Cluster of Excellence PRISMA Precision Physics, Fundamental Interactions and Structure of Matter

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Dark Matter Theory

after first results from LHC 13

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Zurich Phenomenology Workshop
ETH Zurich
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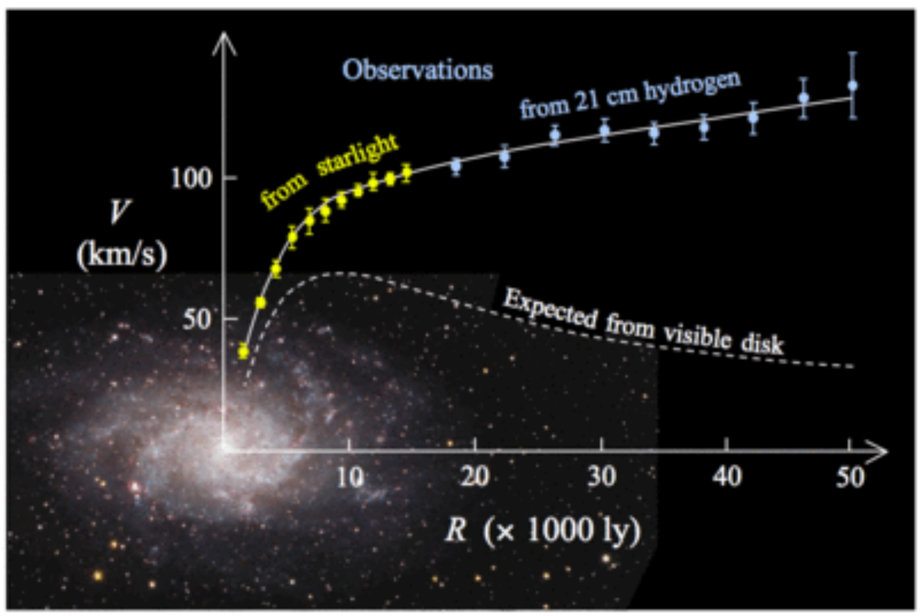
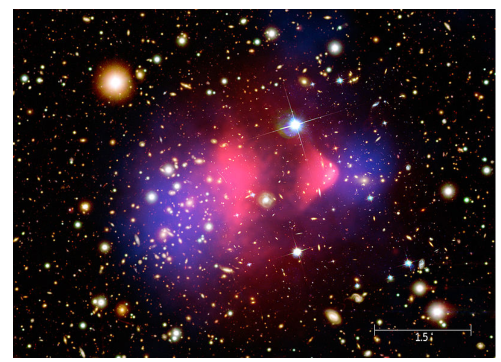
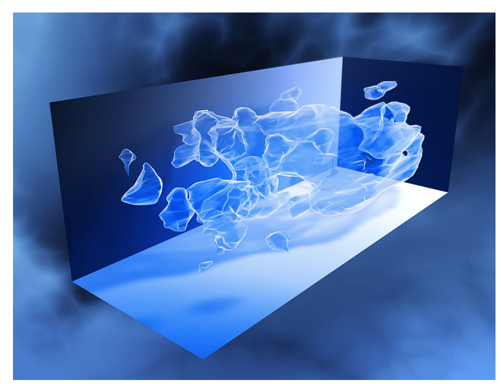
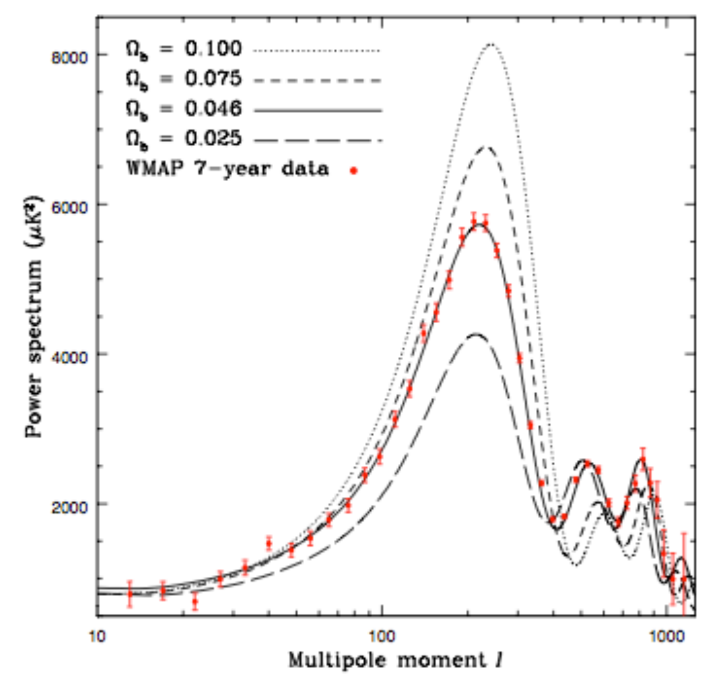
Dark Matter Evidence

- Astrophysical observations and simulations

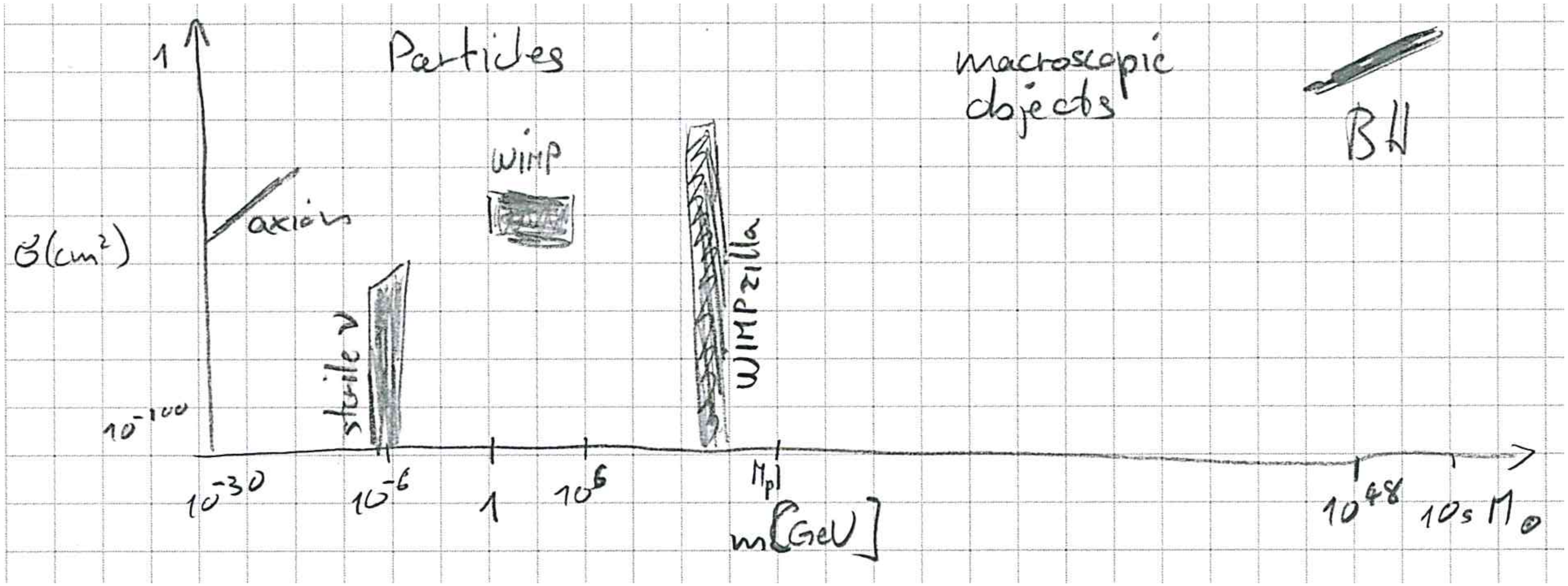


- Nature & interactions with visible matter unknown

What is the Dark Matter?

Allowed Mass Range



$M_{\rm DM} \gtrsim 10^{-22}$ eV

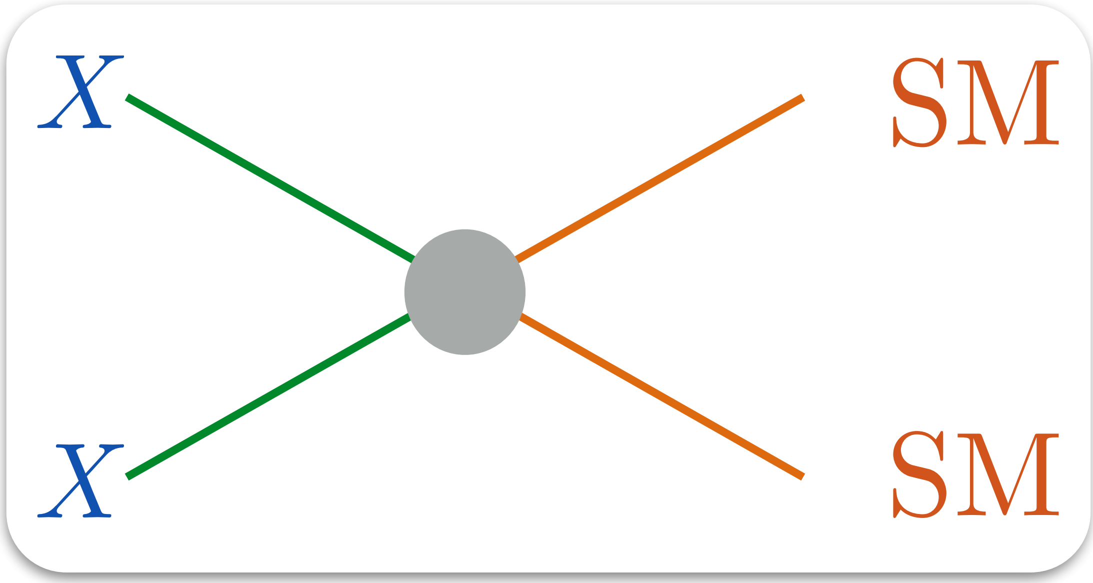
"Fuzzy DM"

