

# New Process for Charged Lepton Flavor Violation Searches:

## $\mu^- e^- \rightarrow e^- e^-$ in a muonic atom

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with

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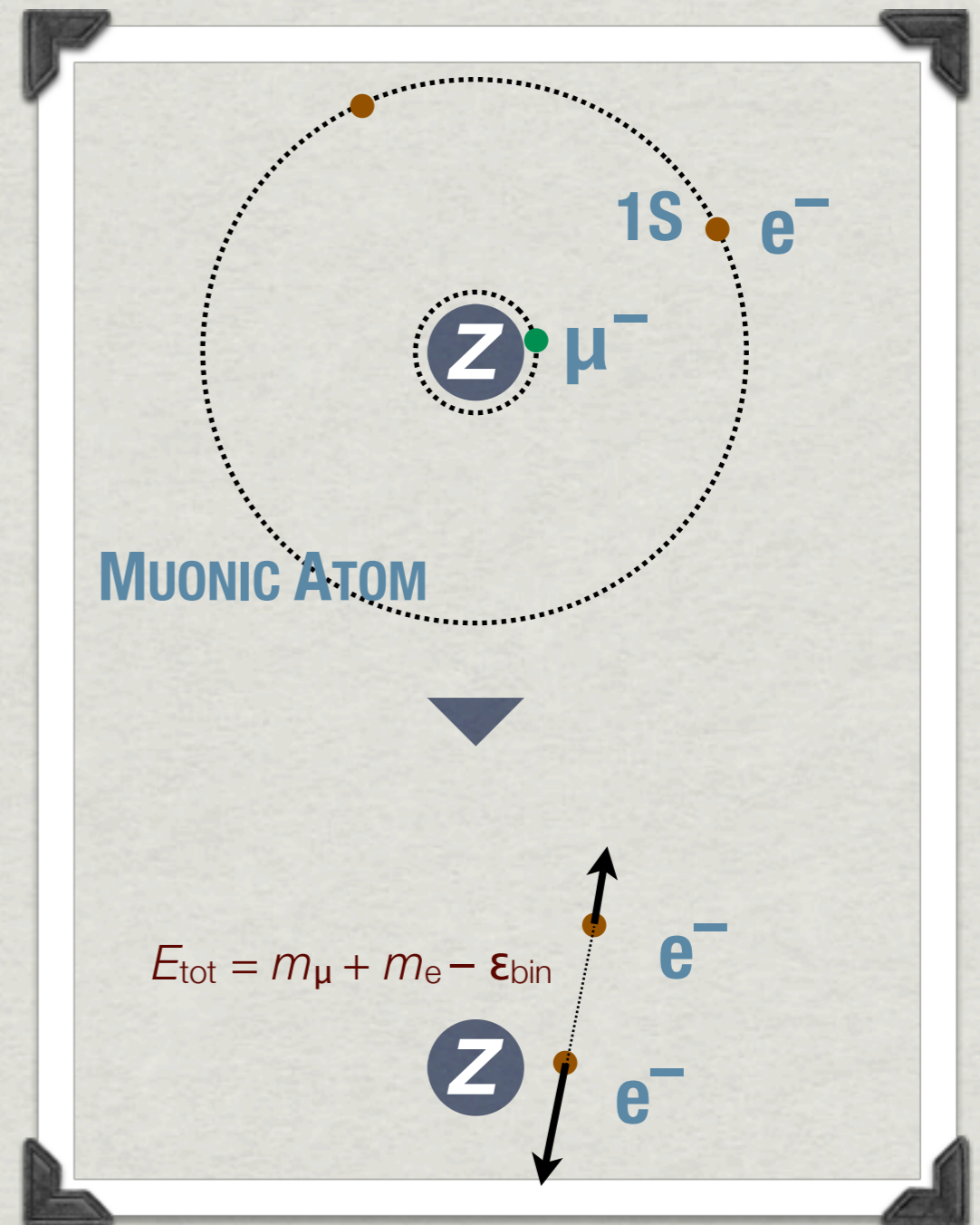
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# Outline

- \* New CLFV process:  $\mu^- e^- \rightarrow e^- e^-$  in the atomic orbital
- \*  $E_{\text{tot}} = m_\mu + m_e - \epsilon_{\text{bin}}$
- \* **Heavy nuclei**, large Coulomb attraction  **favored**
- \* Enhances the transition probability by  $(Z - 1)^3$
- \* Limits from other CLFV searches are estimated





