



**The Abdus Salam
International Centre for Theoretical Physics**



2246-24

**Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the
Neutrino Sky**

20 - 24 June 2011

Dips in the cosmic neutrino spectrum

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(Redshift-Integrated Resonance - zIR)

Dips in the Cosmic Neutrino Spectrum

unpublished work in collaboration with Tom Weiler
to be published, maybe, arXiv: 1xxx.xxxx

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ICTP, Trieste
June 23, 2011

Two famous examples

- **GZK suppression**

- Beam: protons
- Target: CMB
- Resonance: Δ

K. Greisen, Phys. Rev. Lett. 16:748, 1966

G. T. Zatsepin and V. A. Kuzmin, JETP Lett. 4:78, 1966

F. W. Stecker, Phys. Rev. Lett. 21:1016, 1968

- **Photo-dissociation of nuclei**

- Beam: Nuclei
- Target: Photon Background
- Resonance: Giant Dipole Resonance

F. W. Stecker, Phys. Rev. 180:1264, 1969

W. Tkaczyk, J. Wdowczyk and A. Wolfendale, J. Phys. A8:1518, 1975

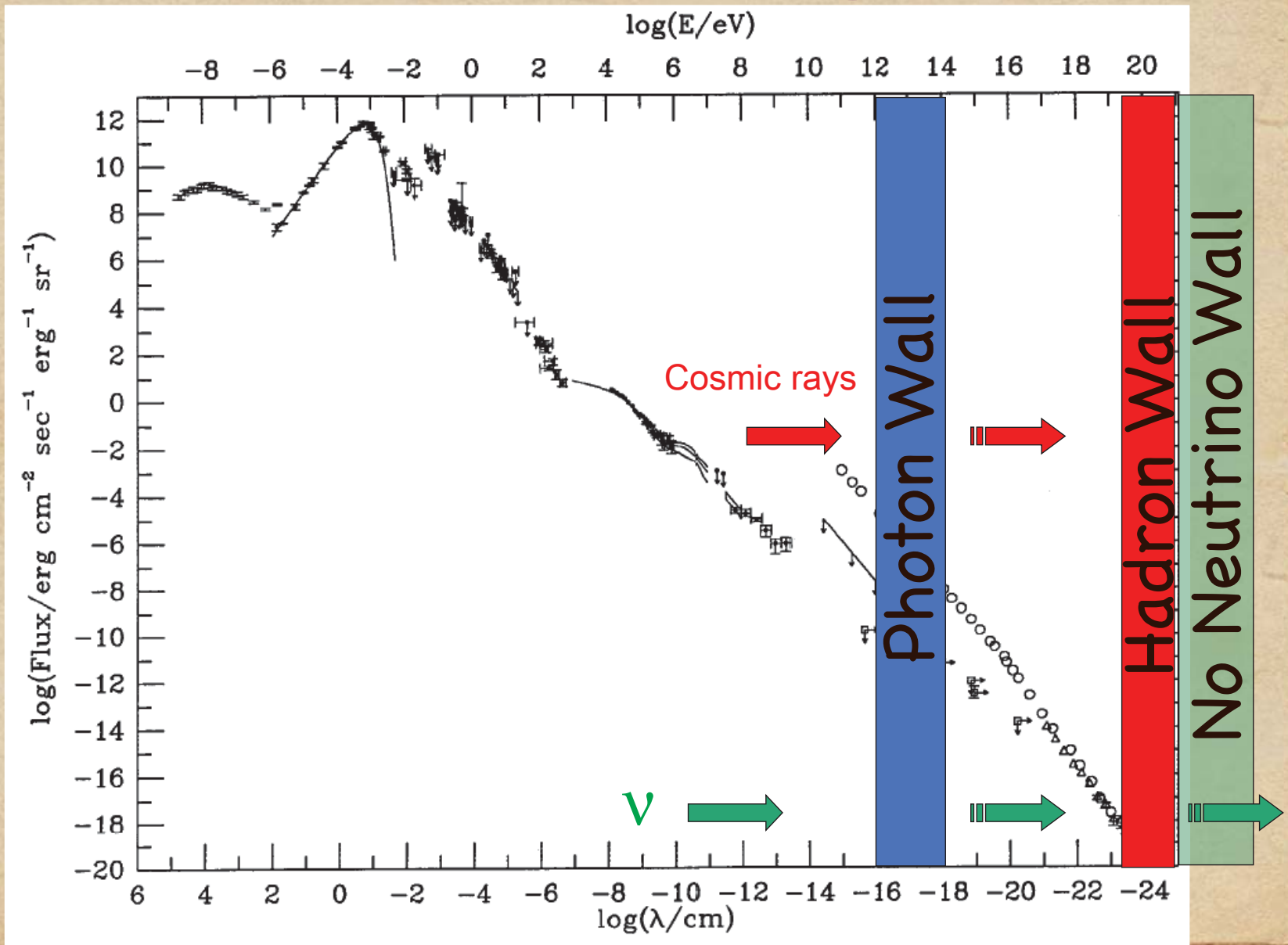
J. L. Puget, F. W. Stecker and J. H. Bredekamp, Astrophys. J. 205:638, 1976

F. W. Stecker, Phys. Rev. Lett. 80:1816, 1998

L. N. Epele and E. Roulet, Phys. Rev. Lett. 81:3295, 1998 and JHEP 9810:009, 1998

F. W. Stecker and M. H. Salamon, Astrophys. J. 512:521, 1999

Neutrinos as Beam



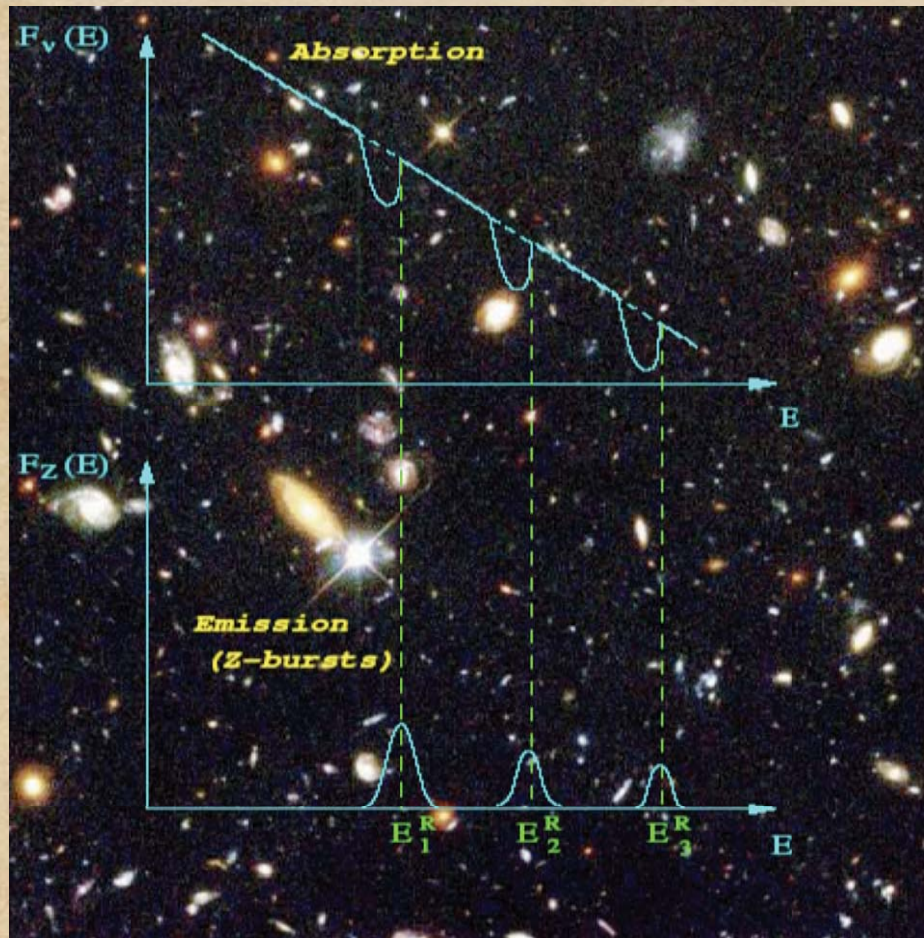
What else about neutrinos as beam?

- Neutrinos point back to their cosmic sources
- Above GZK energy ($\sim 5 \times 10^{19}$ eV), they may be the only propagating primaries
- At high energies, neutrinos are little affected by the ambient matter: carry information about the central engine
- Neutrinos carry a quantum number that cosmic rays and photons do not have: flavor
- Travel over cosmic distances allows studies of their fundamental properties: stability, pseudo-Dirac mass patterns
- Extreme energies allow studies of neutrino cross sections beyond the reach of terrestrial accelerators

A. Kusenko and T. Weiler, Phys.Rev.Lett.88:161101,2002

SPR, A. Irimia and T. Weiler, Phys.Rev.D73:083003,2006

Resonances in the Cosmic ν Spectrum (zIRs)



Absorption features: **Dips**

Three sources of background:

