

# Opportunities for Subdominant Dark Matter Candidates

**A. Ringwald**

<http://www.desy.de/~ringwald>



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

## 0. Introduction

- Progress in observational cosmology

⇒ 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 $< 0.6$ eV	$10^{87}$	$> 0.1\%$ $< 3\%$	
Cold Dark Matter	Wimps?	$\gtrsim 100$ GeV	$\lesssim 10^{77}$	25%	✓
	Axions?	$\lesssim$ meV	$\gtrsim 10^{91}$		
Dark Energy	?	$10^{-33}$ eV	?	70%	✓

⇒ How to detect the **Cosmic Neutrino Background (C $\nu$ B)**?

⇒ Do **wimps** (SUSY  $\leftarrow$  LHC) or **axions** exist?

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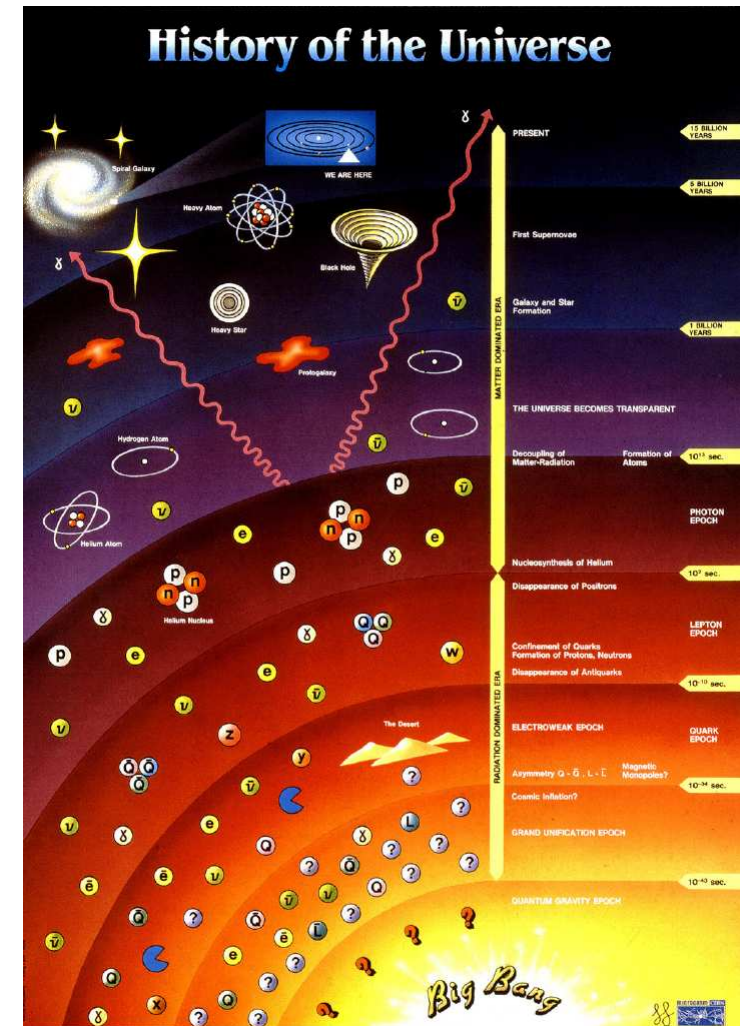
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[CERN]

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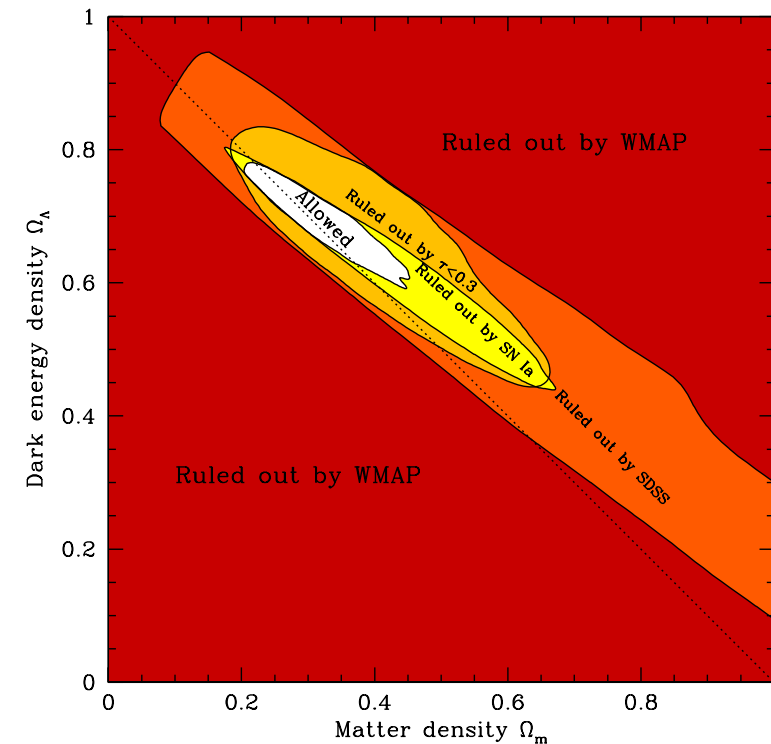
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[Tegmark et al. '04]

– Opportunities for subdominant dark matter candidates –

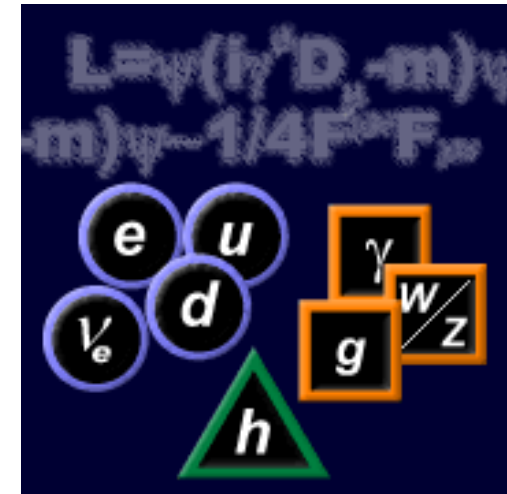
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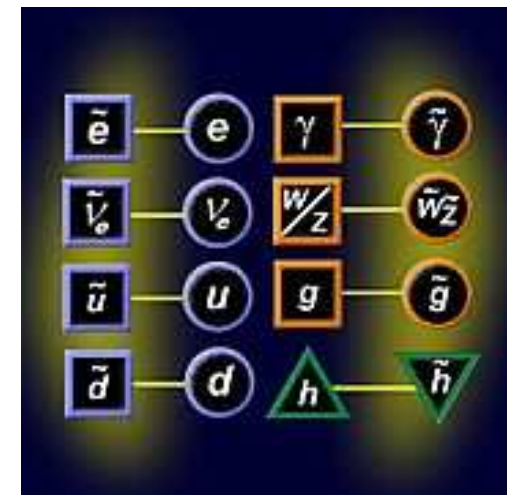
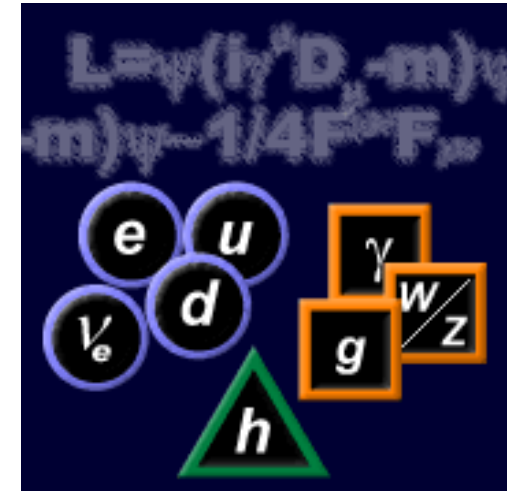
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- Discuss here:

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

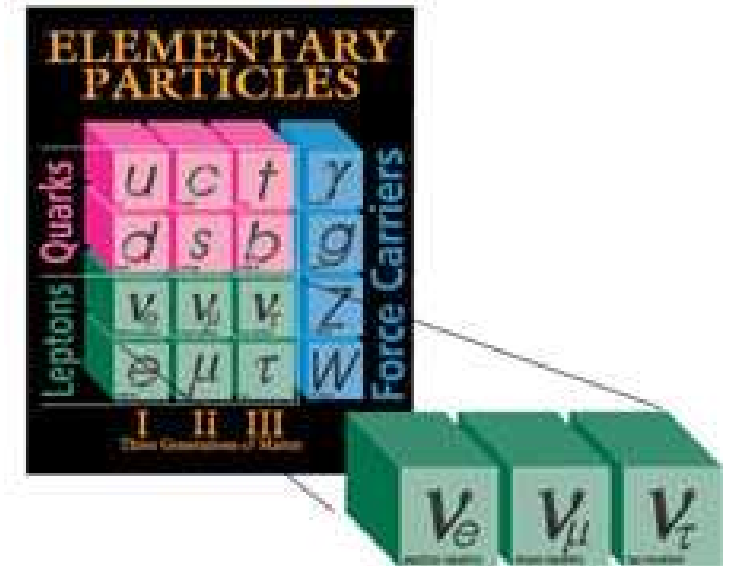
⇒ Direct detection of  $C\nu B$  (“neutrino wind”) within upcoming decade seems hopeless.

[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]



[Fermilab]

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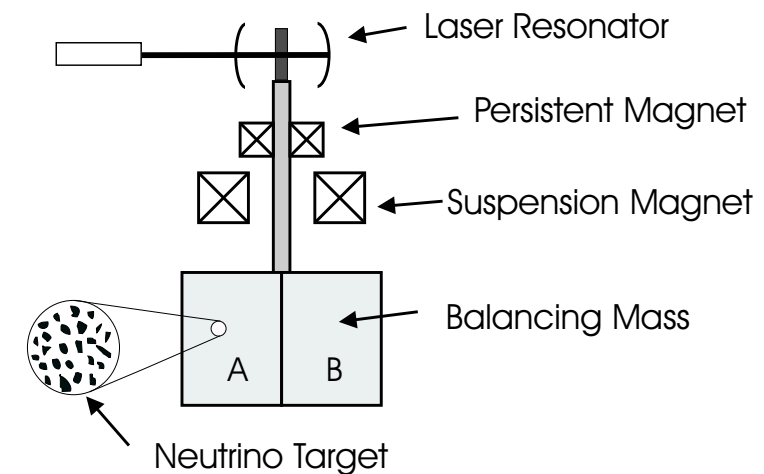
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[Hagmann '99]

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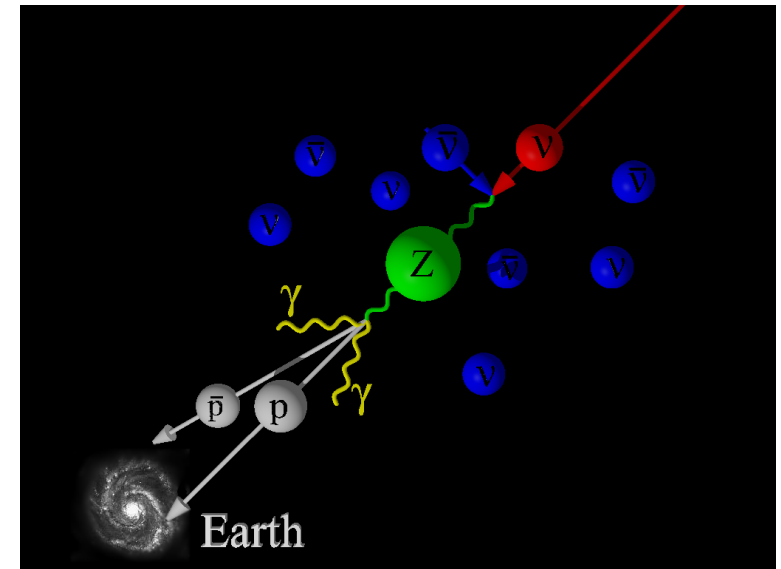
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[Fodor,Katz,AR '02]

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

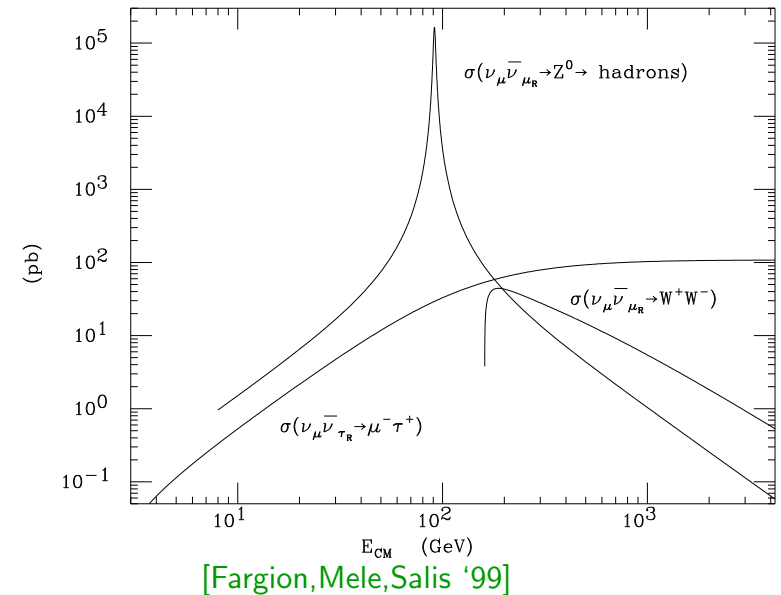
$$E_{\nu_i}^{\text{res}} = M_Z^2 / (2 m_{\nu_i}) = 4 \times 10^{22} \text{ eV} (0.1 \text{ eV} / m_{\nu_i})$$

leading to a “short” mean free path

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

- $\nu_{\text{EHEC}} + \bar{\nu}_{\text{C}\nu\text{B}}$  annihilation mechanism:

- unique process **sensitive to CνB**
- opportunity to determine  $m_{\nu_i}$



– Opportunities for subdominant dark matter candidates –

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

- ◇  $0.04 \text{ eV} \lesssim \sqrt{\Delta m_{\text{atm}}^2} \lesssim m_{\nu_3} \lesssim 0.6 \text{ eV} \Rightarrow$   
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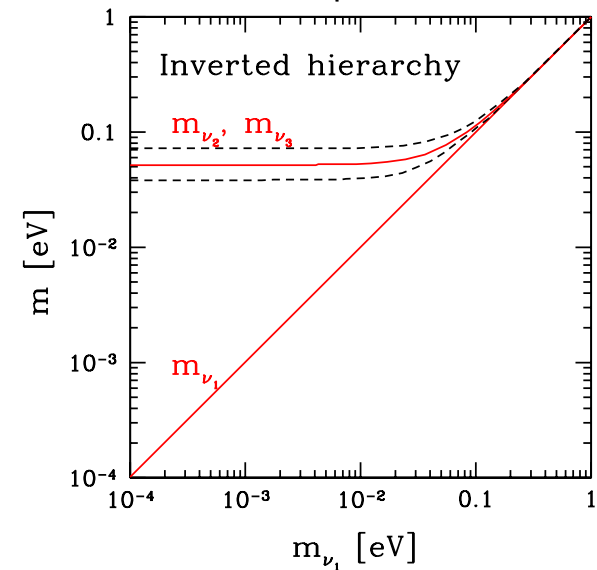
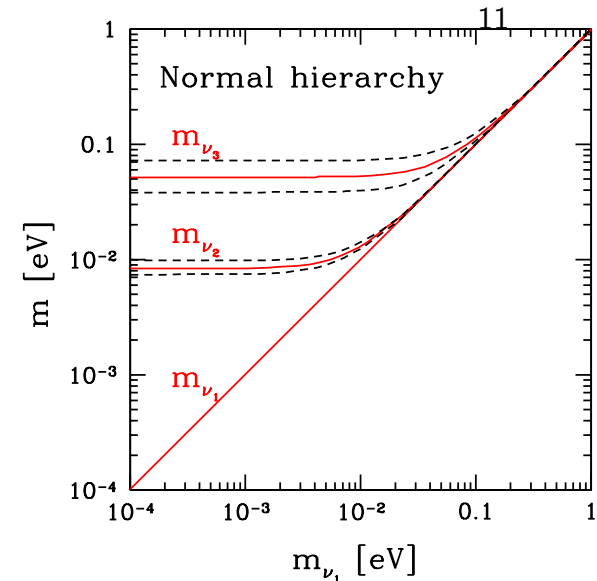
- ◇ Remote possibility to associate related **emission features (Z-bursts)** ( $p$ 's or  $\gamma$ 's from hadronic Z-decay) with the mysterious EHECR events above  $E_{\text{GZK}} = 4 \times 10^{19} \text{ eV}$

[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]

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[Beacom,Bell; Giunti,Laveder]

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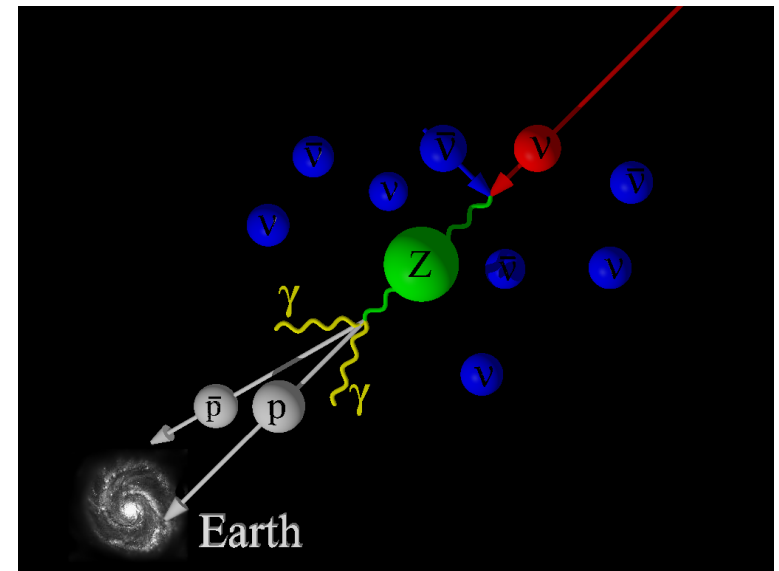
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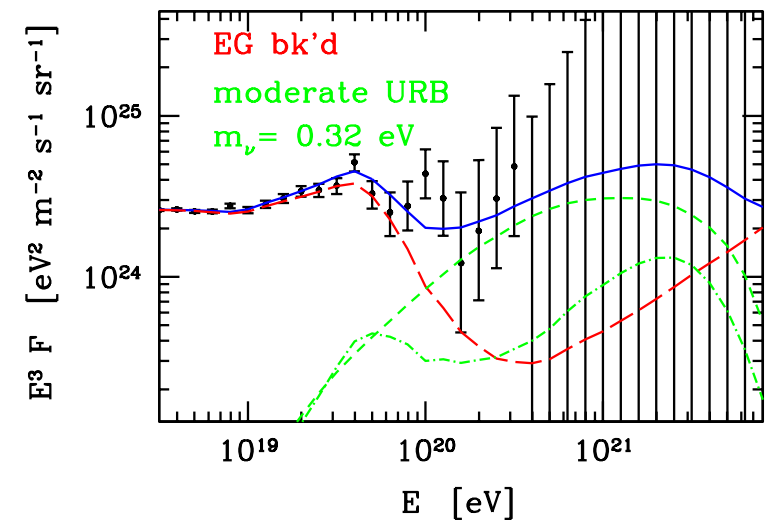
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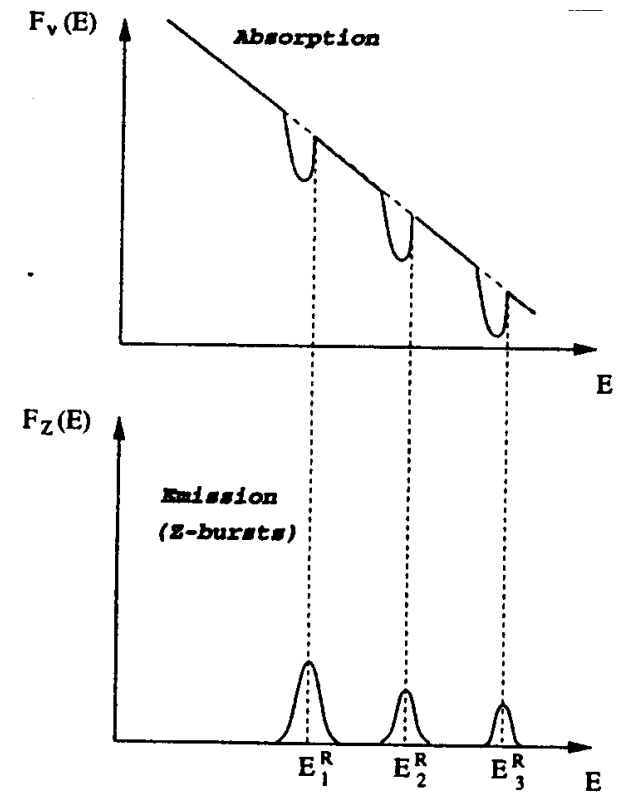
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[Weiler '01]

