Seeing the Landscape on Earth and in the Sky

Philip Schuster, Natalia Toro, and Nima Arkani-Hamed

Harvard University

String Vacua and The Landscape

ICTP Trieste

June 2, 2006

Seeing the Landscape

- The existence of a landscape $\rightarrow$ paradigm shift

Seeing the Landscape

- The existence of a landscape $\rightarrow$ paradigm shift
- Anthropic selection effects play a more prominent role in fundamental physics (ex: Weinberg's prediction of a small CC)

Seeing the Landscape

- The existence of a landscape $\rightarrow$ paradigm shift
- Anthropic selection effects play a more prominent role in fundamental physics (ex: Weinberg's prediction of a small CC)
- Maybe low energy parameters aren't fundamental?

Seeing the Landscape

- The existence of a landscape $\rightarrow$ paradigm shift
- Anthropic selection effects play a more prominent role in fundamental physics (ex: Weinberg's prediction of a small CC)
- Maybe low energy parameters aren't fundamental?

$\rightarrow$ recipe for angry physicists!

Is the String Landscape Testable?

Is the String Landscape Testable?

Of course not!

Is the String Landscape Testable?

~~Of course not!~~

Anthropic predictions provide indirect evidence for a landscape

Is the String Landscape Testable?

~~Of course not!~~

Anthropic predictions provide indirect evidence for a landscape

Perhaps correlations or other sharp features can be predicted

Is the String Landscape Testable?

~~Of course not!~~

Anthropic predictions provide indirect evidence for a landscape

Perhaps correlations or other sharp features can be predicted

Is there more tangible evidence in our vacuum?

Tangible and Intangible Evidence

Intangible:

Tangible and Intangible Evidence

Intangible:

- Anthropic arguments that are genuinely predictive

Tangible and Intangible Evidence

Intangible:

- Anthropic arguments that are genuinely predictive
- Split-Susy at the LHC

Tangible and Intangible Evidence

Intangible:

- Anthropic arguments that are genuinely predictive
- Split-Susy at the LHC
- The weak scale may be tuned for reasons related to dark matter or baryogenesis (hep-th/0501082 N. Arkani-Hamed, S. Dimopoulos, S. Kachru; hep-ph/0507257 L. Senatore; hep-ph/0506079 P.S., N.T.)

Tangible and Intangible Evidence

Intangible:

- Anthropic arguments that are genuinely predictive
- Split-Susy at the LHC
- The weak scale may be tuned for reasons related to dark matter or baryogenesis (hep-th/0501082 N. Arkani-Hamed, S. Dimopoulos, S. Kachru; hep-ph/0507257 L. Senatore; hep-ph/0506079 P.S., N.T.)

Plenty of possibilities (even at the weak scale) for convincing indirect evidence of a landscape

Tangible and Intangible Evidence

Tangible:

Tangible and Intangible Evidence

Tangible:

- Evidence that logically requires the existence of other vacua

Tangible and Intangible Evidence

Tangible:

- Evidence that logically requires the existence of other vacua
- Ideally, we want evidence for many vacua

Tangible and Intangible Evidence

Tangible:

- Evidence that logically requires the existence of other vacua
- Ideally, we want evidence for many vacua
- Where to look?

Tangible and Intangible Evidence

Tangible:

- Evidence that logically requires the existence of other vacua
- Ideally, we want evidence for many vacua
- Where to look?
- Inflation, exotic states?

Two New Probes of the landscape

If we allow ourselves to be a little wishful and creative, can we find any sharp experimental handles on the landscape?

Two New Probes of the landscape

If we allow ourselves to be a little wishful and creative, can we find any sharp experimental handles on the landscape?

Yes, and they’re quite simple!

Two New Probes of the landscape

If we allow ourselves to be a little wishful and creative, can we find any sharp experimental handles on the landscape?

Yes, and they're quite simple!

Part I: Very tangible new states that are strongly suggestive of many vacua

Two New Probes of the landscape

If we allow ourselves to be a little wishful and creative, can we find any sharp experimental handles on the landscape?

Yes, and they're quite simple!

Part I: Very tangible new states that are strongly suggestive of many vacua

Part II: Very sharp anthropic prediction that requires at least one other vacuum

Part I: Landscape NTS/Q-balls

Part I: Landscape NTS/Q-balls

- Other vacua $\Rightarrow$ modified spectrum in **our** vacuum—NTSs or Q-balls

Part I: Landscape NTS/Q-balls

- Other vacua $\Rightarrow$ modified spectrum in **our** vacuum—NTSs or Q-balls
- Many vacua $\Rightarrow$ large multiplicity of new states

Part I: Landscape NTS/Q-balls

- Other vacua $\Rightarrow$ modified spectrum in **our** vacuum—NTSs or Q-balls
- Many vacua $\Rightarrow$ large multiplicity of new states
- These states can be produced in the early universe

Part I: Landscape NTS/Q-balls

- Other vacua $\Rightarrow$ modified spectrum in **our** vacuum—NTSs or Q-balls
- Many vacua $\Rightarrow$ large multiplicity of new states
- These states can be produced in the early universe
- We can detect, capture and test exotic states.

A Toy Landscape

Let’s start with EFT landscapes

A Toy Landscape

Let's start with EFT landscapes

- field multiplicity $N \sim 10^3$
- vacuum structure ($\sim 2^N$)

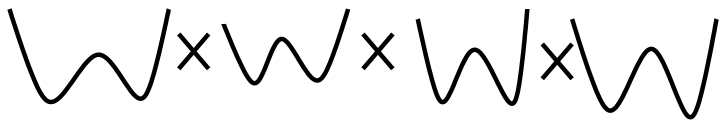
A Toy Landscape

Let's start with EFT landscapes

- field multiplicity $N \sim 10^3$
- vacuum structure ($\sim 2^N$)
- Field-theoretic model

  (hep-th/0501082 Arkani-Hamed,

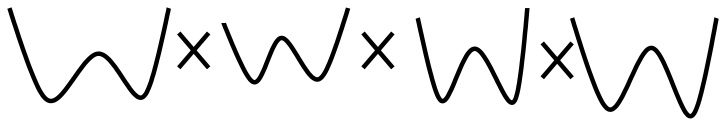
  Dimopolous, Kachru)



A Toy Landscape

Let's start with EFT landscapes

- field multiplicity $N \sim 10^3$
- vacuum structure ($\sim 2^N$)
- Field-theoretic model



