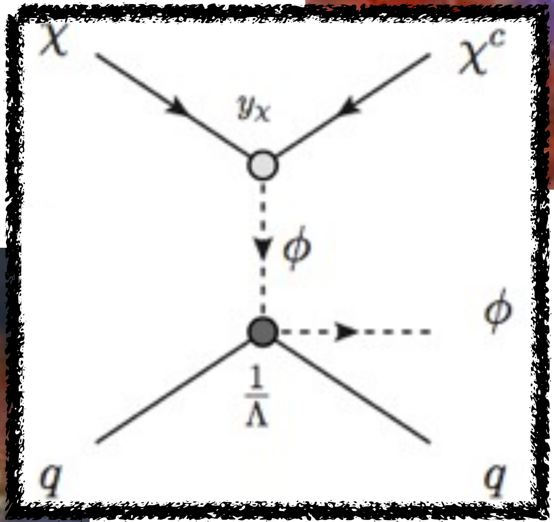
Constraining Doubly Dark Portals



New Perspectives on Dark Matter Worksop
Fermilab
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David Curtin
YITP
Stony Brook University

Based on
arXiv:1312.2618 (DC, Ze'ev Surujon, Yuhsin Tsai)
arXiv:1405.xxxx (DC, Yuhsin Tsai)

Doubly

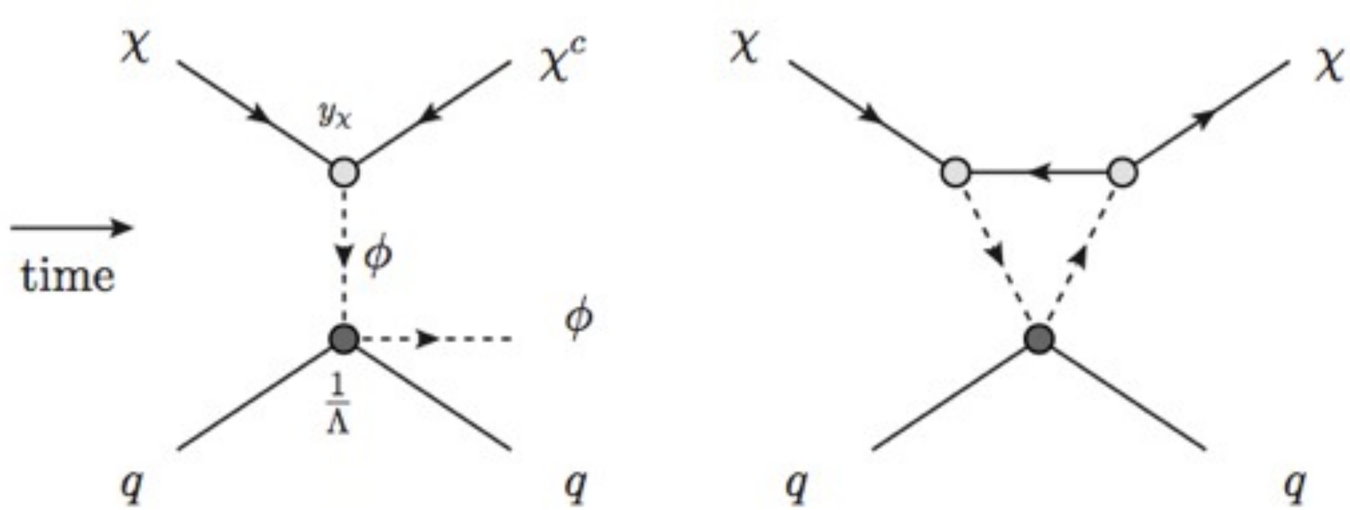
Dark

Portals

Doubly Dark Portals

- There is no particular reason to assume the dark sector is minimal -- the SM certainly isn't!
- DM is usually stabilized by carrying some kind of 'dark charge'. We investigate a *slightly* non-minimal dark sector, which talks to the SM via force carriers which themselves carry dark charge as well: a dark "dark portal".
  $\Rrightarrow$ *Dark Mediator Dark Matter (dmDM)*

$$\mathcal{L}_{\rm DM} \supset \sum_{i,j}^{n_\phi} \frac{1}{\Lambda_{ij}} \bar{q}\, q\, \phi_i \phi_j^* + \sum_i^{n_\phi} \left(y_\chi^i \overline{\chi^c} \chi \phi_i + h.c. \right) + \cdots ,$$



This can realize direct detection as a 2→3 scattering process.
See talk by Yuhsin Tsai

Doubly Dark Portals

- The dark dark portal is defined by light scalars coupling to SM (say quarks) via the operator

$$\frac{1}{\Lambda_{ij}}\bar{q}\,q\,\phi_i\phi_j^*$$

- The interesting mass range of dark mediators ϕ is eV - MeV.

- This operator can be constrained from a variety of low-energy phenomena.
  We *conduct the first systematic investigation* of these constraints.

- We also *review* constraints on the DM self-interaction

$$y_\chi^i\,\overline{\chi^c}\chi\phi_i$$

Constraints on DM Self-Interaction

$$\sum_{i}^{n_\phi} \left(y_\chi^i \overline{\chi^c} \chi \phi_i + h.c. \right)$$

Dark Matter Self Interaction

- Assume one of these Yukawa couplings dominates.

$$\sum_i^{n_\phi} \left(y_\chi^i \overline{\chi^c} \chi \phi_i + h.c. \right)$$

- Requiring χ to be a thermal relic with $\Omega_\chi = \Omega_{CDM}$ implies

$$y_\chi \approx 0.0027 \sqrt{\frac{m_\chi}{\mathrm{GeV}}}.$$

- Bullet Cluster observations give *upper bound*:

$$y_\chi \lesssim 0.13 \left(\frac{m_\chi}{\mathrm{GeV}} \right)^{3/4}$$

Feng, Kaplinghat, Tu, Yu, 0905.3039

Dark Matter Self Interaction

- There might be inconsistencies between N-body simulations and observations (too-big-to-fail, core-cusp).

Carlson, Machacek, Hall, 1992
Spergel, Steinhardt, astro-ph/9909386

  - Could be ameliorated with sizable DM self-interaction: "*Strongly Interacting Dark Matter*" *(SIDM)*

