Dark Matter Part II

The WIMP Hypothesis

Guy Moore, TU Darmstadt

- What dark matter is *not*
- A reasonable hypothesis: $\mathrm{W_{eakly}I_{nteracting}M_{assive}P_{article}s}$
- How to look for $\mathrm{W_{eakly}I_{nteracting}M_{assive}P_{article}s}$
- How far are we and where do we go from here?

Dark matter is Something New

Gravit. clumps: must be "Degrees of Freedom" unlike Dark Energy

Stable particles of the Standard Model:

$\gamma,\ \nu_e,\ e^{\mp},\ p^{\pm}$; certain larger nuclei+weakly bound states

Nothing else. Period.

How can I say that so confidently? Review the model!

Standard Model: organizing by spin

Best way to think of SM is by spin: 1, then $\frac{1}{2}$, then 0.

Spin 1: "gauge group" (EM-like forces)

$$\mathrm{SU}_c(3) \times \mathrm{SU}_w(2) \times \mathrm{U}_h(1) \simeq (8 \text{ gluons}) + (Z^0, W^\pm) + (\gamma)$$

Really Z^0, γ *mix*, but I will ignore that

These fields establish the *key interactions* (strong, weak, E&M) and decide what format other fields must fit into

Spin-1/2 Matter

Spin-1		$SU_c(3)$	$SU_w(2)$	$U_h(1)$	
Spin-$\frac{1}{2}$	Q	yes	yes	$1/6$	
	D	yes	no	$-1/3$	*Quarks*
	U	yes	no	$2/3$	
	L	no	yes	$-1/2$	
	E	no	no	-1	*Leptons*
	N	no	no	0	

Note: each fermion in triplicate (3 "Generations")

3 quarks "glue" together into a *Baryon*

N may not exist (another story for another day)

Spin-0 Matter

		$SU_c(3)$	$SU_w(2)$	$U_h(1)$	
Spin-1					
Spin-$\frac{1}{2}$	Q	yes	yes	$1/6$	
	D	yes	no	$-1/3$	*Quarks*
	U	yes	no	$2/3$	
	L	no	yes	$-1/2$	
	E	no	no	-1	*Leptons*
	N	no	no	0	
Spin-0	ϕ	no	yes	$1/2$	

ϕ couples to two spin-$1/2$ with SU(2) "yes/no" and $\Delta Q_{U(1)} = \pm 1/2$ ($\phi \bar{Q} D$, $\phi^* \bar{Q} U$, $\phi \bar{L} E$, $\phi^* \bar{L} N$)

Higgs takes Vacuum Value (Higgs Mechanism)

Spin-1		$SU_c(3)$	$SU_w(2)$	$U_h(1)$	
Spin-$\frac{1}{2}$	u,d	yes	yes	$1/6$	
	D	yes	no	$-1/3$	*Quarks*
	U	yes	no	$2/3$	
	n,e	no	yes	$-1/2$	
	E	no	no	-1	*Leptons*
	N	no	no	0	
Spin-0	$\phi^+\phi^0$	no	yes	$1/2$	

$uU \to (u, c, t)$; $dD \to (d, s, b)$; $eE \to e, \mu, \tau$; $nN \to \nu_e \nu_\mu \nu_\tau$

Either ϕ, N coupling super-small or N super-heavy Seesaw Mechanism

What are particles?

Weak/EM coupled: $\gamma, \quad \nu_e\,\nu_\mu\,\nu_\tau \quad e\,\mu\,\tau\,; \quad H,\ Z,\ W^\pm$

Strongly coupled: $g\,, \quad (uct)(dsb) \Rightarrow$ "Mesons," "Baryons"

Conserved quantities:

$$(E,\vec{P}),\ B,\ L,\ Q_e\,; \quad \text{Spin}$$

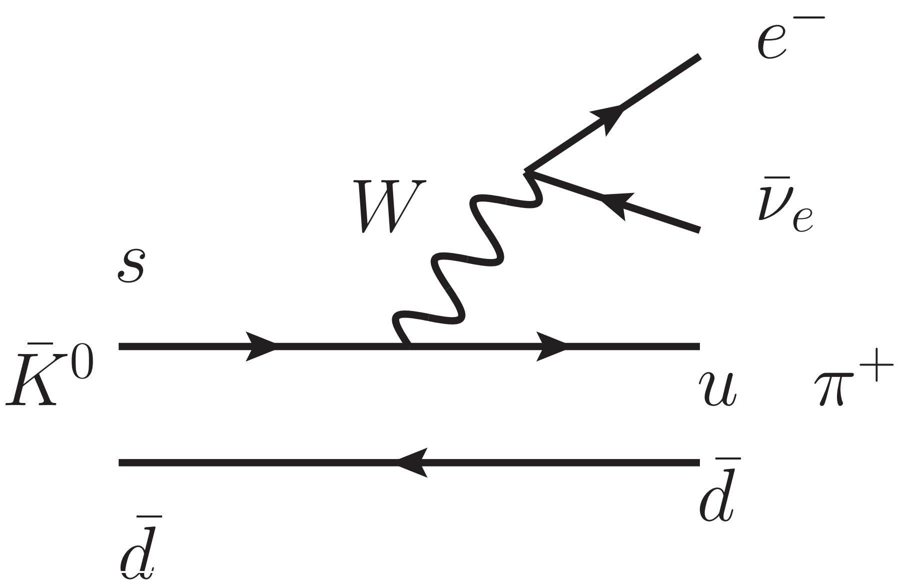
Guaranteed to be stable: lightest particle with each:

$$(E,\vec{P}) \to \gamma \quad L,\text{Spin} \to \nu_e \quad Q_e \to e^\mp \quad B \to p^\pm$$

Every other particle/bound state has a route to decay

Only conserved numbers ensure stability

Example: decay of $\bar{K}^0$ meson $= s\bar{d}$:



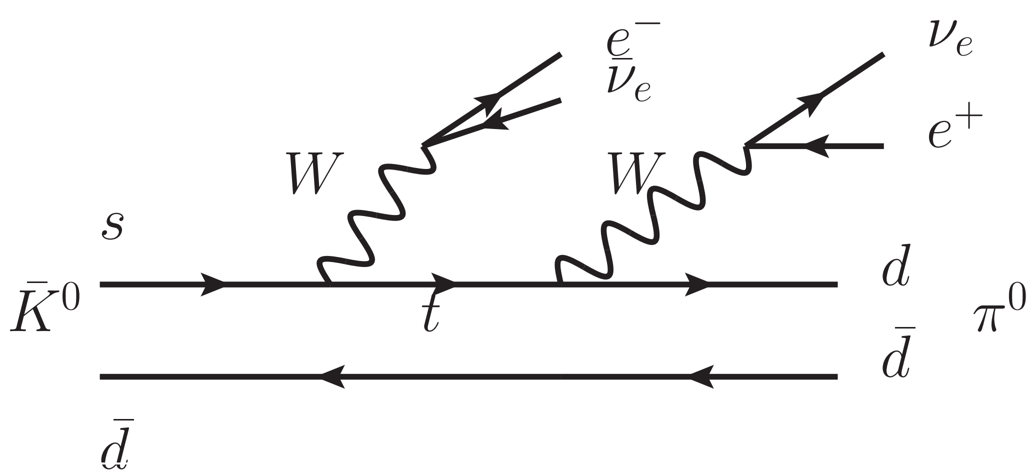
$$\begin{bmatrix} V_{ud} & \underline{V_{us}} & V_{ub} \\ V_{cd} & V_{cs} & V_{ts} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Decay through $W s \bar{u}$ vertex $\propto V_{us}$

W-boson is virtual off-shell particle

I can forbid that decay..

To prevent previous decay, set $V_{us} = 0$



$$\begin{bmatrix} V_{ud} & \mathbf{0} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Now I need to go through virtual W, t, W, using V_{ts} and V_{td}

Decay may take much longer. But it will still happen!