(hep-th/0501082 Arkani-Hamed,

Dimopolous, Kachru)

$$V = \sum_i \frac{\lambda_i^2}{8}(\phi_i^2 - v_i^2)^2 + ...$$

Adding a Stable Particle

Let's add a stable particle ψ coupled to $\{\phi_i\}$ sector

Adding a Stable Particle

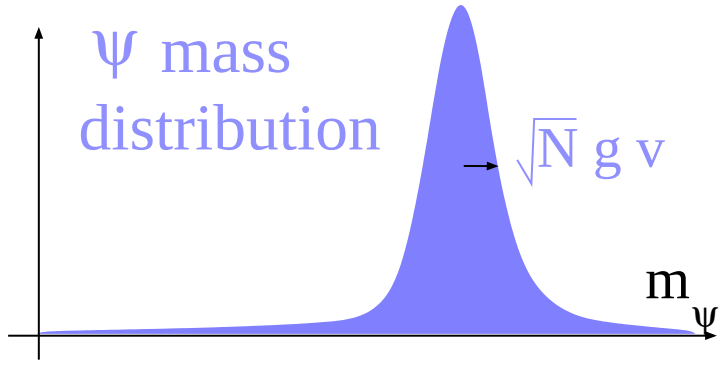
Let's add a stable particle ψ coupled to $\{\phi_i\}$ sector

- Impose a global $U(1)$ or a discrete symmetry to guarantee stability

Adding a Stable Particle

Let's add a stable particle ψ coupled to $\{\phi_i\}$ sector

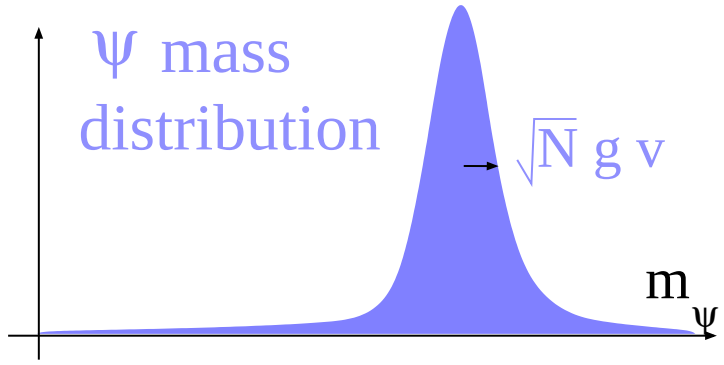
- Impose a global $U(1)$ or a discrete symmetry to guarantee stability
- Coupling to $\{\phi_i\}$ allows ψ mass to scan



Adding a Stable Particle

Let's add a stable particle ψ coupled to $\{\phi_i\}$ sector

- Impose a global $U(1)$ or a discrete symmetry to guarantee stability
- Coupling to $\{\phi_i\}$ allows ψ mass to scan



$$V = \sum_i \frac{\lambda_i^2}{8}(\phi_i^2 - v_i^2)^2 + (m + \sum_i g_i(\phi_i - v_i))^2|\psi|^2.$$

Vacuum Bubbles of One Field

If ψ is lighter in the other vacuum,

Vacuum Bubbles of One Field

If ψ is lighter in the other vacuum,

- ϕ domain wall binds ψ

Vacuum Bubbles of One Field

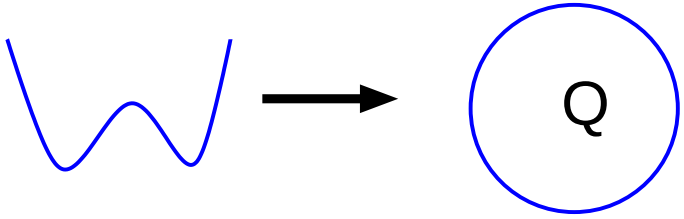
If ψ is lighter in the other vacuum,

- ϕ domain wall binds ψ
- ψ pressure supports wall

Vacuum Bubbles of One Field

If ψ is lighter in the other vacuum,

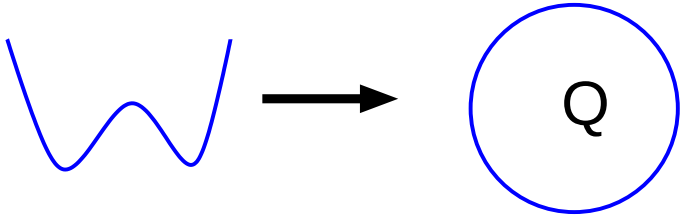
- ϕ domain wall binds ψ
- ψ pressure supports wall



Vacuum Bubbles of One Field

If ψ is lighter in the other vacuum,

- ϕ domain wall binds ψ
- ψ pressure supports wall

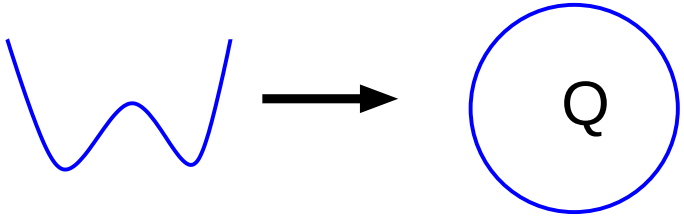


This is the NTS of Friedberg, Lee, Sirlin. We call it a Q-ball.(Phys.Rev.D13:2729,1976)

Vacuum Bubbles of One Field

If ψ is lighter in the other vacuum,

- ϕ domain wall binds ψ
- ψ pressure supports wall



This is the NTS of Friedberg, Lee, Sirlin. We call it a Q-ball.(Phys.Rev.D13:2729,1976)

The spectrum sees the other vacuum!

Simplistic Calculation of Spectrum

Let’s use a particle gas in a box model.

Simplistic Calculation of Spectrum

Let's use a particle gas in a box model.

Confined relativistic scalars: $E \sim \frac{Q}{R} + SR^2$

Simplistic Calculation of Spectrum

Let's use a particle gas in a box model.

Confined relativistic scalars: $E \sim \frac{Q}{R} + SR^2$

$\Rightarrow M(Q) \sim M_0 Q^{2/3}$

Simplistic Calculation of Spectrum

Let's use a particle gas in a box model.

