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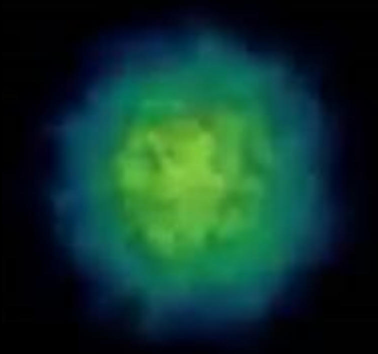
Magnetic Monopoles in the Cosmos and at the LHC

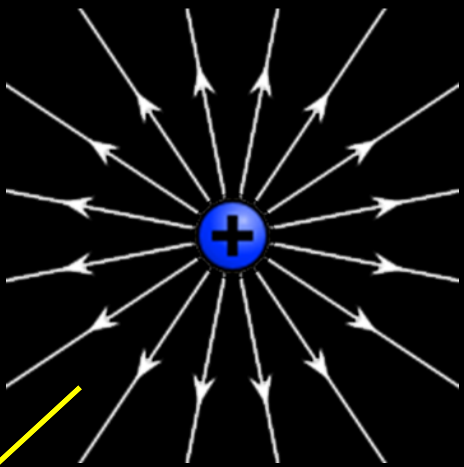


Arttu Rajantie

MoEDAL Physics Workshop

CERN, 20 June 2012

Maxwell Equations



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

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

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

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

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

Dirac Monopole (1931)

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

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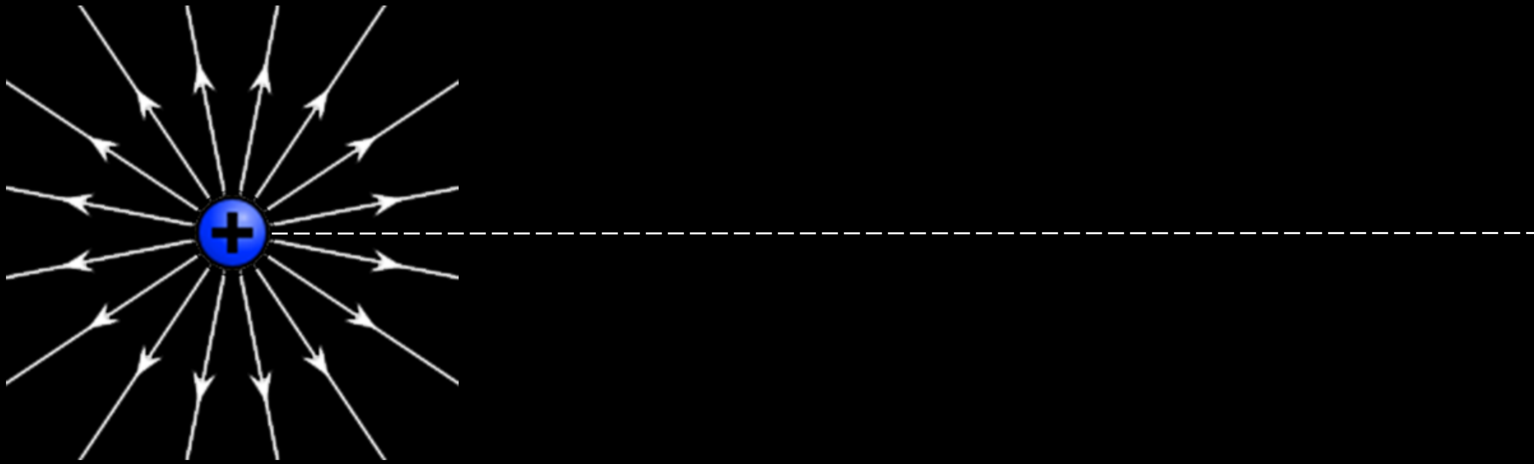
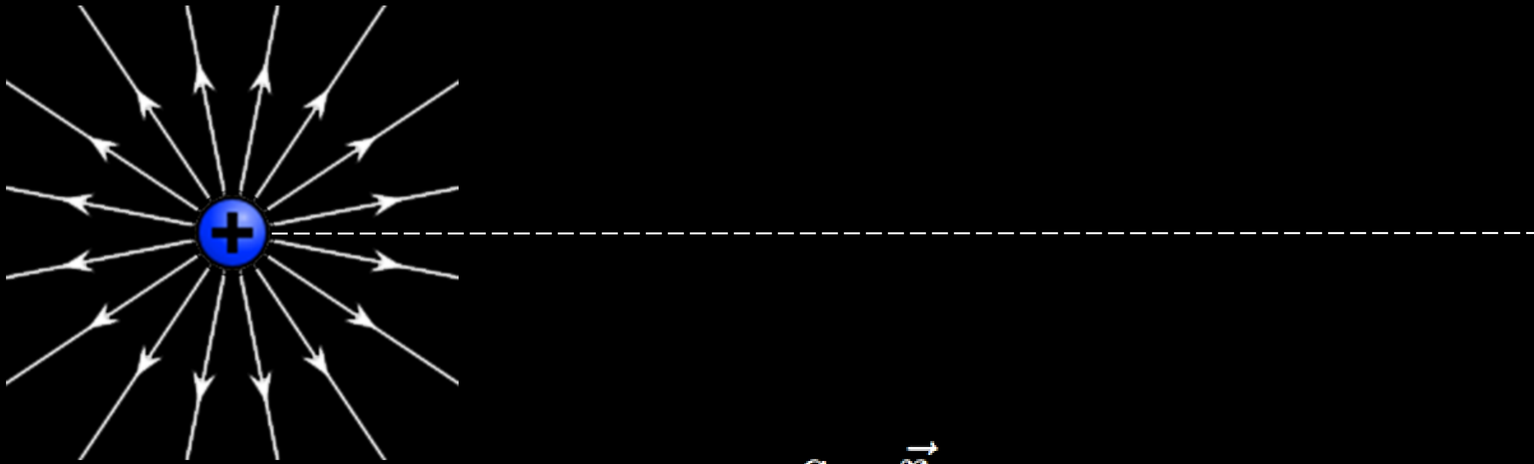
Dirac Monopole (1931)



