Alexander Kusenko (UCLA)

Beijing '06

Searching new physics with ultrahigh-energy cosmic rays

Searching new physics with ultrahigh-energy cosmic rays

New projects that we can do with UHECR and neutrinos (complementary to UHE astronomy).

Searching new physics with ultrahigh-energy cosmic rays

New projects that we can do with UHECR and neutrinos (complementary to UHE astronomy).

- Study p_T distributions in showers, and, possibly, find new physics. [Cao, et al.]

Searching new physics with ultrahigh-energy cosmic rays

New projects that we can do with UHECR and neutrinos (complementary to UHE astronomy).

- Study p_T distributions in showers, and, possibly, find new physics. [Cao, et al.]

- Measure neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$ GeV. [AK, T. Weiler]

Searching new physics with ultrahigh-energy cosmic rays

New projects that we can do with UHECR and neutrinos (complementary to UHE astronomy).

- Study p_T distributions in showers, and, possibly, find new physics. [Cao, et al.]
- Measure neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$ GeV. [AK, T. Weiler]
- Look for dark-matter sterile neutrinos

Several experiments will collect UHECR data above 10^{19} eV in the near future (funded only):

Several experiments will collect UHECR data above 10^{19} eV in the near future (funded only):

- Pierre Auger

Several experiments will collect UHECR data above 10^{19} eV in the near future (funded only):

- Pierre Auger
- Telescope Array

Several experiments will collect UHECR data above 10^{19} eV in the near future (funded only):

- Pierre Auger
- Telescope Array
- TUS (Russian scaled-down version of EUSO/OWL with a 10 m^2 Fresnel mirror; area on the ground ~ 80 km in diameter; launch 2008-2010 expected)

Several experiments will collect UHECR data above 10^{19} eV in the near future (funded only):

- Pierre Auger
- Telescope Array
- TUS (Russian scaled-down version of EUSO/OWL with a 10 m^2 Fresnel mirror; area on the ground ~ 80 km in diameter; launch 2008-2010 expected)

By the year 2010 the spectrum of UHECR will be determined, and one should start using these experiments to do other types of physics and astronomy. Astronomy program depends on magnetic fields and composition.

p_T distributions and energy reconstruction

p_T distributions and energy reconstruction

Water tanks of Pierre Auger are very sensitive to muons (photon yield 20 times higher).

p_T distributions and energy reconstruction

Water tanks of Pierre Auger are very sensitive to muons (photon yield 20 times higher).

Vertical showers: both EM and muon components contribute.

p_T distributions and energy reconstruction

Water tanks of Pierre Auger are very sensitive to muons (photon yield 20 times higher).

Vertical showers: both EM and muon components contribute.

Inclined showers: only the muon component survives.

p_T distributions and energy reconstruction

Water tanks of Pierre Auger are very sensitive to muons (photon yield 20 times higher).

Vertical showers: both EM and muon components contribute.

Inclined showers: only the muon component survives.

More $\boldsymbol{p_T}$ ⇒ Broader shower ⇒ more tanks hit
⇒ **higher apparent energy and** A.

p_T distributions and energy reconstruction

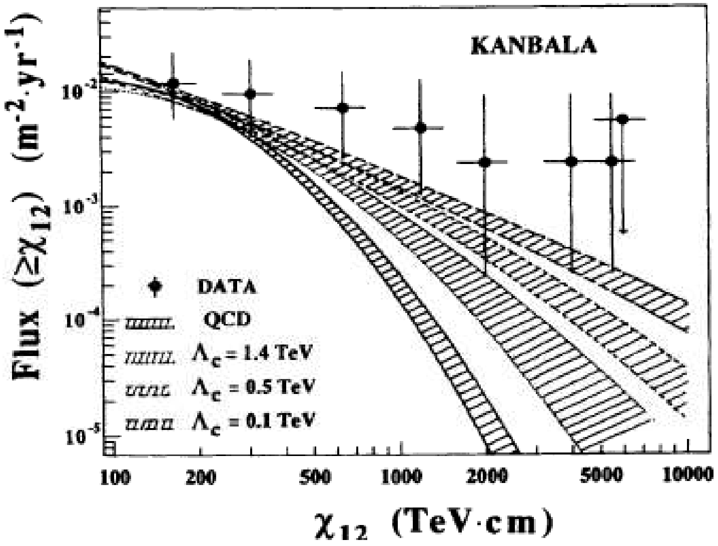
Water tanks of Pierre Auger are very sensitive to muons (photon yield 20 times higher).

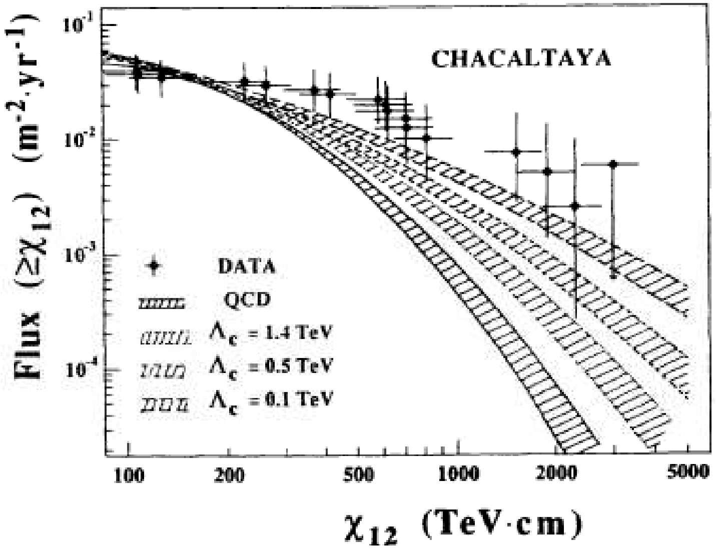
Vertical showers: both EM and muon components contribute.

Inclined showers: only the muon component survives.

More $\boldsymbol{p_T}$ $\Rightarrow$ Broader shower $\Rightarrow$ more tanks hit
$\Rightarrow$ **higher apparent energy and** A.

Pierre Auger may already be seeing this.





The new physics may show up. **[Cao, Ding, Zhu, He, PRL 72, 1794 (1994)]**. Here p_T is represented by $\chi_{12} = \sqrt{E_1 E_2} R_{12}$, where E_1 and E_2 are the energies of two clusters and R_{12} is the energy-weighted distance between them. Cao et al. studied compositeness, but other types of new physics may come in.

UHE neutrinos are out there!

UHE neutrinos are out there!

- Astrophysical sources

UHE neutrinos are out there!

- Astrophysical sources
- $p\gamma$ interactions imply a (predictable) flux of cosmogenic UHE neutrinos.

UHE neutrinos are out there!

- Astrophysical sources
- $p\gamma$ interactions imply a (predictable) flux of cosmogenic UHE neutrinos.

Hopefully, they will be discovered in the near future

UHE neutrinos are out there!

- Astrophysical sources
- $p\gamma$ interactions imply a (predictable) flux of cosmogenic UHE neutrinos.

Hopefully, they will be discovered in the near future

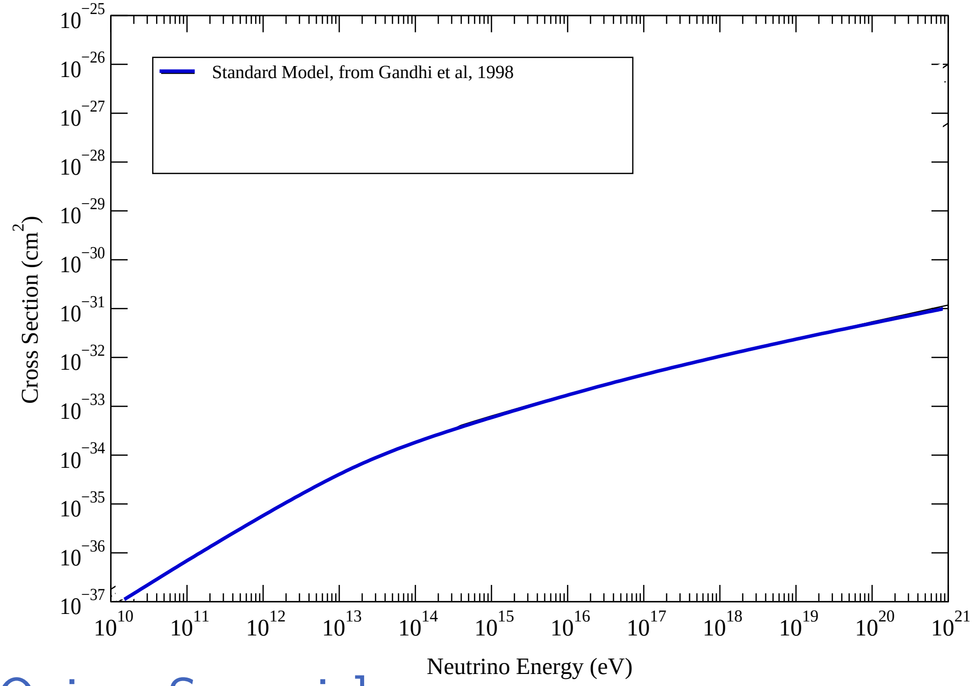
ANITA, ICE CUBE, Pierre Auger...

Detection strategy relies on the knowledge of the neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.

Detection strategy relies on the knowledge of the neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.



[Gandhi, Reno, Quigg, Sarcevic]

Several approved and proposed experiments plan to **detect UHE neutrinos** by observations of nearly **horizontal air showers**.

Neutrinos are the only particles that interact weakly enough to produce horizontal air showers (assuming the cross section $\sigma_{\nu N} \sim 10^{-31}$cm^2 at 10^{20}eV) Hence, particle ID is straightforward.

Several approved and proposed experiments plan to **detect UHE neutrinos** by observations of nearly **horizontal air showers**.

Neutrinos are the only particles that interact weakly enough to produce horizontal air showers (assuming the cross section $\sigma_{\nu N} \sim 10^{-31}$cm^2 at 10^{20}eV) Hence, particle ID is straightforward.

Several approved and proposed experiments plan to **detect UHE neutrinos** by observations of nearly **horizontal air showers**.

Neutrinos are the only particles that interact weakly enough to produce horizontal air showers (assuming the cross section $\sigma_{\nu N} \sim 10^{-31}$cm^2 at 10^{20}eV) Hence, particle ID is straightforward.

How well do we know the neutrino-nucleon cross section? New physics contributions? Can saturation affect the cross section at high energy?

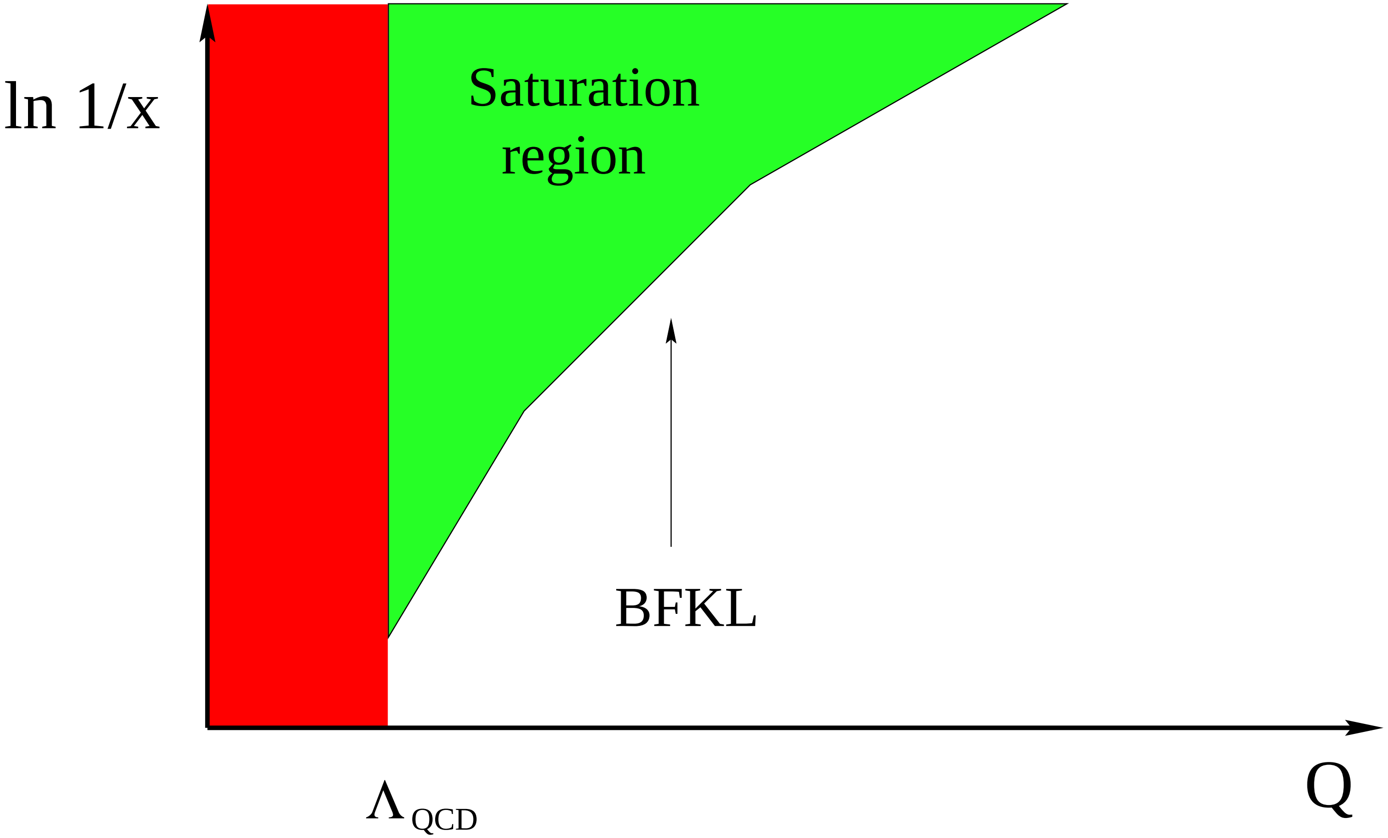
Several approved and proposed experiments plan to **detect UHE neutrinos** by observations of nearly **horizontal air showers**.

Neutrinos are the only particles that interact weakly enough to produce horizontal air showers (assuming the cross section $\sigma_{\nu N} \sim 10^{-31}$cm^2 at 10^{20}eV) Hence, particle ID is straightforward.

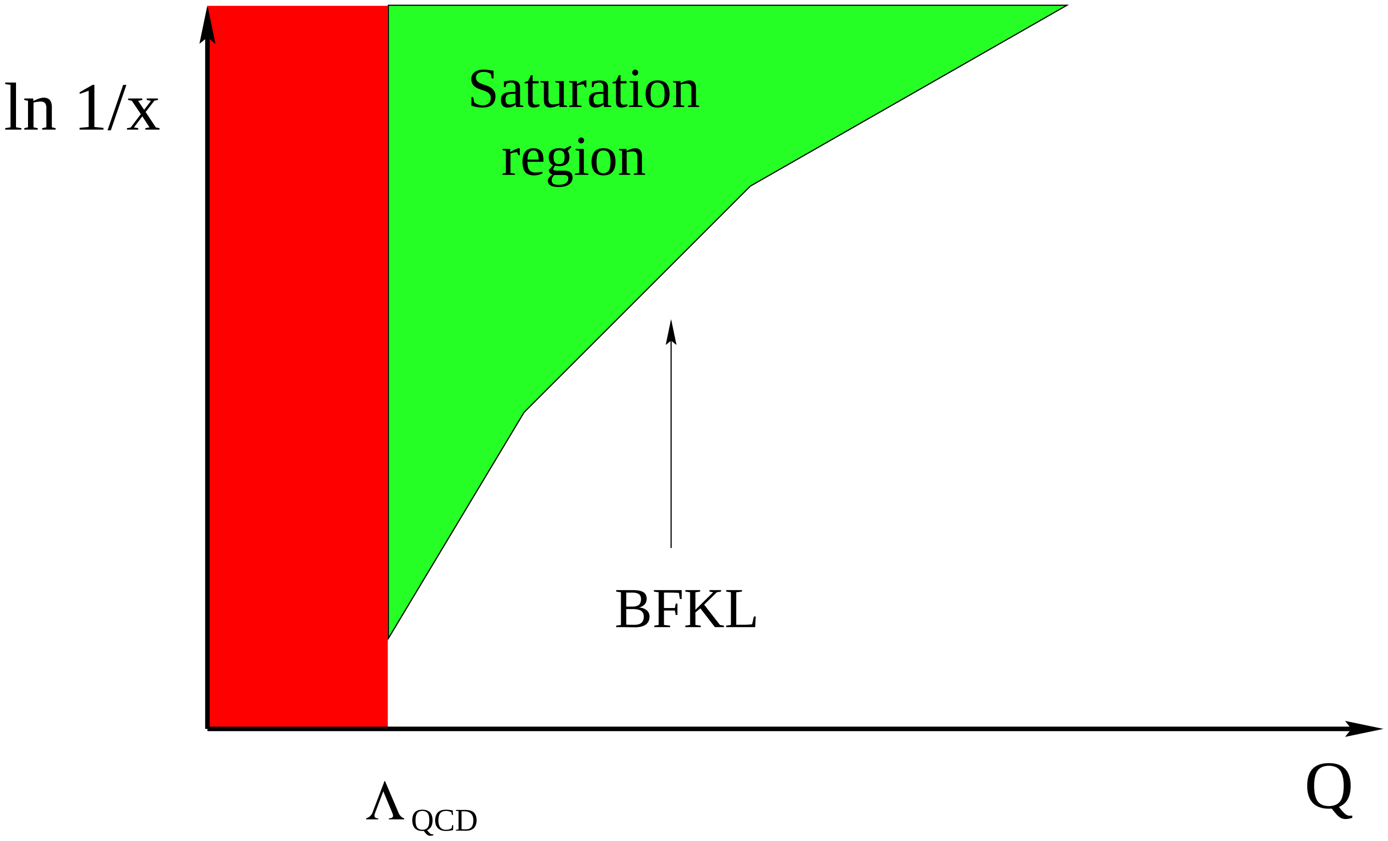
How well do we know the neutrino-nucleon cross section? New physics contributions? Can saturation affect the cross section at high energy?

