Probing Exotic Physics with Neutrino Telescopes

Markus Ahlers

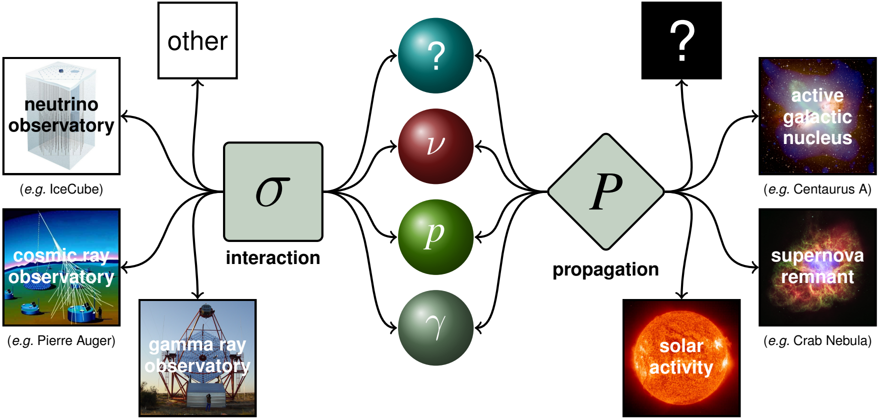
Rudolf Peierls Centre for Theoretical Physics, Oxford

IPPP Seminar

Durham, December 11, 2008

Interfaces for Exotic Physics

A sketch of “standard” astroparticle physics.



other

neutrino observatory

(*e.g.* IceCube)

cosmic ray observatory

(*e.g.* Pierre Auger)

gamma ray observatory

(*e.g.* H.E.S.S.)

σ

interaction

$?$

ν

p

γ

P

propagation

?

active galactic nucleus

(*e.g.* Centaurus A)

supernova remnant

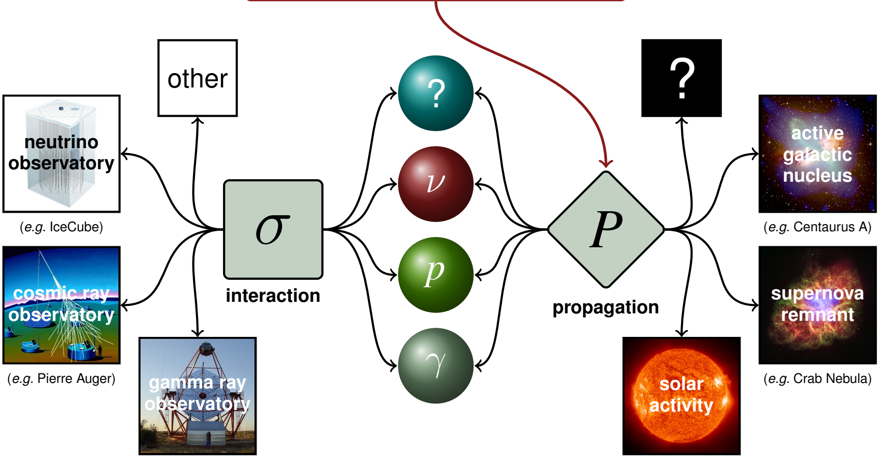
(*e.g.* Crab Nebula)

solar activity

Interfaces for Exotic Physics

Neutrino masses

mixing $\Rightarrow \Delta m^2 \neq 0 \Rightarrow m^2 \neq 0$



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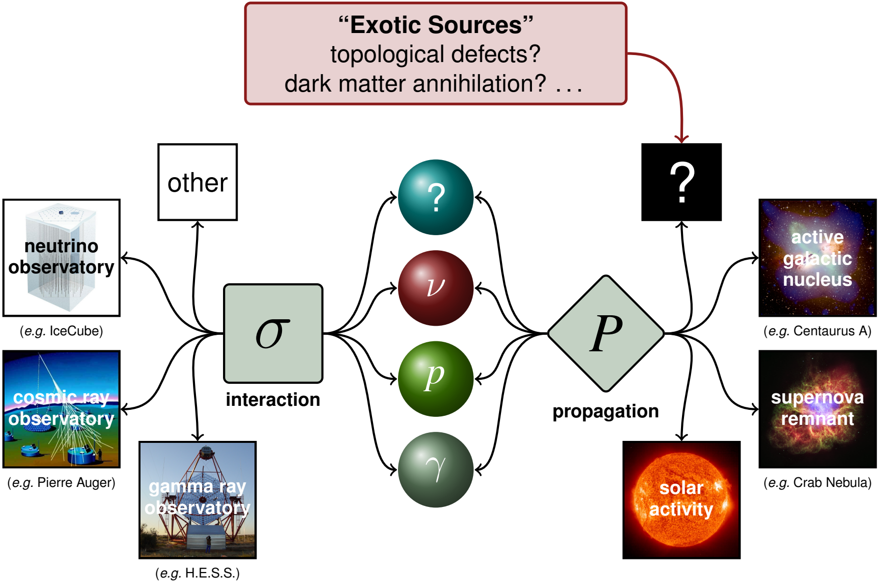

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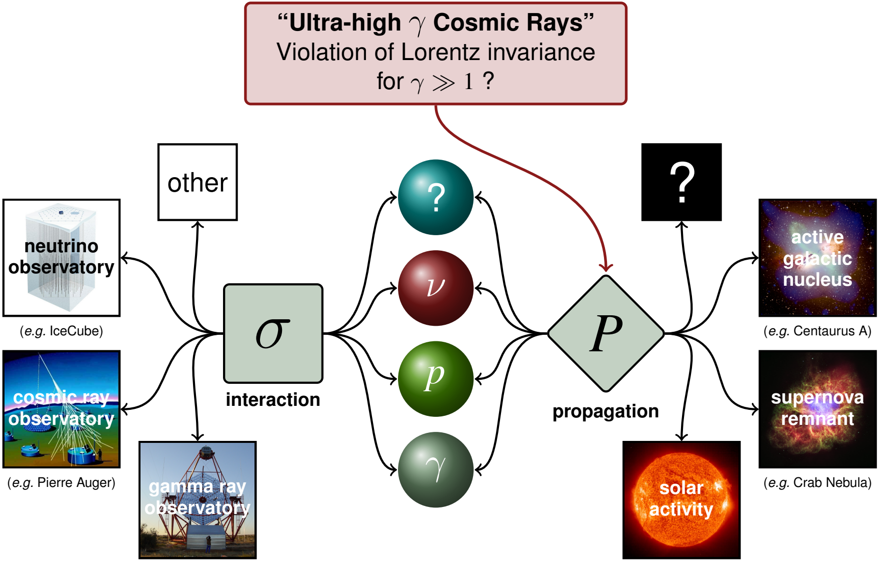
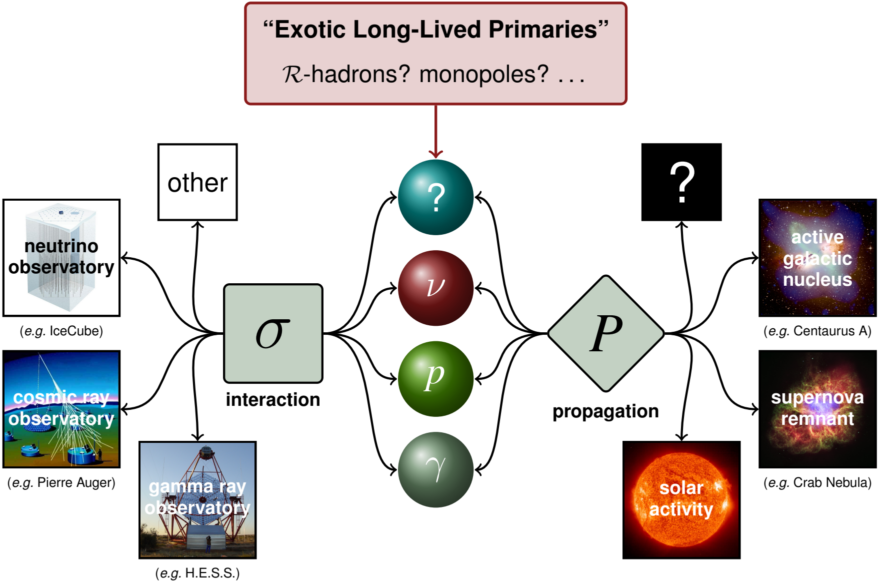


"Ultra-high γ Cosmic Rays"
Violation of Lorentz invariance
for $\gamma \gg 1$?