Confined relativistic scalars: $E \sim \frac{Q}{R} + SR^2$

$\Rightarrow M(Q) \sim M_0 Q^{2/3}$

Confined and degenerate relativistic fermions:

$E \sim \frac{Q^{4/3}}{R} + SR^2$

Simplistic Calculation of Spectrum

Let's use a particle gas in a box model.

Confined relativistic scalars: $E \sim \frac{Q}{R} + SR^2$

$\Rightarrow M(Q) \sim M_0 Q^{2/3}$

Confined and degenerate relativistic fermions:

$E \sim \frac{Q^{4/3}}{R} + SR^2$

$\Rightarrow M(Q) \sim M_0 Q^{8/9}$

Simplistic Calculation of Spectrum

Let's use a particle gas in a box model.

Confined relativistic scalars: $E \sim \frac{Q}{R} + SR^2$

$\Rightarrow M(Q) \sim M_0 Q^{2/3}$

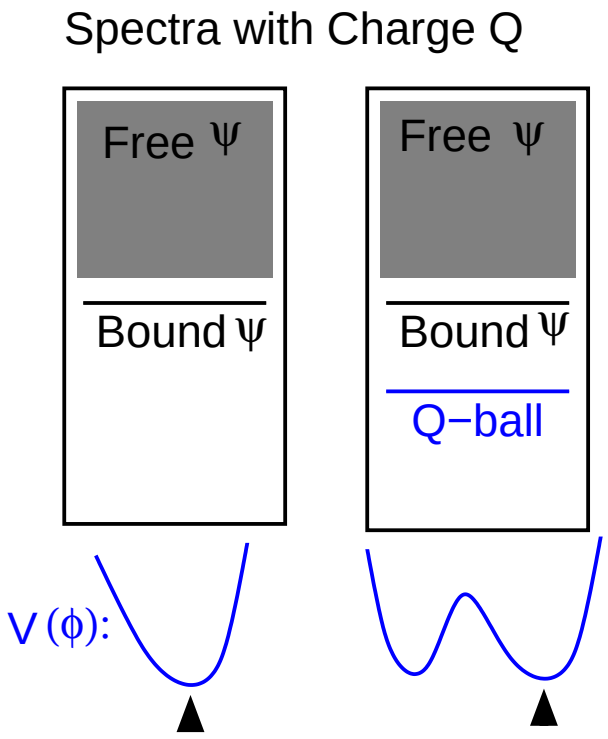
Confined and degenerate relativistic fermions:

$E \sim \frac{Q^{4/3}}{R} + SR^2$

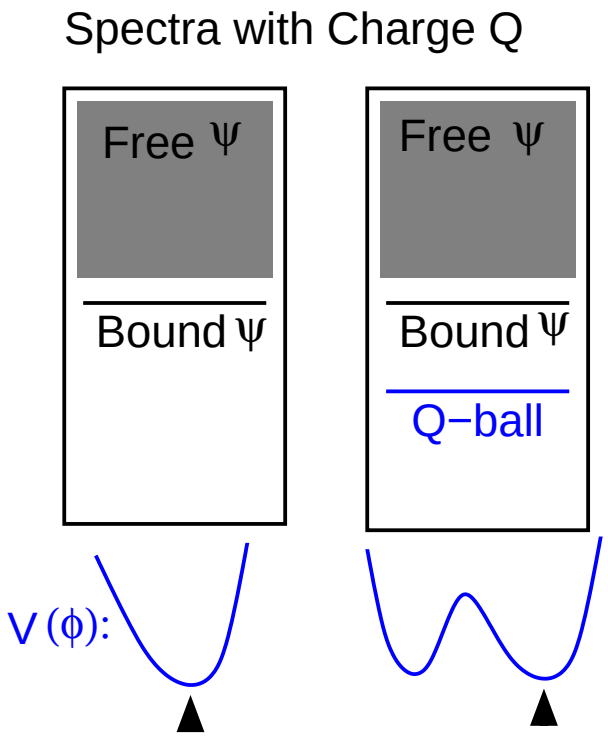
$\Rightarrow M(Q) \sim M_0 Q^{8/9}$

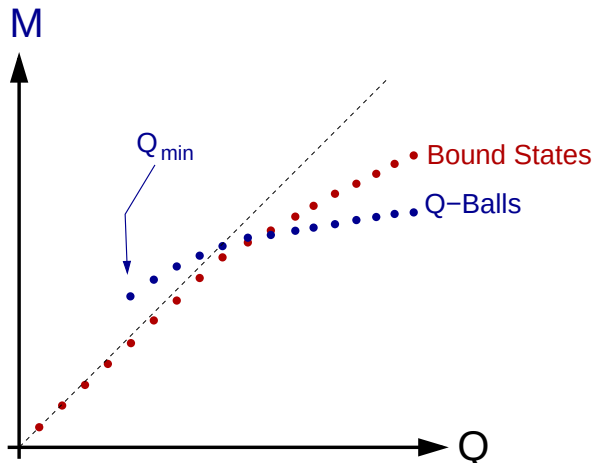
Careful semi-classical results agree with this picture

