# Opportunities for Subdominant Dark Matter Candidates

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**Seminar, Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, June 17, 2004, Barcelona, E**

# 0. Introduction

- Progress in observational cosmology

$\Rightarrow$ Composition of today's universe

| Material | Particles | $\langle E \rangle$ or $m$ | $N$ | $\langle \rho \rangle / \rho_c$ | |
|---|---|---|---|---|---|
| Ordinary matter | $p, n, e$ | MeV-GeV | $10^{78}$ | 5 % | ✓ |
| Radiation | $\gamma$ | $0.1$ meV | $10^{87}$ | 0.005 % | ✓ |
| Hot Dark Matter | Neutrinos | $> 0.04$ eV<br>$< 0.6$ eV | $10^{87}$ | $> 0.1$ %<br>$< 3$ % | |
| Cold Dark Matter | Wimps?<br>Axions? | $\gtrsim 100$ GeV<br>$\lesssim$ meV | $\lesssim 10^{77}$<br>$\gtrsim 10^{91}$ | 25 % | ✓ |
| Dark Energy | ? | $10^{-33}$ eV | ? | 70 % | ✓ |

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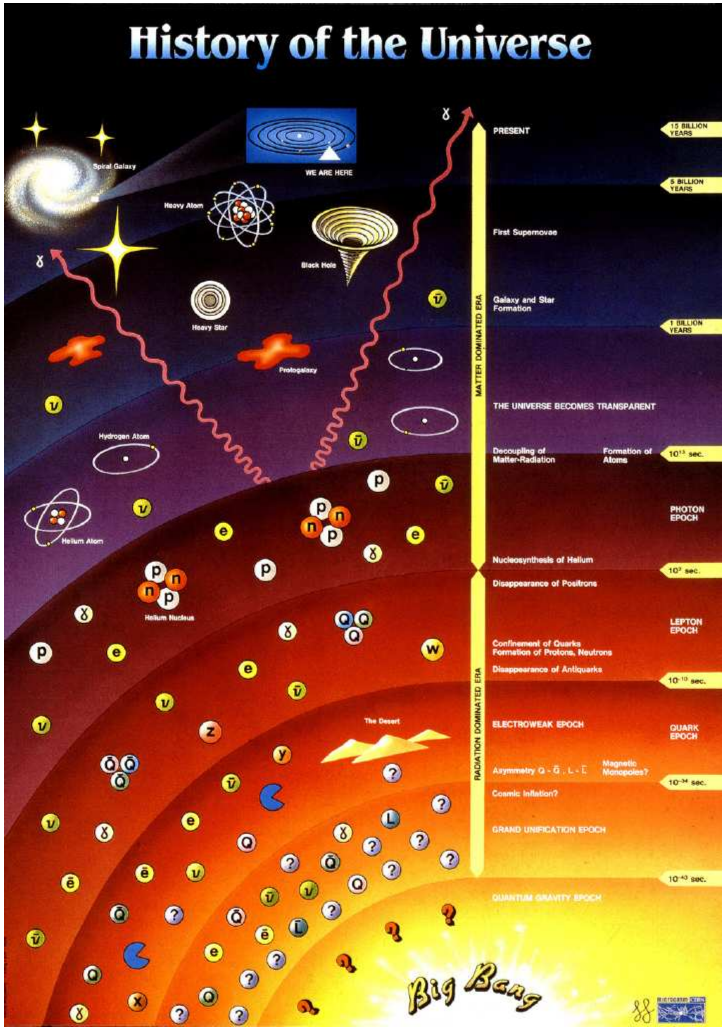


[CERN]

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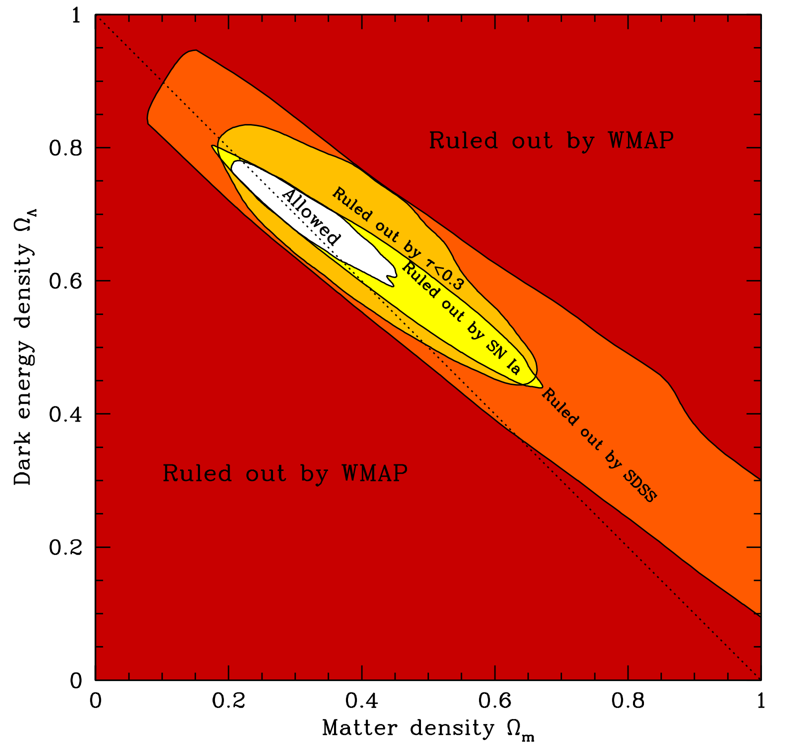


[Tegmark *et al.* '04]

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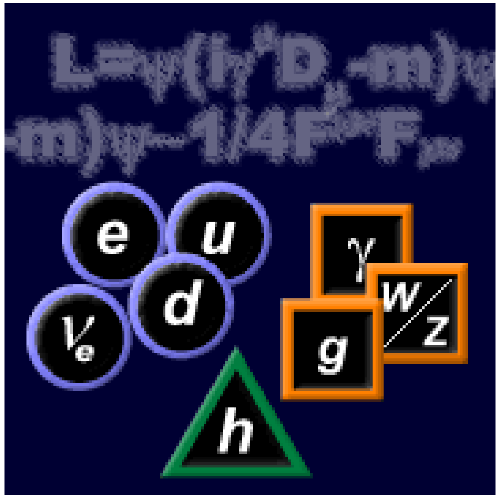

[DESY]

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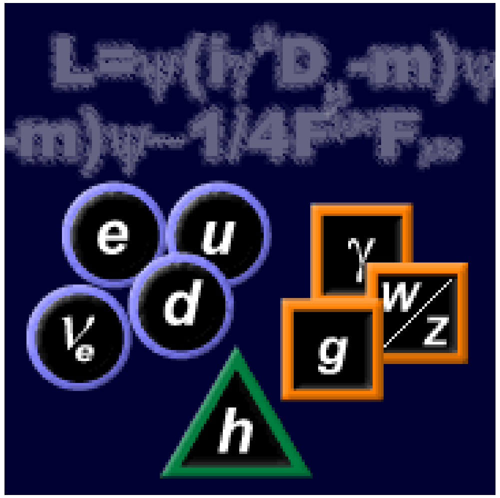
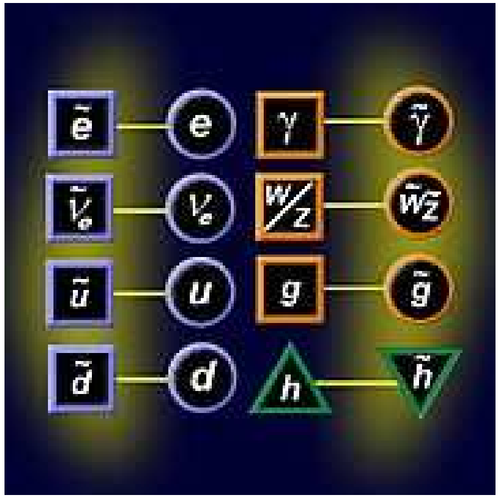