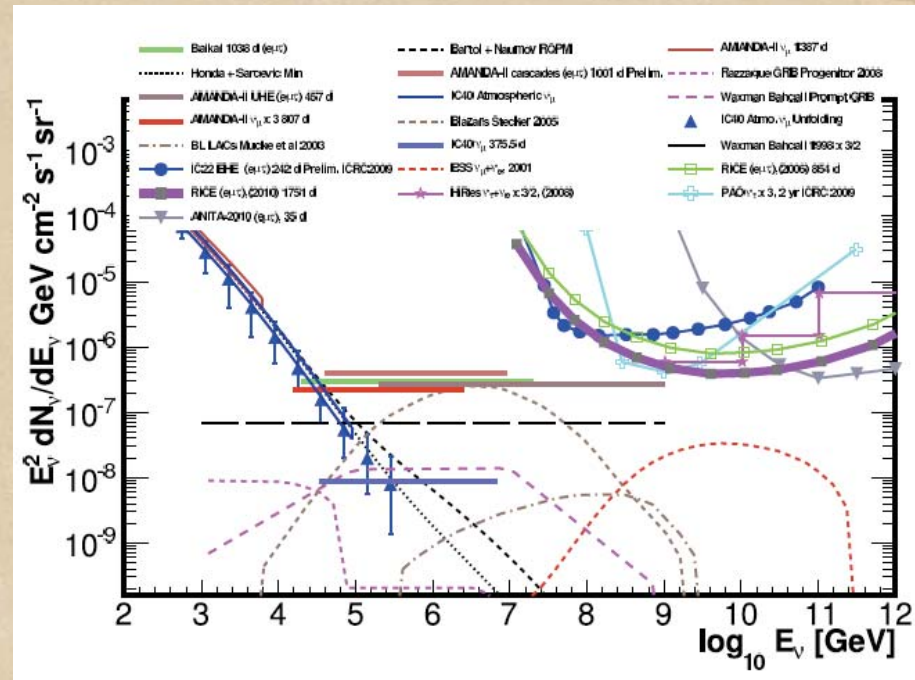
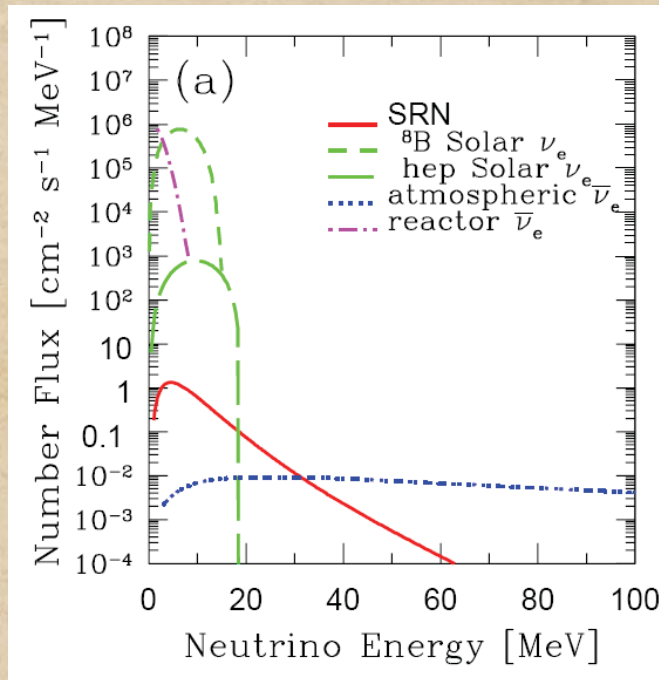
muon-induced spallation products, reactor and atmospheric ν

Emission features: **Bursts**

One source of background:

cosmic rays

Backgrounds for neutrino dips

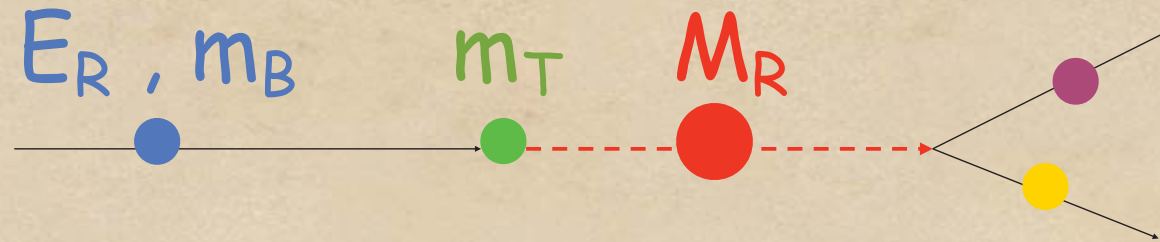


S. Ando, K. Sato and T. Totani, *Astropart. Phys.* 18:307, 2003

I. Kravchenko et al., arXiv:1106.1164

For simplicity, we will consider the windows:
 $10 \text{ MeV} < E < 50 \text{ MeV}$ and $E > 100 \text{ TeV}$

Formalism



- Resonant Energy of the beam

$$E_R = \frac{M_R^2 - m_T^2 - m_B^2}{2m_T} = \omega E_0 \quad \omega = 1 + z$$

- Number density of the target

$$n_0 = 1.26 \left(\frac{\text{keV}}{m_T} \right) \left(\frac{\Omega_T}{\Omega_{DM}} \right) \text{cm}^{-3} \quad \Rightarrow \quad n(\omega) = n_0 \omega^3$$

$$n_0 = 56 \text{ cm}^{-3} \quad [\text{neutrino target}]$$

Formalism

- Cross-Section for $2 \rightarrow 2$ process

$$\sigma = \frac{1}{2s} \frac{1}{S_i} \sum_i \sum_f \int dLIPS_f |M|^2$$

- Integration over the final state phase space

$$|M|^2 = |M_i|^2 \frac{S_R}{(s - M_R^2)^2 + (M_R \Gamma_R)^2} |M_f|^2$$

$$\sigma = \frac{1}{2s} \frac{1}{S_i} \frac{S_R}{(s - M_R^2)^2 + (M_R \Gamma_R)^2} \sum_i |M_i|^2 \sum_f \int dLIPS_f |M_f|^2$$

Formalism

- Partial widths

$$\Gamma_i = \frac{1}{2M_R} \sum_i \int dLIPS_i |M_i|^2 \quad \Gamma_f = \frac{1}{2M_R} \sum_f \int dLIPS_f |M_f|^2$$

$$\int dLIPS_i = \sqrt{\lambda(M_R^2, m_B^2, m_T^2)} / (8\pi M_R^2) \xrightarrow{m_B=0} (8\pi)^{-1} (1 - m_T^2/M_R^2)$$

$$\sigma = \left(\frac{S_R}{S_i} \right) \left(\frac{M_R^2}{s} \right) \frac{16\pi}{(s - M_R^2)^2 + (M_R \Gamma_R)^2} \frac{\Gamma_i \Gamma_f}{(1 - m_T^2/M_R^2)}$$

- Narrow width approximation: $\Gamma_R \ll M_R$

$$B_i B_f \Gamma_R \approx \Gamma_i$$

$$\sigma = \left(\frac{S_R}{S_i} \right) 16\pi^2 \frac{B_i B_f \Gamma_R}{(1 - m_T^2/M_R^2) M_R} \delta(s - M_R^2)$$

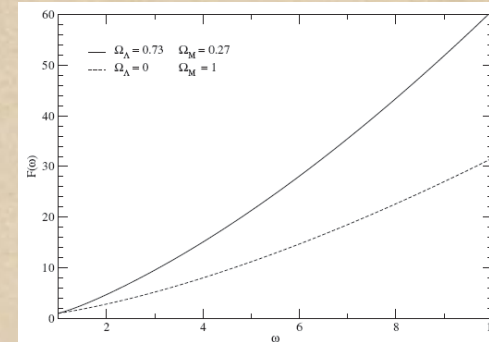
Formalism

Resonant interaction probability

$$\tau = \int \frac{c dt}{\lambda_\nu} = \int d\omega \left(\frac{dt}{d\omega} \right) n(\omega) \sigma(\omega)$$

$$\frac{1}{\omega H(\omega)}$$

$$H(\omega) = H_0 \sqrt{\Omega_\Lambda + \Omega_M \omega^3 + \Omega_R \omega^4 + \Omega_k \omega^2}$$



$$\tau(E_0) = 16 \pi^2 \left(\frac{S_R}{S_i} \right) \left(\frac{\Gamma_i}{M_R} \right) \left(\frac{1}{1 - m_T^2/M_R^2} \right)^2 \left(\frac{n_0}{H_0 M_R^2} \right) \underbrace{\left[\frac{\omega^3}{\sqrt{\Omega_\Lambda + \Omega_M \omega^3}} \right]}_{F(\omega)} \Big|_{\omega = \frac{M_R^2 - m_T^2}{2 m_T E_0}}^{\omega \leq \omega_e \ll \omega_{eq}}$$

Probability to not interact = $e^{-\tau}$

Fraction of flux absorbed: $f = 1 - e^{-\tau}$

Formalism

- **Figure of Merit: minimum absorption of $f=10\%$**

$$\left(\frac{\Gamma_i}{M_R}\right) \left(\frac{1}{1 - m_T^2/M_R^2}\right)^2 \left(\frac{n_0}{H_0 M_R^2}\right) \gtrsim 10^{-3} \ln(1 - f)^{-1} \xrightarrow{f=10\%} 10^{-4}$$

$$z \sim 1.5$$

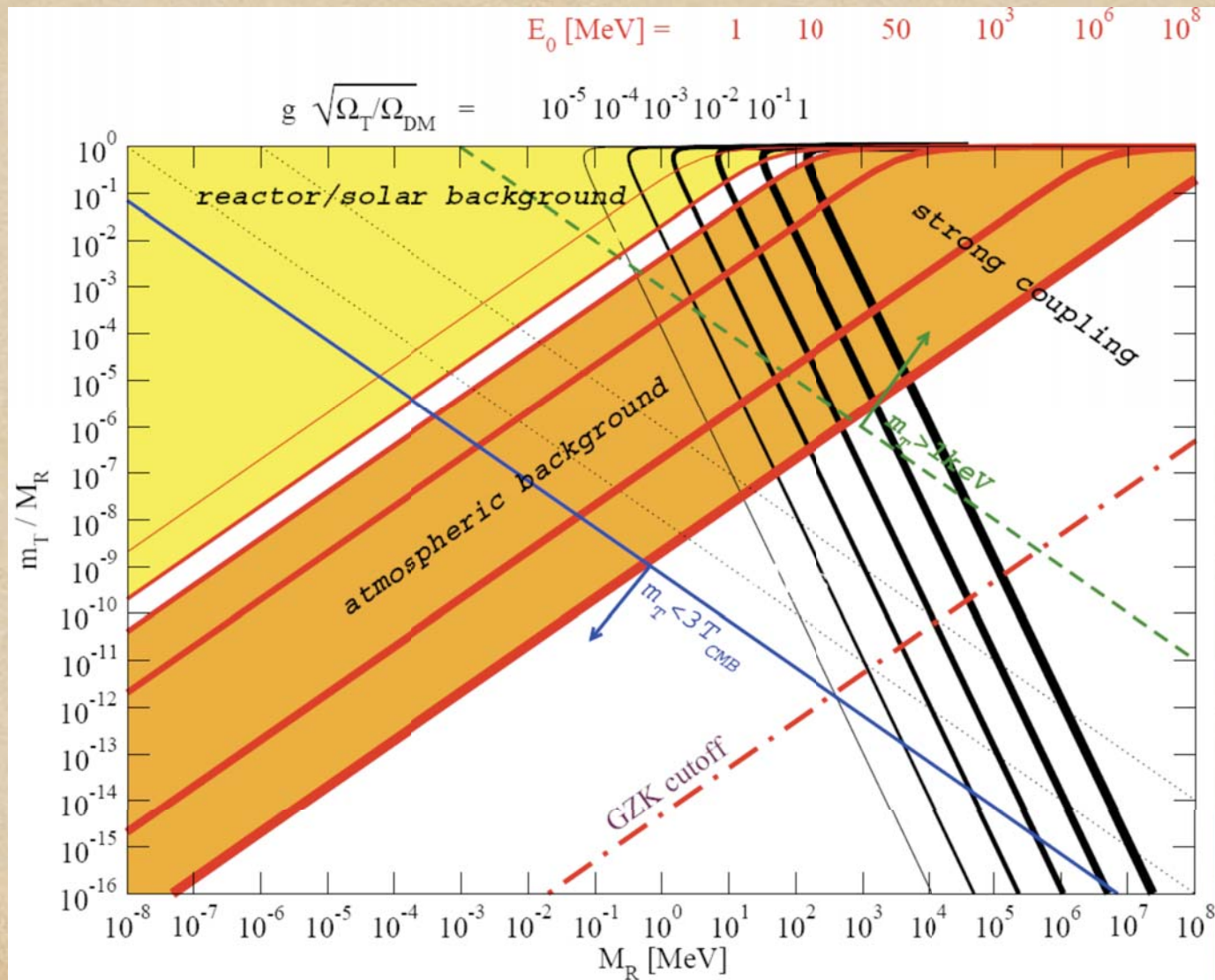
- **For a general term as $g\psi\bar{\psi}\varphi$:** $\frac{\Gamma_i}{M_R} = \frac{g^2}{16\pi} \left(1 - \frac{m_T^2}{M_R^2}\right)$