– Opportunities for subdominant dark matter candidates –

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

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

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

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

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

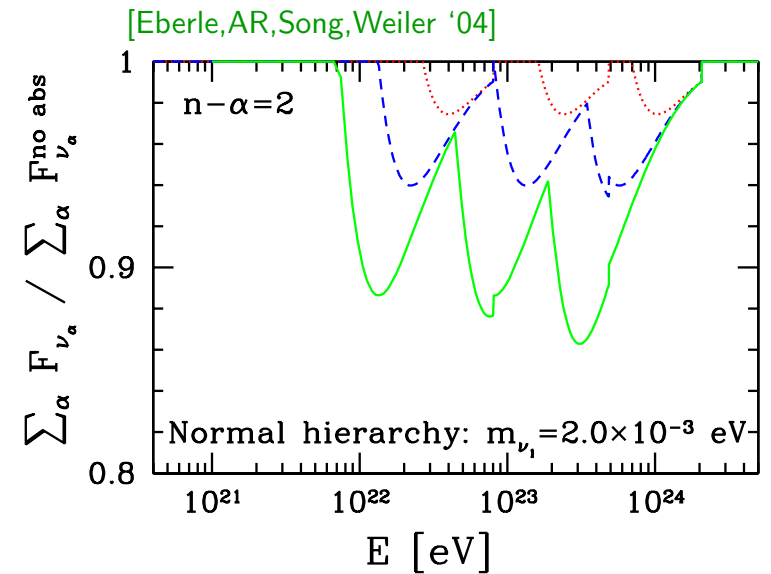
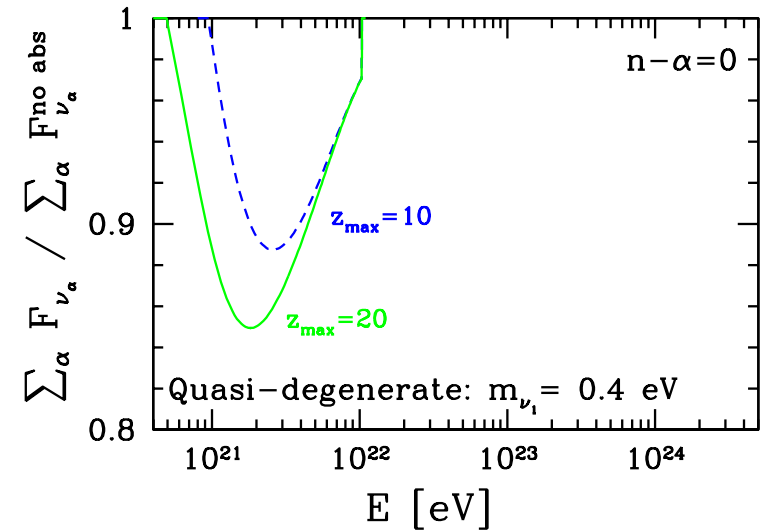
$$J_{\nu\beta}^{(s)}(E) = j_{\nu\beta}^{(s)} E^{-\alpha^{(s)}} \theta(E_{\max}^{(s)} - E)$$

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

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

⇒ **Absorption dips** with a depth **(10 ÷ 20) %**  
at **(0.1 ÷ 0.5)  $E_{\nu_i}^{\text{res}} \gtrsim 10^{21}$  eV**

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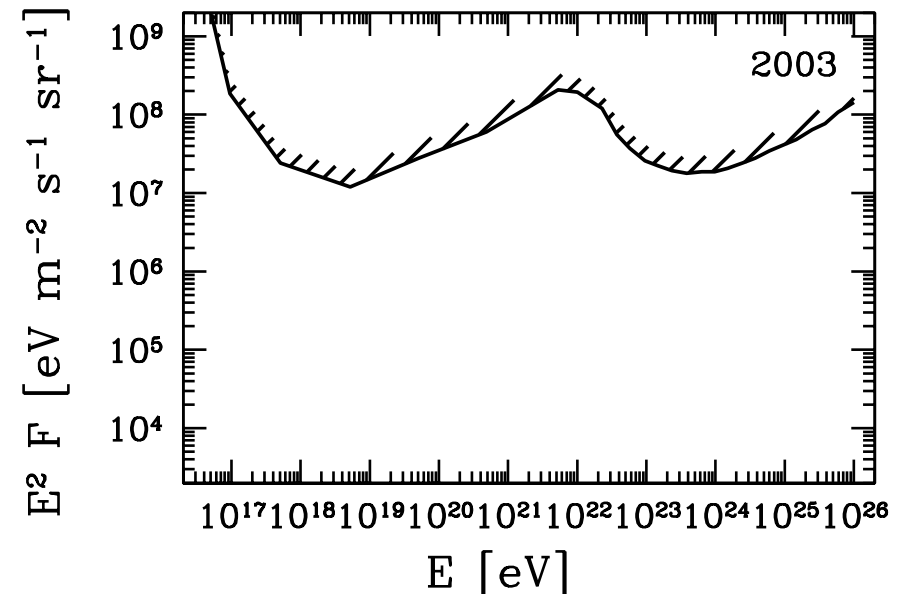
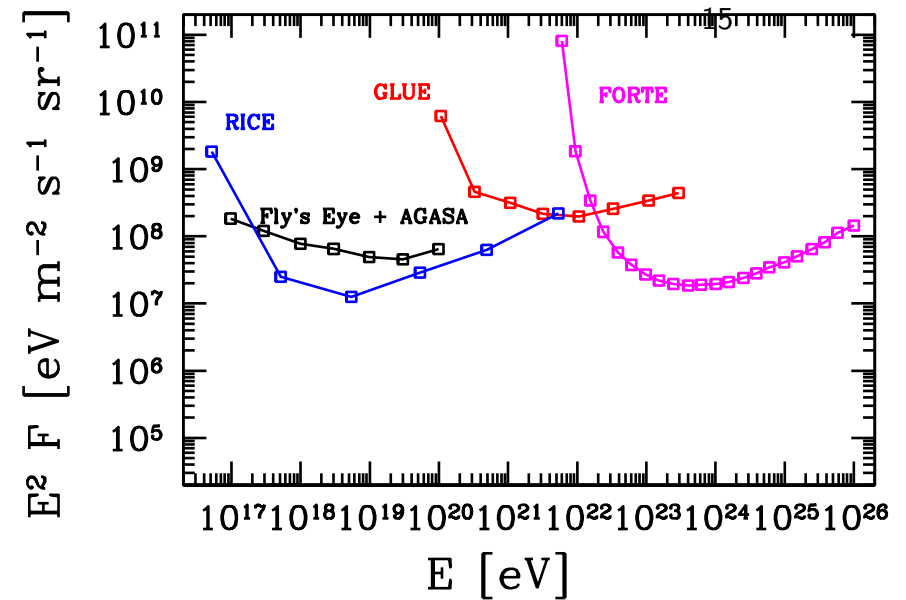
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- Existing **EHEC $\nu$  observatories** have recently put sensible upper limits on flux in relevant energy range
- **New generation** of large EHEC $\nu$  detectors may provide event sample above  $10^{21}$  eV within this decade

