Physics of Neutrino detection

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"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do." W.Pauli

Introduction

Introduction

- The neutrinos has changed our understanding of particle physics in the last decade.
- The neutrino detection developments has been critical for this revolution.
- Neutrino experiments explores most of the known technologies for particle detection, it is also an excellent framework to explore techniques applied in different fields of particle and nuclear physics.

Fundaments

- Neutrinos are detected via the particles produced in interactions of neutrinos with matter:
  - The interaction models play an important role in the detection.
  - They are the goal and the path to the goal at same time.
- The typical cross-section is very low (10^{-40} cm^{-2}) requiring:
  - large neutrino fluxes ($>10^{10}$)
  - large exposure ($>10^{7}$ s)
  - large target mass (with the help of Avogadro's number)
  - low background or ways to reduce it in analysis.

Fundaments

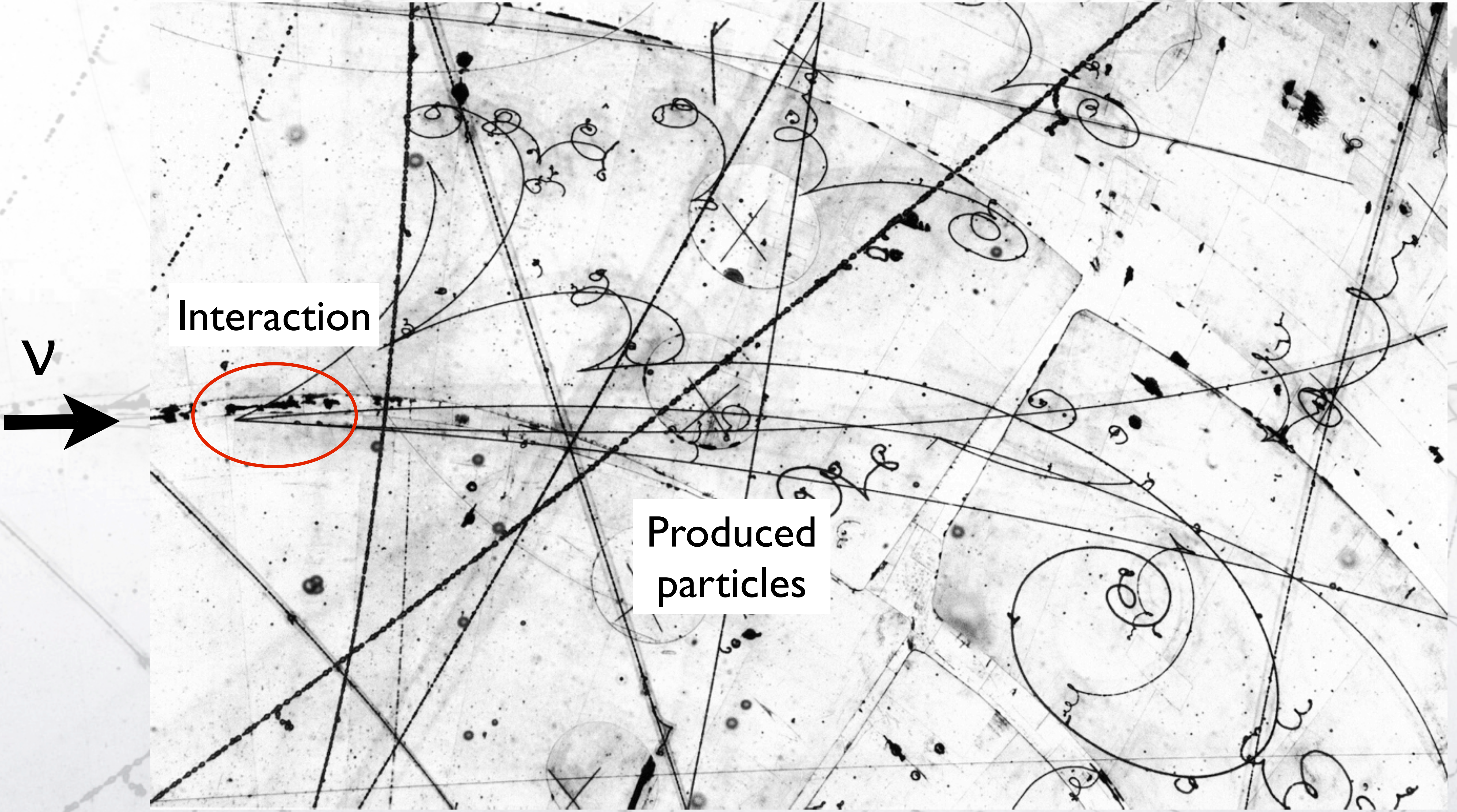
$$N_{obs} = \underbrace{\boxed{\frac{M}{A} \times 6.023 \times 10^{23}}}_{N_{targets}} \times T \int \Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)dE_\nu$$

- $N_{targets}$ is the number of targets
- T is the exposure time.
- Φ is the neutrino flux
- σ is the neutrino cross-section
- ε is the detection efficiency.

Reactor neutrinos

- $N_{targets}$ = 1Ton/12g 6.023 10^{23} = 5 10^{29}
- T = 3.15 10^{7} s (1 year)
- Φ_{1GWth}=1.5 10^{20} ν/s → 1.2 10^{9} cm^{-2} @1km
- $\sigma_{(\nu p \to ne)}$ = 10^{-43} cm^{2} @ 3MeV
- ε = 1
- N_{obs} ~ 1900 ν/year

Fundaments

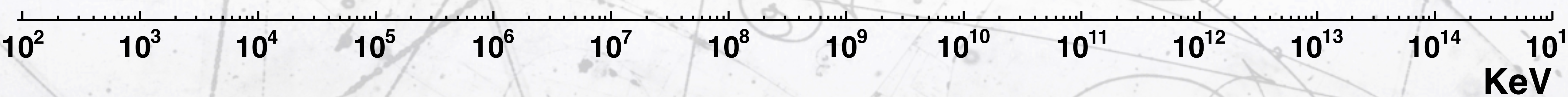


Fundaments

- Detection of neutrinos has additional requirements:
  - Identify the neutrino type: critical for oscillations.
  - Reconstruct the energy of the neutrino:
    - The neutrino sources are not monochromatic.
    - this is not always possible, so the energy of the lepton is used.
  - We need to identify the reaction channel:
    - Neutral current vs Charged current.
    - Different interaction channels in NC or CC.

Fundaments

- Neutrino sources, both artificial and natural, covers few orders of magnitude in Energy.



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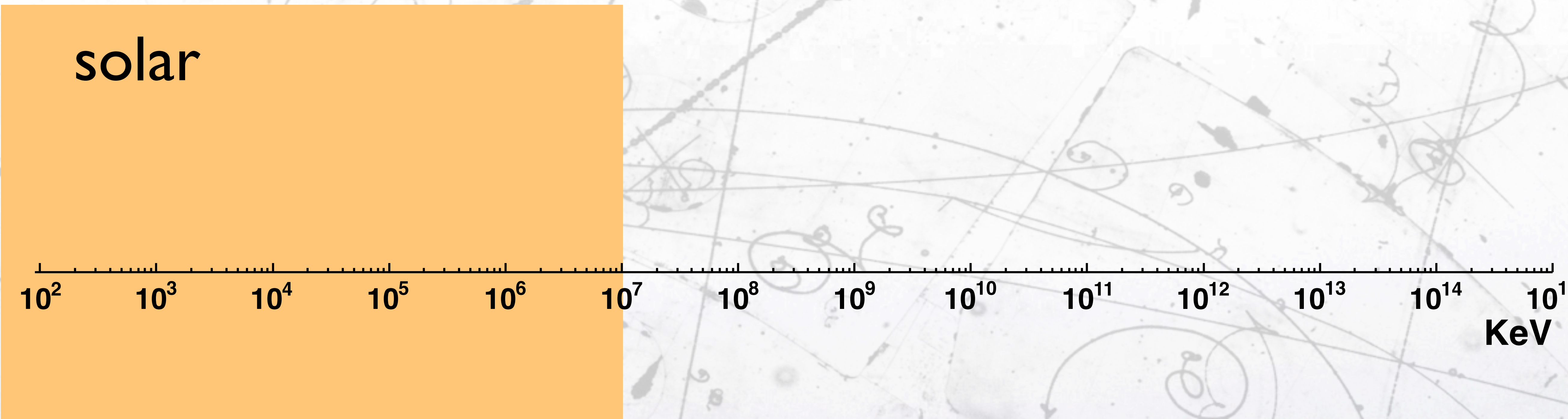

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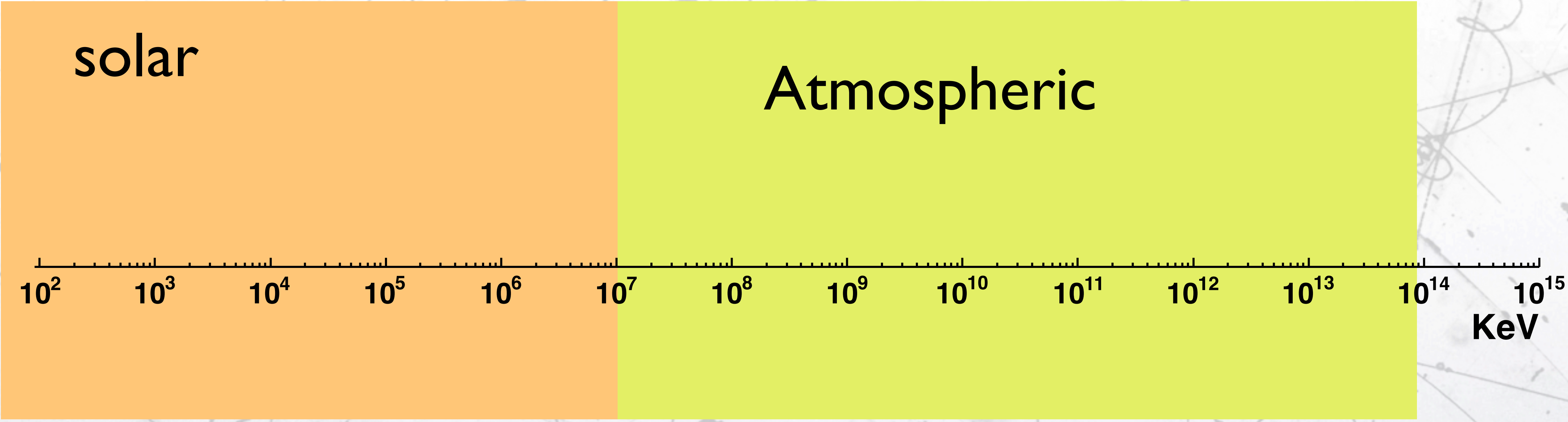

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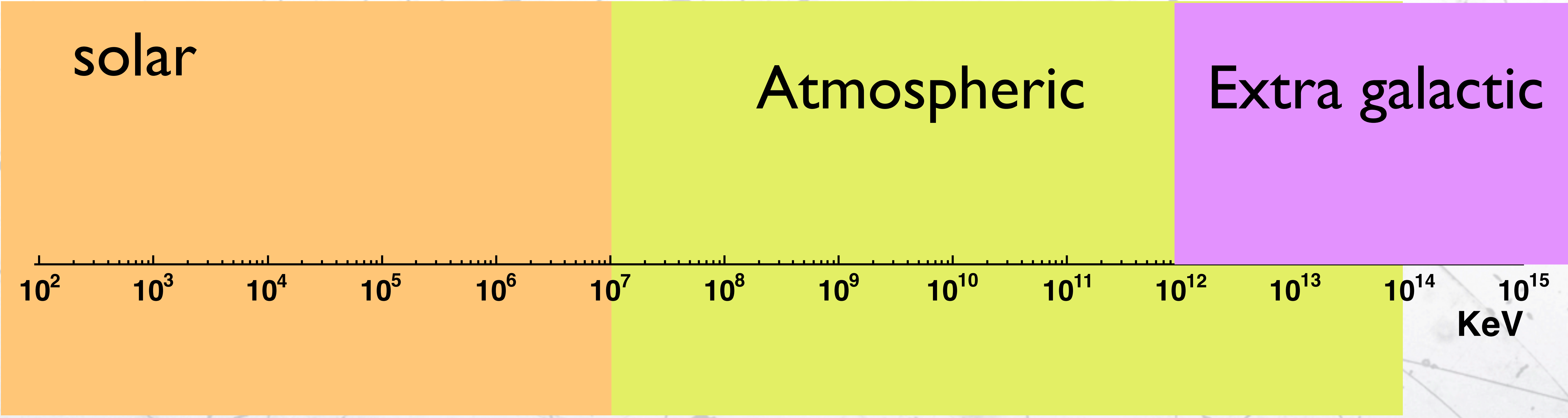