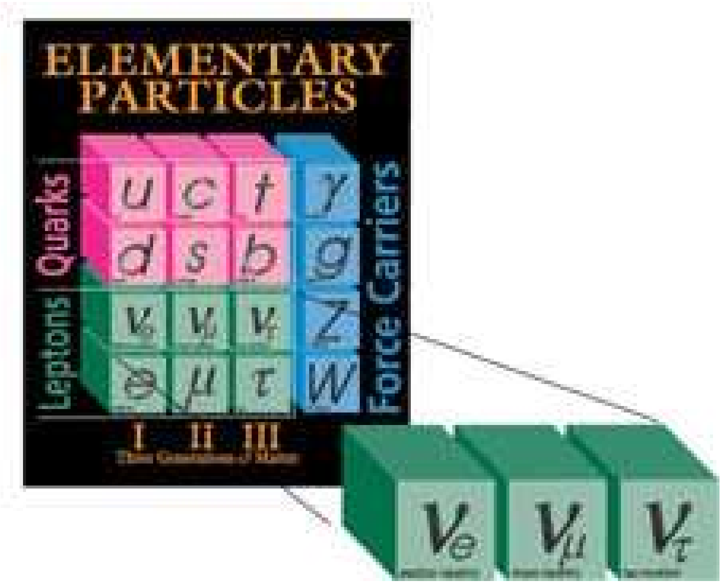

[DESY]

- Discuss here:

  1. **Relic neutrino absorption spectroscopy**
     **B. Eberle, AR, L. Song, T. Weiler, hep-ph/0401203, PRD**
  2. **Production and detection of axions after HERA (LHC)**
     **AR, Phys. Lett. 569 (2003) 51**

# 1. Relic neutrino absorption spectroscopy

- **Neutrinos** amongst elementary particles with weakest interactions




[Fermilab]

⇒ Direct detection of **C$\nu$B** ("neutrino wind") within upcoming decade seems hopeless.

[AR '03]

⇒ Indirect detection possibility?

- **Resonant annihilation** of extremely high energy cosmic $\nu$'s (**EHEC$\nu$'s**) on big bang relic $\bar{\nu}$'s (and vice versa) into **Z-bosons**

[Weiler '82]

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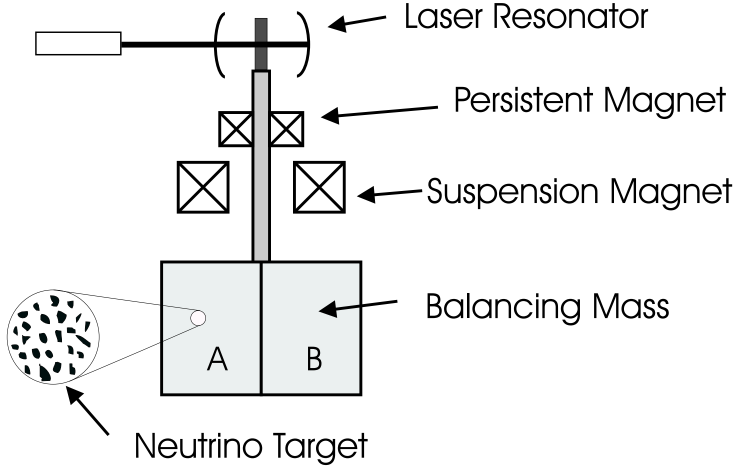


[Hagmann '99]

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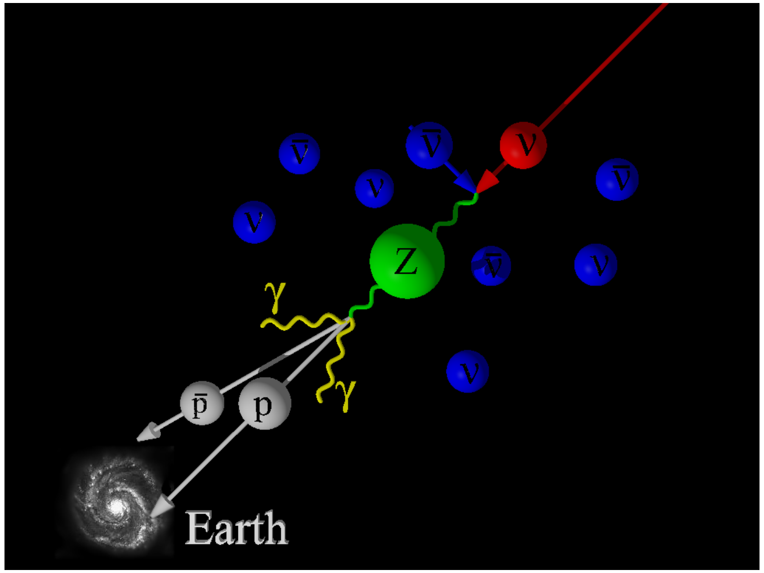


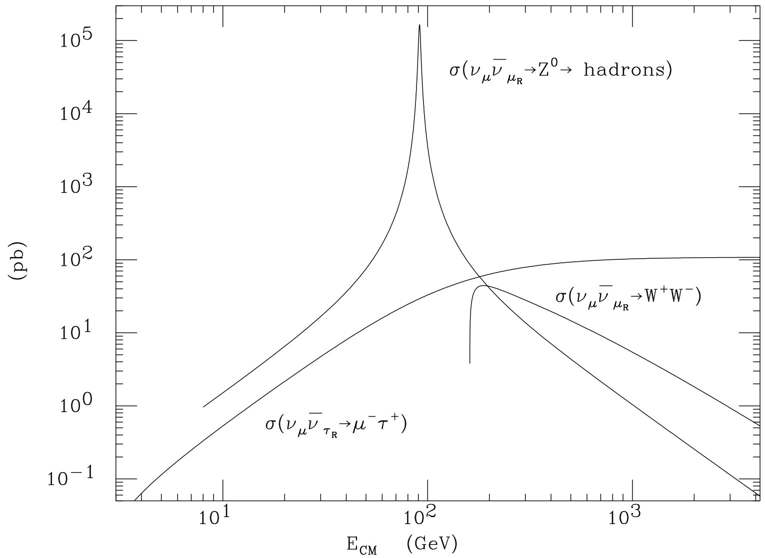

[Fodor,Katz,AR '02]

- Large cross-section at **resonant energies**

$$E_{\nu_i}^{\rm res} = M_Z^2/(2\,m_{\nu_i}) = 4\times 10^{22}\ {\rm eV}\,(0.1\ {\rm eV}/m_{\nu_i})$$

leading to a "short" mean free path

$$\ell_{\nu_i\,0} = \left(\langle n_{\nu_i}\rangle_0 \langle\sigma_{\rm ann}\rangle\right)^{-1} \simeq 10^5\ {\rm Mpc}$$



[Fargion,Mele,Salis '99]

- **$\nu_{\rm EHEC} + \bar\nu_{{\rm C}\nu{\rm B}}$ annihilation mechanism:**
  - unique process **sensitive to C$\nu$B**
  - opportunity to determine $m_{\nu_i}$