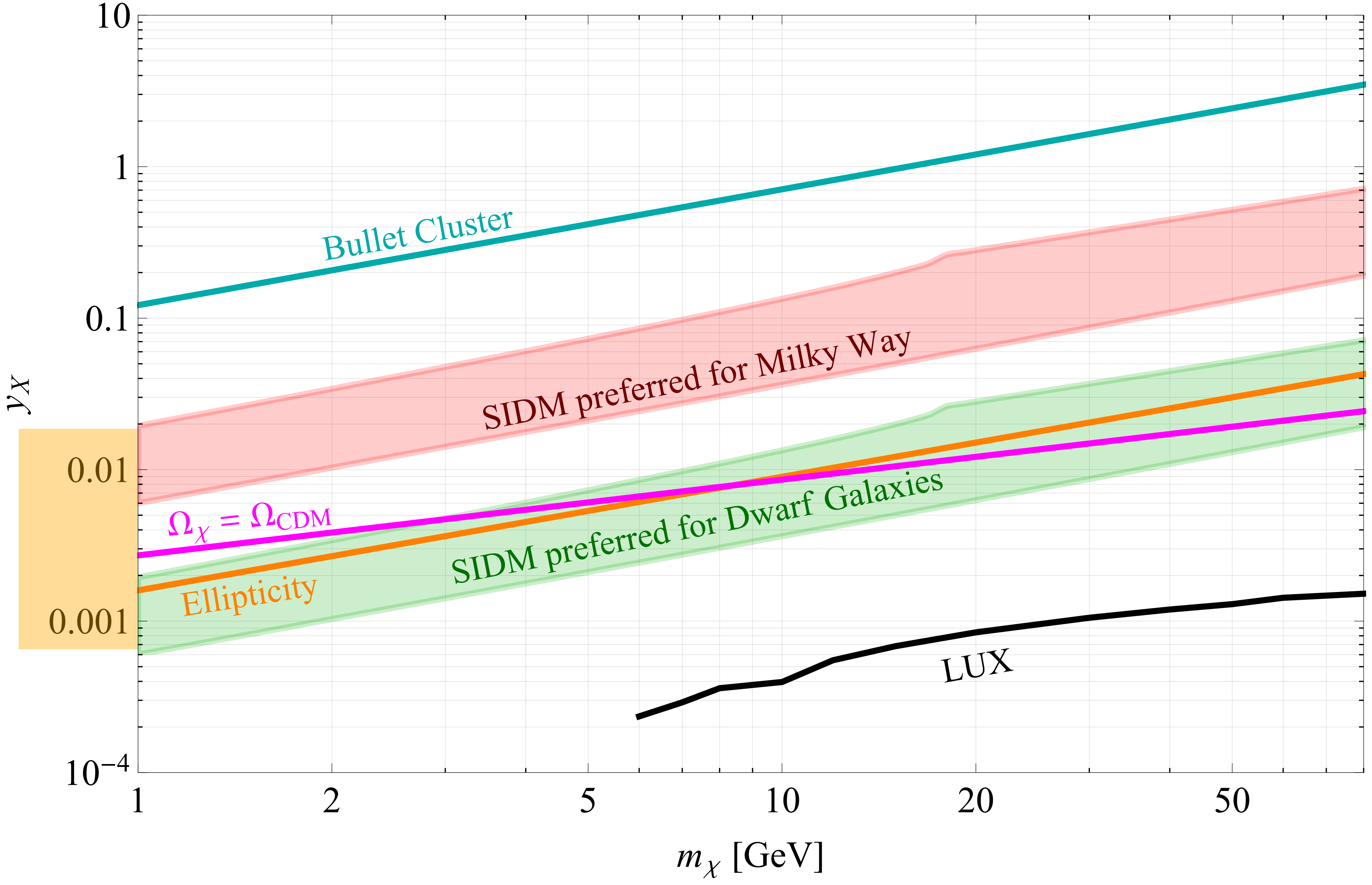
- This requires a certain scattering cross section

$$\sigma_T/m_\chi = 0.5 - 30\,\mathrm{cm}^2/\mathrm{g}$$

Tulin, Yu, Zurek, 1302.3898

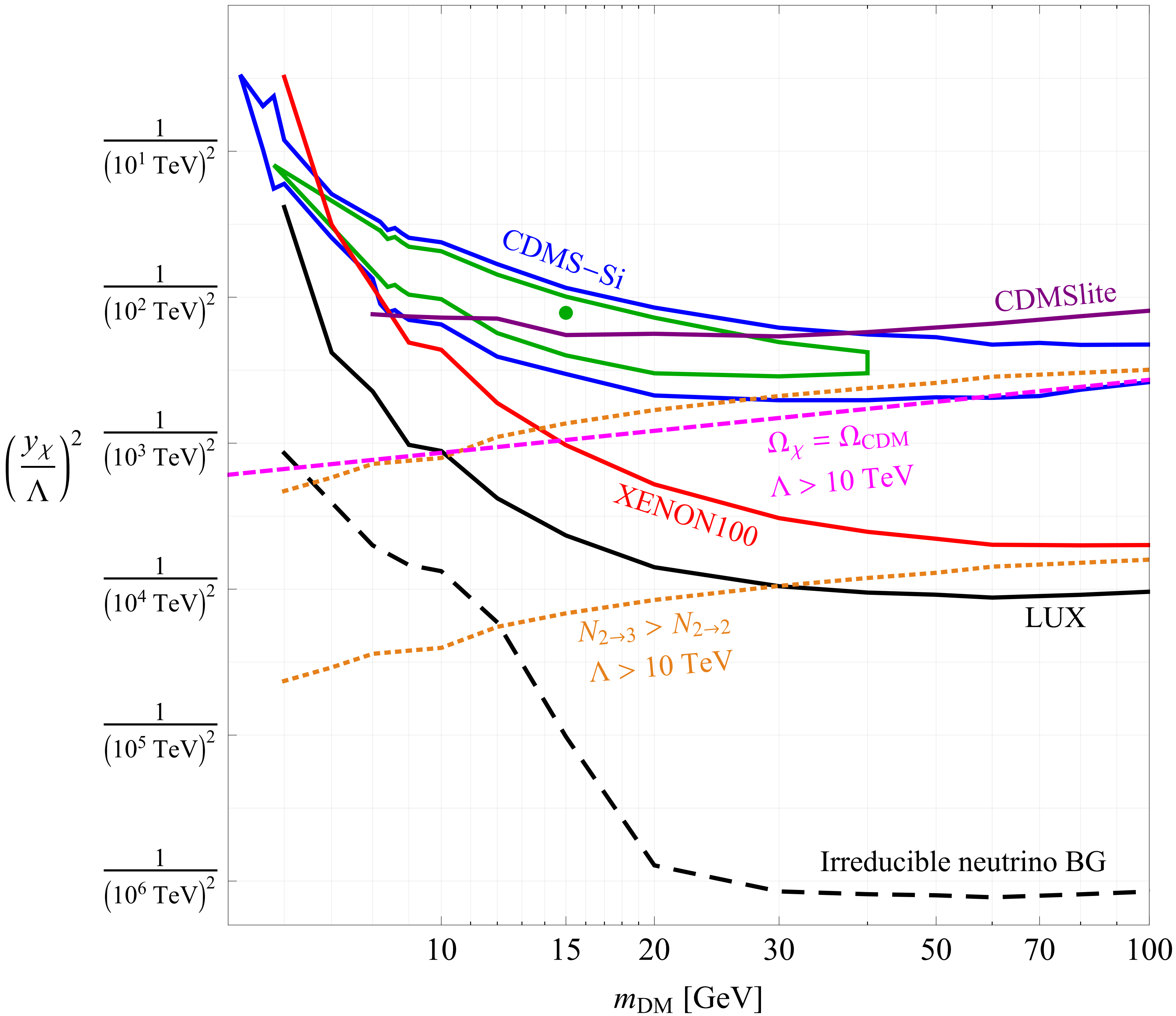
- Can use SIDM to fix inconsistencies between simulations and observations for dwarf galaxies or milky way, but not both.