Interfaces for Exotic Physics



“Exotic Long-Lived Primaries”

$\mathcal{R}$-hadrons? monopoles? . . .

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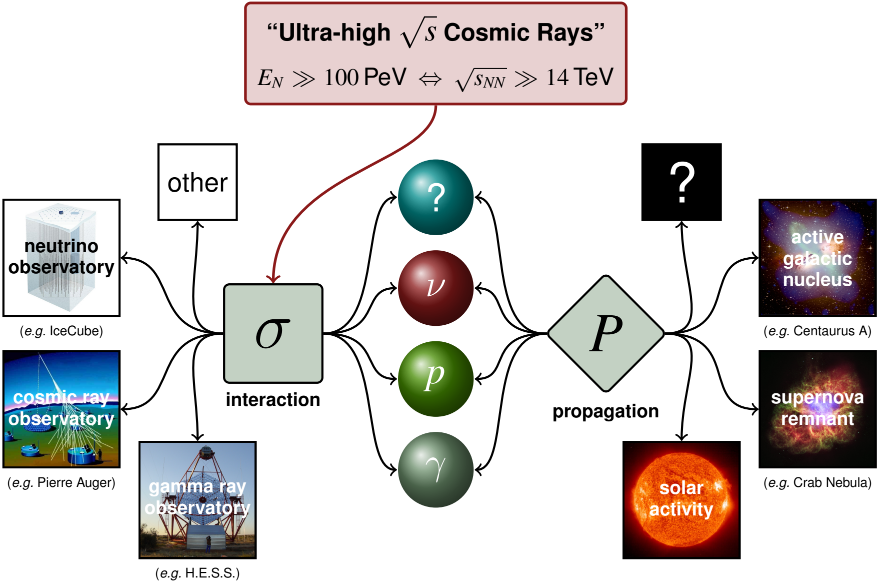
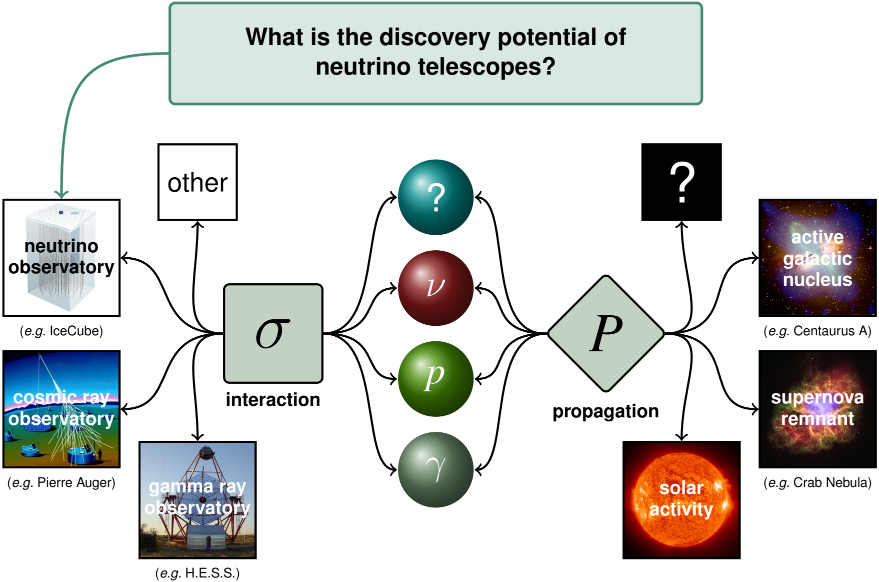


“Ultra-high $\sqrt{s}$ Cosmic Rays”

$E_N \gg 100$ PeV $\Leftrightarrow$ $\sqrt{s_{NN}} \gg 14$ TeV

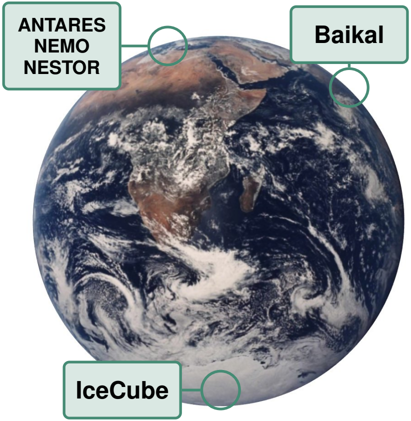
Interfaces for Exotic Physics



What is the discovery potential of neutrino telescopes?

Neutrino Telescopes

Neutrino telescopes are gigantic **“muon chambers”** observing the Cherenkov light of secondary charged particles created in neutrino-nucleon interactions.



Sensitivity for contained events

$$\frac{M_{\rm det}}{m_p}\times(2\pi)\times(EF)\times\sigma_{\nu N}\Big|_{E_\nu\sim 1\,{\rm PeV}}\sim 1\,{\rm yr}^{-1}$$

$$\Rightarrow\; M_{\rm det}\sim 1\,{\rm Gton}\quad\text{and}\quad V_{\rm det}\sim 1\,{\rm km}^3$$

Realization:

Observation of Cherenkov light in km^3-volumes of deep ocean water (Mediterranean), fresh water (Lake Baikal) or ice (Antarctic).

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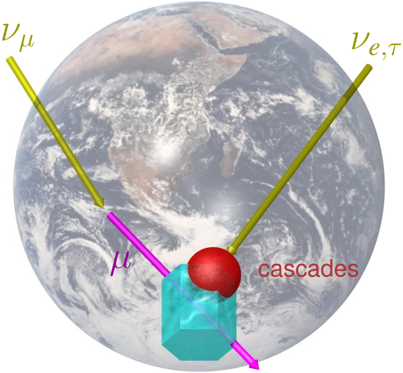

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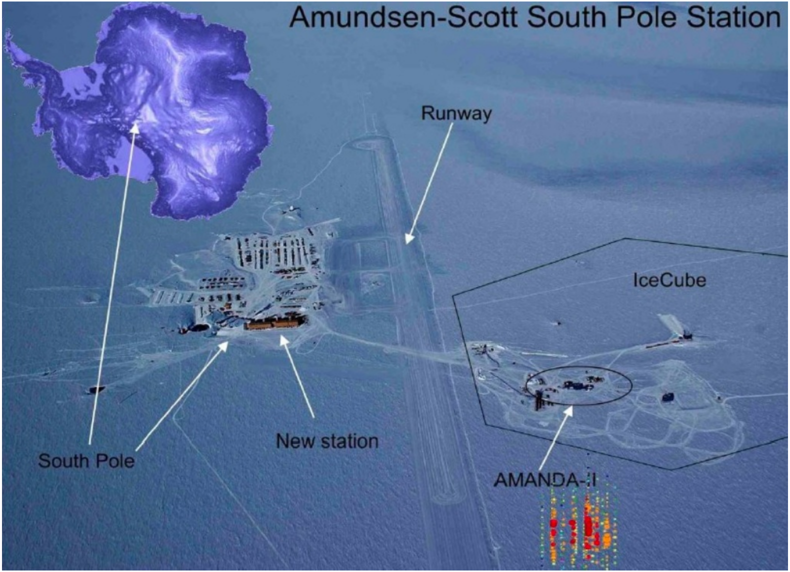
IceCube Neutrino Observatory



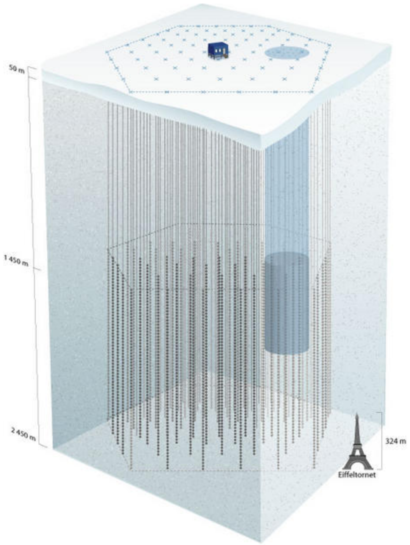
[from Dawn Williams]

IceCube in Depth

The IceCube observatory at the south pole is currently the largest neutrino telescope.

