10 July 2019
CYGNUS 2019 - Roma

What is Dark Matter?

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

10 July 2019
CYGNUS 2019 - Roma

What is Dark Matter?

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

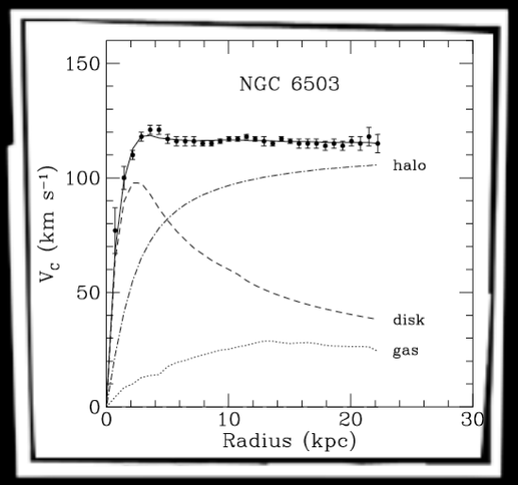
Dark Matter factsheet

Dark Matter factsheet

- DM exists

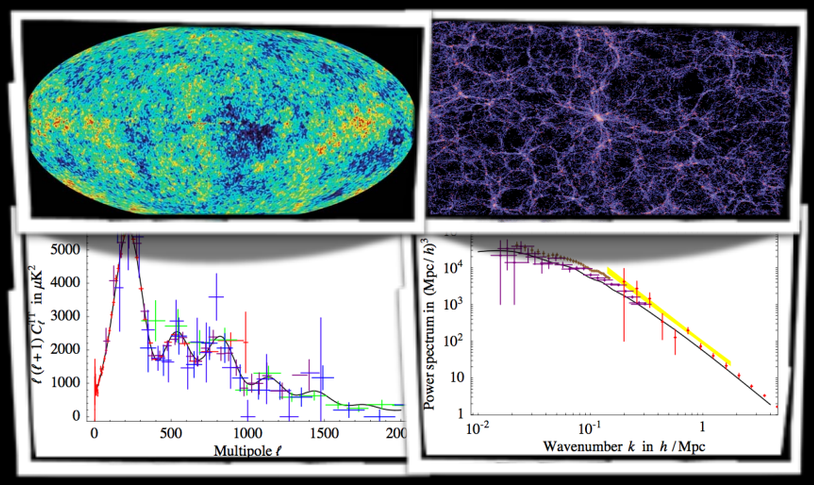
Dark Matter factsheet

- DM exists



galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Dark Matter factsheet

- DM exists
- it's a new, unknown corpuscule

dilutes as $1/a^3$ with universe expansion

Dark Matter factsheet

- DM exists
- it's a new, unknown particle

no SM particle can fulfill

dilutes as $1/a^3$ with universe expansion

Dark Matter factsheet

- DM exists
- it's a new, unknown particle
- makes up 26% of total energy
  82% of total matter

no SM particle can fulfill

dilutes as $1/a^3$ with universe expansion

$$\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$$

(notice error!)

[Planck 2015, 1502.01589]

Dark Matter factsheet

- DM exists
- it's a new, unknown particle
- makes up 26% of total energy
  82% of total matter
- neutral particle *'dark'...*

no SM particle can fulfill

dilutes as $1/a^3$ with universe expansion

$$\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$$

(notice error!)

Dark Matter factsheet

- DM exists
- it's a new, unknown particle — *no SM particle can fulfill* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*

Dark Matter factsheet

- DM exists
- it's a new, unknown particle — *no SM particle can fulfill* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself*
  -with ordinary matter ('collisionless')

Dark Matter factsheet

- DM exists
- it's a new, unknown particle — *no SM particle can fulfill* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself -with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17}{\rm sec}$

Dark Matter factsheet

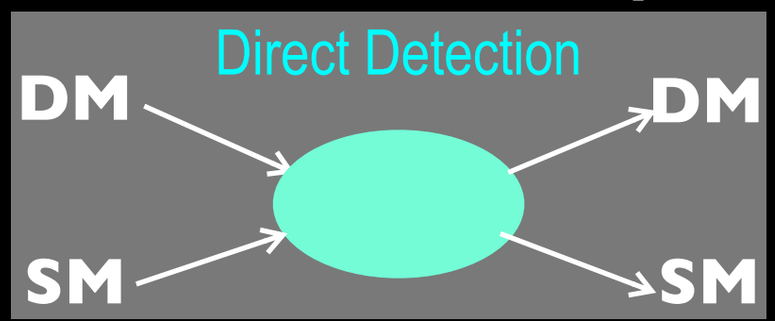
- DM exists
- it's a new, unknown particle — *no SM particle can fulfill* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM}h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself -with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17}{\rm sec}$
- possibly a relic from the EU

Dark Matter factsheet

- DM exists
- it's a new, unknown particle — *no SM particle can fulfill* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM}h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself -with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17}{\rm sec}$
- possibly a relic from the EU
- searched for by

Dark Matter factsheet

- DM exists
- it's a new, unknown particle — *no SM particle can fulfill* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself -with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17}{\rm sec}$
- possibly a relic from the EU
- searched for by



Dark Matter factsheet

- DM exists
- it's a new, unknown particle

no SM particle can fulfill

dilutes as $1/a^3$ with universe expansion

- makes up 26% of total energy
  82% of total matter

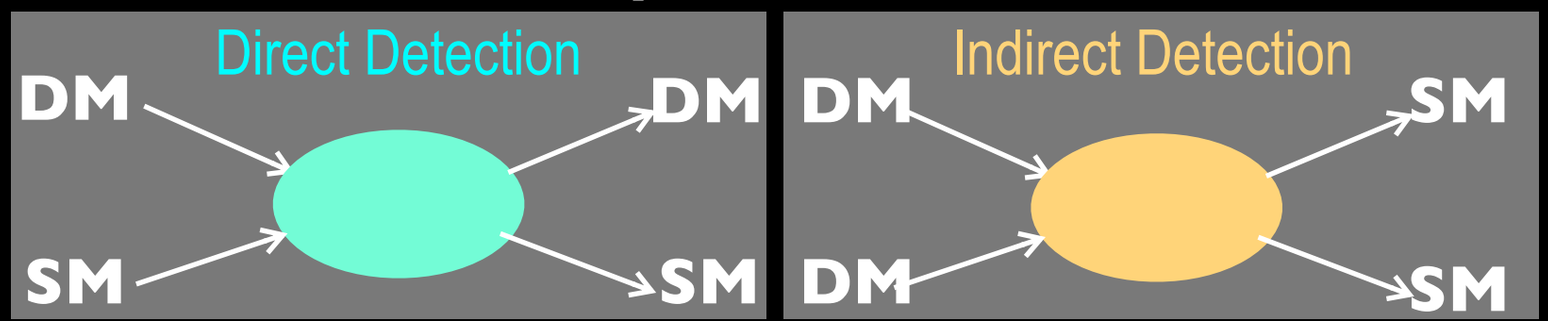
$\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$

(notice error!)

- neutral particle *'dark'...*
- cold or not too warm *p/m <<1 at CMB formation*
- very feebly interacting

-with itself
-with ordinary matter ('collisionless')

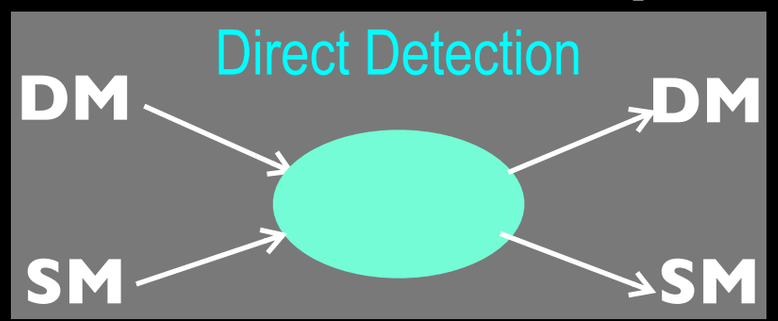
- stable or very long lived $\tau_{\rm DM} \gg 10^{17}{\rm sec}$
- possibly a relic from the EU
- searched for by

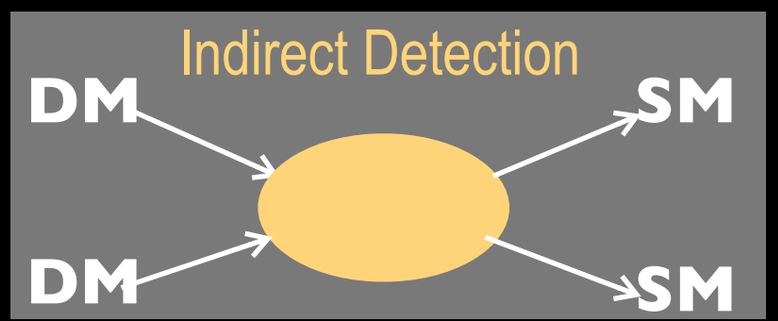


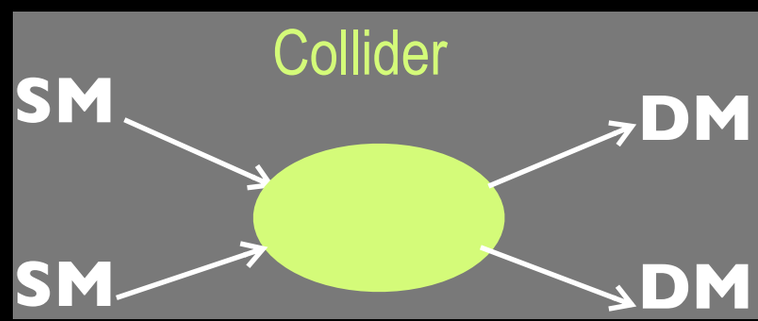
Dark Matter factsheet

- DM exists
- it's a new, unknown particle — *no SM particle can fulfill* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*

- very feebly interacting — *-with itself -with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17}{\rm sec}$
- possibly a relic from the EU
- searched for by







Dark Matter factsheet

- DM exists
- it's a new, unknown particle — *no SM particle can fulfill* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself -with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17}{\rm sec}$
- possibly a relic from the EU

Mass??

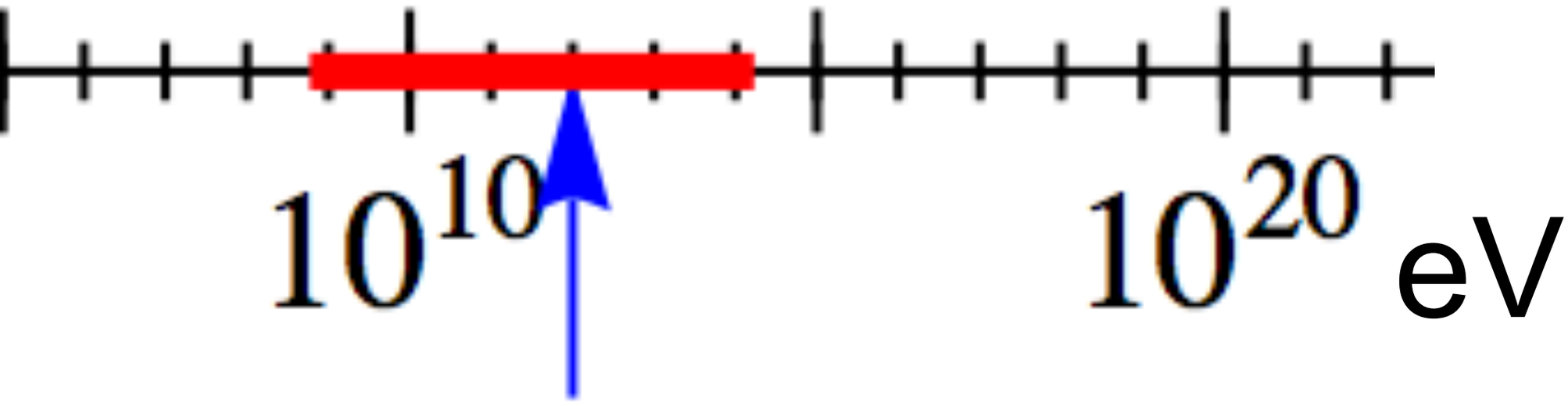
Charge??
Interactions??

Candidates

A matter of perspective: plausible mass ranges

thermal

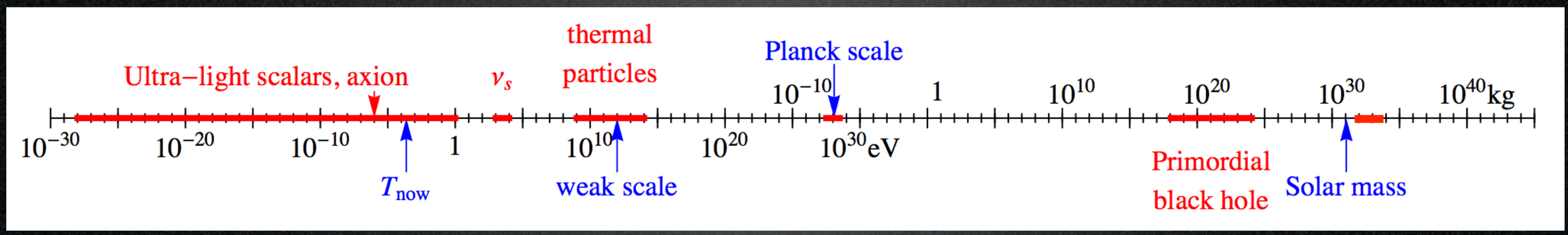
particles



weak scale (1 TeV)

Candidates

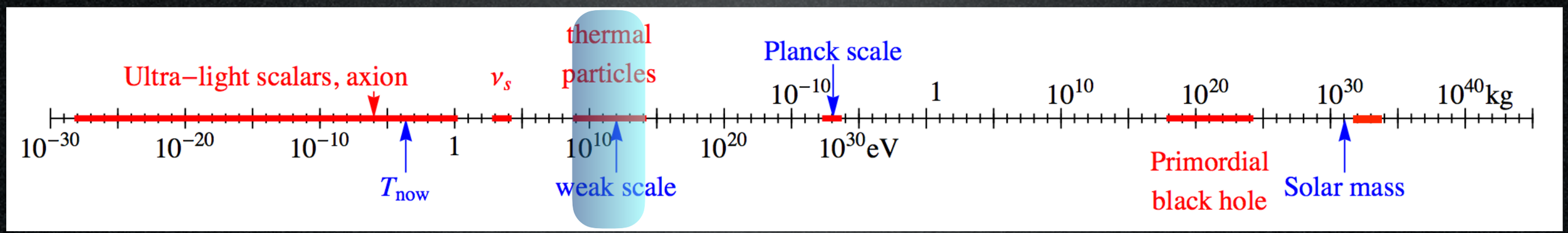
A matter of perspective: plausible mass ranges



‘only’ 90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges



'only' 90 orders of magnitude!

Candidates

WIMPs

Candidates

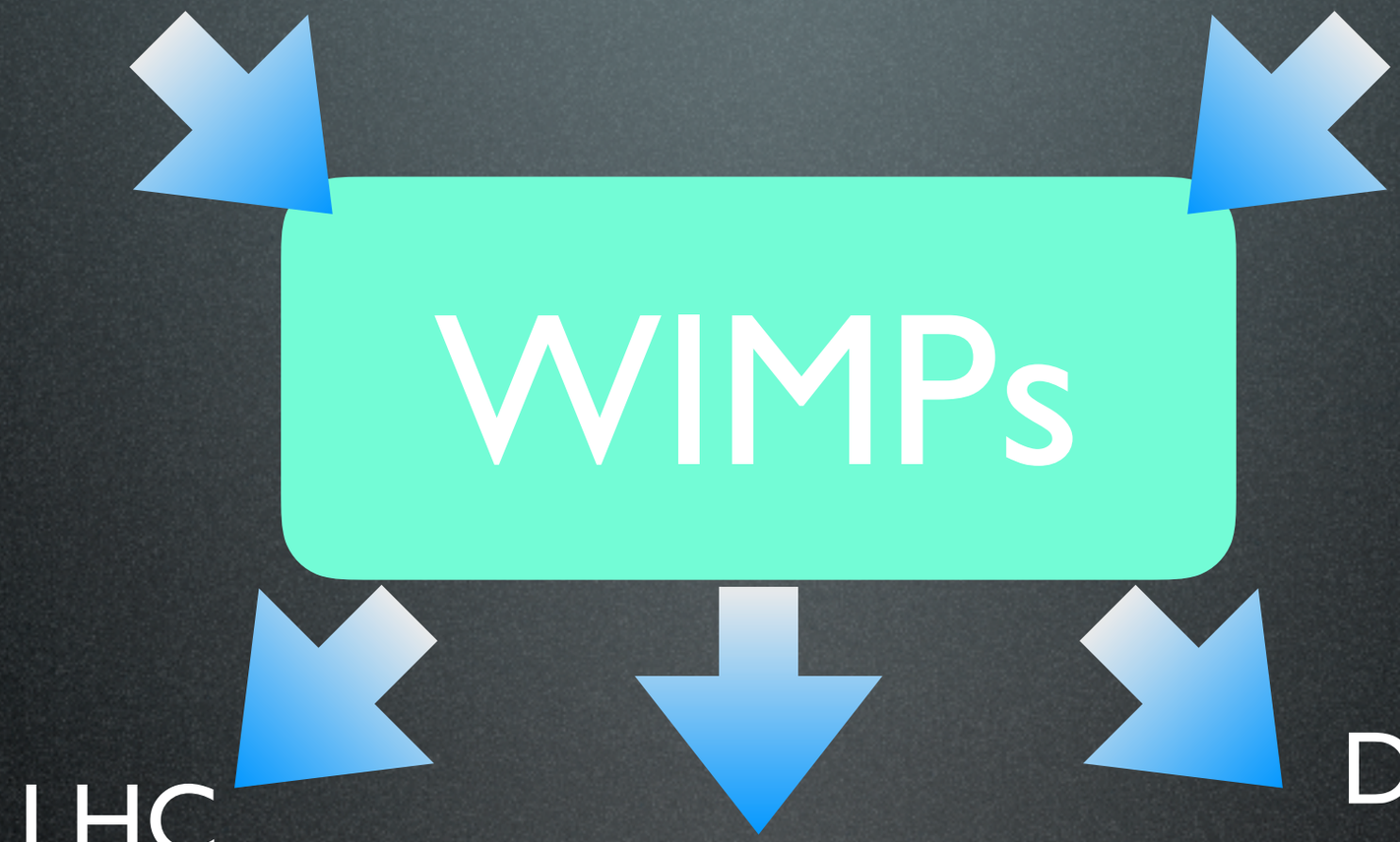
new physics at the TeV scale

thermal freeze-out

Candidates

new physics at the TeV scale

thermal freeze-out



LHC

Indirect Detection

Direct Detection

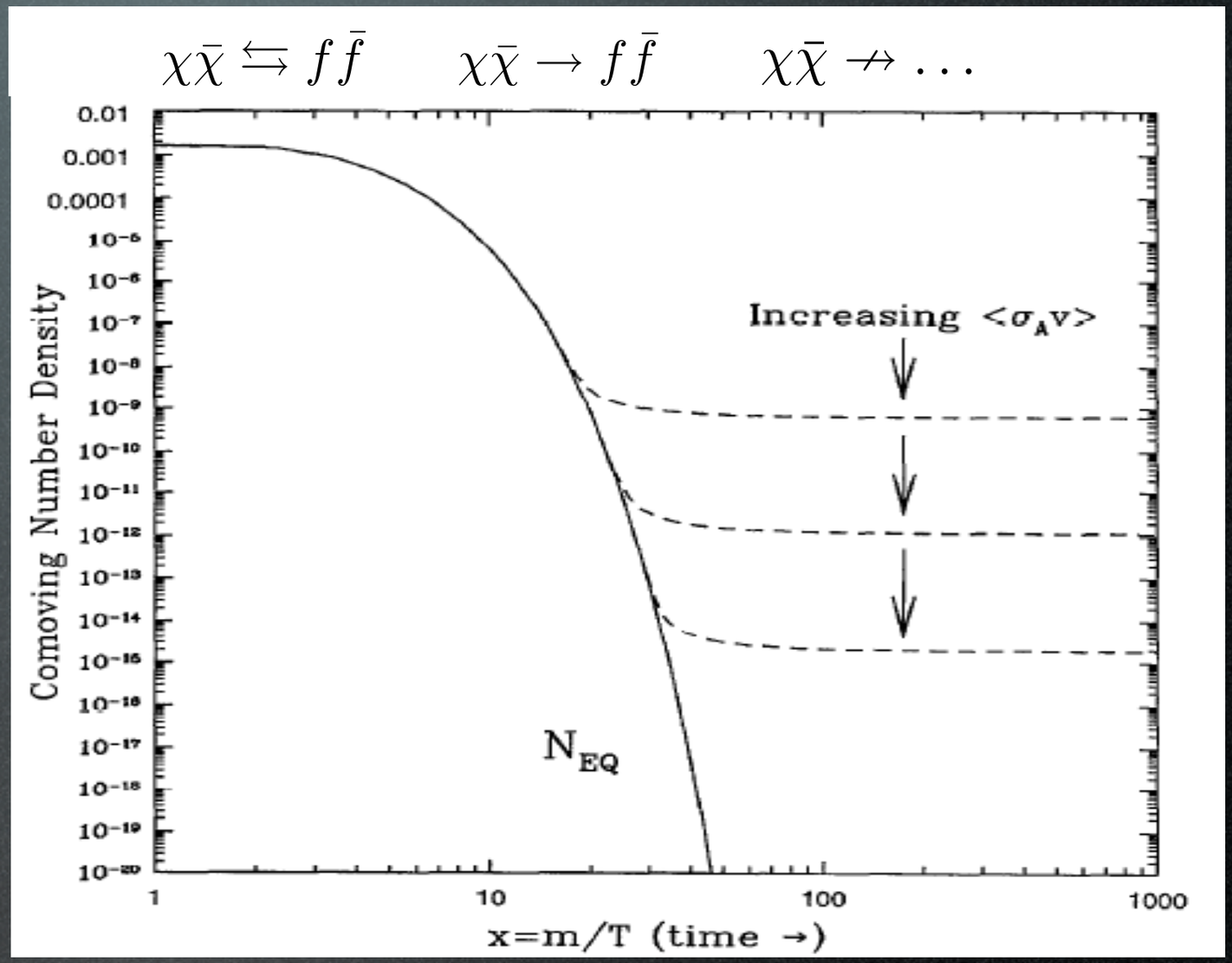
DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}}v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}}v\rangle = 3\cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}}v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\,TeV^2}} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

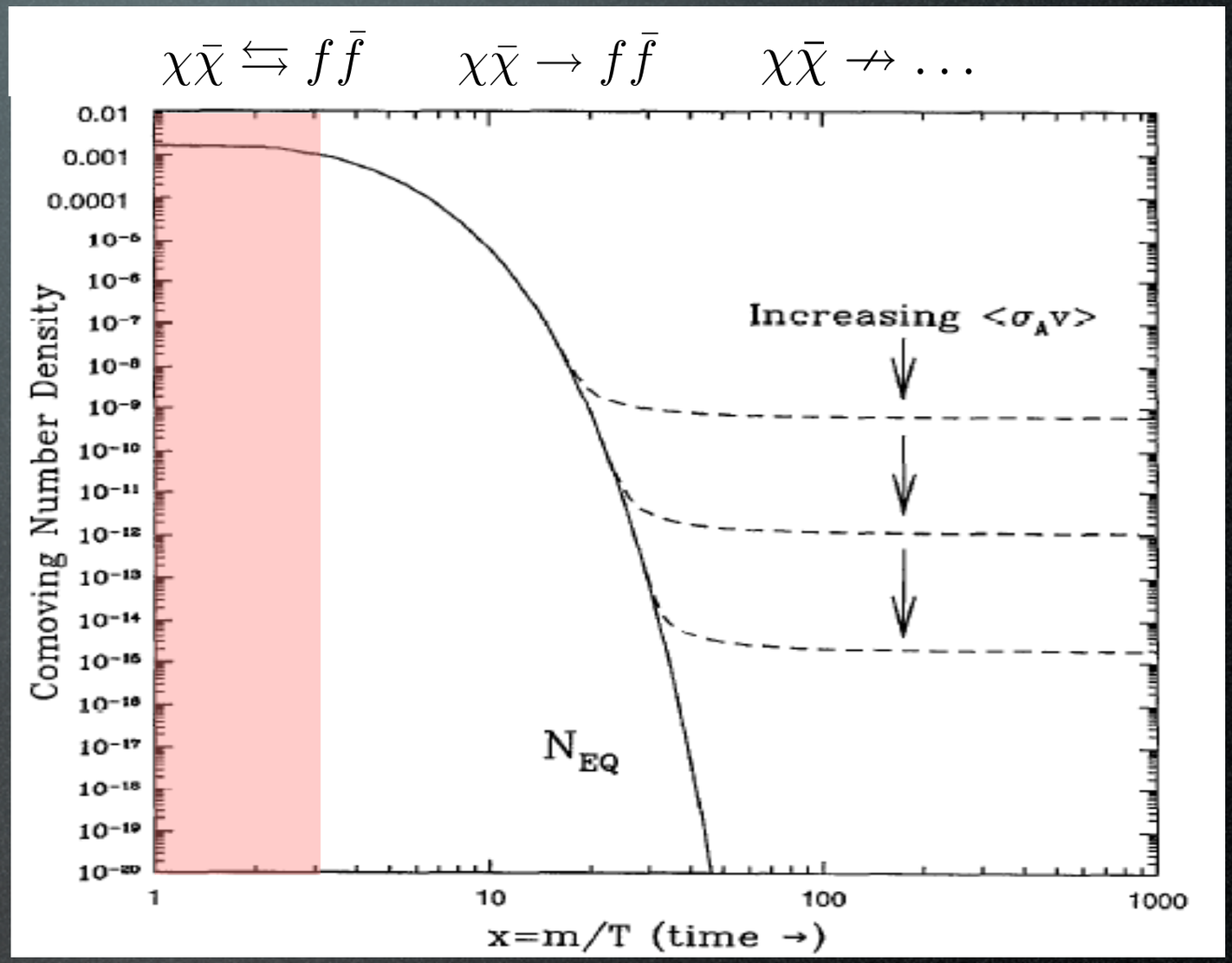
DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}} v\rangle = 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{1\,\mathrm{TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

