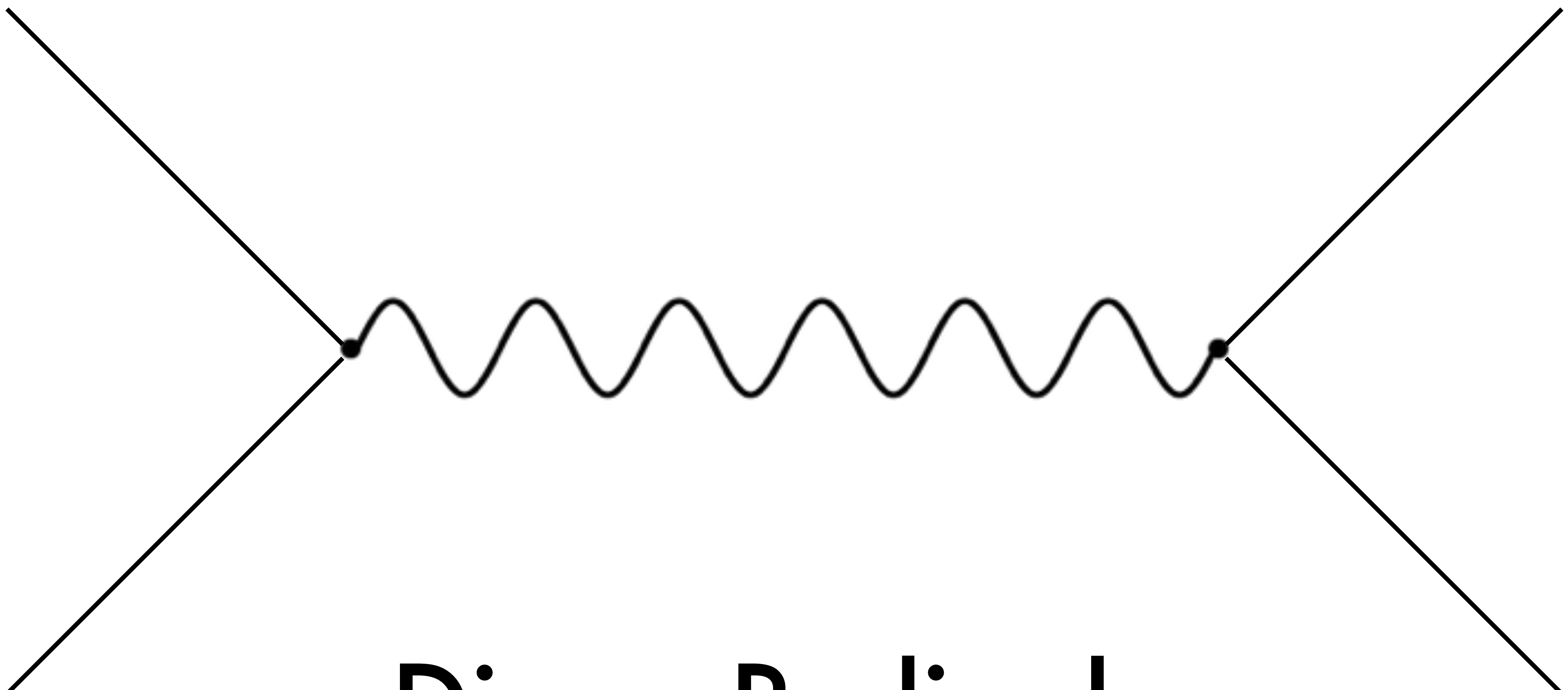
THE HUNT FOR NEW FORCES



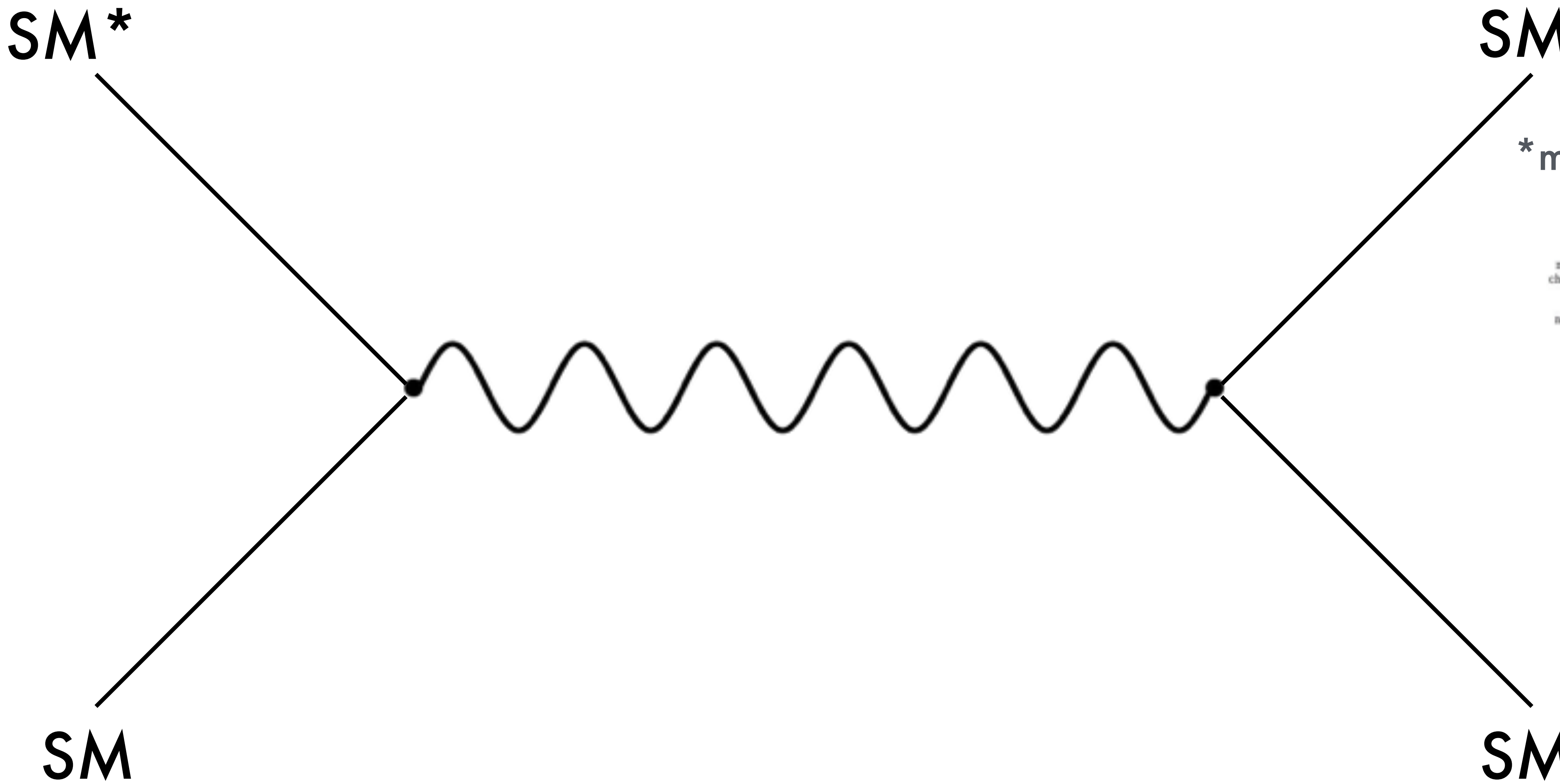
Diego Redigolo

28/10/2019

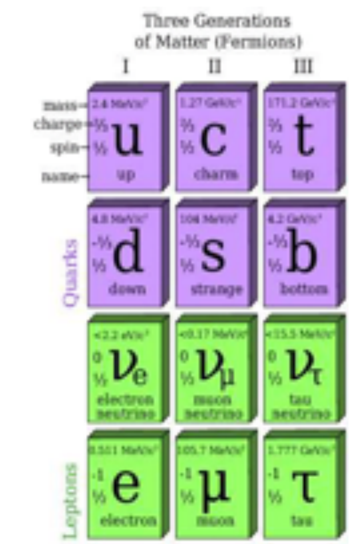
INFN Istituto Nazionale di Fisica Nucleare
Sez. di FIRENZE

THE HUNT FOR NEW FORCES

*SM=Standard Model



*matter we know

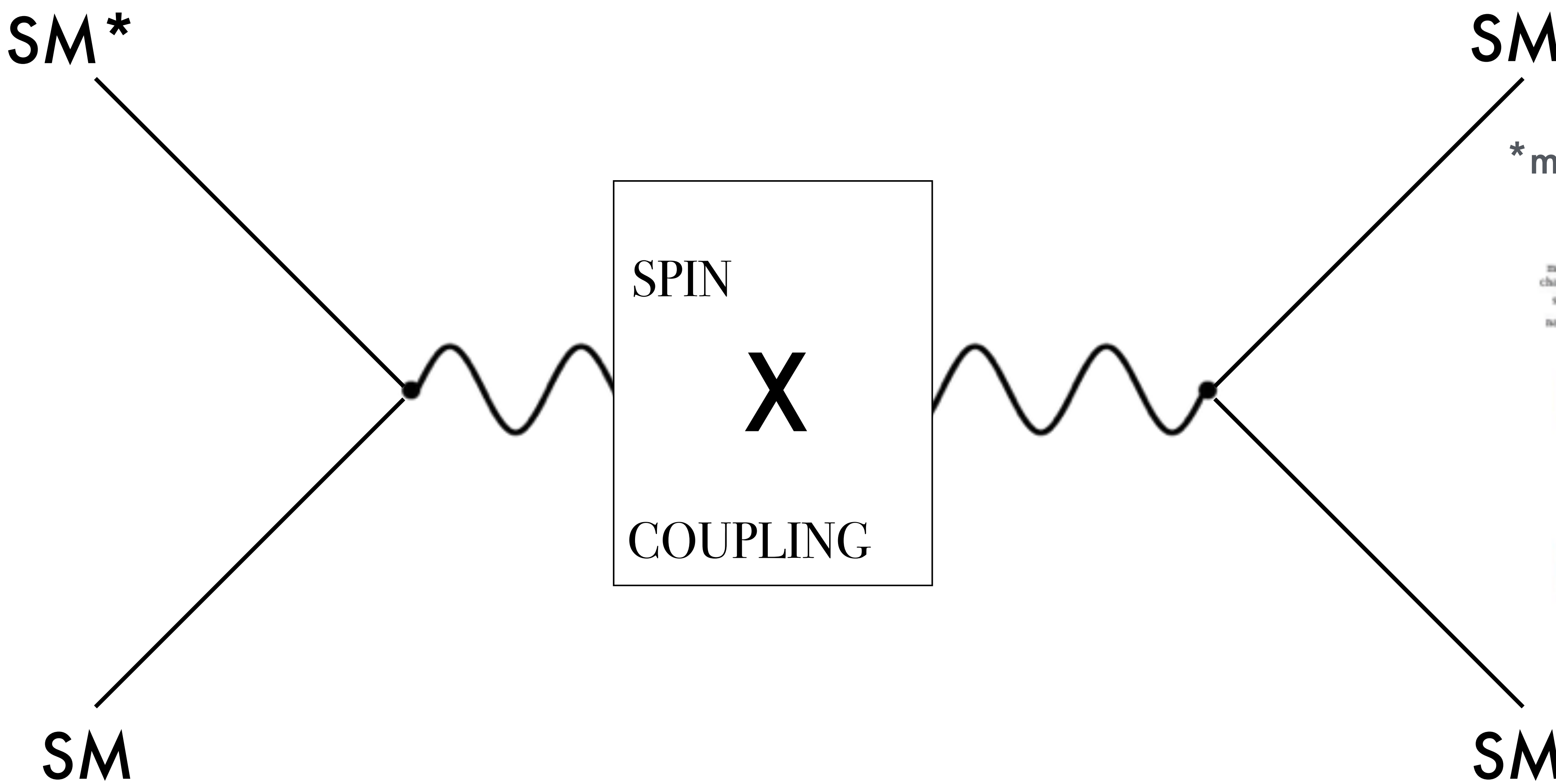


The force properties are encoded in the nature of the *force carrier*

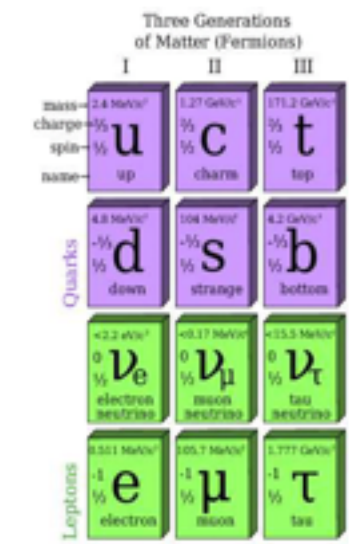
and its interactions with the *matter we know about**

THE CHEMISTRY OF FORCES

*SM=Standard Model



*matter we know



Like chemists

we can classify the types of force careers X

THE FORCES WE KNOW...

Short range

0
1 g
$g_s \simeq 1.2$

80.4 GeV
1 $W^\pm$
$g \simeq 0.64$

90.2 GeV
1 Z
$g' \simeq 0.3$

125 GeV
0 h
yukawas…

fm

pm

- confinement
- symmetry breaking

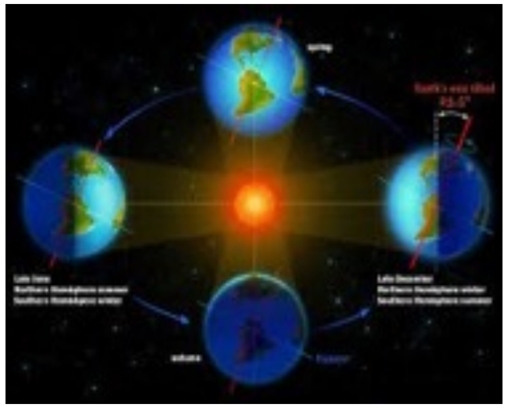
Seen in EU colliders :

Long range

0
1 γ
$e \simeq 0.3$

0
2 $h_{\mu\nu}$
$\frac{m_p}{M_{Pl}} \simeq 10^{-19}$

Seen in everyday life:



THE FORCES WE KNOW...

Short range

0, 1, g, $g_s \simeq 1.2$	80.4 GeV, 1, $W^{\pm}$, $g \simeq 0.64$	90.2 GeV, 1, Z, $g' \simeq 0.3$	125 GeV, 0, h, yukawas…

fm pm

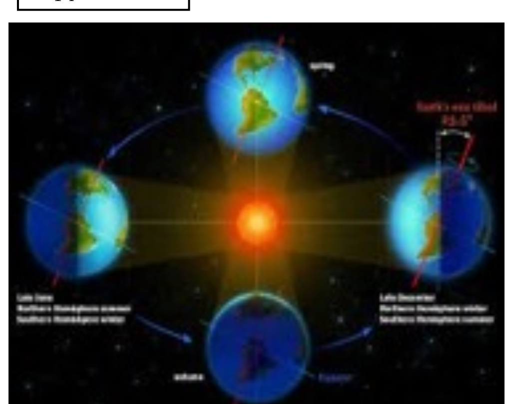
- confinement
- symmetry breaking

Seen in EU colliders :

Long range

0, 1, γ, $e \simeq 0.3$	0, 2, $h_{\mu\nu}$, $\frac{m_p}{M_{\rm Pl}} \simeq 10^{-19}$

Seen in everyday life:



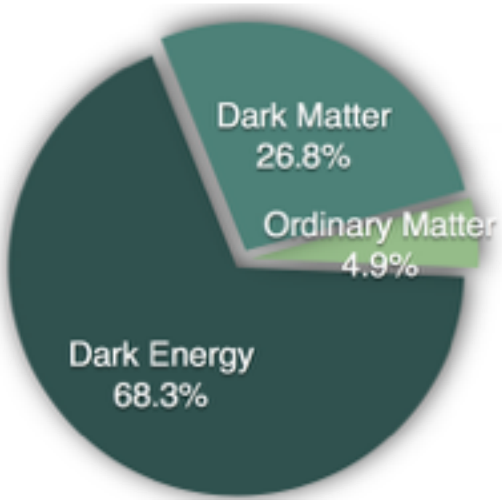
this is all we got so far...

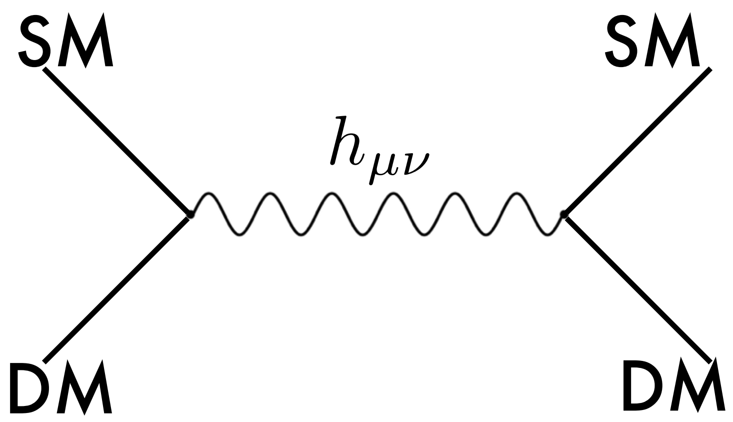
NEW DARK FORCES?

NEW DARK FORCES?

it is plausible to imagine new forces
to be present...

DARK MATTER EXISTS/ED



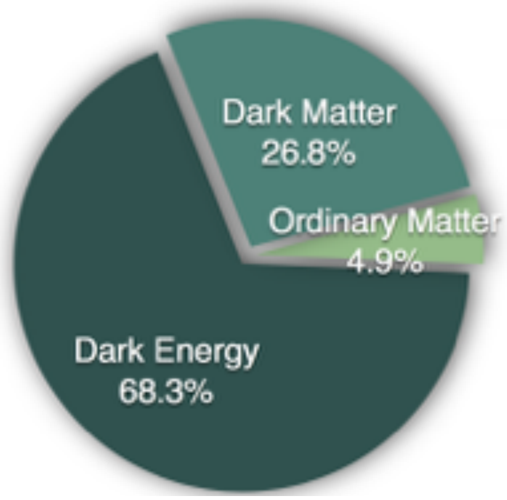


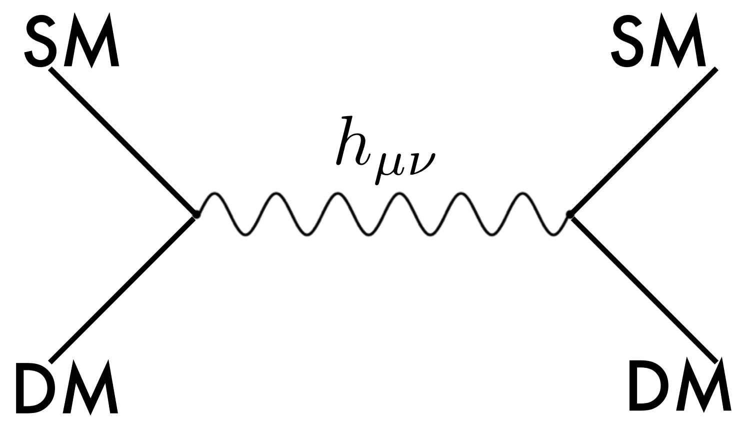
we have many evidences
from its gravitational interactions
with the regular matter

Dark Matter should be a particle of some sort...

even MOND *aficionados* have to introduce
new particles to the SM

DARK MATTER EXISTS/ED



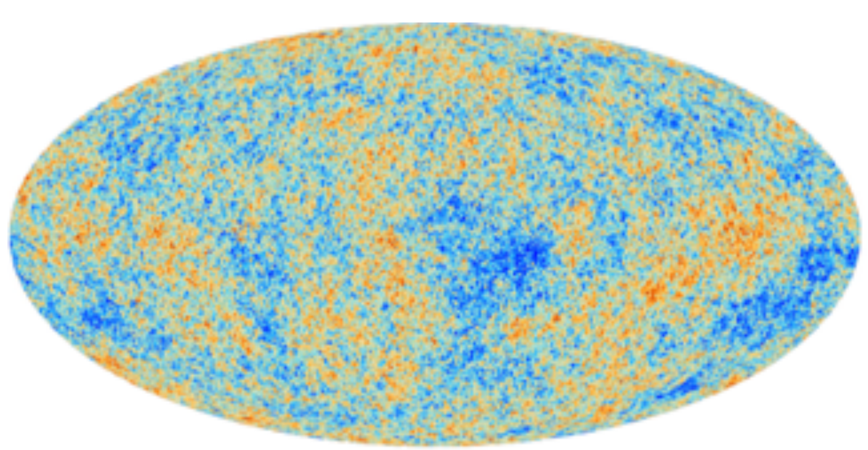


we have many evidences
from its gravitational interactions
with the regular matter

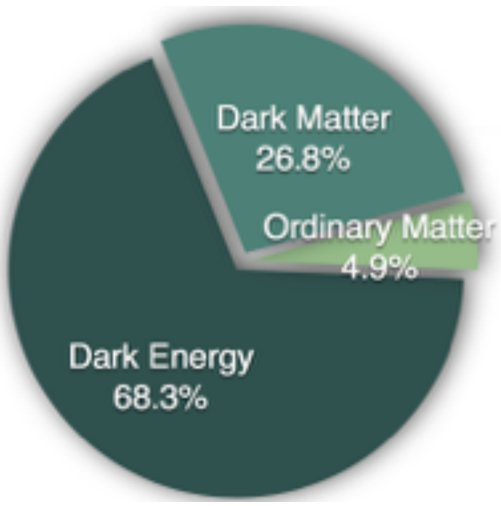
Dark Matter should be a particle of some sort...

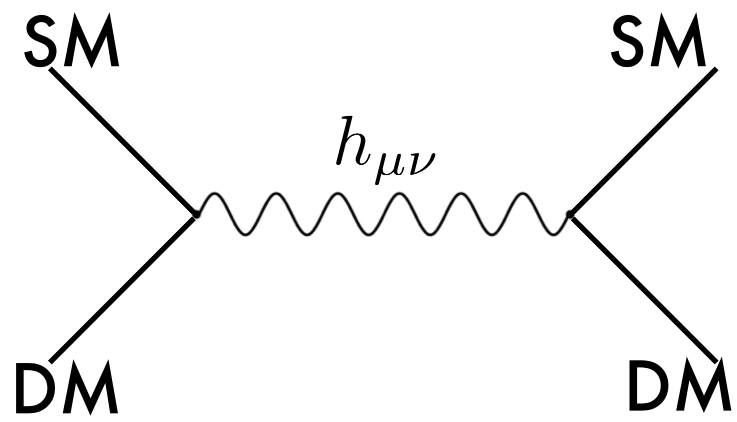
even MOND *aficionados* have to introduce new particles to the SM

CMB Temperature map



DARK MATTER EXISTS/ED



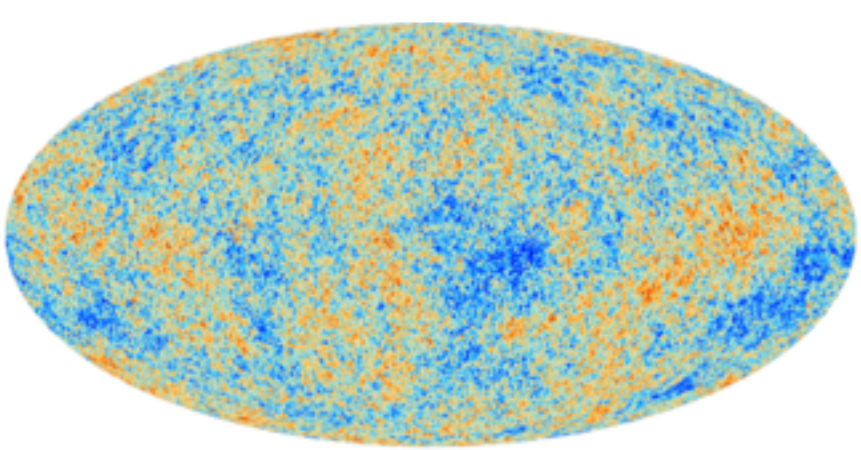


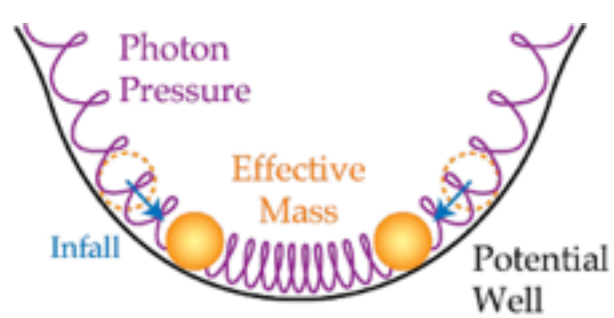
we have many evidences
from its gravitational interactions
with the regular matter