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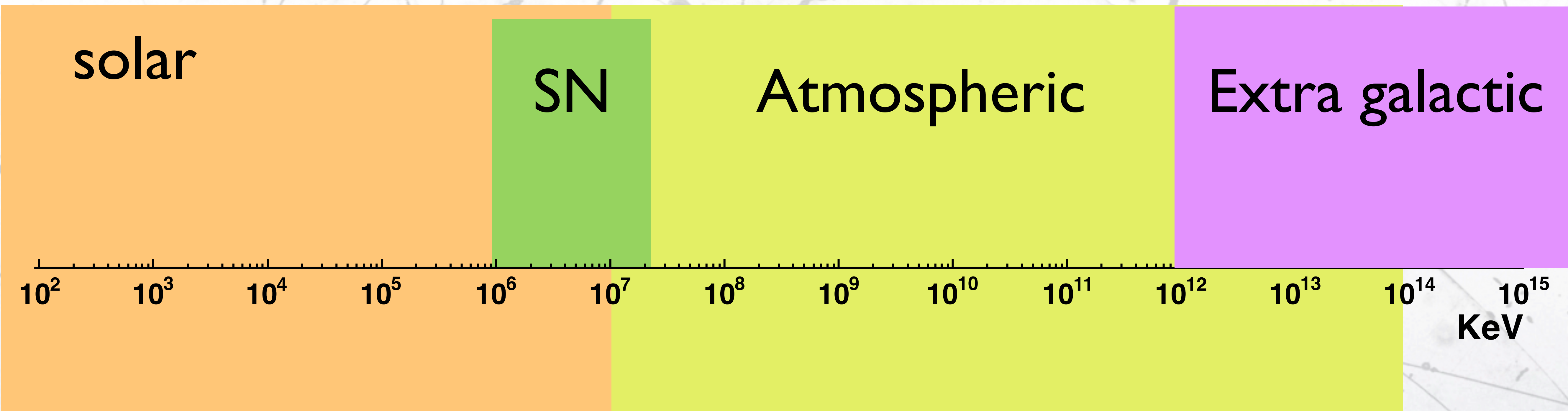

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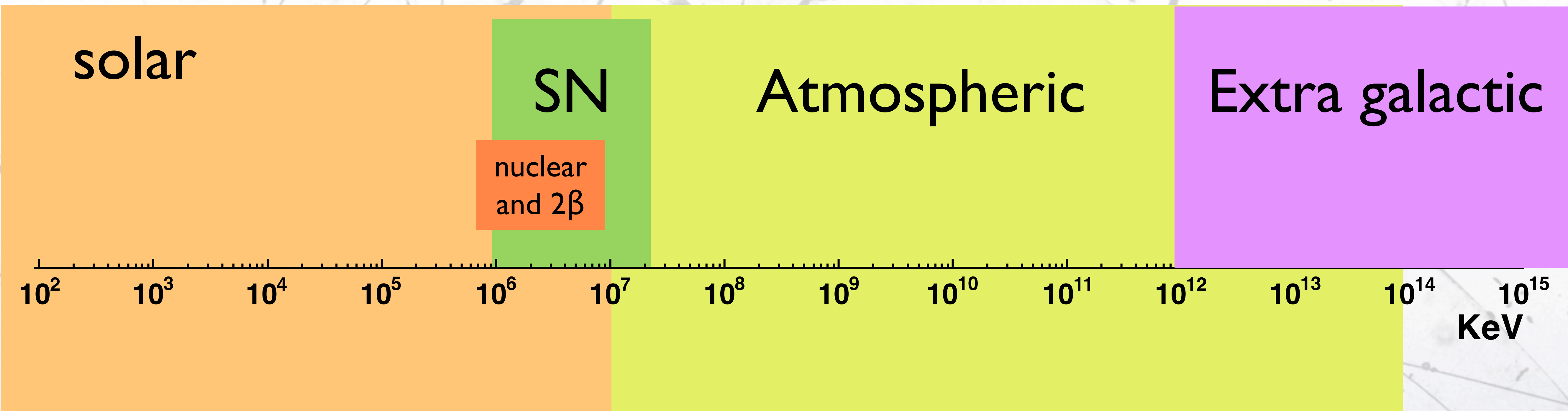

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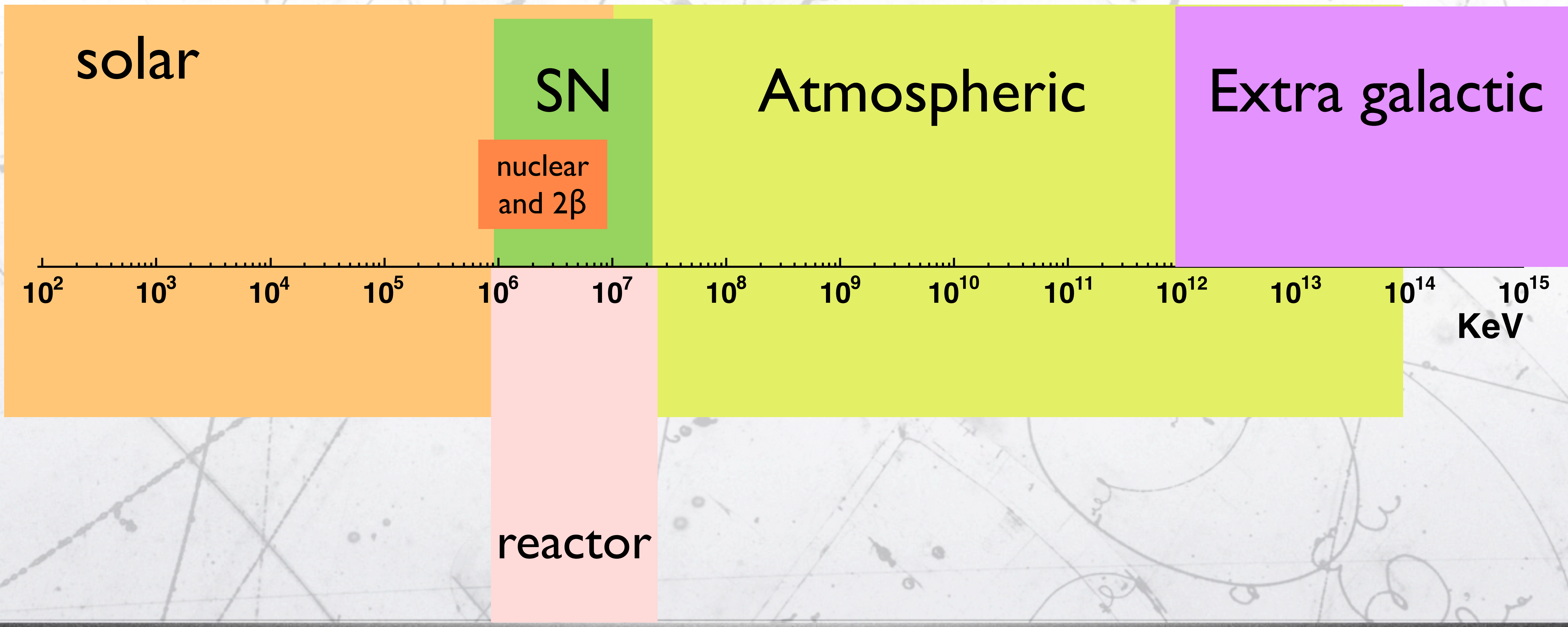

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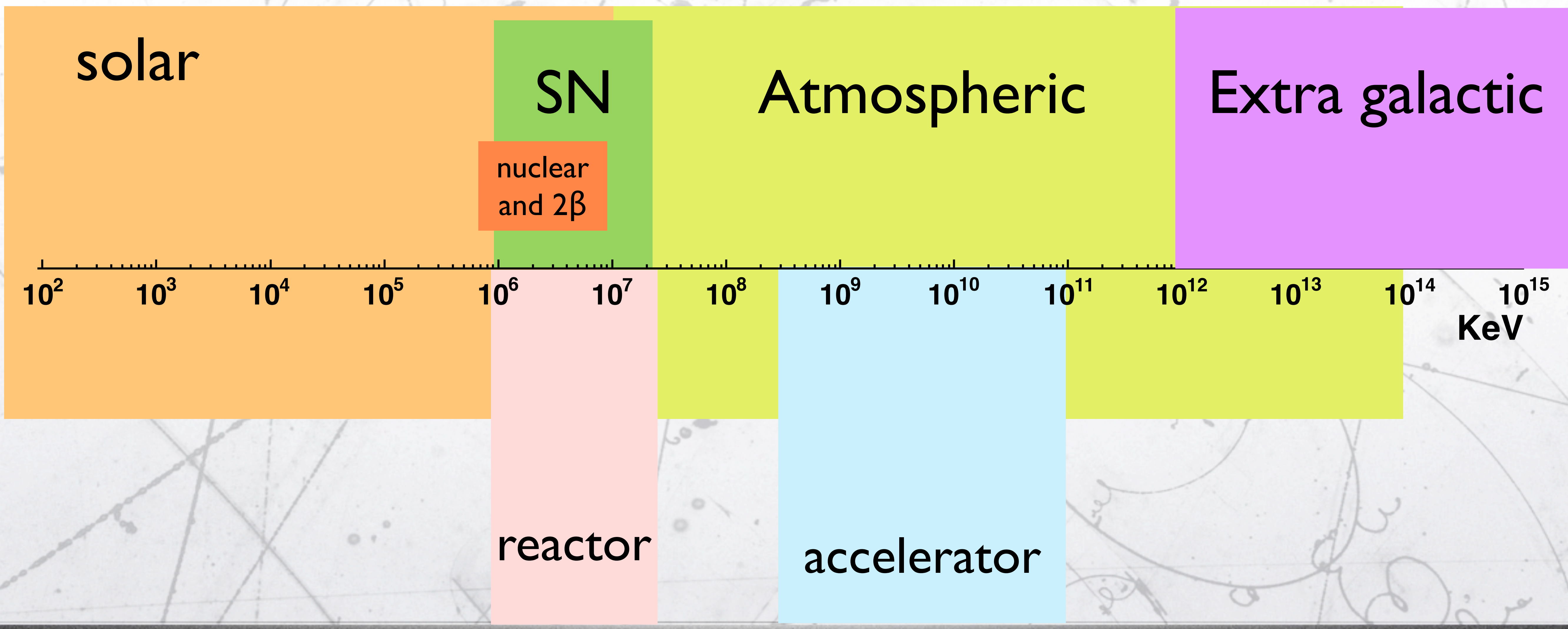

