Resonant Flavor Oscillations:
A New Source for Electroweak Baryogenesis

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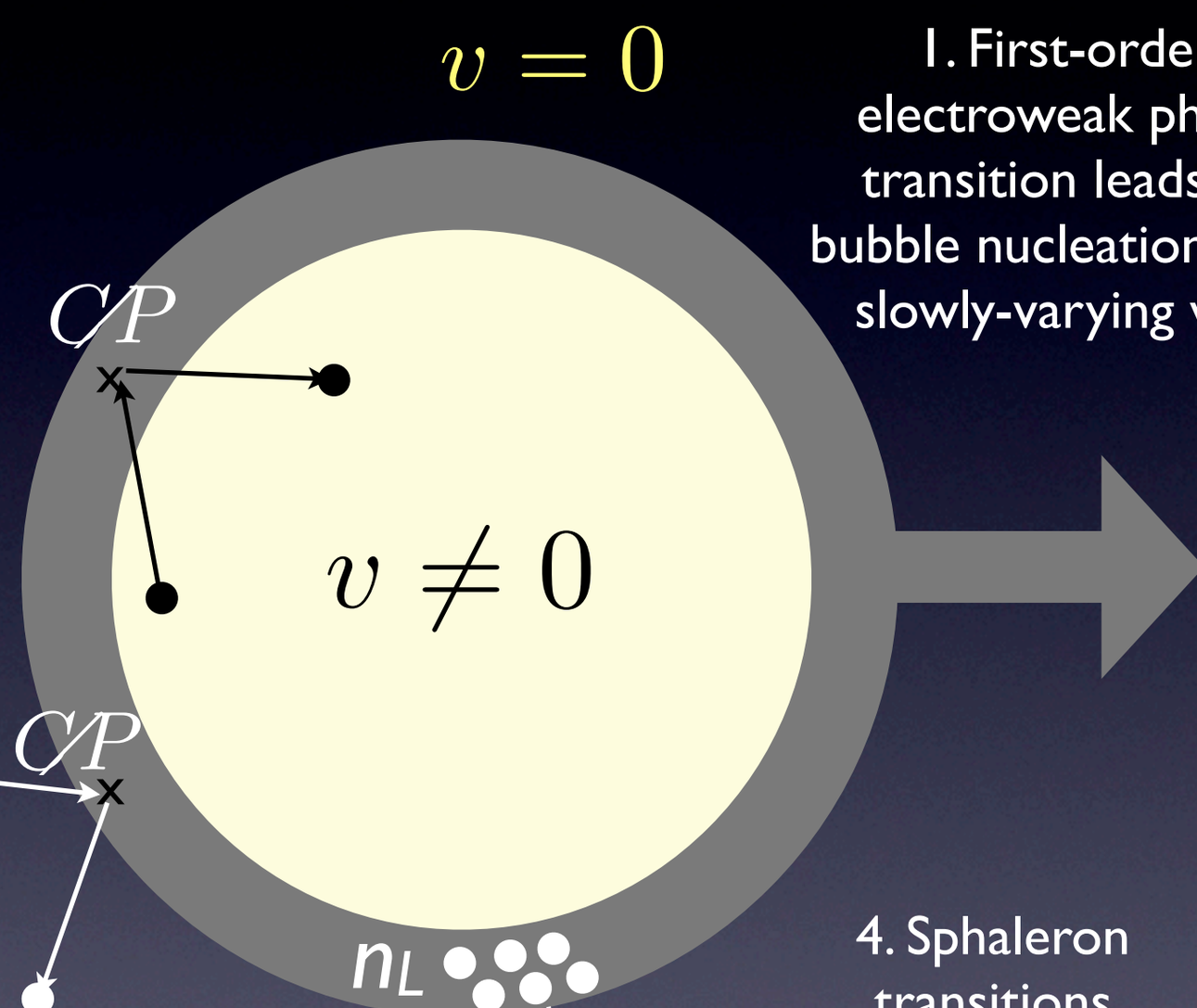
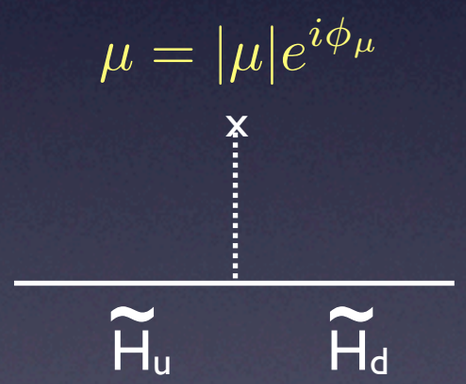
EWB in a Nutshell

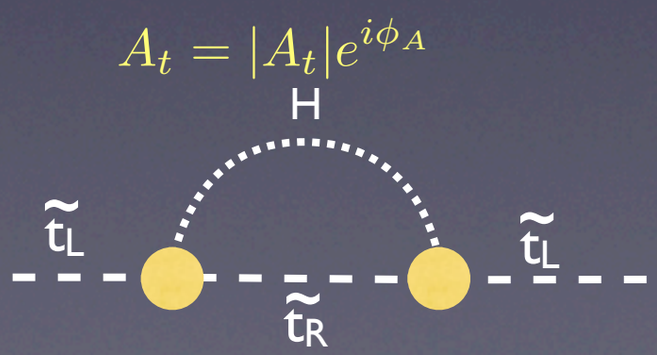
1. First-order electroweak phase transition leads to bubble nucleation with slowly-varying wall

