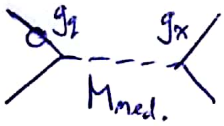
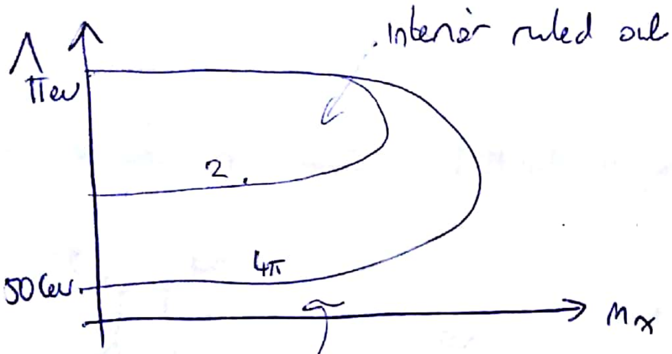
What does $\frac{1}{\Lambda^2}(\bar{\chi}\Gamma\chi)(\bar{q}\Gamma q)$ mean?

"UV complete"  $\longrightarrow \dfrac{g_q g_\chi}{M_{med}^2}(\bar{\chi}\Gamma\chi)(\bar{q}\Gamma q)$

$$\Lambda = \frac{M_{med}}{\sqrt{g_\chi g_q}}$$

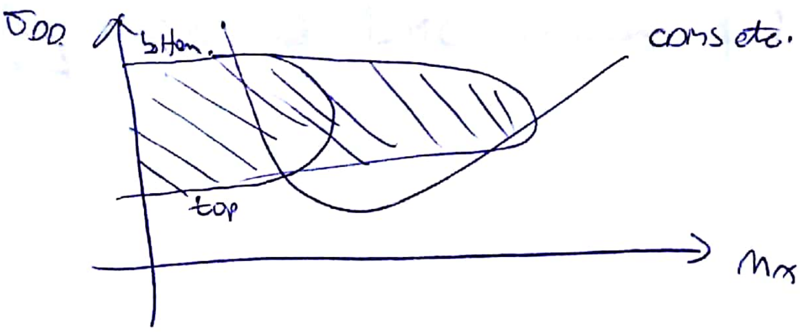
$M_{med} > \hat{s}^{1/2}$ and $g < 4\pi$. $\Rightarrow \Lambda \gtrsim \mathcal{O}(100)$ GeV

makes sense.



no bound since no events w/ $q^2 < M_{med}$.

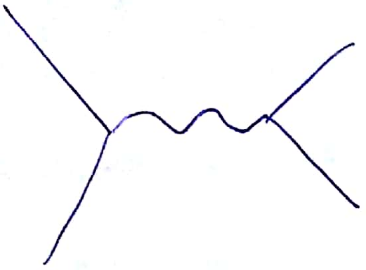
$\Downarrow$ compare to direct detection



LHC complementary to direct detection

Better to go to simplified model. UV completion? Naturalness? Anomalies? Consistent etc?

In simplified model also have mediator ← dijets, dileptons etc.



$$\text{mediator} \propto g_q^2$$

$$\text{mongid} \propto g_q^2 g_\chi^2.$$

to compete w/ direct detection need AV

⇒ anomalies

bounds on $\frac{M_{med}}{m_\chi}$

$$m_\chi \leq \frac{\sqrt{4\pi}}{g_\chi} M_{av}.$$

If mediator is scalar MFV arguments ⇒ largest couplings to b, t.

Many analyses at LHC, recasts of LEP etc.

Indirect detection "Cookbook" 1012.4515 Hooper

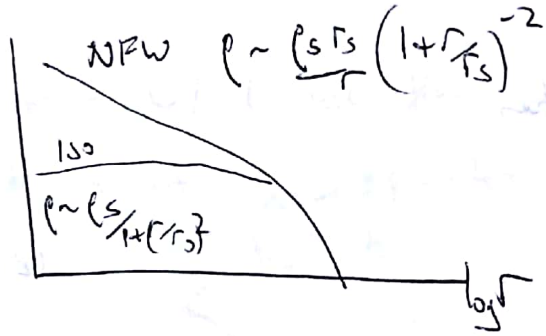
DM annihilates to SM, like at freeze out.