Hu et al, 2000
Witten et al, 2016

$M_{\rm DM} \lesssim 10^{2} M_\odot$

primordial
Black Holes

WIMP Miracle

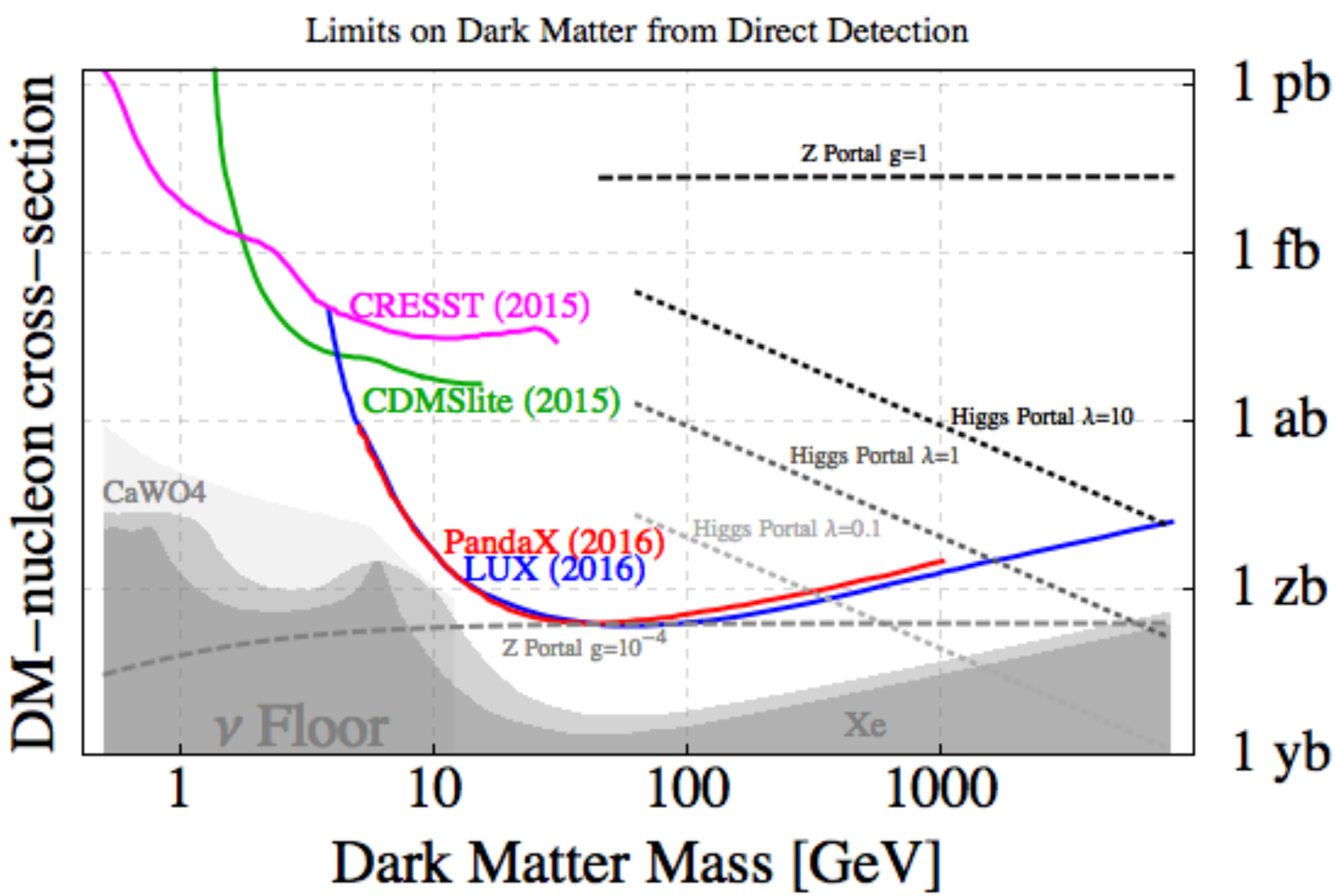


$$\Omega_X \approx \frac{10^9\ \mathrm{GeV}^{-1}}{M_{\mathrm{Pl}}}\frac{1}{\langle \sigma v \rangle}$$

- Correct relic abundance for $\langle \sigma v \rangle \sim \mathrm{pb}$
- Mass range $10^{\pm 2}\mathrm{TeV}$

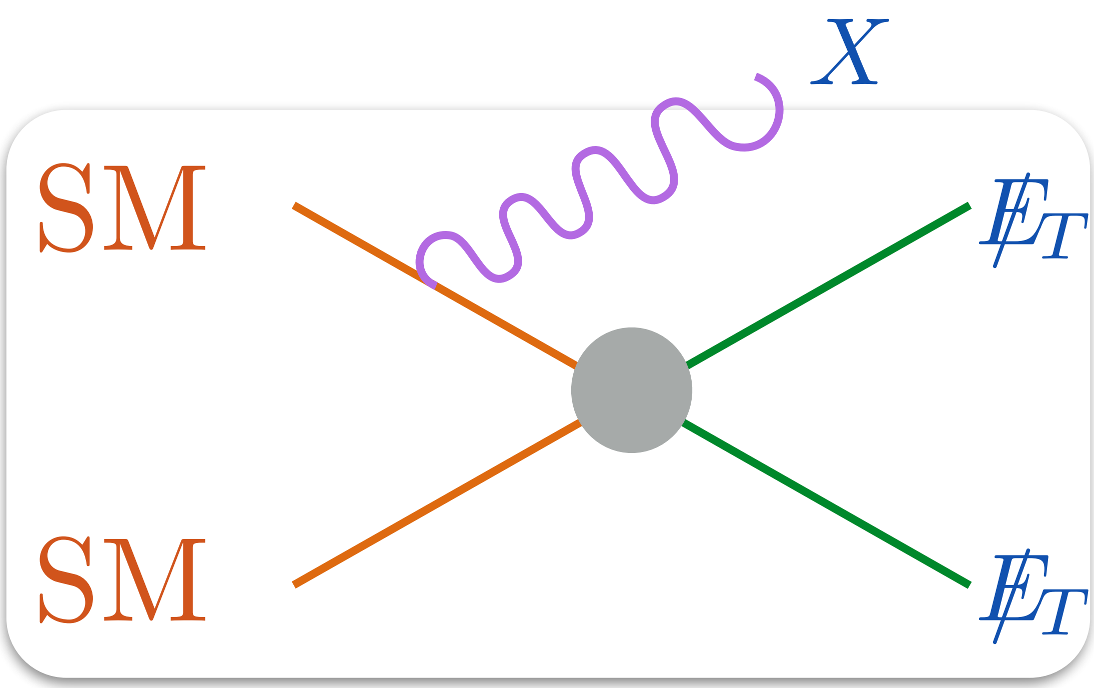
WIMPs under pressure

- Direct Detection → L. Baudis talk



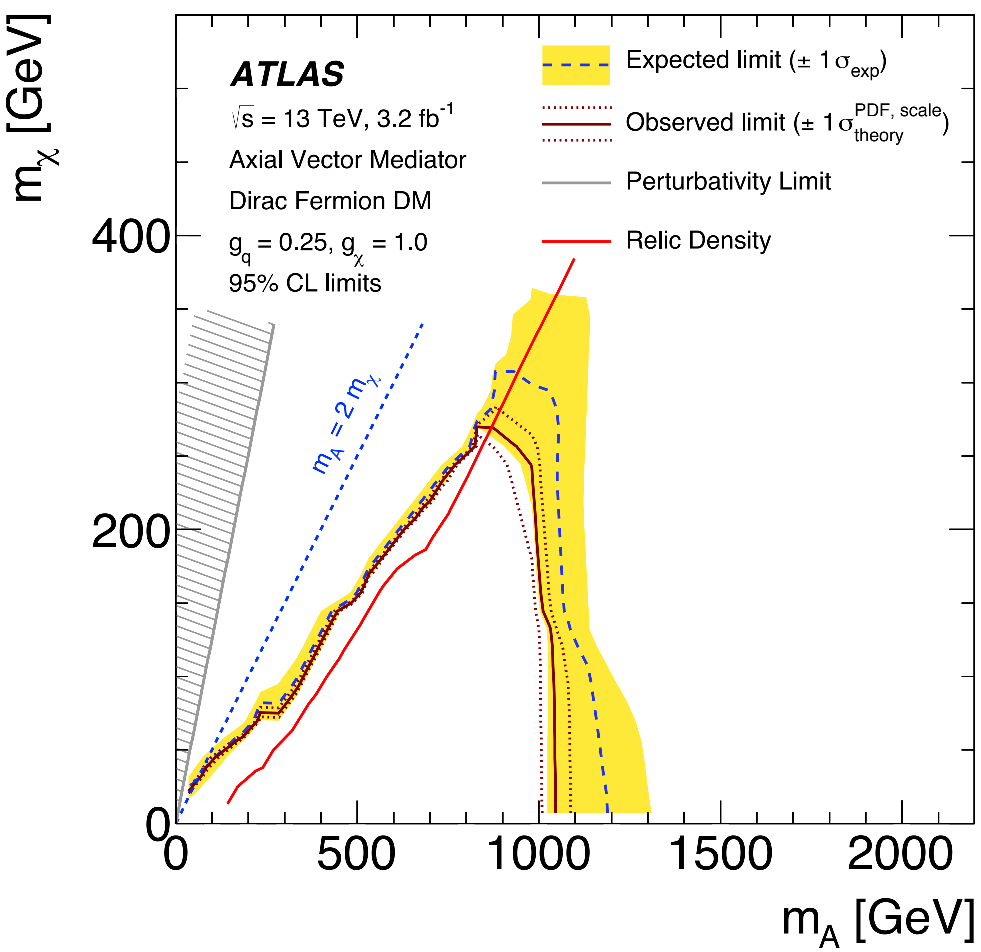
WIMPs @ Colliders

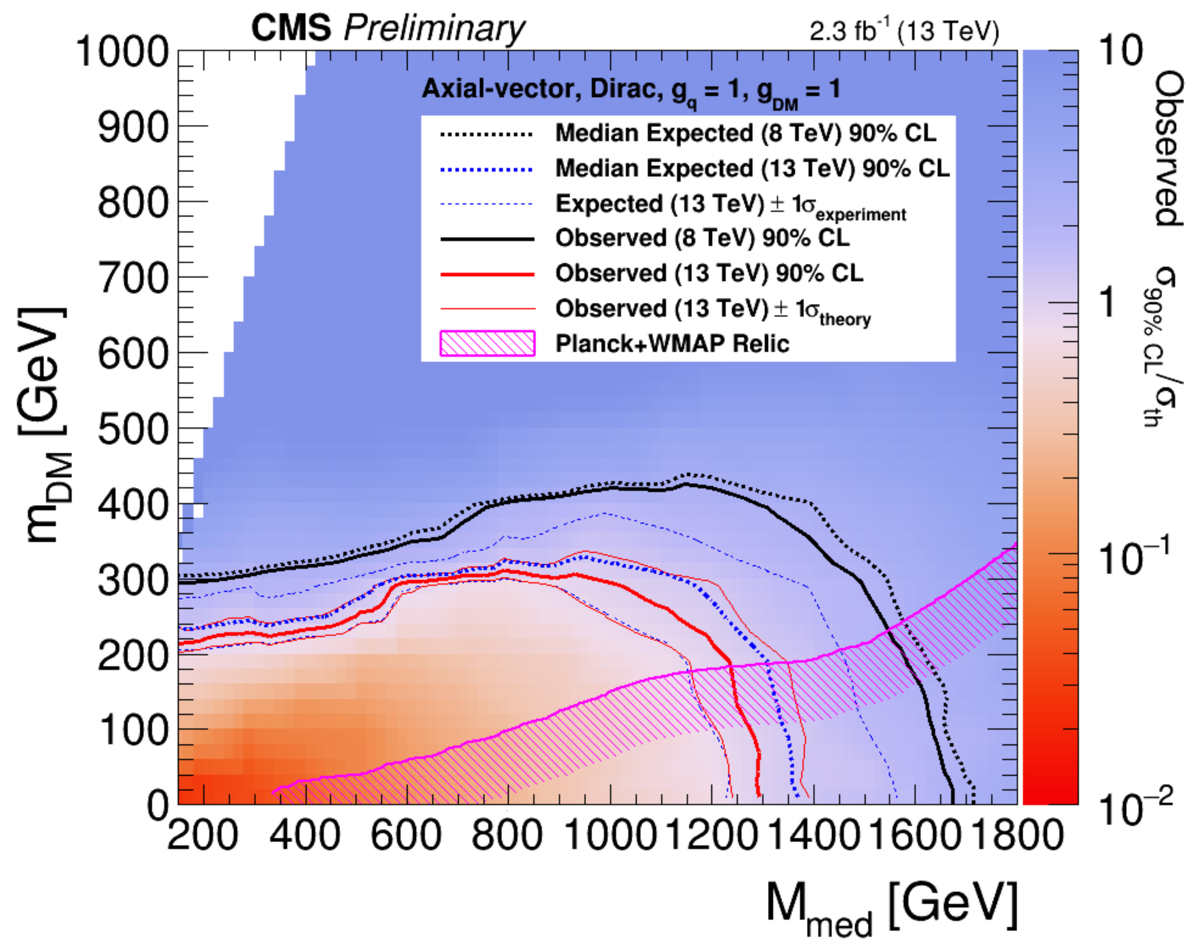
- Collider



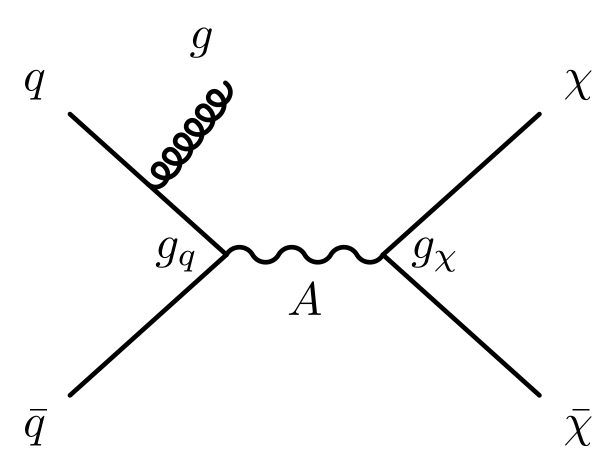
- MET + X (mono-X) signature
  - X = jet, photon, W, Z, single-top, tt, hadronic W/Z,…