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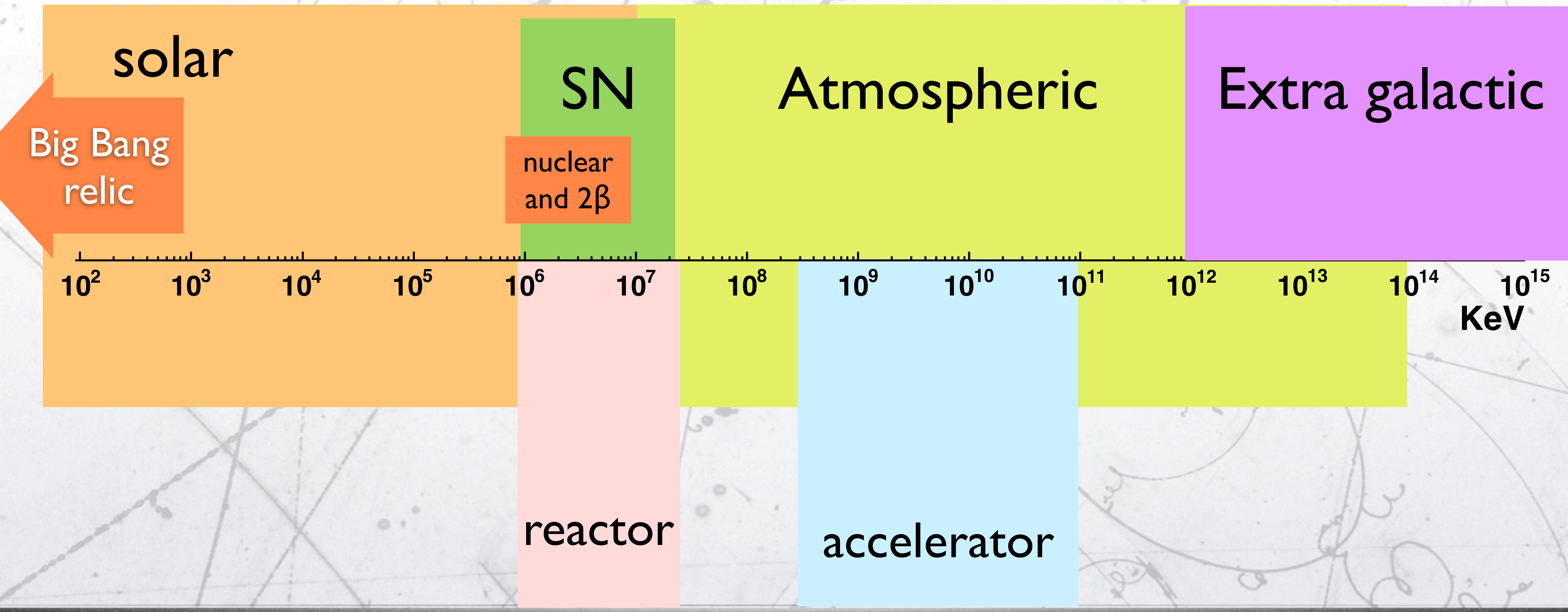


Fundaments

- The final piece of information is the identification of the neutrino type:
  - NC do not distinguish neutrino flavour.
  - CC produce different lepton in the final state:
    - Use the lepton to identify the neutrino. Particle Id
- Neutrinos vs antineutrinos:
  - NC do not distinguish among them.
  - CC produce:
    - leptons with different charge. Charge Id
    - different final hadronic states that might be used. Particle Id

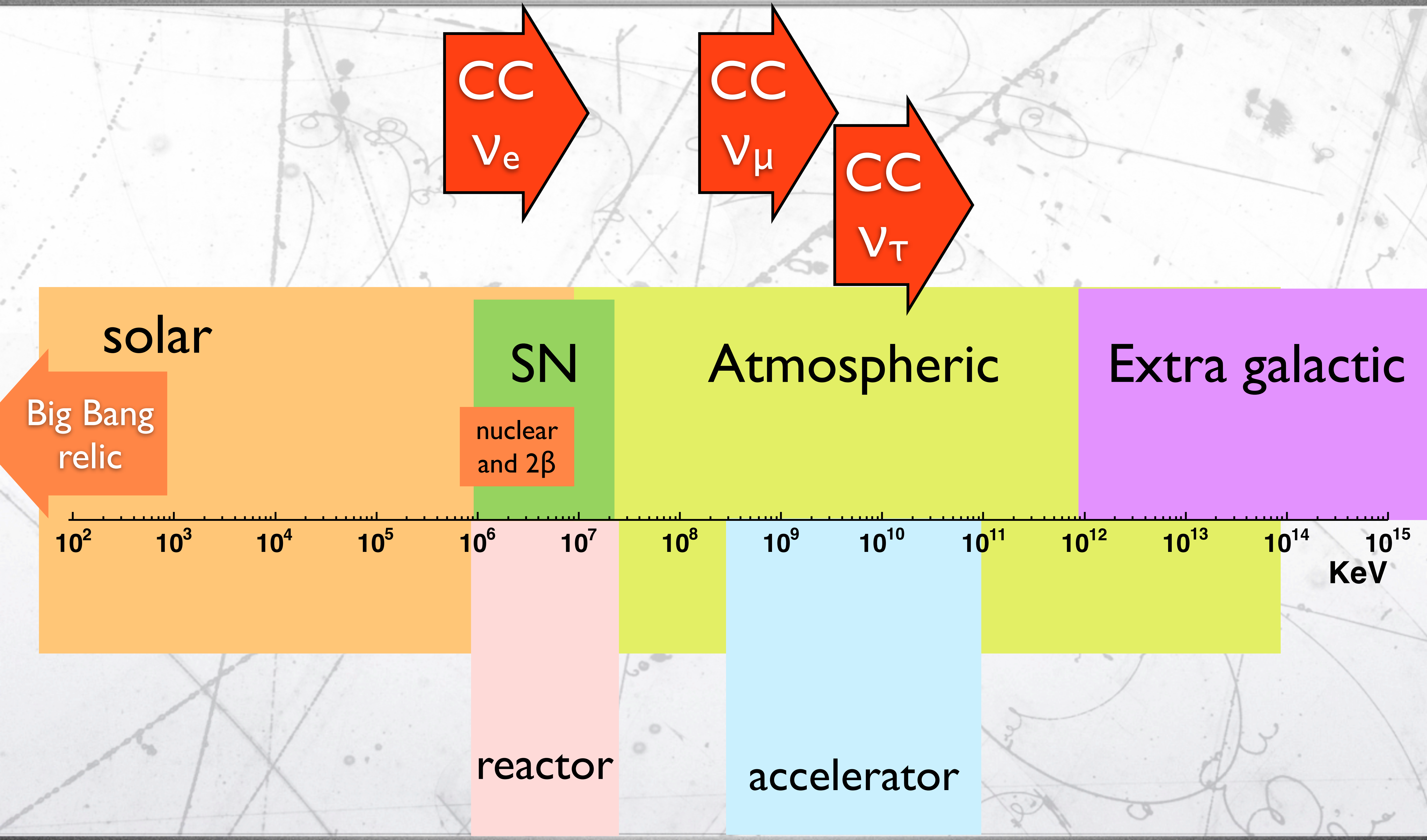
Thresholds

- Along this large range of energies the neutrino interact with different reaction channels with matter.
  - Charge Current interactions require the production of a lepton, so they need a minimum energy.
    - ν_e ~ 500 KeV
    - ν_μ ~ 120 MeV
    - ν_τ ~ 3.5 GeV
  - Neutral Currents can be produced:
    - almost at any energy on electron target
    - and nuclear targets above certain threshold.

Thresholds

- Interactions on nuclei:
  - The interaction of neutrinos with bound nucleons in a nucleus has a threshold of the order of tenths of MeV since we need to extract the nucleon from the Fermi see.
    - depends on the neutrino type, the nucleus and channel (i.e. CC vs NC, …)
  - Lower energy neutrinos interact with matter either on (quasi)free nucleons or electrons.

Fundaments



CC ν_e
CC ν_μ
CC ν_τ
solar
SN
Atmospheric
Extra galactic
Big Bang relic
nuclear and 2β
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}
KeV
reactor
accelerator

Fundaments

- Neutrino detectors should be able to detect all leptons and the low energy hadrons: pions, protons, etc… in a large energy range (from MeV to tenths of GeV).
- These goals requires to exploit several detection techniques and technologies:
    - calorimetry
    - tracking: range & curvature
    - Cherenkov (light and radio)
    - vertexing
    - radiochemical.

Neutrino interactions for neutrino detection

More in Kevin´s lectures with a different scope

Neutrino interactions

- The interactions of neutrinos with matter also differ along the same range of energies.
- Two main categories depending on the weak interaction:
  - Charged Current, which identifies the neutrino type.

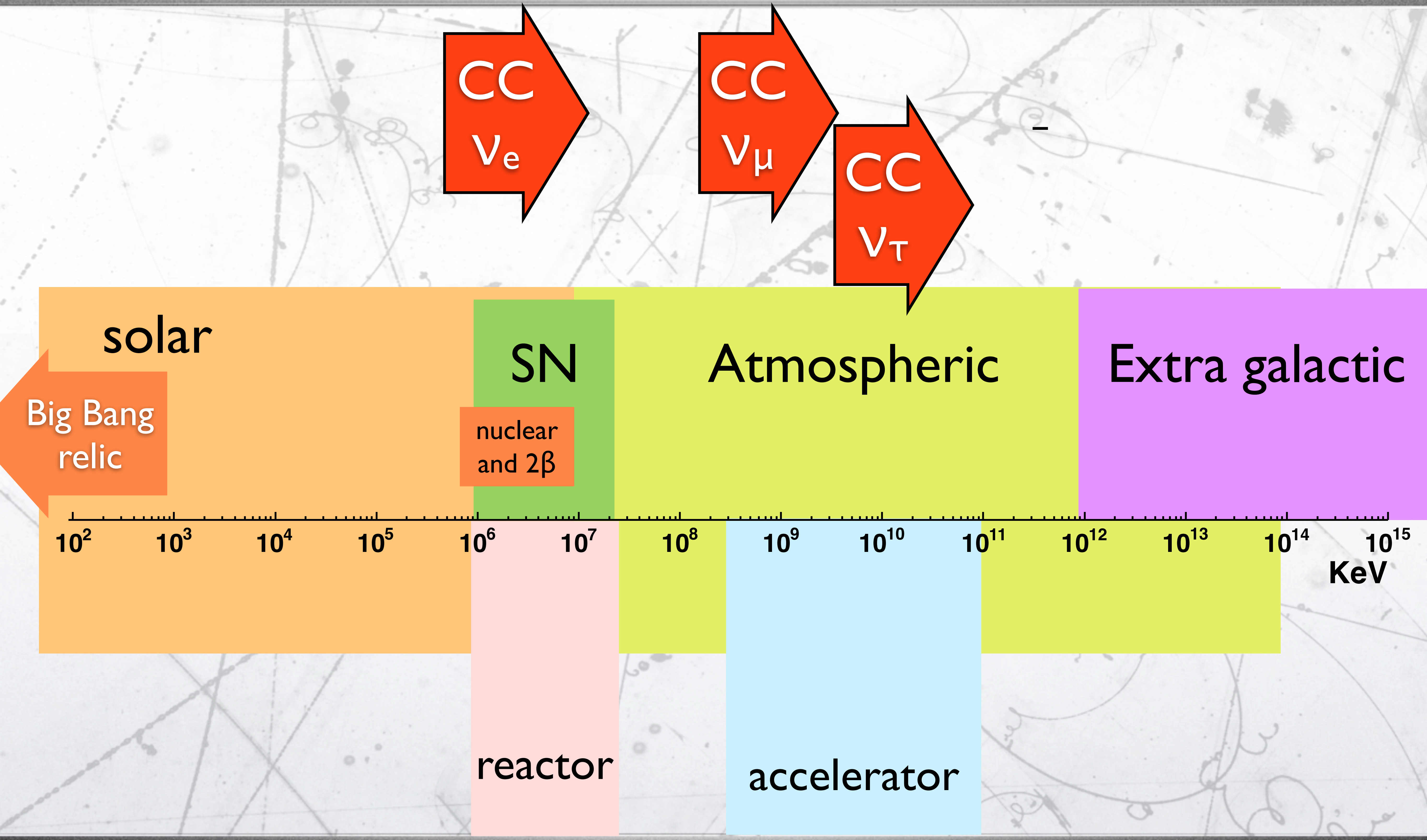
$$\nu_{e,\mu,\tau} \to W^{+-} e, \mu, \tau$$

  - Neutral Current, independent of neutrino type.

$$\nu_{e,\mu,\tau} \to Z^0 \nu_{e,\mu,\tau}$$

- Two main interactions depending on the target:
  - Hadronic target: nucleus, protons,neutrons and quarks.
  - Leptonic target: electrons.

