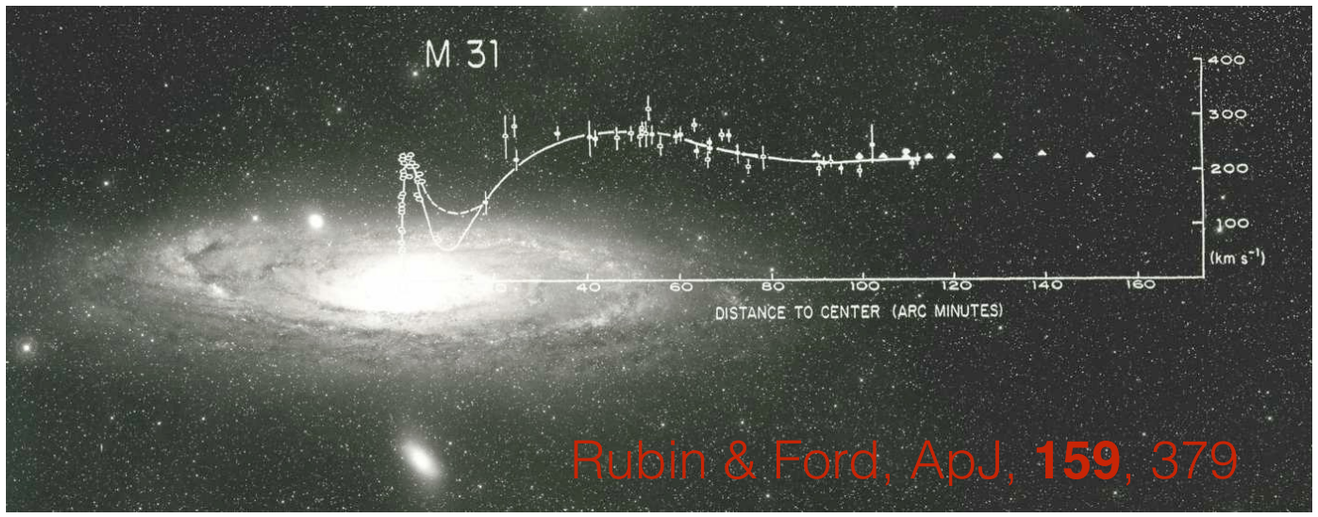
Dark Matter: WIMPS and Beyond

David McKeen

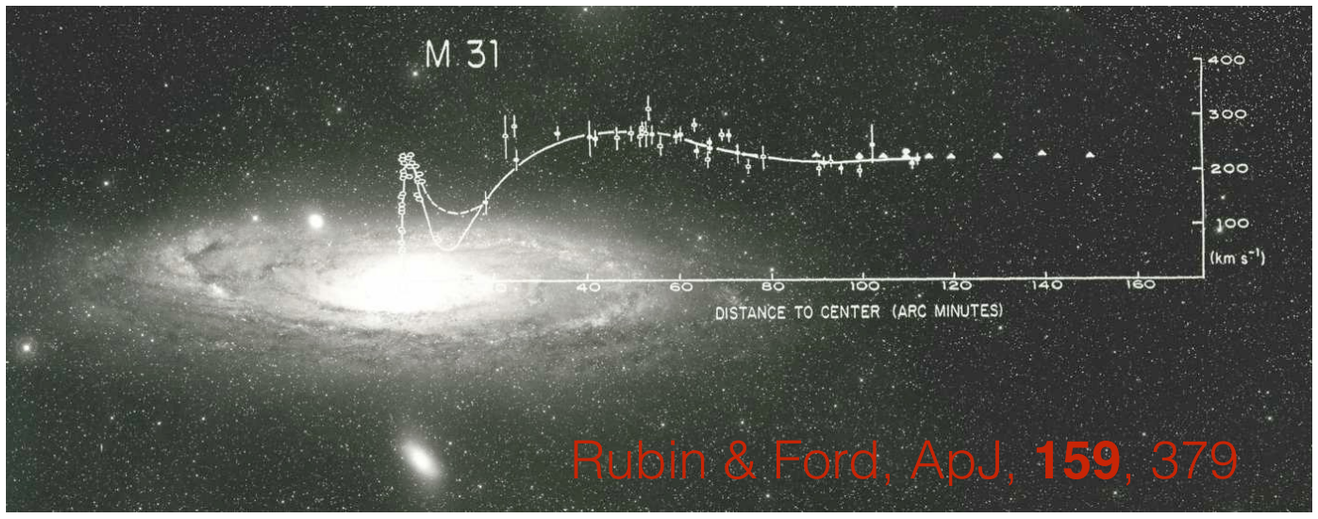
TRIUMF

WNPPC 2019
Banff, February 16, 2019

Why Dark Matter?


M 31
400
300
200
100
(km s⁻¹)
40
60
80
100
120
140
160
DISTANCE TO CENTER (ARC MINUTES)
Rubin & Ford, ApJ, **159**, 379

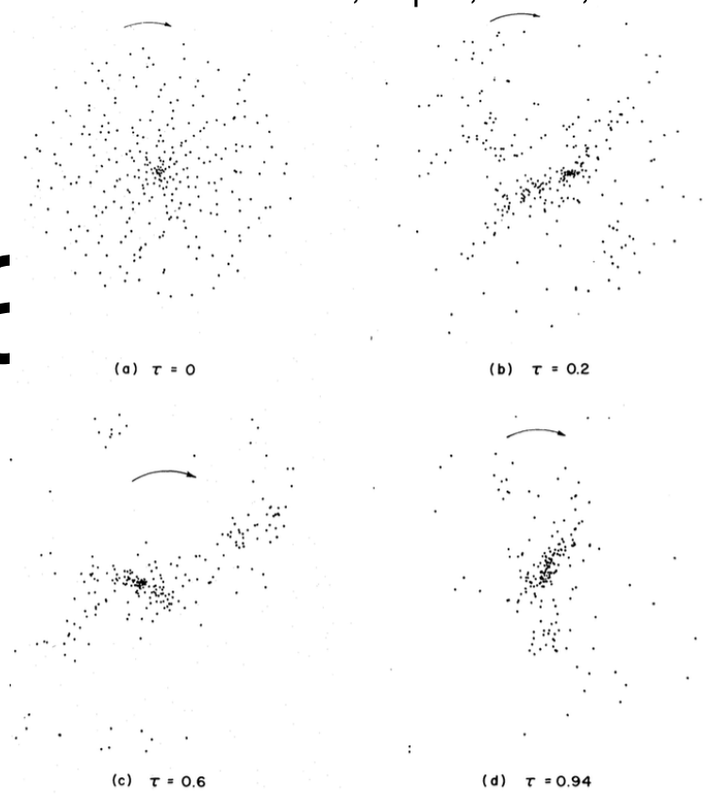
Matter?

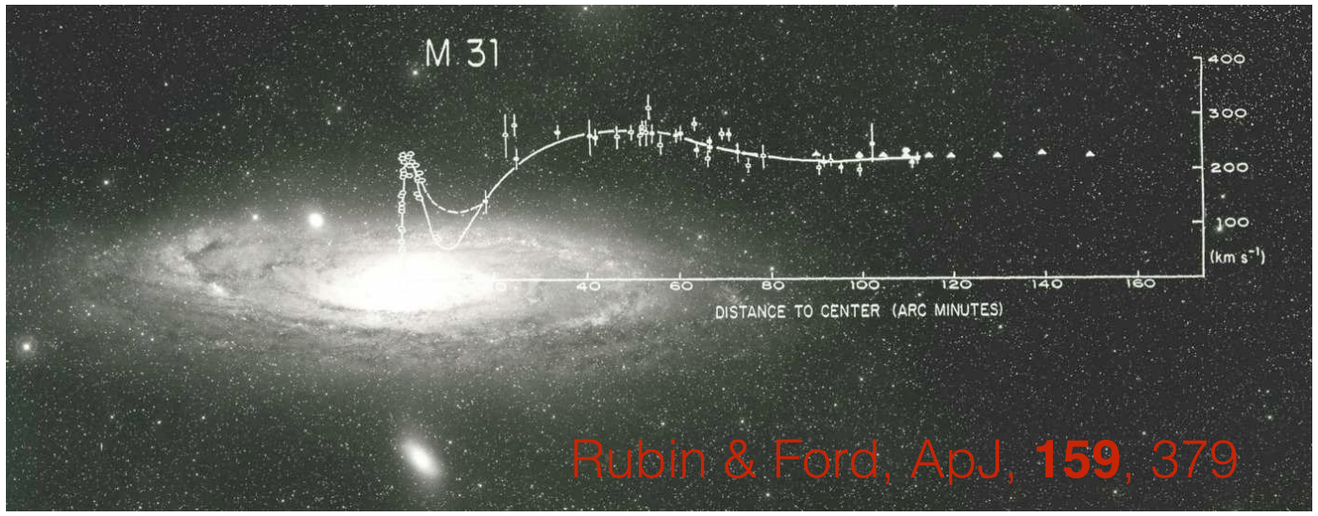


Rubin & Ford, ApJ, **159**, 379

Ostriker & Peebles, ApJ, **186**, 467 ('73)

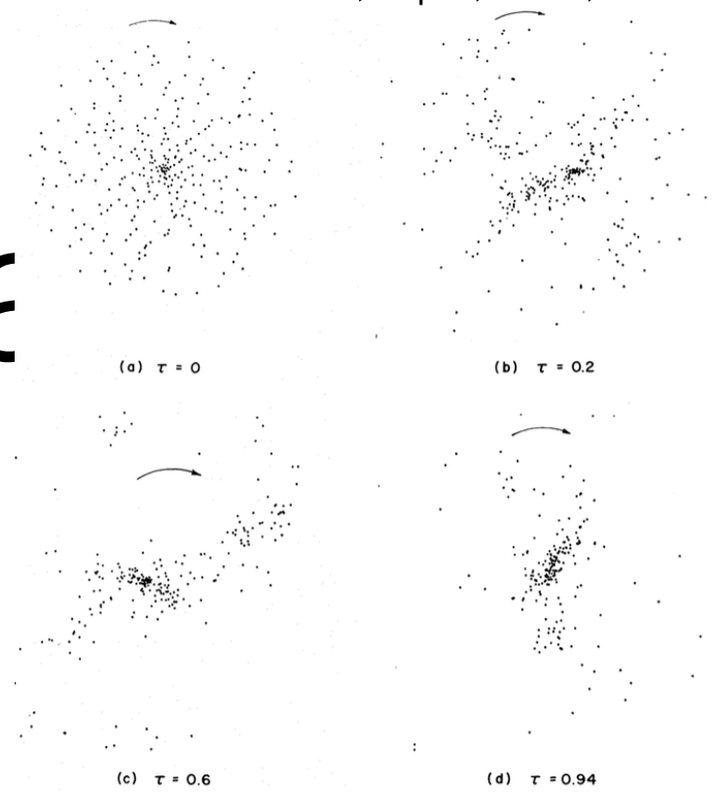
Ma

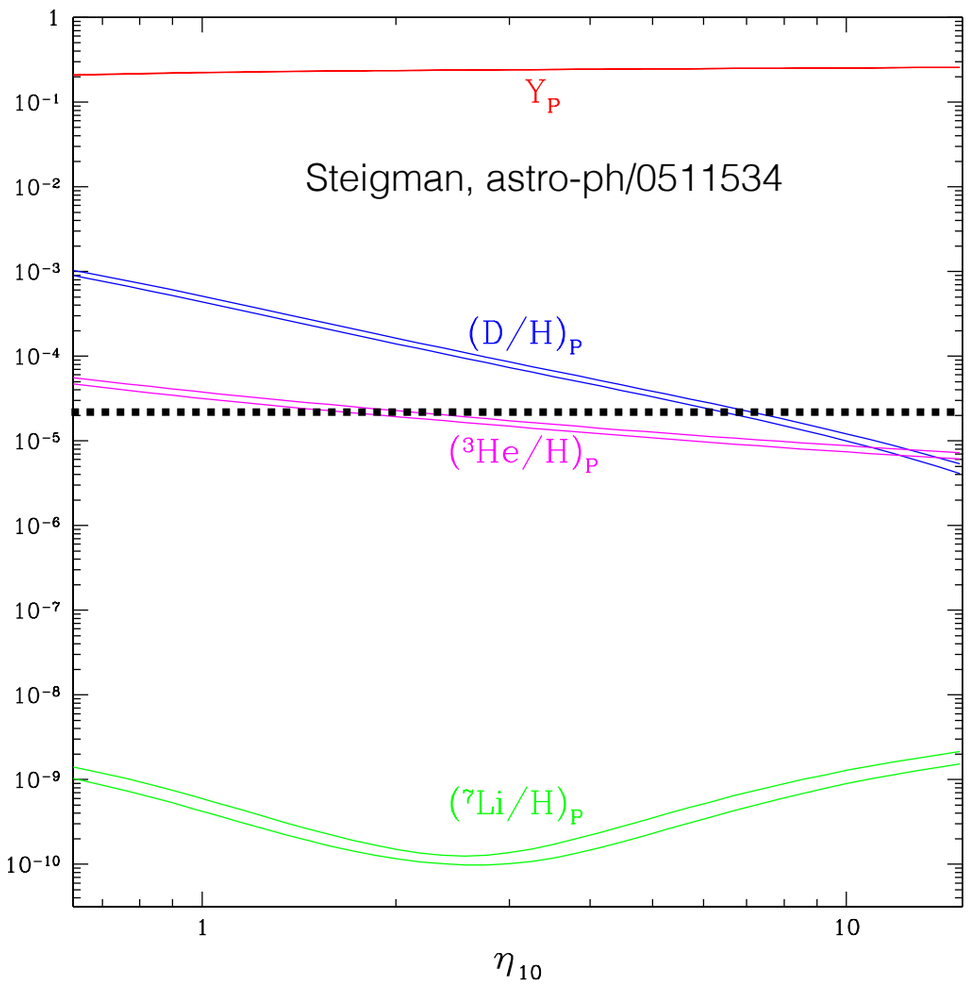


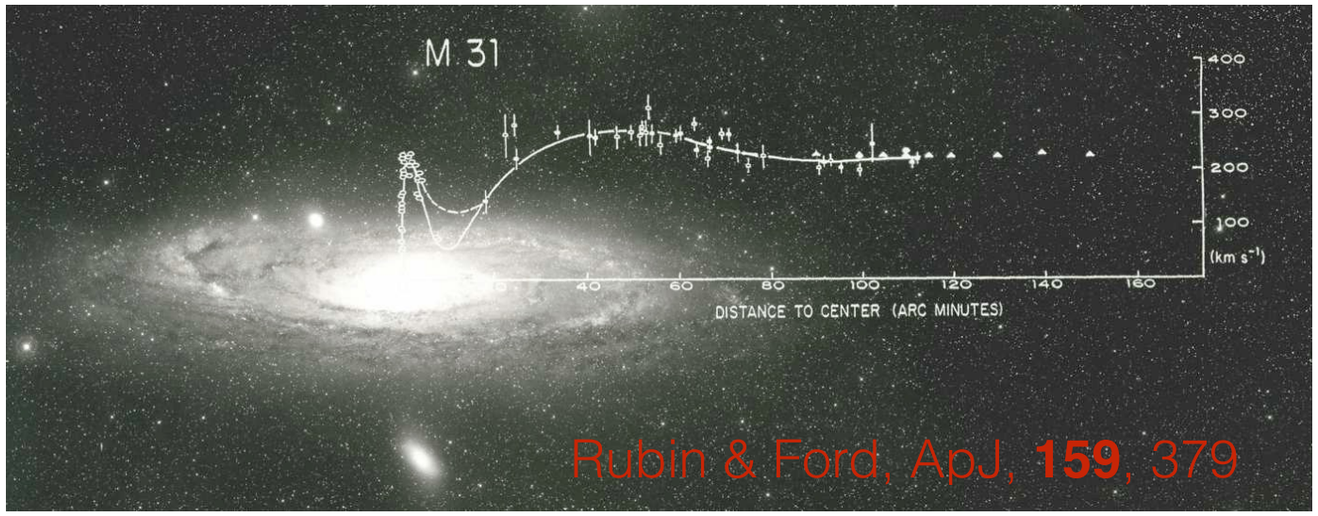


Ostriker & Peebles, ApJ, **186**, 467 ('73)

Ma

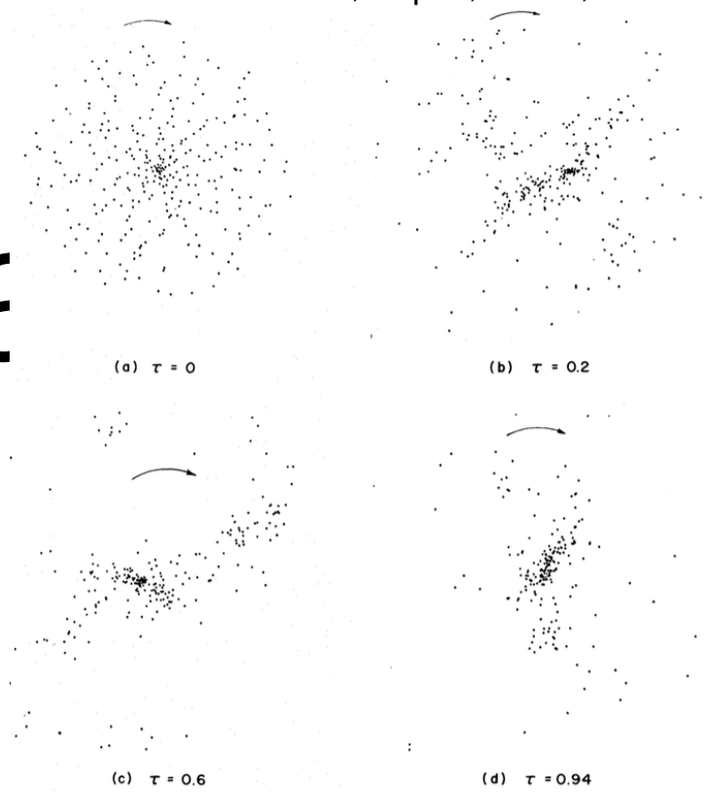


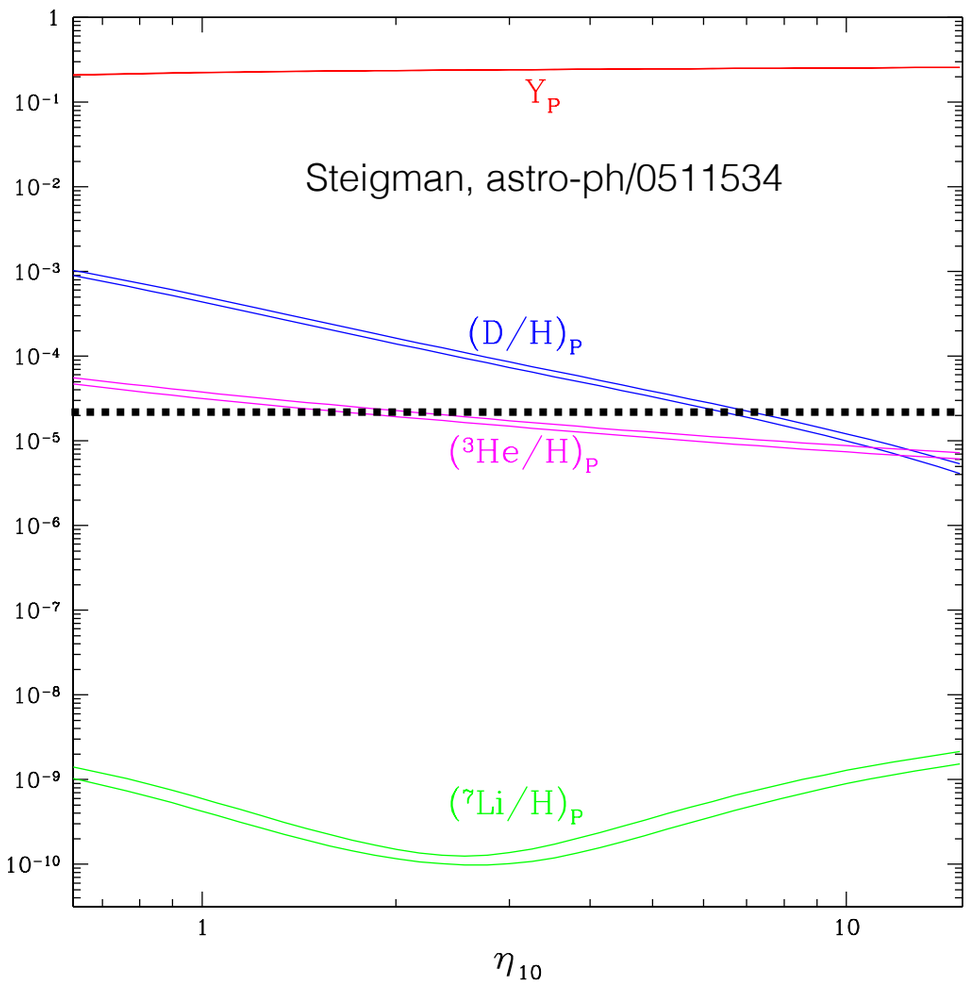


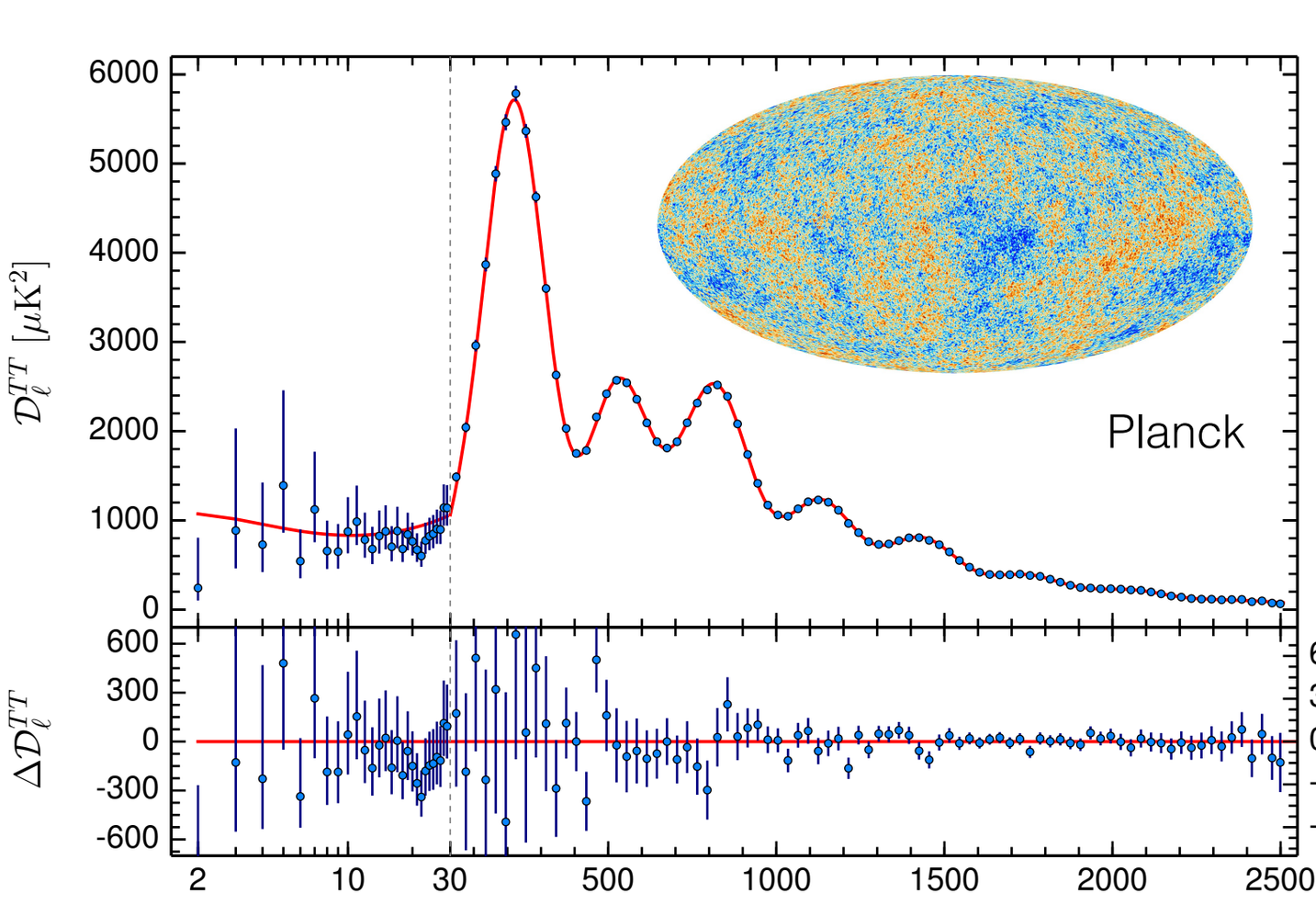


Ostriker & Peebles, ApJ, **186**, 467 ('73)