Is it possible to **measure** the neutrino-nucleon cross section at these energies?

LO and saturation effects may affect the cross section

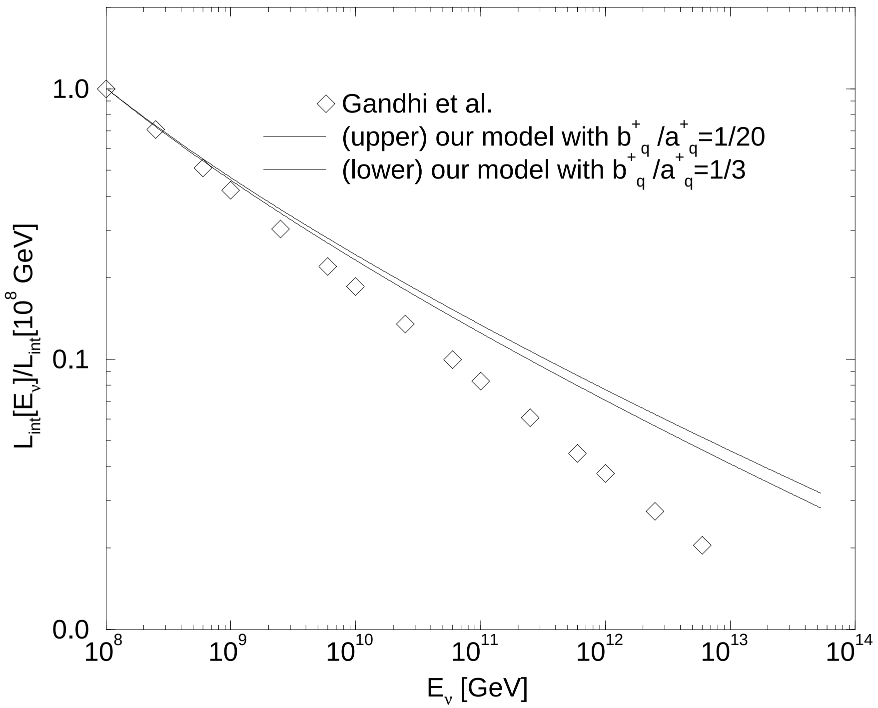


LO and saturation effects may affect the cross section



The cross section σ_{ν_N} **decreases** [R. Fiore, L.L. Jenkovszky, A. Kotikov, F. Paccanoni, A. Papa, E. Predazzi]

LO and saturation effects may affect the cross section



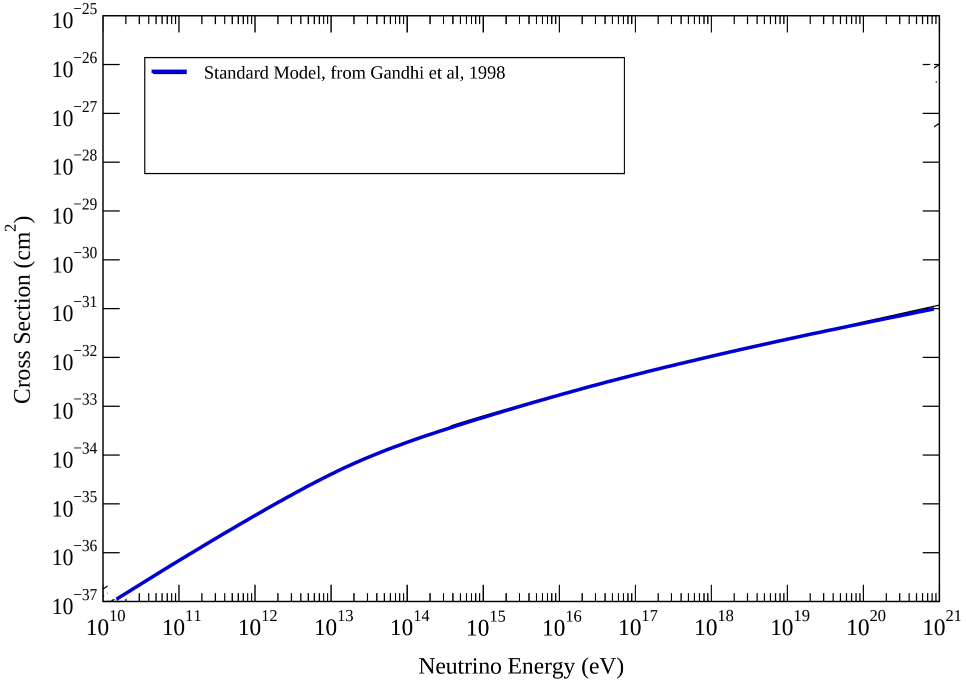
The cross section $\sigma_{\nu N}$ **decreases** [R. Fiore, L.L. Jenkovszky, A. Kotikov, F. Paccanoni, A. Papa, E. Predazzi]

Calculations of neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.

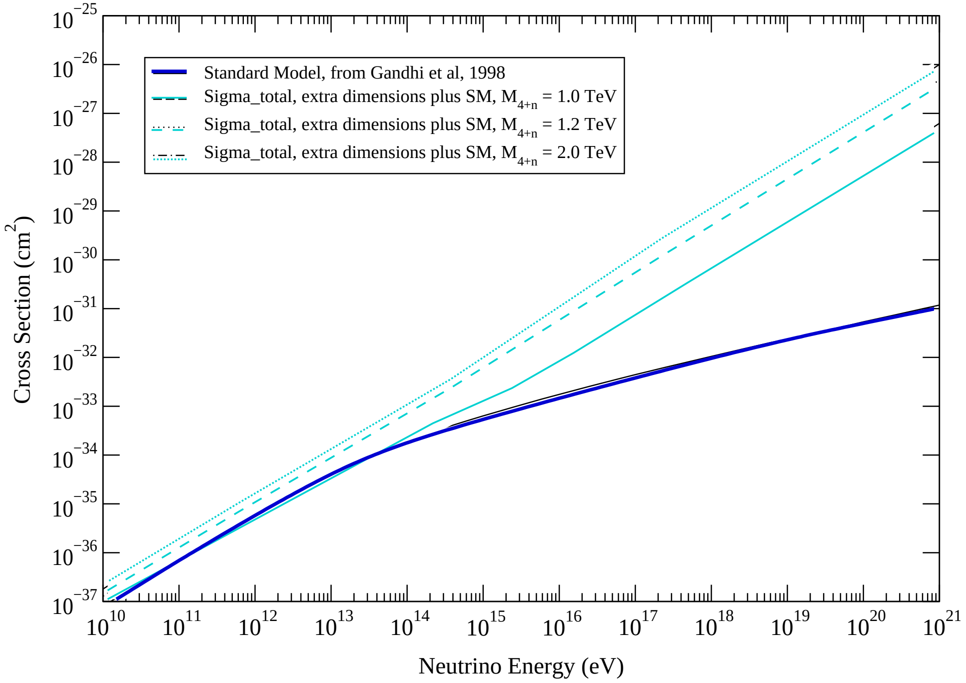
Calculations of neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.



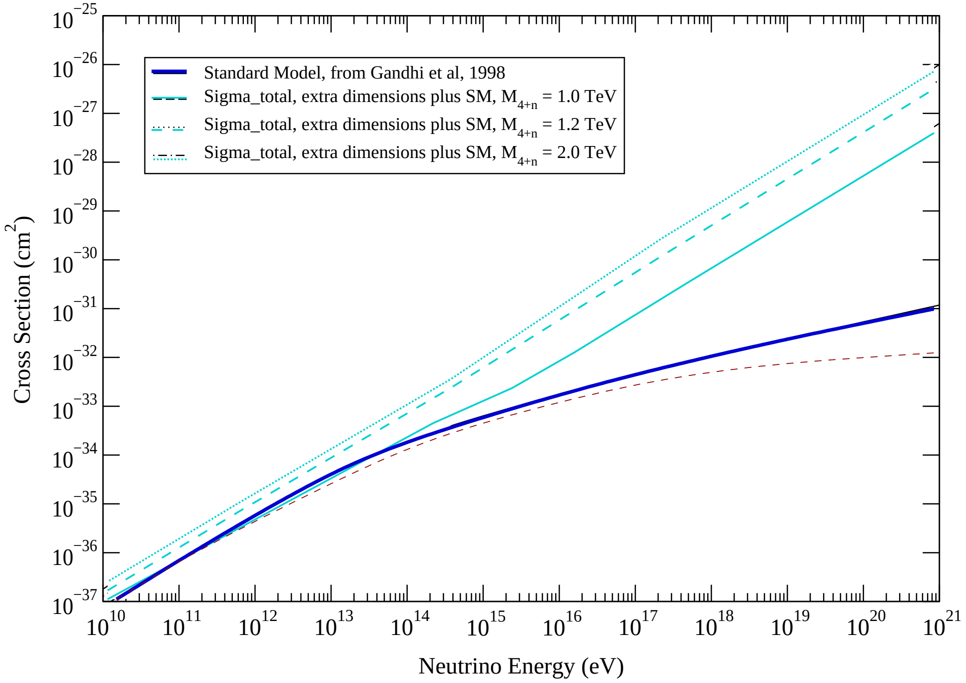
Calculations of neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.



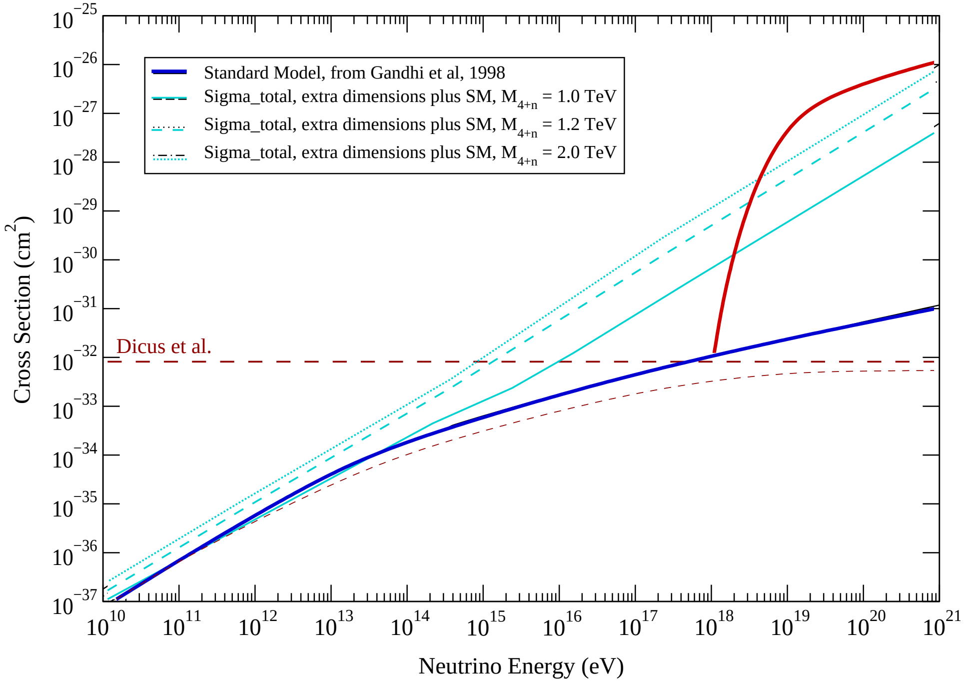
Calculations of neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.



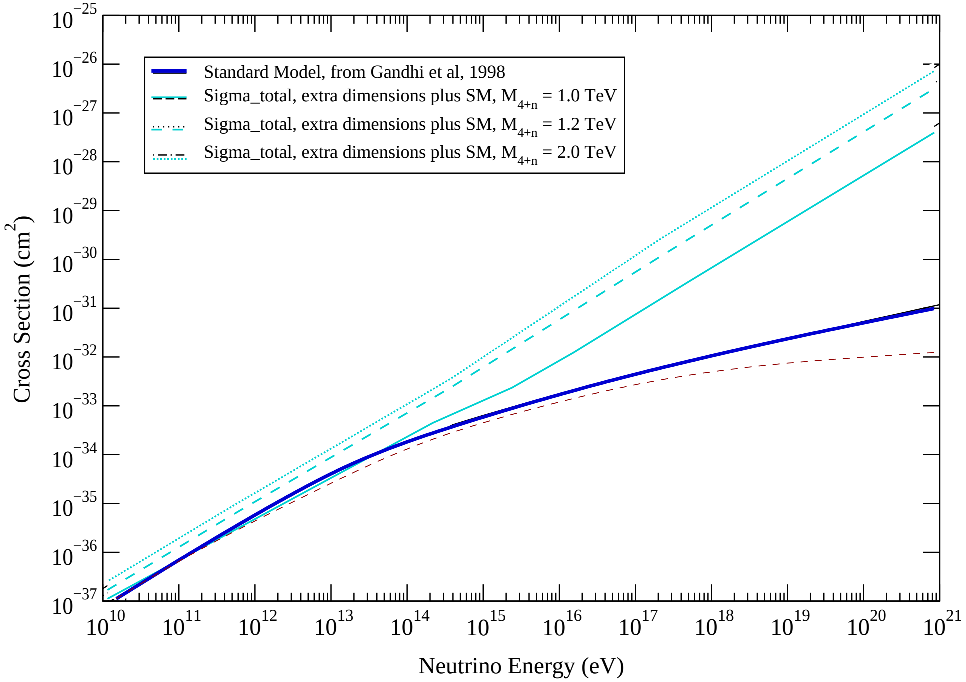
Calculations of neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations of $\sigma_{\nu N}$ at 10^{20}eV necessarily use extrapolations of PDF and standard model parameters.



Neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

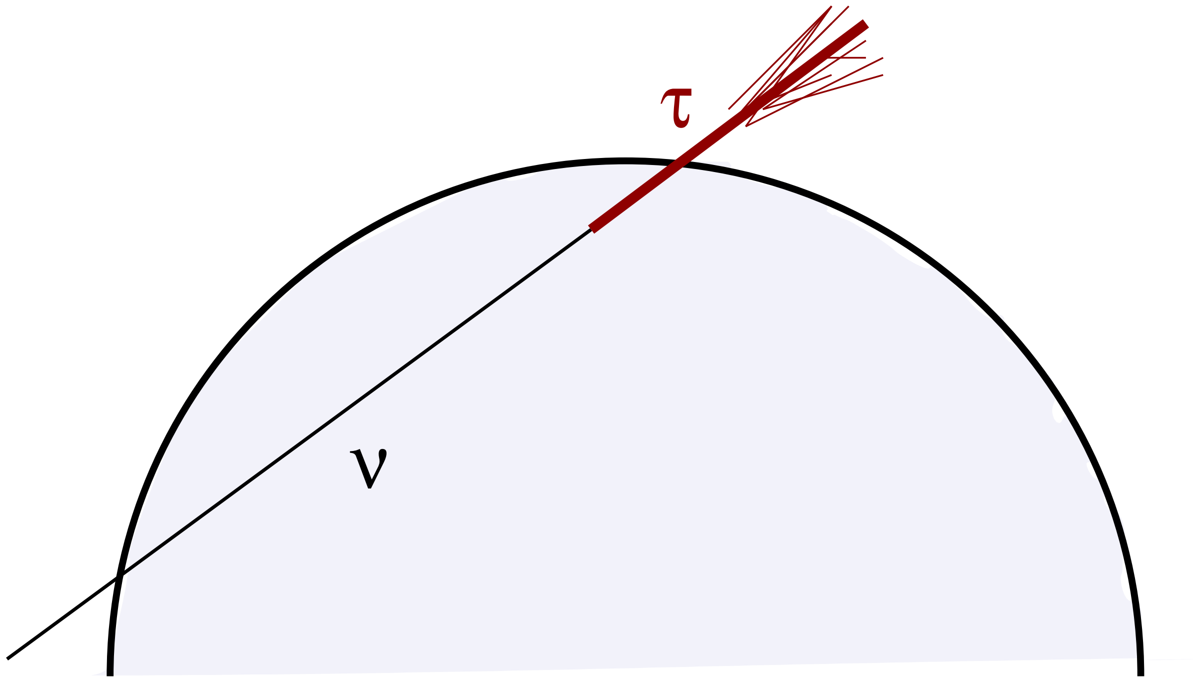
Calculations necessarily use extrapolations of PDF and standard model parameters.



