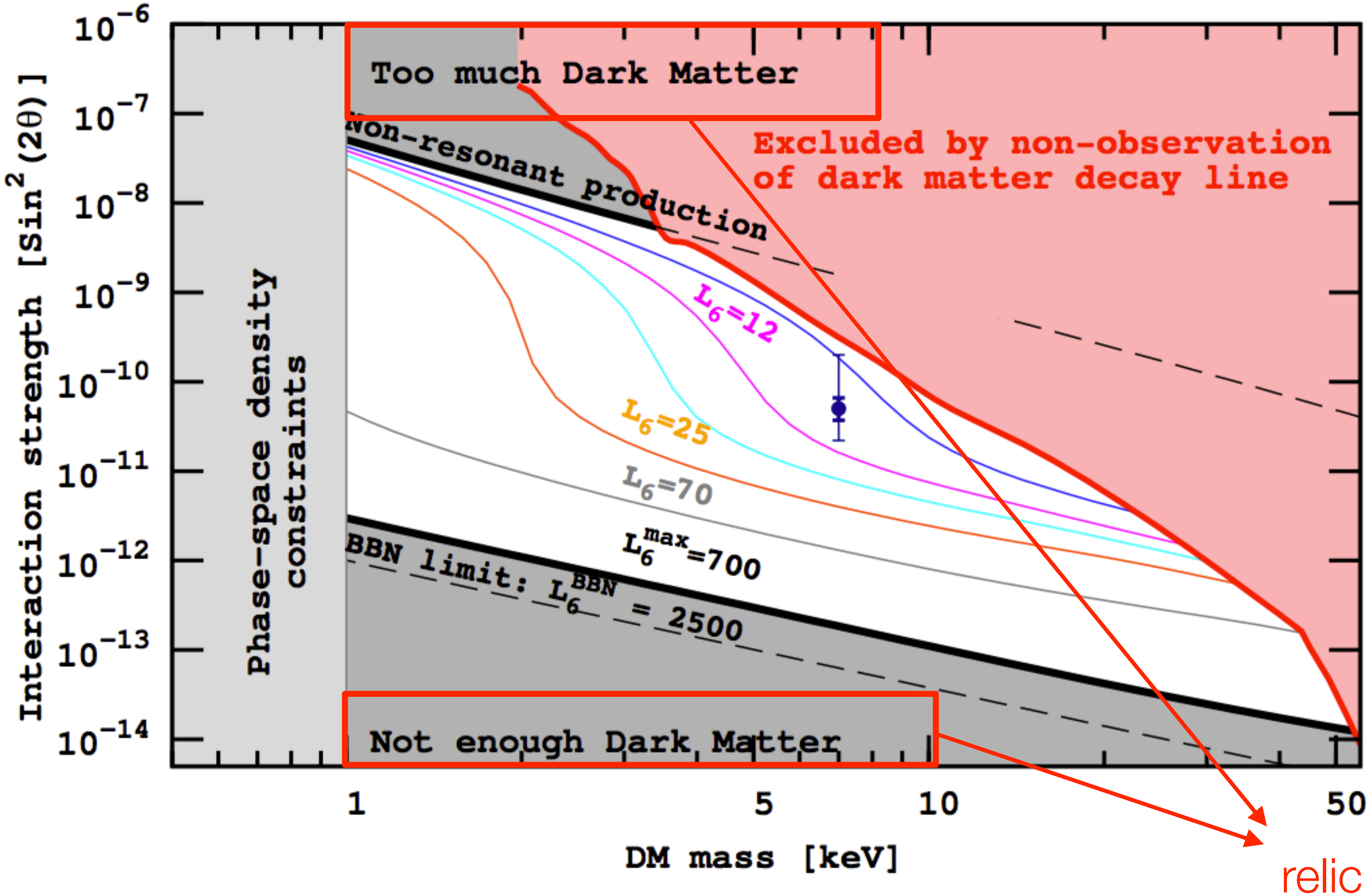
- Unknown masses

**There is a (small) window in (mass, $\theta$) parameter space for $N_1$ to make up dark matter**

# keV-scale sterile neutrinos as dark matter

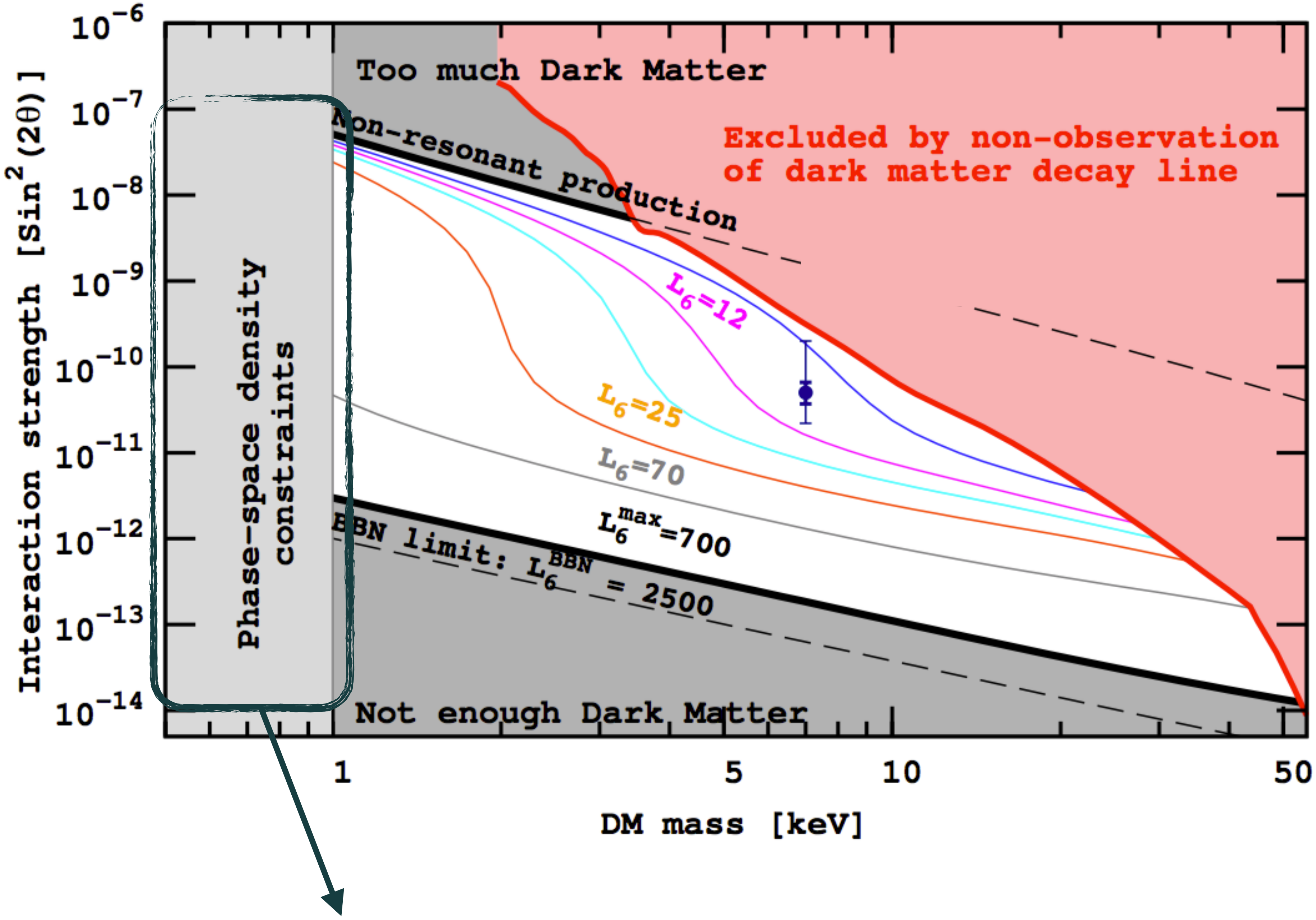


# keV-scale sterile neutrinos as dark matter



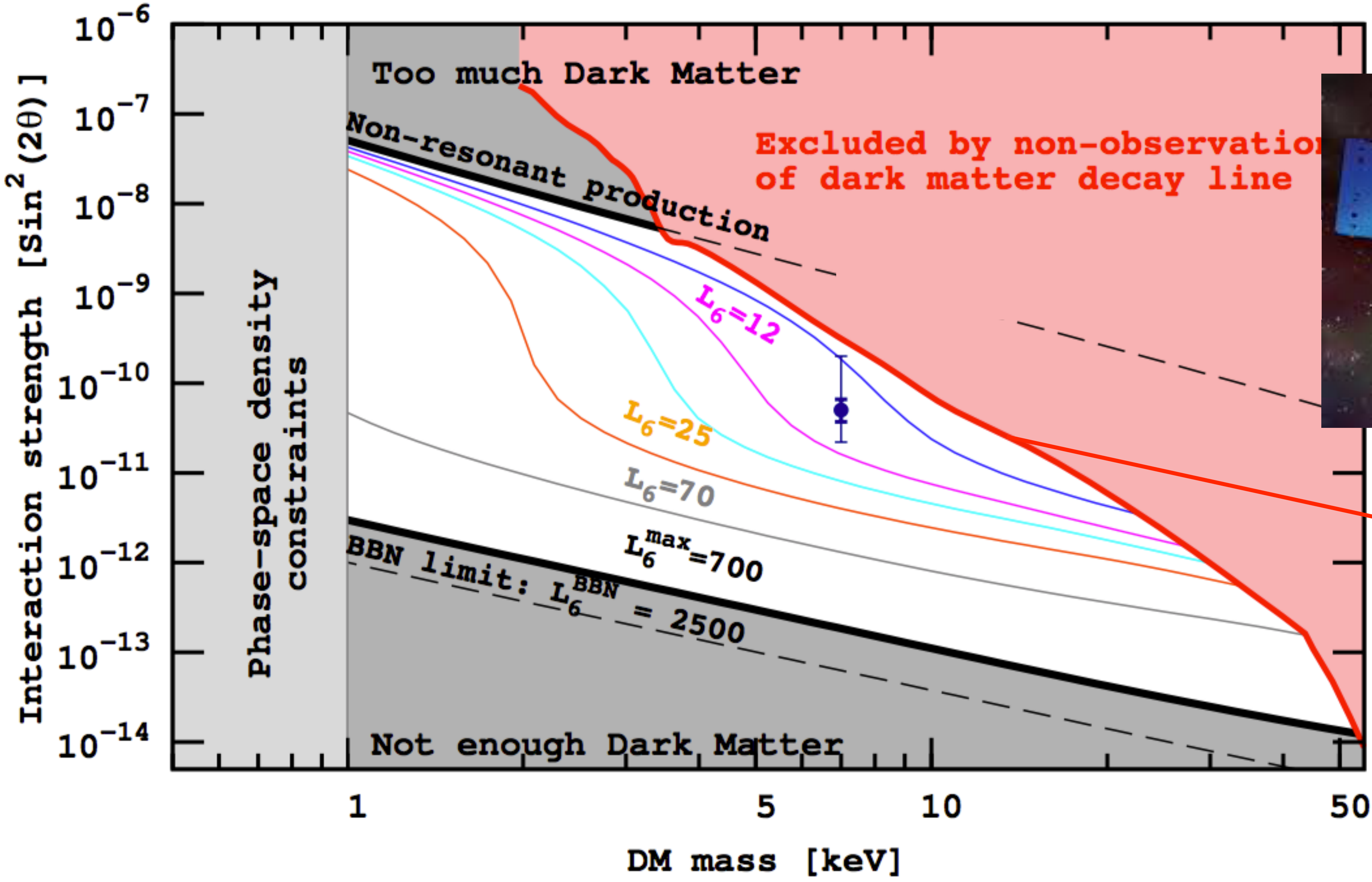
relic abundance of sterile neutrinos scales with mixing *θ*