WIMPs @ LHC





- Mono-jet limits from ATLAS and CMS



WIMPs @ LHC

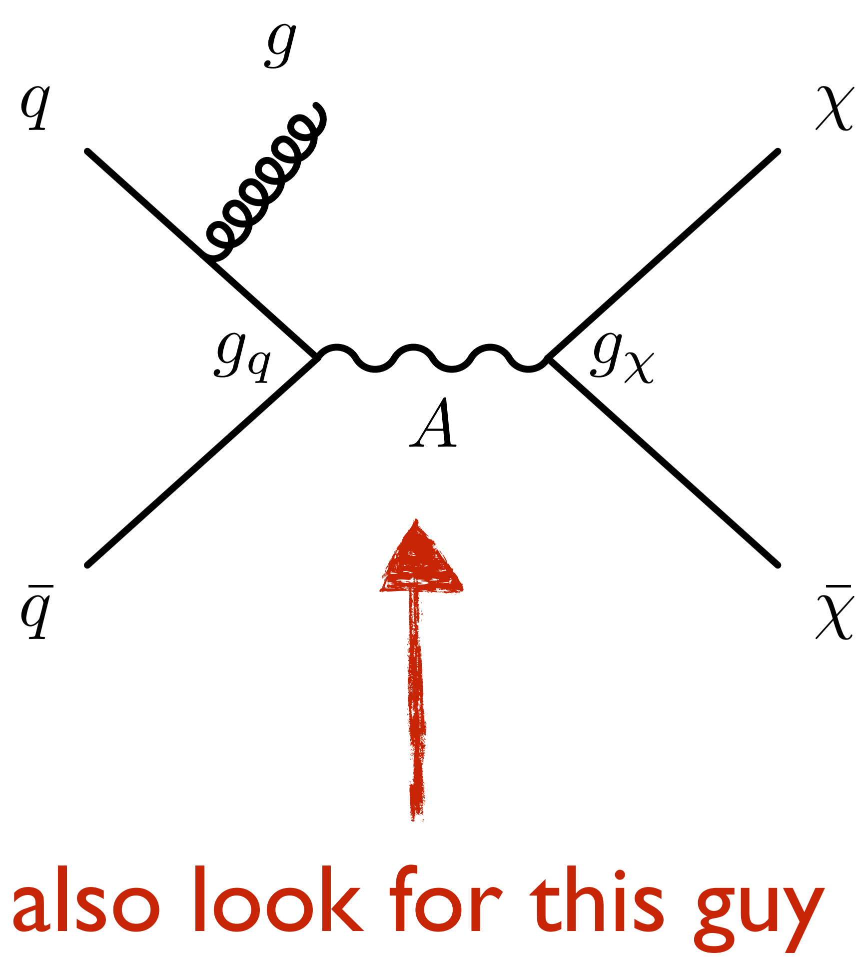
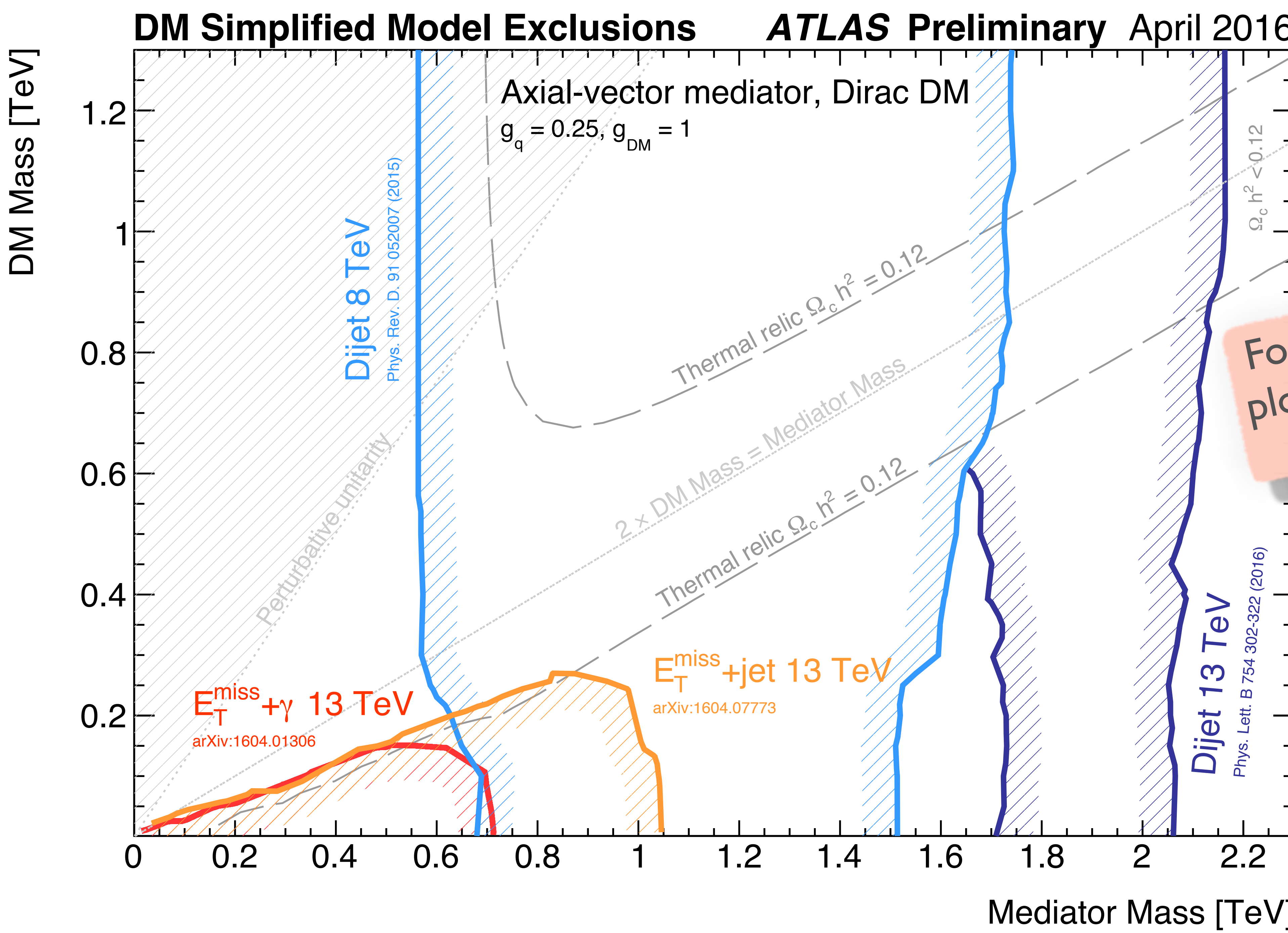


diagram from 1604.07773

- Di-jet resonance - expect strong limits from LHC

WIMPs @ LHC



For up to date plot, see talk by M. Kado

Where else to look?

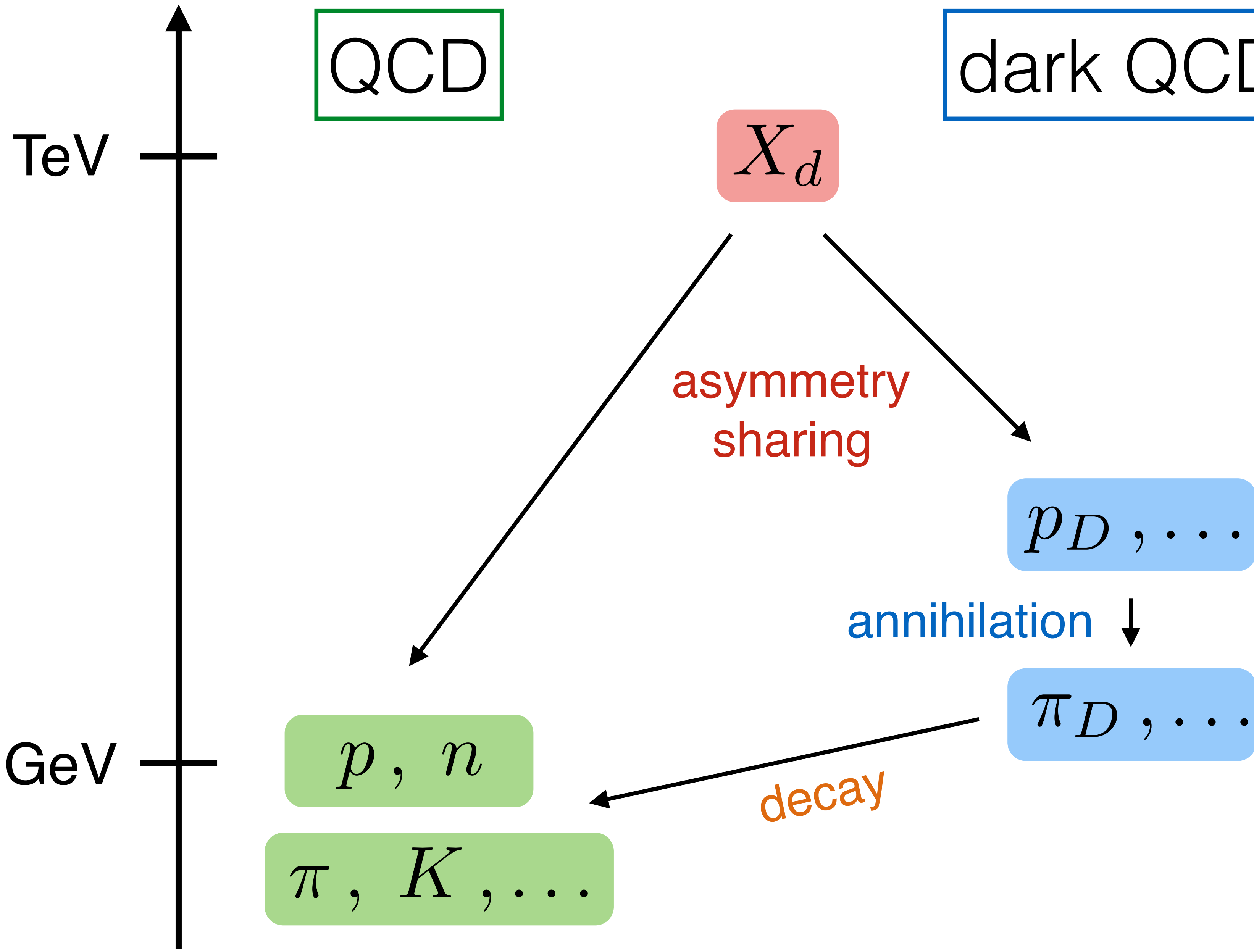
- Non-minimal models
- Displaced frontier
- Simplified models for displaced DM
- Gravitational waves as window to dark sector

Non-minimal models

- Hidden sectors
- Asymmetric dark matter
- SIMP
- Dark QCD
- Dynamical Dark Matter
- Self-interacting DM
- …