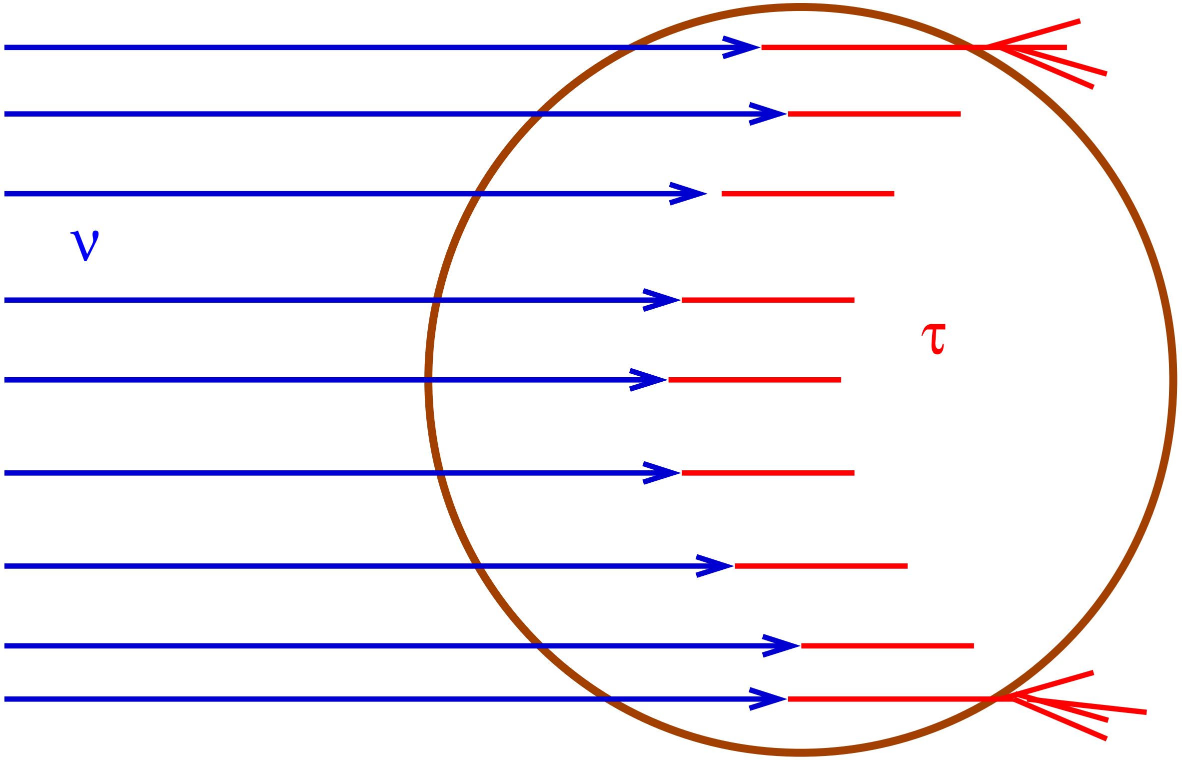
SM calculation [Quigg et al.] is most likely right, but we want to **measure** this cross section.

If the cross section is smaller, the Earth becomes more transparent to neutrinos. More neutrinos can get through the Earth, interact just below the surface and produce a charged lepton that originates an **up-going air shower (UAS)** .

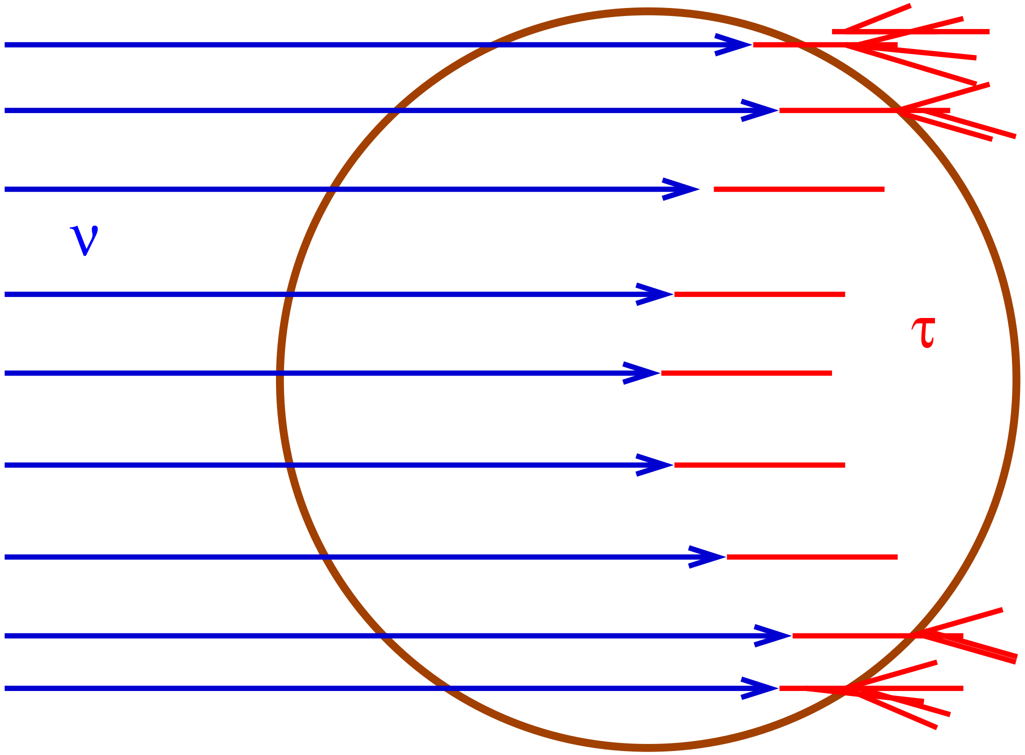
- **The increase in UAS rate compensates for the decrease in HAS.**
- **The comparison of the two rates allows a measurement of the cross section at 10^{11}GeV**
- **Angular distribution of UAS can provide an additional independent information about the cross section**



The probability of a neutrino conversion into an up-going τ grows with the mean free path λ_ν, for $\lambda_\nu < R_\oplus$, because the shadowing by the Earth decreases.

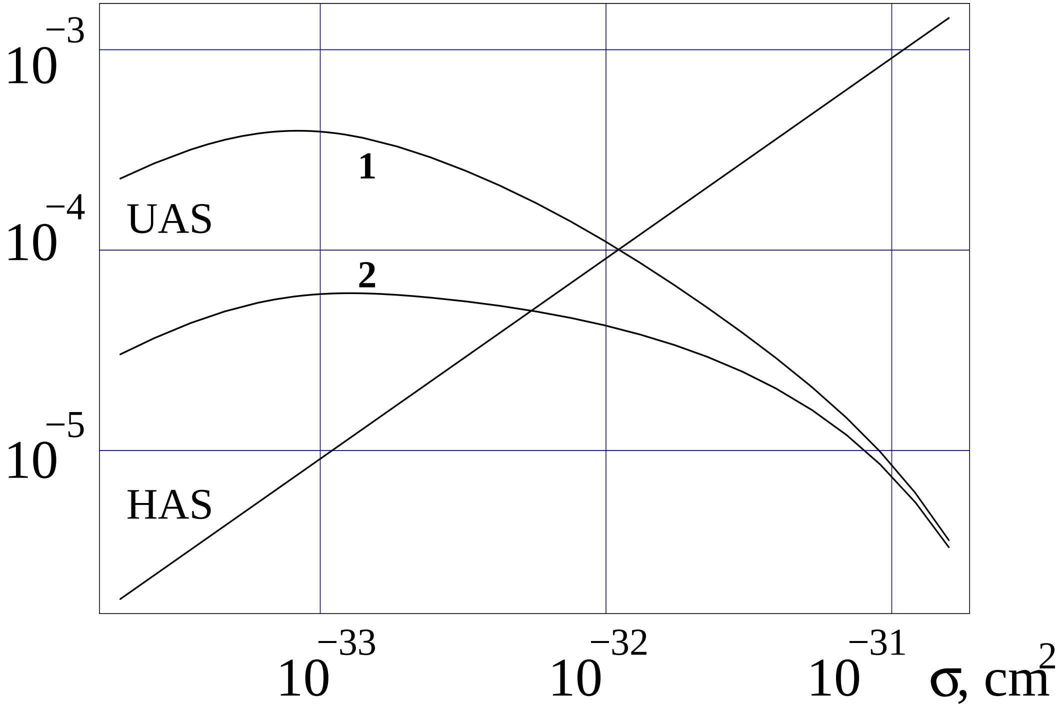


UAS requires a neutrino to interact and produce a τ below the surface.



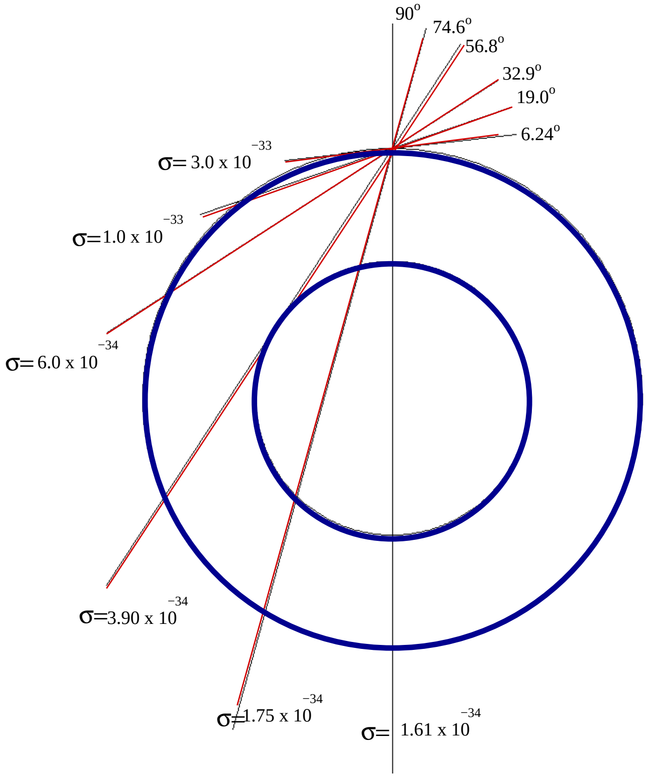
UAS requires a neutrino to interact and produce a τ below the surface. The number of UAS is higher for a smaller cross section.

The shower probability per incident neutrino:



The energy threshold for detection of UAS was assumed $E_{\rm th} = 10^{18}$eV for curve 1 and $E_{\rm th} = 10^{19}$eV for curve 2. Additional UAS events, not included here, can be detected by EUSO or OWL via Cerenkov radiation of tau leptons.

In addition, the angular distributing depends on the cross section.



Most probable UAS corresponds to chord length close to mean free path

Can one disentangle the *unknown flux* from the *unknown cross section*?

Can one disentangle the *unknown flux* from the *unknown cross section*?

Rate of HAS: $\propto \boldsymbol{F_\nu \sigma_{\nu_N}}$

Can one disentangle the *unknown flux* from the *unknown cross section*?

Rate of HAS: $\propto \boldsymbol{F_\nu \sigma_{\nu_N}}$

Rate of UAS: $\propto \boldsymbol{F_\nu / \sigma_{\nu_N}}$

Can one disentangle the *unknown flux* from the *unknown cross section*?

Rate of HAS: $\propto F_\nu \sigma_{\nu_N}$

Rate of UAS: $\propto F_\nu / \sigma_{\nu_N}$

Angular distribution: $\cos\theta_{\rm peak} \propto 1/\sigma_{\nu_N}$

Can one disentangle the *unknown flux* from the *unknown cross section*?

Rate of HAS: $\propto \boldsymbol{F_\nu \sigma_{\nu_N}}$

Rate of UAS: $\propto \boldsymbol{F_\nu / \sigma_{\nu_N}}$

Angular distribution: $\boldsymbol{\cos\theta}_{\rm peak} \propto \boldsymbol{1/\sigma_{\nu_N}}$

$\Rightarrow$ **can determine $\sigma_{\nu N}$ and F_ν independently**

Can one disentangle the *unknown flux* from the *unknown cross section*?

Rate of HAS: $\propto \boldsymbol{F_\nu \sigma_{\nu_N}}$

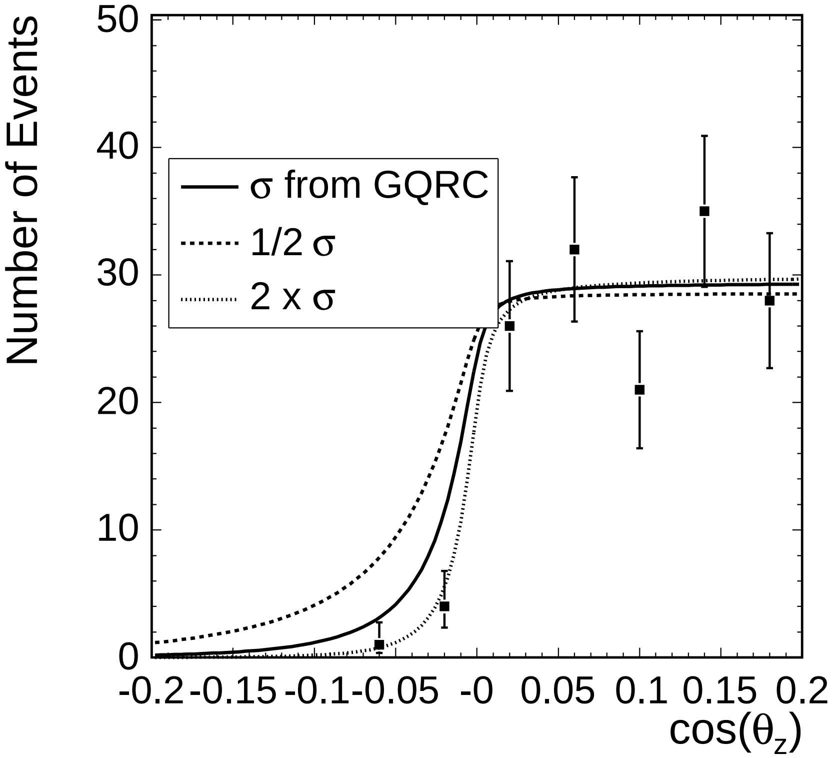
Rate of UAS: $\propto \boldsymbol{F_\nu / \sigma_{\nu_N}}$

Angular distribution: $\mathbf{cos}\, \boldsymbol{\theta}_{\rm peak} \propto \mathbf{1}/\boldsymbol{\sigma_{\nu_N}}$

$\Rightarrow$ **can determine $\sigma_{\nu N}$ and F_ν independently**

All one needs is enough statistics. Need neutrino telescopes.

ARIANNA



Plot by A. Connolly

Dark matter

Dark matter

The evidence for dark matter is very strong:

Dark matter

The evidence for dark matter is very strong:

- galactic rotation curves cannot be explained by the disk alone

Dark matter

The evidence for dark matter is very strong:

- galactic rotation curves cannot be explained by the disk alone
- cosmic microwave background radiation

Dark matter

The evidence for dark matter is very strong:

- galactic rotation curves cannot be explained by the disk alone
- cosmic microwave background radiation
- gravitational lensing of background galaxies by clusters is so strong that it requires a significant dark matter component.