Dark Matter Self Interaction



Relevant values of dominant $y_\chi \sim 10^{-3}$ - 10^{-2}

Most interesting values for Λ?



This tells us that the Λ_{ij} which controls direct detection

$$\frac{1}{\Lambda_{ij}}\bar{q}\,q\,\phi_i\phi_j^*$$

should be

$\Lambda_{ij} < 10^4$ TeV

to give observable signal.

See Yuhsin Tsai's Talk!

Constraints

on

Dark Mediators

$$\frac{1}{\Lambda_{ij}}\bar{q}\,q\,\phi_i\phi_j^*$$

Dark Mediators $\frac{1}{\Lambda_{ij}}\bar{q}\,q\,\phi_i\phi_j^*$

Three main sources of constraints:

Cosmological

Avoid overclosure, BBN, Structure Formation

Direct Production at Colliders

LHC mono/dijet + MET searches

Production inside of stars

sun, white dwarfs, neutron stars, supernovae

Cosmological Constraints

- The relic density of a light scalar is given by

$$\Omega_\phi h^2 \equiv 7.83 \times 10^{-2} \frac{g_\phi}{g_{*S}} \frac{m_\phi}{eV}$$

so to avoid overclosure, the heaviest stable ϕ must have $m_\phi < \text{eV}$

- Structure Formation bounds for thermally produced sterile neutrino apply to these light scalars as well. Satisfied for $m_\phi < \text{eV}$

Wyman, Rudd, Vanderveld, Hu 1307.7715

- During BBN era, additional light degrees of freedom speed up the expansion of the universe and freeze out n/p ratio at a larger value. Measured BBN $N_{eff} = 3.3 \pm 0.6$ (Plank+WMAP+HighL CMB measurements) limits the number of real scalar dof to ≤ 2 at 95%CL.

LHC Constraints

- Can use 20/fb Monojet + MET searches to constrain $pp \to \phi\phi$ + jets

ATLAS-CONF-2012-147
CMS-PAS-EXO-12-048

Require $\Lambda_{\rm eff} \gtrsim 2$ TeV, where

$$\Lambda_{\rm eff} = \left(\sum_{i \geq j} \frac{1}{\Lambda_{ij}^2} \right)^{-2}$$

- LHC can also probe the UV completion of dmDM. The operator

$$\frac{1}{\Lambda_{ij}} \bar{q}\, q\, \phi_i \phi_j^*$$

Can be generated by exchange of dark vector quarks. CMS 20/fb dijet+MET search constrains $M_Q > 1.5$ TeV