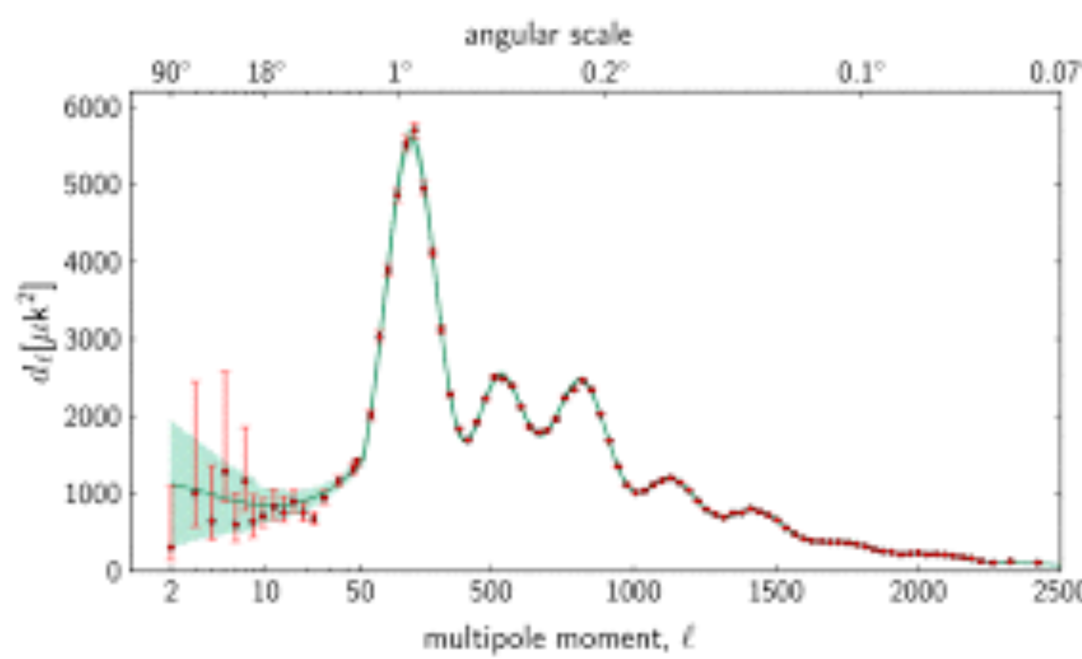
Dark Matter should be a particle of some sort…

even MOND *aficionados* have to introduce new particles to the SM

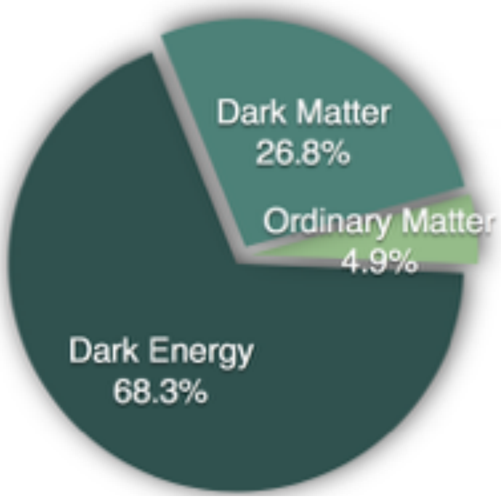
CMB Temperature map

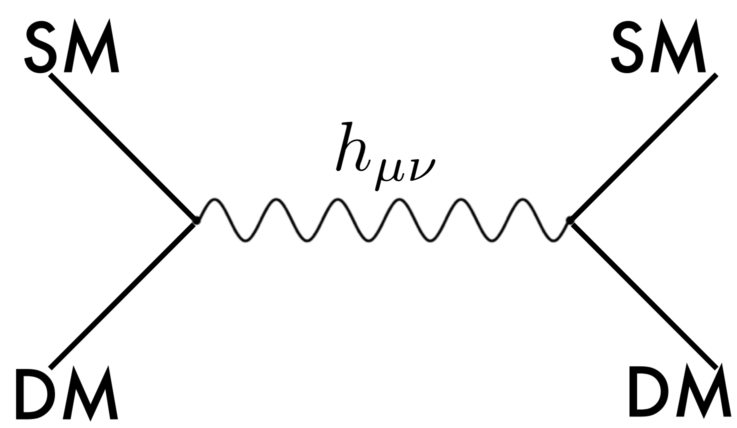






DARK MATTER EXISTS/ED



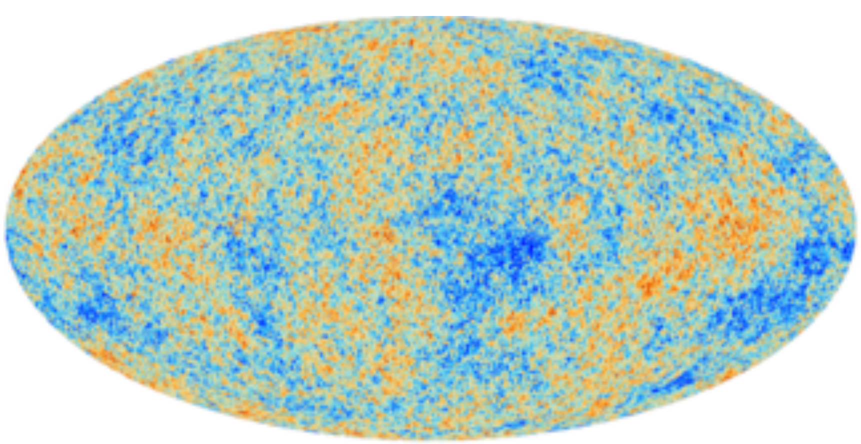


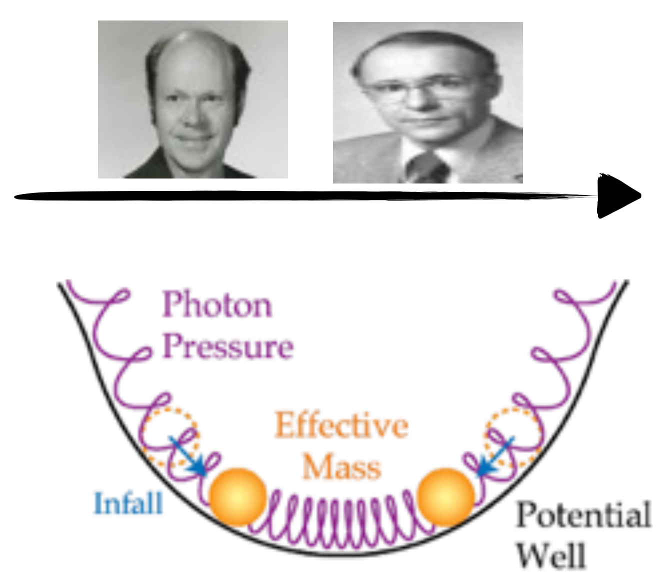
we have many evidences
from its gravitational interactions
with the regular matter

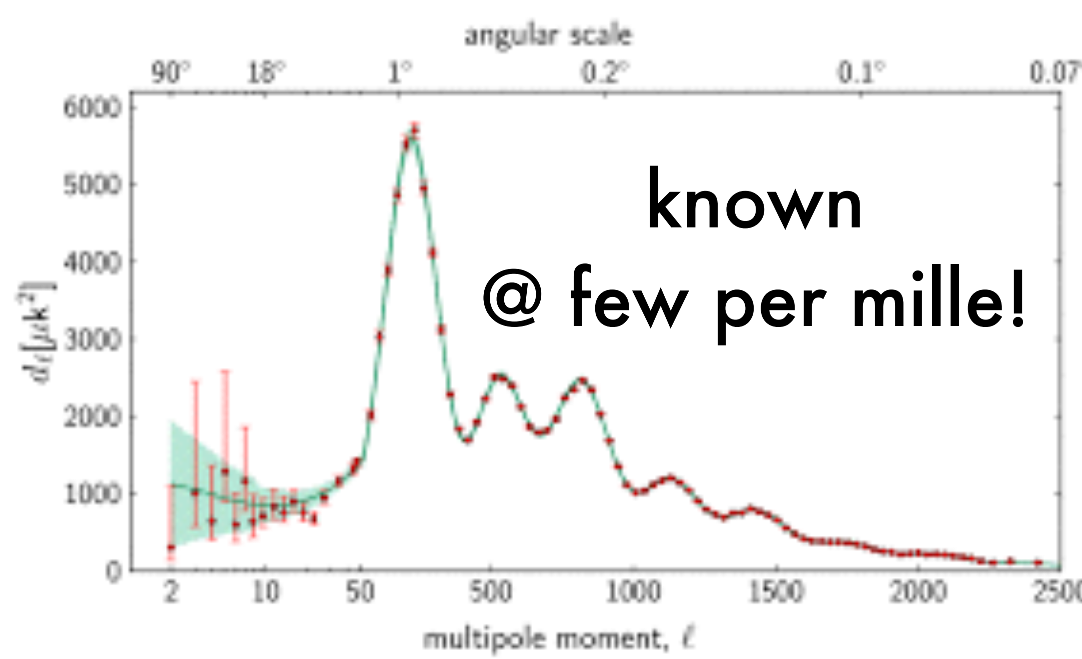
Dark Matter should be a particle of some sort...

even MOND *aficionados* have to introduce
new particles to the SM

CMB Temperature map

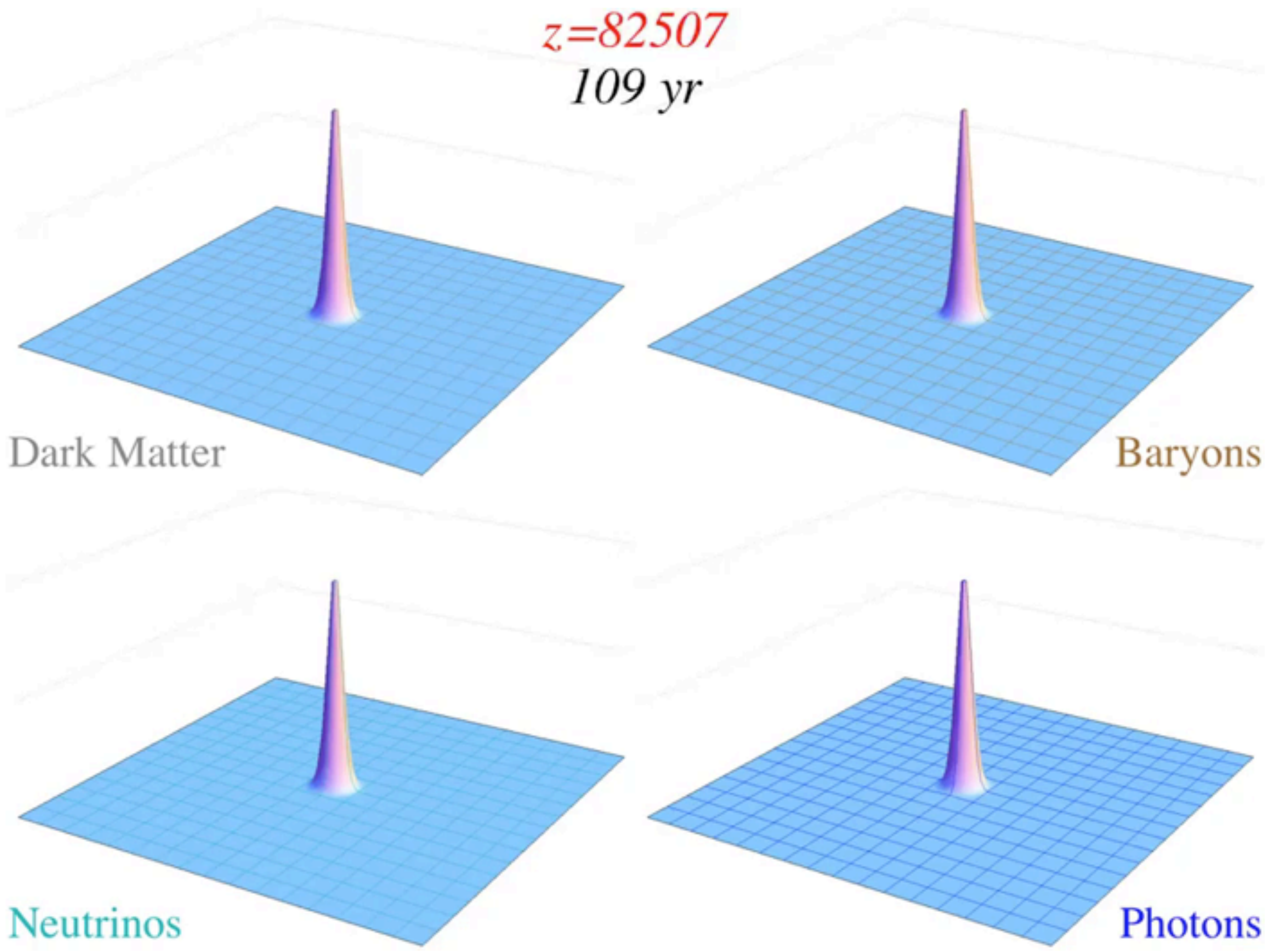




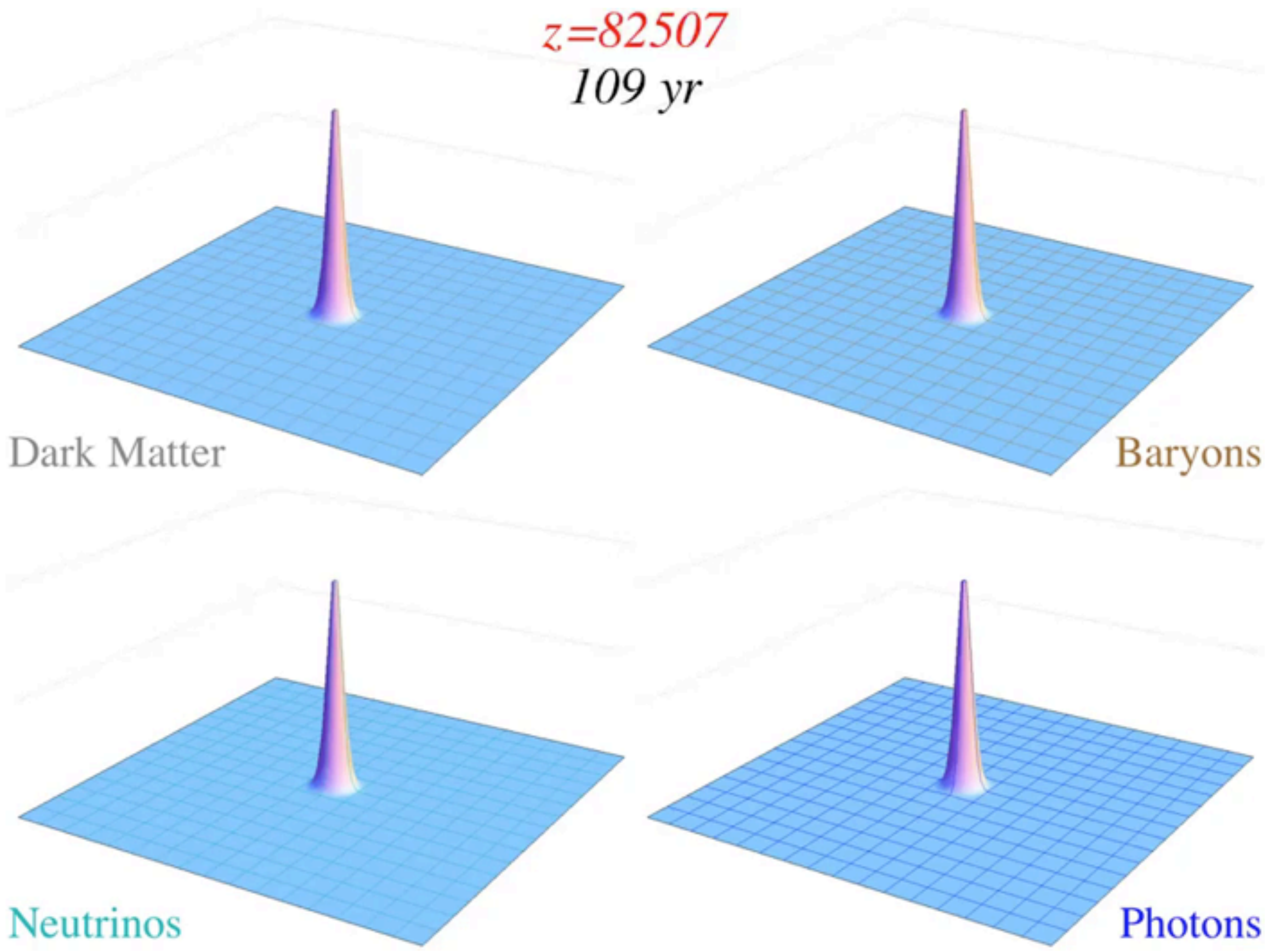


known
@ few per mille!

