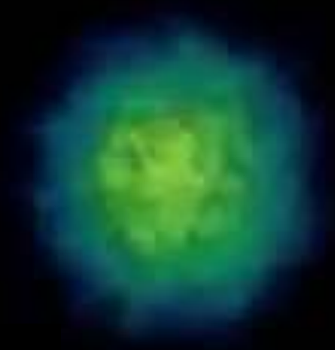
Imperial College London

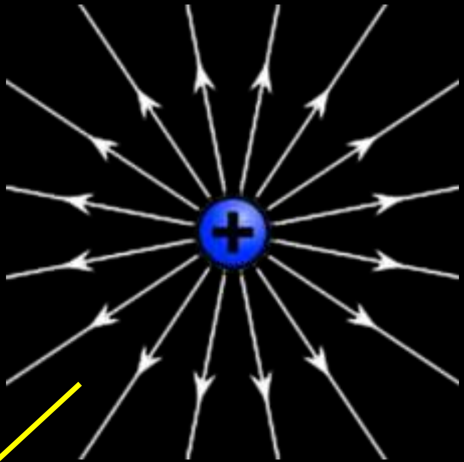
Magnetic Monopoles - an Overview



Arttu Rajantie

Exotic Physics with Neutrino Telescopes 2013
Marseille, 3 April 2013

Maxwell Equations



$$\vec{\nabla} \cdot \vec{E} = \rho_{\rm E}$$

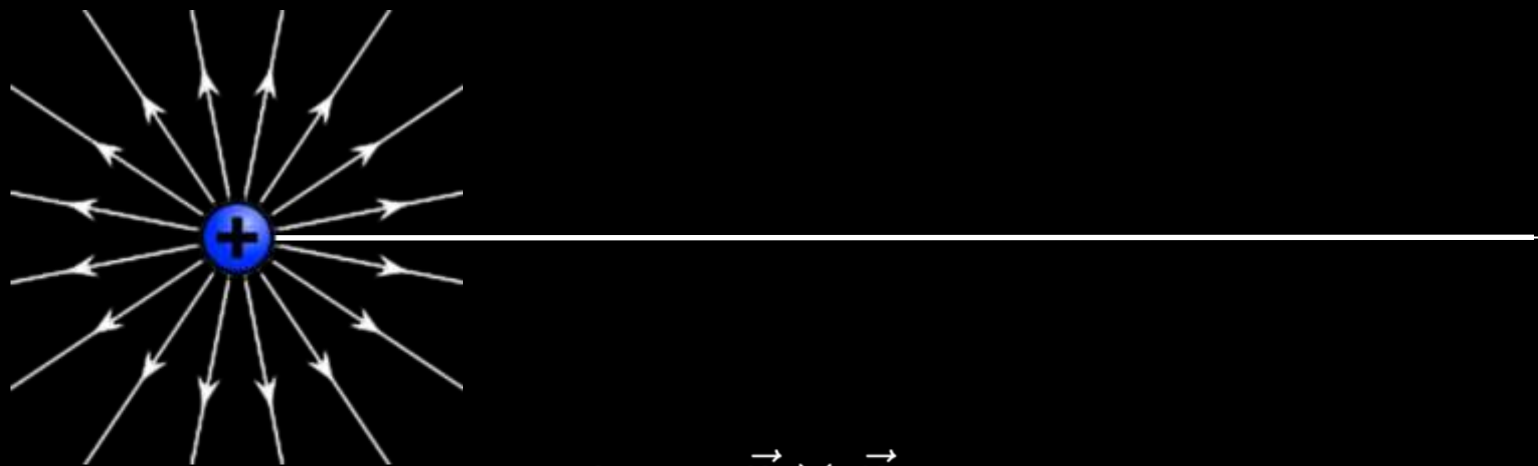
$$\vec{\nabla} \cdot \vec{B} = \rho_{\rm M}$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} - \vec{j}_{\rm M}$$

$$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + \vec{j}_{\rm E}$$

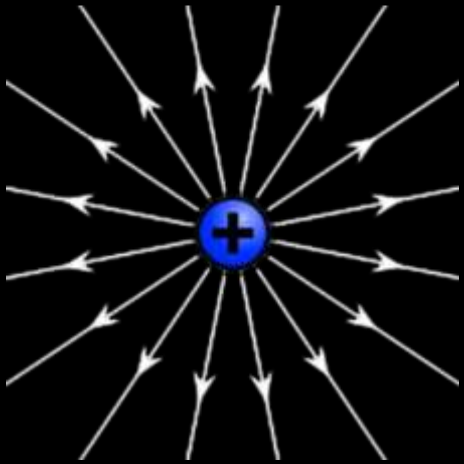
Duality $\vec{E} \leftrightarrow \vec{B}$

Dirac Monopole (1931)



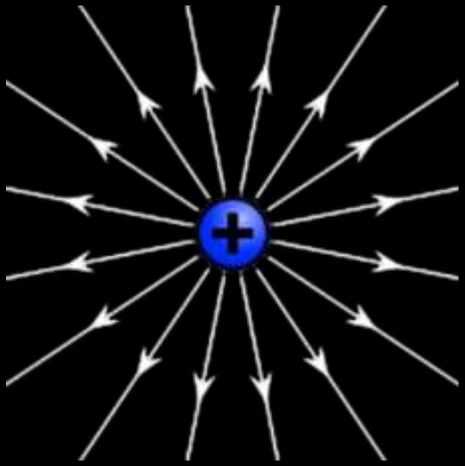
- Vector potential $\vec{A}(\vec{r}) = \dfrac{g}{4\pi|\vec{r}|}\dfrac{\vec{r}\times\vec{n}}{|\vec{r}|-\vec{r}\cdot\vec{n}}$
- Dirac string: Singularity along $\vec{n}$
- QM: Unobservable if $g = g_0 = 2\pi/e$