2. Left- and right-handed particle and antiparticles scatter in bubble wall with CP-violating interactions

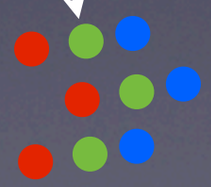


5. Expanding bubble subsumes baryon density and "locks in" to present day

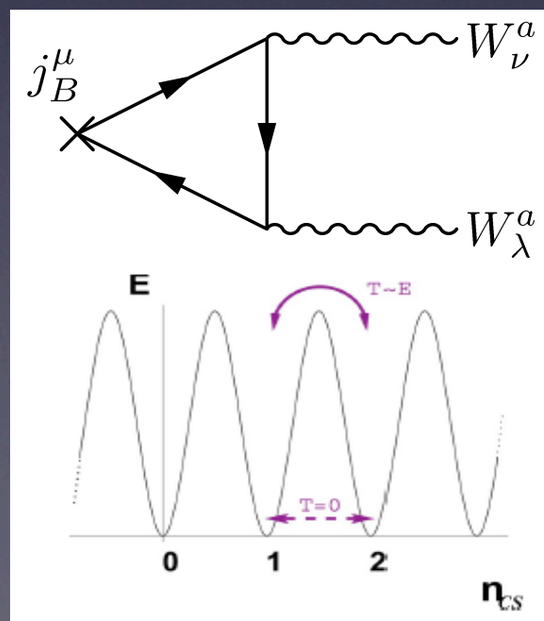




3. Excess left-handed density built up in wall, diffuses outside

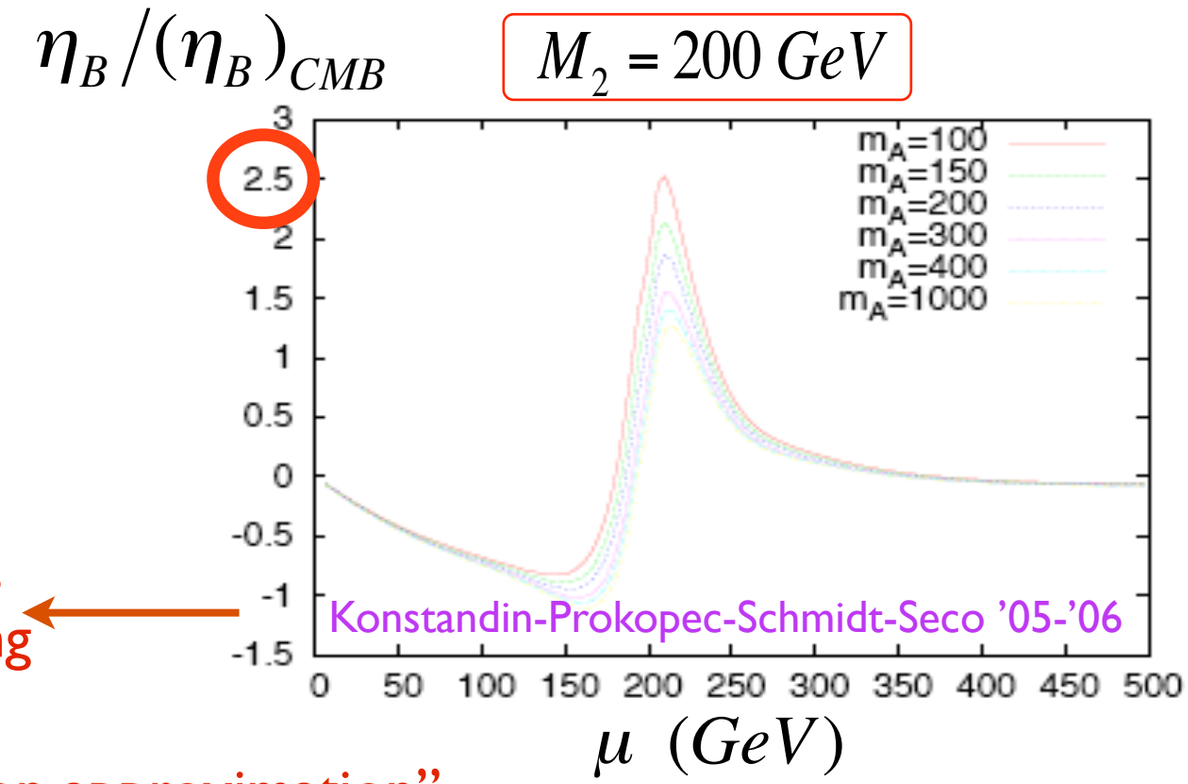


4. Sphaleron transitions convert n_L into B



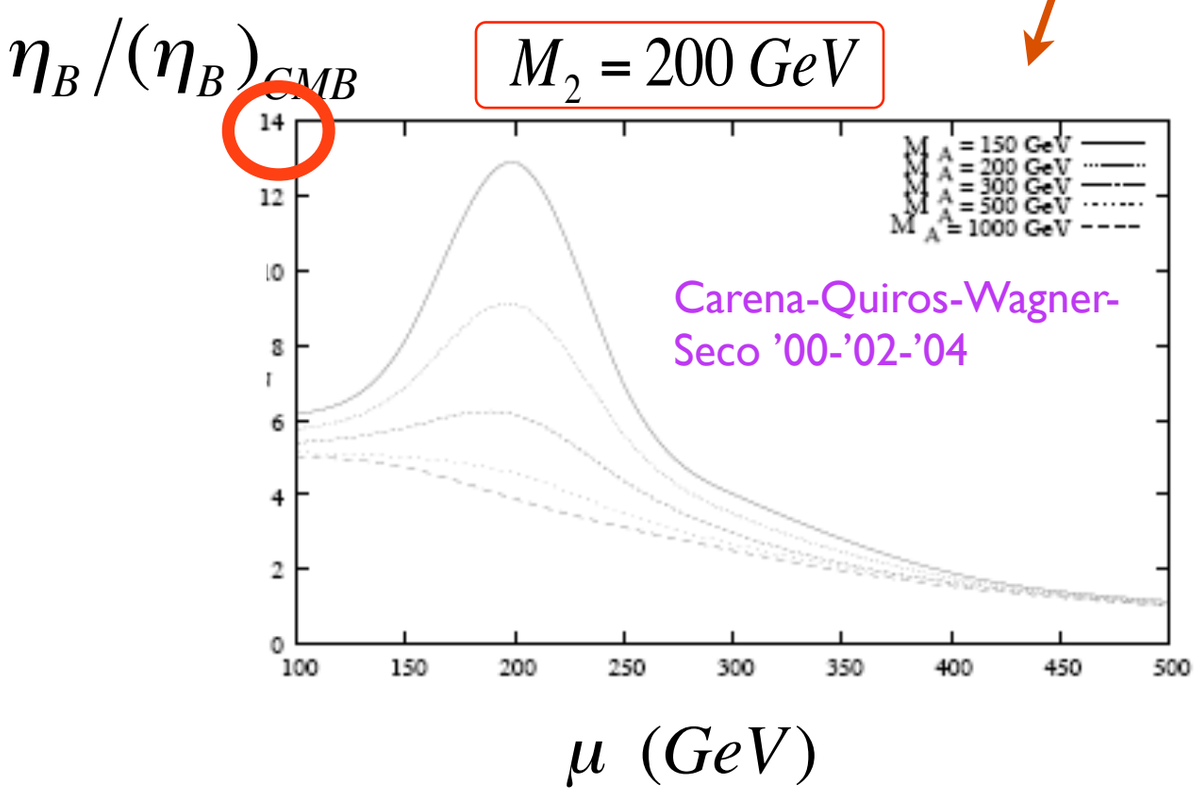
Status of transport calculations

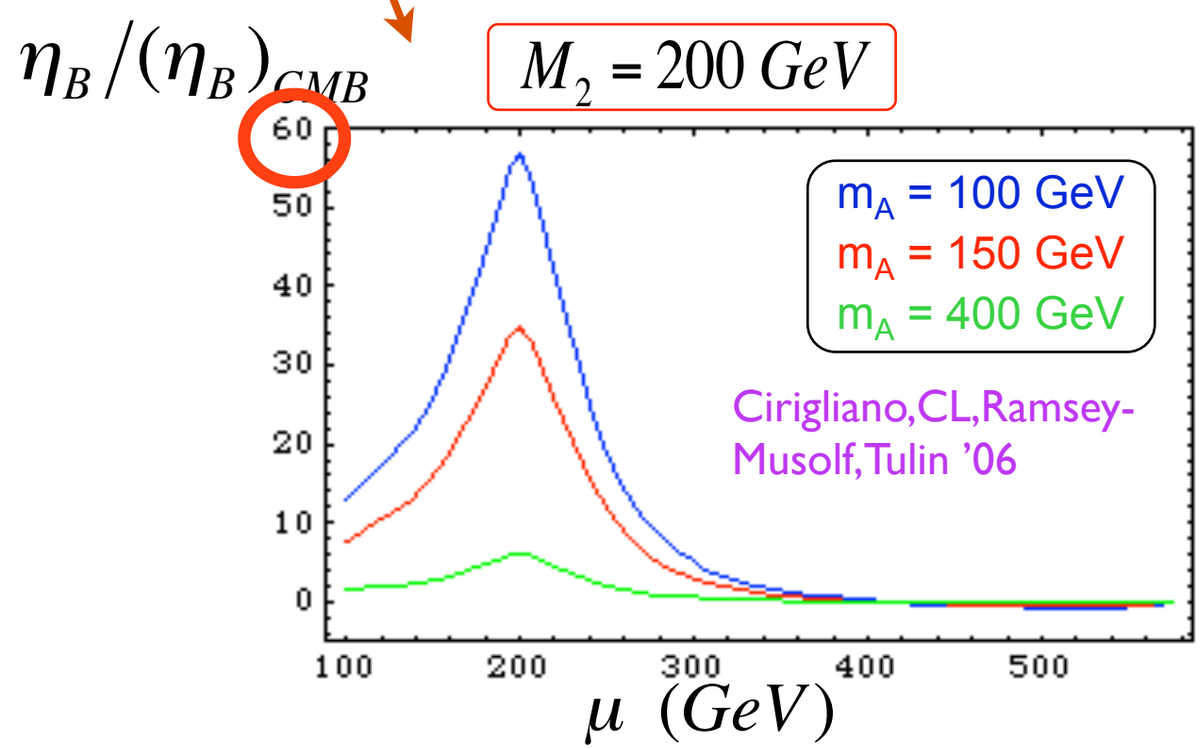
- SUSY: order of magnitude spread in existing results for n_B
- Dramatic implications for EWB viability



full quantum kinetic equations,
but questionable power counting

"vev insertion approximation"





Study quantum transport in simple 2-scalar model

$$\Phi = \begin{pmatrix} \Phi_L \\ \Phi_R \end{pmatrix}$$

e.g. Squarks in MSSM

$$\mathcal{L}(x) = \partial_\mu \Phi^\dagger \partial^\mu \Phi - \Phi^\dagger M^2(x) \Phi - \frac{1}{2} A^2 \Phi^\dagger y \Phi$$

CP-violating phase

$$M^2(x) = \begin{pmatrix} m_L^2 & v(x)e^{-ia(x)} \\ v(x)e^{ia(x)} & m_R^2 \end{pmatrix}$$