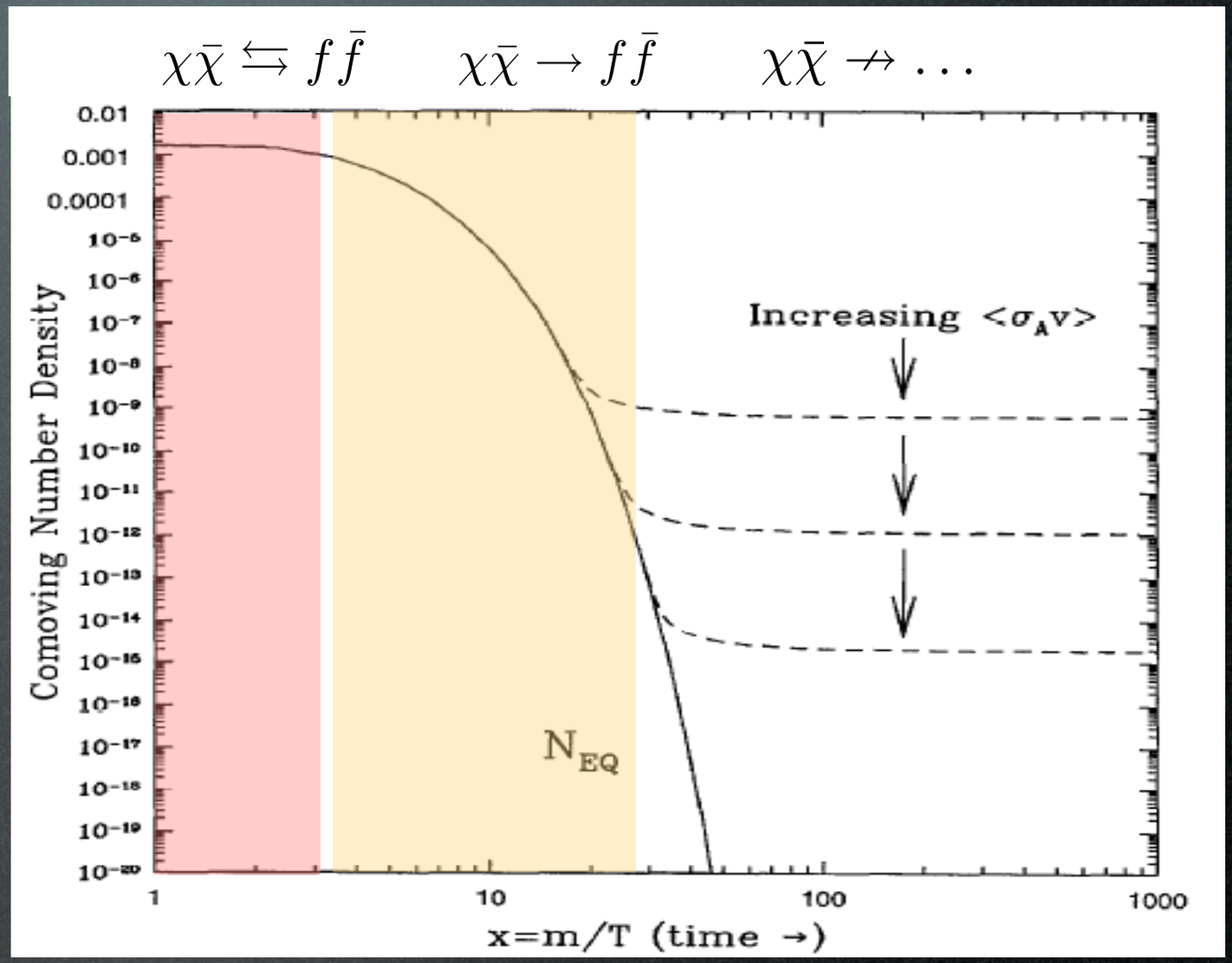
DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}} v\rangle = 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\,TeV^2}} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

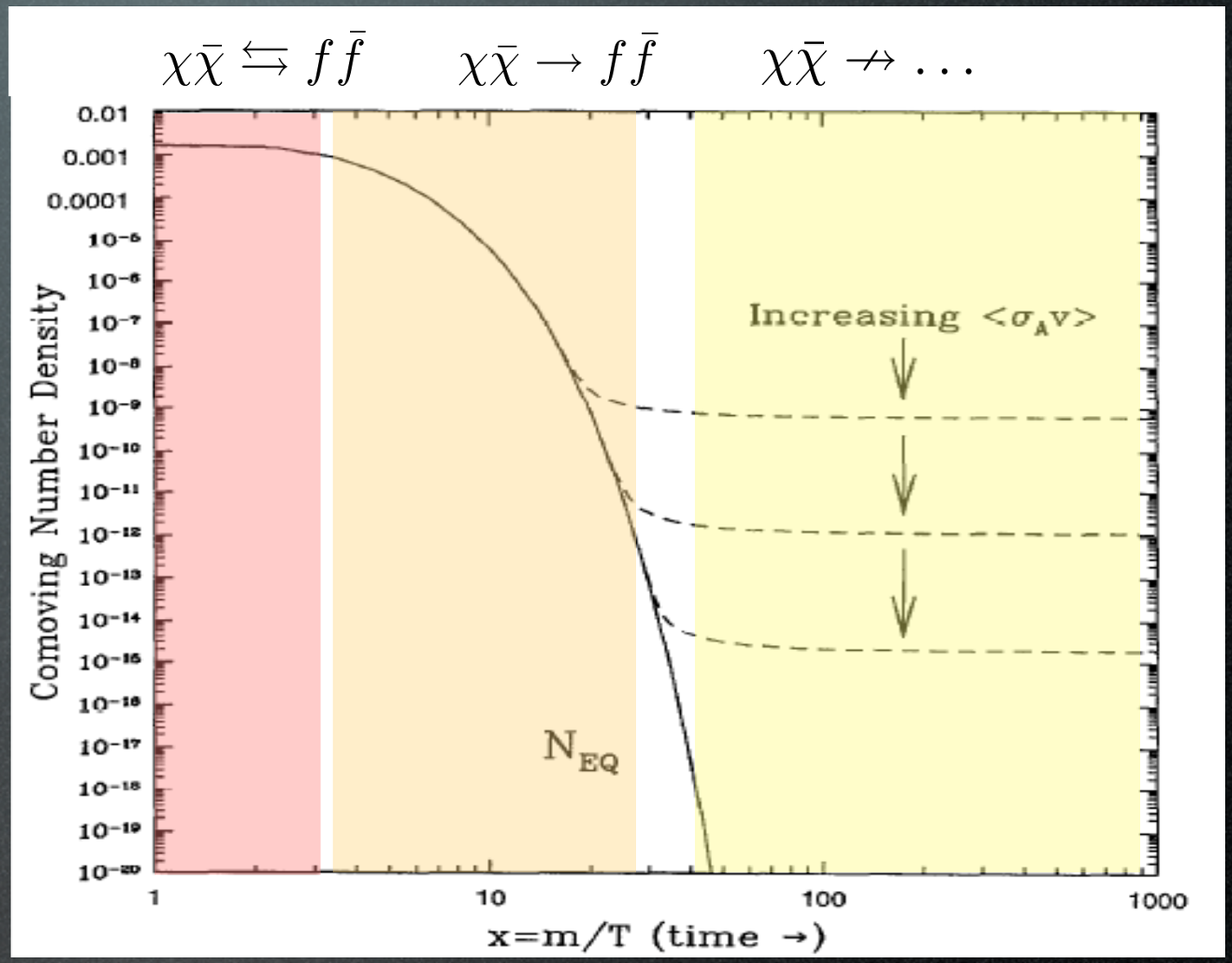
DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}} v\rangle = 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

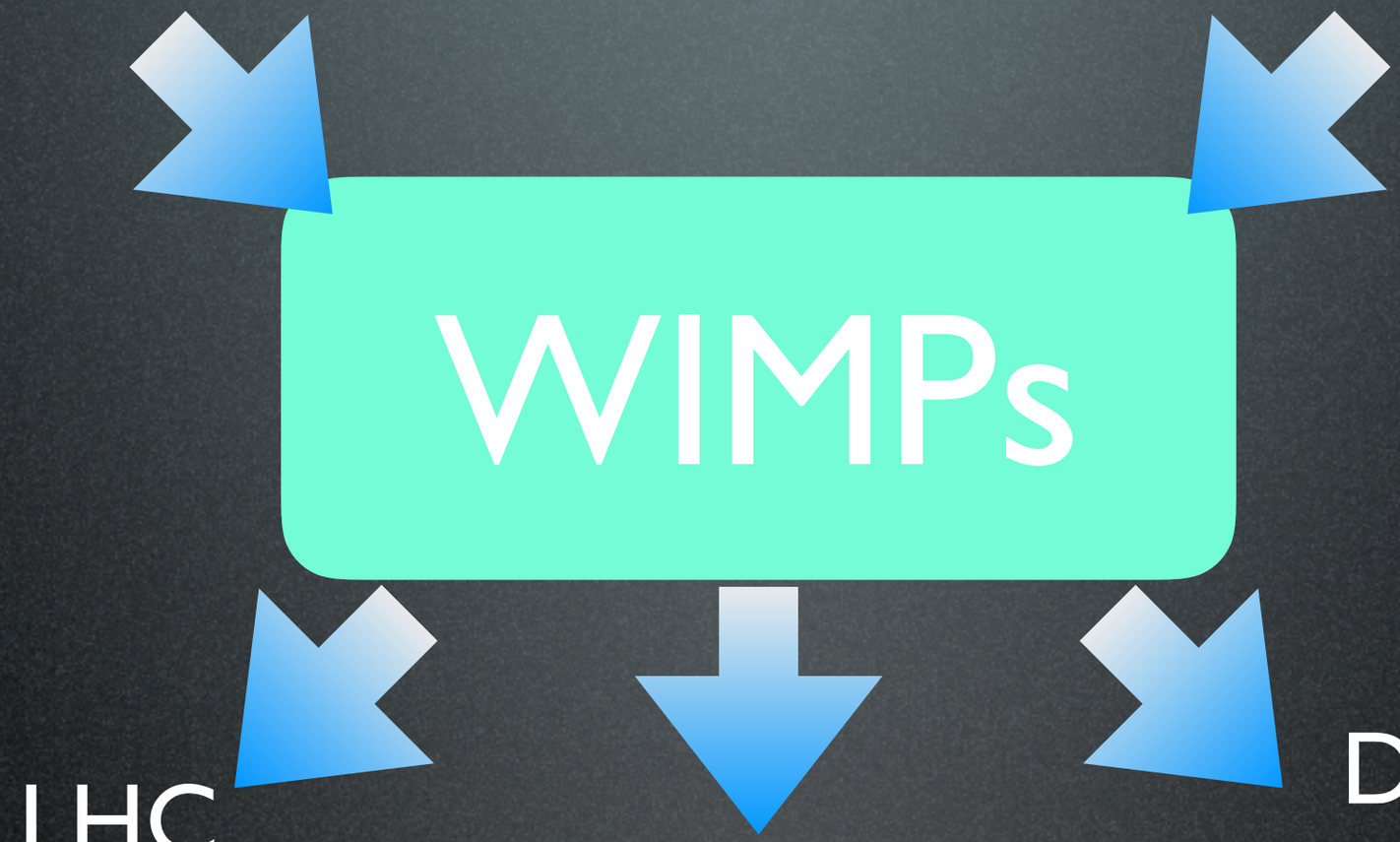
$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\,TeV^2}} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

Candidates

new physics at the TeV scale

thermal freeze-out



LHC

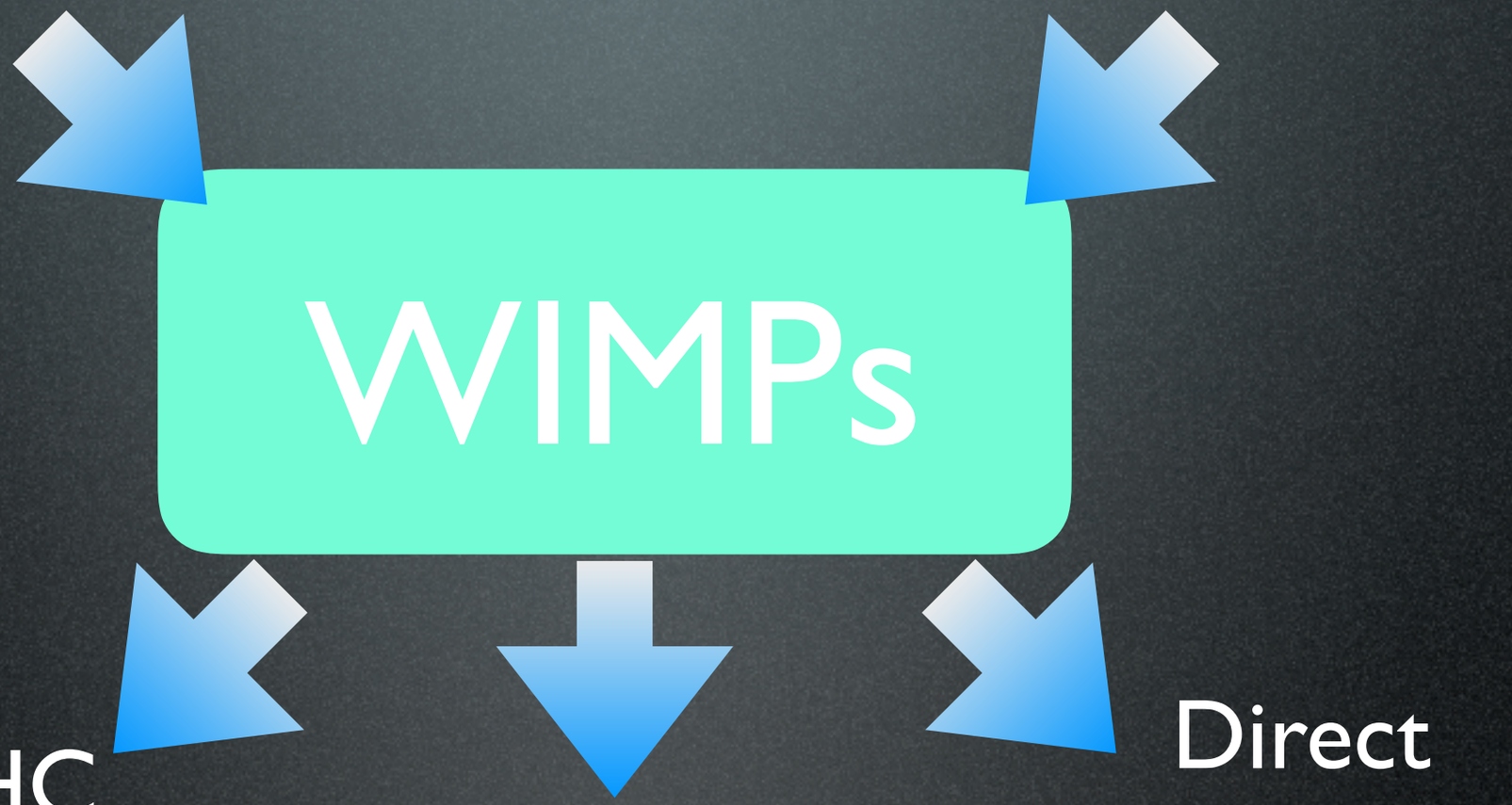
Indirect Detection

Direct Detection

Candidates

new physics at the TeV scale

thermal freeze-out



LHC

Indirect Detection

Direct Detection

1.
2.

Candidates

new physics at the TeV scale

thermal freeze-out

WIMPs

LHC

Indirect Detection

Direct Detection

1. even without a larger framework, WIMPs are still appealing
2.

Candidates

new physics at the TeV scale

thermal freeze-out

WIMPs

LHC

Indirect Detection

Direct Detection

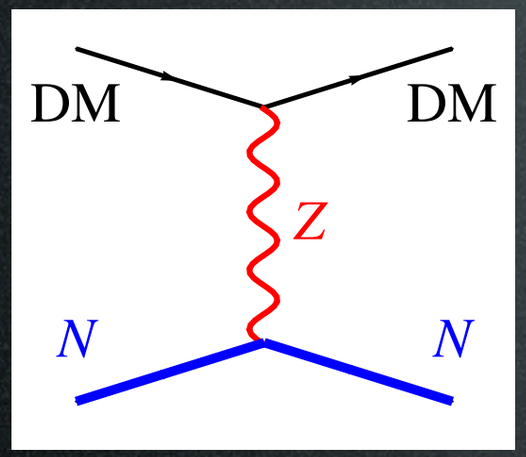
1. even without a larger framework, WIMPs are still appealing
2. the three search strategies are complementary

WIMP DD: '**theory**'

SM weak scale SI interactions

WIMP DD: 'theory'

SM weak scale SI interactions

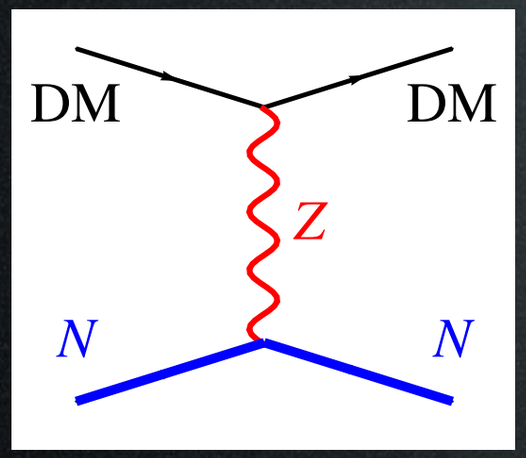


tree level, vector

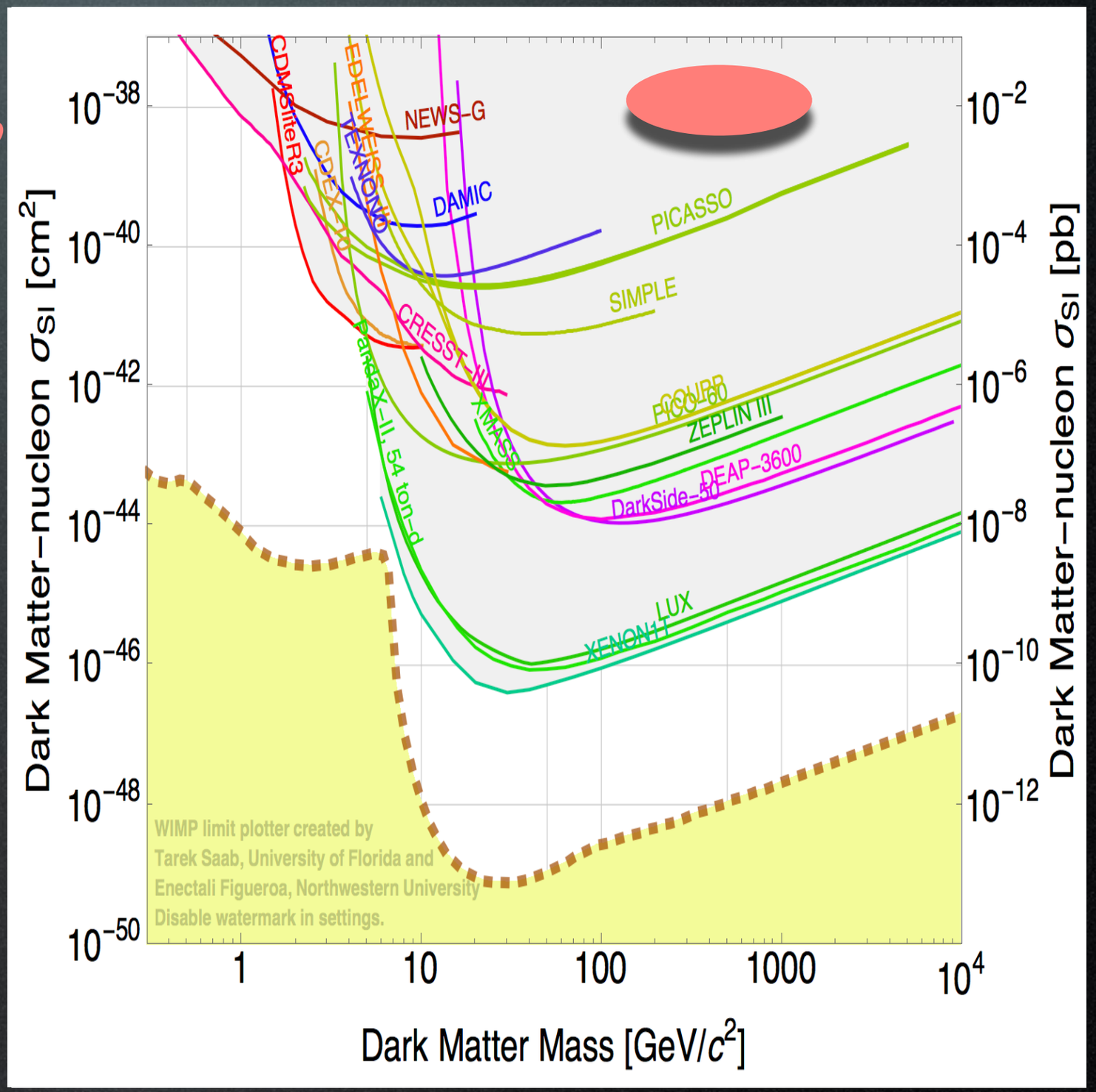
$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^2}{M_Z^4}$$

WIMP DD: 'theory'

SM weak scale SI interactions

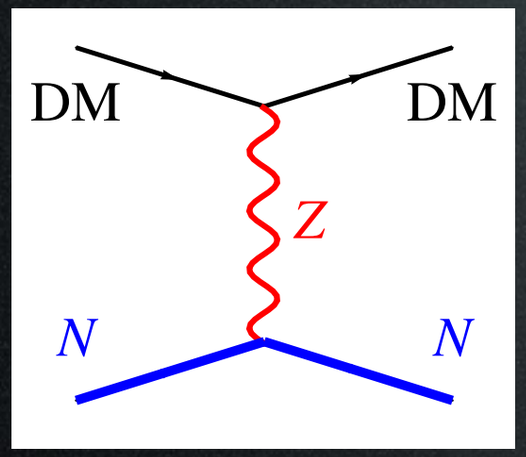


tree level, vector

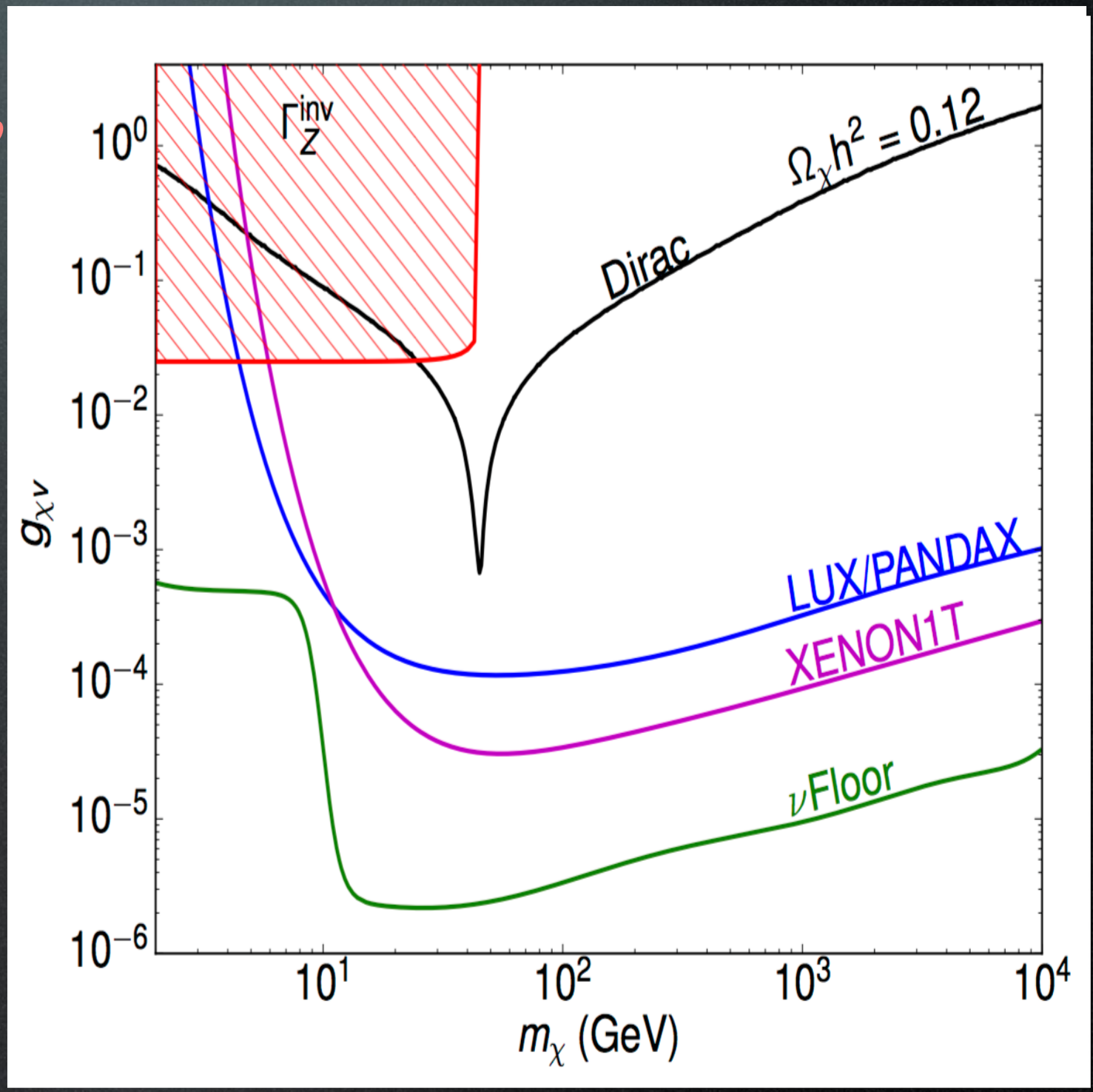


WIMP DD: 'theory'