Bai, PS, PRD 89, 2014

Dark QCD



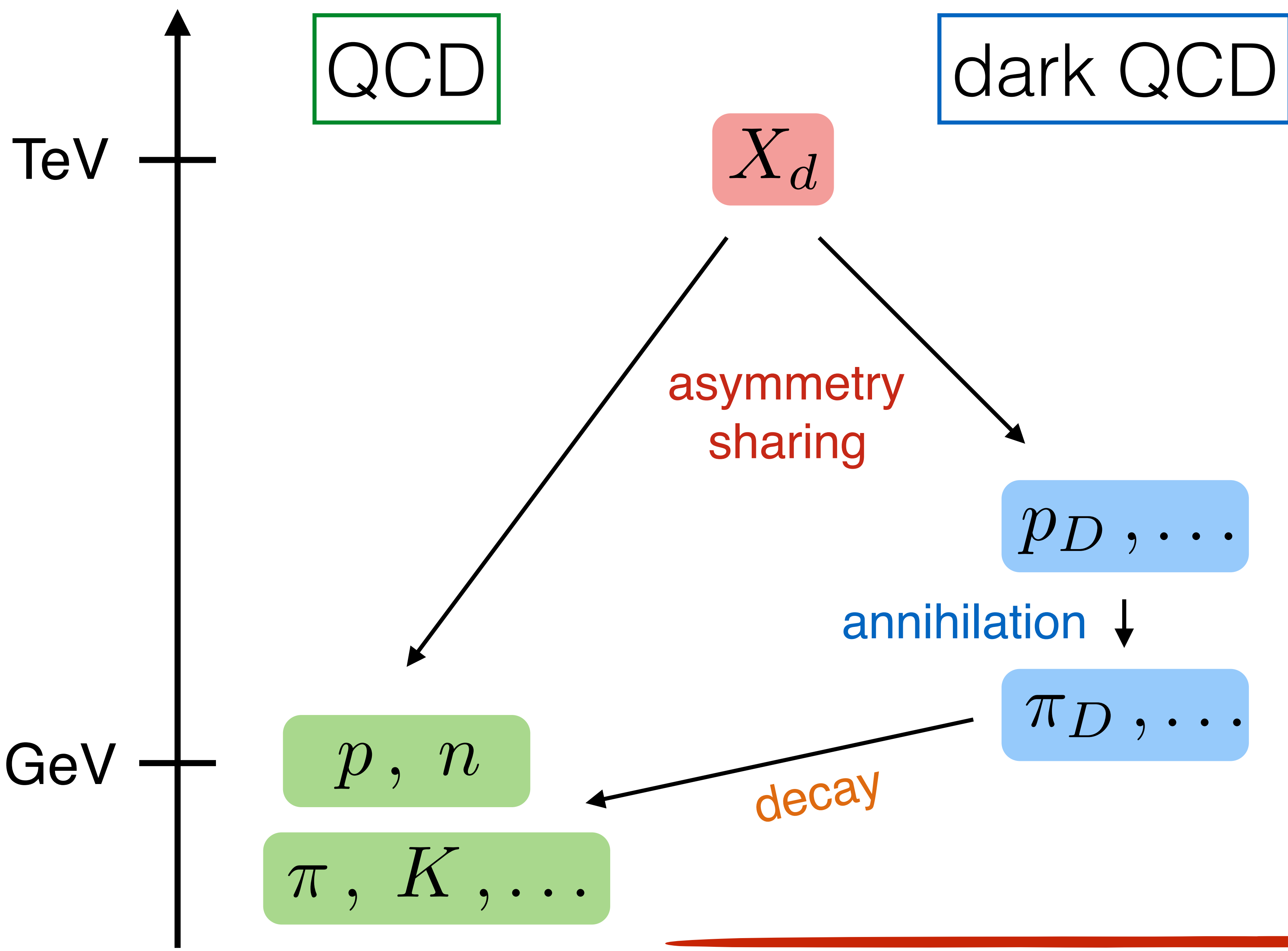
- SU(N) dark sector with neutral "dark quarks"
- Confinement scale

$$\Lambda_{\mathrm{darkQCD}}$$

- DM is composite "dark proton"
- "Dark pions" unstable, long lived

Bai, PS, PRD 89, 2014

Dark QCD



New Phenomenology!

Advantages:

- Alternative explanation of relic density
- Avoids stringent direct/indirect detection limits
- Self interaction solves small scale structure problems

Dark QCD

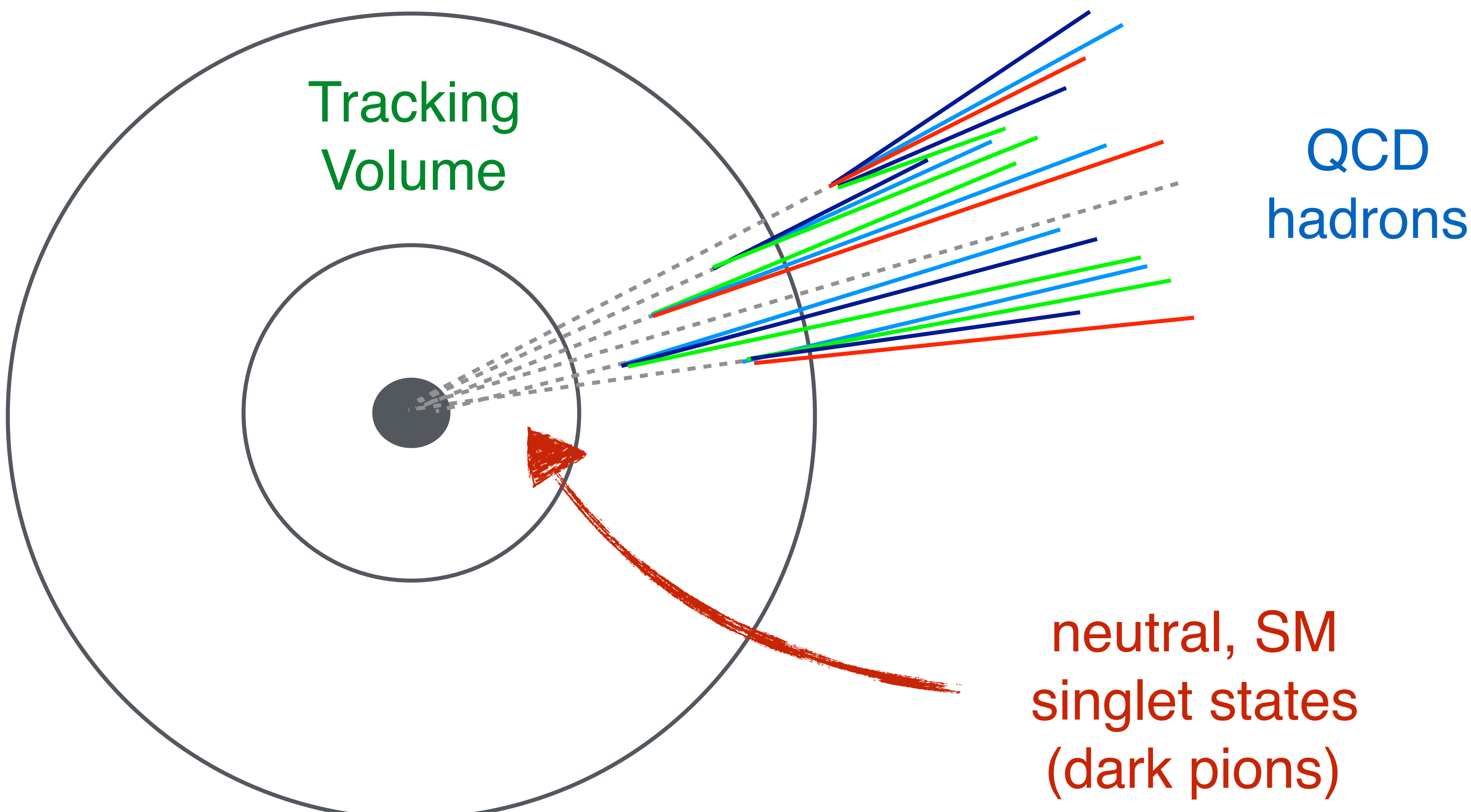
- Asymmetric DM motivates $\Lambda_{\rm Dark} \sim \text{few GeV}$
  - e.g.

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \sim \frac{M_{\rm DM}}{M_{\rm B}}$$

- Dark pion lifetime possibly macroscopic

$$c\tau(\pi_D \to \text{SM}) \sim \frac{M_X^4}{m_{\pi_D}^5} \sim \text{cm} \times \left(\frac{\text{M}_\text{X}}{\text{TeV}}\right)^4 \left(\frac{\text{GeV}}{\text{m}_{\pi_\text{D}}}\right)^5$$