- Significant advances in **cosmology, neutrino physics, and EHECR and EHEC$\nu$ physics**

  ◇ $0.04\ \text{eV} \lesssim \sqrt{\Delta m^2_{\rm atm}} \lesssim m_{\nu_3} \lesssim 0.6\ \text{eV} \Rightarrow$

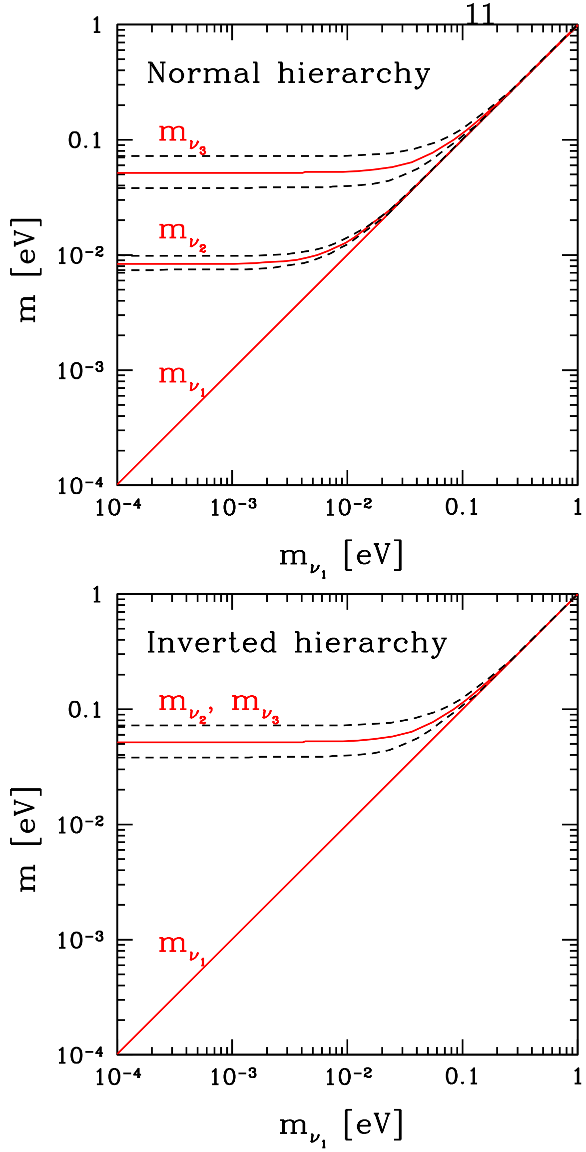
  $$10^{22}\ \text{eV} \lesssim E^{\rm res}_{\nu_3} \lesssim 10^{23}\ \text{eV}$$

  ◇ Remote possibility to associate related **emission features (Z-bursts)** ($p$'s or $\gamma$'s from hadronic Z-decay) with the mysterious EHECR events above $\boldsymbol{E_{\rm GZK} = 4 \times 10^{19}}$ **eV**

  [Fargion,Mele,Salis '99; Weiler '99]

  Requires very large flux, but neutrino mass window for this scenario coincides with present knowledge [Fodor,Katz,AR '01;'02; Gelmini *et al.* '04]

$\Rightarrow$ Prospects of **C$\nu$B absorption spectroscopy** in the upcoming decade? [Eberle,AR,Song,Weiler '04]




[Beacom,Bell; Giunti,Laveder]

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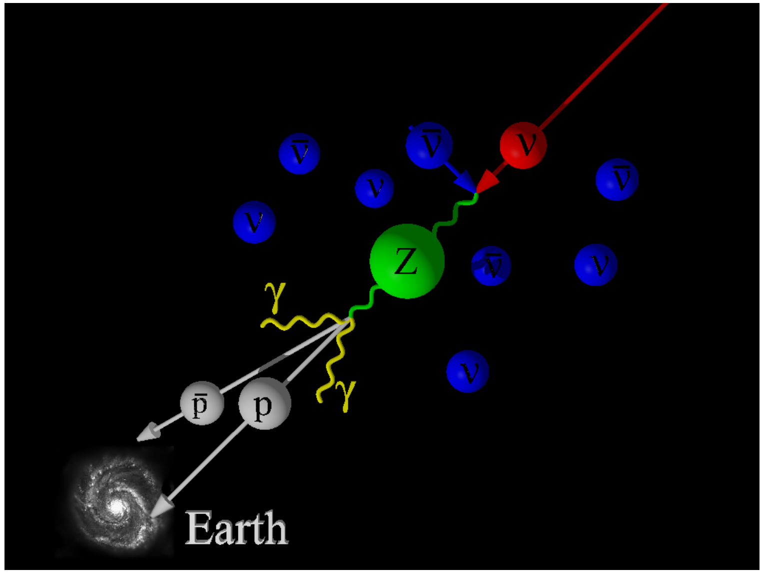
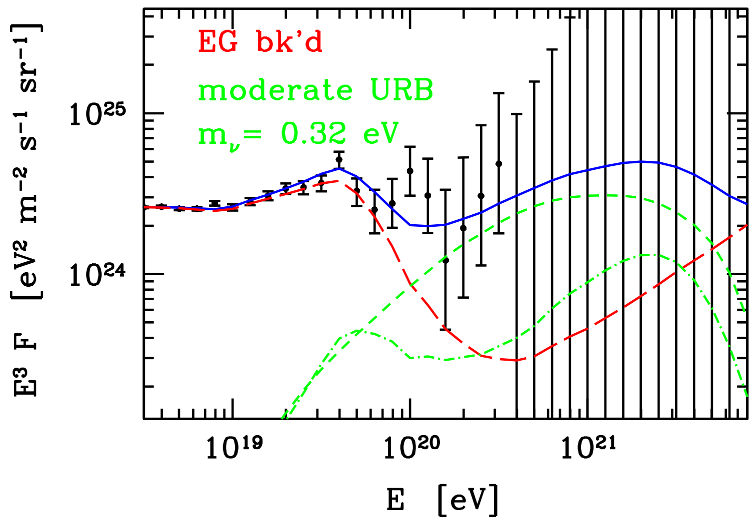



[Fodor,Katz,AR '01,'02]



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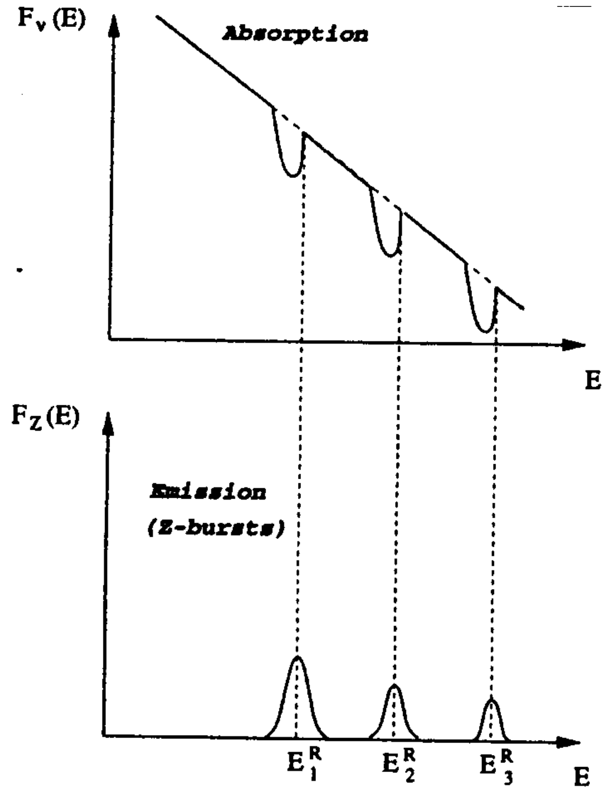