- up to 80 strings placed at a distance of 125m on a triangular grid
- 60 digital optical modules (DOMs) per string distributed along 1 km below a depth of ~ 1.5 km; each DOM is an autonomous unit with optical waveform recording and digitization
- 80 pairs of surface detectors (IceTop) for air shower detection
- embedded predecessor experiment AMANDA (blue cylinder)
- **current status:**
  more than 40 stations (sring & tanks) deployed

➜ **final instrumented volume:** $V \sim 1$**km**^{3}



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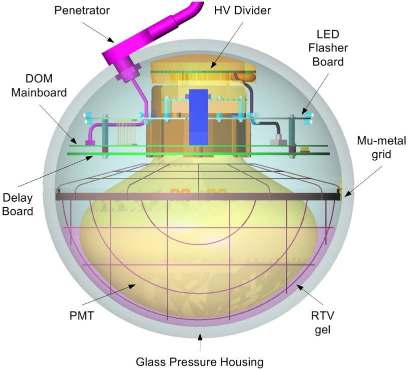
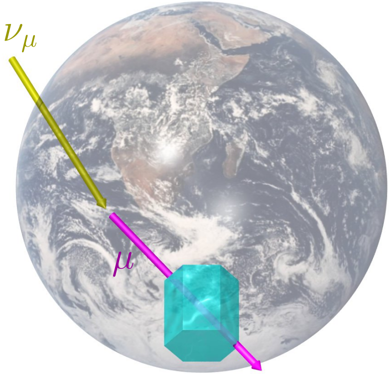
Sketch of a DOM

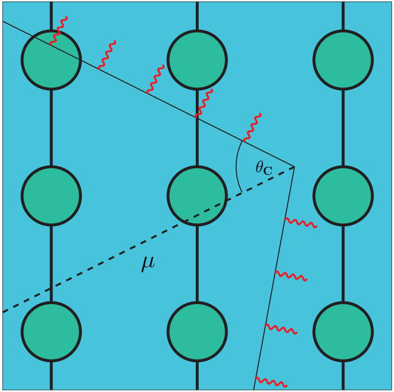


Neutrino Signals

Detection of ν_μ by up-going muon tracks:

- ✔ good angular resolution: $\Delta\theta \simeq 0.8^\circ - 2^\circ$
- ✘ energy resolution: $\Delta \log_{10} E_\mu \simeq 0.25 - 0.5$
- ✔ increased *effective* detection volume

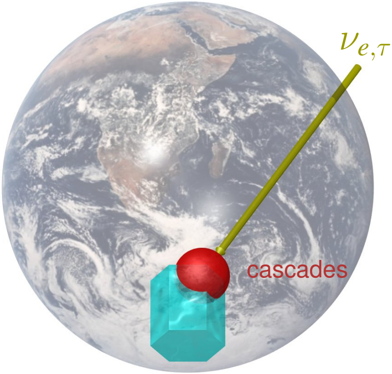


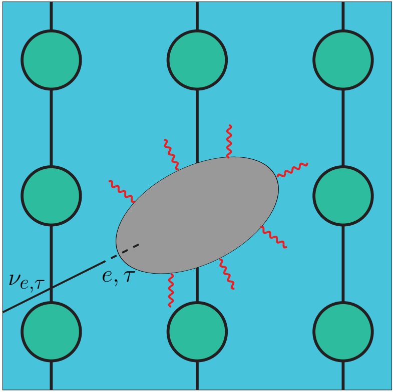


Neutrino Signals

Detection of ν_e and ν_τ by electromagnetic and hadronic cascades:

- ✗ poor angular resolution
- ✓ energy resolution: $\Delta \log_{10} E_\nu \simeq 0.1 - 0.2$
- ✓ full 4π sky coverage below 1 PeV

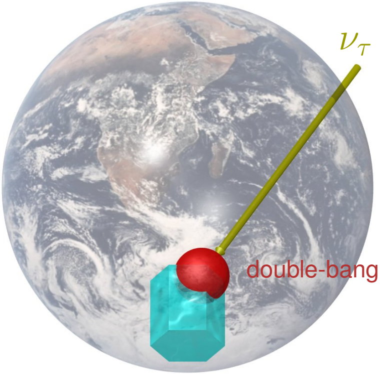


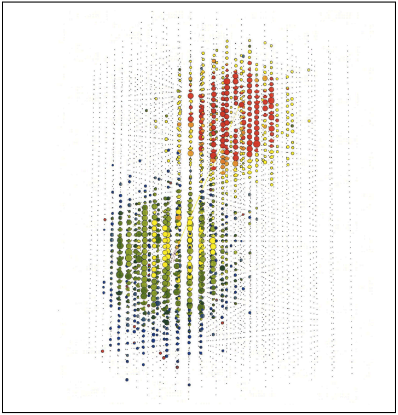


Neutrino Signals

Detection of high-energy ν_τ ($E_\nu > 1$PeV) by "double bang"

- ✓ also partial signals: "lollipop", "popillol", etc.
- ✓ good energy and angular resolution
- ✓ low background





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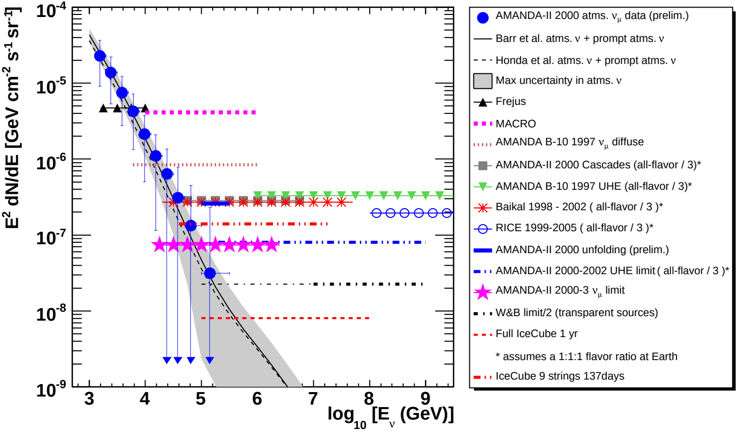
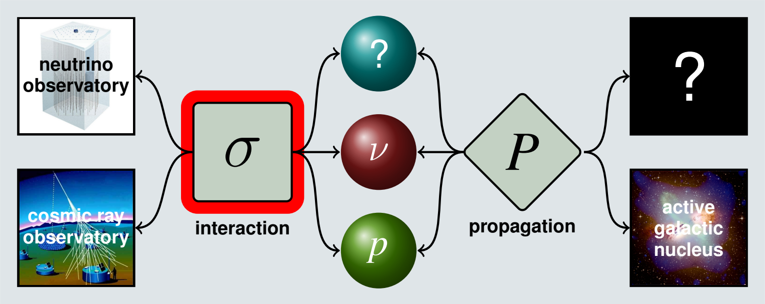


Upper limit on the diffuse ν_μ-flux from E^{-2}-sources for the 2000-2003 AMANDA-II data and expected sensitivity for IceCube. [ICRC, IceCube Collaboration'07]

Exotic Interactions:

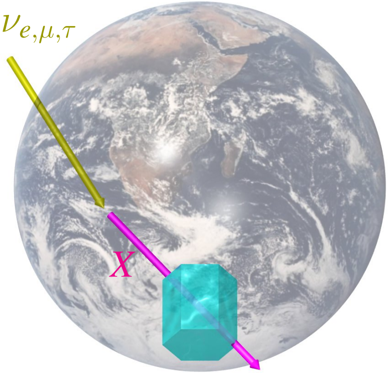
Ultra-High $\sqrt{s}$ Cosmic Rays



Exotic Signals?

Cosmic rays or neutrinos ($E \gtrsim 1$ PeV) may produce new long-lived charged particles (X) in interactions with nucleons in the atmosphere or the Earth's interior.