- **FOM:**

$$\left(1 - \frac{m_T^2}{M_R^2}\right) \left(\frac{m_T}{M_R}\right) \lesssim 10^6 \frac{g^2 \Omega_T}{\Omega_{DM}} \left(\frac{\text{MeV}}{M_R}\right)^3 \left(\frac{F(\omega)}{F(2)}\right)$$

$$\left(\frac{M_R}{\text{MeV}}\right) \lesssim 2 \left(\frac{g}{10^{-5}}\right) \left(\frac{F(\omega)}{F(2)}\right)^{1/2} \quad [\text{neutrino target}]$$

The $M_R - m_T / M_R$ plane



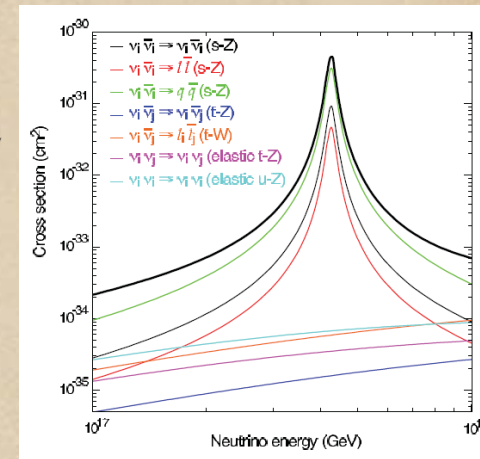
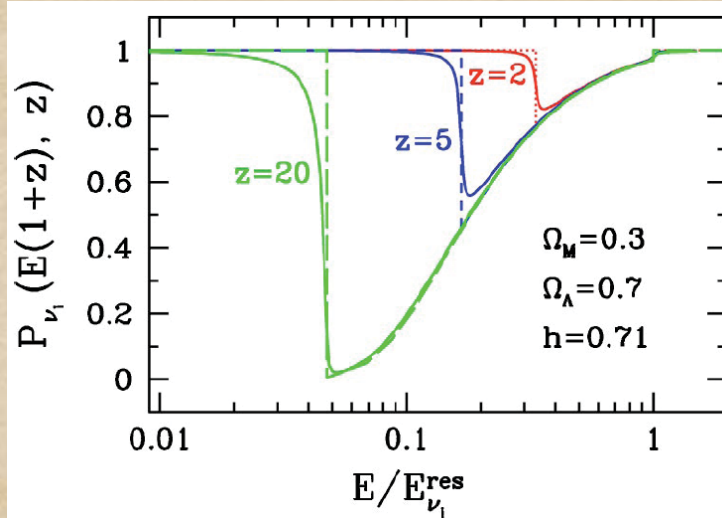
Standard Model Z-dips

• Interaction with CVB: $E_R = 4 \times 10^{21} \text{ eV (eV/m}_\nu)$

- T. J. Weiler, Phys. Rev. Lett. 49:234, 1982 and Astrophys. J. 285:495, 1984
- E. Roulet, Phys. Rev. D47:5247, 1993
- B. Eberle, A. Ringwald, L. Song and T. J. Weiler, Phys. Rev. D70:023007, 2004
- G. Barenboim, O. Mena and C. Quigg, Phys. Rev. D71:083002, 2005
- J. C. D'Olivo, L. Nellen, S. Sahu and V. Van Elewyck, Astropart. Phys. 25:47, 2006

$$\sigma \approx 2\sqrt{2} \pi G_F$$

$$\Gamma_{Z \rightarrow \nu\bar{\nu}} = \frac{G_F M_Z^3}{12\sqrt{2} \pi} \Rightarrow g_Z^2 = \frac{4}{3\sqrt{2}} G_F M_Z^3 \cong (0.3)^2$$

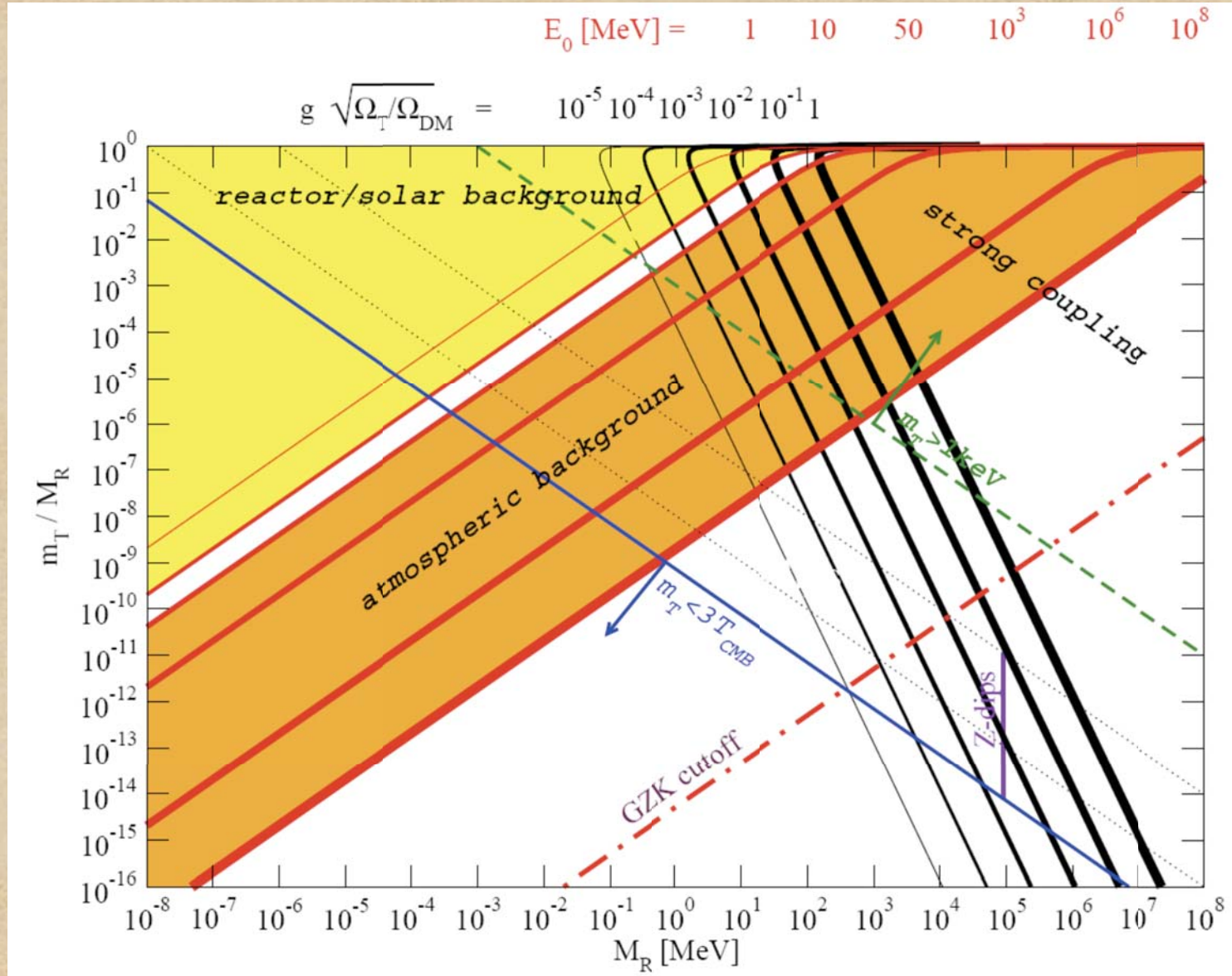


G. Barenboim, O. Mena and C. Quigg, Phys. Rev. D71:083002, 2005

FOM: $M_Z < 60 \text{ GeV (F(w)/F(2))}^{1/2}$

DIPS for ν sources at $z > 1.7$

B. Eberle, A. Ringwald, L. Song and T. J. Weiler, Phys. Rev. D70:023007, 2004



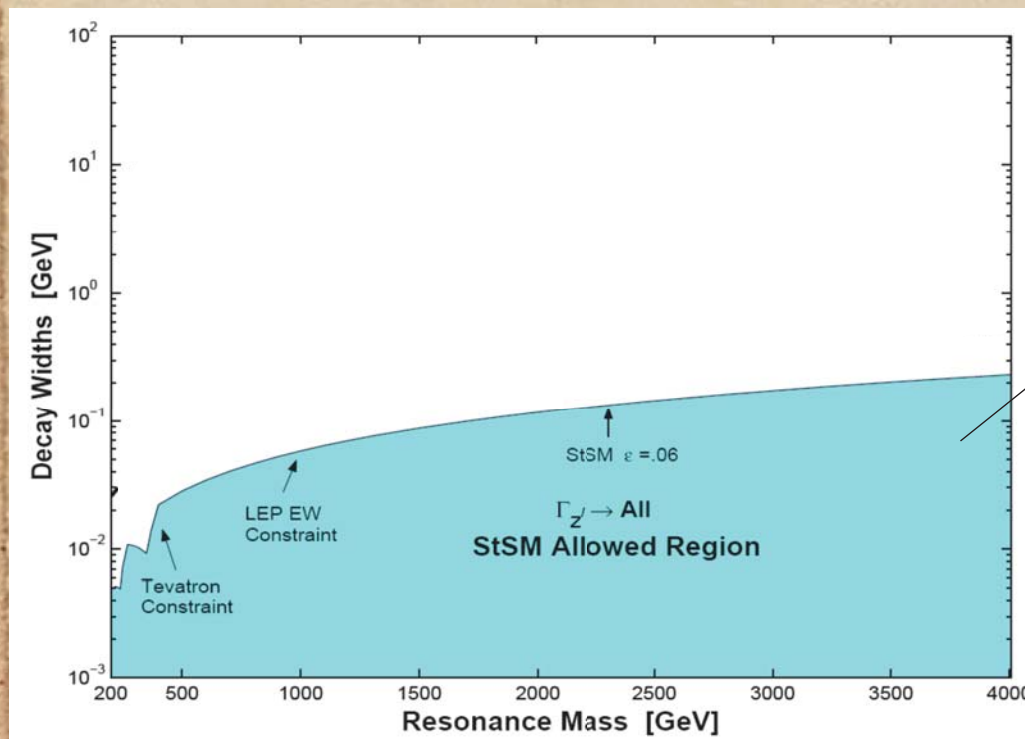
SPR and T. Weiler, in preparation

Z-related dips

Z'-dips with/without Stueckelberg

- Stueckelberg extensions of SM: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$