Dirac Monopole (1931)



- Dirac quantisation condition:
  All electric and magnetic charges must satisfy $\frac{eg}{2\pi} \in \mathbb{Z}$
- Existence of monopoles would explain observed quantisation of electric charge
- *"…one would be surprised if Nature had made no use of it"*

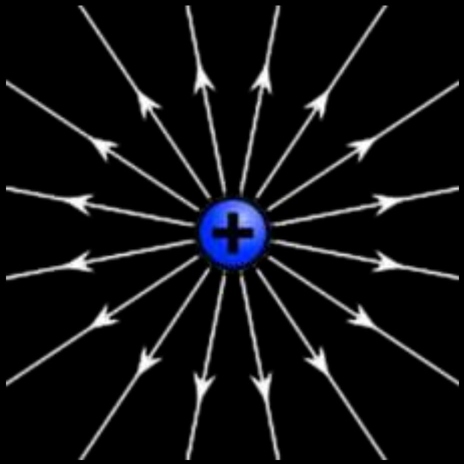
Dyons



- Both electric and magnetic charge
- Quantisation condition (Schwinger 1966):

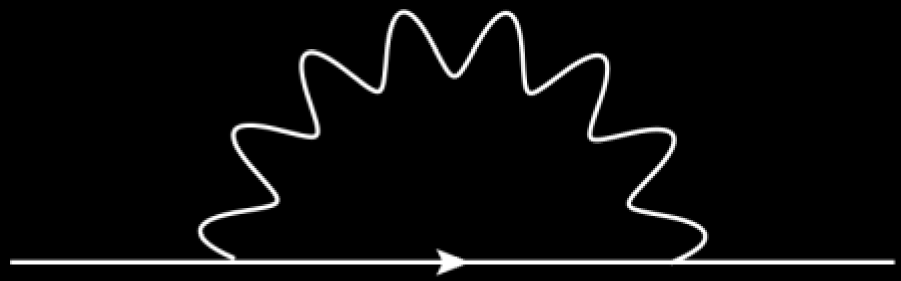
$$q_1 g_2 - q_2 g_1 \in 2\pi\mathbb{Z}$$

Mass Estimate



- Magnetic Coulomb field: $\vec{B}(\vec{r}) = \frac{g}{4\pi}\frac{\vec{r}}{|\vec{r}|^3}$
- Magnetic charge localised at a point
- Divergent energy: $E = \int d^3x \frac{\vec{B}^2}{2} \sim g^2\Lambda \sim \frac{\Lambda}{e^2}$

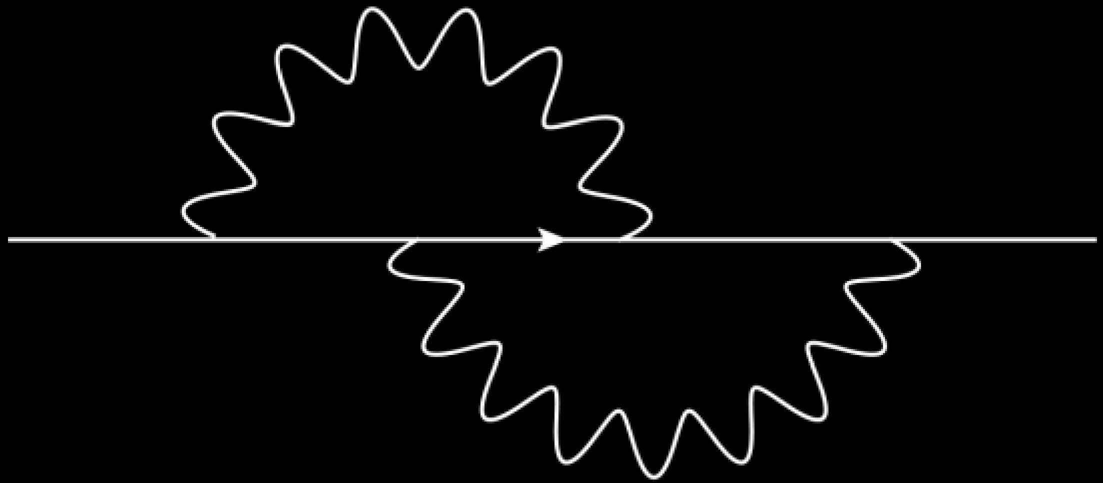
QFT of Monopoles



- Full quantum field theory calculation: Monopole loops
- Compare with electron mass correction