# keV-scale sterile neutrinos as dark matter



(sterile) neutrinos are fermions

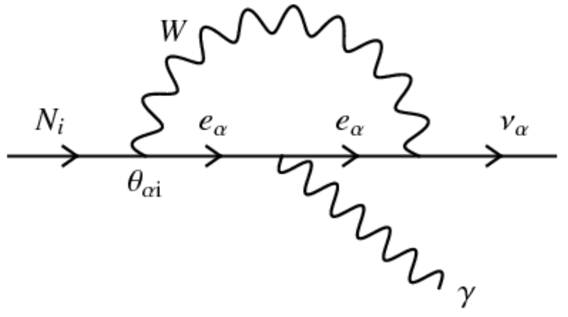
# keV-scale sterile neutrinos as dark matter



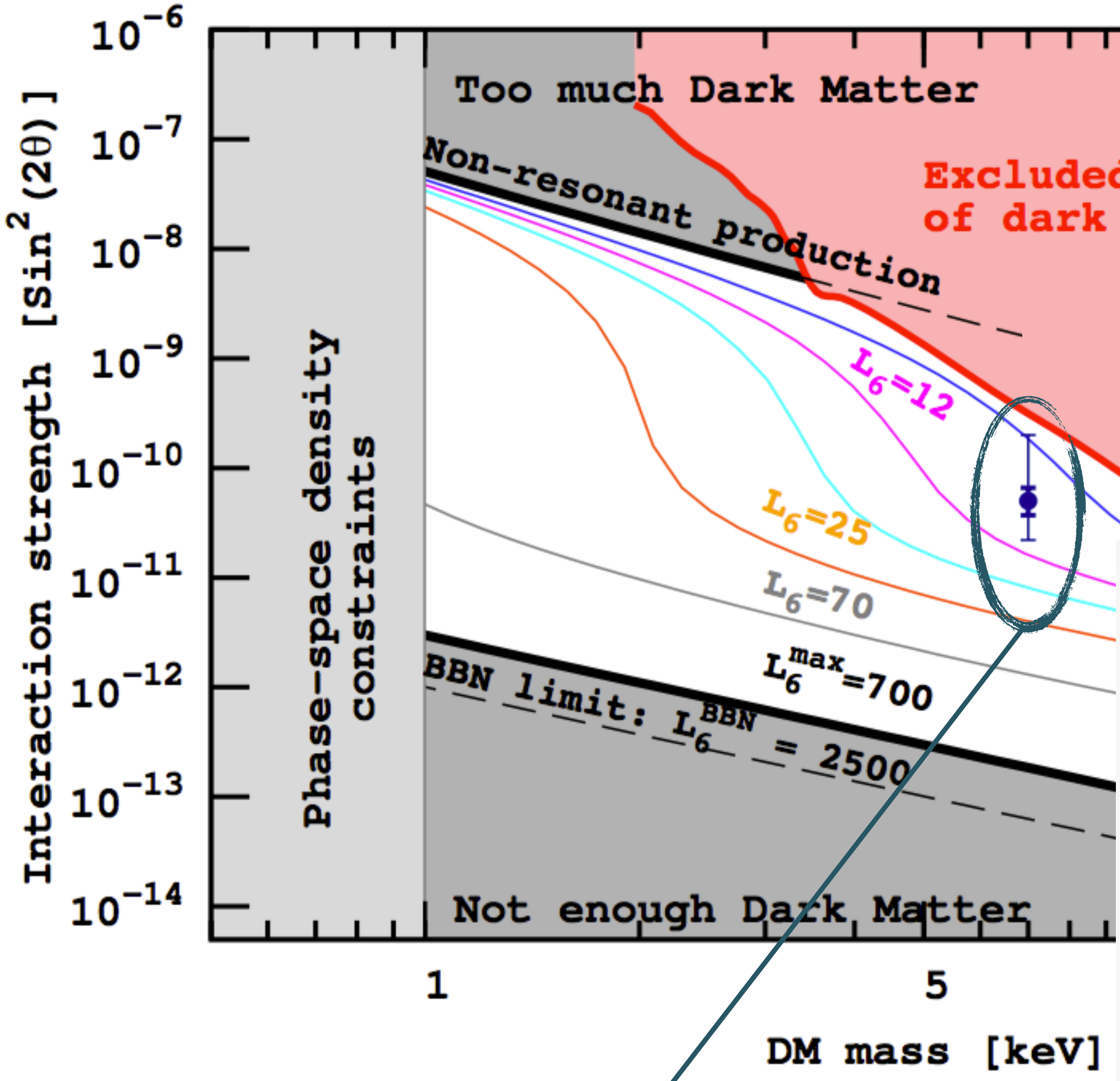
XMM-Newton (ESA, 1999-...)

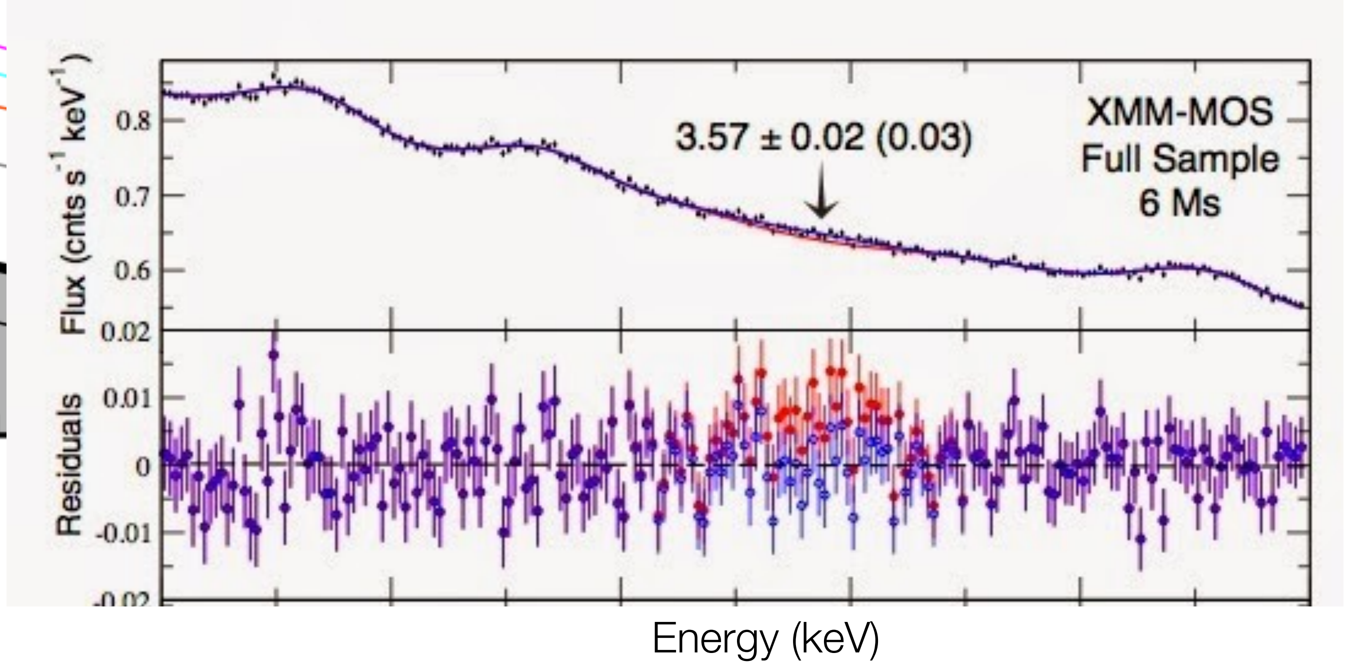
X-ray emission from astrophysical objects with dark matter