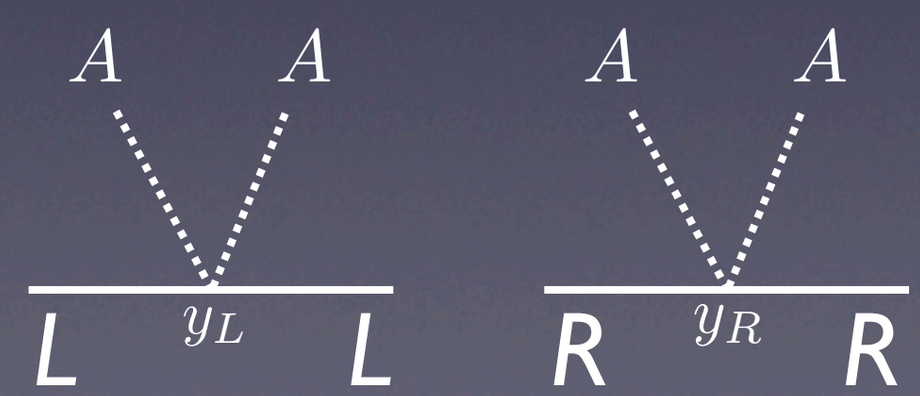
"Flavor basis"

$$y = \begin{pmatrix} y_L & 0 \\ 0 & y_R \end{pmatrix}$$

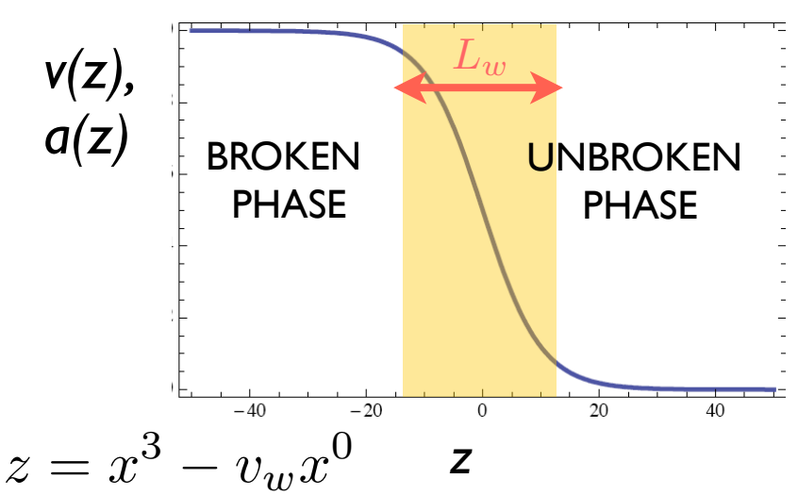
a(x) must vary with *x* for nontrivial CP violation

system exhibits **CP violating flavor oscillations**

interaction with thermal bath leads to equilibration



Model for Higgs vev profile in "bubble wall":



Rotate to Mass Basis

"Mass basis" $\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = U^\dagger \Phi$ → Rotation is **spacetime-dependent**!

$$U(x) = \begin{pmatrix} \cos\theta & -\sin\theta\, e^{-i\sigma} \\ \sin\theta\, e^{i\sigma} & \cos\theta \end{pmatrix}$$

$$\mathcal{L}(x) = \phi^\dagger(\overleftarrow{\partial}_\mu - \Sigma_\mu)(\partial^\mu + \Sigma^\mu)\phi - \phi^\dagger m^2(x)\phi - \frac{1}{2}A^2\phi^\dagger Y\phi$$

$$\Sigma_\mu = U^\dagger \partial_\mu U$$

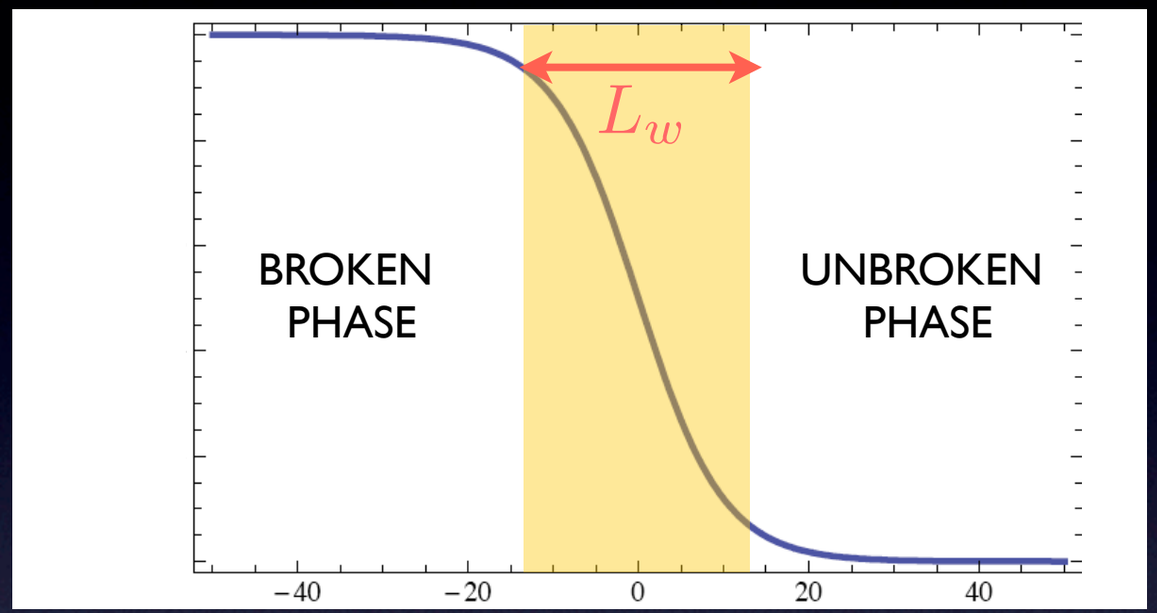
CP-violating "potential"