What if I make that zero too?

Make $V_{ts} = 0$ to forbid that decay.
Unitary matrix: requires
$V_{cd} = 0 = V_{cb}$

$$\begin{bmatrix} V_{ud} & 0 & V_{ub} \\ 0 & V_{cs} & 0 \\ V_{td} & 0 & V_{tb} \end{bmatrix}$$

$\bar{K}^0$ is now stable!
But now N_{c+s} ("2-gen. baryon number") is also conserved.
And $\bar{K}^0$ is lightest particle with this conserved number.

Lesson: particles stable only only due to conservation laws
SM: only $\gamma, \nu_1, e^\pm, p^\pm$, certain nuclei + QED bound states

What Dark Matter is NOT

- SM particle (e^-, p^+ accounted for; ν too light)
- Something strongly-interacting (sticks in nuclei)
- Something charged more properly, Q/M must be exceedingly small
- Something with $v \sim c$ at redshift $z < 10000$
- Something with large/modest interactions with
  - Ordinary Matter (we would see it/capture it)
  - Itself (it would sink into galaxies...)

Excludes *most* possibilities (SIMP, CHAMP,...)

What's Left

"Particle-Like" Dark Matter

- Mass $\mathrm{KeV} < M \lesssim 10^{16}\mathrm{GeV}$ (?)
- Coupling $\leq$ experiment but $\geq$ gravitational strength

or "Field-like" Dark Matter

- Nonthermal prod: large occupancy in small-p modes
- Weak self-interactions, int. with matter
- mass $M > 10^{-22}\mathrm{eV}$ (or so)

Primordial black holes?

BH exist. Could they be DM? All mass ranges excluded:

- $M > 10^{31}$ kg: accretion distorts microwave sky arXiv:0912.5297
- 20^{24} kg $< M < 10^{31}$ kg: microlensing EROS/MACHO/OGLE arXiv:1901.07120
- 10^{19} kg $< M < 10^{24}$ kg: microlensing SUBARU arXiv:1701.02151
- $M < 10^{21}$ kg: captured in, eat neutron stars arXiv:1301.4984

Appears to be excluded observationally not without controversy

Simplest Example: Real Singlet Extension

		$SU_c(3)$	$SU_w(2)$	$U_h(1)$	
Spin-1					
Spin-$\frac{1}{2}$	u,d	yes	yes	$1/6$	
	D	yes	no	$-1/3$	*Quarks*
	U	yes	no	$2/3$	
	n,e	no	yes	$-1/2$	
	E	no	no	-1	*Leptons*
	N	no	no	0	
	$\phi^+ \phi^0$	no	yes	$1/2$	
Spin-0	s	no	no	0	

One added scalar, without charges. Burgess Pospelov ter Veldhuis

arXiv:hep-ph/0011335; Cline Scott Kainulainen Weniger 1306.4710

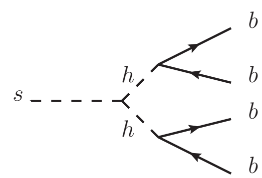
Possible Lagrangian terms

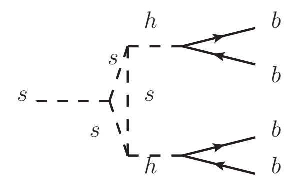
$$-\mathcal{L}_s = \frac{1}{2}\partial_\mu s \partial^\mu s + \frac{m_s^2}{2}s^2 + \frac{g}{3}s^3 + \frac{\lambda_s}{4}s^4 + g' s\phi^*\phi + \frac{\lambda_{hs}}{2}s^2\phi^*\phi$$

No interactions with spin-$\frac{1}{2}$ or gauge bosons possible.

If *red, s-odd* terms present, s particle unstable

$s \to hh_{\mathrm{off-shell}} \to b\bar{b}b\bar{b}$ etc





If terms absent: discrete Z_2 symmetry $s \to -s$.

If $m^2 < -\lambda_{hs}v^2/2$, Domain Wall Problem.

But $m^2 > -\lambda_{hs}v^2/2$ and Z_2 present: s stable!

Is s a good Dark Matter candidate?

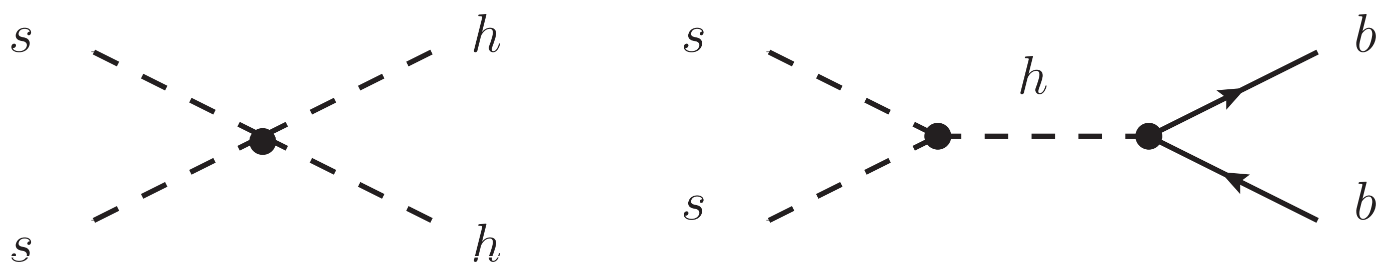
Would be Cold, Dark, and Matter. But need to check:

- Would the *right amount* of s occur?
- Would the s avoid attempts at *detection*,
  - ∗ Direct (laboratory)?
  - ∗ Indirect (astrophysical/cosmological observations)?

General strategy: stability? coldness? darkness? abundance? detection?

Abundance: Freeze-out, WIMP Miracle

At high T (early Universe), S made, destroyed in pairs



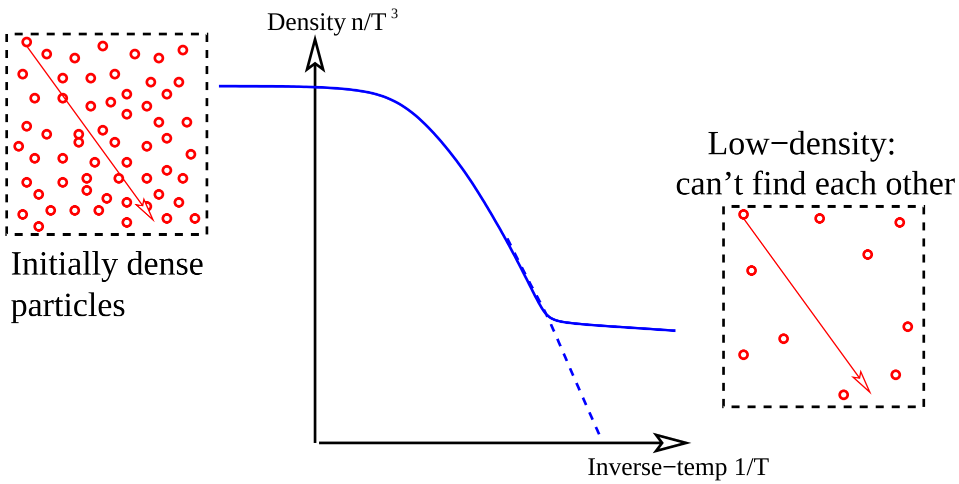
$ss \to hh$ or $ss \to h^* \to b\bar{b}$ or ...

Rate $\sim v\sigma\rho T \gg H \sim T^2/m_{\rm pl}$. Equilibrium population:

$$n_s = \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{\sqrt{m^2+p^2}T} - 1} \simeq \begin{cases} \frac{\zeta(3)T^3}{\pi^2} & T \gg m \\ \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T} & m \gg T \end{cases}$$

Freeze-out, WIMP miracle

As temperature falls, $n_s \to e^{-m/T}(mT)^{3/2}$. Density falls!