New gauge field has no coupling with the visible sector: the physical Z' boson connects with the visible sector only via mixing with SM gauge bosons → narrow width



$$g_{Z'} < 0.1 g_Z$$

$$M_{Z'} < 6 \text{ GeV } (F(\omega)/F(2))^{1/2}$$

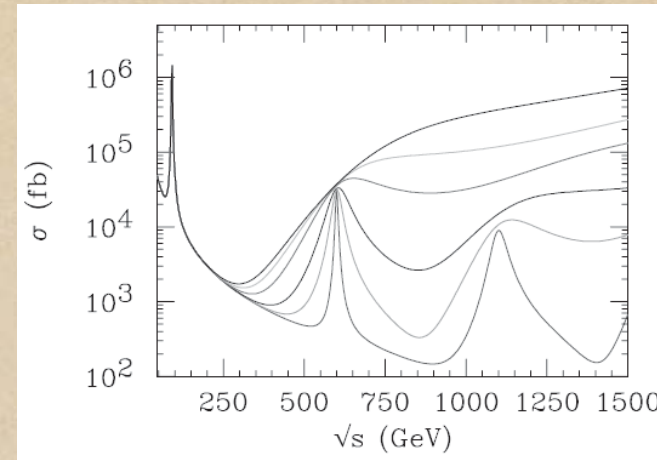
NO DIP

D. Feldman, Z. Liu and P. Nath, JHEP11:007, 2006

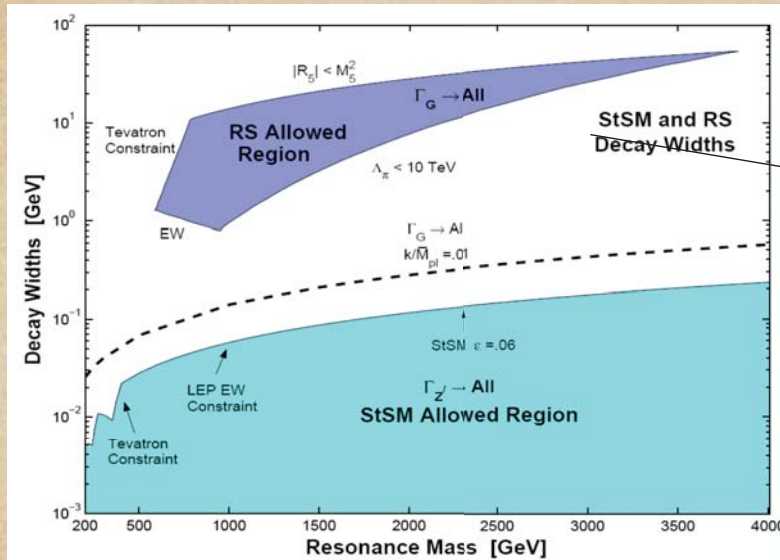
ZIRs towers from extra-Dim

- Gravi-bursts: based on the Randall-Sundrum model of localized gravity \rightarrow prediction of a KK tower of spin-2 gravitons with masses starting at the weak scale and weak couplings

H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Lett. B549:267, 2002



H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Rev. Lett. 84:2080, 2000



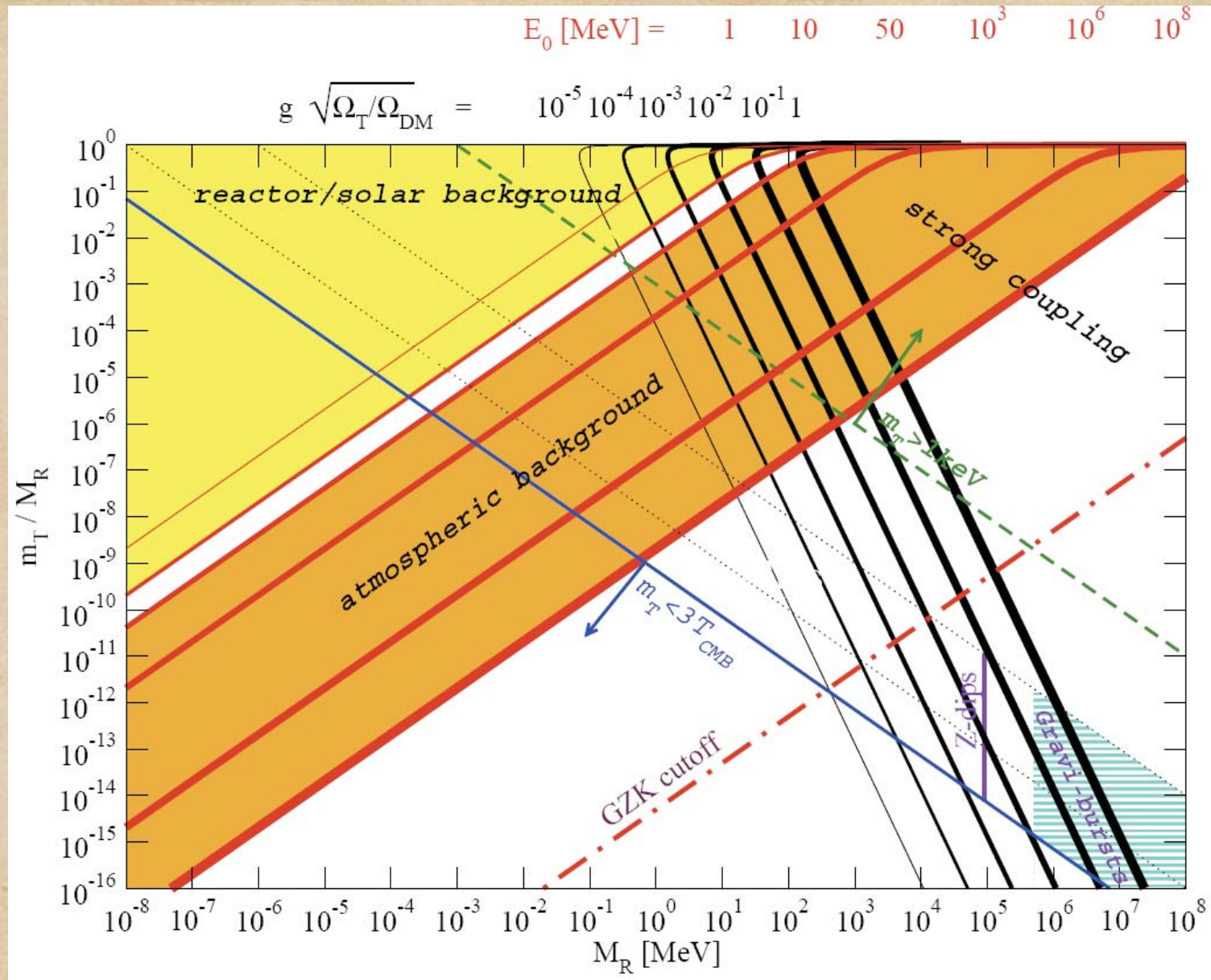
D. Feldman, Z. Liu and P. Nath, JHEP11:007, 2006
 H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Rev. Lett. 84:2080, 2000
 and Phys. Rev. D63:075004, 2001

$$g_G < g_Z$$

$$M_G < 60 \text{ GeV} (F(\omega)/F(2))^{1/2}$$

NO DIP

It would need ν sources at $z > 30$

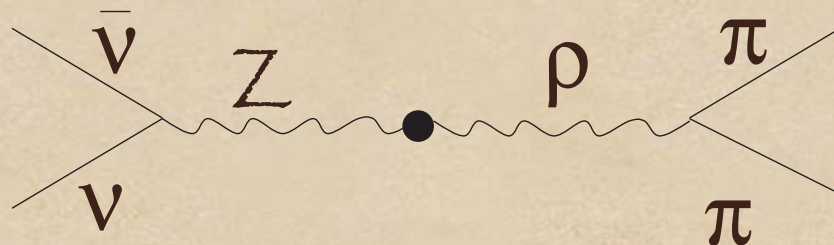


SPR and T. Weiler, in preparation

vector (ρ) Meson-dips

E. A. Paschos and O. Lalakulich, hep-ph/0206273

- Annihilation through ρ meson $\rightarrow \epsilon_R$ is a factor $M_Z/m_\rho \sim 120$ lower than for Z-dips



$$g \approx \sqrt{2} g_Z g_\rho \frac{m_\rho^2}{M_Z^2}$$

- From data on the coupling of the process $\tau \nu_\tau \rightarrow \rho$ and CVC relations $g_\rho = 2 \times 10^{-2} \rightarrow g = 8 \times 10^{-7} \rightarrow$ from our FOM, this would imply $m_\rho < 0.1(F(\omega)/F(2))^{1/2} \text{ MeV}$

NO DIP

U-dips

- Annihilation through a light and weakly coupled U -boson which could help explaining the 511 keV line from the galactic bulge: LDM particles annihilate via U -boson exchange to produce e^+e^- pairs

C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, Phys. Rev. Lett. 92:101301, 2004

C. Boehm, P. Fayet and J. Silk, Phys. Rev. D69:101302, 2004

- Mass and coupling of U are strongly constrained from measurements in accelerator experiments

- Assuming universality, from $g_\mu \sim 2$, the coupling to leptons is found to be $g_e < 1.5 \times 10^{-3}$ for $m_U < m_\mu$

P. Fayet, Phys. Rev. D74:054034, 2006

- From ν - e scattering experiments: $g_e g_\nu < G_F m_U^2$

C. Boehm and P. Fayet, Nucl. Phys. B683:219, 2004

$$4 \times 10^5 g_e^{1/2} g_\nu^{1/2} \leq \left(\frac{m_U}{\text{MeV}} \right) \leq 2 \times 10^5 g_\nu$$