⇒ Is there any hope of detection of absorption dips in the next decade or beyond?

⇒ Study benchmark flux scenarios

[Eberle,AR,Song,Weiler '04]



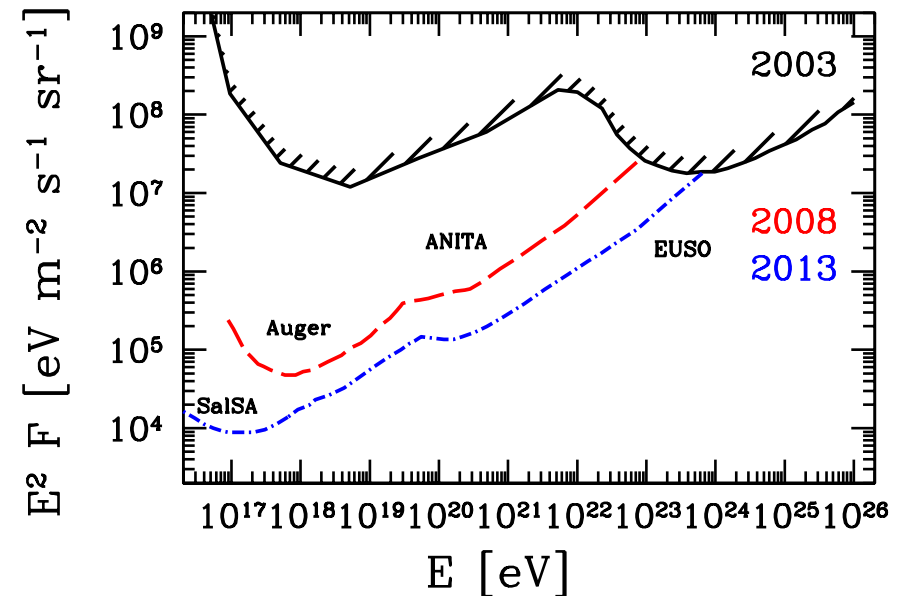
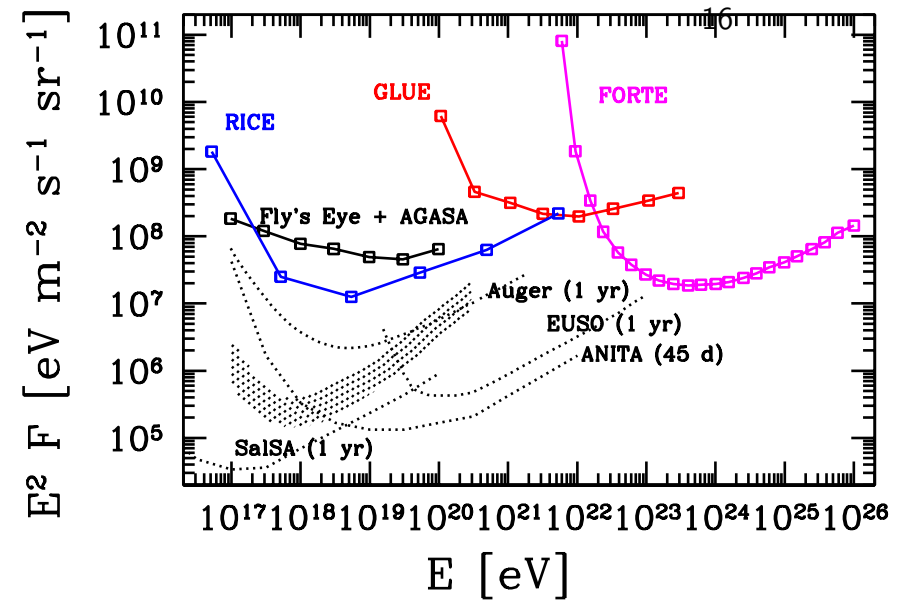
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– Opportunities for subdominant dark matter candidates –

- **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  $10^{21\div 22}$  eV interval in year 2013, need depth of **11 %** (**19 %**)