Decay process: monochromatic line $E_X = m_N/2$



# keV-scale sterile neutrinos as dark matter





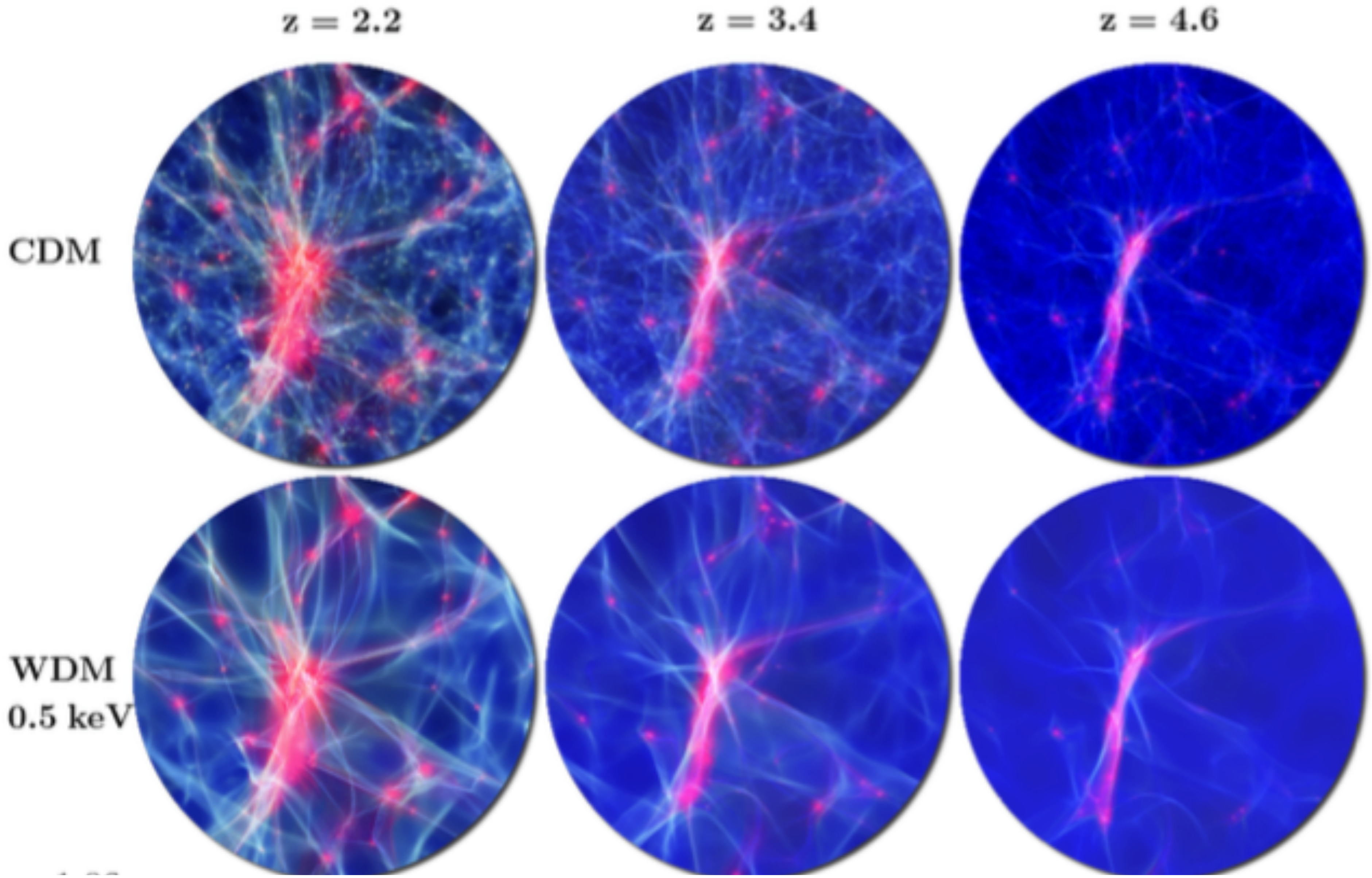
Indications for an X-ray line @ 3.5keV in some astrophysical objects
7keV sterile neutrinos ?? (controversial)

# Impact on large scale structures

Sterile neutrinos: example of **Warm Dark Matter (WDM)**

Still mildly relativistic at equality : structures erased at $\lambda \lesssim \lambda_{\text{free streaming}}$

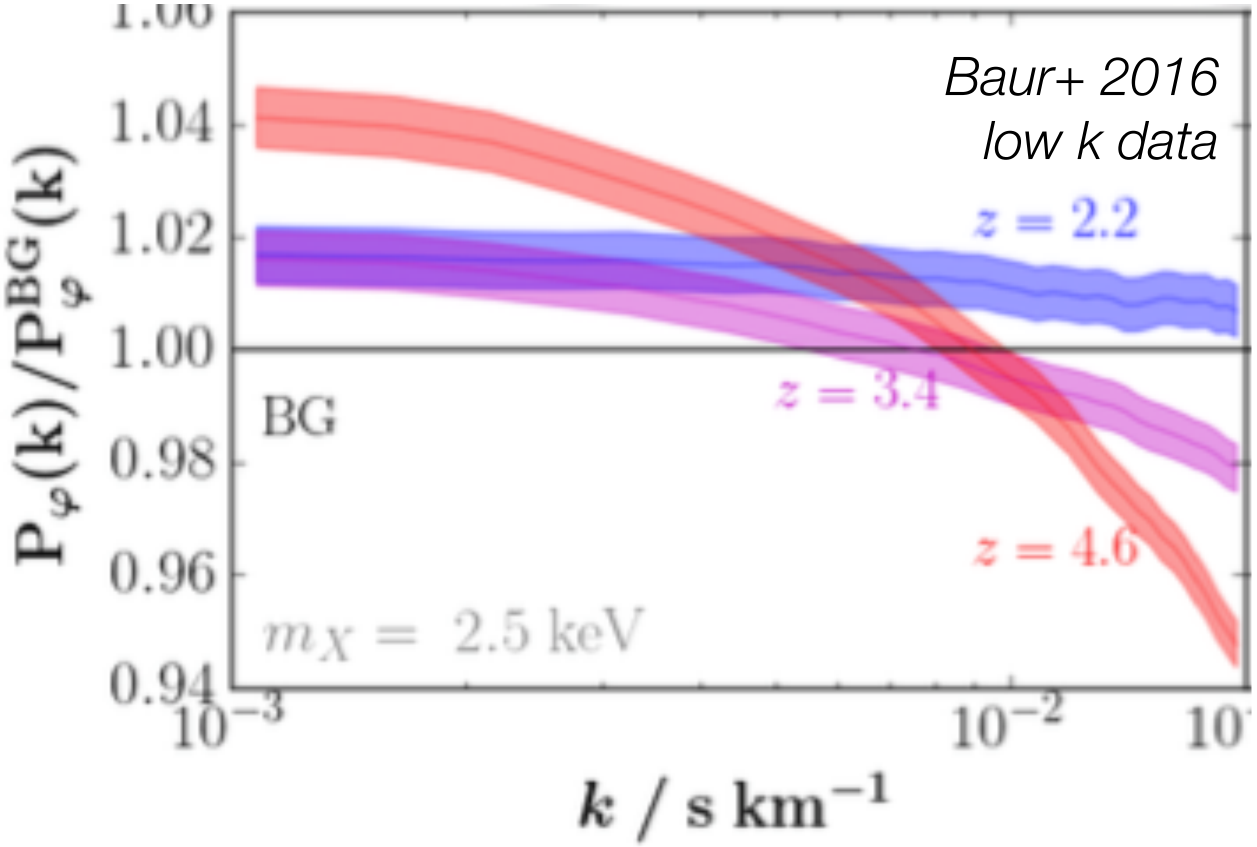
Exact cutoff position is model-dependent (non-thermal velocity distribution)