ANIMATION TO SHOW OFF

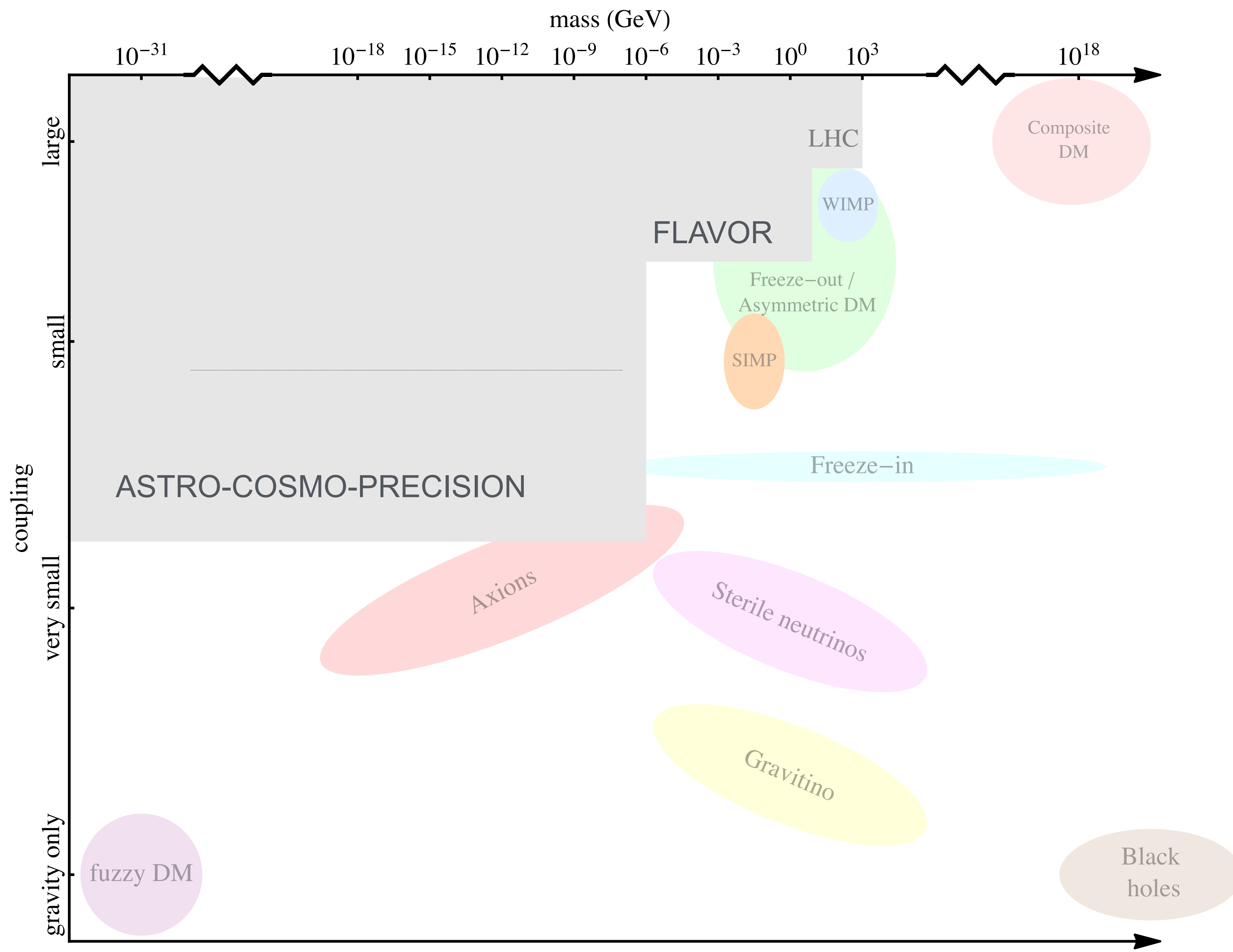


ANIMATION TO SHOW OFF



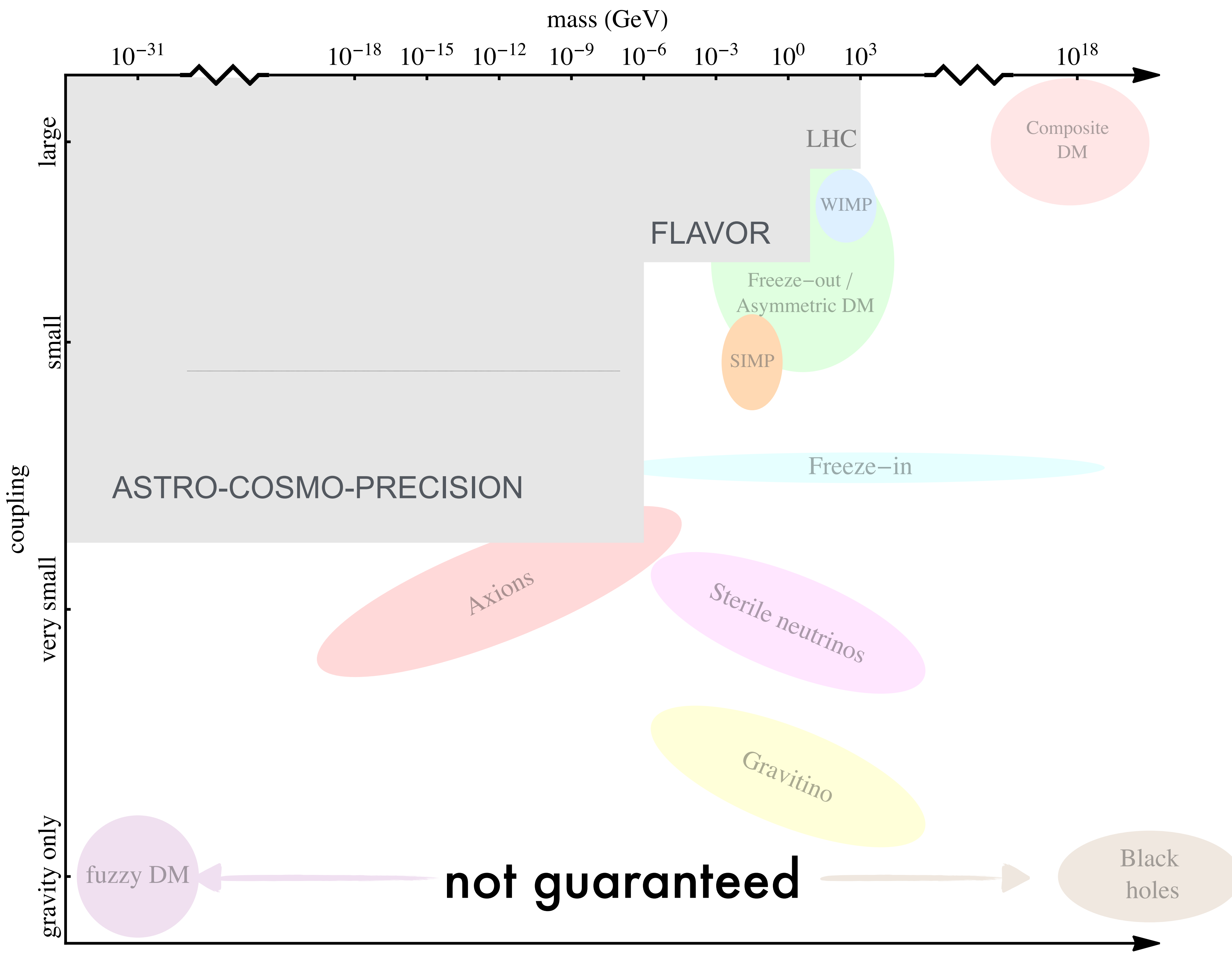
DARK MATTER PRODUCTION

Production mechanisms require a NEW FORCE

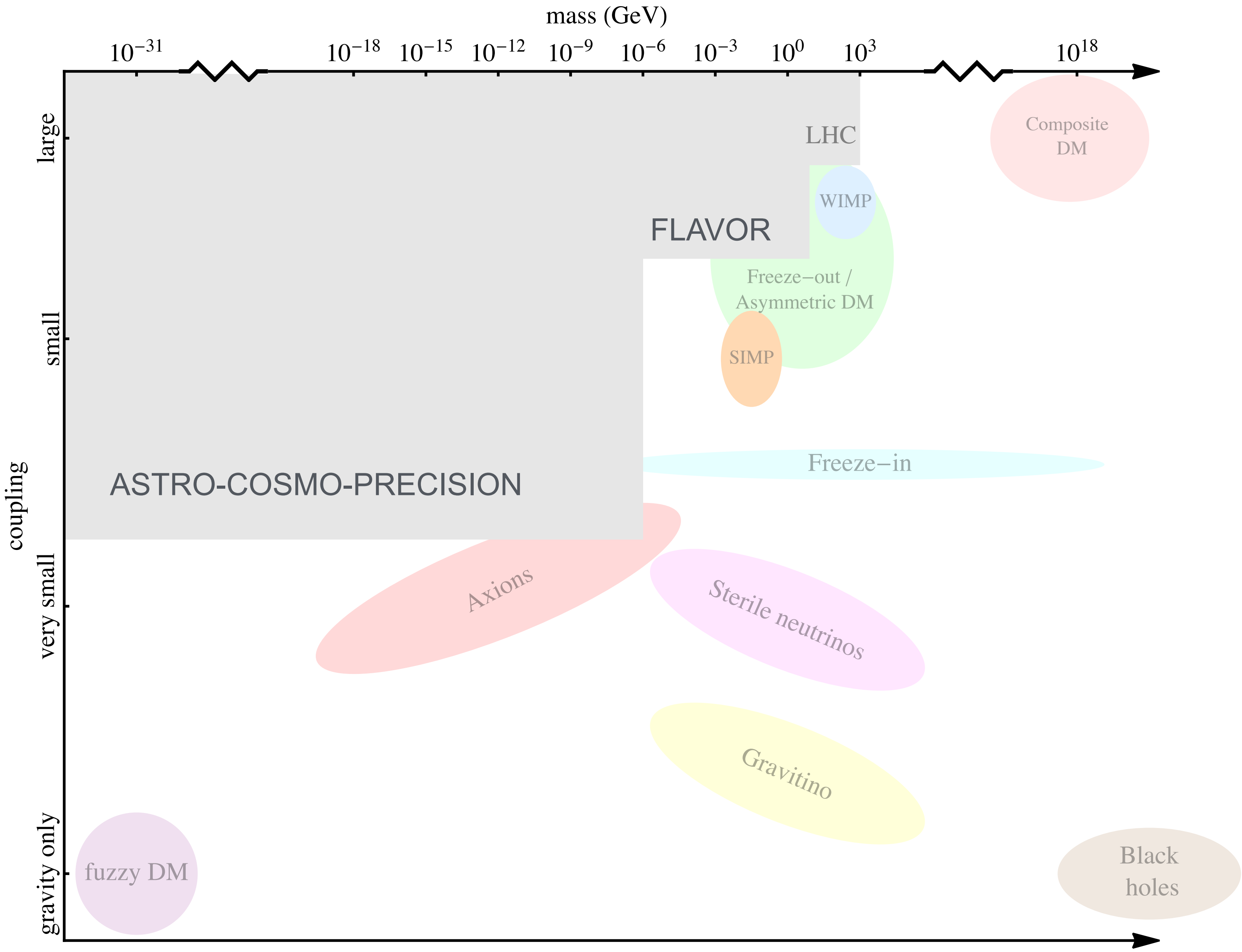


DARK MATTER PRODUCTION

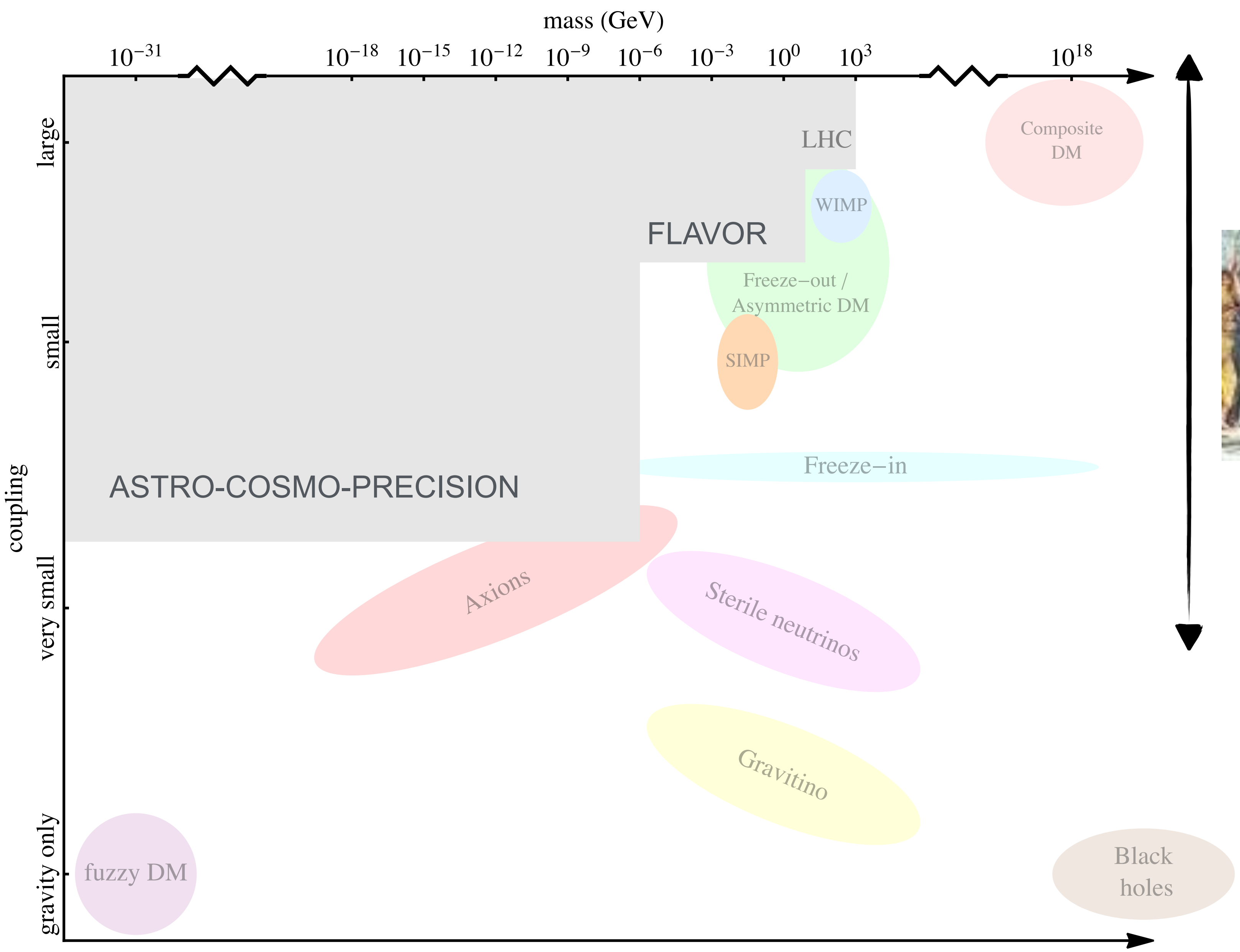
Production mechanisms require a NEW FORCE



ANALOGY VS MINIMALITY



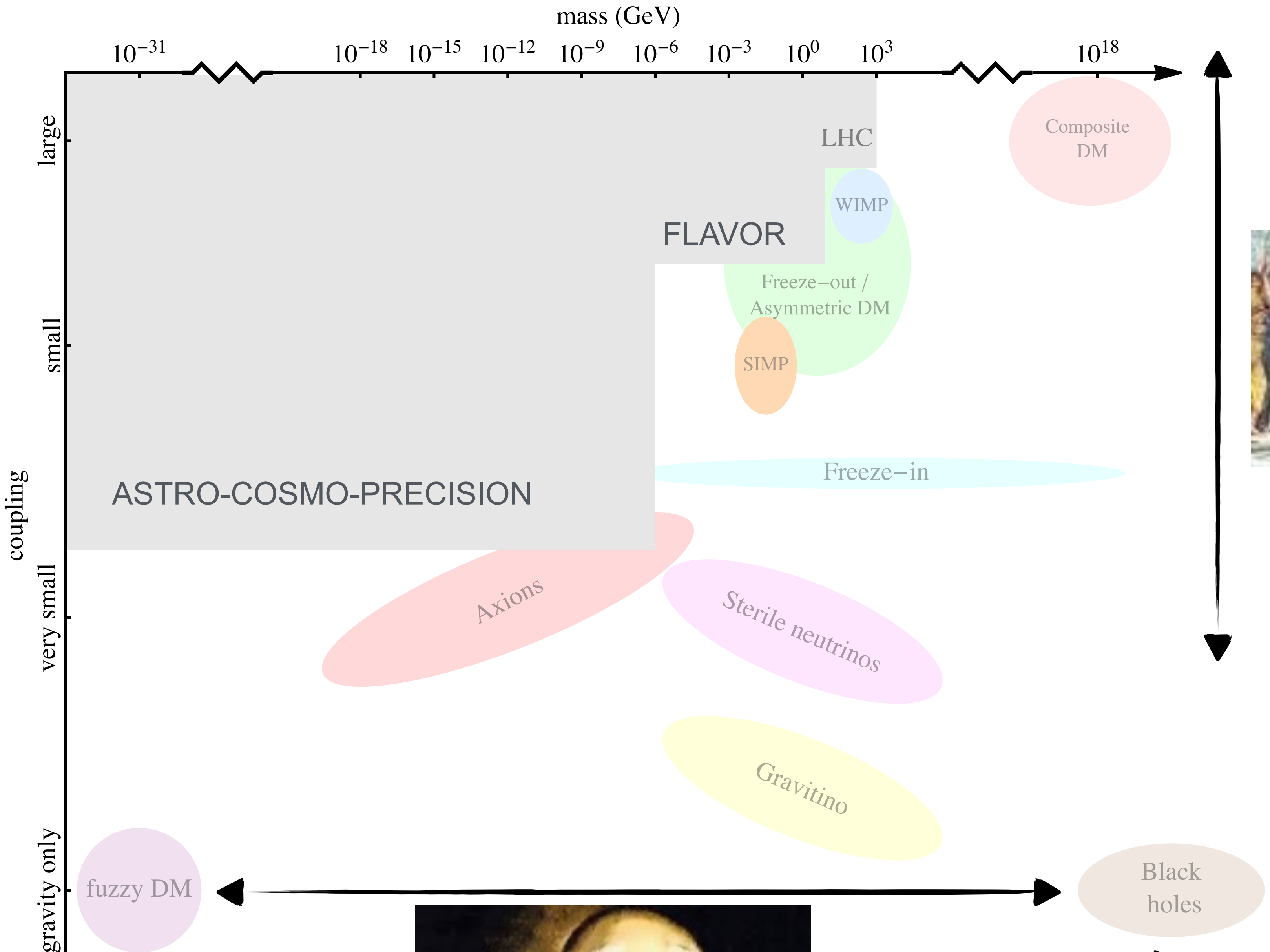
ANALOGY VS MINIMALITY



ANALOGY

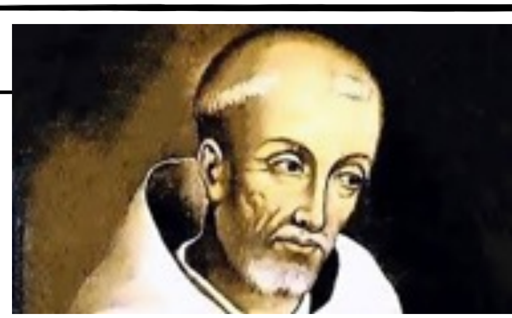
it is plausible that New Forces are present

ANALOGY VS MINIMALITY



ANALOGY

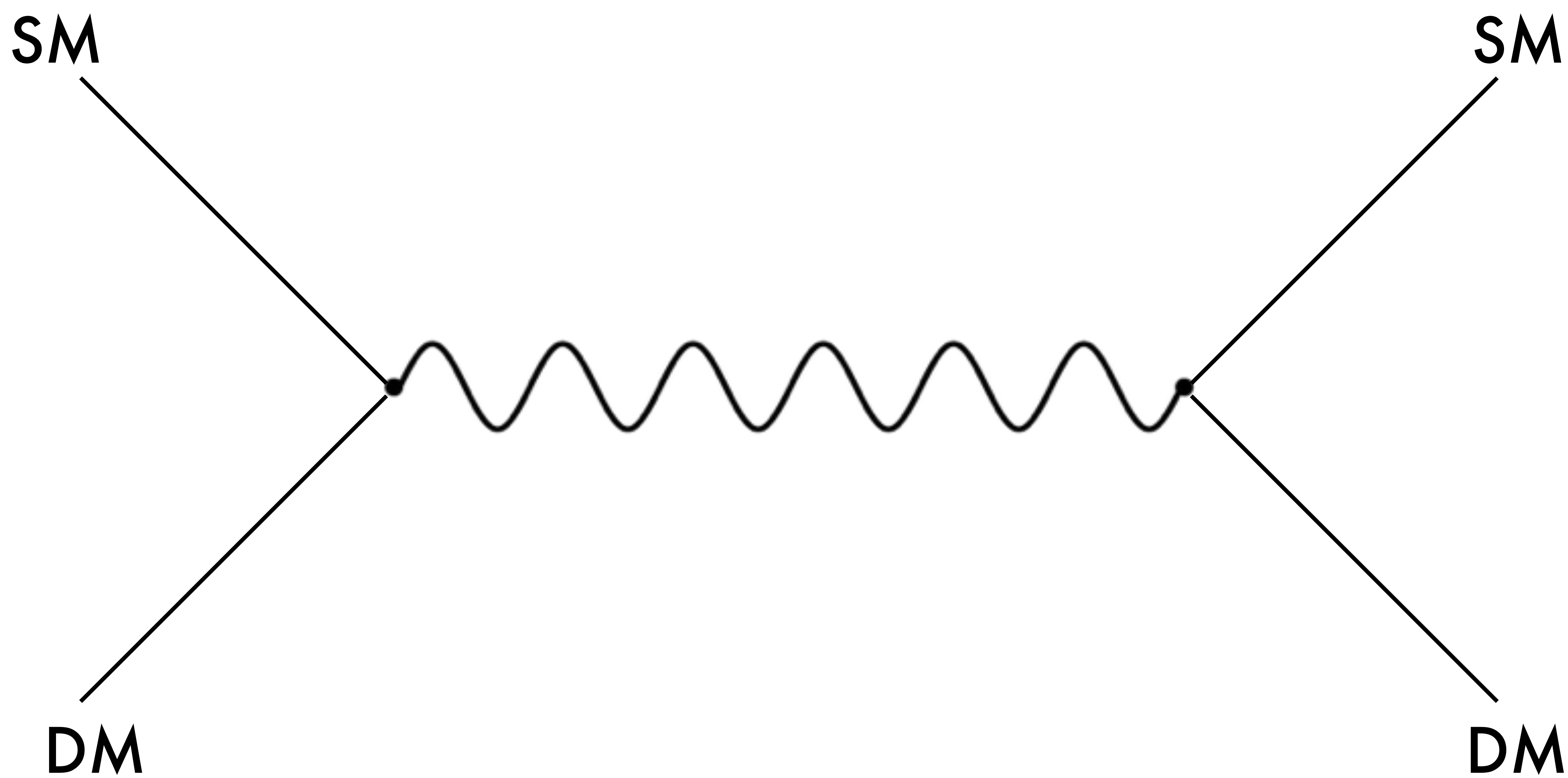
it is plausible that
New Forces
are present



MINIMALITY disfavours a New Force

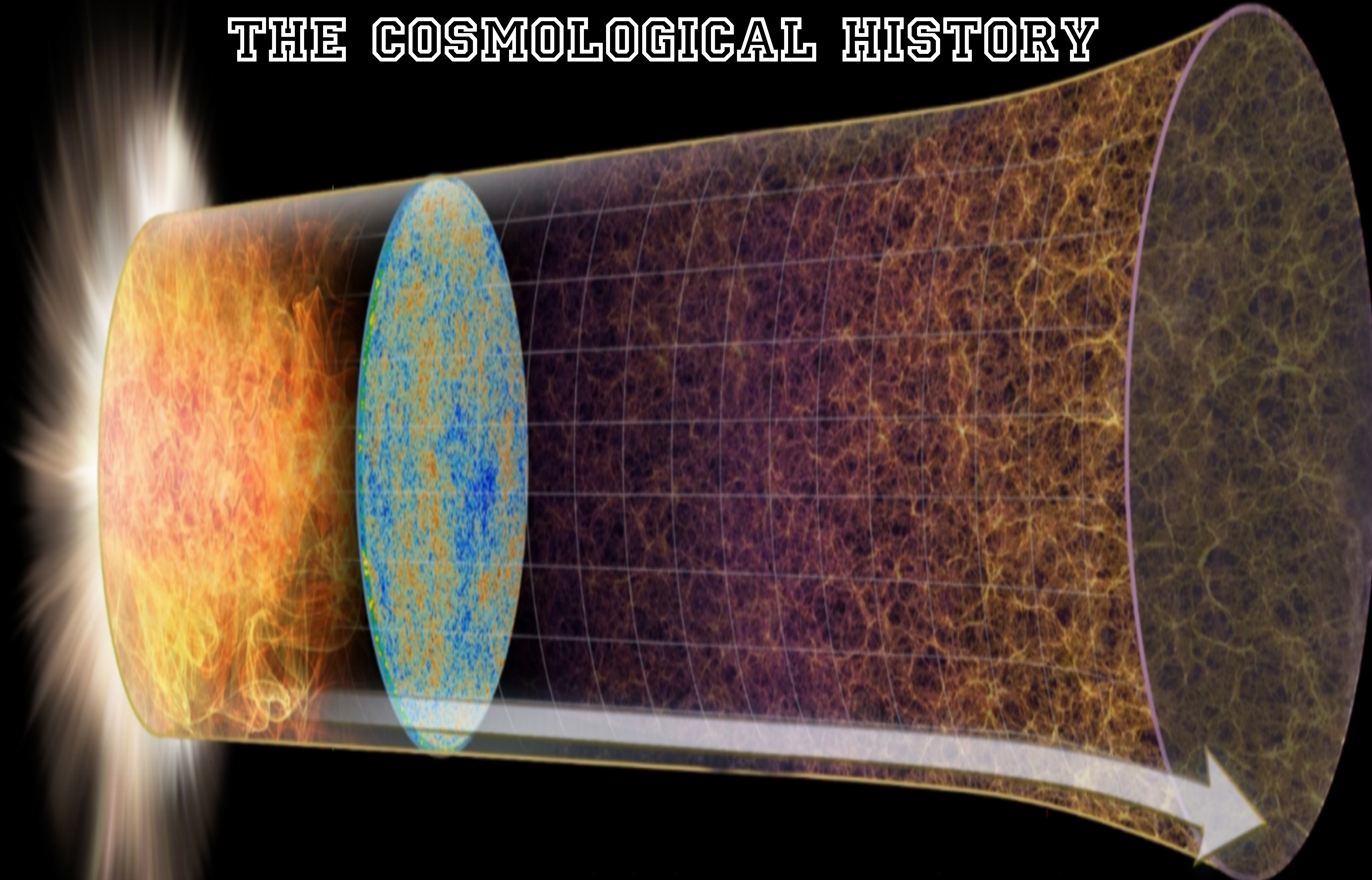
HOW TO PROBE NEW FORCES?

*one way out of many...



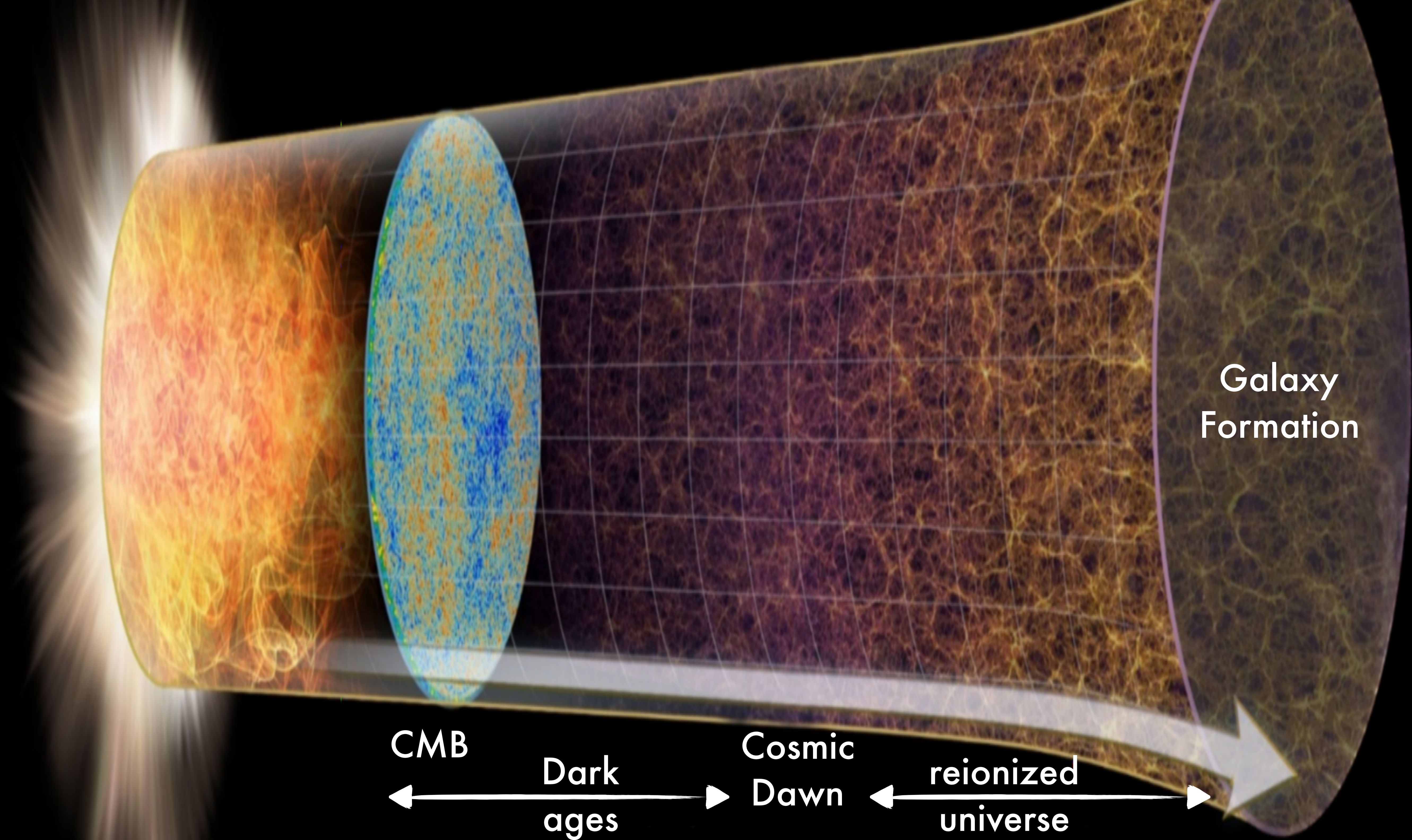
A new force induces a
new scattering of Dark Matter with baryons*