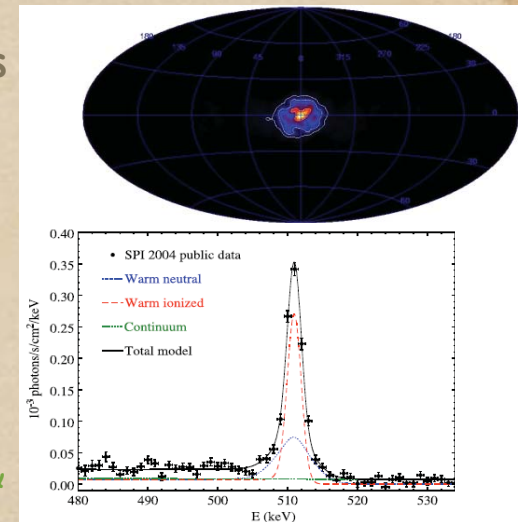
FOM

- To get the right relic density, then

P. Fayet, Phys. Rev. D74:054034, 2006

$$g_e \geq 10^{-7} \left(\frac{|m_U^2 - 4m_{LDM}^2|}{\text{MeV}^2} \right) \left(\frac{\text{MeV}}{m_{LDM}} \right)$$

J. Knodlseder et al.,
Astron. Astrophys. 441:513, 2005



P. Jean et al.,
Astron. Astrophys. 445:579, 2006

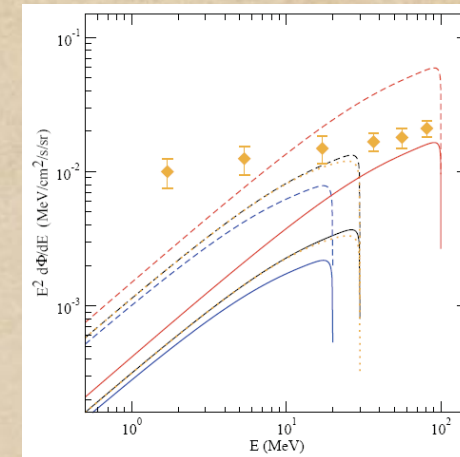
- To avoid an excess of γ -rays from bremsstrahlung:

$$m_{\text{LDM}} < 30 \text{ MeV}-100\text{MeV}$$

C. Boehm, T. A. Ensslin, J. Silk, J. Phys. G30:279, 2004

J. F. Beacom, N. F. Bell and G. Bertone, Phys. Rev. Lett. 94:171301, 2005

C. Boehm and P. Uwer, hep-ph/0606058



C. Boehm and P. Uwer, hep-ph/0606058

- From core-collapse arguments: $m_{\text{LDM}} > 10 \text{ MeV}$

P. Fayet, D. Hooper and G. Sigl, Phys. Rev. Lett. 96:211302, 2006

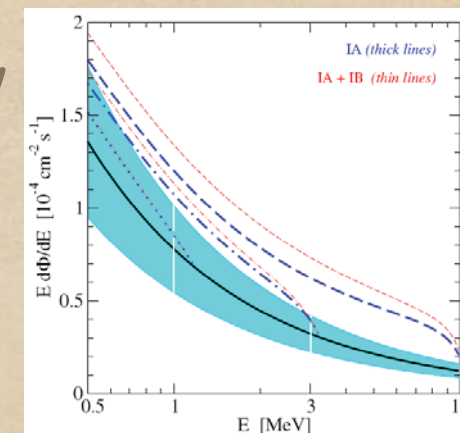
- From in-flight annihilations constraints by the diffuse Galactic γ -ray data:

$$m_{\text{LDM}} < 3-7.5 \text{ MeV}$$

J. F. Beacom and H. Yuksel, Phys. Rev. Lett. 97:071102, 2006

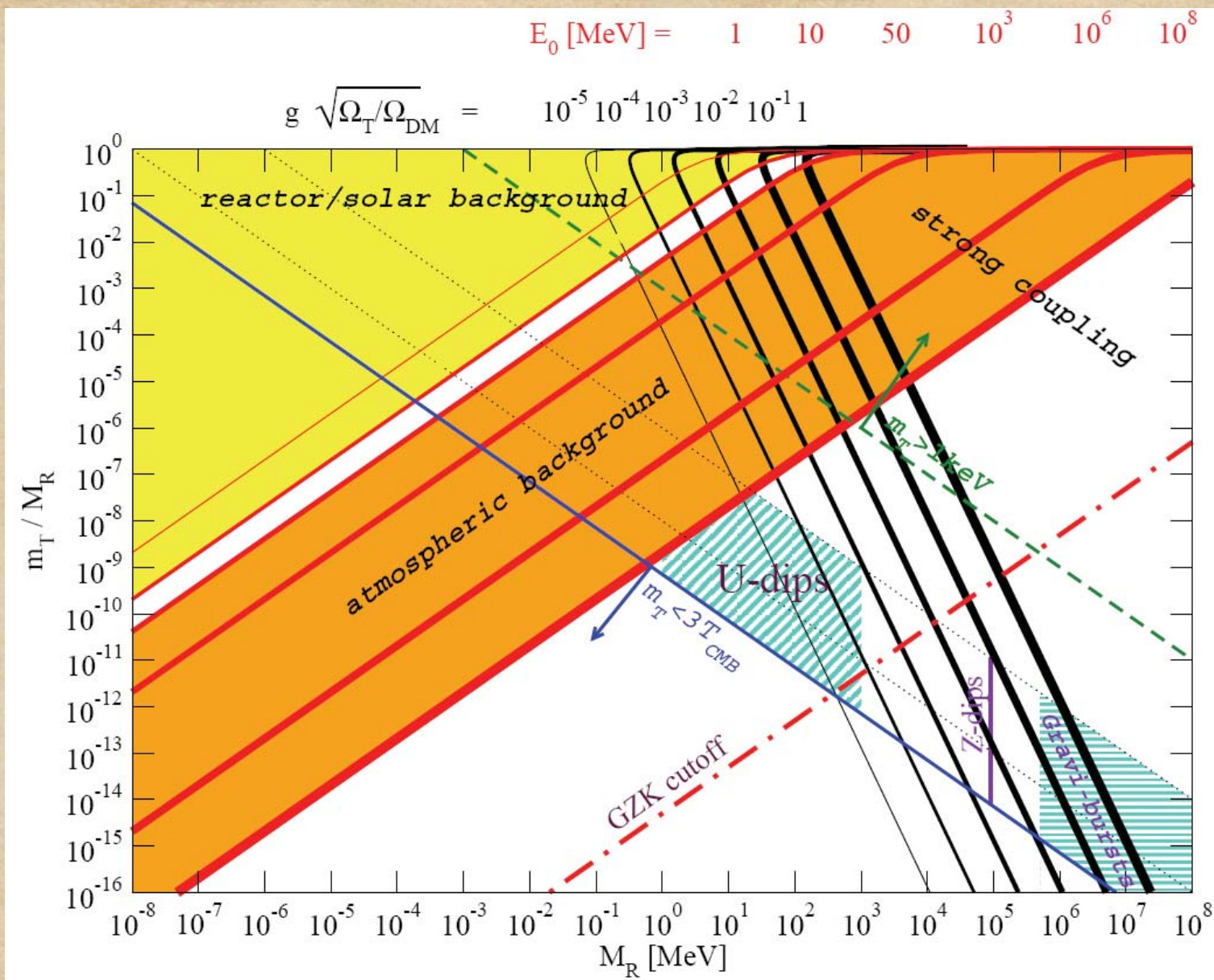
P. Sizon, M. Casse and S. Schanne, Phys. Rev. D74:063514, 2006

- Conservatively: $0.1 \text{ MeV} < m_{\nu} < 1 \text{ GeV}$



J. F. Beacom and H. Yuksel,
Phys. Rev. Lett. 97:071102, 2006

See also D. Hooper, Phys. Rev. D75:123001, 2007



SPR and T. Weiler, in preparation

Scalars coupled to neutrinos

GPS ϕ -dips

- Neutrino mass generation due to a low scale (f) of symmetry breaking: $m_\nu = g f \rightarrow$ after SB a term like $g\nu\nu\phi$ is induced

Z. Chacko, L. J. Hall, T. Okui and S. J. Oliver, Phys. Rev. D70:085008, 2004

Z. Chacko, L. J. Hall, S. J. Oliver and M. Perelstein, Phys. Rev. Lett. 94:111801, 2005

H. Davoudiasl, R. Kitano, G. D. Kribs and H. Murayama, Phys. Rev. D71:113004, 2005

L. J. Hall, H. Murayama and G. Perez, Phys. Rev. Lett. 95:111301, 2005

- If $m_\phi \sim \text{keV} \rightarrow E_R \sim \text{MeV} / m_\nu(\text{eV})$: DSN interact with CVB resonantly

