Dark Matter II

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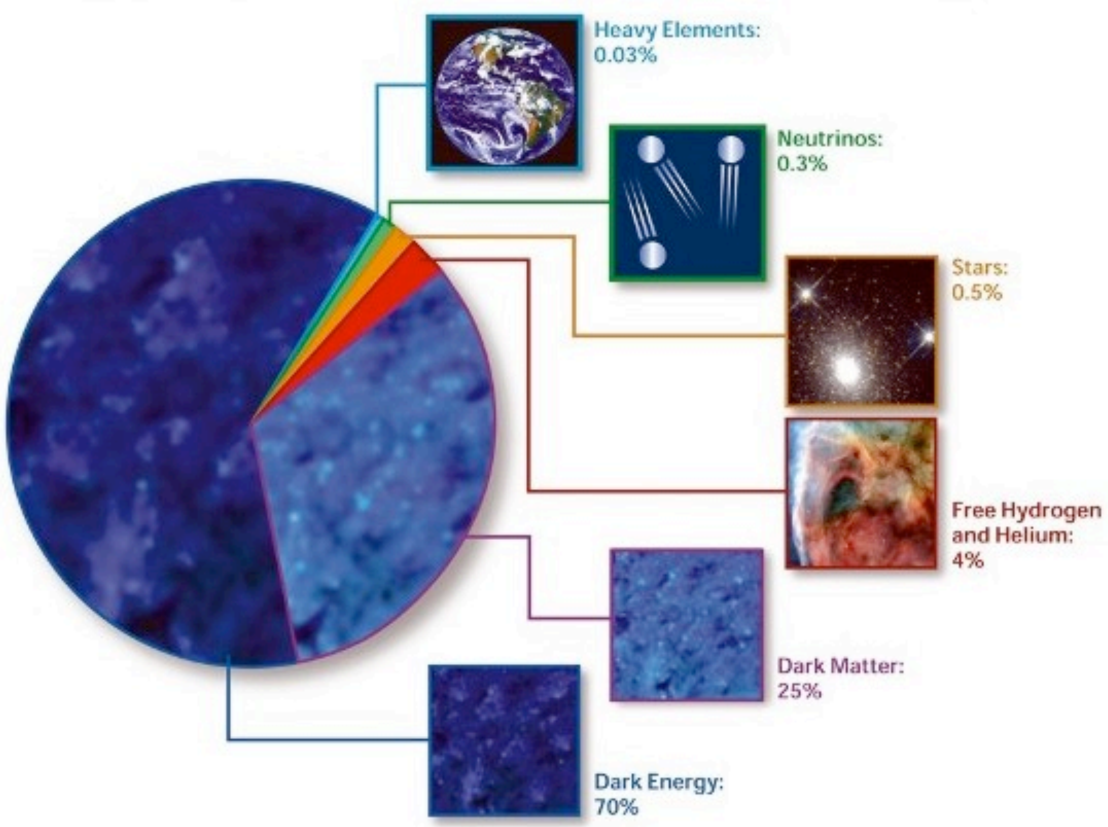
Reminder

Constituents of the present Universe:



What is Dark Matter?

Properties of Dark Matter

- Nature of dark matter
  - Is it baryonic?
  - Is it a new type of elementary particle?
- Mass
- Lifetime
  - Must be long lived or stable.
- Kinetic energy expressed in Temperature
- Spin
- Cross section of self-interaction
- Cross section of interaction with ordinary matter

'Temperature' of Dark Matter

- Hot
  - Moving fast
  - Can overcome and escape potential wells
  - If all dark matter was hot, structure could not form
    - Contradicts findings of WMAP.
- Warm
- Cold
  - Moving slowly
  - Could seed structure

Baryonic Dark Matter

- Cold hydrogen
  - 25% of the hydrogen is in single-atom state.
- Massive Compact Halo Objects (MACHOs)
  - Brown dwarfs/Large planets
    - Not enough around to explain all dark matter
  - Compact stars, such as White Dwarfs
    - Too many of them will need more He than could be produced by Big Bang nucleosynthesis
  - Neutron stars and Black holes
    - Rarer than white dwarfs.
- Constraints from micro-lensing
  - Observed several millions stars for years
    - In Large Magellan Cloud, found 4 candidates
    - Near the galactic centre, found 45 candidates
  - < 20% of the Milky Way halo is MACHOS with

Non-baryonic Dark Matter

- Hot - Neutrinos
- Warm -Sterile neutrinos, gravitino
- Cold
  - LSP (Lightest Super-symmetric Particle, eg. neutralino, axino)
  - LKP (Lightest Kaluza-Klein particle)
  - Axions, axion clusters
  - Solitons (Q-balls, B-balls)
  - WIMPs (Weakly Interacting Massive Particles), wimpzilla

Finding The Correct Dark-matter Candidate

- In early Universe, candidate x is in thermal equilibrium by annihilation and couples to ordinary matter:

$$x + \bar{x} \Leftrightarrow f + \bar{f}$$

Number density follows the Boltzmann distribution:

$$n_x^{eq} \propto (mT)^{3/2} e^{-m/kT}$$

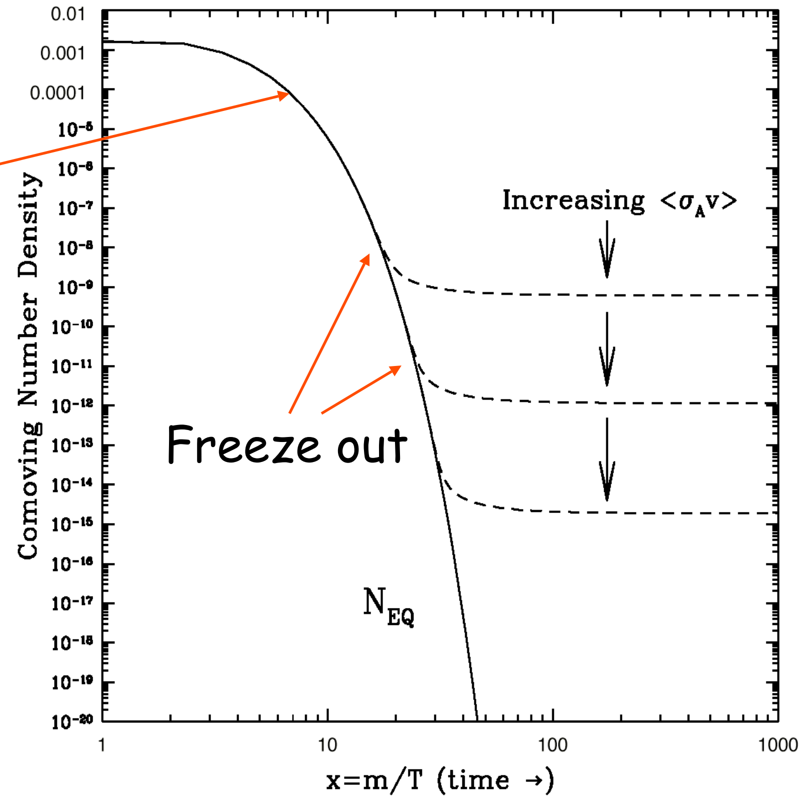
When $H(t) > \Gamma_{ann} \sim n_x \langle \sigma_a v \rangle$,

n_x freezes.

After freeze out:

$$\Omega_x = \frac{n_x(now)m}{\rho_c(now)} \approx \frac{3\times10^{-27}\,cm^3\sec^{-1}}{\langle\sigma_a v\rangle h^2}$$

Hubble parameter
≈ 0.73



- How to find the correct dark-matter candidate?
  - choose a particle
  - work out all the possible annihilation channels
  - calculate Ω_x

Dark-matter Candidate: Neutrinos

- Promising candidate
  - Neutral
  - Weakly interacting
  - Possess mass
  - Their abundance in the Universe is known
- From relic abur $\Omega_\nu \approx \frac{\sum m_\nu}{50\text{ev}}$ = 113/cm^3 per favour :
- From WMAP+BAO+H_0 combined result (2010):

$$\sum m_\nu < 0.58\ eV$$

$$\Omega_\nu \ll \Omega_m$$

- Active neutrinos are not abundant and massive enough to account for dark matter.

Dark-matter Candidate: Sterile Neutrinos

- Mass of sterile neutrinos < ~keV (Tremaine-Gann bound)
- Have no coupling to W and Z
  - Interact with ordinary matter extremely weakly through mixing with the active neutrinos:

Strength $\sim\theta_\nu G_F$

where $\theta_\nu \ll 1$ is the mixing angle

$$\theta_\nu^2 = \sum_{\alpha=e,\mu,\tau} \frac{v^2 \lambda_{\alpha\nu}^2}{M_\nu^2}$$

Majorana neutrino mass, $M_\nu < 10^{-7}$ GeV

Yukawa couplings $\lambda_{ij} \sim 10^{-7}\sqrt{M_\nu/\text{GeV}}$ (proportional to Δm^2)

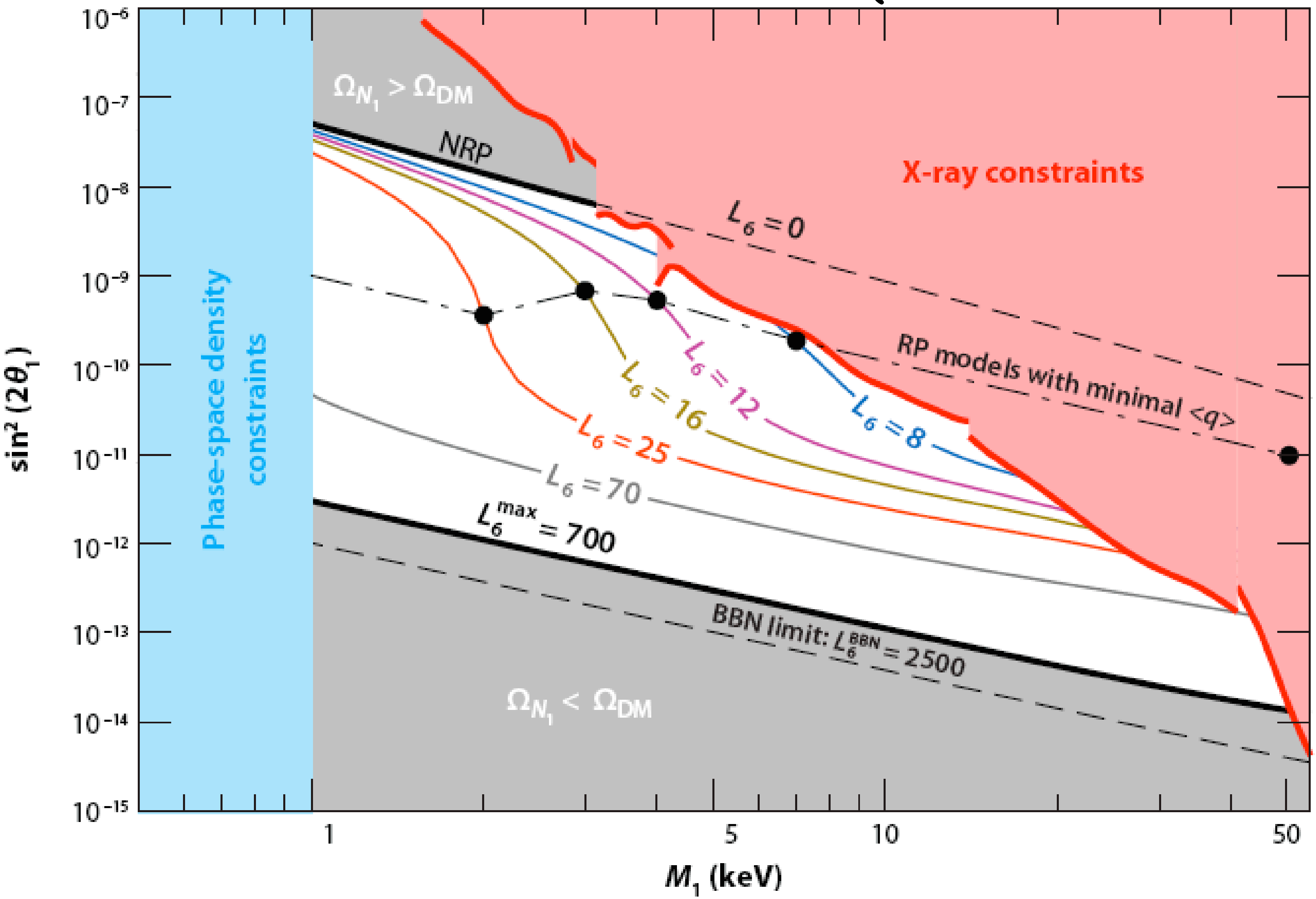
- Sterile neutrinos can decay to active neutrinos