[Weiler '01]

- **Neutrino flux** of flavor $\alpha = e, \mu, \tau$ **at Earth**:

$$F_{\nu_\alpha}(E) \simeq \frac{1}{4\pi} \int_0^\infty \frac{\mathrm{d}z}{H(z)} \times$$

$$\times \sum_{\beta,s} \underbrace{P_{\alpha\beta}(E\,(1+z), z)}_{\text{survival probability}} \; \underbrace{\eta^{(s)}(z)}_{\text{src. activity}} \; \underbrace{J^{(s)}_{\nu_\beta}(E\,(1+z))}_{\text{src. inj. spectr.}}$$

- For **sources**, **case studies** based on:

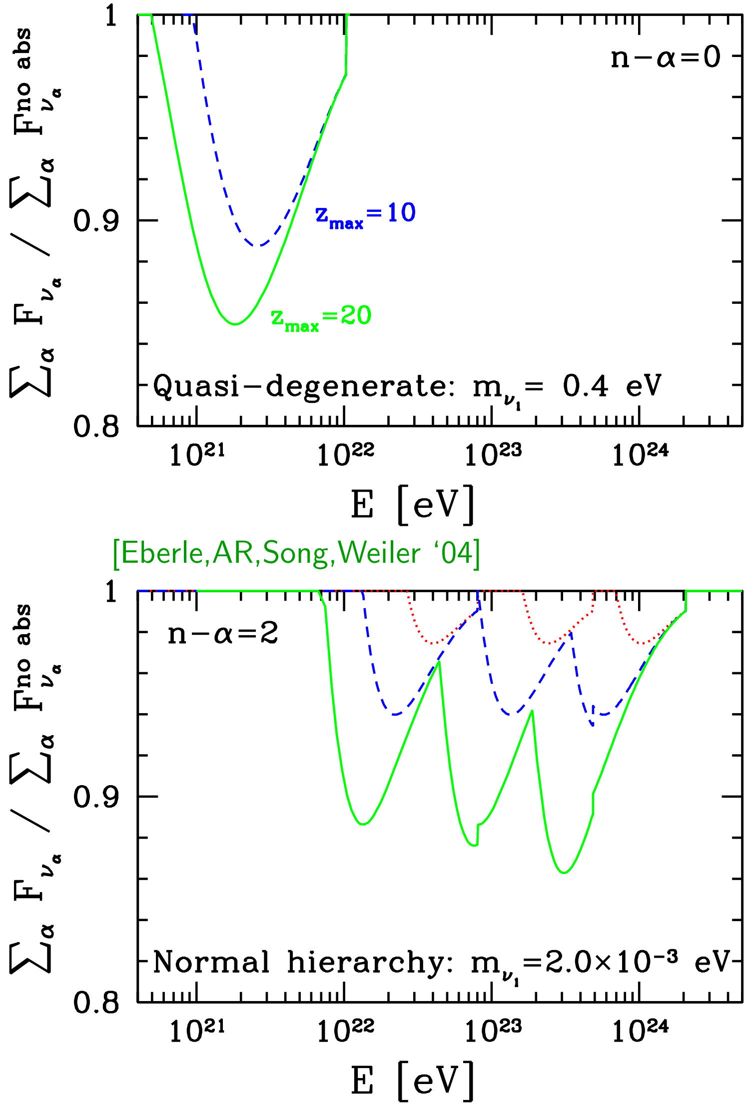
$$\eta^{(s)}(z) = \eta_0^{(s)}\,(1+z)^{n^{(s)}}\,\theta(z^{(s)}_{\max} - z)$$

$$J^{(s)}_{\nu_\beta}(E) = j^{(s)}_{\nu_\beta}\,E^{-\alpha^{(s)}}\,\theta(E^{(s)}_{\max} - E)$$

accel.: $n \gtrsim 3, z_{\max} \lesssim 10, \alpha \gtrsim 2, E_{\max} \simeq 0.05\,E_{p\ \max}$

top. def.: $n \simeq 1.5, z_{\max} \gg 10, \alpha \simeq 1.5, E_{\max} \simeq 0.1\,M_X$

$\Rightarrow$ **Absorption dips** with a depth $(10 \div 20)\,\%$ at $(0.1 \div 0.5)\,E^{\text{res}}_{\nu_i} \gtrsim 10^{21}$ **eV**




[Eberle,AR,Song,Weiler '04]

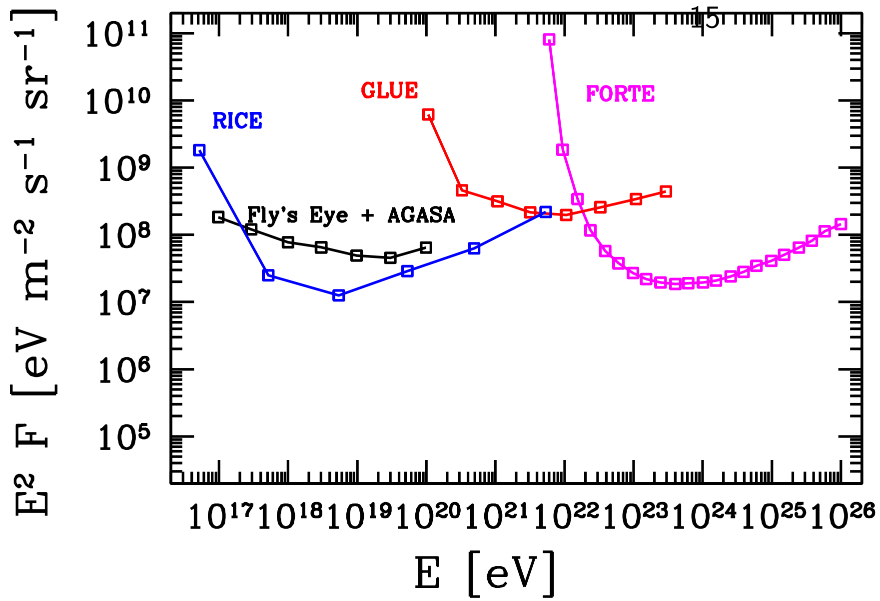
- Existing **EHEC$\nu$ observatories** have recently put sensible upper limits on flux in relevant energy range

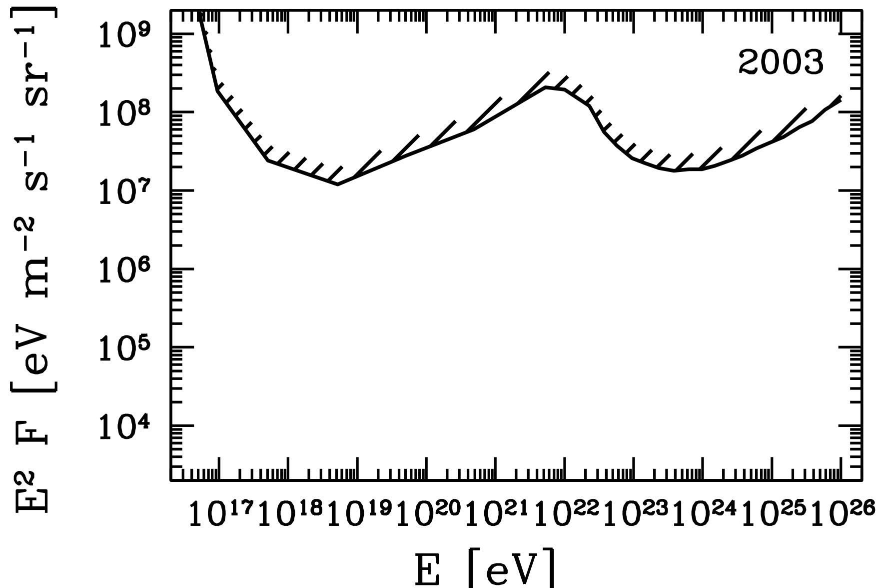
- **New generation** of large EHEC$\nu$ detectors may provide event sample above $10^{21}$ eV within this decade

$\Rightarrow$ Is there any hope of detection of absorption dips in the next decade or beyond?