- 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"*

Dirac Monopole (1931)



- 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: $E = \int d^3x \frac{\vec{B}^2}{2} \sim g^2\Lambda \sim \frac{\Lambda}{e^2}$

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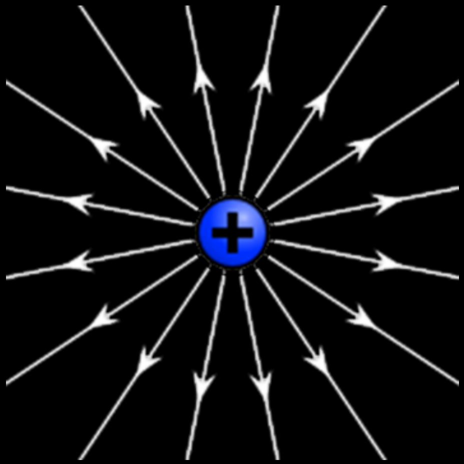
QFT of Monopoles



- Full quantum calculation: Monopole loops
- Difficult to formulate:
  Two vector potentials (Schwinger 1975)
- Strong coupling $g = \frac{2\pi}{e} \gg 1$

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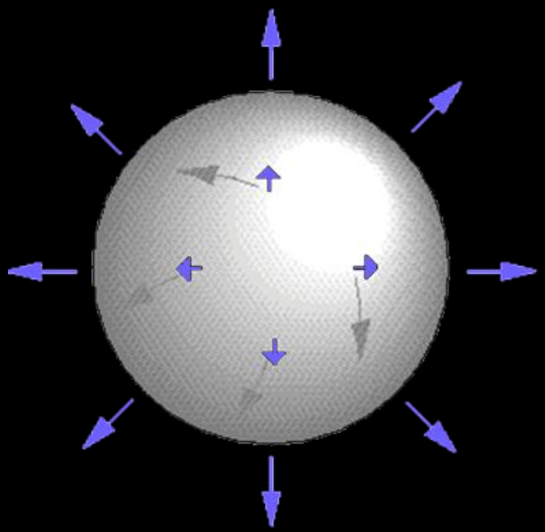
‘t Hooft-Polyakov Monopole (1974)



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

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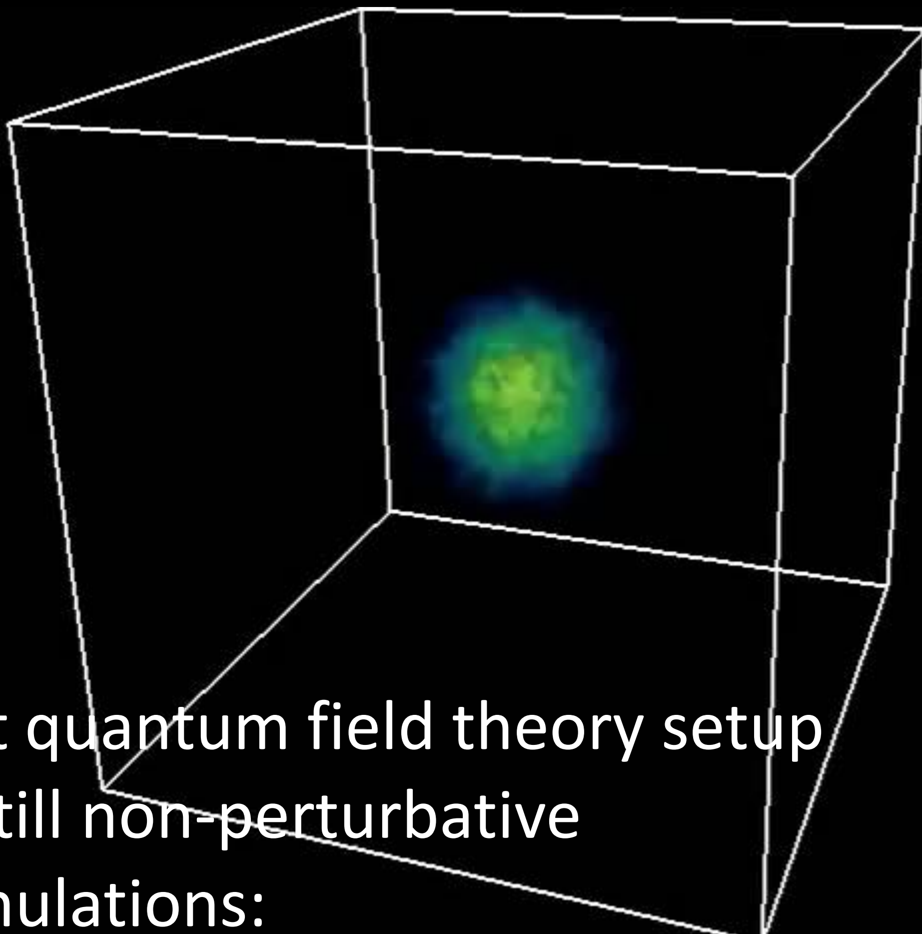
‘t Hooft-Polyakov Monopole (1974)



Visualisation: www.vapor.ucar.edu

- Consistent quantum field theory setup
- Large g: Still non-perturbative
- Lattice simulations:
  Mass, scattering (AR&Weir 2011)