$$\delta m = -\frac{e^2}{2\pi^2}\log\frac{\Lambda}{m} \ll e^2\Lambda$$

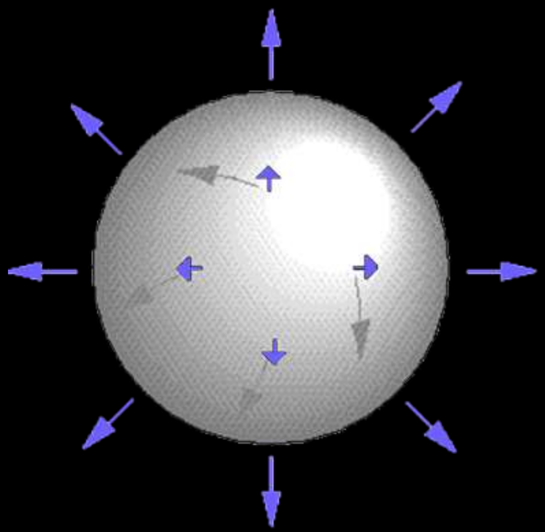
QFT of Monopoles



$$\propto g^4$$

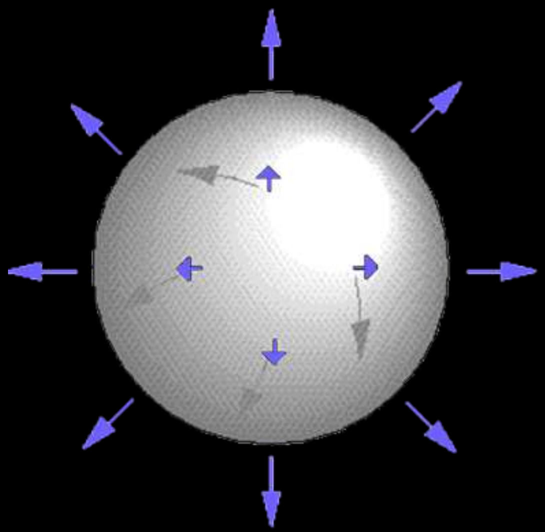
- Difficult to formulate:
  Two vector potentials (Schwinger 1975)
- Strong coupling $g = \frac{2\pi}{e} \gg 1$
  Non-perturbative!

‘t Hooft-Polyakov Monopole (1974)



- Smooth “hedgehog” solution in SU(2)+adjoint Higgs
- Magnetic charge $g = 2g_0 = 4\pi/e$
- Finite mass $M \approx \frac{4\pi v}{e} \sim \frac{m}{e^2}$

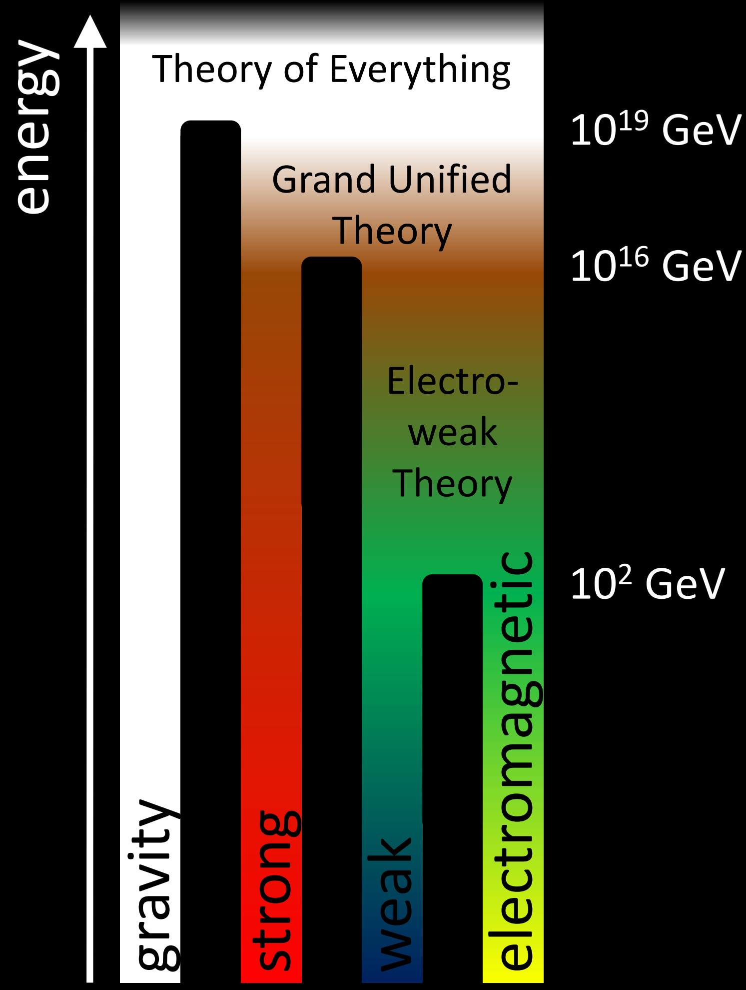
‘t Hooft-Polyakov Monopole (1974)



- Exists whenever simple Lie group broken to something with a U(1) factor: Grand Unification