$$\nu_s \rightarrow \nu + \gamma$$

- to be a dark-matter candidate, ν_s must have a very long lifetime greater than the age of the Universe, setting a bound on θ_ν.

Bound on Mass of Sterile Neutrinos

Mass of sterile neutrinos < ~keV (Tremaine-Gann bound)



Boyarsky, ARNPS**59**(2009)191

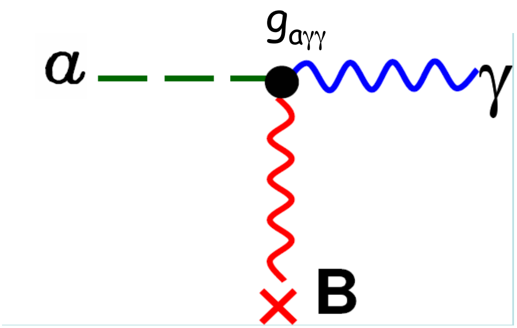
Dark-matter Candidate: Axion

- Arise from the Peccei-Quinn's idea to solve the strong CP problem.
- Axion got its mass during the QCD phase transition:

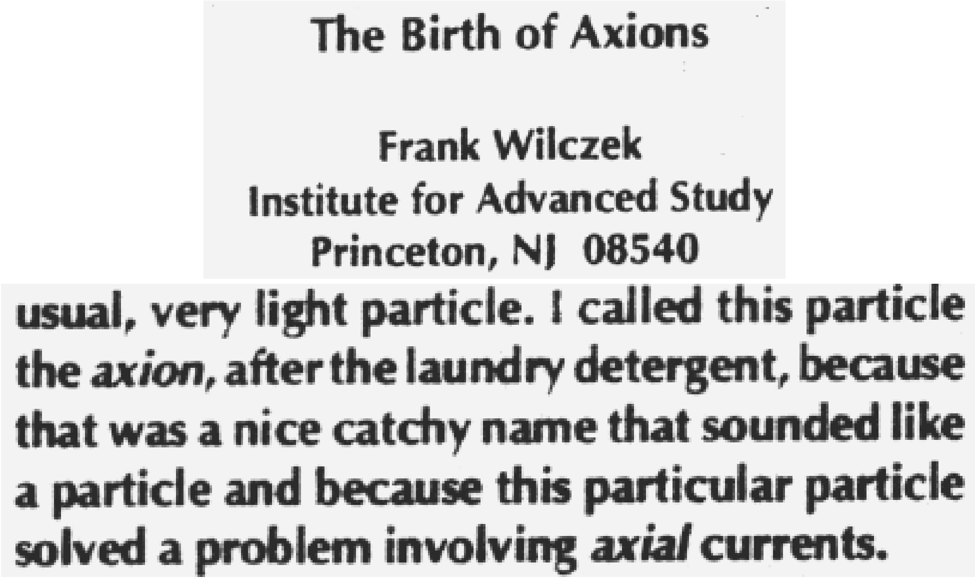
$$m_a \approx 0.62 eV \frac{10^7 GeV}{f_a}$$

f_a = energy scale of the transition

- For cold dark matter, $f_a < 10^{12}$ GeV, implying $m_a = 10^{-6}$-10^{-4} eV.
- Axion is extremely weakly interacting.
- It can couple to electromagnetic field:



$$g_{a\gamma\gamma} \approx \left(\frac{\alpha}{4\pi}\right)\frac{1}{f_a}$$



The Birth of Axions

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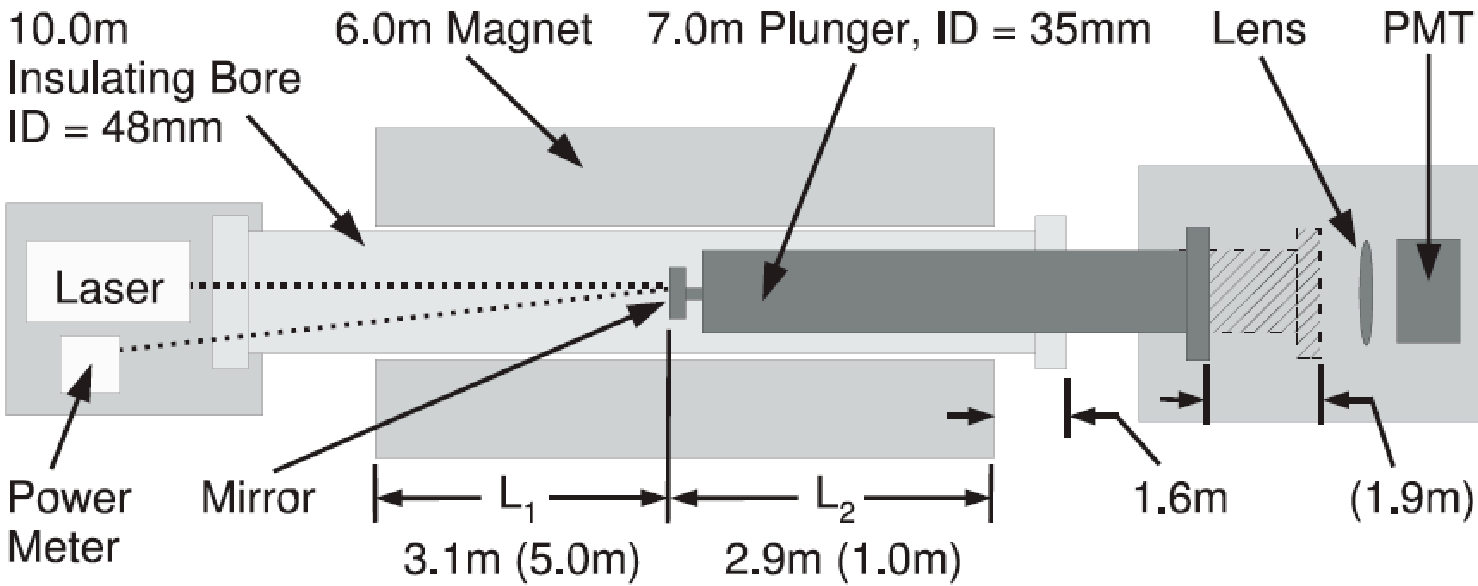
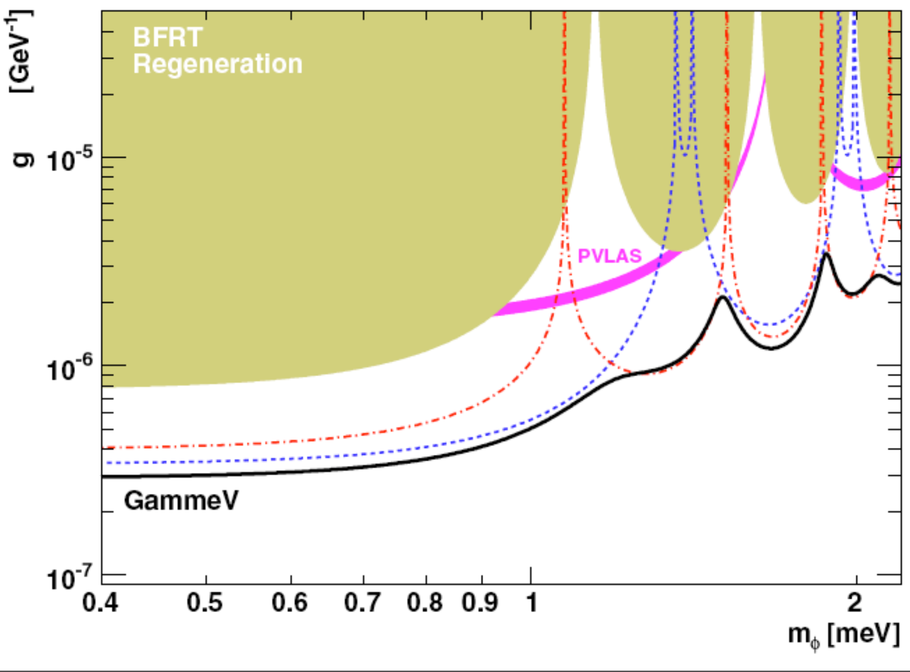
usual, very light particle. I called this particle the *axion*, after the laundry detergent, because that was a nice catchy name that sounded like a particle and because this particular particle solved a problem involving *axial* currents.