Dark matter

The evidence for dark matter is very strong:

- galactic rotation curves cannot be explained by the disk alone
- cosmic microwave background radiation
- gravitational lensing of background galaxies by clusters is so strong that it requires a significant dark matter component.
- clusters are filled with hot X-ray emitting intergalactic gas (without dark matter, this gas would dissipate quickly).

Dark matter: what is it?

Can take guesses based on...

Dark matter: what is it?

Can take guesses based on...

- ...compelling theoretical ideas, e.g. supersymmetry

Dark matter: what is it?

Can take guesses based on...

- ...compelling theoretical ideas, e.g. supersymmetry
- **...simplicity**

Dark matter: what is it?

Can take guesses based on...

- ...compelling theoretical ideas, e.g. supersymmetry
- **...simplicity**
- **...observational clues**

Dark matter: a simple (minimalist) solution

Dark matter: a simple (minimalist) solution

Need **one** particle ⇒ add just **one** particle

Dark matter: a simple (minimalist) solution

Need **one** particle ⇒ add just **one** particle

If a fermion, must be gauge singlet (anomalies)

Dark matter: a simple (minimalist) solution

Need **one** particle ⇒ add just **one** particle
If a fermion, must be gauge singlet (anomalies)
Interactions only through mixing with neutrinos

Dark matter: a simple (minimalist) solution

Need **one** particle ⇒ add just **one** particle
If a fermion, must be gauge singlet (anomalies)
Interactions only through mixing with neutrinos

⇒ **sterile neutrino**

Dark matter: a simple (minimalist) solution

Need **one** particle ⇒ add just **one** particle
If a fermion, must be gauge singlet (anomalies)
Interactions only through mixing with neutrinos

⇒ sterile neutrino

Small mass and, therefore, **stability!** No symmetries required.

Sterile neutrinos

Бруно Понтекорво

The name "sterile" was coined by **Bruno Pontecorvo** in a paper [JETP, **53**, 1717 (1967)], which also discussed

- lepton number violation
- neutrinoless double beta decay
- rare processes (e.g. $\mu \to e\gamma$)
- vacuum neutrino oscillations
- detection of neutrino oscillations
- astrophysical neutrino oscillations

Pontecorvo: neutrino oscillations can *"convert potentially active particles into particles that are, from the point of view of ordinary weak interactions,* **sterile***, i.e. practically unobservable, since they have the "incorrect" helicity"* [JETP, **53**, 1717 (1967)]

Sterile neutrinos with a small mixing to active neutrinos

$$\left\{ \begin{array}{l} |\nu_1\rangle = \cos\theta|\nu_e\rangle - \sin\theta|\nu_s\rangle \\ |\nu_2\rangle = \sin\theta|\nu_e\rangle + \cos\theta|\nu_s\rangle \end{array} \right. \tag{1}$$

The almost-sterile neutrino, $|\nu_2\rangle$ was never in equilibrium. Production of ν_2 could take place through oscillations.

The coupling of ν_2 to weak currents is also suppressed, and $\sigma \propto \sin^2\theta$.

The probability of $\nu_e \to \nu_s$ conversion in presence of matter is

$$\langle P_{\rm m}\rangle = \frac{1}{2}\left[1 + \left(\frac{\lambda_{\rm osc}}{2\lambda_{\rm s}}\right)^2\right]^{-1} \sin^2 2\theta_m, \tag{2}$$

where $\lambda_{\rm osc}$ is the oscillation length, and $\lambda_{\rm s}$ is the scattering length.

Sterile neutrinos in the early universe

Sterile neutrinos are produced in primordial plasma through

Sterile neutrinos in the early universe

Sterile neutrinos are produced in primordial plasma through

- off-resonance oscillations. [Dodelson, Widrow; Abazajian, Fuller; Dolgov, Hansen; Shaposhnikov et al.]

Sterile neutrinos in the early universe

Sterile neutrinos are produced in primordial plasma through

- off-resonance oscillations. [Dodelson, Widrow; Abazajian, Fuller; Dolgov, Hansen; Shaposhnikov et al.]
- oscillations on resonance, if the lepton asymmetry is non-negligible [Fuller, Shi]

Mixing is suppressed at high temperature [Dolgov, Barbiieri; Stodolsky]

Mixing is suppressed at high temperature [Dolgov, Barbiieri; Stodolsky]

$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V(T))^2}, \quad (3)$$

Mixing is suppressed at high temperature [Dolgov, Barbiieri; Stodolsky]

$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V(T))^2}, \quad (3)$$

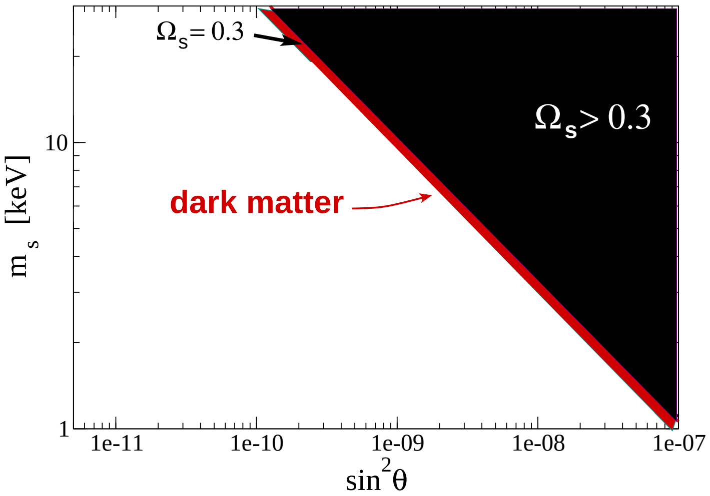
For small angles,

$$\sin 2\theta_m \approx \frac{\sin 2\theta}{1 + 0.79 \times 10^{-13} (T/\mathrm{MeV})^6 (\mathrm{keV}^2/\Delta m^2)} \quad (4)$$

Production of sterile neutrinos peaks at temperature

$$T_{\max} = 130\,\mathrm{MeV} \left(\frac{\Delta m^2}{\mathrm{keV}^2} \right)^{1/6}$$

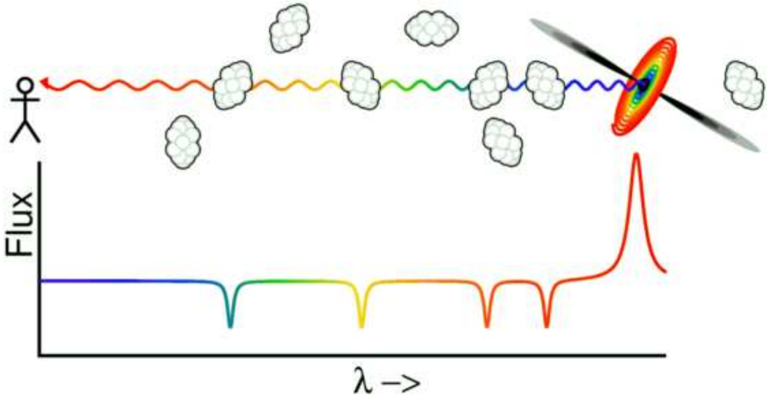
The resulting density of relic sterile neutrinos in conventional cosmology, in the absence of a large lepton asymmetry:

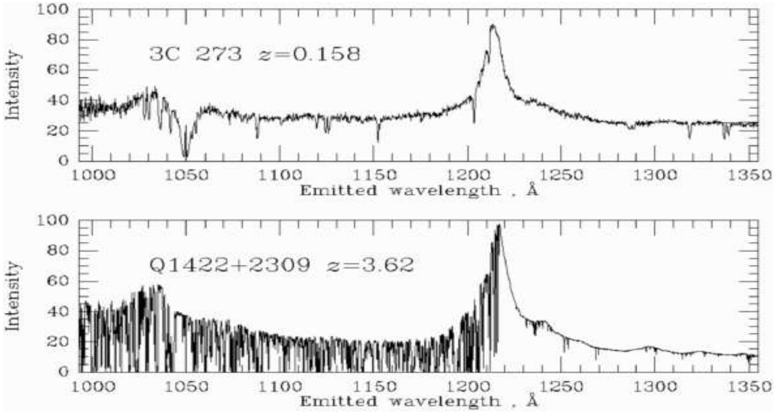


$$\Omega_{\nu_2} \sim 0.3 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{\text{keV}}\right)^2$$

[Dodelson, Widrow; Dolgov, Hansen; Fuller, Shi; Abazajian, Fuller, Patel]

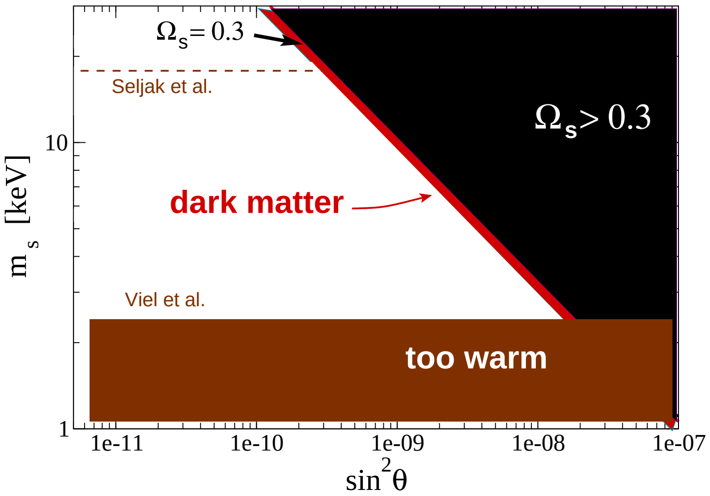
Lyman-α forest: a look at the small-scale structure





The resulting density of relic sterile neutrinos in conventional cosmology, in the absence of a large lepton asymmetry:

$$\Omega_{\nu_2} \sim 0.3 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{\mathrm{keV}}\right)^2$$



Lyman-α forest clouds show significant structure on small scales. Dark matter must be cold enough to preserve this structure.

Cold or warm dark matter?

CDM works well, but...

Cold or warm dark matter?

CDM works well, but...

There are problem problems with cold dark matter on small scales

Some CDM problems eliminated by WDM

Some CDM problems eliminated by WDM

- overproduction (by an order of magnitude!) of the satellite halos for galaxies of the size of Milky Way.

Some CDM problems eliminated by WDM

- overproduction (by an order of magnitude!) of the satellite halos for galaxies of the size of Milky Way.

- WDM can reduce the number of halos in low-density voids. [Peebles]

Some CDM problems eliminated by WDM

- overproduction (by an order of magnitude!) of the satellite halos for galaxies of the size of Milky Way.

- WDM can reduce the number of halos in low-density voids. [Peebles]

- observed densities of the galactic cores (from the rotation curves) are lower than what is predicted based on the ΛCDM power spectrum. [Dalcanton et al.; van den Bosch et al.; Moore; Abazajian]

Some CDM problems eliminated by WDM

- overproduction (by an order of magnitude!) of the satellite halos for galaxies of the size of Milky Way.

- WDM can reduce the number of halos in low-density voids. [Peebles]

- observed densities of the galactic cores (from the rotation curves) are lower than what is predicted based on the ΛCDM power spectrum. [Dalcanton et al.; van den Bosch et al.; Moore; Abazajian]

- The "angular-momentum problem": in CDM halos, gas should cool at very early times into small halos and lead to massive low-angular-momentum gas cores in galaxies. [Dolgov]

Some CDM problems eliminated by WDM

- overproduction (by an order of magnitude!) of the satellite halos for galaxies of the size of Milky Way.

- WDM can reduce the number of halos in low-density voids. [Peebles]

- observed densities of the galactic cores (from the rotation curves) are lower than what is predicted based on the ΛCDM power spectrum. [Dalcanton et al.; van den Bosch et al.; Moore; Abazajian]

- The "angular-momentum problem": in CDM halos, gas should cool at very early times into small halos and lead to massive low-angular-momentum gas cores in galaxies. [Dolgov]

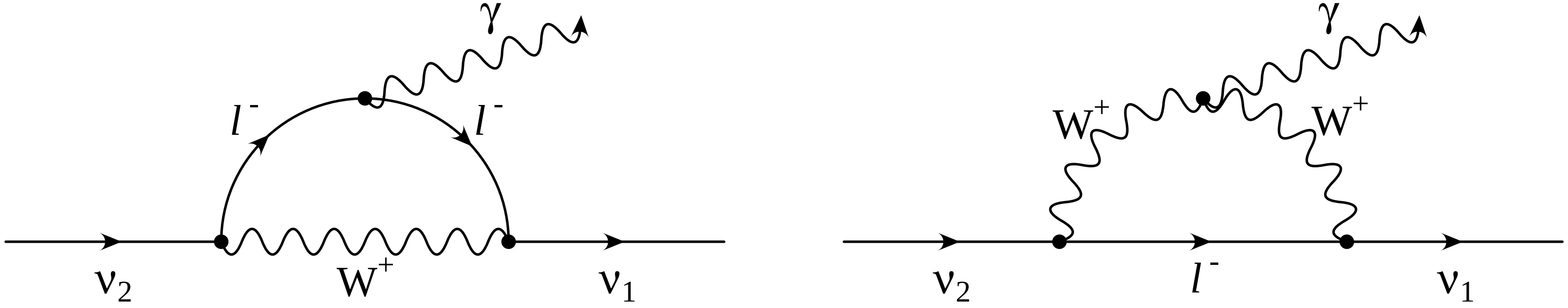
- disk-dominated (pure-disk) galaxies are observed, but not produced in CDM because of high merger rate. [Governato et al.; Kormendy et al.]

Some CDM problems eliminated by WDM

- overproduction (by an order of magnitude!) of the satellite halos for galaxies of the size of Milky Way.
- WDM can reduce the number of halos in low-density voids. [Peebles]
- observed densities of the galactic cores (from the rotation curves) are lower than what is predicted based on the ΛCDM power spectrum. [Dalcanton et al.; van den Bosch et al.; Moore; Abazajian]
- The "angular-momentum problem": in CDM halos, gas should cool at very early times into small halos and lead to massive low-angular-momentum gas cores in galaxies. [Dolgov]
- disk-dominated (pure-disk) galaxies are observed, but not produced in CDM because of high merger rate. [Governato et al.; Kormendy et al.]
- observations of dwarf spheroidal galaxies $\Rightarrow m \sim$ keV [Gilmore et al.]