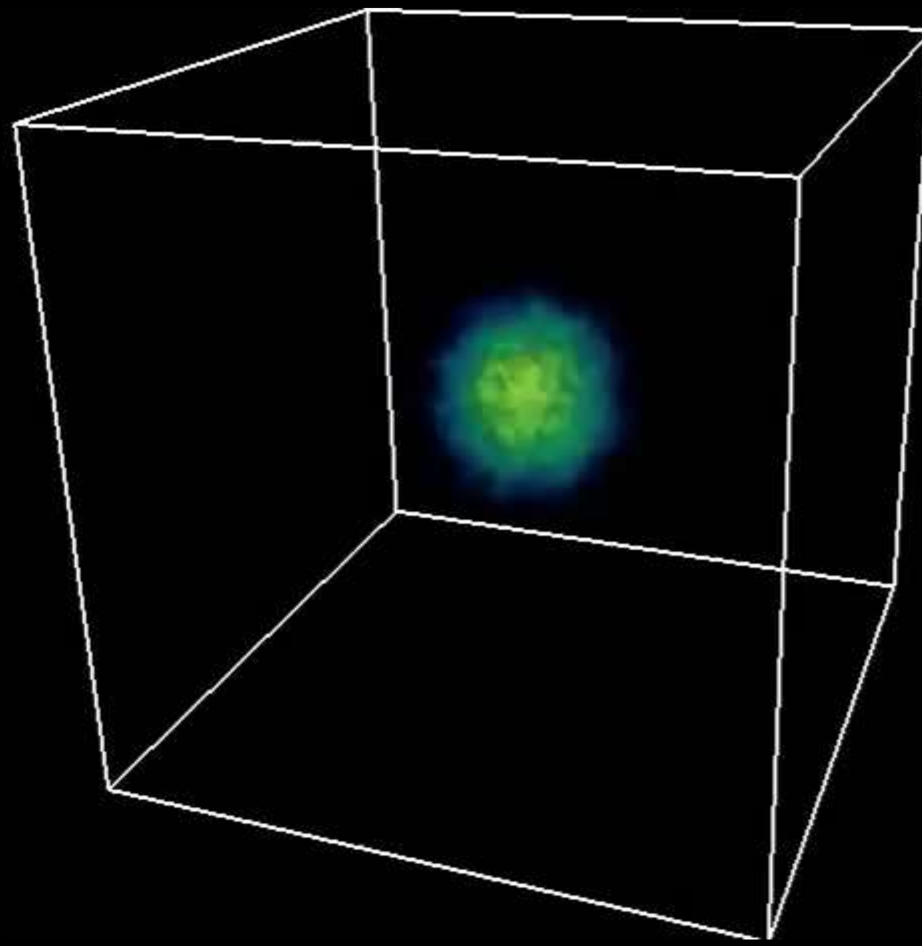
Grand Unification

- Standard Model:
  EM & weak forces unified above 100 GeV
- Grand Unified Theory (GUT):
  Electroweak & strong forces unified above 10^{16} GeV
  - e.g.
    $SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$



GUT Monopoles

- Generic prediction of GUTs (and ToEs)
- Mass typically at GUT scale $M \sim 10^{17}$ GeV
- Lightest singly-charged
  $$g = g_0 = e/2\pi$$
- Catalyse proton decay (Rubakov, Callan 1981)

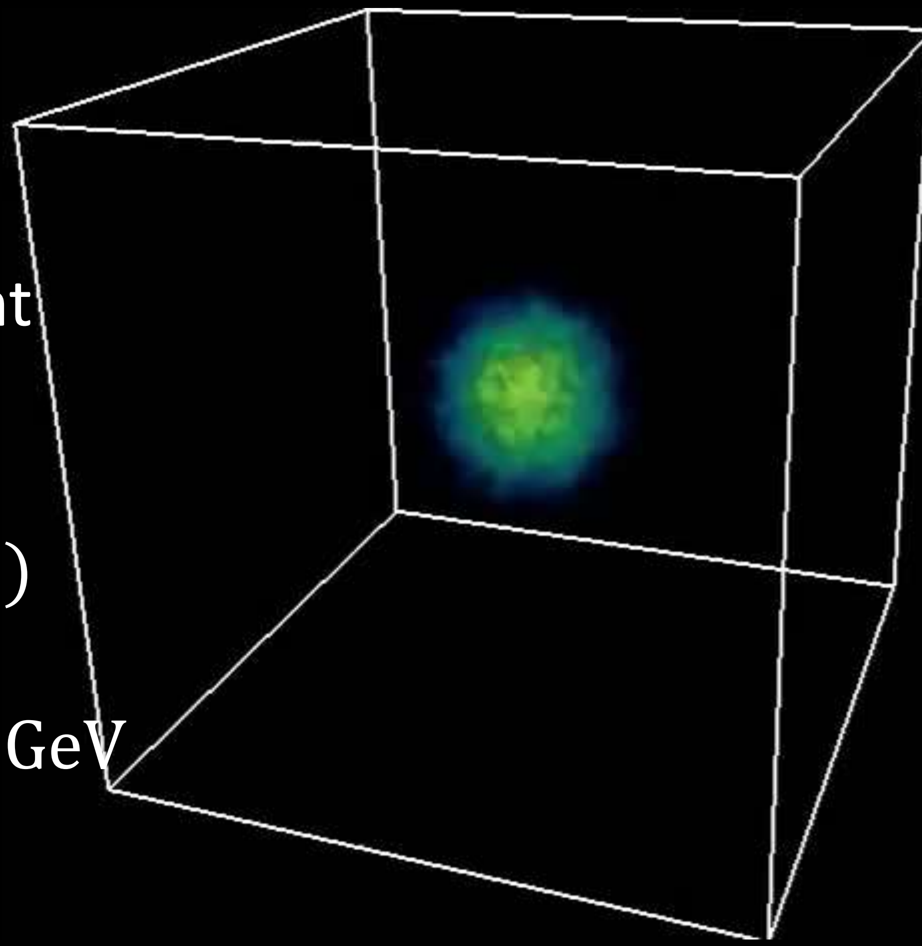


Visualisation: www.vapor.ucar.edu

Simulation of a quantum monopole (AR 2005)

GUT Monopoles

- More complex GUTs, e.g. $SO(10)$
- Monopoles with different charges
- Can be lighter: $SU(4) \times SU(3) \times SU(3)$ has multiply-charged monopoles with $M \sim 10^7 \,\mathrm{GeV}$ (Kephart et al)



Visualisation: www.vapor.ucar.edu

Simulation of a quantum monopole (AR 2005)