CMS-PAS-SUS-13-012

Supernovae

White Dwarfs

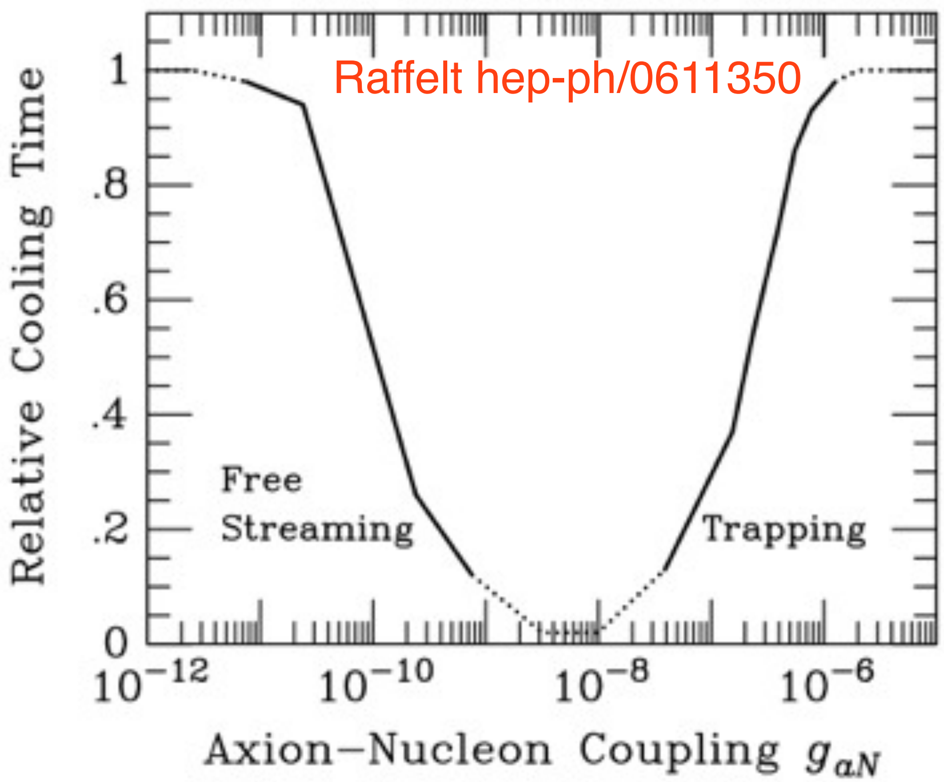
Stellar Astrophysics Constraints

Neutron Stars

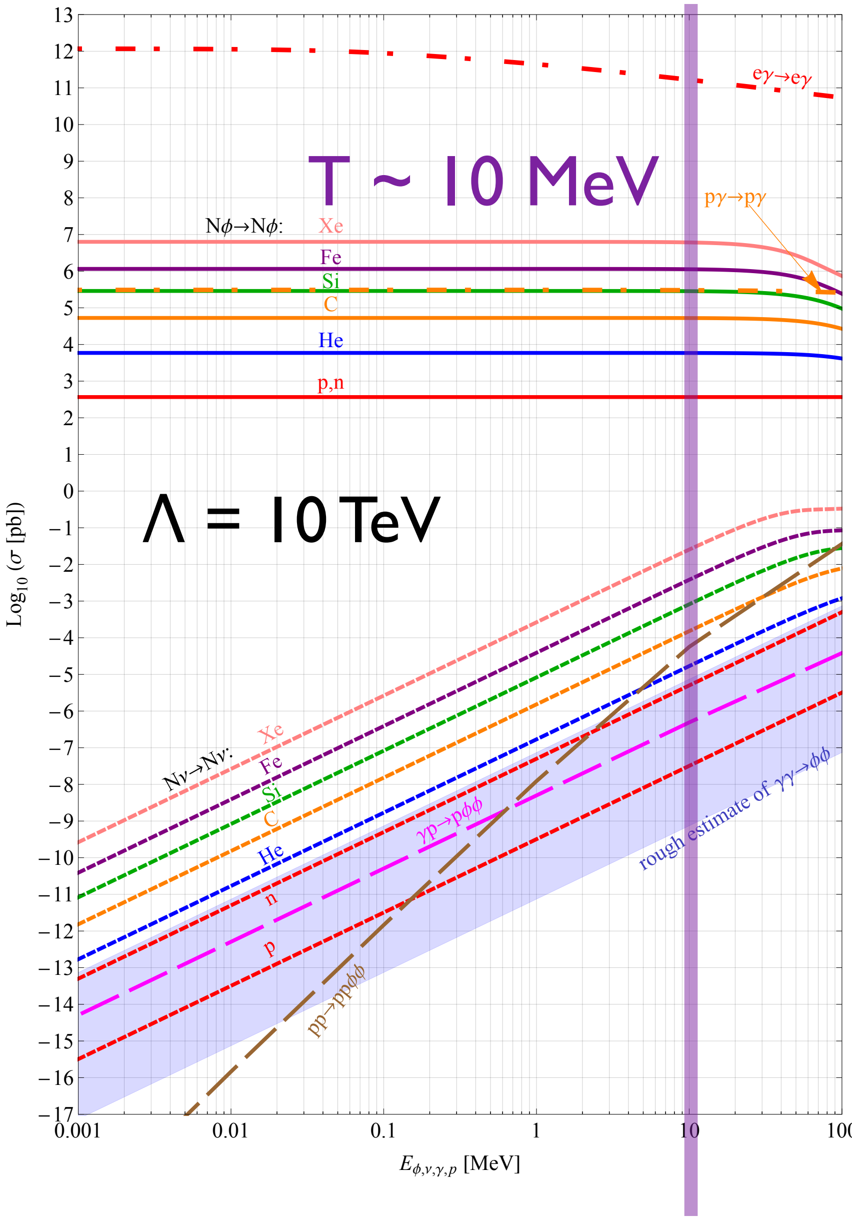
The Sun

Supernovae

Production of light particles can lead to rapid energy loss during supernova explosions. This can be constrained by measuring the duration of the SN1987 neutrino burst.



$$\frac{\bar{q}q\phi\phi^*}{\Lambda}$$



Our ϕ particles interact much more strongly than neutrinos at low energies → completely trapped in SN core!

$$\boxed{\Lambda \lesssim 10^6\ \mathrm{TeV}}$$

(for such large Λ we may not even produce the ϕs)

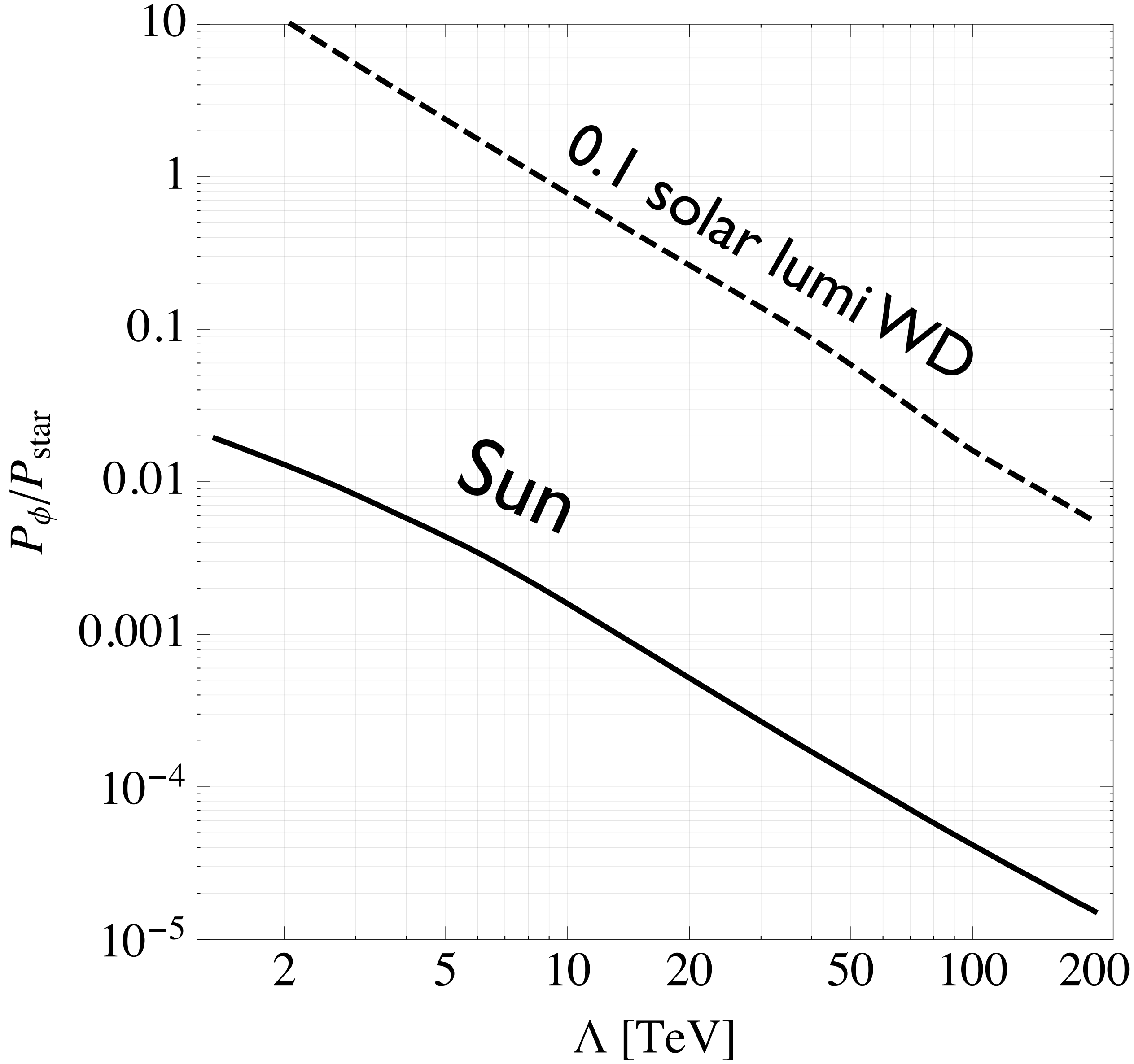
The Sun

- Dark mediators ϕ can be produced in the sun, dominantly by the process N γ → N ϕ ϕ, as long as $m_\phi \lesssim T_{core} \sim 1$ keV.
  $\sigma_{N\gamma \to N\phi\phi}, T(R), \rho(R) \Rrightarrow$ ϕ creation rate as function of R
- Production is dominated by the core, > 90% is within 0.2 R_{sun}.
- The ϕ cannot be destroyed in the stellar medium but diffuses outwards, staying in thermal contact with the stellar medium through the scattering process N ϕ → N ϕ.
- At some radius, the ϕ mean free path > distance to surface. ϕ escapes with the temperature at that radius, T_{escape}.
- At equilibrium, ϕ escape rate = total ϕ production rate
- This gives power of ϕ emission to be $P_\phi \approx \frac{3}{2} T_\phi^{\mathrm{escape}} \mathcal{R}_\phi^{\mathrm{create}}$

All cross sections evaluated in MadGraph

The Sun

Power output of ϕ emission as a fraction of total star luminosity



Requiring this to be smaller than neutrino emission (2%) sets constraint

$\Lambda \gtrsim 3$ TeV

The Sun

- A stronger constraint can be derived by requiring ϕ to give a subdominant contribution to radiative energy transfer within the Sun.
- This requires a crude estimate of the ϕ equilibrium number density.

$$\frac{dN_\phi}{dt} = \mathcal{R}_\phi^{\rm create} - \frac{N_\phi}{t_\phi^{\rm escape}} = 0$$

- Compare radiative heat flux of ϕs to photons:

$$\frac{F_\phi}{F_\gamma} \sim \frac{n_\phi L_\phi}{n_\gamma L_\gamma}$$

- For this to be < 1%, require $\Lambda \gtrsim 10\,\mathrm{TeV}$

White Dwarf Cooling

- Calculation of ϕ emission in WD proceeds identically to the sun, but WD cooling is constrained *statistically* by the relative abundances of WD with different brightness in the sky. Do we have to model a whole population of WD?