Bound States to Stable Q-balls

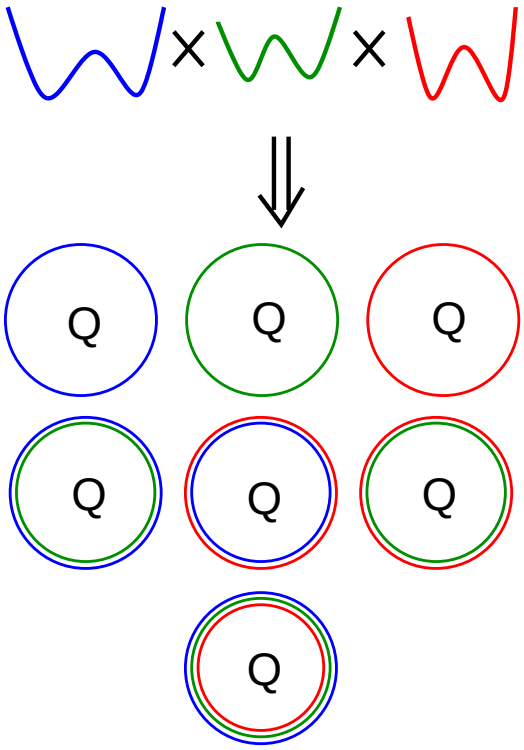


Bound States to Stable Q-balls



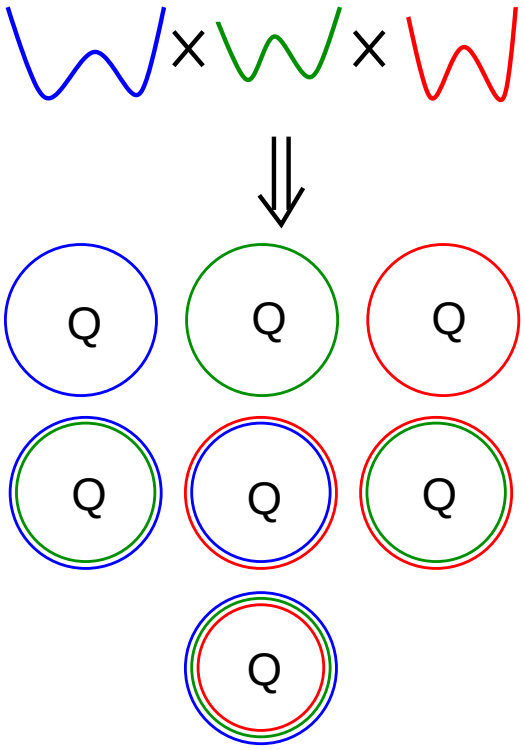


Vacuum Bubbles in a Toy Landscape



- Weakly interacting domain walls $\Rightarrow$ multiple walls can overlap

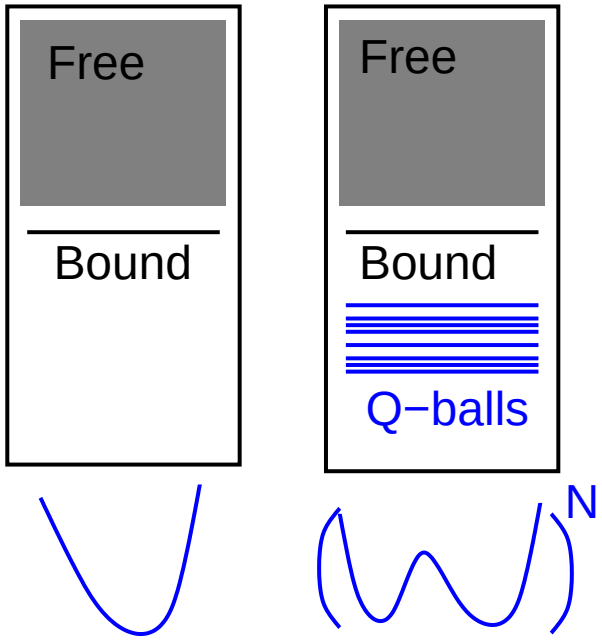
Vacuum Bubbles in a Toy Landscape



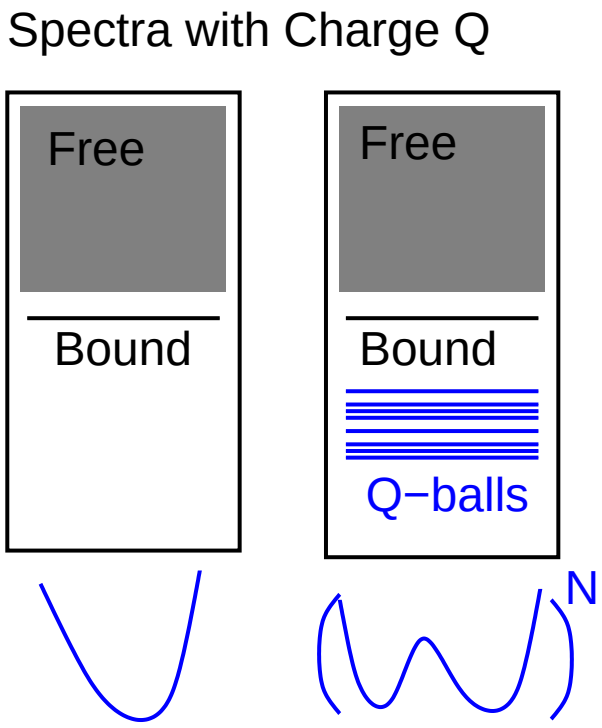
- Weakly interacting domain walls $\Rightarrow$ multiple walls can overlap
- Existence/stability of solutions can be checked in the thin wall semi-classical limit