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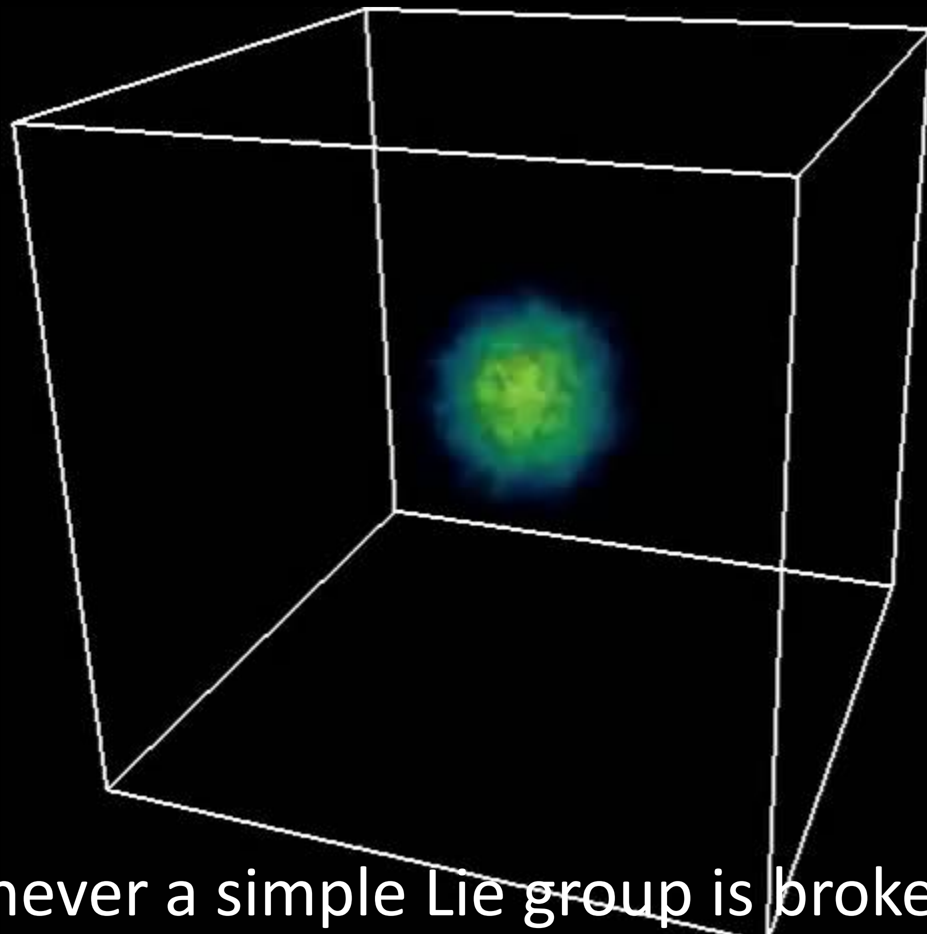
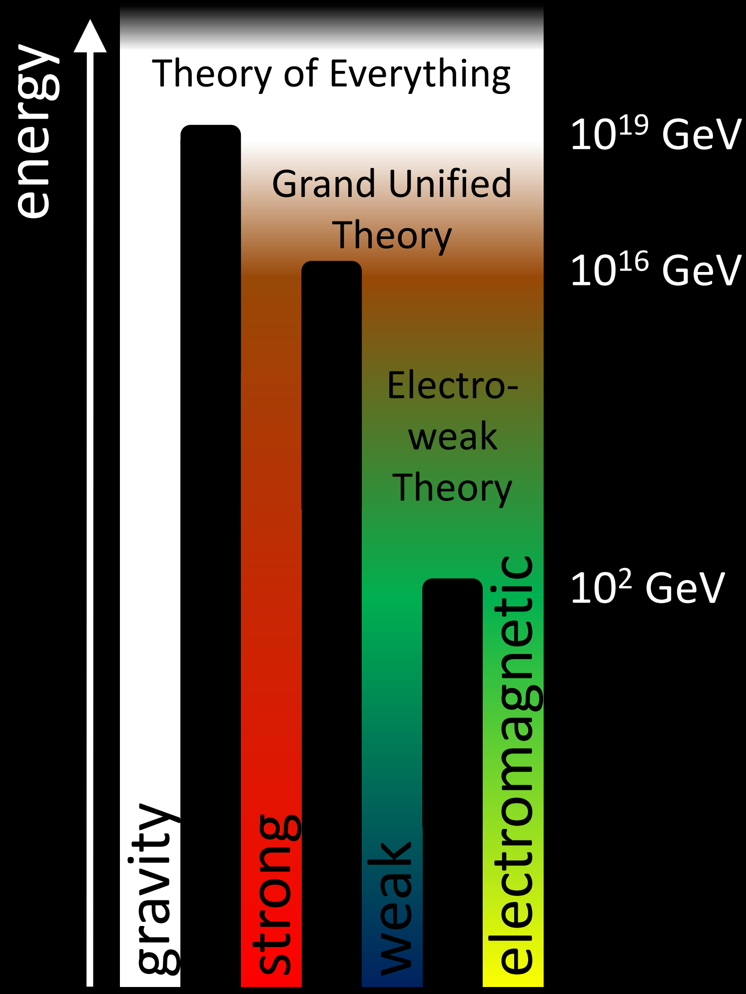
't Hooft-Polyakov Monopole (1974)