THE COSMOLOGICAL HISTORY



AS DARK MATTER DETECTOR

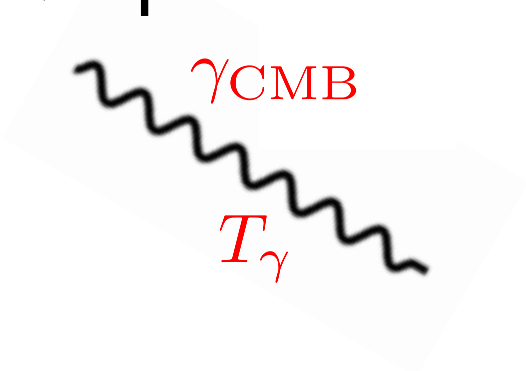
THE COSMOLOGICAL HISTORY

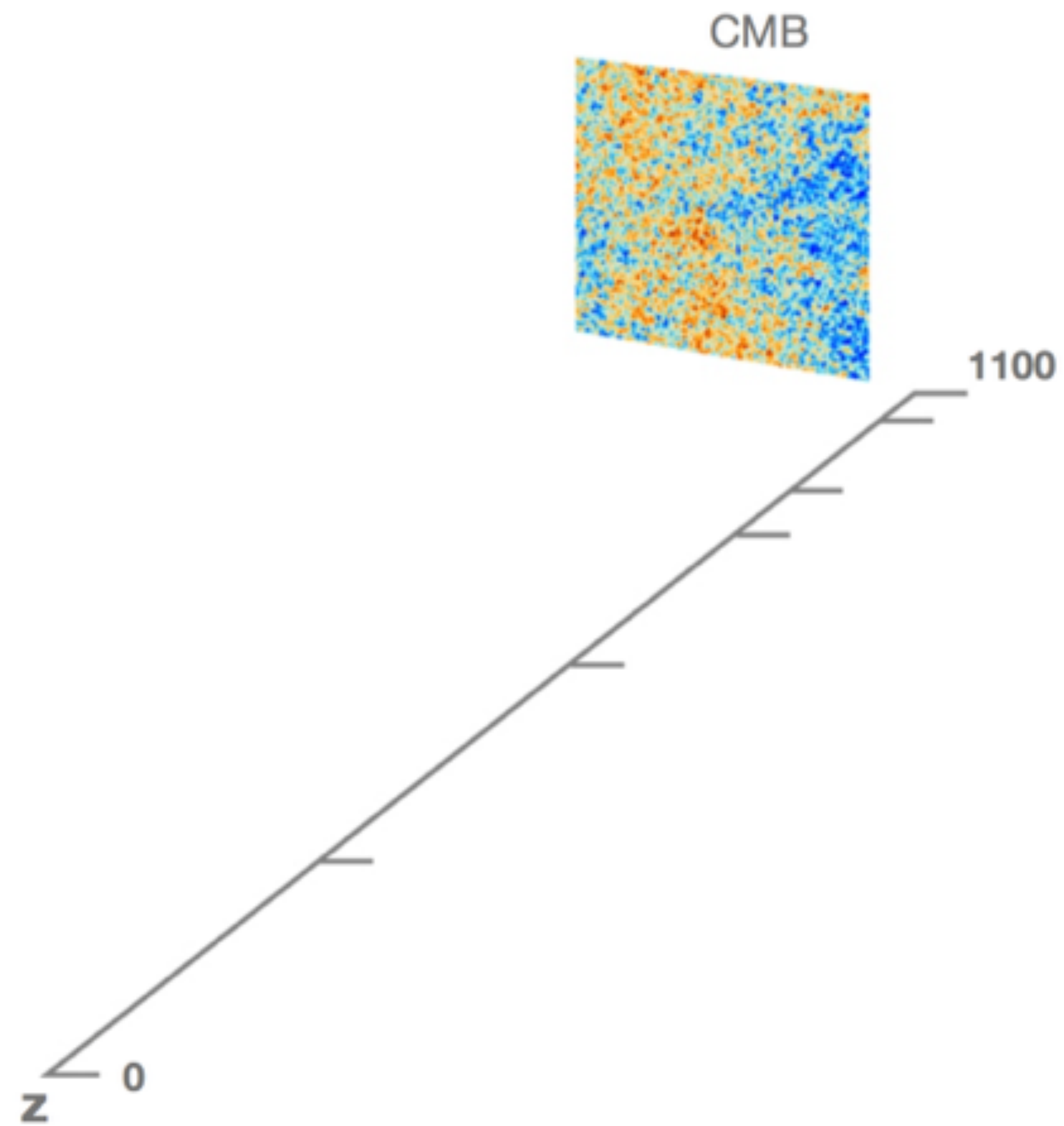


AS DARK MATTER DETECTOR

21 CM COSMOLOGY PRIMER

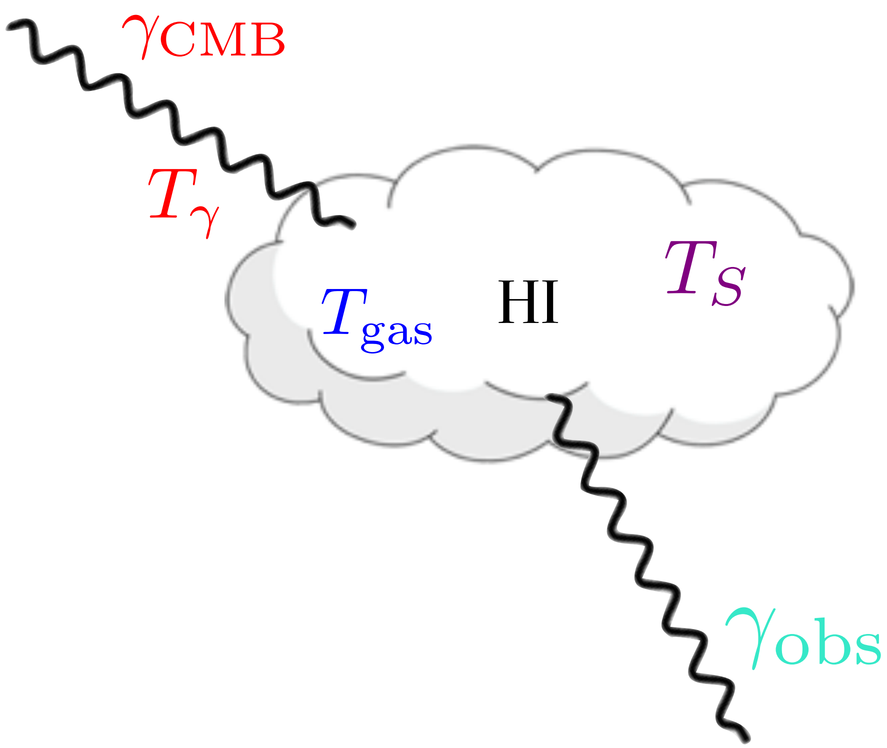
CMB photons

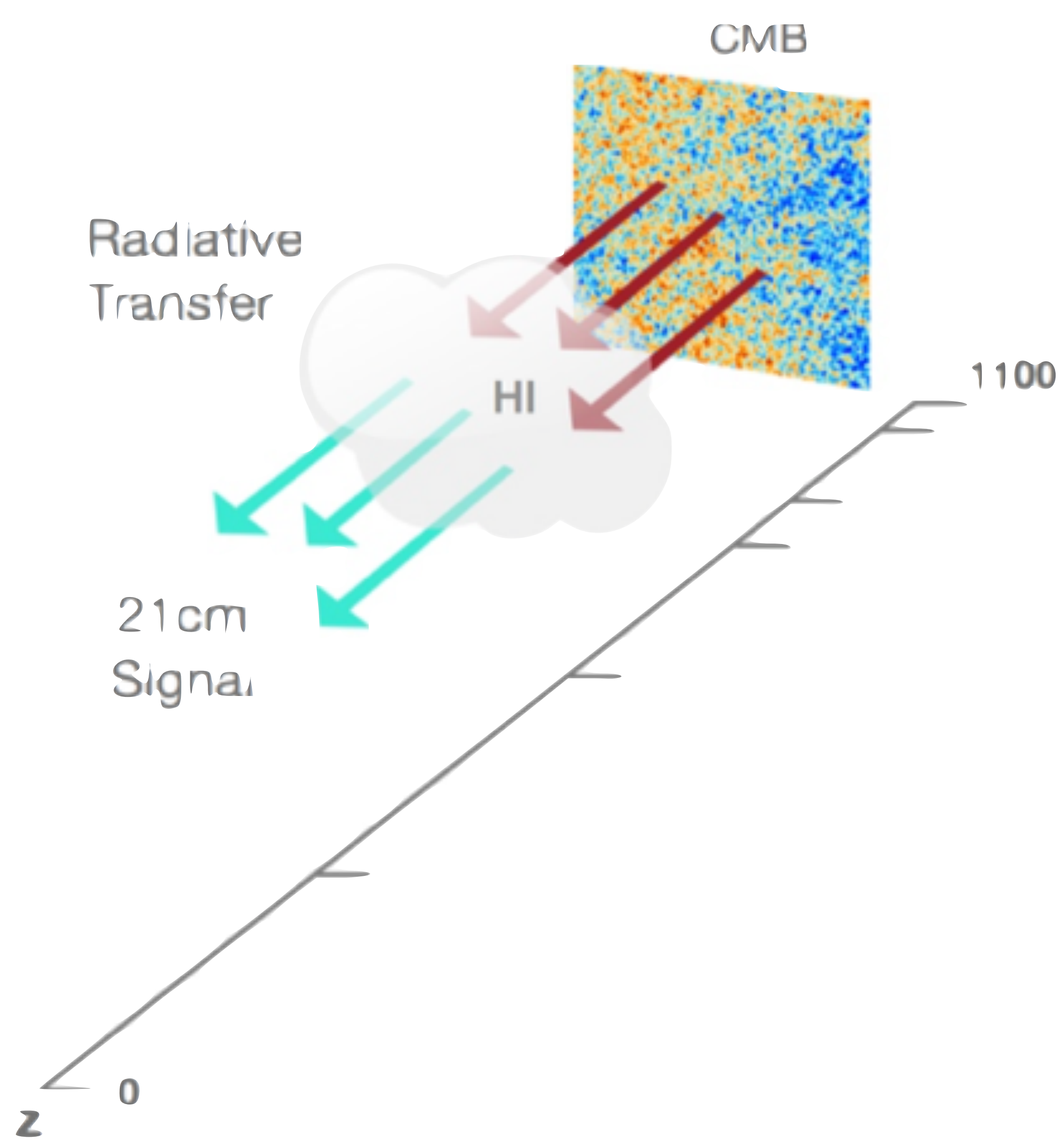




21 CM COSMOLOGY PRIMER

CMB photons





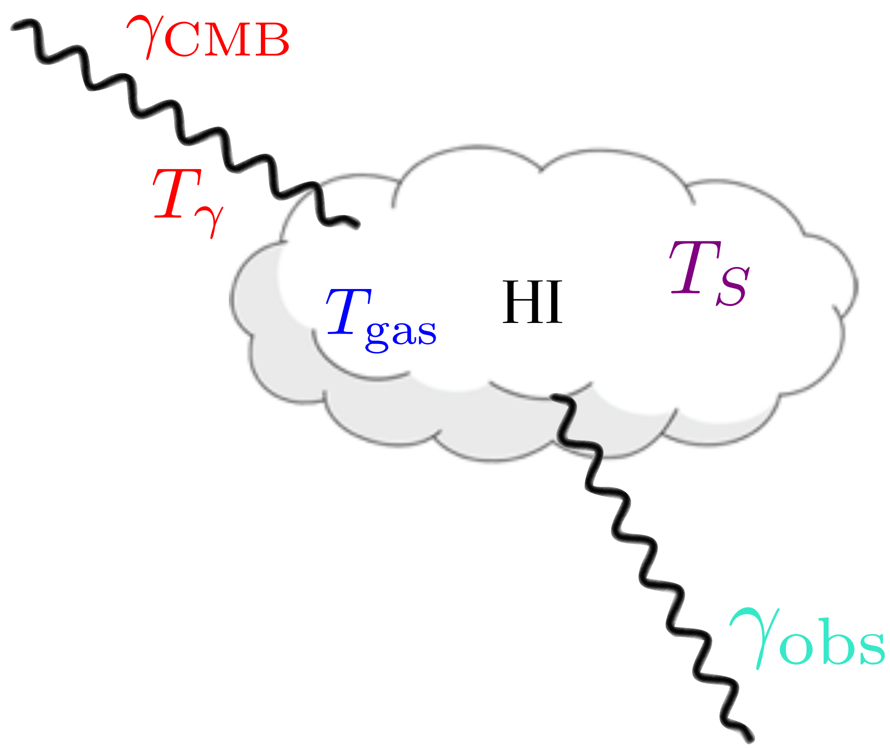
The HI is described by 2 temperatures

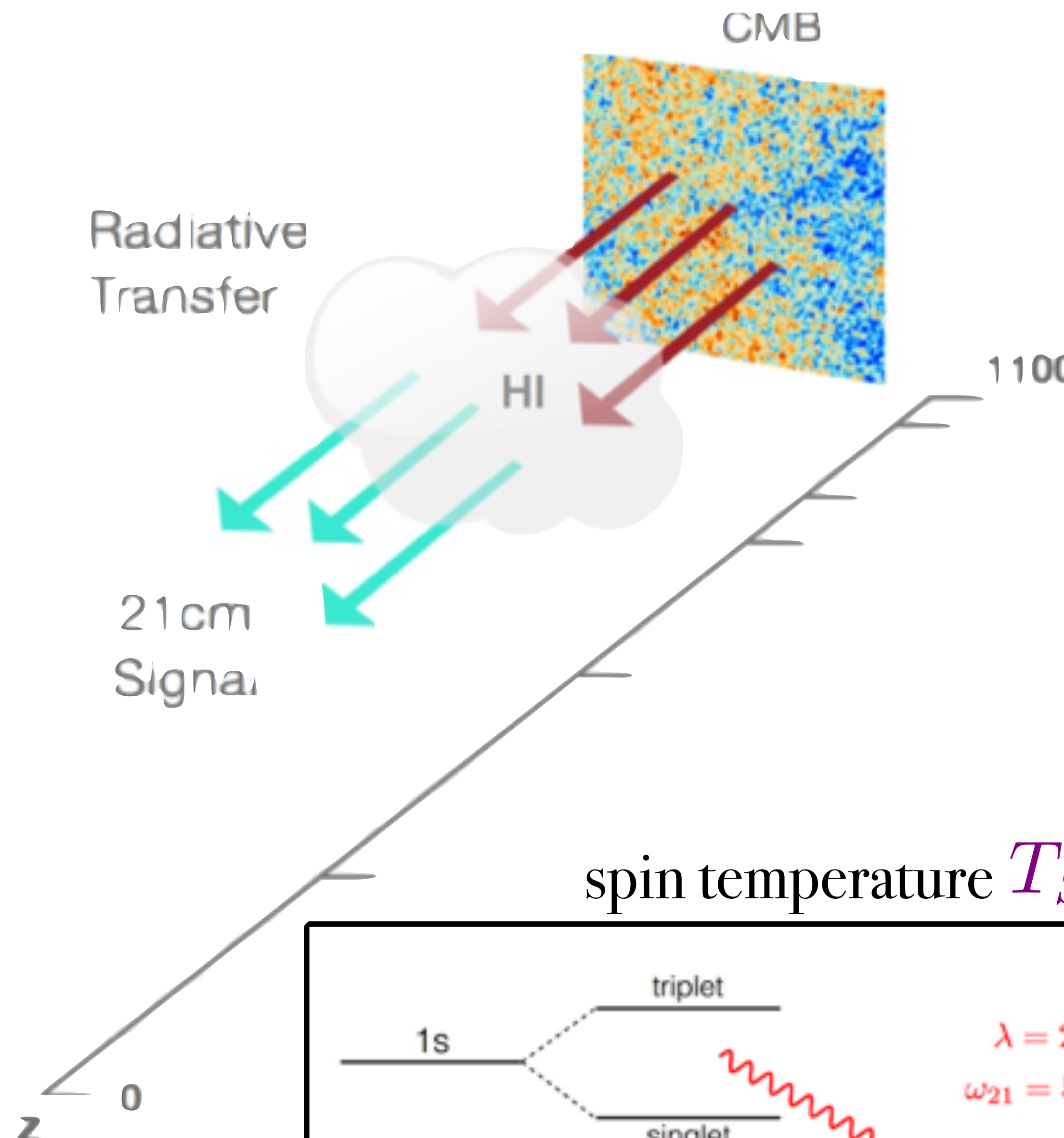
T_S ratio of number densities

$T_{\rm gas}$ is just the kinetic energy of the gas

21 CM COSMOLOGY PRIMER

CMB photons





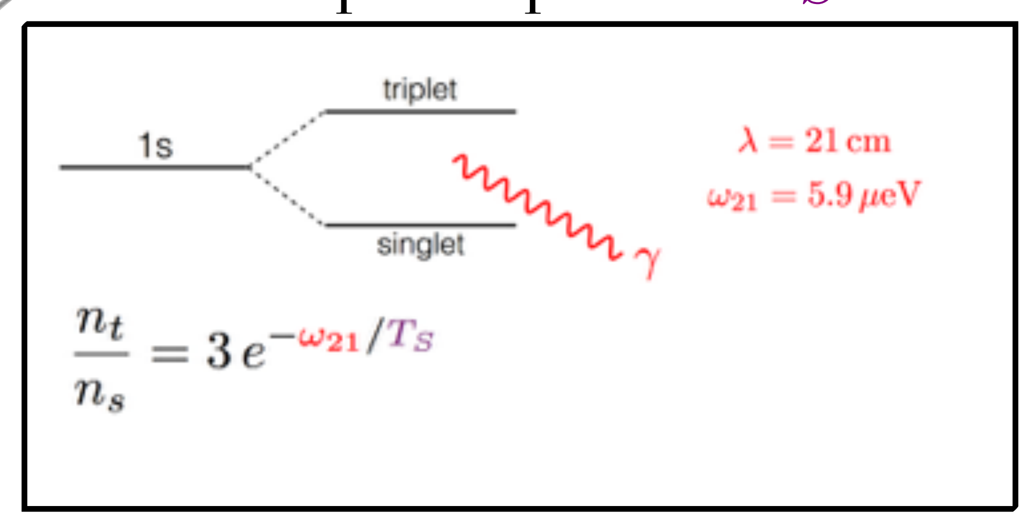
The HI is described by 2 temperatures

T_S ratio of number densities

T_{gas} is just the kinetic energy of the gas

T_{21} is what we see after CMB is subtracted

spin temperature T_S

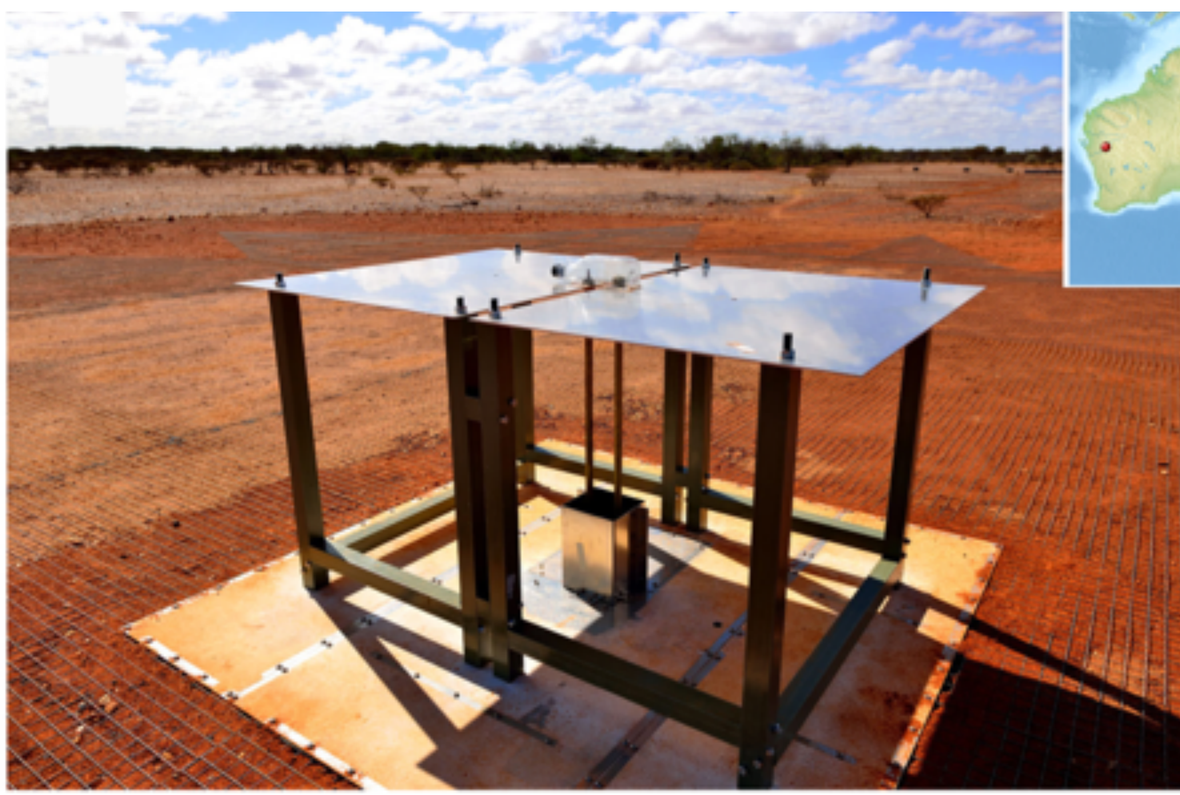


THE FIRST MEASUREMENT ?

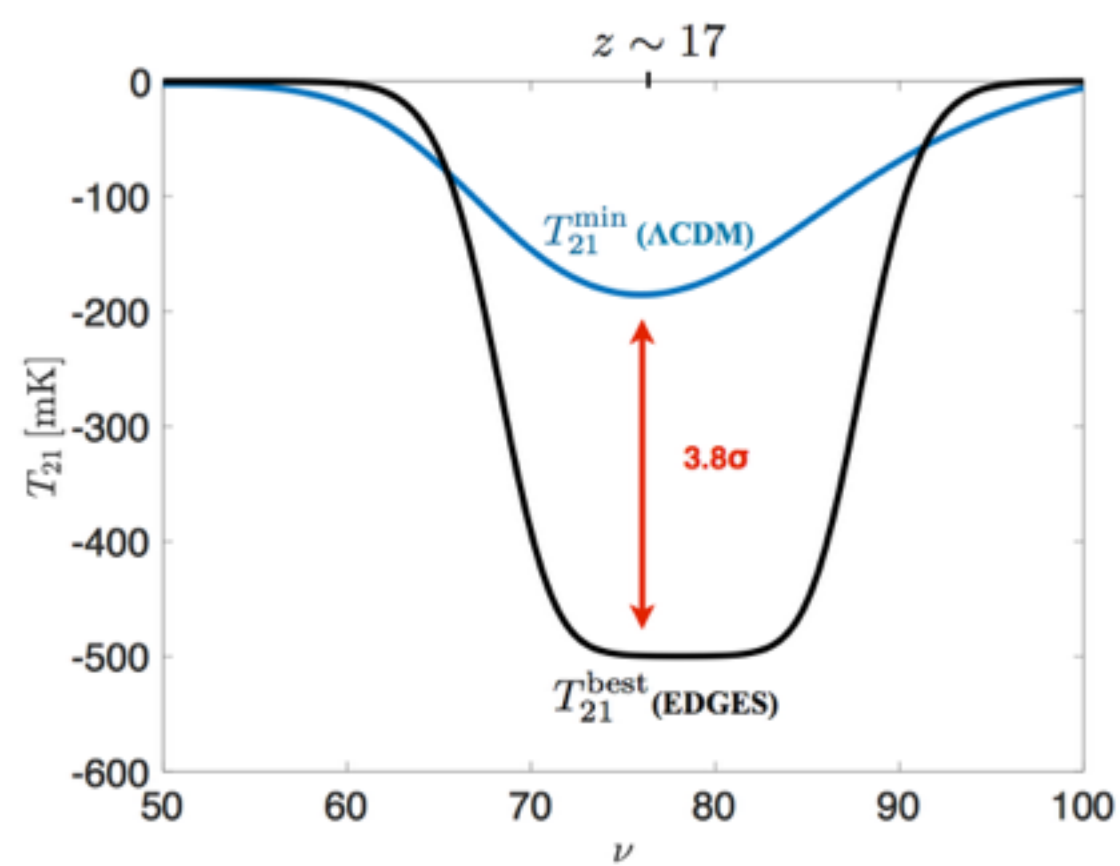
The observed temperature COLDER than the COLDEST prediction from DM + GRAVITY only

EDGES

Experiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature



$$T_{21} = \frac{1}{1+z}\left(T_S - T_{\rm CMB}\right)\left(1 - e^{-\tau}\right)$$



A NEW FORCE TO EXPLAIN EDGES

$\star\, T_S \sim T_{\rm gas}$

$$T_{21} = \frac{1}{1+z}\left(T_S^{\star} - T_{\rm CMB}\right)\left(1 - e^{-\tau}\right)$$

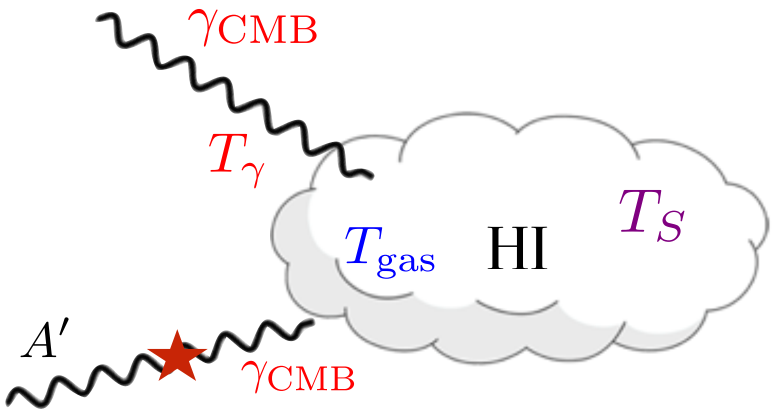
A NEW FORCE TO EXPLAIN EDGES

$\star\, T_S \sim T_{\rm gas}$

$$T_{21} = \frac{1}{1+z}\left(T_S^{\star} - \boxed{T_{\rm CMB}}\right)\left(1 - e^{-\tau}\right)$$

- Modifying the R.J. tail of the CMB

  M. Pospelov,J. Pradler,J. Ruderman,A. Urbano (2018)



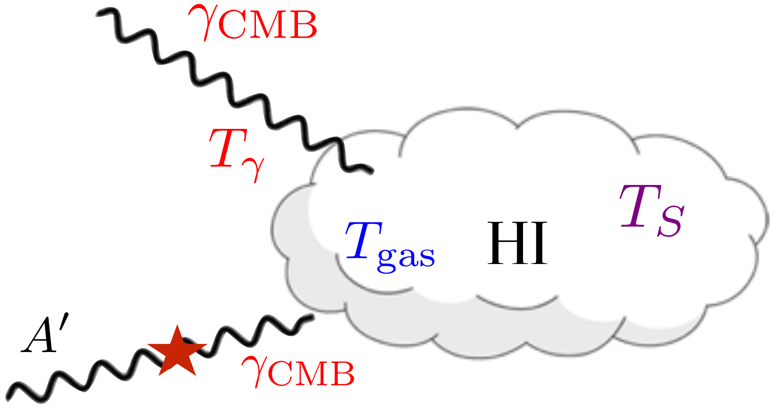
A NEW FORCE TO EXPLAIN EDGES

$$T_{21} = \frac{1}{1+z}\left(T_S^{*} - T_{\rm CMB}\right)\left(1 - e^{-\tau}\right)$$

$\star\, T_S \sim T_{\rm gas}$

- Modifying the R.J. tail of the CMB

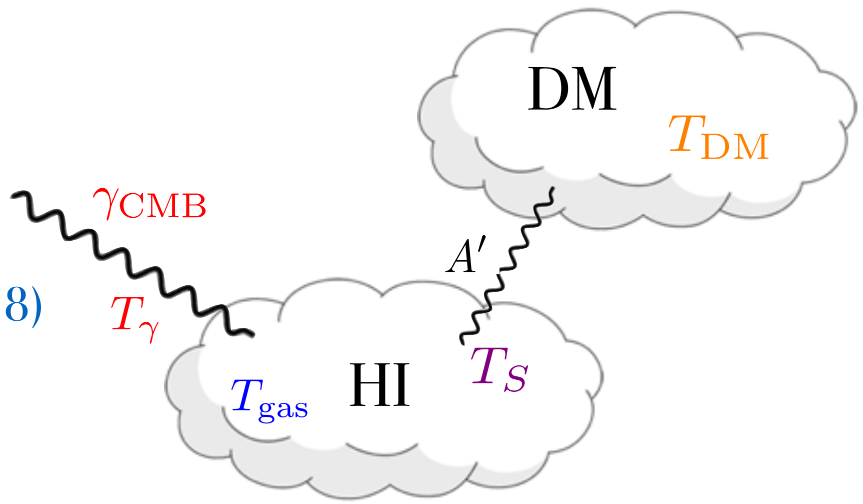
M. Pospelov,J. Pradler,J. Ruderman,A. Urbano (2018)



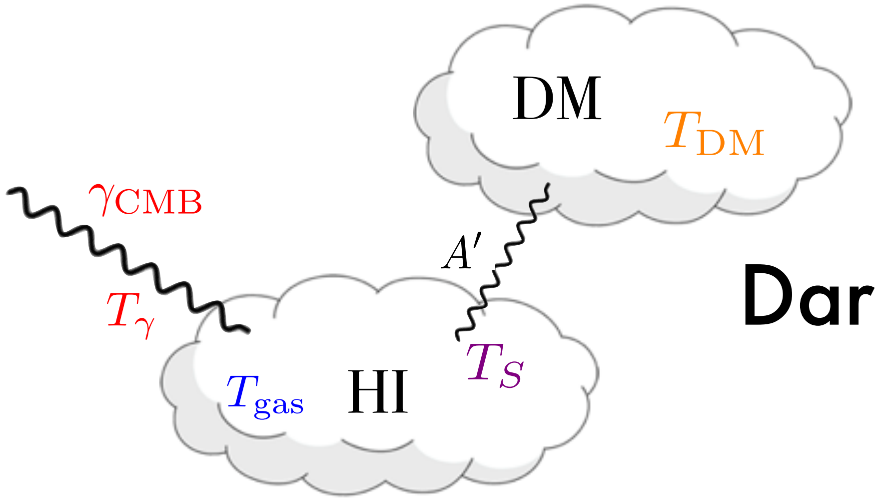
- Cooling the gas with Dark Matter scattering

Kadota,Silk,Tashiro, (2014) Ali-Haimoud,Kovetz,Munoz (2015)

Barkana (2018); Loeb,Munoz (2018) Berlin,Hooper,Krnjaic,McDermott (2018)
Barkana,Outmezguine,**D.R.** ,Volanksy, (2018) Liu,Slatyer, (2018)……