Population saturates when s can't find each other any more

Larger λ_{hs}: larger cross-section. Better at finding each other, lower density. Large density for Small coupling

Coincidence: $m \sim 100$ GeV and $\sigma \sim \frac{\pi\alpha_{\rm w}^2}{m^2}$ gives $\rho \sim \rho_{\rm CDM}$

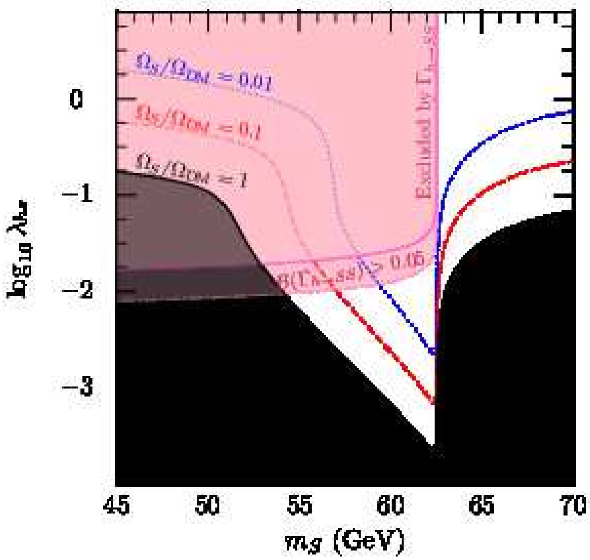
Annihilation really stops...?

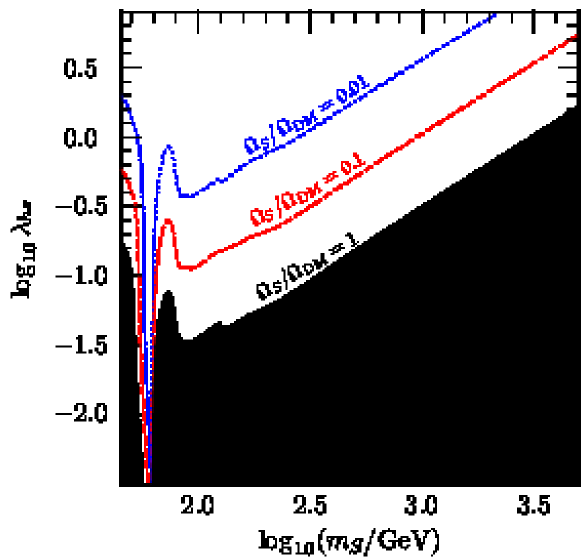
What's relevant is $v\sigma\,\rho\,t$.

- $v\sigma \to \mathrm{const}$ (for scalars. spin/model dependent)
- Time $t \sim 1/H \propto T^{-2}$ increases, but
- Density $\rho \sim a^{-3} \sim T^3$ falls faster.

Falling density more than compensates longer available time.
Annihilation rate really shuts off, remaining s survive

Freeze-out: Subtleties





Resonance near $m_s = \frac{m_h}{2}$

Cline et al arXiv:1306.4710

Subtleties which can occur in other theories:

- Another Z_2-odd particle has $m = m_{min} + \epsilon$ (Coannihilation)
- Attractive interactions $\Rightarrow$ nearly bound states (Sommerfeld enhancement or other α/v type corrections)

Freeze-out: Alternatives

Theorists are active. Many alternatives:

- DM too heavy to ever be in equilibrium (freeze-in, WIMPzilla)
- DM has conserved U(1) charge and is asymmetric
  Analogy to baryon, lepton numbers
  Maybe even connected to B, L?
- DM in "secluded sector" at very different T than visible
- Very light DM produced coherently (next lecture)
- And .. and .. and ..

Annihilation today?

Some structures now highly *overdense* in DM.
Annihilation might not be negligible.

$$ss \to h^* \to b\bar{b} \quad \text{or} \ \ldots \qquad \to \gamma + \ldots$$

Annihilation can make something we can see from Earth.
Stable particles: $e^{\pm}$, $p^{\pm}$, γ, ν.
γ, ν fly in straight lines. Only γ easy to detect

Look for DM annihilation from dense regions in γ-rays

The Hooperon

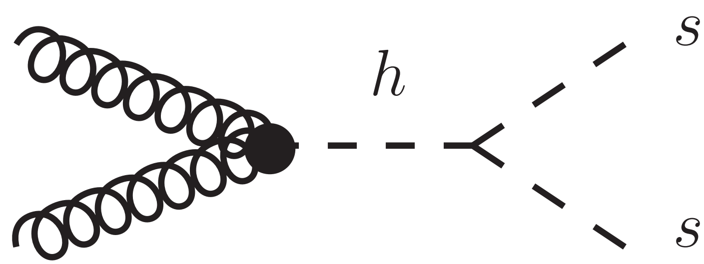
Modern instruments to look for cosmic γ rays:

- Fermi-LAT: arXiv:0902.1089 space-based gamma ray observer, large-area large-angle, up to $\gtrsim 100$ GeV
- HESS: arXiv:astro-ph/0607333 ground based, very large effective area but narrow-angle, *minimum* energy ~ 100 GeV.

Observations of galactic center and dwarf galaxies suggest γ excess above astrophysical background See for instance arXiv:1402.6703
Christened *"The Hooperon"* after Dan Hooper
Interpretation disputed. Astrophysical origin possible?

Direct production?

Turn annihilation diagram around: DM pair production!



For our case: ss are invisible. No signature

"Missing Higgs boson" signature if $m_s < m_h/2$

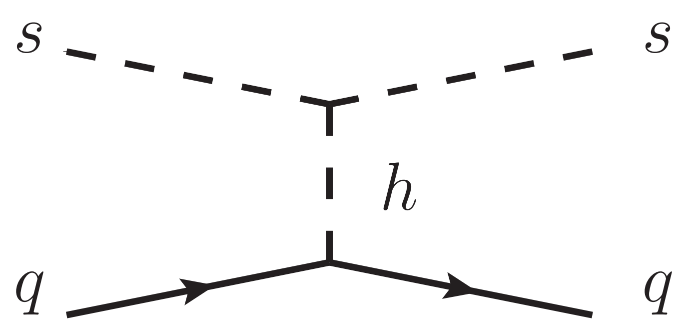
Other models: production of higher-mass new particles which decay to DM + SM particles

Signature: multiple particle production, missing energy

the search is on. No evidence to date.

Scattering with Matter

Turn annih. diagram
on its side:
Now it's scattering!



Scattering $\rightarrow$ "kick" to nucleus. Detectable (?!)

s-boson can scatter with q, and therefore with nucleus.
Coupling ssh is λ_{sh}. What about hpp or hnn?

Higgs coupling to p or n

The Higgs boson gives $W, Z, udscbt, e\mu\tau$ their masses.

Higgs field couples "according to mass"

Careful: coupling to proton is

$$h p \bar{p} \text{ vertex } = \frac{1}{v} \sum_i \frac{d m_p}{d \ln m_{q_i}}$$

Proton $= uud$ bound state. Depends on m_u, m_d.