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

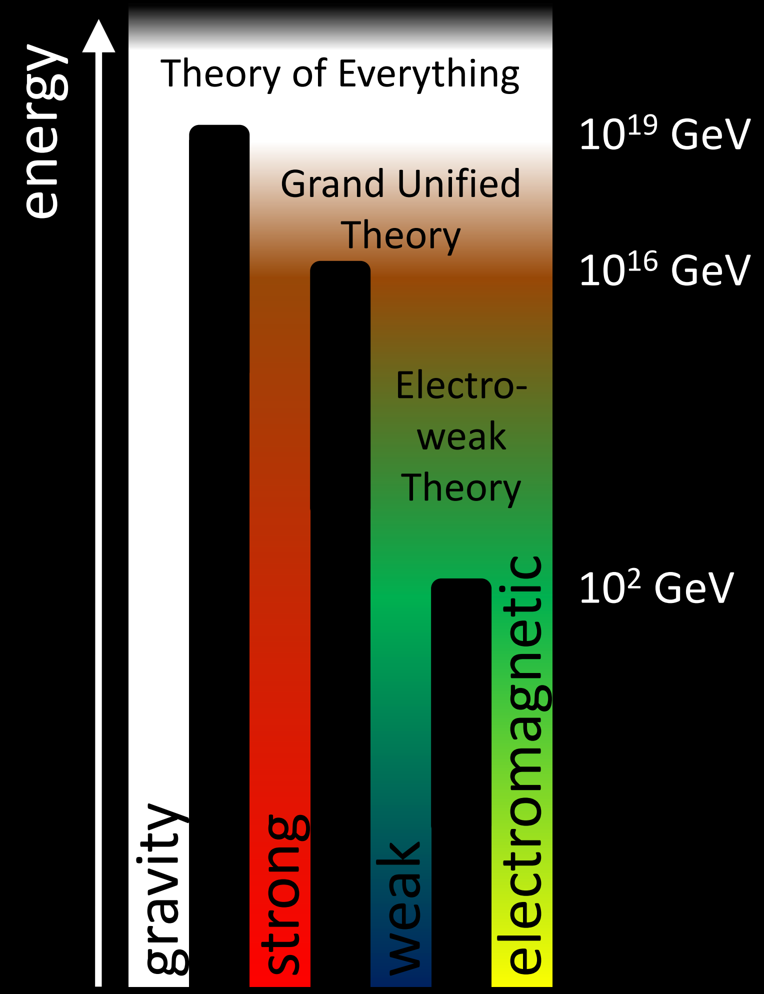
Grand Unification

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



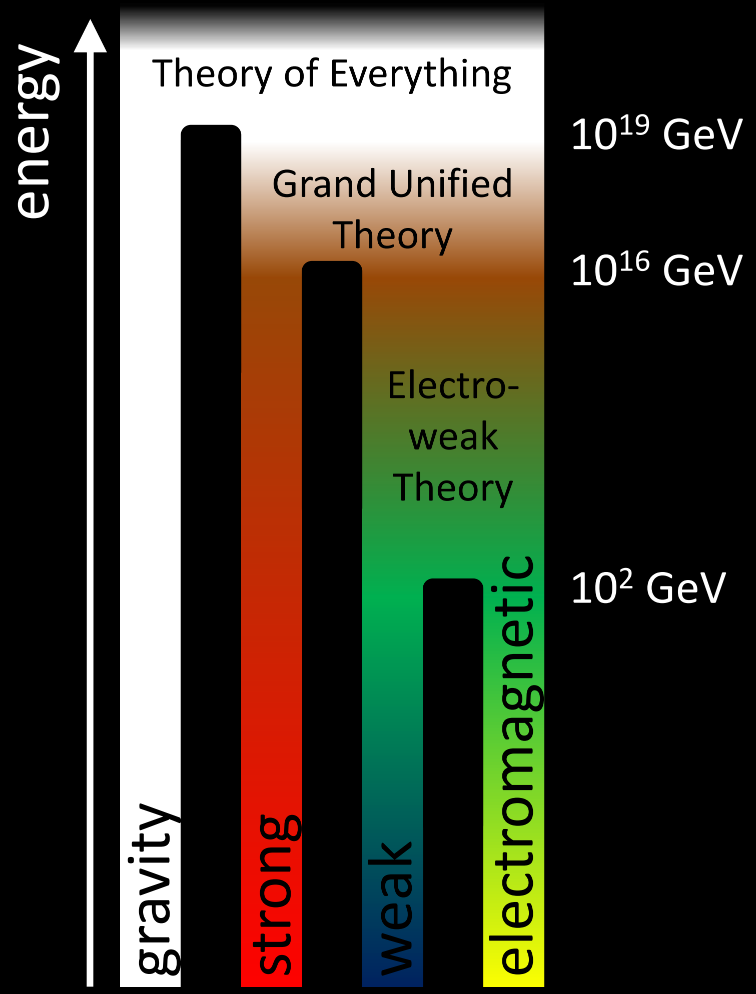
GUT Monopoles

- Generic prediction of GUTs
- Mass typically at GUT scale $M \sim 10^{17}$ GeV
- Also dyons with both electric and magnetic charge



GUT Monopoles

- More complex GUTs, e.g. $SO(10)$
- Monopoles with different charges
- Can be lighter e.g. $\sim 10^7\,\mathrm{GeV}$ in an $SO(10)$ family unification model (Kephart et al)



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String Theory Monopoles

- S-duality:
  Any superstring theory has magnetic monopoles
- Typical mass $M \sim \frac{M_{\mathrm{Pl}}}{e} \sim 10^{20}\ \mathrm{GeV}$
- Can be reduced by large extra dimensions or warped compactification, perhaps even to $M \sim 10\ \mathrm{TeV}$ (Witten 2002)

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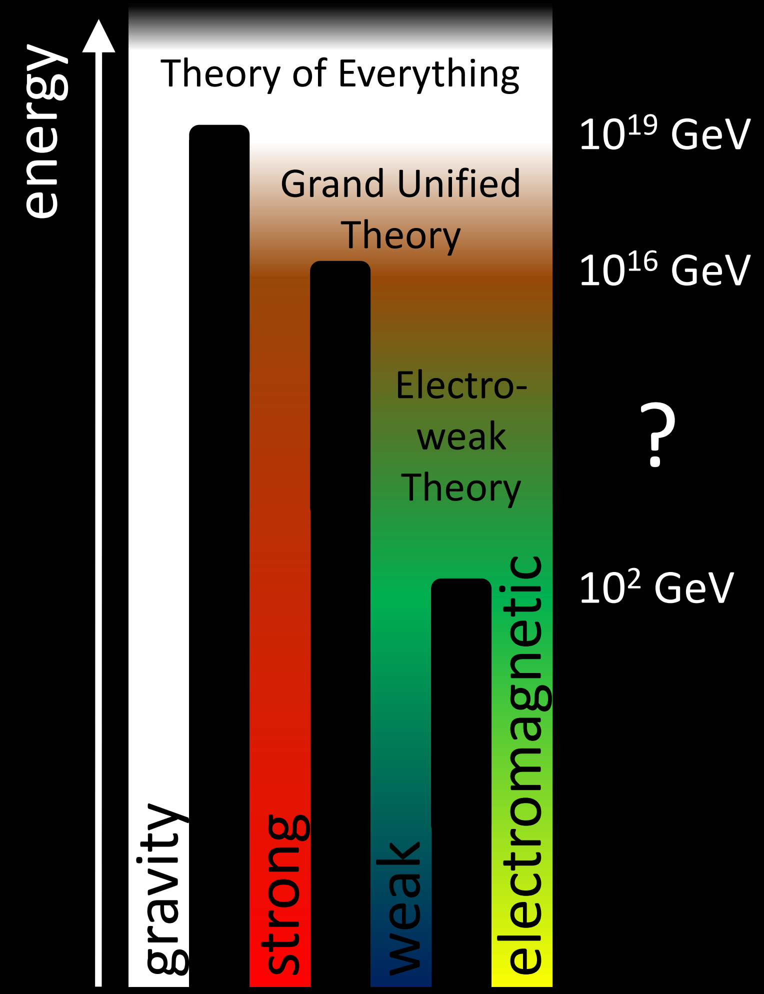
Other Light Monopoles