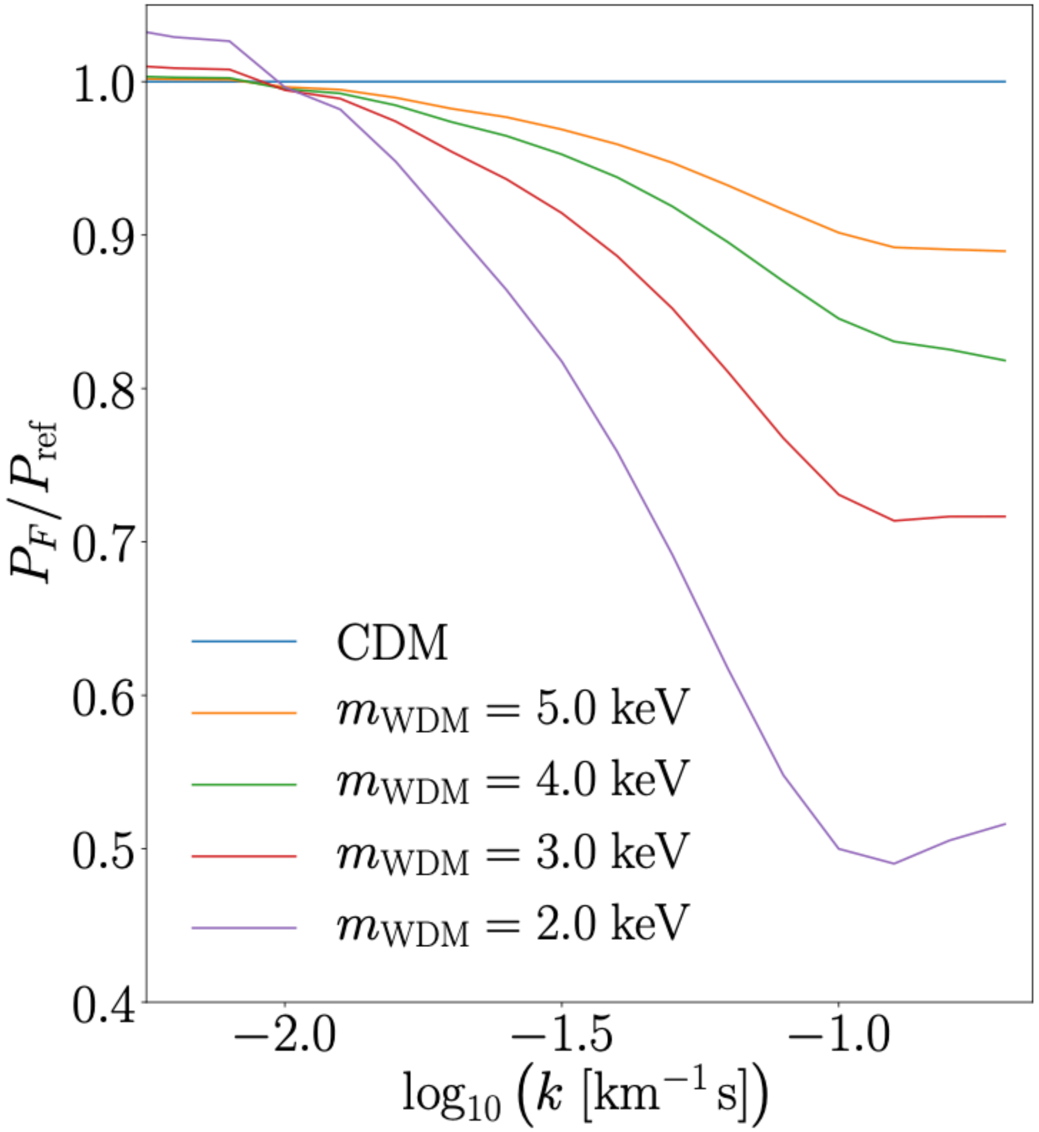


# Impact on Lya P1D

$P_{lin}(k)$ has a cut-off at high k ⇒ $P_{1D}$ attenuation

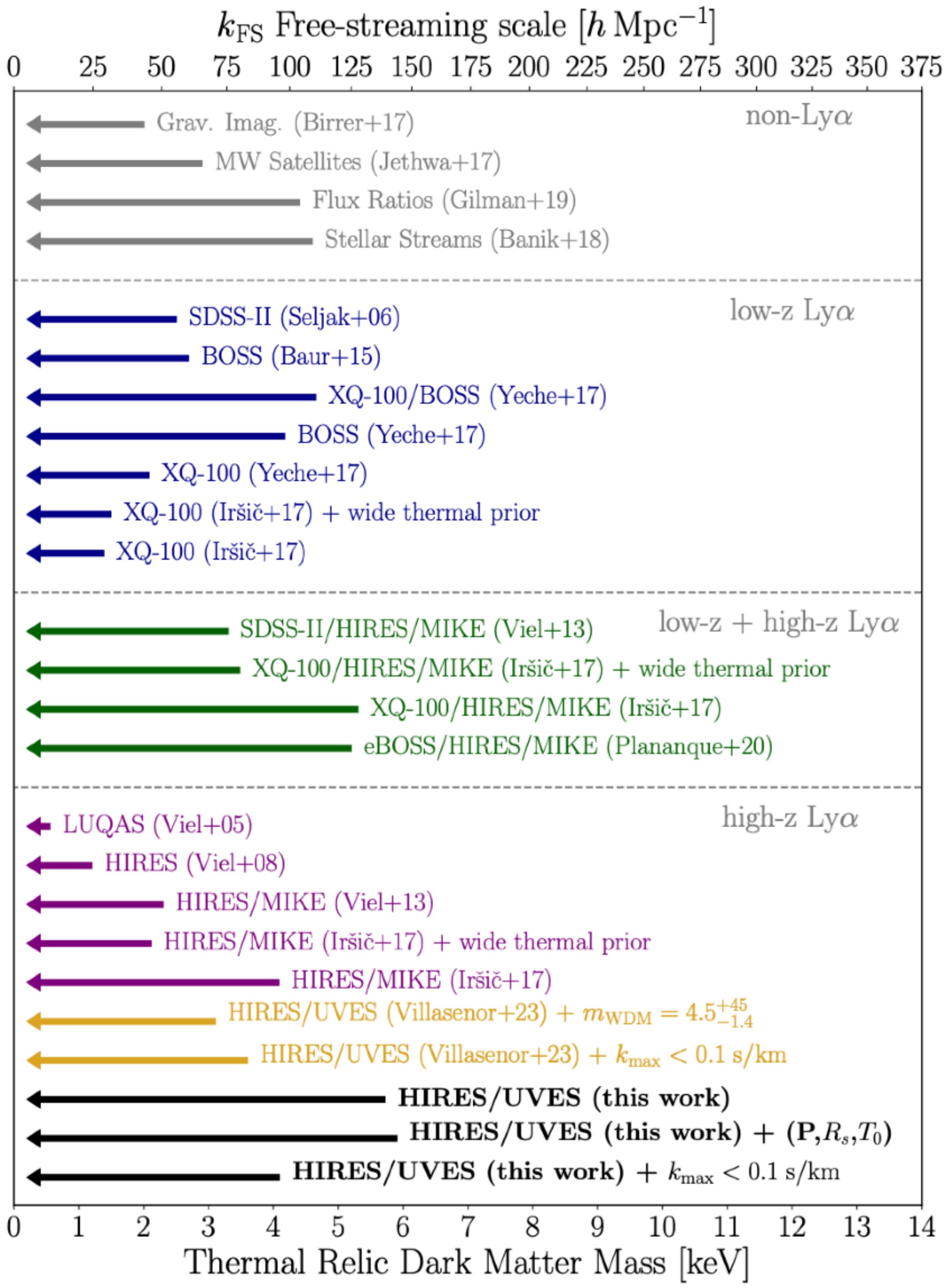
Irsic+ 2309.04533
high k, z=4.6





- Fit P1D as before, adding one parameter modelling the cut-off in $P_{lin}(k)$
- Rely on model for IGM thermal history