Fundaments



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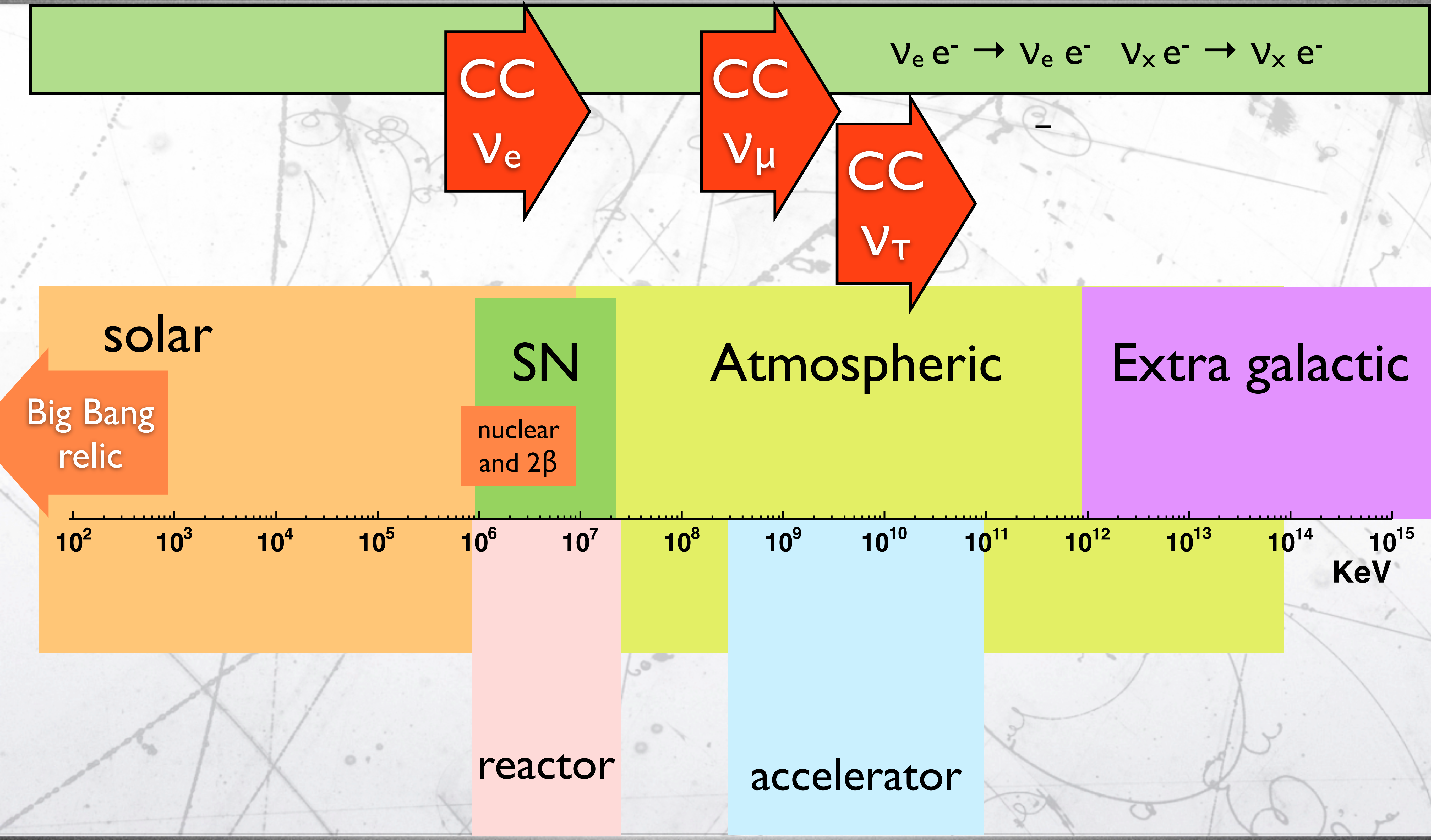

$\nu_e e^- \rightarrow \nu_e e^-$ $\nu_x e^- \rightarrow \nu_x e^-$
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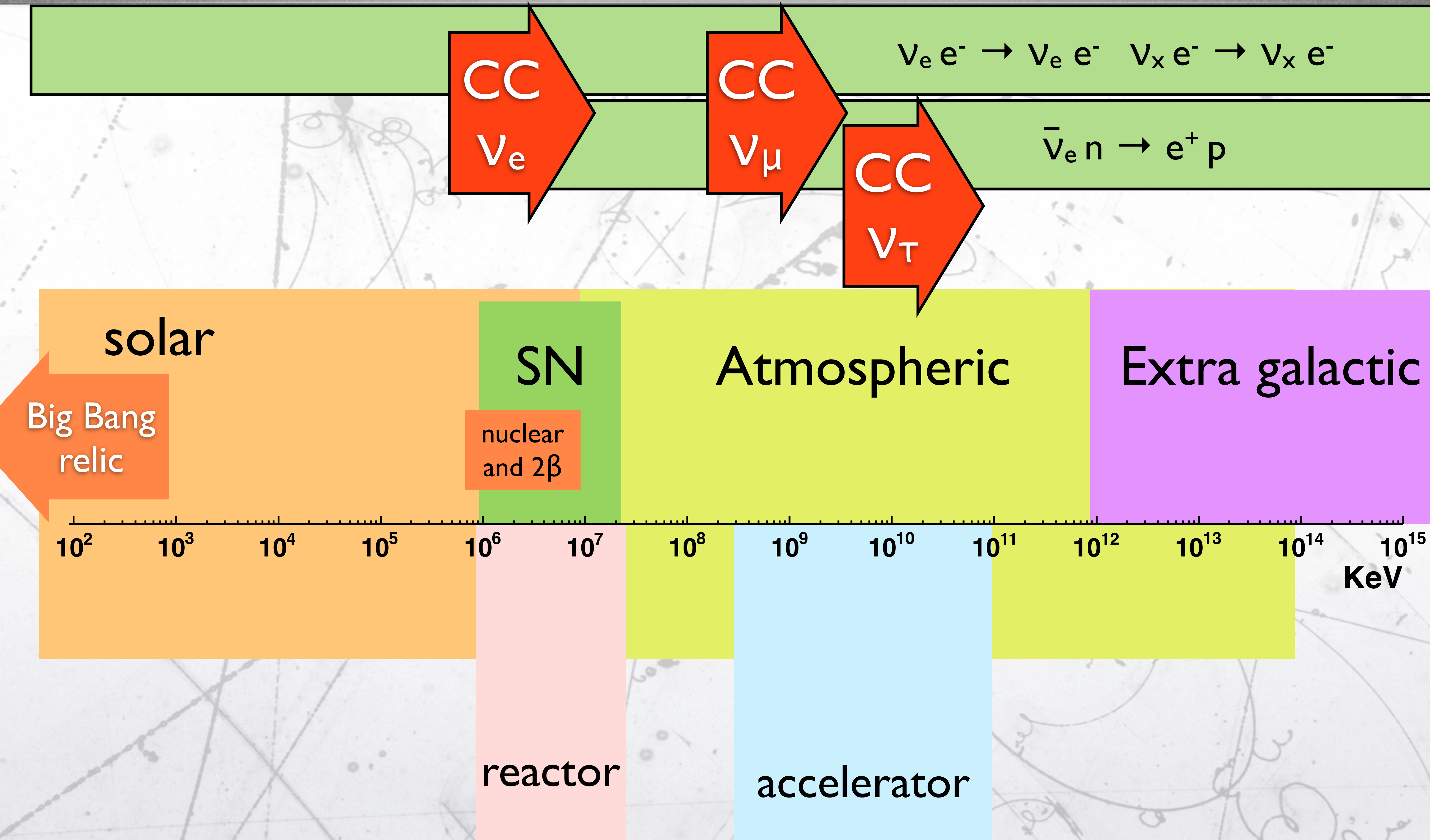
CC
νe
CC
νμ
CC
ντ
νe e- → νe e- νx e- → νx e-
ν̄e n → e+ p
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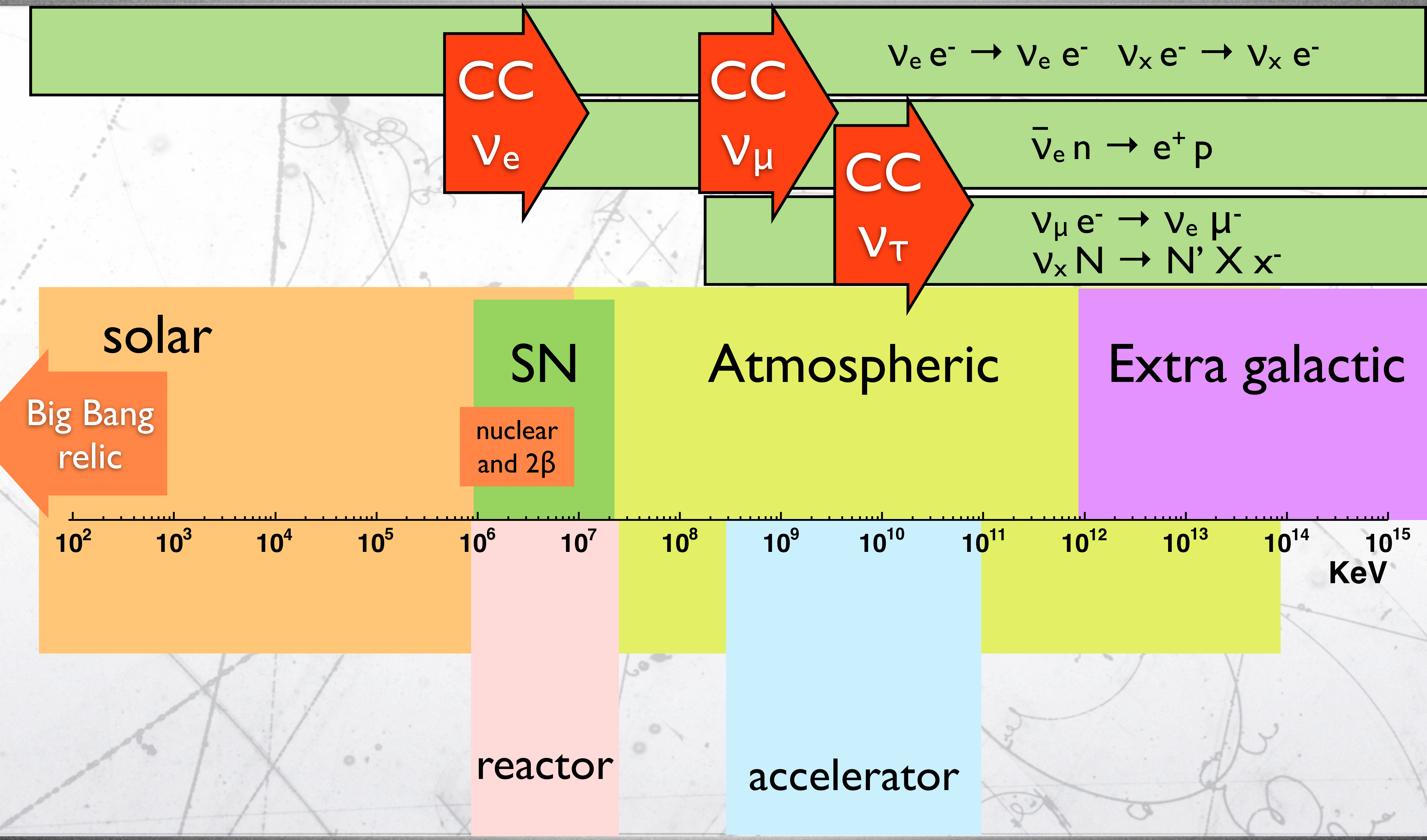

CC ν_e
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$\nu_e e^- \rightarrow \nu_e e^-$ $\nu_x e^- \rightarrow \nu_x e^-$
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Neutrino interactions