SM weak scale SI interactions



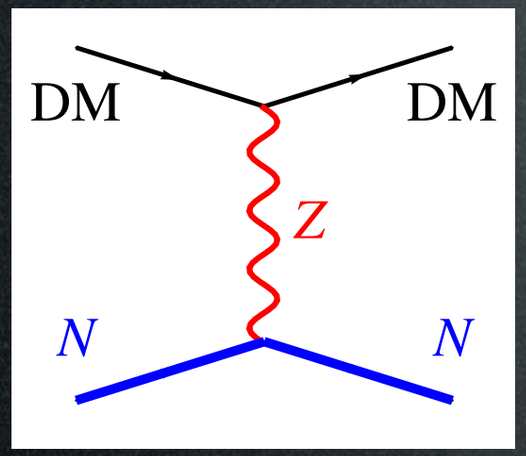
tree level, vector



Escudero, Berlin, Hooper, Lin 1609.09079

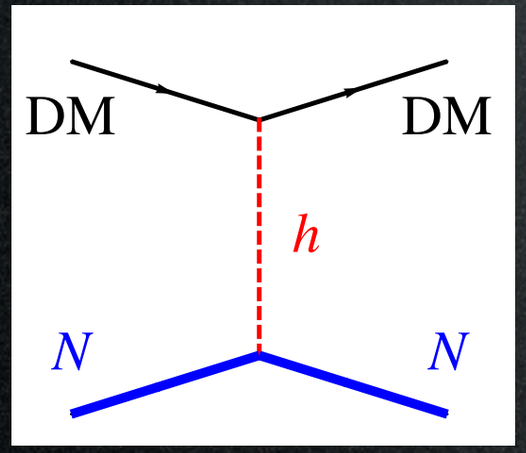
WIMP DD: 'theory'

SM weak scale SI interactions



tree level, vector

$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^2}{M_Z^4}$$

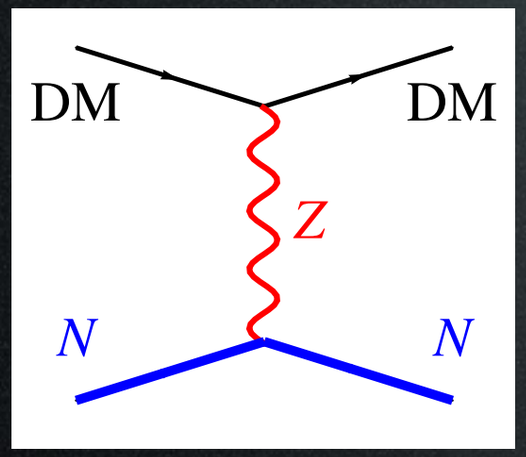


tree level, scalar

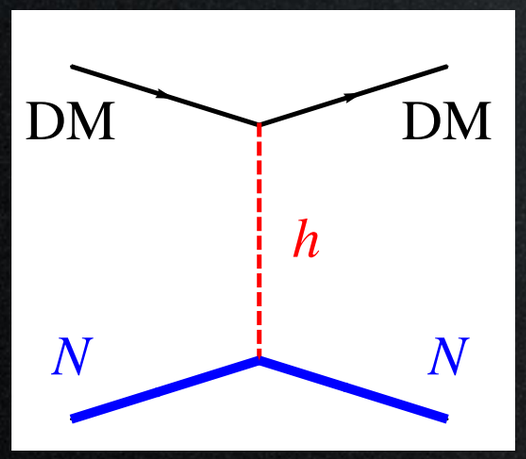
$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^4}{M_h^6}$$

WIMP DD: 'theory'

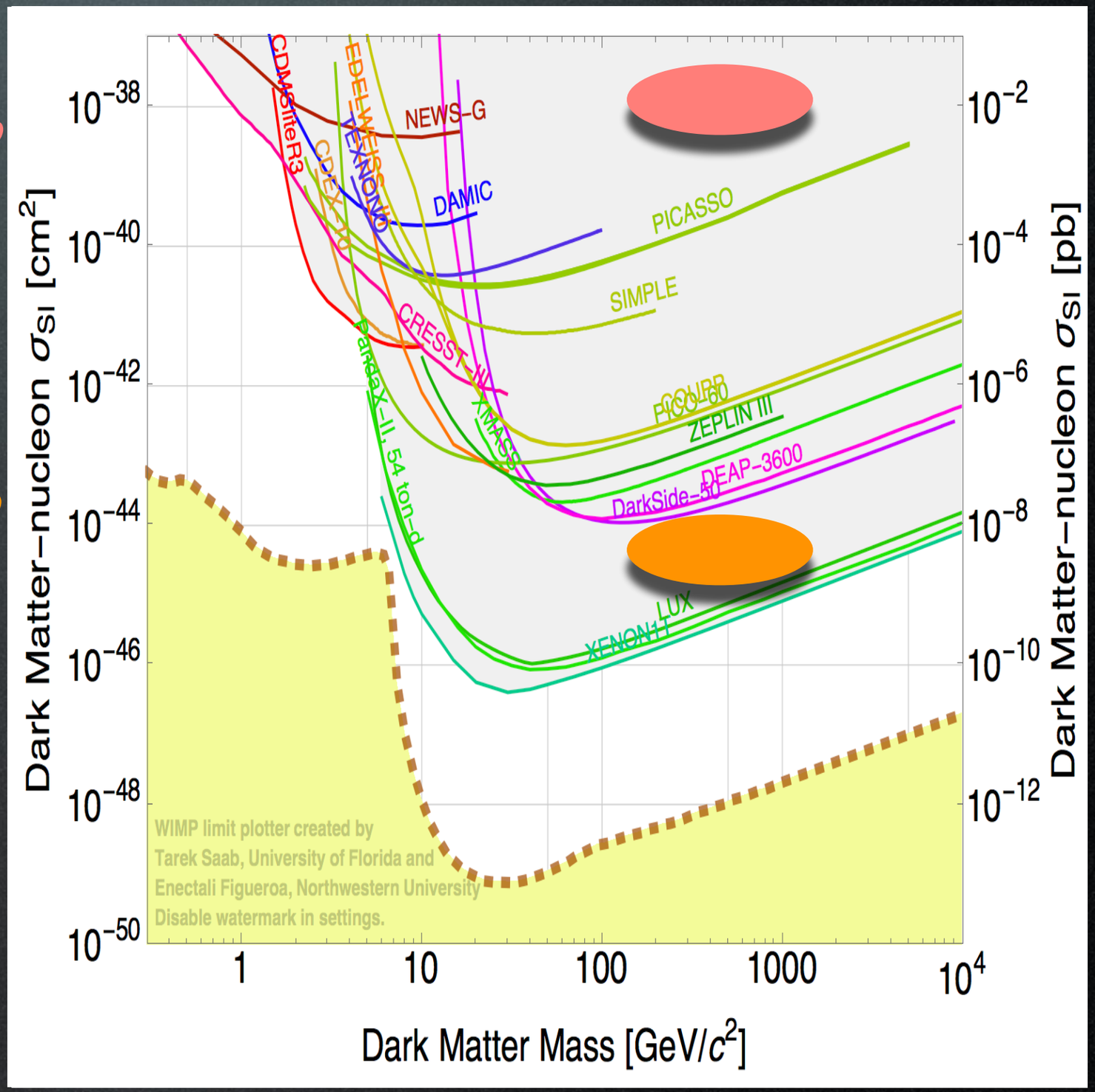
SM weak scale SI interactions



tree level, vector

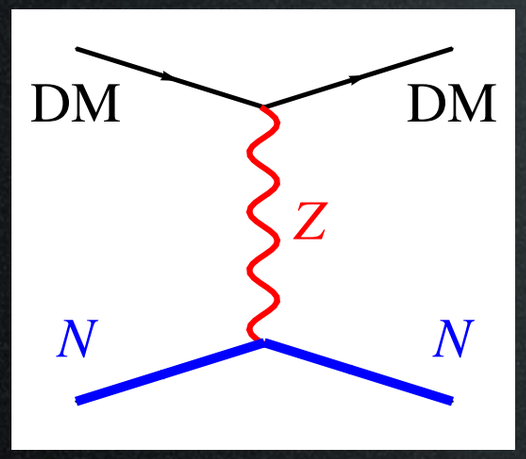


tree level, scalar

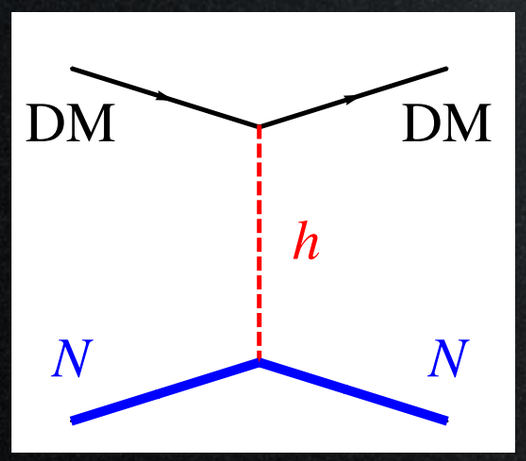


WIMP DD: 'theory'

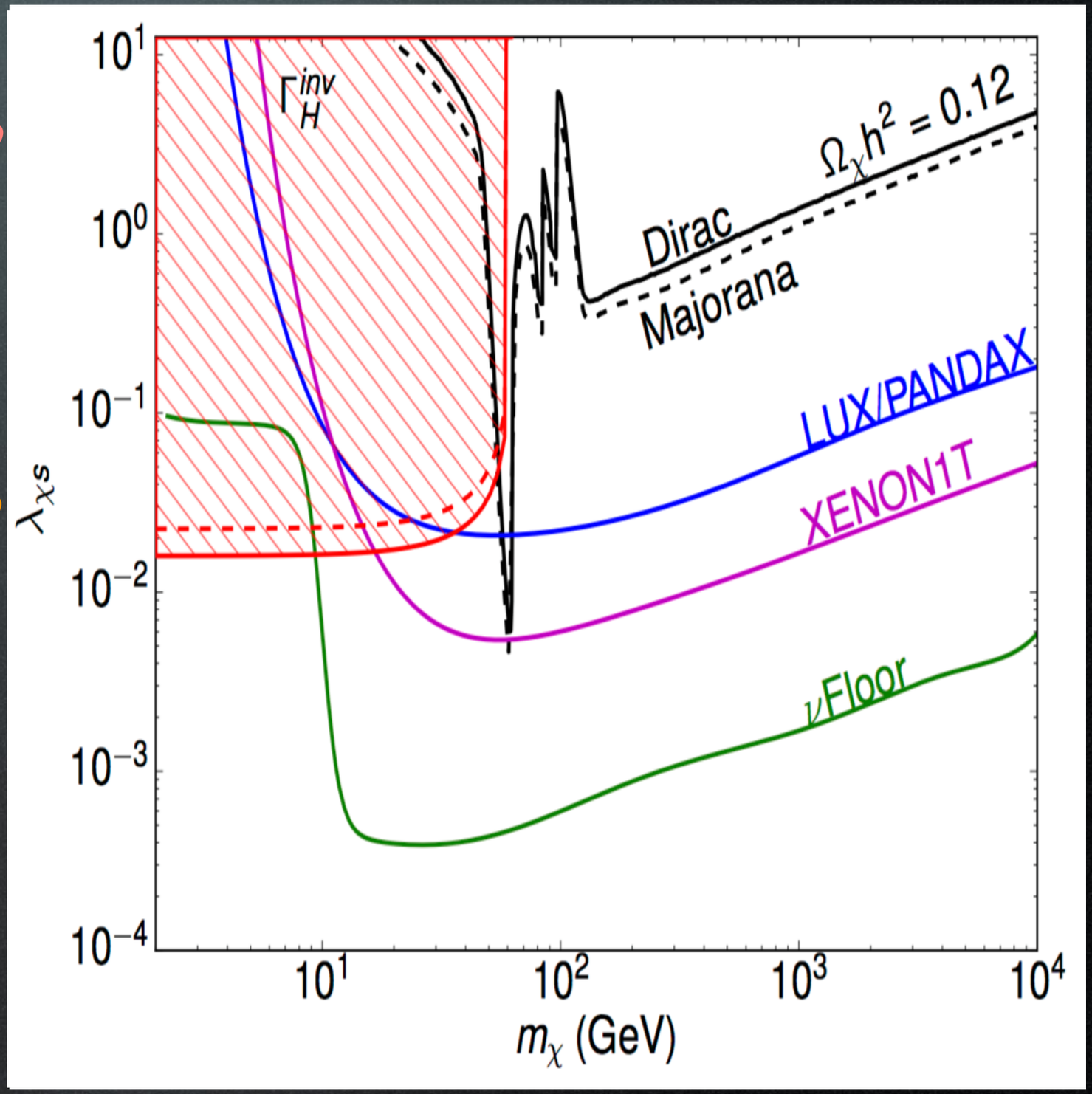
SM weak scale SI interactions



tree level, vector



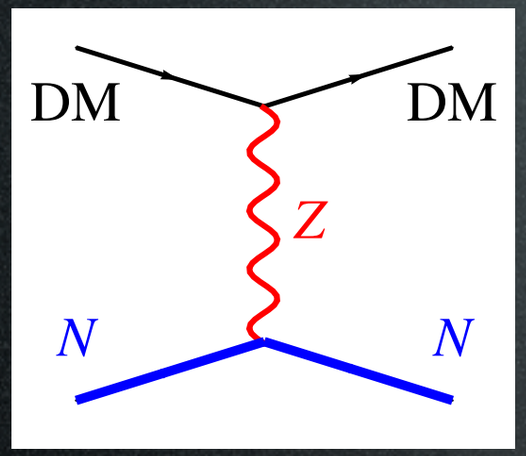
tree level, scalar



Escudero, Berlin, Hooper, Lin 1609.09079

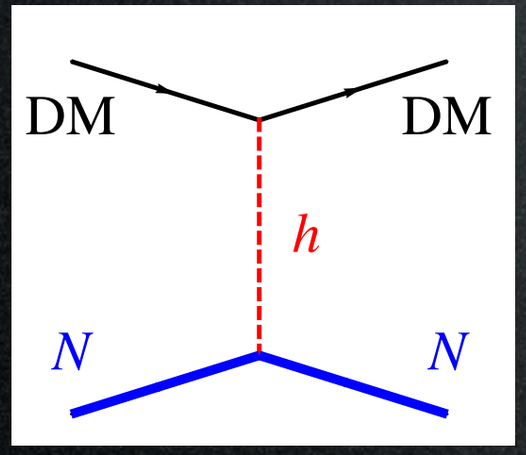
WIMP DD: 'theory'

SM weak scale SI interactions



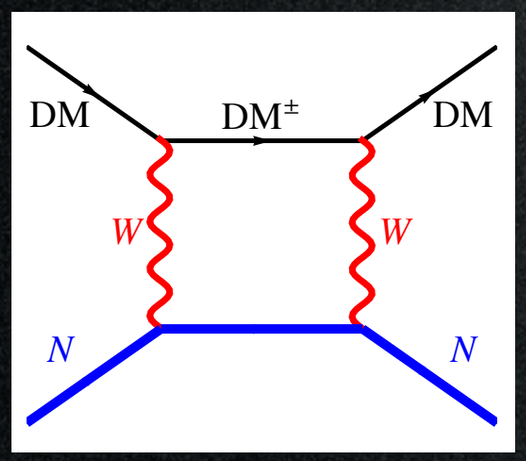
tree level, vector

$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^2}{M_Z^4}$$



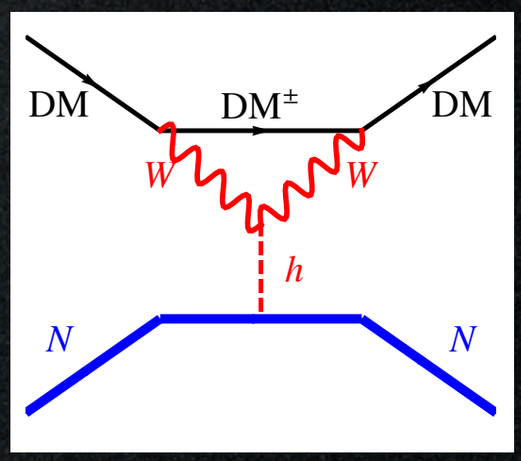
tree level, scalar

$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^4}{M_h^6}$$



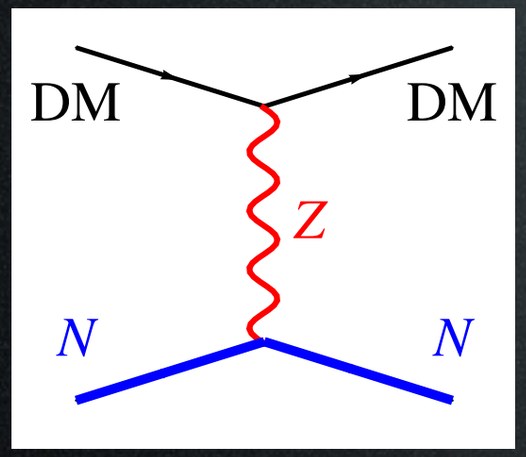
one loop

$$\sigma_{\rm SI} \sim \frac{\alpha^4 \ m_N^4}{M_W^6}$$

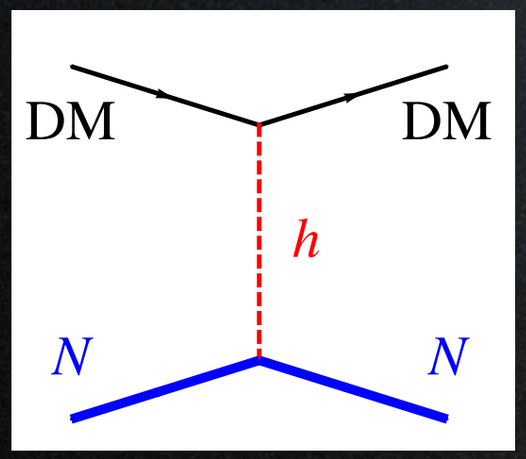


WIMP DD: 'theory'

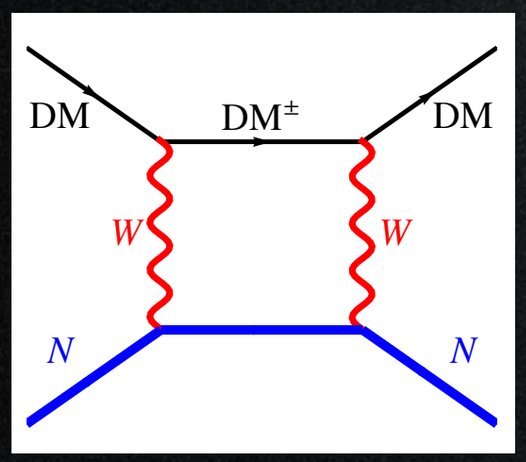
SM weak scale SI interactions



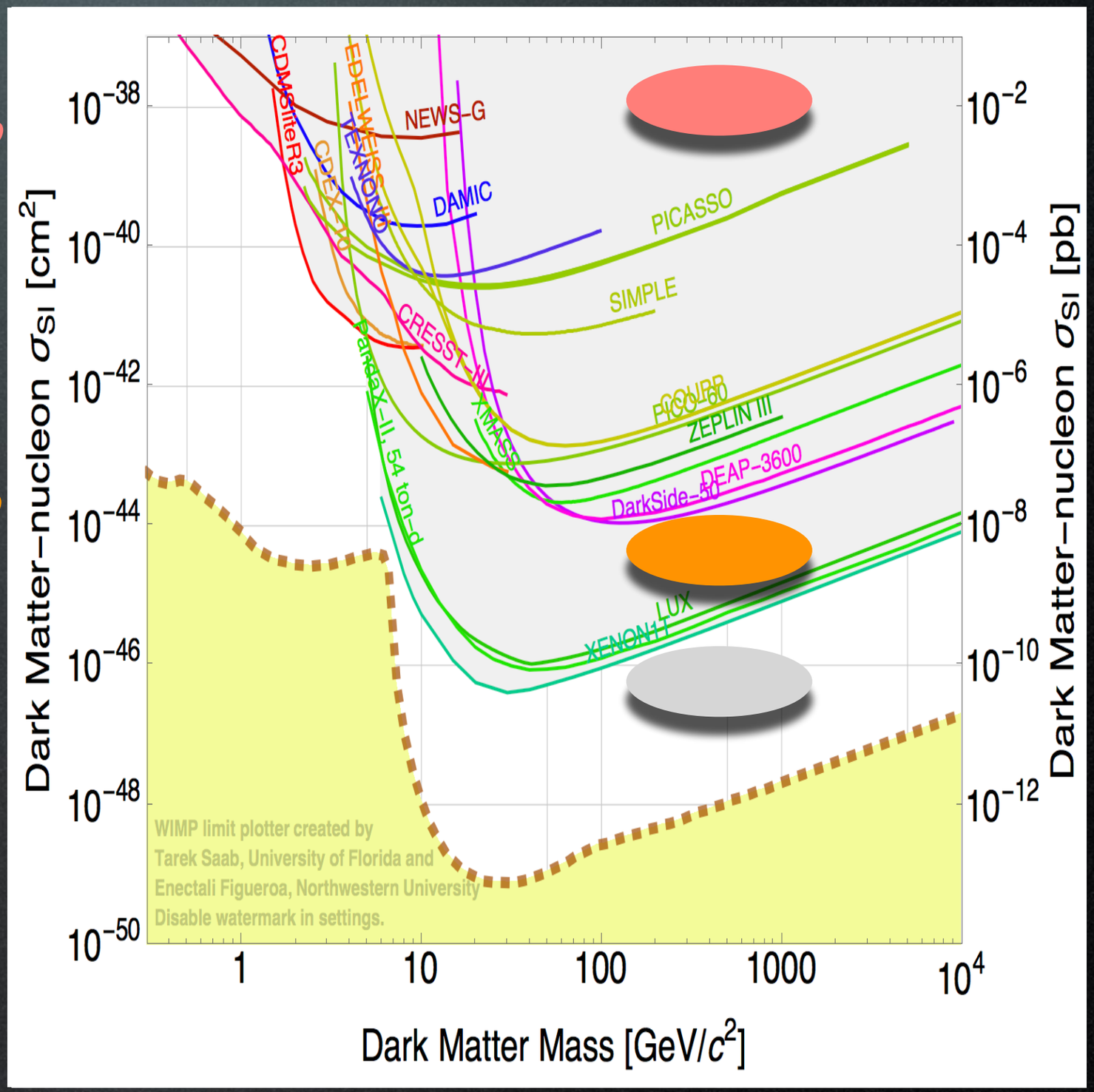
tree level, vector



tree level, scalar

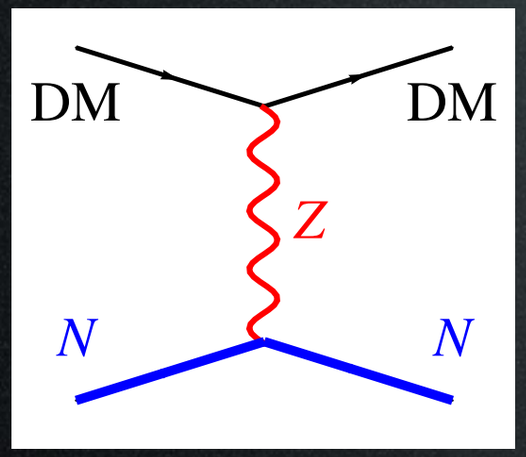


one loop

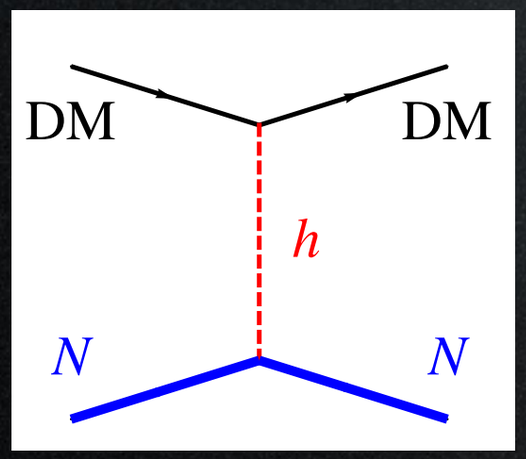


WIMP DD: 'theory'