# Bounds on WDM from Lya

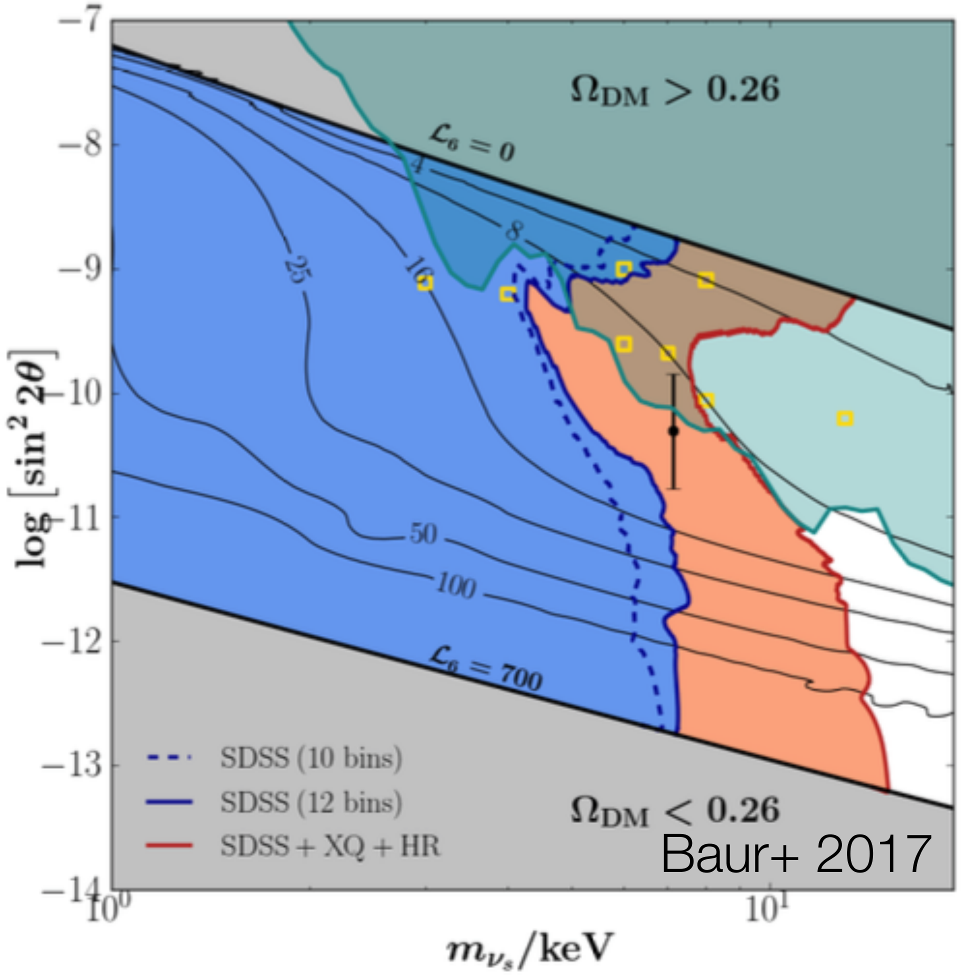


arxiv:2309.04533

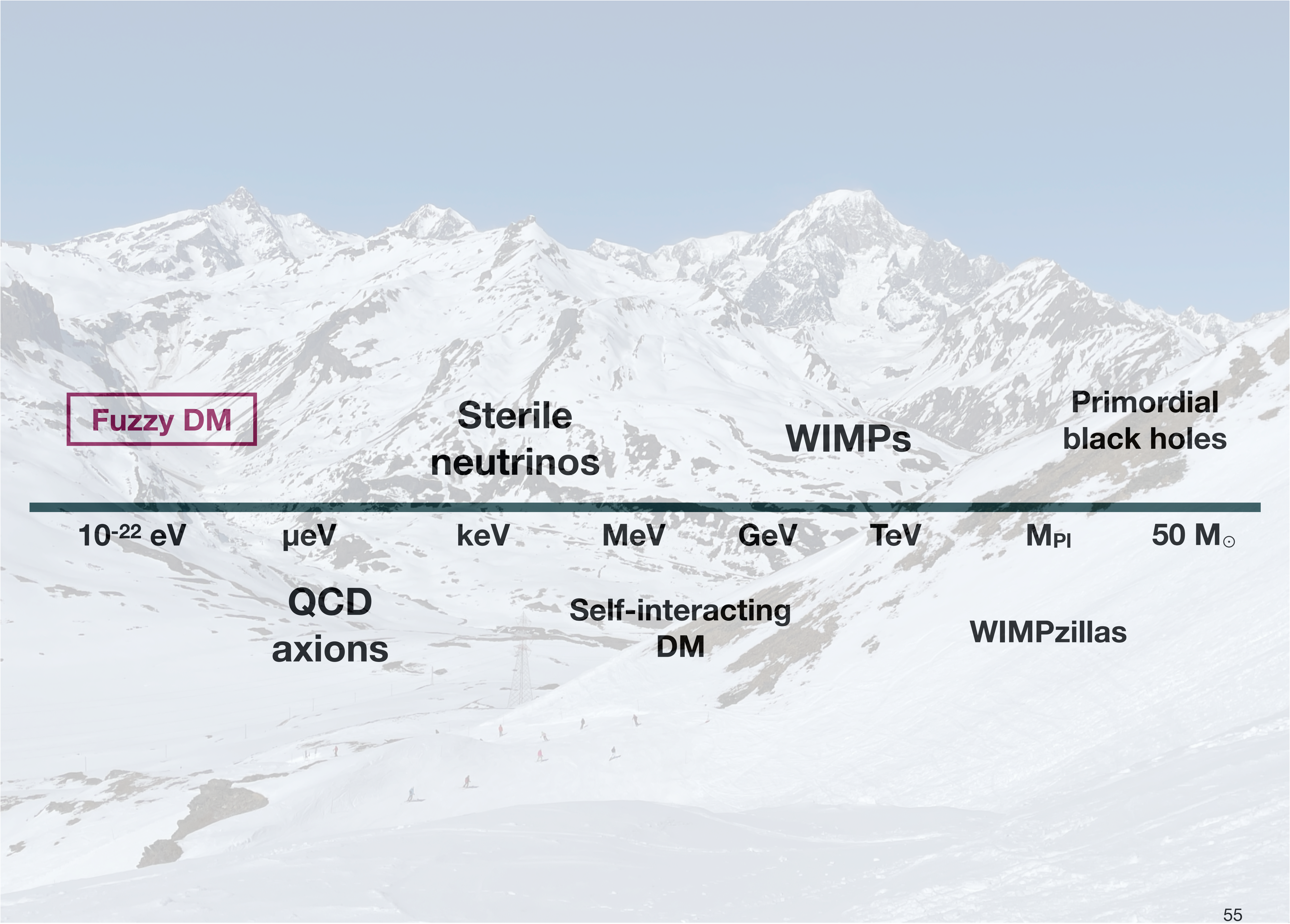
$\lambda_{\rm FS} \lesssim 70$ kpc

⇒ constraint on physical models

- thermal relic $m_X > 4 - 5$ keV
- (non thermal) sterile neutrinos: impact on $P_{\rm lin}$ ~ mixed CDM+WDM model



Baur+ 2017



**Fuzzy DM**

Sterile neutrinos

WIMPs

Primordial black holes

$10^{-22}$ eV   μeV   keV   MeV   GeV   TeV   $M_{Pl}$   50 $M_{\odot}$

QCD axions

Self-interacting DM

WIMPzillas

# FDM: impact on large scale structures

**m ~ $10^{-22}$ eV** - lower bound on the mass of DM
quantum wave effects smooth density fluctuations on scales relevant to structure formation or DM halo dynamics

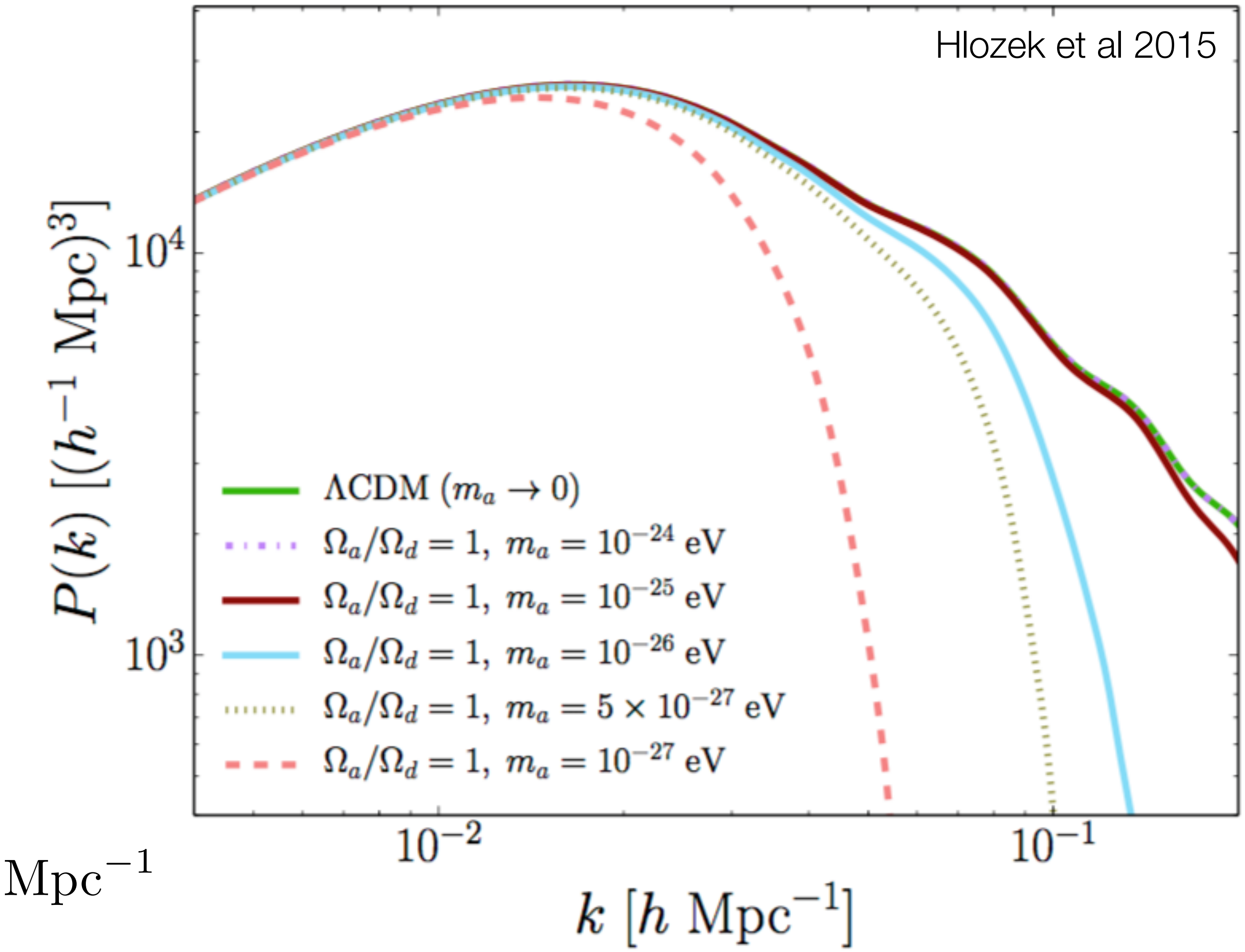
Linear perturbations : FDM ~ fluid with effective speed of sound

$$c_s^2 = \frac{k^2/4m_a^2a^2}{1+k^2/4m_a^2a^2}$$

Jeans smoothing

**Cut-off in linear matter power spectrum for scales smaller than Jeans scale at the time of equality**

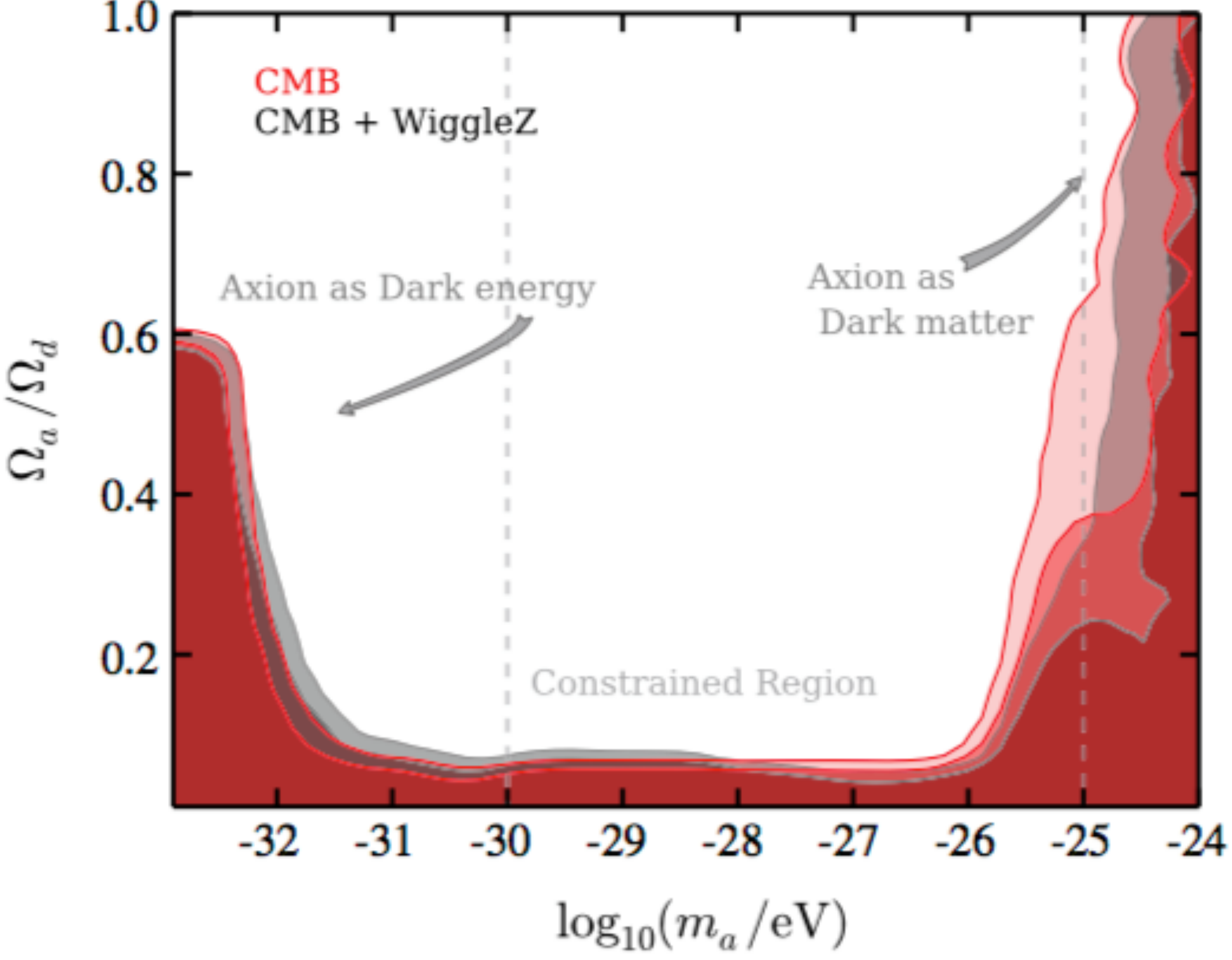
$$k_J = 67\, a^{1/4} \left(\frac{\Omega_a h^2}{0.12}\right)^{1/4} \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} \mathrm{Mpc}^{-1}$$