- Low energy cross-section is very low (~ 10^{-44} cm^2)

$$\sigma_{\nu_e e^- \to \nu_e e^-} = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}+\xi\right)^2+\frac{1}{3}\xi^2\right] \approx 9.5 \cdot 10^{-49}\ \mathrm{m}^2\left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$$

$$\sigma_{\bar{\nu}_e e^- \to \bar{\nu}_e e^-} = \frac{G_F^2 s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2}+\xi\right)^2+\xi^2\right] \approx 4.0 \cdot 10^{-49}\ \mathrm{m}^2\left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$$

$$\sigma_{\nu_\mu e^- \to \nu_\mu e^-} = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}-\xi\right)^2+\frac{1}{3}\xi^2\right] \approx 1.6 \cdot 10^{-49}\ \mathrm{m}^2\left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$$

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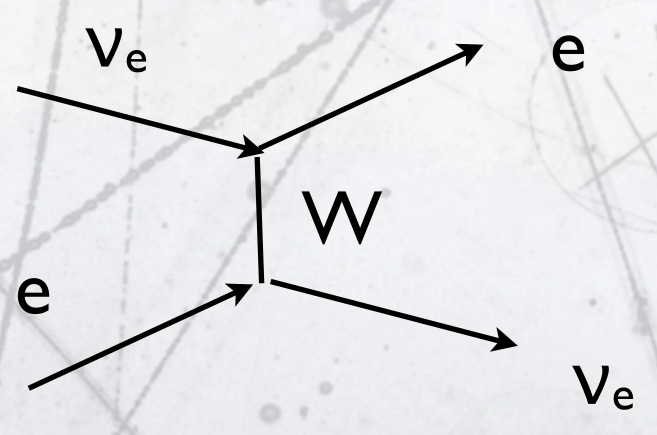
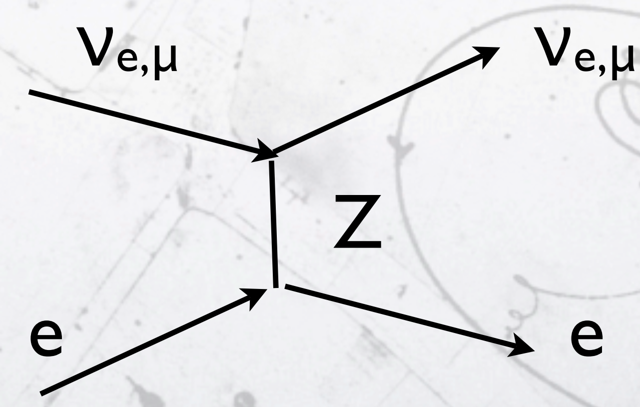




Neutrino interactions

- First neutrino-nucleon reactions take place from E_ν > 1.8 MeV.

- The experiment can be done on free protons (H) since the threshold for bound nucleons is larger.
- The experiment should have free protons (i.e. organic molecules).
- The cross-section is 10 times the ($\nu_e\, e^- \rightarrow \nu_e\, e^-$)

$$\sigma(E_{\bar{\nu}_e}) = 9.6 \times 10^{-44} cm^2 (E_\nu(MeV) - 1.2)\sqrt{(E_\nu(MeV) - 1.2)^2 - m_e^2}$$

Neutrino interactions

- The reaction $\overline{\nu}_e\, p \rightarrow e^+ n$ has the advantage that we can reconstruct the energy of the incoming neutrino.
- The technique we'll see also for other reactions, asume the neutrino beam direction:

$$E_{\overline{\nu}_e} = \frac{1}{2}\frac{2M_p E_{e^+} + M_n^2 - M_p^2 - m_e^2}{M_p - E_{e^+} + \sqrt{E_{e^+}^2 - m_e^2}\cos\theta_{e^+}}$$

- If the angle neutrino positron (θ_{e+}) is taken as 0.

$$E_{\text{vis}} = E_{e^+} + m_e \simeq E_{\overline{\nu}_e} - \Delta + m_e$$

- This is an important input to oscillation analysis where we need to know with precision the neutrino energy and the distance to the source.

Neutrino interactions

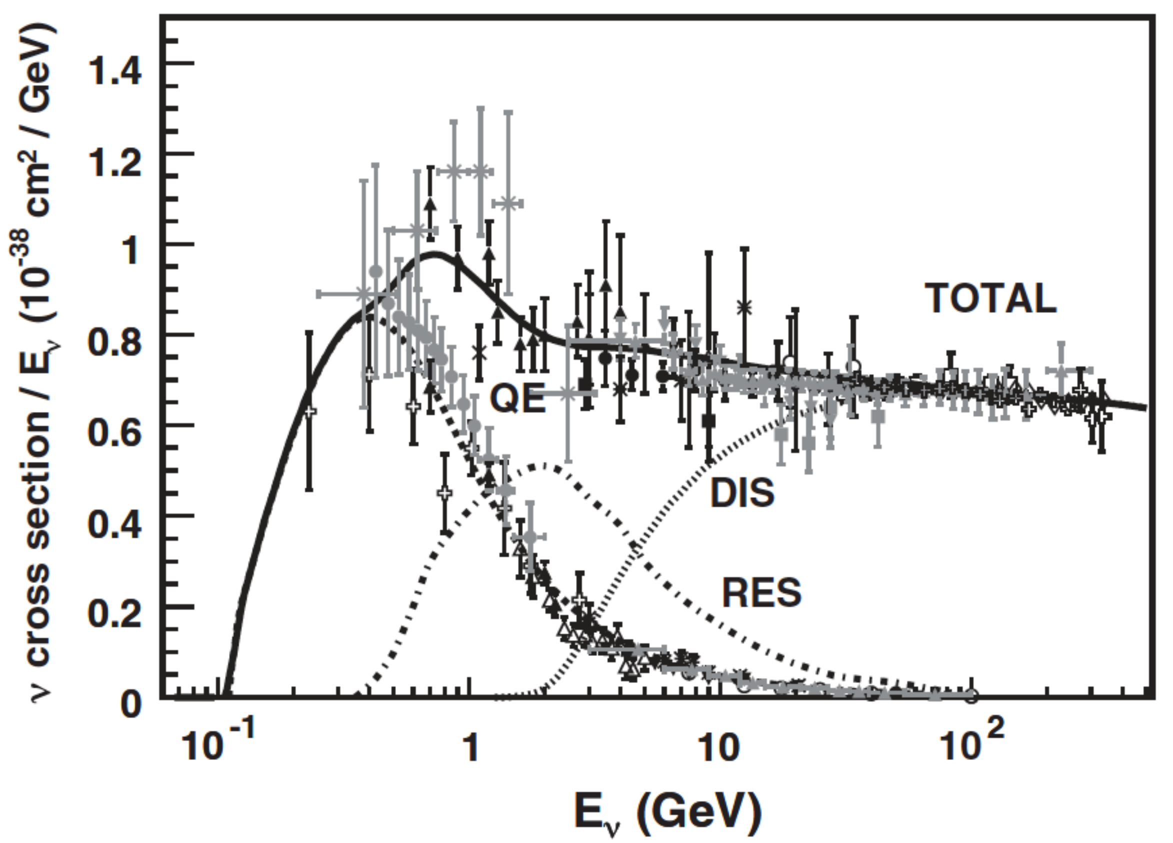
- This is possible only for anti-neutrinos, with neutrinos we need to look for the reaction $\nu_e\, n \rightarrow e^- p$.
  - This is not possible in similar foot as the inverse beta decay because there are no neutrons free in matter.
  - Option is to use nuclear targets:
    - Deuterium: low threshold (~2 MeV)
      - $\sigma \sim 0.5 \times 10^{-40}\ \mathrm{cm}^2$ @ $E \sim 37$ MeV
    - Carbon: higher thresholds (~20 MeV wich is the difference between the ^{12}C and ^{12}N masses = 17 MeV). The final estate is a ^{12}N nucleus with no free nucleons:
      - $\sigma \sim 1.5 \times 10^{-41}\ \mathrm{cm}^2$ @ $E \sim 40$ MeV

These channels dominate over the electron scattering above threshold.

Neutrino interactions

- The next level of neutrino interactions happens when we can interact with neutrinos in a nucleus extracting nucleons from the Fermi sea.
  - $\nu_l\ N(A,Z) \rightarrow l^-\ N^*(A-1,Z)\ \ p$
- With increases of energy the picture gets more and more complex:
  - produce resonance nucleon states: ($E_\nu > 0.5$ GeV)
    - $\nu_l\ N(A,Z) \rightarrow l^-\ N'(A',Z')\ \ \Delta^{0,+,++}$
  - finally Deep Inelastic scattering when resolving the quarks in a nucleon ($E_\nu > 2$ GeV)

Neutrino interactions



- The problem at higher energies is the superposition of reaction channels.
- One of the purposes of the neutrino detection is to reconstruct the neutrino energy and this is affected by this complex picture.

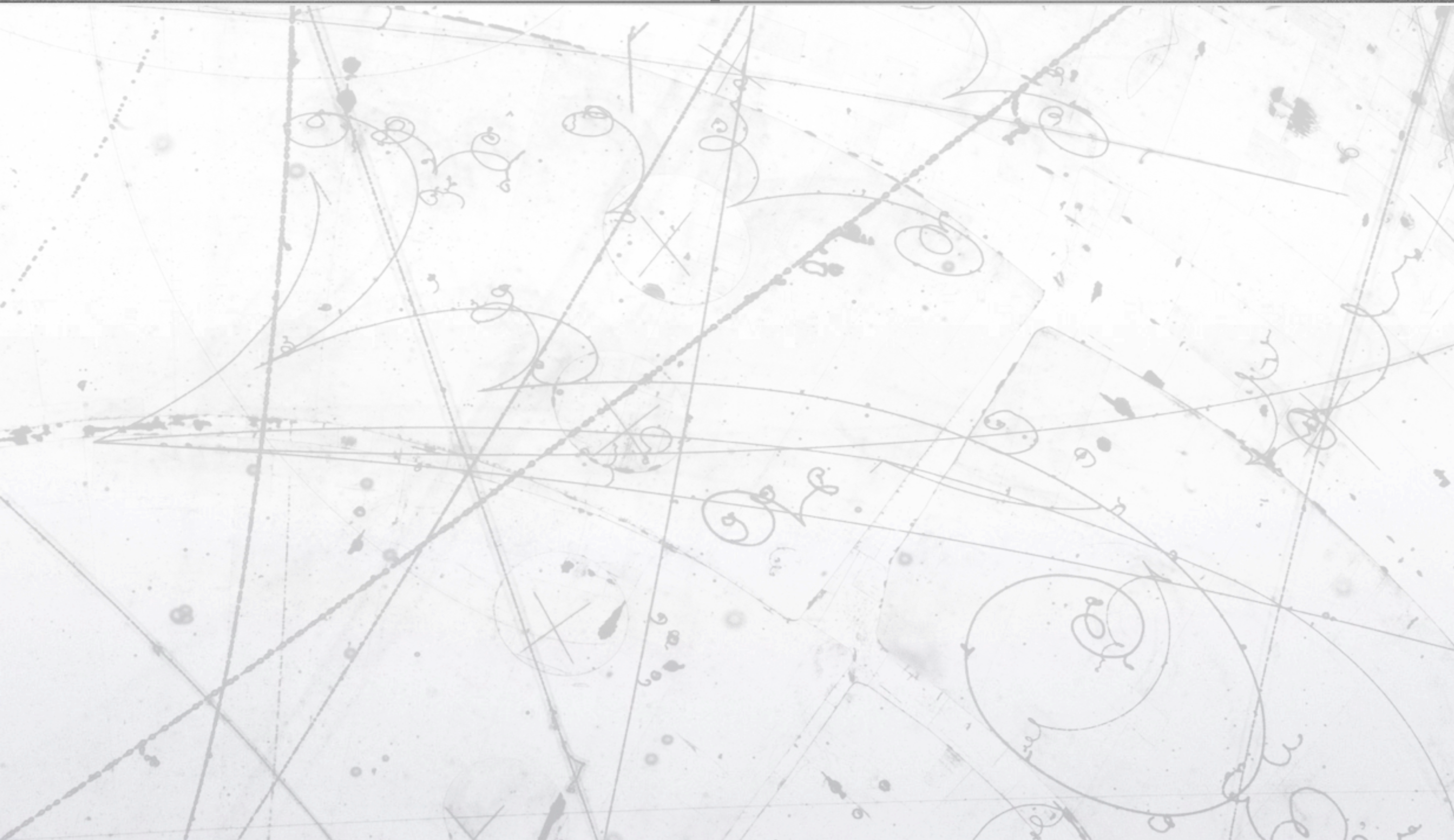
- The neutrino energy in the QE channel can be reconstructed assuming a 2body to 2body reaction using the lepton kinematics.

$$E_{\overline{\nu}_e} = \frac{1}{2}\frac{2M_pE_{e^+} + M_n^2 - M_p^2 - m_e^2}{M_p - E_{e^+} + \sqrt{E_{e^+}^2 - m_e^2}\cos\theta_{e^+}}$$

- The same for the Resonance, but with different equation (Δ != p)

- DIS requires the measurement of the interaction products.