- Luckily, WD population is very homogenous with masses strongly peaked around 0.5-0.7 solar masses.
  We can study one representative benchmark dwarf.

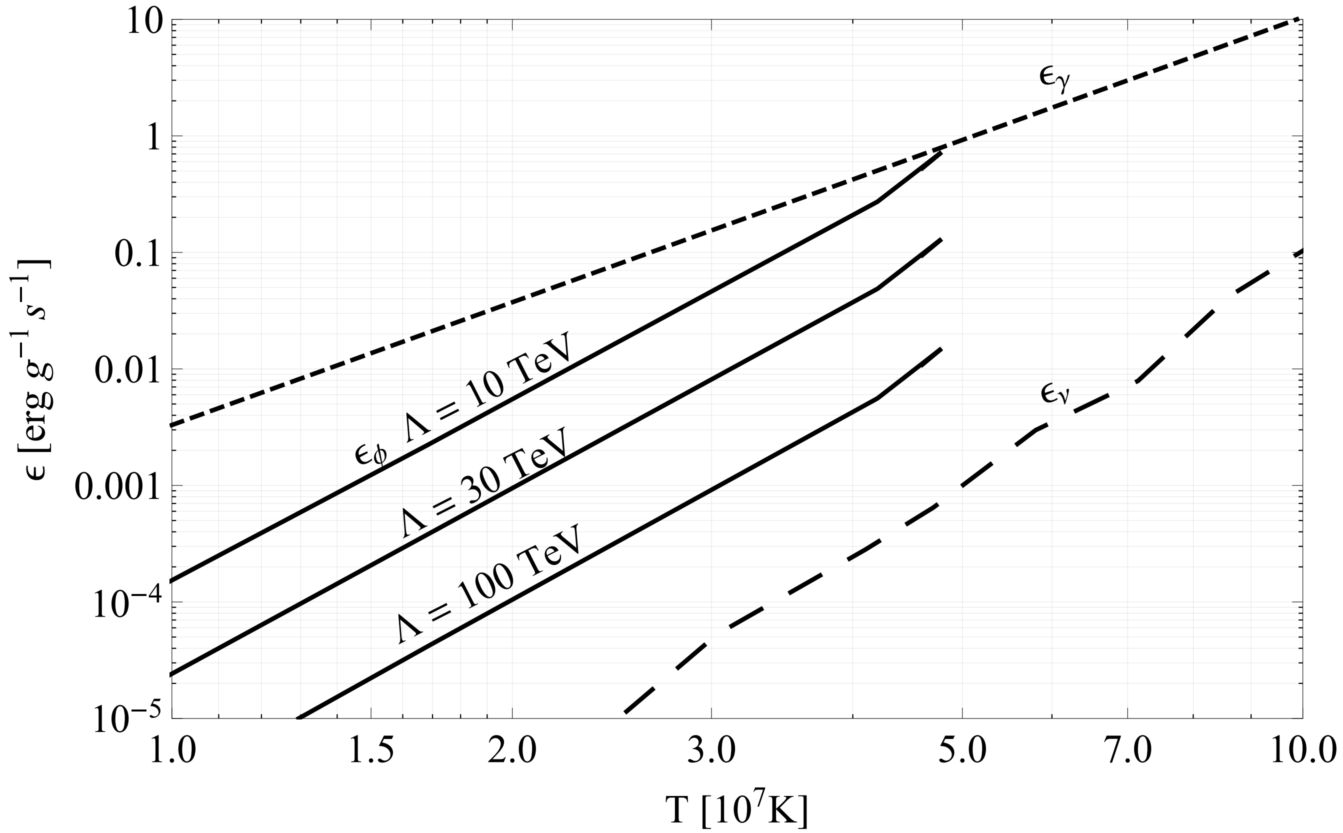
Thank you!!

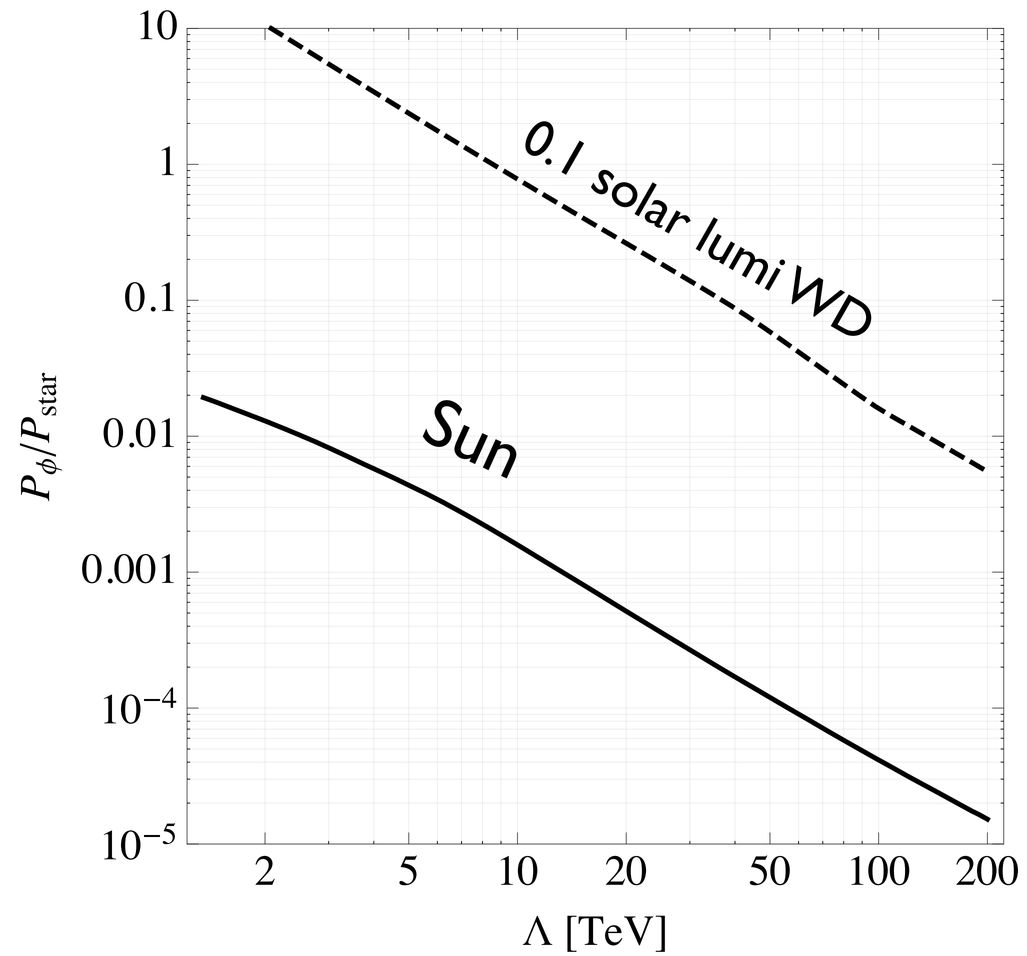
- Max Katz (graduate student of Michael Zingale @ SB) helped us by simulating the evolution of a sun-like star to a typical 0.5 - 0.6 solar mass white darf using the MESA stellar evolution code (stellar astrophysics "gold standard").