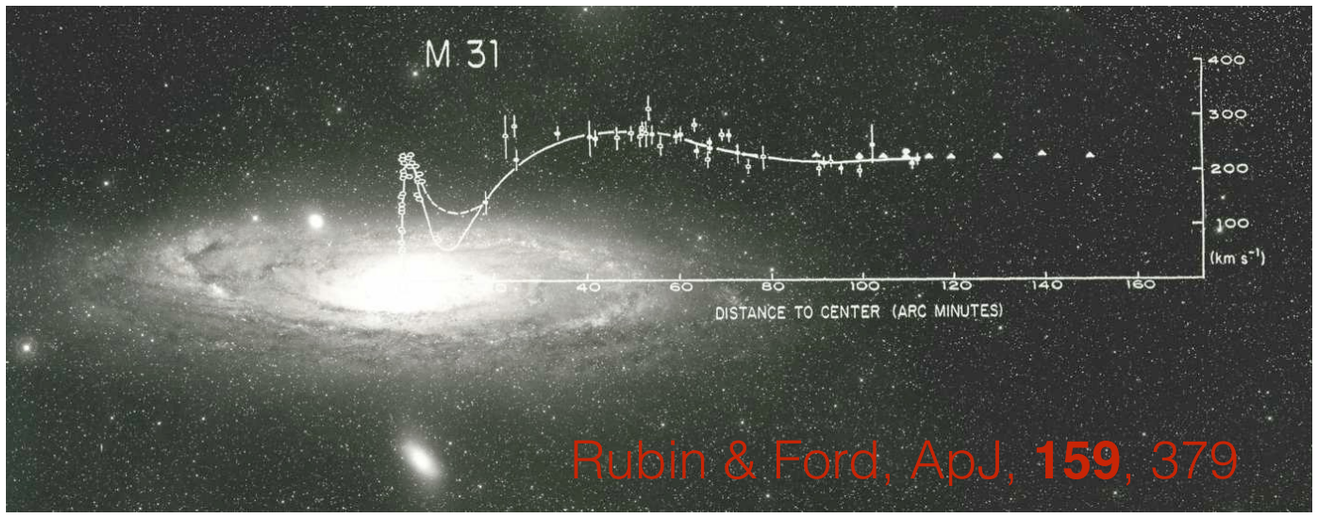
Ma





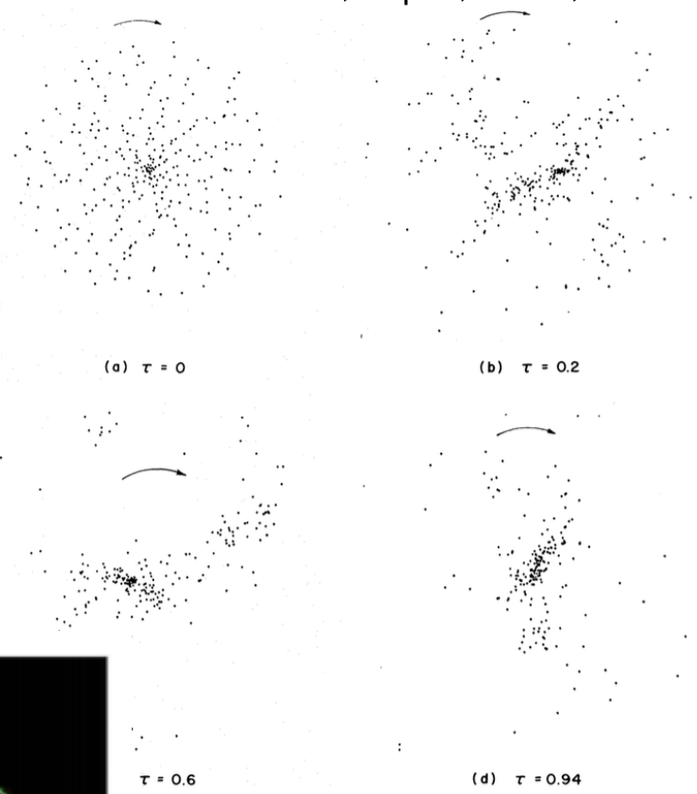


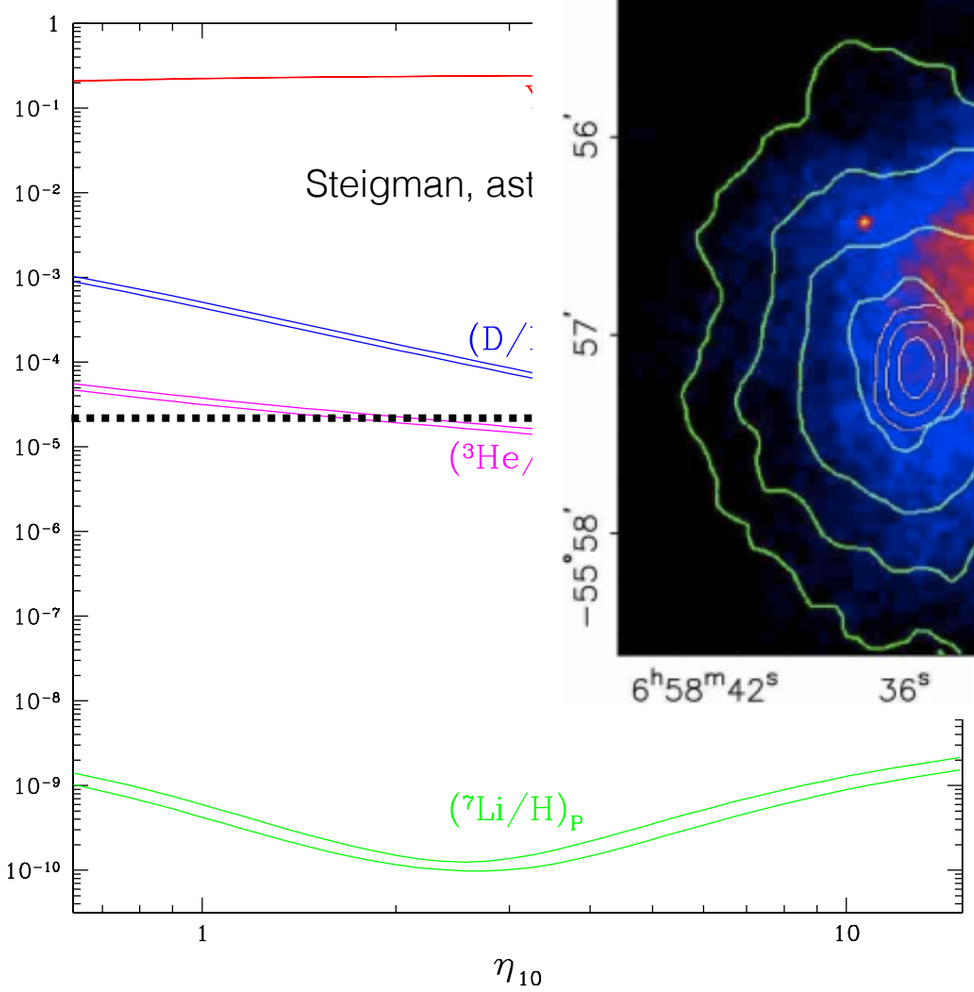
Ostriker & Peebles, ApJ, **186**, 467 ('73)



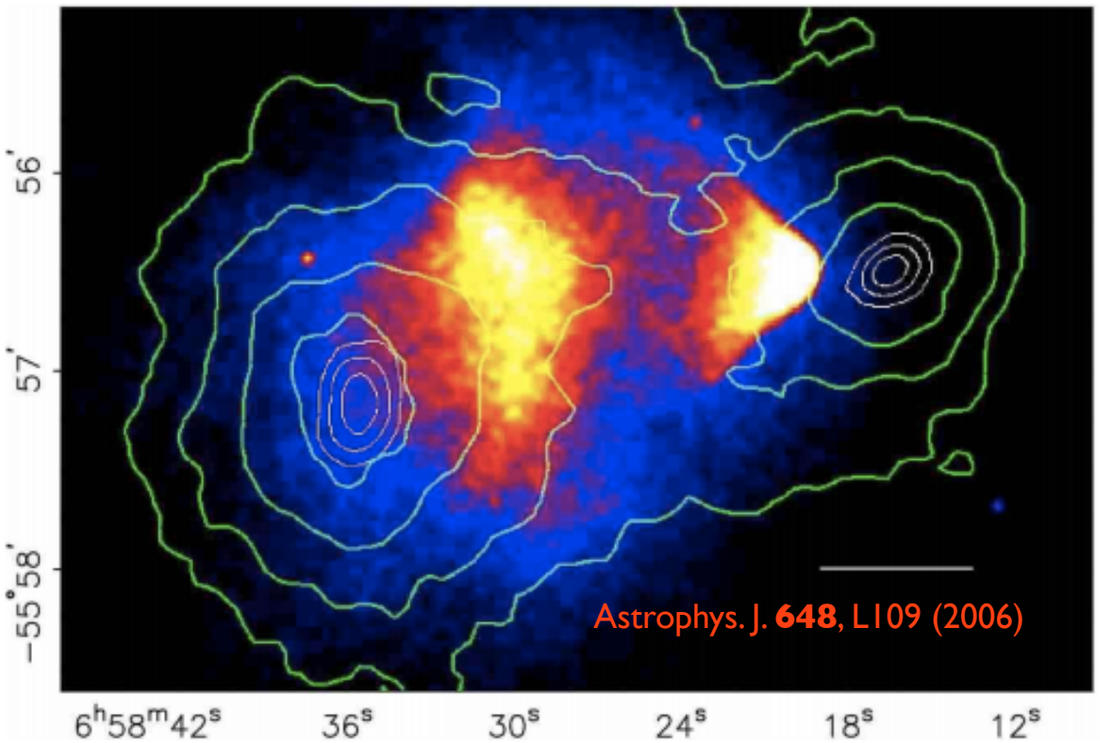
Rubin & Ford, ApJ, **159**, 379

Ma

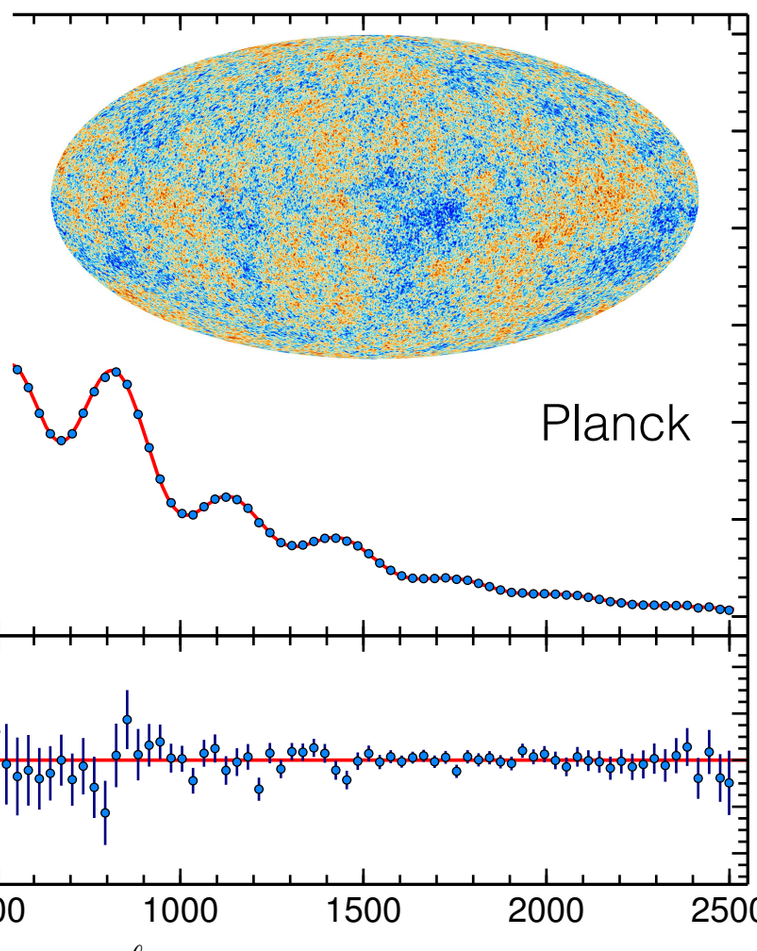




Steigman, ast



Astrophys. J. **648**, L109 (2006)

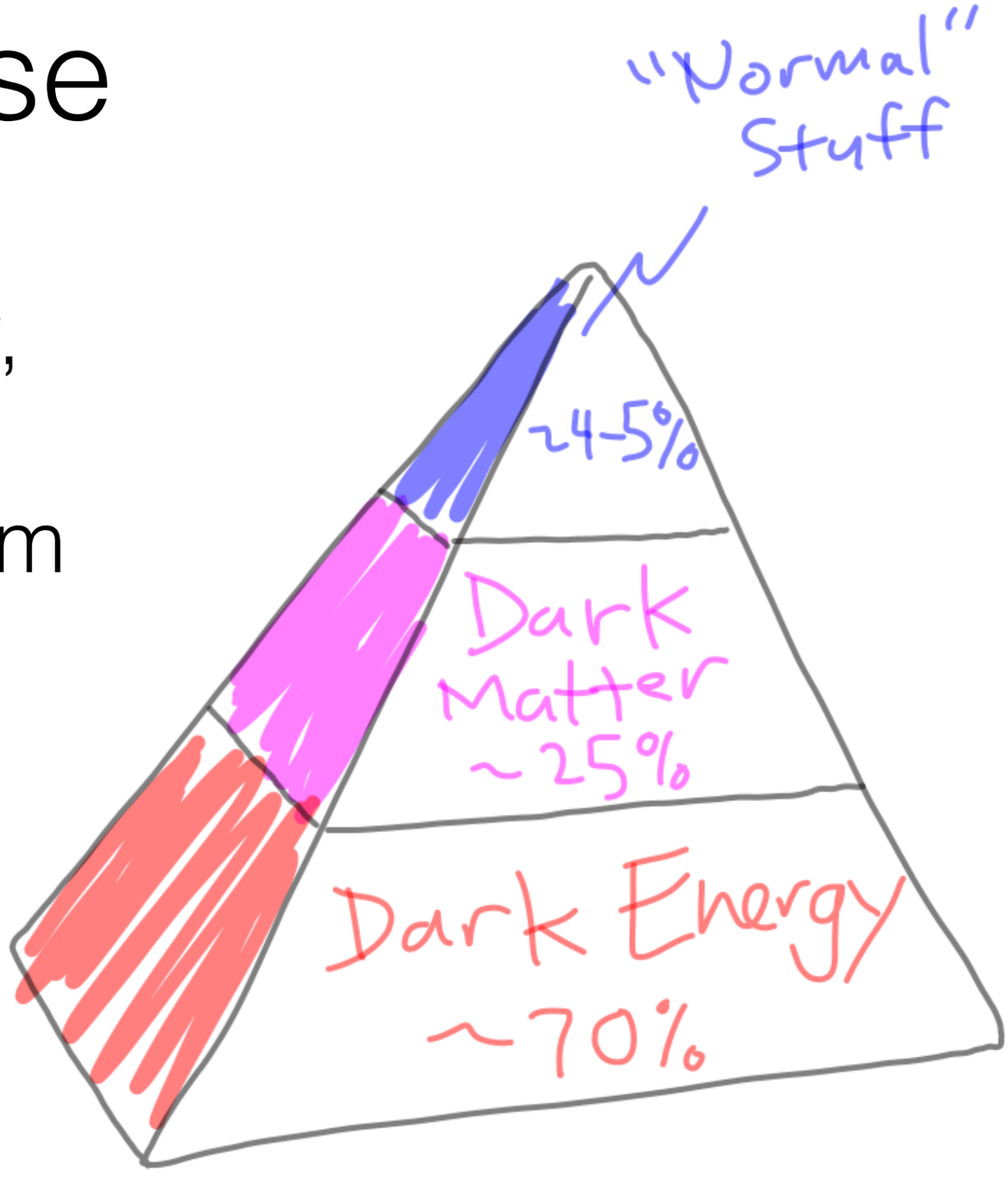


Planck

Energy Budget of the Universe

Energy Budget of the Universe

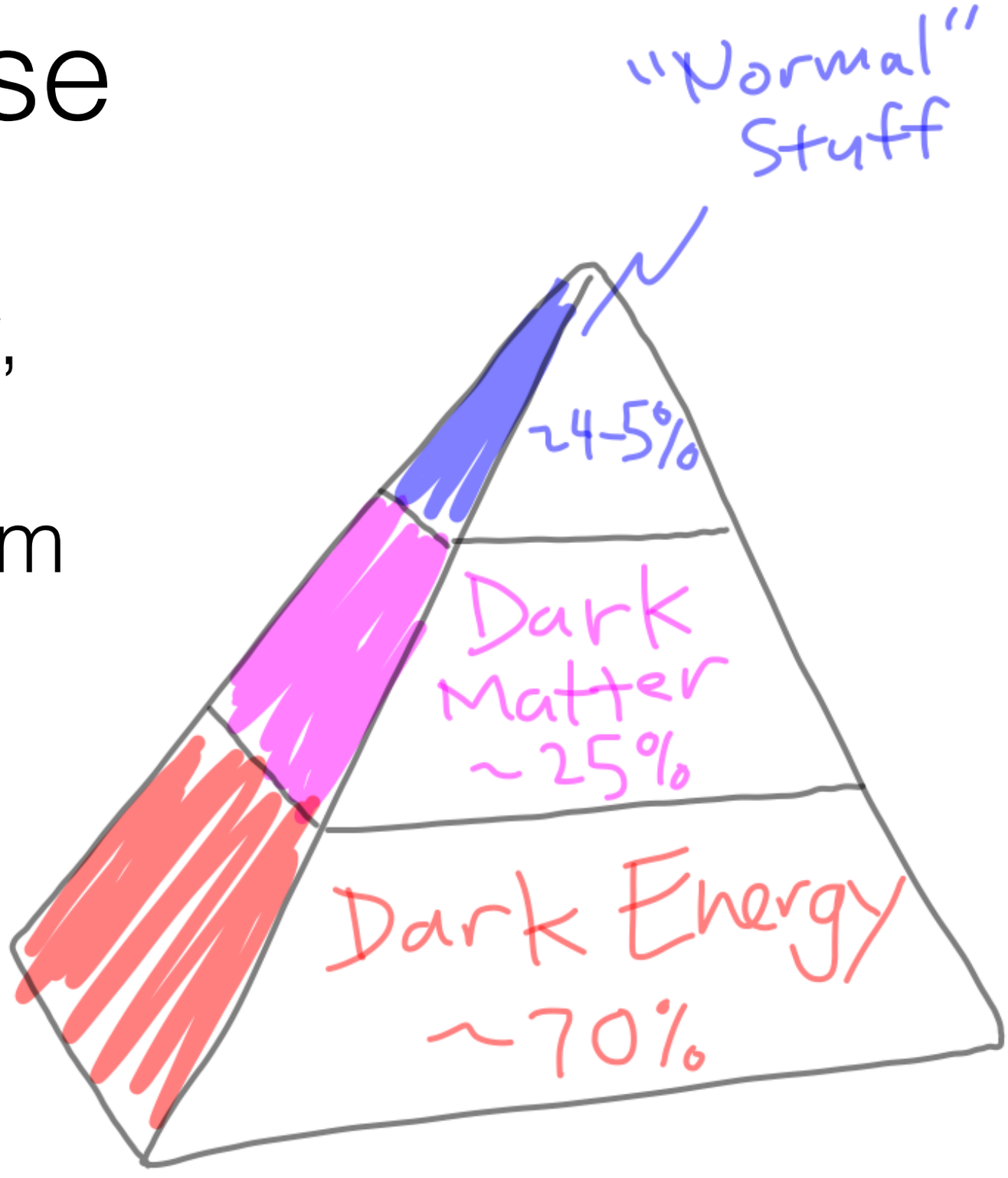
DM: something new, doesn't interact too strongly, isn't too warm



Energy Budget of the Universe

DM: something new, doesn't interact too strongly, isn't too warm

So what is it?