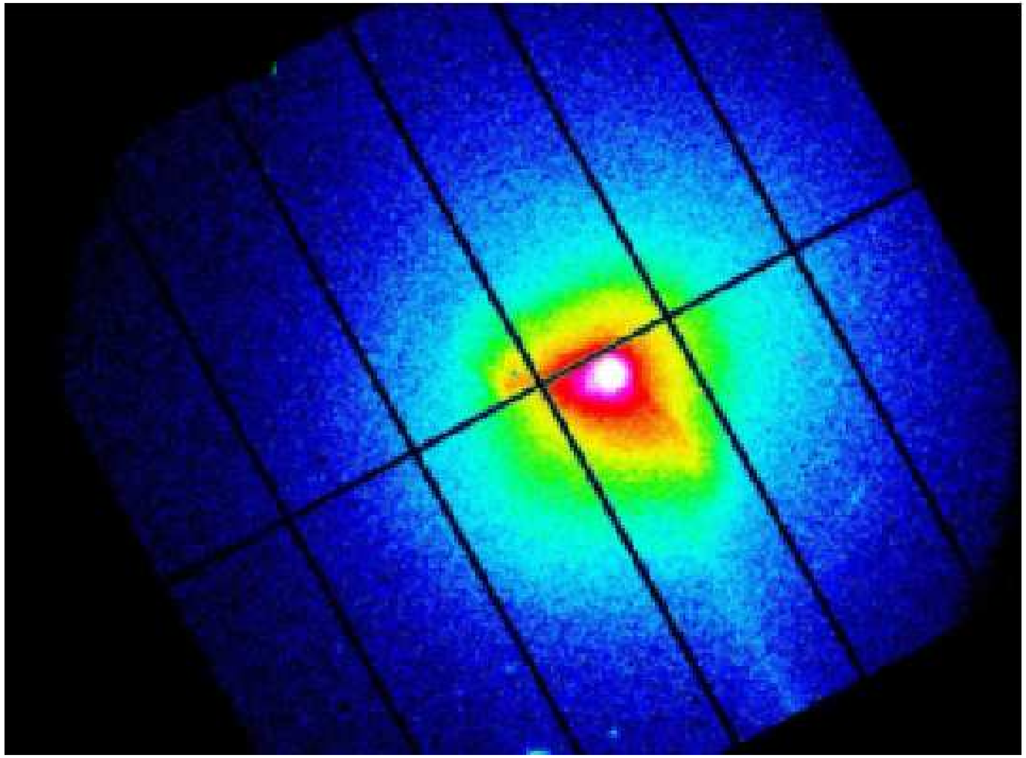
Radiative decay

Sterile neutrino in the mass range of interest have lifetimes **longer than the age of the universe**, but they do decay:



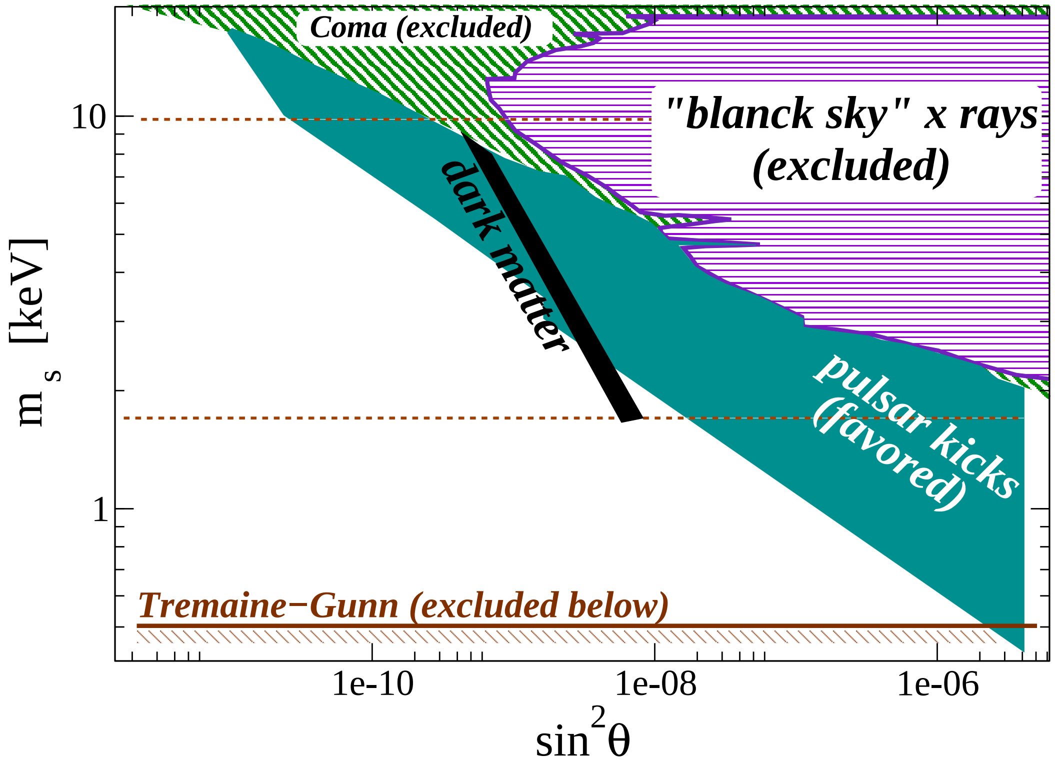
Photons have energies $m/2$: X-rays. Large lumps of dark matter emit some X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

X-ray observations



Virgo cluster image from XMM-Newton

Chandra, XMM-Newton can see photons: $\nu_s \longrightarrow \nu_e \gamma$



[Abazajian et al; Boyarsky et al. ("total flux"); Hansen et al.]

Emission of sterile neutrinos from a supernova

Emission of sterile neutrinos from a supernova

- Sterile neutrino emission from a supernova is anisotropic

Emission of sterile neutrinos from a supernova

- Sterile neutrino emission from a supernova is anisotropic
- Sterile neutrinos with masses and mixing angles consistent with dark matter can explain the pulsar velocities

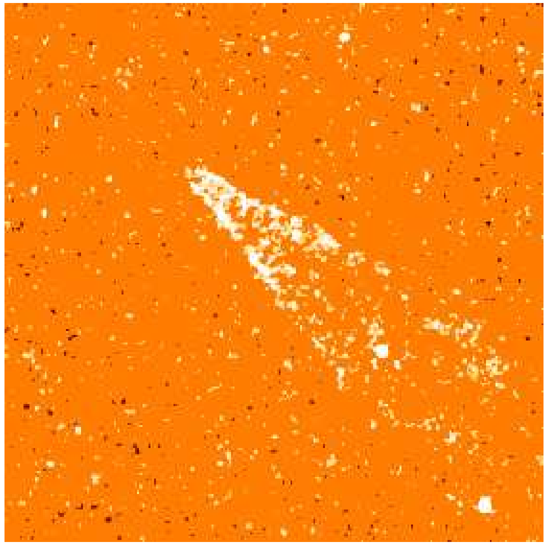
[AK, Segrè; Fuller, AK, Mocioiu, Pascoli]

The pulsar velocities.

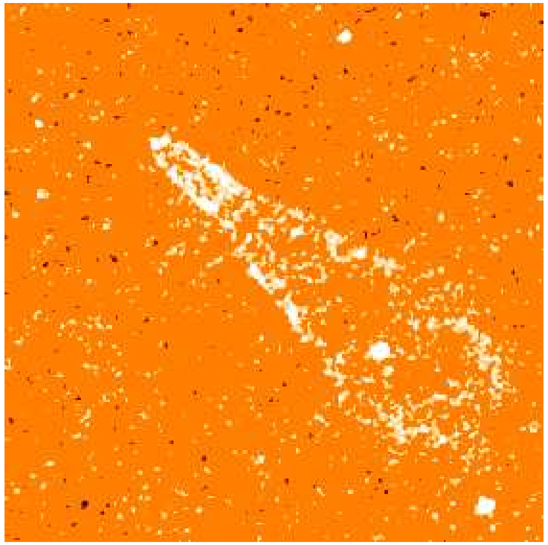
The pulsar velocities.

Pulsars have large velocities, $\langle v \rangle \approx \mathbf{250 - 450\ km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]
A significant population with $v > \mathbf{700\ km/s}$,
about **15 %** have $v > \mathbf{1000\ km/s}$, up to $\mathbf{1600\ km/s}$.
[Arzoumanian *et al.*; Thorsett *et al.*]

A very fast pulsar in Guitar Nebula

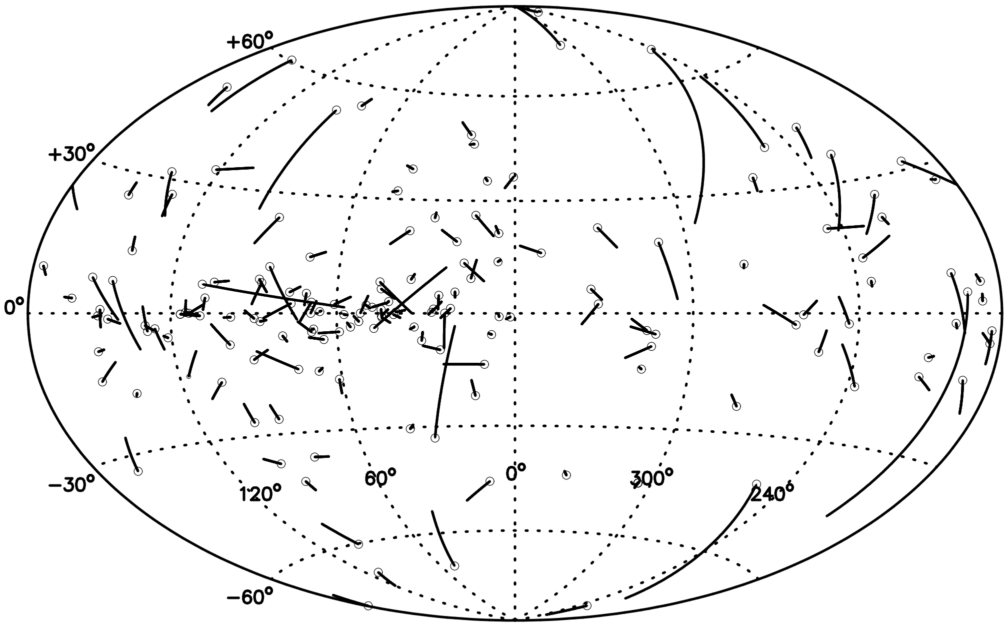


HST, December 1994



HST, December 2001

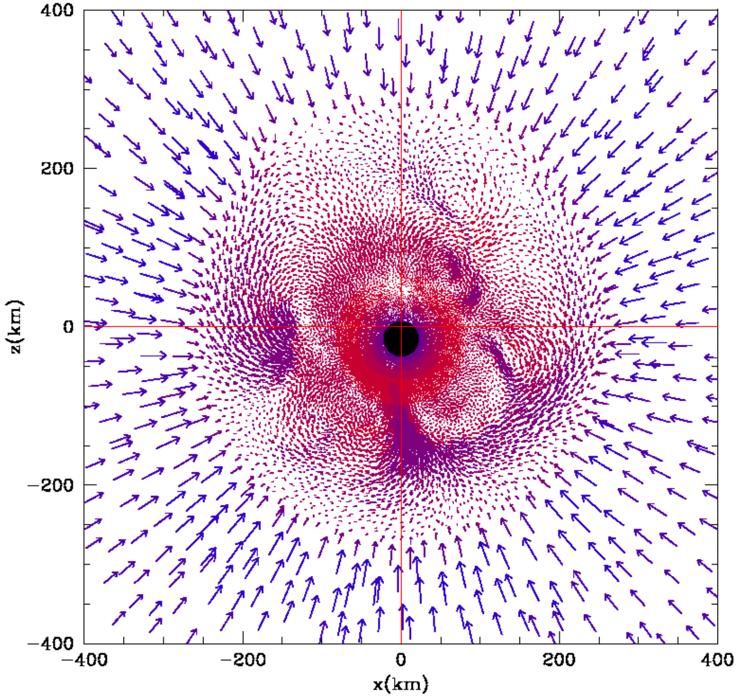
Map of pulsar velocities

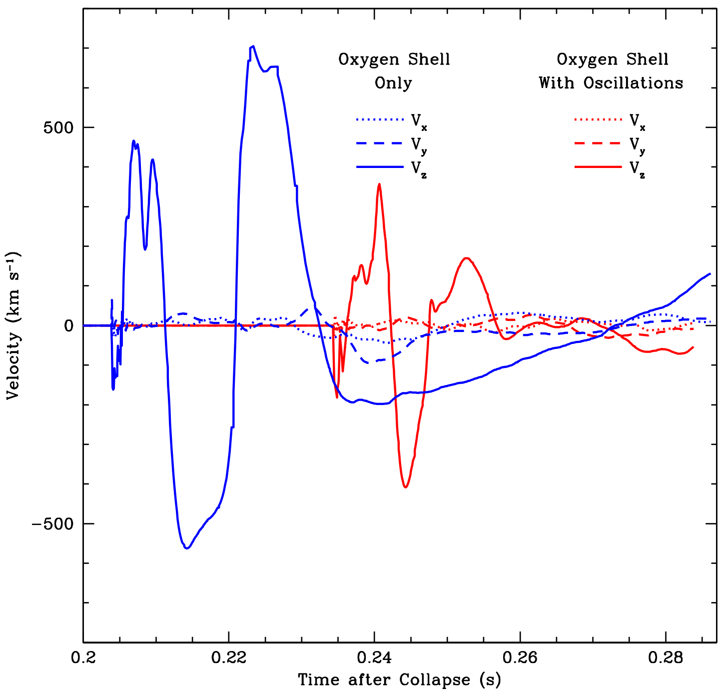


Proposed explanations:

- asymmetric collapse [Shklovskii] (small kick)
- evolution of close binaries [Gott, Gunn, Ostriker] (not enough)
- acceleration by EM radiation [Harrison, Tademaru] (kick small, predicted polarization not observed)
- asymmetry in EW processes that produce neutrinos [Chugai; Dorofeev, Rodinov, Ternov] (asymmetry washed out)
- "cumulative" parity violation [Lai, Qian; Janka] (it's *not* cumulative)

Asymmetric collapse





"...the most extreme asymmetric collapses
do not produce final neutron star velocities above 200km/s" [Fryer '03]

Supernova neutrinos

Nuclear reactions in stars lead to a formation of a heavy iron core. When it reaches $M \approx 1.4 M_\odot$, the pressure can no longer support gravity. $\Rightarrow$ collapse.

Energy released:

$$\Delta E \sim \frac{G_N M_{\rm Fe\ core}^2}{R} \sim 10^{53} {\rm erg}$$

Supernova neutrinos

Nuclear reactions in stars lead to a formation of a heavy iron core. When it reaches $M \approx 1.4 M_{\odot}$, the pressure can no longer support gravity. ⇒ collapse.

Energy released:

$$\Delta E \sim \frac{G_N M_{\text{Fe core}}^2}{R} \sim 10^{53} \text{erg}$$

99% of this energy is emitted in neutrinos

Pulsar kicks from neutrino emission?

Pulsar with $v \sim 500$ km/s has momentum

$$\boldsymbol{M_\odot v \sim 10^{41}}\ \mathrm{g\,cm/s}$$

Pulsar kicks from neutrino emission?

Pulsar with $v \sim 500$ km/s has momentum

$$\boldsymbol{M_\odot v \sim 10^{41}}\ \mathrm{g\,cm/s}$$

SN energy released: 10^{53} erg $\Rightarrow$ in neutrinos. Thus, the total neutrino momentum is

$$\boldsymbol{P_{\nu;\,\mathrm{total}} \sim 10^{43}}\ \mathrm{g\,cm/s}$$

Pulsar kicks from neutrino emission?

Pulsar with $v \sim 500$ km/s has momentum

$$\boldsymbol{M_{\odot} v \sim 10^{41}}\ \mathrm{g\,cm/s}$$

SN energy released: 10^{53} erg $\Rightarrow$ in neutrinos. Thus, the total neutrino momentum is

$$\boldsymbol{P_{\nu;\,\mathrm{total}} \sim 10^{43}}\ \mathrm{g\,cm/s}$$

a **1% asymmetry** in the distribution of **neutrinos**

is sufficient to explain the pulsar kick velocities

Pulsar kicks from neutrino emission?

Pulsar with $v \sim 500$ km/s has momentum

$$\boldsymbol{M_\odot v \sim 10^{41}}\ \mathrm{g\,cm/s}$$

SN energy released: 10^{53} erg ⇒ in neutrinos. Thus, the total neutrino momentum is

$$\boldsymbol{P_{\nu;\,\mathrm{total}} \sim 10^{43}}\ \mathrm{g\,cm/s}$$

a **1% asymmetry** in the distribution of **neutrinos**

is sufficient to explain the pulsar kick velocities

But what can cause the asymmetry??

Magnetic field?

Neutron stars have large magnetic fields. A typical pulsar has surface magnetic field $B \sim 10^{12} - 10^{13}$ **G**.

Recent discovery of *soft gamma repeaters* and their identification as *magnetars*

$\Rightarrow$ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16}$ **G**.

$\Rightarrow$ **magnetic fields inside can be $10^{15} - 10^{16}$ G.**

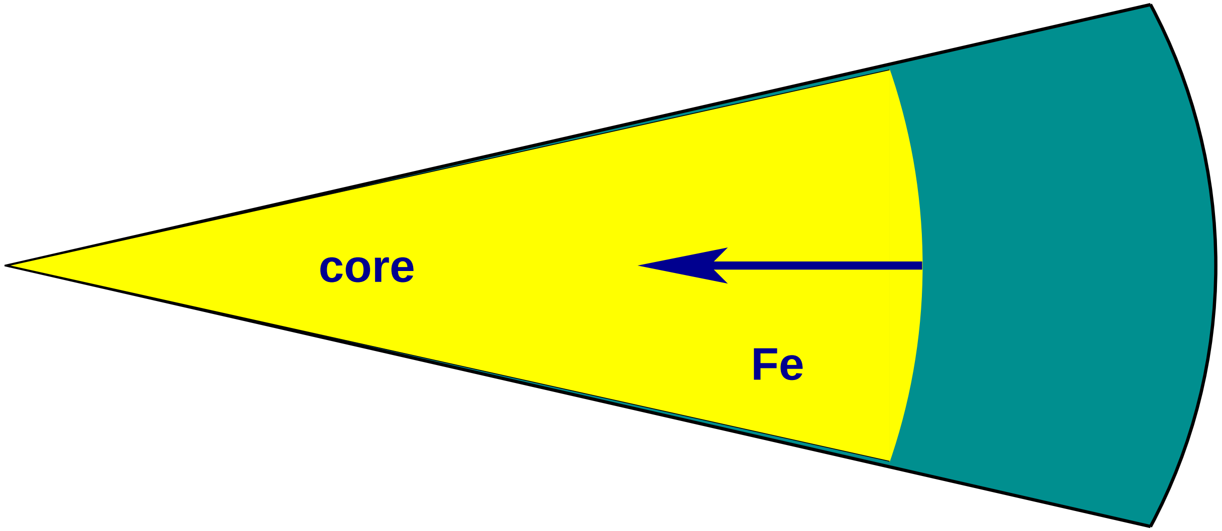
Neutrino magnetic moments are negligible, but the **scattering of neutrinos off polarized electrons and nucleons** is affected by the magnetic field.

