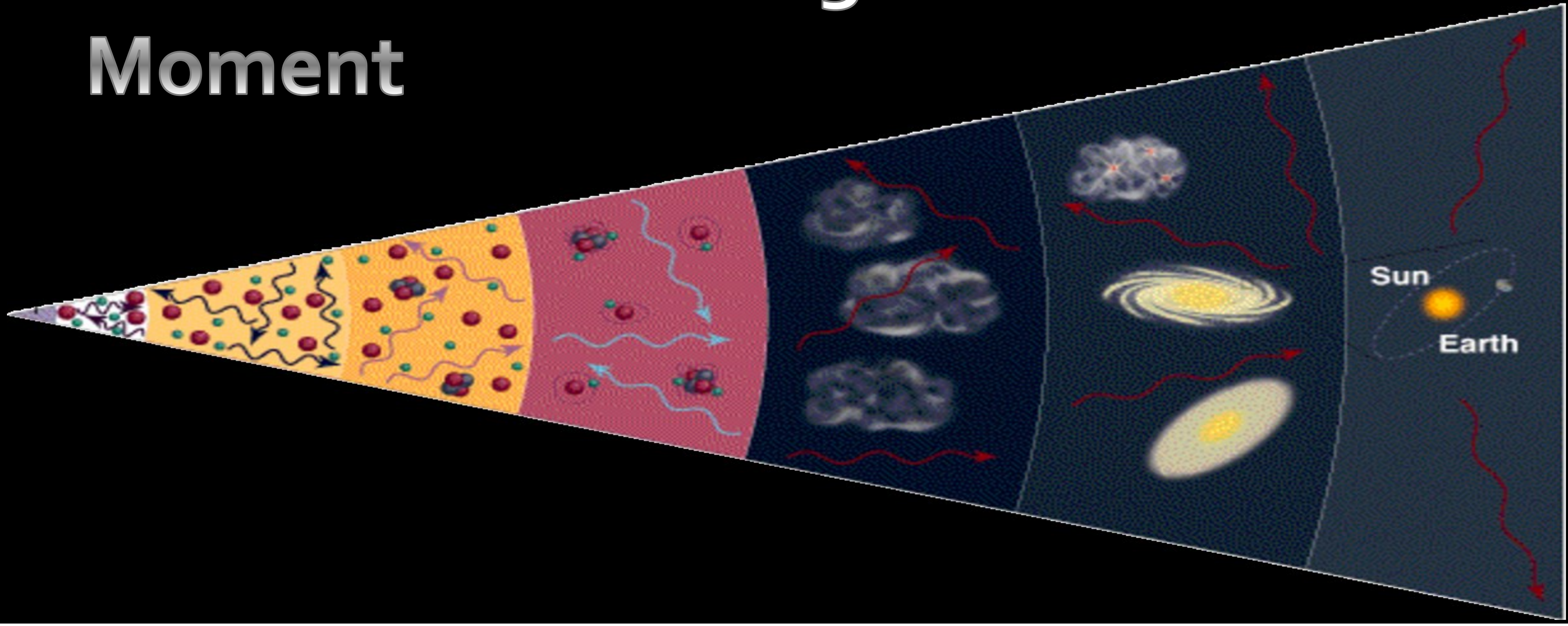
Big Bang Nucleosynthesis and Limits on the Neutrino Magnetic Moment

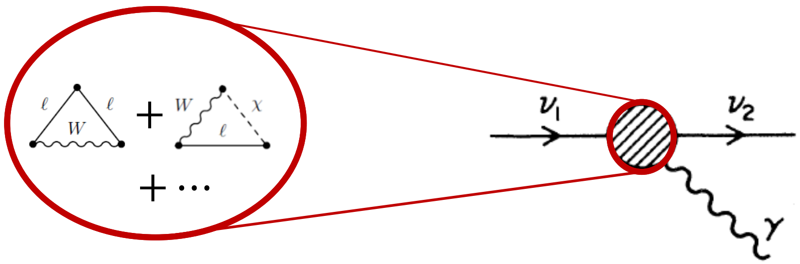


The ν WGV : Nicole Vassh (Analysis) , Panos Gastis (Code) , and Don Willcox (Parameters)