$$m^2(x) = \begin{pmatrix} m_1^2(x) & 0 \\ 0 & m_2^2(x) \end{pmatrix}$$

$$Y = U^\dagger y U$$

Hierarchy of length scales

V. Cirigliano, CL, M. Ramsey-Musolf, S. Tulin (2010)

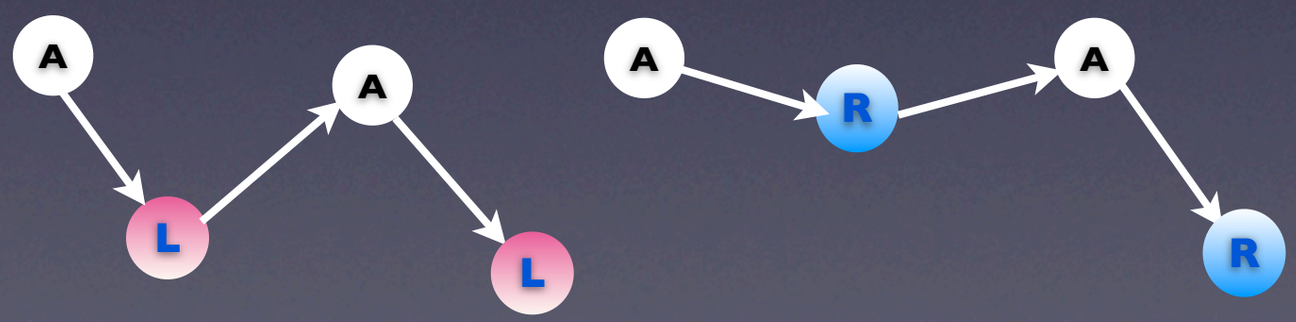


expansion parameter:

wall length L_w $\epsilon_w \sim \frac{1/T}{L_w}$

"gradient expansion"

flavor oscillation wavelength $L_{\rm osc}$ $\epsilon_{\rm osc} \sim \frac{1/T}{L_{\rm osc}}$



mean free path $L_{\rm coll}$ $\epsilon_{\rm int} \sim \frac{1/T}{L_{\rm coll}}$

$\gg$

de Broglie wavelength $\lambda \sim 1/T$

Kinetic Equations

V. Cirigliano, CL, S.Tulin (2011)

$$G_{ij}(k;X) = 2\pi\delta(k^2 - m_{ij}^2)[\theta(k^0) f_{ij}(\mathbf{k}, X) + \theta(-k^0)(\delta_{ij} + \bar{f}_{ij}(-\mathbf{k}, X))]$$

Green's functions

Particle densities

Anti-particle densities

$$v_{\rm rel}\partial_z \begin{pmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{pmatrix} = -i[\omega, f] - v_{\rm rel}[\Sigma_z, f] + C[f, \bar{f}]$$

$$v_{\rm rel} = \frac{k\cos\theta_{\mathbf{k}}}{\bar{\omega}_{\mathbf{k}}} - v_w$$

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$$-i(\omega_1 - \omega_2)\begin{pmatrix} 0 & f_{12} \\ -f_{21} & 0 \end{pmatrix}$$

off-diagonal oscillations at frequency $\sim (\omega_1 - \omega_2)$

$$v_{\rm rel} = \frac{k\cos\theta_{\mathbf{k}}}{\omega_{\mathbf{k}}} - v_w$$

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CPV potential couples diagonal and off-diagonal densities

$$\begin{pmatrix} \Sigma_{12} f_{21} - \Sigma_{21} f_{12} & -\Sigma_{12}(f_{11} - f_{22}) + (\Sigma_{11} - \Sigma_{22}) f_{12} \\ \Sigma_{21}(f_{11} - f_{22}) - (\Sigma_{11} - \Sigma_{22}) f_{21} & \Sigma_{21} f_{12} - \Sigma_{12} f_{21} \end{pmatrix}$$

→ CP-violating "source"

Previous Work

- Konstandin, Prokopec, Schmidt, Seco (2004-05) made set of approximations decoupling the components of the kinetic equation:

$$\begin{pmatrix} \Sigma_{12} f_{21} - \Sigma_{21} f_{12} & -\Sigma_{12}(f_{11}^{eq} - f_{22}^{eq}) + (\Sigma_{11} - \Sigma_{22}) f_{12} \\ \Sigma_{21}(f_{11}^{eq} - f_{22}^{eq}) - (\Sigma_{11} - \Sigma_{22}) f_{21} & \Sigma_{21} f_{12} - \Sigma_{12} f_{21} \end{pmatrix}$$

Logic:

- Since $f_{12,21}$ are nonzero only if wall is turned on, they must be $\mathcal{O}(\epsilon_w)$
- Thus drop terms of order ϵ_w^2
- Plug in equilibrium forms $n_B(k^0)$ for $f_{11,22}$ in off-diagonal equations
- Equations for diagonal and off-diagonal densities **decoupled**.

Flaw in the Logic

- Flaw: $f_{12,21}$ can be $\mathcal{O}(\epsilon_w^0)$

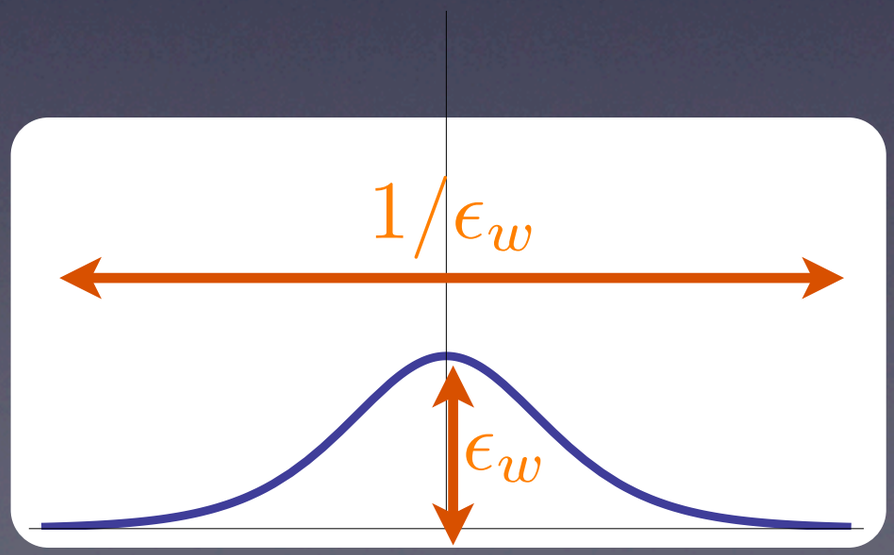
- Explicit solution of "decoupled" equations:

$$f_{12}(k;z) = \int_{-\infty}^{z} dz' \Sigma_{12}(z')[n_B(\omega_1) - n_B(\omega_2)](z')$$

$$\times \exp\left\{\int_{z'}^{z} dz''[-i\Delta\omega - v_{\rm rel}(\Sigma_{11} - \Sigma_{22}) + \Gamma_{12}](z'')\right\}$$

this is $\mathcal{O}(\epsilon_w)$

but integral is over a region of size $L_w \sim \dfrac{1}{\epsilon_w}$



Consistent Power Counting

Restore full source term in $\mathcal{O}(\epsilon_w)$ kinetic equation:

$$\begin{pmatrix} \Sigma_{12} f_{21} - \Sigma_{21} f_{12} & -\Sigma_{12}(f_{11} - f_{22}) + (\Sigma_{11} - \Sigma_{22}) f_{12} \\ \Sigma_{21}(f_{11} - f_{22}) - (\Sigma_{11} - \Sigma_{22}) f_{21} & \Sigma_{21} f_{12} - \Sigma_{12} f_{21} \end{pmatrix}$$

Our procedure:

- Solve full set of coupled equations for f_{ij}'s (numerically), making no assumption about their form or power counting.
- Only power count explicit prefactors or derivatives in equations of motion.
- Impose equilibrium boundary conditions far away from wall.

The Magnetic Analogy

Decompose 2x2 matrix of distributions in the basis:

$$f(k,z) = \begin{pmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{pmatrix} \equiv I p_0(k,z) + \vec{\sigma} \cdot \vec{p}(k,z)$$

total occupation — flavor "orientation"

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Kinetic Equations can be rewritten in the suggestive form:

particles $$\frac{d\vec{p}}{dt} = (\vec{B}_0 + \vec{B}_\Sigma) \times \vec{p} + C[f, \bar{f}]$$

antiparticles $$\frac{d\vec{\bar{p}}}{dt} = -(\vec{B}_0 - \vec{B}_\Sigma) \times \vec{\bar{p}} + C[\bar{f}, f]$$

Look like precession in a magnetic field! (with damping by collisions)

The Magnetic Analogy

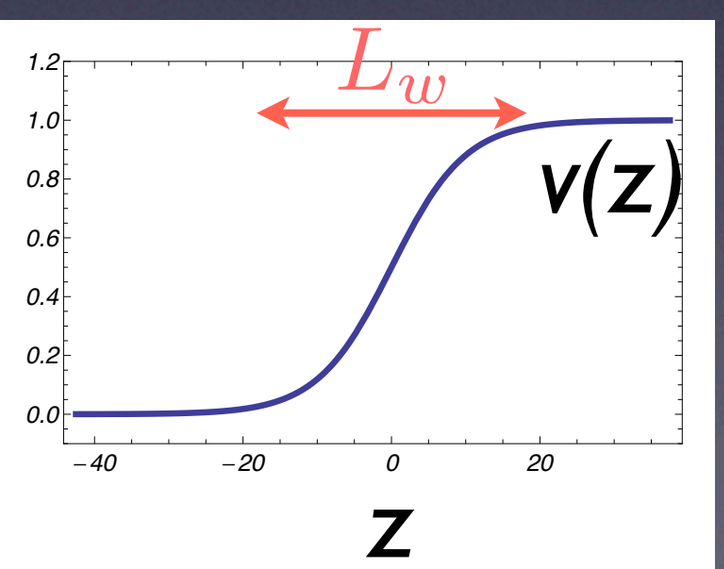
particles $$\frac{d\vec{p}}{dt} = (\vec{B}_0 + \vec{B}_\Sigma) \times \vec{p} + C[f, \bar{f}]$$

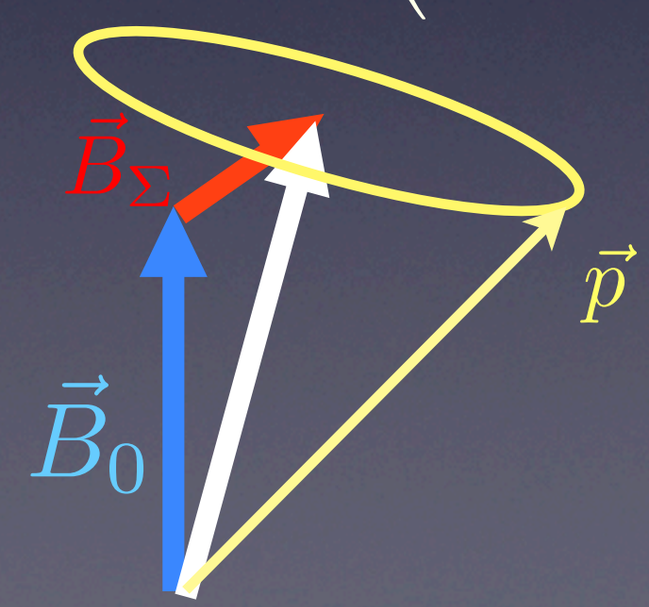
antiparticles $$\frac{d\vec{\tilde{p}}}{dt} = -(\vec{B}_0 - \vec{B}_\Sigma) \times \vec{\tilde{p}} + C[\bar{f}, f]$$