Look for annihilation products, high energy, antimatter

Rate $\sim \rho_\chi^2$. Look at places of high DM density, gravitational clumps

e.g. GC, Dwarf Galaxies, Inside stars ...

GC



Annihilation modes:

$p\bar{p}$, e^+e^- ...	Antimatter in cosmic rays. PAMELA, AMS, Fermi	Does not point, limited range. Diffusion-loss eqn.
$\nu\bar{\nu}$	Points. Hard to see. Icecube, Antares, super-K	
$\gamma\gamma$	Points. Line, low rate (loop) Fermi HESS	
SM SM $\hookrightarrow \gamma\gamma ... \gamma\gamma$ eg π^0, b, τ etc	Points. Continuum w/ edge, difficult bckgd. Fermi HESS	

Antiparticle prop. complicated: leaky box

Leave to Dan

PTO

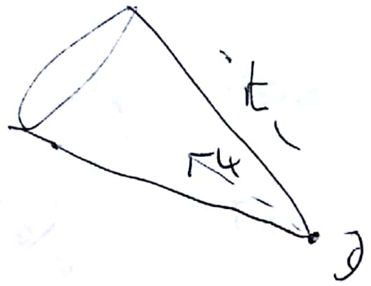
$$\frac{\partial f}{\partial t} - \nabla\left(K(E,\vec{x})\nabla f\right) - \frac{\partial}{\partial E}\left(b_{loss}(E,\vec{x})f + K_{EE}\frac{\partial f}{\partial E}\right) + \frac{\partial}{\partial z}\left(\mathrm{sign}(z)V_c f\right) = Q_s$$

$$Q_s = \left(\frac{\rho}{m}\right)^2 \sum_i \langle\sigma v_i\rangle \frac{dN_i}{dE}$$

Concentrate on γ signal $\Leftarrow$ GCE excess in Fermi

Hooper + Goodenough, 2009.

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \underset{\text{direction}}{\psi}) = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{los} dl' \, \frac{1}{2}\left(\frac{\rho(r(l,\psi))}{m_\chi}\right)^2 \sum_i \langle\sigma_i v\rangle \frac{dN_i}{dE_\gamma}$$



shape of γ spec. from ann. in channel i

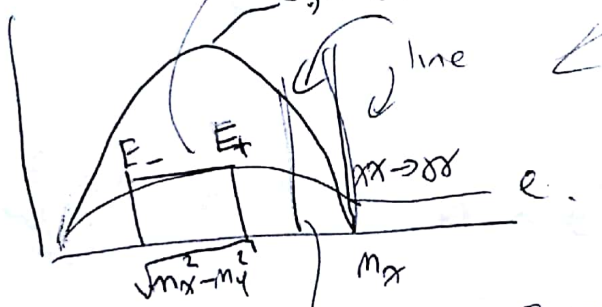
Note vol grows w/ l^2 but flux to us $\sim 1/l^2$ $\Rightarrow$ for const density each slice equally important

$\chi\chi \to \phi\phi \to 4\gamma$

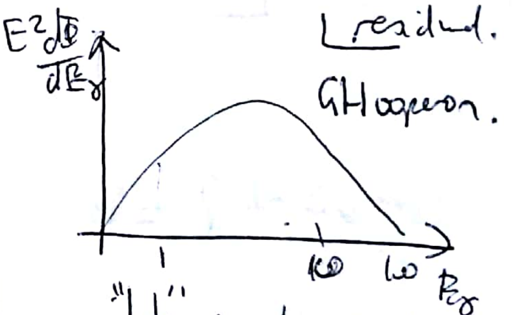
b, τ etc.

line

see 1012.4515.