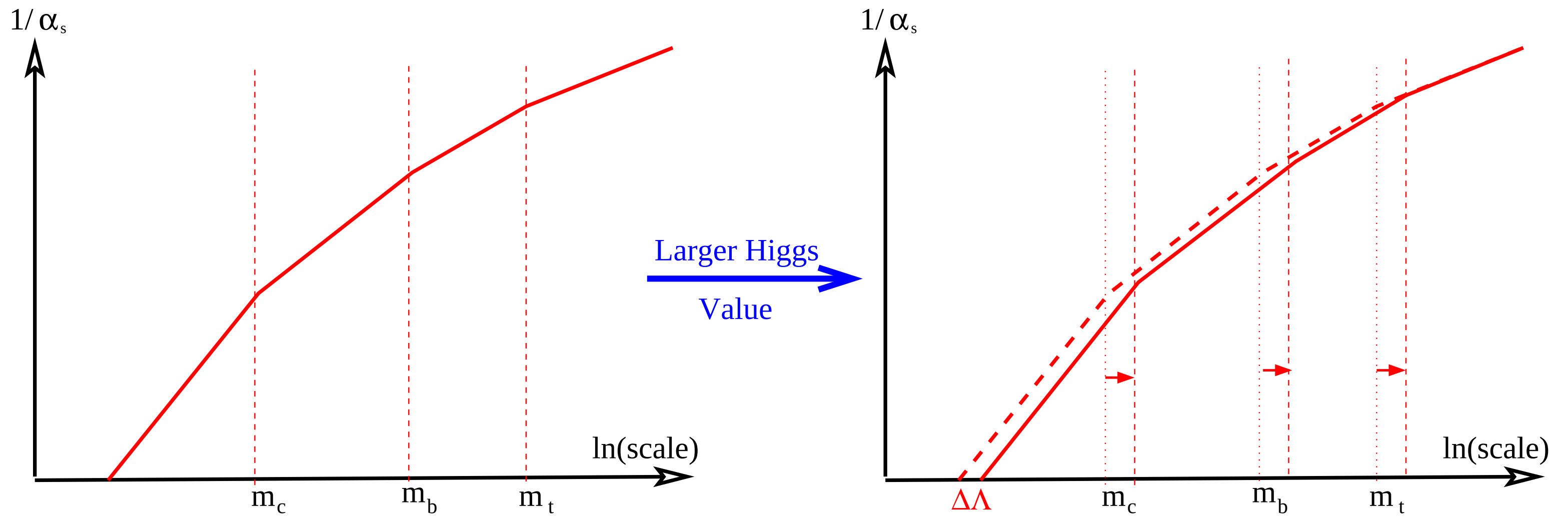
But $m_u \sim 2.2\,\text{MeV}$, $m_d \sim 4.7\,\text{MeV} \ll m_p = 938\,\text{MeV}$.

Most of m_p is "some kind of binding energy" $\propto \Lambda_{\text{QCD}}$

Dependence of m_p on m_u, m_d quite small.

What is Λ_{QCD}?

Scale where "running" QCD coupling α_{s} gets large.



Shifts when we shift m_t, m_b, m_c.

This effect *dominates* h-dependence of m_p

Combine with lattice dependence of m_u, m_d, m_s sensitivity

Bad news: tiny cross-section

Higgs-proton coupling is tiny

$$\sigma = \frac{\lambda_{hs}^2 f_N^2}{4\pi} \frac{m_n^4}{m_h^4 m_s^2}$$

with $f_N = \sum_i dm_p/d\ln m_q \simeq 0.3$.

Local density of DM: $0.3\,\mathrm{g/cm^3}$

Leads to very low event rates

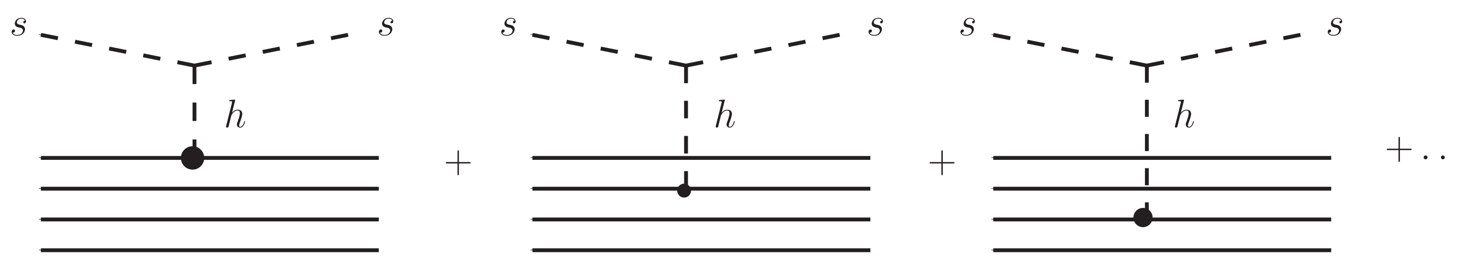
More bad news: energy scale

Typical DM velocity in galaxy $\sim v_{\mathrm{virial}} \sim 10^{-3}c$.
Best case: scatter from nucleus with $m_N = m_s$:

- DM mass $m_s \sim 50\,\mathrm{GeV}$
- DM momentum $m_s v \sim 50\,\mathrm{MeV}$
- DM energy $m_s v^2/2 \sim 25\,\mathrm{KeV}$

maximum recoil energy is $\sim 25\,\mathrm{KeV}$.
That's $1/100$ of a typical nuclear decay energy. *Ouch!*

Good news: coherence!



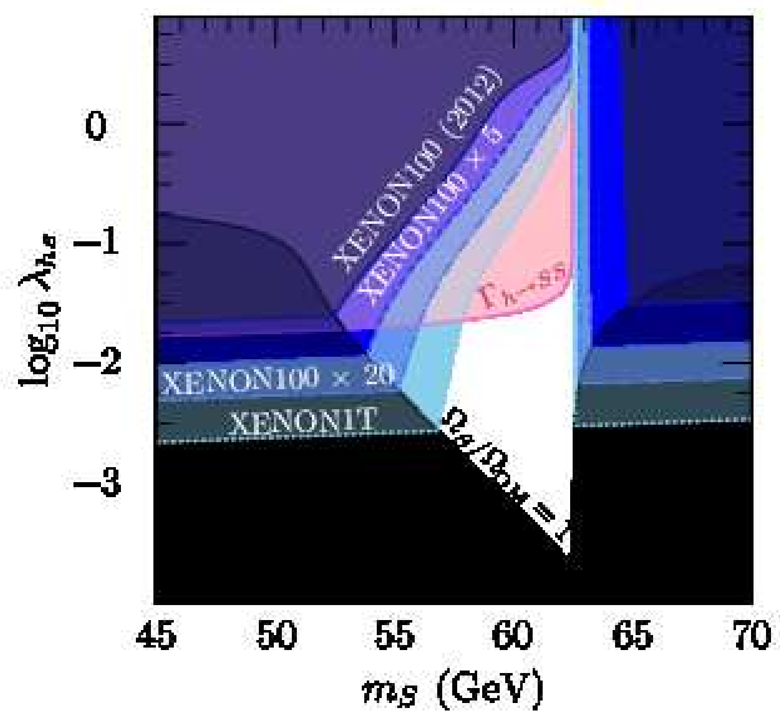
Amplitude is sum of amplitudes for each p, n in nucleus.

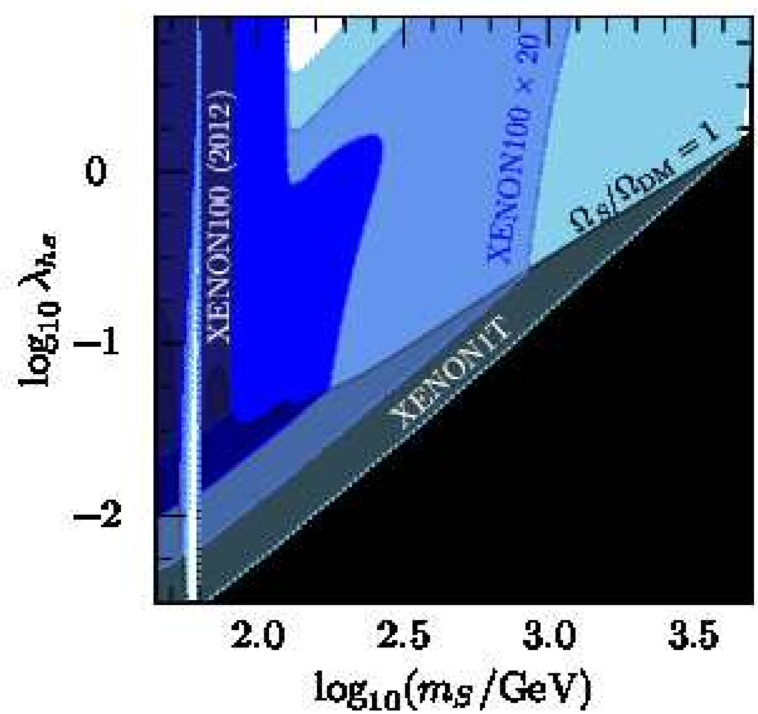
Wave-length $\lambda \sim 2\pi/Q > 2\pi/(50\,\mathrm{MeV}) > 24\,\mathrm{fm}$

Amplitudes add coherently, $\sigma \propto A^2$ atomic number^2

Large nucleus: σ much larger!