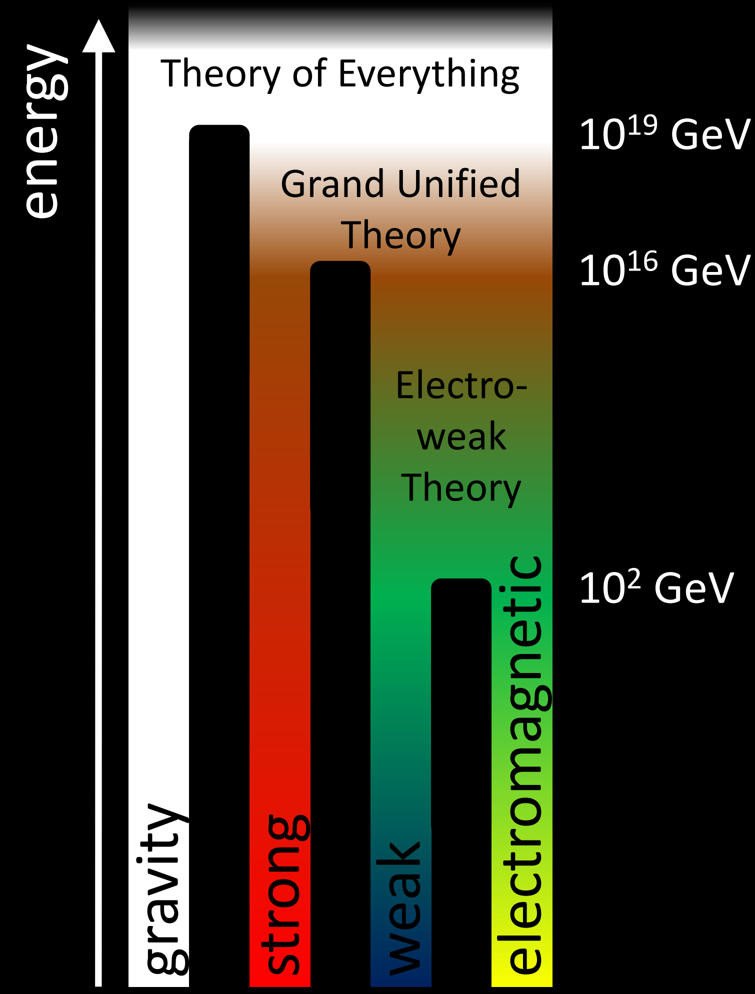
String Theory Monopoles

- S-duality:
  Any superstring theory has magnetic monopoles
- Kaluza-Klein monopole (Gross&Perry, Sorkin):
  Compactified dimension $\leftrightarrow$ U(1) of electrodynamics
- Typical mass $M \sim \frac{M_{\rm Pl}}{e} \sim 10^{20}\ {\rm GeV}$

Cho-Maison Monopole (1996)

- Dirac solution generalised to electroweak theory
- Needs a source particle
- Demonstrates that TeV-scale monopoles are possible
- Massive range of energies between EW and GUT
- Mass estimate

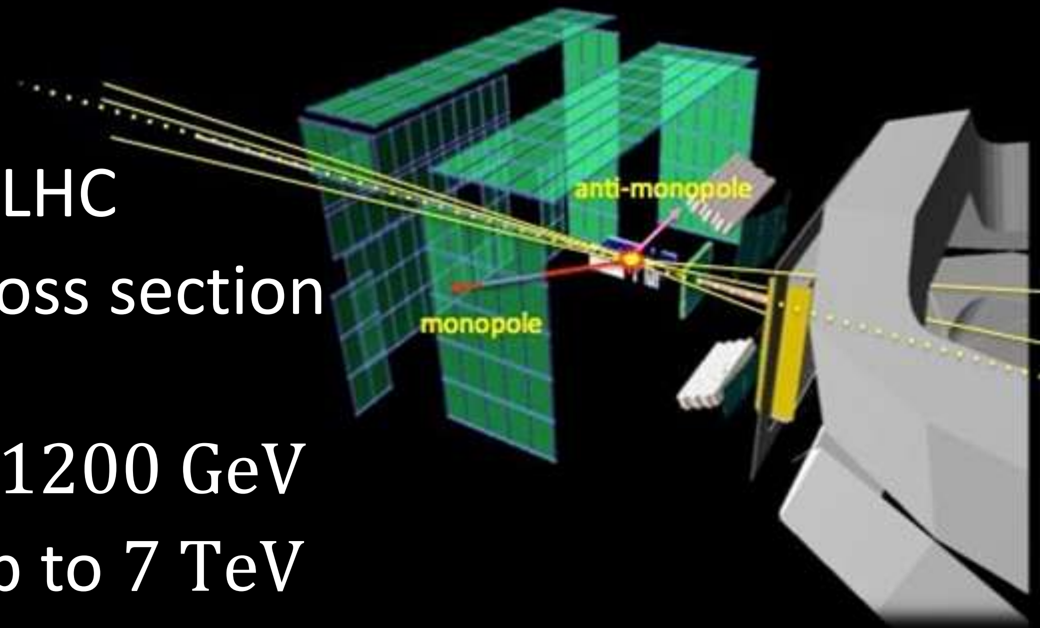
$$M \gtrsim \frac{m_W}{e^2} \sim \text{few } TeV$$



Probes of New Physics

- Strong, precisely known EM interactions
- Electrodynamics $\Rightarrow$ Stable particles
- Interaction with charged fermions depends on core structure (Rubakov, Callan 1981)
- Properties related to beyond the SM physics:
  - Unification of forces
  - Fundamental properties of electromagnetism