$\chi\chi \to \gamma X$ $\quad E_\gamma = m_\chi\left(1 - \frac{m_X^2}{4m_\chi^2}\right)$



L residual.

GHooperon.

"fits" w/ b, τ at $50\,\text{GeV}$

$\sigma \sim 3\times10^{-26}\,\text{cm}^3\text{s}^{-1}$.

tension.

$$E_\pm = \frac{m_\chi}{2}\left(1 \pm \sqrt{1 - \frac{m_\phi^2}{m_\chi^2}}\right)$$

$$J\text{-factor}: \quad \frac{1}{\Delta\Omega}\int d\Omega \int_{los} dl\, \rho^2$$

Dwarf $10^{19-20}\,\text{GeV}^2\text{cm}^{-5}$

Andromeda $10^{20}\,\text{GeV}^2\text{cm}^{-5}$

M. Way $10^{22-25}\,\text{GeV}^2\text{cm}^{-5}$

but Dwarf has smallest bckgnd.

Capture

Cookbook 1312.6408 Gould.

$$\frac{dN}{dt} = \Gamma_{capt} - 2\Gamma_{ann} - \Gamma_{evap.} \quad (1)$$

evaporation: only relevant for $m_\chi \lesssim 4$ GeV.

$v \sim \sqrt{2T_\odot/m_\chi}$ $T_\odot \sim 1$ keV. if $v > v_{esc} \sim 130\,\text{km s}^{-1}$ then evaporation

$$\left[\; e^{-\frac{1}{2} m v_{esc}^2/T_\odot} \left(\frac{R_\odot}{V_{esc}} \frac{1}{\tau_\odot}\right)^{-1} \lesssim 1 \Rightarrow m \lesssim 4\text{ GeV} \;\right].$$

$\Gamma_{ann} \sim \frac{1}{2}\int_{sun} n^2 \langle \sigma v \rangle$. $n \sim e^{-m_\chi \varphi(r)/T}$ $\varphi = \int_0^r dr \frac{G_N M(r)}{r^2}.$

$\rho = \rho_{const.} \Rightarrow n = n_0 e^{-r^2/r_{DM}^2}$ $r_{DM} = \left(\frac{3T_\odot}{2\pi G_N \rho_\odot m_\chi}\right)^{1/2} \simeq 0.01 R_\odot \times \sqrt{\frac{100\text{ GeV}}{m_\chi}}$

DM confined to very small ball inside sun.

Point source.

Now can do integral. $\Gamma_{ann} = \frac{1}{2} \overbrace{\langle \sigma v \rangle \left(\frac{G_N m_\chi \rho_\odot}{3T_\odot}\right)^{3/2}}^{C_{ann}} \cdot N^2.$

Solve (1) (ignore evap.) $N = \frac{\Gamma_{capt}}{2}\tanh^2\left(\frac{t}{\tau}\right) \xrightarrow{t \gg \tau} \frac{\Gamma_{capt}}{2},$

$\tau = \frac{1}{(\Gamma_{capt} C_{ann})^{1/2}}.$

For Sun $t \gg \tau$, for Earth not.

In equilibrium. DM annihilates away as fast as it arrives

What is Γ_{capt}? DM falls in scatters to < local vesc.

Complicated.

DM speed in Sun frame ↓ effect of fall in ↓

$$\Gamma_{capt} = n_\chi \sum_i \sigma_i \int_0^{R_\odot} dr\, 4\pi r^2 n_i(r) \int_0^\infty dv\, 4\pi v^2 f_\odot(v) \frac{v^2 + v_{esc}^2}{v} \times P_{cap}.$$

$$P_{cap} \sim \frac{\Delta E_{max} - \Delta E_{min}}{\Delta E_{max}}$$, max min energy loss for capture.

