Announcements:
- Preflight 4 was due today
- Problem Set 4 out, due in class next Friday

Lingering issues from Last time: Supersymmetry
★ key point: \( m(\tilde{x}) > m(x) \) always—spartners heavier
  so \( \tilde{x} \to x + \text{junk} \) if allowed by \( R \)-parity
  Why? otherwise SUSY trivially dead—no spartners found (yet!)
  How? not automatic—SUSY symmetry “breaking” required
    many schemes exist; least elegant SUSY aspect (in my view)
★ SUSY decays: obey normal conservation laws + \( R \)-parity
e.g., squark \( \tilde{q} \to q + \tilde{\gamma} \)
  check electric charge, baryon \# , angular momentum

Q: WIMP detection methods?
The Particle Dark Matter Trifecta

**Create in Accelerators**
Tevatron/LHC creates TeV WIMP
or more likely: detects new physics implying WIMPS (e.g., SUSY)

**Directly Detect in Underground Experiments**
see signal WIMP-nucleus scattering
note: DAMA experiment claims signal at high confidence!
www: DAMA signal
...but nobody else sees it...

**Indirectly Detect Annihilation Products**
- locally: see products as anomalous cosmic rays
  2009: $e^+$ excess seen! ...but could have astrophysical origin
- at Galactic center
  Q: why is this an interesting region?
**Indirect Detection: Galactic Center Annihilation**

Galactic center is $\rho_{\text{DM}}$ peak $\rightarrow$ annihilation goldmine!?!?

**Direct Photon Production**

$\star\ \psi\bar{\psi} \rightarrow \gamma\gamma$ line: $E_\gamma = m_\psi$, and

$\star\ \psi\bar{\psi} \rightarrow q\bar{q} \rightarrow \pi^0 \rightarrow \gamma\gamma$ continuum $E_\gamma < m_\psi$

Galactic center seen in GeV range (1990’s: EGRET)
  with poorly understood “GeV excess”!?!?
But new $\gamma$-ray observatory [www: Fermi](#)
  launched last year, finds no GeV excess

Galactic center seen in TeV range

[www: HESS](#)
  but point source too localized(?!), energy spectrum a power-law
Synchrotron Radiation
if $\psi\bar{\psi} \rightarrow e^+e^-$: source of high-energy $e^+$
moves in strong Galactic $B$ field*:
  accelerated (spiral path) $\rightarrow$ synchrotron radiation
  emission from radio bands, possibly up to X-ray
$\rightarrow$ recent claim: radio & sub-mm observations currently
  strongest astronomical DM constraint!
  beat out $\gamma$s! (but less clean, no direction info)

Neutrino Production
from $\psi\bar{\psi} \rightarrow \nu\bar{\nu}$, but more from $\psi\bar{\psi} \rightarrow q\bar{q} \rightarrow \pi^\pm \rightarrow \nu_e\nu_\mu\bar{\nu}_\mu$

www: http://icecube.wisc.eduICECUBE
use South Pole ice as target
monitor with array of buried photomultipliers
  observe $e^-\tilde{\text{C}}$erenkov light from elastic $\nu e \rightarrow \nu e$

* no relation to instructor
Supersymmetric Dark Matter: Where Do We stand?

Obviously, no clear detections thus far

Current status:
accelerator and astrophysical constraints are:
competitive: both place strong constraints
  on allowed MSSM SUSY parameters \((m_0, m_3/2, \mu, A, \tan \beta)\)
complementary: different methods strong in different parts of parameter space

Upgrades coming soon on all fronts
→ the race is on!
→ an answer will emerge in the non-distant future!
If confirmed WIMP detection:
• DM found
• need particle physics beyond Standard Model
  ★ payoff big!

If no WIMP signature
• SUSY much less attractive
• dark matter not a cold relic → what is it?
  an asymmetric relic? but why asymmetrical?
  modified gravity?
  hidden in braneworld?
Baryogenesis: Origin of Matter/Antimatter Asymmetry

Observed Matter (Baryon) Asymmetry of Univ.

As far as we are able to observe, a cosmic asymmetry exists: baryons and leptons dominate over antibaryons and antileptons.

www: schematic of scenarios

Q: What is evidence for different scales? Solar System, solar neighborhood, MW Galaxy, galaxy clusters, Hubble volume?
# Evidence for Baryon Excess

<table>
<thead>
<tr>
<th>Matter-only System</th>
<th>Asymmetry Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar system</td>
<td>landings, solar wind, proto-⊙ neb</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>consistent with in-flight origin, e.g., $p_{cr}p_{ism} \rightarrow ppp\bar{p}$</td>
</tr>
<tr>
<td>MW Galaxy</td>
<td>cosmic rays, no annihilation $\gamma$s</td>
</tr>
<tr>
<td>Galaxy clusters</td>
<td>no $\gamma$ from galaxy-intracluster gas interface</td>
</tr>
<tr>
<td></td>
<td>nor in colliding clusters</td>
</tr>
<tr>
<td></td>
<td>$\Rightarrow$ all matter or all antimatter</td>
</tr>
<tr>
<td>Hubble volume</td>
<td>too few 1–10 MeV $\gamma$, no CMB distortion</td>
</tr>
</tbody>
</table>

*no evidence for antimatter “domains” anywhere*

strictly: if antimatter domains exist

- segregated from matter on scales $\gtrsim 10^{14} M_\odot$
- and probably $> d_H = 2 \text{ Gpc}$
Conclude:

Cosmic baryon asymmetry exists

\[ Y_B = \frac{n_B}{s} \simeq \frac{n_B}{7n_\gamma} = \frac{\eta}{7} \sim 10^{-10} \]

At \( T \gtrsim \Lambda_{\text{QCD}} \simeq 200 \text{ MeV} \), \( q\bar{q} \) pairs abundant,

\( n_q \simeq n_{\bar{q}} \sim n_\gamma \), so asymm was

\[
\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10} \tag{1}
\]

For every 1,000,000,000 antiquarks

there were 1,000,000,001 quarks

a tiny but crucial excess!

but on theoretical grounds, expect particle creation in pairs

so how did this happen?