Introduction to μ_ν and BSM Sensitivity

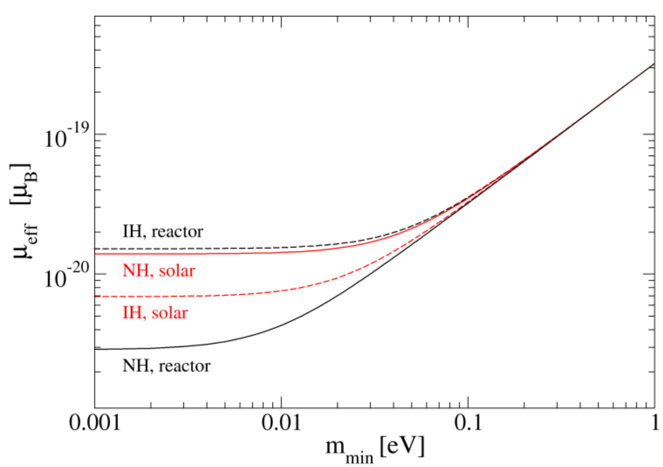
- Minimally Extended Standard Model predicts very small values for magnetic moments of the 3 active flavors

$$\mu_{ij} = -\frac{eG_F}{8\sqrt{2}\pi^2}(\mathrm{m}_i + m_j)\sum_l U_{li}U_{lj}^* f\left(\frac{{m_l}^2}{{M_W}^2}\right)$$

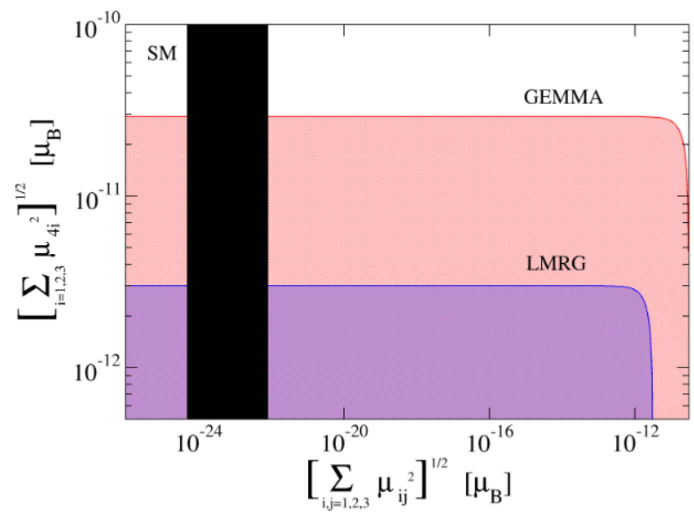


- Additional BSM physics (such as sterile neutrino) can increase the effective neutrino magnetic moment

$$\mu_{eff}^2 \leq \sum_{i=1}^{3}\mu_{i4}^2 + (1 - |U_{e4}|^2)\sum_{i\neq j=1}^{3}\mu_{ij}^2 \quad \text{(for Majorana electron } \nu\text{)}$$