# Lepton Flavor Violation

- \* Direct search for the New Physics
- \* Various channels, complementary to each other

Channel	Br	Record Holder
$\mu^+ \rightarrow e^+ \gamma$	$< 1.2 \times 10^{-11}$	MEGA (1999)      MEG (2011) ?
$\mu^+ \rightarrow e^+ e^+ e^-$	$< 1.0 \times 10^{-12}$	SINDRUM (1988)
$\mu^- \text{Au} \rightarrow e^- \text{Au}$	$< 7 \times 10^{-13}$	SINDRUM II (2006)

PDG 2008

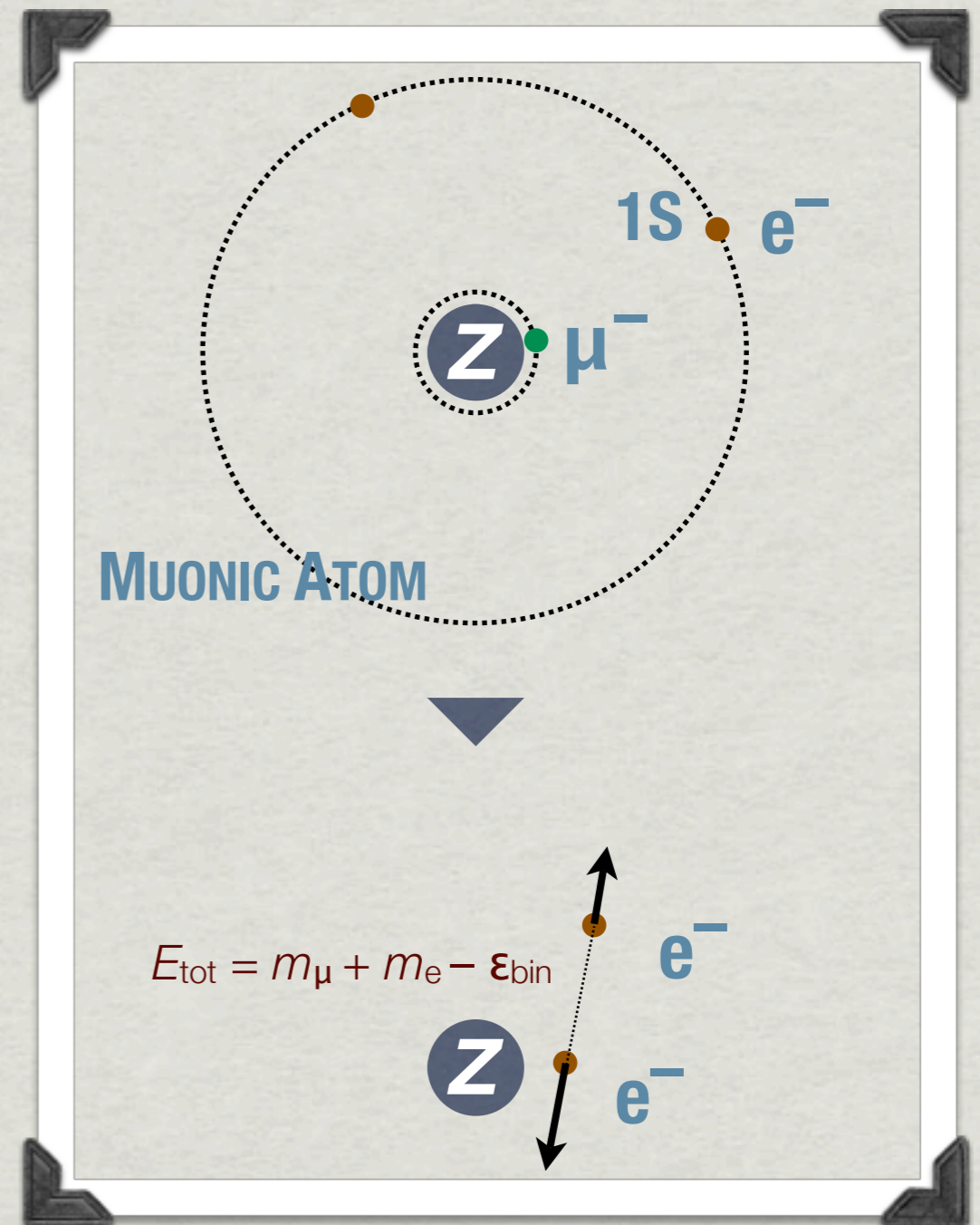
- \* Next gen. (and beyond) **muon** sources offer new opportunities