Neutrino production



Neutrino production

- Man made
  - Accelerator
  - nuclear reactors

- Initial conditions are known.
- ON/OFF or pulsed
- Tune properties of the beam.
- Low intensity

Neutrino production

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- Initial conditions are known.
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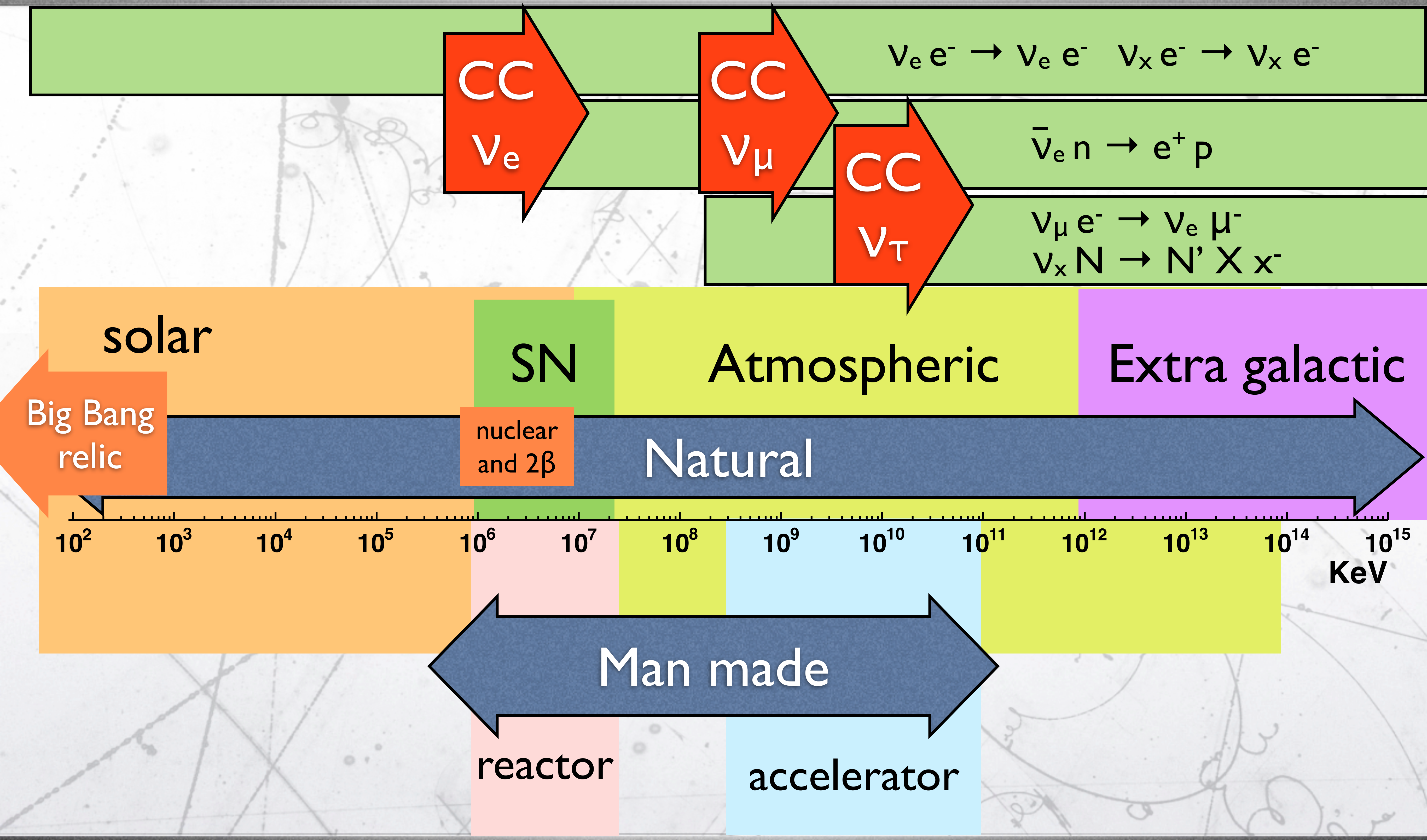
- Tune properties of the beam.
- Low intensity

- Natural
  - Natural radioactivity
  - Sun
  - SuperNovas
  - Atmospheric

- Initial conditions poorly known (sometimes this is the target)
- Continuous
- Beam properties through detection
- Large intensity.

Fundaments



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Backgrounds

- Low interaction rate measurements are also compromised by the presence of backgrounds.

$$\frac{\sigma_{N_{signal}}}{N_{signal}} = \frac{1.}{\sqrt{N_{signal}}}$$

$$\frac{\sigma_{N_{signal}}}{N_{signal}} = \frac{\sqrt{N_{signal} + N_{back}}}{N_{signal}} \geq \frac{1.}{\sqrt{N_{signal}}}$$

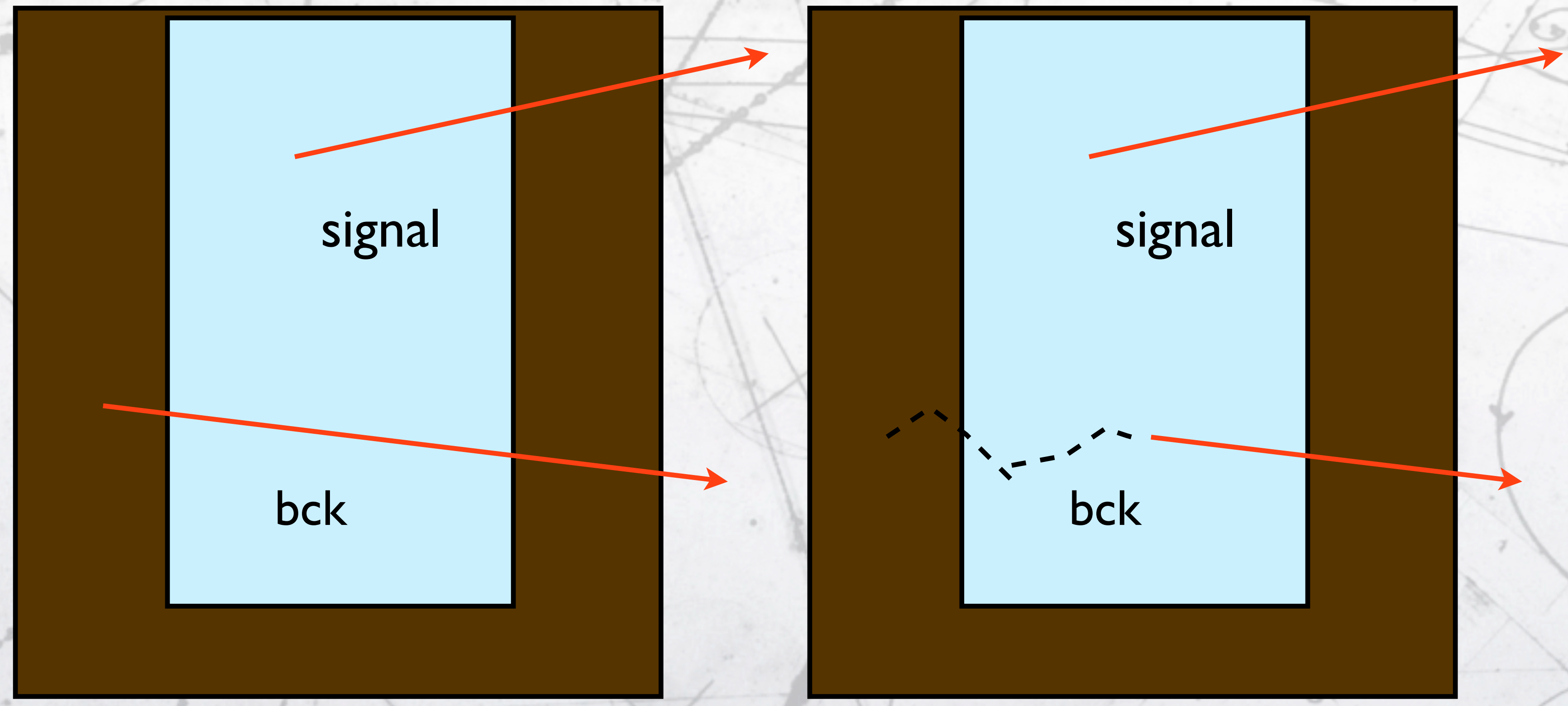
- Backgrounds can be measured, but they always affect the statistical significance of the measurement.
- Neutrino detection implies also background reduction and measurement.
- The selection of a target neutrino interaction might be caused by the presence of backgrounds.
- Backgrounds depend also on the energy of the neutrinos: it is not the same a 2 MeV neutrino than a 2 PeV.

Backgrounds

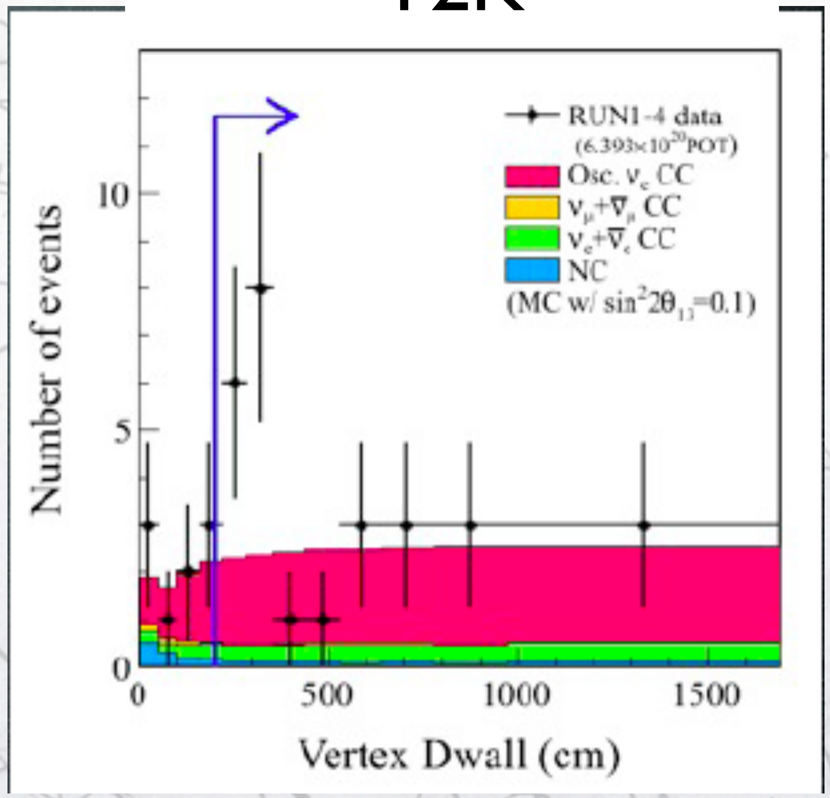
- Low energy background (<10MeV) are mainly related to radioactive decays:
  - Low radioactivity detectors (Borexino)
  - Search for reactions with little background (Reines & Cowan experiment or reactor neutrinos)
  - Identify the source with a directional detection. (SuperKamiokande)
- But also man made neutrinos, like those from reactors, can be significant in some of the measurements: place detectors far from reactors. (Important for GeoNeutrinos)
- Cosmic rays might activate nuclei in the detector, so the background is dynamically generated:
  - go underground. (almost all of them)
  - detect neutrinos in anti-coincidence with the presence of cosmic rays (reactor neutrinos).