- Massive range of energies between EW and GUT: Plenty of room for new physics
- Cho-Maison monopole (1996): Dirac solution generalised to electroweak theory
- Monopoles do not have to arise from unification



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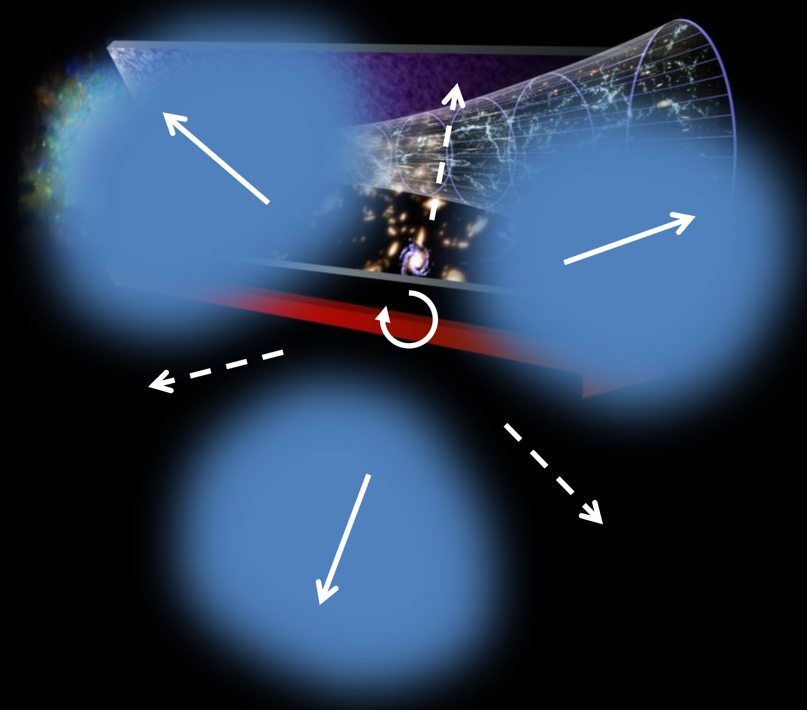
Monopoles in Cosmology

- 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 $\rightarrow n_{\text{mon}} \sim H^{-3}$



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Monopole Problem

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

$$n_{\mathrm{mon}} \sim 10^{-9} \left(\frac{M}{10^{16}\ \mathrm{GeV}} \right) T^3 \sim 10^{-2} \left(\frac{M}{10^{16}\ \mathrm{GeV}} \right) \mathrm{m}^{-3}$$

(Zel'dovich & Khlopov 1979, Preskill 1979)

- Total energy density in the universe: $\rho \sim 6\ \mathrm{GeV\ m}^{-3}$
- Monopoles exceed this unless $M \lesssim 10^{10}\mathrm{GeV}$
- Guth (1981):
  Period of inflation (accelerating expansion) dilutes monopoles away

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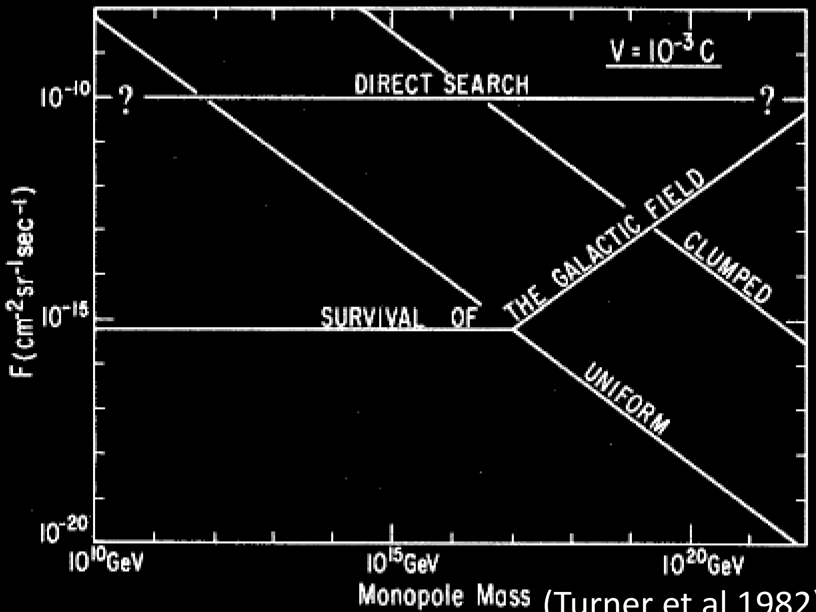
Monopole Problem

- Density constraint in terms of flux F: Monopoles hitting unit area per unit time



(Turner et al 1982)