Direct detection constraints on s





Recent rapid improvement in constraints.

All but narrow window $57\,\mathrm{GeV} < m_s < 62.5\,\mathrm{GeV}$ excluded

arXiv:13064710

Motivation for new particles: Hierarchy Problem

Let's look at the Standard Model Lagrangian (sorry)

$$
\begin{aligned}
-\mathcal{L} \quad = \quad & \frac{1}{4g_1^2} B_{\mu\nu} B^{\mu\nu} + \frac{1}{g_2^2} W^a_{\mu\nu} W_a^{\mu\nu} + \frac{1}{g_3^2} G^A_{\mu\nu} G_A^{\mu\nu} \\
& + \frac{1}{2} \bar{E}_i \not{D} E_i + \bar{L}_i \not{D} L_i + \bar{U}_i \not{D} U_i + \bar{D}_i \not{D} D_i + \bar{Q}_i \not{D} Q_i \\
& + \left(f_{ij} \bar{L}_i P_{\mathrm{R}} E_j \phi + h_{ij} \bar{Q}_i P_{\mathrm{R}} U_j \tilde{\phi} + g_{ij} \bar{Q}_i P_{\mathrm{R}} D_j \phi \right) + \mathrm{h.c.} \\
& + D_\mu \phi^\dagger D^\mu \phi + \lambda \left(\phi^\dagger \phi \right)^2 - \mu^2 \phi^\dagger \phi + m_{\mathrm{pl}}^2 R + \varepsilon_0 \\
& + k_{ij} \tilde{\phi} \bar{L}_i P_{\mathrm{R}} L_j \tilde{\phi} \text{ or } \frac{m_{ij}}{2} \bar{N}_i N_j + n_{ij} \bar{L}_i P_{\mathrm{R}} N_j \tilde{\phi} + \mathrm{h.c.}
\end{aligned}
$$

Terms in blue are dimension-4 (renormalizable)

Terms in red are dimension-2, in green dimension 0

Subject to large renormalizations!

Hierarchy problem, Cosmological Constant Problem

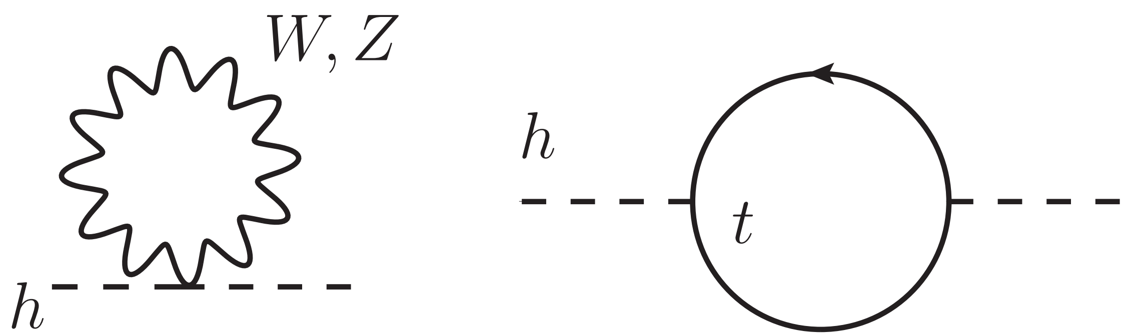
Scales in the Standard Model

Parameters which are scale-dependent:

- Planck mass $m_{\rm pl} = G_N^{-1/2} \sim 10^{19}\,\rm GeV$
- Neutrino "seesaw" scale $1/|k_{ij}|$ or m_{ij}, $\sim 10^{14}\,\rm GeV$
- Higgs mass scale $|\mu| \sim m_h = 126\,\rm GeV$
- Vacuum energy $\varepsilon_0^{1/4} = 2.4 \times 10^{-12}\,\rm GeV$

Hierarchy problem: why isn't μ at seesaw or Planck scale?

Renormalization of μ^2



Loop effects *generate* $\mu^2 \propto h^2\Lambda^2$, $g_2^2\Lambda^2$ with Λ some UV scale ($m_{\rm pl}$??)

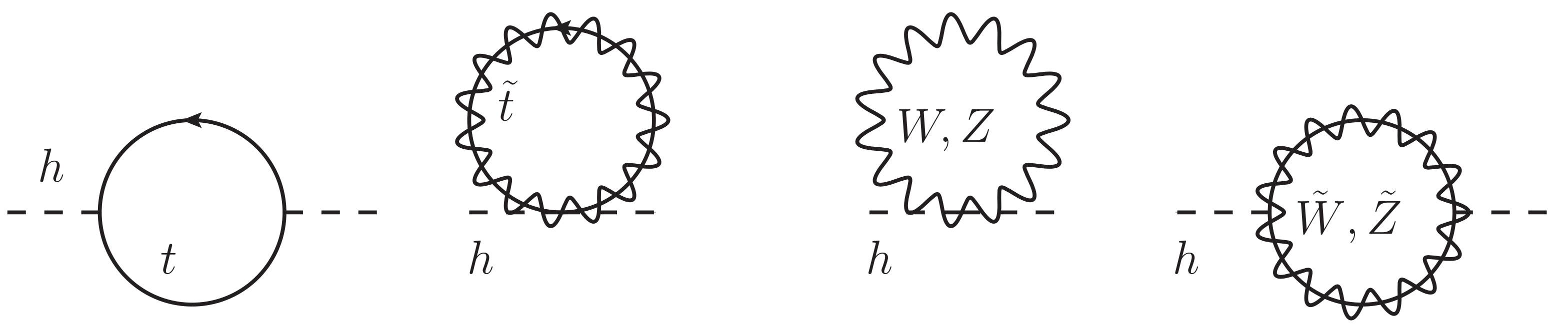
Many (other) loop effects experimentally verified.

Physical value $= \mu^2_{\rm Lagrangian} + \mu^2_{\rm loops}$

Need extreme cancellation if Λ scale large ...

Supersymmetry

In a SUSY theory, each particle, each loop has SUSY partner:



Contributions to μ *cancel*

Break SUSY softly with masses: *divergences* cancel.

Natural that $\mu^2 \sim \alpha m^2_{\mathrm{SUSY}}$

Suggests SUSY at about the TeV scale

SUSY's Ugly Secret

Introduce scalar copies of all spin-$\frac{1}{2}$ fields

Allows new Yukawa interactions!

$$\bar{D} P_{\mathrm{R}} U \tilde{D}\,,\ \bar{Q} P_{\mathrm{R}} L \tilde{D}\,,\ \bar{L} P_{\mathrm{R}} E \tilde{L}\,,\ \textit{etc.}$$

Break Baryon or Lepton number! $n \to e^- \pi^+$ in $t_p \sim 10^{-7}\,\mathrm{s}$

Solved with discrete R-parity $R = 2S - L + 3B$ (mod 2)

Only R-even terms are allowed. Restores B, L.