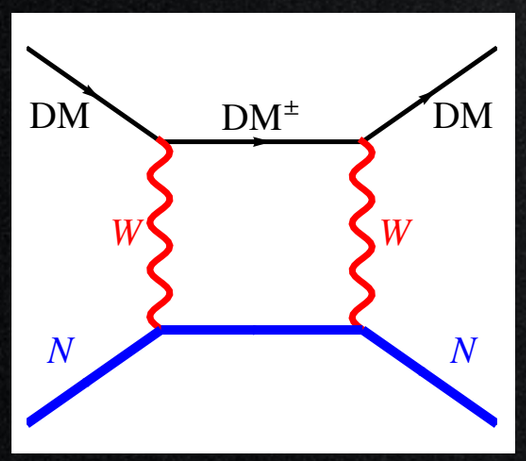
SM weak scale SI interactions



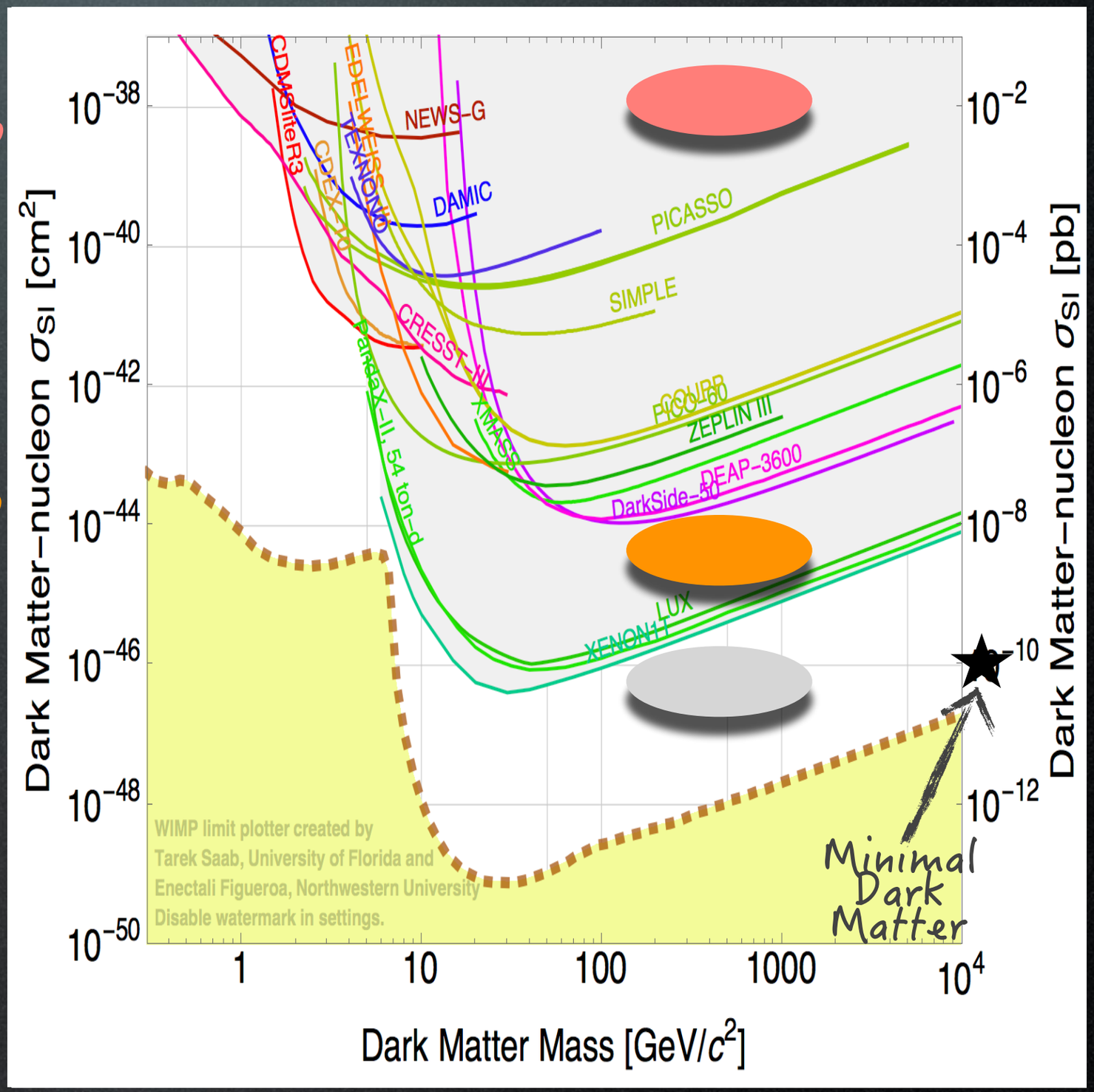
tree level, vector



tree level, scalar



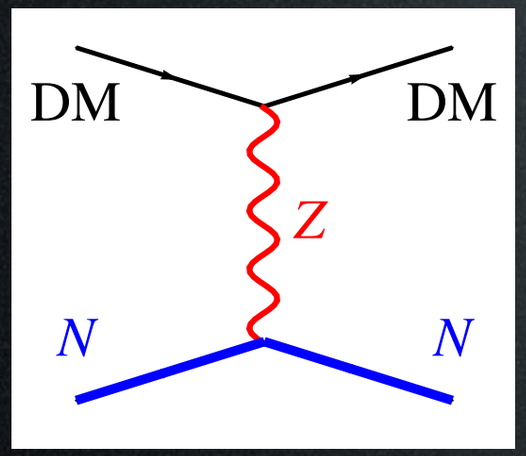
one loop



Cirelli, Fornengo, Strumia hep-ph/0512090

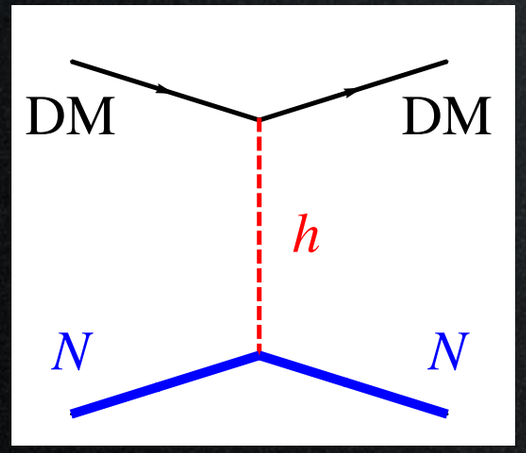
WIMP DD: 'theory'

SM weak scale SI interactions

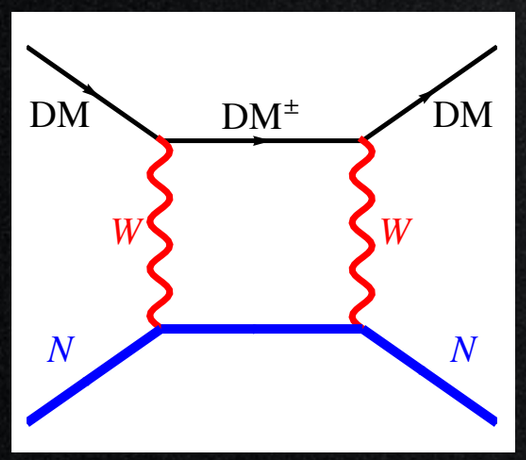


tree level, vector

Still viable under which conditions?



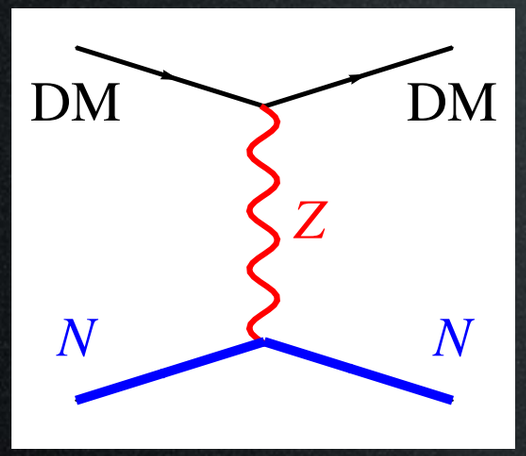
tree level, scalar



one loop

WIMP DD: 'theory'

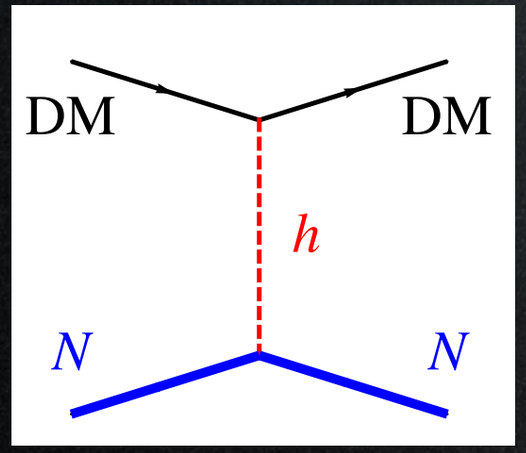
SM weak scale SI interactions



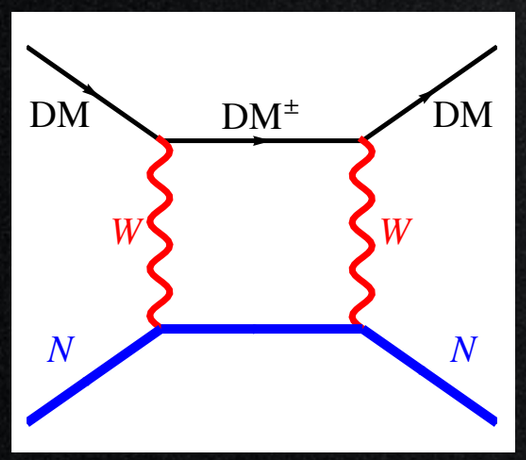
tree level, vector

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)



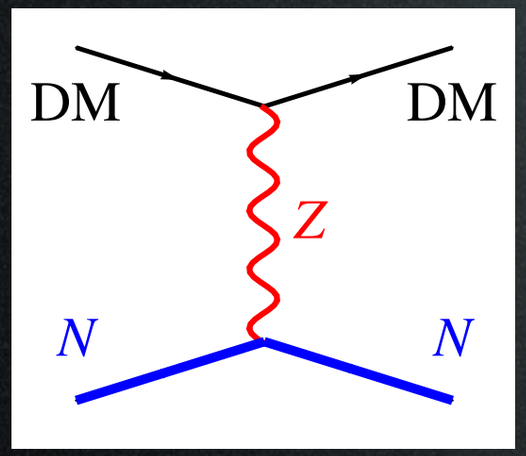
tree level, scalar



one loop

WIMP DD: 'theory'

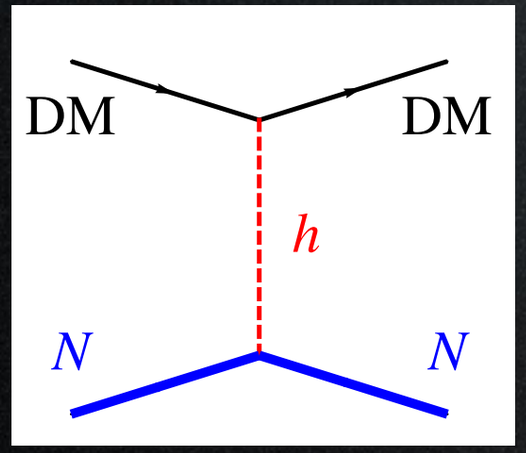
SM weak scale SI interactions



~~tree level, vector~~

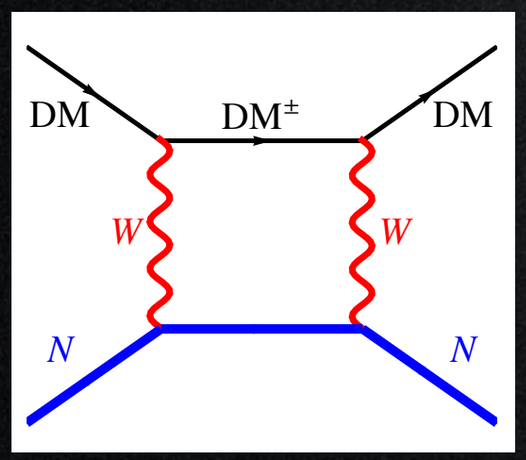
Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)



~~tree level, scalar~~

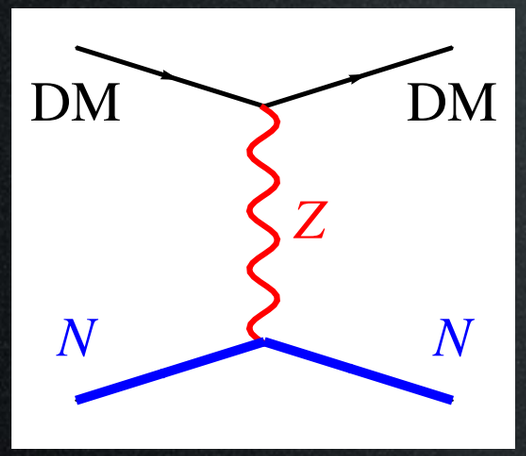
- hypercharge $Y = 0$



one loop

WIMP DD: 'theory'

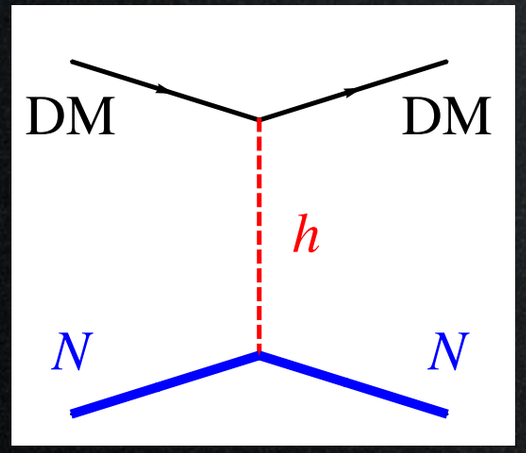
SM weak scale SI interactions



~~tree level, vector~~

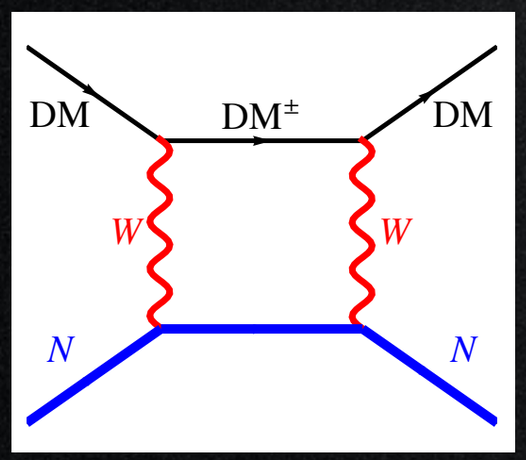
Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)

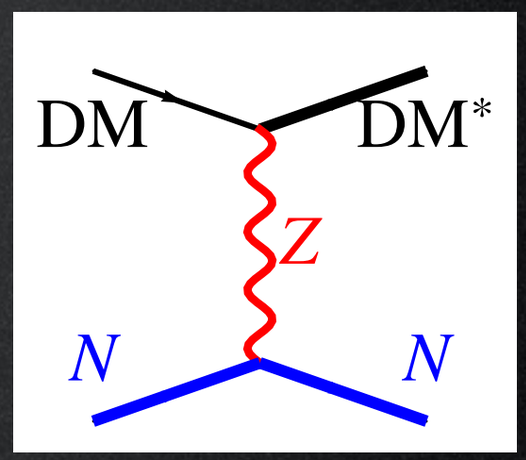


~~tree level, scalar~~

- hypercharge $Y = 0$
- SD interactions only
- inelastic scattering



one loop



Candidates

new physics at the TeV scale

thermal freeze-out

WIMPs

LHC

AMS, Fermi, CTA
Antares, Icecube

Direct Detection

1. even without a larger framework, WIMPs are still appealing
2. the three search strategies are complementary

Asymmetric DM: a completely different relic

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5$$

Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

Asymmetric DM: a completely different relic

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5$$

Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

Baryogenesis:

$$\eta_{\rm B} = \frac{n_{\rm B} - n_{\bar{\rm B}}}{n_\gamma} = 6 \cdot 10^{-10}$$

BBN, CMB...

$$\Omega_{\rm B} \propto m_{\rm B}\, \eta_{\rm B}$$

'Darko'genesis:

$$\eta_{\rm DM} = \frac{n_{\rm DM} - n_{\overline{\rm DM}}}{n_\gamma} \stackrel{?}{=} \eta_{\rm B}$$

$$\Omega_{\rm DM} \propto m_{\rm DM}\, \eta_{\rm DM}$$

Asymmetric DM: a completely different relic

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5$$

Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

Baryogenesis:

$$\eta_{\rm B} = \frac{n_{\rm B} - n_{\bar{\rm B}}}{n_\gamma} = 6 \cdot 10^{-10}$$

BBN, CMB...

$$\Omega_{\rm B} \propto m_{\rm B}\, \eta_{\rm B}$$

'Darko'genesis:

$$\eta_{\rm DM} = \frac{n_{\rm DM} - n_{\overline{\rm DM}}}{n_\gamma} \stackrel{?}{=} \eta_{\rm B}$$

$$\Omega_{\rm DM} \propto m_{\rm DM}\, \eta_{\rm DM}$$

$$m_{\rm DM} \simeq 5 \text{ GeV}$$

Asymmetric DM: a completely different relic

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5$$

Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

Baryogenesis:

$$\eta_{\rm B} = \frac{n_{\rm B} - n_{\bar{\rm B}}}{n_\gamma} = 6 \cdot 10^{-10}$$

BBN, CMB...

'Darko'genesis:

$$\eta_{\rm DM} = \frac{n_{\rm DM} - n_{\overline{\rm DM}}}{n_\gamma} \stackrel{?}{=} \eta_{\rm B}$$

A variety of specific models/ideas:

transferring or co-genesis

cfr J. March-Russell

DM stores the anti-B number

via leptogenesis

connection to neutrino masses

Asymmetric DM: a completely different relic

$$\chi\bar{\chi} \leftrightarrows f\bar{f} \quad \chi\bar{\chi} \to f\bar{f} \qquad \chi\,? \nrightarrow \ldots$$

Consider a particle χ:

- subject to $\chi\bar{\chi} \to \ldots$
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- **A**symmetric abundance
- large annihilation cross sec

Asymmetric DM: a completely different relic

$$\chi\bar{\chi} \leftrightarrows f\bar{f} \quad \chi\bar{\chi} \to f\bar{f} \qquad \chi\,? \nrightarrow \ldots$$

Consider a particle χ:

- subject to $\chi\bar{\chi} \to \ldots$
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- **A**symmetric abundance
- large annihilation cross sec

Asymmetric DM: a completely different relic

Consider a particle χ:

- subject to $\chi\bar{\chi} \to \ldots$
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- **A**symmetric abundance
- large annihilation cross sec

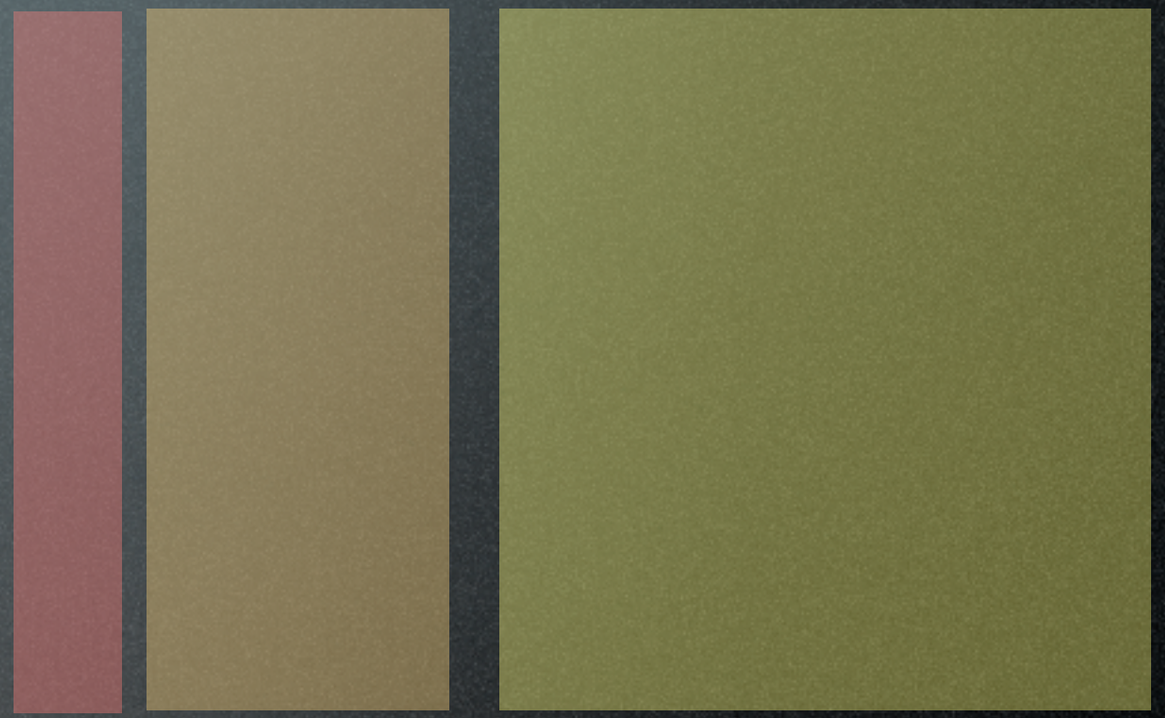
$\chi\bar{\chi} \leftrightarrows f\bar{f} \quad \chi\bar{\chi} \to f\bar{f} \qquad \chi ? \nrightarrow \ldots$

Asymmetric DM: a completely different relic

$\chi\bar{\chi} \leftrightarrows f\bar{f}$ $\chi\bar{\chi} \to f\bar{f}$ $\chi\,? \nrightarrow \ldots$

Consider a particle χ:

- subject to $\chi\bar{\chi} \to \ldots$
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- **A**symmetric abundance
- large annihilation cross sec

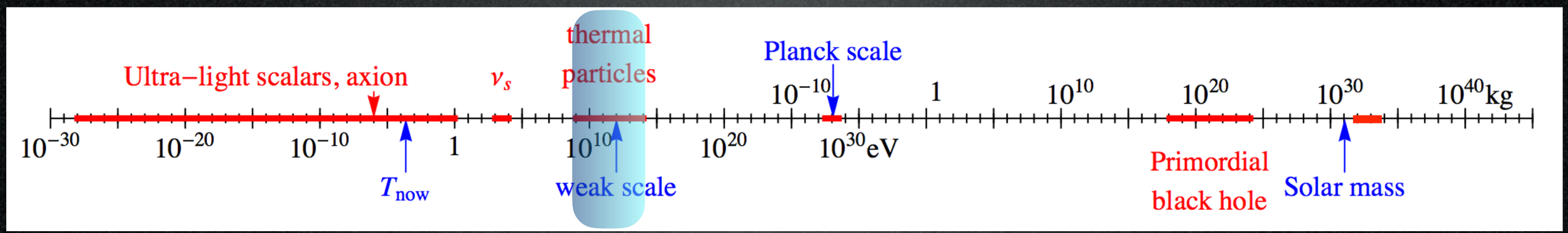


$$\Omega_{\rm X} \simeq \frac{m_{\rm X}\, s}{\rho_{\rm crit}} \eta_0$$

The relic abundance is determined by η_0 and $m_{\rm X}$.

Candidates

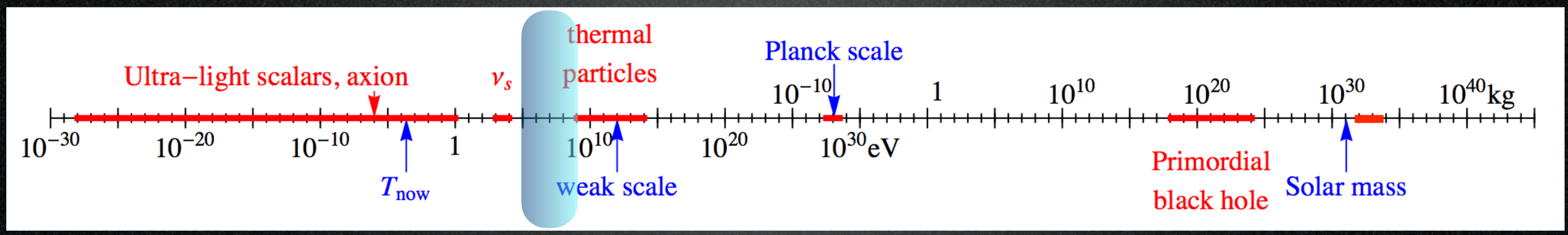
A matter of perspective: plausible mass ranges



'only' 90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges

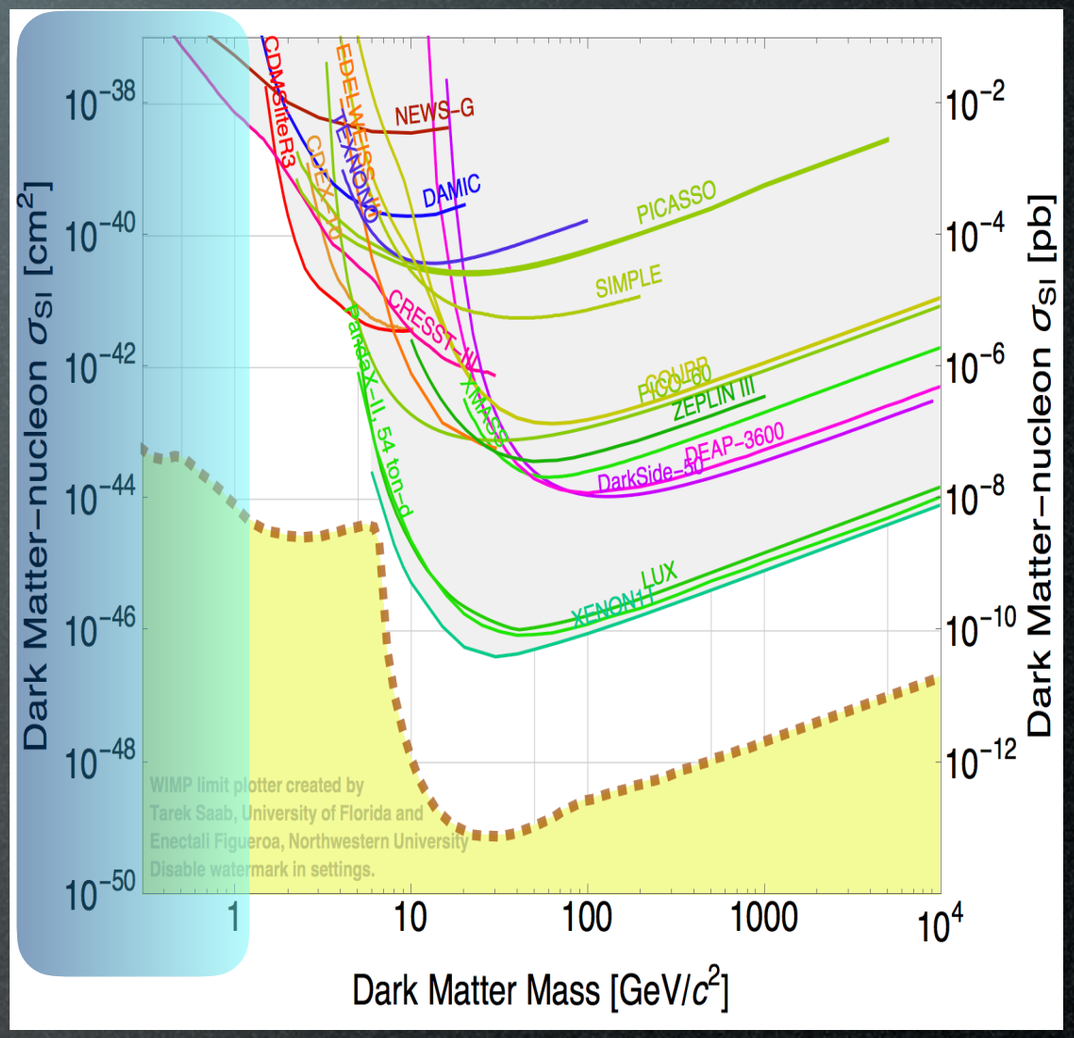


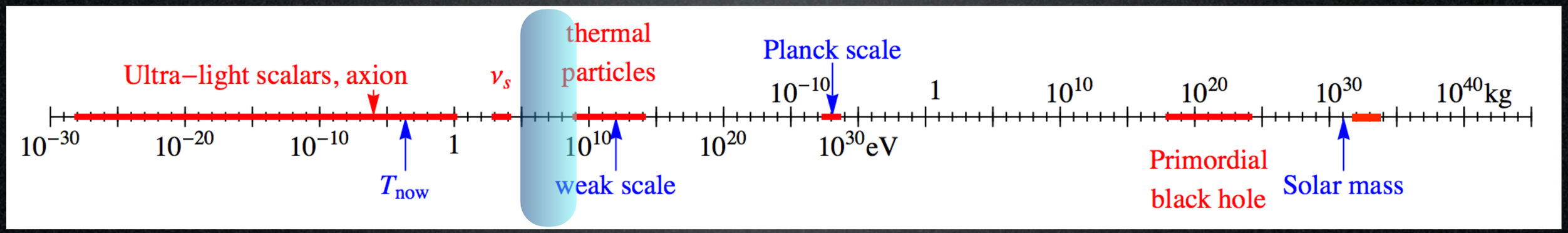
‘only’ 90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges

Sub-GeV DM?