- Uniform distribution:

$$F \approx \frac{n_{\rm mon} v}{4\pi} \lesssim 10^{-15} \left(\frac{10^{16}\,{\rm GeV}}{M}\right)\left(\frac{v}{10^{-3}c}\right) {\rm cm}^{-2}\,{\rm s}^{-1}{\rm sr}^{-1}$$

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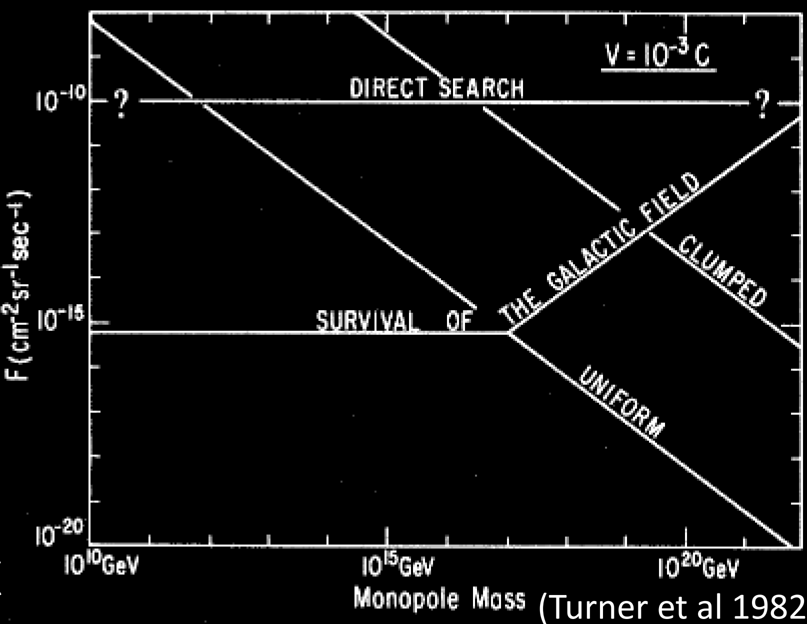
Parker Bound (1970)

- Galactic magnetic fields $B \sim 1\mu G$
- If $M \lesssim 10^{17}\mathrm{GeV}$, this creates a magnetic current, which dissipates the field
- Sets an upper bound on flux



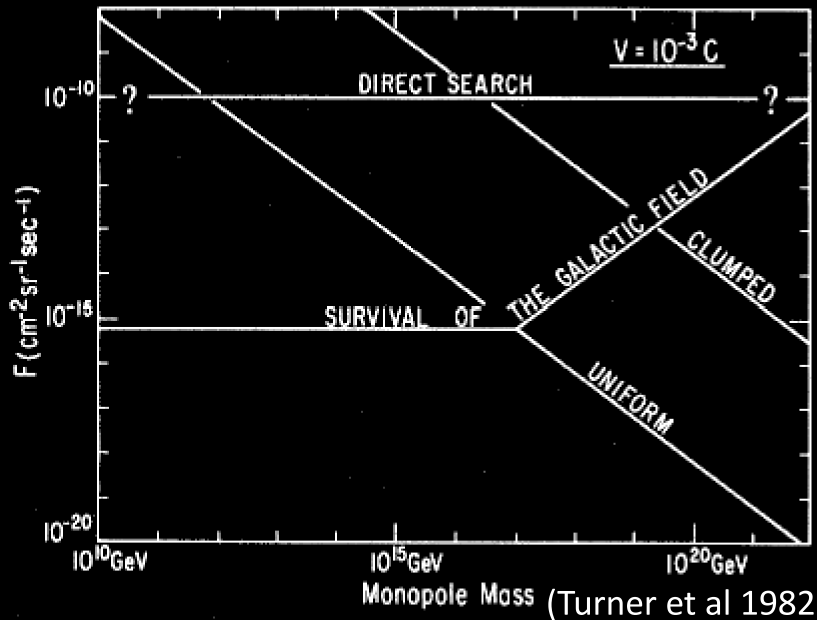
(Turner et al 1982)

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

- Bound gets weaker at higher M

Parker Bound (1970)

- If $M \gtrsim 10^{17}\,\mathrm{GeV}$, monopoles remain bound to galaxies
- Constraint from the total mass of the Milky Way:



(Turner et al 1982)

$$F \lesssim 10^{-13} \left(\frac{10^{16}\mathrm{GeV}}{M}\right)\left(\frac{v}{10^{-3}c}\right) \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

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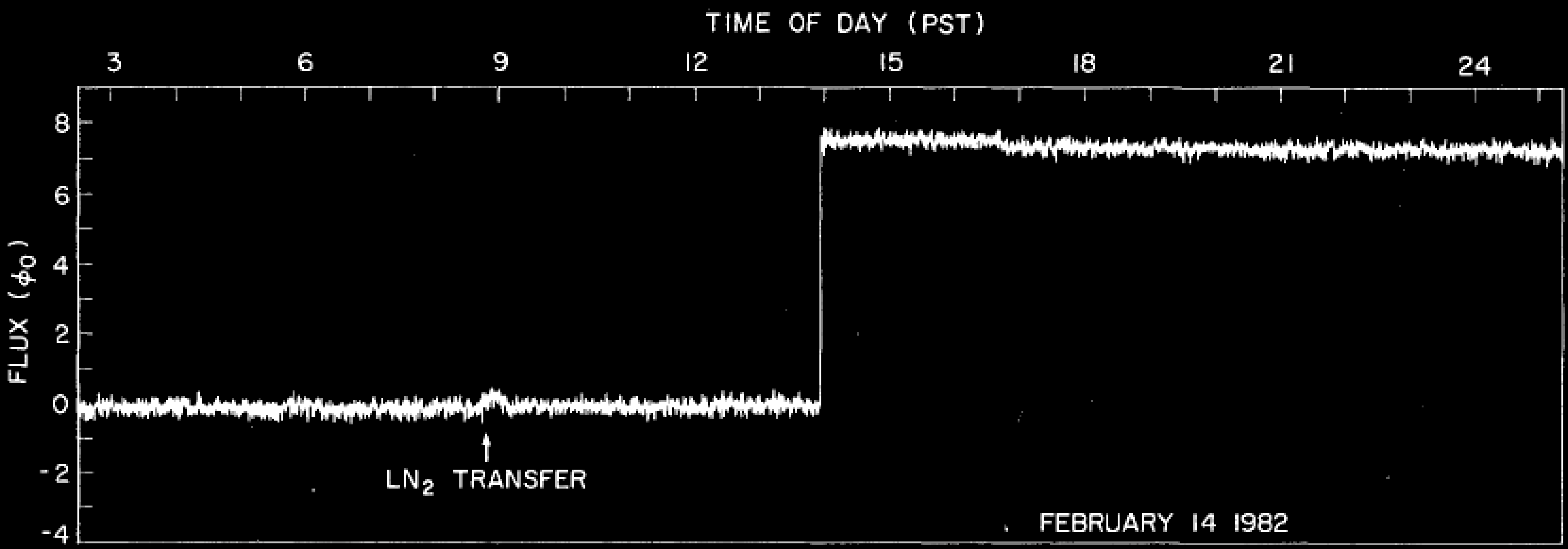
Cosmic Rays