$\Rightarrow$ Study benchmark flux scenarios

[Eberle,AR,Song,Weiler '04]



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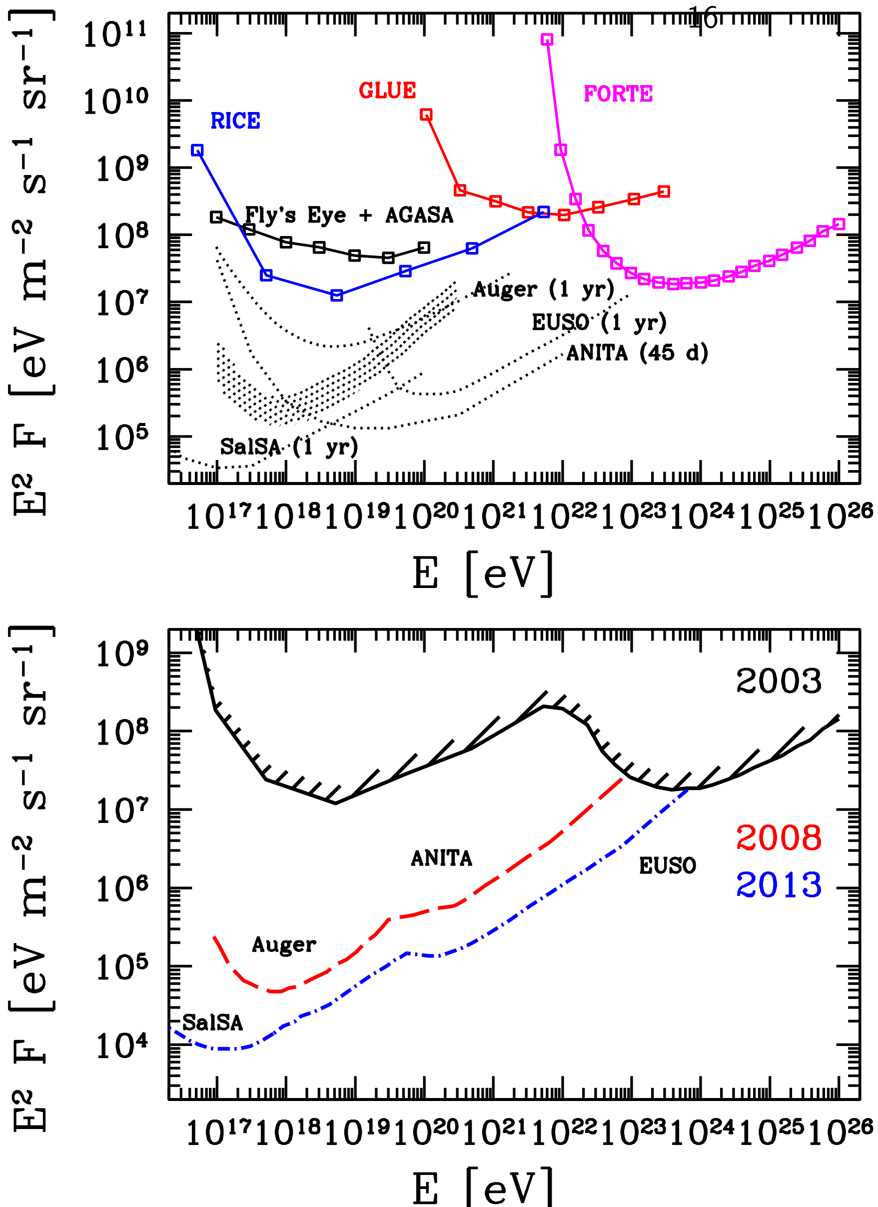


- **Most optimistic scenario:** flux saturates **observational limit**

⇒ Secondary fluxes of $p$'s (and $\gamma$'s) from Z-decay of right order of magnitude to explain cosmic rays above GZK energy by Z-bursts

- For 3-$\sigma$ evidence (5-$\sigma$ discovery) of dip, in $10^{21\div22}$ eV interval in year 2013, need depth of $11\,\%$ ($19\,\%$)

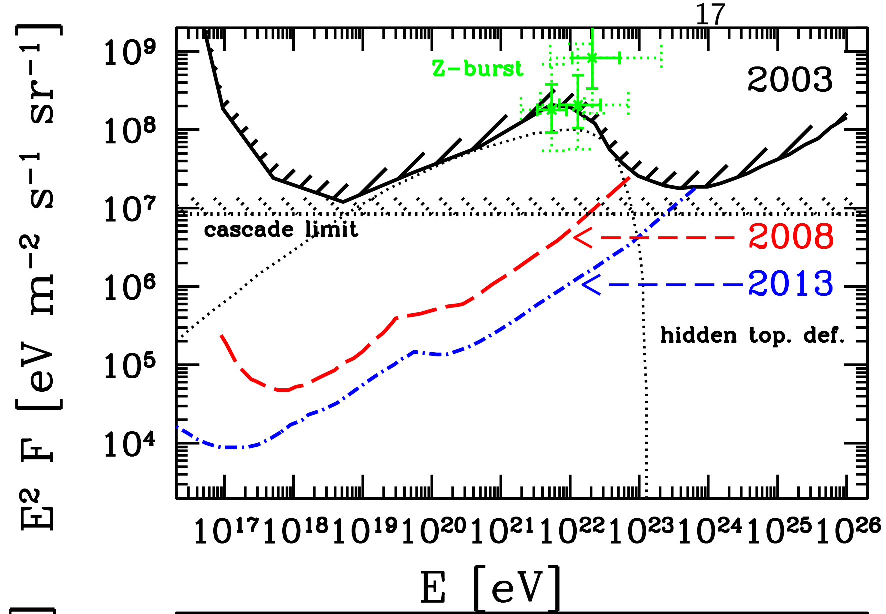
⇒ Easily achievable, if neutrinos quasi-degenerate ($m_{\nu_1} \gtrsim 0.1$ eV)