Core collapse supernova

Onset of the collapse: $t = 0$

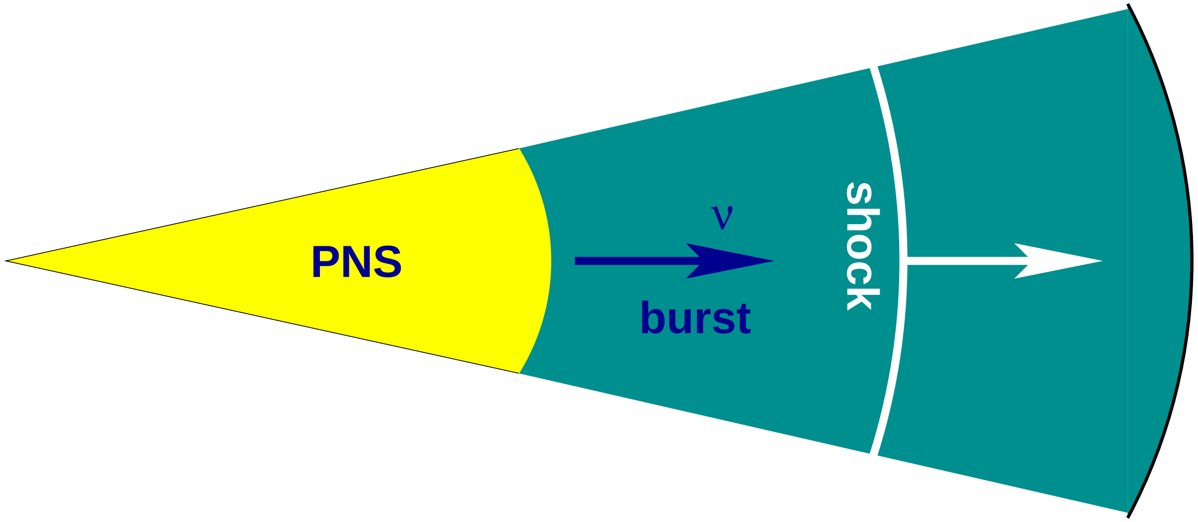
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

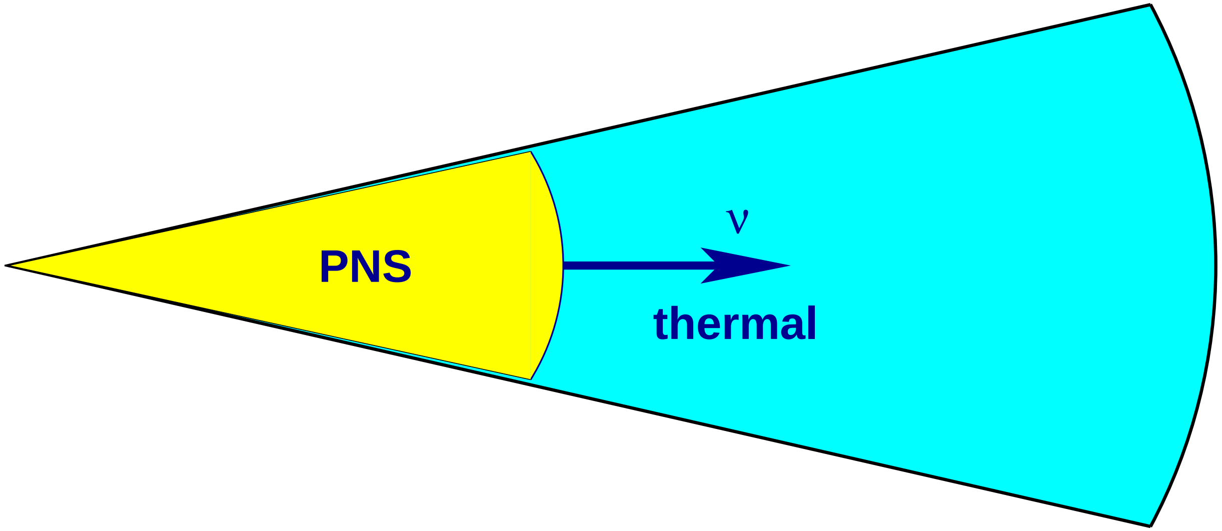
Shock formation and "neutronization burst": $t = 1 - 10$ ms



Protoneutron star formed. Neutrinos are trapped. The shock wave breaks up nuclei, and the initial neutrino come out (a few %).

Core collapse supernova

Thermal cooling: $t = 10 - 15$ s



Most of the neutrinos emitted during the cooling stage.

Electroweak processes producing neutrinos (urca),

$$p + e^- \rightleftharpoons n + \nu_e \text{ and } n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

have an asymmetry in the production cross section, depending on the spin orientation.

Electroweak processes producing neutrinos (urca),

$$p + e^- \rightleftharpoons n + \nu_e \text{ and } n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

have an asymmetry in the production cross section, depending on the spin orientation.

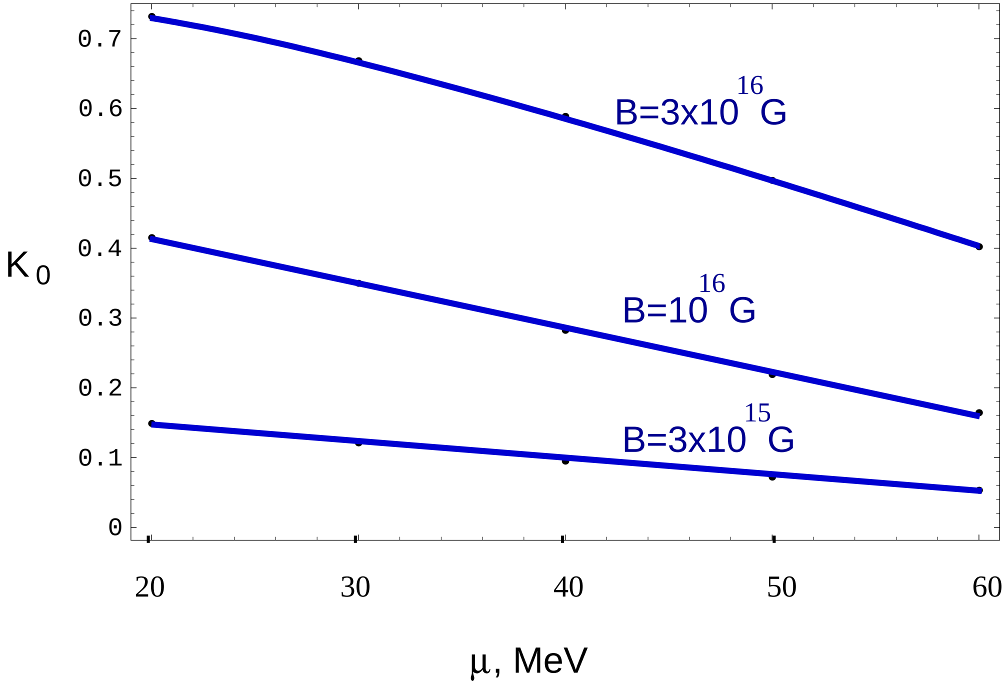
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

The asymmetry:

$$\tilde{\epsilon} = \frac{g_V^2 - g_A^2}{g_V^2 + 3g_A^2} k_0 \approx 0.4\, k_0,$$

where k_0 is the fraction of electrons in the lowest Landau level.

In a strong magnetic field,



k_0 is the fraction of electrons in the lowest Landau level.

Pulsar kicks from the asymmetric production of neutrinos?
[Chugai; Dorofeev, Rodionov, Ternov]

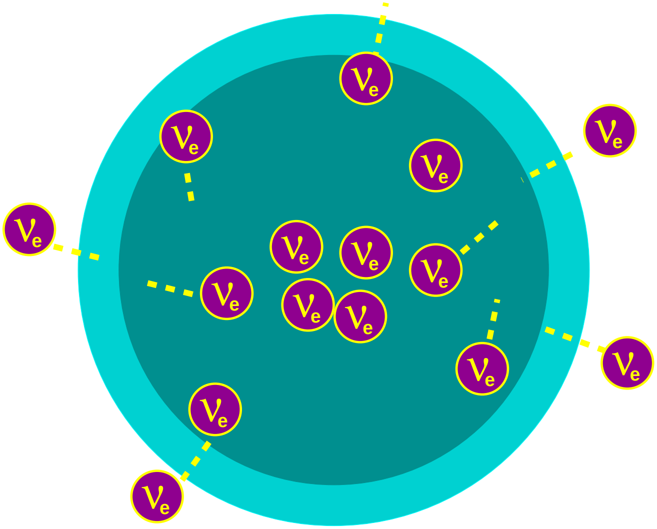
Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

No

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

No



Neutrinos are trapped at high density.

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

No

Rescattering washes out the asymmetry

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

No

Rescattering washes out the asymmetry

In approximate thermal equilibrium the asymmetries in scattering amplitudes do not lead to an anisotropic emission. Only the outer regions, near neutrinospheres, contribute (a negligible amount). [Vilenkin,AK, Segrè]

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

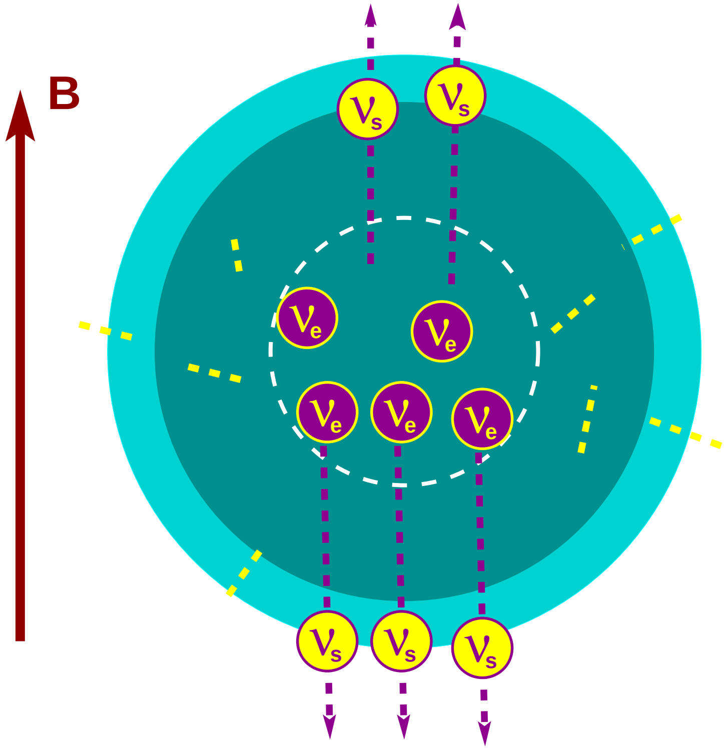
No

Rescattering washes out the asymmetry

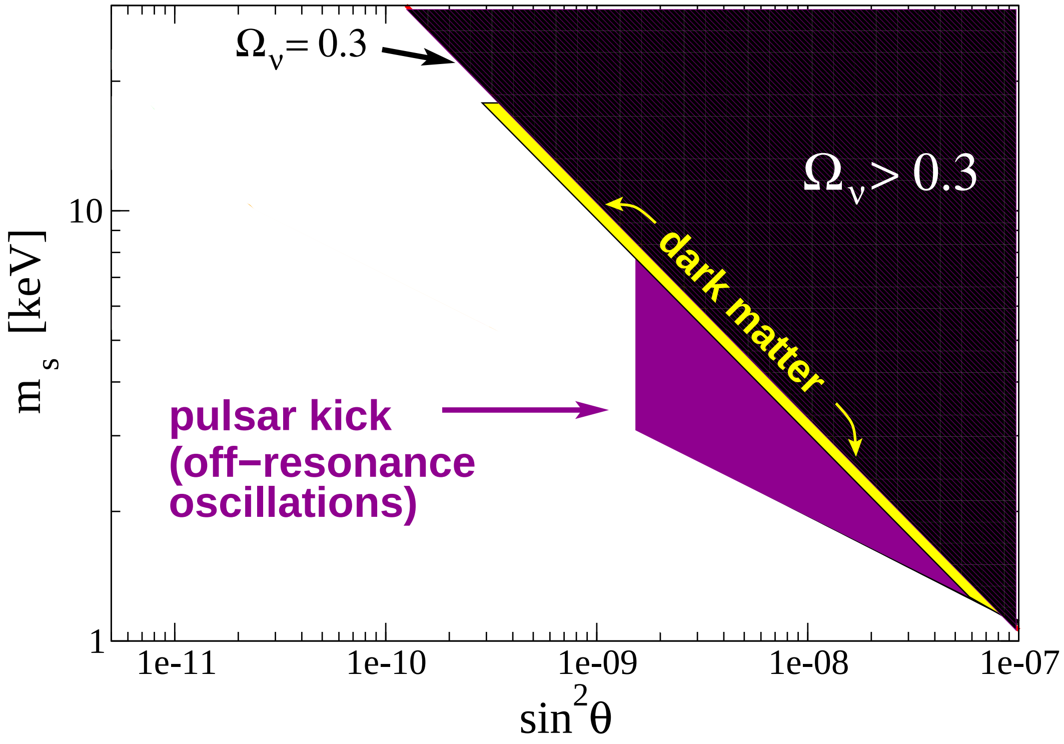
In approximate thermal equilibrium the asymmetries in scattering amplitudes do not lead to an anisotropic emission. Only the outer regions, near neutrinospheres, contribute (a negligible amount). [Vilenkin,AK, Segrè]

However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

Sterile neutrinos leave the star without scattering. Hence, they give the pulsar a kick.



Allowed range of parameters (time scales, fraction of total energy emitted):



[Fuller, AK, Mocioiu, Pascoli]

Resonant active-sterile neutrino conversions in matter

Matter potential:

$$\begin{aligned} V(\nu_s) &= 0 \\ V(\nu_e) &= -V(\bar{\nu}_e) = V_0\,(3\,Y_e - 1 + 4\,Y_{\nu_e}) \\ V(\nu_{\mu,\tau}) &= -V(\bar{\nu}_{\mu,\tau}) = V_0\,(Y_e - 1 + 2\,Y_{\nu_e}) \;+\; c_{_L}^{z}\,\frac{\vec{k}\cdot\vec{B}}{k} \end{aligned}$$

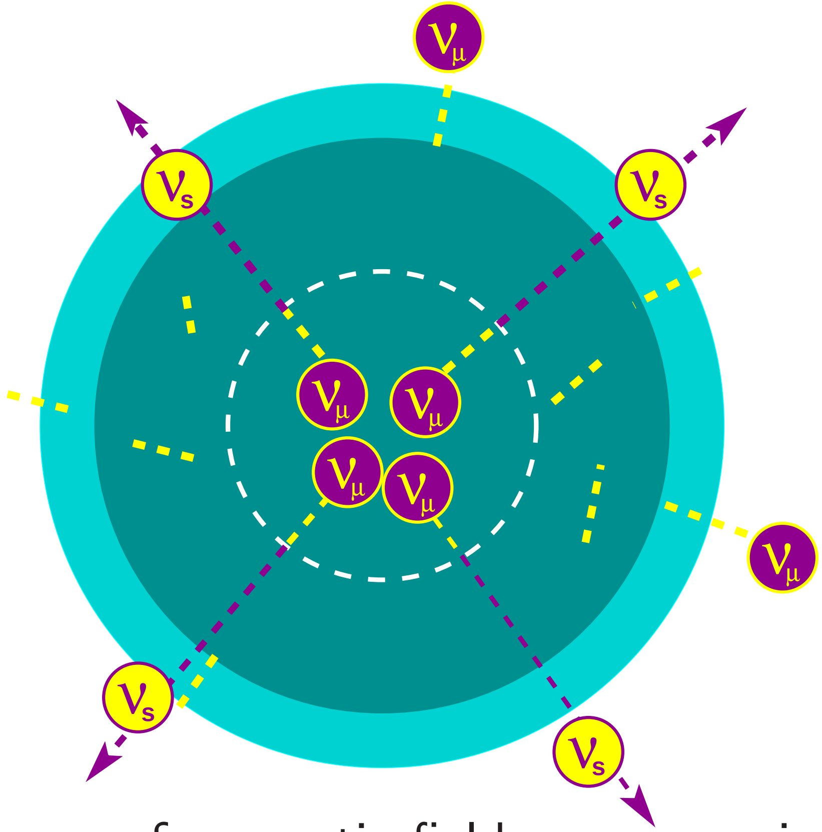
Resonant active-sterile neutrino conversions in matter