Project	Intensity Reach
COMET / PRISM	$10^{18} - 10^{19} \mu/\text{year}$
$\nu$ factories	$10^{21} \mu/\text{year}$



# A New Process: $\mu^- e^- \rightarrow e^- e^-$

- \* Same elementary process as  $\mu^+ \rightarrow e^+ e^+ e^-$
- \* Photonic, non-photonic interactions
- \* Initial muons are negatively charged
- \* Two-body final state
  - \*  $E_{\text{tot}} = m_\mu + m_e - \epsilon_{\text{bin}}$





# Initial and Final States

- \* Initial State

- \* Non-relativistic 1S state

- \* Final State

- \* Plane wave
- \* Equal energy,  $E = (m_\mu + m_e)/2$
- \* Back-to-back momenta

- \*  $\Gamma(\mu^- e^- \rightarrow e^- e^-) = 2\sigma v_{\text{rel}} |\psi^{(e)}_{1S}(0; Z - 1)|^2$



# Effective Lagrangian

Y.KUNO & Y.OKADA, REV. MOD. PHYS. 73,151 (2001)

## PHOTONIC INTERACTIONS

$$\begin{aligned}
 \mathcal{L}_{\mu^- e^- \rightarrow e^- e^-} = & -\frac{4G_F}{\sqrt{2}} \left[ m_\mu A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L \bar{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu} \right. \\
 & + g_1 (\bar{\mu}_R e_L) (\bar{e}_R e_L) + g_2 (\bar{\mu}_L e_R) (\bar{e}_L e_R) \\
 & + g_3 (\bar{\mu}_R \gamma^\mu e_R) (\bar{e}_R \gamma_\mu e_R) + g_4 (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_L \gamma_\mu e_L) \\
 & + g_5 (\bar{\mu}_R \gamma^\mu e_R) (\bar{e}_L \gamma_\mu e_L) + g_6 (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_R \gamma_\mu e_R) \\
 & \left. + (\text{H.c.}) \right]
 \end{aligned}$$

## FOUR-FERMI INTERACTIONS



# Four-Fermi Interactions

## BRANCHING RATIO

$$\text{Br}(\mu^- e^- \rightarrow e^- e^-)$$

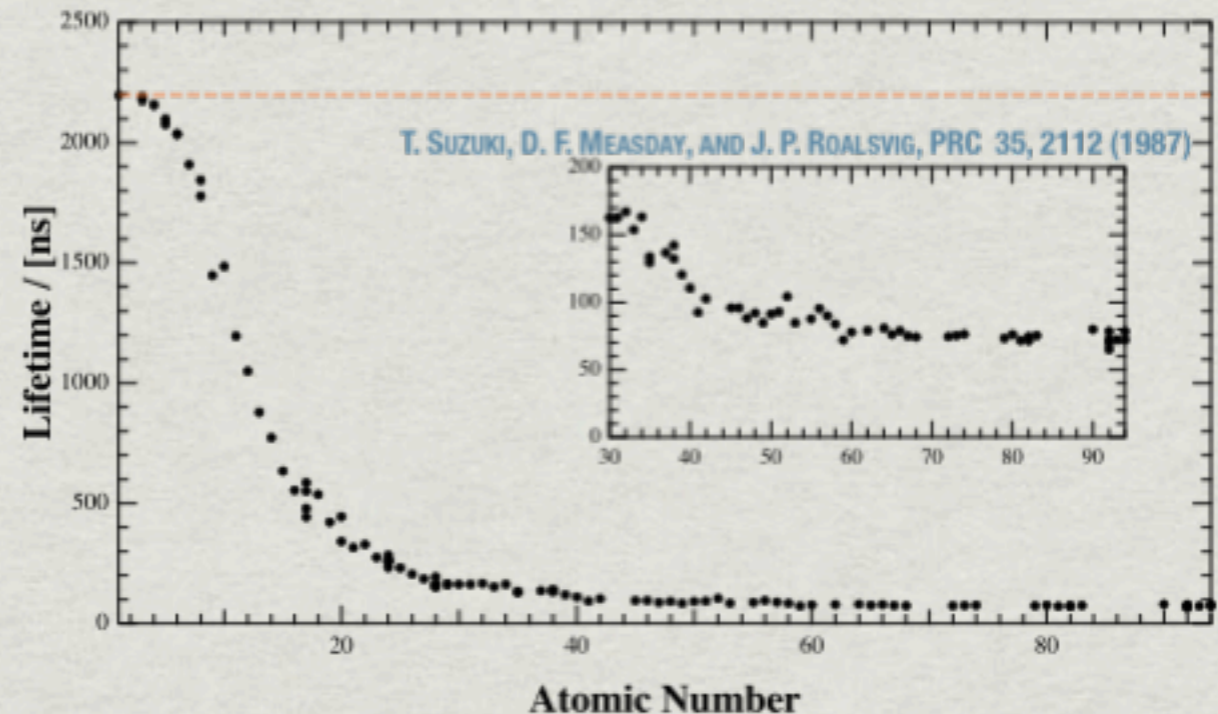
$$\equiv \tilde{\tau}_\mu \Gamma(\mu^- e^- \rightarrow e^- e^-)$$