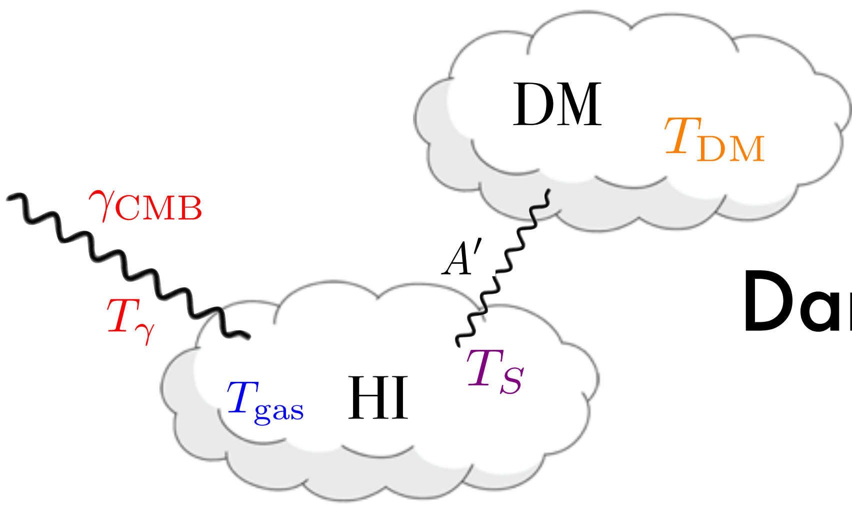
A NEW FORCE TO EXPLAIN EDGES



$$T_{\rm DM} \ll T_{\rm gas}$$

Dark Cooling induced by new forces between Dark Matter and baryons

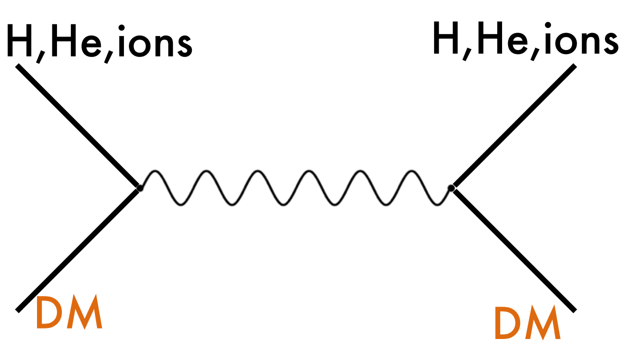
A NEW FORCE TO EXPLAIN EDGES



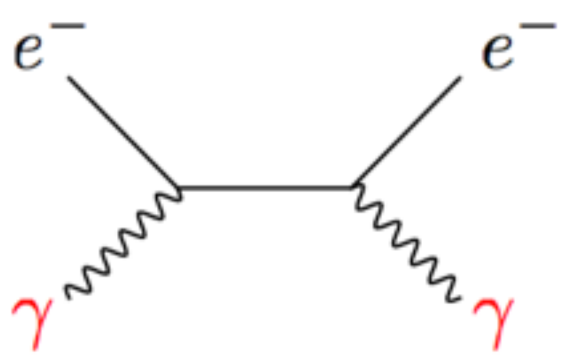
$$T_{\rm DM} \ll T_{\rm gas}$$

Dark Cooling induced by new forces between Dark Matter and baryons

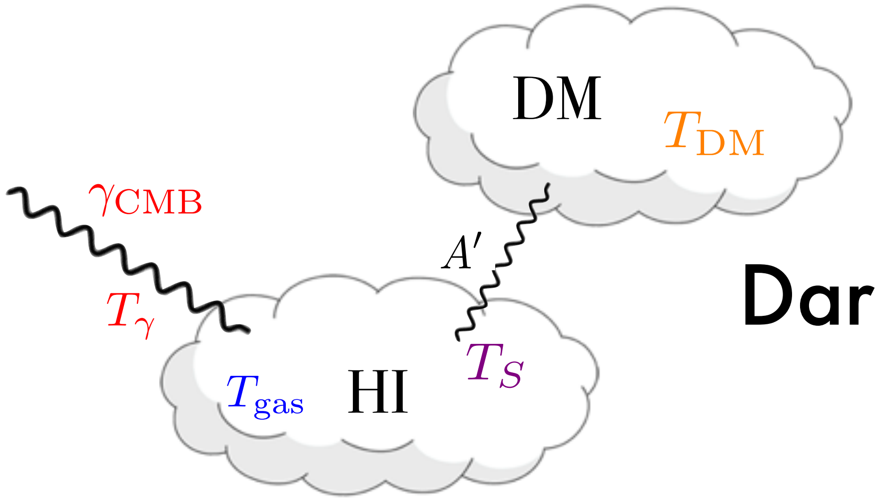
- DM cooling rate vs Compton rate → large cross section



vs



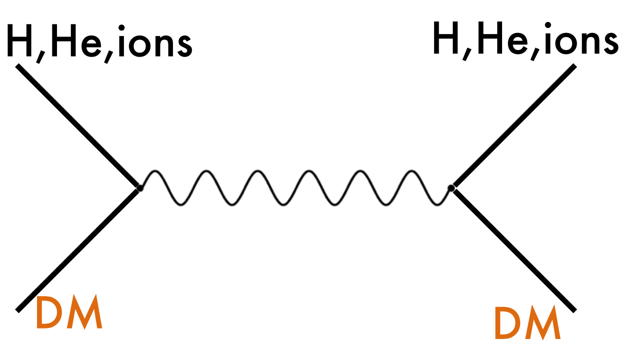
A NEW FORCE TO EXPLAIN EDGES



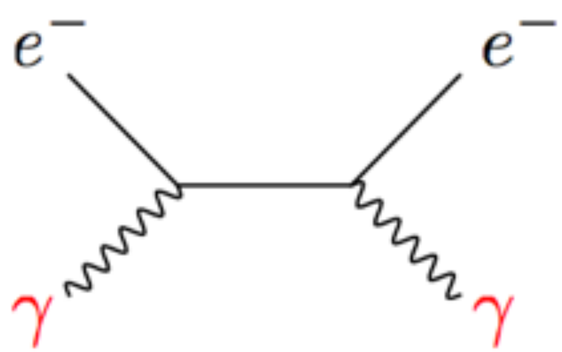
$$T_{\rm DM} \ll T_{\rm gas}$$

Dark Cooling induced by new forces between Dark Matter and baryons

- DM cooling rate vs Compton rate ⟶ large cross section



vs



- cooling needs to overcome heating ⟶ DM lighter than HI

LONG RANGE FORCE TO EXPLAIN EDGES

DM cooling rate needs to overcome Compton rate

LONG RANGE FORCE TO EXPLAIN EDGES

DM cooling rate needs to overcome Compton rate

↓

cross section excluded by CMB unless $\sigma_{\text{cosmic-dawn}} \gg \sigma_{\text{CMB}}$

LONG RANGE FORCE TO EXPLAIN EDGES

DM cooling rate needs to overcome Compton rate

↓

cross section excluded by CMB unless $\sigma_{\text{cosmic-dawn}} \gg \sigma_{\text{CMB}}$

↓

$$v_{\text{rel}}\big|_{\text{cosmic-dawn}} \ll v_{\text{rel}}\big|_{\text{CMB}} \longleftrightarrow \sigma_{\chi I} \sim v_{\text{rel}}^{-4}\hat{\sigma}_{\chi I}$$

LONG RANGE FORCE TO EXPLAIN EDGES

DM cooling rate needs to overcome Compton rate

↓

cross section excluded by CMB unless $\sigma_{\text{cosmic-dawn}} \gg \sigma_{\text{CMB}}$

↓

$v_{\text{rel}}\big|_{\text{cosmic-dawn}} \ll v_{\text{rel}}\big|_{\text{CMB}}$ ⟷ $\sigma_{\chi I} \sim v_{\text{rel}}^{-4} \hat{\sigma}_{\chi I}$

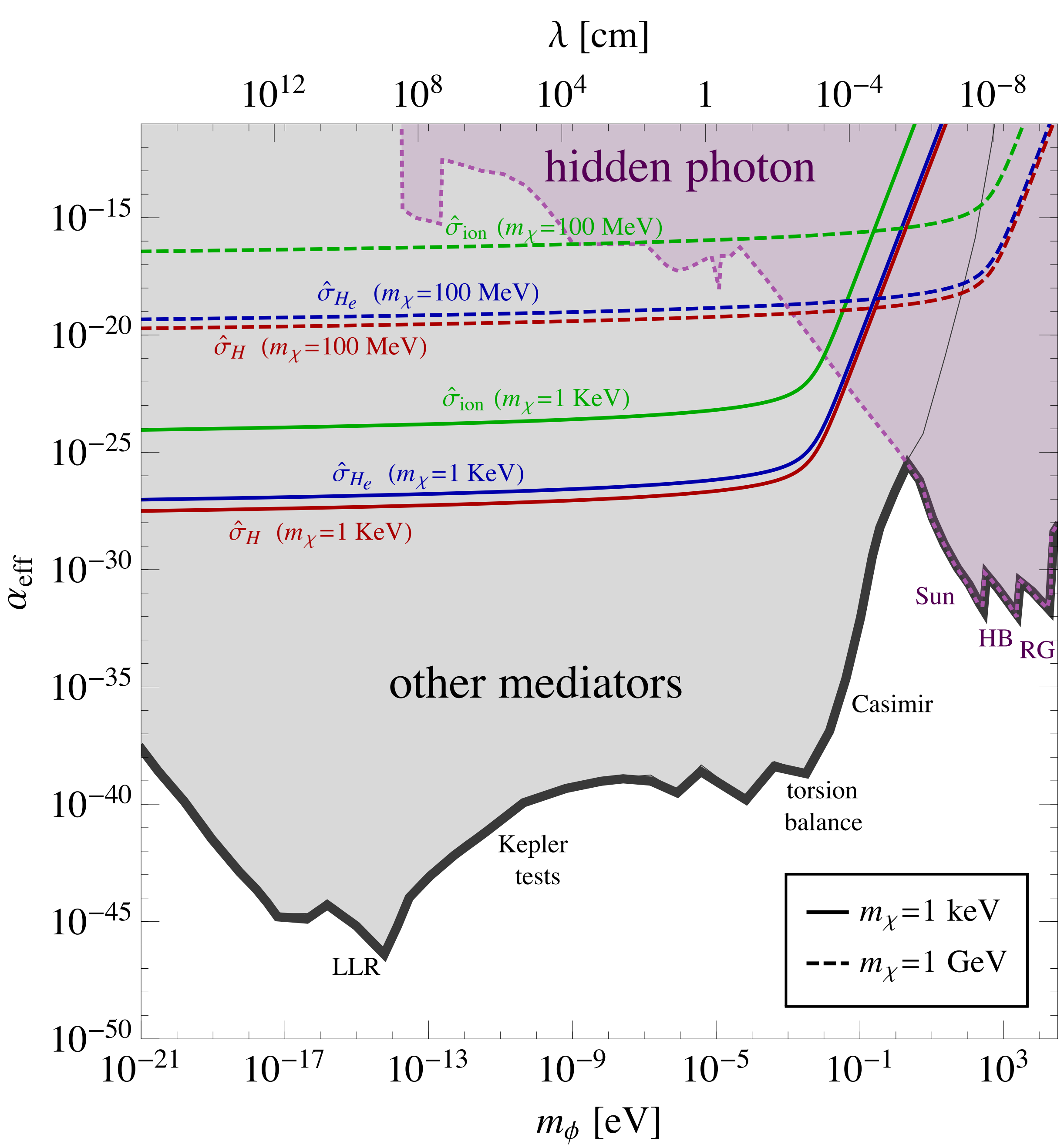
↓

light mediator: $m_X \lesssim \mu_I v_{\text{rel}} \simeq 1 \text{ KeV} \cdot \frac{\mu_I}{\text{GeV}}$

DM lighter than HI

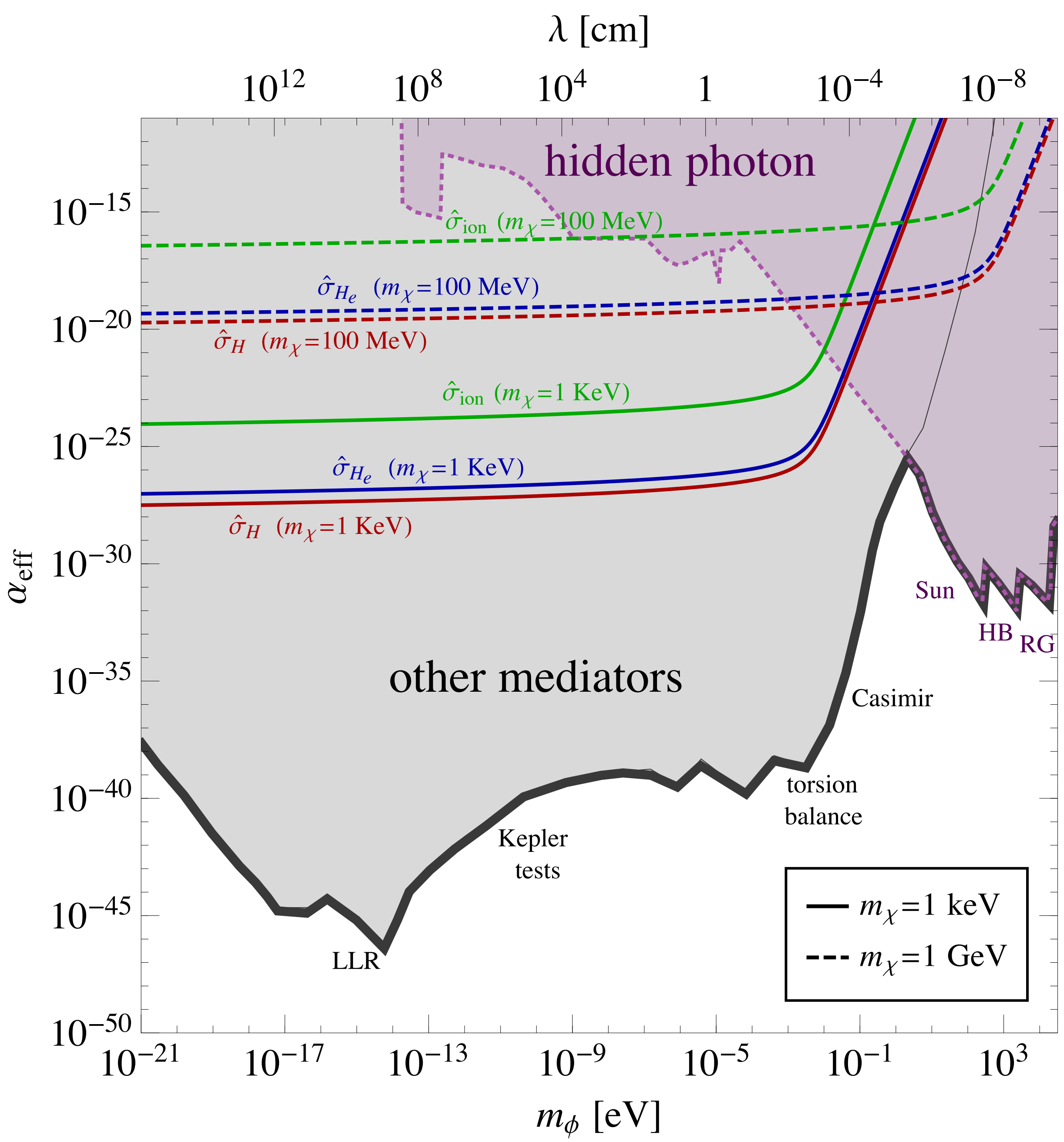
TYPE OF FORCES ALLOWED

Long range interactions with hydrogen or helium are excluded!



TYPE OF FORCES ALLOWED

Long range interactions with hydrogen or helium are excluded!



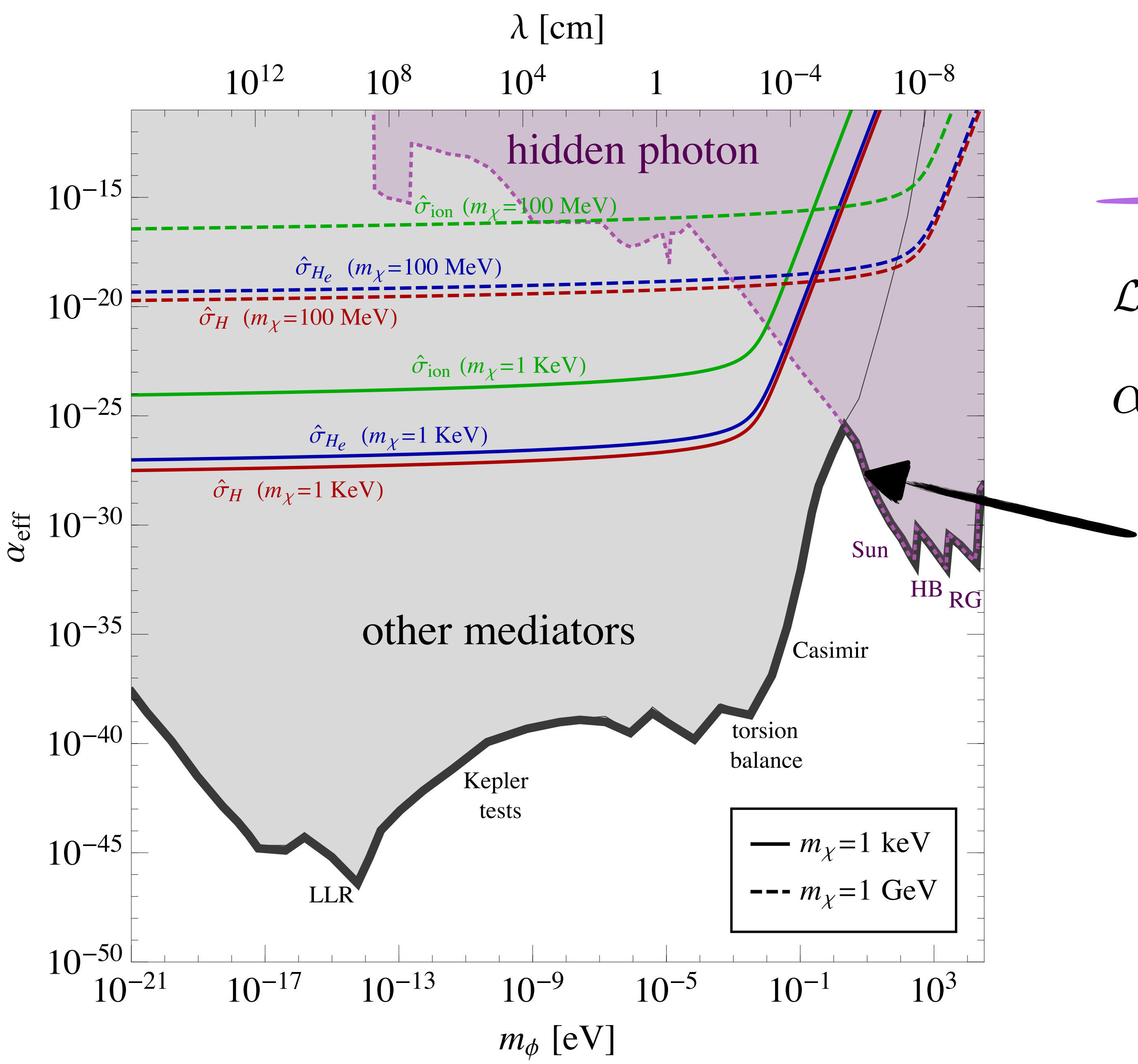
The (dark photon) is special

$$\mathcal{L} = \frac{1}{4}F'_{\alpha\beta}F'^{\,\alpha\beta} + \frac{m^2_{A'}}{2}A'_\alpha A'^\alpha + \frac{\epsilon}{2}F_{\alpha\beta}F'^{\,\alpha\beta}$$

$$\alpha_{\rm eff} = \epsilon^2\alpha_{\rm em}$$

TYPE OF FORCES ALLOWED

Long range interactions with hydrogen or helium are excluded!



The (dark photon) is special

$$\mathcal{L} = \frac{1}{4}F'_{\alpha\beta}F'^{\,\alpha\beta} + \frac{m_{A'}^2}{2}A'_\alpha A'^\alpha + \frac{\epsilon}{2}F_{\alpha\beta}F'^{\,\alpha\beta}$$

$$\alpha_{\text{eff}} = \epsilon^2\alpha_{\text{em}}$$

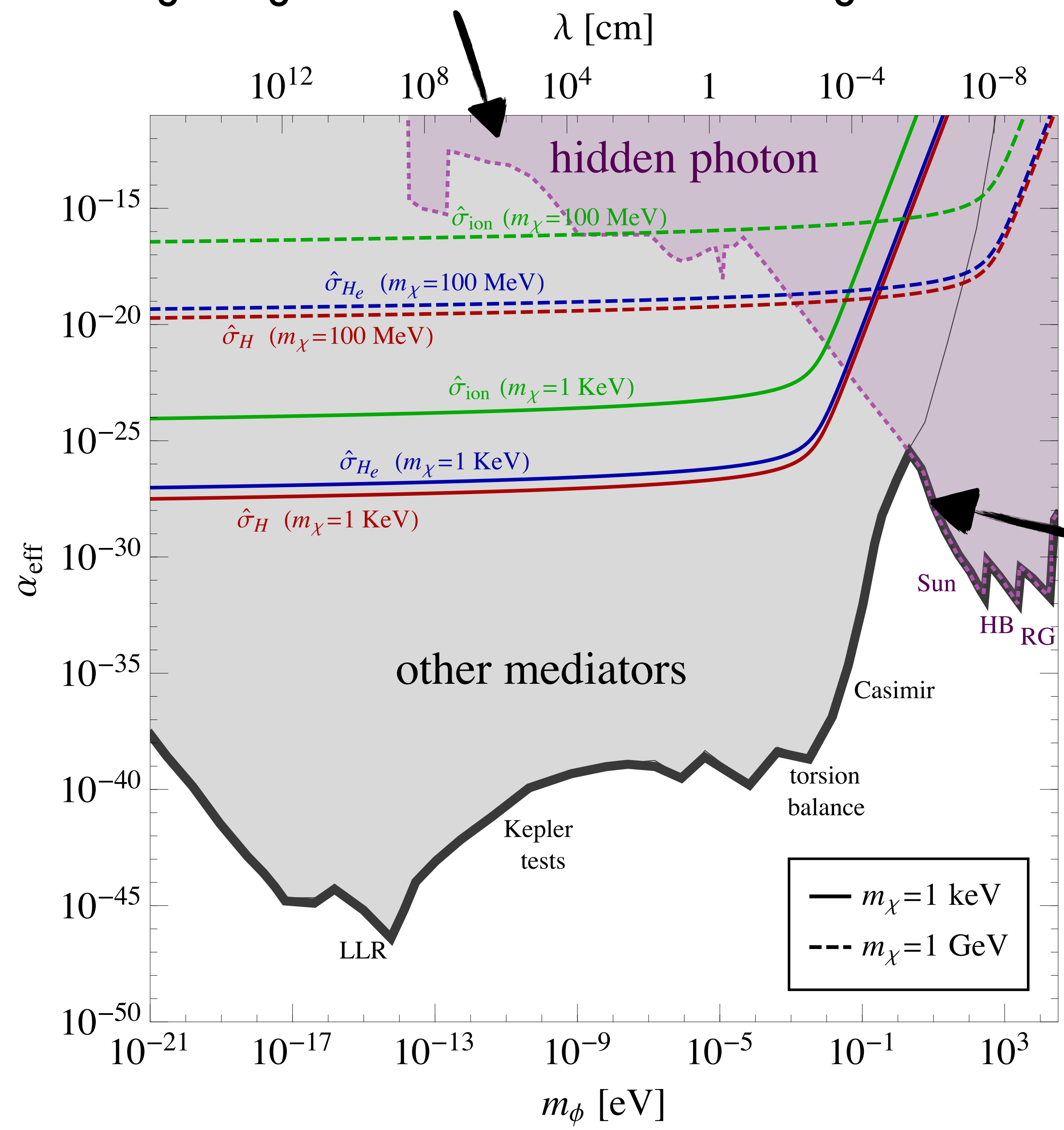
on-shell production of dark photon is suppressed

$$\sim \frac{m_{A'}^2}{T_{\text{star}}^2}$$

TYPE OF FORCES ALLOWED

Long range interactions with hydrogen or helium are excluded!