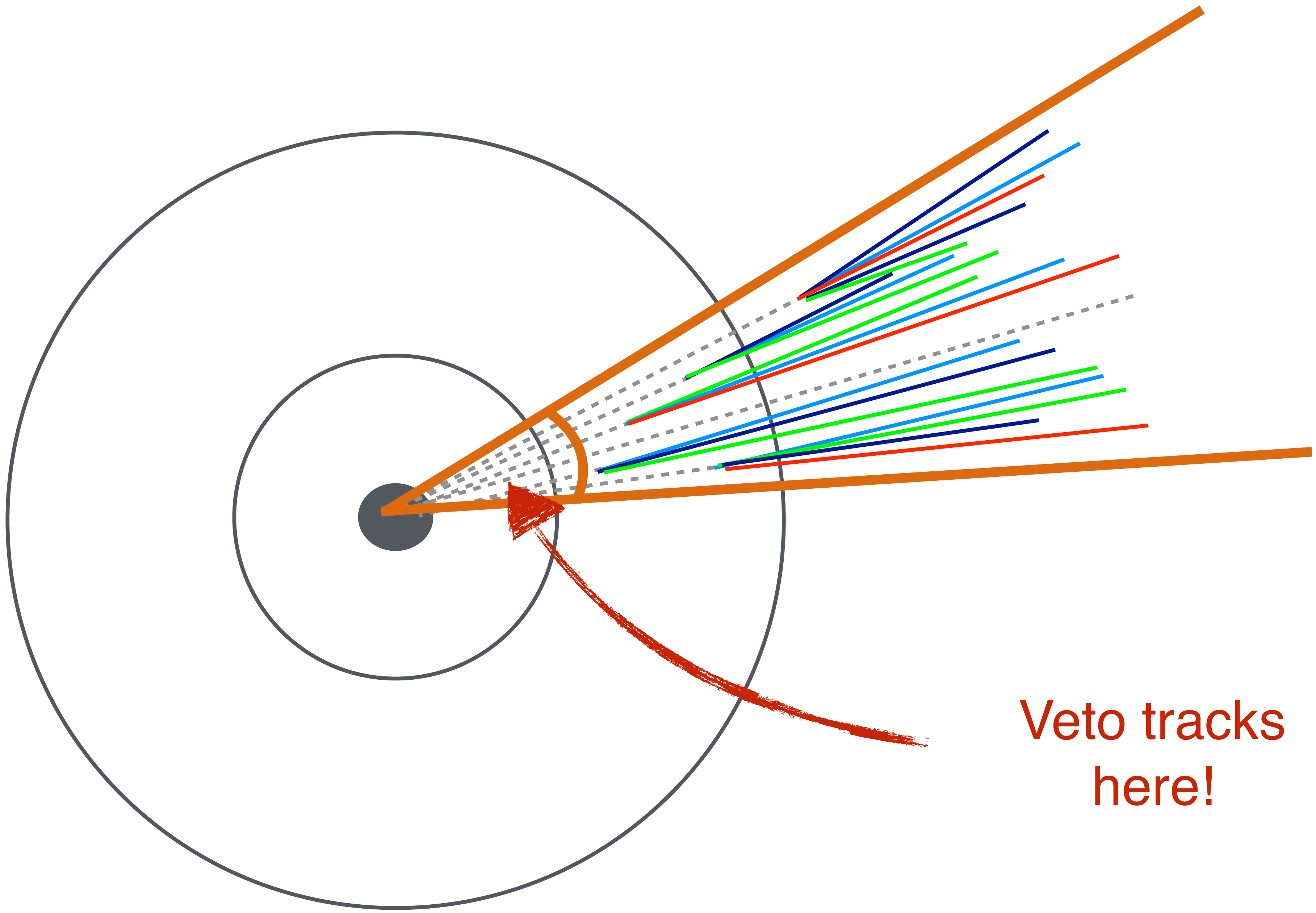
New signature: Emerging Jets



PS, Stolarksi, Weiler, JHEP 2015

Related work:
Strassler, Zurek, 2006,2007
Han, Strassler, Zurek, 2007

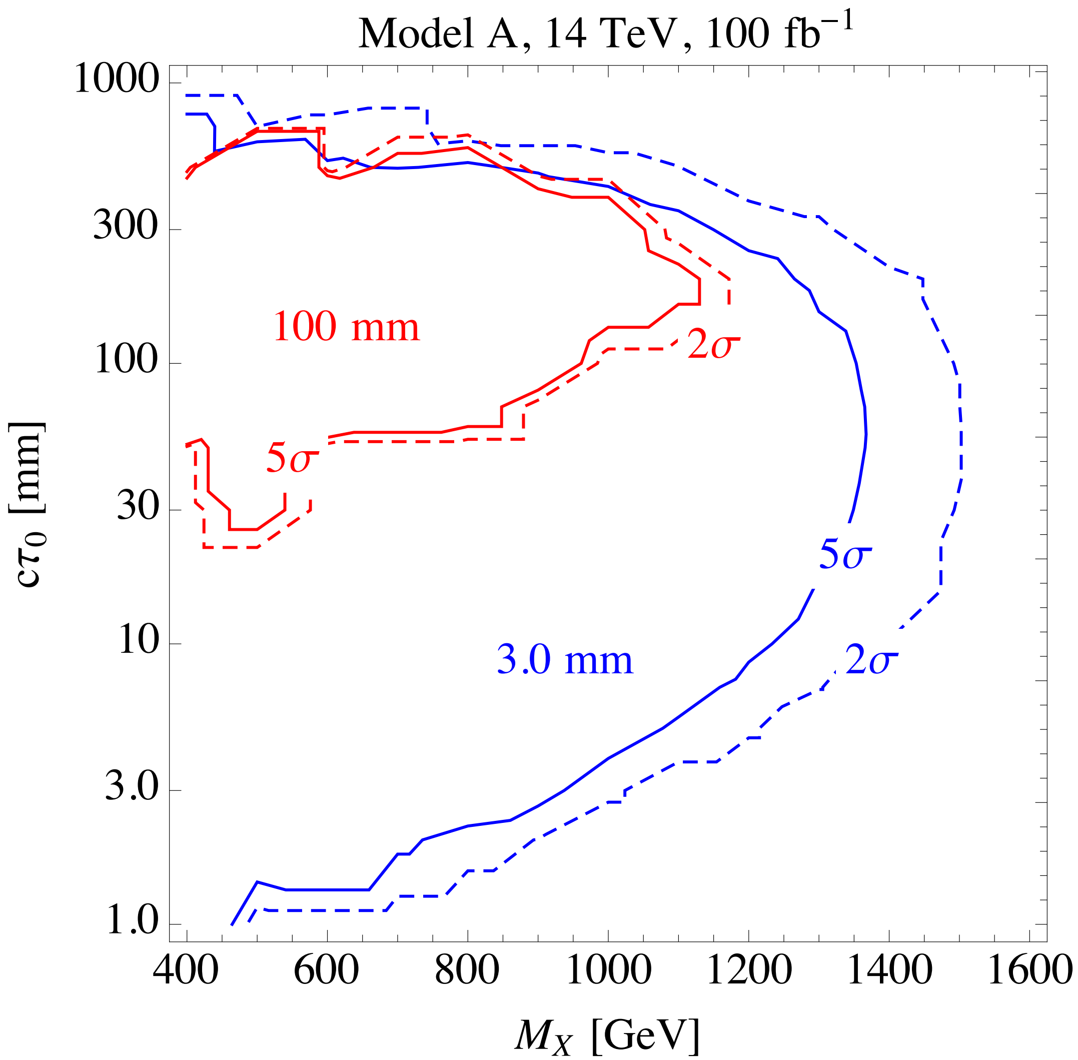
Strategy

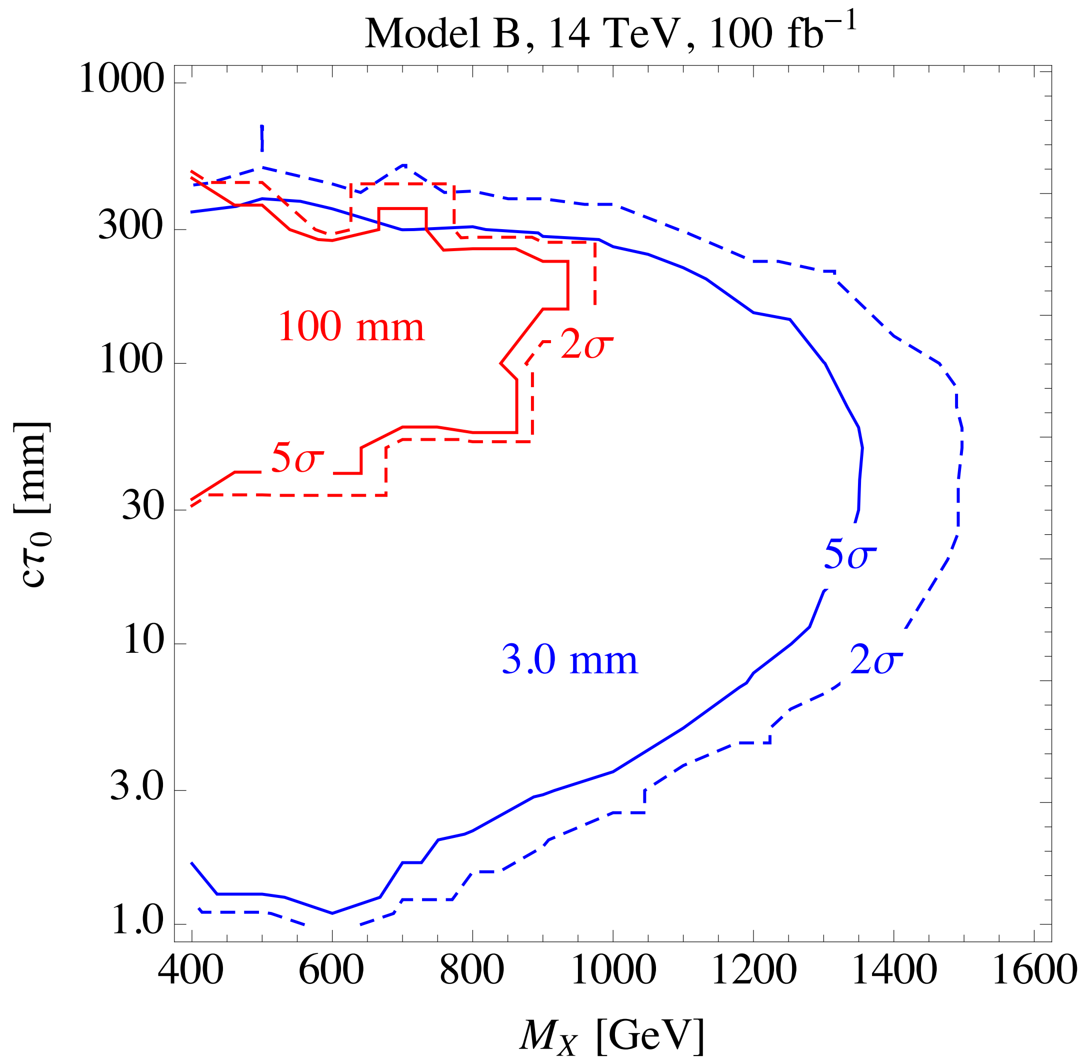


PS, Stolarksi, Weiler, JHEP 2015

PS, Stolarksi, Weiler, JHEP 2015

Reach ATLAS/CMS





- Optimistic scenario (no non-collisional BGs)
- More realistic studies under way at ATLAS/CMS

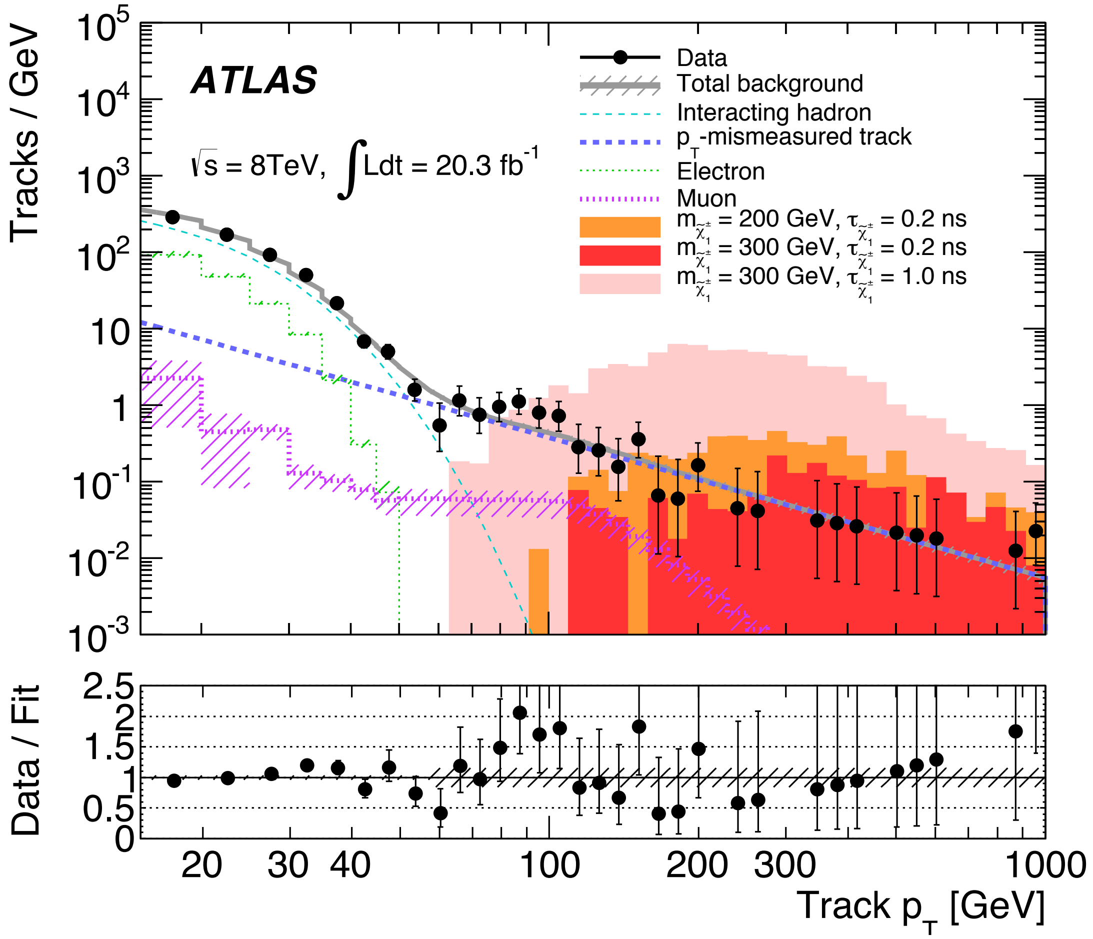
The displaced frontier and dark matter

The displaced frontier

- Exotic collider objects:
  - Long lived charged particles
  - Displaced decays, vertices
  - Collimated objects: Dark jets, lepton jets
- No (intrinsic) SM backgrounds
  - Can design BG free searches
  - Sensitivity scales linearly with luminosity → great for high lumi LHC

Minimal example

- Minimal SU(2) doublet or triplet DM (Wino/Higgsino)
- DM state accompanied with nearly degenerate charged state (chargino)
- Lifetime few cm → disappearing charged track
- Strongest limit on Wino DM