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

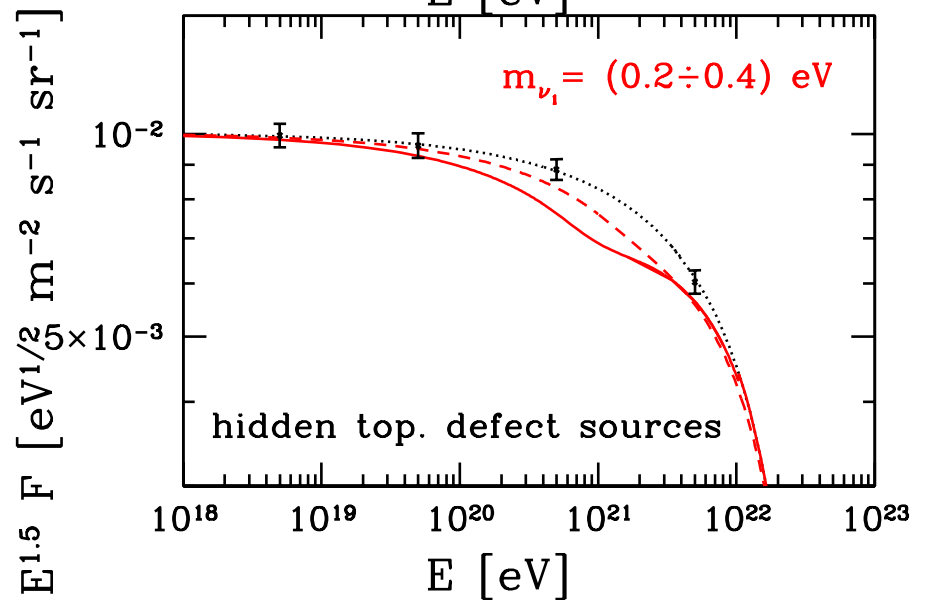
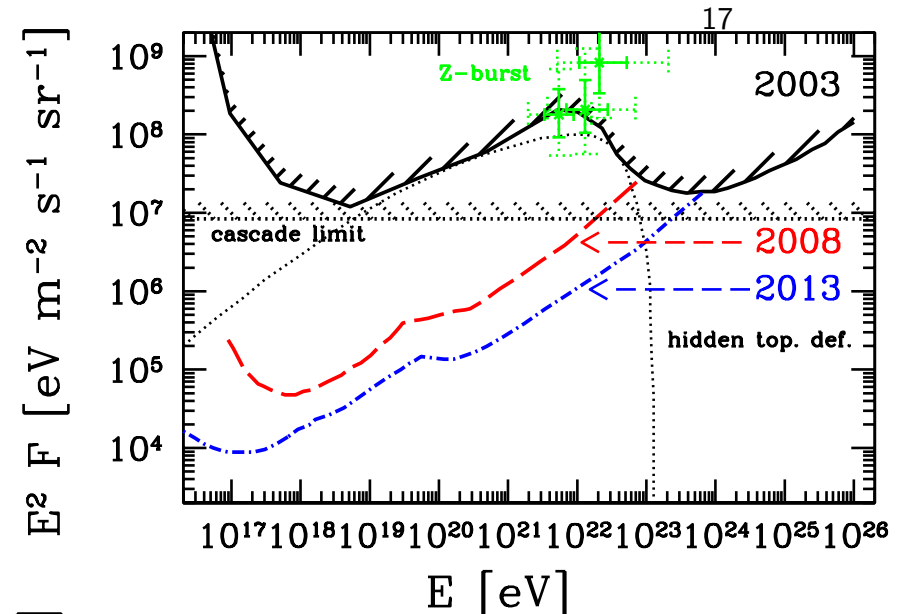
- Source scenario? Has to avoid cascade limit ( $\Leftarrow$  EGRET)

– 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  $E_{p \text{ max}} \gtrsim 10^{23}$  eV

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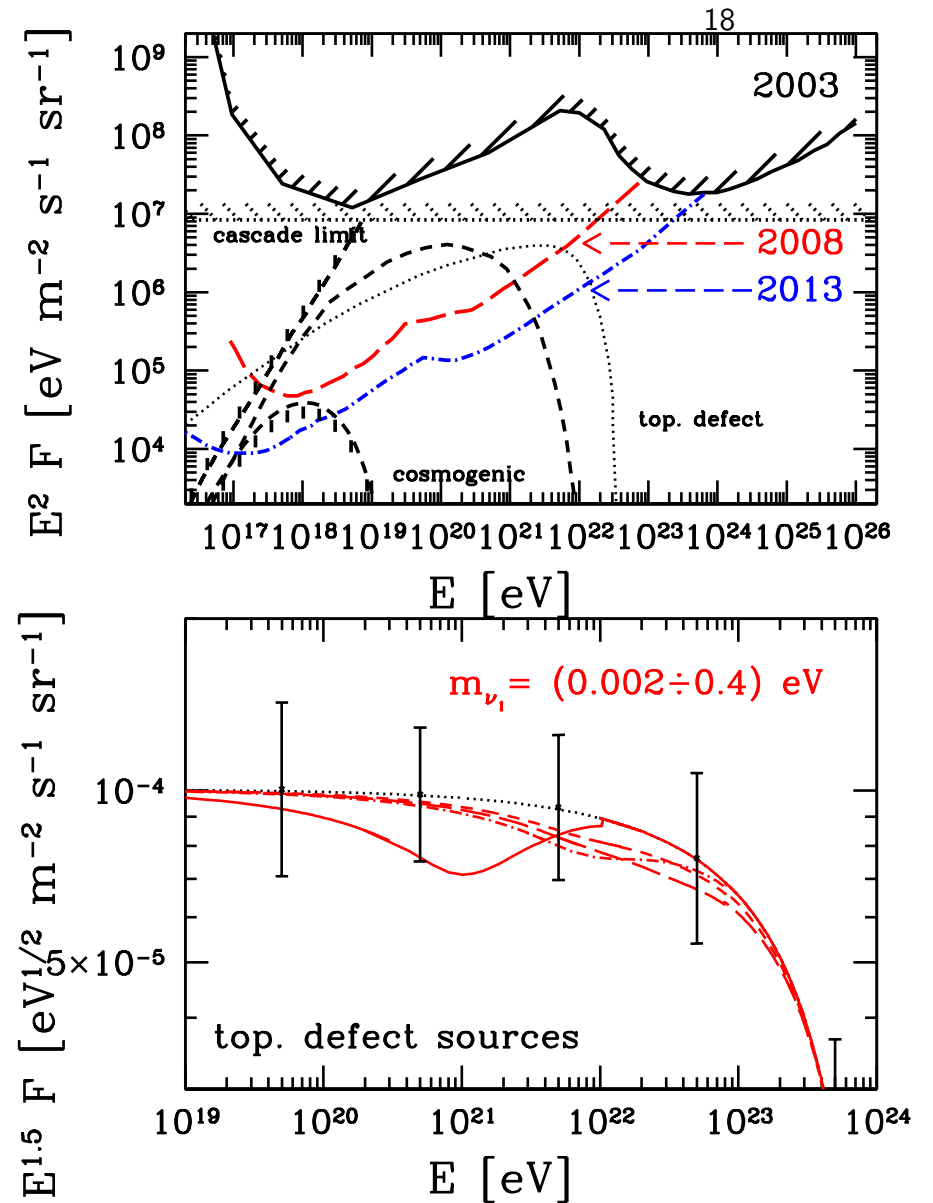


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– Opportunities for subdominant dark matter candidates –

- **Less optimistic scenario:** flux saturates **cascade limit**
  - For a 3-sigma **evidence** of an absorption dip, in  $10^{21\div 22}$  eV interval in year 2013, need depth of **48 %**
- ⇒ 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  $p\gamma_{\text{CMB}}$  pion production
    - Accelerators with  $E_{p \text{ max}} \gtrsim 10^{23}$  eV
    - Topological defects ( $M_X \gtrsim 10^{14}$  GeV)

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## 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

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

so small,  $\theta_{\text{eff}} \lesssim 10^{-9}$  ( $\Leftarrow$  electric dipol moment of neutron)?