Matter potential:

$$\begin{aligned} V(\nu_s) &= 0 \\ V(\nu_e) &= -V(\bar{\nu}_e) = V_0\,(3\,Y_e - 1 + 4\,Y_{\nu_e}) \\ V(\nu_{\mu,\tau}) &= -V(\bar{\nu}_{\mu,\tau}) = V_0\,(Y_e - 1 + 2\,Y_{\nu_e}) \; + \; c_{_L}^{^Z} \frac{\vec{k}\cdot\vec{B}}{k} \end{aligned}$$

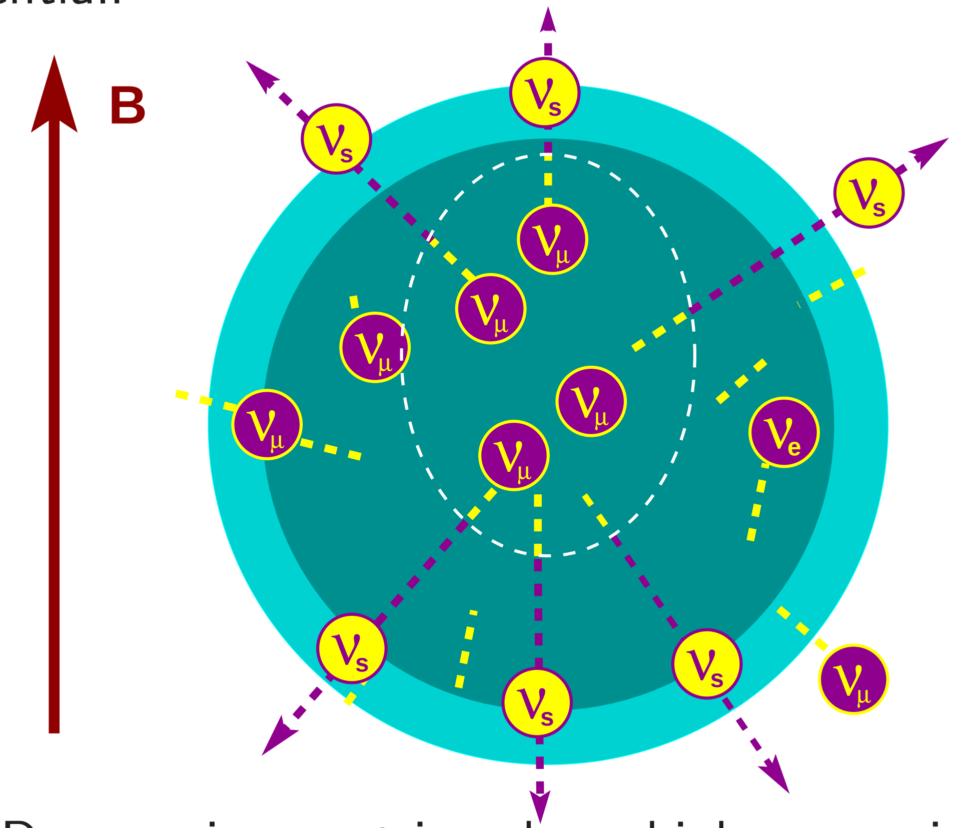
$$c_{_L}^{^Z} = \frac{eG_{_F}}{\sqrt{2}}\left(\frac{3N_e}{\pi^4}\right)^{1/3}$$

The magnetic field shifts the position of the resonance because of the $\frac{\vec{k}\cdot\vec{B}}{k}$ term in the potential:



In the absence of magnetic field, ν_s escape isotropically

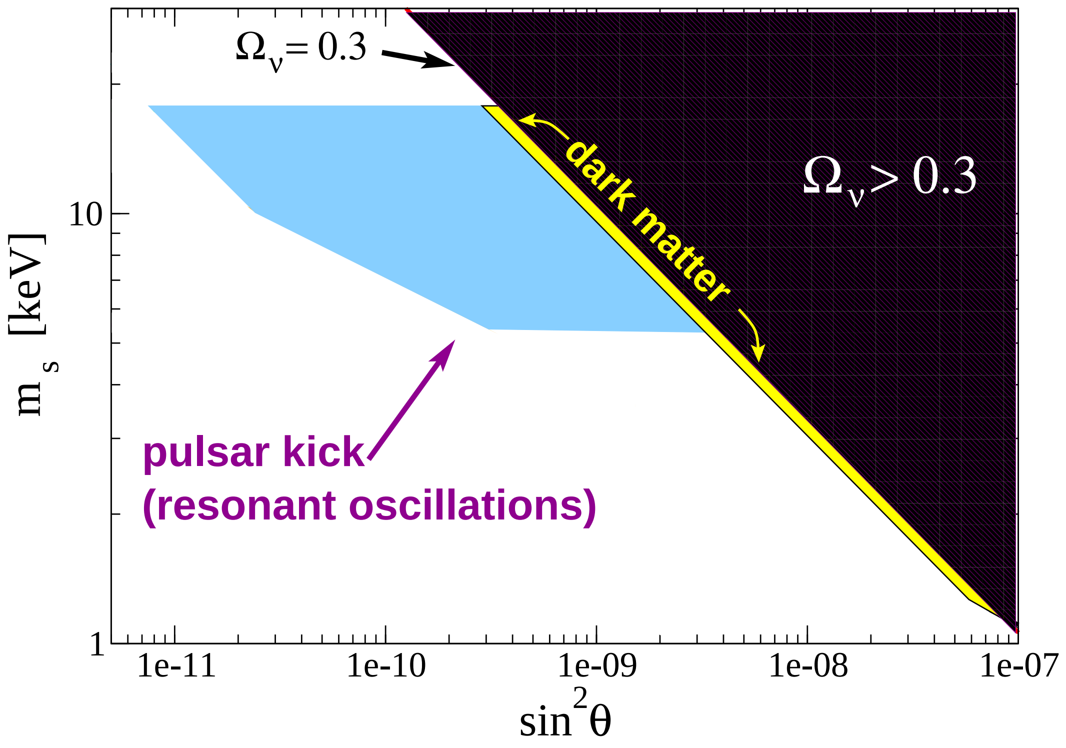
The magnetic field shifts the position of the resonance because of the $\frac{\vec{k}\cdot\vec{B}}{k}$ term in the potential:



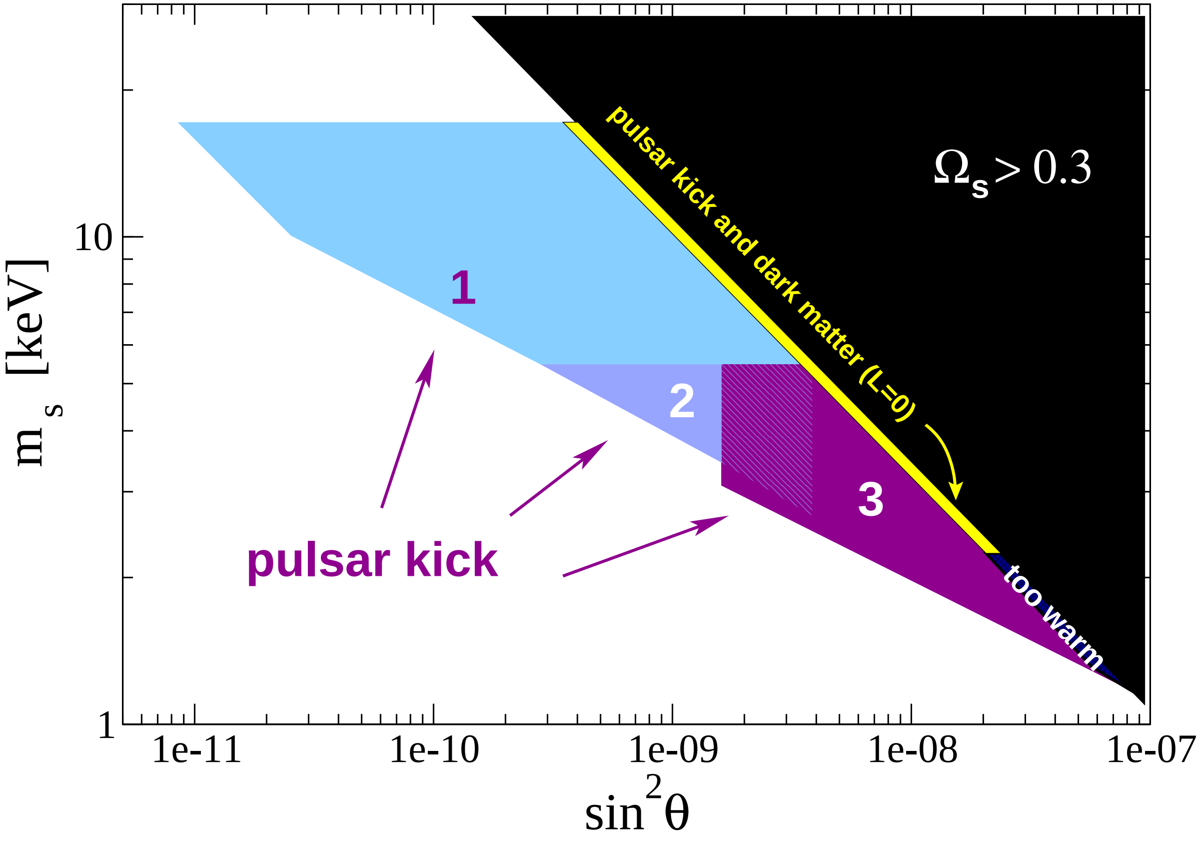
Down going neutrinos have higher energies

of the

The range of parameters (resonance, adiabaticity, weak damping):



Resonance & off-resonance oscillations



[A.K., Segrè, PL **B396**, 197 (1997); Fuller, A.K.,Mocioiu,Pascoli, PR **D 68**, 103002 (2003)]

Reionization

Reionization

WMAP, three years of data, reionization redshift: $\boldsymbol{z_{\rm r} = 10.9^{+2.7}_{-2.3}}$.
(This confirms and improves the one-year WMAP result, $z_{\rm r} = 17 \pm 5$.)

Reionization

WMAP, three years of data, reionization redshift: $\boldsymbol{z_{\rm r} = 10.9^{+2.7}_{-2.3}}$.
(This confirms and improves the one-year WMAP result, $z_{\rm r} = 17 \pm 5$.)

Observations of distant quasars: reionization must be completed by $\boldsymbol{z = 6}$.

Reionization

WMAP, three years of data, reionization redshift: $\boldsymbol{z_{\rm r} = 10.9^{+2.7}_{-2.3}}$.
(This confirms and improves the one-year WMAP result, $z_{\rm r} = 17 \pm 5$.)
Observations of distant quasars: reionization must be completed by $\boldsymbol{z = 6}$.
First stars can ionize gas, but can they form so early?

Reionization

WMAP, three years of data, reionization redshift: $\boldsymbol{z_{\rm r} = 10.9^{+2.7}_{-2.3}}$.
(This confirms and improves the one-year WMAP result, $z_{\rm r} = 17 \pm 5$.)

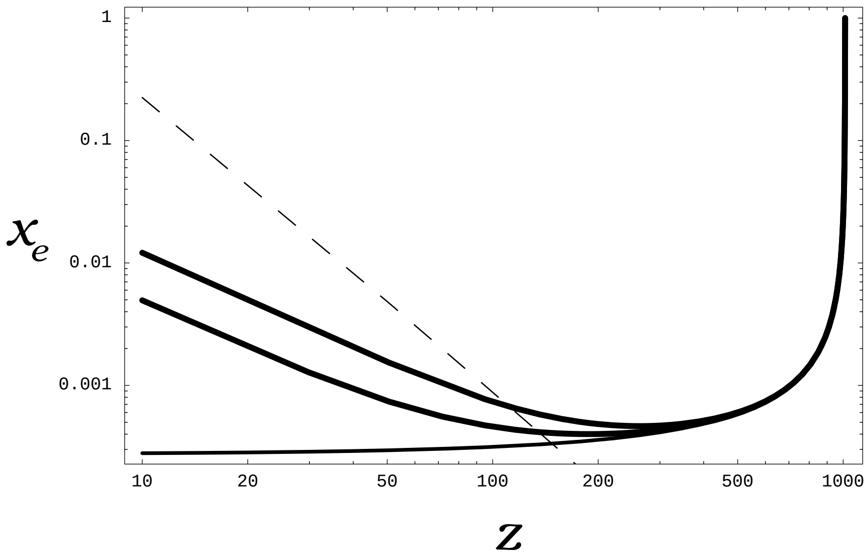
Observations of distant quasars: reionization must be completed by $\boldsymbol{z = 6}$.

First stars can ionize gas, but can they form so early?

WMAP 3 yrs ⇒ new challenge: can one end reionization by $z = 6$ without exceeding the optical depth $\tau_{\rm WMAP} = 0.10 \pm 0.03$?

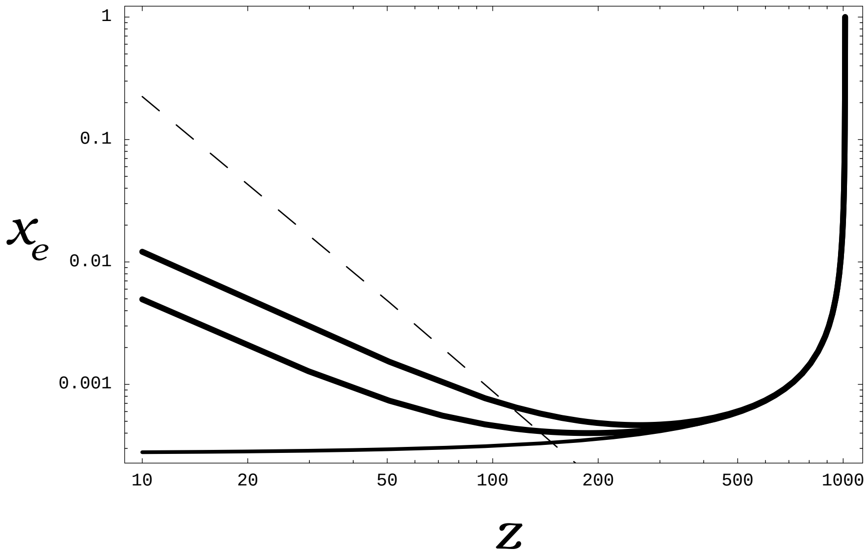
Small halos collapse first and start ionizing gas. If reionization is to be completed by $z = 6$, small halos shine to early, too bright, and exceed $\tau_{\rm WMAP}$.

Sterile neutrino decays: direct ionization



The ions too few to explain the WMAP results [Ferrara, Mapelli]...

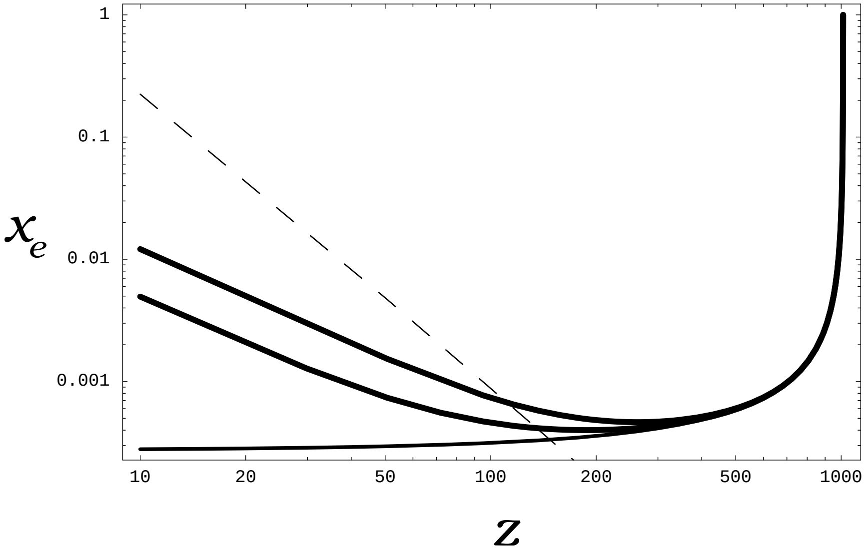
Sterile neutrino decays: direct ionization



The ions too few to explain the WMAP results [Ferrara, Mapelli]...