(Cabrera 1982)

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

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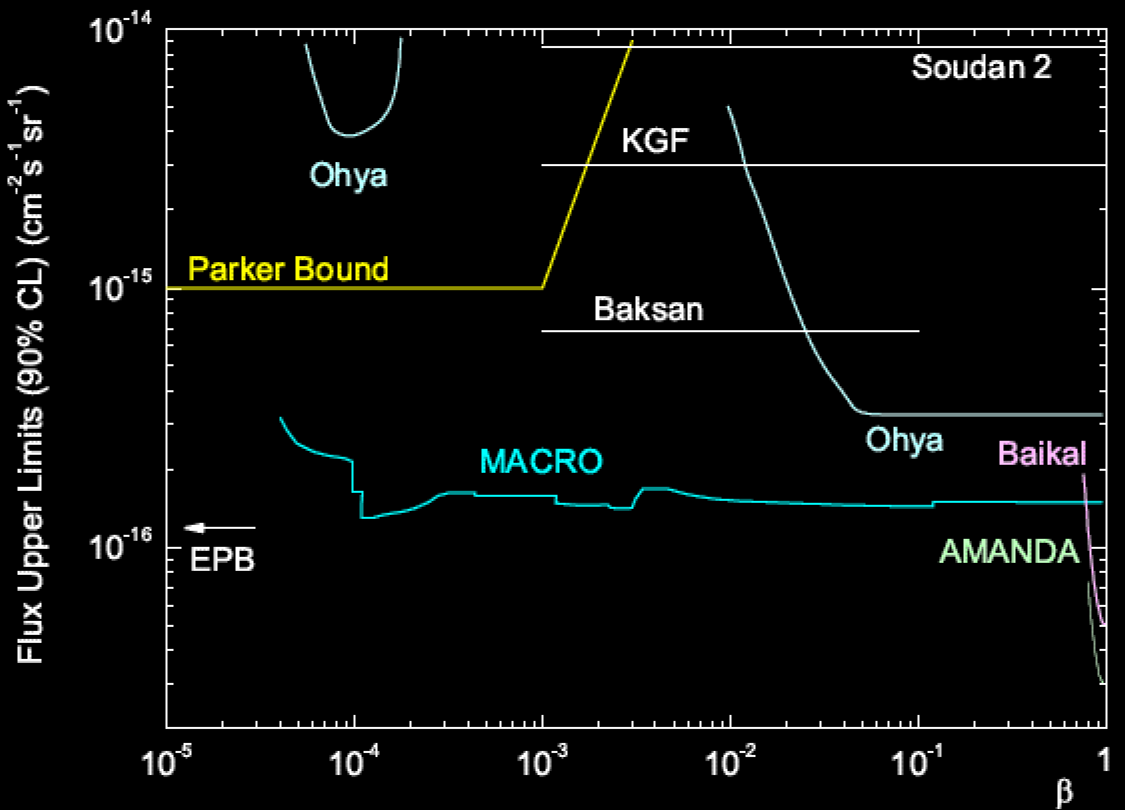
Cosmic Rays



(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

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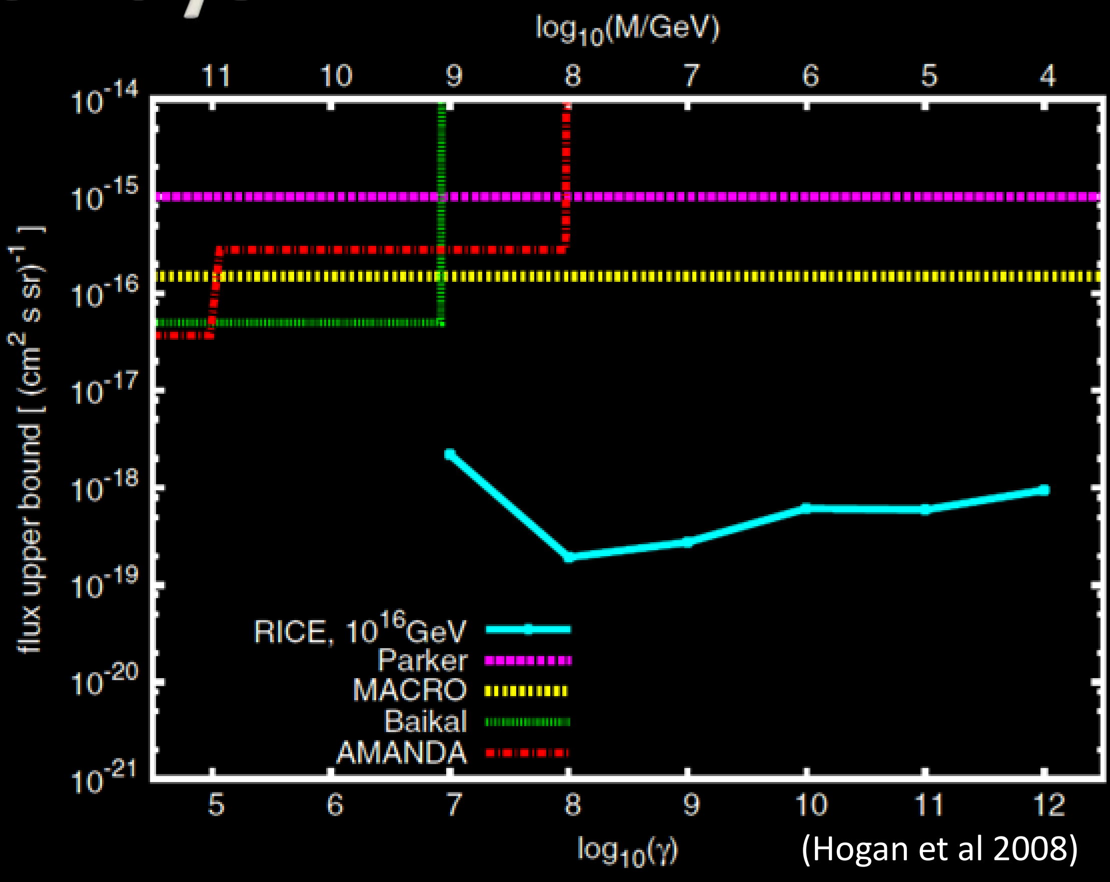
Cosmic Rays