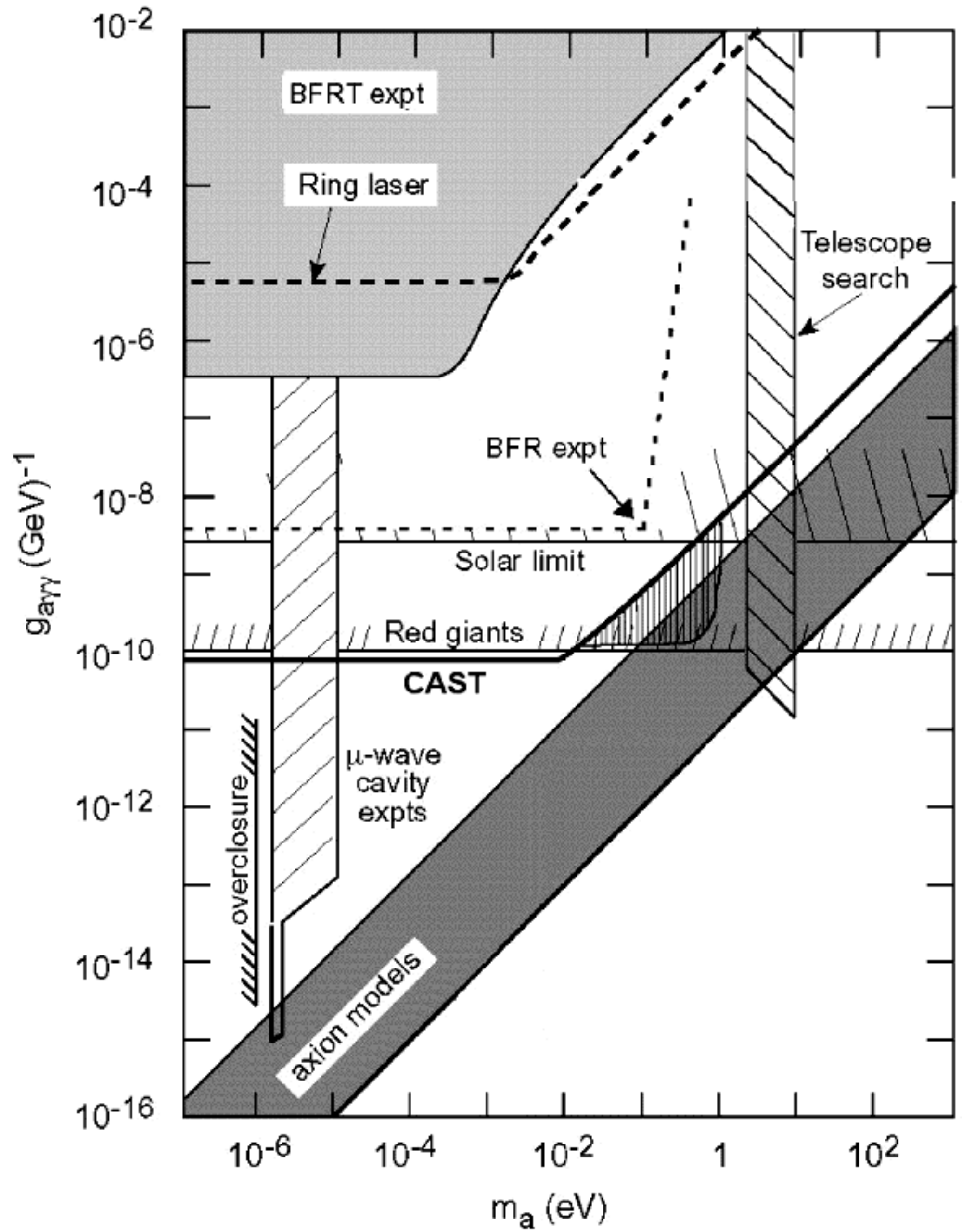
GammeV: Search For Axion



Bargain. Wester (*left*) and Chou say their experiment offers high potential payoff at low cost.



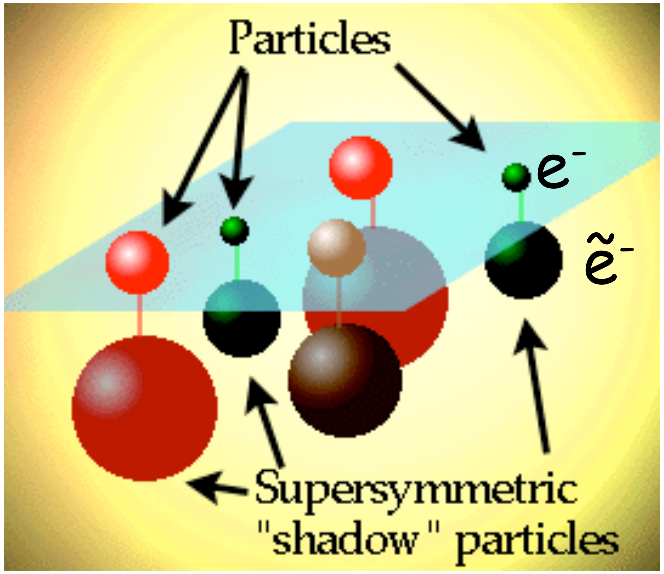
Limits on Axion



Supersymmetry (SUSY)

- A new kind of symmetry between fermions and bosons
  - Every particle in SM has a superpartner with same quantum numbers

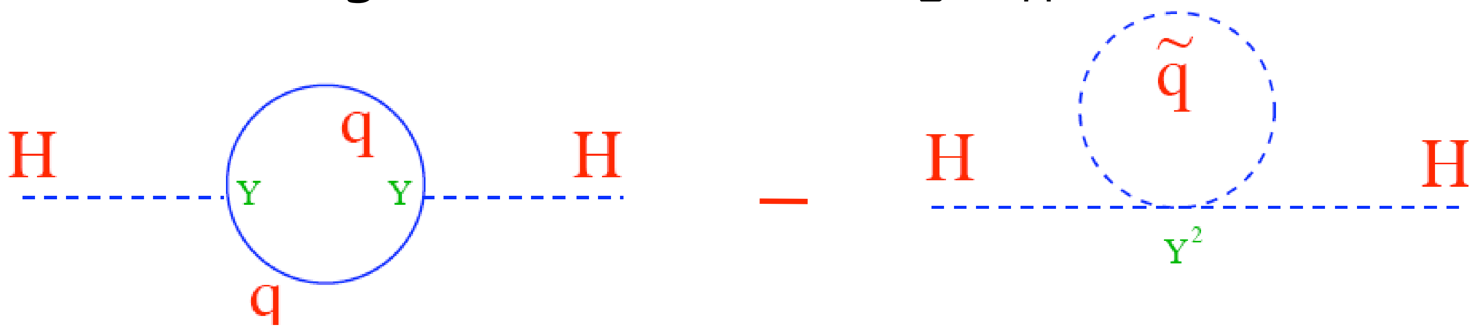
Ordinary Particles		Supersymmetric Partners	
Higgs Boson (spin-0)		Higgsino (spin-1/2)	
Fermions (spin-1/2)		Bosons (spin-0)	
Quarks	Leptons	Squarks	Sleptons
Gauge Bosons (spin-1)		Gauginos (spin-1/2)	
$W^{\pm}$	Z, B gluons, photons	Winos	Zinos, Binos gluinos, photinos
charged	*neutral*	*charginos*	*neutralinos*
Graviton (spin-2)		Gravitino (spin-3/2)	