Accelerator Searches

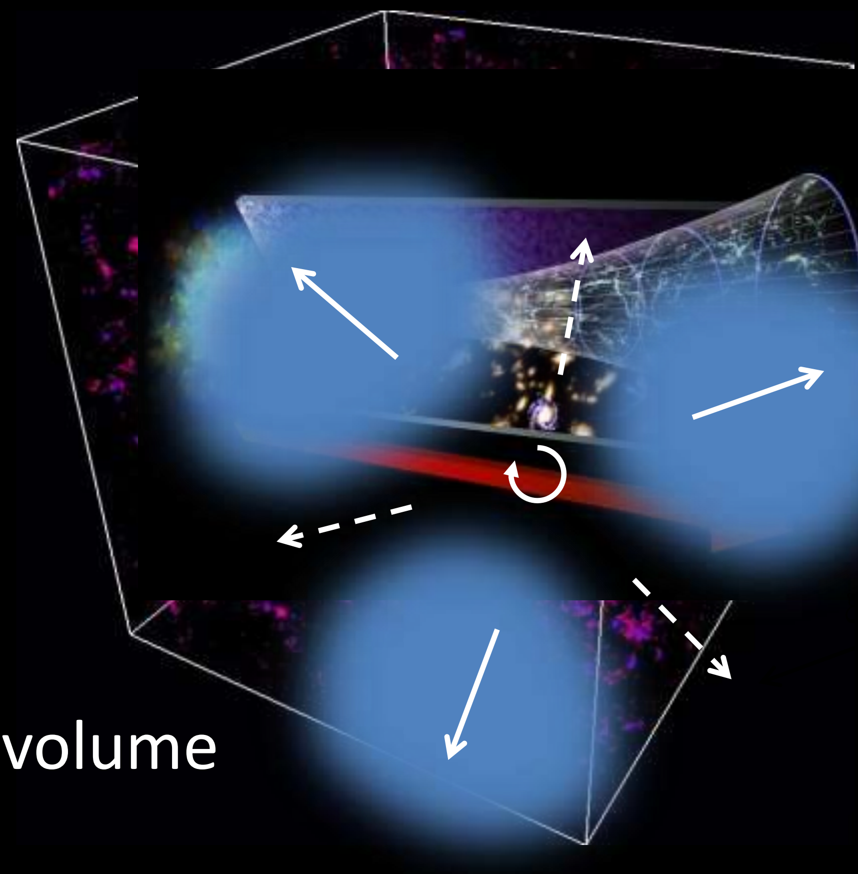


- Direct searches:
  - Tevatron, LEP, HERA, LHC
  - ATLAS: production cross section $\sigma < 16 - 145$ fb for $200 \text{ GeV} < M < 1200 \text{ GeV}$
  - MoEDAL (Pinfold): Up to 7 TeV
- Large theoretical uncertainties
  - Production cross section $\sim e^{-2/\alpha}$? (Drukier&Nussinov, Demidov&Levkov)

Imperial College London

Cosmic Monopoles

- Hot Big Bang:
  GUT symmetry breaks
  in a phase transition
- The Higgs field chooses
  a direction randomly
- Kibble (1976):
  Monopoles form,
  at least one per horizon volume
  $\rightarrow n_{\mathrm{mon}} \sim H^{-3}$



Simulation: AR & D.J.Weir
Visualisation: www.vapor.ucar.edu

Cosmic Monopoles

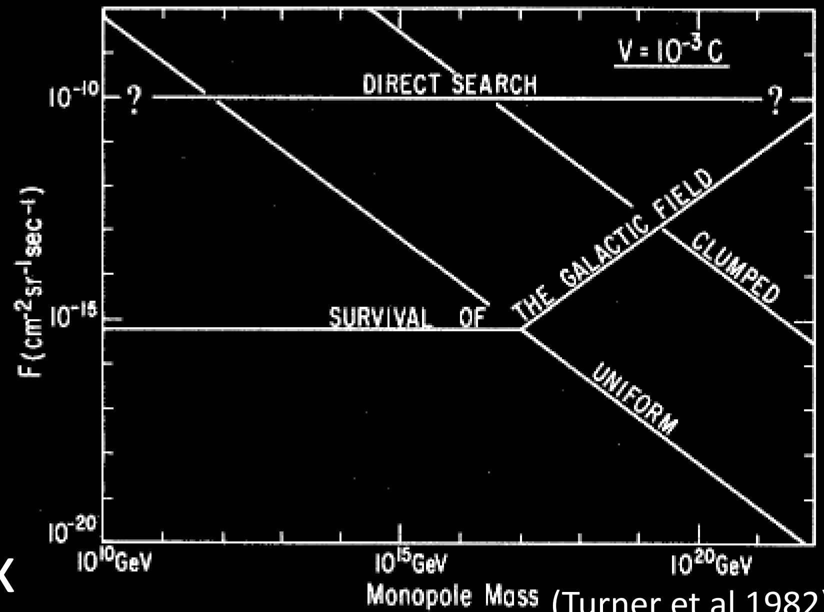
- Monopoles annihilate until they cannot find partners: Density decreases to

$$n_{\mathrm{mon}} \sim 10^{-8} \left(\frac{M}{10^{17}\ \mathrm{GeV}} \right) T^3 \sim 10^{-1} \left(\frac{M}{10^{17}\ \mathrm{GeV}} \right) \mathrm{m}^{-3}$$

(Zel'dovich & Khlopov 1979, Preskill 1979)

- Mass density higher than observations unless $M \lesssim 10^{10}\mathrm{GeV}$: Monopole problem
- Guth (1981): Inflation wiped monopoles away
  - Monopole production after inflation?

Parker Bound (1970)



(Turner et al 1982)

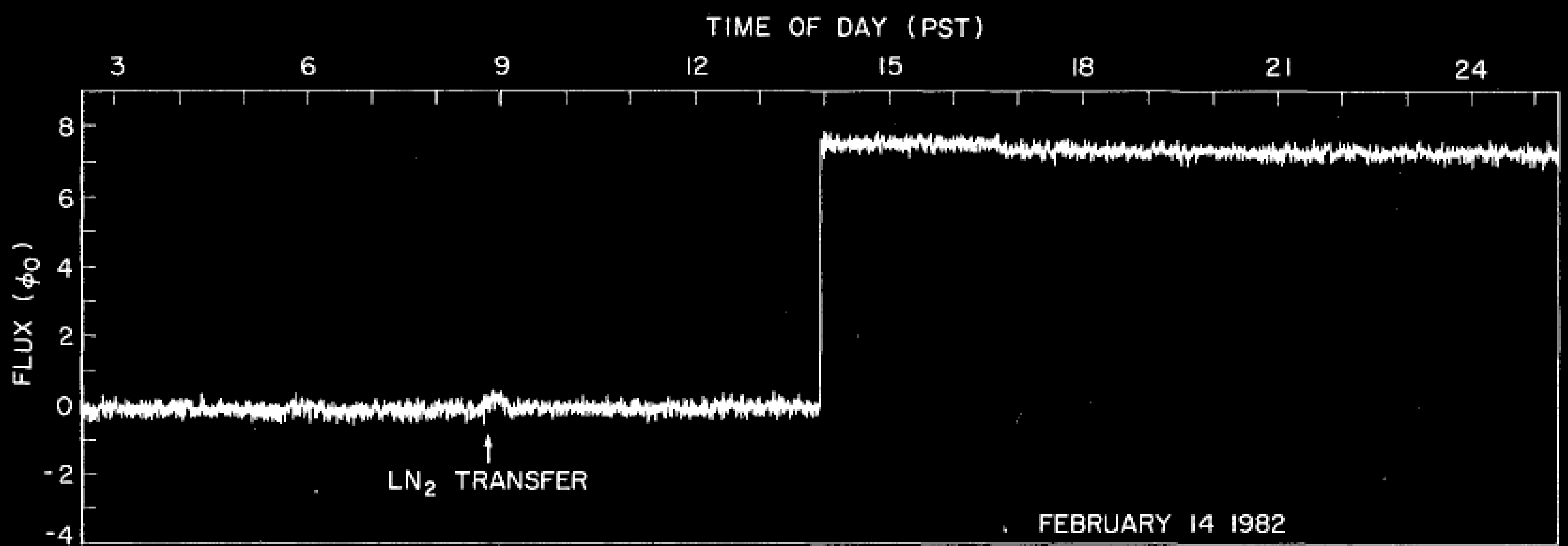
- Galactic magnetic fields $B \sim 3\mu G$
- If $M \lesssim 10^{17}\mathrm{GeV}$, this creates a magnetic current, which dissipates the field
- Sets an upper bound on flux