Superpartners "Superfriends" all R-odd.

Lightest superpartner = lightest R-odd $\to$ stable.

MSSM under tension

LHC (and other) results put the MSSM under "tension"

- null searches up to ever higher energy
- Higgs mass $m_h = 126\,\mathrm{GeV} > M_Z = 91.2\,\mathrm{GeV}$
  Requires multi-TeV scalar-top. "Fine tuning" returns
- Absence of new CP violation constrains scalar masses

Alternatives exist ("Little Higgs"), also under tension, typically also need Z_2 symmetry akin to R-symmetry

But we will push forward

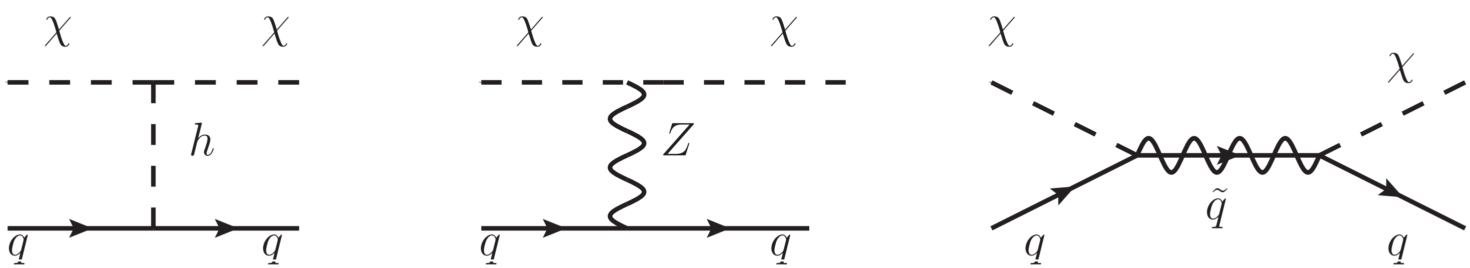
Dark matter candidates in MSSM

Must be neutral, colorless, partner of standard particle:

- Spin-0 neutrino partner $\tilde{\nu}$ "Sneutrino"
- Spin-$\frac{1}{2}$ partner of γ, Z, H_U, H_D (2 doublets)

Sneutrino is "too" predictive. Experimentally excluded!
$\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}_U$, $\tilde{H}_D$ mix into 4 "neutralinos"
Lightest neutralino can be DM. Couplings depend on (unknown) mixing

Three channels to interact



Higgs exchange Z-exchange s-channel scalar

Higgs, Z exchange each spin-independent and coherent:

$$A \propto c_1 Z + c_2 N$$

with c_1, c_2 dependent on state admixture.

Scalar exchange relates χ, q spins; spin-dependent.
Often cancels for 0^{++} nuclei, separate p, n couplings

Direct detection: Background Challenge

Things which can cause 10-20 KeV nuclear/electron recoils:

- Muons. Cosmic ray showers $\rightarrow 100\mu/\mathrm{m}^2\mathrm{s}$ at surface
  $\Rightarrow$ Need to go deep underground ($\gtrsim 1.5\,\mathrm{km}$)
- Nuclear decays. ${}^{238}\mathrm{U} \rightarrow \ldots \rightarrow {}^{206}\mathrm{Pb}$ has 8α, 6β, $\geq 0\,\gamma$
  $\Rightarrow$ Need extreme radiopurity
- Neutrons (from μ interactions outside system)
  $\Rightarrow$ need μ veto $+$ dead time, ...

Radio purity issue

obviously we need materials which can be highly purified against U, Th and daughters, and to avoid Rn.

also need to worry about trace cosmogenics. Example: Kr

$^{78}\mathrm{Kr}$, $^{80}\mathrm{Kr}$, $^{82}\mathrm{Kr}$, $^{83}\mathrm{Kr}$, $^{84}\mathrm{Kr}$, $^{86}\mathrm{Kr}$ stable, naturally abundant.

$^{81}\mathrm{Kr}$ halflife 230,000 yr, $^{85}\mathrm{Kr}$ halflife 11 yr.

None left from Earth formation. Traces $\sim 10^{-12}$ from μ spallation in atmosphere.

Kr from atmosphere radioactive enough to be useless ...

One radioisotope with $\sim \mathrm{yr}$ lifetime is already too much!

Shielding: electroformed copper, Roman lead

Copper is great:

- No long-lived isotopes
- Can be ultra-purified via electroforming.
  Now-a-days done *in situ* underground

Lead has a problem:

- $^{210}\mathrm{Pb}$ in $^{238}\mathrm{U}$ chain. $t_{1/2} = 22$ yr.
  Present in newly-smelted lead.
- Lead smelted by Romans 2000 yr ago is OK!

Nuclear vs Electron Recoil

Huge advantage to run "background-free" $< 1 \frac{\text{event}}{\text{detector}*\text{yr}}$

nuclear recoil: achievable in some systems

Current wisdom: *not* achievable for e^-, X-rays

Need to *distinguish*, with high efficiency, between nuclear recoil and e^- or X-ray ("electronic") recoil

Typically achieved with *two or more* detection channels, which two event types excite differentially.

Some modern DM detection plans

Medium	Mode 1	Mode 2	Experiments
Ge, Si	e^-/hole	phonons	CoGeNT, CDMS, EDELWEISS
$CaWO_4$	scintillation	phonons	CRESST, EURECA
Ar, Ne	scintillation	delayed scint	DEAP/CLEAN, DarkSide
Xe	scintillation	e^-, ions	LUX/LZ, PandaX, Xenon1T
C_3F_8	optical	acoustic	PICO

Arguably, Xe detectors currently most sensitive.

For spin-dependent proton, superheated bubbles are in lead

Example: Xenon detectors

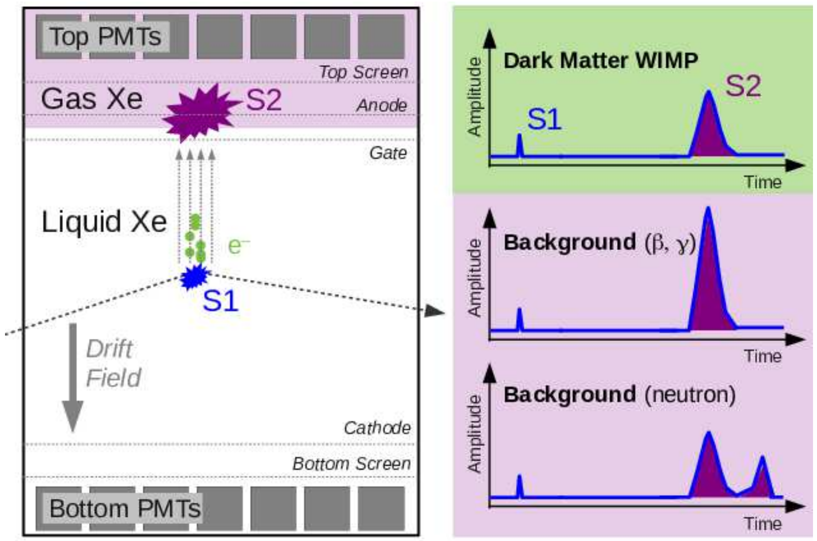
Xenon 1T: arXiv:1708.07051, 1805.12562, 1902.03234

When nucleus/electron/X ray goes through Xe, it

- knocks e^- out of Xe atoms, producing e^-, Xe^+
  Drift in E-field, count at boundary of fluid
- Excites Xe atoms to higher electronic state Xe^*
  Xe^* forms dimer (molecule) with another atom
  De-excites (few ns) through 178nm scintillation light
  Xe is transparent to this light