[Albuquerque/Burdman/Chacko '03,MA/Illana/Masip/Meloni '07,Ando/Beacom/Profumo/Rainwater'07]

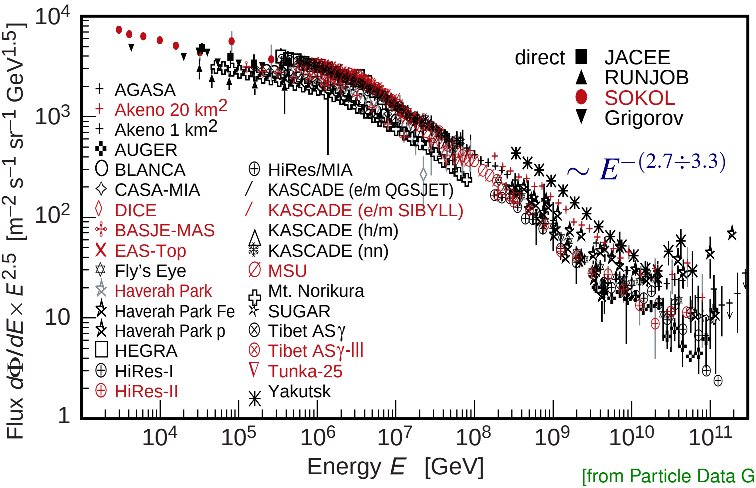


$$\boxed{\#\text{events} \sim \int \mathrm{d}t\,\mathrm{d}\Omega \left(\frac{\sigma^{\text{new}}}{\sigma^{\text{SM}}}\right) \times A_{\text{eff}}(\Omega) \times F}$$

- production of exotics X is **suppressed** by the mass scale: $\sigma^{\text{new}} \propto m_X^{-2}$
- average energy loss range **increases** with mass: $R_X / R_\mu \sim m_X / m_\mu$
- effective area **increases**: $A_{\text{eff}} \propto R_X^2(E_0, E) \propto m_X^2$
- **What is the flux F of particles?**

The Cosmic Leg

The all-particle spectrum (as $E^{2.5} \times F$) of cosmic rays.



[from Particle Data Group '05]

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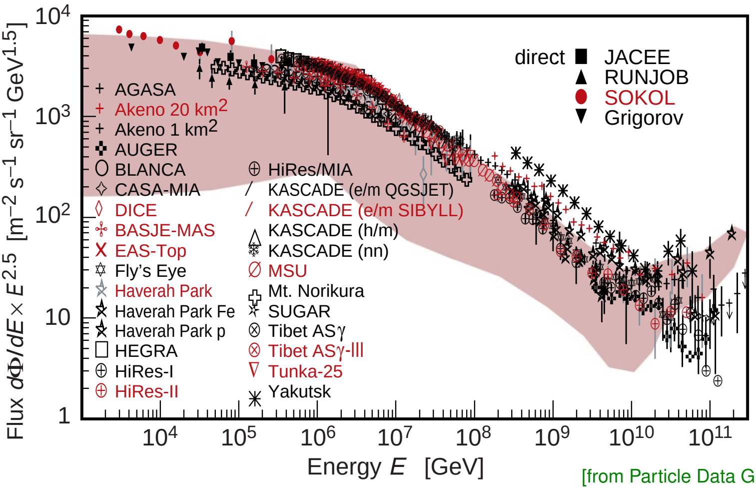
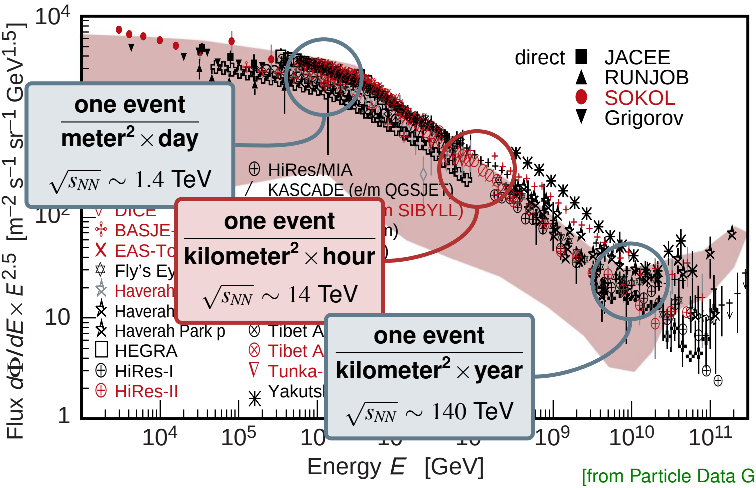


[from Particle Data Group '05]

The Cosmic Leg

On collision with nucleons $\sqrt{s} \sim \sqrt{2m_pE}$ $\Rightarrow$ **event rate** $\sim (\sqrt{s})^{-4}$



one event / **meter^2 × day**

$\sqrt{s_{NN}} \sim 1.4$ TeV

one event / **kilometer^2 × hour**

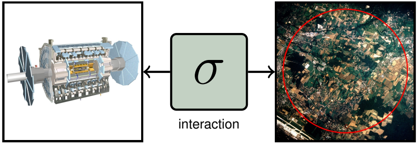
$\sqrt{s_{NN}} \sim 14$ TeV

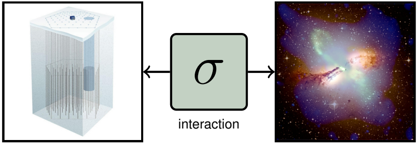
one event / **kilometer^2 × year**

$\sqrt{s_{NN}} \sim 140$ TeV

[from Particle Data Group '05]

Terrestrial vs. Cosmic Laboratories





Large Hadron Collider

✗ **energy:** $\sqrt{s_{pp}} = 14$ TeV
or $\sqrt{s_{\text{PbPb}}} = 1.15$ PeV

✓ **mode:** p-p or Pb-Pb

✓ **luminosity** (p-p):
$\mathcal{L}_{pp}^{\text{peak}} \sim 10^{34}$ cm^{-2} s^{-1}

Cosmic Laboratory

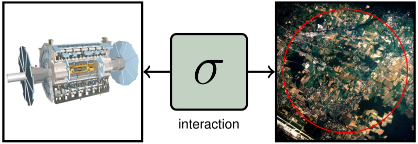
✓ **energy:** $\sqrt{s_{NN}}$ up to 100 TeV
(N : nucleon)

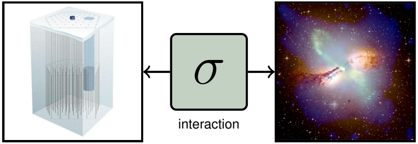
✗ **mode:** "multi-messenger"

✗ **luminosity** ($\sqrt{s_{NN}} \sim 14$ TeV):
$\mathcal{L}_{NN} \sim (2\pi) \times (EF) \sim 10^{-13}$ cm^{-2} s^{-1}

CR luminosity (at $\sqrt{s_{pN}} \sim 14$ TeV) is about 47 orders of magnitude below state-of-the-art terrestrial accelerators like the LHC … *fortunately*!

Terrestrial vs. Cosmic Laboratories





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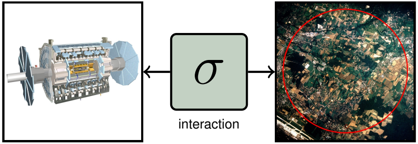

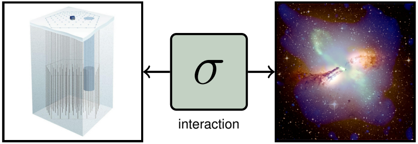

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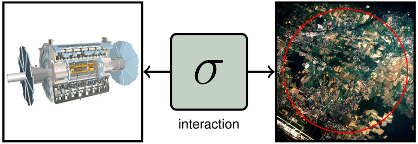

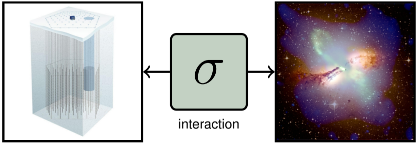

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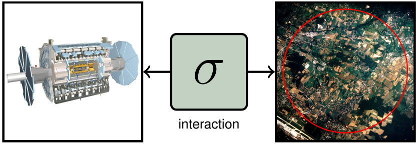

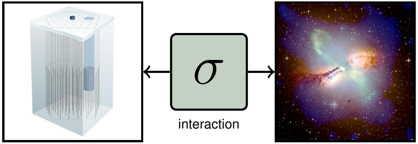

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“global” luminosity: $\mathcal{L}_{N\oplus} \sim N_{\oplus}\mathcal{L}_{NN}$ ($N_{\oplus}$ **: nucleon targets**)