Backgrounds

- At high energies the backgrounds are different:
  - They are related to the same production process, for example events generated outside the detection volume. Experiments veto particles from outside the detector by segmenting the detector or having vertex capabilities.



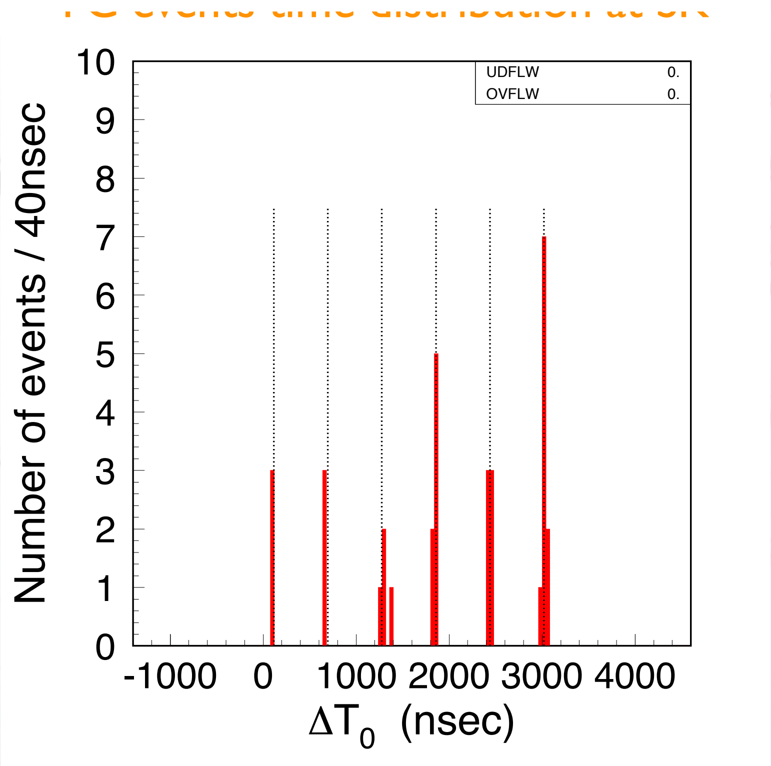
T2K



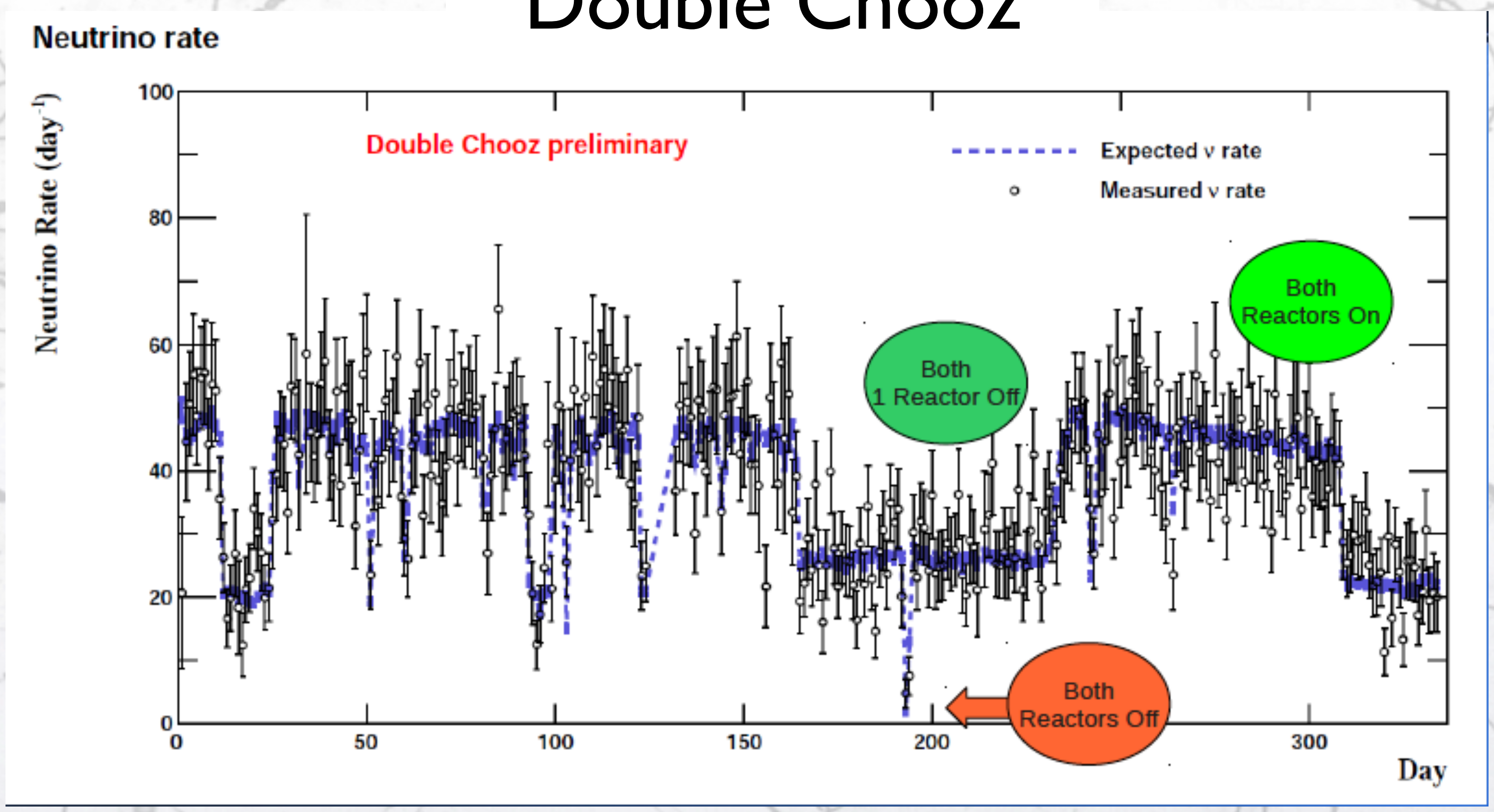
Backgrounds

- Timing the measurement:
  - running with beam off might help in measuring the background.

T2K



Double Chooz



Notice the different scale

Neutrino detection

- LHC experiments use one beam, one detector to provide a lot of physics.
- In neutrino physics, due to the requirements:
  - large target mass,
  - large neutrino flux,
  - natural sources.
- the experiments tune:
  - neutrino flux and energy (when possible)
  - neutrino interaction channel.
  - detection technology.
- for few (but critical) physics topics.

You need to do the same to design neutrino experiments in the future.

The neutrino "beam" and the detector technology are the two main degrees of freedom.

Detecting particles

Detecting particles

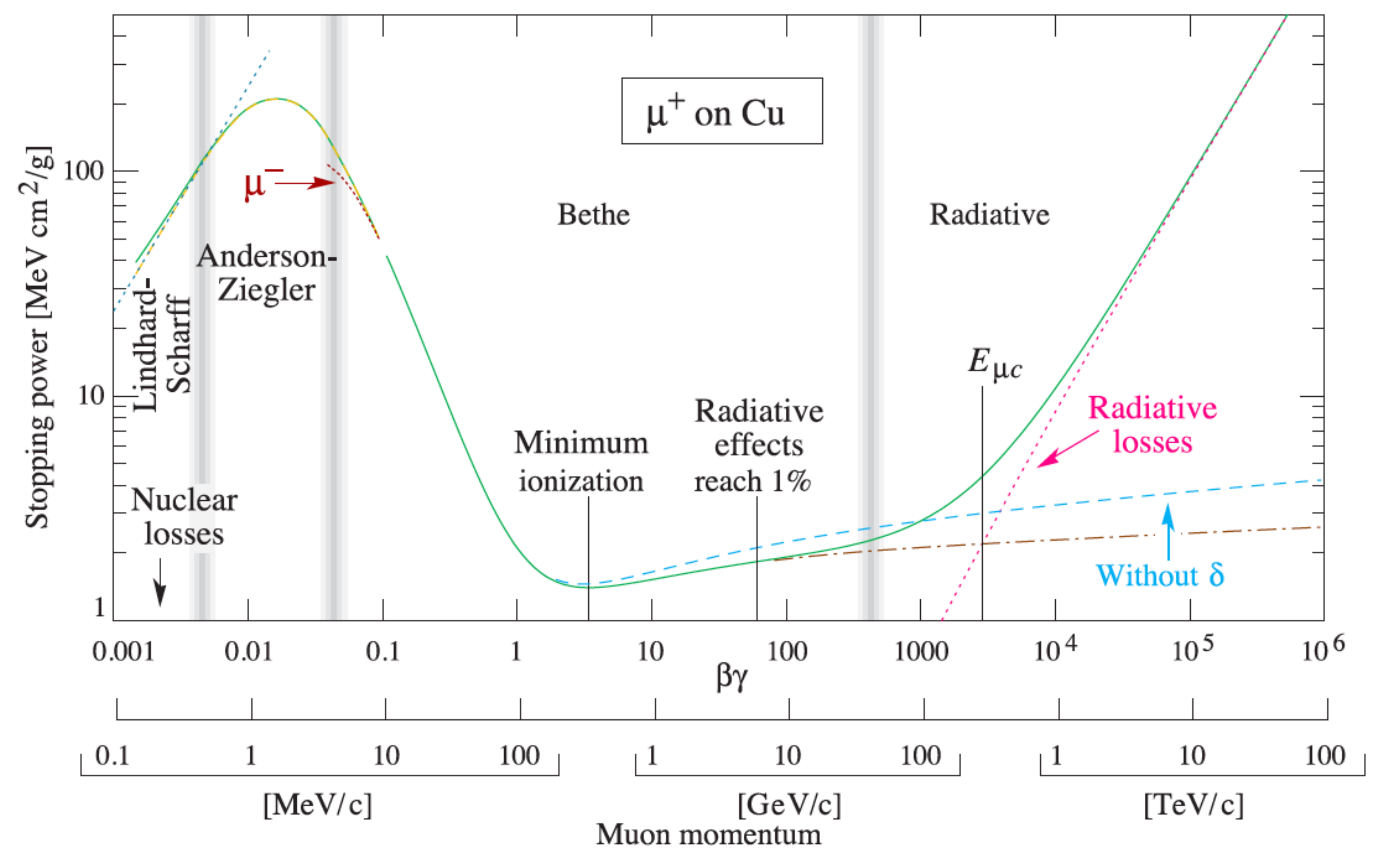
- The passage of a particle through a material introduces several interactions:
  - Particles interact with the media producing other particles:
    - compton, Breemstrahlung, pair conversion, photoelectric, hadronic interactions, etc…
    - These interactions drive the evolution of the particle in the detector. It is (normally) not used for the detection, but its products.
  - The particle ionize the media extracting electrons from the atoms.
  - The particle excites the atoms in the media and emit lights.
  - The particle emits Cherenkov light.
  - The particle changes the matter chemical composition or state

Detectors transform this signal into recordable observables

Ionisation

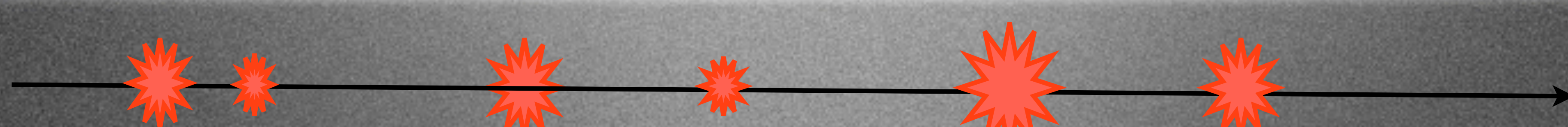
- Particles crossing a detector will lose energy through several collisions.
- At every collision the energy will vary.
- Combining both we can estimate the energy loss by a particle.
- At high energies there are also:
  - radiative loses or energy loss by breemstrahlug.
  - delta ray production or hard ionisation with electron emission.

