Effective WIMP Decoupling

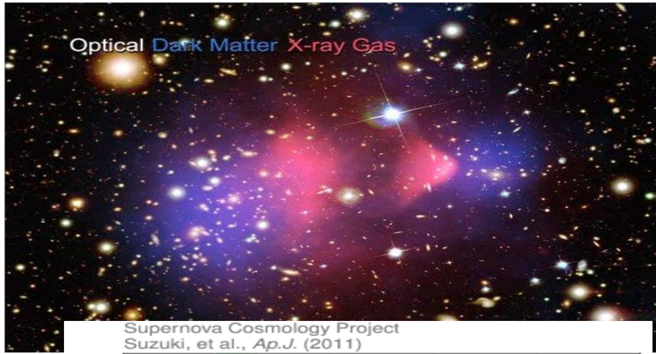
William Shepherd, UC Santa Cruz

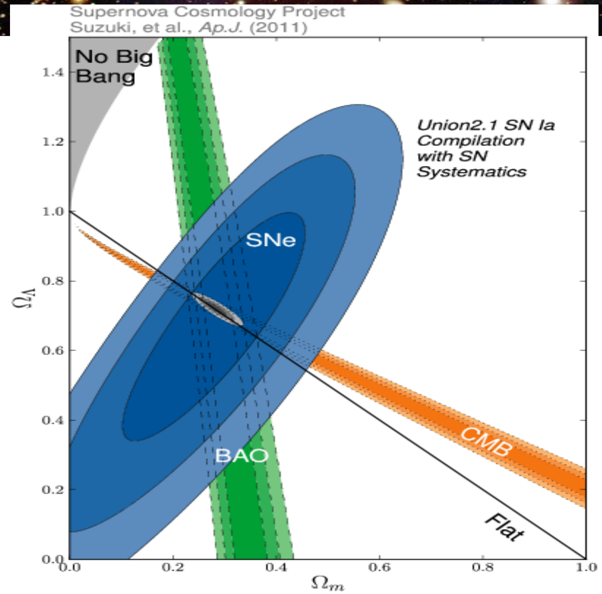
DPF 2013 Meeting

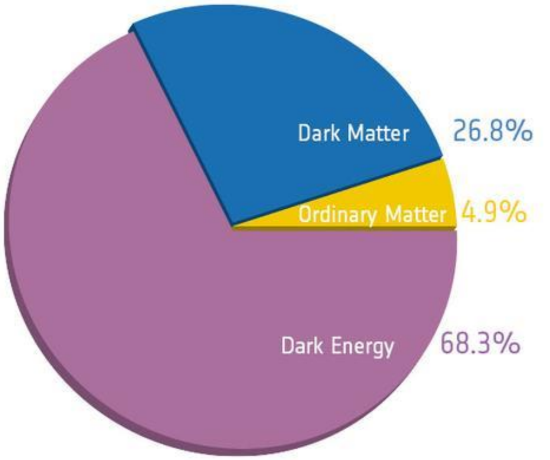
August 15 2013

Based on 1305.4676
in collaboration with
Jonathan Cornell and
Stefano Profumo

Dark Matter







- The evidence for dark matter is myriad and well-known.
- This evidence is one of the only truly experimental signs that we must have physics beyond the Standard Model.
- Cosmological observations tell us how much dark matter is needed to match observations.
- From the particle physics perspective, we're left asking what dark matter is and how it fits into a microscopic understanding of nature.

WIMP Dark Matter

- One of the most attractive proposals to explain dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally lead to the correct amount of dark matter in the universe.
  - WIMPs are automatic ingredients of many models of physics beyond the Standard Model, such as supersymmetric models.
- Instead of the usual approach of assuming a specific particle model for dark matter, I'll look for generic behavior common to all of them.