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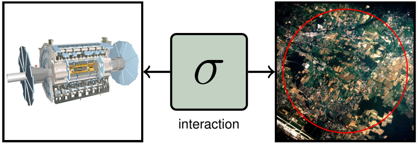

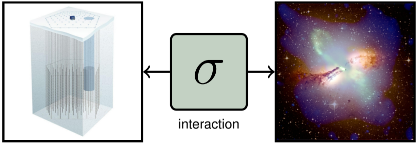

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$$N_\oplus \sim \frac{A_{\text{eff}}}{\sigma^{\text{SM}}} \ll \frac{4\pi R_\oplus^2}{\sigma^{\text{SM}}} \sim \begin{cases} 10^{43}\ \textbf{for nucleons}\ (\sigma_{NN} \sim 100\,\text{mb}) \\ 10^{50}\ \textbf{for neutrinos}\ (\sigma_{\nu N} \sim 10\,\text{nb}) \end{cases}$$

Detection Strategy

$$\boxed{\#\text{events} \sim \int \mathrm{d}t\,\mathrm{d}\Omega \left(\frac{\sigma^{\text{new}}}{\sigma^{\text{SM}}}\right) \times A_{\text{eff}}(\Omega) \times F}$$

- **primary fluxes**
  - chemical compostion at $\sqrt{s} \sim 14$ TeV ($E \sim 10^8$ GeV) dominated by nucleons
  - neutrinos fluxes at least one order of magnitude smaller at these energies
- **integrated aperture**
  - large detection areas (*e.g.* $\mathcal{O}(10^6)\,\text{km}^2 \sim \mathcal{O}(10^{-3}) \times A_\oplus$ at EUSO)
  - *effective* detection area: $A_{\text{eff}} \sim V/\lambda_{\text{int}}$ ➜ Gigaton/Teraton detectors
  - *longevity* of secondary particles increase V (*e.g.* μ from ν_μ-interactions)
- **relative production probability**
  - beyond the SM typically $\sigma^{\text{new}} \ll \sigma^{\text{SM}}$ (*e.g.* supersymmetry)
  - new interaction channels more probable ($\sigma^{\text{new}}/\sigma^{\text{SM}}$) under otherwise weakly interacting particles (*e.g.* neutrinos)

! **signal to background ratio**

  - "Today's signal: tomorrow's background."
  - typically $\mathcal{O}(1)$ event per year requires an extremely low SM background

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$$\#\text{events} \sim \int \mathrm{d}t\,\mathrm{d}\Omega \left(\frac{\sigma^{\text{new}}}{\sigma^{\text{SM}}}\right) \times A_{\text{eff}}(\Omega) \times F$$

- **primary fluxes**
  - chemical compostion at $\sqrt{s} \sim 14$ TeV ($E \sim 10^8$ GeV) dominated by nucleons
  - neutrinos fluxes at least one order of magnitude smaller at these energies
- **integrated aperture**
  - large detection areas (*e.g.* $\mathcal{O}(10^6)$ km^2 $\sim \mathcal{O}(10^{-3}) \times A_\oplus$ at EUSO)
  - *effective* detection area: $A_{\text{eff}} \sim V/\lambda_{\text{int}}$ ➜ Gigaton/Teraton detectors
  - *longevity* of secondary particles increase V (*e.g.* μ from ν_μ-interactions)
- **relative production probability**
  - beyond the SM typically $\sigma^{\text{new}} \ll \sigma^{\text{SM}}$ (*e.g.* supersymmetry)
  - new interaction channels more probable ($\sigma^{\text{new}}/\sigma^{\text{SM}}$) under otherwise weakly interacting particles (*e.g.* neutrinos)

! **signal to background ratio**
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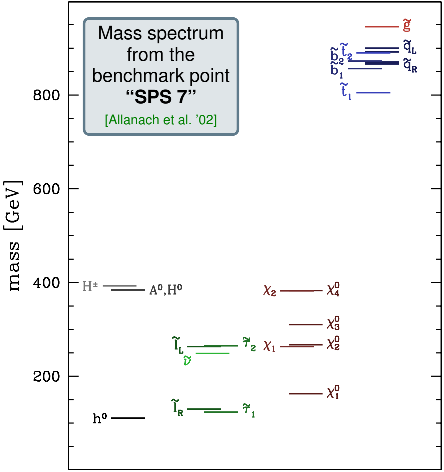
Candidate Signal: Supersymmetry

The minimal supersymmetric extension of the Standard Model (MSSM).

Names	Spin	$P_{\mathcal{R}}$	Mass Eigenstates
Higgs bosons	0	$+1$	h^0 H^0 A^0 $H^\pm$
squarks	0	-1	$\widetilde{u}_L$ $\widetilde{u}_R$ $\widetilde{d}_L$ $\widetilde{d}_R$ $\widetilde{s}_L$ $\widetilde{s}_R$ $\widetilde{c}_L$ $\widetilde{c}_R$ $\widetilde{t}_1$ $\widetilde{t}_2$ $\widetilde{b}_1$ $\widetilde{b}_2$
sleptons	0	-1	$\widetilde{e}_L$ $\widetilde{e}_R$ $\widetilde{\nu}_e$ $\widetilde{\mu}_L$ $\widetilde{\mu}_R$ $\widetilde{\nu}_\mu$ $\widetilde{\tau}_1$ $\widetilde{\tau}_2$ $\widetilde{\nu}_\tau$
neutralinos	$1/2$	-1	χ_1^0 χ_2^0 χ_3^0 χ_4^0
charginos	$1/2$	-1	χ_1 χ_2
gluino	$1/2$	-1	$\widetilde{g}$
gravitino	$3/2$	-1	$\widetilde{G}$


Mass spectrum from the benchmark point **“SPS 7”**

[Allanach et al. ’02]

Candidate Signal: Supersymmetry

$\mathcal{R}$-parity conservation: next-to-lightest SUSY particle (NLSP) can only decay into states containing the lightest SUSY particle (LSP).

Names	Spin	$P_\mathcal{R}$	Mass Eigenstates
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ne		-1	χ_1^0 χ_2^0 χ_3^0 χ_4^0
c		-1	χ_1 χ_2
gluino	$1/2$	-1	$\tilde g$
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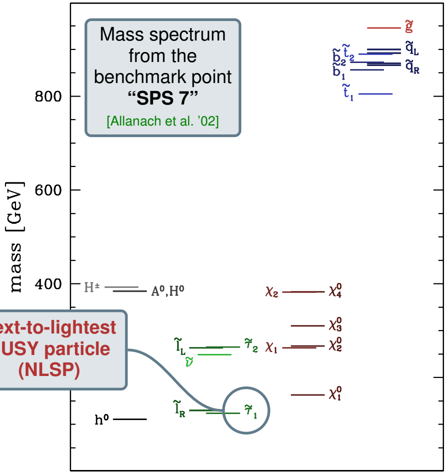
$\mathcal{R}$**-parity**

lightest SUSY particle (LSP)

next-to-lightest SUSY particle (NLSP)


Mass spectrum from the benchmark point **"SPS 7"**

[Allanach et al. '02]

Long-lived Stau NLSPs

- A stau NLSP can be considered as stable if $\tau\beta\gamma$ is larger than the Earth's diameter $2R_\oplus$ (or energy loss range).
- Above production threshold $E_{\rm CM} > 2m_{\tilde\tau} \ \Rightarrow\ \gamma \gtrsim m_{\tilde\tau}/m_p$ and $\beta \sim 1$:

$$\tau \gtrsim \tau_\oplus \simeq 0.4{\rm ms}\left(\frac{m_{\tilde\tau}}{100\,{\rm GeV}}\right)^{-1}$$