Allows for dual detection: drifted e^- and scintillation light

Detector: idea



arXiv:1708.07051

Liquid + gas on top

Prompt scintillation

e^- reach gas: spark

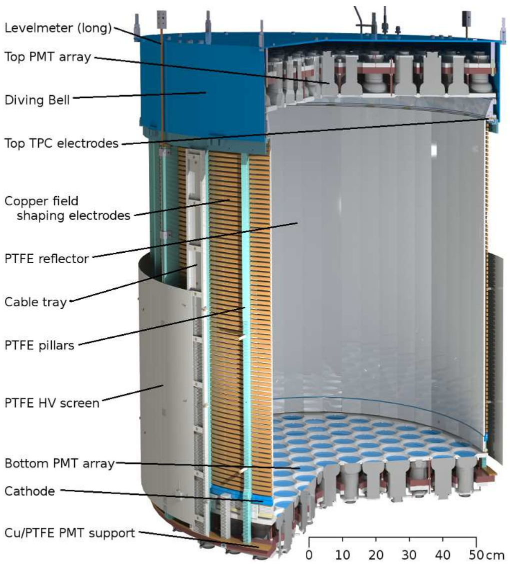
PMTs above+below

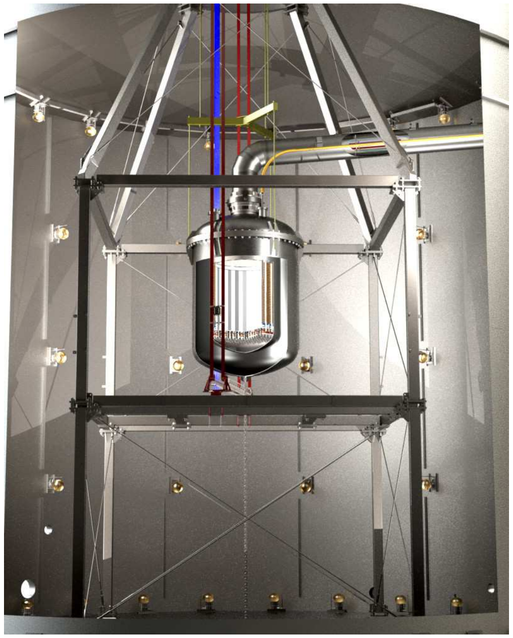
3D reconstruction

Electrons: more e^-. Nuclear recoil: more scintillation

Neutrons usually give multiple strikes: multiple drift times

Detector: some details





arXiv:1708.07051

3 tons Xe in stainless steel cryostat

Hamamatsu PMTs above and below

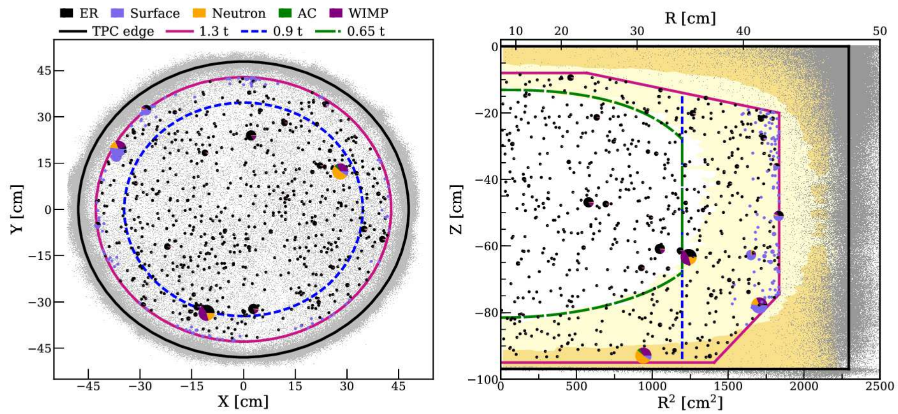
All in ultrapure water bath for shielding and μ detection

Purity and Background

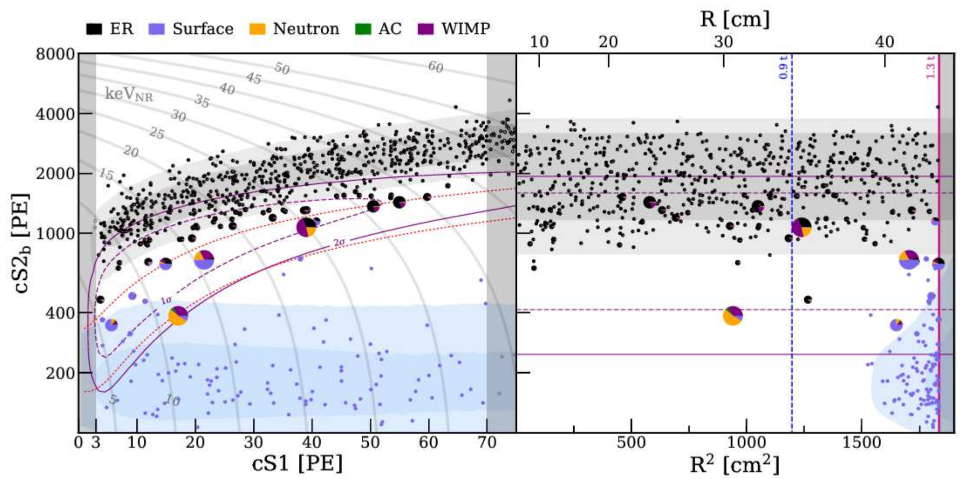
- Xe inherently pure: cryogenic noble gas
  No long-lived radioisotopes Except $^{136}\mathrm{Xe}$ $\nu\nu\beta\beta$
- Ultra-purified from Kr, Rn contamination
- "Self-shielding": dense, high-Z: short radiation length.
  Interior much lower-background than surfaces

Nevertheless, irreducible e^-, X backgrounds: solar ν on e recoil, $2\nu\beta\beta$ of $^{136}\mathrm{Xe}$. Need "electronic" rejection!