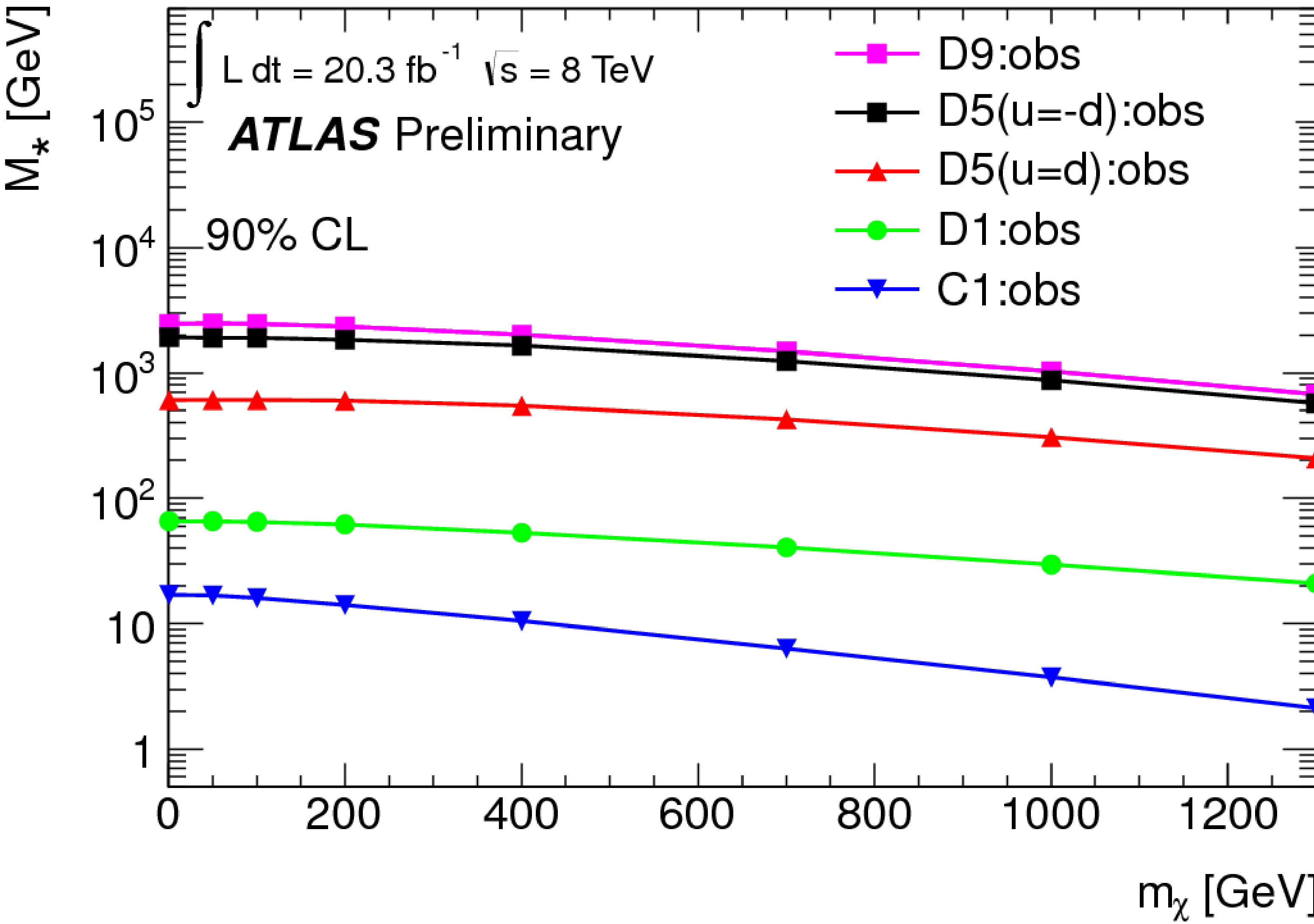
WIMP Interactions

- When it comes to searching for dark matter, WIMPs are also quite exciting, since they have "strong" interactions with the Standard Model.
  - "Strong" means similar to electroweak strength here – much stronger than gravity.
  - The interesting point is that we can actually search for these particles outside gravitational observations.
  - A non-gravitational observation would teach us a lot.