- **SUSY scenarios with quasi-stable stau NLSP include:**
  - gravitino LSP in supergravity-inspired SUSY breaking scenarios (mSUGRA)
    [Feng/Su/Takayama'04,Ellis/Olive/Santoso/Spanos'04,Ellis/Raklev/Oye'06]
  - gravitino LSP in gauge-mediated SUSY breaking (GMSB)
    [Dine&Nelson'93,Dicus/Dutta/Nandi'97,Feng&Moroi'98,Giudice/Rattazzi'99]
  - stau-neutralino near-degeneracy: $m_{\tilde\tau} - m_\chi \lesssim 1$ GeV
    [Griest&Seckel'91,Ellis/Falk/Olive/Srednicki'97,Gladyshev/Kazakov/Paucar'05,Jittoh et al.'06]
  - axino LSP scenarios [Covi/Roszkowski/Ruis de Austri/Small'04,Brandenburg et al.'05]
  - sneutrino LSP scenarios
    [Arkani-Hamed et al.'00,Hooper/March-Russell/West'05,Asaka/Ishiwata/Moroi'06]

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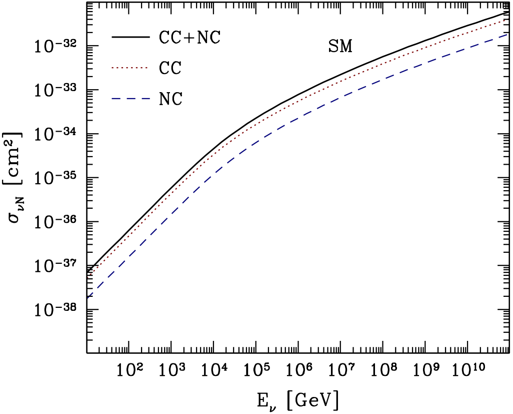
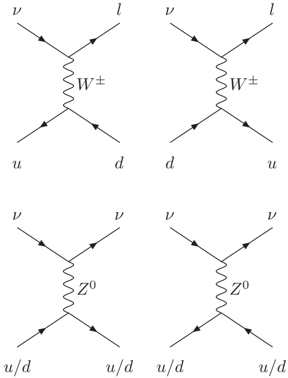
Staus from Astrophysical Neutrinos

Two SUSY mass spectra with a $\widetilde{\tau}_R$ NLSP:

- **"min $\widetilde{m}$"**: $m_{\chi} = m_{\chi^0} = m_{\widetilde{l}} = 100$ GeV and $m_{\widetilde{q}} = 300$ GeV
- **"SPS 7"**: SUSY masses corresponding to the benchmark point SPS 7

[*"The Snowmass Points and Slopes"*, Allanach et al. '02]





[Albuquerque/Chacko/Burdman '04,'06;MA/Kersten/Ringwald '06]

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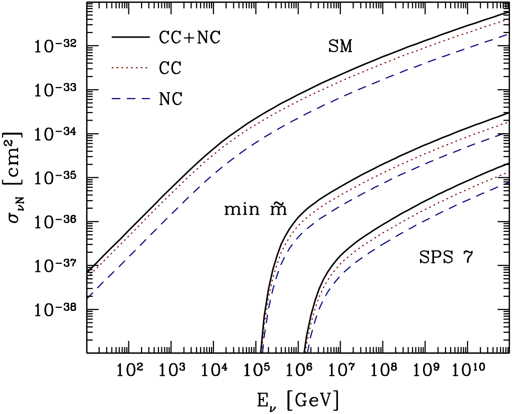
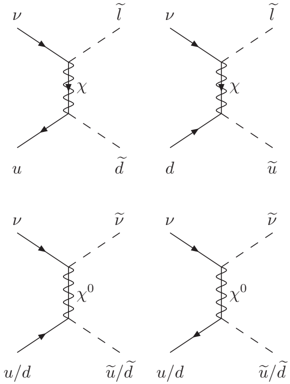




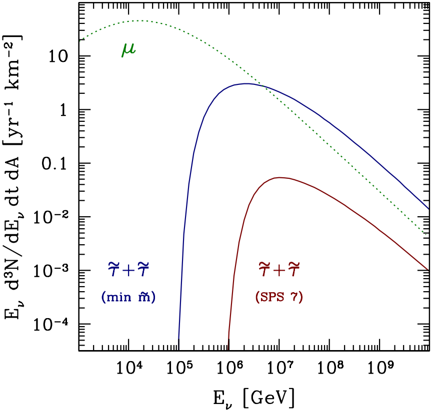
[Albuquerque/Chacko/Burdman ’04,’06;MA/Kersten/Ringwald ’06]

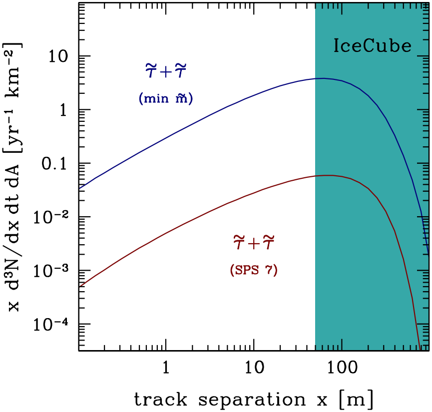
Staus from Astrophysical Neutrinos

- Neutrino benchmark flux: $E_\nu^2\, F_{\rm WB}(E_\nu) \approx 2\times 10^{-8}$ cm^{-2} s^{-1} sr^{-1} GeV (per flavor)

  [Waxman/Bahcall '98]

- only small background from SM processes (coincident muons, di-muons from decaying hadrons) [Albuquerque/Burdman/Chacko'06]



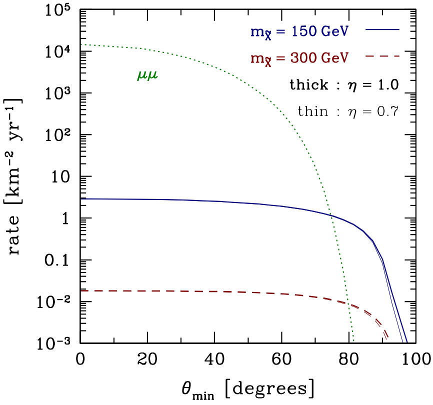


Staus from Cosmic Rays

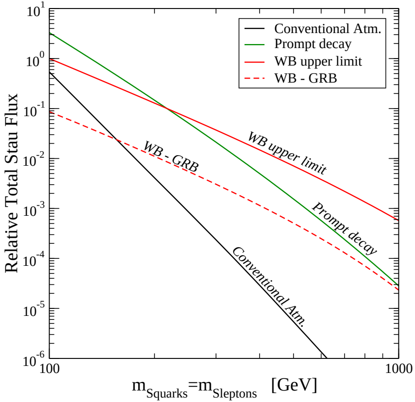
- Flux of cosmic rays is (reasonably) well-known at around 10^6 GeV.
- Two channels have been considered:

  “direct”: prompt staus from gluino and squark production

  “indirect”: staus from atmospheric neutrinos



[MA/Illana/Masip/Meloni ’07]



[Ando/Beacom/Profumo/Rainwater ’07]

Stau NLSPs at Neutrino Telescopes

1. Life-time of a $\widetilde{\tau}$ NLSP with $\widetilde{G}$ LSP

$$\frac{\tau}{1\text{ms}} \simeq \left(\frac{m_{3/2}}{100\text{ keV}}\right)^2 \left(\frac{m_{\widetilde{\tau}}}{100\text{ GeV}}\right)^{-5} + \mathcal{O}\left(\frac{m_{3/2}}{m_{\widetilde{\tau}}}\right)$$

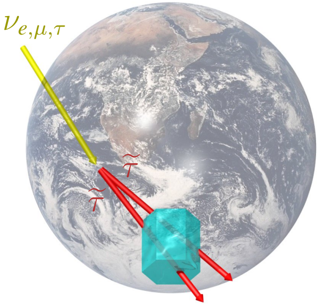
Cosmic Neutrinos:

- rates depend on fluxes and SUSY mass spectrum
- $\mathcal{O}(1)$ stau pair per year possible for **light mass spectrum and WB flux**

2. Energy loss length of a $\widetilde{\tau}$ NLSP

$$\left(\frac{L}{L_\mu}\right) \sim \left(\frac{m_{\widetilde{\tau}}}{m_\mu}\right) \times \mathcal{O}(1)$$

[*e.g.* Huang/Reno/Sarcevic/Uscinski '05,'06]



[Albuquerque/Burdman/Chacko '04,'06]

[MA/Kersten/Ringwald '06]

3. $\mathcal{R}$-parity conservation

➜ pair-production of strongly boosted $\widetilde{\tau}$ NLSPs appearing as quasi-parallel tracks