$$F = \frac{nv}{4\pi} \lesssim 10^{-15}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\mathrm{sr}^{-1}$$

- Extended Parker bound (Adams et al 1993)

$$F \lesssim 10^{-16}\left(\frac{M}{10^{17}\ \mathrm{GeV}}\right)\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\mathrm{sr}^{-1}$$

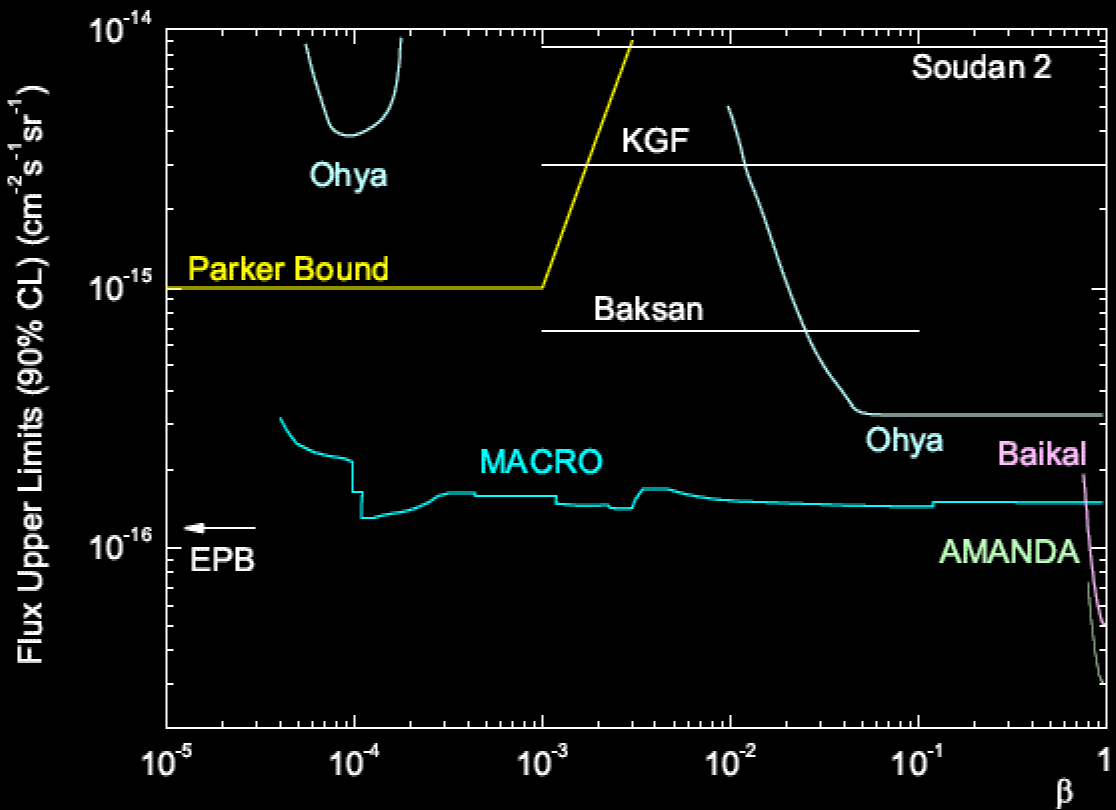
Cosmic Rays



(Cabrera 1982)

- Early detections:
  - Berkeley 1975, Stanford 1982, Imperial 1986
  - All turned out to be false