VS. BOUND MUON LIFETIME

$$= 24\pi (Z - 1)^3 \alpha^3 \left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu} G$$

$$G = G_{12} + 16G_{34} + 4G_{56} + 8G'_{14} + 8G'_{23} - 8G'_{56}$$

$$G_{ij} \equiv |g_i|^2 + |g_j|^2 \quad G'_{ij} \equiv \text{Re}(g_i^* g_j)$$





# Four-Fermi Interactions

$$\text{Br}(\mu^- e^- \rightarrow e^- e^-) = 24\pi(Z-1)^3 \alpha^3 \left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu} G$$

## LIMIT FROM $\mu^+ \rightarrow e^+ e^+ e^-$

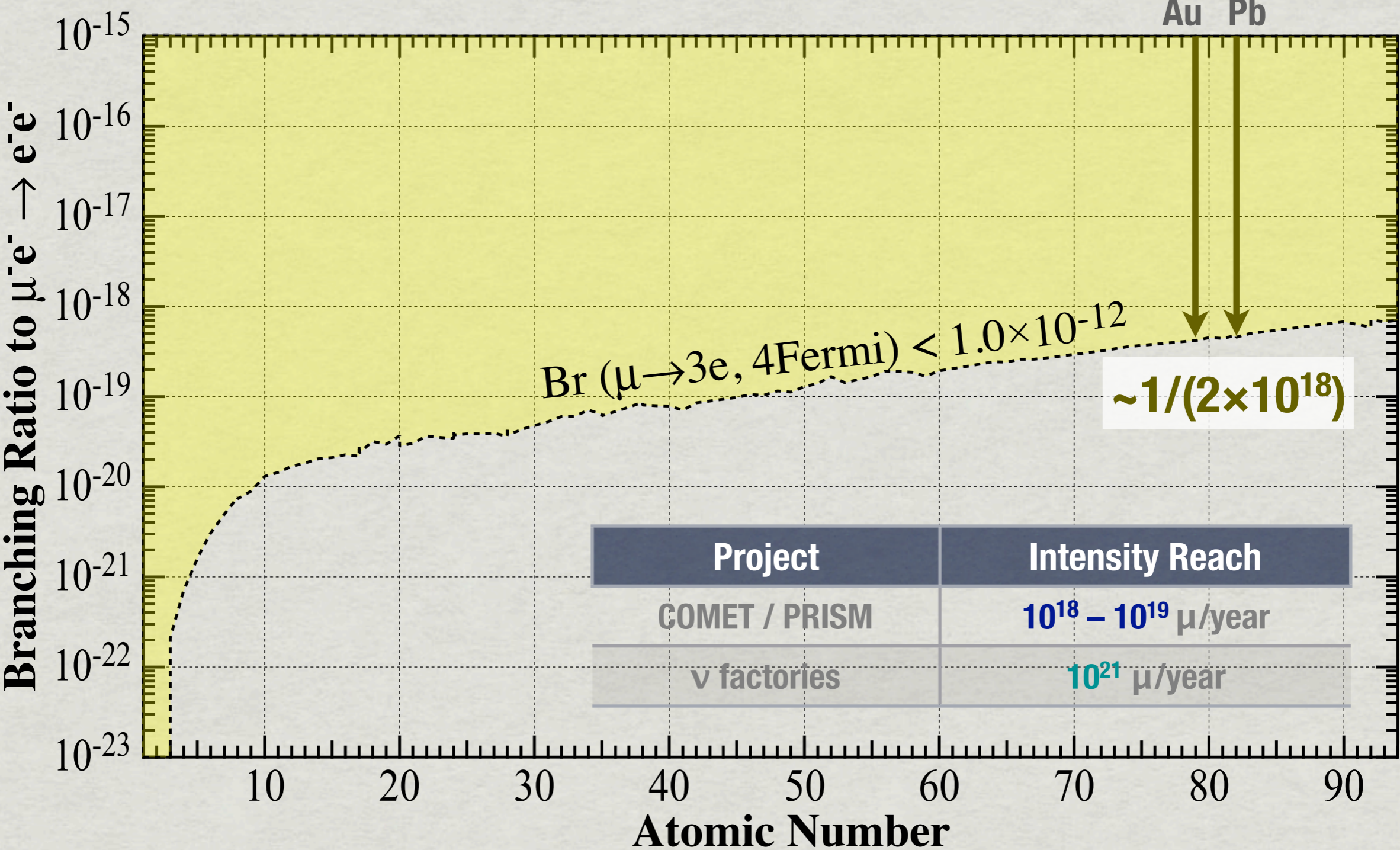
$$\text{Br}(\mu^+ \rightarrow e^+ e^+ e^-) = \frac{1}{8}(G_{12} + 16G_{34} + 8G_{56}) < B_{\text{max}}^{\mu \rightarrow 3e} = 1.0 \times 10^{-12}$$