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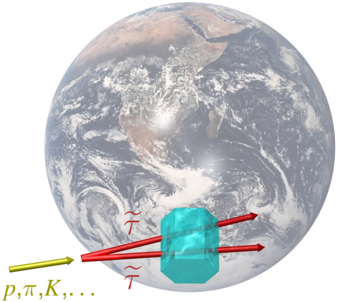
CRs & atmospheric neutrinos:

- $\mathcal{O}(1)$ "prompt" stau pair per year for **light squarks and gluinos**
- $\mathcal{O}(1)$ stau pair per year from **large prompt atmospheric ν-fluxes** possible



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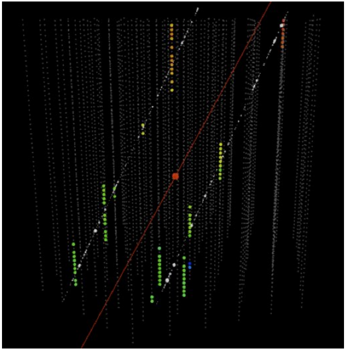
Work in Progress for IceCube:

- **MC for signal and background**

➜ trigger/filtering estimates



[courtesy of A.Olivas]

Other Candidate Signals

- **quasi-horizontal showers compared to Earth-skimming ν_τ**
  - #showers *rise* with cross section ↔ flux of ν_τ *depleted* by a large cross section
  - test of QCD parton distributions at small Bjorken-x :
    $x \sim M^2_{Z/W}/(2m_pE_\nu) \sim 10^4\text{GeV}/E_\nu$
  - test of exotic neutrino interactions like low-scale gravity effects or non-perturbative electroweak instanton-mediated processes

[Anchordoqui/Han/Hooper/Sarkar ’05; Anchordoqui/Cooper-Sarkar/Hooper/Sarkar ’06]

- **inelasticity measurement and particle multiplicity**
  - “anomalous” inelasticities as a probe of *e.g.* leptoquark production and quantum black holes of low-scale gravity

[Kowalski/Ringwald/Tu ’02; Anchordoqui et al. ’06; Anchordoqui/Glenz/Parker ’07]

- **non-standard neutrino oscillations**
  - quantum gravity effects [Lisi/Marrone/Montanino ’00,’03,Anchordoqui et al. ’05]
  - neutrino decay [Barger et al. ’99,Beacom et al. ’02]
- . . .

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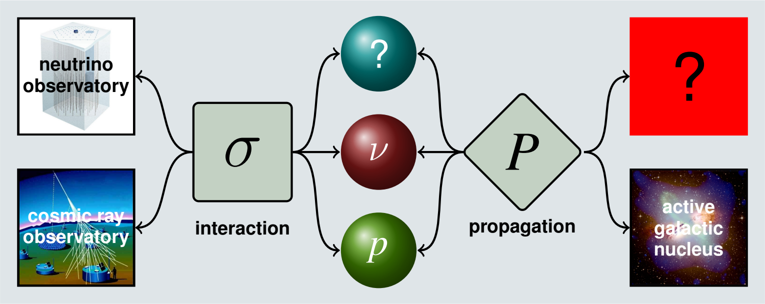
Exotic Sources:

Indirect Signals of Dark Matter



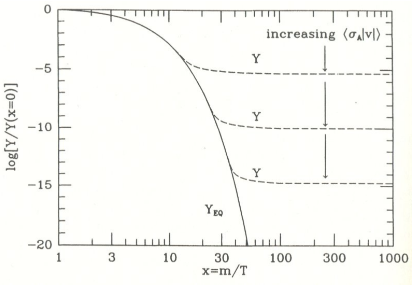
Dark Matter WIMPs

- observed dark matter density:
  $\Omega_{\rm DM}h^2 \sim 0.1$ [WMAP, Spergel et al.'07]
- comoving number density Y of a thermal relic X (Boltzmann equation):

$$\frac{x}{Y_{\rm EQ}}\frac{{\rm d}Y}{{\rm d}x} = -\frac{\langle\sigma_A|v|\rangle\, sY_{\rm EQ}}{H}\left[\left(\frac{Y}{Y_{\rm EQ}}\right)^2 - 1\right]$$

$$Y_{\rm EQ} \propto x^{3/2}\exp(-x) \quad (x = m/T \gg 1)$$

$$H(x) = x^{-2}H(m)$$



[Kolb&Turner'90]

- annihilation rate $\langle\sigma_A|v|\rangle\, n_{\rm EQ}$ Boltzmann-suppressed at late times

➜ number per comoving volume "freezes out" for $n_{\rm EQ}\,\langle\sigma_A|v|\rangle \lesssim H$

- weak-scale solution: $\Omega_X h^2 \sim \Omega_{\rm DM}h^2 \times \dfrac{c\alpha^2(100{\rm GeV})^{-2}}{\langle\sigma_A|v|\rangle}$
- popular WIMP candidate:
  neutralino (χ) LSP in R-parity conserving supersymmetric extensions of the Standard Model

Indirect WIMP Detection

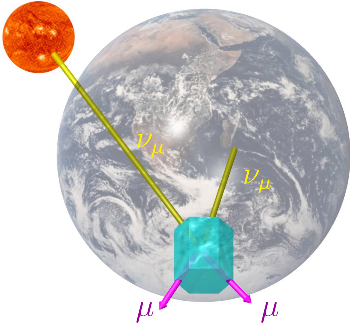
- WIMP accumulation in massive celestial bodies (Sun and Earth): $\dot{N} = C - AN^2$
- annihilation rate: $A = \langle \sigma_{\mathrm{A}} |v| \rangle / V_{\mathrm{eff}}$
- capture rate C depend on the elastic scattering of WIMPs off nuclei:
  - *spin-independent* (scaling with target mass) and
  - *spin-dependent* (scaling with target spin)
- equilibrium: $N \simeq \sqrt{C/A}$ $(t \gg 1/\sqrt{AC})$ ➜ annihilation rate today: $\Gamma = C/2$

✔ annihilation channels:
$\chi\chi \to W^+W^-$ / $b\bar{b}$ / $c\bar{c}$ / $\tau^+\tau^- \to \nu$'s + . . .

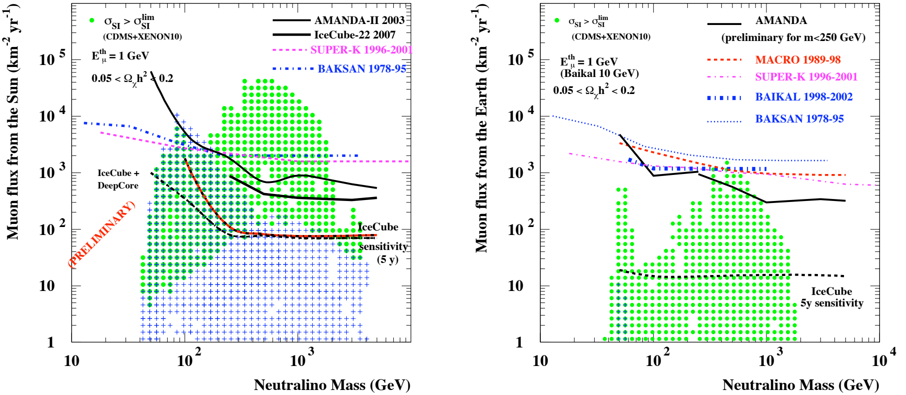
➜ Neutrinos are the unique messengers of these processes.

✘ $\langle E_\mu \rangle \simeq (1-y) \langle E_\nu \rangle \simeq \frac{m_\chi}{3}$ to $\frac{m_\chi}{6}$

➜ Use the dense AMANDA inner core with lower energy threshold at low WIMP masses.



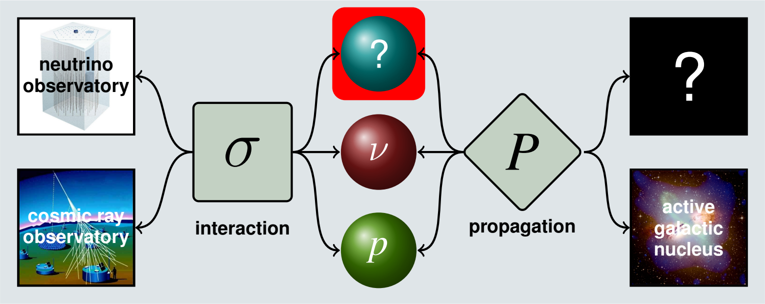
IceCube WIMP sensitivity



90% CL upper limit on the muon flux form hard χ annihilations in the Sun (left) and in the center of the Earth (right). Markers (✚) show cosmologically relevant MSSM models and dots (●) the parameter space excluded by XENON [Angle et al.'07].