Rejecting electronic + surface



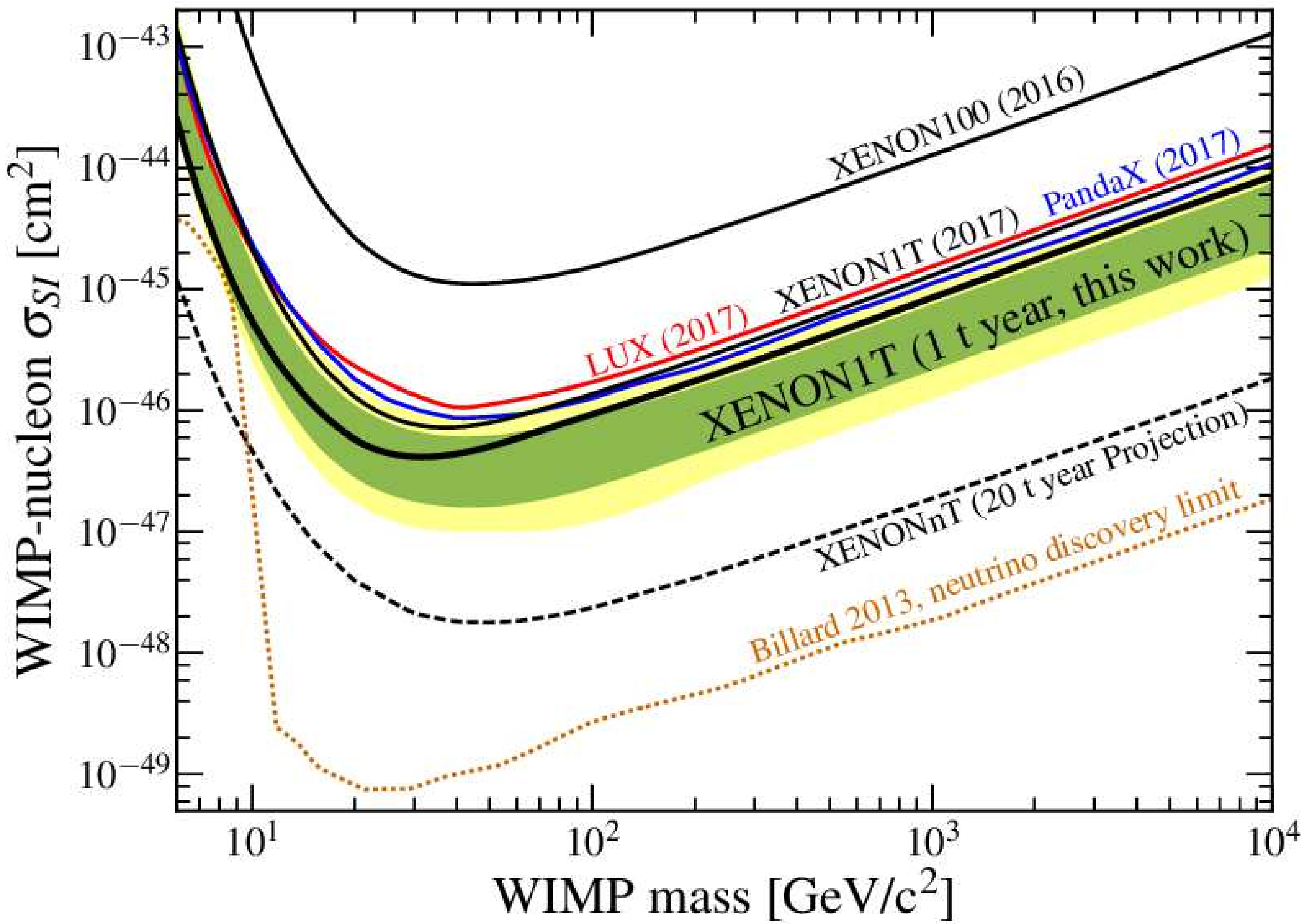
Spatial distribution of events,



Scintillation (horiz.) ionization (vert) also vs. radius

2 possible events. Expected background: 1

90% exclusion Limits so far



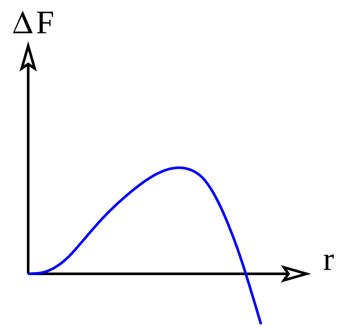
arXiv:1805.12562

PICO: Superheated Fluid

arXiv:1510.07754, 1902.04031

Superheat a liquid. When will it boil? Free energy of bubble:

$$F(r) = +4\pi\sigma r^2 - \frac{4\pi\,\Delta F}{3} r^3$$



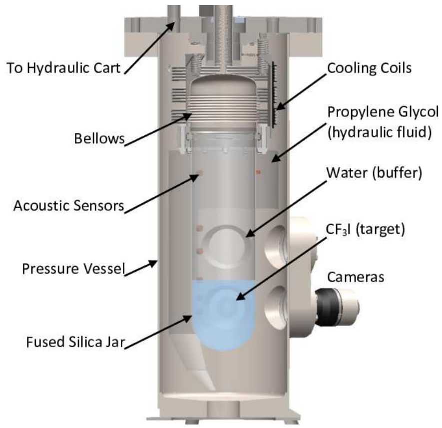
Bubble must reach size $r = 2\sigma/\Delta F$ before it's stable

Choose temperature so $\Delta E_{\rm bubble} \sim 2\,{\rm keV} \gg kT$

Nucleation only if $\sim 2\,{\rm keV}$ energy deposited in $< 2r$ length.

X-ray, e^- path length $\gg r$. Only nuclear recoil does it!

PICO detector arXiv:1510.07754



Chamber: $\sim 52\,\mathrm{kg}\ \mathrm{C_3F_8}$ or $\mathrm{CF_3I}$

Heating/hydraulics control P, T

Passivated surfaces: no surface nucl.

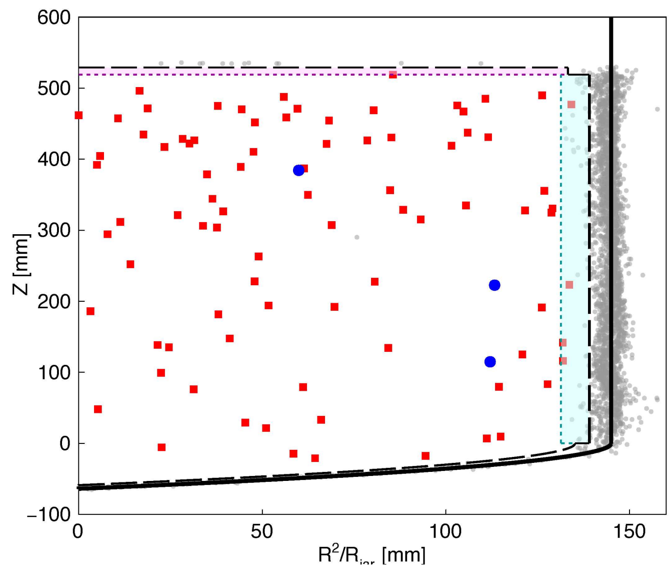
Optical and acoustic readout

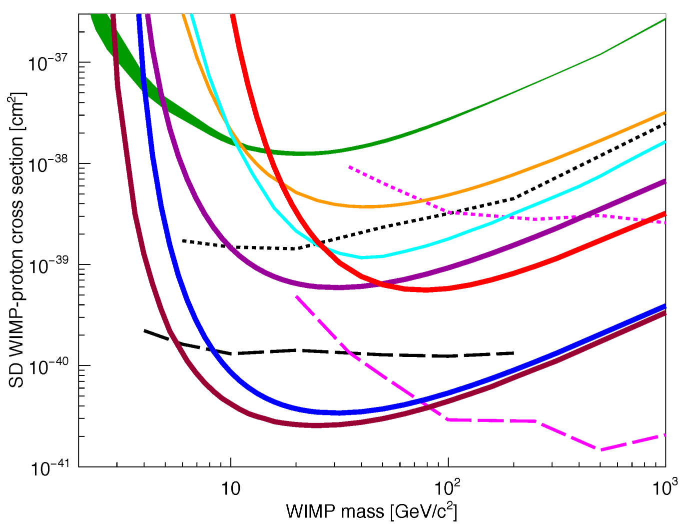
e^-, X-rays: no nucleation!

Alphas: "sound" different!

Neutrons: multiple hits, multiple bubbles

Each nucleation: lower piston, raise P, re-liquify





Many events near wall

3 events in fiducial vol

1 BG event expected

No detection, only limits

Best limits to date

for spin-dependent WIMP-p

For spin-independent,

10^3 weaker than Xenon

arXiv:1902.04031

What does the future hold?

Some technologies think they can continue with ≤ 1 BG/detector for another 1-2 orders of magnitude size:

- Xenon
- $\mathrm{C_3F_8}$
- Possibly Ar etc.

Life gets tough after that: coherent scattering between nucleus and atmospheric/Supernova bg neutrinos

Astrophysical bounds may also improve

Summary (lecture 2)

- Dark Matter does *NOT* fit into the Standard Model
- Lots of things it is *NOT*, huge range it *CAN* be
- W$_{\text{eakly}}$I$_{\text{nteracting}}$M$_{\text{assive}}$P$_{\text{article}}$ Miracle, thermal relic dark matter
- Dual-mode detectors, the triumph of Xenon
- Limits to date and the Neutrino Background Wall

What about DAMA/LIBRA?

scattering in NaI scintillation crystals

Large background: look for “annual modulation”

Alledged $> 8\sigma$ detection

Community skepticism

Appears to be strongly ruled out by other experiments

Background rapidly falling with energy

Detection only in lowest energy bins considered

Most proposed error sources don’t explain it

Richard Gaitskell private communication: drift in amplifier gain?