A.B. Balantekin, N. Vassh arXiv:1404.1393

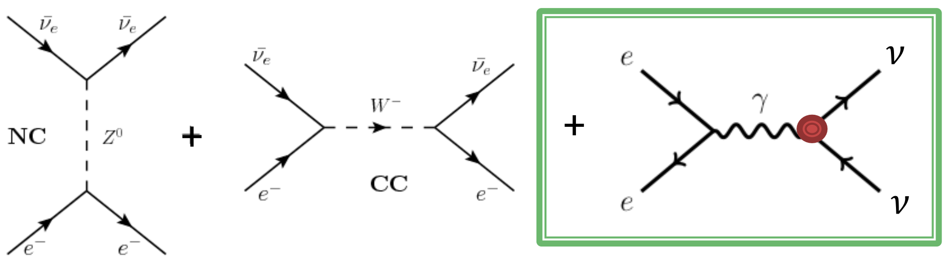


A.B. Balantekin, N.Vassh Phys.Rev. D 89, 073013

Effect of μ_ν on BBN

- Additional ν-e coupling keeps neutrino in thermal equilibrium longer

$$\boldsymbol{e^+ + e^- \rightleftarrows \nu + \bar{\nu}}$$



effects abundances via

$$\nu_e + p \rightleftarrows e^+ + n$$

$$\bar{\nu}_e + n \rightleftarrows e^- + p$$

$$p + n \rightleftarrows d + \gamma$$

- To implement in code must reset neutrino decoupling temperature

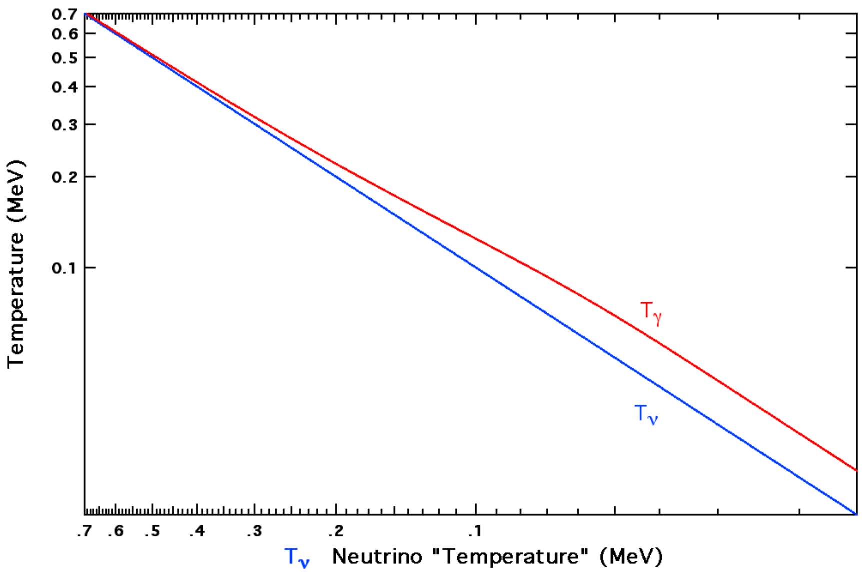
$$\Gamma \sim G_F^2 T^5 + \frac{a^2\pi}{6m_e^2}\mu_{eff}^2 T^3 \qquad \text{(reaction rate)}$$

$$H \sim \frac{T^2}{M_p} \qquad \text{(expansion rate)}$$

$$\Gamma \sim H \quad \Longrightarrow \quad \boxed{T^3 + \frac{1}{G_F^2}\frac{a^2\pi}{6m_e^2}\mu_{eff}^2 T - \frac{1}{G_F^2 M_p} \sim 0}$$