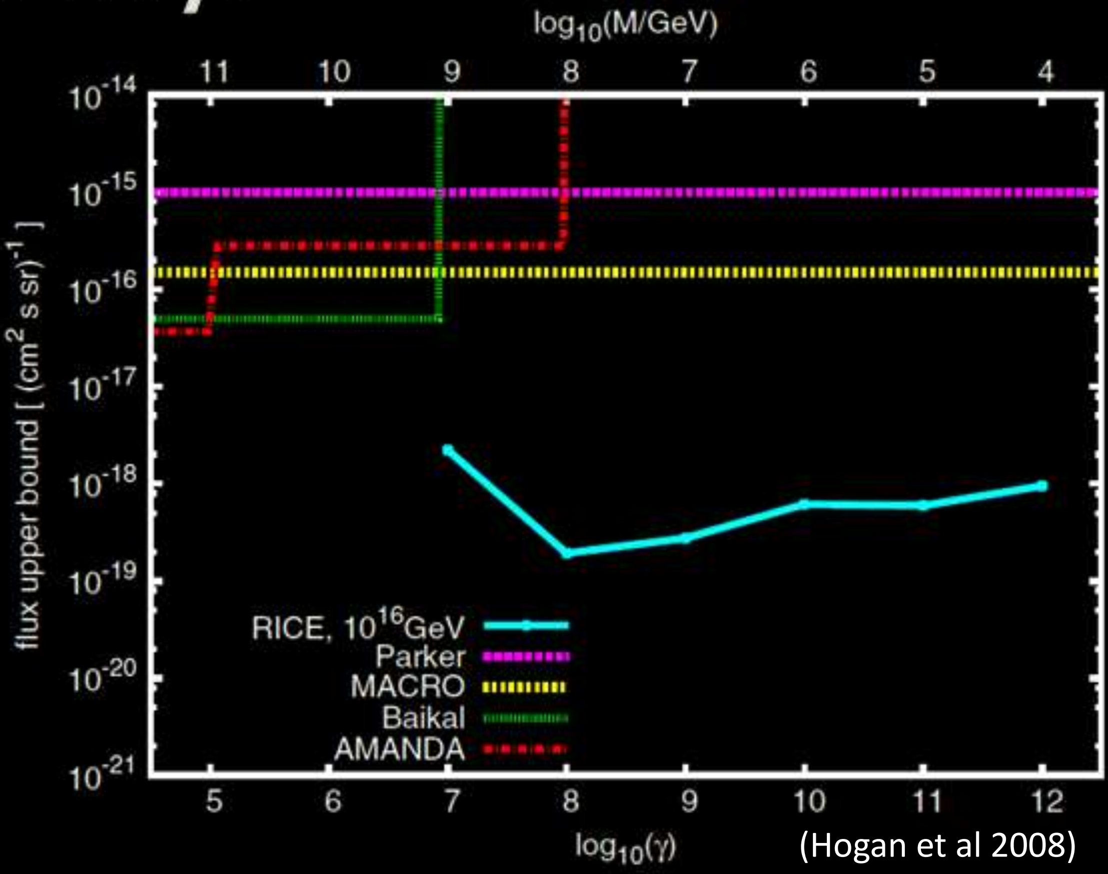
Cosmic Rays



(Giacomelli et al 2011)

- MACRO (Gran Sasso, Italy):
  - Upper bound $F \lesssim 10^{-16}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\mathrm{sr}^{-1}$ over wide mass range

Cosmic Rays



(Hogan et al 2008)

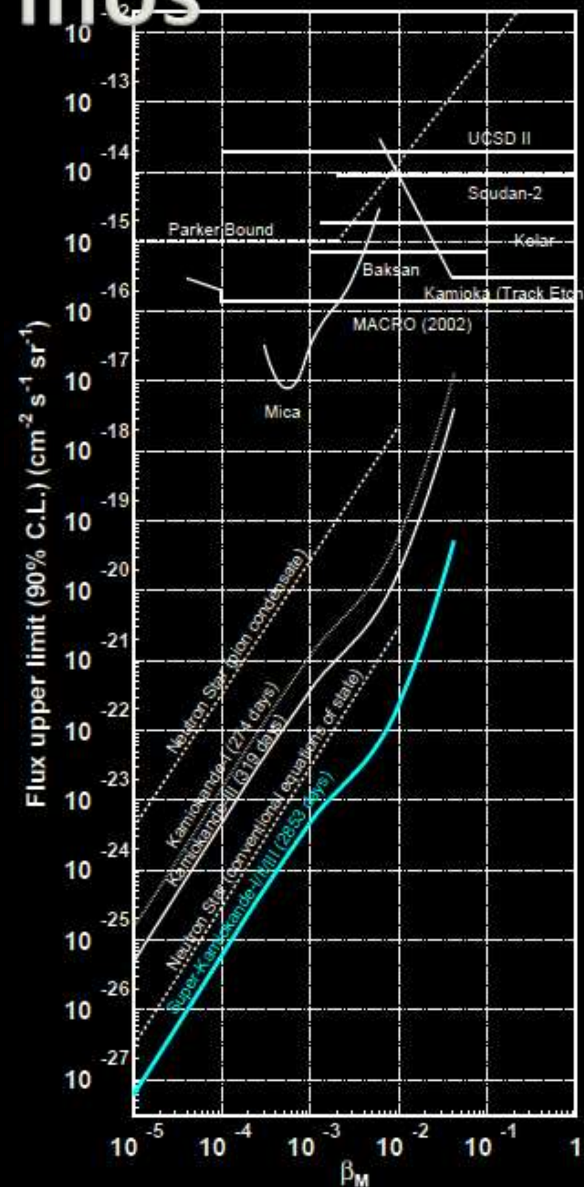
- RICE (South Pole):
  - Intermediate mass monopoles $F \lesssim 10^{-18}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\mathrm{sr}^{-1}$

Monopole-Induced Neutrinos

- Monopoles accumulate in the Sun
- GUT monopoles catalyse p decay: Produces neutrinos (Rubakov 1981) Super-K bound (2012 - Mijakowski):

$$F \lesssim 10^{-23} \left(\frac{\beta_M}{10^{-3}} \right)^2 \mathrm{cm}^{-2}\, \mathrm{s}^{-1} \mathrm{sr}^{-1}$$

- Model-dependent



Summary

- Monopoles are among the best motivated new particles
  - Explain charge quantisation $e \in (2\pi/g)\mathbb{Z}$
  - Predicted by GUTs, string theory
  - Would open up a window to exciting new physics
- Cosmic monopoles
  - Produced copiously in the early universe?
  - Stringent bounds from astrophysics, experiments
- TeV-scale Cho-Maison monopoles possible
  - Detectable in MoEDAL