A Zoo of States

Spectra with Charge Q

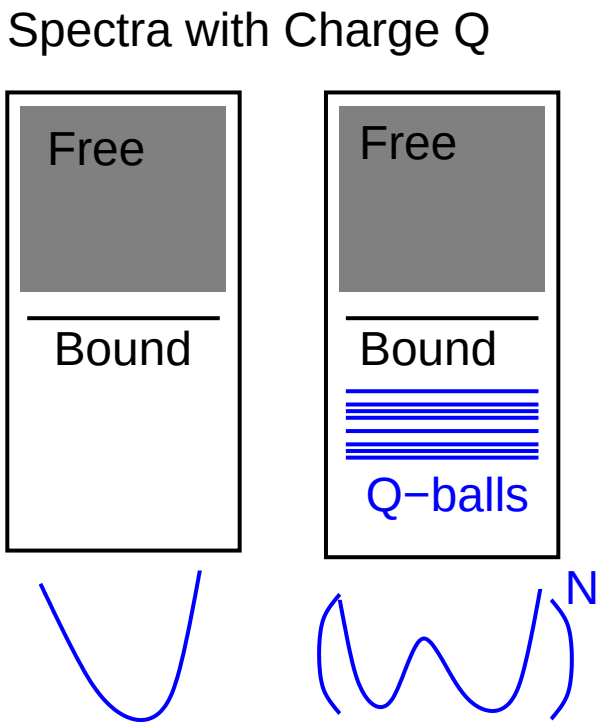


A Zoo of States



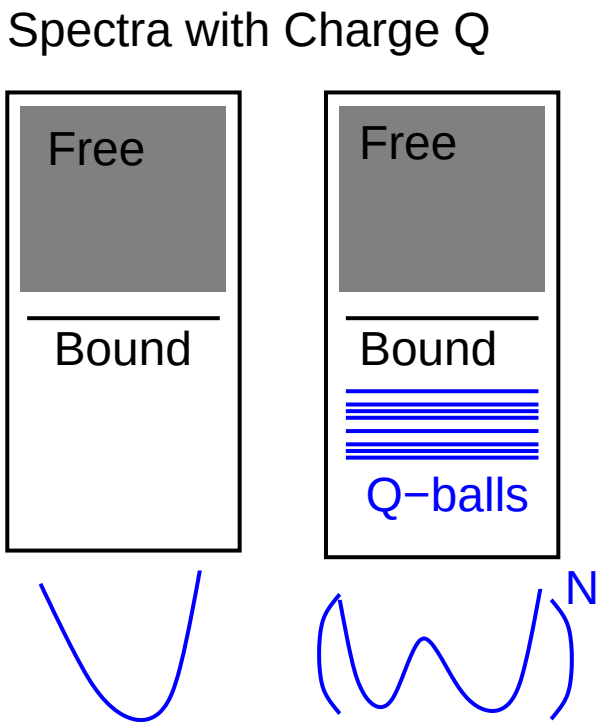
- Tunneling goes like $e^{-S_E} \Rightarrow$ cosmologically long-lived states

A Zoo of States



- Tunneling goes like $e^{-S_E} \Rightarrow$ cosmologically long-lived states
- Multiplicity of vacua $\Rightarrow$ multiplicity of states

A Zoo of States



- Tunneling goes like $e^{-S_E} \Rightarrow$ cosmologically long-lived states
- Multiplicity of vacua $\Rightarrow$ multiplicity of states
- Naive counting: $N_Q \sim \binom{N}{k}$ where N is number of walls and k is number of supportable walls.

Production of Q-balls

How can these vacuum bubbles be made?

Production of Q-balls

How can these vacuum bubbles be made?

The early universe provides a suitable environment for production,

Production of Q-balls

How can these vacuum bubbles be made?

The early universe provides a suitable environment for production, with luck!

Production of Q-balls

How can these vacuum bubbles be made?

The early universe provides a suitable environment for production, with luck!

- Thermal production and synthesis from bound states

Production of Q-balls

How can these vacuum bubbles be made?

The early universe provides a suitable environment for production, with luck!

- Thermal production and synthesis from bound states
- Non-thermal production of domain walls and ψ

Production of Q-balls

How can these vacuum bubbles be made?

The early universe provides a suitable environment for production, with luck!

- Thermal production and synthesis from bound states
- Non-thermal production of domain walls and ψ

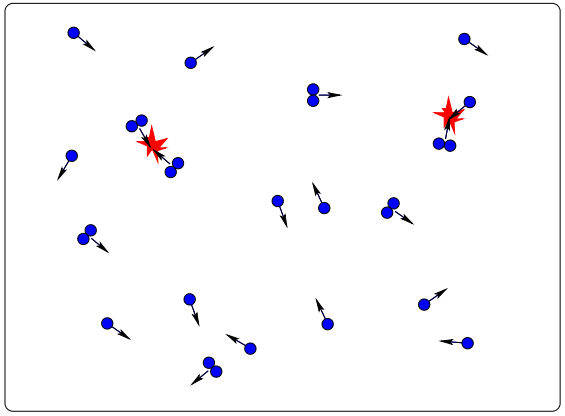
For heavy stable ψ, equilibrium abundance is dangerous $\Rightarrow$ most thermal production modes don't work in practice

The ϵ^{Q} Problem

The ϵ^Q Problem

Thermal production yields,

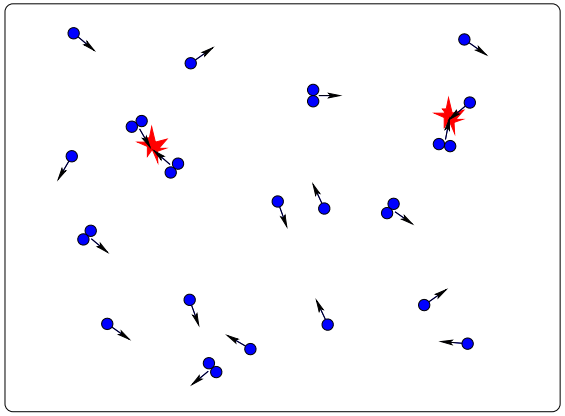
$$\frac{n_{QB}}{s} \equiv Y_{QB} \sim (Y_Q)^{Q_{min}}$$



The ϵ^Q Problem

Thermal production yields,

$$\frac{n_{QB}}{s} \equiv Y_{QB} \sim (Y_Q)^{Q_{min}}$$



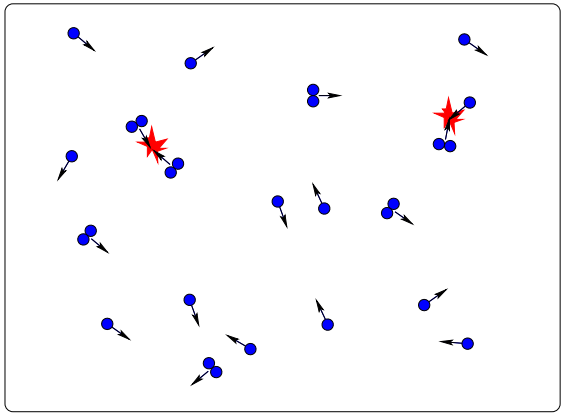
Relic Density:

$$\Omega h^2 \sim 10^{24}(Y)(\frac{m}{10^{16}GeV})$$

The ϵ^Q Problem

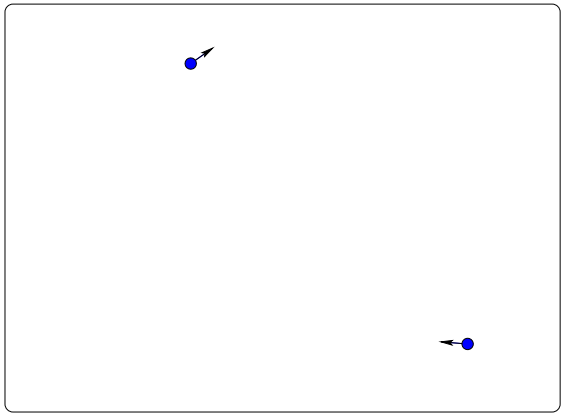
Thermal production yields,

$$\frac{n_{QB}}{s} \equiv Y_{QB} \sim (Y_Q)^{Q_{min}}$$



Relic Density:

$$\Omega h^2 \sim 10^{24}(Y)(\frac{m}{10^{16}GeV})$$



$$\Omega_\psi h^2 \lesssim 0.1 \Rightarrow Y_Q \lesssim 10^{-25}$$

Low Scales and High Entropy

Possible ways to avoid over-production problems

Low Scales and High Entropy

Possible ways to avoid over-production problems

- If $m_\psi, m_\phi \lesssim 10 - 100$ TeV, thermal production is not entirely dangerous