- **Peccei-Quinn scale  $f_A$**  determines mass,

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

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

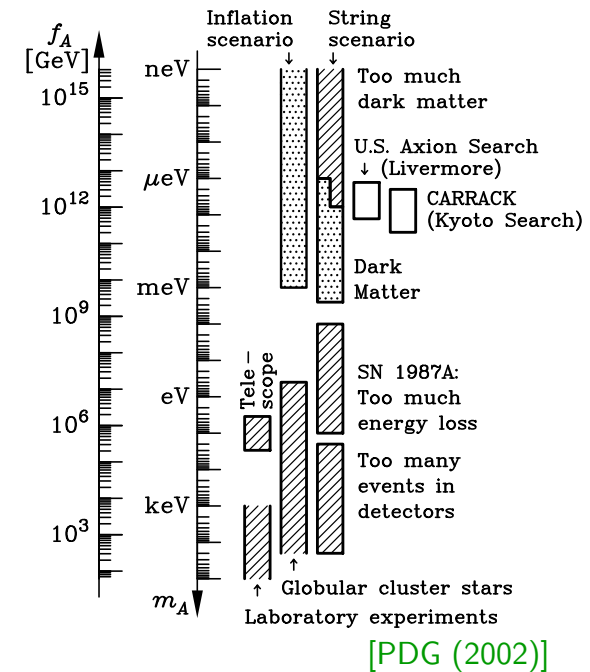
$$\mathcal{L}_{\text{WW}} = -g_{A\gamma} A \mathbf{E} \cdot \mathbf{B}; \quad g_{A\gamma} = \frac{\alpha}{2\pi f_A} \left( \frac{E}{N} - 1.92 \right)$$

- 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  $\Rightarrow$  constraints on interaction strengths with photons, electrons, nucleons  $\Rightarrow$  constraints on  $g_{A\gamma}$  ( $\Rightarrow f_A$  and  $m_A$ )



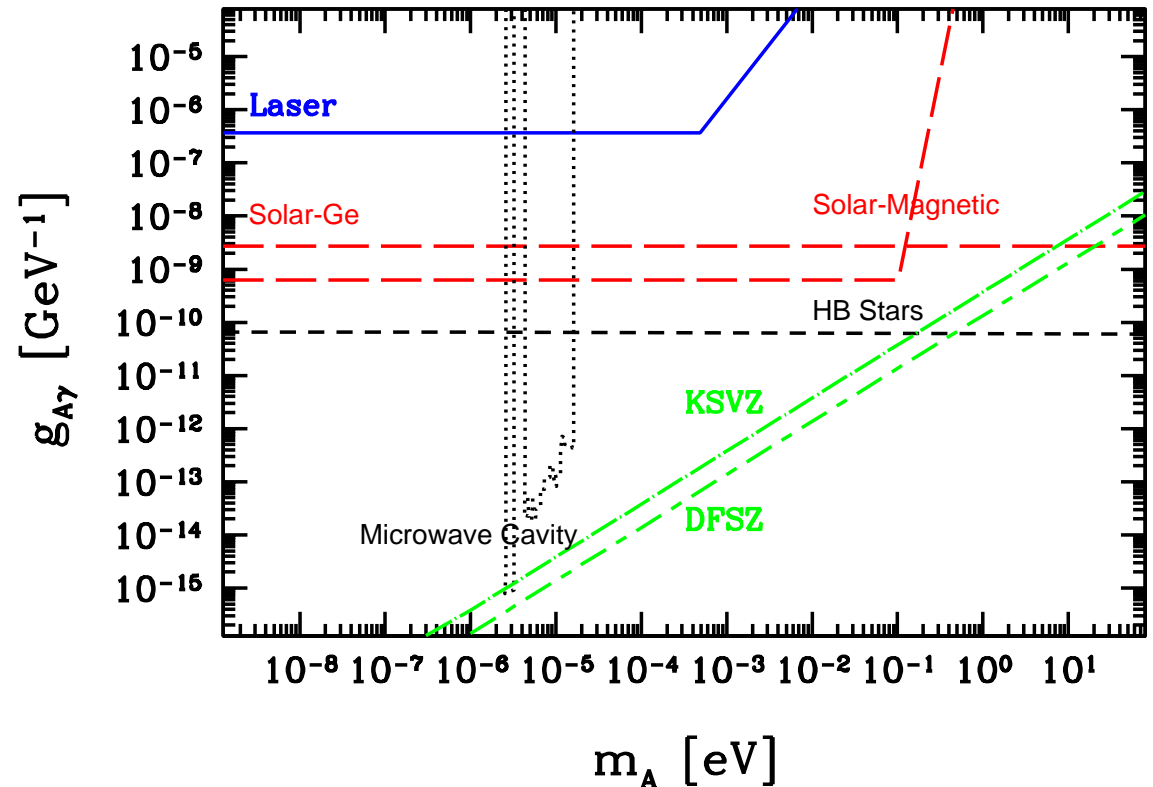
- **Experimental limits:**

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

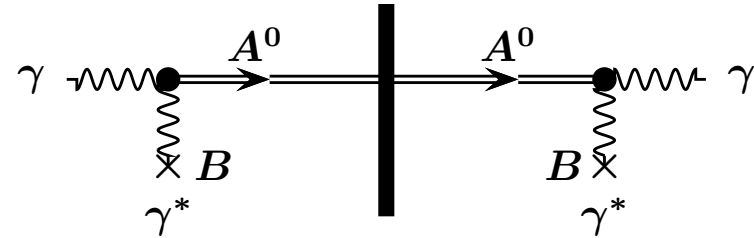
- **Production:** Polarised laser beam in superconducting dipole magnet, such that  $\mathbf{E} \parallel \mathbf{B} \Rightarrow$  conversion  $\gamma \rightarrow A$
- Absorb laser beam in wall
- **Detection:** Detect photons behind the wall from back conversion ( $A \rightarrow \gamma$ ) in second magnetic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

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

Coherence condition (in vacuum)

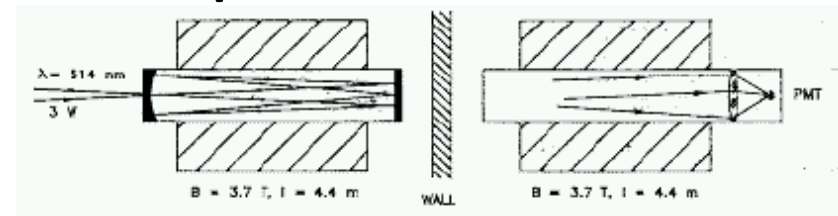
$$m_A \ll 1.1 \cdot 10^{-4} \text{ eV} \left( \frac{\hbar \omega}{1 \text{ eV}} \frac{1 \text{ m}}{\ell} \right)^{1/2}$$

“Light shining through a wall”



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

Pilot experiment:



[Cameron *et al.* (1993)]