Theories of Dark Matter

?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

Dark Photon

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Asymmetric DM

Light Force Carriers

Extra Dimensions

Dynamical DM

Warm DM

Sterile Neutrinos

Solitonic DM

Quark Nuggets

UED DM

6d

5d

Warped Extra Dimensions

RS DM

Axion DM

T-odd DM

Little Higgs

QCD Axions

Axion-like Particles

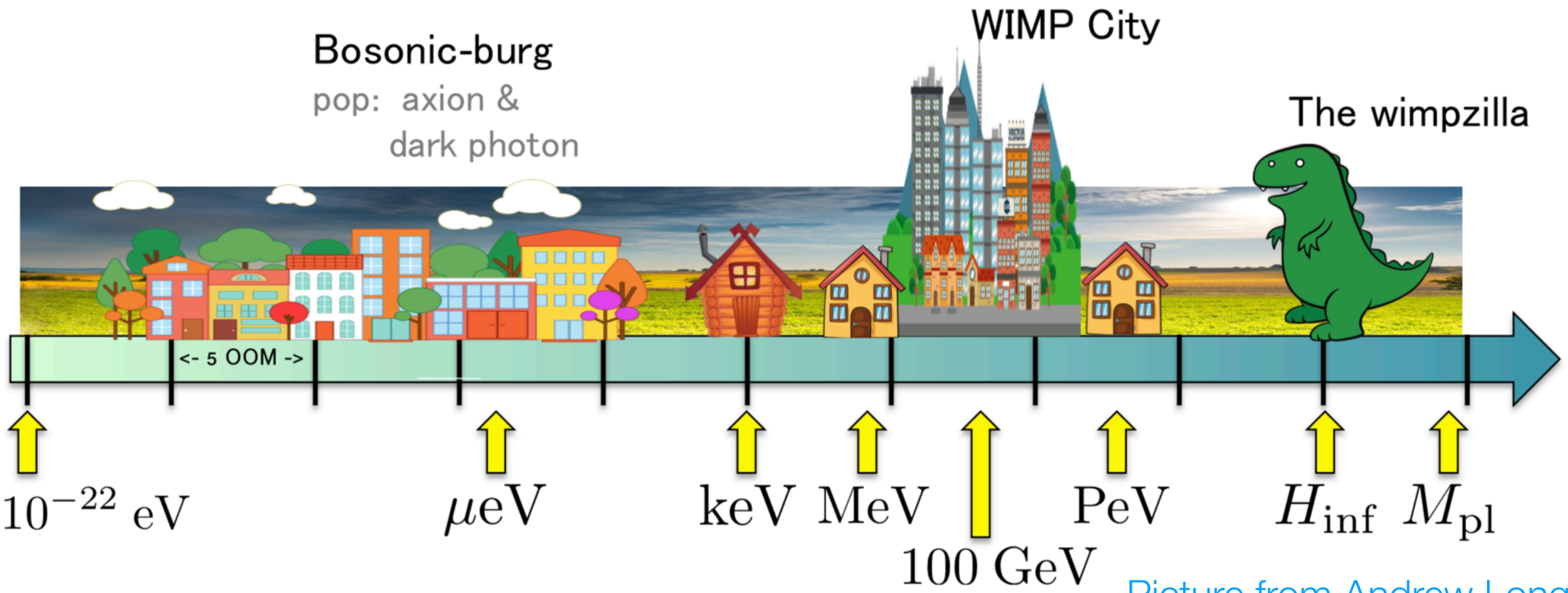
Littlest Higgs

No Lack of Options...

by Tim Tait

T Tait

Dark matter candidates span orders of magnitude in mass

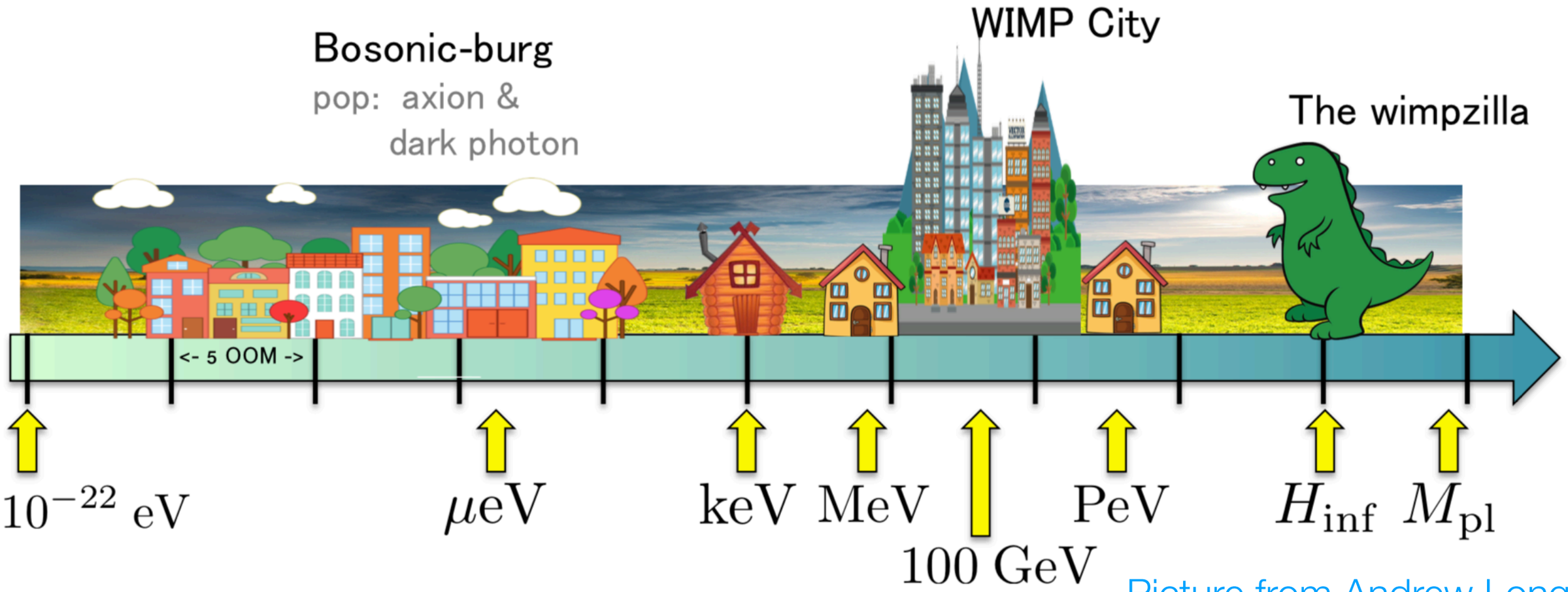


Picture from Andrew Long

Boson

Boson or Fermion

Dark matter candidates span orders of magnitude in mass



Picture from Andrew Long

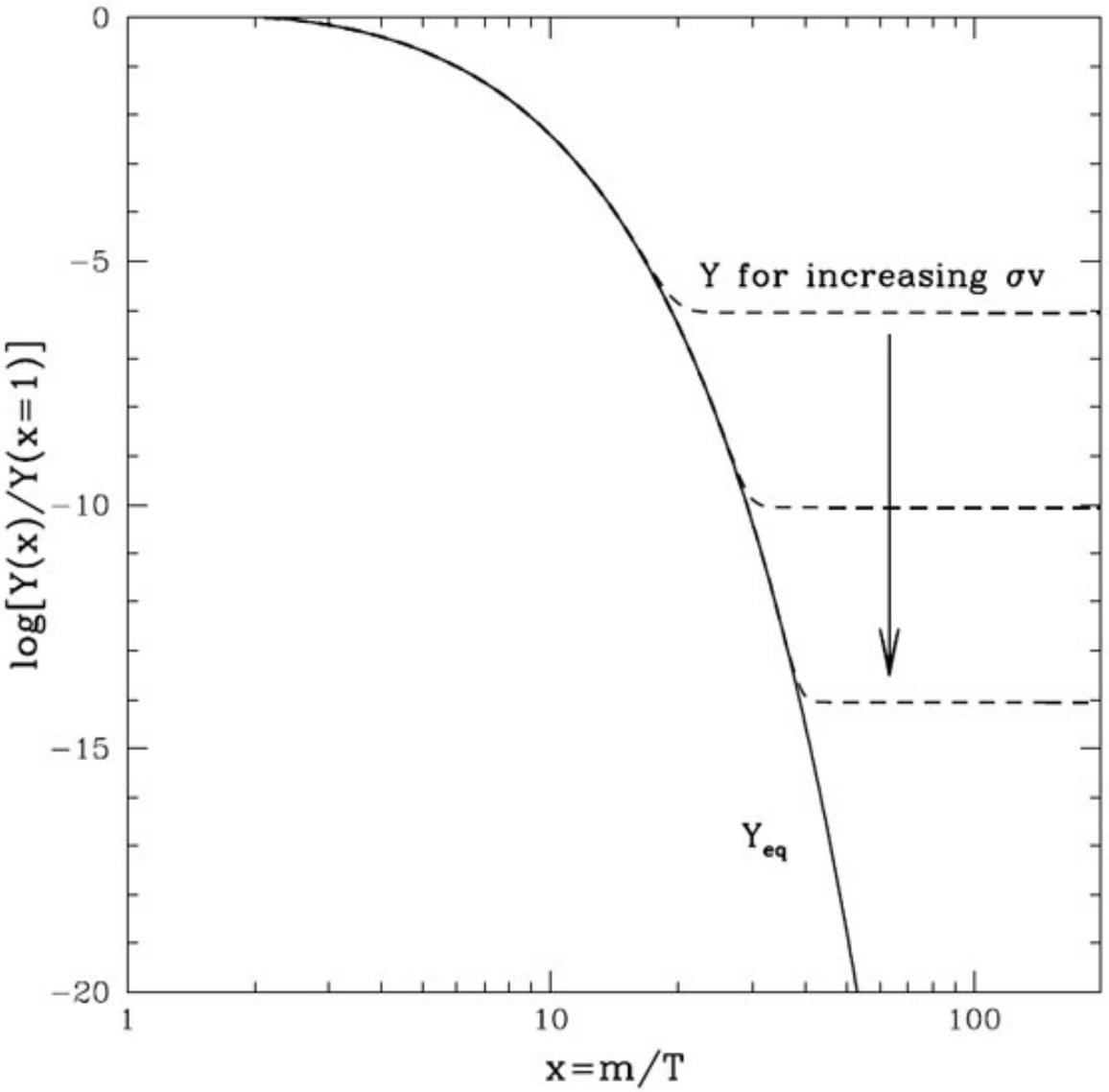
Boson

Boson or Fermion

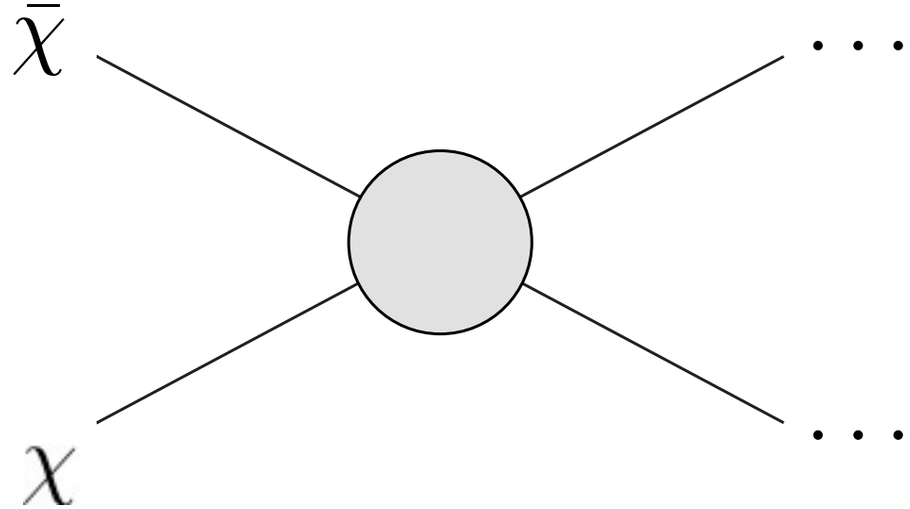
We'll cover a large range of this parameter space

How did the dark matter get here?

Option 1: thermal relic DM



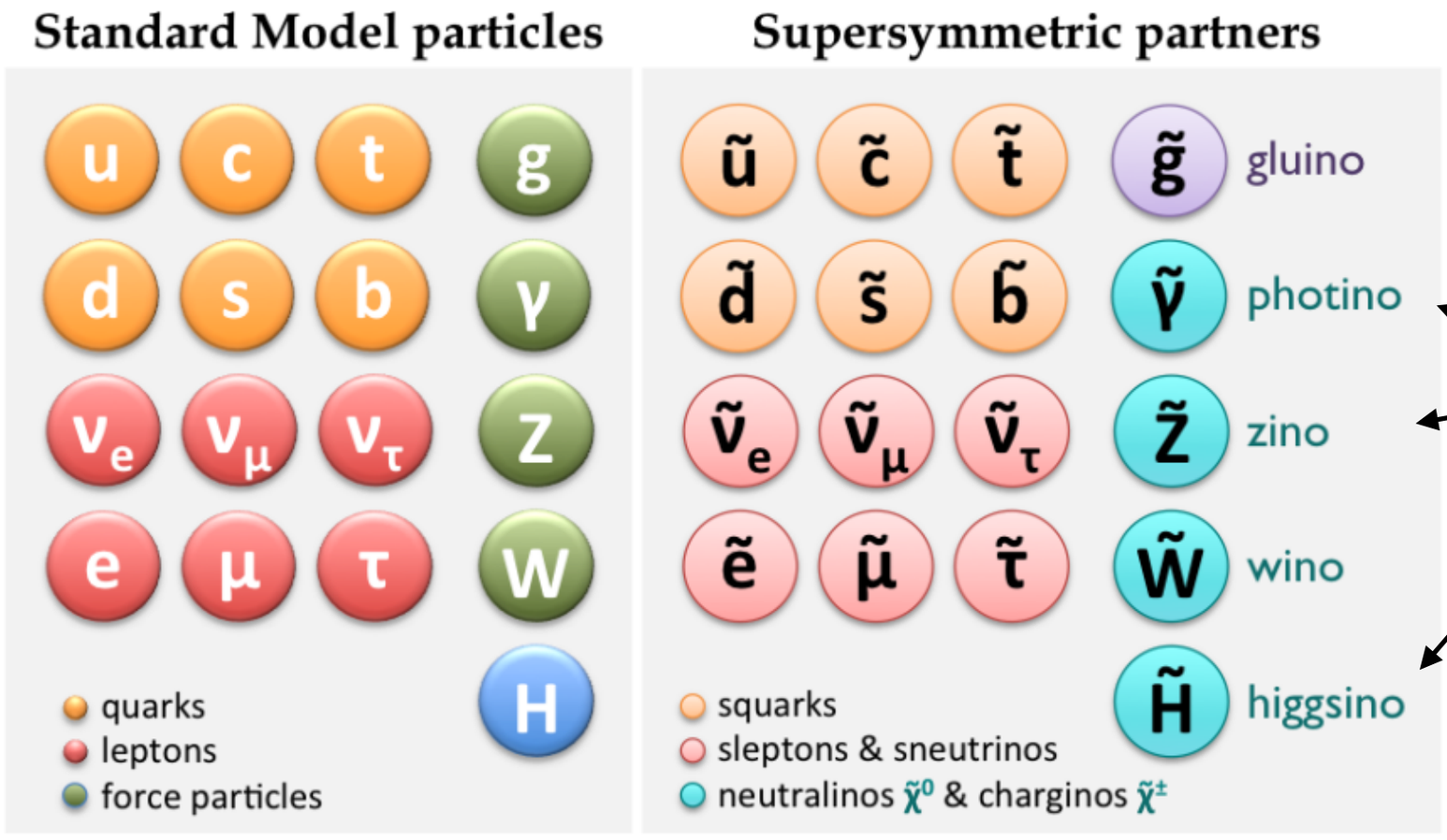
Requires non-grav. interaction:



$$\Omega h^2 \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2}{g^4} \sim 0.1 \left(\frac{m}{m_{\rm EW}} \right)^2 \left(\frac{g_{\rm EW}}{g} \right)^4$$

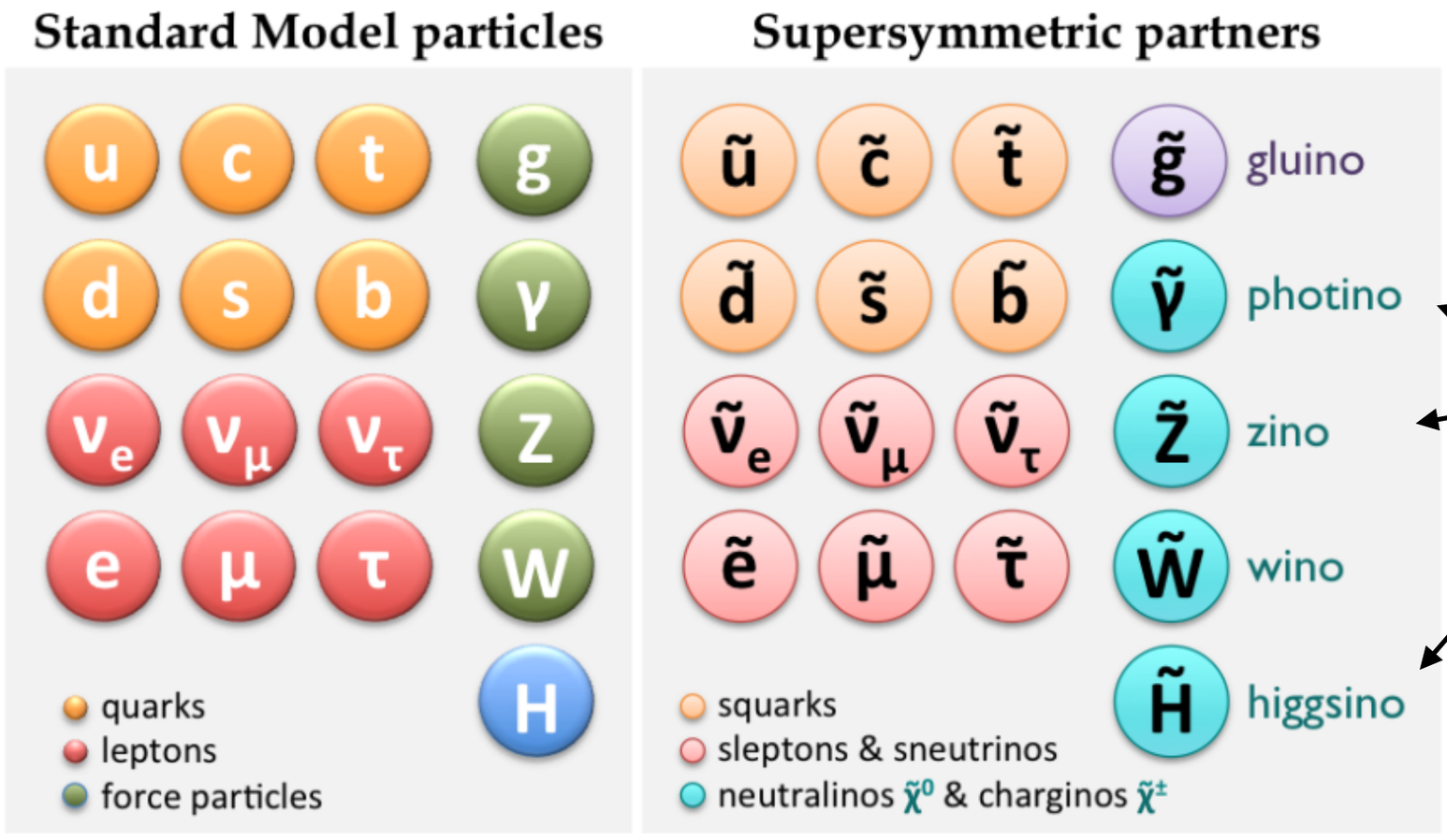
"WIMP Miracle"

(Weak Scale) SUSY has WIMP candidates



Some admixture of these could be stable, good DM candidate

(Weak Scale) SUSY has WIMP candidates

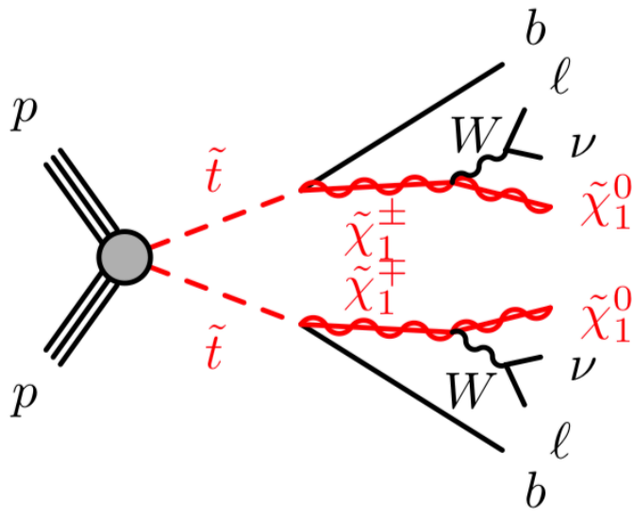


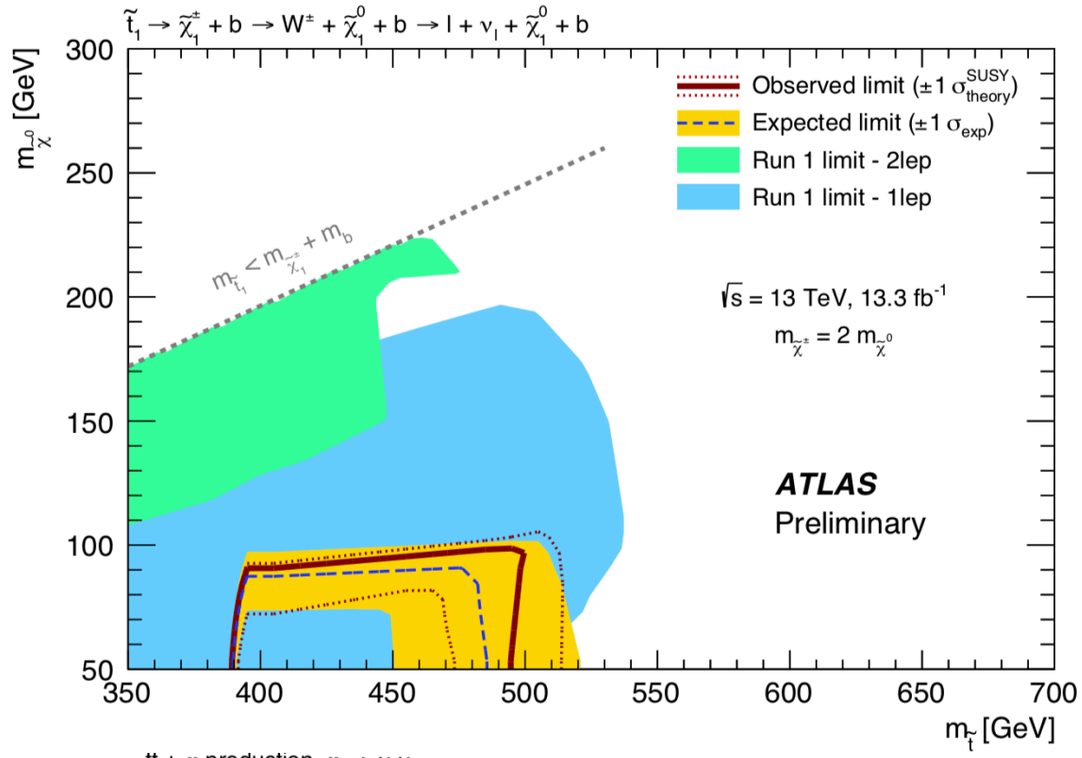
Some admixture of these could be stable, good DM candidate

Great, let's go look for it!