Low Scales and High Entropy

Possible ways to avoid over-production problems

- If $m_\psi, m_\phi \lesssim 10 - 100$ TeV, thermal production is not entirely dangerous
- If $10 - 100$ TeV $\lesssim m_\psi, m_\phi \lesssim 10^5 - 10^7$ TeV, entropy from late decaying $\{\phi_i\}$ can plausibly reduce the abundance of ψ and Q-balls to acceptable levels

Low Scales and High Entropy

Possible ways to avoid over-production problems

- If $m_\psi, m_\phi \lesssim 10 - 100$ TeV, thermal production is not entirely dangerous
- If $10 - 100$ TeV $\lesssim m_\psi, m_\phi \lesssim 10^5 - 10^7$ TeV, entropy from late decaying $\{\phi_i\}$ can plausibly reduce the abundance of ψ and Q-balls to acceptable levels

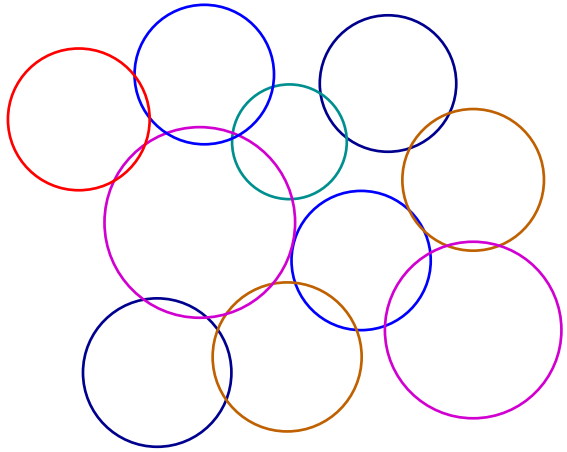
Thermal production viable for low landscape scales or with an additional entropy source

Formation After a Phase Transition

- Reheat above T_c of some ϕ_i

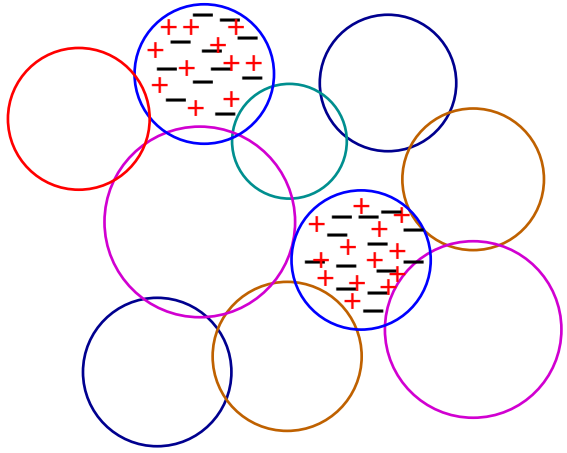
Formation After a Phase Transition

- Reheat above T_c of some ϕ_i
- Hubble-size regions populate vacua



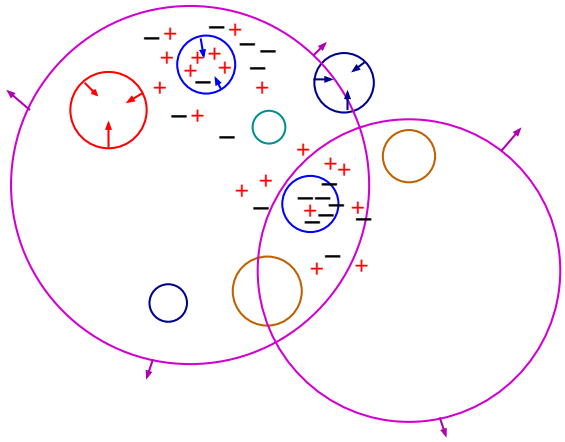
Formation After a Phase Transition

- Reheat above T_c of some ϕ_i
- Hubble-size regions populate vacua
- Only make ψ's in vacua where $m_\psi \lesssim T_R$



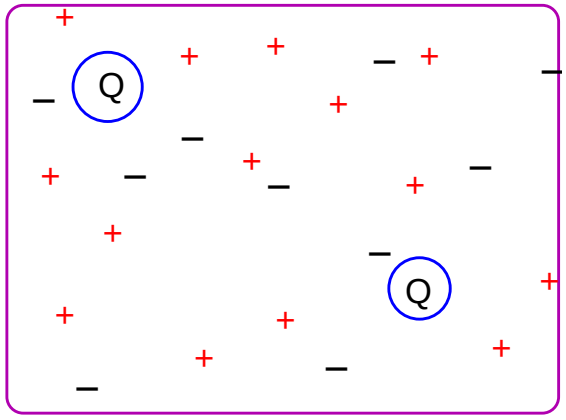
Formation After a Phase Transition

- Reheat above T_c of some ϕ_i
- Hubble-size regions populate vacua
- Only make ψ's in vacua where $m_\psi \lesssim T_R$
- Walls collapse, ψ evaporate

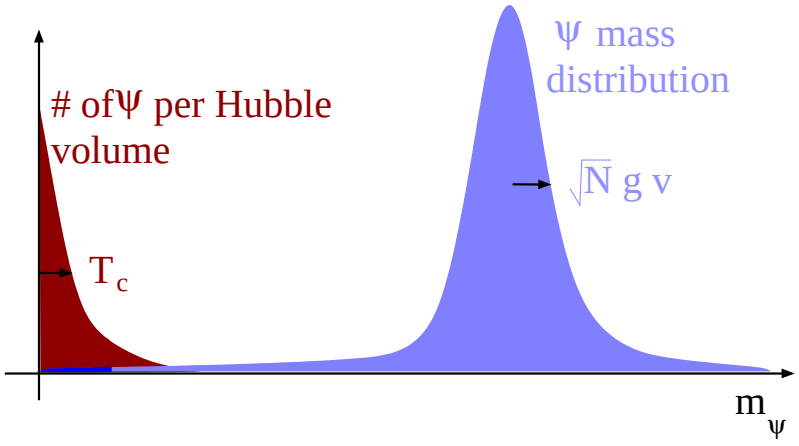


Formation After a Phase Transition

- Reheat above T_c of some ϕ_i
- Hubble-size regions populate vacua
- Only make ψ's in vacua where $m_\psi \lesssim T_R$
- Walls collapse, ψ evaporate
- Trapped charge asymmetry $\longrightarrow$ Q-balls

