# Constraints on millicharged particles from thunderstorms on the Solar system planets.

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# Introduction

- Production of particles in an intense external electric field
  - Schwinger effect
  - The necessary field for electron $E_{cr} = m^2/e \approx 1.3 \times 10^{18}$ V/m
- Production of millicharged particles
  - Particles with a charge much smaller than the charge of an electron
  - The required electric field strength is less
- Field strength in thunderclouds
  - Clouds are like a huge capacitor
  - Two ways of discharge: lightning and the production of millicharged particles
- Consideration of the atmospheres of other planets
  - The expected field amplitude is greater than in the Earth's atmosphere
  - More distance between storm clouds $\longrightarrow$ larger capacitor
- Consideration of both bosons and fermions
  - For bosons, Bose-enhancement accelerates the process
  - For fermions, the Pauli blocking slows down the process

# The Schwinger pair-production

Probability per unit volume per unit time for scalar particles and fermions

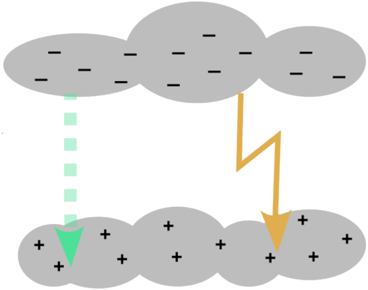
$$\Gamma_S = \frac{(qE)^2}{(2\pi)^3} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} e^{-\frac{\pi m^2}{qE} n},$$

$$\Gamma_F = \frac{(qE)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\frac{\pi m^2}{qE} n}.$$

The process is exponentially suppressed when $qE \ll m^2$
In the limit $qE \gg m^2$:

$$\Gamma_S = \frac{(qE)^2}{96\pi}, \qquad \Gamma_F = \frac{(qE)^2}{24\pi}.$$

# The estimate for particle charge



The particles create a current $J_{mc}$ associated with the discharge of the cloud capacitor

$$J_{mc} \simeq 2 \times q \times \Gamma_{S(F)} \times L^3$$

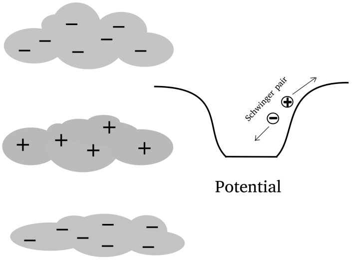
Lightning is observed $\Longrightarrow$ discharging the capacitor through it, and not through the production of particles

$$J_{\mathrm{mc}} < J_{\mathrm{lightning}} \times \frac{t_{\mathrm{lightning}}}{t_{\mathrm{pause}}}$$

Charge constraints

$$q > \left( \frac{48\pi}{s \times E^2 \times L^3} \times J^{\mathrm{amp}}_{\mathrm{lightning}} \times \frac{t_{\mathrm{lightning}}}{t_{\mathrm{pause}}} \right)^{1/3}$$

# Bose-enhancement




The structure of charged thunderclouds and a potential well for generated particles

- Negatively charged particles from the pair remain in the potential well.
  - The Bose-Einstein condensate is formed
  - The condensate growth acceleration (Bose-enhanecment)
- Length scale is the size of the capacitor $\Longrightarrow$ Compton wavelength $d_C \sim 1/m_\chi$
  - The production of a couple is suppressed at $d \gtrsim d_C$
  - The production is not suppressed when $d \lesssim d_C$
- The Schwinger process is not suppressed if

$$q > \frac{\pi \max(m^2, L^{-2})}{E}$$

# Pauli blocking

Fermi statistics in a potential well $\Longrightarrow$ there is a maximal number of states
The momentum range $L^{-1} \lesssim p \lesssim \sqrt{qE}$
The number of quantum states

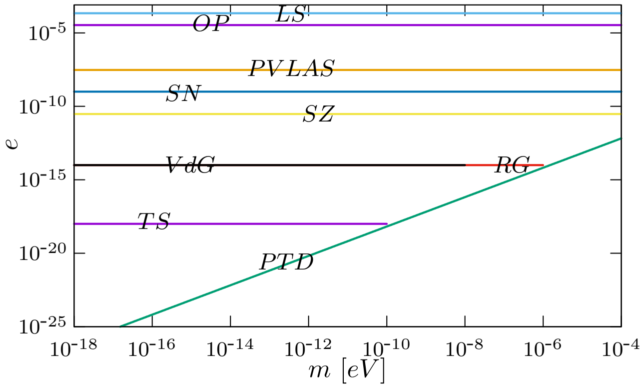
$$N_F = \frac{V}{\pi^2} \int_{L^{-1}}^{\sqrt{qE}} p^2 dp = \frac{L^3 (qE)^{3/2} - 1}{3\pi^2} \tag{1}$$

$V = L^3$, $\varepsilon$ - dielectric permittivity, $S = L^2$ - area of the capacitor plates
the number of mCPs, that are necessary to discharge the cloud capacitor:

$$N_Q = \frac{Q}{q} = \frac{E\varepsilon S}{q}, \tag{2}$$

The constraint on $q$ can be obtained solving equation $N_F = N_Q$ with respect to q.