"Magnetic field" in z-direction in absence of wall: $\vec{B}_0 = (0, 0, \omega_1 - \omega_2)$

CP-violating "Magnetic field" generated by spacetime-varying wall:

$$\vec{B}_\Sigma = \begin{pmatrix} 2\sin\sigma\,\dot{\theta} + \sin 2\theta\,\cos\sigma\,\dot{\sigma} \\ -2\cos\sigma\,\dot{\theta} + \sin 2\theta\,\sin\sigma\,\dot{\sigma} \\ 2\sin^2\theta\,\dot{\sigma} \end{pmatrix}$$

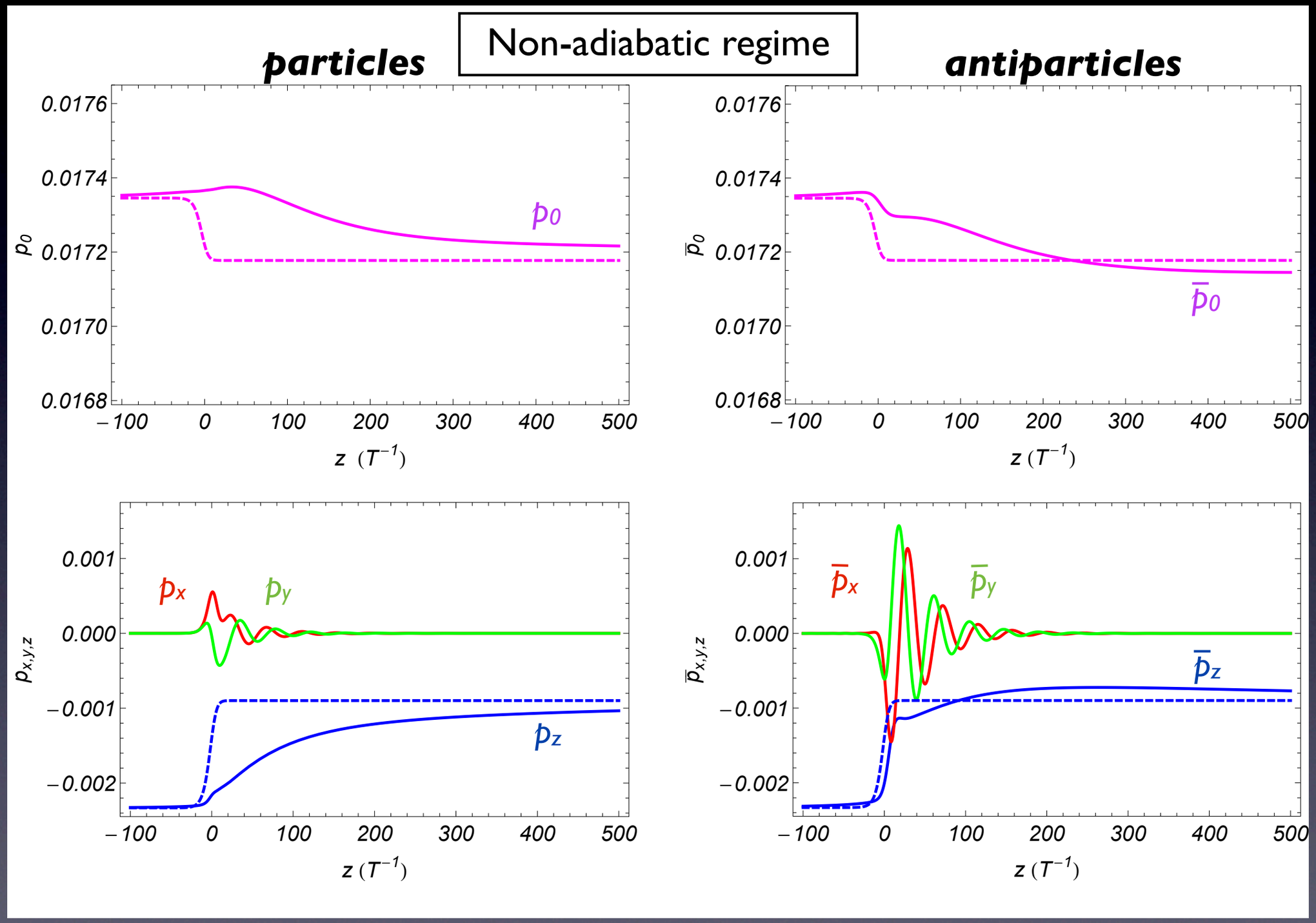




$p_{x,y} \Rightarrow f_{12,21}$

$p_0 \pm p_z \Rightarrow f_{11,22}$

Solutions for flavor polarizations



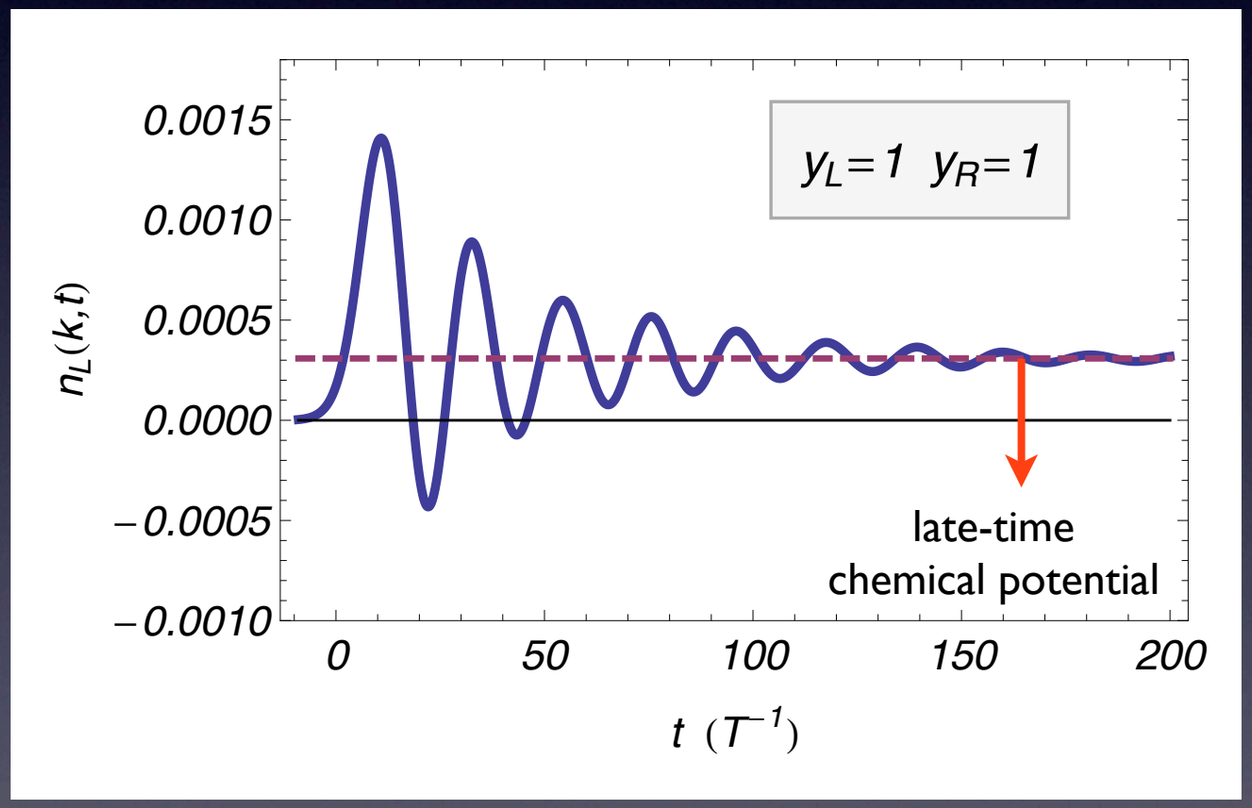