Effective Theory

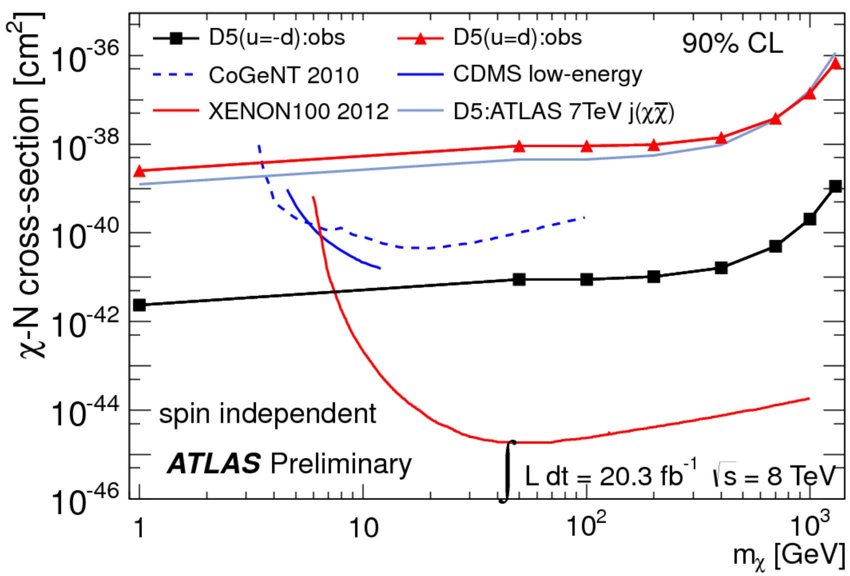
- We can hope to capture the physics of WIMP models in a way that is fairly insensitive to the details of the models themselves – effective theories give us a tool to try and do just that.
- As effective theories, they can only describe physics correctly within some energy range, and they have very specific assumptions built into them. Whether they work or not will depend on what kind of WIMP nature has given us for study.
- They provide a dictionary for studying the interactions of WIMPs with Standard Model fields. Using this dictionary we can translate results from one type of experiment onto the signal space of another.