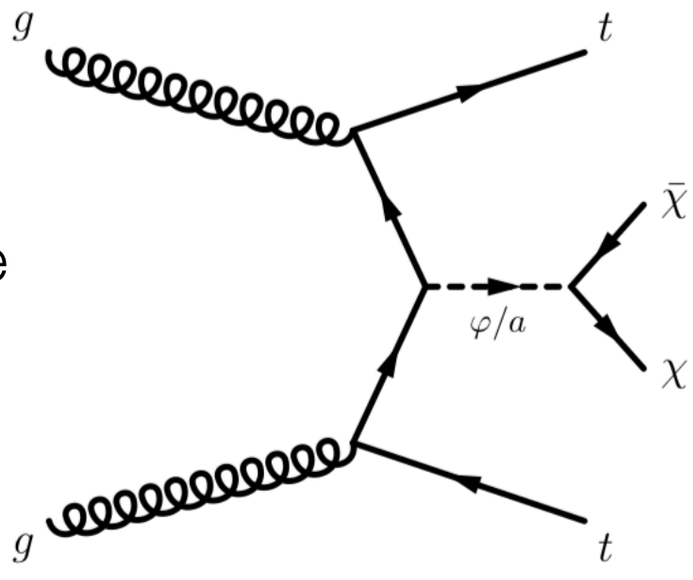
(Weak Scale) SUSY is under siege

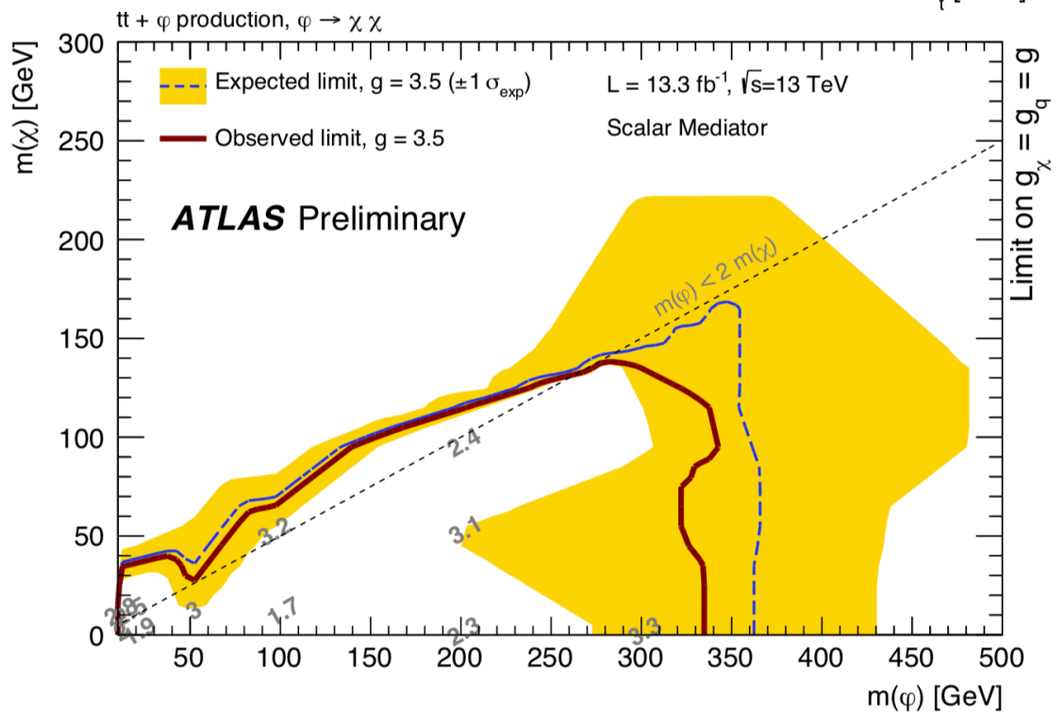
For example, at the LHC



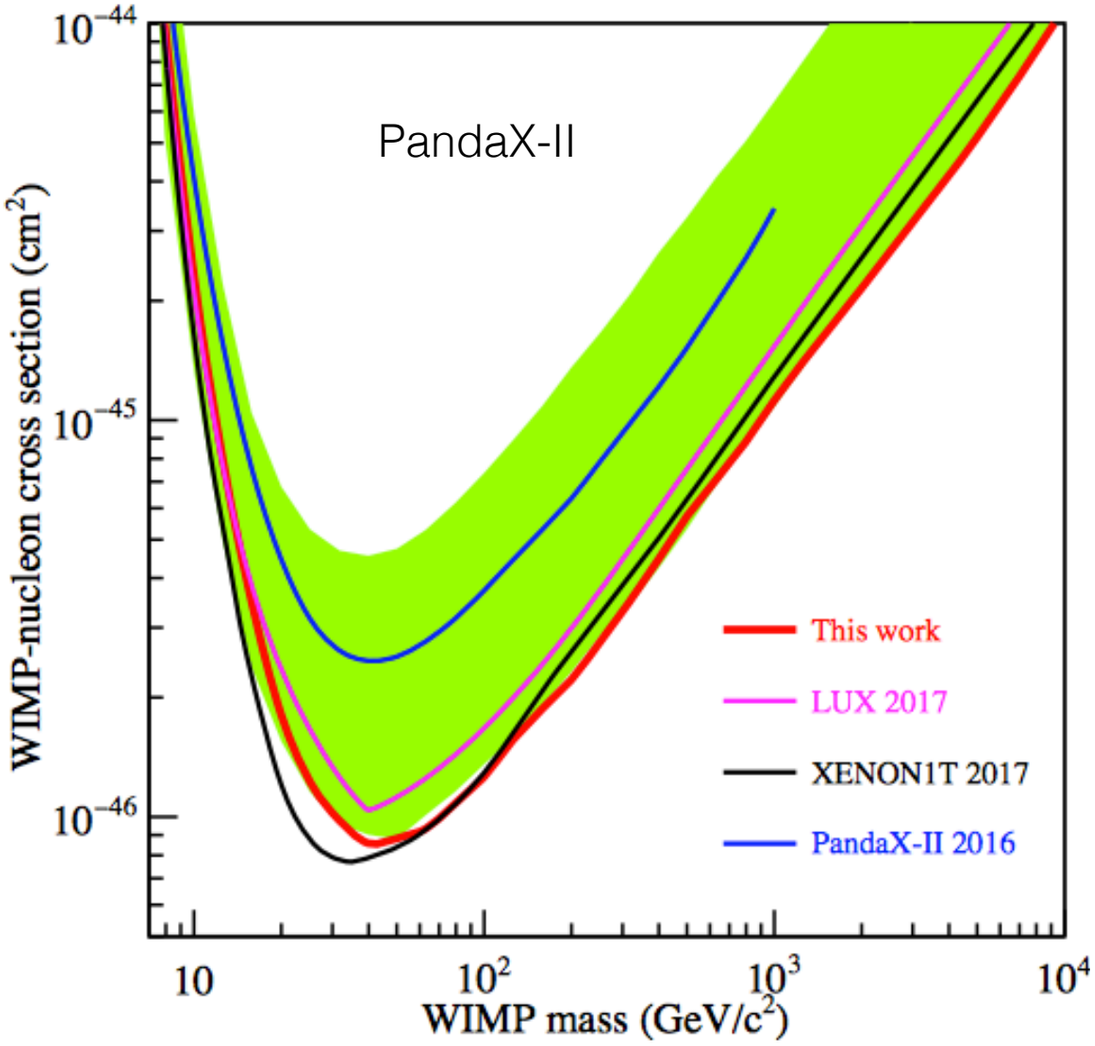


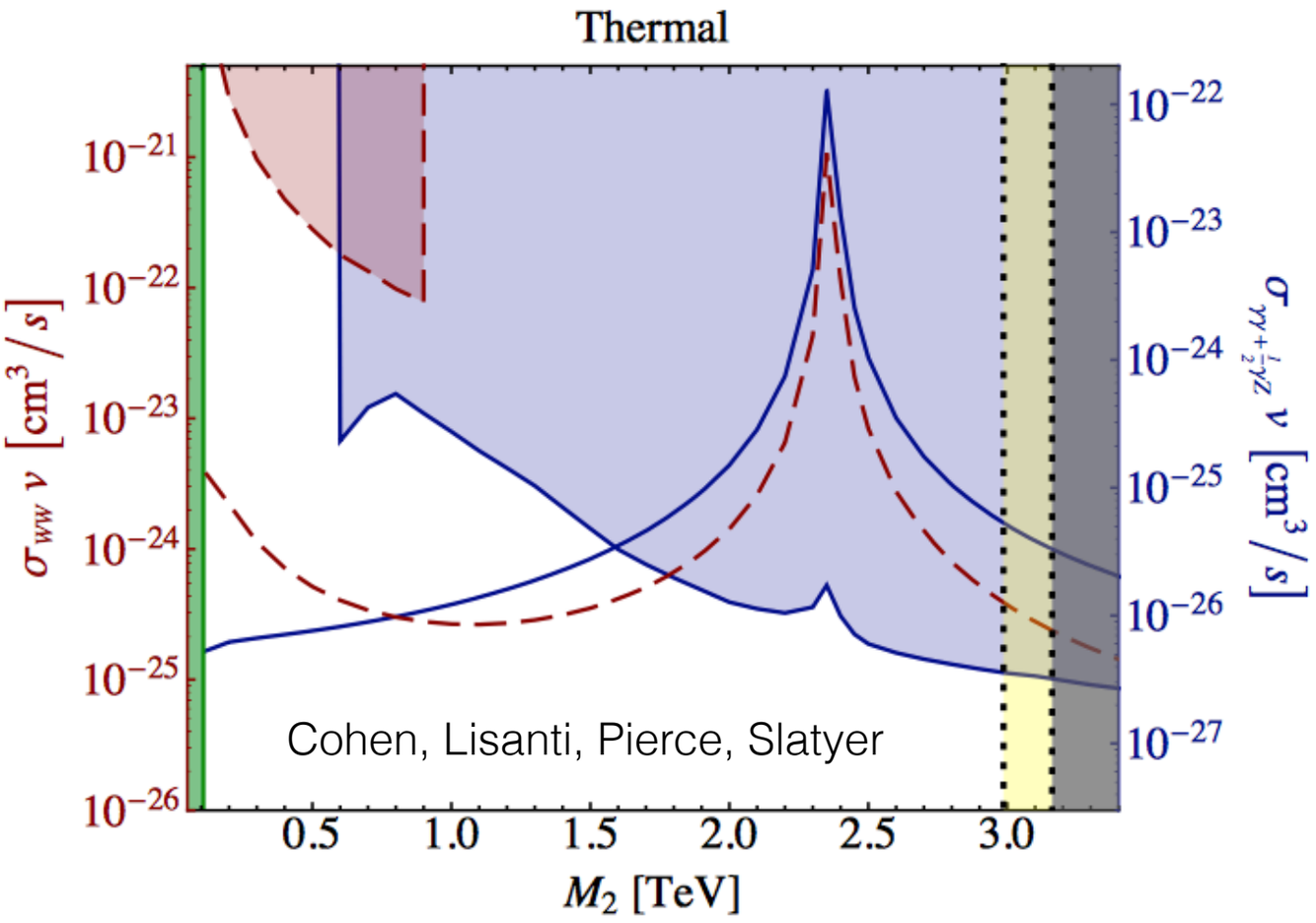
(And WIMPs more generally)





WIMPs in (in)direct detection:

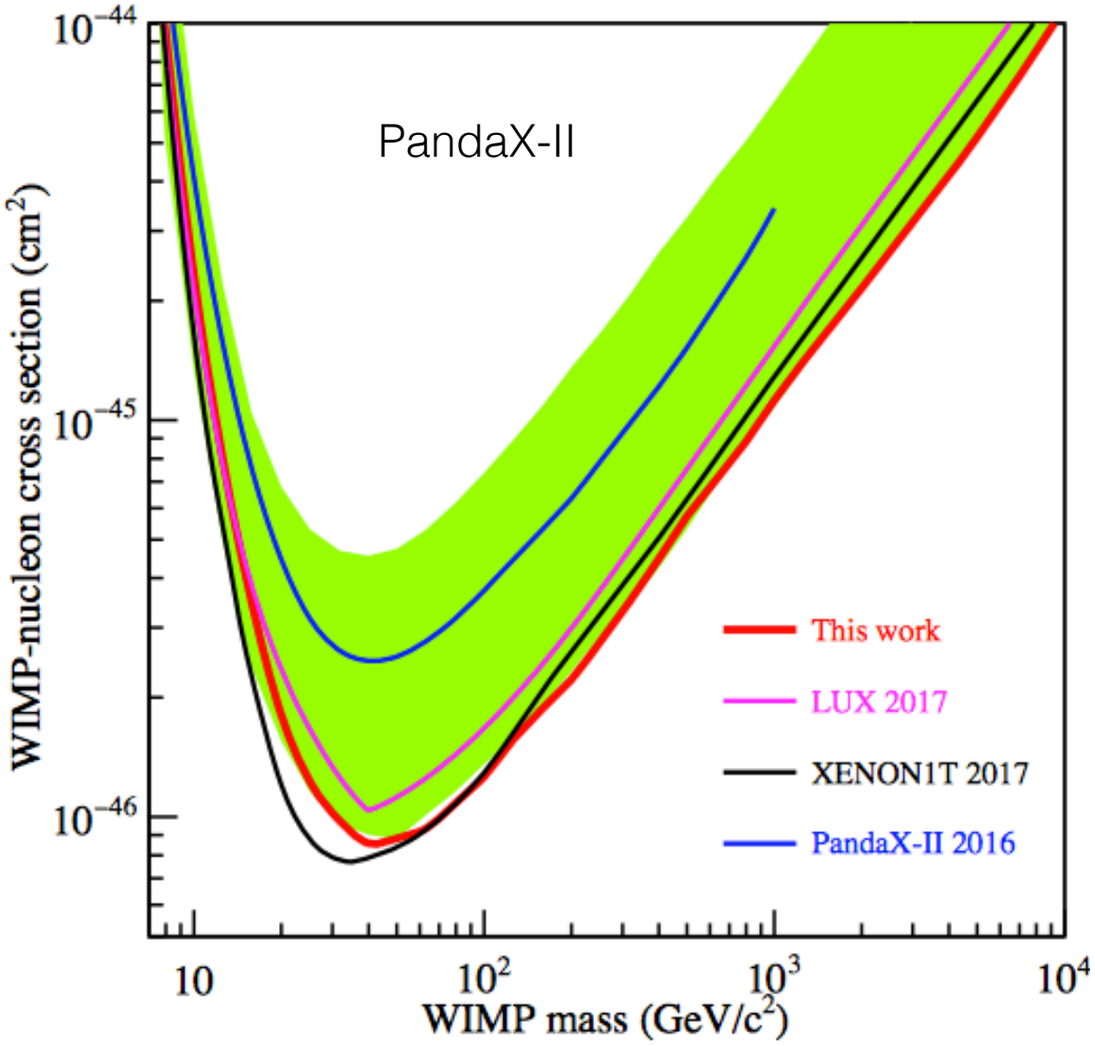


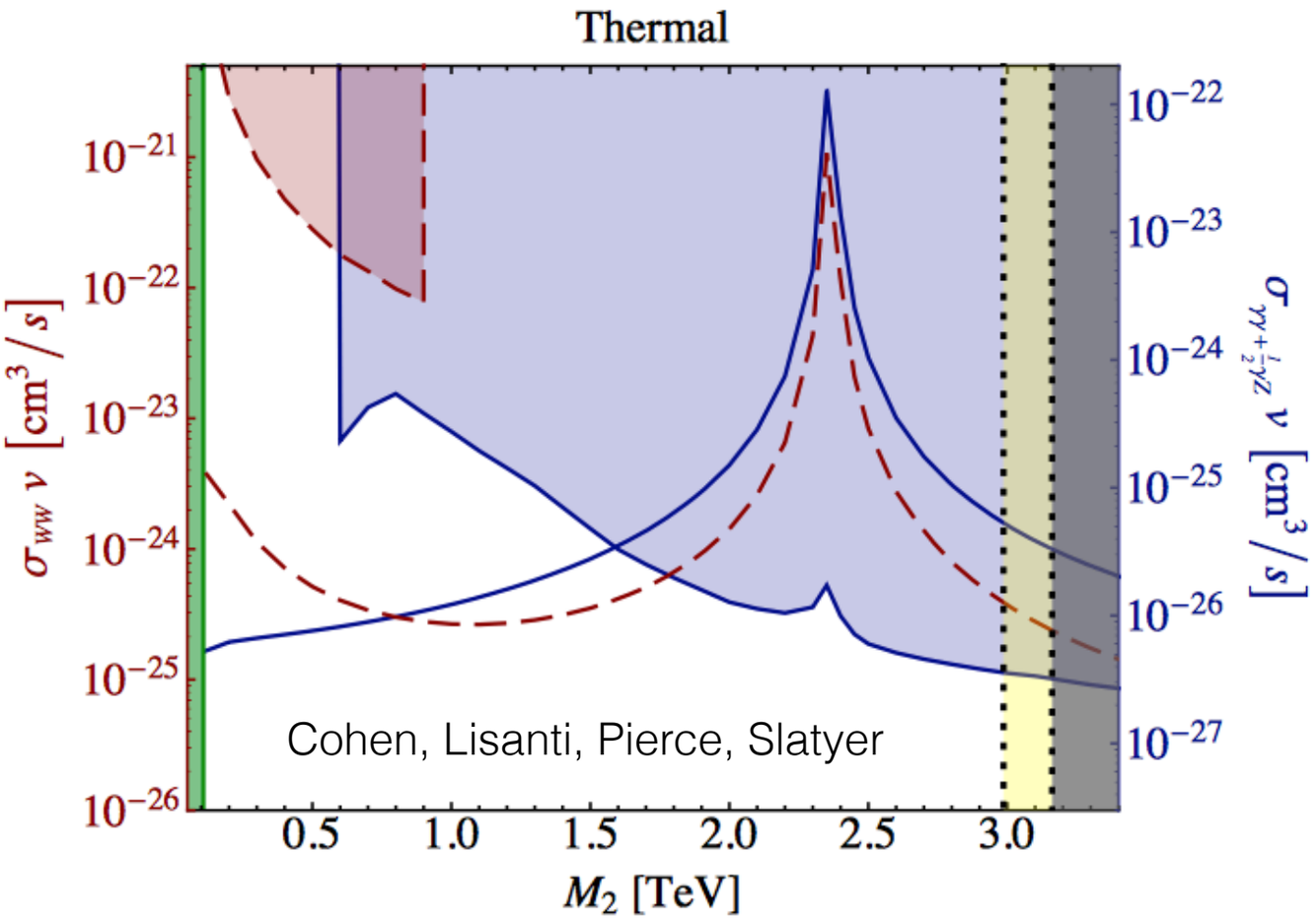


Simplest possible WIMP:

$$\sigma_{\rm DD} \sim \frac{G_F^2 \mu^2}{\pi} Y^2 \sim 10^{-39}\ {\rm cm}^2 \left(\frac{Y}{1/2}\right)^2$$

WIMPs in (in)direct detection:





Simplest possible WIMP:

$$\sigma_{\rm DD} \sim \frac{G_F^2 \mu^2}{\pi} Y^2 \sim 10^{-39}\ {\rm cm}^2 \left(\frac{Y}{1/2}\right)^2$$

What are the other possibilities?