'only' 90 orders of magnitude!

Candidates

Sub-GeV DM

- WIMPless Dark Matter

  Feng & Kumar 0803.4196

  a.k.a. hidden sector DM

  ~secluded DM

Candidates

Sub-GeV DM

- WIMPless Dark Matter
  Feng & Kumar 0803.4196

  $$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\rm TeV^2}$$

  a.k.a. hidden sector DM
  ~secluded DM

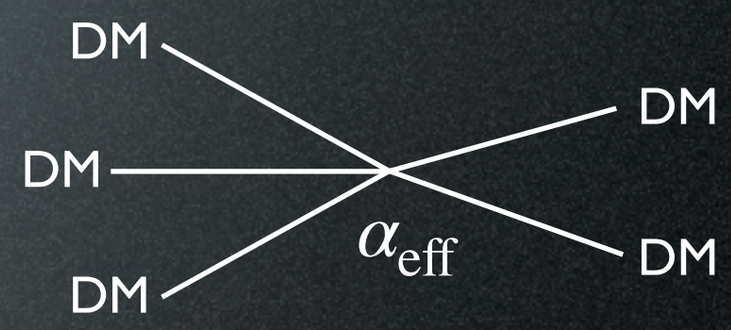
  $$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_x^2}{m^2}$$

Candidates

Sub-GeV DM

- ‘SIMP miracle’:

  scalar DM with relic abundance set by 3 -> 2 processes



  points to $$m_{\rm DM} \sim \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100 \text{ MeV}$$

  Hochberg et al 1402.5143

‘naturally realized’ in a dark-QCD-like setup

Candidates

Sub-GeV DM

- 'MeV (scalar) DM' (for the Integral 511 KeV excess?)

Boehm & Fayet hep-ph/0305261

> In conclusion, scalar Dark Matter particles can be significantly lighter than a few GeV's (thus evading the generalisation of the Lee-Weinberg limit for weakly-interacting neutral fermions) if they are coupled to a new (light) gauge boson or to new heavy fermions F (through non chiral couplings and poten-

Candidates

Sub-GeV DM

- ‘simplified (light) DM models’ Knapen, Lin, Zurek 1709.07882

Candidates

Sub-GeV DM

- ‘simplified (light) DM models’

  scalar DM and hadrophilic scalar mediator

$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n\phi\bar{n}n,$$

Knapen, Lin, Zurek 1709.07882

Candidates

Sub-GeV DM

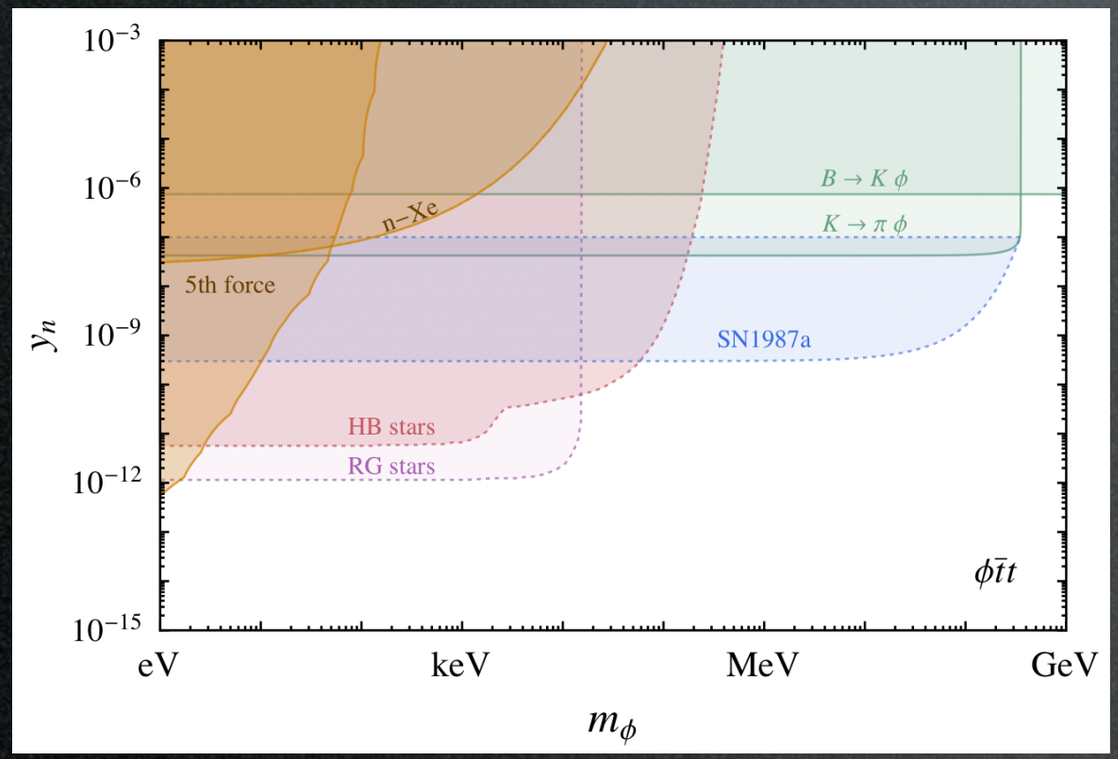
- 'simplified (light) DM models'

scalar DM and
hadrophilic
scalar mediator

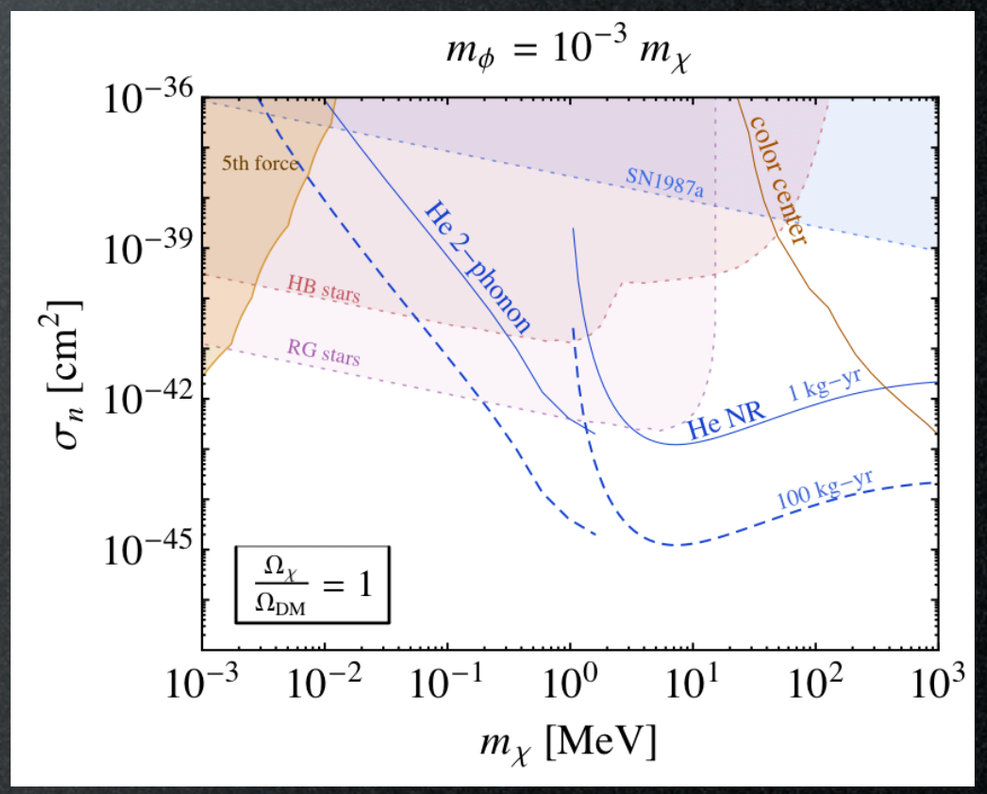
$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n \phi \bar{n} n,$$

Knapen, Lin, Zurek 1709.07882

constraints on the mediator



constraints on the DM



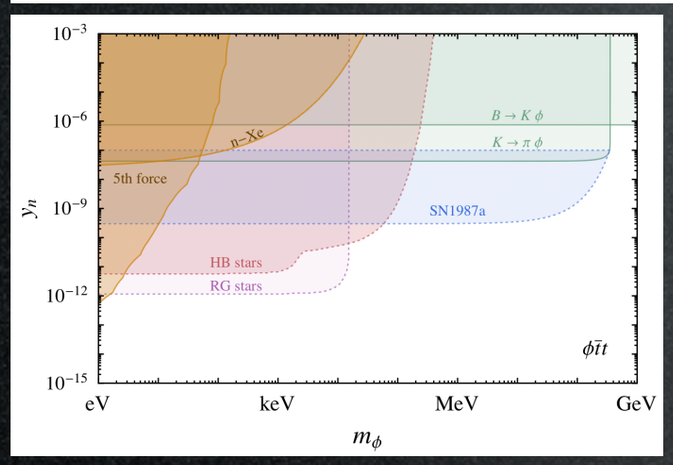
Candidates

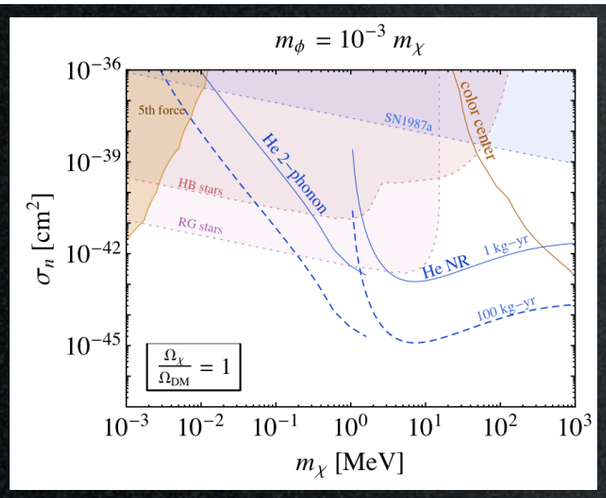
Sub-GeV DM

- ‘simplified (light) DM models’ Knapen, Lin, Zurek 1709.07882

scalar DM and
hadrophilic
scalar mediator

$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n \phi\bar{n}n,$$





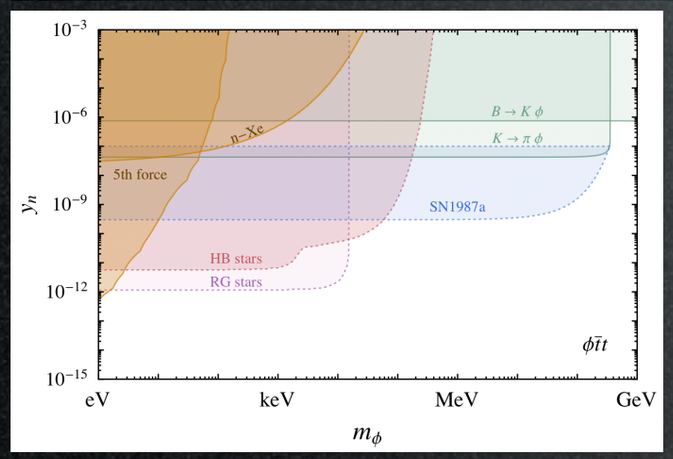
Candidates

Sub-GeV DM

- ‘simplified (light) DM models’ Knapen, Lin, Zurek 1709.07882

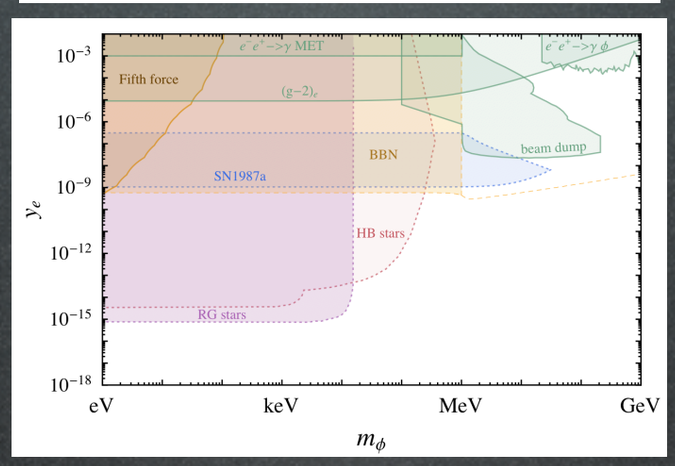
scalar DM and hadrophilic scalar mediator

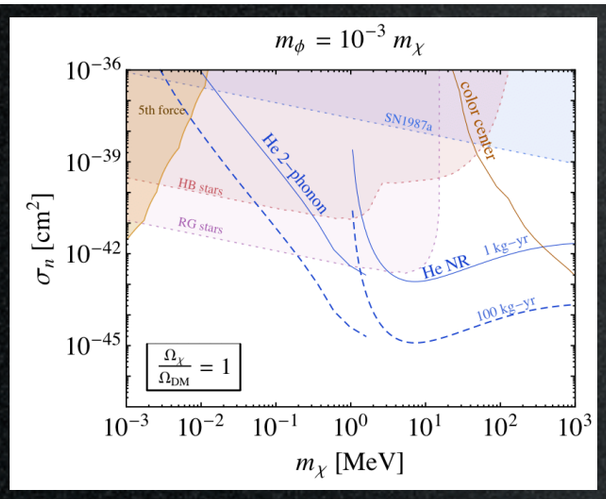
$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n \phi\bar{n}n,$$

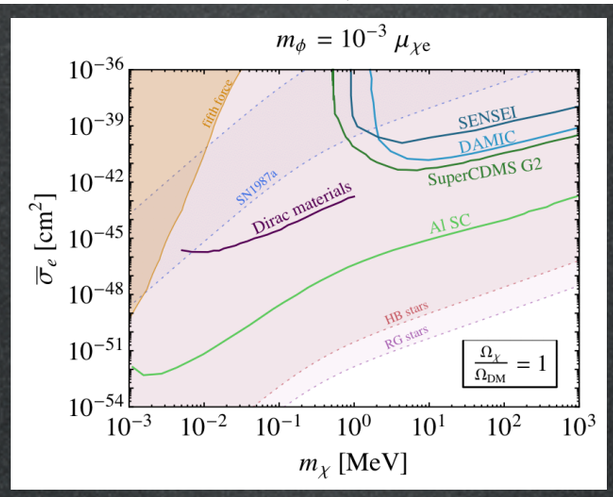


scalar DM and leptophilic scalar mediator

$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_e \phi\bar{e}e.$$







Candidates

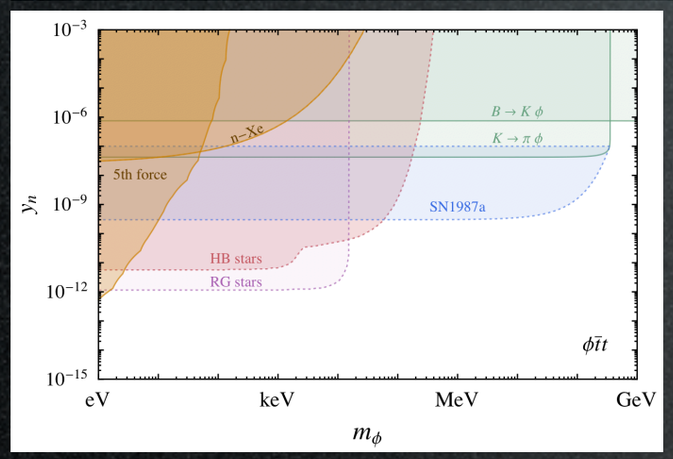
Sub-GeV DM

- 'simplified (light) DM models'

Knapen, Lin, Zurek 1709.07882

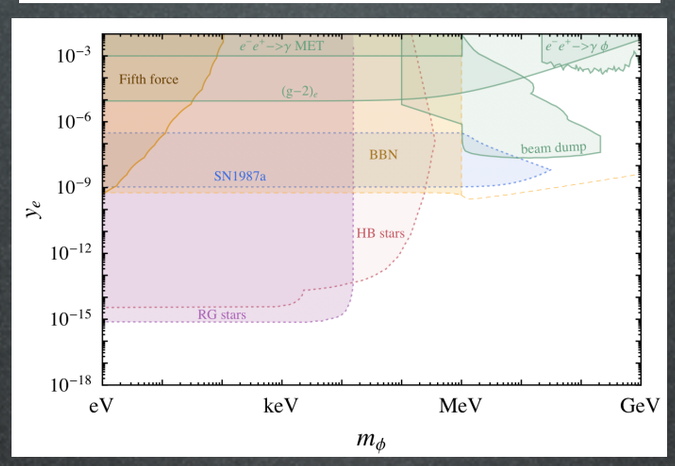
scalar DM and hadrophilic scalar mediator

$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n \phi\bar{n}n,$$



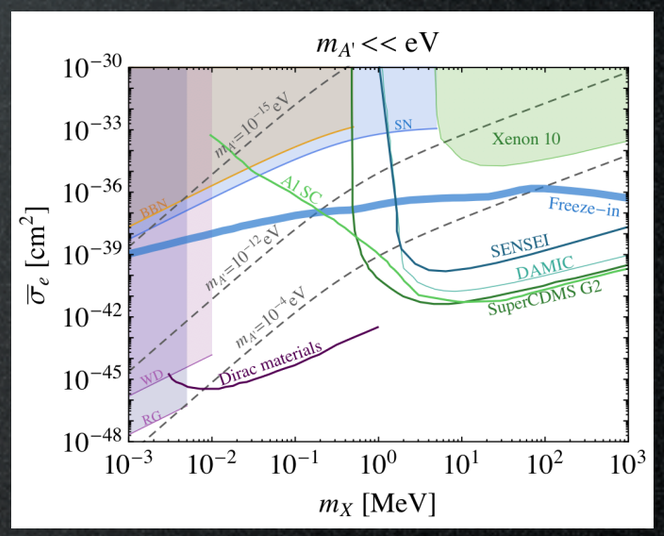
scalar DM and leptophilic scalar mediator

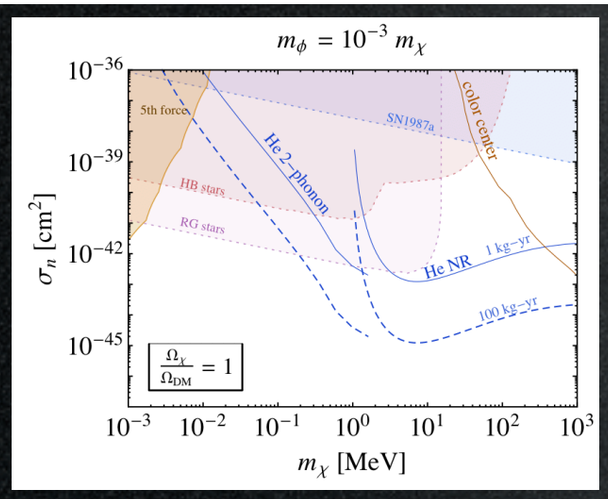
$$\mathcal{L} \supset -\frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_e \phi\bar{e}e.$$

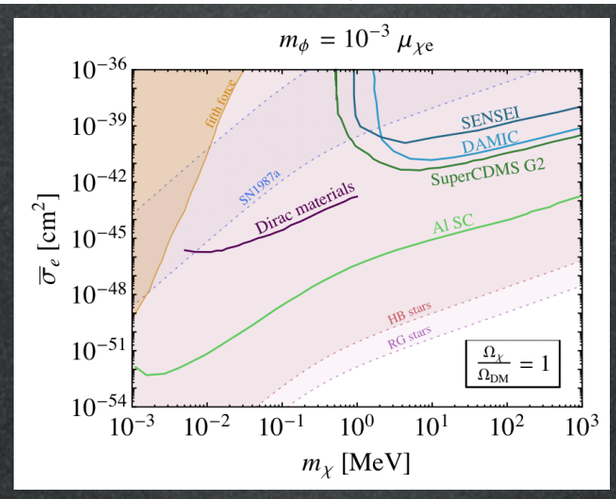


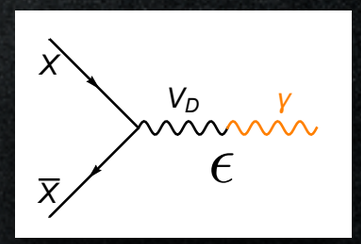
fermionic DM and vector mediator (e.g. dark photon)

$$\mathcal{L} \supset= -\frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} - y_\chi A'_\mu \bar{\chi}\gamma^\mu\chi$$





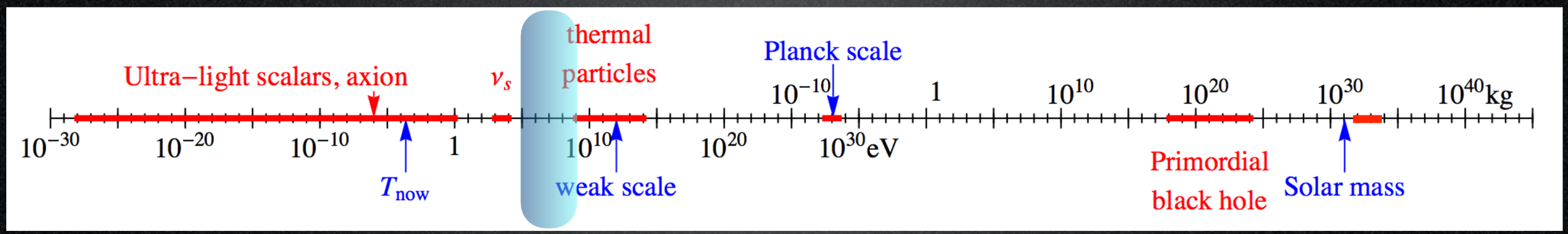




Candidates

Sub-GeV DM?

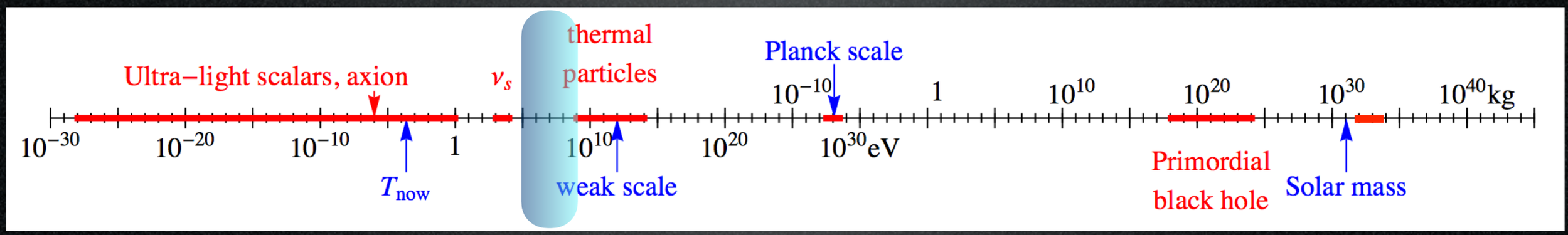
Why not!



'only' 90 orders of magnitude!

Candidates

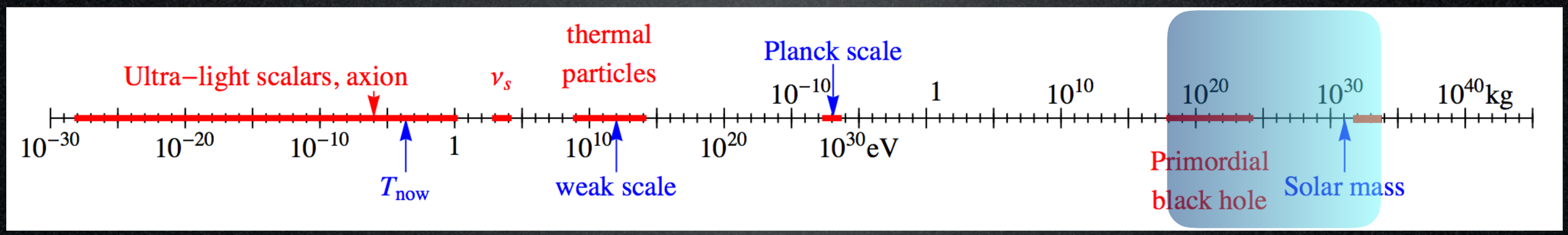
A matter of perspective: plausible mass ranges



‘only’ 90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges



'only' 90 orders of magnitude!