Favours low speed tail of MB.

$$\Gamma_{capt} \simeq \frac{6 \times 10^{26}}{s} \left(\frac{\rho_\chi}{0.3\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{270\,\mathrm{km\,s^{-1}}}{v_0}\right)^3 \frac{\sigma_{SD} + 1200\,\sigma_{SI}}{pb.}$$

σ_{SD} (off H, little N) most important.

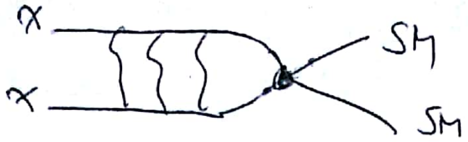
Only ν can get out.

Need $\frac{dB}{dE}$. Decay in flight eg τ better than decay when stopped eg μ.

Oscillations in Sun, and on way to Earth.

Pointing ($0.01 R_\odot$) suppresses bckgrd. Icecube, Super-K etc.

Sommerfeld



If there is a long range force, can affect annihilation eg relic, indirect.

Analogy to gravitational case $\quad \sigma \neq \pi R_E^2 \quad$ but $\pi R_E^2 \left(1 + \frac{V_{esc}^2}{V^2}\right)$

$\uparrow$ speed at ∞.

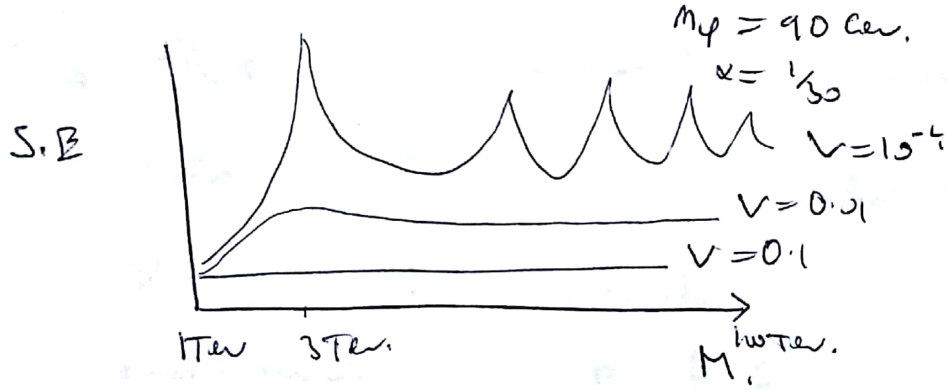
Comes from slow speed. Resum ladders $\Longleftrightarrow$ solve NR Schroedinger eqn.

In c.o.m frame want to know $|\psi(0)|^2 \leftarrow$ prob. to annihilate.

$$-\frac{1}{2\mu} \nabla^2 \psi + V(r)\psi = E\psi.$$

$$V(r) - \frac{\alpha}{r} e^{-m_\phi r}.$$

radial S.E $\quad \frac{d^2 u}{dr^2} - m_\chi V(r) u = -(m_\chi E) u.$

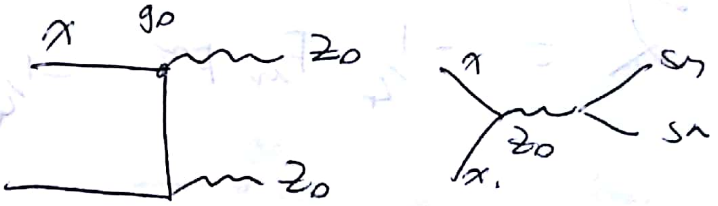


Beyond WIMPs

DM has more than weak interactions, new gauge forces/mediators,

DM sits in a larger dark sector (already hinted at w/ coannihilation; DM etc.).

New annihilation processes eg



g_D, M_{med} ← new parameters.

thermal
^ m_χ below 1 GeV (Lee-Weinberg).