DM through “portals”

Standard Model symmetries

$$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$$

$$G^a_\mu,\ W^b_\mu,\ B_\mu \to G^a_\mu,\ A_\mu$$

Standard Model particle content

$$H = \begin{pmatrix} \rho^+ \\ v + h + \rho^0 \end{pmatrix}$$

$$\left.\begin{aligned} \ell &= \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad e_R \\ q &= \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad u_R \ \ d_R \end{aligned}\right\} \times 3$$

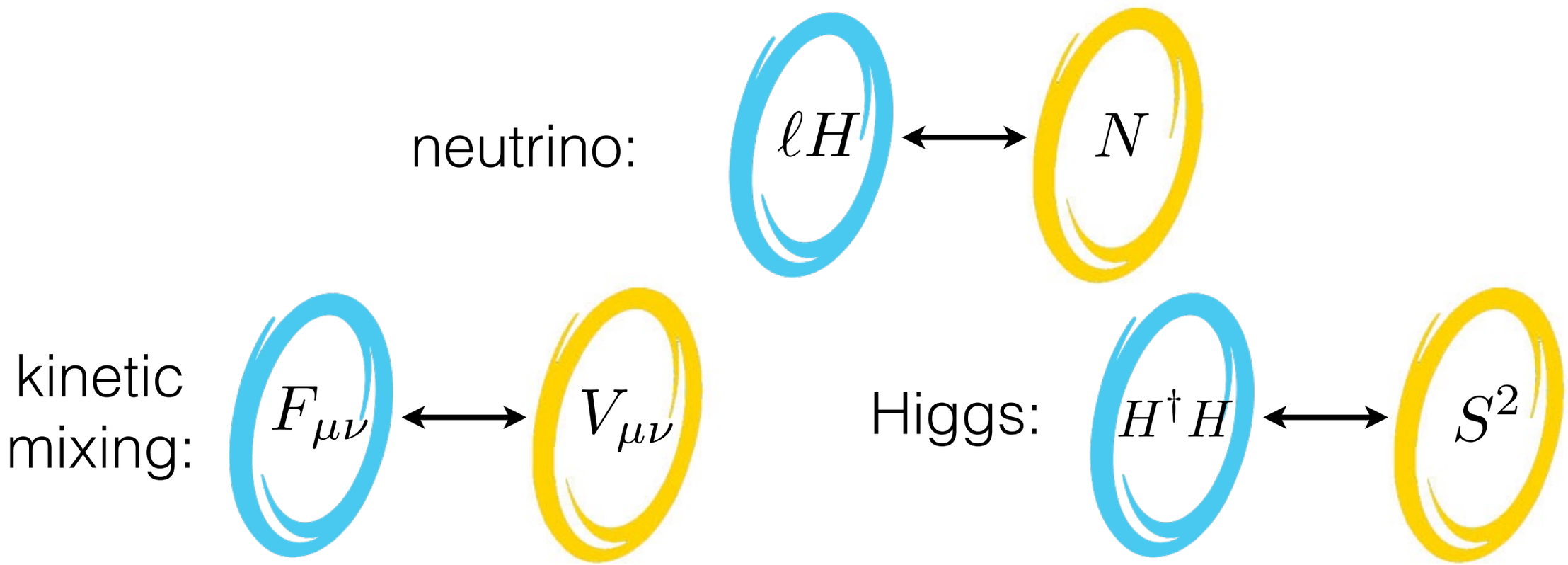
Renormalization: lower dim. operators (fewer fields/particles) more important

DM through “portals”

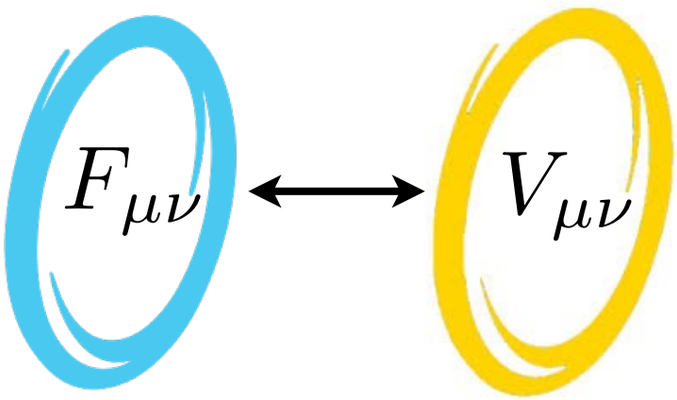
Standard Model symmetries $SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$

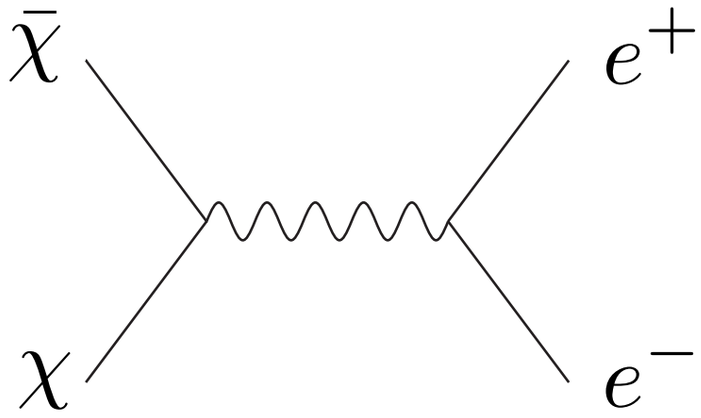
Portals: coupling via stuff uncharged w.r.t. SM

Lead to minimal difficulties incorporating hidden sectors

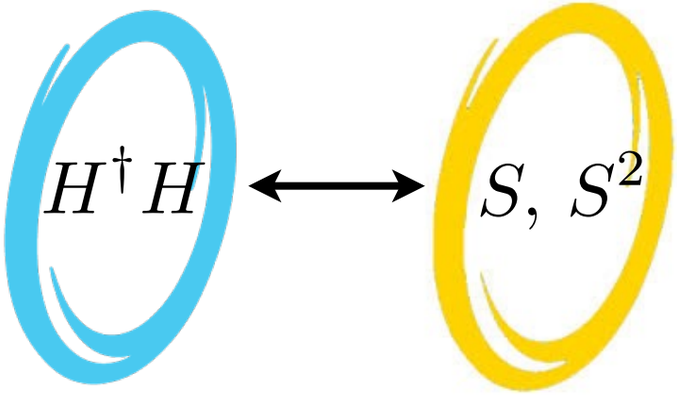


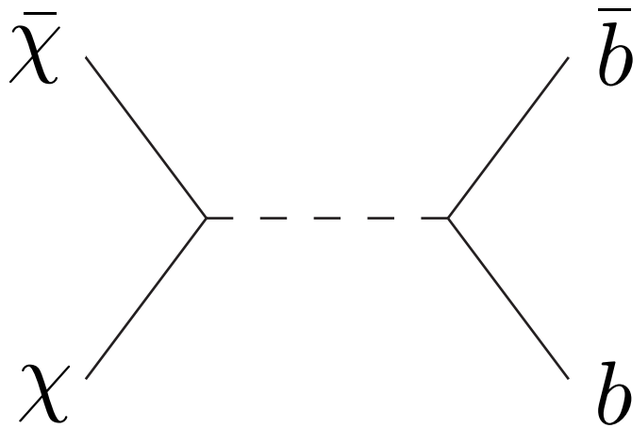
DM annihilation through portals



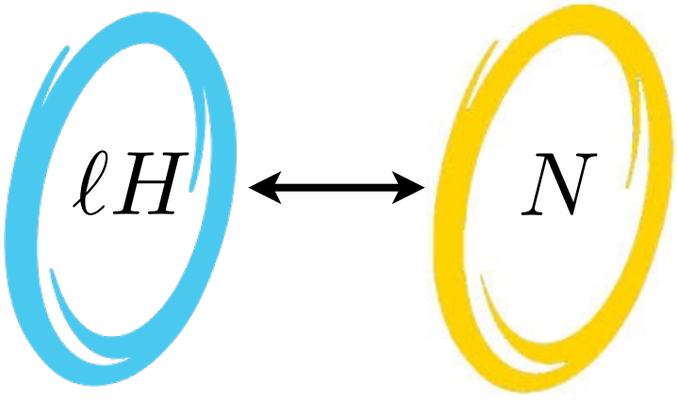


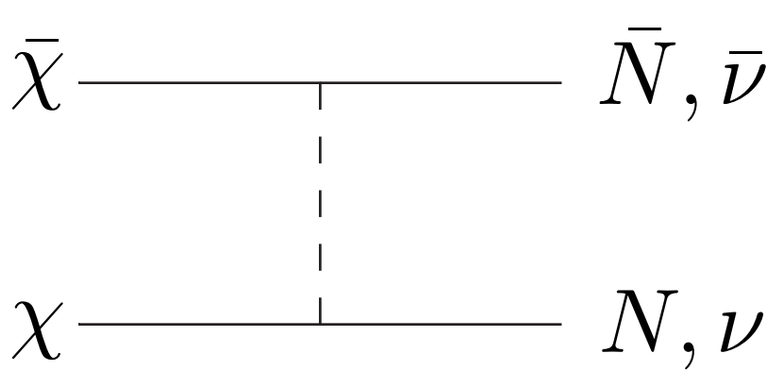
Vector Portal





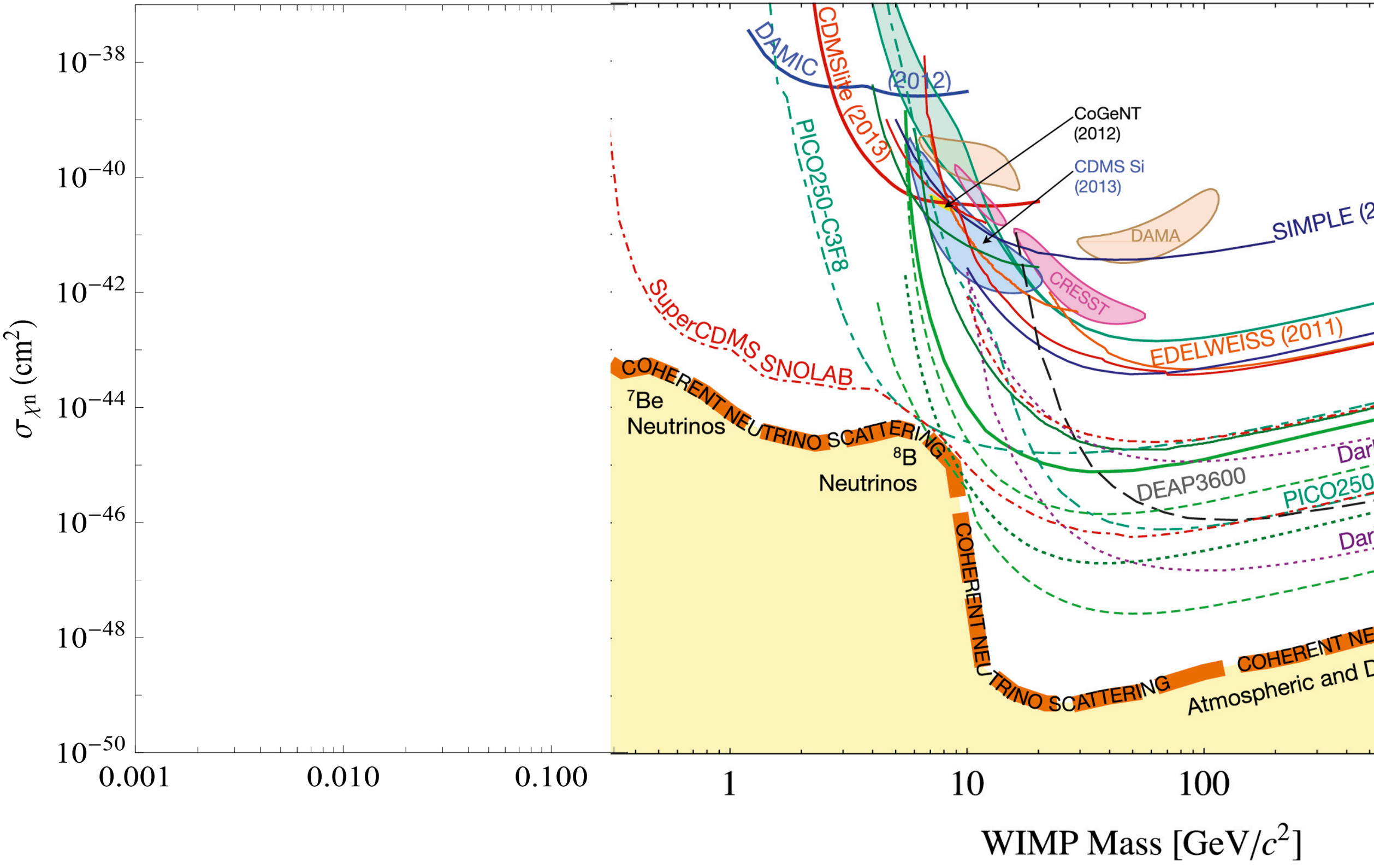
Higgs Portal





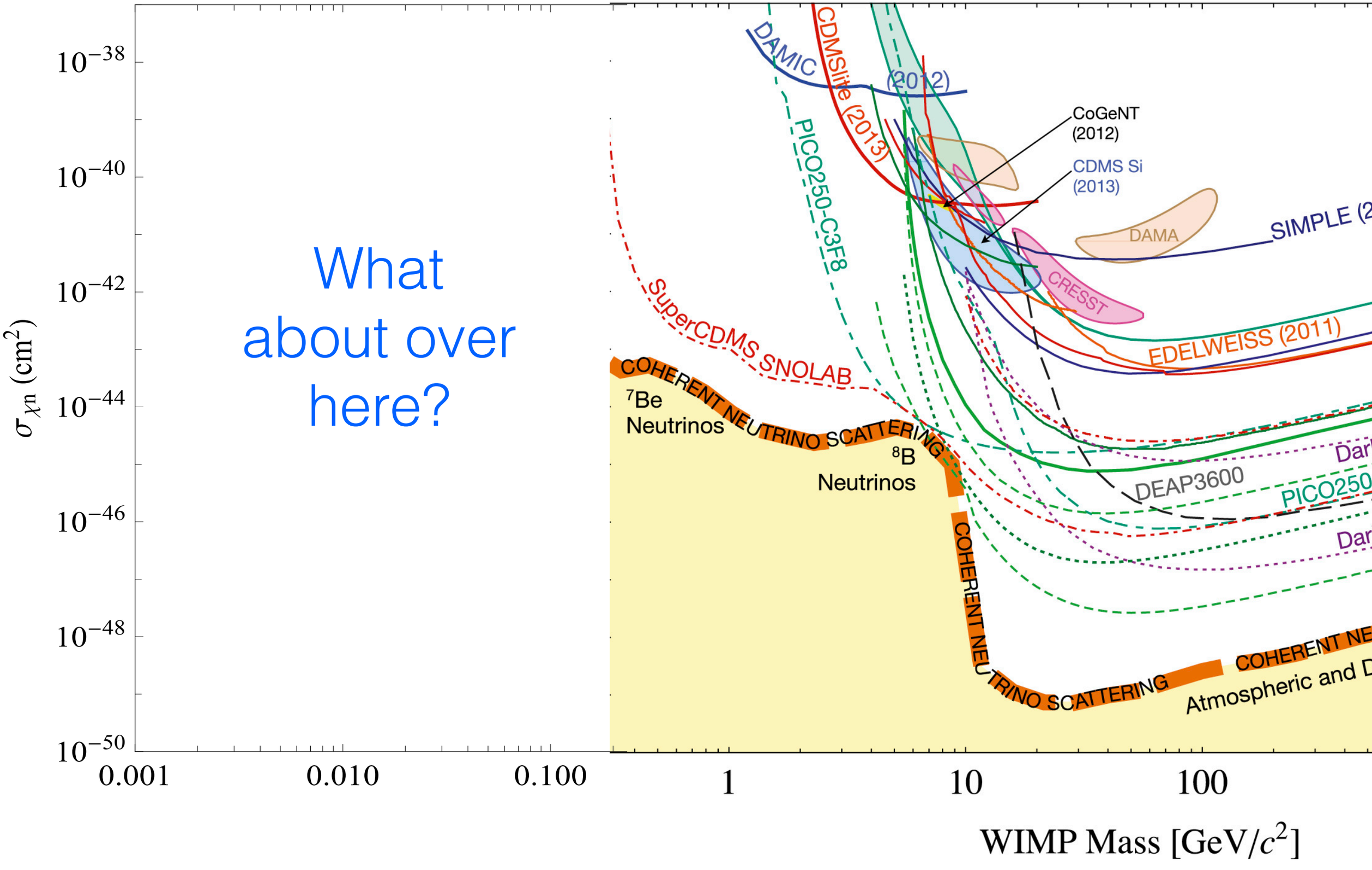
Neutrino Portal

Direct Detection Limits weaken at low mass



Direct Detection Limits weaken at low mass

What about over here?

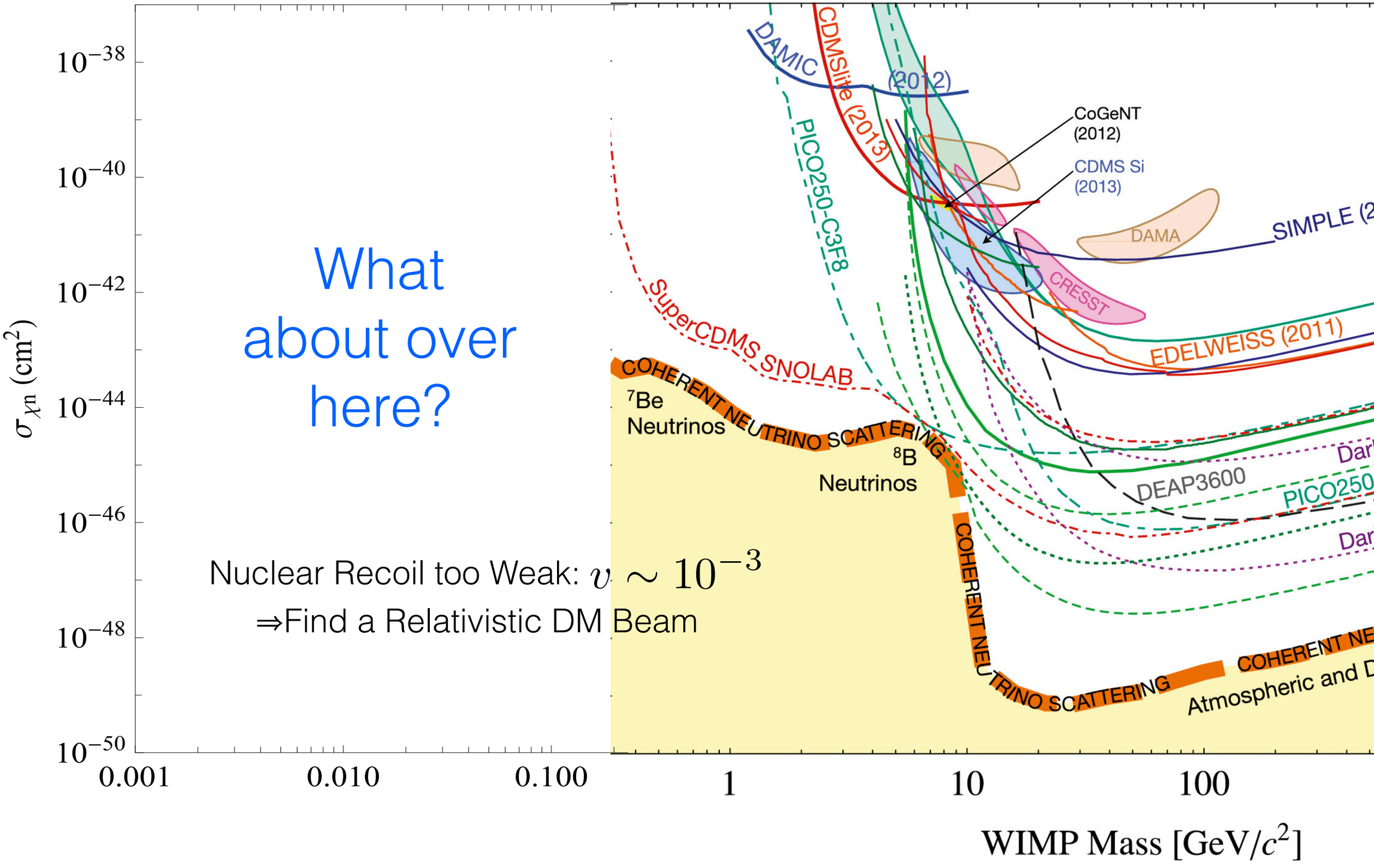


Direct Detection Limits weaken at low mass

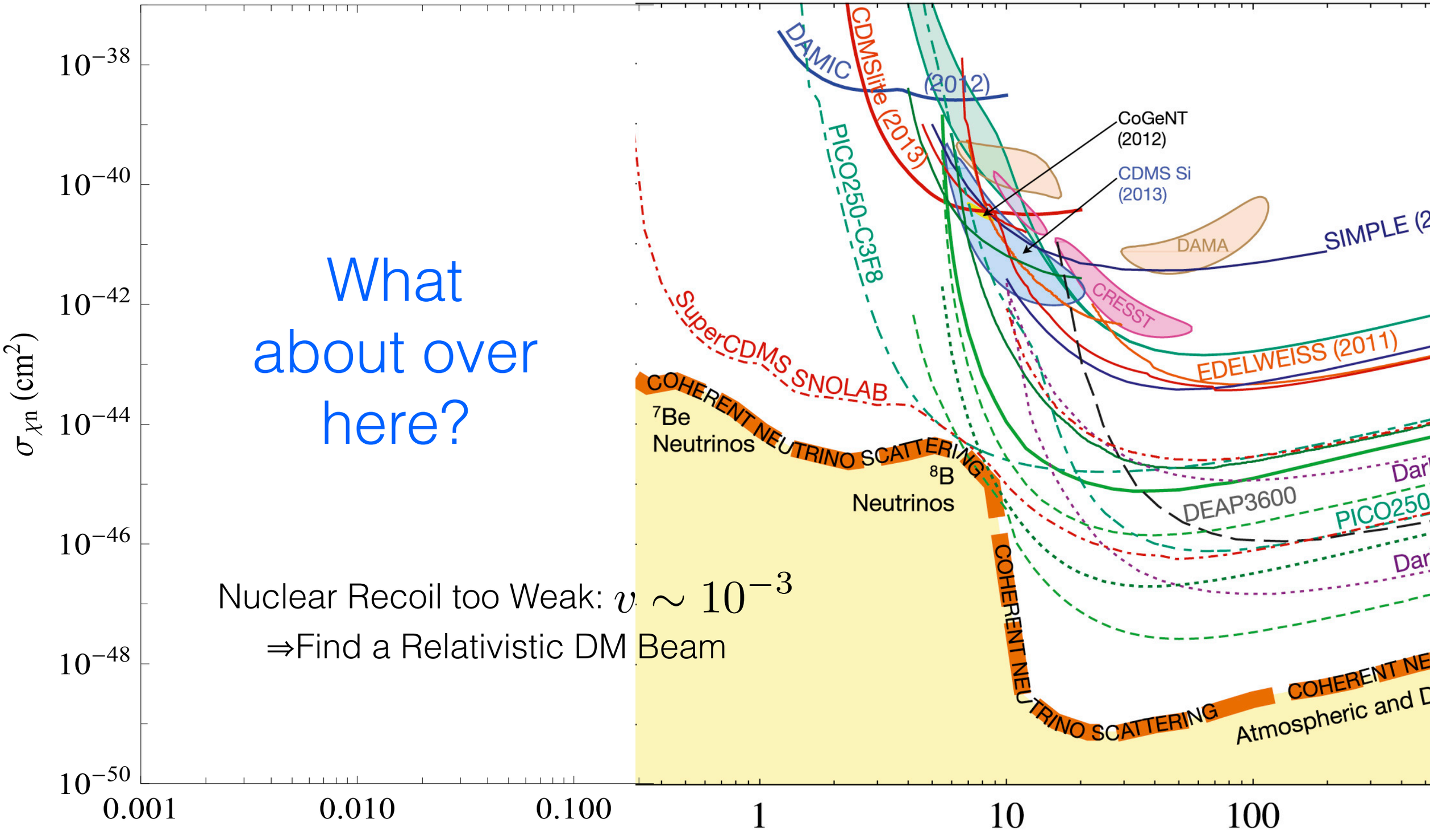
What about over here?