...but it's a much higher fraction than in the absence of sterile neutrinos. Ionization catalyzes formation of molecular hydrogen

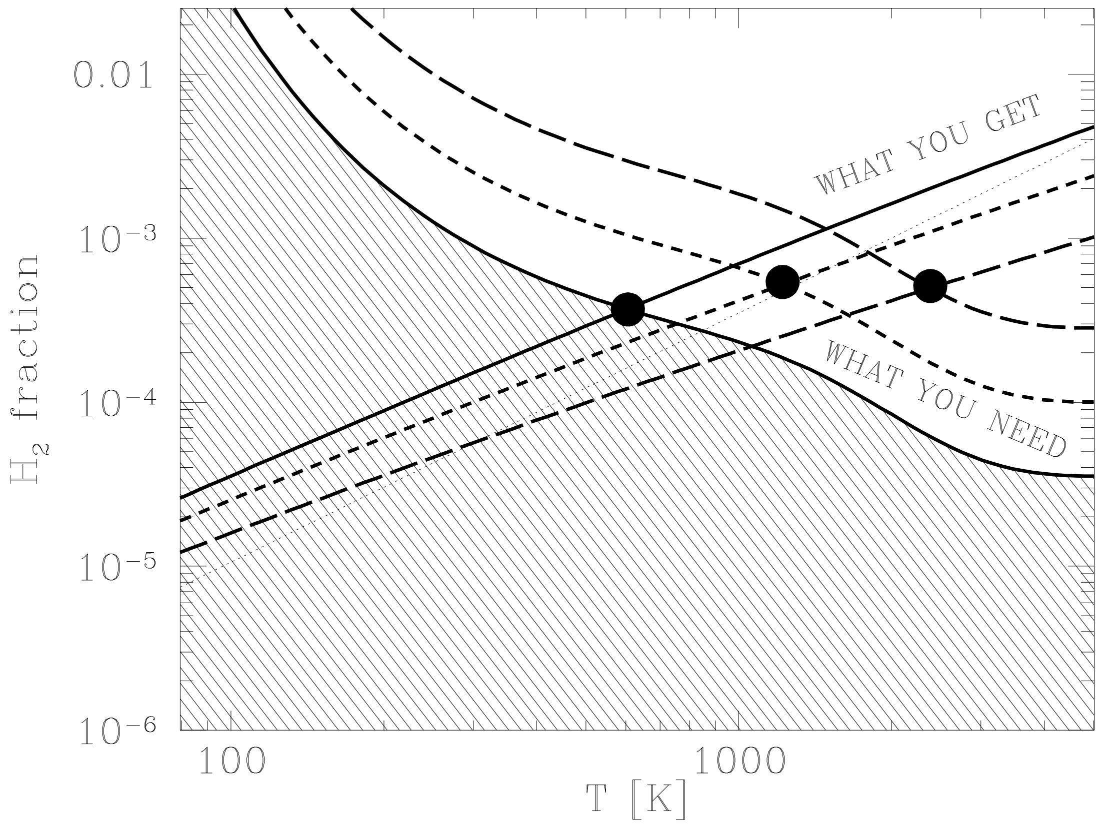
Sterile neutrino decays: direct ionization



The ions too few to explain the WMAP results [Ferrara, Mapelli]...

...but it’s a much higher fraction than in the absence of sterile neutrinos. Ionization catalyzes formation of molecular hydrogen

production of molecular hydrogen speeds up gas cooling, halo collapse and star formation



[Tegmark, et al., ApJ **474**, 1 (1997)]

Molecular hydrogen

$$\boldsymbol{H+H \longrightarrow H_2+\gamma} \quad - \quad \text{very slow!}$$

Molecular hydrogen

$$H + H \rightarrow H_2 + \gamma \quad - \quad \text{very slow!}$$

In the presence of ions the following reactions are faster:

$$\begin{aligned} H^+ + H &\rightarrow H_2^+ + \gamma, \\ H_2^+ + H &\rightarrow H_2 + H^+. \end{aligned}$$

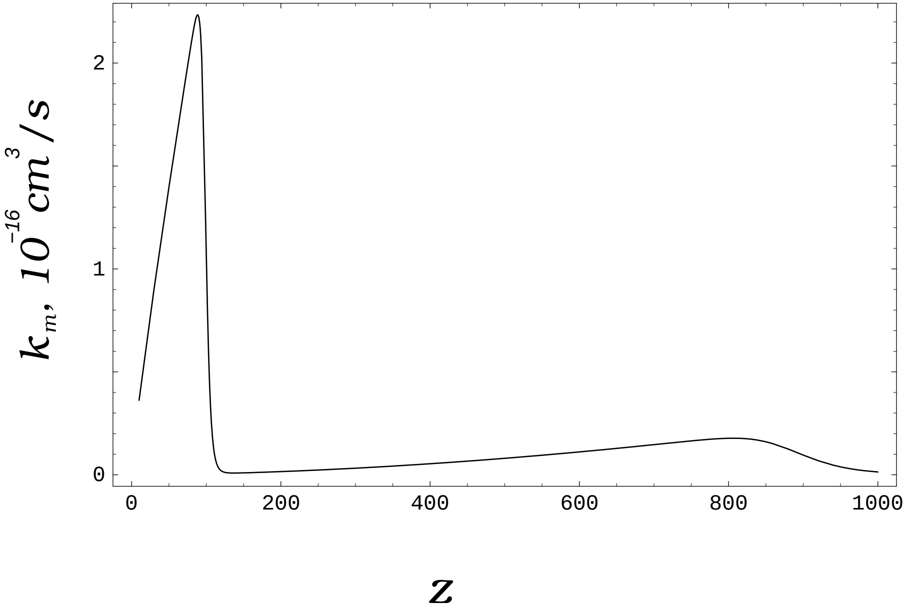
Molecular hydrogen

$$\boldsymbol{H + H \longrightarrow H_2 + \gamma} \quad - \quad \text{very slow!}$$

In the presence of ions the following reactions are faster:

$$\begin{aligned} \boldsymbol{H^+ + H} &\longrightarrow \boldsymbol{H_2^+ + \gamma}, \\ \boldsymbol{H_2^+ + H} &\longrightarrow \boldsymbol{H_2 + H^+}. \end{aligned}$$

H^+ catalyze the formation of molecular hydrogen!
[Biermann, AK, PRL **96**, 091301 (2006)]



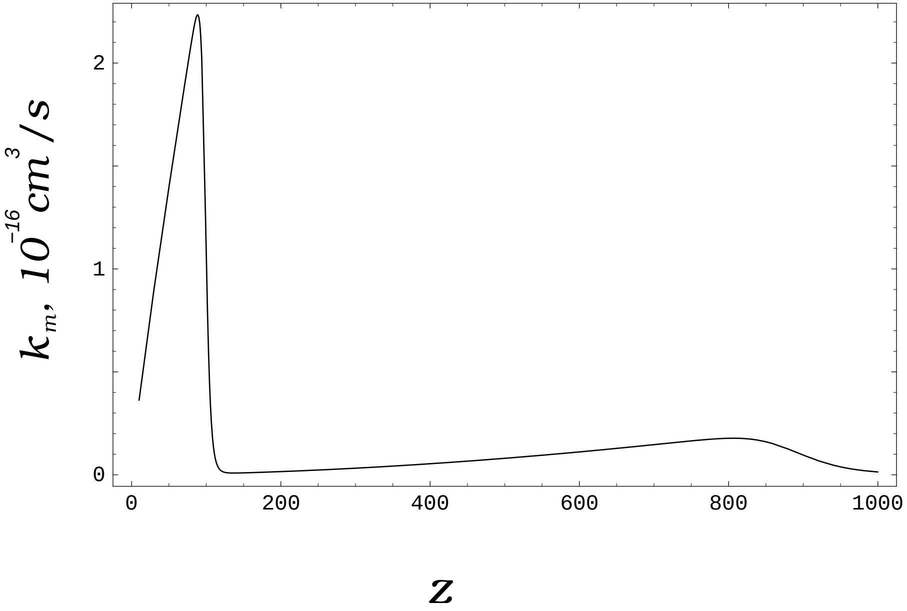
The fraction of molecular hydrogen f

$$\dot{f} \approx k_m(t)\, n_H(t)\, x_e(t),$$

where k_m is the rate shown

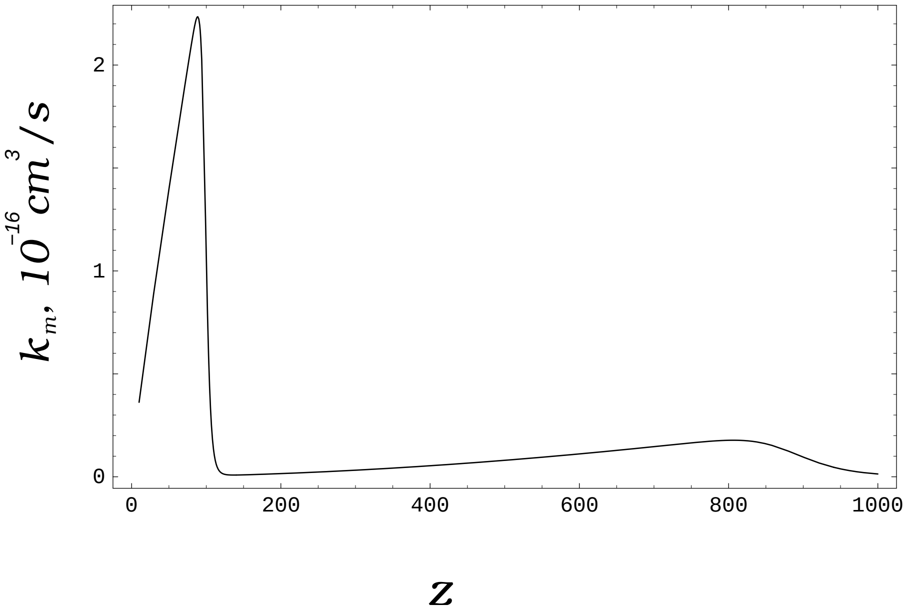
The fraction of molecular hydrogen f

$$\dot{f} \approx k_m(t)\, n_H(t)\, x_e(t),$$



where k_m is the rate shown

End result: H_2 production is enhanced at $z \sim 100$



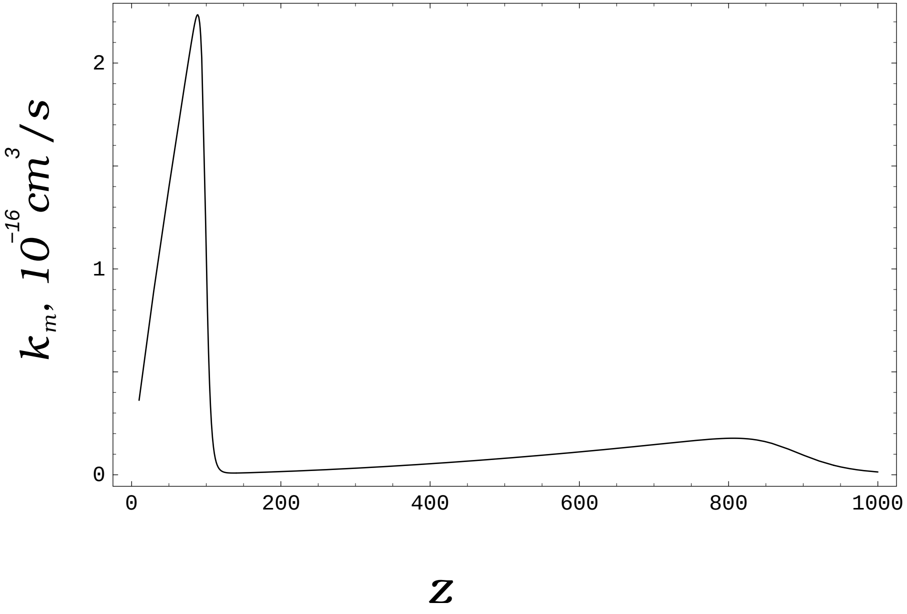
The fraction of molecular hydrogen f

$$\dot{f} \approx k_m(t)\, n_H(t)\, x_e(t),$$

where k_m is the rate shown

End result: H_2 production is enhanced at $z \sim 100$

Sterile neutrino decays can precipitate the early star formation.



The fraction of molecular hydrogen f

$$\dot{f} \approx k_m(t)\, n_H(t)\, x_e(t),$$

where k_m is the rate shown

End result: H_2 production is enhanced at $z \sim 100$

Sterile neutrino decays can precipitate the early star formation.

Stars can reionize the universe by redshif $z_r = 11 \pm 3$ (WMAP) while avoiding the minihalo problem

Can these neutrinos be detected by neutrino telescopes?

MSW resonance:

$$\frac{\Delta m^2}{En} = 2\sqrt{2}G_F$$

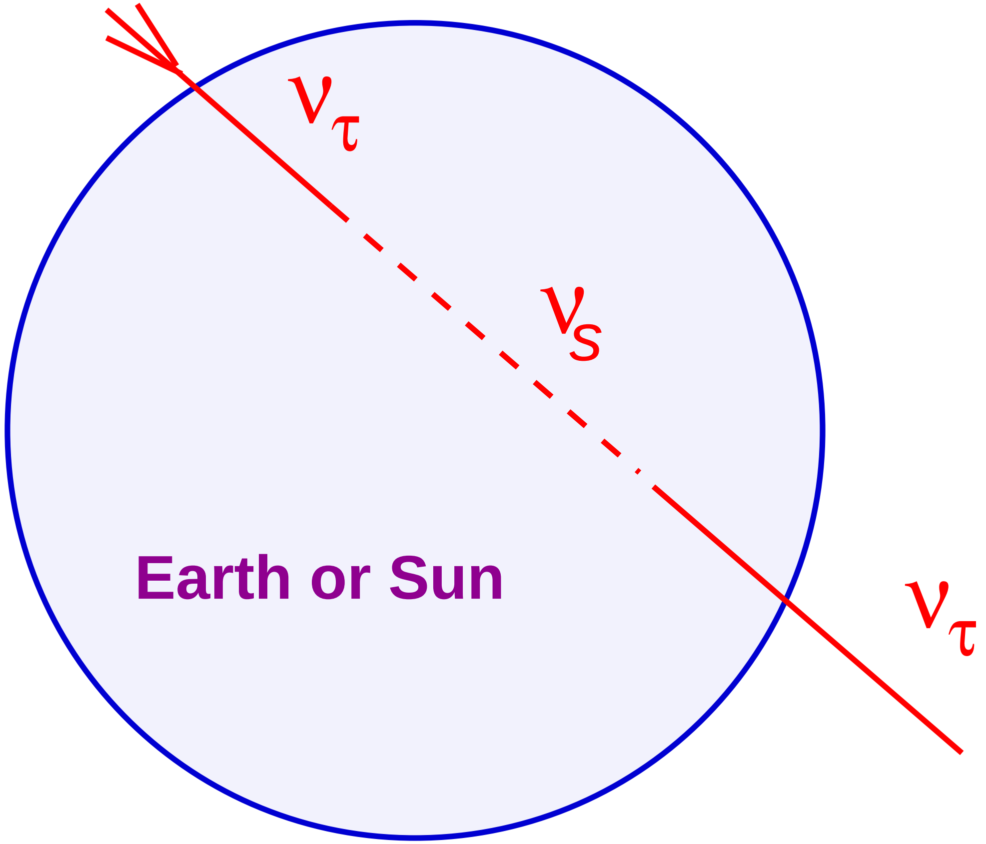
Can these neutrinos be detected by neutrino telescopes?

MSW resonance:

$$\frac{\Delta m^2}{E n} = 2\sqrt{2} G_F$$

Same for MeV neutrinos in neutron stars and for EeV neutrinos in Earth and Sun:

supernova neutrinos:	$E \sim 10^7 \mathrm{eV}$, matter density $\rho \sim 10^{11} - 10^{14} \mathrm{g/cm}^3$
UHE neutrinos:	$E \sim 10^{18} - 10^{20} \mathrm{eV}$, matter density $\rho \sim 1 - 12 \mathrm{g/cm}^3$



Perhaps, one can see these events with neutrino telescopes

Conclusion

Conclusion

- UHECR experiments will allow an exciting physics program complementary to UHE astronomy:

Conclusion

- UHECR experiments will allow an exciting physics program complementary to UHE astronomy:
  - one can learn about small-x, high Q processes in QCD

Conclusion

- UHECR experiments will allow an exciting physics program complementary to UHE astronomy:
  - one can learn about small-x, high Q processes in QCD
  - one may be able to test new physics ideas in neutrino interactions

Conclusion

- UHECR experiments will allow an exciting physics program complementary to UHE astronomy:
  - one can learn about small-x, high Q processes in QCD
  - one may be able to test new physics ideas in neutrino interactions
  - one may find dark matter