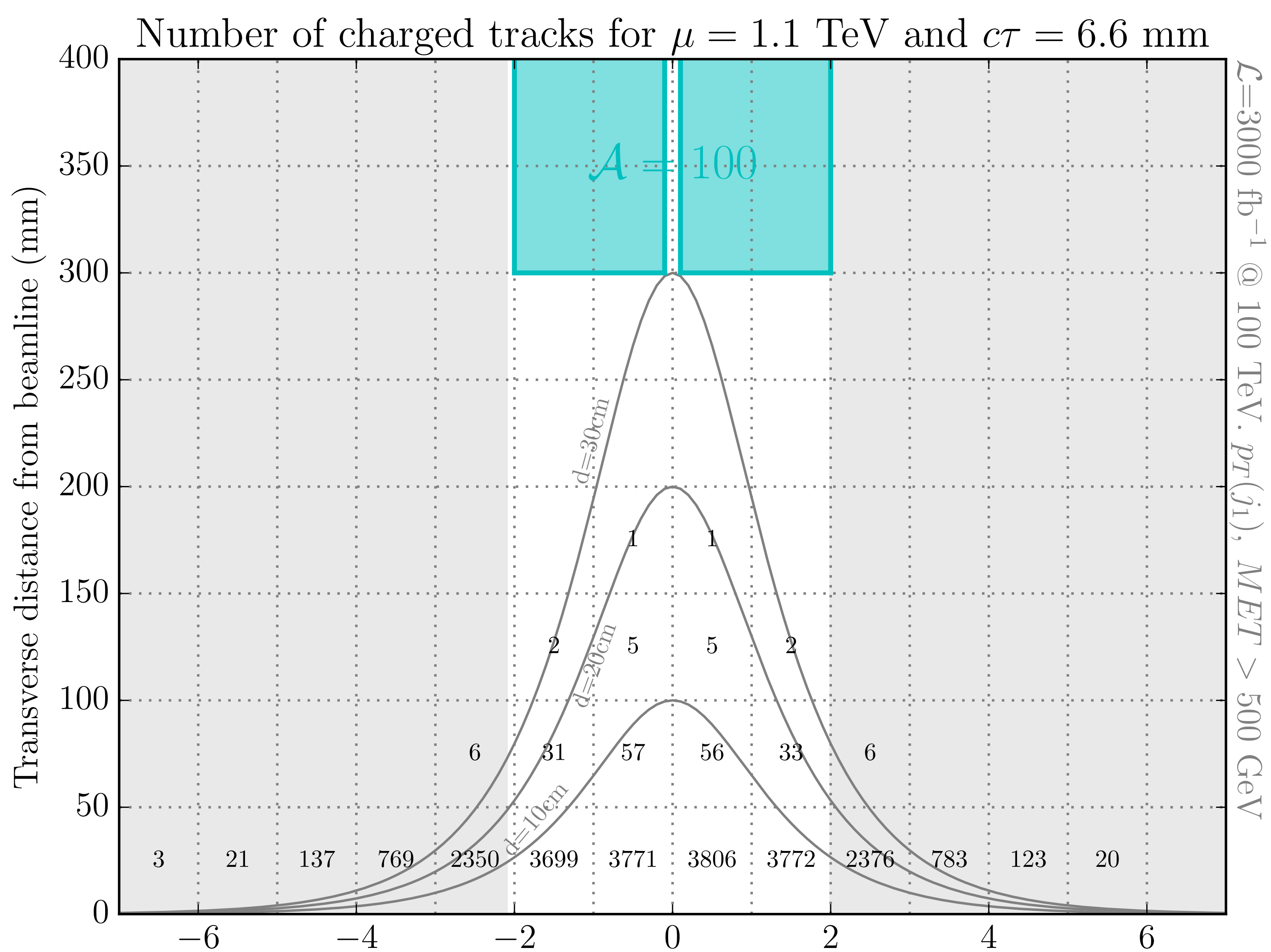


Higgsinos

- For doublets: Shorter lifetime! Requiring TRT hits (~30 cm transverse distance) not viable

- Option 1: Bring the tracker closer

- 14/100 TeV analysis in progress

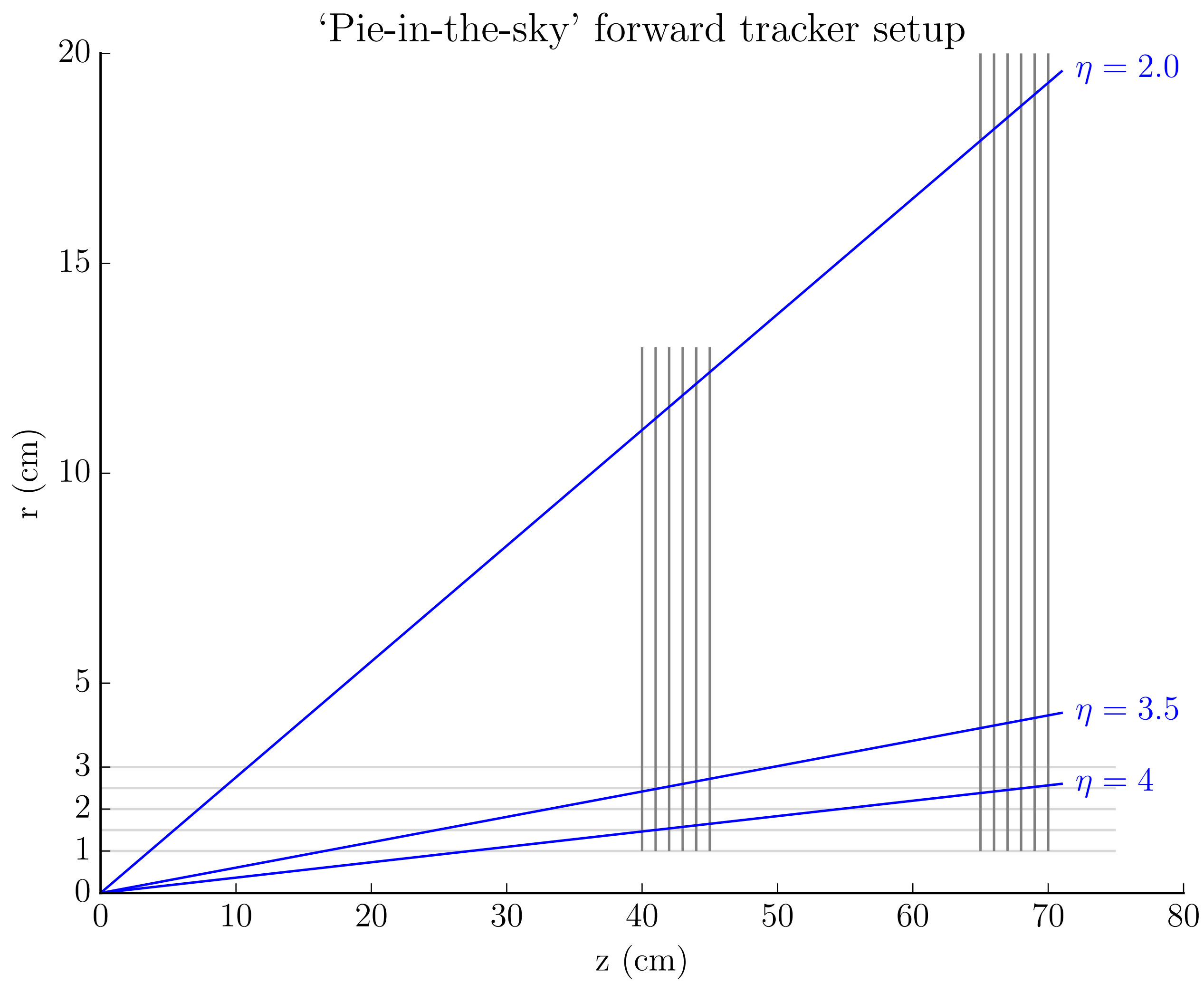


Mahbubani, PS, Zurita, in progress

Higgsinos

- For doublets: Shorter lifetime! Requiring TRT hits (~30 cm transverse distance) not viable

- Option 2:
  Use forward direction



Mahbubani, PS, Zurita, in progress

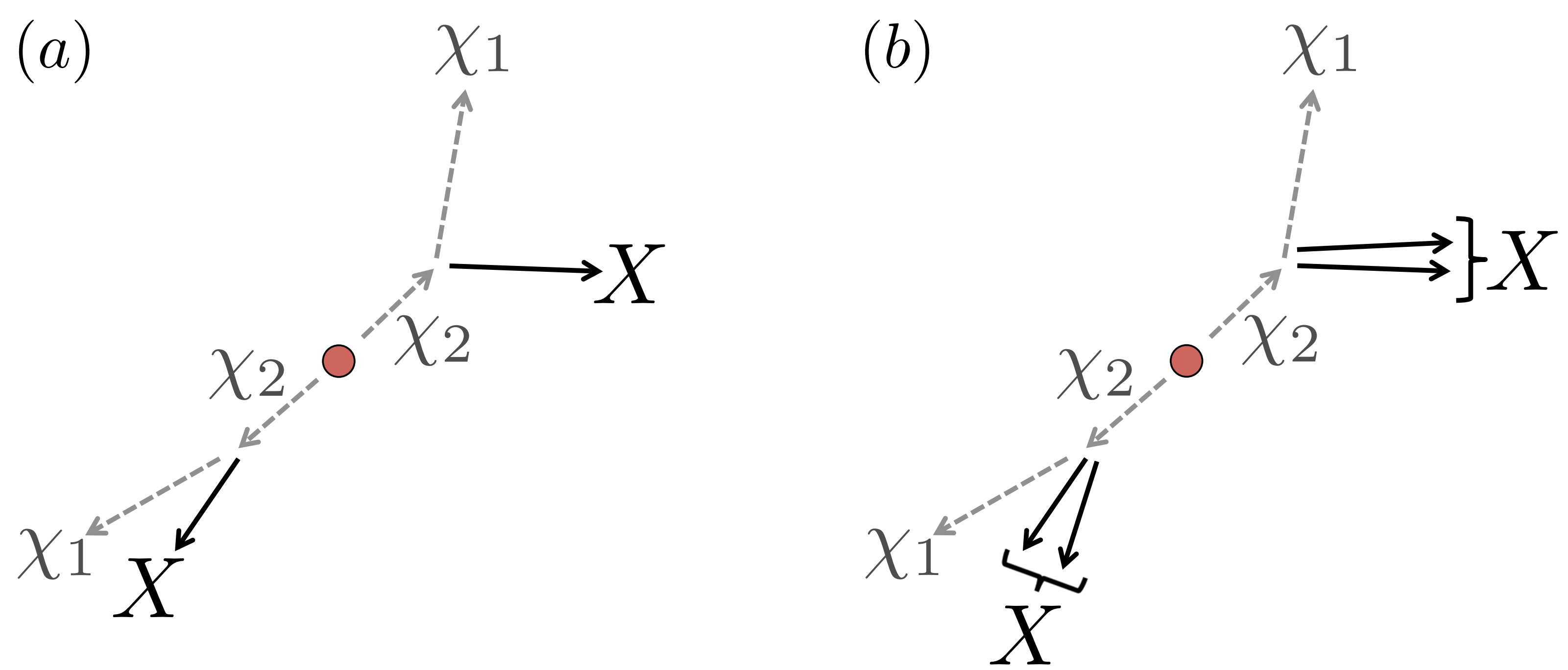
Simplified models for displaced DM

Simplified models

- Successful way to present collider searches in a less model dependent way
  - Two masses (DM & mediator) and two couplings
- Minimal extension to include displaced decays
  - Add second “dark” state with mass $m_2 > m_{\rm DM}$
  - Lifetime $\Gamma(\chi_2 \to \chi_1 X)$
- Underlying models e.g. “GMSB SUSY” and “split Higgs portal”

Buchmueller, De Roeck, McCullough, PS, Yu, in progress

Signatures



- X can be any set of SM particles
- Can also imagine charged χ_2
- Use ISR (jets, Z, photon) + MET to trigger