Nuclear Recoil too Weak: $v \sim 10^{-3}$

⇒Find a Relativistic DM Beam



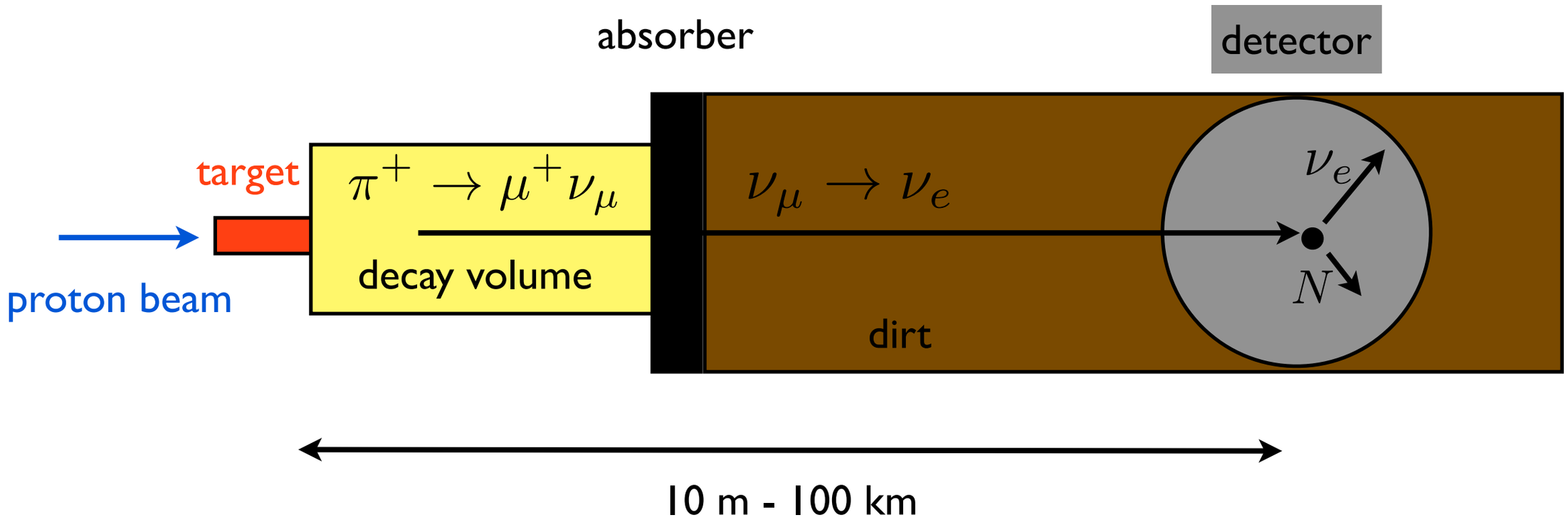
Direct Detection Limits weaken at low mass



(Need a portal to deplete DM density)

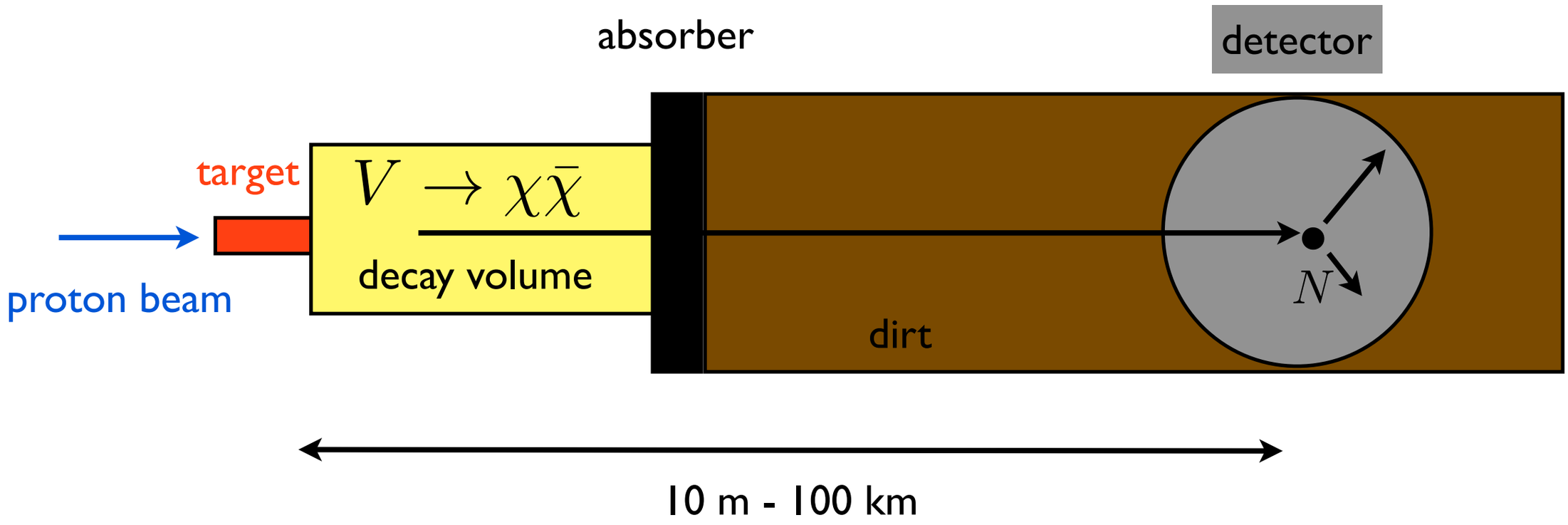
Work by Batell, deNiverville, DM,
Pospelov, Ritz; Dobrescu & Frugiuele, …

Neutrino Beams



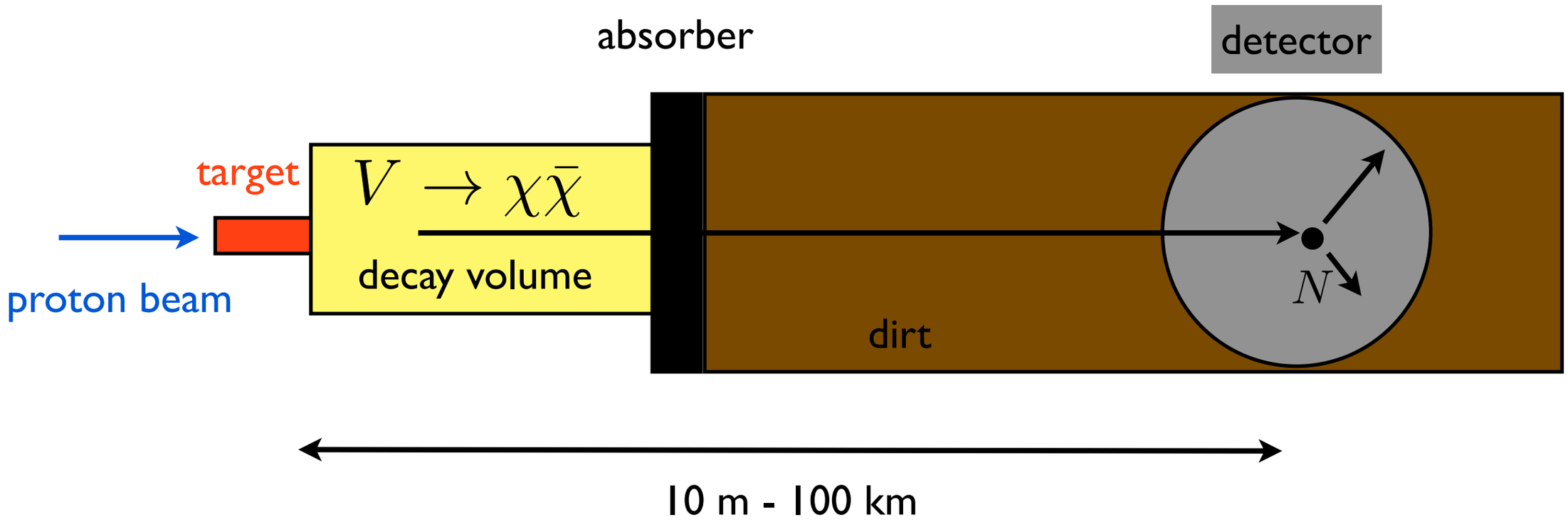
Work by Batell, deNiverville, DM,
Pospelov, Ritz; Dobrescu & Frugiuele, …

Dark Matter Beams



Work by Batell, deNiverville, DM,
Pospelov, Ritz; Dobrescu & Frugiuele, …

Dark Matter Beams

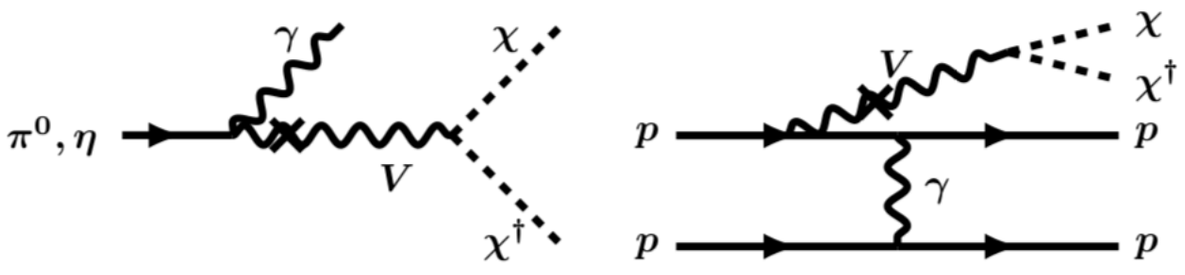


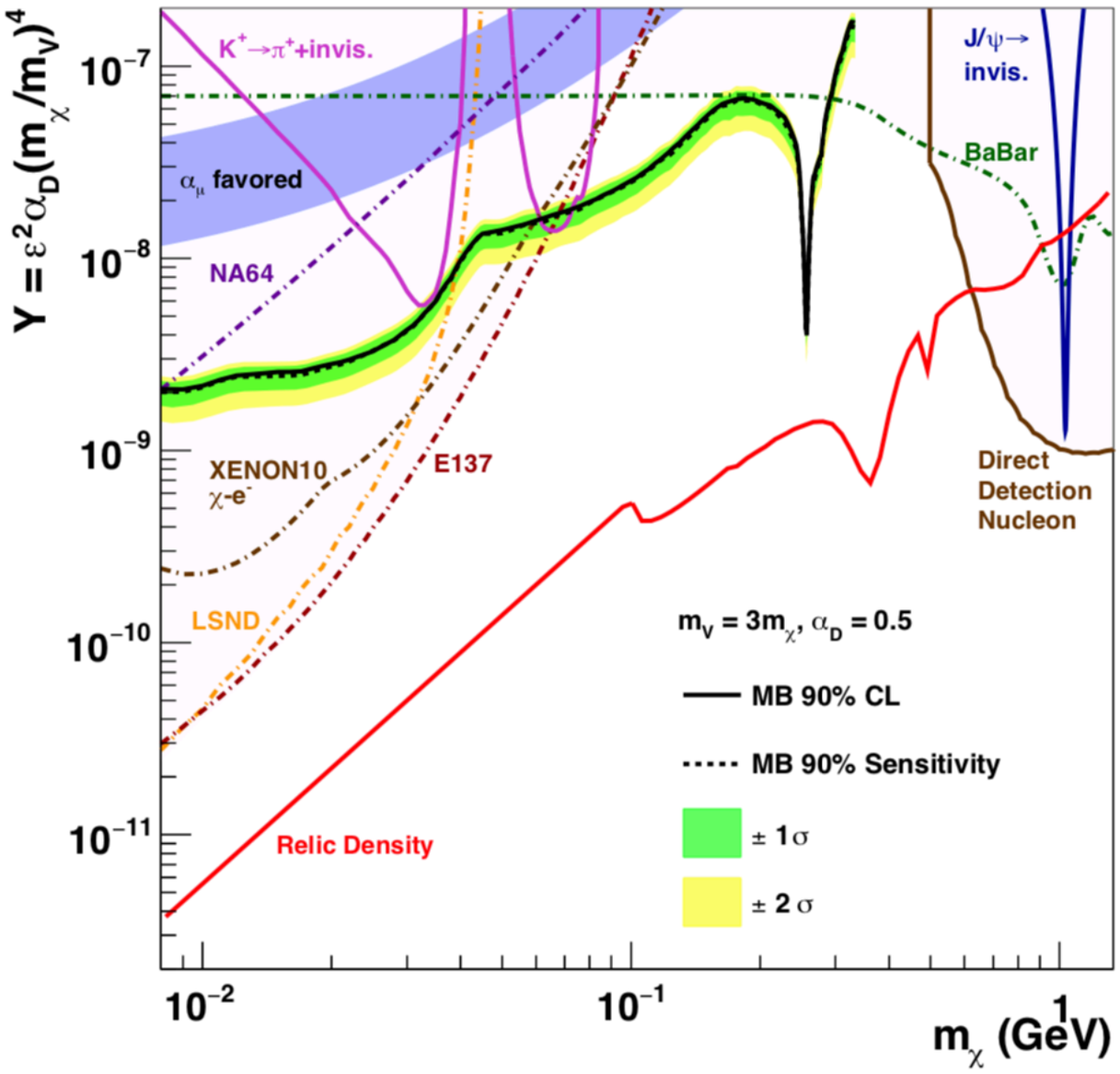
Such a search performed at MiniBooNE…

MiniBooNE Search (PRL 118, 221803)

Kinetic Mixing/ Vector Portal

DM production:

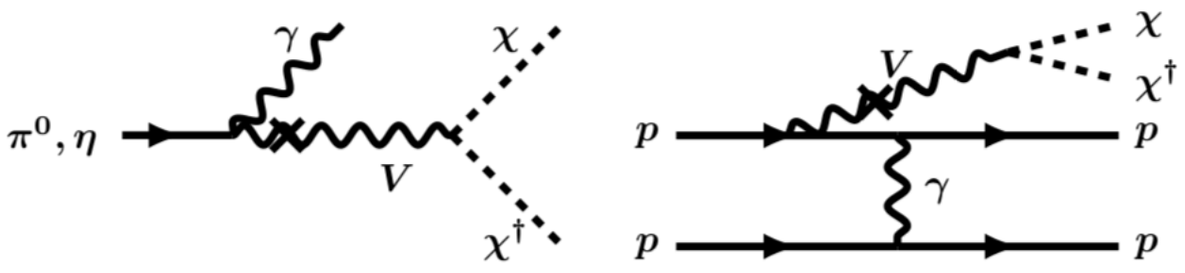


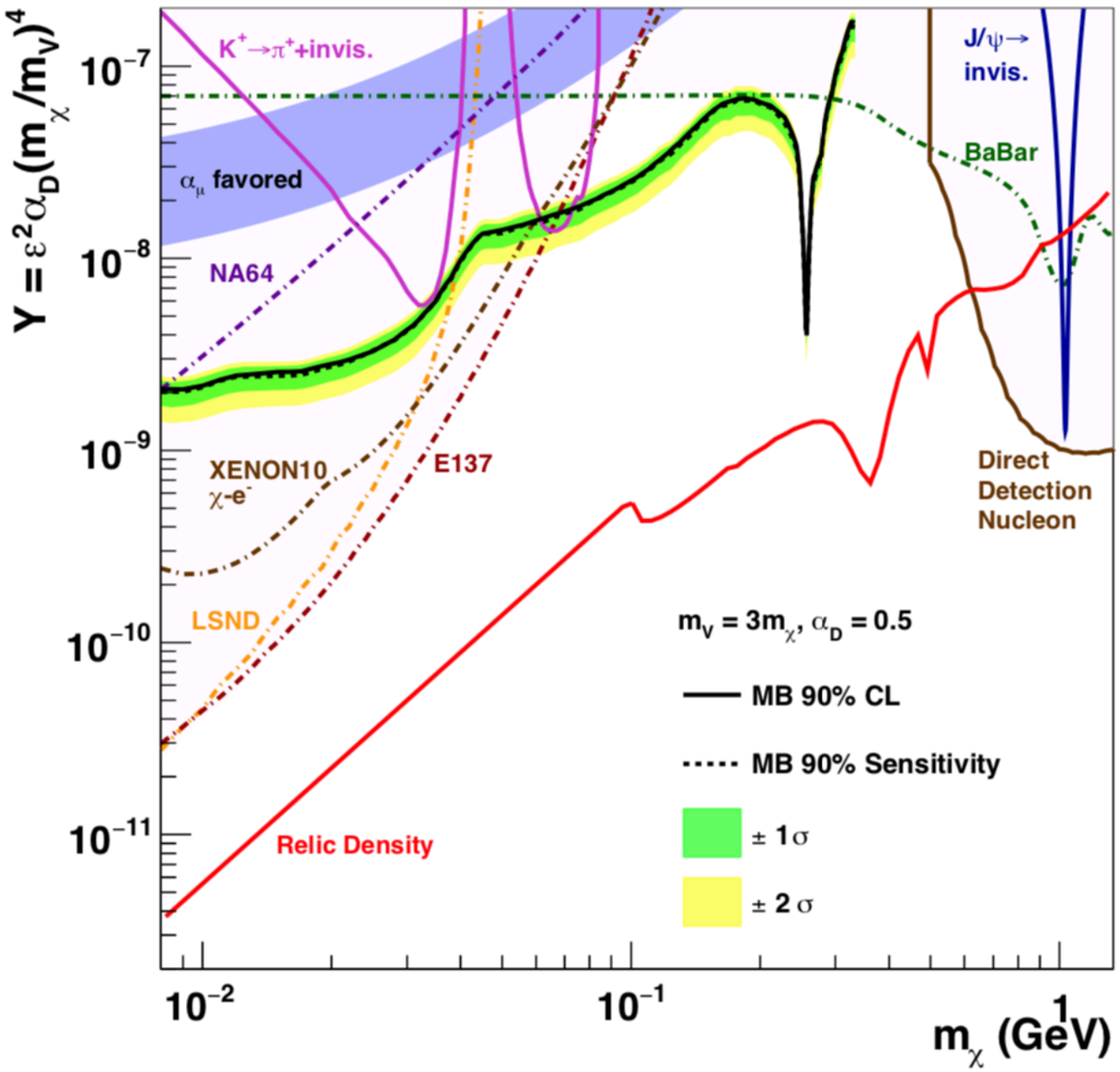


MiniBooNE Search (PRL 118, 221803)

Kinetic Mixing/ Vector Portal

DM production:



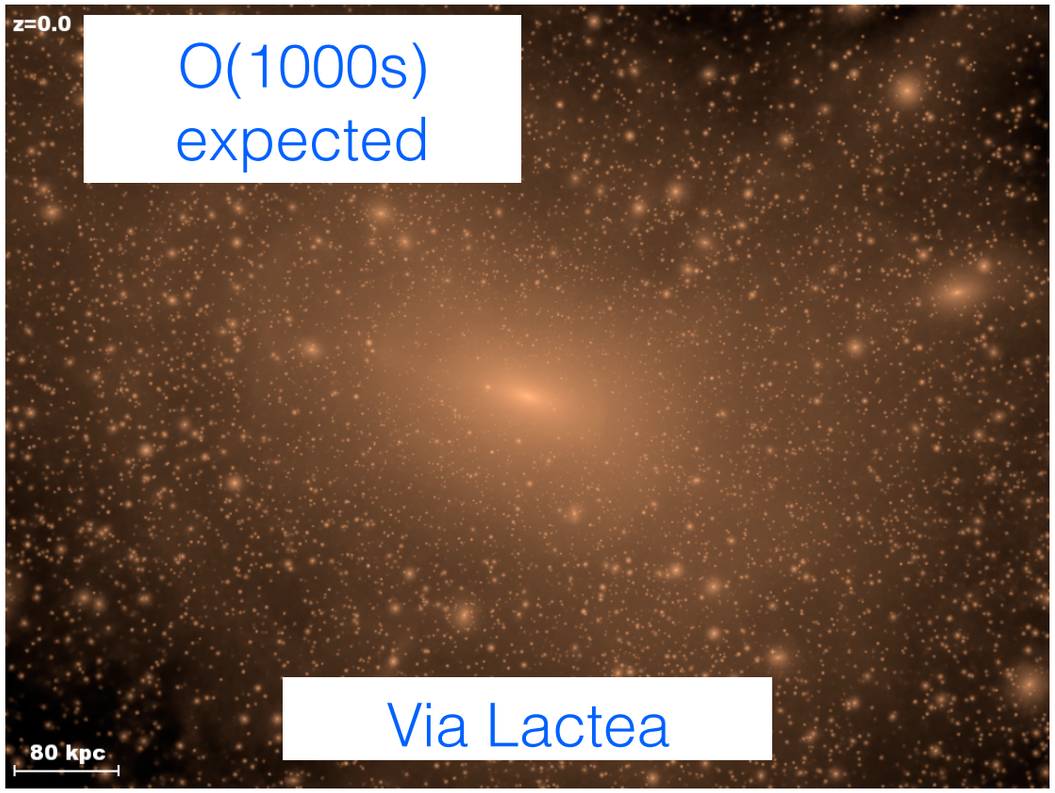


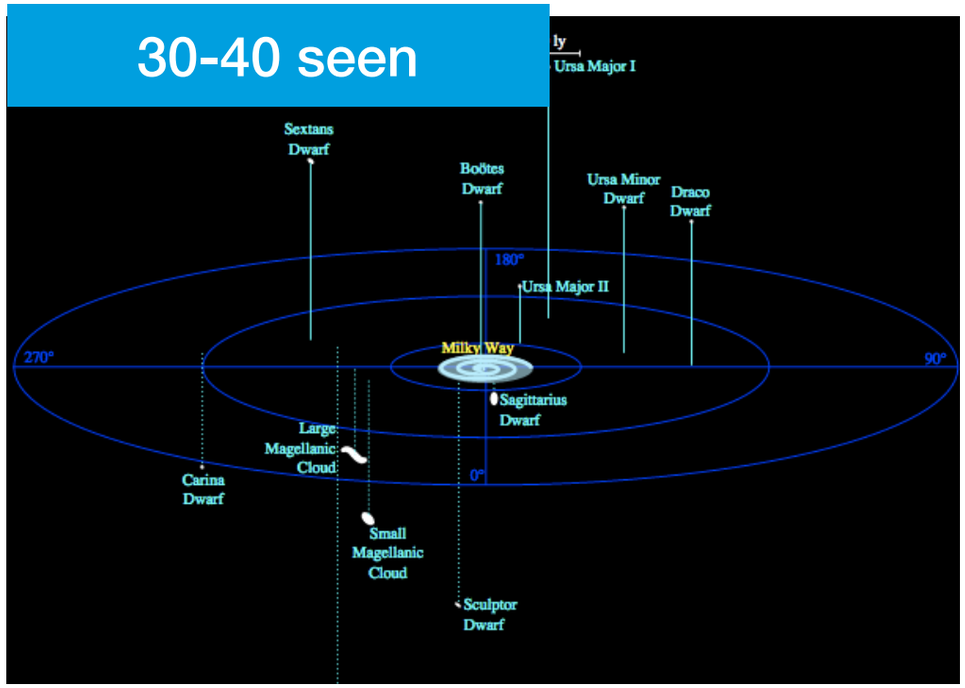
Similar searches will happen at e.g. T2K, DUNE, …

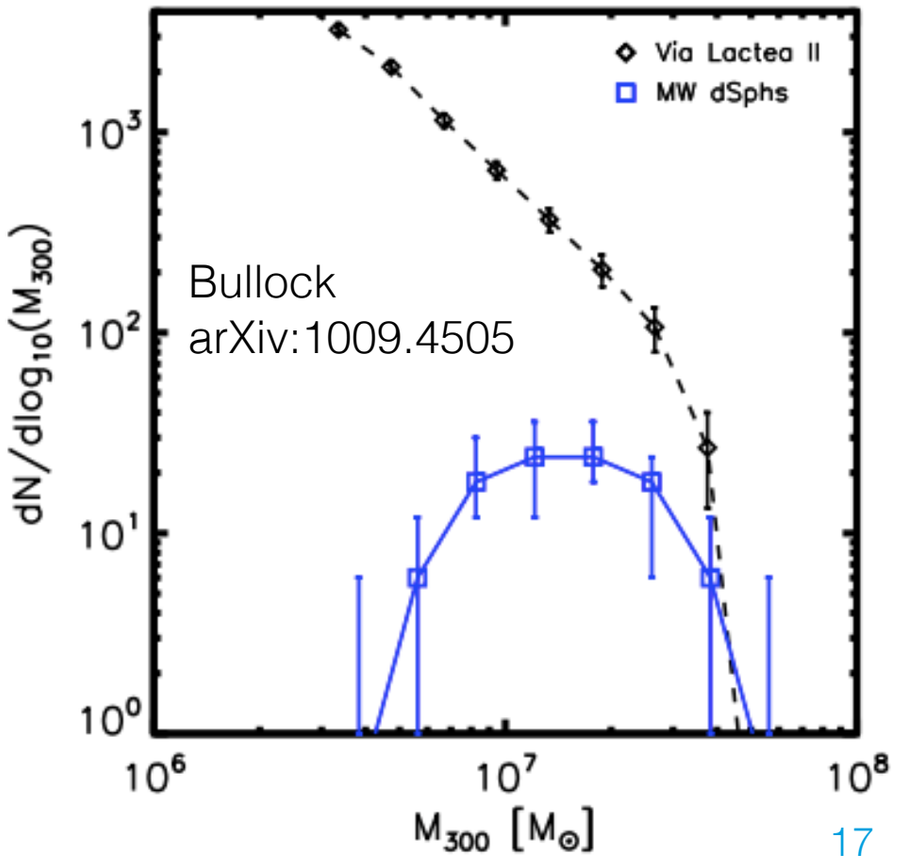
Dark matter that interacts via portal can affect things like small scale structure

Structure formation

Count satellites of Milky Way galaxy:





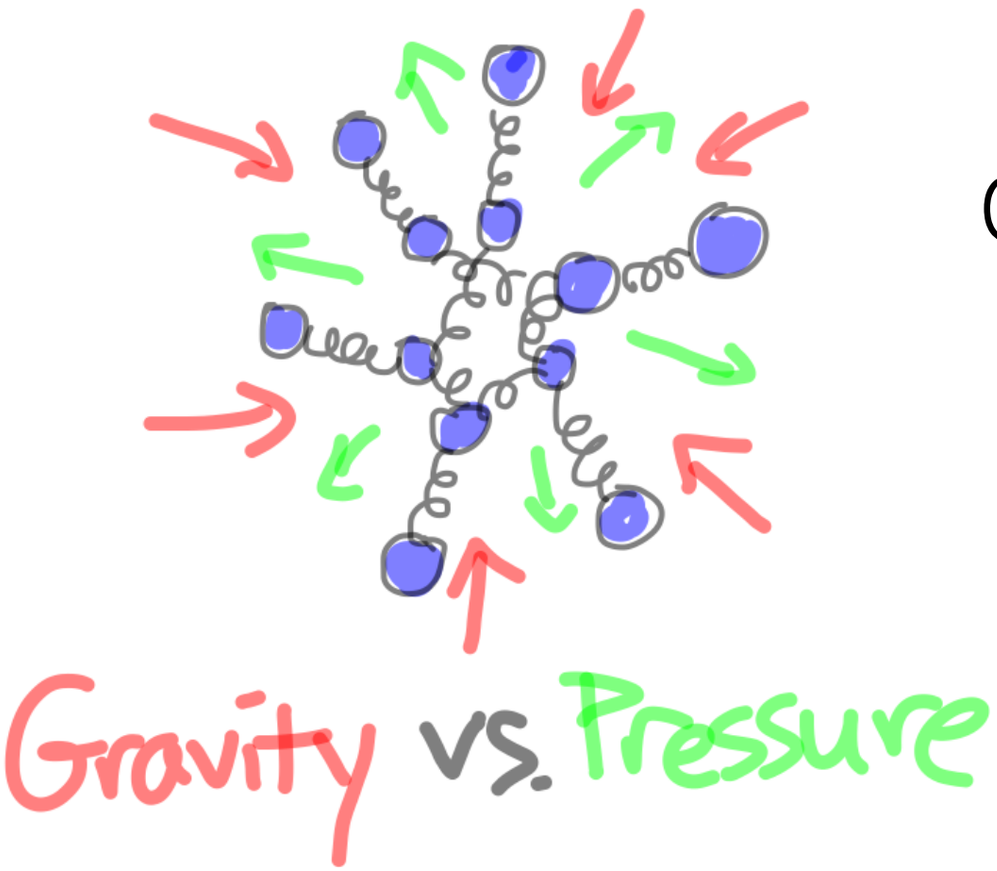


Could be observational bias or scattering on e.g. neutrinos

Boehm et al.
van den Aarssen et al.
Shoemaker et al.
Bertoni, Ipek, DM, & Nelson
Hooper, Kaplinghat, Strigari, & Zurek

Structure formation

Basic physics that sets the scales of structure formation



Consider massive particles coupled to a light force (not gravity) carrier, i.e. radiation

e.g. baryon collapse resisted by photons

structure starts to form when no pressure (i.e. particles decouple from force carrier)

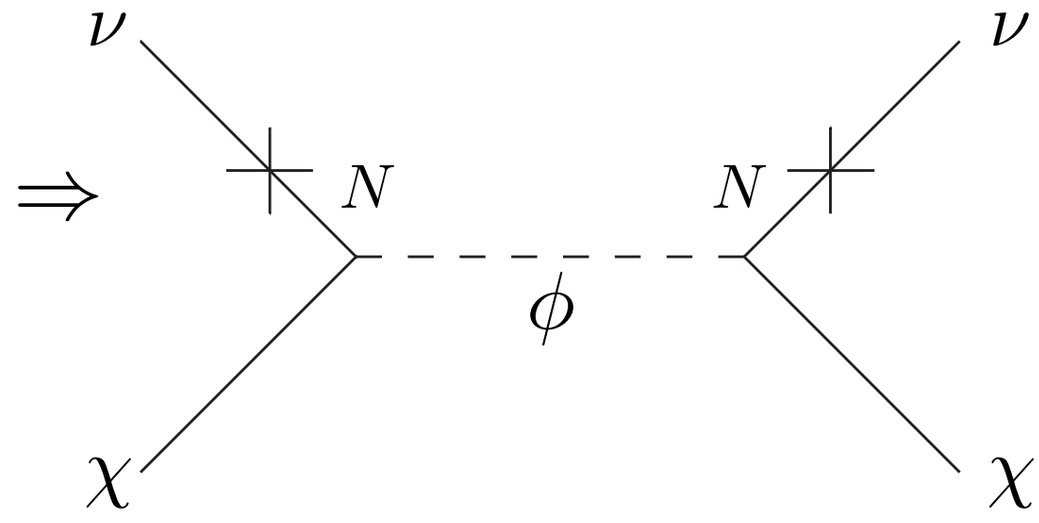
structures smaller than horizon size at decoupling are suppressed

see Bertoni, Ipek, DM, & Nelson;
Batell, Han, DM, Shams Es Haghi

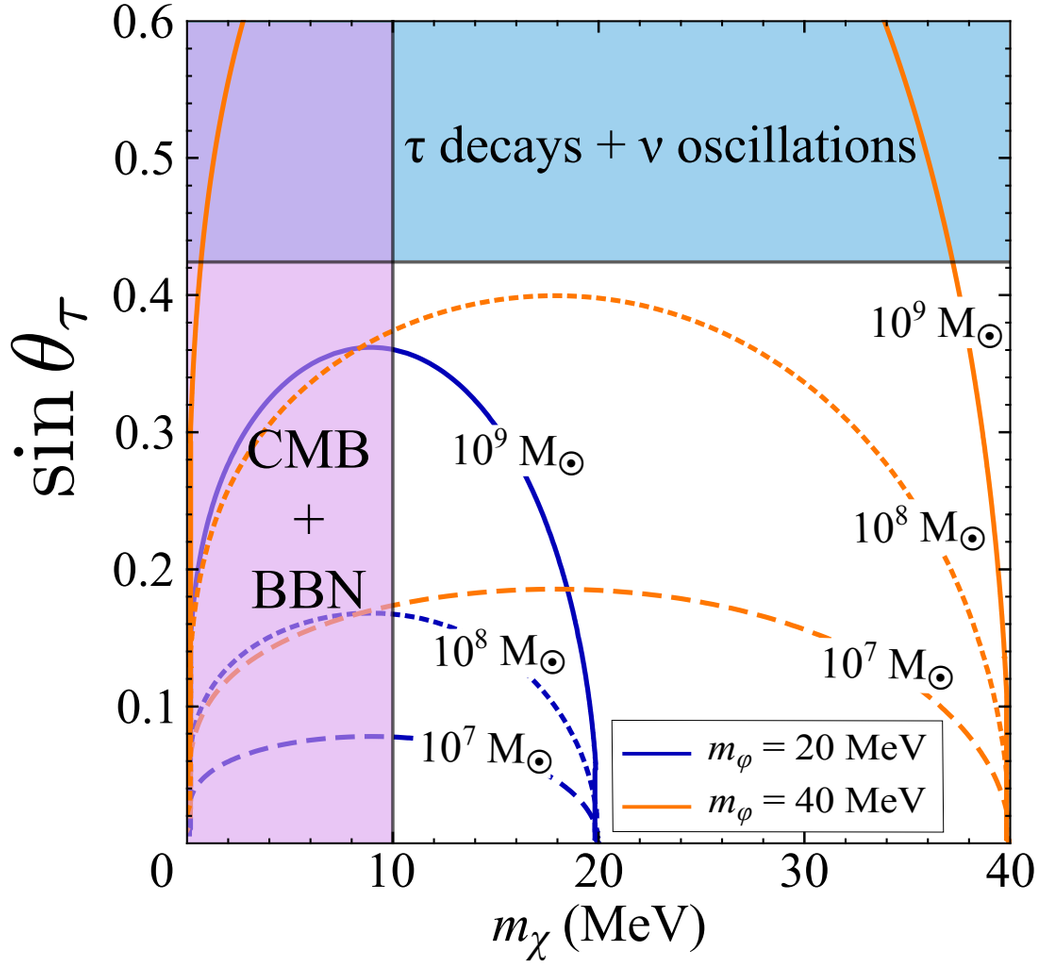
DM-neutrino interactions

Neutrino Portal:

$$\mathcal{L} \supset -\lambda \bar{\ell} H N - y \bar{N} \chi \phi + \text{h.c.}$$



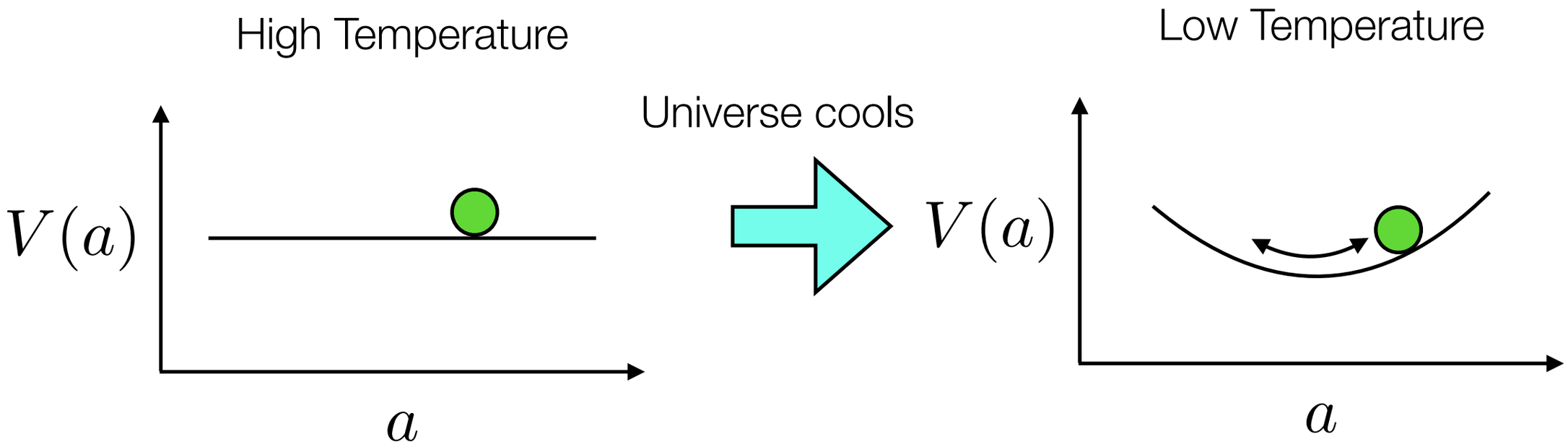
Can suppress growth of small scale structure in this setup



Switching gears…

Option 2: Nonthermal production

Canonical example: Axion



Axion field oscillates, behaves like cold DM

$$\frac{d^2a}{dt^2} - 3H\frac{da}{dt} + m_a^2 a = 0 \quad \Rightarrow \quad a(t) = \frac{\sqrt{2\rho_{\rm dm}}}{m_a}\cos m_a t$$

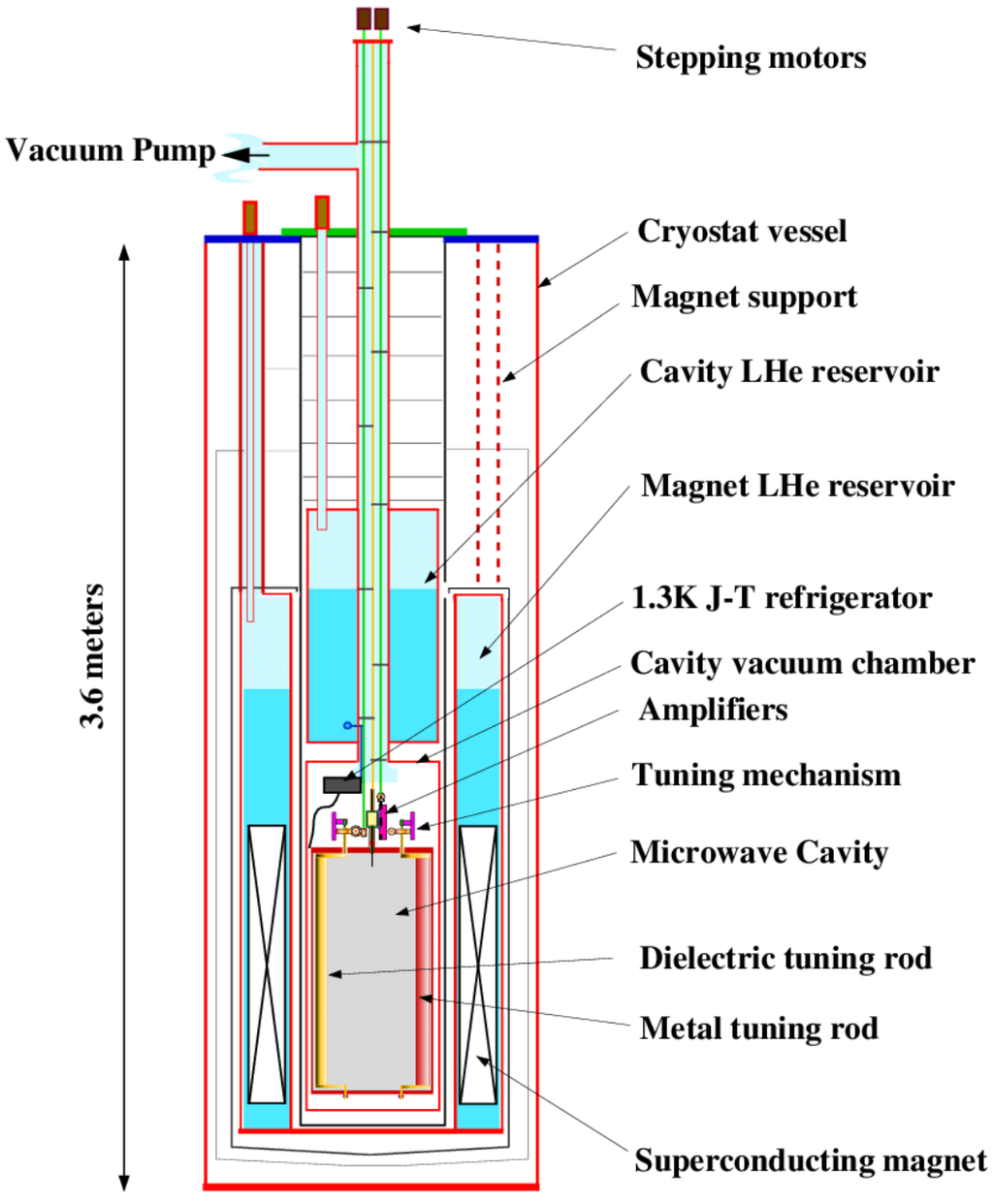
Can be DM for $m_a \lesssim 10^{-3}$ eV (GHz)