for range larger than the Earth radius charge is screened



The (dark photon) is special

$$\mathcal{L} = \frac{1}{4} F'_{\alpha\beta} F'^{\,\alpha\beta} + \frac{m_{A'}^2}{2} A'_\alpha A'^{\alpha} + \frac{\epsilon}{2} F_{\alpha\beta} F'^{\,\alpha\beta}$$

$$\alpha_{\text{eff}} = \epsilon^2 \alpha_{\text{em}}$$

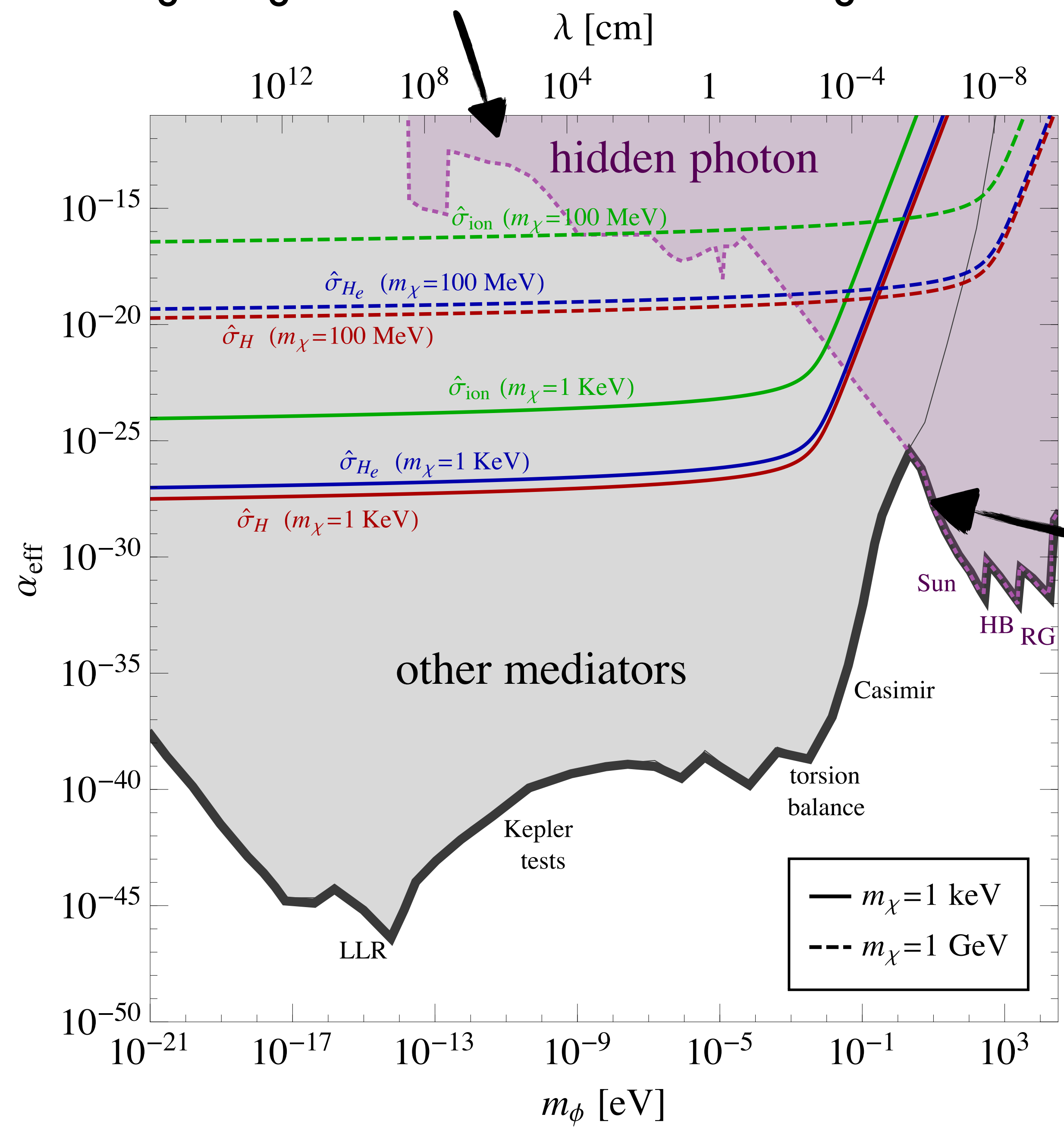
on-shell production of dark photon is suppressed

$$\sim \frac{m_{A'}^2}{T_{\text{star}}^2}$$

TYPE OF FORCES ALLOWED

Long range interactions with hydrogen or helium are excluded!

for range larger than the Earth radius charge is screened



The (dark photon) is special

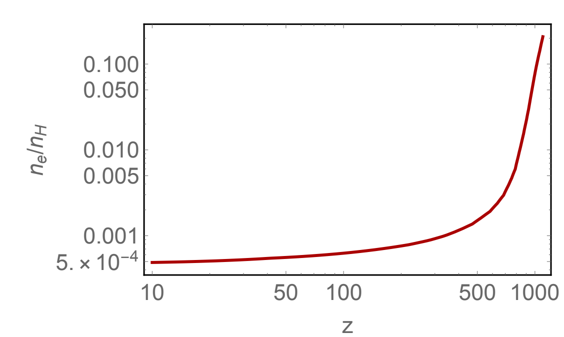
$$\mathcal{L} = \frac{1}{4} F'_{\alpha\beta} F'^{\,\alpha\beta} + \frac{m_{A'}^2}{2} A'_\alpha A'^{\alpha} + \frac{\epsilon}{2} F_{\alpha\beta} F'^{\,\alpha\beta}$$

$$\alpha_{\rm eff} = \epsilon^2 \alpha_{\rm em}$$

on-shell production of dark photon is suppressed

$$\sim \frac{m_{A'}^2}{T_{\rm star}^2}$$

$1/v^4$ with the ionized fraction only



MILLICHARGE DARK MATTER

As far as DM-baryon scattering is concerned
we can directly couple the DM to the photon by giving it a small EM charge

$$\mathcal{L} = Qe\gamma_\alpha J^\alpha_{DM}$$

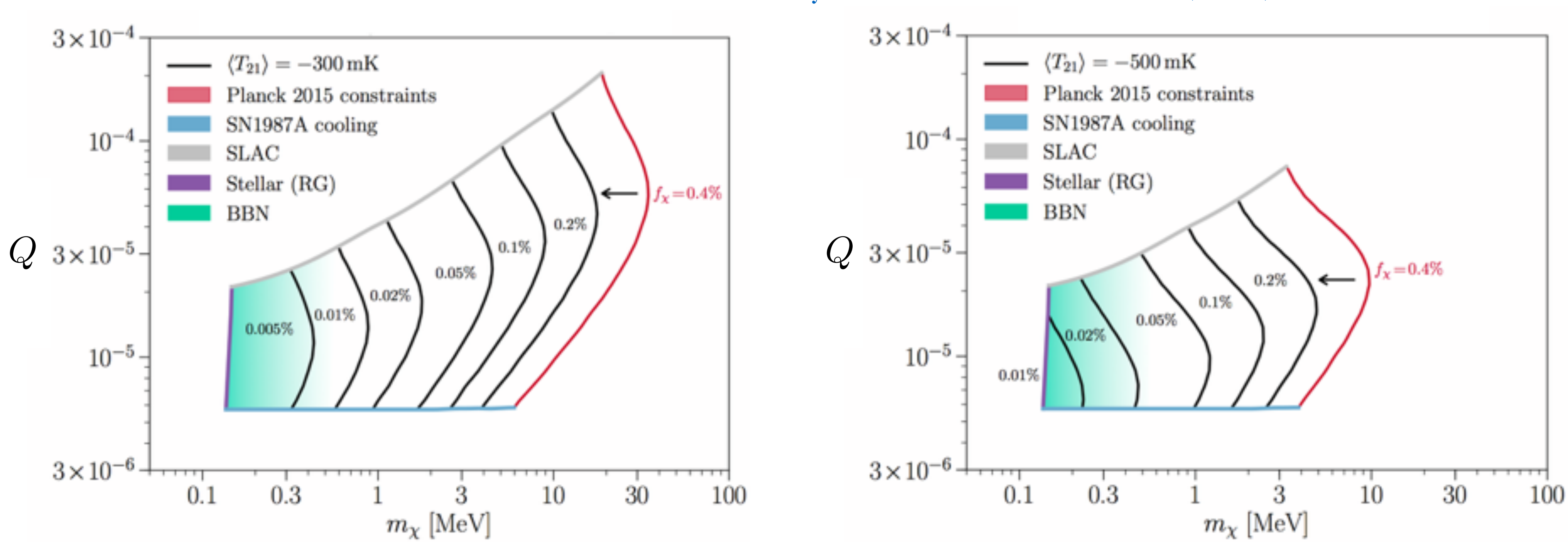
MILLICHARGE DARK MATTER

As far as DM-baryon scattering is concerned
we can directly couple the DM to the photon by giving it a small EM charge

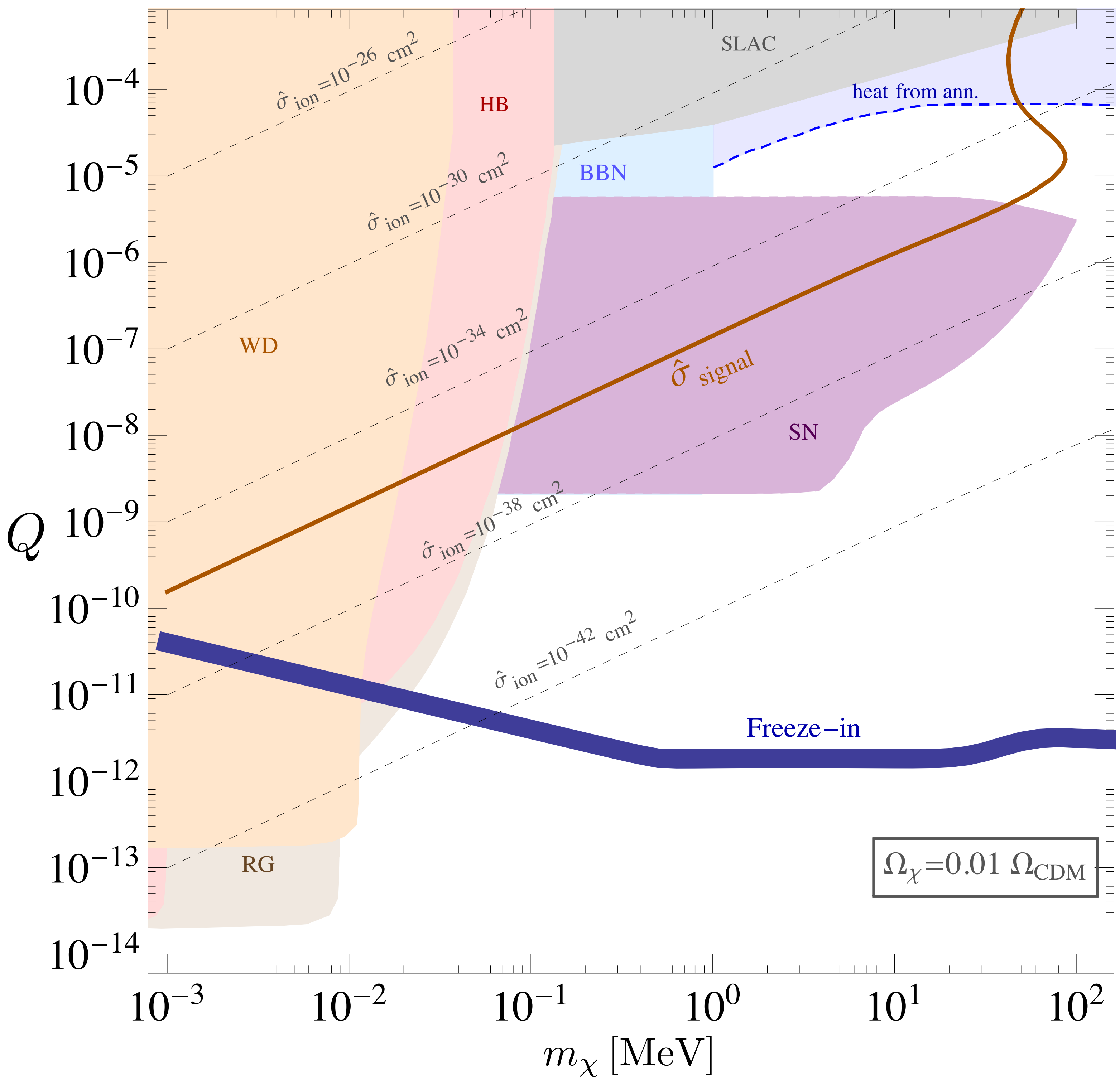
$$\mathcal{L} = Qe\gamma_\alpha J^\alpha_{DM}$$

A fraction of "millicharge" DM is a viable explanation for EDGES

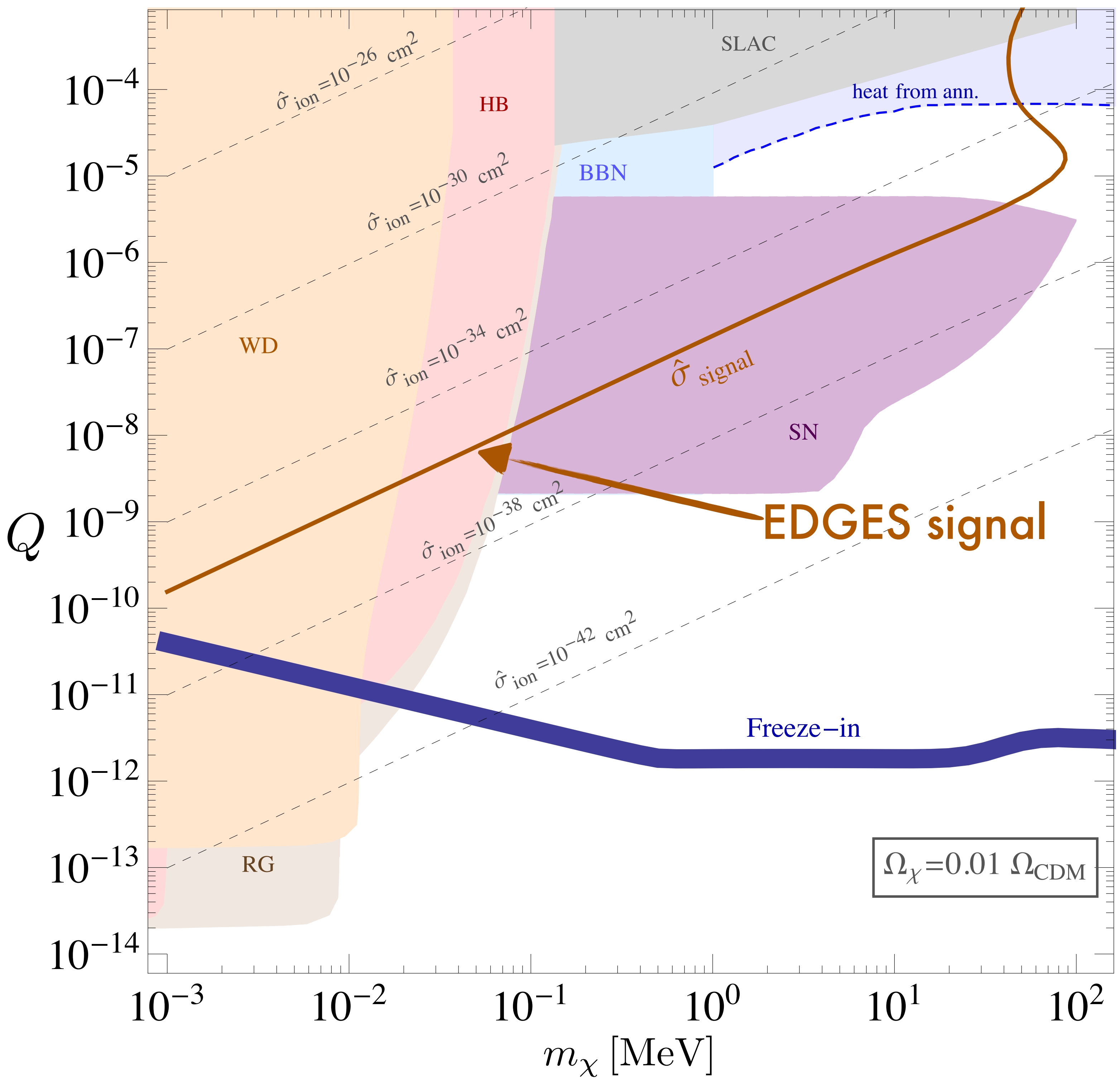
Kovetz, Poulin, Gluscevic, Boddy, Barkana and Kamionkowski (2018)



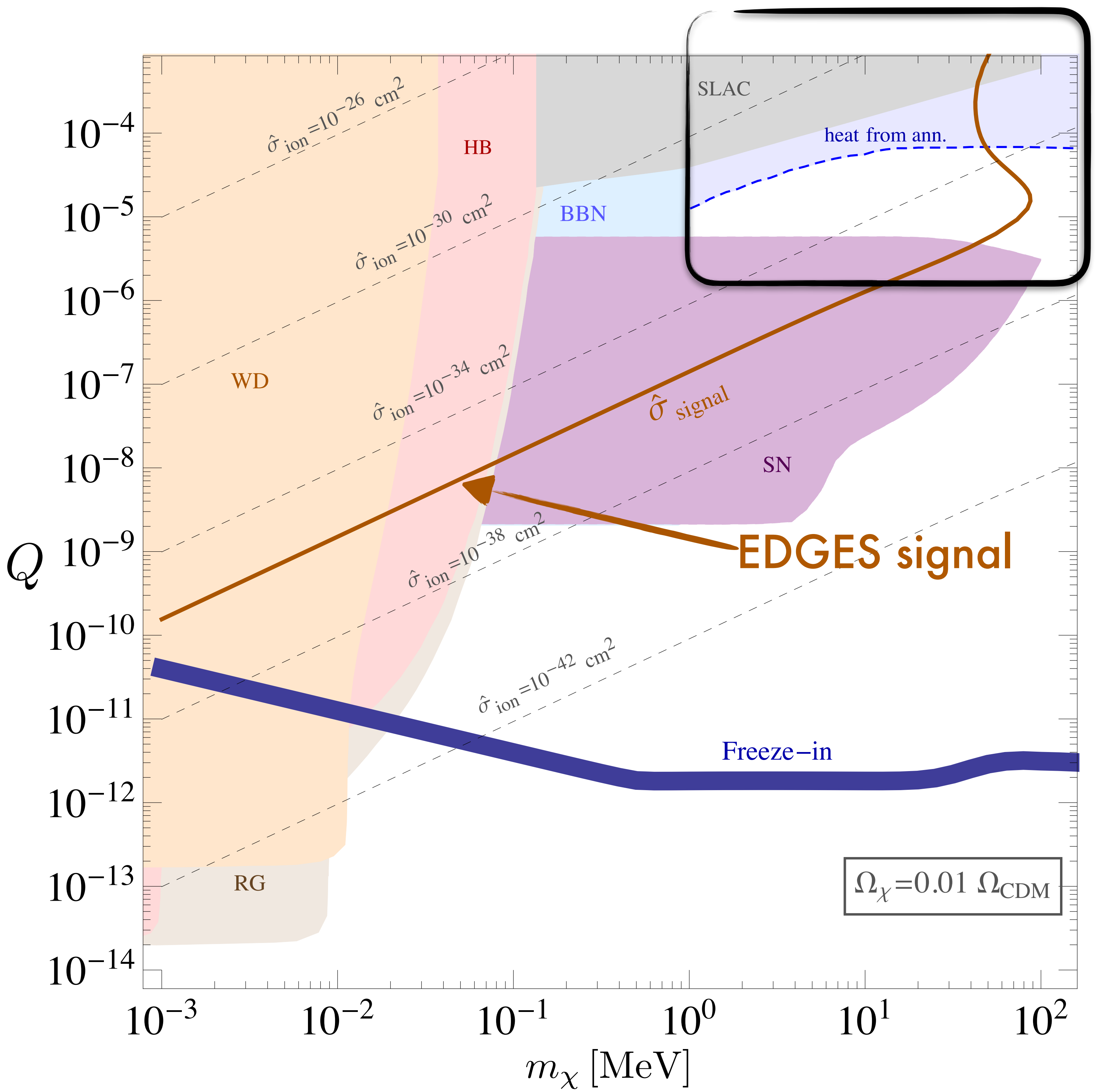
EDGES VS DIRECT DETECTION



EDGES VS DIRECT DETECTION

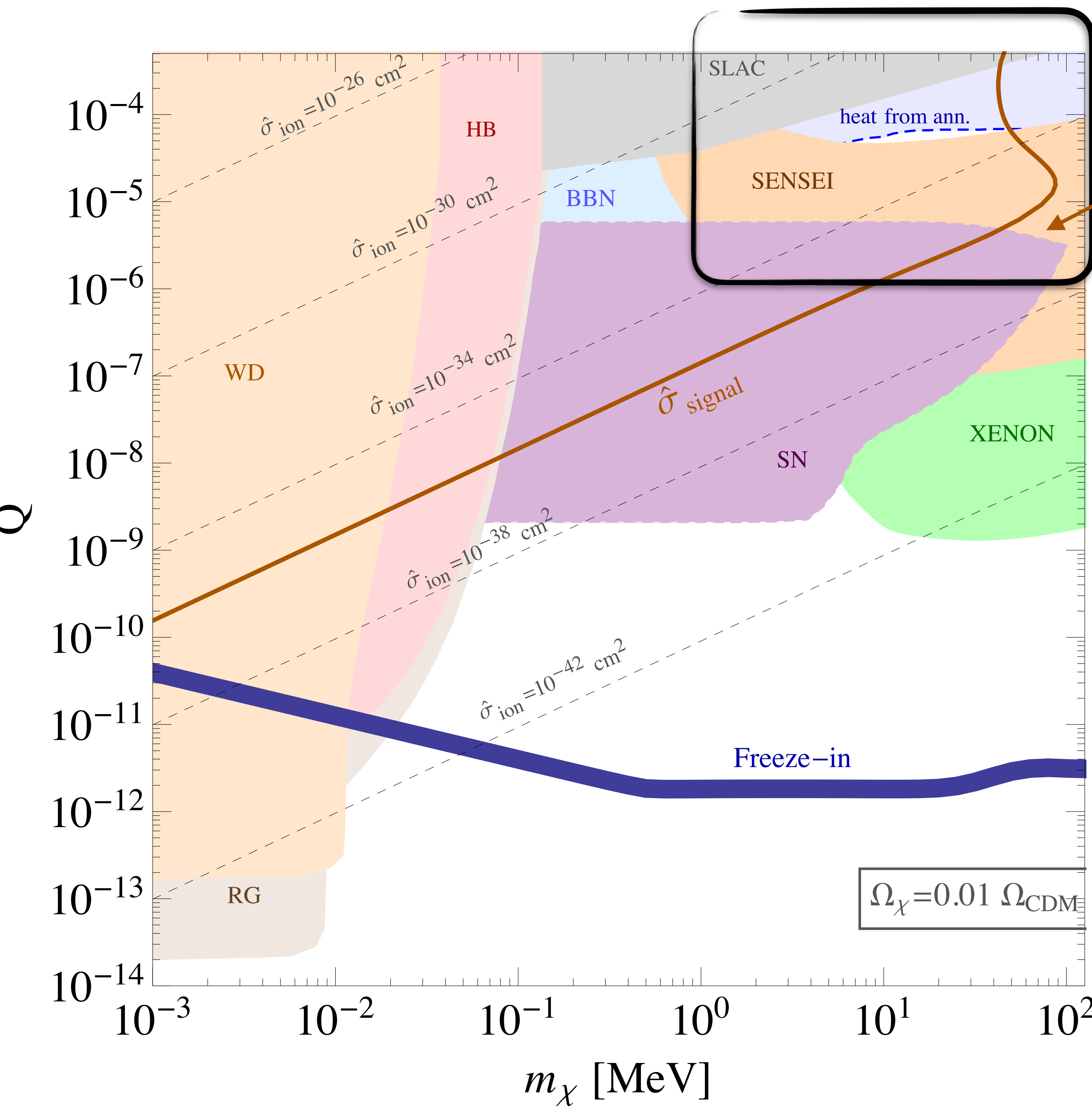


EDGES VS DIRECT DETECTION



CAN WE TEST
THE ALLOWED REGION in
direct detection experiments?