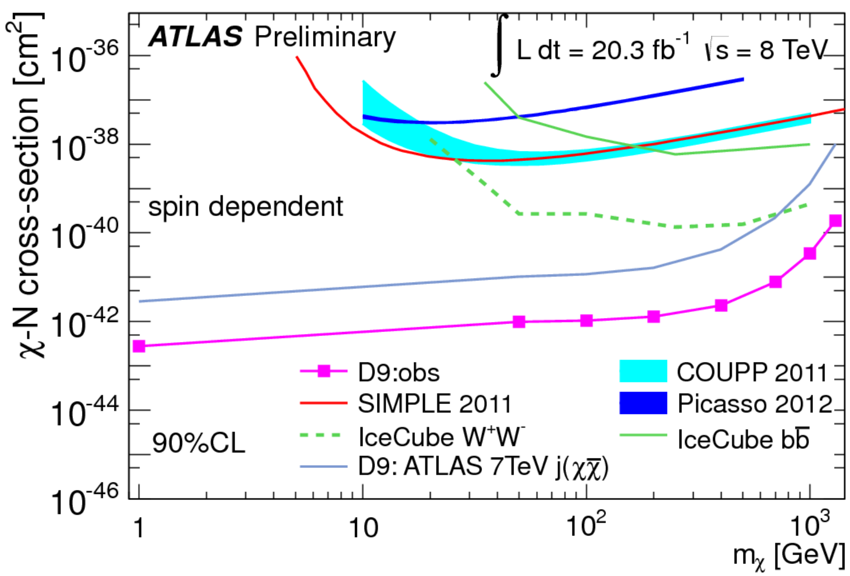
Collider Searches



ATLAS-CONF-2013-073

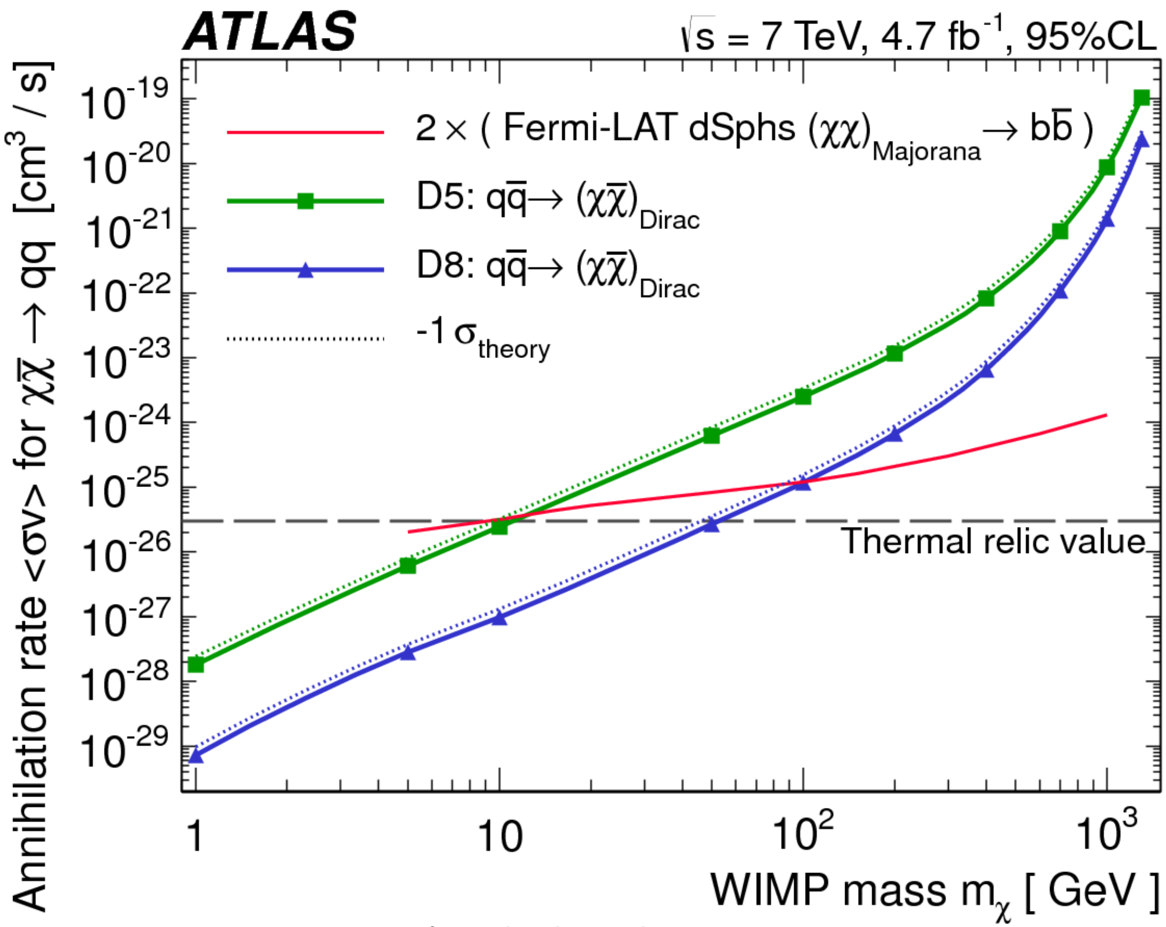
Mapping to Direct Detection





ATLAS-CONF-2013-073

Total* Annihilation Cross Section

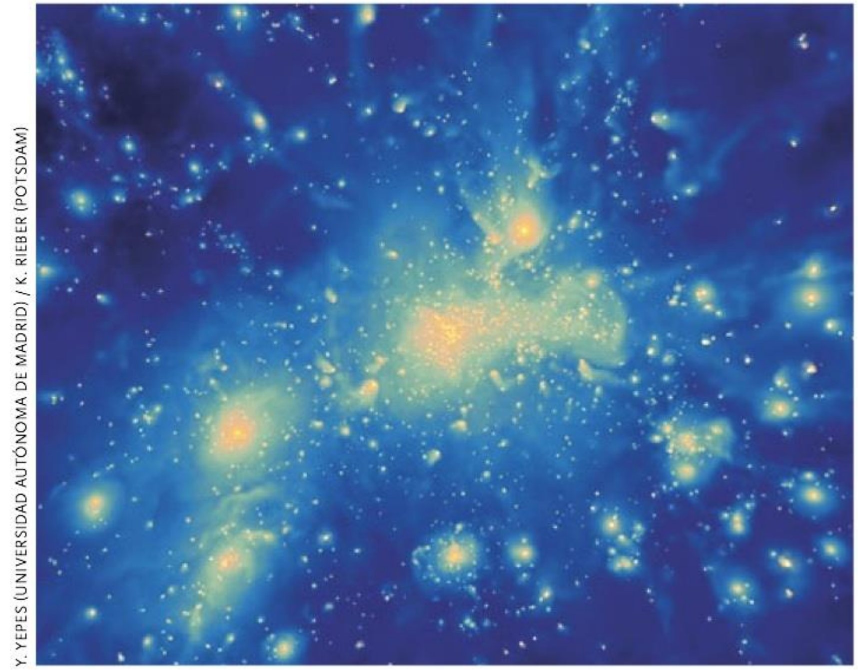


arXiv:1210:4491

Dark Matter Cosmology

- There's more to dark matter than just particle physics
  - Seeds structure in the universe
- Interactions can have measurable effects on DM (and thus baryon) distributions at large scales

Gas distribution from BigBolshoi simulation



Direct Detection (in Space)

- An important characteristic of structure formation is the halo mass cutoff
  - This is determined in the usual story by the temperature of kinetic decoupling, which is where DM-SM scatterings become rare
  - We can investigate this behavior using effective interactions as well

Kinetic Decoupling

- Decoupling can be characterized by the last temperature at which DM is kinetically coupled to the thermal bath
- The dark matter temperature is governed by the scattering rate:

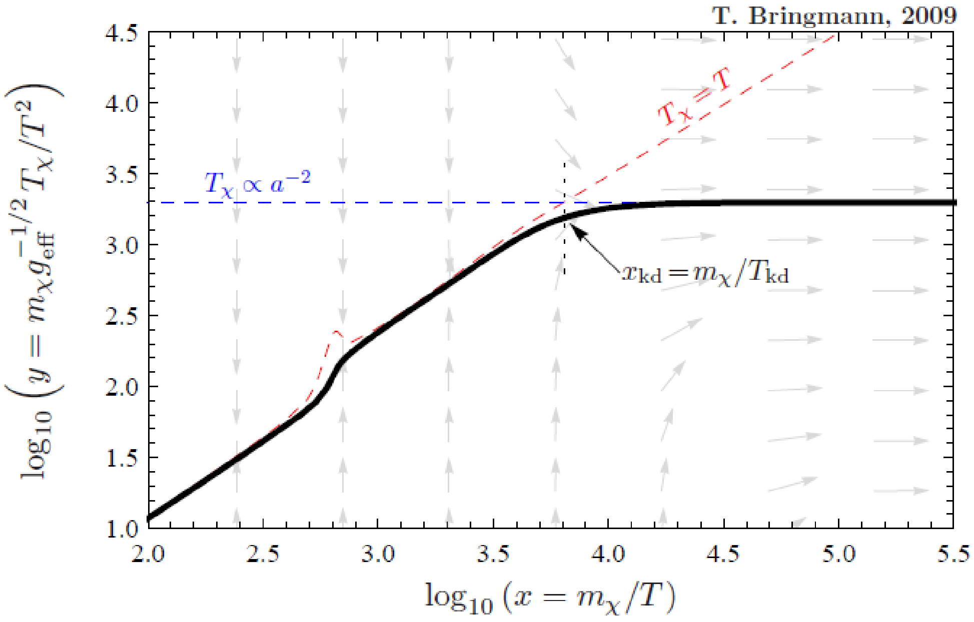
$$(\partial_t + 5H)\, T_\chi = 2m_\chi c(T)(T - T_\chi)$$

Basic Decoupling Temp Calc

- We take the sudden approximation to kinetic decoupling
- Choose T_{kd} such that

$$H\left(T_{kd}\right) \sim c\left(T_{kd}\right)$$

- A good approximation away from other fast cosmological processes



0903.0189

Mass Cutoff from Decoupling Temp

- There are two distinct mechanisms that can lead to a low-mass cutoff of DM haloes
  - Free Streaming and Viscosity with the bath

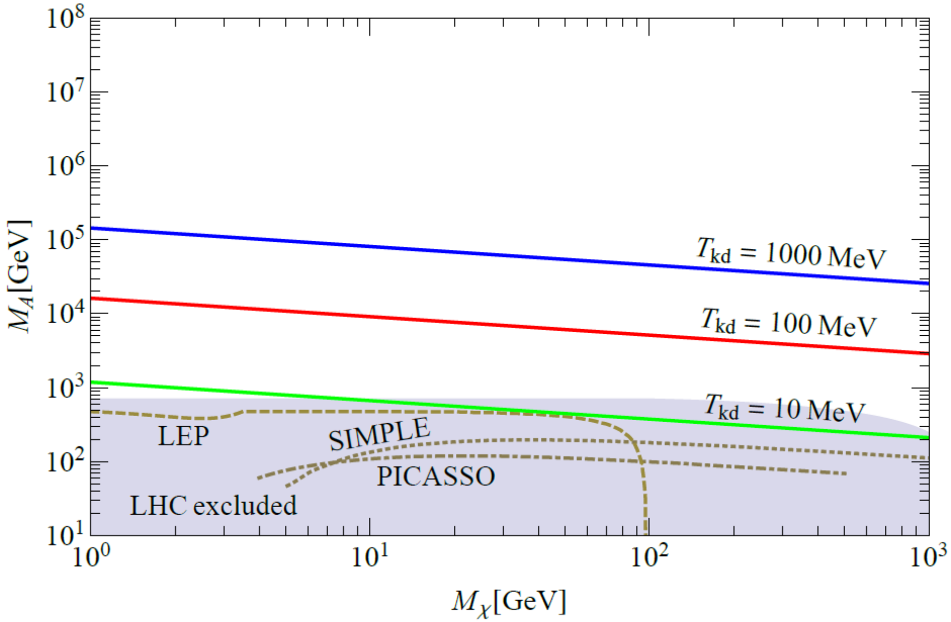
$$M_{\rm fs} \approx \frac{4\pi}{3}\rho_\chi \left(\frac{\pi}{k_{\rm fs}}\right)^3 = 2.9\times 10^{-6} M_\odot \left(\frac{1+\ln\left(g_{\rm eff}^{1/4} T_{\rm kd}/30\ {\rm MeV}\right)/18.56}{(m_\chi/100\ {\rm GeV})^{1/2}\, g_{\rm eff}^{1/4}\, (T_{\rm kd}/50\ {\rm MeV})^{1/2}}\right)^3$$