Detect through coupling to E&M: $\mathcal{L} \supset g_{a\gamma\gamma} a\, \boldsymbol{E}\cdot\boldsymbol{B}$

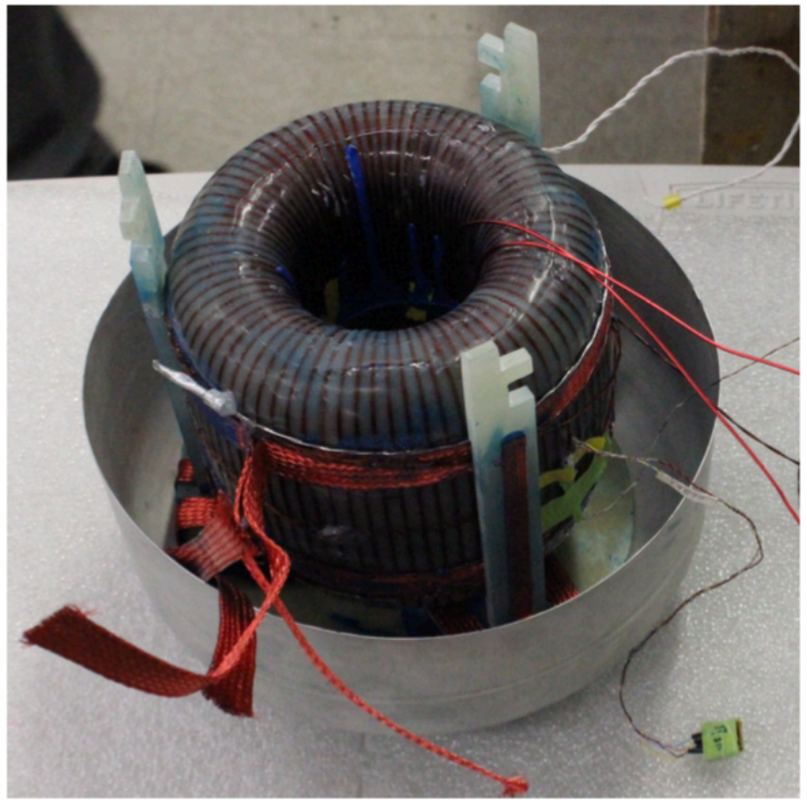
Searching for Axion DM

Making use of $\mathcal{L} \supset g_{a\gamma\gamma} a \, \boldsymbol{E} \cdot \boldsymbol{B}$

ADMX at UW



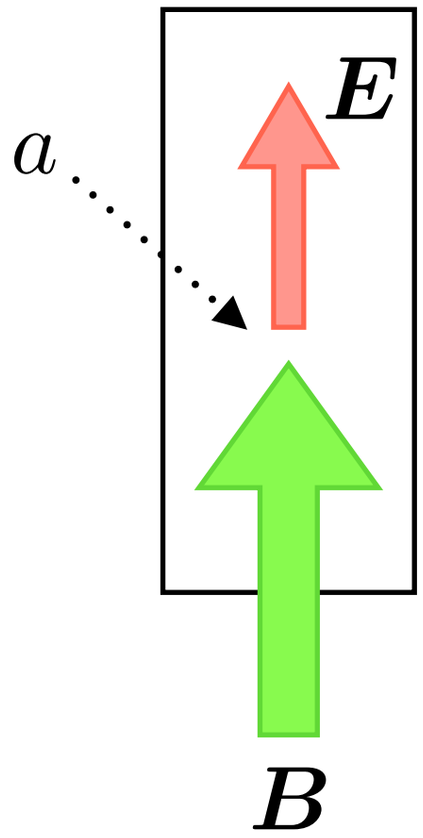
ABRACADABRA at MIT



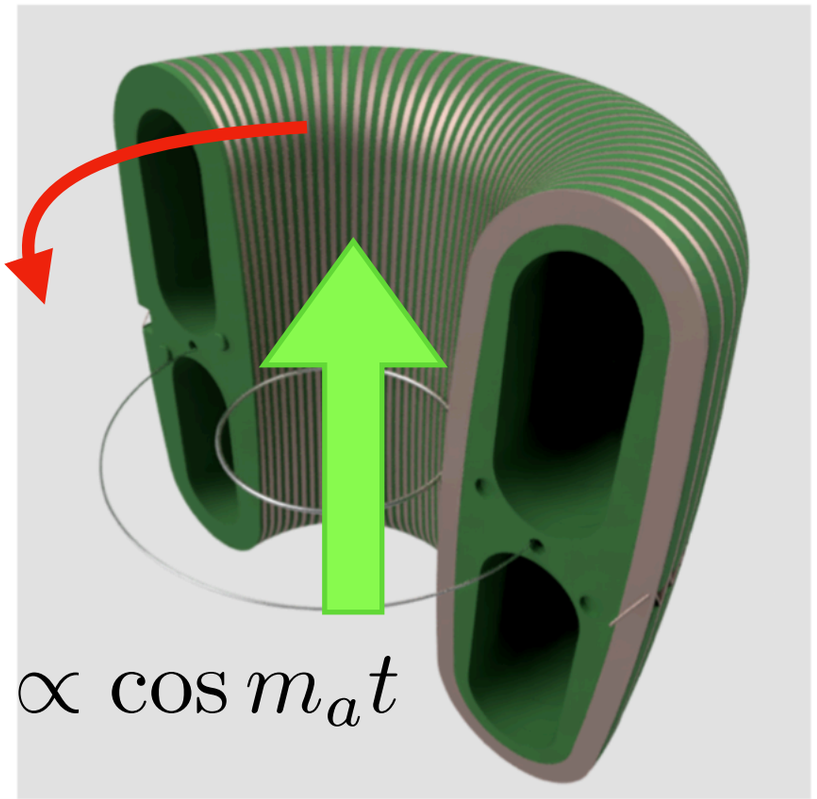
Searching for Axion DM

Making use of $\mathcal{L} \supset g_{a\gamma\gamma} a \, \boldsymbol{E} \cdot \boldsymbol{B}$

ADMX at UW



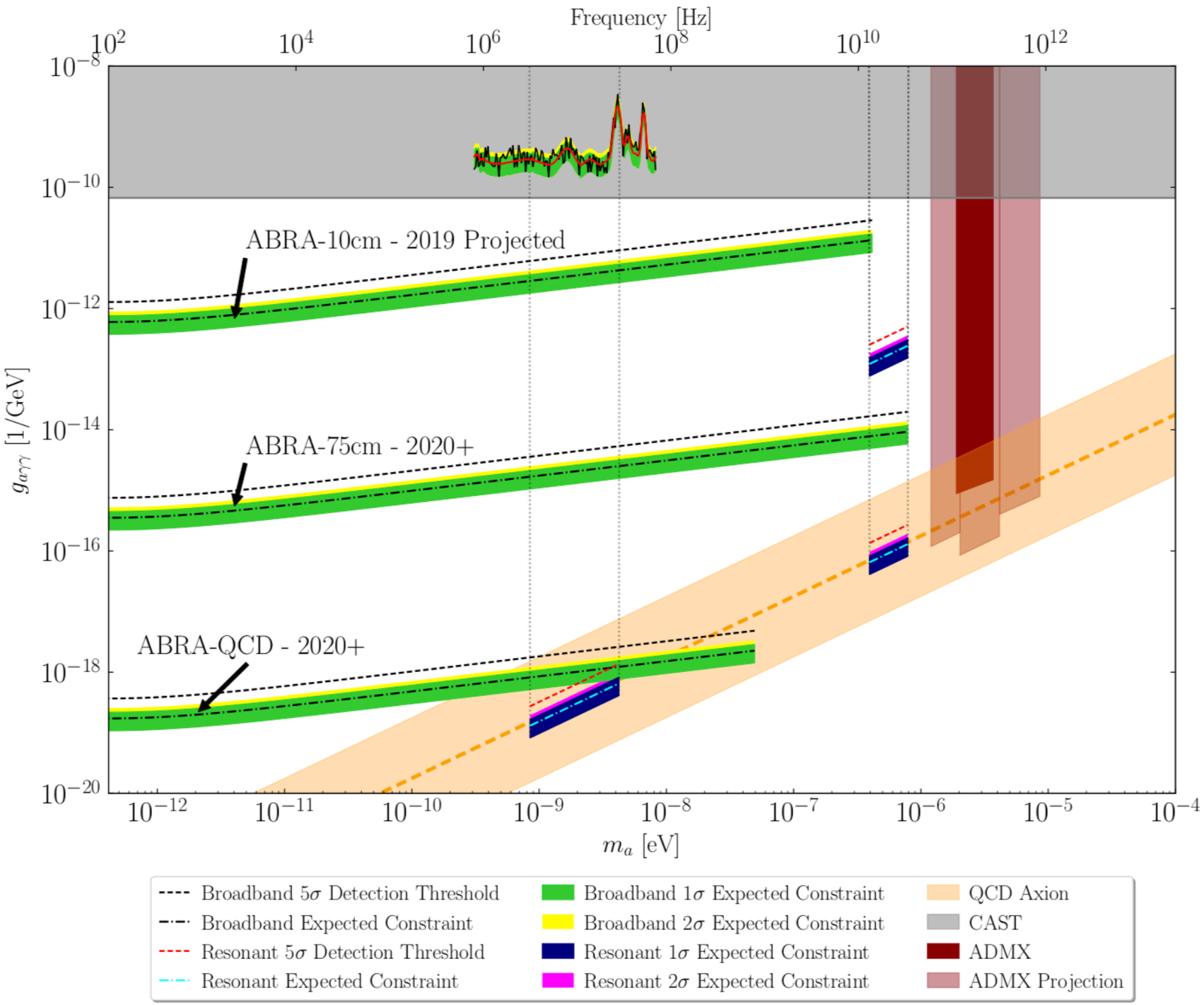
ABRACADABRA at MIT



$$\boldsymbol{\nabla} \times \boldsymbol{B} = -g_{a\gamma\gamma} \boldsymbol{B}_0 \frac{da}{dt}$$

Searching for Axion DM

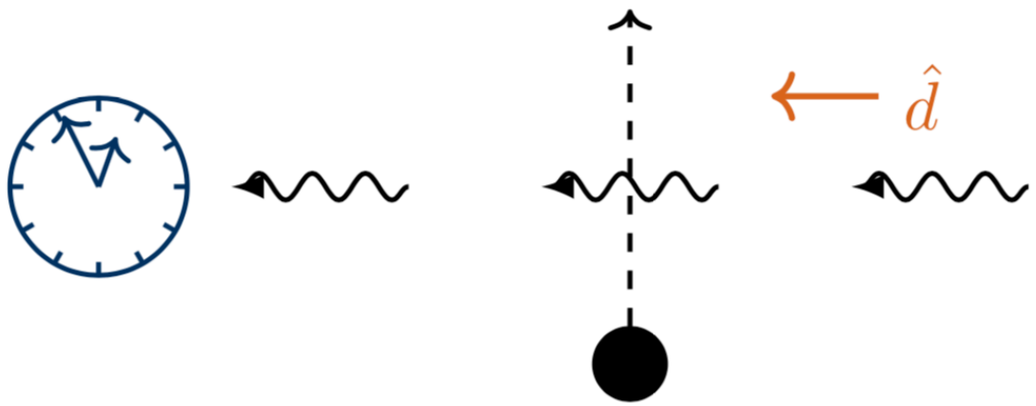
Recent results!



What about very heavy DM? Primordial Black Holes?

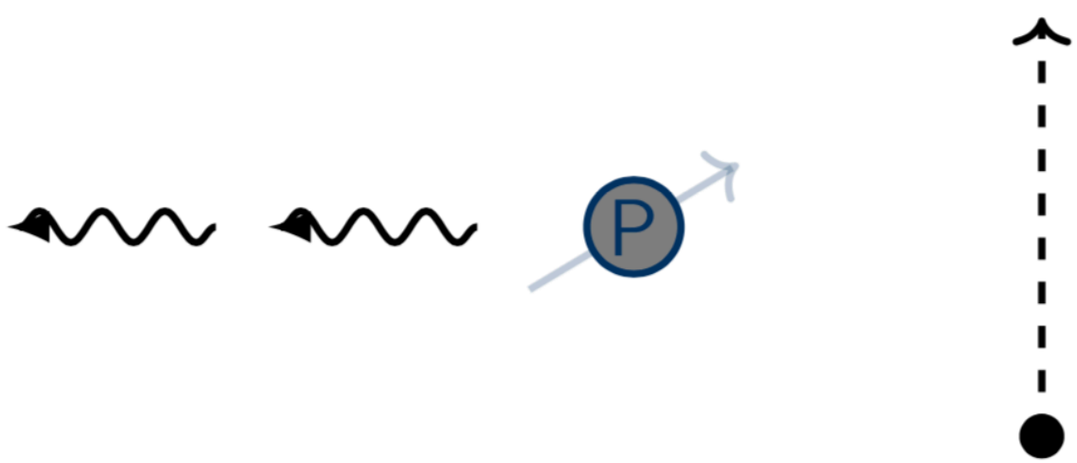
Pulsar Timing and large DM Structures

What if something massive passes by a pulsar (very regular oscillating source)?



Shapiro time delay

$$\frac{\delta\nu}{\nu} = 2GM \int dz \frac{\dot{r}}{r^2}$$

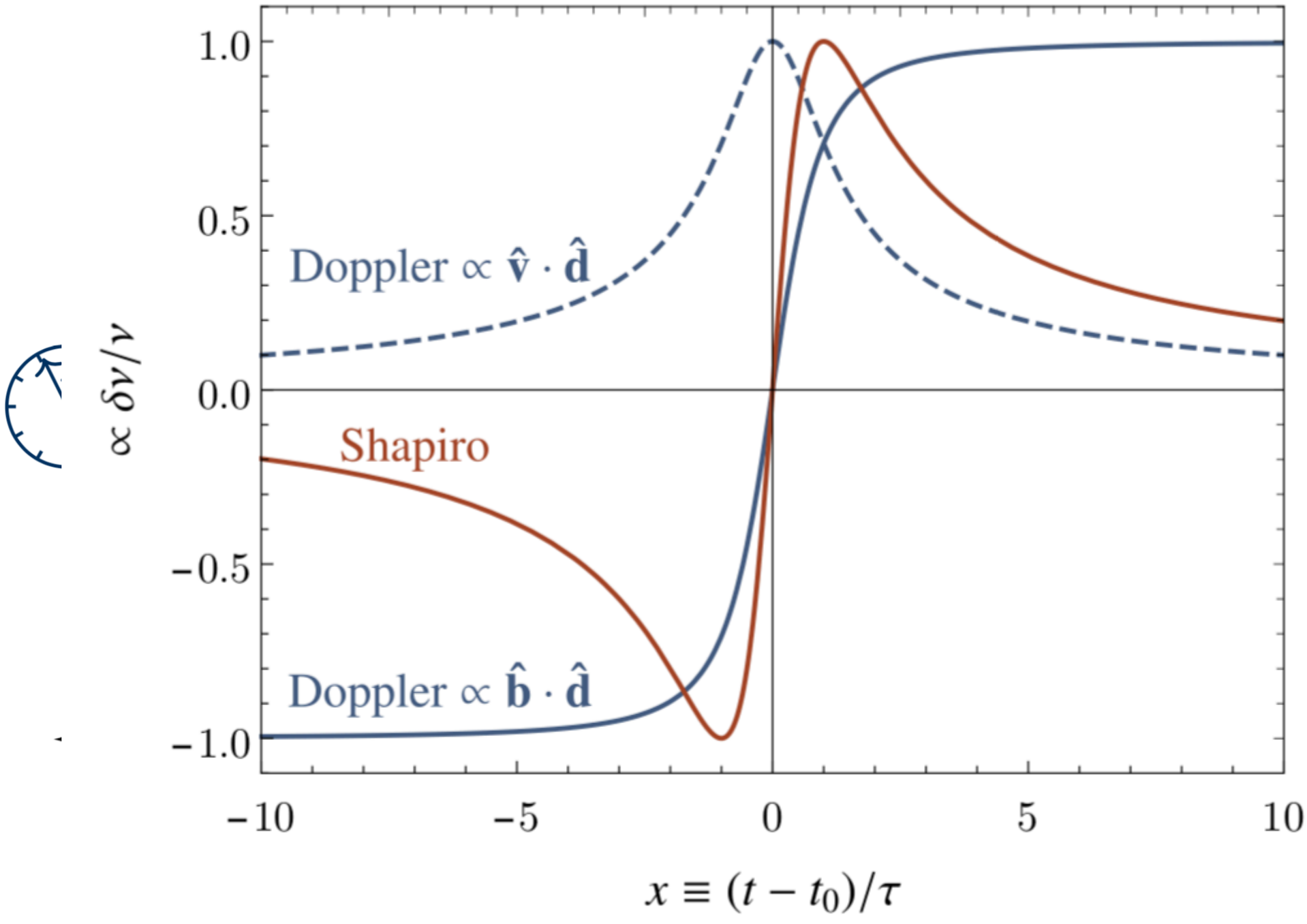


Doppler shift

$$\frac{\delta\nu}{\nu} = \dot{\boldsymbol{r}} \cdot \hat{\boldsymbol{d}}$$

Dror, Ramani, Trickle, Zurek 1901.04490

Pulsar Timing and large DM Structures



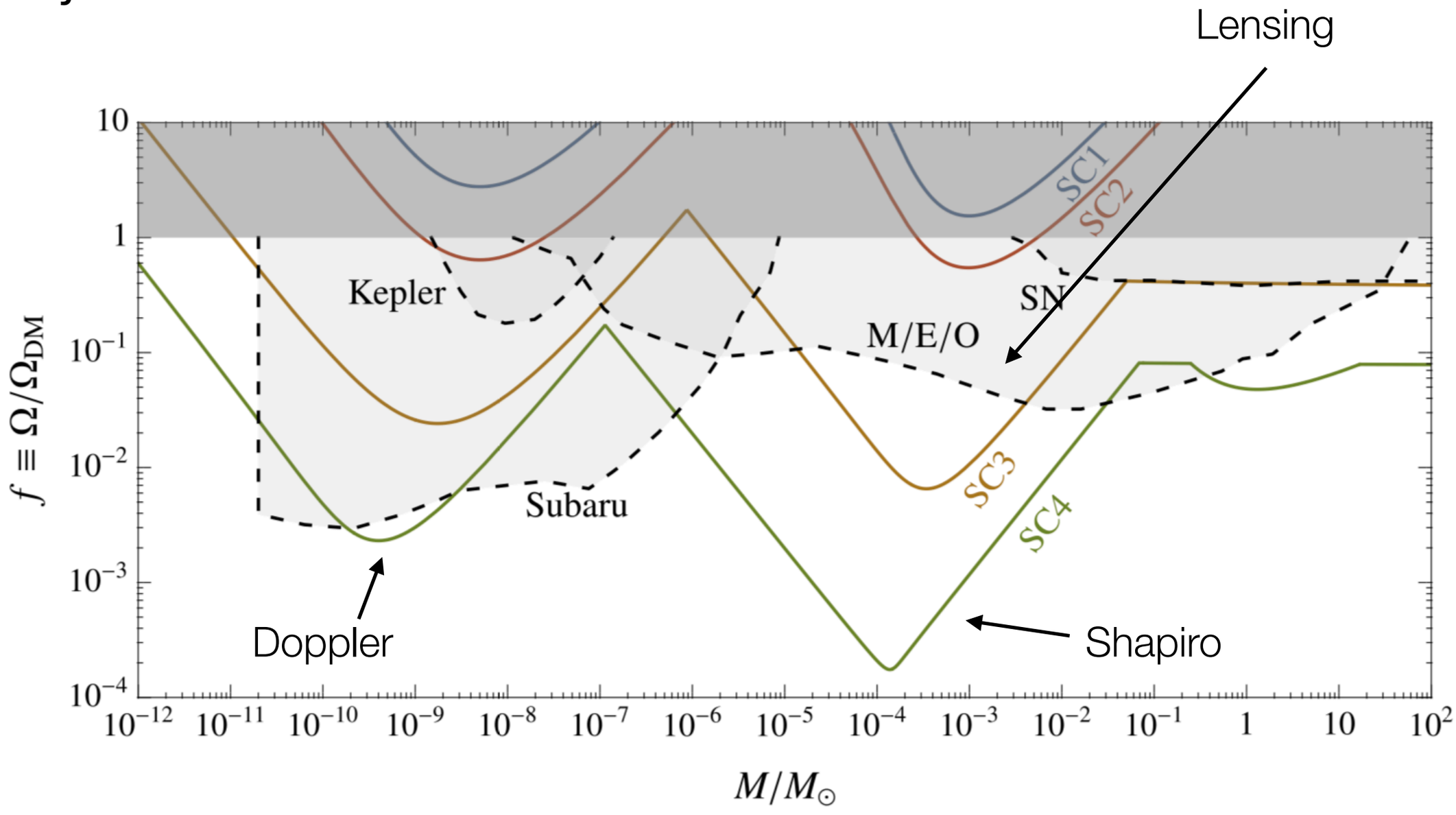
ıe delay

$$\int dz \frac{\dot{r}}{r^2}$$

Dror, Ramani, Trickle, Zurek 1901.04490

Pulsar Timing and large DM Structures

Projections



Dror, Ramani, Trickle, Zurek 1901.04490

Wrap up

Dark matter required by numerous observations but little guidance about its properties (needs to couple to gravity, anything else?)

WIMPs (in SUSY or beyond) are excellent candidates for thermal relic DM but null searches have closed parameter space

Other possibilities (dark sectors interacting via “portals,” axions, very heavy DM) could solve problems but require different search techniques

I’ve only scratched the surface—there are many other possibilities and opportunities. Stay tuned!