# Experimental estimates for millicharged particles




LS - Lamb shift, OP - Ortho-Positronium, PVLAS - PVLAS experiment, BBN - Big-Bang Nucleosynthesis, SN - SN1987A, SZ - CMB observations of the Sunaev-Zel'dovich effect, WD - white dwarfs, RG - red giant, VdG - Van de Graaff, TS - thunderstorms, PTD - photon time delay with pulsars

# The thunderstorms on planets of Solar system

*Detection of planetary lightning via optical, VLF (very low frequency) radio emissions (whistlers or sferics below ionospheric cut-off frequency) and HF (high frequency) radio emissions above the ionospheric cut-off frequency. Question marks denote ambiguous detections (e.g. small number of signals or other possible explanations).*

| *Planet/detection* | *Optical* | *VLF* | *HF radio* |
|---|---|---|---|
| Venus | Yes? | Yes? | Yes? |
| Earth | Yes | Yes | Yes |
| Jupiter | Yes | Yes | No |
| Saturn | Yes | Yes? | Yes |
| Titan (moon) | No | Yes? | No |
| Uranus | No | No | Yes |
| Neptune | No | Yes | Yes? |

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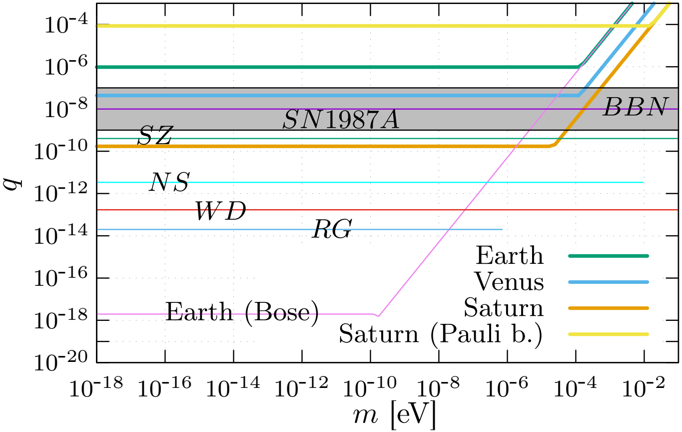
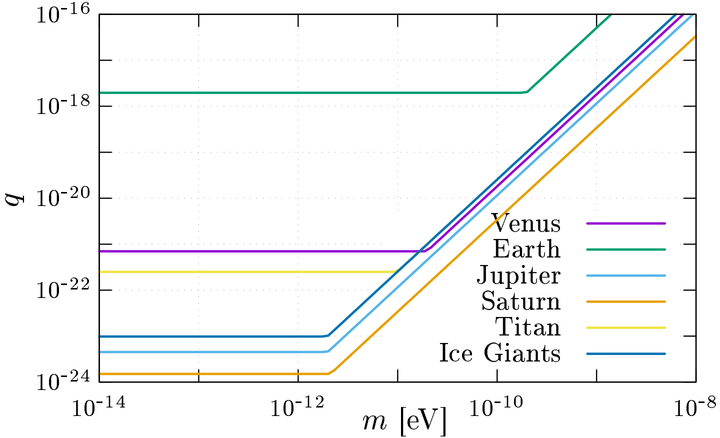
# Estimates without taking into account Bose-enhancement and taking into account the Pauli blocking




| Earth | Venus | Saturn |
|---|---|---|
| $q_V \gtrsim 4 \times 10^{-8}$ | $q_V \gtrsim 4 \times 10^{-8}$ | $q_S \gtrsim 1.7 \times 10^{-10}$ |
| $m_V \ll 1.3 \times 10^{-4}$ eV | $m_V \ll 1.3 \times 10^{-4}$ eV | $m_S \ll 2 \times 10^{-5}$ eV |

# Estimates based on Bose-enhancement




| Earth | Venus | Saturn |
|---|---|---|
| $q_E \gtrsim 10^{-18}$ | $q_V \gtrsim 7 \times 10^{-22}$ | $q_S \gtrsim 1.3 \times 10^{-24}$ |
| $m_E \lesssim 10^{-10}$ eV | $m_V \lesssim 2 \times 10^{-11}$ eV | $m_S \lesssim 2 \times 10^{-12}$ eV |

# Conclusion

- The best limits correspond to thunderstorms on the gas giants, in particular Saturn

$$q_S > 10^{-4}, \qquad \text{Fermi}$$
$$q_S > 10^{-24}, \qquad \text{Bose.}$$

  The obtained constraints for bosons are among the best in the literature.

- Constraints on bosons are better than those on fermions by more than 10 orders of magnitude. The reason is Bose-enhancement, taking into account the Pauli blocking further worsens the constraints
- We expect that improved data on planetary atmospheres, in particular on Jupiter, may improve the constraints

*Thank you for your attention!*

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