H. Goldberg, G. Perez and I. Sarcevic, JHEP11:023, 2006

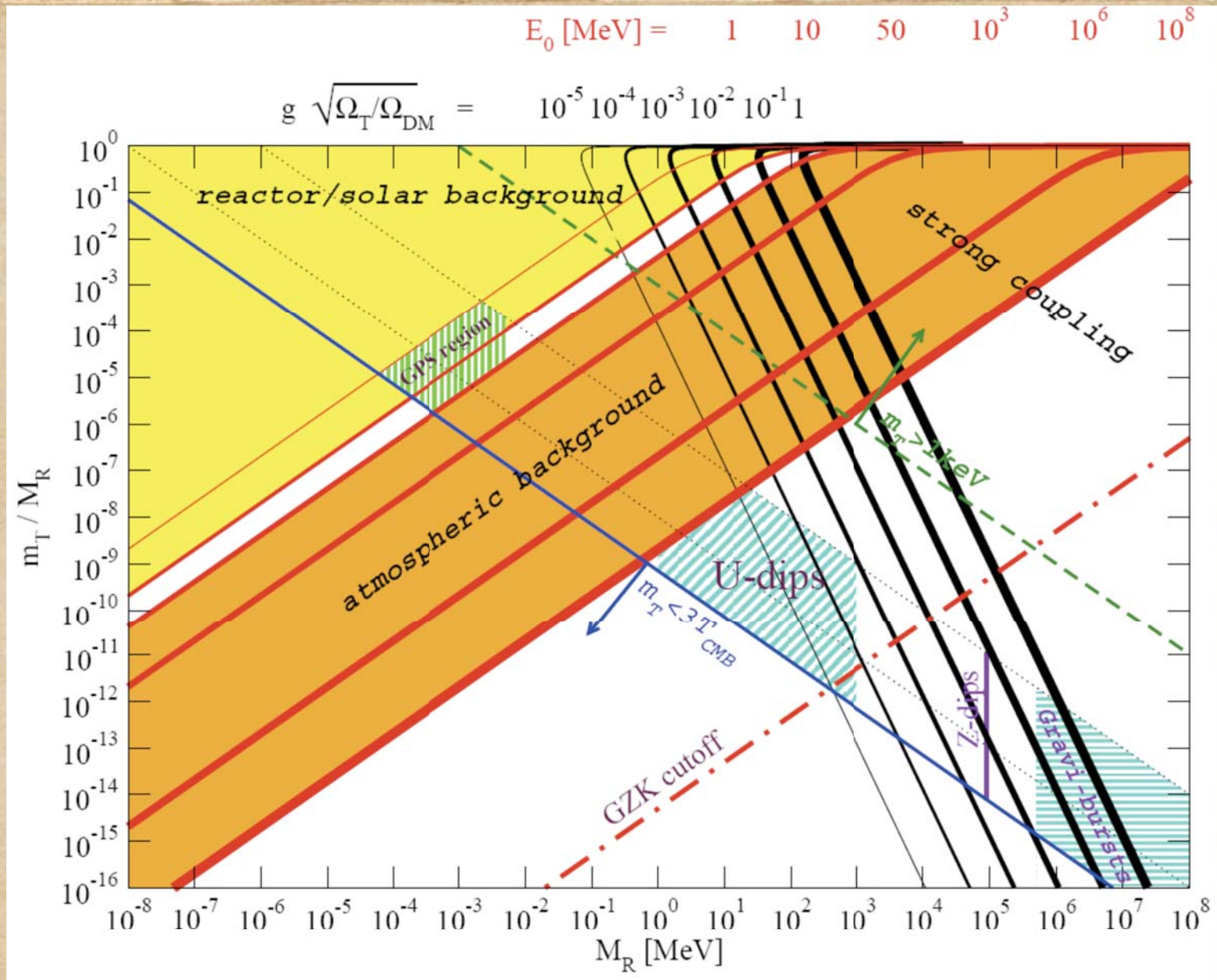
J. Baker, H. Goldberg, G. Perez and I. Sarcevic, Rev. D76:063004, 2007

- For ϕ not to be in thermal equilibrium during BBN:

$$g < 10^{-5}$$

- Combining this bound with the FOM: GPS region

$$M_\phi < 2 \text{ MeV}$$



SPR and T. Weiler, in preparation

PPS ϕ -target

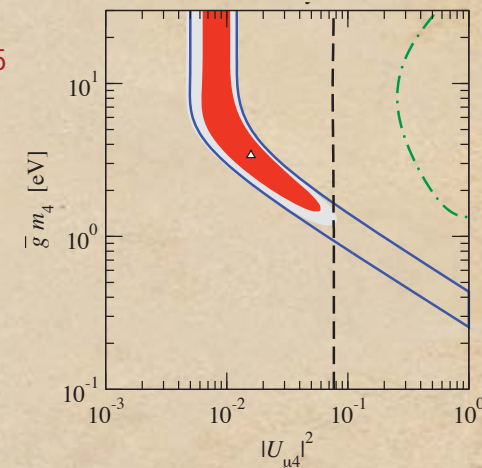
- Interaction term which explained the LSND result via the decay of a (mostly) sterile neutrino

SPR, S. Pascoli and T. Schwetz, JHEP0509:048, 2005

$$L_{\text{int}} = -\sum_{l,h} g_{hl} \bar{\nu}_{lL} N_{hR} \phi + h.c.$$

- ν_{μ} produced in π and μ decay
- N_4 produced in a fraction given by $|U_{\mu 4}|^2$
- Subsequently N_4 decays into light neutrinos

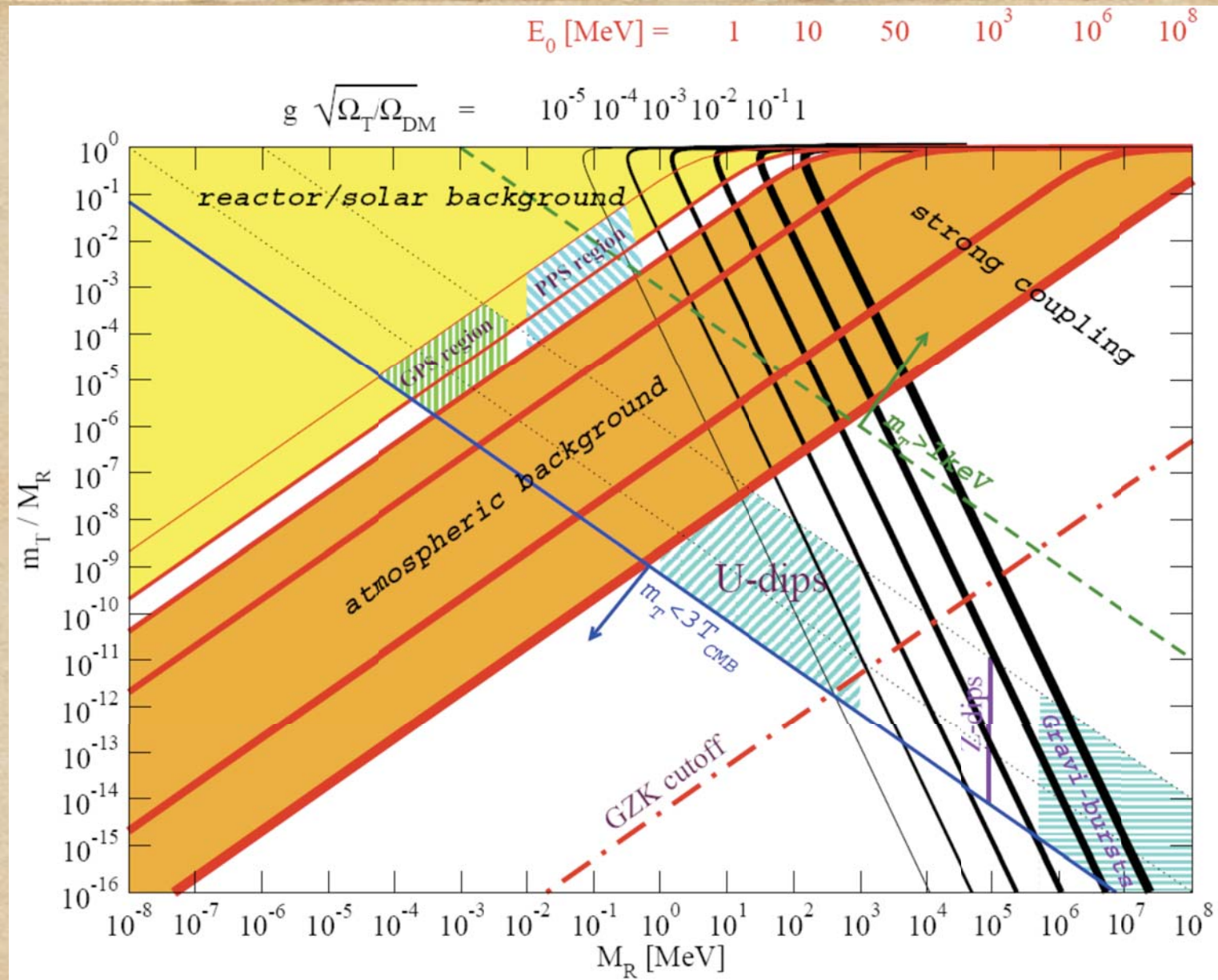
As far as $g_e = \sum U_{e l} g_{4l} \neq 0$, we expect ν_e and $\bar{\nu}_e$ appearance



PPS ϕ -target

- In the model, ϕ is let (almost) free $m_\phi < m_N$
- If ϕ is stable (DM?) \rightarrow target for the Diffuse Supernova Neutrino flux: same effect as in GPS
- Our FOM:

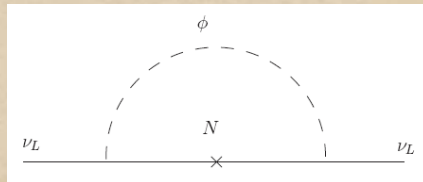
$$\left(\frac{m_\phi}{M_N}\right) \lesssim 5 \times 10^{-4} \left(\frac{\text{MeV}}{M_N}\right)^5 \left(\frac{g M_N}{10 \text{ eV}}\right)^2 \left(\frac{\Omega_T}{\Omega_{\text{DM}}}\right)$$



SPR and T. Weiler, in preparation

BFHPP ϕ -target

- Neutrino mass generation at low scales linked with dark matter
- Same lagrangian as PPS, $g\phi N\nu$, and ϕ the dark matter
- Neutrinos acquire (Majorana) mass via 1-loop correction



$$m_{\nu_L} = \frac{g^2}{16\pi^2} m_N \left[\ln\left(\frac{\Lambda^2}{m_N^2}\right) - \frac{m_\phi^2}{m_N^2 - m_\phi^2} \ln\left(\frac{m_N^2}{m_\phi^2}\right) \right]$$

- If ϕ DM:

$$\langle \sigma v_r \rangle \cong \frac{g^4}{2\pi} \frac{m_N^2}{(m_\phi^2 + m_N^2)^2} \approx 3 \times 10^{-26} \text{ cm}^3 / \text{s} \Rightarrow g \approx 10^{-3} \sqrt{\frac{m_N}{10 \text{ MeV}}}$$