- This gave us the radial stellar profiles we need to repeat the solar calculation of ϕ emission.

White Dwarf Cooling

- ϕ emissivities in benchmark dwarf as it cools from 0.1 to 0.0001 solar luminosities:

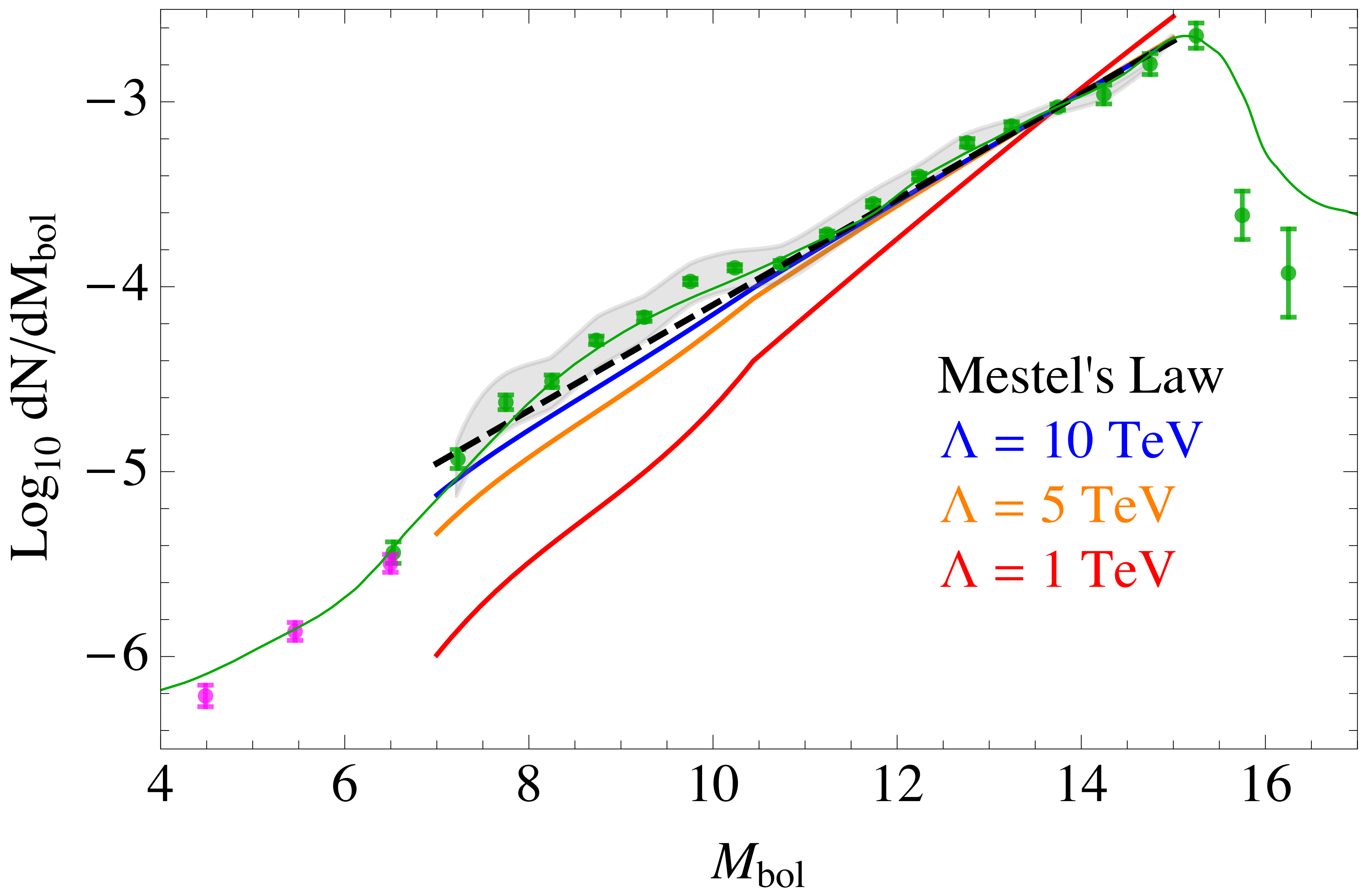




- This allows us to compute approximate White Dwarf Luminosity Function:

$$\log_{10}\left[\frac{dN}{dM_{\rm bol}}\right] = \mathrm{C} + \frac{2}{7}M_{\rm bol} + \log_{10}\left[\frac{\epsilon_\gamma}{\epsilon_\gamma + \epsilon_\nu + \epsilon_\phi}\right]$$

White Dwarf Cooling



Sensitivity of Mestel's Law implies bound $\Lambda \gtrsim 10\,\mathrm{TeV}$

Neutron Star Cooling

- Neutron star cooling is constrained by ~20 observed NS with known age and surface temperature, *but each with unknown mass.*