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

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

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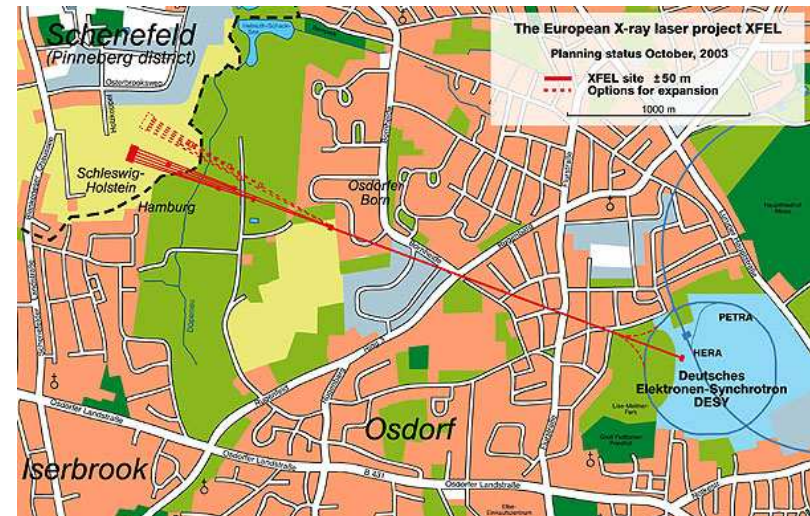
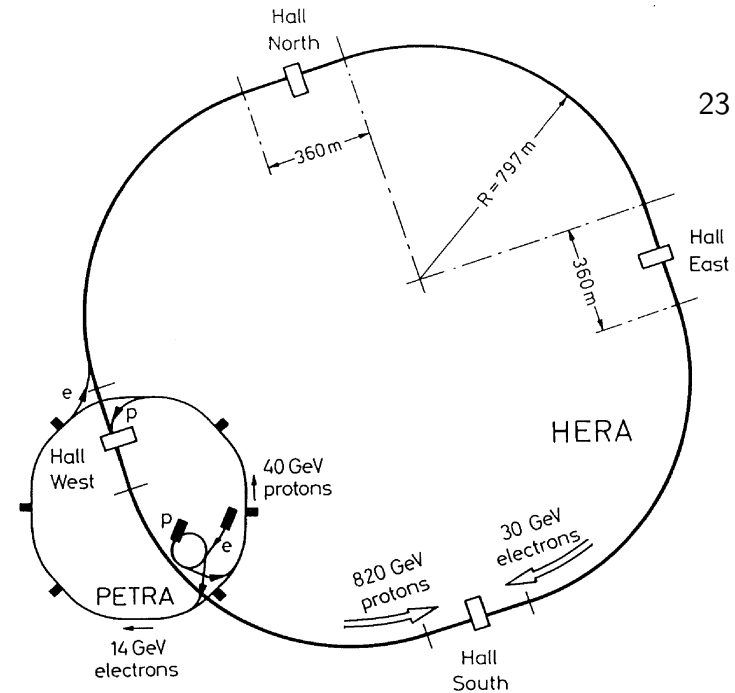
- Unique opportunity for searches for light scalar or pseudoscalar particles:

- End of 2006, **HERA** will be **de-commissioned**.

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

- ⇒ used for a **photon regeneration experiment**.

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– Opportunities for subdominant dark matter candidates –

- Projected sensitivities of photon regeneration exploiting **decommissioned HERA magnets**

– **in HERA tunnel:**

$$B = 5 \text{ T}, \ell = (17 + 17) \times 10 \text{ m}$$

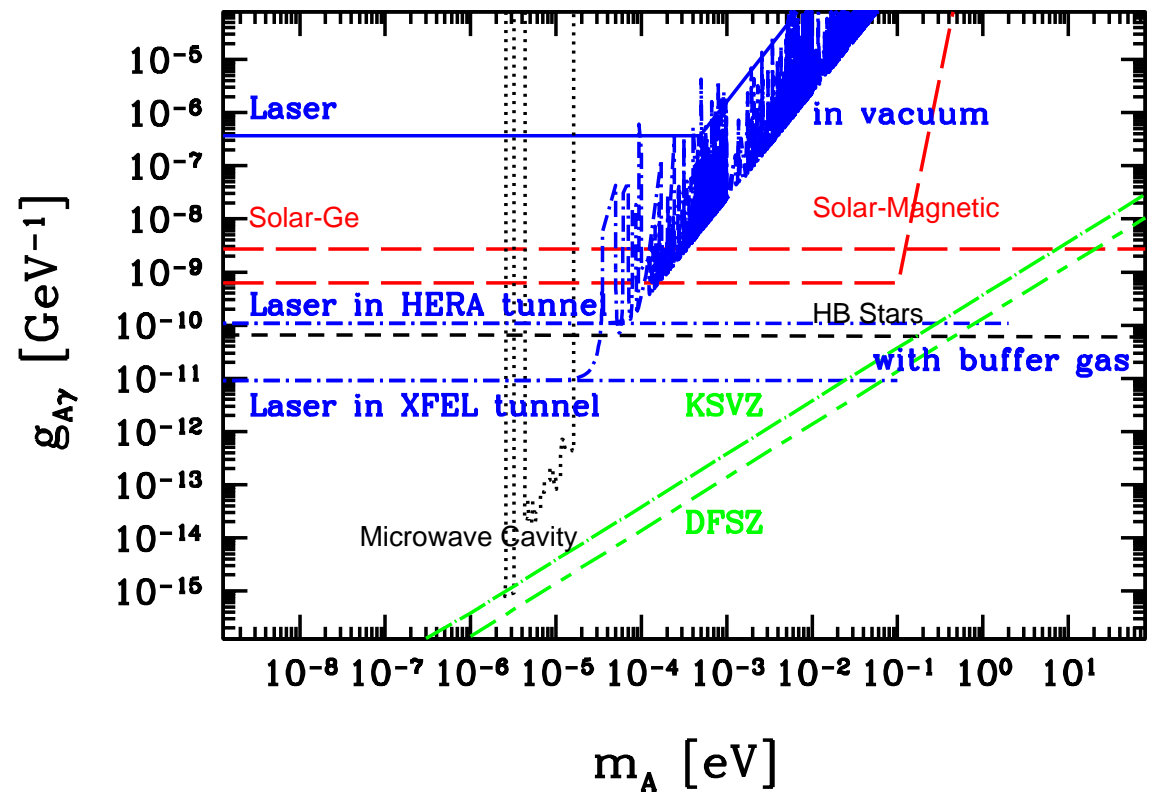
– **in XFEL tunnel:**

$$B = 5 \text{ T}, \ell = (200 + 200) \times 10 \text{ m}$$

- May extend sensitivity to larger masses by filling in **buffer gas**

⇒ Competitive with astrophysical limits and **CAST** sensitivity

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



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### 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!**