[SINDRUM (1988)]

➔  $\text{Br}(\mu^- e^- \rightarrow e^- e^-) < 192\pi(Z-1)^3 \alpha^3 \left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu} B_{\text{max}}^{\mu \rightarrow 3e}$

assuming  $G/(G_{12}+16G_{34}+8G_{56}) \sim O(1)$







# Photonic Interactions

$$\text{Br}(\mu^- e^- \rightarrow e^- e^-) = 1536\pi^2 (Z - 1)^3 \alpha^4 (|A_R|^2 + |A_L|^2) \frac{m_e}{m_\mu} \frac{\tilde{\tau}_\mu}{\tau_\mu}$$

## LIMIT FROM $\mu^+ \rightarrow e^+ e^+ e^-$

$$\text{Br}(\mu^+ \rightarrow e^+ e^+ e^-) = 128\pi\alpha (|A_R|^2 + |A_L|^2) \left[ \log\left(\frac{m_\mu}{m_e}\right)^2 - \frac{11}{4} \right] < B_{\text{max}}^{\mu \rightarrow 3e} = 1.0 \times 10^{-12}$$

[SINDRUM (1988)]

➔  $\text{Br}(\mu^- e^- \rightarrow e^- e^-) < 12\pi (Z - 1)^3 \alpha^3 \frac{m_e}{m_\mu} \frac{\tilde{\tau}_\mu}{\tau_\mu} \left[ \log\left(\frac{m_\mu}{m_e}\right)^2 - \frac{11}{4} \right]^{-1} B_{\text{max}}^{\mu \rightarrow 3e}$