EDGES VS DIRECT DETECTION

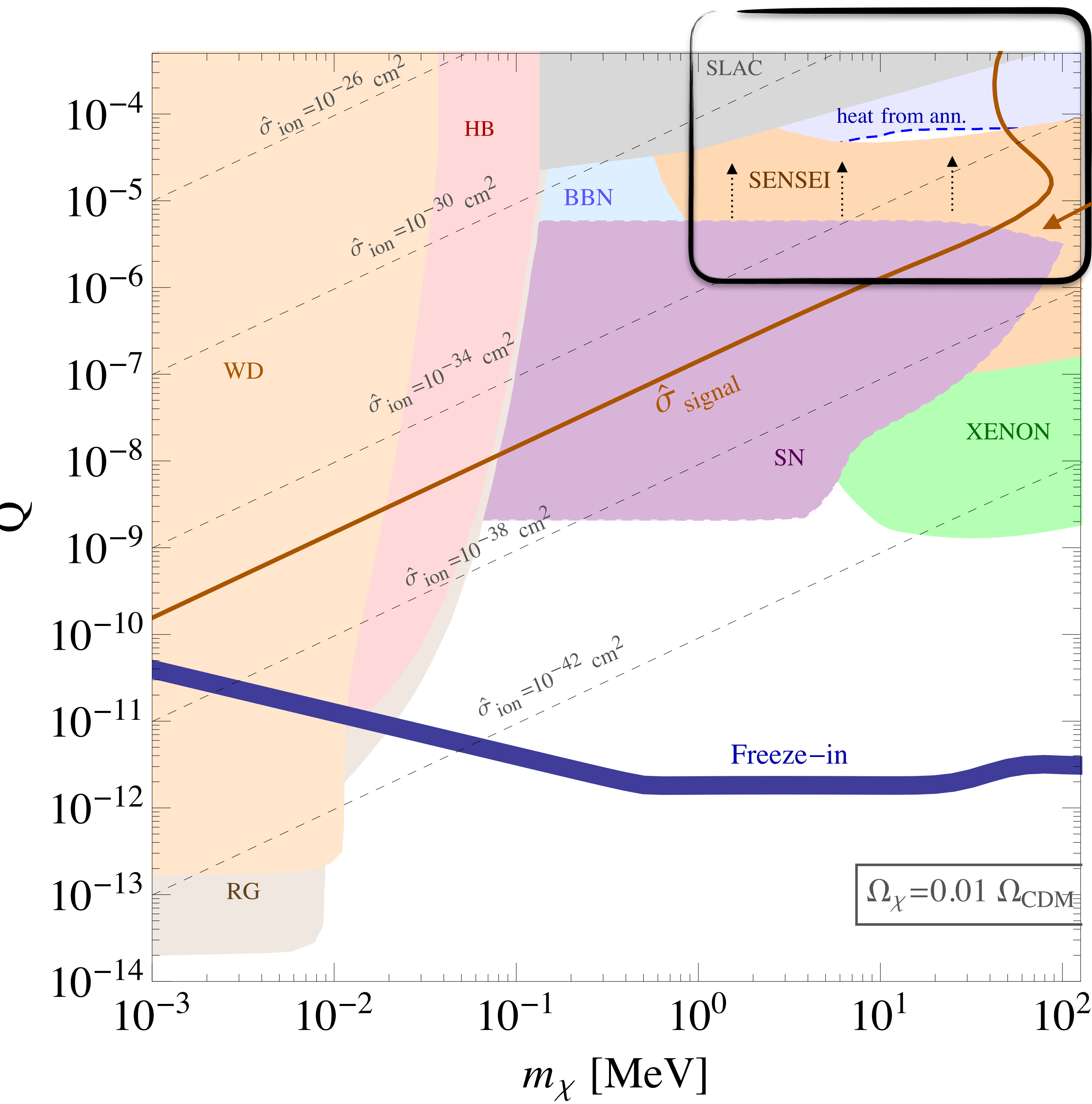


Surface run SENSEI with 1gram

the bound stops at high Q because of terrestrial effects

Emken, R.Essig, C. Kouvaris, Sholapurkar (2018)

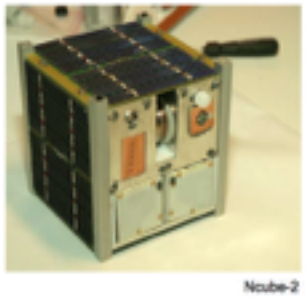
EDGES VS DIRECT DETECTION



Surface run SENSEI with 1gram

the bound stops at high Q because of terrestrial effects

Emken, R.Essig, C. Kouvaris, Sholapurkar (2018)



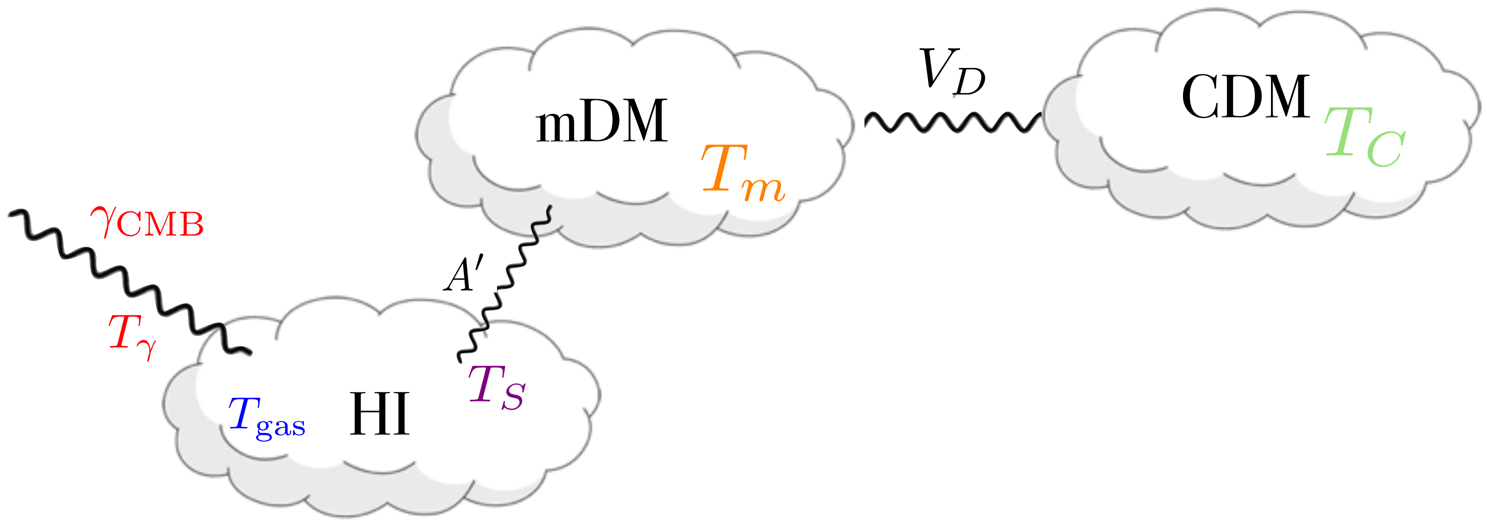
SENSEI on a satellite?

Is millicharge DM accelerated like cosmic rays?

Chang , Essig, **D.R.**, Outmezguine, Volansky (to appear)

A NEW REFRIGERATOR AT 21 CM

Liu,Outmezguine,**D.R.** ,Volanksy, (2019)



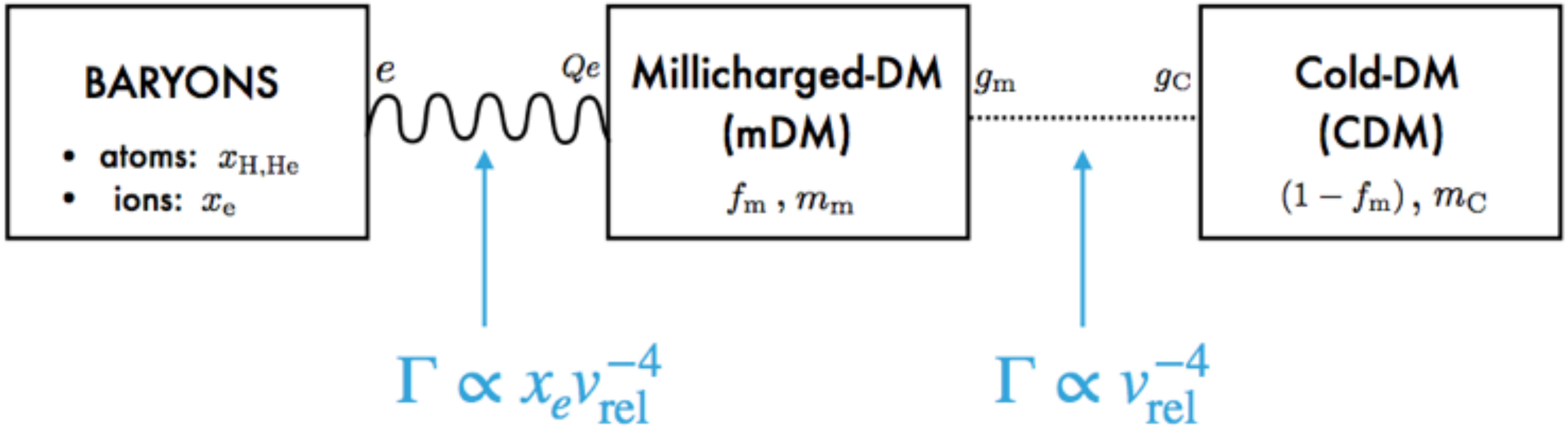
- We have few droplets of millicharge Dark Matter (mDM) *ice* in the baryon soup

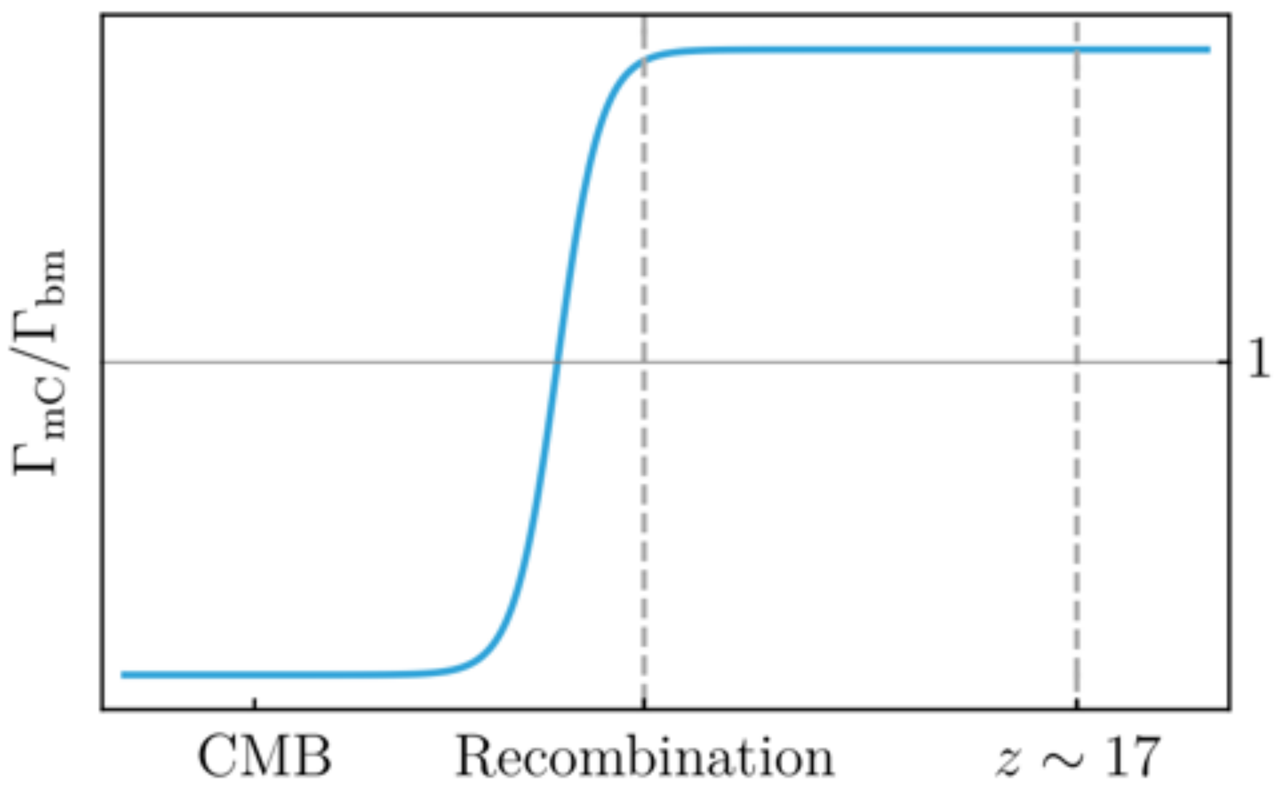
- These are constantly cooled via a gigantic Cold Dark Matter (CDM) fridge

IT IS EASIER TO COOL THE BARYONS!

A NEW REFRIGERATOR AT 21 CM

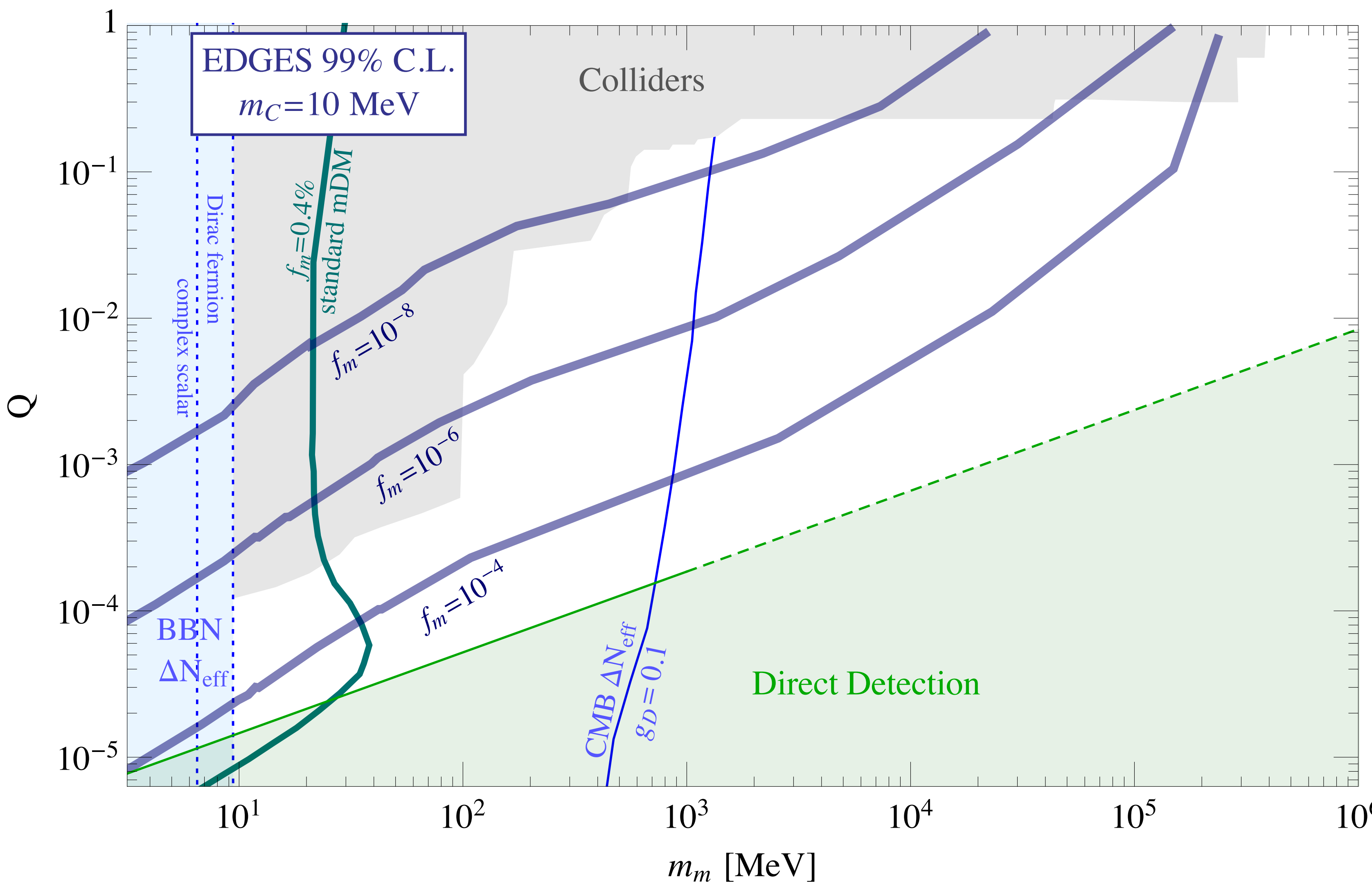
Liu, Outmezguine, **D.R.** , Volanksy, (2019)





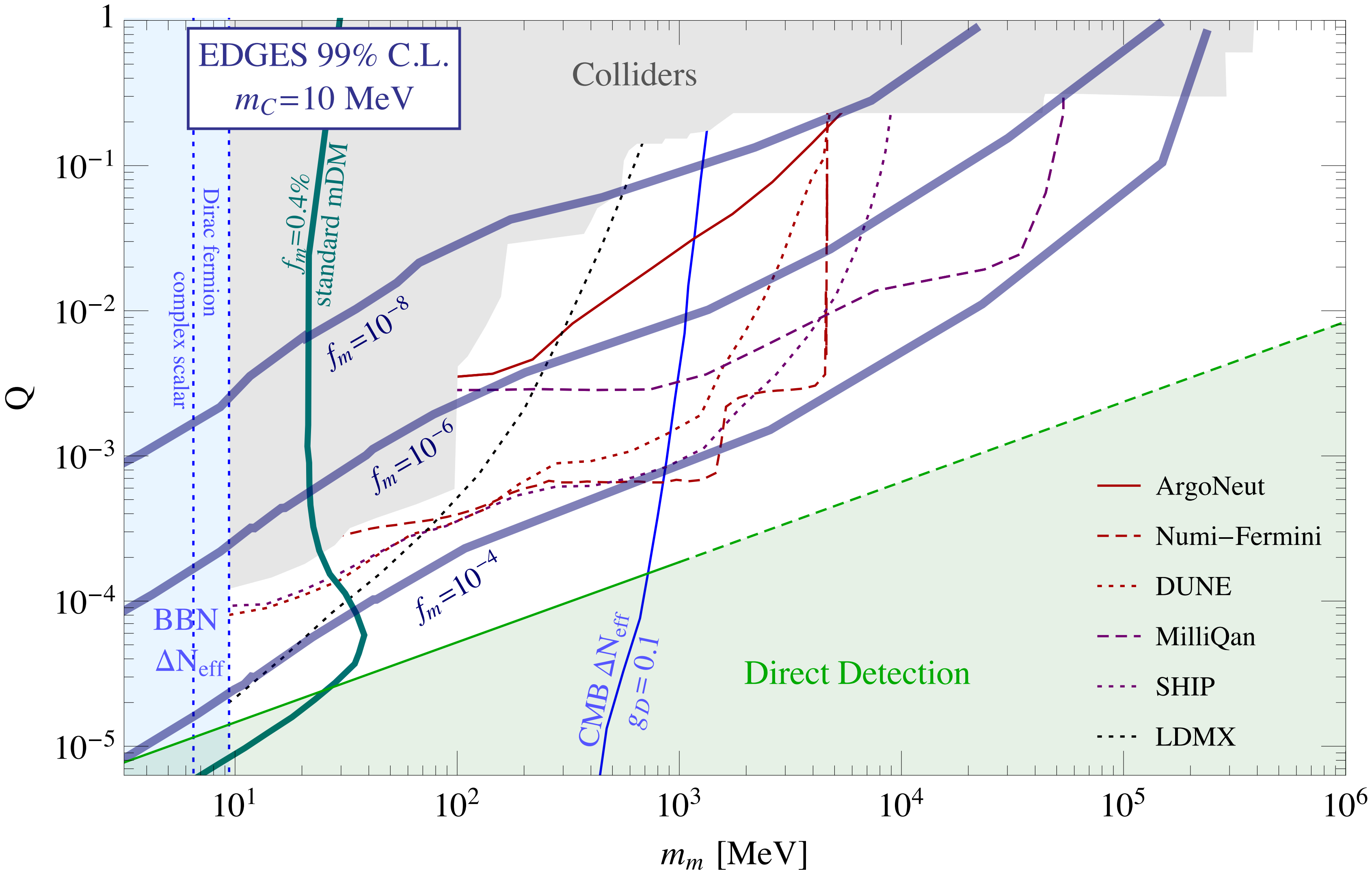
- At CMB the mDM is tight to the baryons
- After recombination mDM is tight to CDM

WHAT CAN WE SEE?



- mDM tiny fraction $f_m > 10^{-8}$
- up to 200 GeV in mass
- in between direct-detection shielding and collider constraints

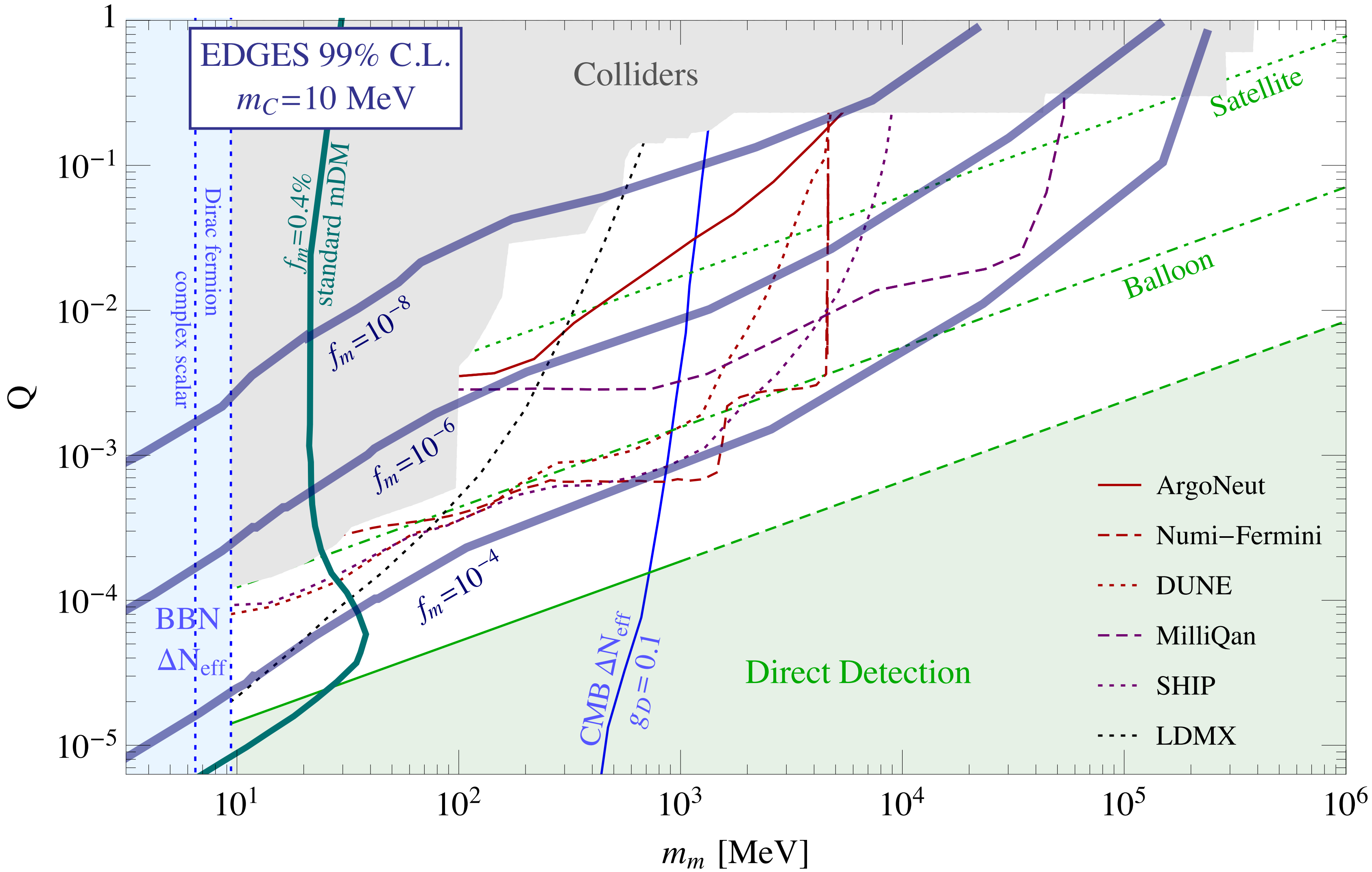
WHAT CAN WE SEE?



- FUTURE COLLIDERS (soon)

- mDM tiny fraction $f_m > 10^{-8}$
- up to 200 GeV in mass
- in between direct-detection shielding and collider constraints

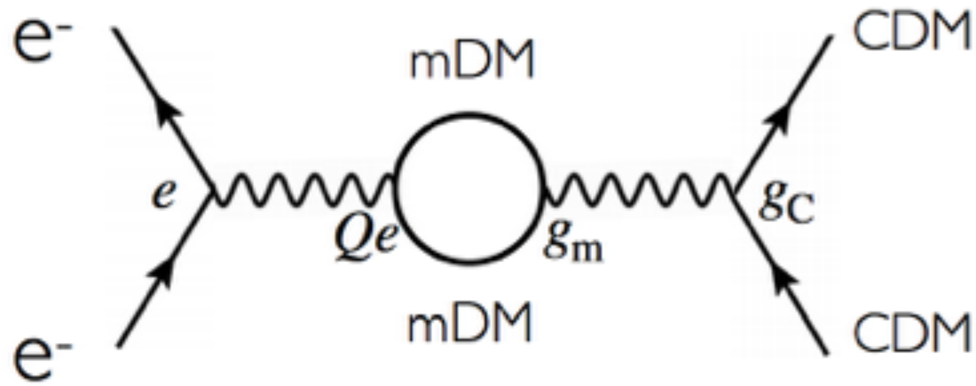
WHAT CAN WE SEE?