(Hogan et al 2008)

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

Monopole Problem?

- Preskill (1979):

  Monopole density today $n_{\mathrm{mon}} \sim 10^{-2} \left(\frac{M}{10^{16}\ \mathrm{GeV}}\right) \mathrm{m}^{-3}$

- Light monopoles $M \lesssim 10^{11}\mathrm{GeV}$ are relativistic, so

$$F \approx \frac{n_{\mathrm{mon}} c}{4\pi} \approx 10 \left(\frac{M}{10^{16}\ \mathrm{GeV}}\right) \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

- Compatible with RICE bound only if $M \lesssim 1\mathrm{MeV}$
- Therefore we do need inflation to wipe out the monopoles!

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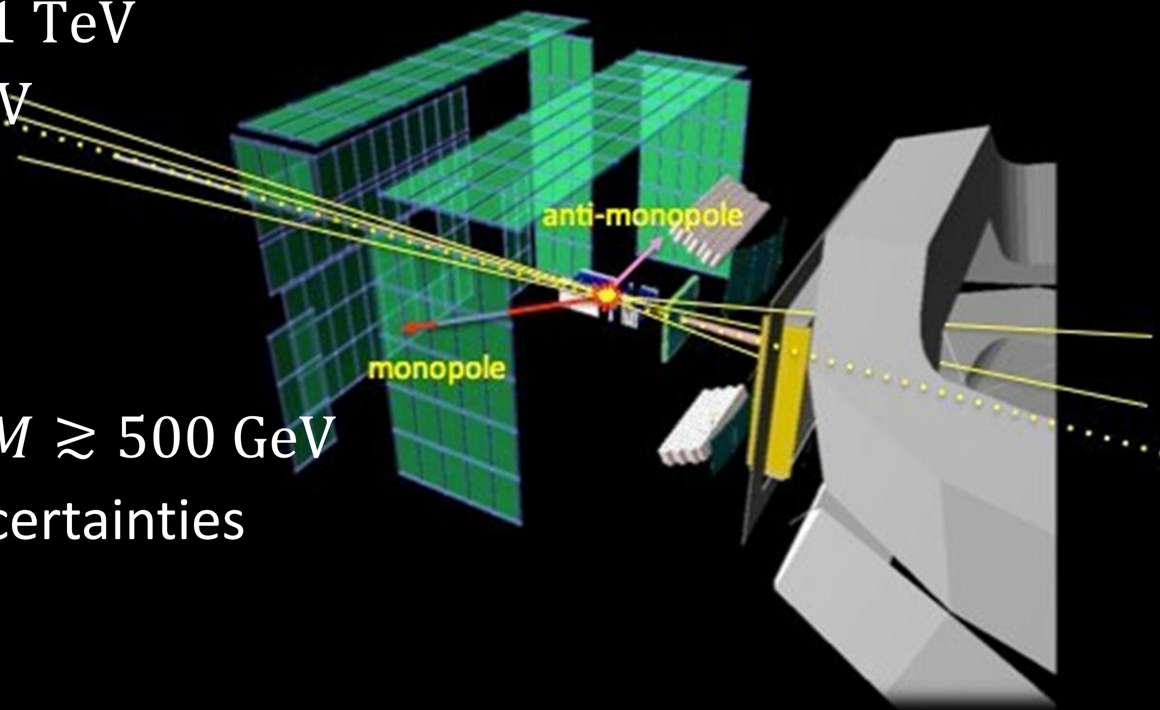
Accelerator Searches

- Direct searches:
  - Tevatron, LEP, HERA

  → Lower bound $M \gtrsim 1\ \mathrm{TeV}$
  - MoEDAL: Up to 7 TeV

- Indirect searches:
  - Virtual monopoles

    $M \gtrsim 500\ \mathrm{GeV}$
  - Large theoretical uncertainties



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TeV-scale monopoles

- Possible, but not really predicted by any theory
  - Perhaps large extra dimensions, or simply unrelated to unified theories
- Mass relation $M \sim \frac{\Lambda}{e^2}$ means there would be lots of new exciting physics at accessible energies
- Monopoles would be a fantastic probe:
  - Absolutely stable
  - Strong EM interaction
  - Easy to handle

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Summary

- Monopoles are perhaps the best motivated new particles:
  - Explain charge quantisation
  - Exist in GUTs, string theory
- Produced copiously in the early universe, wiped away by inflation:
  - Stringent bounds from astrophysics, cosmic rays
- TeV-scale monopoles possible
  - Detectable in MoEDAL
  - Would open up a window to exciting new physics
- (For more: See AR, Contemporary Physics 2012)