Exotic Particles:

Direct Signals of Monopoles



Magnetic Monopoles

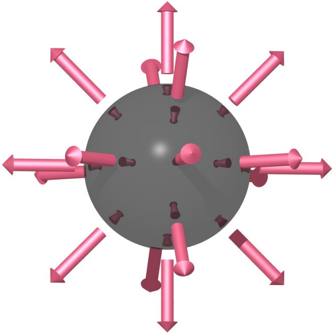
- Spontaneous breaking of gauge symmetry $\mathcal{G} \to \mathcal{H}$ allows for monopole defects if $\pi_2(\mathcal{G}/\mathcal{H}) \neq \mathbf{1}$.
- $\pi_1(\mathcal{G}) = \mathbf{1}$ (*simply connected*) ➜ $\pi_2(\mathcal{G}/\mathcal{H}_{\text{SM}}) = \pi_1(\mathcal{H}_{\text{SM}}) \neq \mathbf{1}$
- *e.g.* "hedgehog solution" for $\mathrm{SO}(3) \to \mathrm{U}(1)$ with triplet Higgs field ϕ^a

['t Hooft'74,Polyakov'74]

$$V(\phi^a) = \frac{\lambda}{8}(\phi^a\phi^a - \sigma^2)^2$$

$$\phi^a \xrightarrow{r\to\infty} \sigma\hat{r}_a \quad \text{and} \quad A_i^a \xrightarrow{r\to\infty} \epsilon_{iab}\frac{\hat{r}_b}{er}$$

$$\Rightarrow B_i = \frac{1}{2}\epsilon_{ijk}F^3_{jk} \xrightarrow{r\to\infty} \frac{1}{e}\frac{\hat{r}_i}{r^2}$$



➜ **magnetic monopole** with

mass $m_{\text{M}} \sim \dfrac{m_{\text{V}}}{\alpha}$ and carge $g = \dfrac{4\pi}{e}$

Magnetic Monopoles

- **Kibble mechanism:** [Kibble'80]
  Monopole production in the early universe at $T_{\text{cr}} \sim m_{\text{V}}$ gives roughly one monopole per correlated volume ($\sim$ horizon size in 2nd order phase transition).

- "naive" monopole abundance:

$$\Omega_{\text{M}} h^2 \simeq 10^{13} \left(\frac{T_{\text{cr}}}{10^{14}\,\text{GeV}}\right)^3 \left(\frac{m_{\text{M}}}{10^{16}\,\text{GeV}}\right)$$

"monopole problem"

- standard solution: inflationary phase for $T < T_{\text{cr}}$ leaving typical monopole fluxes unobservable

➜ Searches for relic monopoles are only promising for non-inflationary models ("flatness and horizon problem"?) and/or light monopoles ($m_{\text{M}} \lesssim 10^{11}$ GeV) produced after inflation.

- **overclosure bound:** $\Omega_{\text{M}} h^2 < \Omega_{\text{tot}} h^2 < 1$ and uniform monopole distribution

$$J_{\text{M}} \lesssim 10^{-15} \text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1} \left(\frac{v}{10^{-3}c}\right)\left(\frac{10^{16}\,\text{GeV}}{m_{\text{M}}}\right)$$

Magnetic Monopoles

- **Kibble mechanism:** [Kibble'80]
  Monopole production in the early universe at $T_{\mathrm{cr}} \sim m_{\mathrm{V}}$ gives roughly one monopole per correlated volume ($\sim$ horizon size in 2nd order phase transition).

- "naive" monopole abundance:

$$\Omega_{\mathrm{M}} h^2 \simeq 10^{13} \left(\frac{T_{\mathrm{cr}}}{10^{14}\,\mathrm{GeV}}\right)^3 \left(\frac{m_{\mathrm{M}}}{10^{16}\,\mathrm{GeV}}\right)$$

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Limits on Monopole Fluxes

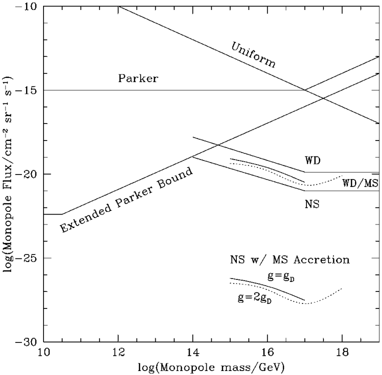
- **Parker bound:** [Parker'70]
  "monopole short-circuit" vs. "galactic dynamo"

$$J_{\rm M} \lesssim 10^{-15}{\rm cm}^{-2}{\rm sr}^{-1}{\rm s}^{-1}\left(\frac{B}{3\,\mu{\rm G}}\right)\left(\frac{3\times10^{7}\,{\rm yr}}{\tau}\right)\left(\frac{r}{30\,{\rm kpc}}\right)^{1/2}\left(\frac{300\,{\rm pc}}{\ell}\right)^{1/2}$$

- **"extended" Parker bound:** [Adams et al.'93]
  survival and growth of small magnetic seed fields

- **monopole catalysis:** [Rubakov'81,Callan'81]
  strong limits from nucleon decay in white dwarfs (WD) or neutron stars (NS)
  [Kolb/Colgate/Harvey'82,Dimopoulos/Preskill/Wilczek'82]
  [Freese/Turner/Schramm'83]

➜ experimental focus on **non-catalyzing** monopoles [e.g. Kephart/Shafi'01]



[Freese&Krasteva'99]

Magnetic Monopoles at Cherenkov Telescopes

- **Relativistic** monopoles mimic heavy ions with $Z \sim \dfrac{1}{2\alpha} \sim 68$.

➜ $0.75 \lesssim \beta$: direct Cherenkov photons N_γ per path dx and wavelength $d\lambda$

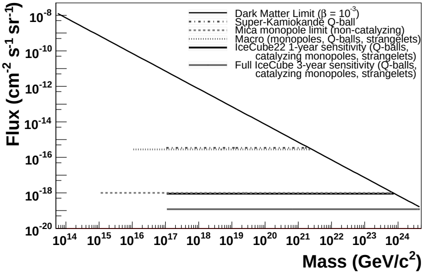
$$\frac{\mathrm{d}^2 N_\gamma^M}{\mathrm{d}x\mathrm{d}\lambda} = \left(\frac{\alpha_{\mathrm{M}}}{\alpha} n_{\mathrm{ice}}^2\right) \times \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n_{\mathrm{ice}}^2}\right) \simeq 8300 \times \frac{\mathrm{d}^2 N_\gamma^e}{\mathrm{d}x\mathrm{d}\lambda}$$

➜ $0.5 \lesssim \beta \lesssim 0.75$: Cherenkov light from “delta electrons”

- **Non-relativistic nucleon-catalyzing monopoles** (also **Q-balls and strangelets**) are discriminated from BG by the duration of their photon signal.

Relativistic monopoles:

- **AMANDA-II** prelim. limit (90%C.L.)
  $J_{\mathrm{M}} \lesssim 3.7 \times 10^{-17}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$
  (upward MPs with $M \gtrsim 10^{11}$ GeV and $\beta \sim 1$)
- **IC80** estimated sensitivity $(\beta \sim 1)$
  $J_{\mathrm{M}} \sim 7 \times 10^{-18}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$



Conclusions

- IceCube construction runs smoothly and will reach the instrumented volume of **one cubic-kilometer** in about two years.
- Neutrino astronomy is a **key contribution to “classical” physics**, like the
  - observation of extremely distant and old sources,
  - particle acceleration in CR sources,
  - cosmic ray composition and propagation,
  - . . .
- IceCube is also **sensitive to “exotic” physics** in the form of
  - long-lived charged particles (**stau NLSPs**) from high-energy cosmic ray and neutrino interactions,
  - neutrino fluxes from **WIMP** annihilations,
  - relic **monopoles**, **Q-balls**, **stranglets**,
  - . . .