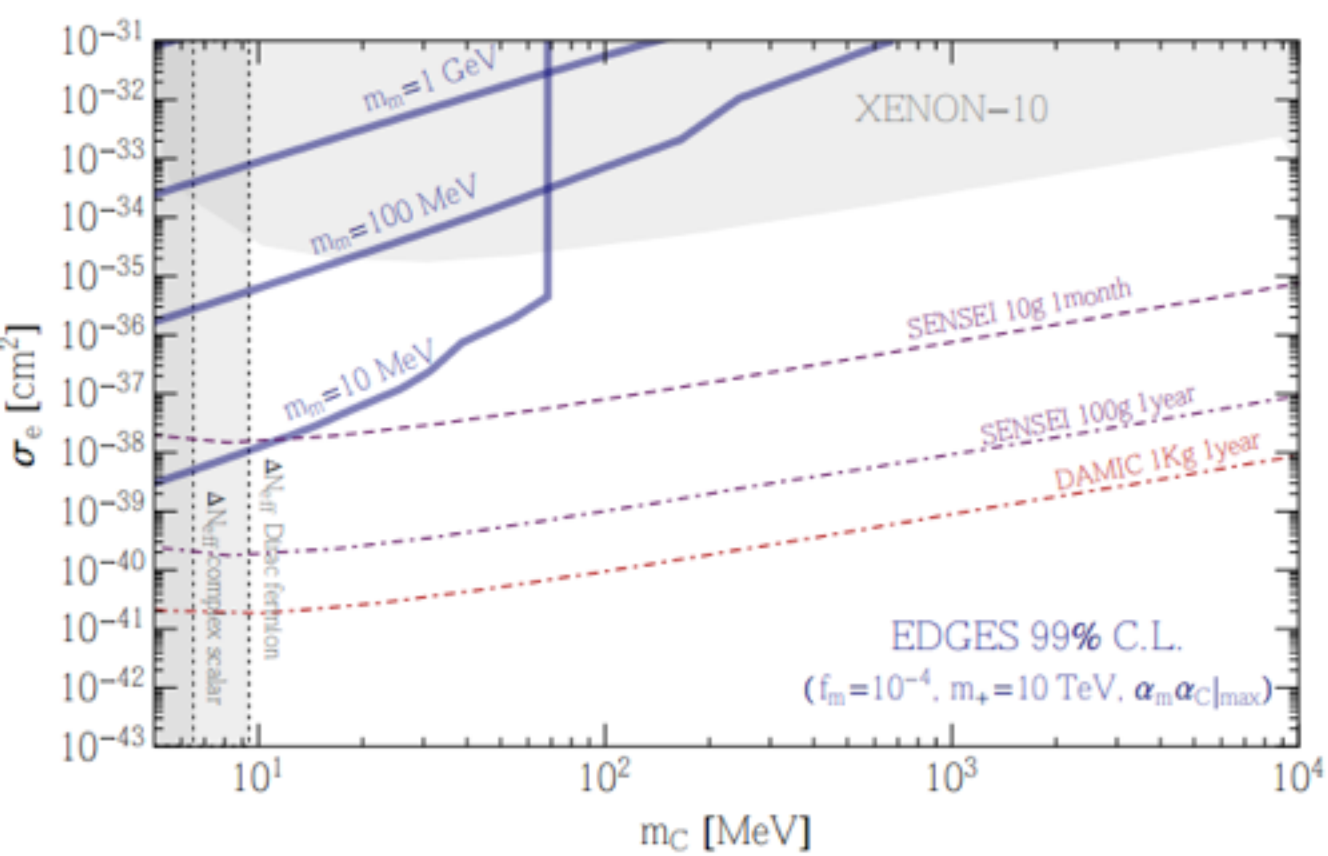
- FUTURE COLLIDERS (soon)
- Direct Detection in the Sky

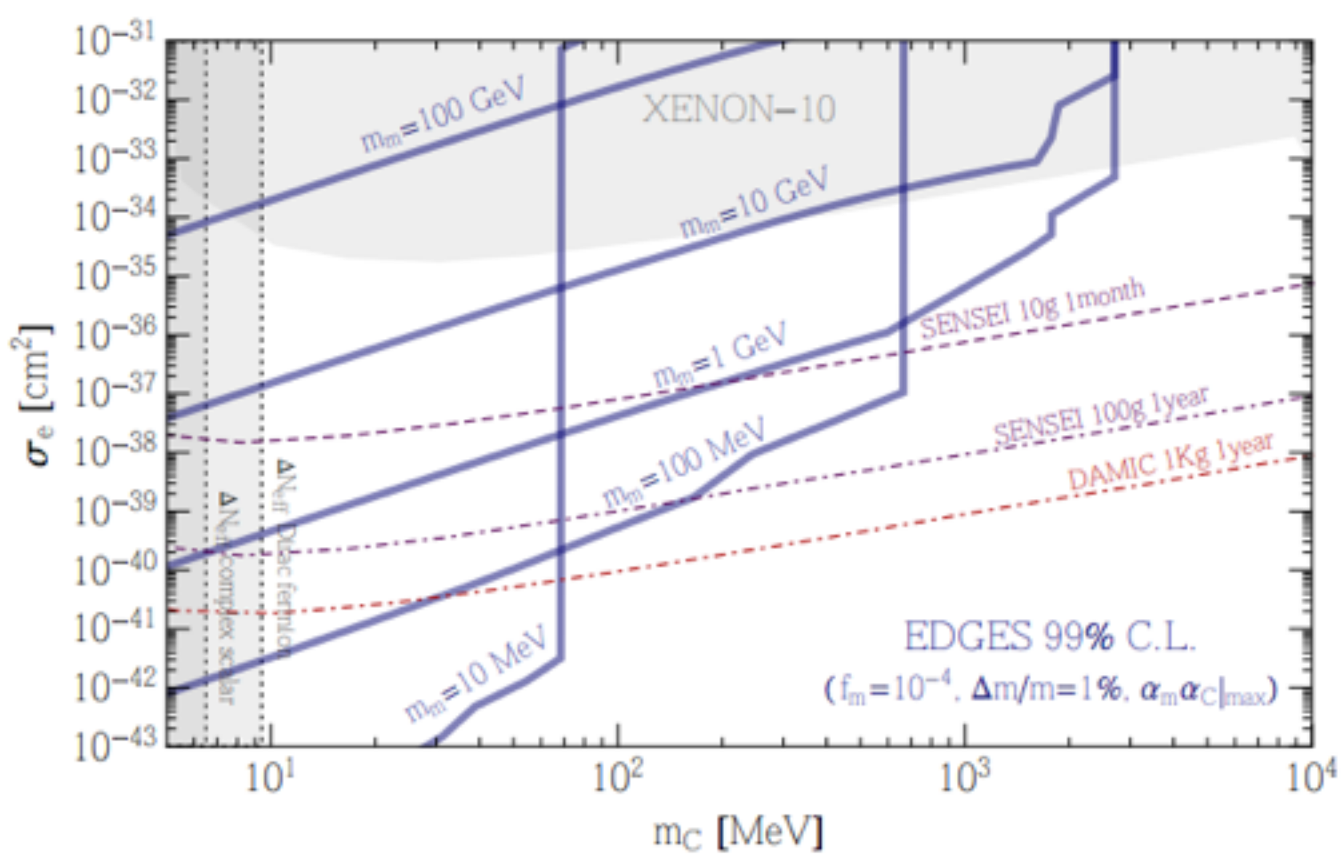
- mDM tiny fraction: $f_m > 10^{-8}$
- up to 200 GeV in mass
- in between direct-detection shielding and collider constraints

WHAT CAN WE SEE?



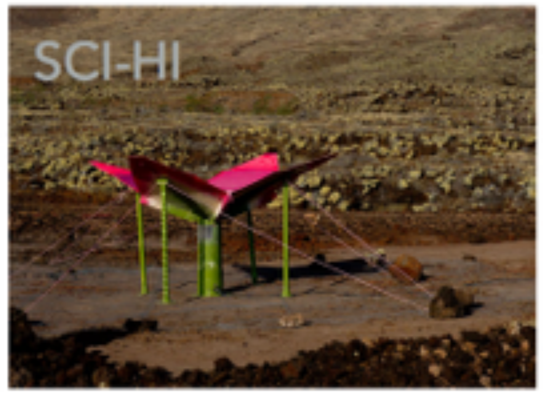
- CDM is below 6 GeV
- interactions with electrons via a loop of mDM
- perfect target for low-threshold direct detection

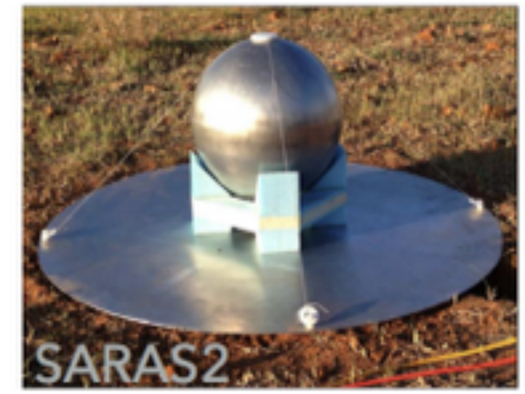




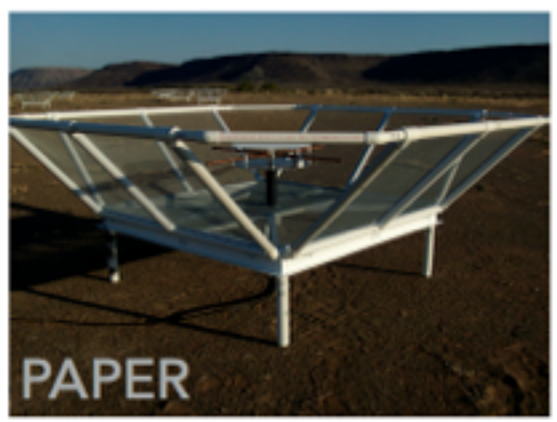
21 CM COSMOLOGY IS BLOOMING

global 21 cm spectrum





21 cm fluctuations



TIME FOR THEORISTS TO IMPROVE THE PREDICTIONS!

The Standard Model

with R. Barkana, N. J. Outzmezguine, T. Volansky

Boltzmann equation for the singlet density

$$\dot{n}_0 + 3Hn_0 = -n_0(C_{01} + B_{01} + L_{01}) + n_1(C_{10} + A_{10} + B_{10} + L_{10})$$

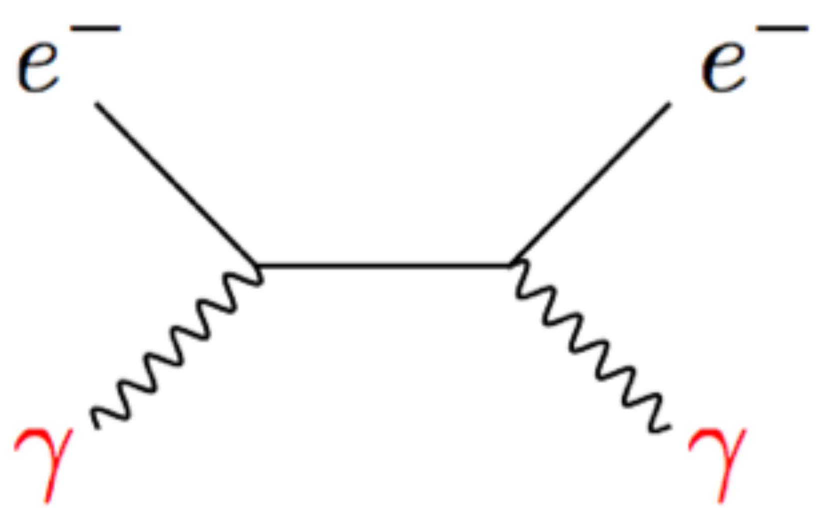
All the rates are bigger than Hubble down to z=10 & T_S is defined by an equilibrium equation

$$\Delta T_s \simeq \frac{y_{\rm col}\ \Delta T_{\rm gas} + y_{{\rm Ly}\alpha}\ \Delta T_{{\rm Ly}\alpha}}{1 + y_{\rm col} + y_{{\rm Ly}\alpha}}$$

$$\Delta T = T - T_{\rm CMB}$$

$$y_{{\rm Ly}\alpha} = \frac{E_{21}}{T_{{\rm Ly}\alpha}}\frac{L_{10}}{A_{10}}$$

$$y_{\rm col} = \frac{E_{21}}{T_{\rm gas}}\frac{C_{10}}{A_{10}}$$



At high enough redshift Compton scattering dominates

$$T_S \simeq T_{\rm gas} \simeq T_\gamma$$

Lowering the redshift the gas temperature decouples!

$$T_\gamma \sim (1+z) \qquad T_{\rm gas} \sim (1+z)^2$$

The Standard Model

with R. Barkana, N. J. Outzmezguine, T. Volansky

Boltzmann equation for the singlet density

$$\dot{n}_0 + 3Hn_0 = -n_0(C_{01} + B_{01} + L_{01}) + n_1(C_{10} + A_{10} + B_{10} + L_{10})$$

All the rates are bigger than Hubble down to z=10 & T_S is defined by an equilibrium equation

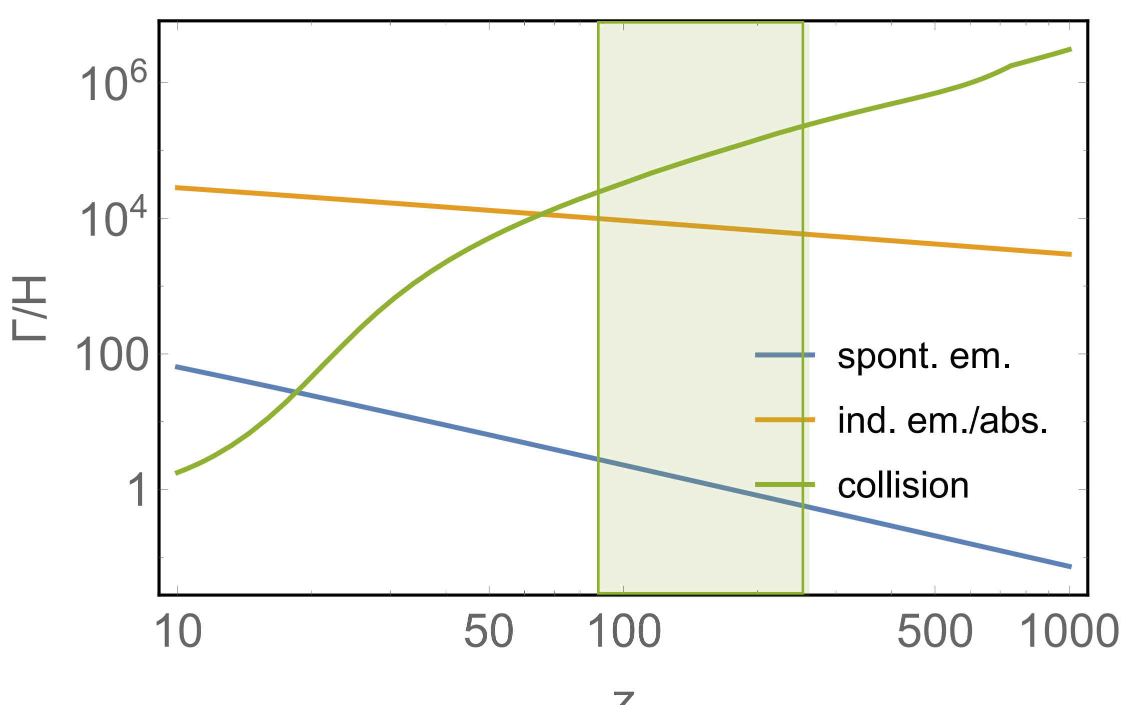
$$\Delta T_s \simeq \frac{y_{\rm col}\ \Delta T_{\rm gas} + y_{\rm Ly\alpha}\ \Delta T_{\rm Ly\alpha}}{1 + y_{\rm col} + y_{\rm Ly\alpha}}$$

$$\Delta T = T - T_{\rm CMB}$$

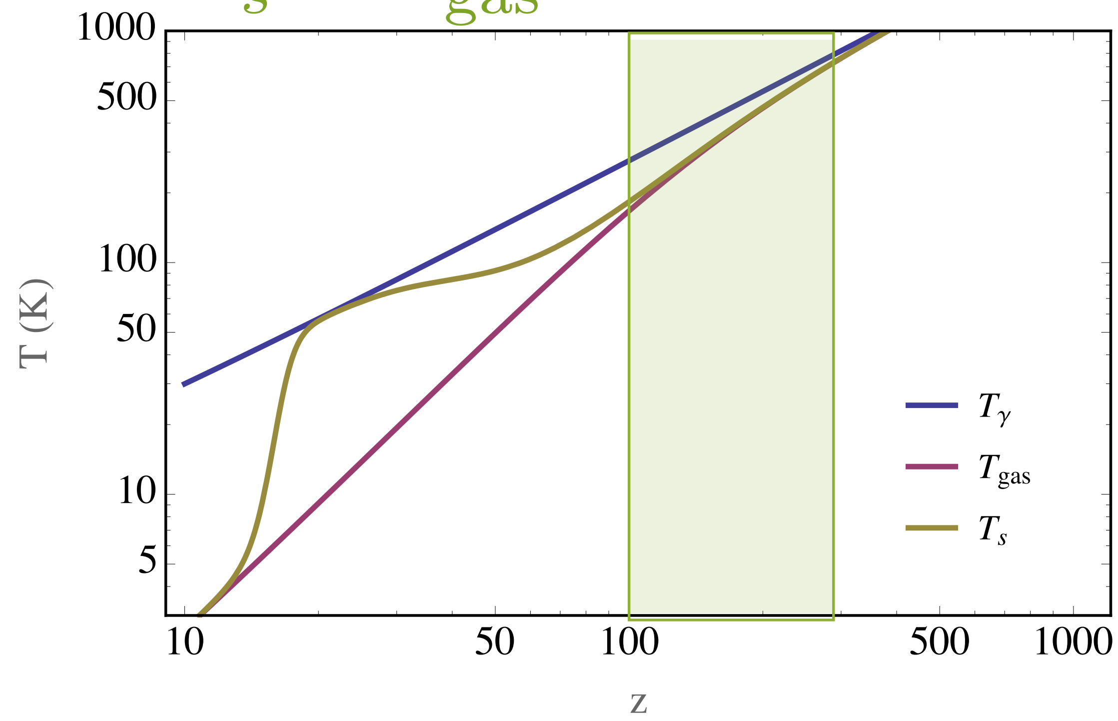
$$y_{\rm Ly\alpha} = \frac{E_{21}}{T_{\rm Ly\alpha}}\frac{L_{10}}{A_{10}}$$

$$y_{\rm col} = \frac{E_{21}}{T_{\rm gas}}\frac{C_{10}}{A_{10}} \gg 1$$

HI-HI & HI-e dominates



$T_s \simeq T_{\rm gas}$



The Standard Model

with R. Barkana, N. J. Outzmezguine, T. Volansky

Boltzmann equation for the singlet density

$$\dot{n}_0 + 3Hn_0 = -n_0(C_{01} + B_{01} + L_{01}) + n_1(C_{10} + A_{10} + B_{10} + L_{10})$$

All the rates are bigger than Hubble down to z=10 & T_S is defined by an equilibrium equation

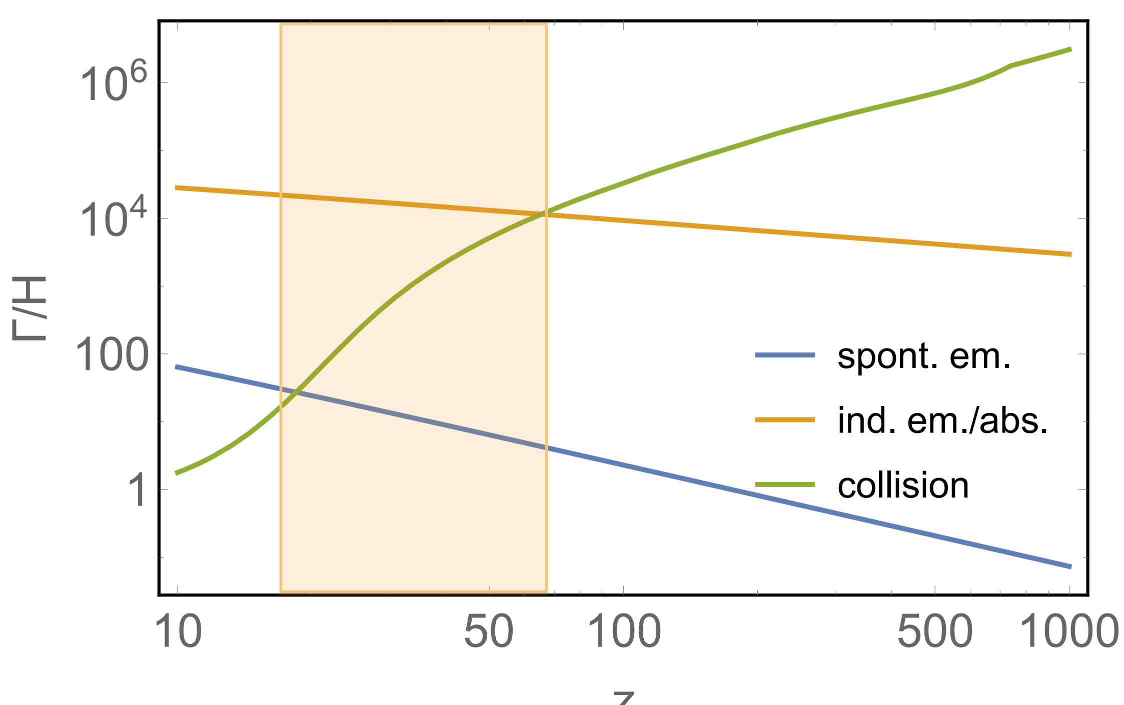
$$\Delta T_s \simeq \frac{y_{\rm col}\ \Delta T_{\rm gas} + y_{\rm Ly\alpha}\ \Delta T_{\rm Ly\alpha}}{1 + y_{\rm col} + y_{\rm Ly\alpha}}$$

$$\Delta T = T - T_{\rm CMB}$$

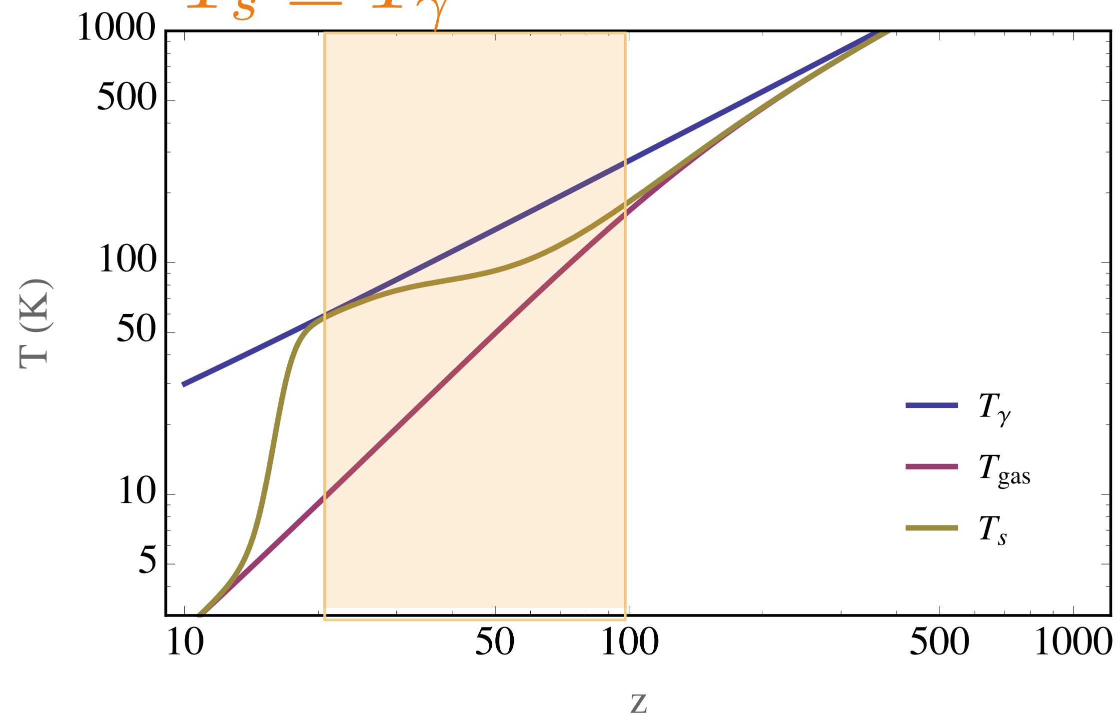
$$y_{\rm Ly\alpha} = \frac{E_{21}}{T_{\rm Ly\alpha}} \frac{L_{10}}{A_{10}}$$

$$y_{\rm col} = \frac{E_{21}}{T_{\rm gas}} \frac{C_{10}}{A_{10}}$$

CMB Emissions/Abs. dominates



$T_s \simeq T_\gamma$



The Standard Model

with R. Barkana, N. J. Outzmezguine, T. Volansky

Boltzmann equation for the singlet density

$$\dot{n}_0 + 3Hn_0 = -n_0(C_{01} + B_{01} + L_{01}) + n_1(C_{10} + A_{10} + B_{10} + L_{10})$$

All the rates are bigger than Hubble down to z=10 & T_S is defined by an equilibrium equation

$$\Delta T_s \simeq \frac{y_{\rm col}\ \Delta T_{\rm gas} + y_{\rm Ly\alpha}\ \Delta T_{\rm Ly\alpha}}{1 + y_{\rm col} + y_{\rm Ly\alpha}}$$

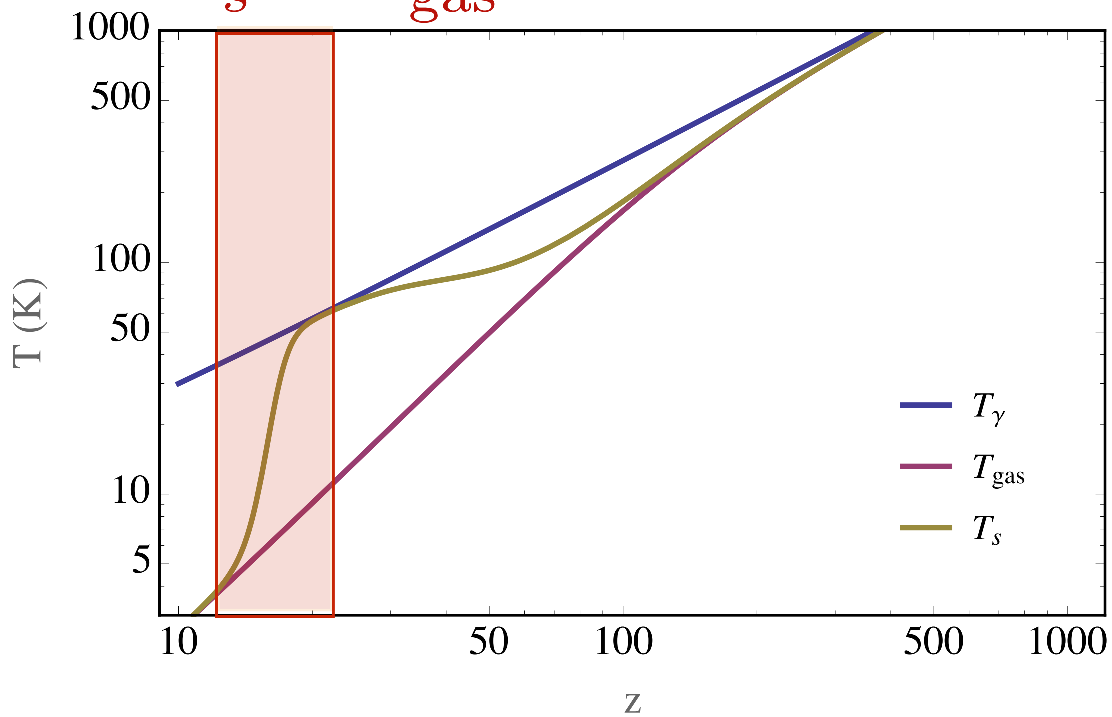
$$\Delta T = T - T_{\rm CMB}$$

$$y_{\rm Ly\alpha} = \frac{E_{21}}{T_{\rm Ly\alpha}} \frac{L_{10}}{A_{10}} \gg 1$$

$$y_{\rm col} = \frac{E_{21}}{T_{\rm gas}} \frac{C_{10}}{A_{10}}$$

@ z=30 **W**ou**T**uysen-**F**ield (WF effect)

$T_s \simeq T_{\rm gas}$



getting WF-effect right requires modelling of first star X-ray heating and Lya fluxes

see . T. Venumadhav, L. Dai , A.A. Kaurov, M. Zaldarriaga 2018