DM can **NOT** be:

an astro *je ne sais pas quoi*:

DM can **NOT** be:

an astro *je ne sais pas quoi*:

- gas

- Black Holes
- brown dwarves

DM can **NOT** be:

an astro *je ne sais pas quoi*:

- ~~gas~~

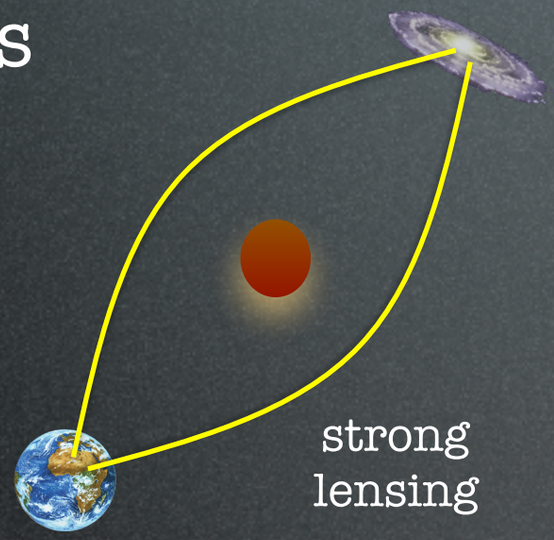
- Black Holes
- brown dwarves

DM can **NOT** be:

an astro *je ne sais pas quoi*:

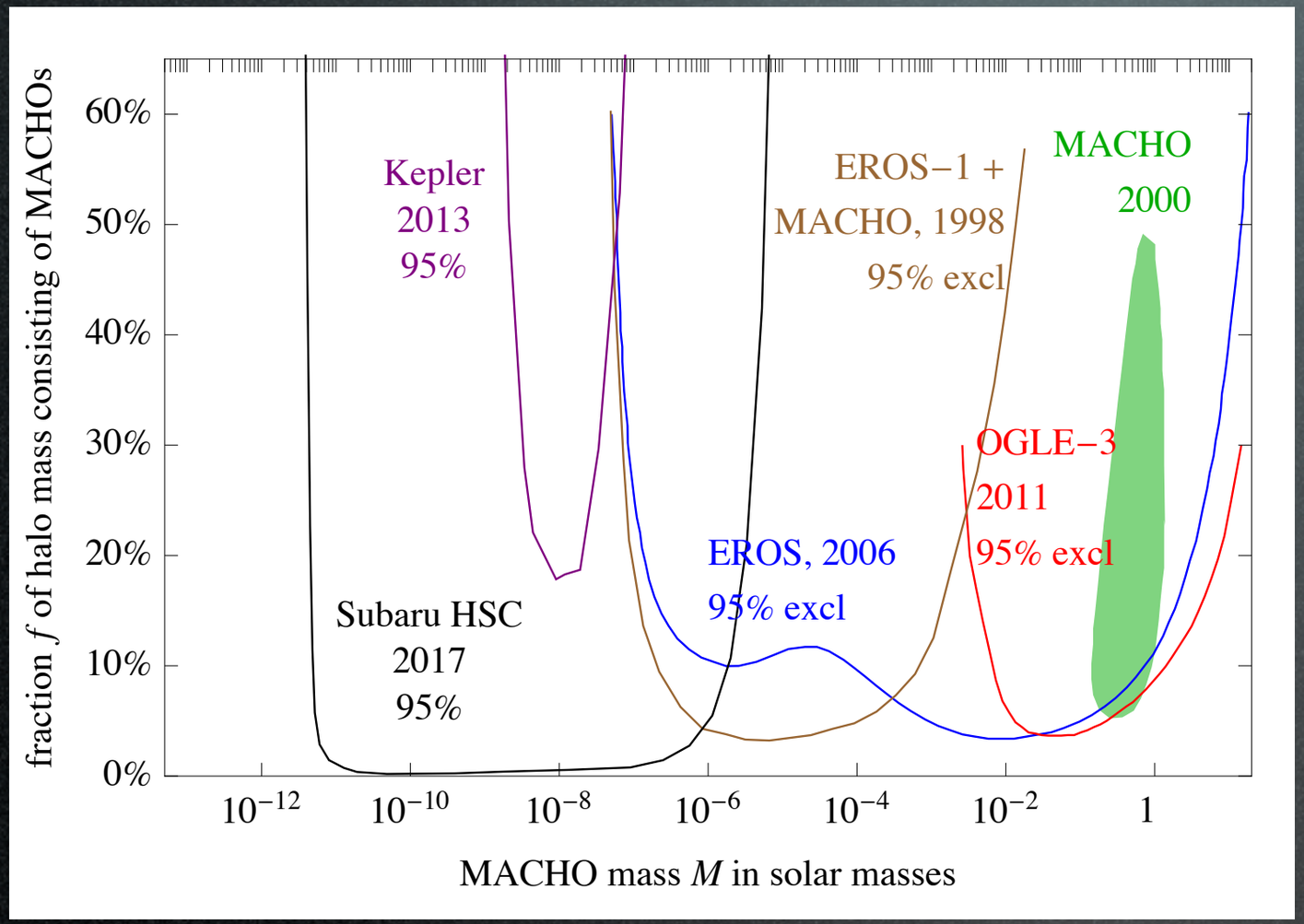
- ~~gas~~

- ~~Black Holes~~
- ~~brown dwarves~~



strong
lensing

MACHOs or PBHs as DM

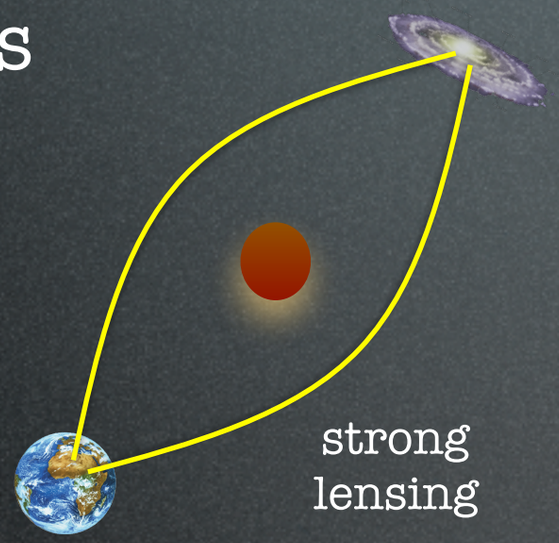


DM can **NOT** be:

an astro *je ne sais pas quoi*:

- ~~gas~~

- ~~Black Holes~~
- ~~brown dwarves~~



strong lensing

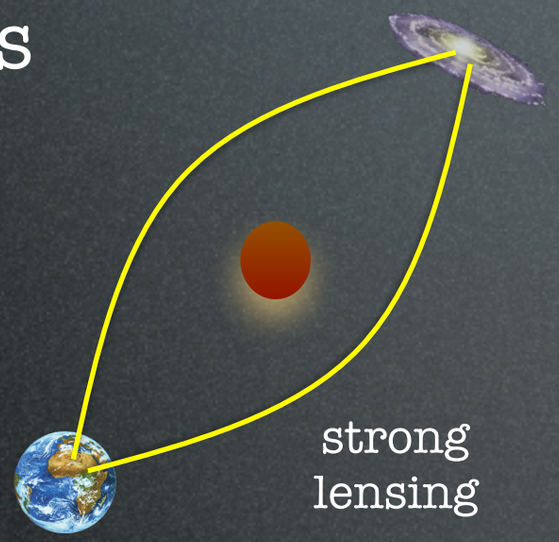
a baryon of the SM:

DM can **NOT** be:

an astro *je ne sais pas quoi*:

- ~~gas~~

- ~~Black Holes~~
- ~~brown dwarves~~



strong lensing

a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons:
  too much baryons => Universe full of Helium

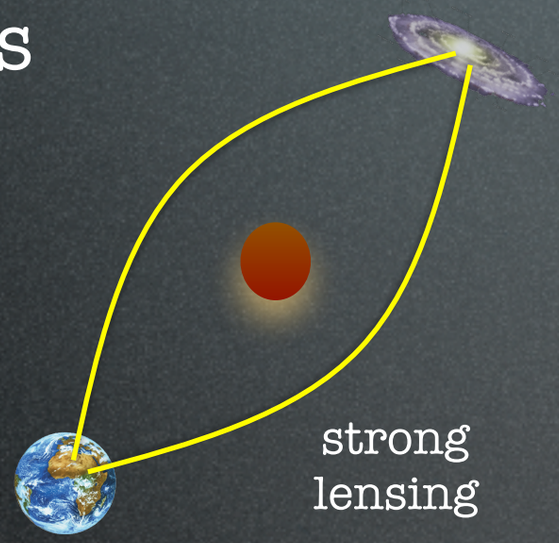
- CMB says baryons are 4% max

DM can be:

an astro *je ne sais pas quoi*:

- ~~gas~~

- ~~Black Holes~~
- ~~brown dwarves~~



a ~~baryon of the SM~~:

- BBN computes the abundance of He in terms of primordial baryons:
  too much baryons => Universe full of Helium

- CMB says baryons are 4% max

A loophole: Primordial Black Holes!

- produced before BBN
- with masses too small/large to lens
- perhaps LIGO is seeing them?

PBHs as DM

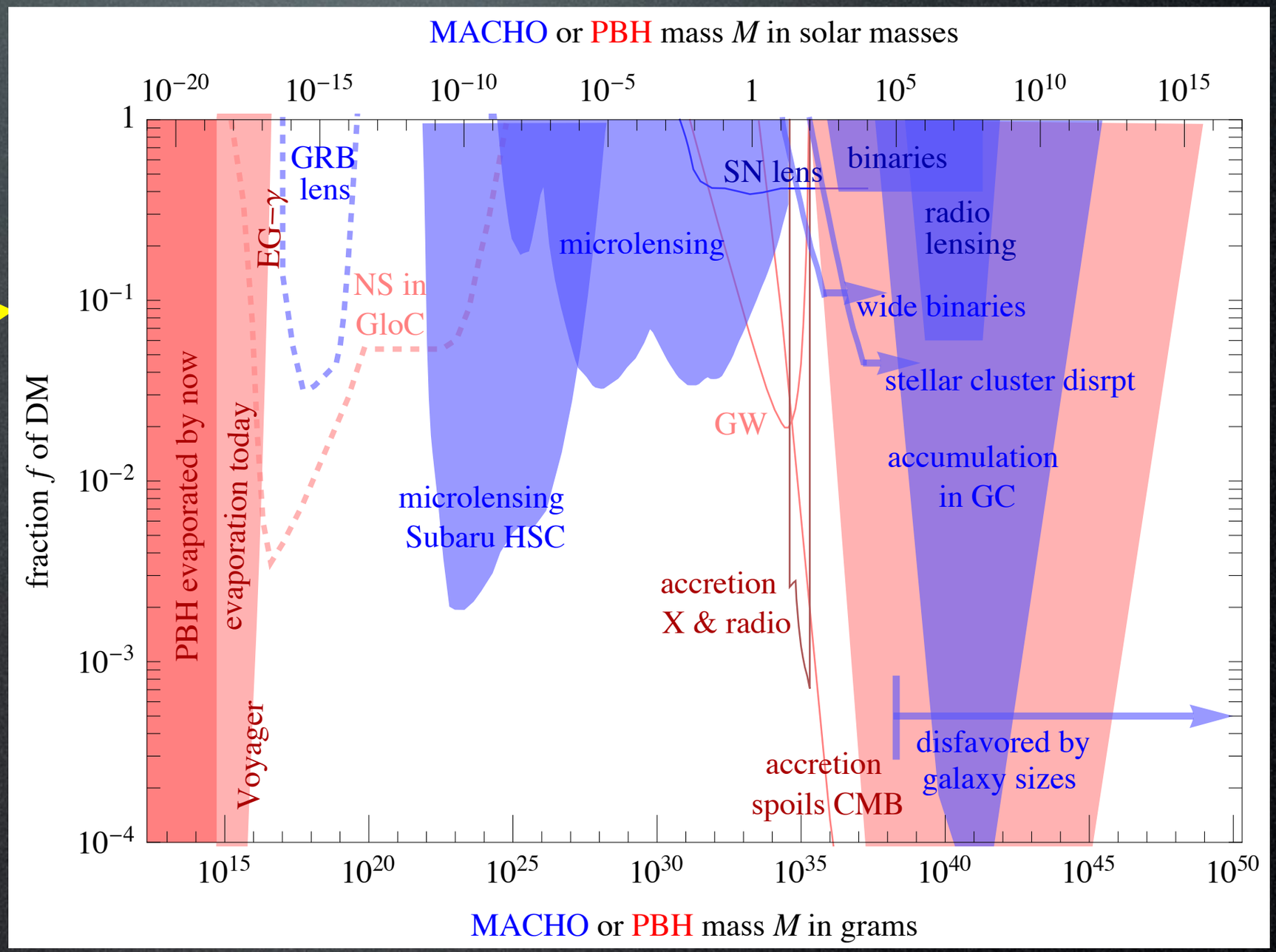
Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15}(t/10^{-23}\ \text{sec})\ \text{g}$$

constraints



M. Cirelli, A. Strumia, J. Zupan to appear

PBHs as DM

Constraints on Primordial Black Holes

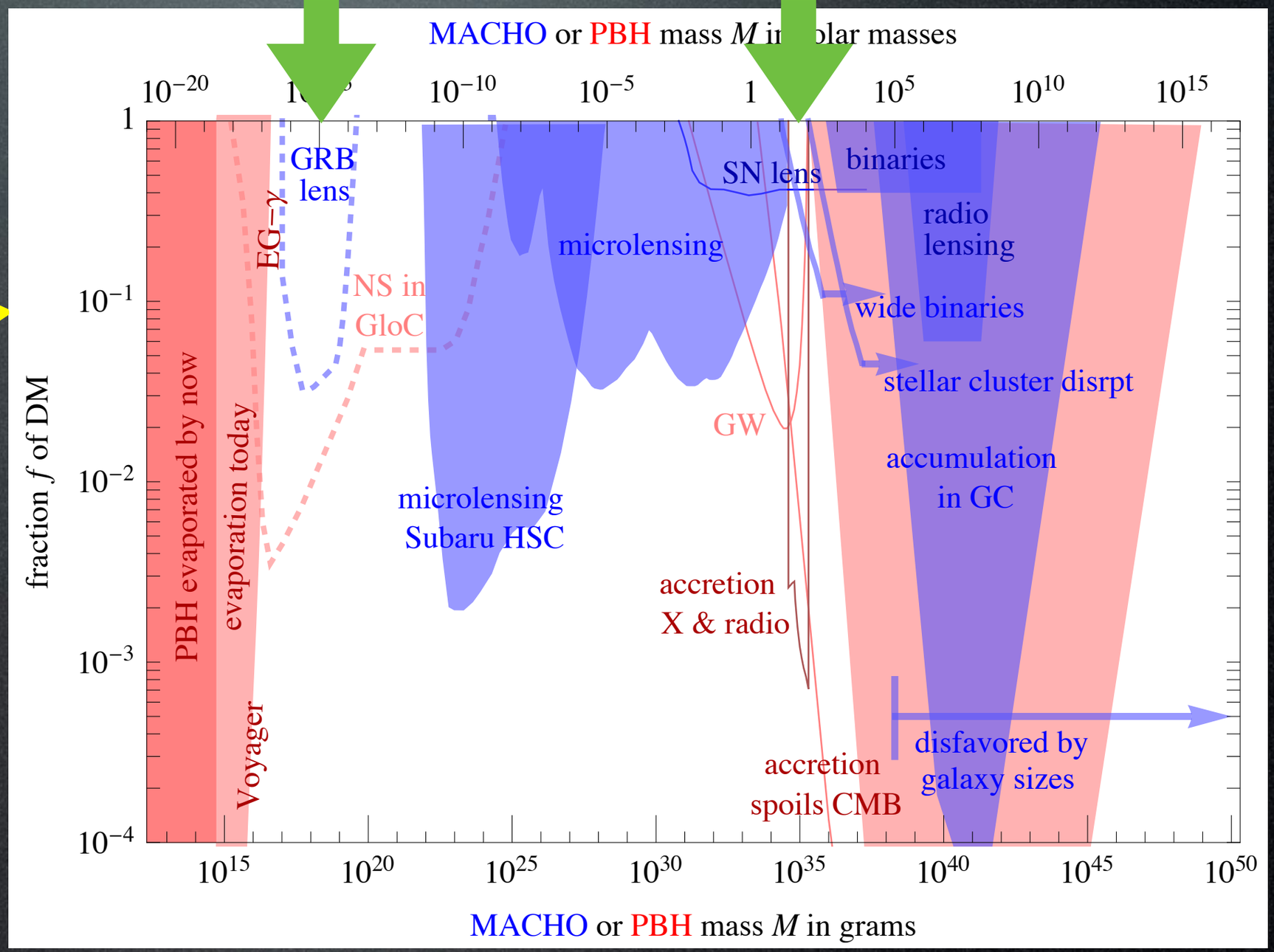
slivers still open?

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15} (t/10^{-23}\ \text{sec})\ \text{g}$$

constraints



M. Cirelli, A. Strumia, J. Zupan to appear

PBHs as DM

Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15} (t/10^{-23}\ \text{sec})\ \text{g}$$

constraints

‘small’ PBHs emit today by Hawking evaporation

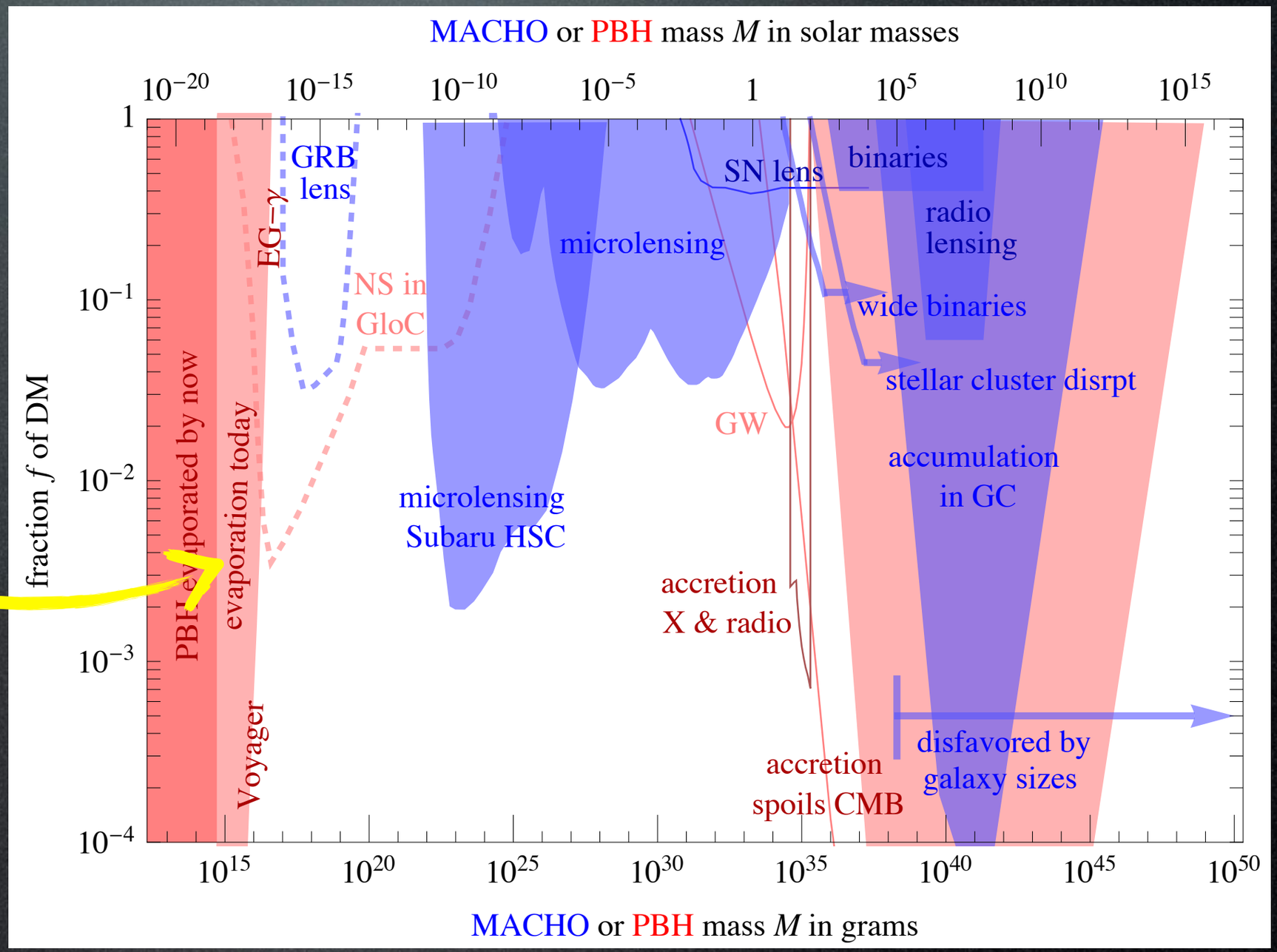
$$T = \frac{1}{8\pi G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5 \times 10^{25}\, f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$

spectrum

$$\frac{dN}{dt\, dE} = \frac{27}{2\pi} \frac{G^2 M^2 E^2}{e^{E/T} + 1}$$



M. Cirelli, A. Strumia, J. Zupan to appear

PBHs as DM

Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15} (t/10^{-23}\ \text{sec})\ \text{g}$$

constraints

‘small’ PBHs emit today by Hawking evaporation

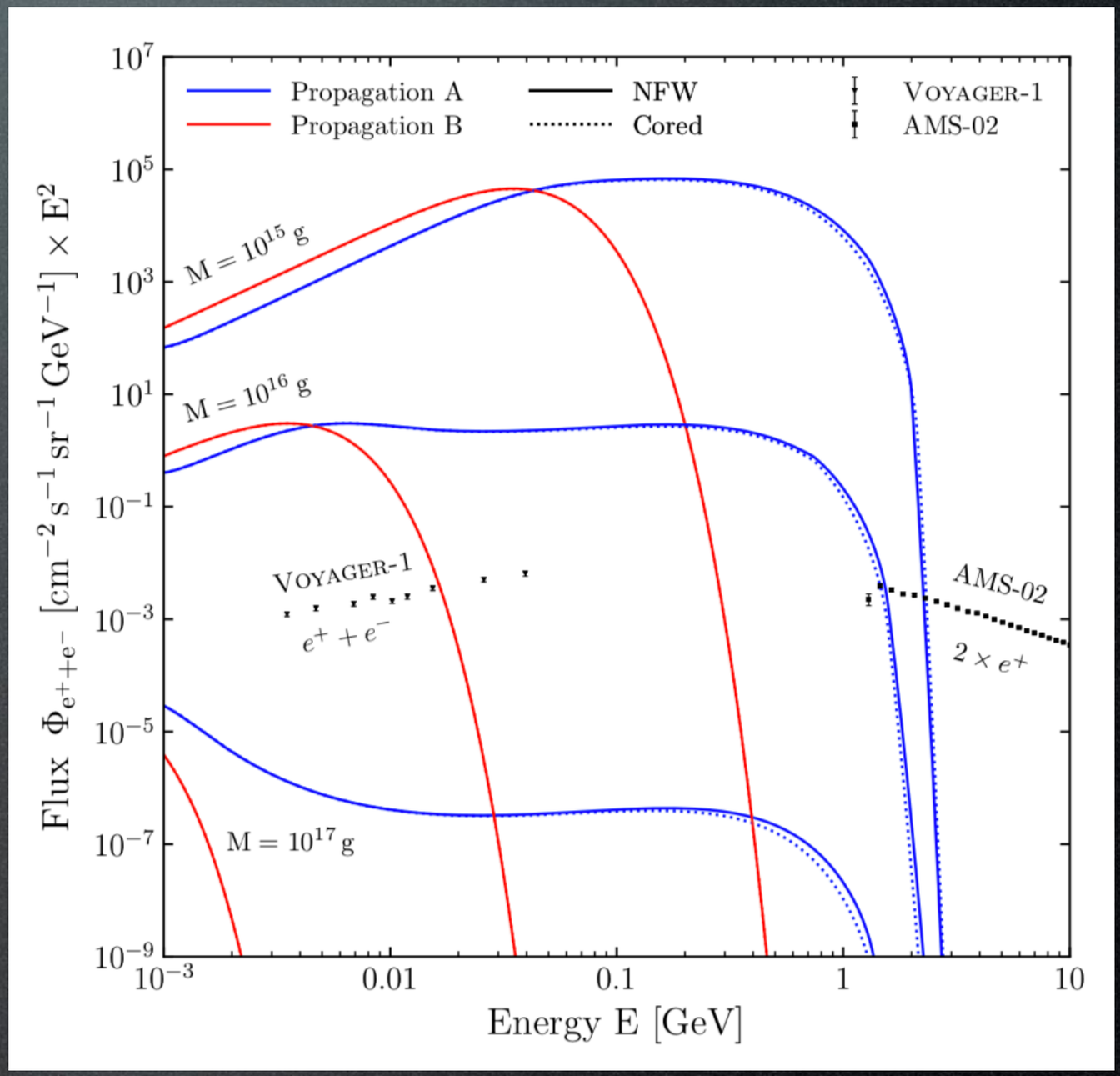
$$T = \frac{1}{8\pi G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5 \times 10^{25}\, f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$

spectrum

$$\frac{dN}{dt\, dE} = \frac{27}{2\pi} \frac{G^2 M^2 E^2}{e^{E/T} + 1}$$



Boudaud, Cirelli 1807.03075, PRL in press

PBHs as DM

Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15} (t/10^{-23}\ \text{sec})\ \text{g}$$