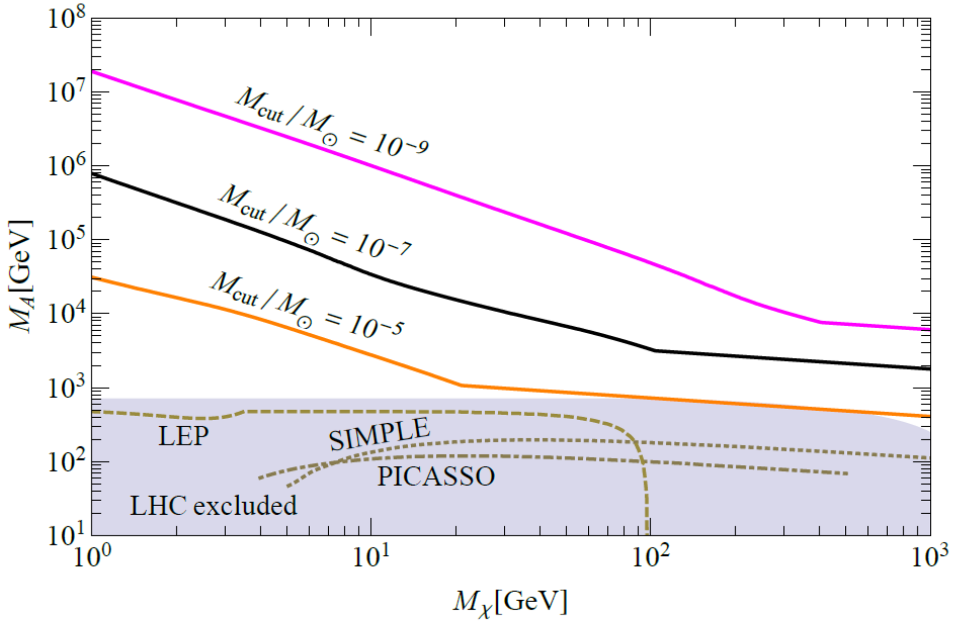
  - Acoustic Oscillations inherited from the bath

$$M_{\rm ao} \approx \frac{4\pi}{3}\frac{\rho_\chi}{H^3}\bigg|_{T=T_{\rm kd}} = 3.4\times 10^{-6} M_\odot \left(\frac{T_{\rm kd}\, g_{\rm eff}^{1/4}}{50\ {\rm MeV}}\right)^{-3}$$