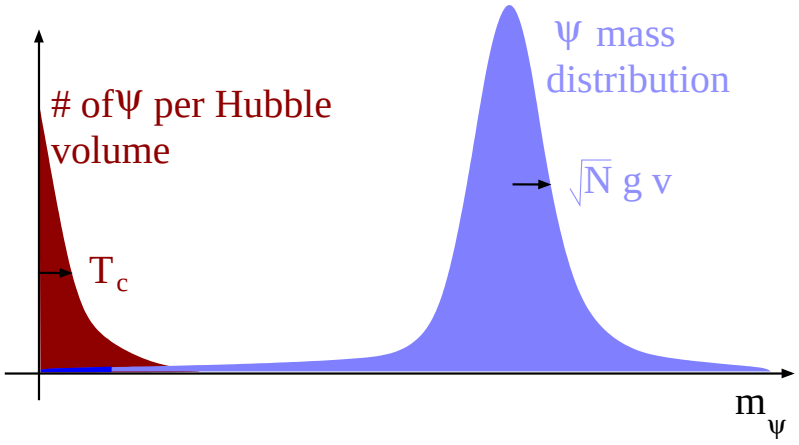


Abundance of Q-balls



Power-law tails in mass distribution $\Rightarrow$ both ψ and Q-ball production dominated by ψ-friendly vacua on tail where $m'_\psi \sim T_R$.

Abundance of Q-balls



Power-law tails in mass distribution $\Rightarrow$ both ψ and Q-ball production dominated by ψ-friendly vacua on tail where $m'_\psi \sim T_R$.

Ω_ψ controlled by fraction of vacua that are ψ-friendly and $\frac{T_R}{m_\psi}$.

$\frac{n_{\text{Q ball}}}{n_\psi} \lesssim 1/Q_{min}^2$ determined by evaporation.

Final Thoughts on Production

- Domain walls are hard to make!

Final Thoughts on Production

- Domain walls are hard to make!
- Ordinary thermal production resulting in sizable Q-ball production $\rightsquigarrow$ over-production of free ψ

Final Thoughts on Production

- Domain walls are hard to make!
- Ordinary thermal production resulting in sizable Q-ball production $\rightsquigarrow$ over-production of free ψ
- Low landscape scales or additional entropy sources helpful

Final Thoughts on Production

- Domain walls are hard to make!
- Ordinary thermal production resulting in sizable Q-ball production $\rightsquigarrow$ over-production of free ψ
- Low landscape scales or additional entropy sources helpful
- Landscape sector phase transition offers a potentially simple way out of over-production problem

Final Thoughts on Production

- Domain walls are hard to make!
- Ordinary thermal production resulting in sizable Q-ball production $\rightsquigarrow$ over-production of free ψ
- Low landscape scales or additional entropy sources helpful
- Landscape sector phase transition offers a potentially simple way out of over-production problem
- Other possibilities?

Q-ball Detection and Identification

Q-ball Detection and Identification

- Detection of landscape Q-balls is feasible only if they are charged.

Q-ball Detection and Identification

- Detection of landscape Q-balls is feasible only if they are charged.
- ψ_{QB} looks like a strong, weak, or electromagnetically charged heavy particle. Mass: $\sim 10^3 - 10^{17}$ GeV

Q-ball Detection and Identification

- Detection of landscape Q-balls is feasible only if they are charged.
- ψ_{QB} looks like a strong, weak, or electromagnetically charged heavy particle. Mass: $\sim 10^3 - 10^{17}$ GeV
- Objects with these properties go by the name SIMPs, CHAMPs, neutra-CHAMPs, and so on...

Q-ball Detection and Identification

- Detection of landscape Q-balls is feasible only if they are charged.
- ψ_{QB} looks like a strong, weak, or electromagnetically charged heavy particle. Mass: $\sim 10^3 - 10^{17}$ GeV
- Objects with these properties go by the name SIMPs, CHAMPs, neutra-CHAMPs, and so on...
- These particles can be detected passing through a chunk of material

Q-ball Detection and Identification

- Detection of landscape Q-balls is feasible only if they are charged.
- ψ_{QB} looks like a strong, weak, or electromagnetically charged heavy particle. Mass: $\sim 10^3 - 10^{17}$ GeV
- Objects with these properties go by the name SIMPs, CHAMPs, neutra-CHAMPs, and so on...
- These particles can be detected passing through a chunk of material
- If particles stop, they can be looked for in the earth, moon, meteoritic material...etc

Q-Ball Identification

Q-Ball Identification

- Distinguished from generic heavy relic by large multiplicity of long-lived states with same charge and different masses.

Q-Ball Identification

- Distinguished from generic heavy relic by large multiplicity of long-lived states with same charge and different masses.
- May need to collect Q-balls in order to verify multiplicity.

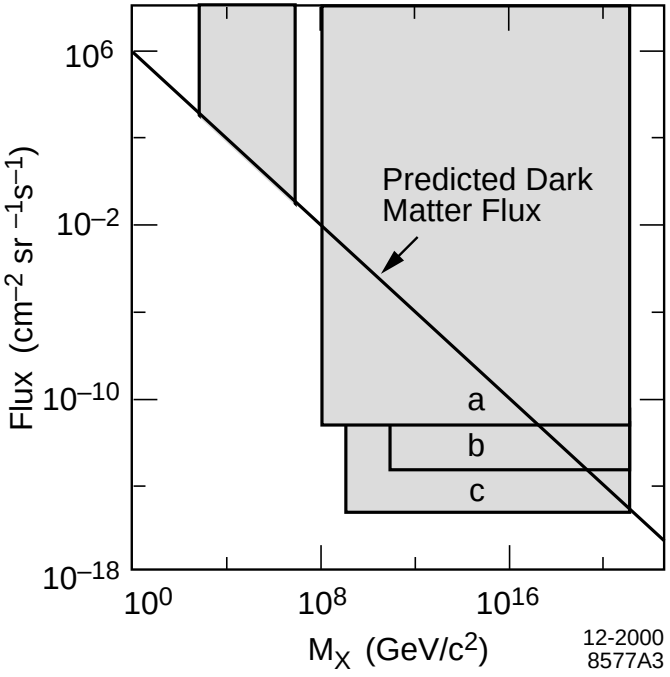
Q-Ball Identification

- Distinguished from generic heavy relic by large multiplicity of long-lived states with same charge and different masses.
- May need to collect Q-balls in order to verify multiplicity.
- In principle, spectrum can reconstructed $\Rightarrow$ strong evidence for vacuum bubble interpretation