constraints

‘small’ PBHs emit today by Hawking evaporation

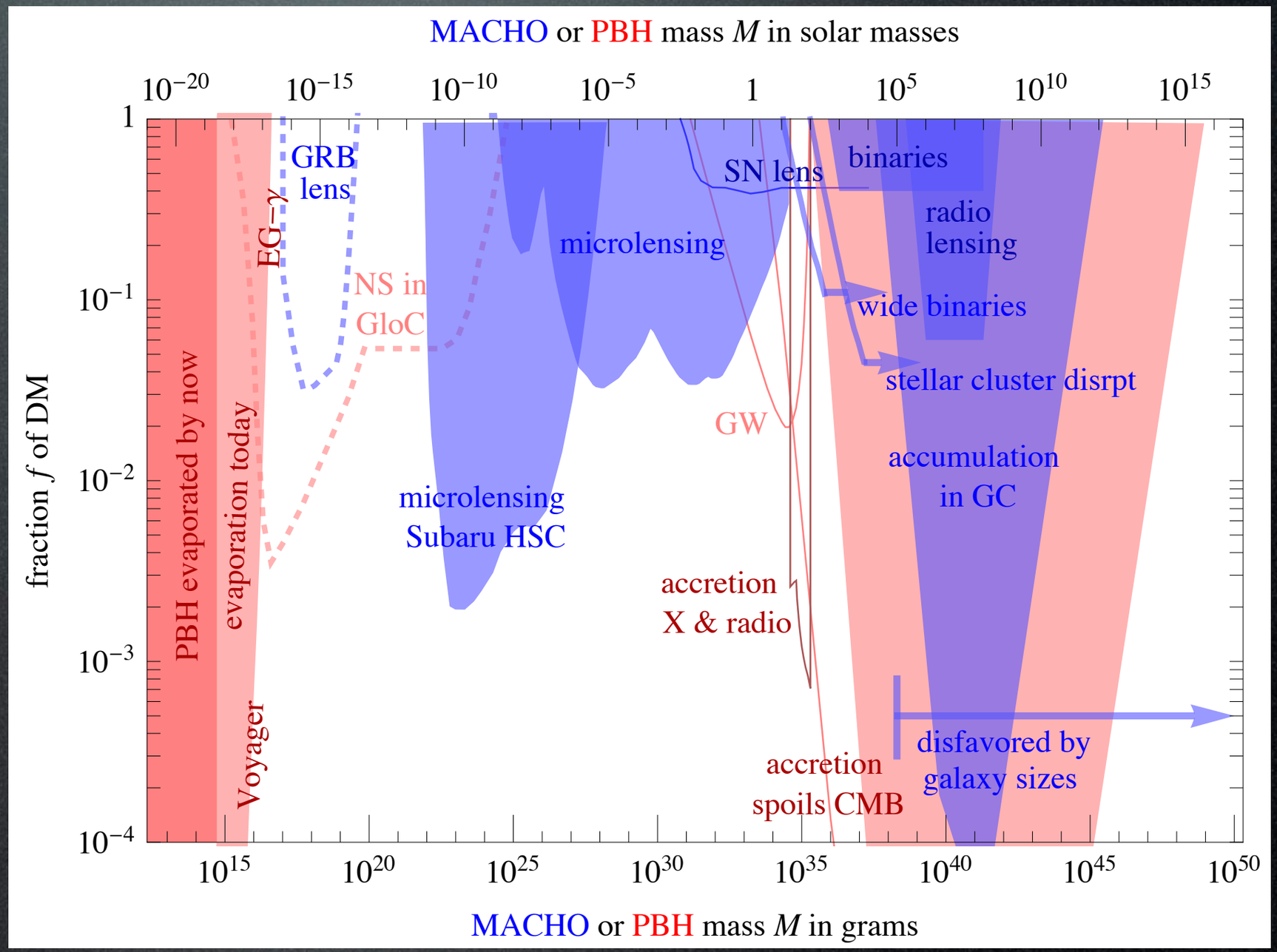
$$T = \frac{1}{8\pi G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5 \times 10^{25}\, f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$

spectrum

$$\frac{dN}{dt\, dE} = \frac{27}{2\pi} \frac{G^2 M^2 E^2}{e^{E/T} + 1}$$



M. Cirelli, A. Strumia, J. Zupan to appear

PBHs as DM

Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15} (t/10^{-23}\ \text{sec})\ \text{g}$$

constraints

‘small’ PBHs emit today by Hawking evaporation

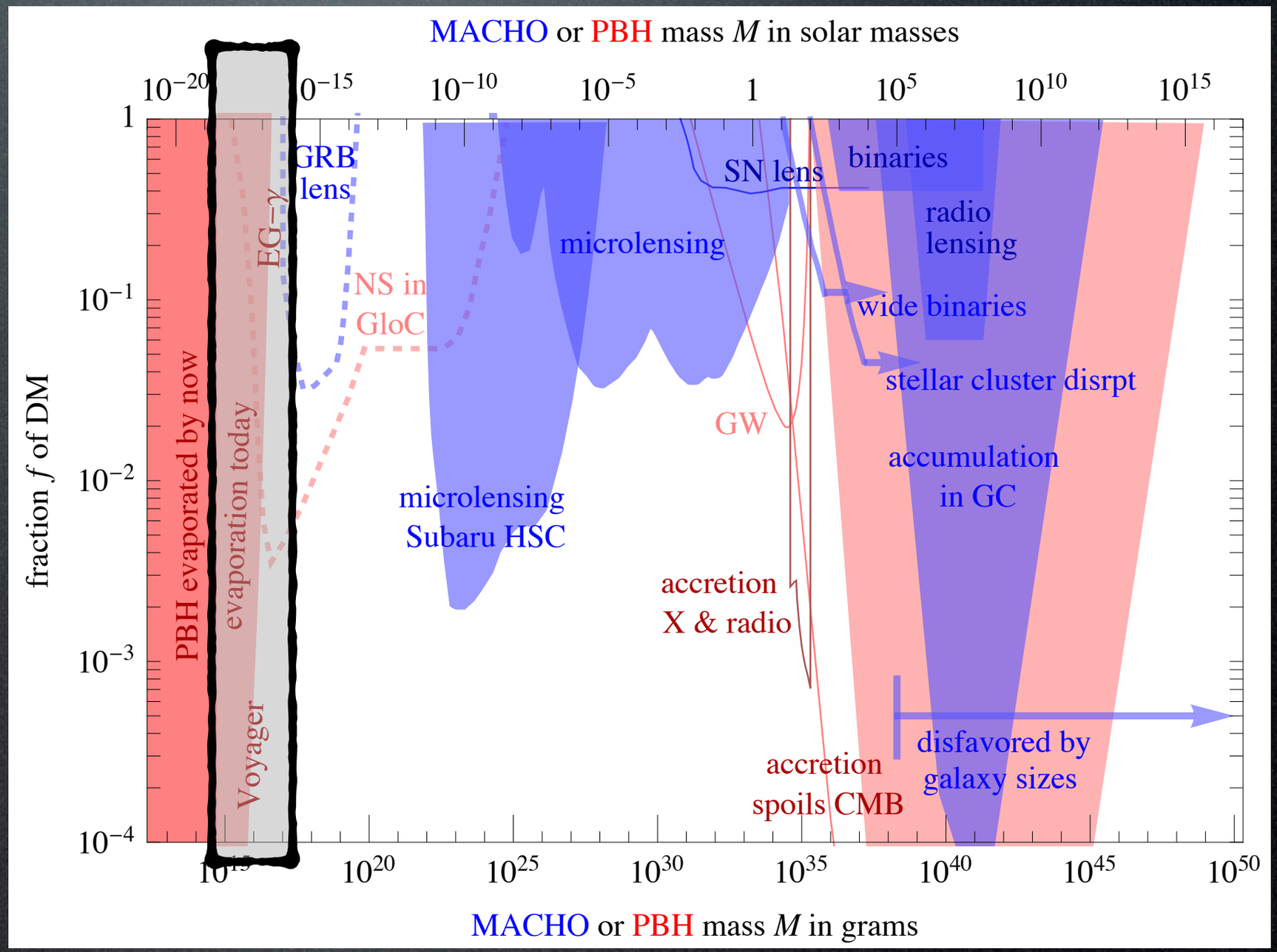
$$T = \frac{1}{8\pi G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5 \times 10^{25}\, f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$

spectrum

$$\frac{dN}{dt\, dE} = \frac{27}{2\pi} \frac{G^2 M^2 E^2}{e^{E/T} + 1}$$



M. Cirelli, A. Strumia, J. Zupan to appear

PBHs as DM

Constraints on Primordial Black Holes

DM could consist of PBHs

huge range of sizes:

$$M \simeq 10^{15} (t/10^{-23}\ \text{sec})\ \text{g}$$

constraints

‘small’ PBHs emit today by Hawking evaporation

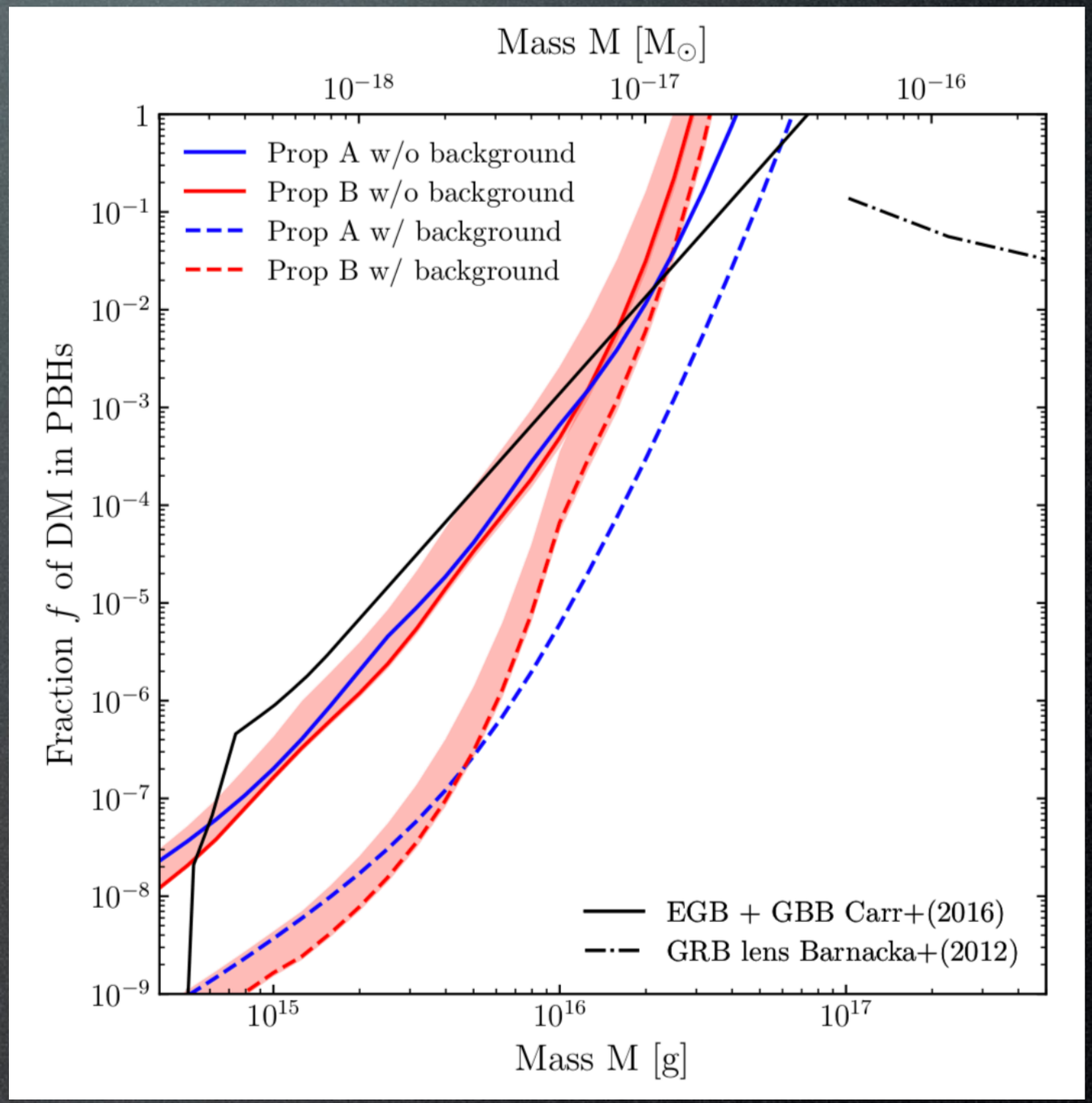
$$T = \frac{1}{8\pi G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5 \times 10^{25}\, f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$

spectrum

$$\frac{dN}{dt\, dE} = \frac{27}{2\pi} \frac{G^2 M^2 E^2}{e^{E/T} + 1}$$



Boudaud, Cirelli 1807.03075, PRL in press

PBHs as DM

Constraints on Primordial Black Holes

Science

An illustration of Voyager 1, now 21.7 billion kilometers away JPL CALTECH/NASA

Aging Voyager 1 spacecraft undermines idea that dark matter is tiny black holes

By Adrian Cho | Jan. 9, 2019 , 2:25 PM

Forbes

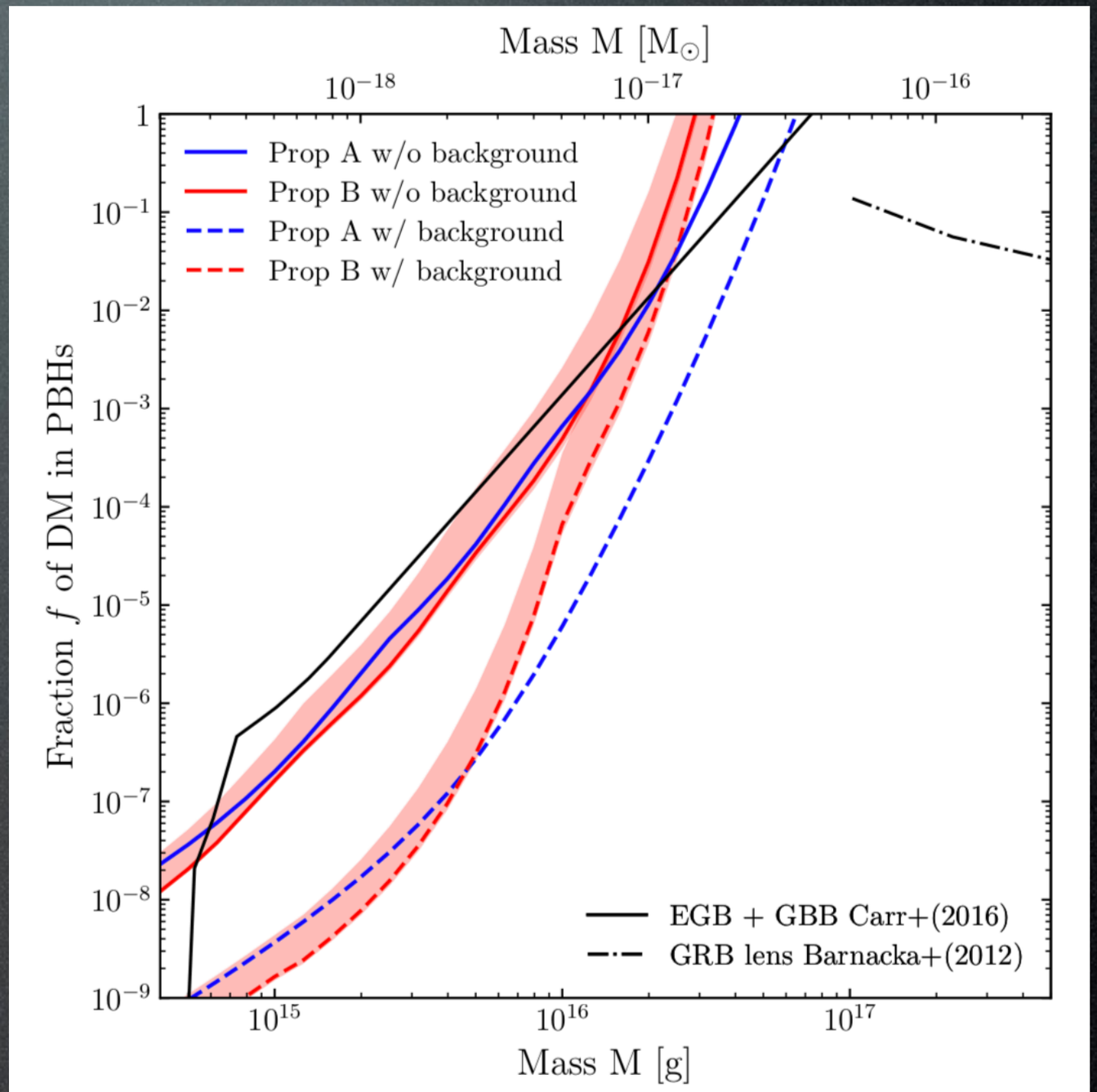
25,121 views | Jul 10, 2018, 05:59pm

NASA's Voyager-1 Spacecraft Opens Door On New Way To Look For Dark Matter

Bruce Dorminey Contributor

Science

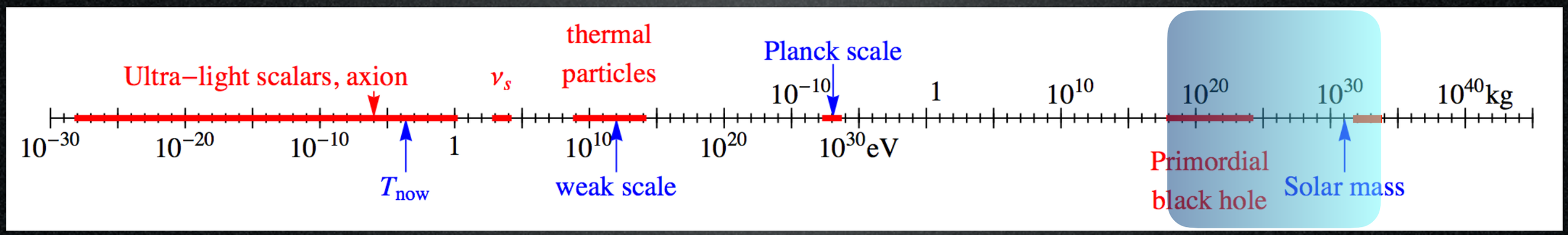
I cover over-the-horizon technology, aerospace and astronomy.



Boudaud, Cirelli 1807.03075, PRL in press

Candidates

A matter of perspective: plausible mass ranges

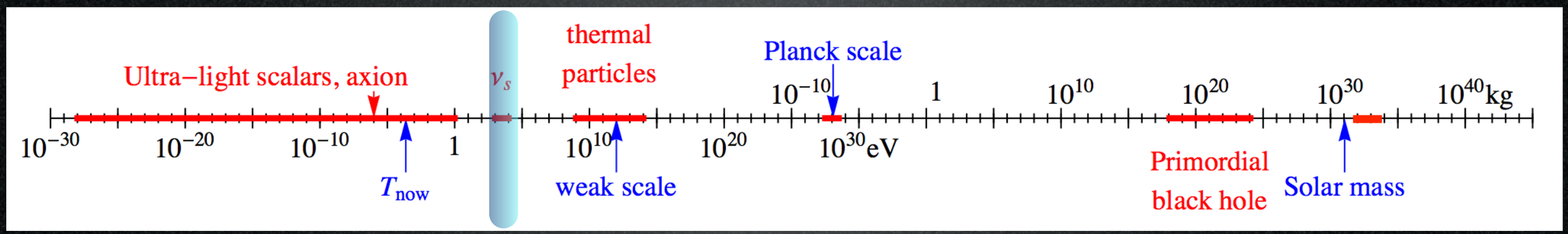


'only' 90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges

KeV DM?



'only' 90 orders of magnitude!

X-ray line

Bulbul et al., 1402.2301

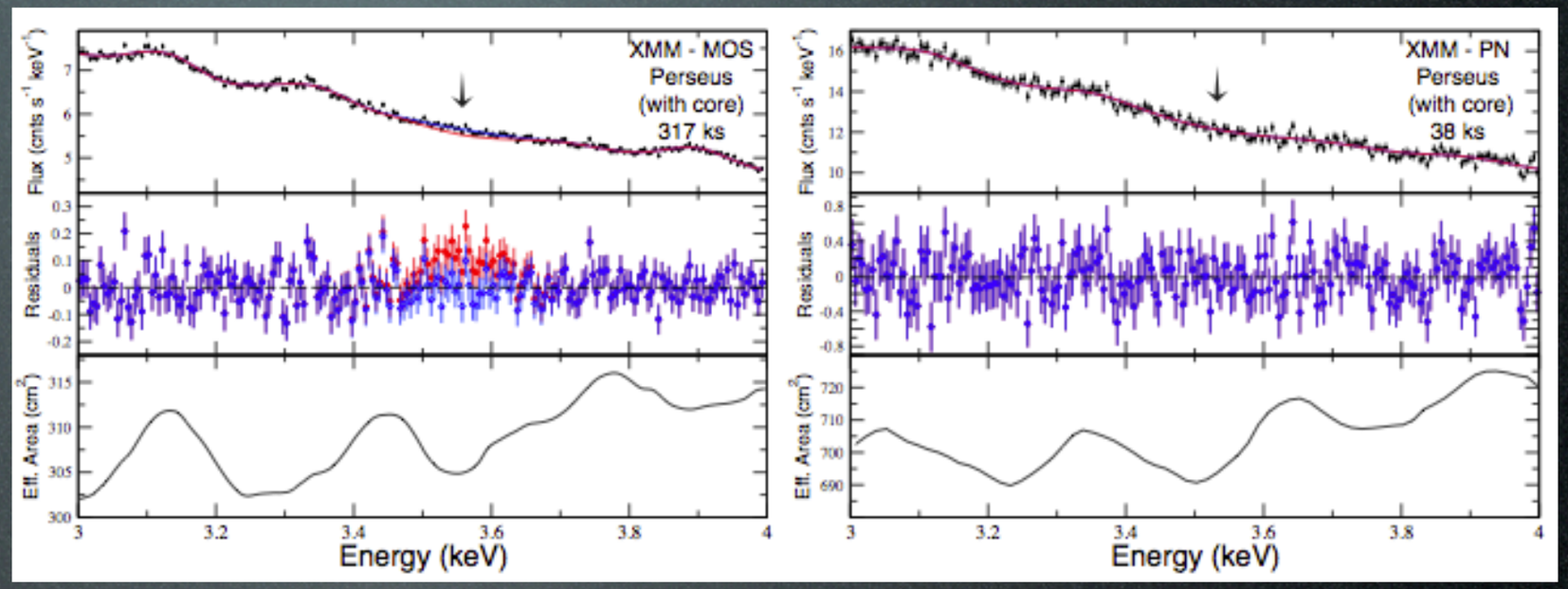
3.55 - 3.57 ± 0.03 KeV

73 clusters

(Chandra & XMM-Newton)

z = 0.01 - 0.35

$\gtrsim 4\sigma$



Boyarsky, Ruchayskiy, 1402.4119

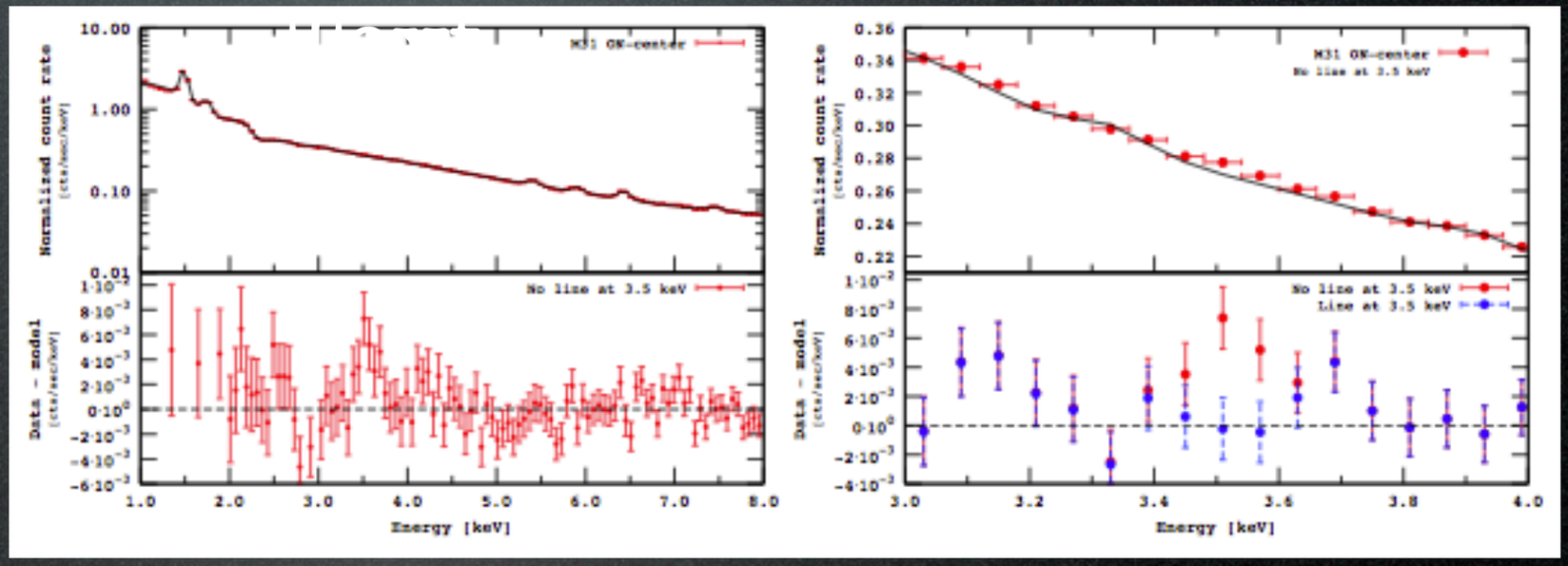
3.5 KeV

Andromeda galaxy
+ Perseus cluster

(XMM-Newton)