Check of Working Non-Zero μ_ν in BBN

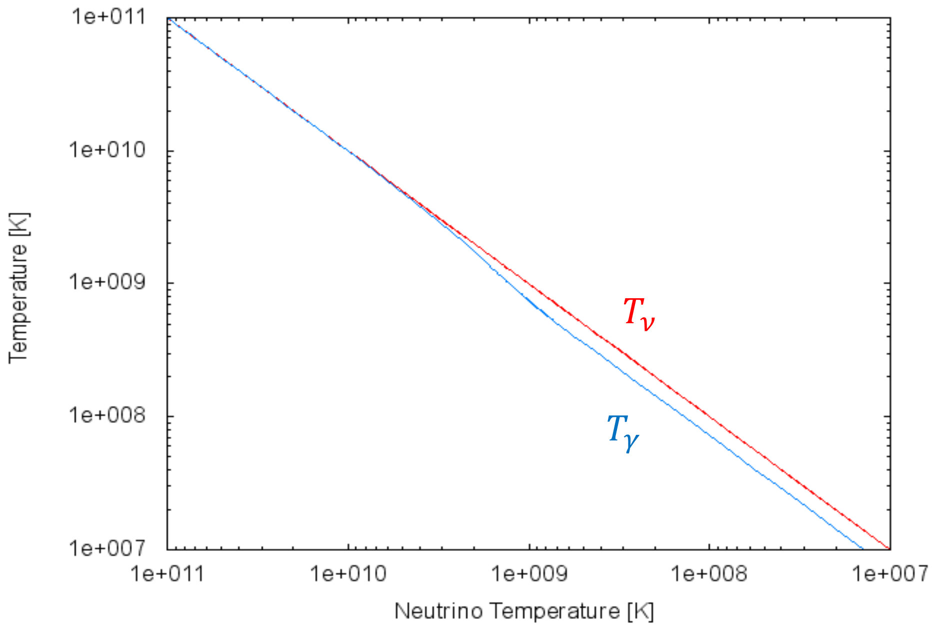
$$\mu_\nu = 0$$



From G.Fuller lecture ii.weakuniverse

$$T_\nu^{decoup} \sim 0.2\ MeV = 2\ GK$$

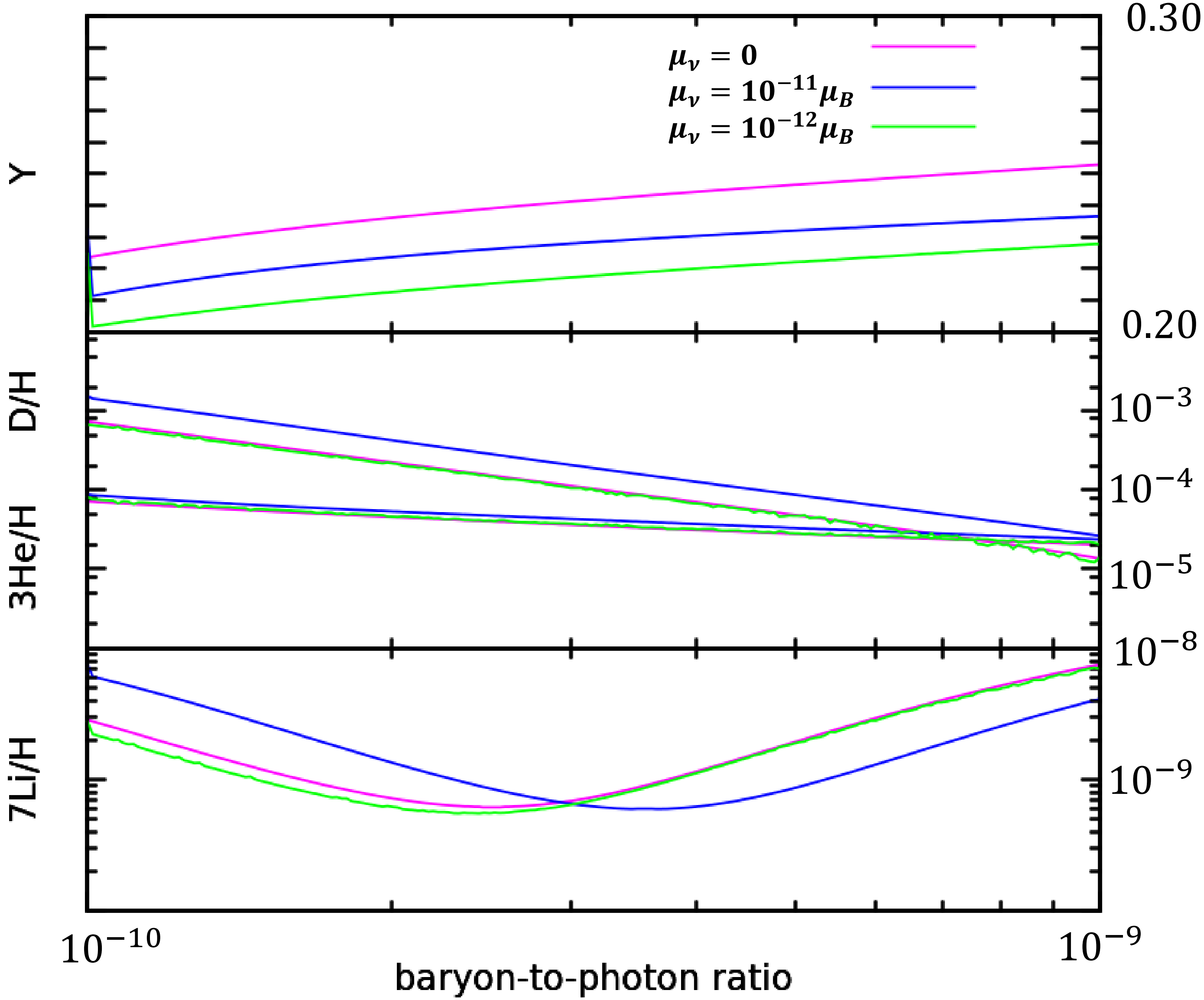
$$\mu_\nu = 10^{-12}\mu_B$$



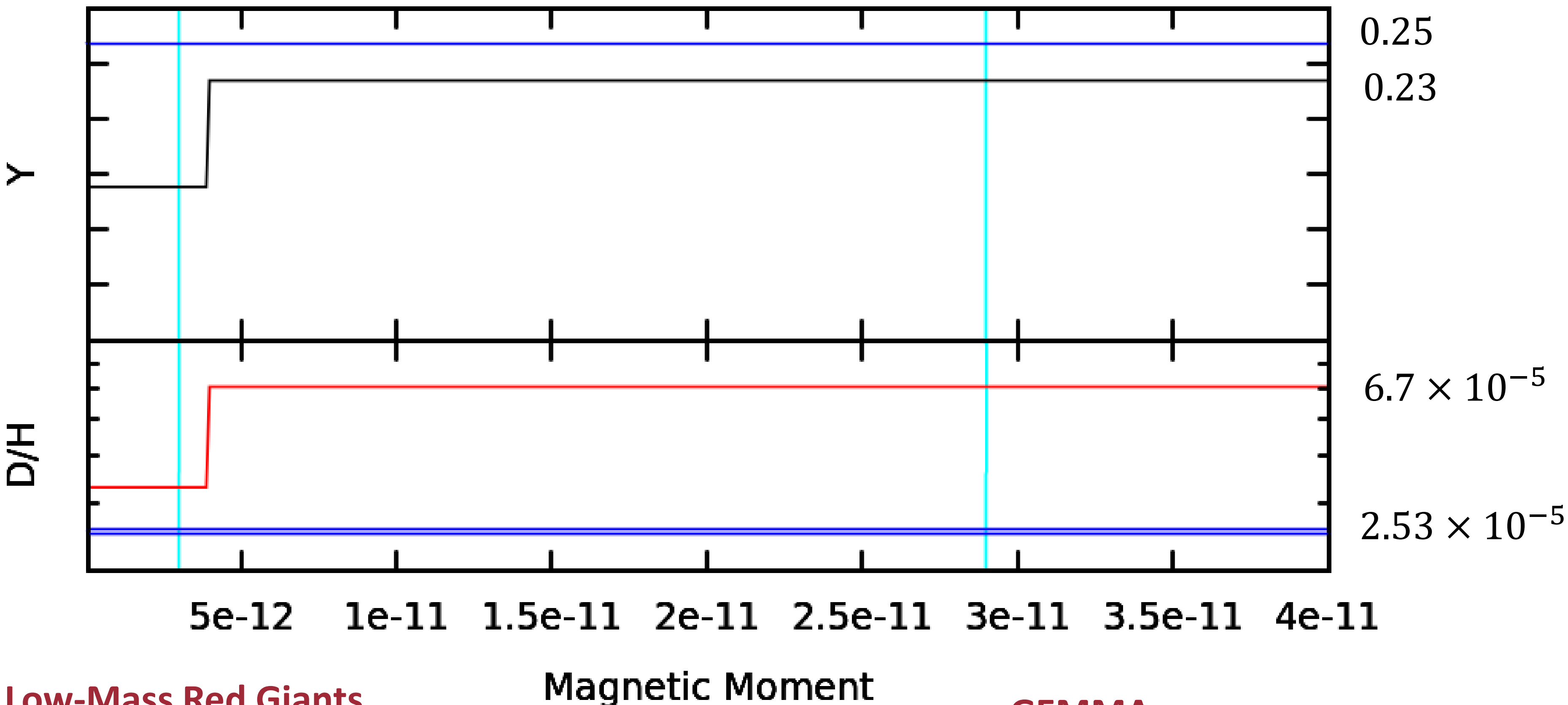
WGV Results using BBN Code

$$T_\nu^{decoup} \sim 1.5\ GK$$

Schramm Plot Results



Limits on μ_ν Using Observed Abundances



Low-Mass Red Giants

$\mu_\nu \lesssim 3 \times 10^{-12} \mu_B$

[Raffelt Phys.Rep. 320]

GEMMA

$\mu_\nu \lesssim 2.9 \times 10^{-11} \mu_B$

Conclusions

- Although BBN code is a 30,000 line nightmare, we were (with help) able to find where to adjust the code and successfully produce reasonable results but a few unexpected features to examine further