Buchmueller, De Roeck, McCullough, PS, Yu, in progress

Gravitational Waves and DM

Dark QCD

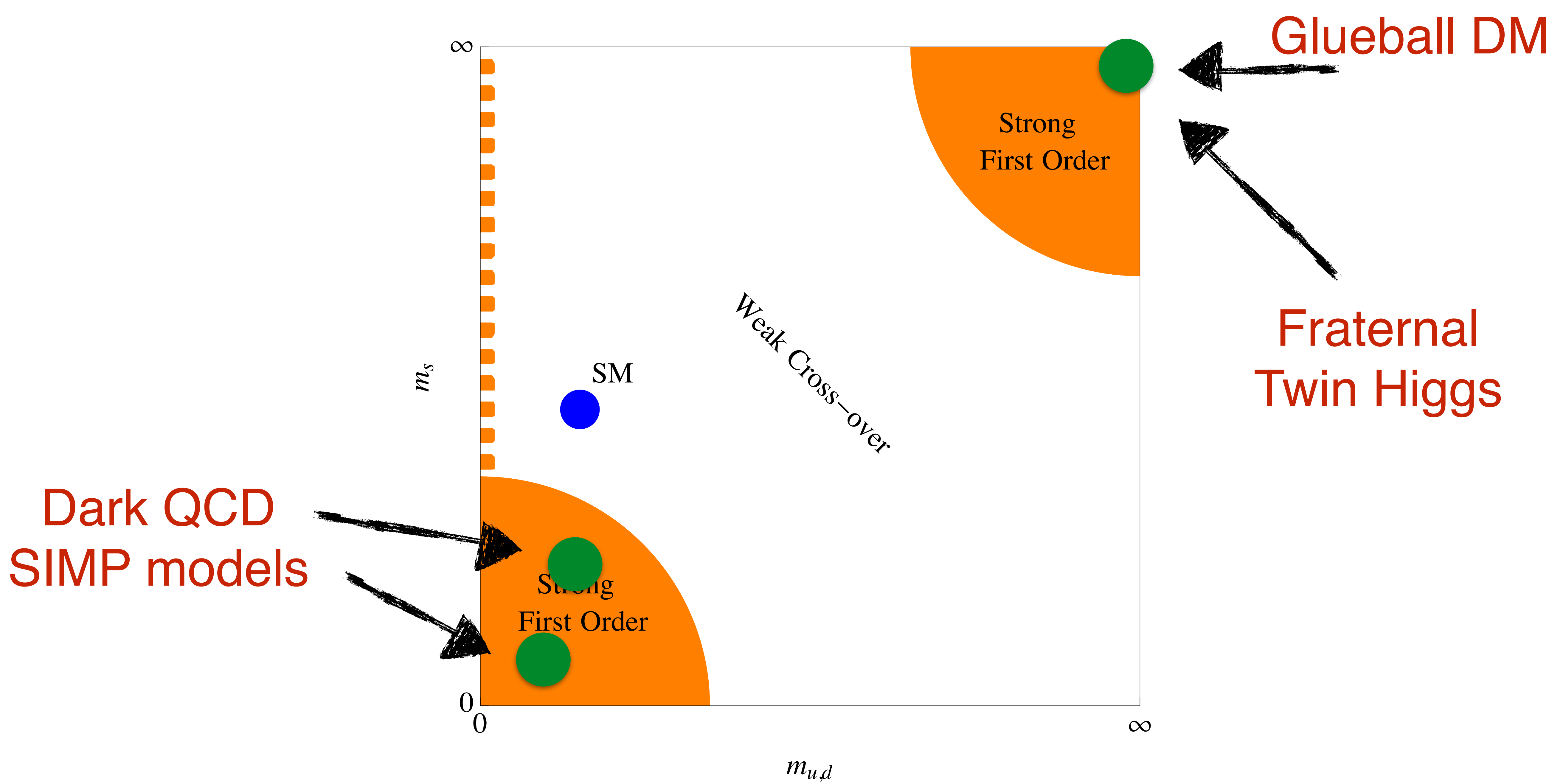
- Remember that model from before!
- Nonabelian SU(N) dark sector, confinement scale Λ_d
- n_f light/massless flavours

$n_f = 0$	$n_f > 0$
Glueball DM	Dark Baryons or Dark Pions
PT from center symmetry restoration	Chiral Symmetry Breaking

Phase Transition

- Confinement/chiral symmetry breaking phase transition at scale Λ_d
  - DM: $\Lambda_d \sim M_{\mathrm{DM}}$ (MeV - 100 TeV)
  - Naturalness: $\Lambda_d \sim \mathrm{few} \times \Lambda_{\mathrm{QCD}}$
- First order PT in large class of models
- Still possible if LHC finds no new physics

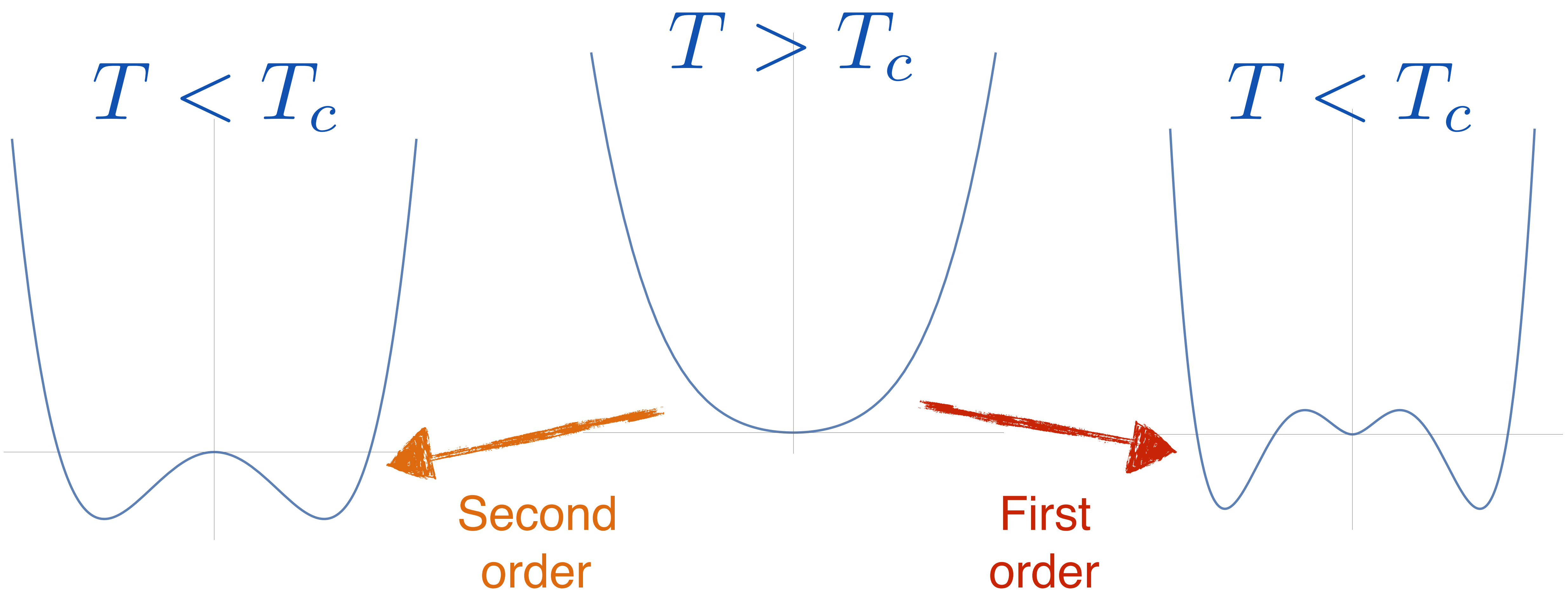
Phase Diagram



PS, 2016

Cosmological Phase Transitions

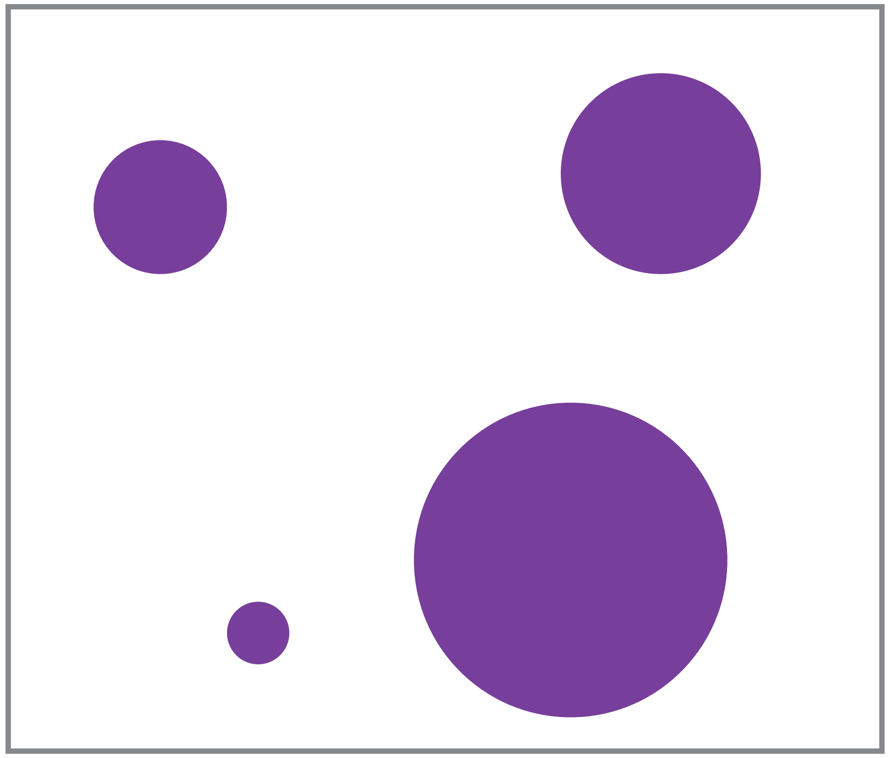
- Early Universe in symmetric phase (e.g. unbroken electroweak symmetry)

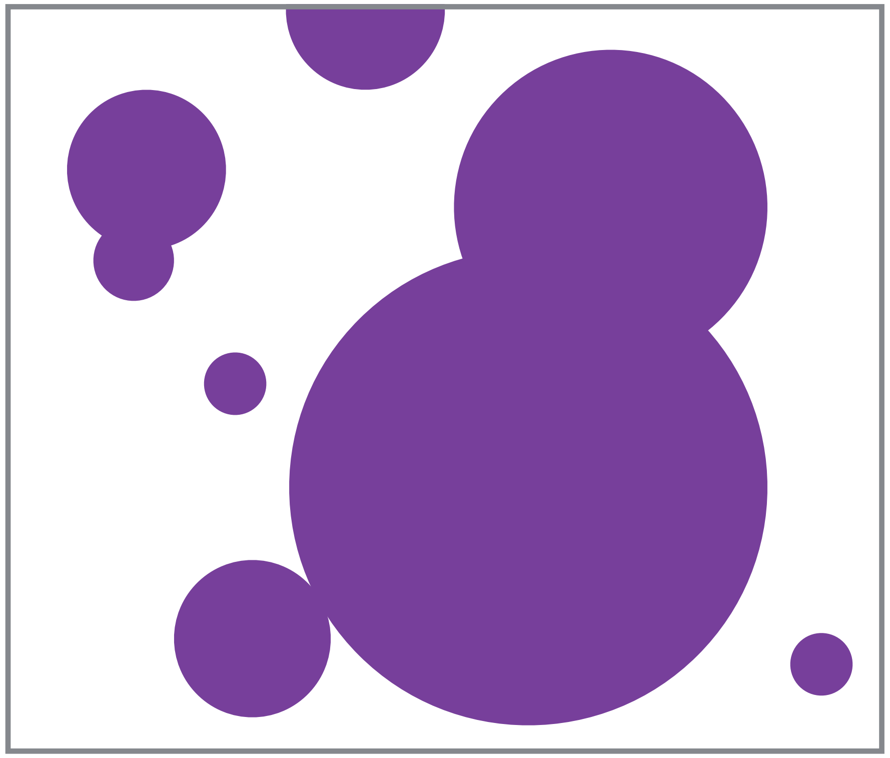


GWs from PTs

First order PT ➞ Bubbles nucleate, expand

Bubble collisions ➞ Gravitational Waves





Peak Frequency

- Redshift:

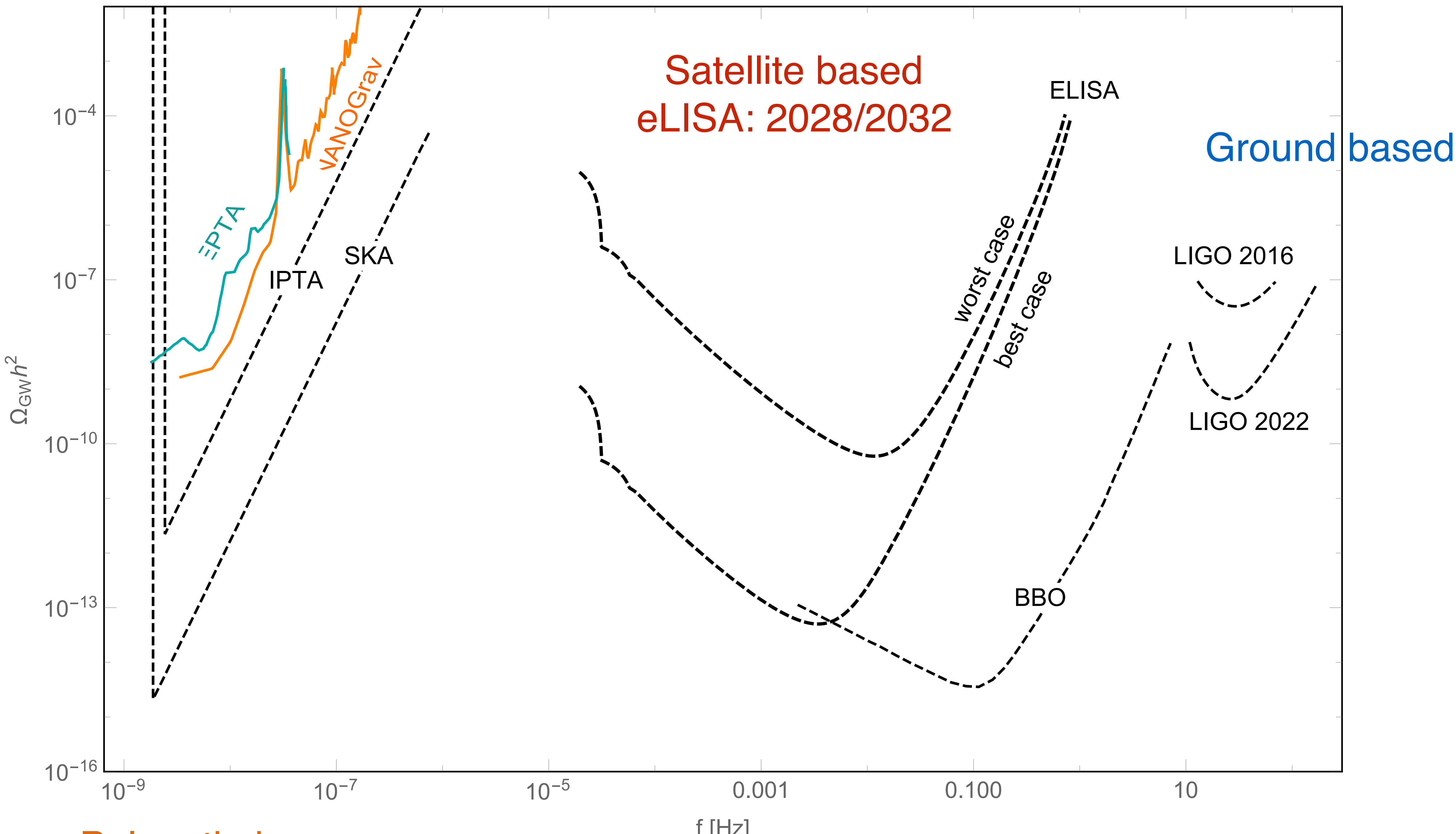
$$f = \frac{a_*}{a_0} H_* \frac{f_*}{H_*} = 1.59 \times 10^{-7}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \times \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \times \frac{f_*}{H_*}$$

PT Temperature
~ DM Mass

- Peak regions: $k/\beta \approx (1 - 10)$

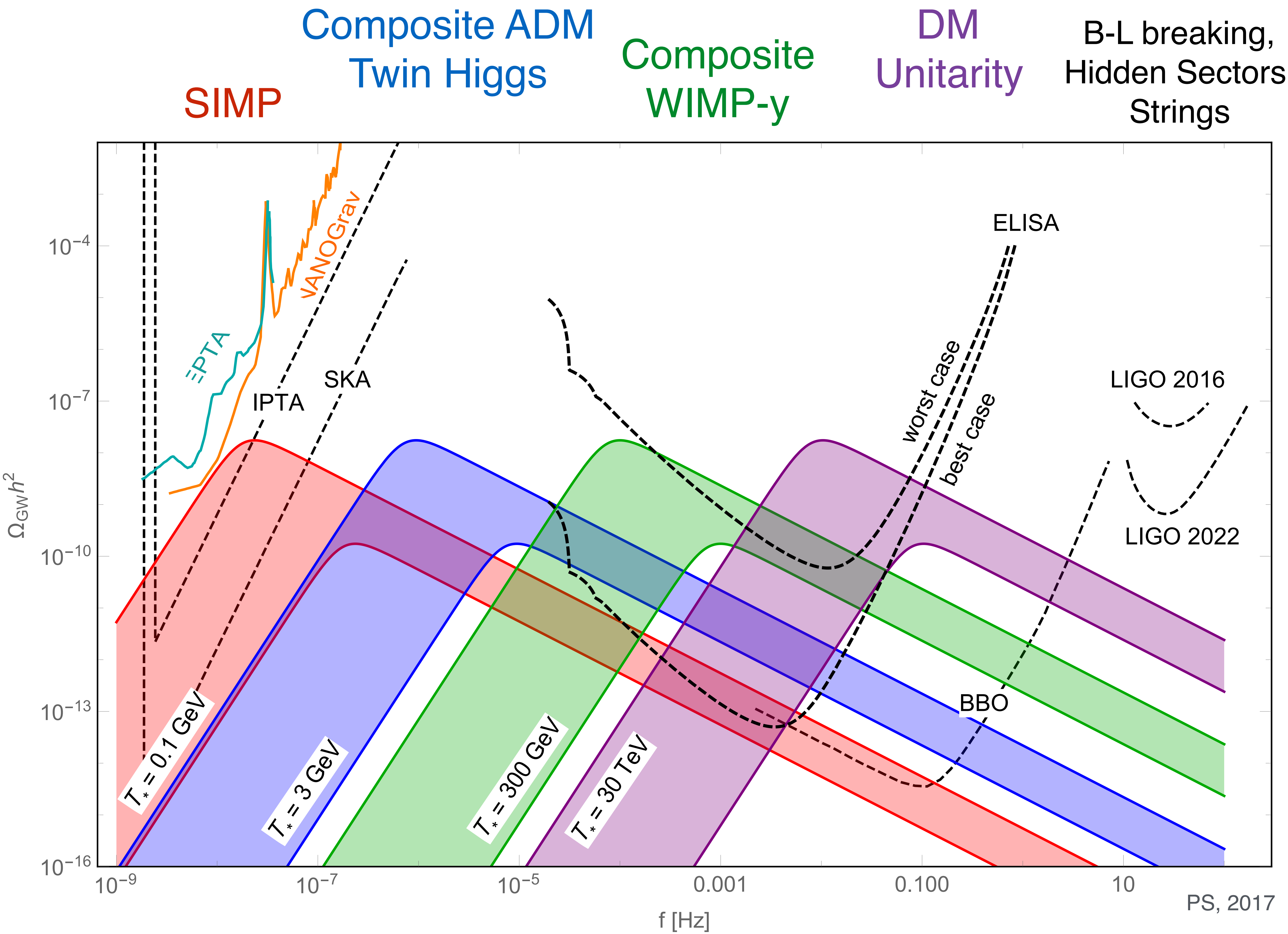
$$f_{\mathrm{peak}}^{(B)} = 3.33 \times 10^{-8}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \left(\frac{\beta}{\mathcal{H}_*}\right)$$

GW Soundscape



Pulsar timing arrays
Data already available

PS, 2017



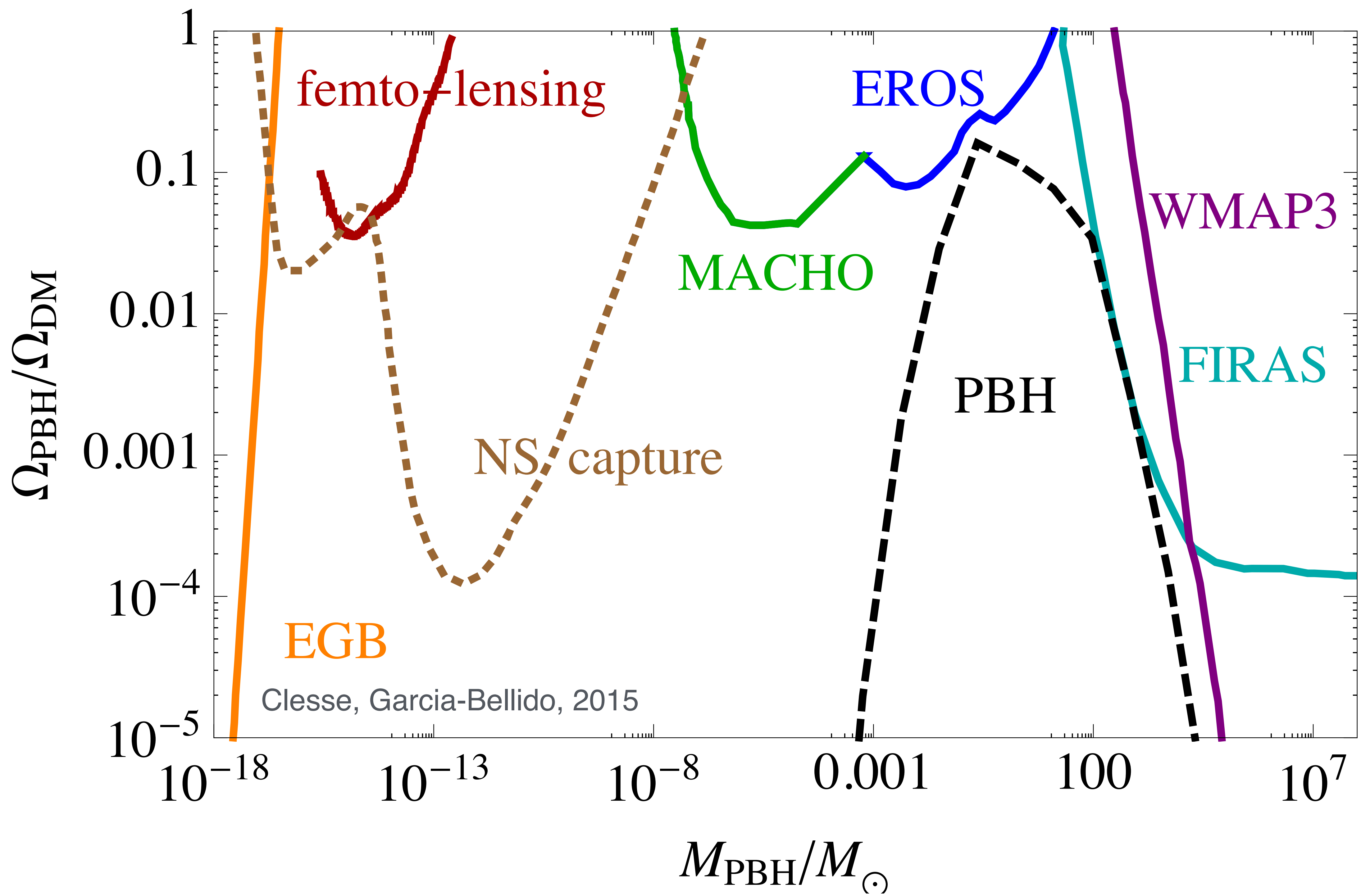
SIMP
Composite ADM
Twin Higgs
Composite
WIMP-y
DM
Unitarity
B-L breaking,
Hidden Sectors,
Strings
EPTA
NANOGrav
IPTA
SKA
ELISA
worst case
best case
LIGO 2016
LIGO 2022
BBO
$T_* = 0.1$ GeV
$T_* = 3$ GeV
$T_* = 300$ GeV
$T_* = 30$ TeV
$\Omega_{GW} h^2$
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-9}
10^{-7}
10^{-5}
0.001
0.100
10
f [Hz]
PS, 2017

Summary

- Quest for dark matter is more pressing than ever
- Non-minimal models can motivate new collider searches
  - Emerging jets
  - Displaced frontier - new simplified models
- GWs could be unique window into the physics of dark sector

Backup

Primordial BH Dark Matter



SU(N) - PT

- Consider $SU(N_d)$ with n_f massless flavours

- PT is first order for
  - $N_d \geq 3 \;\; , \quad n_f = 0$ — Svetitsky, Yaffe, 1982; M. Panero, 2009
  - $N_d \geq 3 \;\; , \quad 3 \leq n_f < 4N_d$ — Pisarski, Wilczek, 1983

- Not for:
  - $n_f = 1$ (no global symmetry, no PT)
  - $n_f = 2$ (not yet known)