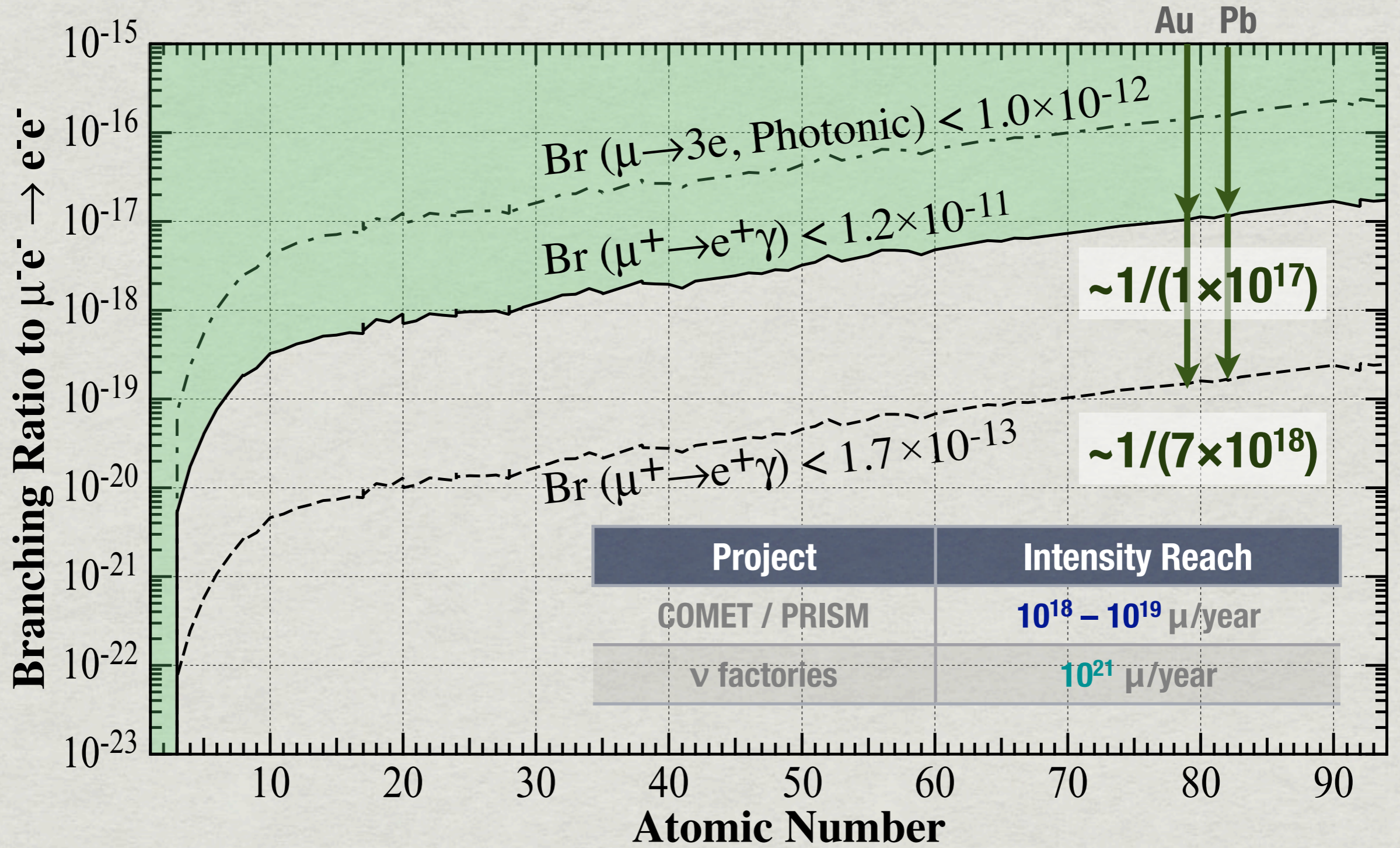
## LIMIT FROM $\mu^+ \rightarrow e^+ \gamma$

$$\text{Br}(\mu^+ \rightarrow e^+ \gamma) = 384\pi^2 (|A_R|^2 + |A_L|^2) < B_{\text{max}}^{\mu \rightarrow e\gamma} = 1.2 \times 10^{-11}$$