Q-Ball Detection

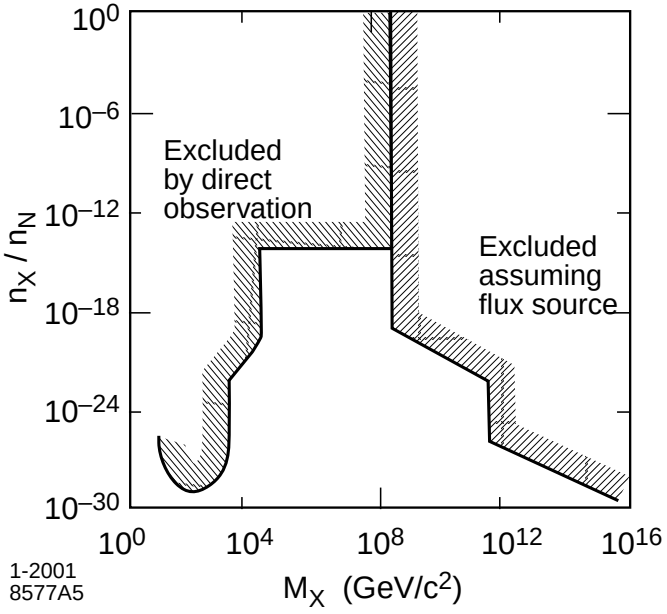
CHAMP Flux limits from IMP 8, MACRO:

(figure from M. Perl et al hep-ex/0102033)

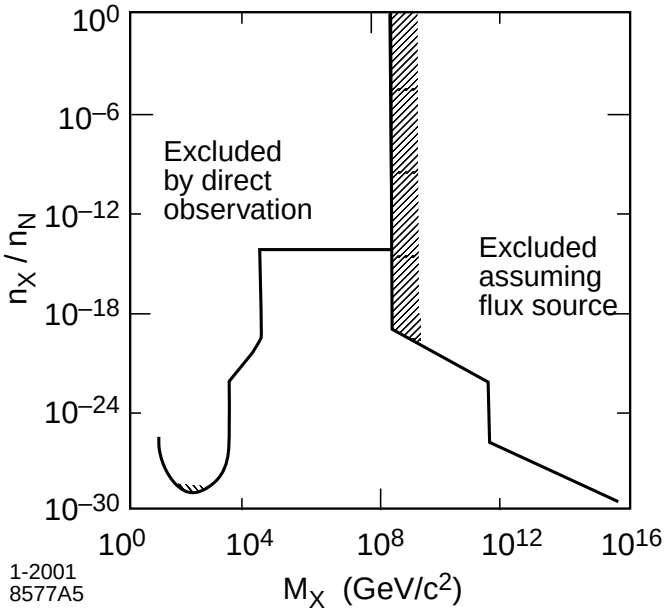


A flux of $\frac{10^{-13}}{cm^2 \cdot sr \cdot s}$ stopping in Earth $\rightarrow$ one ψ per ton of matter in the Earth, probably tens of Q-balls per kton.

Future Search Prospects

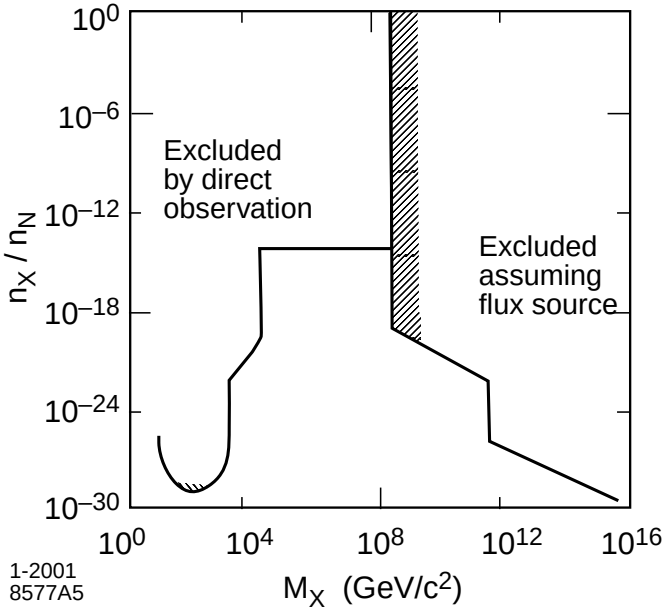


Future Search Prospects



- Typical energy loss: GeV/cm (charged) and KeV/cm (strong and neutral)

Future Search Prospects



- Typical energy loss: GeV/cm (charged) and KeV/cm (strong and neutral)
- Stopping in earth: $m_{QB} \lesssim 10^{16-18}$ Gev (charged) and $m_{QB} \lesssim 10^{10-12}$ GeV (neutral and strong)

Conclusions

- The landscape could be visible—other vacua can leave an imprint on the spectrum (Q-balls).

Conclusions

- The landscape could be visible—other vacua can leave an imprint on the spectrum (Q-balls).
- Q-balls could be produced in the early universe and visible in exotic particle searches.

Conclusions

- The landscape could be visible—other vacua can leave an imprint on the spectrum (Q-balls).
- Q-balls could be produced in the early universe and visible in exotic particle searches.
- Given current limits, collecting and studying Q-balls could be very challenging.

Conclusions

- The landscape could be visible—other vacua can leave an imprint on the spectrum (Q-balls).
- Q-balls could be produced in the early universe and visible in exotic particle searches.
- Given current limits, collecting and studying Q-balls could be very challenging.
- No guarantee of discovery, but positive discovery would be profound! If nature is kind, exotics may offer an important experimental probe of the landscape.