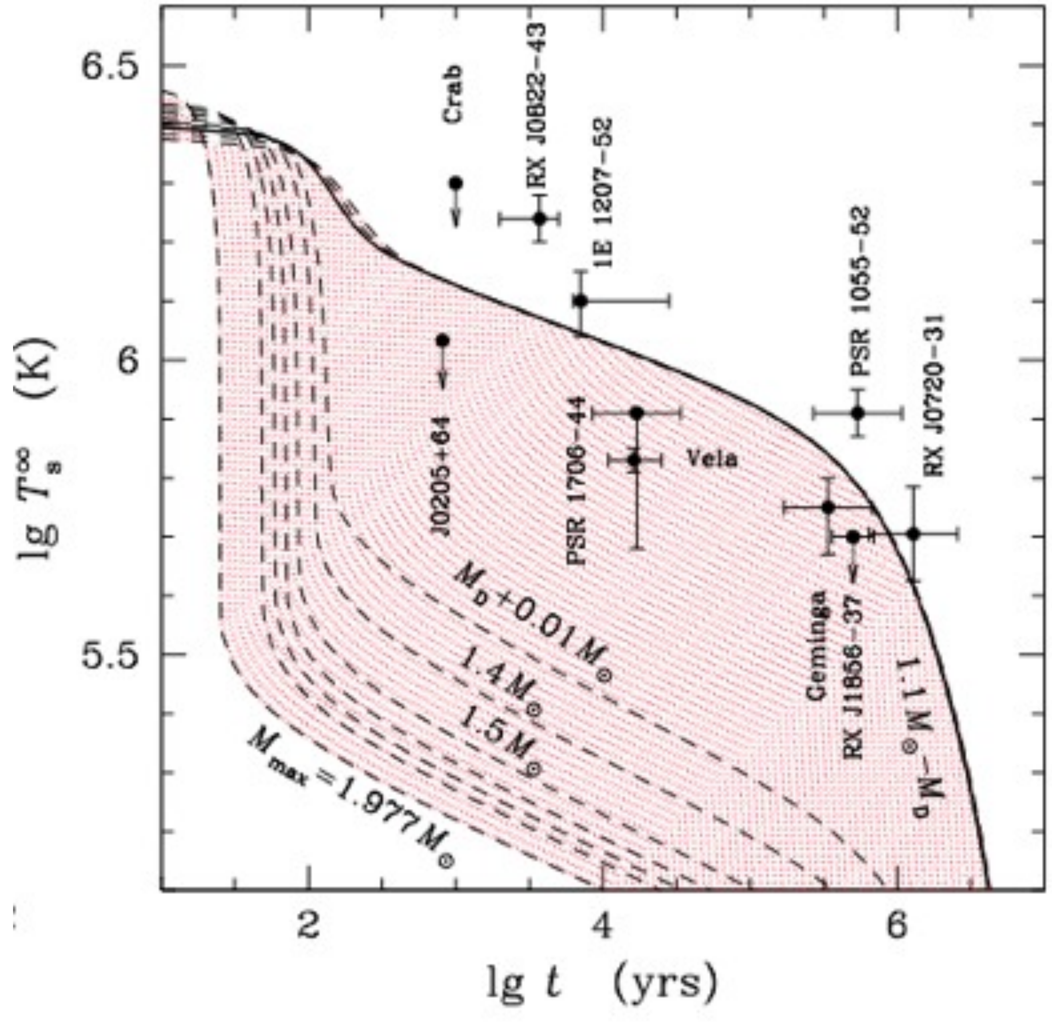
- Each equation of state fixes neutron star properties and, for a given mass, fixes the cooling curve T(t).

  Assume nucleonic matter. Demorest et al. 1010.5788

- The *range* of allowed cooling curves has to include the individual NS observations.

- NS are powerful ϕ-factories, and we have to ensure that ϕ emission does not alter the standard cooling curves by too much.

Yakovlev, Pethick, astro-ph/0402143



Neutron Star Cooling

- To bound the space of allowed cooling curves, compute ϕ emission for two benchmark neutron stars:

$M/M_{\rm sun}$	R (km)	$R_{\rm core}$ (km)	ρ_c/ρ_0
1.1	13	11	2
2.0	11	10	10

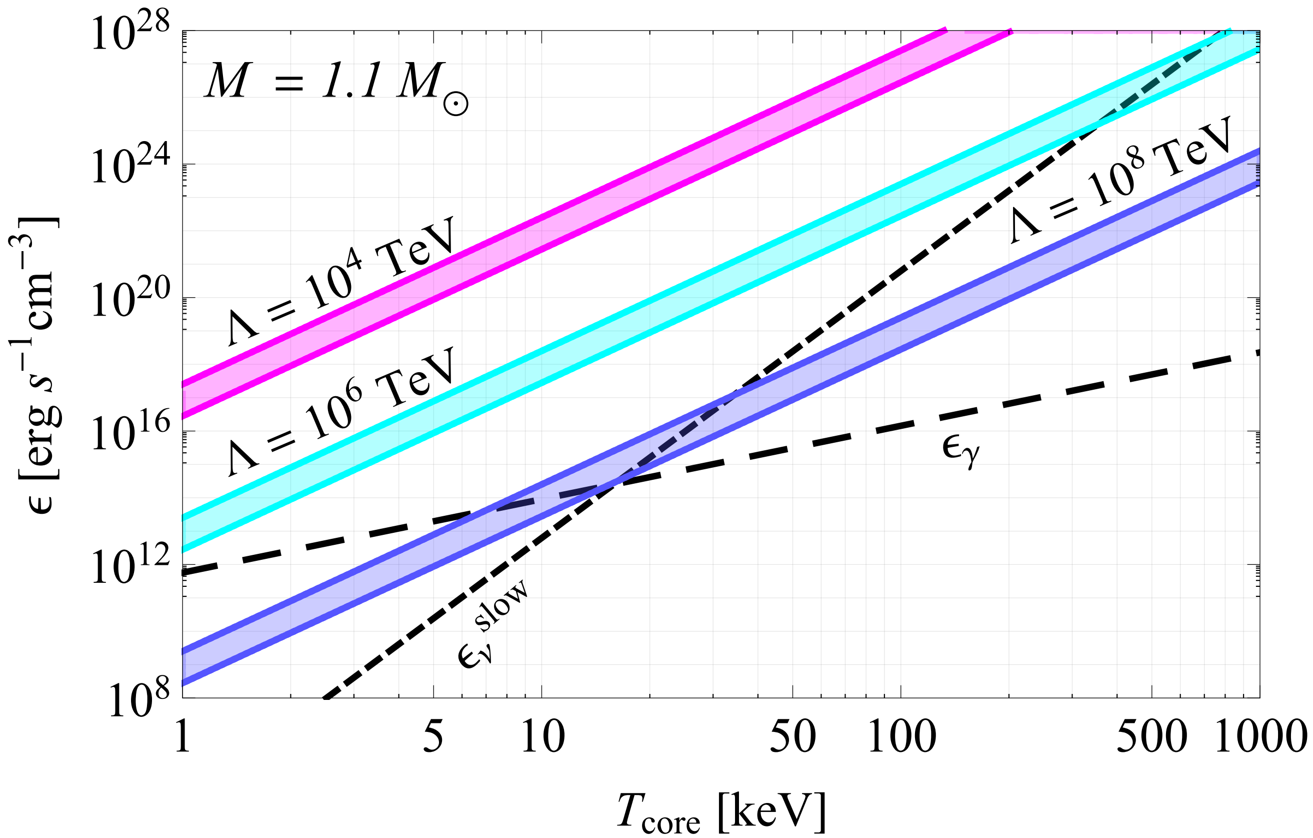
- Model NS as sphere of constant temperature and density.
- NS Core is degenerate: take Pauli Blocking into account when estimating production cross section for $n\, n \to n\, n\, \phi\, \phi$.
- Constraints are very strong. For the relevant Λ values, ϕ is *free-streaming!* Also, there is no annihilation from $\phi\phi \to \gamma\gamma$.
- Again we compute an approximate cooling curve:

$$\frac{dT_{\rm core}}{dt} = -\frac{\epsilon_\nu + \epsilon_\gamma + \epsilon_\phi}{c_V}$$