- As expected non-zero magnetic moment effected abundances, particularly ^{4}He and D
- Using BBN code could allow to find a limit on the neutrino magnetic moment and thus BSM neutrino interactions

Thanks to all the Jina TALENT 2014 Organizers!!!

Implementing Non-zero μ_ν in BBN Code

```
! initialization of the quadrature abcissas and weights
      if (ifirst .eq. 0) then
       ifirst = 1
       call bb_gauleg(ylo,yhi,xquad,wquad,nquad)

! a constant that depends on the number of neutrino families
       con1 = xnnu * 7.0d0/8.0d0
      end if



! don't do any integration if x is large enough
  !    if (x .gt. 50.0) then
  !     wien2 = 1.0d0 + con1*con2**fthirds

! do the integration
      !else
       xcom = x
       planckiemass = 1.0d22
       gfermico = 1.0d-11

       magmomplease = 1.0d-12

       sigmasofine =((1.0/137.0)*(1.0/137.0)*3.14/(6.*0.511*0.511))*(magmomplease**2)
       firsties = (0.5/(planckiemass*gfermico*gfermico))
       termie1 =  (1.0/27.0)*((sigmasofine**3)/(gfermico**2))
       termie2 = (0.25d0/(planckiemass**2))
       secondies = (1.0/(gfermico*gfermico))*sqrt(termie1+termie2)

       Tnewdecoup = (((firsties+secondies)**third) + ((firsties-secondies)**third))
       bazinga = 0.511/Tnewdecoup


!      call bb_qromb(func2,ylo,yhi,tol,f2)
       call bb_qgaus(func2,xquad,wquad,nquad,f2)
       !wien2 = 1.0d0 + con1 * (con2 * wien1(x))**fthirds + con3 * f2
       wien2 = 1.0d0 + con1 * (min(1.0d0,(wien1(x)/wien1(bazinga))))**fthirds + con3 * f2
      !end if

      return
      end
```