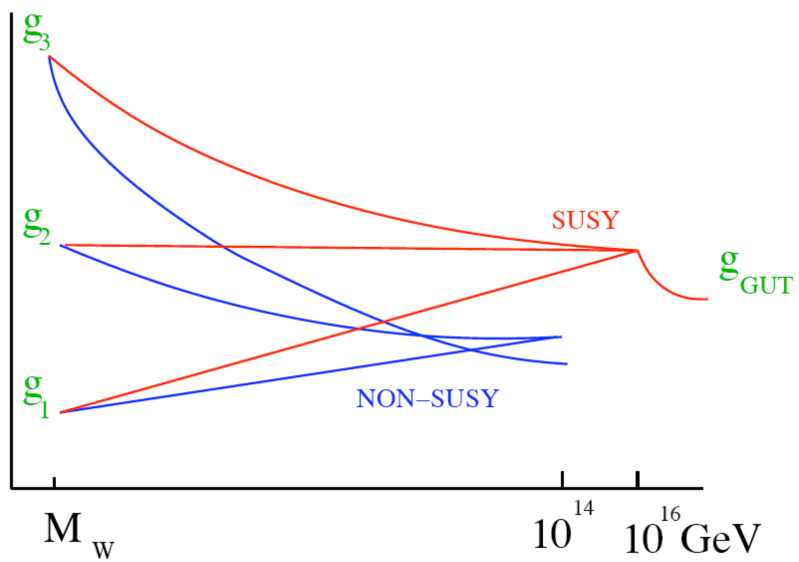
- Interactions of SUSY particles = interactions of quarks and leptons.
- If SUSY was exact, $m_{sparticle} = m_{particle}$ and would have contributed to the Z decay width → SUSY is broken

Goodies of SUSY

- Remove divergences in calculating m_H:



- Coupling constants are unified to a single coupling constant at M^{SUSY}:



$$\boxed{M_X^{SUSY} = 10^{16}\ \mathrm{GeV}}$$

MSSM

- MSSM (Minimal Supersymmetric Standard Model) contains the smallest number of new particles and new interactions as well as all supersymmetry-breaking terms.

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \qquad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

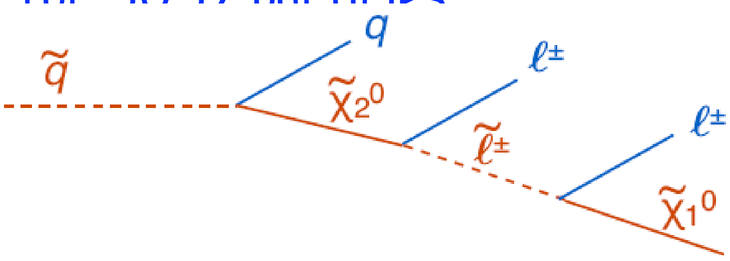
with vacuum expectation values:

$$\langle H_d \rangle_0 = \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \qquad \langle H_u \rangle_0 = \begin{pmatrix} 0 \\ v_u \end{pmatrix}$$

such that

$$v_d^2 + v_u^2 = v^2 \qquad \tan\beta = \frac{v_u}{v_d} \qquad 0 \le \beta \le \frac{\pi}{2}$$

- R-parity (to prevent proton decay):
  - $R = (-1)^{3B+L+2s}$ B = baryon no., L = lepton no., s = spin
  - R = +1 (even) for particles; R = -1 (odd) for SUSY particles
  - R-parity is conserved
  - The lightest sparticle (LSP) is absolute stable, e.g. gravitino, neutralino



The Lightest SUSY Particle

- Gravitinos
  - Could be overproduced in the early Universe and destroy abundance of primordial elements
- Sneutrinos
  - Scattering cross section is much larger than the limits found by direct-detection experiments
- Neutralinos
  - 4 Majorana fermionic eigenstates arise from mixing of bino, wino and higgsinos

$$M_{\chi^0} = \begin{pmatrix} m_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & m_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

m_1 = bino mass parameter $\quad c_\beta = \cos\theta_\beta \quad s_\beta = \sin\theta_\beta$

m_2 = wino mass parameter $\quad c_W = \cos\theta_W \quad s_W = \sin\theta_W$

μ = higgsino mass parameter

Minimal Supergravity (mSUGRA)

- Reduce to the ~100 parameters to 4 parameters and 1 sign:

$\tan\beta$	
$M_{1/2}$	unified gaugino mass at M_{Gut}
m_0	unified scalar masses at M_{GUT} ($M_\chi \approx 0.4\ m_0$)
A_0	trilinear soft-breaking mass
sign(μ)	sign of higgsino mass parameter

- The lightest neutralino in mSUGRA:

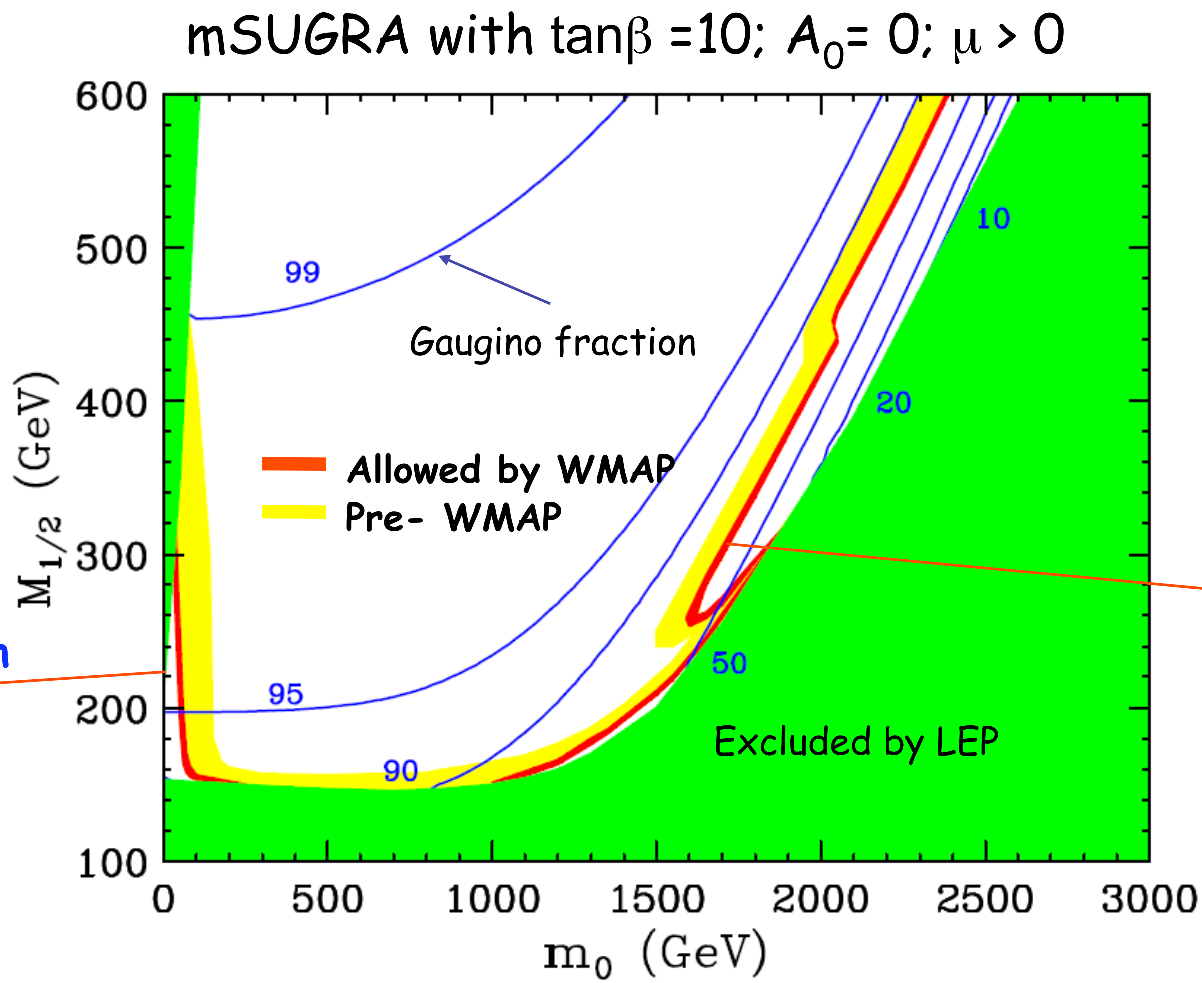
$$\chi_1^0 = c_1\tilde{B} + c_2\tilde{W} + c_3\tilde{H}_u^0 + c_4\tilde{H}_d^0$$

Photino Wino Higgsinos

$$\Rightarrow \quad \chi_1^0 = c_U\left(\tilde{B} + \tilde{W} + \tilde{H}_u^0 + \tilde{H}_d^0\right)$$

- The mass of χ_1 : 100 GeV - 1 TeV, weak scale.

Where To Look For Neutralino ?



Co-annihilation region

Bino-like

Focus point region

Higgsino-like

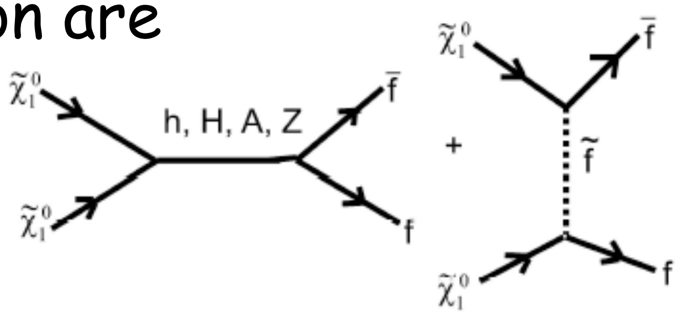
K. Matchev hep-ph/0402088

Neutralino As Dark Matter Candidate

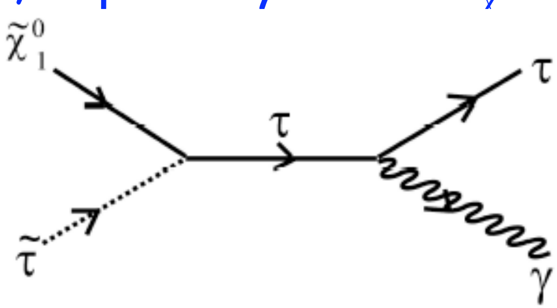
- At present, neutralinos are moving at non-relativistic speed:

$$\sigma_a v = a + bv^2 + O(v^4) \approx a$$

- The dominant modes of annihilation are
  - Fermion-antifermion pairs
  - Gauge boson pairs
  - Final states containing the Higgs



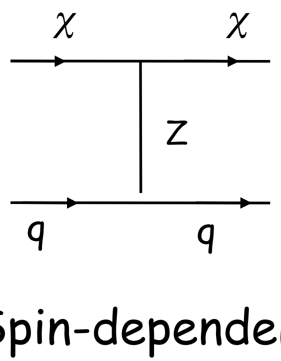
- Other interactions for dark-matter searches are:
  - Co-annihilation, especially when $M_\chi \approx M_{\tilde{\tau}}$