(Thermal hot DM bound of 1 keV)

Idea of <u>portals</u>

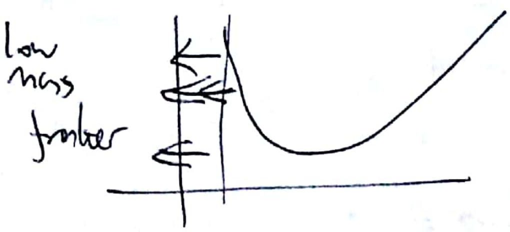
eg $U(1)_D$: $\varepsilon F'_{\mu\nu} F^{\mu\nu}$ ← really $B^{\mu\nu}$. ← (PTO)

scalar : $|\varphi_D|^2 |H|^2$ $\varphi_D |H|^2$

ν : $L H N_D$.

axion (pseudoscalar) : $a F \tilde{F}$

New objects to search for! New dynamics. New mass range.



Kinetic mixing

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\kappa}{2} F_{\mu\nu} F'^{\mu\nu} - \frac{m^2}{2} A'_\mu A'^\mu + A^\mu \underbrace{\bar{\psi}\gamma^\mu\psi}_{J^\mu_\psi} + A'_\mu \underbrace{\bar{\chi}\gamma^\mu\chi}_{J^\mu_\chi}$$

Diagonalize kinetic terms.

$$A_\mu \to A_\mu - \kappa A'_\mu$$

SM picks up a coupling to A', DM does not pick up millicharge.

Maybe dark forces are strong? → Composite DM

DM Form factors.

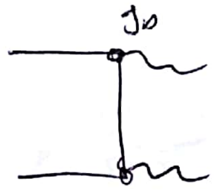
~~Atomic~~ 3→2 annihilation.

DM – DM self interactions.

Concept of Secluded DM

$m_\chi > m_{A'}$

$\uparrow$ unstable thru kinetic mixing



decouples direct detection from relic

Light DM + CMB (Slatyer).

Annihilation of DM @ CMB can distort CMB.

Energy deposition rate $\sim n^2 \langle\sigma v\rangle|_{T\sim eV} \times m \sim \frac{\langle\sigma v\rangle|_{T\sim eV}}{m}$.

Strong bound for $m_\chi \leq 10$ GeV and s-wave.

—

Exciting new direct detection technologies can go after light DM.

Other ways to probe – long-lived states?

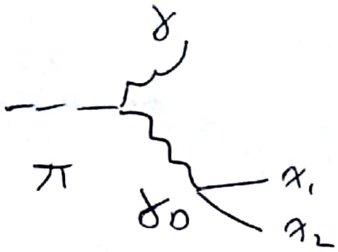
– beam dump.

– rare meson decays

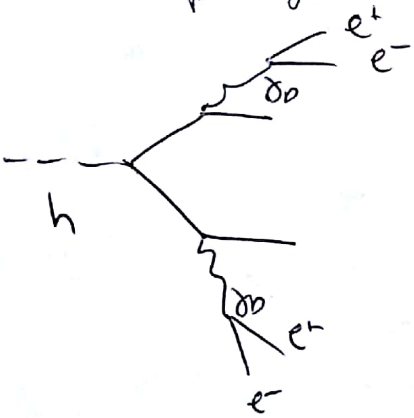
– bremsstrahlung

Beam

rare decays



LHC - lepton jets



Make DM + obs. (ν ND)

"direct detection" in boosted regime.

Direct detection

$$E_{NR} = \frac{q^2}{2m_N} \lesssim \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim 190\,\text{eV} \left(\frac{m_\chi}{500\,\text{MeV}}\right)^2 \left(\frac{16\,\text{GeV}}{m_N}\right)$$

$$E_e \lesssim \tfrac{1}{2} m_\chi v_\chi^2 \lesssim 3\,\text{eV} \left(\frac{m_\chi}{\text{MeV}}\right)$$

← cf e b.e. ≃ 1eV.

New technologies

SENSEI, Superfluid He, Colour centres, ...

Accelerator probes for A' etc.