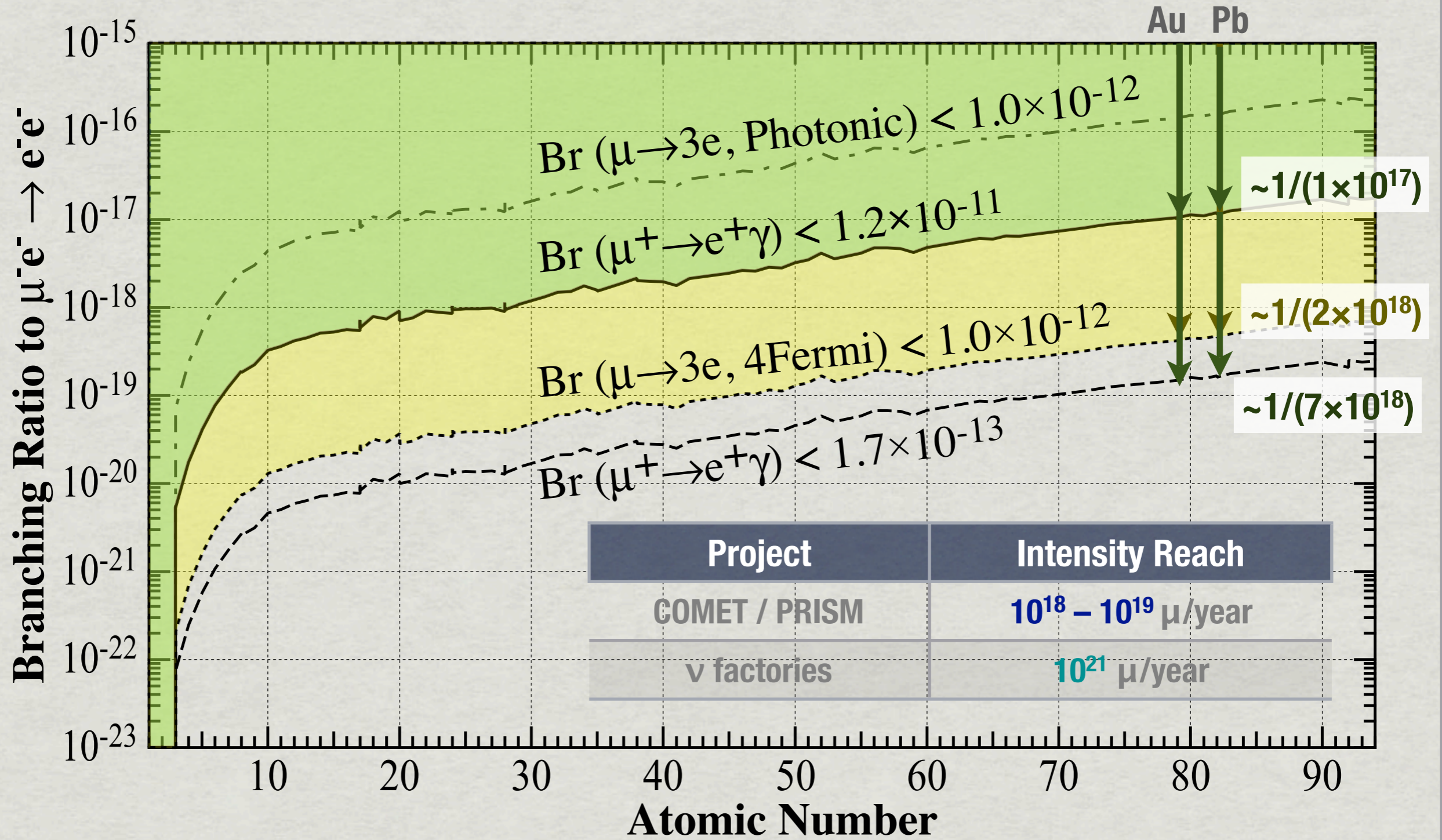
[MEGA (2002)]

➔  $\text{Br}(\mu^- e^- \rightarrow e^- e^-) < 4(Z - 1)^3 \alpha^4 \frac{m_e}{m_\mu} \frac{\tilde{\tau}_\mu}{\tau_\mu} B_{\text{max}}^{\mu \rightarrow e\gamma}$











# Elaborations awaited

- \* Bound effects
- \* Energy, momentum distribution of the final  $e^-$
- \* Nuclear charge distribution, relativistic effects
- \* Interaction between initial  $\mu^-$  and  $e^-$
- \* Contribution from  $nS$  electrons
- \* Standard Model backgrounds (chiefly  $\mu^-e^- \rightarrow e^-e^- \nu_\mu \bar{\nu}_e$ )



# Summary

- \*  $\mu^- e^- \rightarrow e^- e^-$ : Another channel for LFV search
- \* Elementary process same as  $\mu^+ \rightarrow e^+ e^+ e^-$ , but with opposite charge
- \* *Effective Interactions*: Photonic, non-photonic
- \* *Signal*:  $E_{\text{tot}} = m_\mu + m_e - \epsilon_{\text{bin}}$
- \* Heavy nuclei are favored,  $\text{Br} \sim (Z - 1)^3 (\tilde{\tau}_\mu / \tau_\mu)$
- \* Within the reach of high-intensity muon beams
- \* Awaits further elaboration