z = 0 and 0.0179

4.4σ



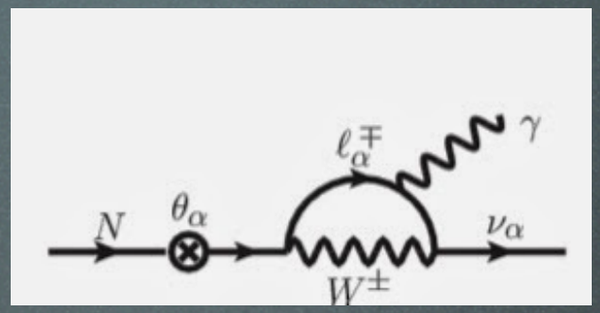
X-ray line

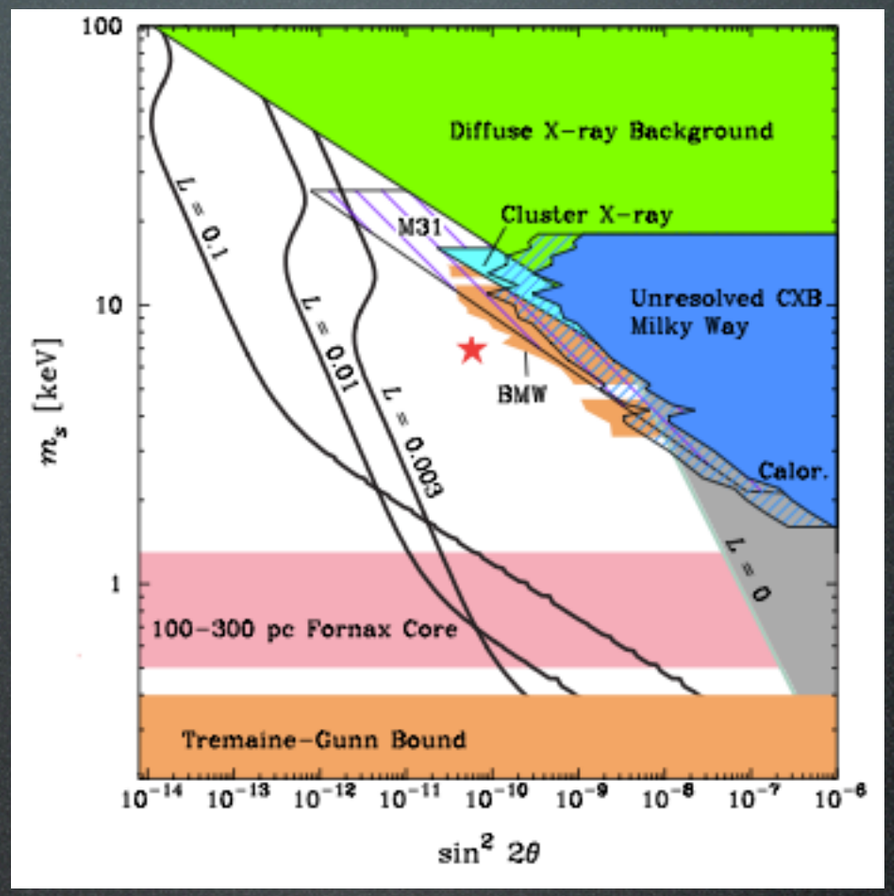
Sterile neutrino decay

$m_\nu = 7.1$ KeV

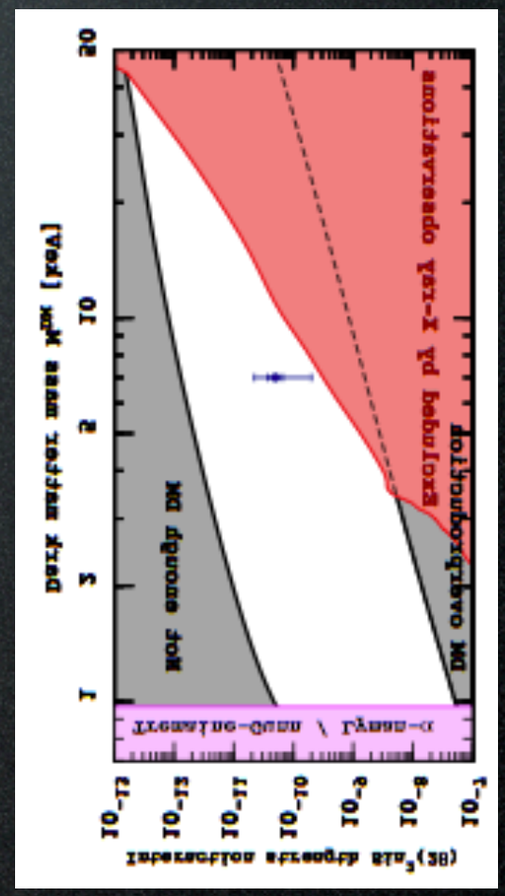
$\tau \simeq 10^{29}$ sec

$\sin^2 2\theta \sim$ few 10^{-11}





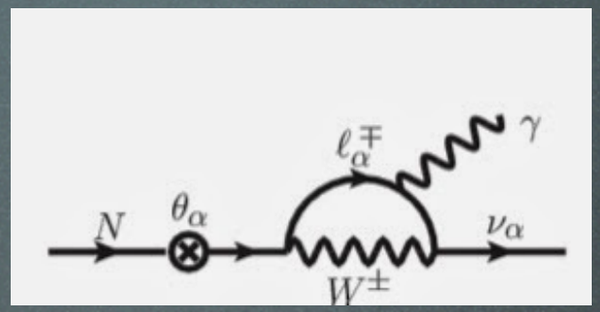
Bulbul et al., 1402.2301



X-ray line

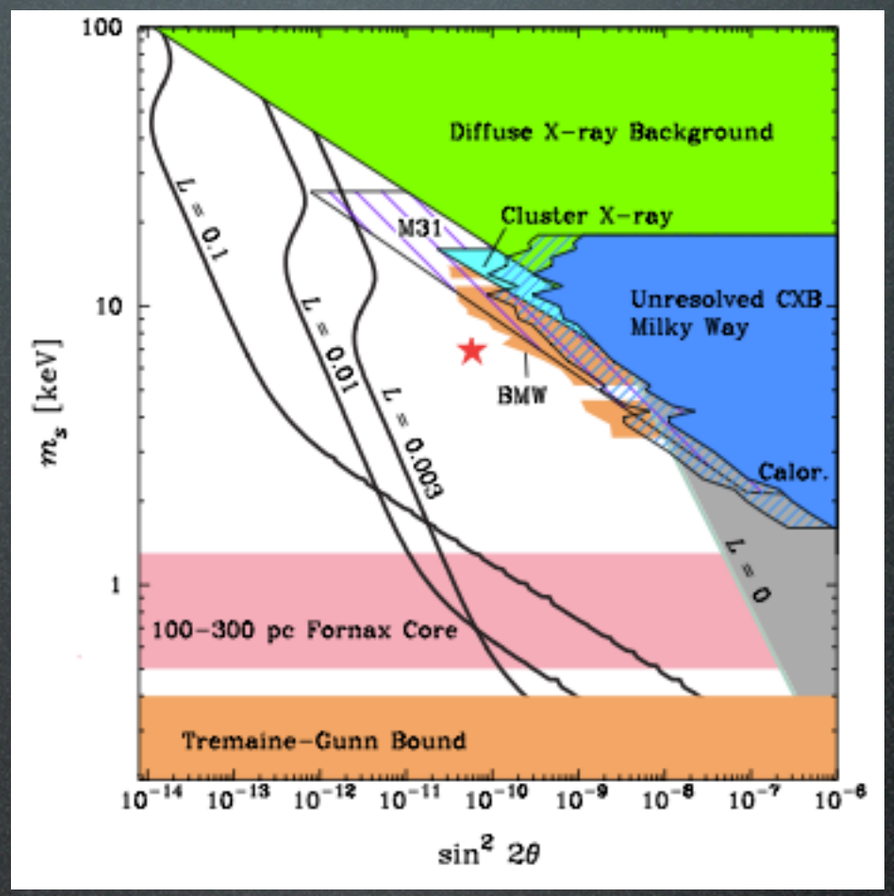
Sterile neutrino decay

$$m_\nu = 7.1 \text{ KeV}$$
$$\tau \simeq 10^{29} \text{ sec}$$
$$\sin^2 2\theta \sim \text{few } 10^{-11}$$

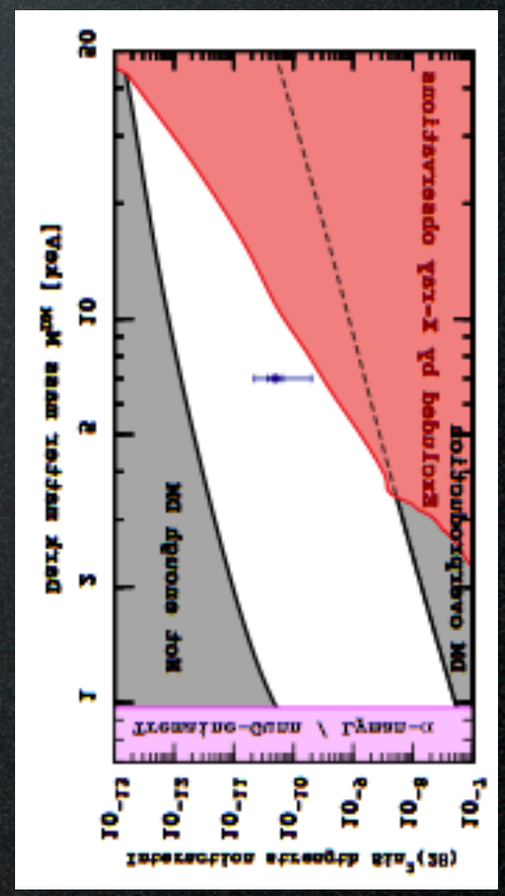


Possible challenges:

- EU production?
- Perseus flux too large?



Bulbul et al., 1402.2301

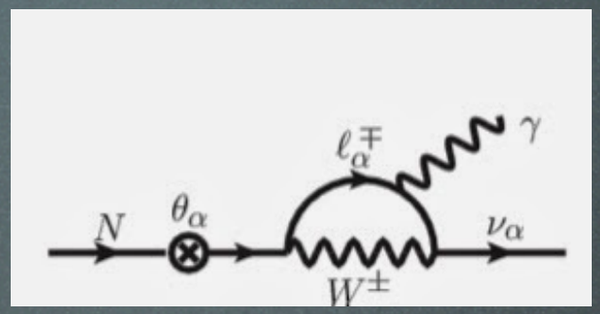


Boyarsky, Ruchayskiy et al., 1402.4119

X-ray line

Sterile neutrino decay

$$m_\nu = 7.1 \text{ KeV}$$
$$\tau \simeq 10^{29} \text{ sec}$$
$$\sin^2 2\theta \sim \text{few } 10^{-11}$$



Possible challenges:

- EU production?
- Perseus flux too large?

Caveat:

Riemer-Sørensen, 1405.7943

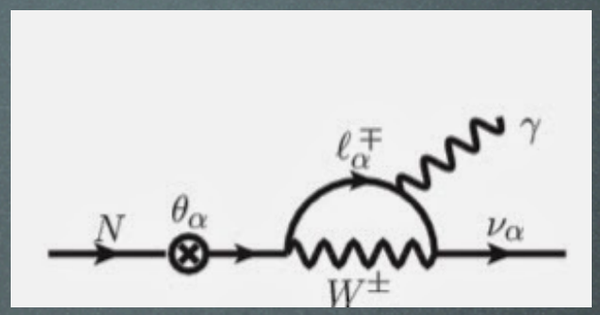
- no line seen with Chandra in the Galactic Center (but conclusion depends on how one models the local background)
- no line seen in dSphs (but results are not conclusive) Malyshev et al., 1408.3531
- no line seen in other galaxies (but errors might be underestimated? says Boyarski's group) Anderson et al., 1408.4115
- no line seen in other clusters (but seen in Perseus with Suzaku! maybe it's proper of Perseus?)
- morphology incompatible with DM Carlson, Profumo², 1411.1758 Urban, Strigari et al., 1411.0050
- but seen in Milky Way halo with NuStar, and Chandra! Neronov, Malyshev, 1607.07328 Cappelluti+ 1701.07932

Perhaps reconciled if it is excited DM? Cline & Frey, 1410.7766

X-ray line

Sterile neutrino decay

$$m_\nu = 7.1 \text{ KeV}$$
$$\tau \simeq 10^{29} \text{ sec}$$
$$\sin^2 2\theta \sim \text{few } 10^{-11}$$



Possible challenges:

- EU production?
- Perseus flux too large?

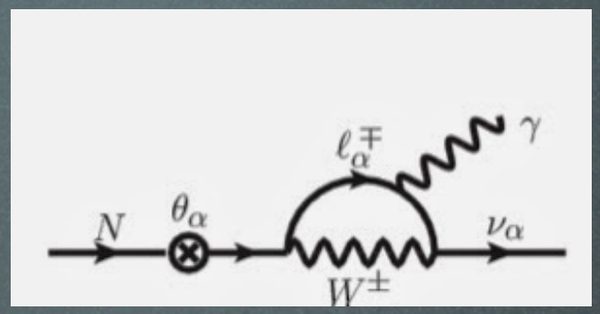
Caveat 2:

- Jeltema & Profumo, 1408.1699: it's just Potassium/Clorine lines
- Bulbul et al. 1409.4143, Boyarsky at al. 1409.4388: bulls#!t
- Jeltema & Profumo, 1411.1759: insist...

X-ray line

Sterile neutrino decay

$$m_\nu = 7.1 \text{ KeV}$$
$$\tau \simeq 10^{29} \text{ sec}$$
$$\sin^2 2\theta \sim \text{few } 10^{-11}$$



Possible challenges:

- EU production?
- Perseus flux too large?

Caveat 2:

- Jeltema & Profumo, 1408.1699: it's just Potassium/Clorine lines
- Bulbul et al. 1409.4143, Boyarsky at al. 1409.4388: bulls#!t
- Jeltema & Profumo, 1411.1759: insist...

POTASSIUM FLARES

ROBERT F. WING, MANUEL PEIMBERT, AND HYRON SPINRAD
Berkeley Astronomy Department
University of California

Received April 14, 1967

The appearance of intense emission lines of neutral potassium at λλ 7665, 7699 on coudé spectrograms of three stars obtained at the Haute-Provence Observatory has prompted us to conduct a survey of 162 bright stars for emission at λ 7699, using a photoelectric scanner. No definite potassium flares were observed. We discuss the advantages of using a scanner for such a survey and for measuring potassium absorption in late-type dwarfs.

An artificial origin of the emission lines is suggested by the fact that the infrared resonance lines of K I are by far the strongest features in the spectra of matches. Experiments at the Lick and Haute-Provence coudé spectrographs have shown that if a match is struck at certain positions in the coudé room during the exposure of an infrared spectrogram, the resulting potassium emission lines can appear very similar to those previously observed.

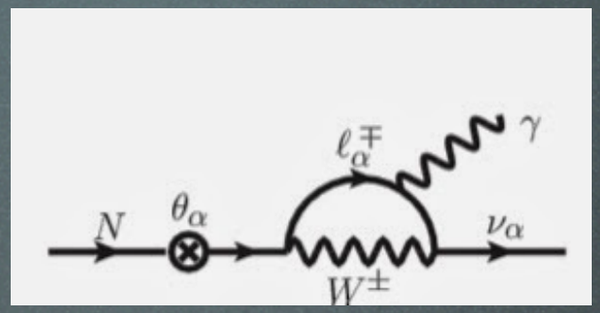
Introduction

Publications of the Astronomical Society of the Pacific, Vol. 79, No. 469, p.351
hat-tip: S. Profumo, Brian Siana

X-ray line

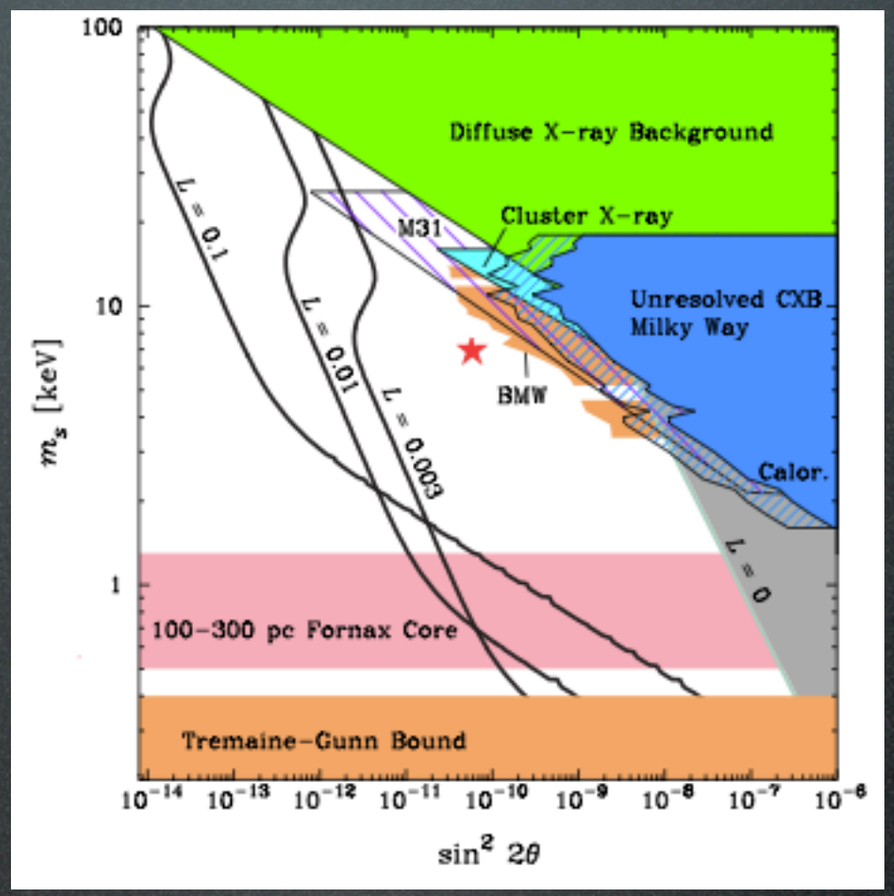
Sterile neutrino decay

$$m_\nu = 7.1 \text{ KeV}$$
$$\tau \simeq 10^{29} \text{ sec}$$
$$\sin^2 2\theta \sim \text{few } 10^{-11}$$

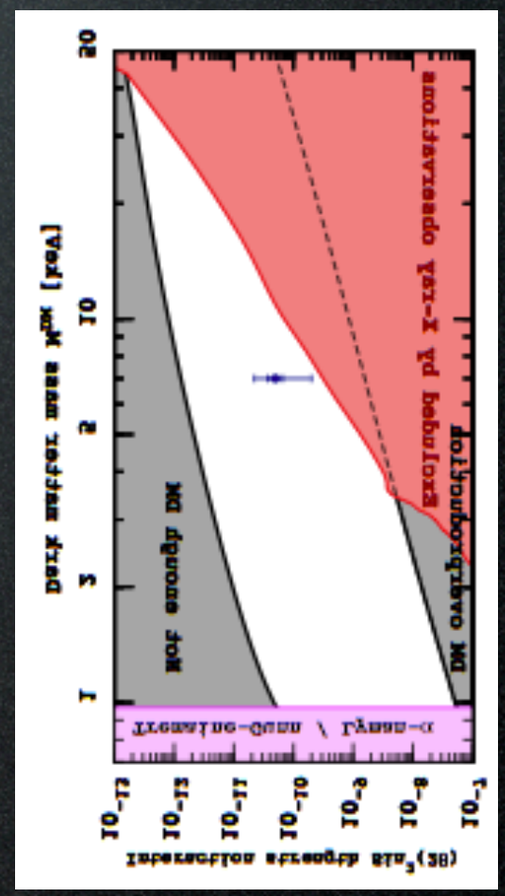


Possible challenges:

- EU production?
- Perseus flux too large?



Bulbul et al., 1402.2301



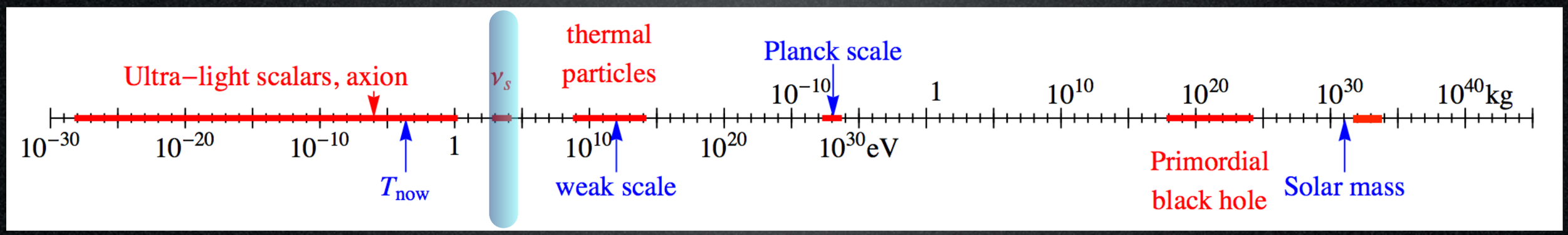
Boyarsky, Ruchayskiy et al., 1402.4119

Other possibilities:

axion (1402.7335), axino (1403.1536, 1403.1782, 1403.6621), modulus (1403.1733), ALP (1403.2370), gravitino (1403.6503), excited DM (1404.4795), the good the bad and the unlikely (1403.1570), sgoldstino (1404.1339), magnetic DM (1404.5446), majoron (1404.1400), annihilating effective DM (1404.1927), 7KeV scalar DM (1404.2220)...

Candidates

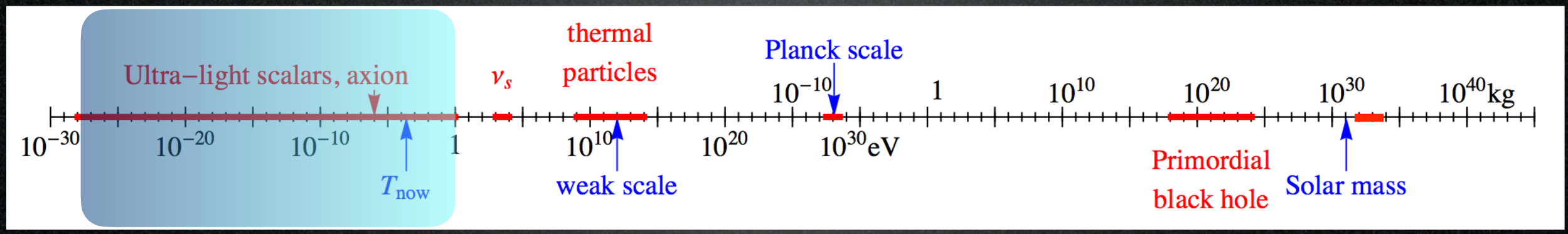
A matter of perspective: plausible mass ranges



'only' 90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges



‘only’ 90 orders of magnitude!

Axions

Theoretically motivated:

one can add to the SM $\mathscr{L} = \mathscr{L}_{\rm SM} - \theta \dfrac{g_3^2}{64\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$ $\left(\tilde{G}^a_{\mu\nu} \equiv \dfrac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^a_{\alpha\beta} \right)$

which induces $d_n \approx \theta \; e \; m_\pi^2 / m_N^2 \approx 10^{-16} \; \theta \; e\,\text{cm}$

but experimentally $|d_n| \lesssim 3 \; 10^{-26} \; e\,\text{cm}$

so why is $|\theta| \lesssim 10^{-11}$?

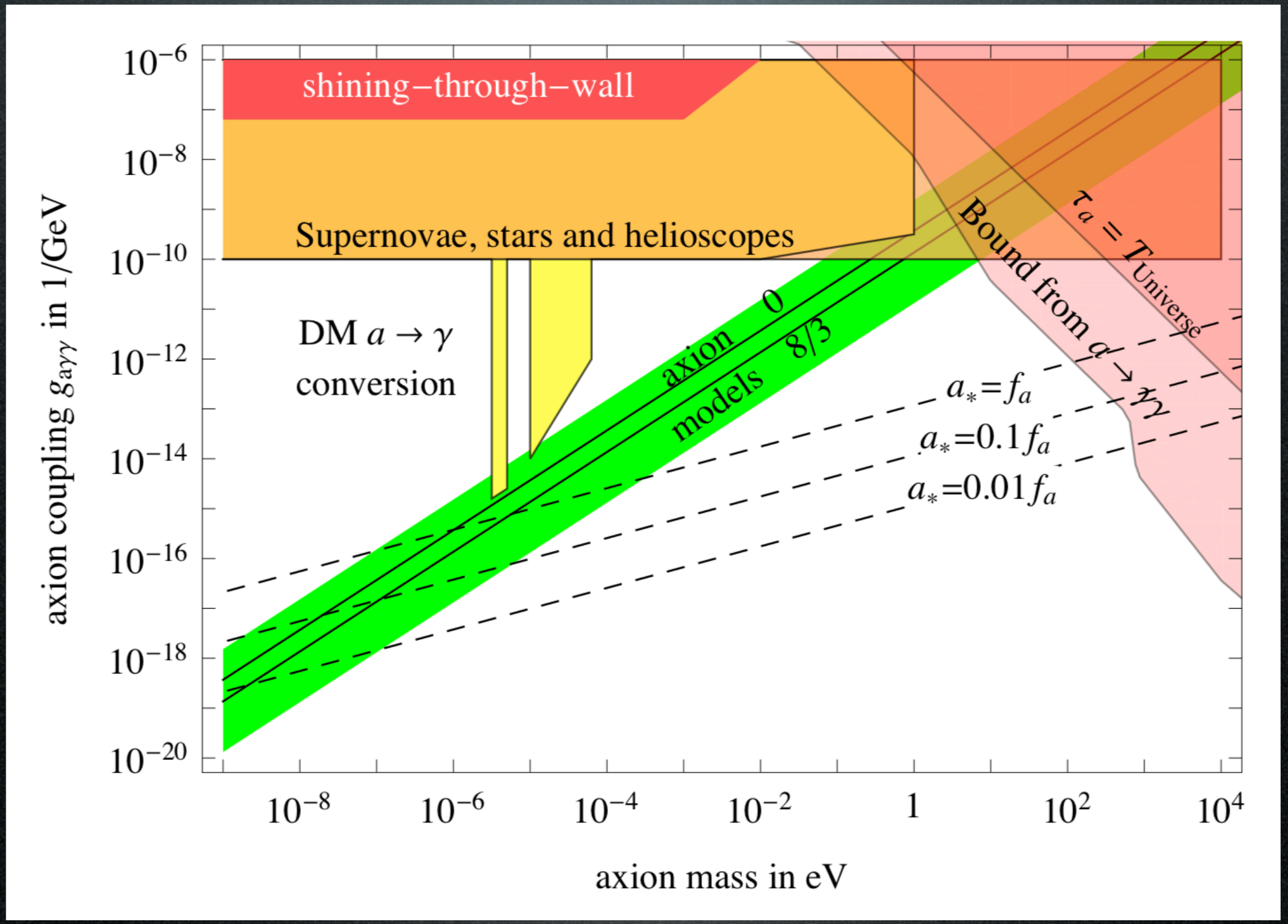
Perhaps because θ is dynamical (a field)

and driven to (almost) zero by its potential (symmetrical under $\mathrm{U(1)_{PQ}}$).

In this case $m_a \approx 0.6\,\text{meV} \dfrac{10^{10}\ \text{GeV}}{f_a}$

Axions

Searches:



M. Cirelli, A. Strumia, J. Zupan to appear

Conclusions

Conclusions

The physics of Dark Matter is
in an experiment driven phase

Conclusions

The physics of Dark Matter is
in an experiment driven phase

Theory can (does) point to preferred directions,
but actually too many...