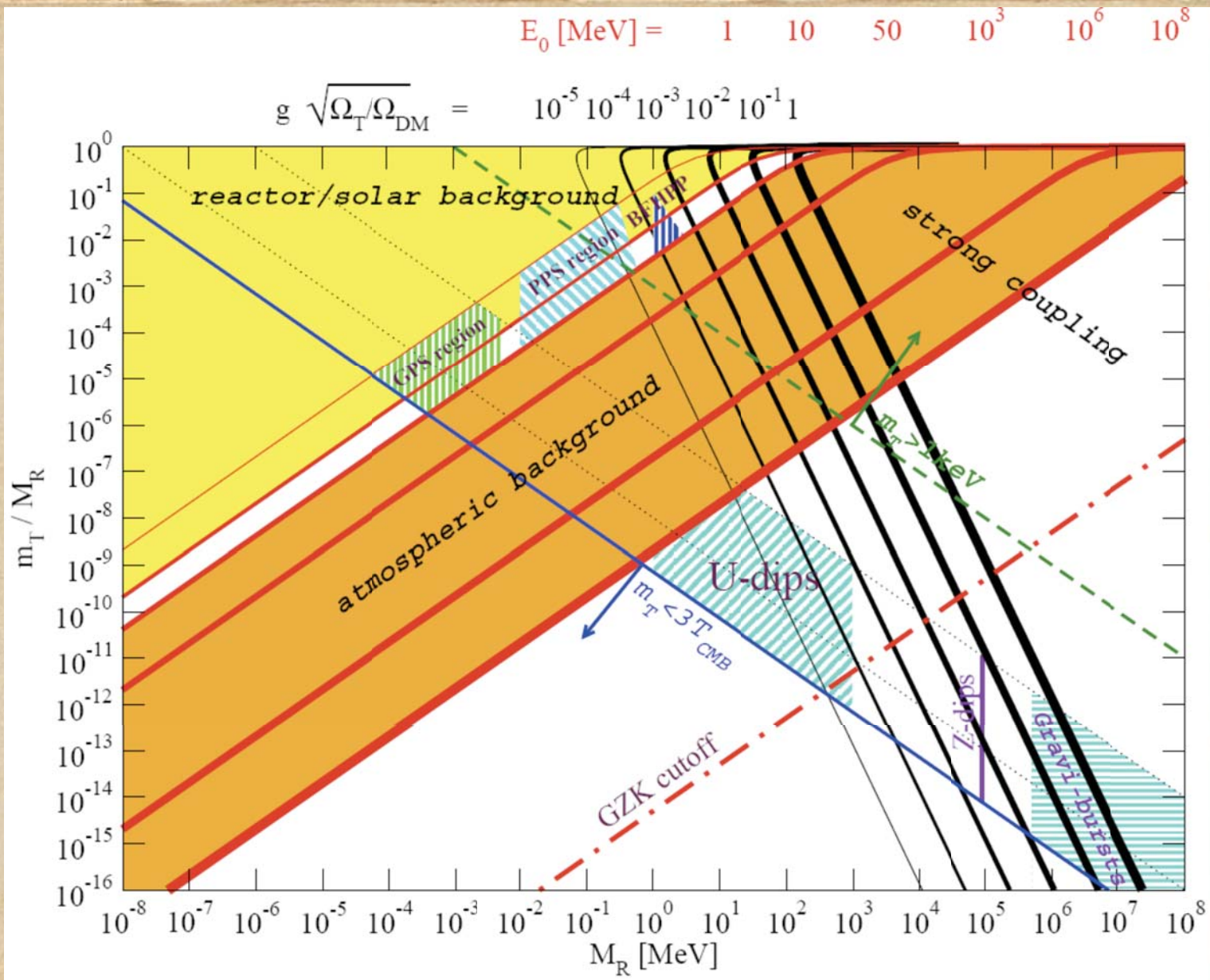
$$m_{\nu_L} \approx \sqrt{\frac{\langle \sigma v_r \rangle}{128\pi^3}} m_N^2 \left(1 + \frac{m_\phi^2}{m_N^2} \right) \ln\left(\frac{\Lambda^2}{m_N^2}\right)$$

FOM

$$0.05 \text{ eV} < m_\nu < 1 \text{ eV}$$

$$O(1) \text{ MeV} < m_N < 10 \text{ MeV}$$

$$m_\phi < 0.1 \text{ (MeV}/M_N) \text{ MeV} \rightarrow E_R > 5 \text{ (} M_N / \text{MeV)}^3 \text{ MeV}$$



SPR and T. Weiler, in preparation

Axions and axion-like particles

- If the PQ axion couples to neutrinos:

$$L_{a\nu\bar{\nu}} = \frac{m_\nu}{f_a} a \bar{\nu}_2 \gamma_5 \nu_1$$

- CDM axions as targets

- From accelerator searches, the evolution of red giants and SN1987a $\rightarrow m_a < 3 \times 10^{-3}$ eV

J. E. Kim, Phys. Rept. 150:1, 1987
 M. S. Turner, Phys. Rept. 197:67, 1990
 G. Raffelt, Phys. Rept. 198:1, 1990

- For axions not to overclose the Universe $\rightarrow m_a > 10^{-6}$ eV

L. F. Abbott and P. Sikivie, Phys. Lett. B 120:133, 1983
 J. Preskill, M. B. Wise and F. Wilczek, Phys. Lett. B 120:127, 1983
 M. Dine and W. Fischler, Phys. Lett. B 120:137, 1983

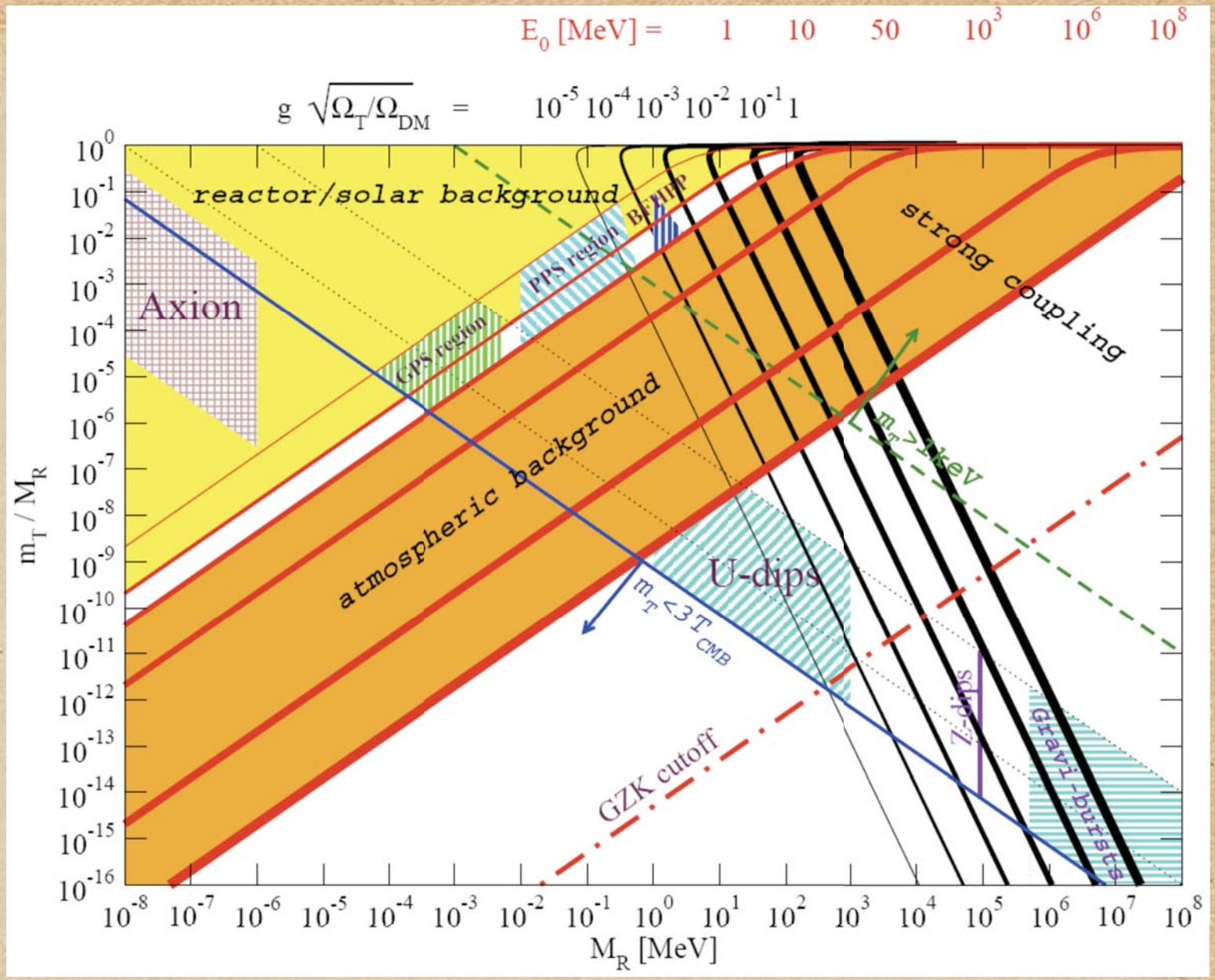
$$0.2 (m_{\nu_2}/\text{eV})^2 \text{ keV} < E_R < 0.5 (m_{\nu_2}/\text{eV})^2 \text{ MeV}$$

NO DIP

- But $f_a m_a = 0.5 f_\pi m_\pi = 6 \times 10^{15} \text{ eV}^2$

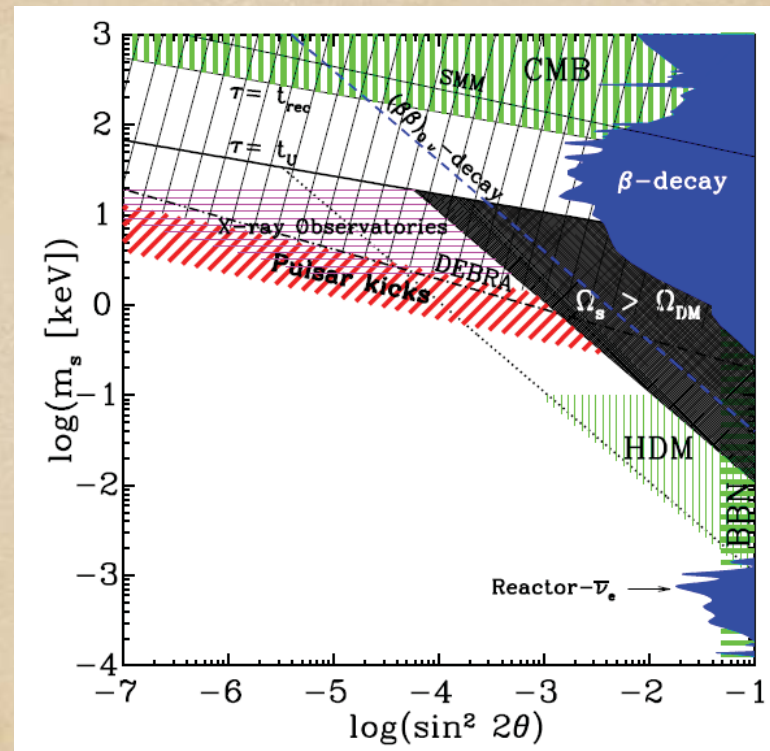
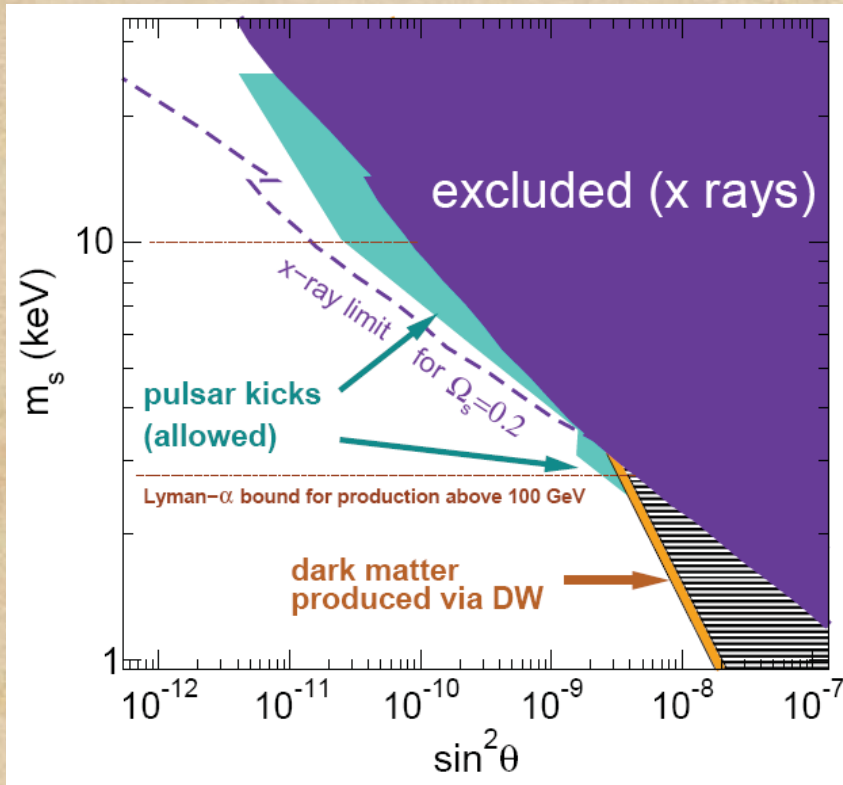
$$g_a < 5 \times 10^{-19} (m_{\nu_2}/\text{eV})$$