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-passage-particles-matter.pdf



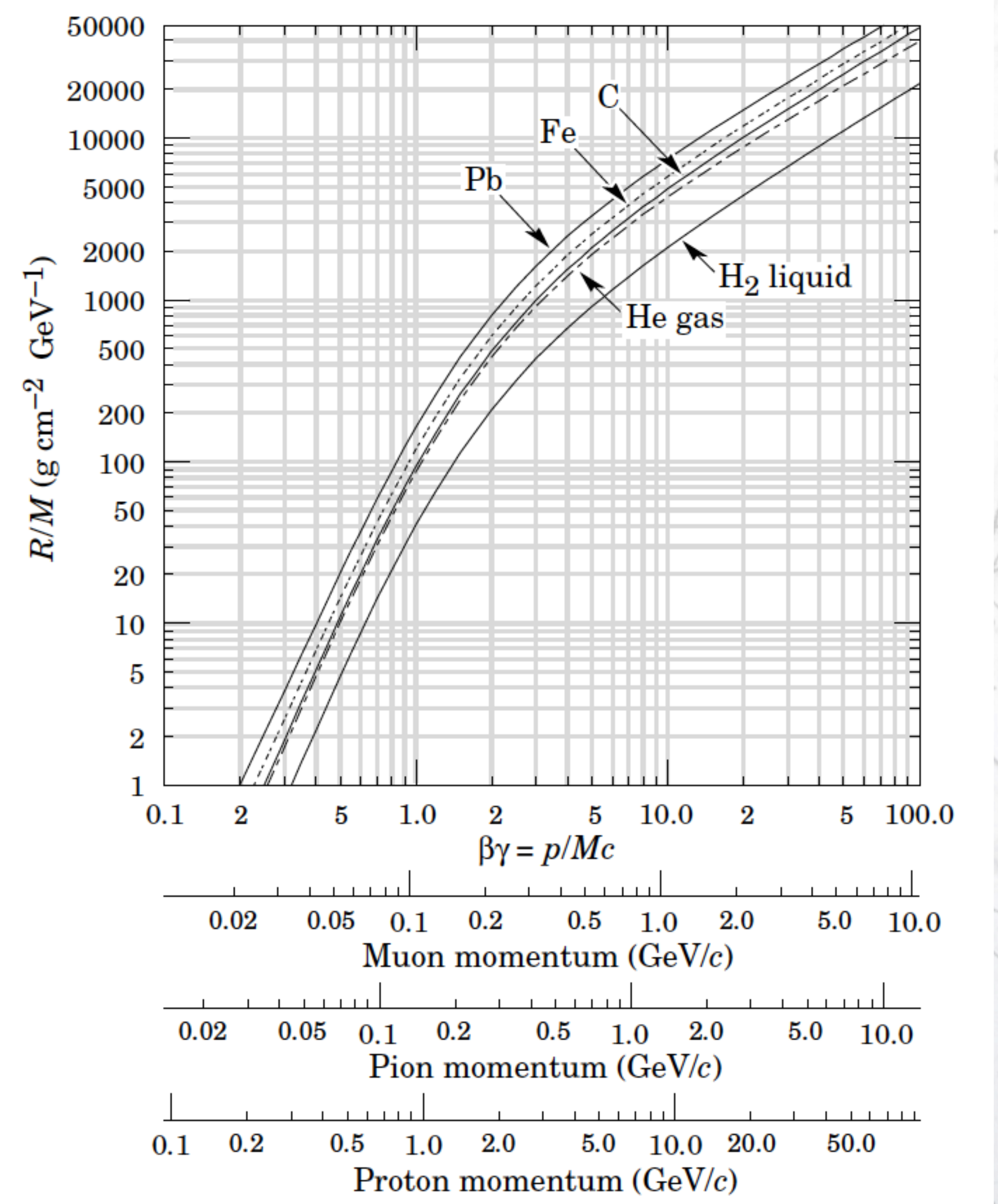
Bethe-Block approach is valid in a large range of βγ
0.1 < βγ < 1000

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



Ionisation

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-passage-particles-matter.pdf



- Particles crossing infinitively thick detectors will lose all its kinetic energy until stop.
- The range depends on $\beta\gamma$ so it will be different for every particle type and momentum.
- Through the range, we could compute the $\beta\gamma$, and then compute the momentum and energy of the particle if identified.
- Range/Mass has almost a power low dependency for $\beta\gamma > 5$ and $\beta\gamma < 1$
  - for $\beta\gamma > 5$: $R/M = \alpha\, p^l + \beta$

Ionisation

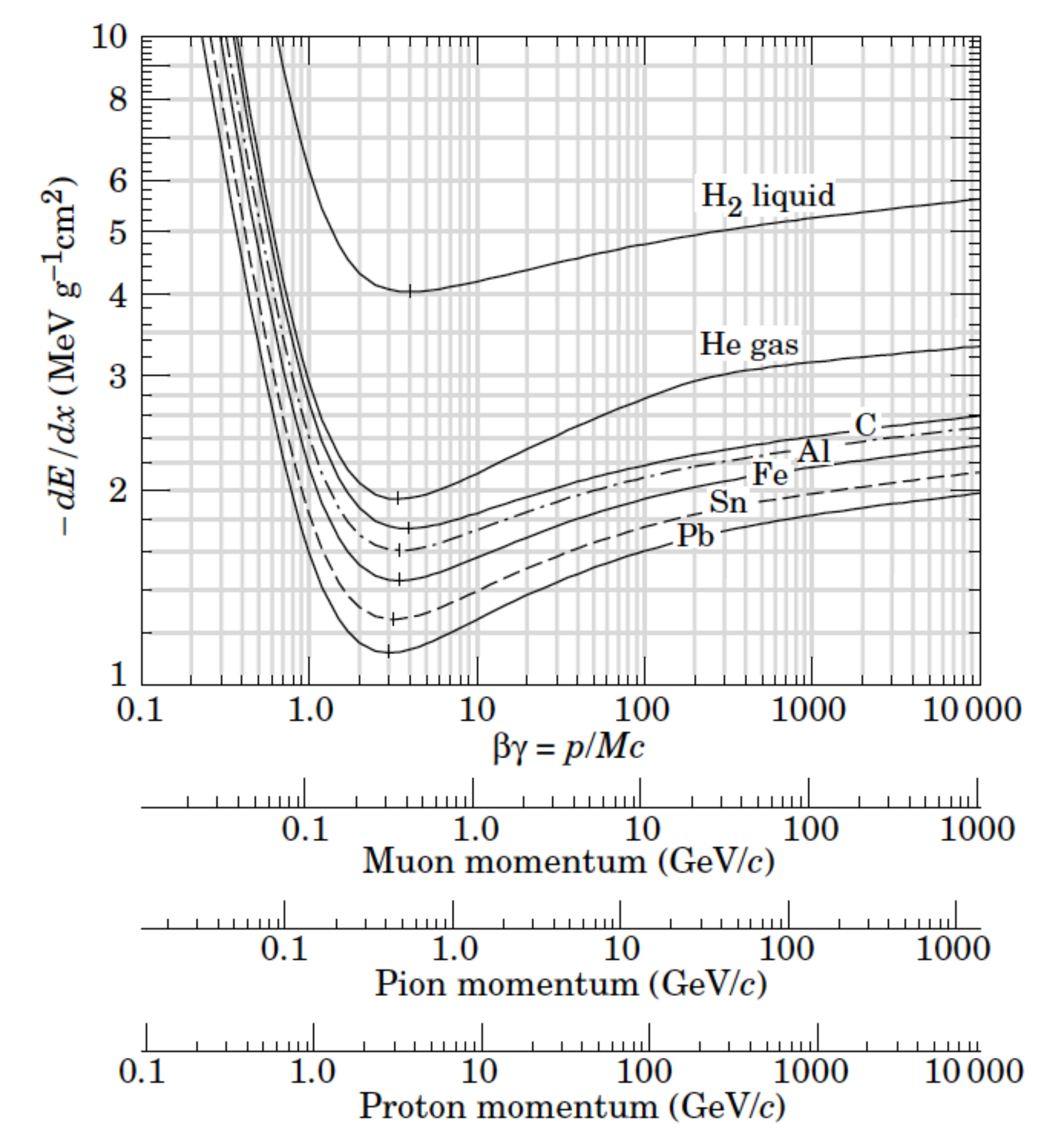
- The energy loss depends on βγ, so it is different for different particle masses.
- Measuring both the dE/dx and the momentum of the particle we could compute its mass: identify the particle.

Particle Id

- This will be the same with the particle range, because the kinetic energy of a particle is:

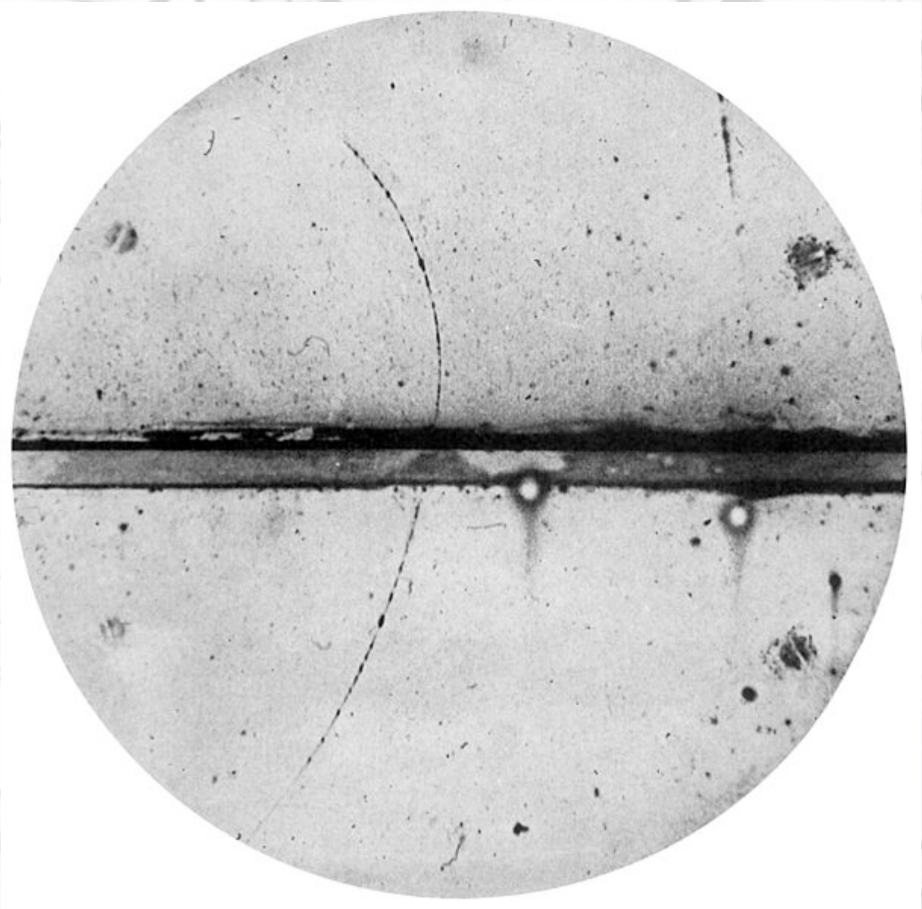
$$E_{kin} = \sqrt{p*p+m*m} - m = m(\sqrt{(\beta\gamma)^2+1}-1)$$

  - measuring range and energy deposit also identifies the particle.



Cloud chamber

e^+ discovery



- The cloud chamber is the simplest ionising detector one could build.
- It is a supersaturated environment of alcohol. The particle ionise ions and the alcohol saturates around the ions leaving visible traces.