# Constraints on FDM

**CMB**: exclude m$_a$ ~ $10^{-24}$ eV

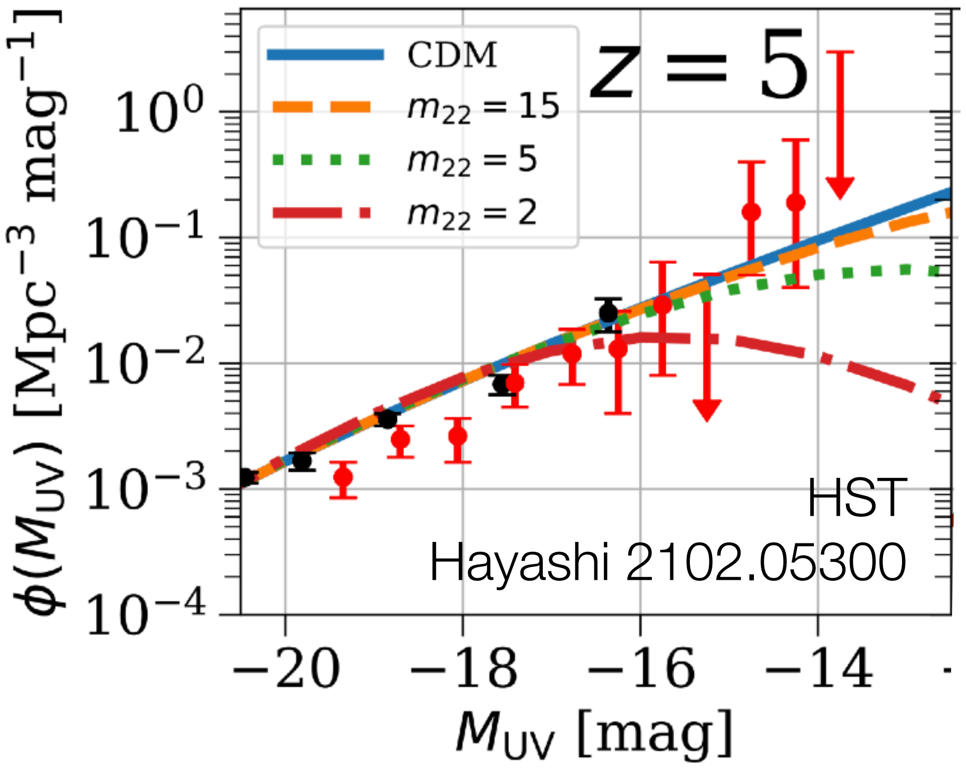
Hlozek+ 2015



**+ dynamics of dwarf galaxies**

**LSS-like probes** ~ $10^{-22}$ - $10^{-21}$ eV

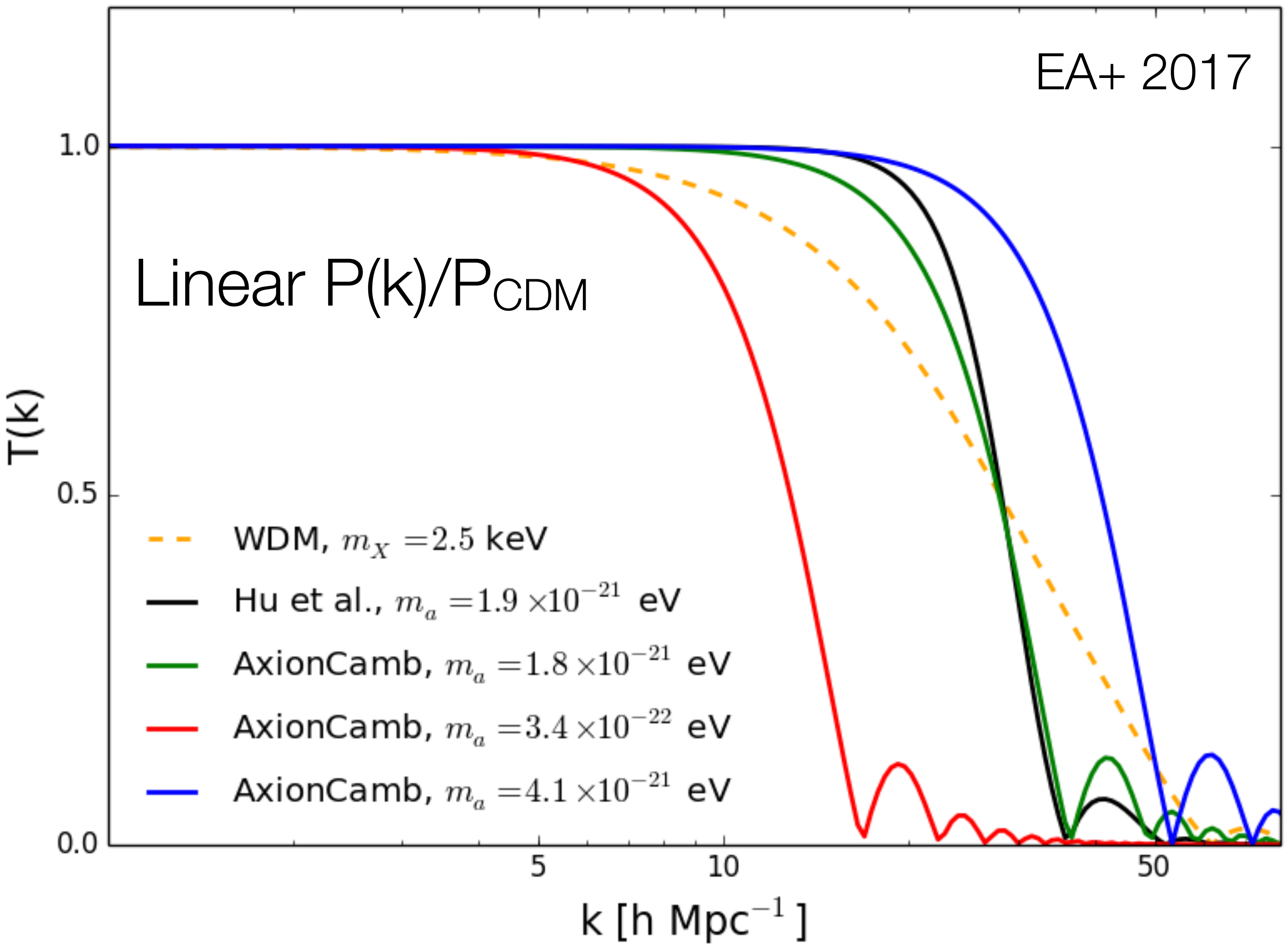
- Galaxy luminosity function / high-redshift galaxy counts
  (low-mass halos)
- Reionization, 21cm
- Strong lenses
- Lyman-$\alpha$ forest

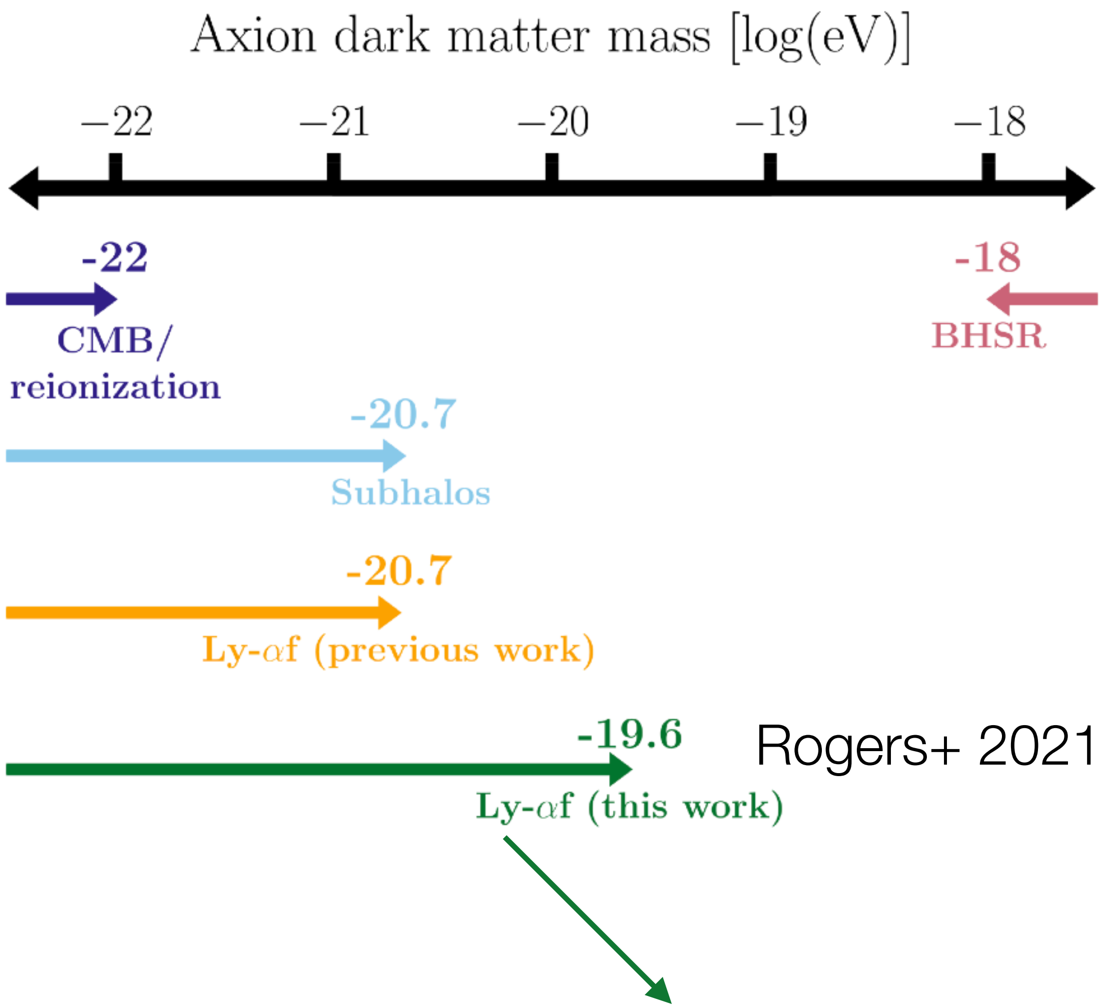


HST
Hayashi 2102.05300

# Lyman-α constraints on FDM

~ Same phenomenology as for WDM





Rogers+ 2021

uses higher resolution spectra

exclude up to $m_a \sim 10^{-20} - 10^{-21}$ eV

# Black Hole Super Radiance

Instability of (scalar) field around spinning black hole
**Compton wavelength ~ BH ergosphere**