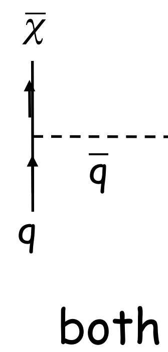


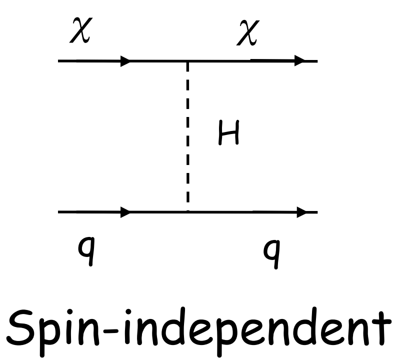
  - Elastic scattering of nucleons

Elastic Scattering of Neutralinos

- Processes for detecting neutralinos with ordinary matter:







- The cross sections of these processes:

$$\sigma_A = 4G_F^{\ 2}\left(\frac{m_\chi M_A}{m_\chi + M_A}\right)^2 C_A F(q^2)$$

C_A^{SI} : for spin-independent coherent interaction $\propto A^2$

C_A^{SD} : for spin-dependent interaction $\propto \langle S_{p,n}\rangle^2$

$F(q^2)$: nuclear form factor, important for large q^2 and large A

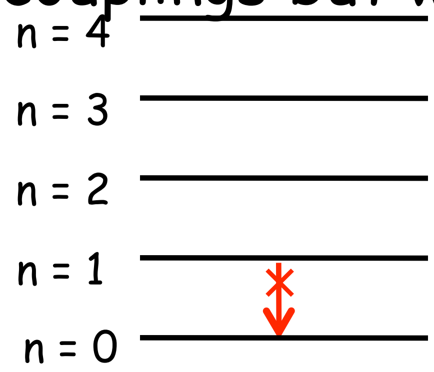
Universal Extra Dimensions (UED)

- All particles can move into the extra compact dimensions with R ~ 1 TeV^{-1}.

- For each particle, there is an infinite tower of states with identical quantum numbers and couplings but with masses given by

$$M_n^2 \propto \frac{n^2}{R^2}$$

SM particles have n = 0.



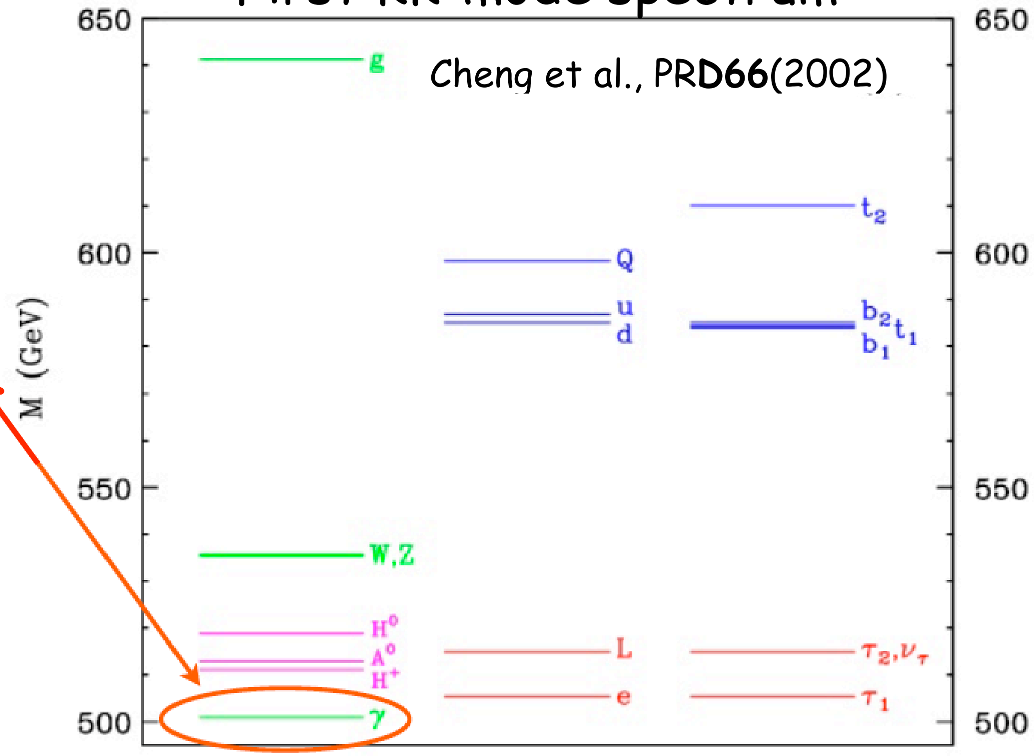
- In the simplest UED model, along the fifth dimension
  - The lightest Kaluza-Klein (KK) state is stable

Lightest Kaluza-Klein Particle

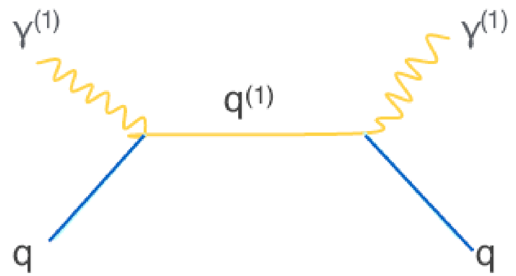
First KK-mode spectrum

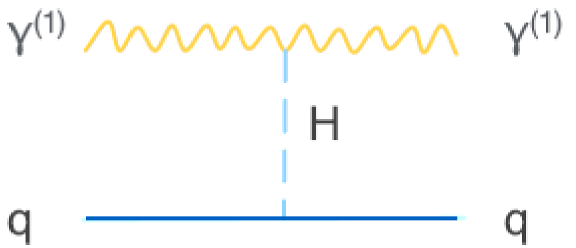
Most likely LKP

$\gamma^{(1)}$



- Possible interactions of LKP with ordinary matter:





Dark-matter Candidates : Summary