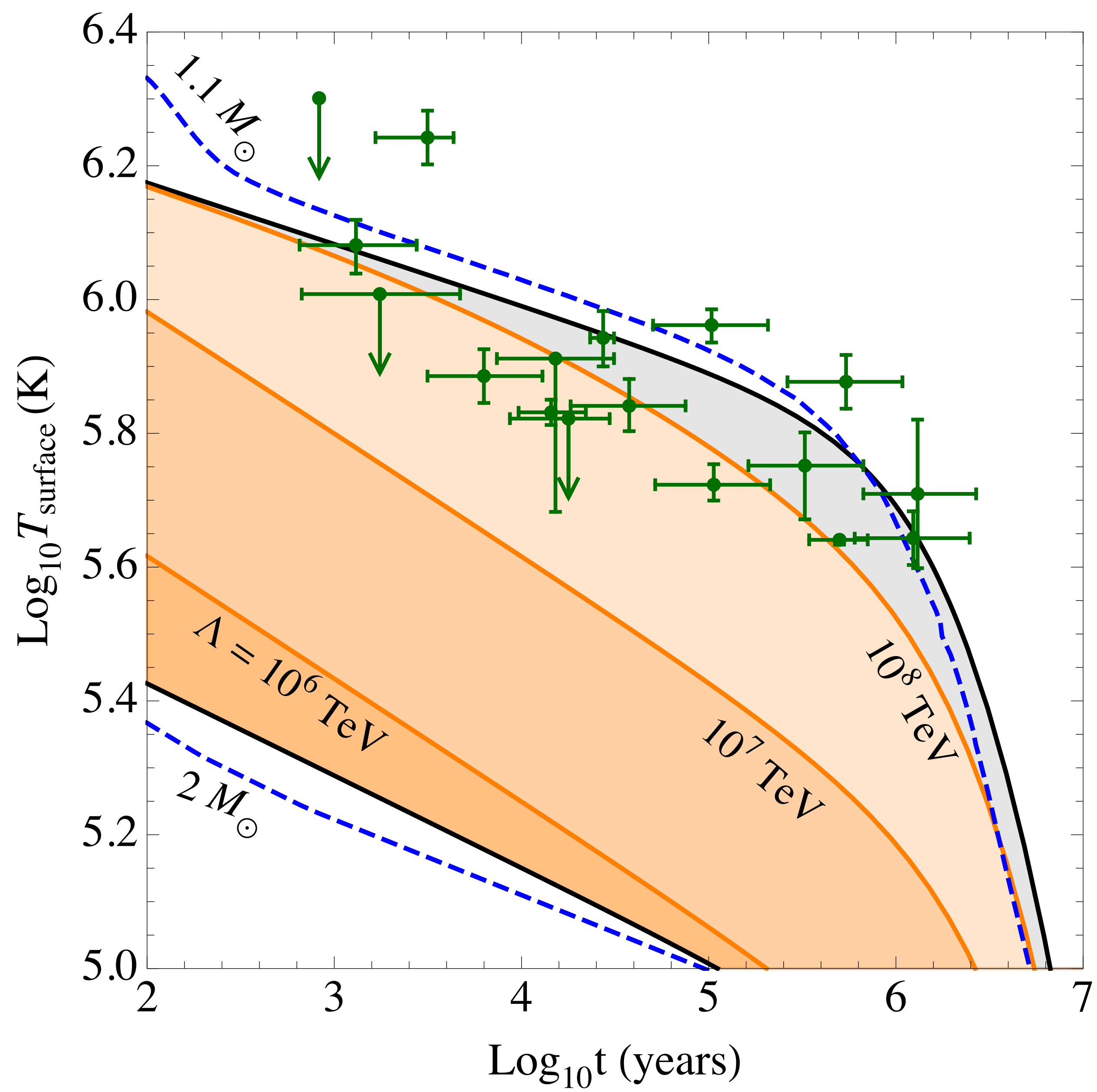
Kouvaris, 0708.2362

Neutron Star Cooling

ϕ emissivity in light NS



Cooling Curves vs observations



The standard cooling curves are extremely modified unless

$\Lambda \gtrsim 10^8$ TeV (!!)

(Allowing for uncertainty due to mantle properties and NS core superconductivity)

Interpretation

Constraint Summary

Avoiding ϕ-overclosure	Heaviest stable ϕ must have $m_\phi \lesssim$ eV
$N_{\rm eff}$ during BBN	At most two real light scalars: $n_\phi \leq 2$
LHC direct searches	$\Lambda_{\rm eff} = \left(\sum_{i \geq j} \Lambda_{ij}^{-2}\right)^{-2} > 2\,\mathrm{TeV}$.
Solar Heat Transfer	$\Lambda_{ij} \gtrsim 10\,\mathrm{TeV}$ if $m_{\phi_{i,j}} \lesssim$ keV
White Dwarf Cooling	$\Lambda_{ij} \gtrsim 10\,\mathrm{TeV}$ if $m_{\phi_{i,j}} \lesssim$ keV
Neutron Star Cooling	$\Lambda_{ij} \gtrsim 10^8\,\mathrm{TeV}$ if $m_{\phi_{i,j}} \lesssim 100\,\mathrm{keV}$
Supernovae	$\Lambda_{ij} \lesssim 10^6\,\mathrm{TeV}$ if $m_{\phi_{i,j}} \lesssim 10\,\mathrm{MeV}$

$n_\phi = 1$ is "completely" excluded by neutron star cooling.

Very strong result.

$$\frac{1}{\Lambda_{ij}} \bar{q}\, q\, \phi_i \phi_j^*$$

Evading Constraints

Can easily imagine an $n_\phi = 2$ scenario that evades all constraints while giving strong 2→3 direct detection signal:

$$\mathcal{L}_{\rm DM} \supset \bar{q}q\left(\frac{1}{\Lambda_{HH}}\phi_H\phi_H + \frac{1}{\Lambda_{LL}}\phi_L\phi_L + \frac{1}{\Lambda_{HL}}\phi_H\phi_L\right)$$
$$+\, \overline{\chi^c}\chi\left(y_\chi^H\phi_H + y_\chi^L\phi_L\right) + h.c.$$
$$+\, \lambda\phi_H\phi_L^3$$

$m_{\phi H}$ = MeV $m_{\phi L}$ = eV

ϕ_H decays to ϕ_L

NS, WD, solar bounds apply to Λ_{LL}. SN bound applies to Λ_{LH}, Λ_{HH}.

(Λ_{LL} can avoid SN bound by being very large)

Λ_{LH} induces Λ_{LL}, so a weaker NS constraint still applies: $\Lambda_{LH} \gtrsim 10$ TeV

Λ_{LH} operator gives identical direct detection as n_ϕ = 1 model!

Conclusion

Conclusion

- SM could couple to dark matter candidate via force carriers which carry dark charge: a dark dark portal.

$$\frac{1}{\Lambda_{ij}}\bar{q}\,q\,\phi_i\phi_j^*$$

- This leads to unique direct detection signatures: existence proof of $2\rightarrow3$ nuclear scattering.
- We conduct first comprehensive study of bounds on light scalars coupled in this way.
    - $2\rightarrow3$ direct detection ruled out by neutron star cooling for one dark mediator. ($2\rightarrow2$ is fine, just make $m\phi \sim$ MeV)
    - $2\rightarrow3$ direct detection is viable for 2 dark mediators.