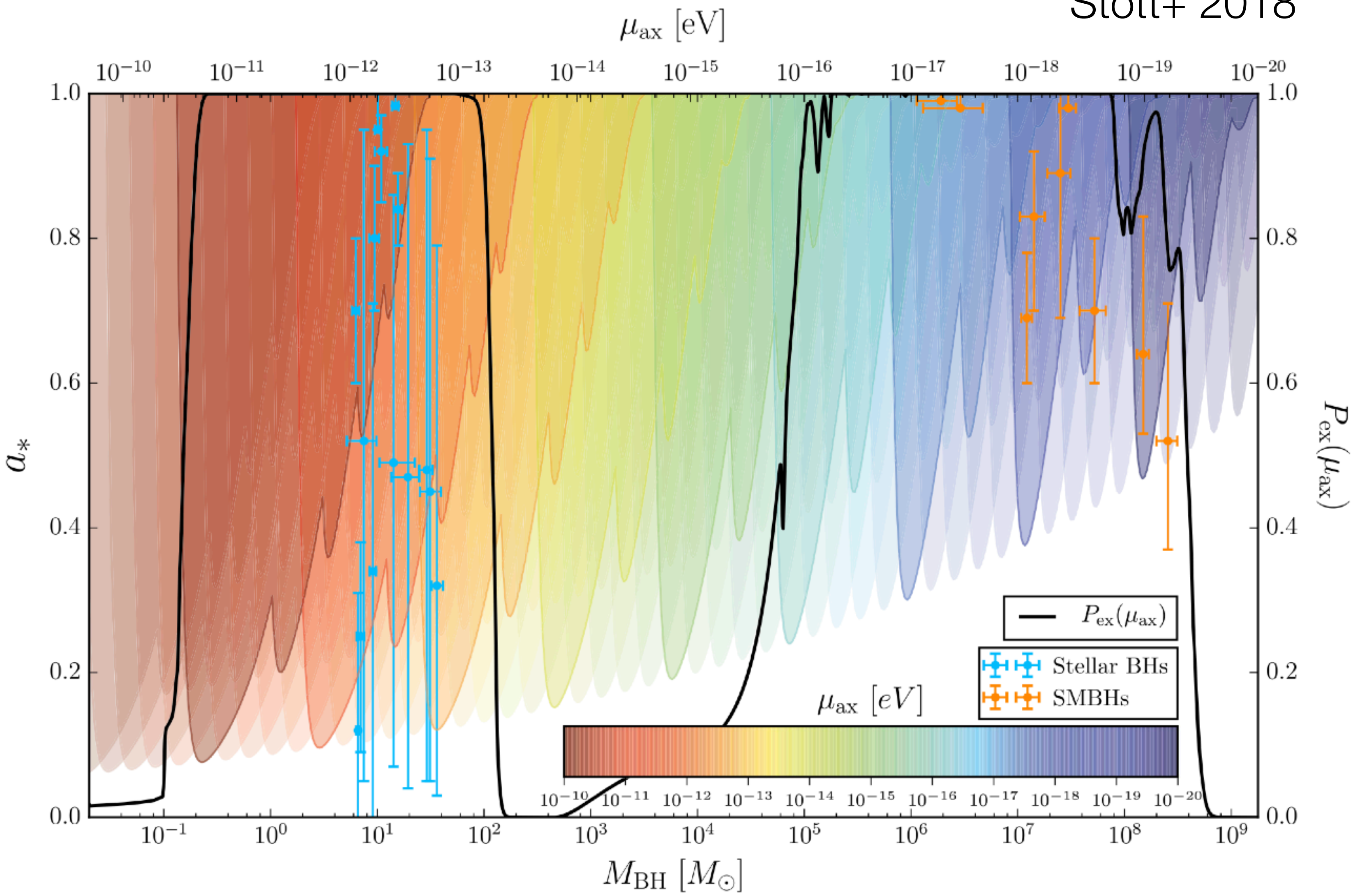
Independent of DM hypothesis

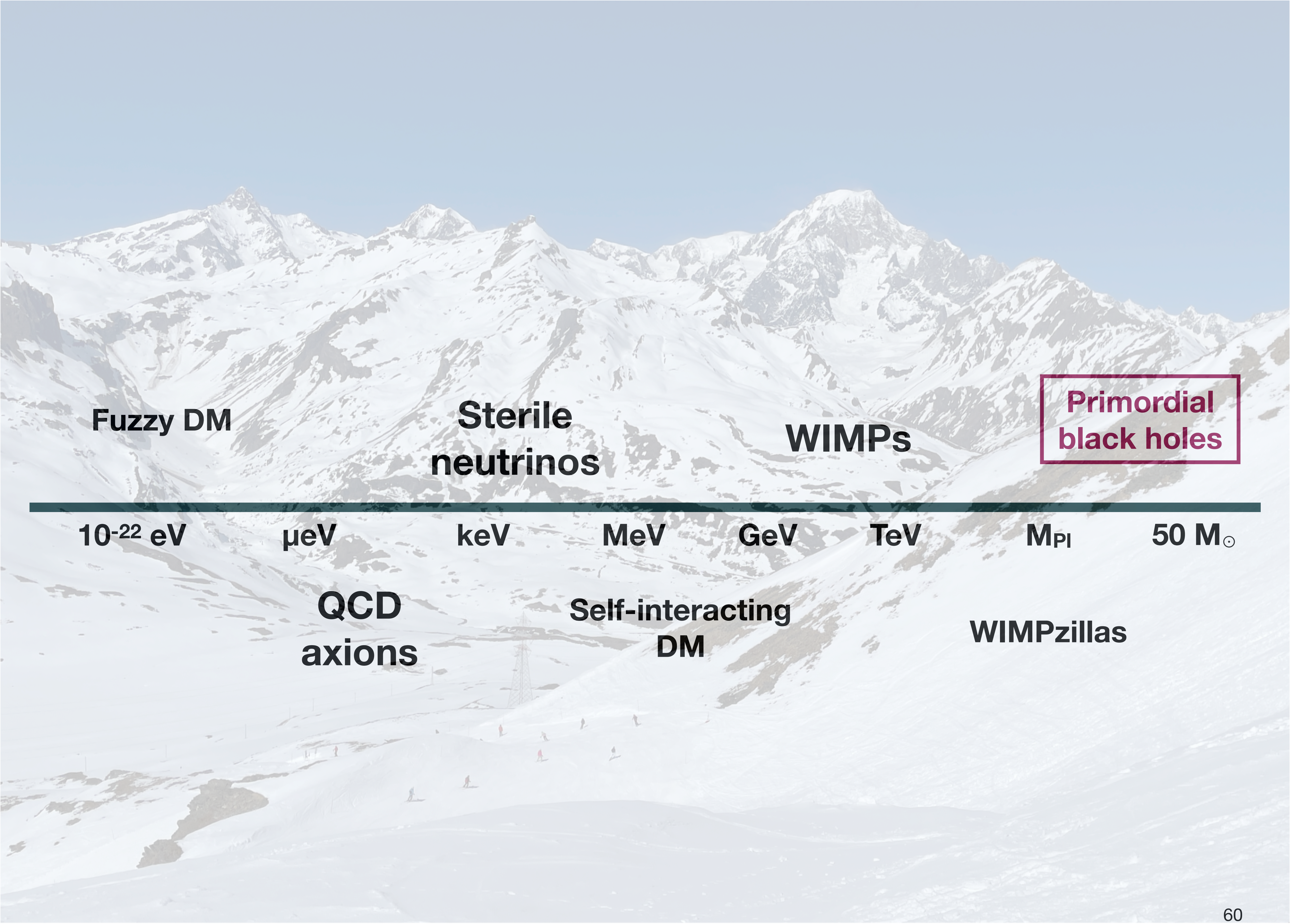
Observe spinning BH ⇒ exclude existence of light field

$m_a \sim 10^{-17}$ - $10^{-19}$ eV constrained by observation of spinning SMBHs

(X-ray emission spectra from inner accretion disk of nearby AGNs)