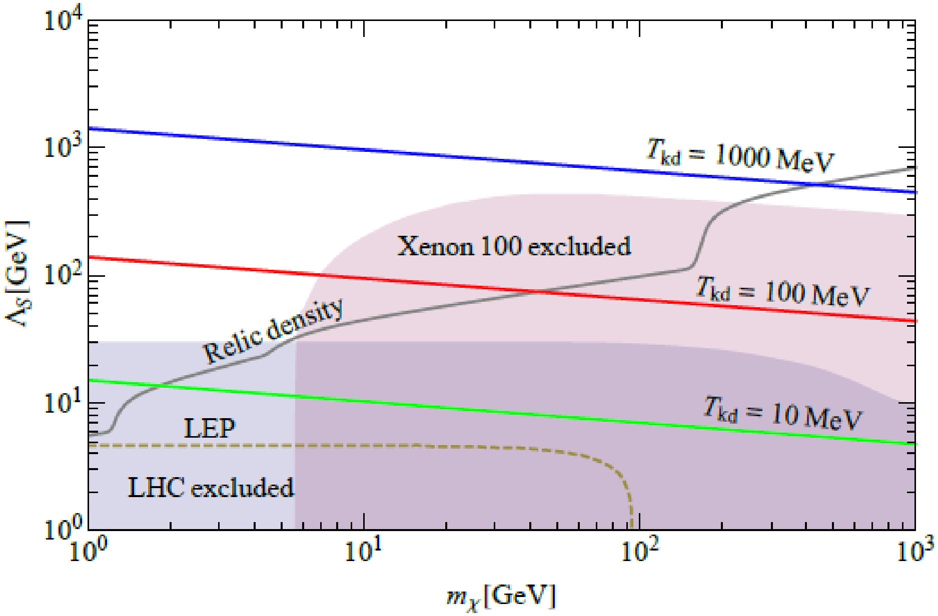
Decoupling in Effective Theories

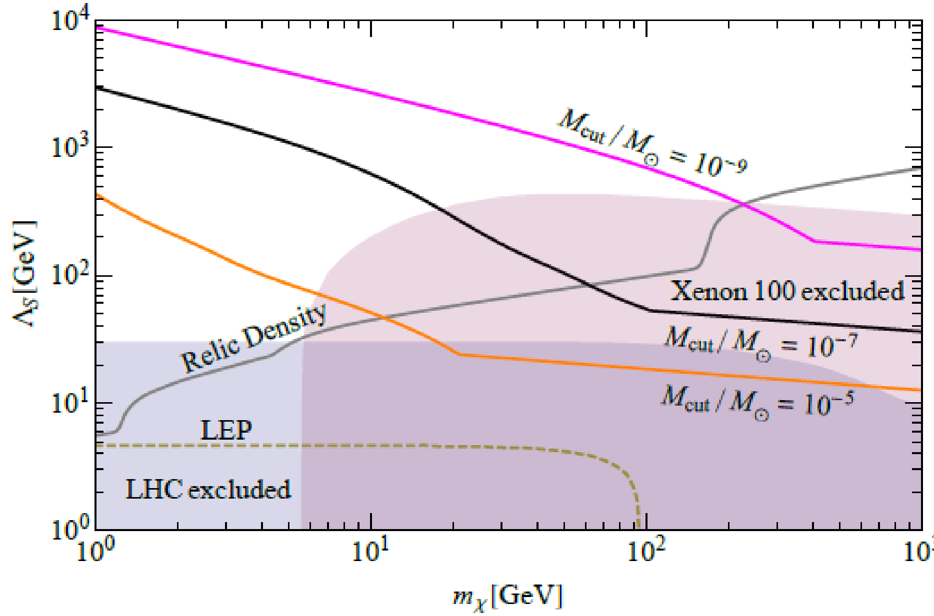
Axial operator



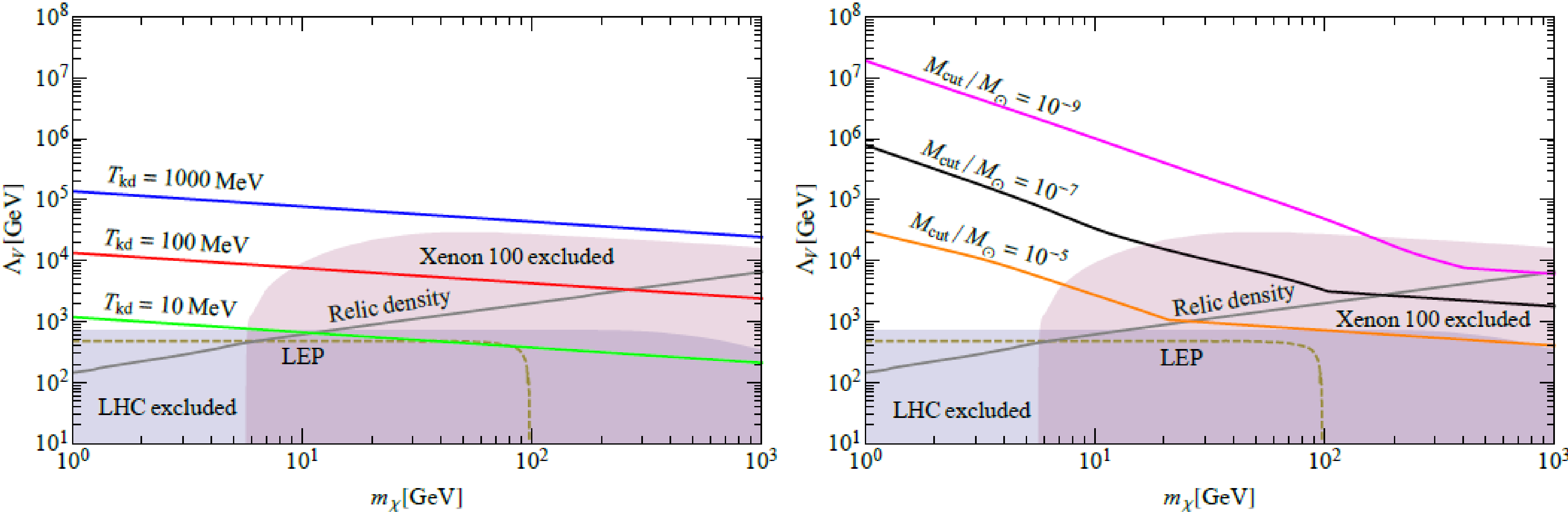


Scalar Operator





Vector Operator



Pion Scattering

- These scatterings are off of whatever is present in the thermal bath
  - Below the QCD phase transition, that means pions
- Two operators have correct properties to allow scattering off of pions:
  - Scalar

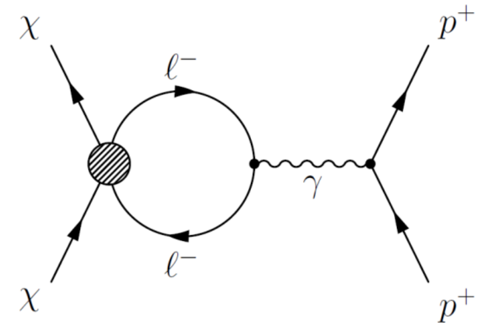
$$\langle \pi^a | \bar{q} q | \pi^a \rangle = \frac{m_\pi^2}{2} \langle \pi^a | \vec{\pi} \cdot \vec{\pi} | \pi^a \rangle$$

  - Vector

$$\langle \pi^a | \bar{q} \gamma^\mu q | \pi^a \rangle = (a_u - a_d) \langle \pi^a | \vec{\pi} \times \partial^\mu \vec{\pi} | \pi^a \rangle$$

Loop-Induced Scattering

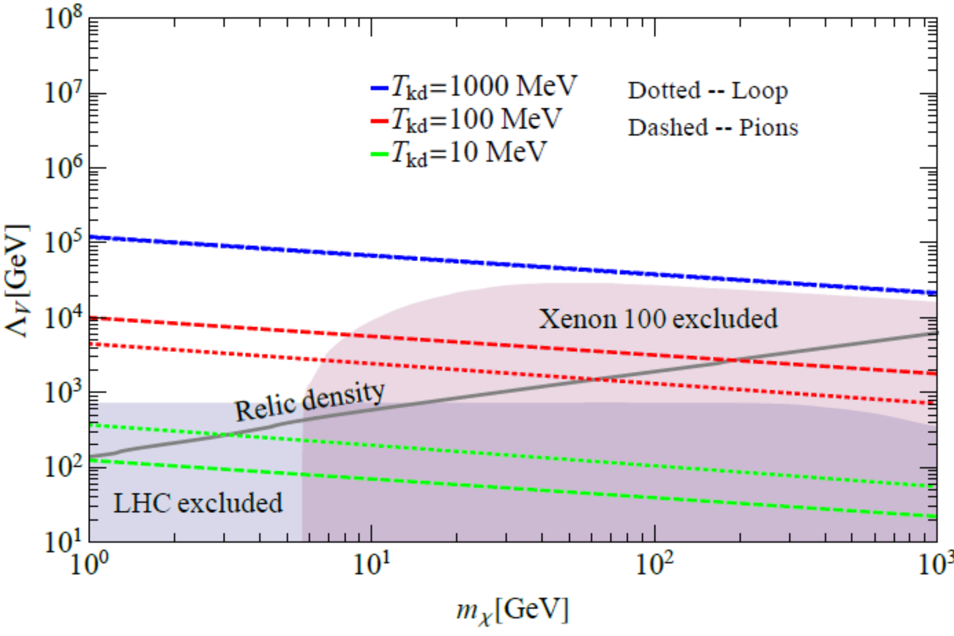
- All operators will generically mix under renormalization flow
  - Vector operator mixes most strongly, as it allows diagrams with photons at one loop



- Simple treatment: Use cutoff scale as renormalization scale and calculate finite effects

Pions and Loops

- This shows the decoupling behavior for a quark-only operator
- Compares effects of pions and loop-induced lepton couplings at low temperatures
  - Pions win for higher T, loops matter most at lowest T



Conclusions

- Decoupling temperatures can easily be low enough that the QCD phase transition matters
  – Not all WIMPs scatter off of leptons efficiently
- Loop-induced couplings can be important
- Late decoupling cannot solve the missing substructure ‘problem’ in Effective WIMP models
  – Detection prospects for the decoupling temperature in these models live in the substructure boost factor