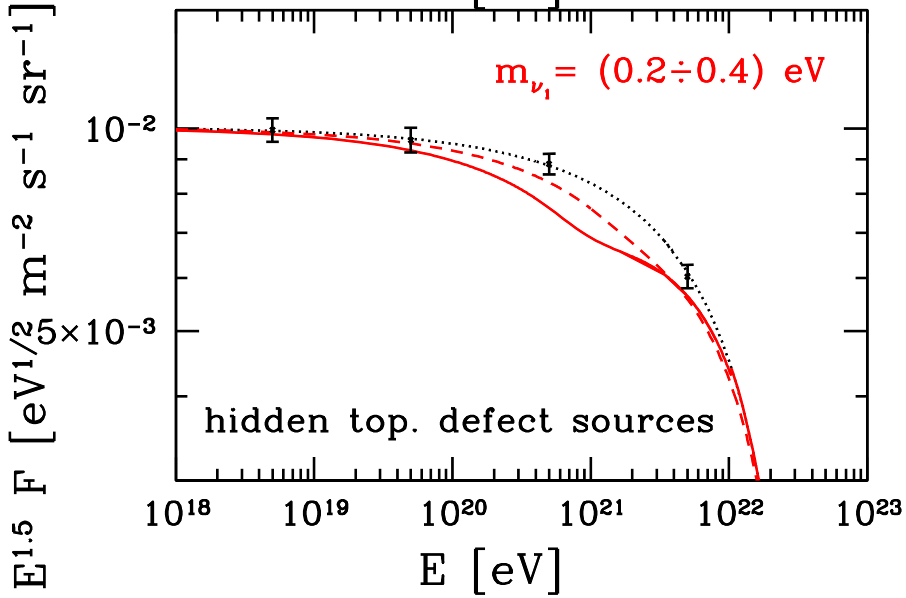
- Source scenario? Has to avoid cascade limit ($\Leftarrow$ EGRET)

  - Topological defects ($M_X \gtrsim 10^{14}$ GeV) which couple only to hidden sector

    [Berezinsky,Vilenkin '00]

  - Hidden accelerators, i.e. opaque to $p$'s and $\gamma$'s, with $E_{p\ \max} \gtrsim 10^{23}$ eV

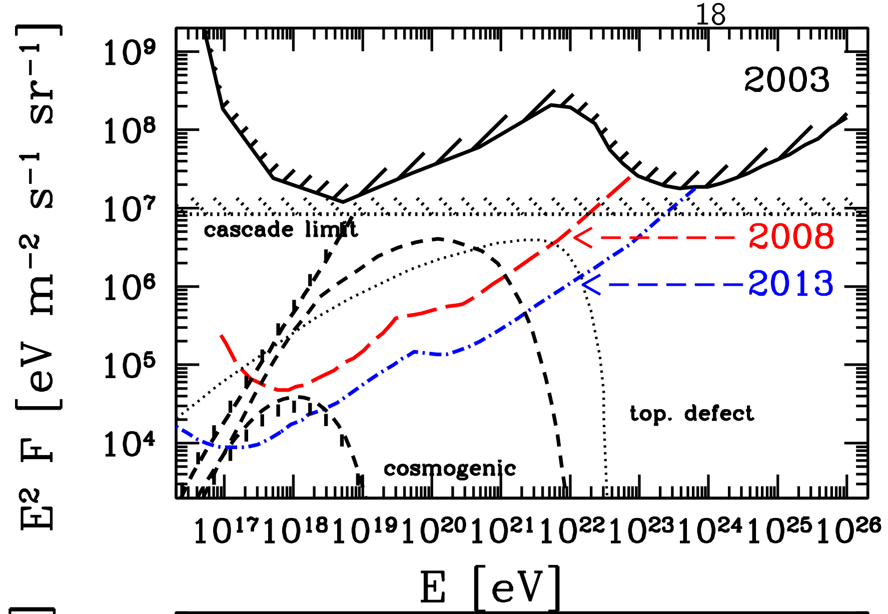


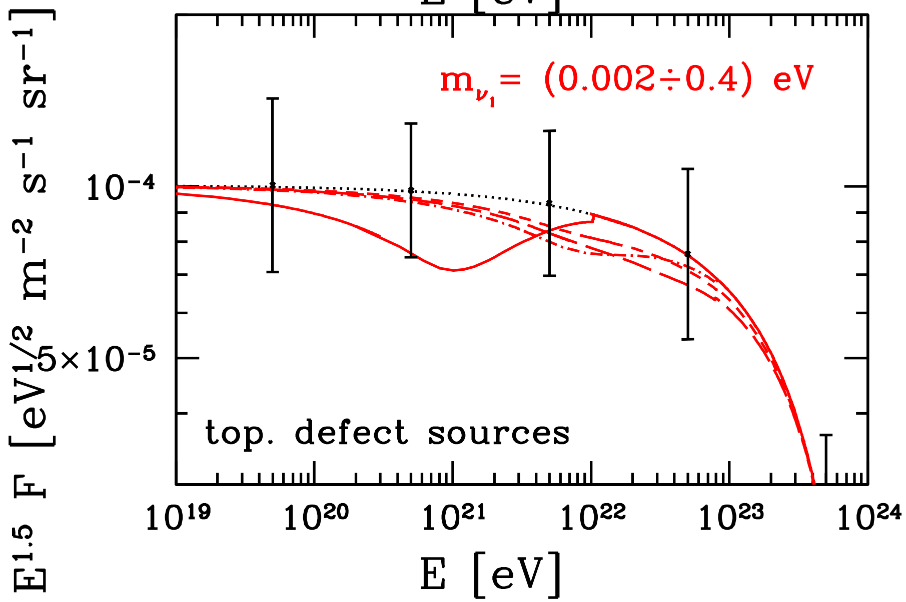



- **Less optimistic scenario:** flux saturates **cascade limit**
- For a 3-sigma evidence of an absorption dip, in $10^{21\div22}$ eV interval in year 2013, need depth of $48\,\%$

$\Rightarrow$ Dips in this category possible for extreme activities of the sources and a quasi-degenerate ($m_{\nu_1} \gtrsim 0.1$ eV) neutrino spectrum

- Increase in statistics by factor 10 reduces required depth to $15\,\%$ ($25\,\%$) for 3-$\sigma$ evidence (5-$\sigma$ discovery)
- Source scenario?
  - Neutrinos from $p\gamma_{\rm CMB}$ pion production
  - Accelerators with $E_{p\ \rm max} \gtrsim 10^{23}$ eV
  - Topological defects ($M_X \gtrsim 10^{14}$ GeV)



# 2. Production and detection of axions after HERA (LHC)

- **Axion:** [Peccei, Quinn (1977); S. Weinberg (1978); Wilczek (1978)]
  - Hypothetical, very light, weakly coupled (pseudo-)scalar particle, $A^0$: "pseudo Nambu-Goldstone boson"
  - Natural solution of **strong $CP$ problem**:
    Why is the effective $\theta$-parameter in the QCD Lagrangean

$$\mathcal{L}_\theta = \theta_{\rm eff} \frac{\alpha_s}{8\pi} F^{\mu\nu a} \tilde{F}_{\mu\nu a}$$

    so small, $\theta_{\rm eff} \lesssim 10^{-9}$ ($\Leftarrow$ electric dipol moment of neutron)?
  - **Peccei-Quinn scale $f_A$** determines mass,

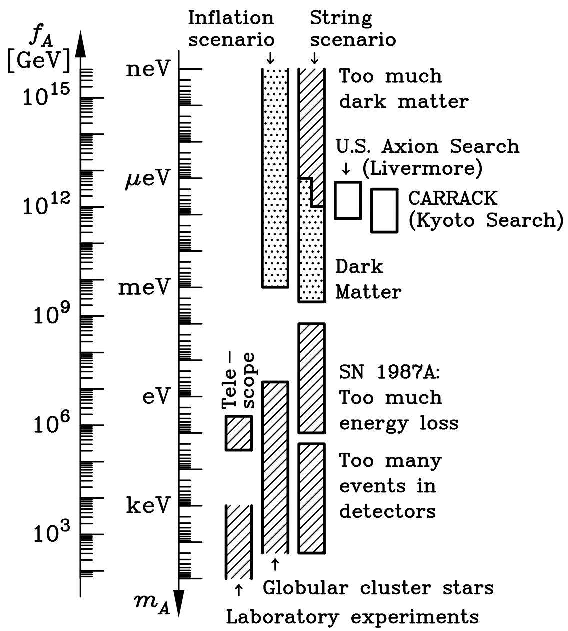
$$m_A = 0.62 \cdot 10^{-3}\ {\rm eV}\ \times \left( \frac{10^{10}\ {\rm GeV}}{f_A} \right)$$