Stott+ 2018





Fuzzy DM

Sterile neutrinos

WIMPs

Primordial black holes

$10^{-22}$ eV | μeV | keV | MeV | GeV | TeV | $M_{Pl}$ | 50 $M_{\odot}$

QCD axions

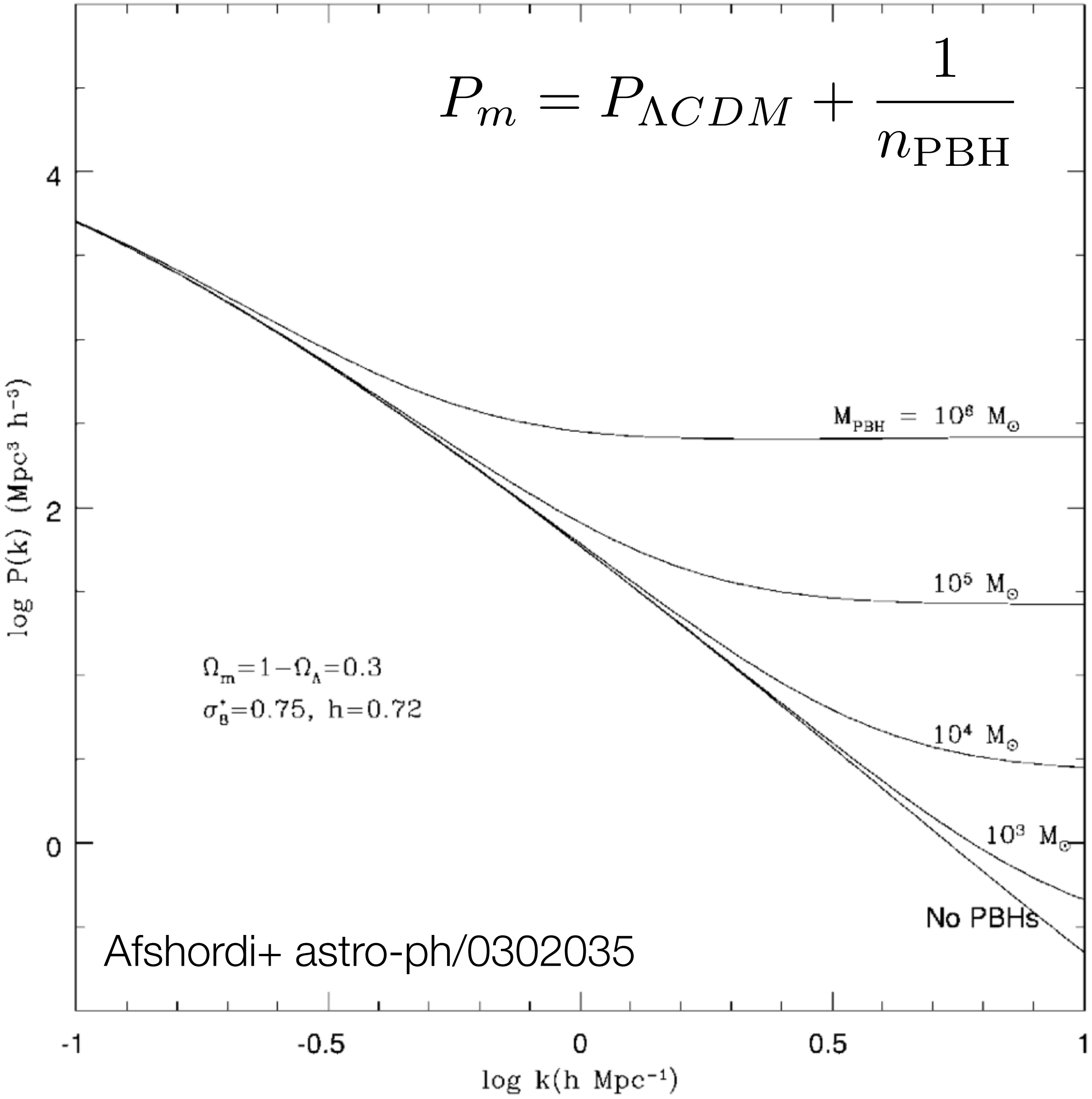
Self-interacting DM

WIMPzillas

# Massive Primordial Black Holes and Ly$\alpha$

- Very massive DM ⇒ low number density

**Shot noise**

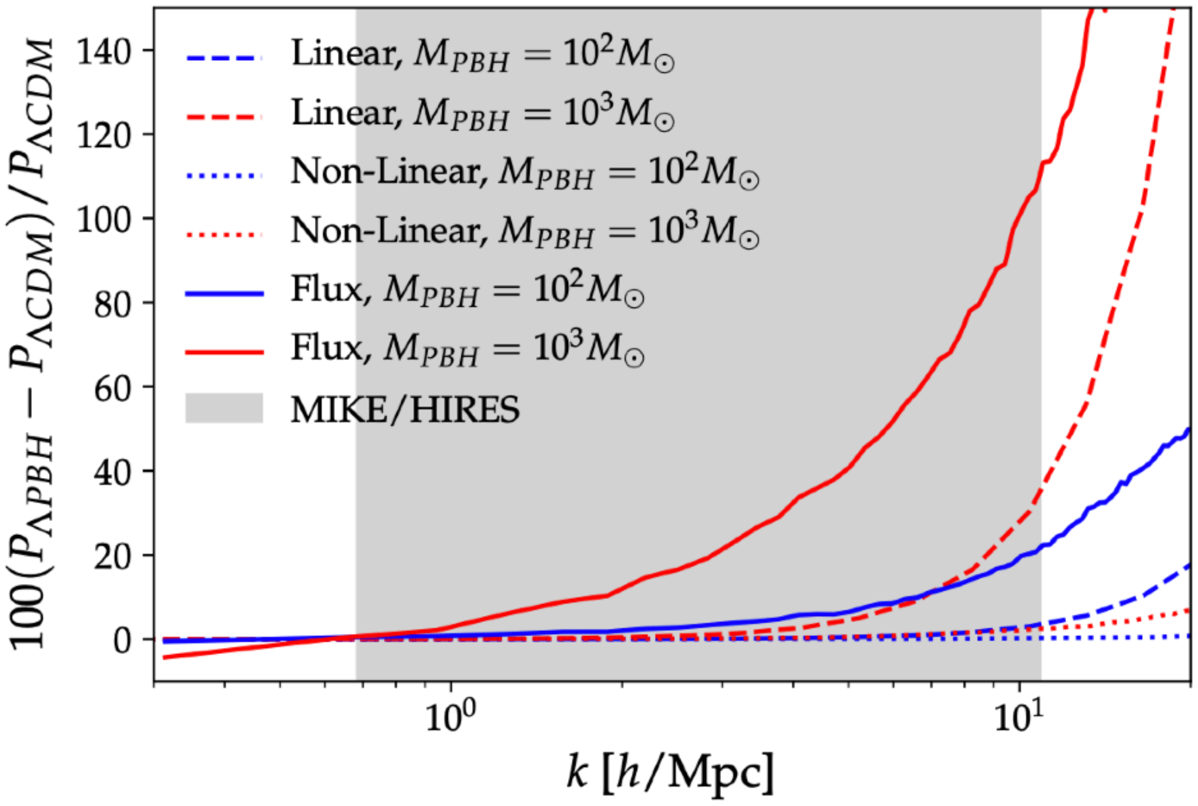


$$P_m = P_{\Lambda CDM} + \frac{1}{n_{\rm PBH}}$$

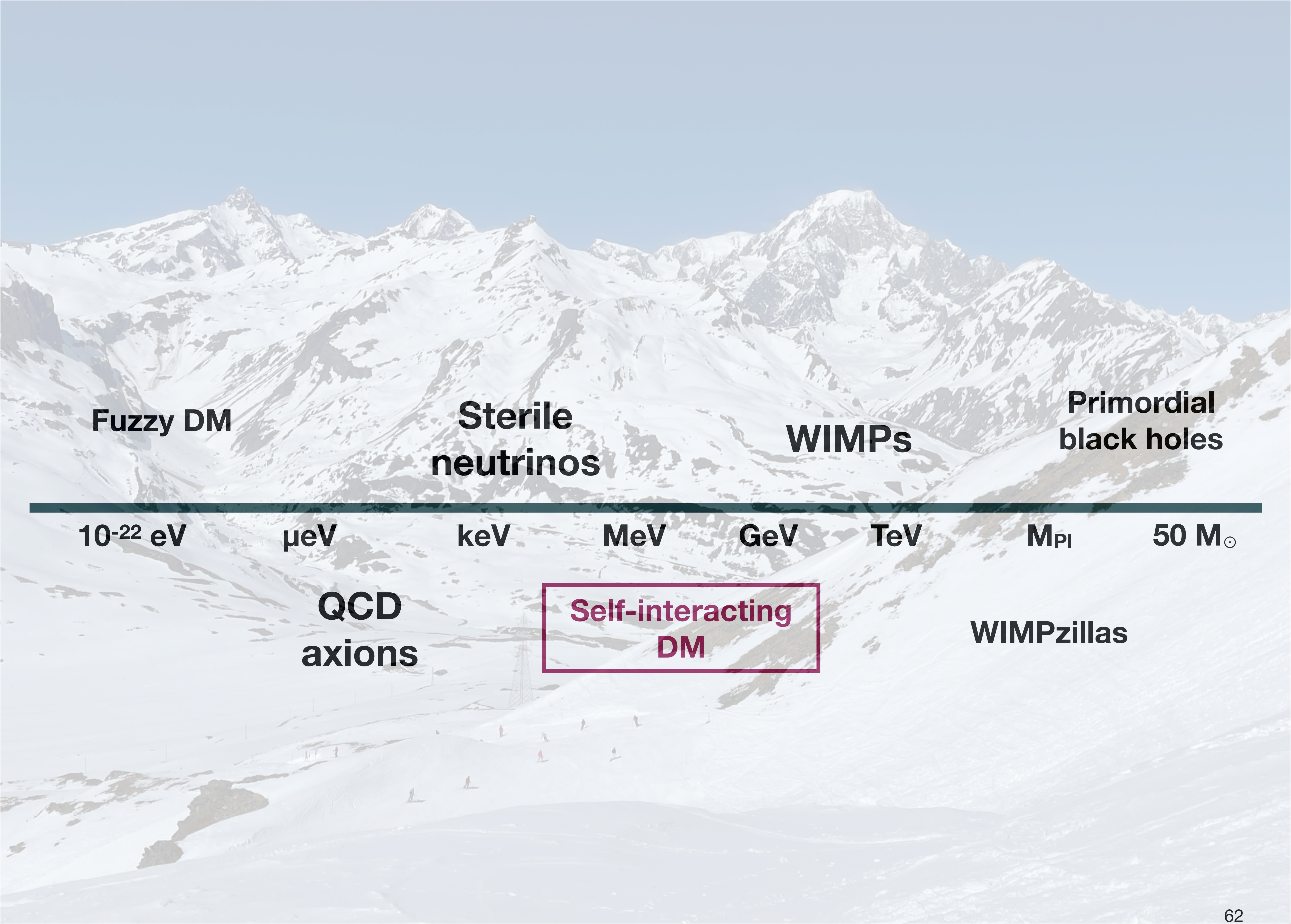
Afshordi+ astro-ph/0302035

- **Boost** P1D at high k (opposite to free-streaming)

Murgia+ 1903.10509



$$f_{\rm PBH}\, M_{\rm PBH} \lesssim 100\, M_\odot$$



**Fuzzy DM**

**Sterile neutrinos**

**WIMPs**

**Primordial black holes**

**$10^{-22}$ eV** **μeV** **keV** **MeV** **GeV** **TeV** **$M_{Pl}$** **$50\ M_\odot$**

**QCD axions**

**Self-interacting DM**

**WIMPzillas**

# SIDM

Similar to WDM

Better bounds from dynamical observations inside halos