$$10^{-6} \left(\frac{\text{eV}}{m_{\nu_2}} \right) \lesssim \left(\frac{m_a}{m_{\nu_2}} \right) \lesssim 10^{-12} \left(\frac{\text{eV}}{m_{\nu_2}} \right)^3 \left(\frac{F(\omega)}{F(2)} \right)$$



Other dark matter-related dips

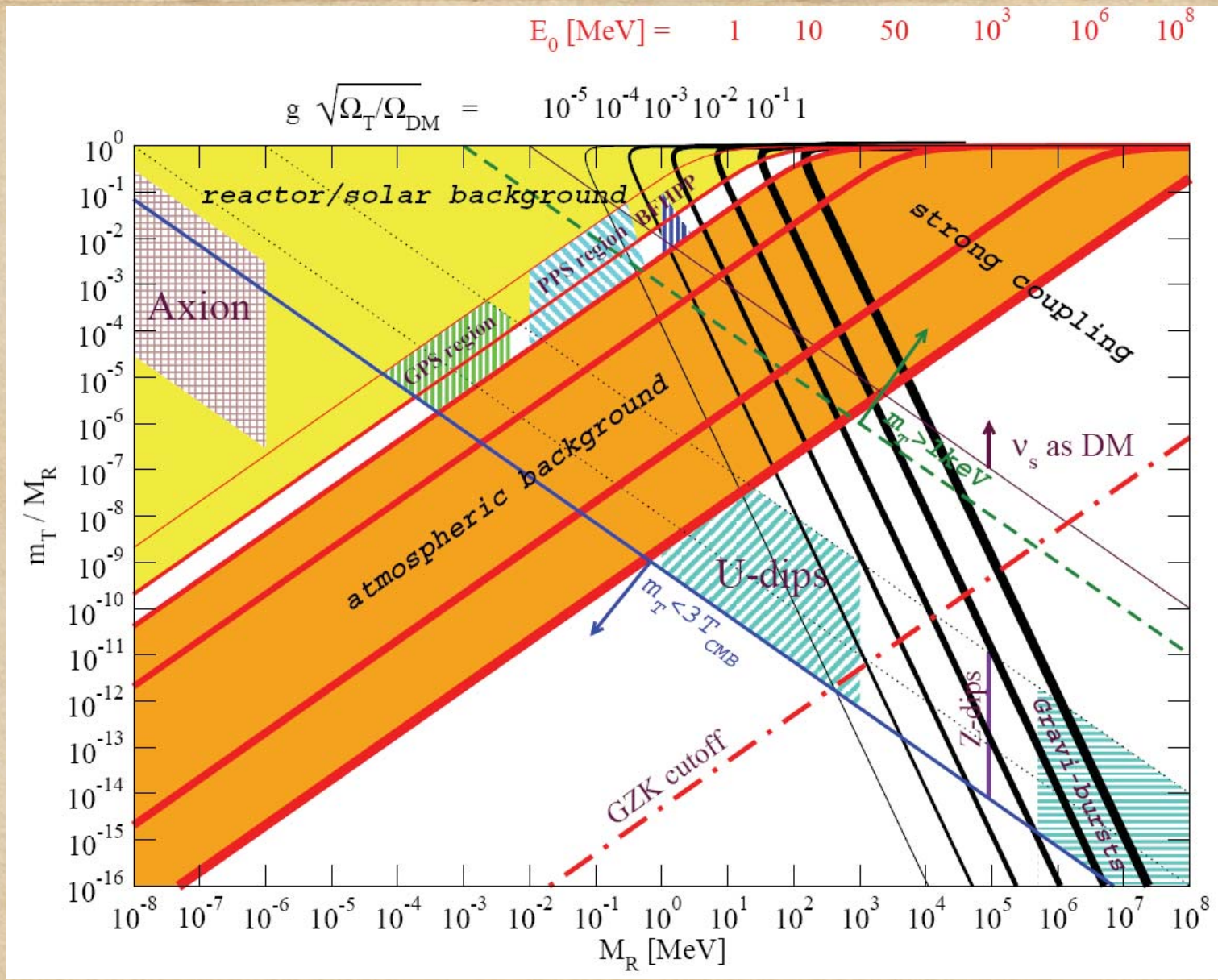
KeV neutrino dark matter



A. Kusenko, Phys. Rev. Lett. 97:241301, 2006
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NO DIP



SPR and T. Weiler, in preparation

Supersymmetric dark matter

- Lightest supersymmetric particle (dark matter) as target
- Eg., neutralino dark matter: $\nu \chi \rightarrow \tilde{\nu}$
- SUSY masses: $m_T, M_R \sim 0.1-1 \text{ TeV} \rightarrow$

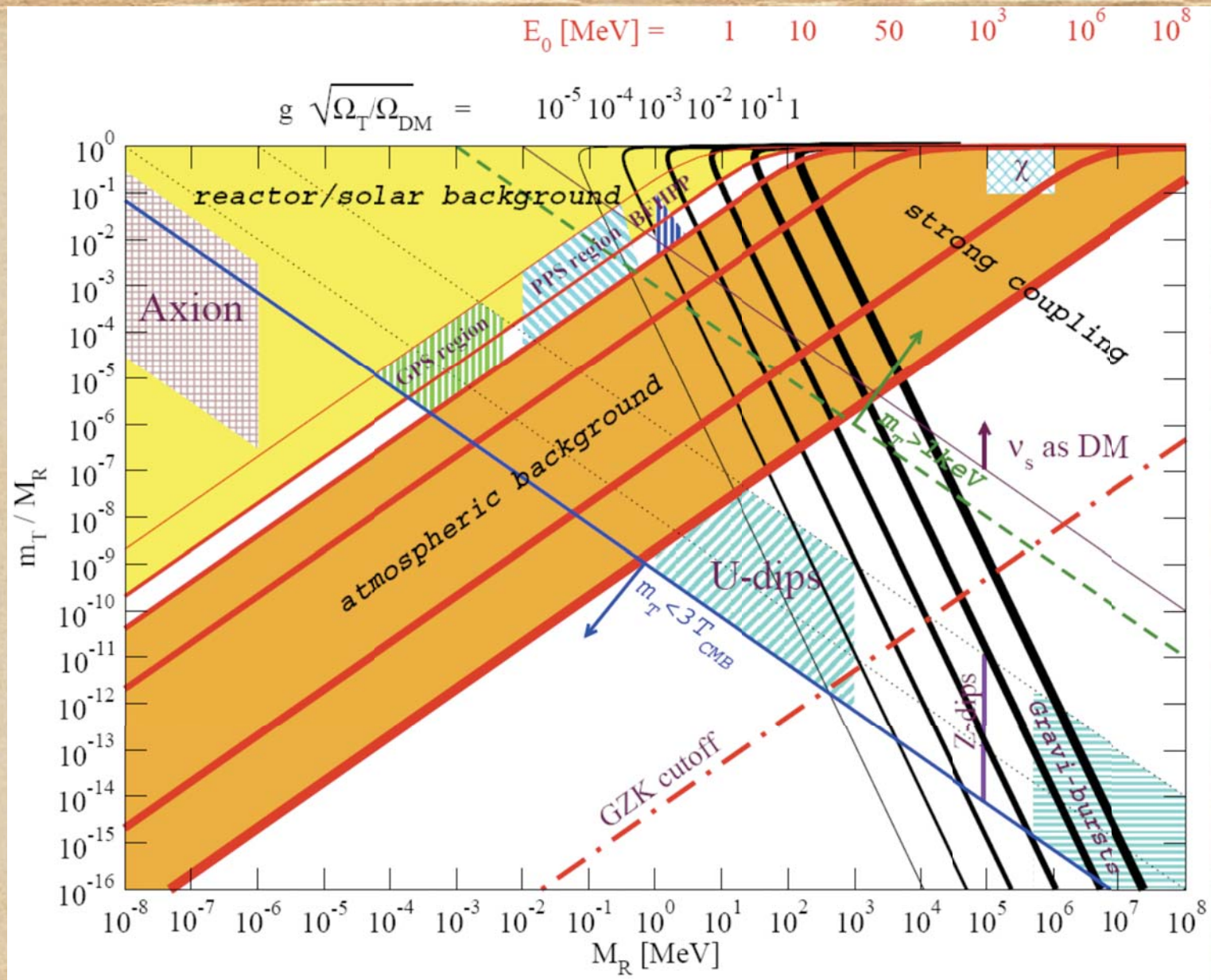
$$5 \text{ GeV} < E_R < 5 \text{ TeV}$$

NO DIP

- $g_{\text{SUSY}} \sim 0.3 g_Z$

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SPR and T. Weiler, in preparation

Conclusions

- We have considered absorption dips in the cosmic neutrino spectrum
- We have analyzed a variety of models with possible signals in two energy regions without atmospheric or reactor neutrino background: around 10-50 MeV (DSN) and above 100 TeV
- We have defined a figure of merit for observable absorption and used a convenient graphical representation to study all cases in a simplified way
- We have shown that dips in the cosmic neutrino spectrum could be used to test the presence of new physics linked to neutrinos

We just need neutrinos!