– Interactions with Standard Model particles **model dependent**, e. g. axion-photon coupling,

$$\mathcal{L}_{\rm WW} = -g_{A\gamma}\, A\, \mathbf{E}\cdot\mathbf{B}\,; \qquad g_{A\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - 1.92\right)$$

- **Candidate for dark matter ($f_A \gtrsim 10^{10}$ GeV)**

- **Astrophysical constraints** [Raffelt . . . ]
  - Axions are generated in hot plasmas and lead there to energy losses
  - Observed limits of star evolution scales ⇒ constraints on interaction strengths with photons, electrons, nucleons ⇒ constraints on $g_{A\gamma}$ (⇒ $f_A$ and $m_A$)




[PDG (2002)]

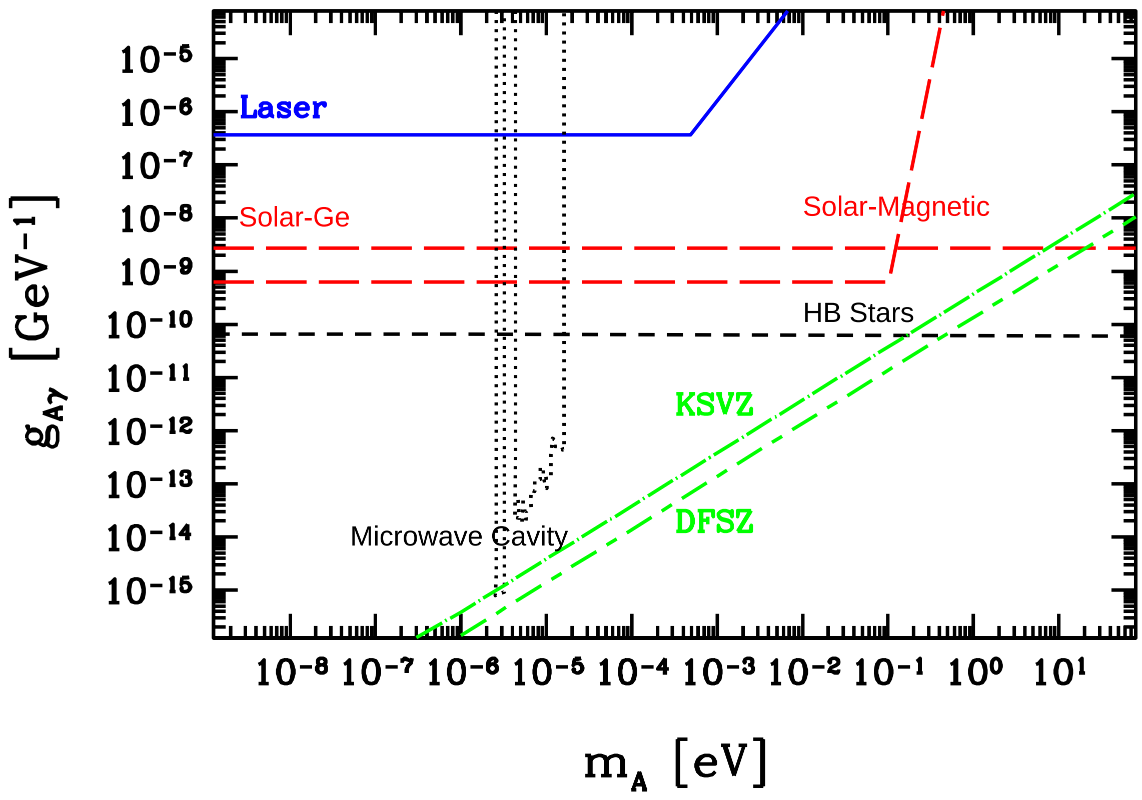
- **Experimental limits:**

Strongest bounds:
Production in **early universe** or in **astrophysical sources**;
detection in laboratory:

- Search for **dark matter**
  - Microwave-cavity-experiments
- Search for **solar axions**
  - Solar-magnetic
    (**CAST**: Improvement by one order in 2004)
  - Solar-Germanium

Much looser:
**Pure laboratory experiments**
(detection **and** production in laboratory):

- **Laser experiments**




[PDG (2002); AR '03]

# Photon regeneration

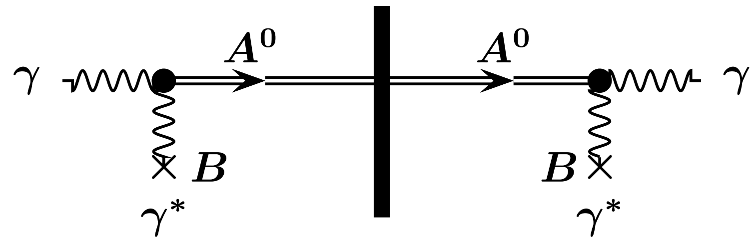
- **Production:** Polarised laser beam in superconducting dipole magnet, such that $\mathbf{E} \,||\, \mathbf{B} \Rightarrow$ conversion $\gamma \longrightarrow A$
- Absorb laser beam in wall
- **Detection:** Detect photons behind the wall from back conversion ($A \longrightarrow \gamma$) in second magnetic field

$$\textbf{Rate} \propto \underbrace{\frac{1}{16}\left(g_{A\gamma}\, B\, \ell\right)^4}_{P^2_{\gamma\leftrightarrow A}} \frac{\langle P \rangle}{\omega}\, \epsilon$$

Coherence condition (in vacuum)

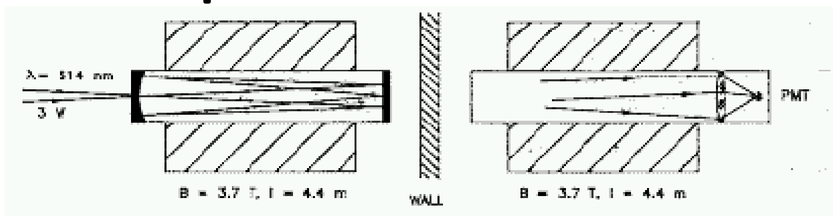
$$m_A \ll 1.1 \cdot 10^{-4}\ \mathrm{eV} \left( \frac{\hbar\omega}{1\ \mathrm{eV}} \frac{1\ \mathrm{m}}{\ell} \right)^{1/2}$$

"Light shining through a wall"




[Ansel'm (1985); Van Bibber *et al.* (1987)]

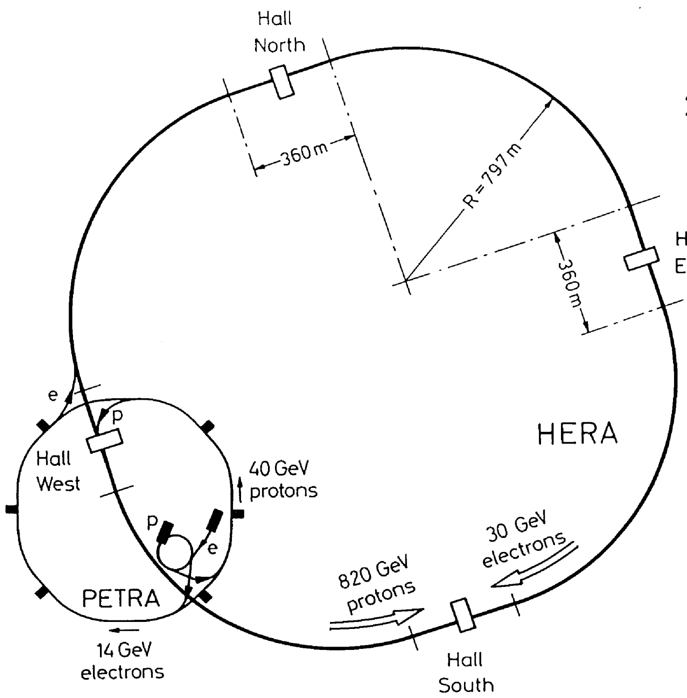
## Pilot experiment:




[Cameron *et al.* (1993)]

$B = 3.7\ \mathrm{T}, \ell = 4.4\ \mathrm{m}, \langle P \rangle = 3\ \mathrm{W}, \lambda = 514\ \mathrm{nm}$

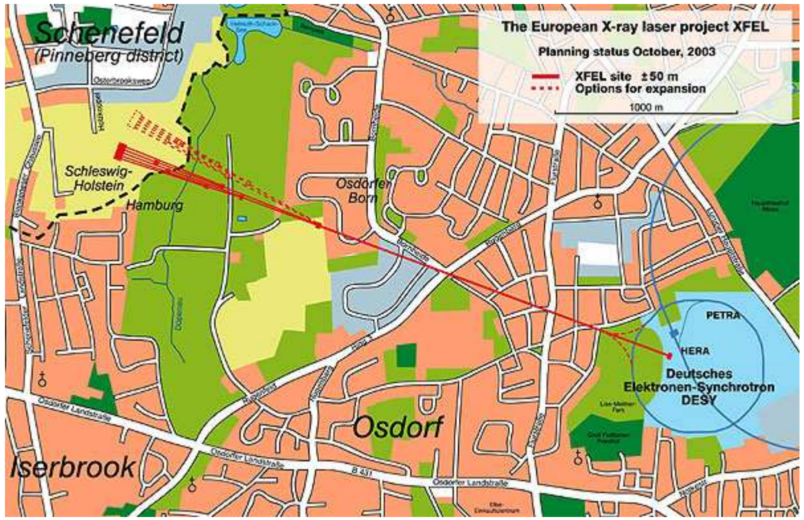
$\Rightarrow g_{A\gamma} < 6.7 \cdot 10^{-7}\ \mathrm{GeV}^{-1}$ for $m_A < 10^{-3}\ \mathrm{eV}$




- Unique opportunity for searches for light scalar or pseudoscalar particles:
  - End of 2006, **HERA** will be **decommissioned**.

  $\Rightarrow$ Its $\approx 400$ superconducting **dipole magnets**, each of which achieving $B = 5$ T and having $\ell = 10$ m, can be **recycled** and

  $\Rightarrow$ used for a **photon regeneration experiment**. [AR '03]



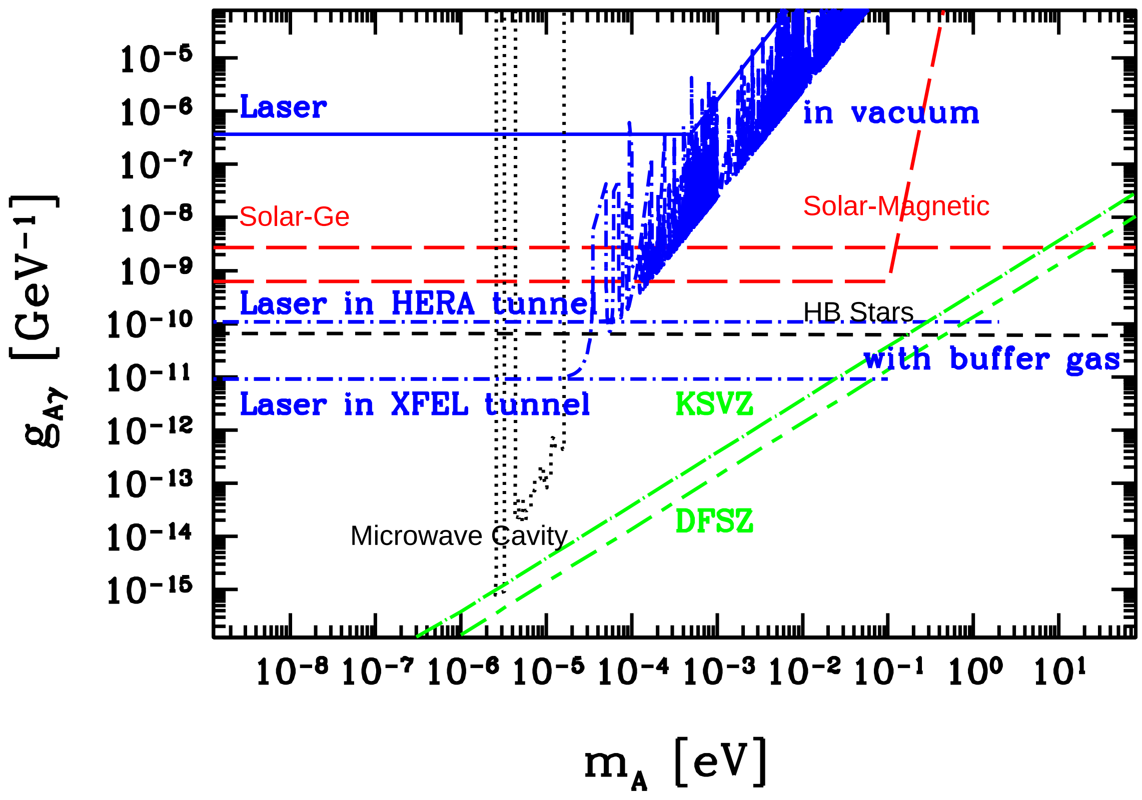
- Projected sensitivities of photon regeneration exploiting **decommissioned HERA magnets**
  - **in HERA tunnel:**

    $B = 5\ \mathrm{T}, \ell = (17 + 17) \times 10\ \mathrm{m}$
  - **in XFEL tunnel:**

    $B = 5\ \mathrm{T}, \ell = (200 + 200) \times 10\ \mathrm{m}$
- May extend sensitivity to larger masses by filling in buffer gas

$\Rightarrow$ Competitive with astrophysical limits and **CAST** sensitivity

- Exploiting **LHC** magnets: improvement by factor ten $\Rightarrow$ probes **axion** $\sim$ **dominant CDM**




[AR '03]

# 3. Conclusions

- Opportunities for dark matter candidates:
  - **C$\nu$B absorption spectroscopy:**
    - Detection of dips within next decade needs huge $\nu$ flux and $m_{\nu_1} \gtrsim 0.1$ eV
    - If pre-2008 observatories do not see any $\nu$ flux in $10^{21 \div 23}$ eV region $\Rightarrow$ absorption dips won't be observed within next $10 \div 20$ y!
  - **Axion production and detection with lasers:**
    - Recycling of HERA magnets allows to improve current pure laboratory limits on $g_{A\gamma}$ by $3 \div 4$ orders of magnitude within the upcoming decade $\Rightarrow$ competitive with pure/halfway astrophysical limits
    - Recycling of LHC magnets will probe parameter range in $(g_{A\gamma}, m_A)$ in which axion $\sim$ dominant CDM

$\Rightarrow$ **Not guaranteed, but exciting!**