large oscillations in $p_{x,y}$, large deviations from equilibrium for $p_{0,z}$

Flavor-Blind Collisions, CP Violation

Start in CP-invariant, equilbrium initial state:

$$f = \bar{f} = \begin{pmatrix} n_B(\omega_1(k)) & 0 \\ 0 & n_B(\omega_2(k)) \end{pmatrix}$$

CP-Violating left-handed density in flavor basis

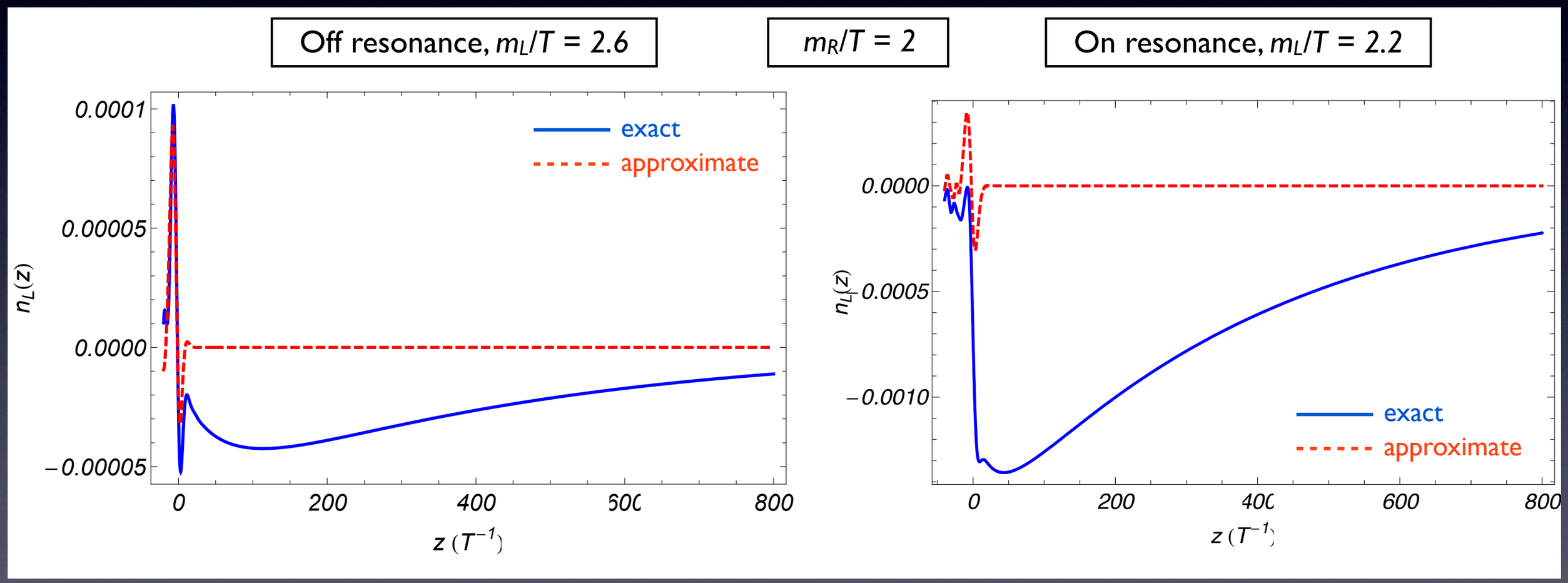


mL = 2.2 T, mR = 2 T

(plots of $k = 3T$ mode)

Comparison to previous work

- Exact and approximate solutions for flavor diagonal densities nL, nR exhibit large discrepancies outside bubble wall:



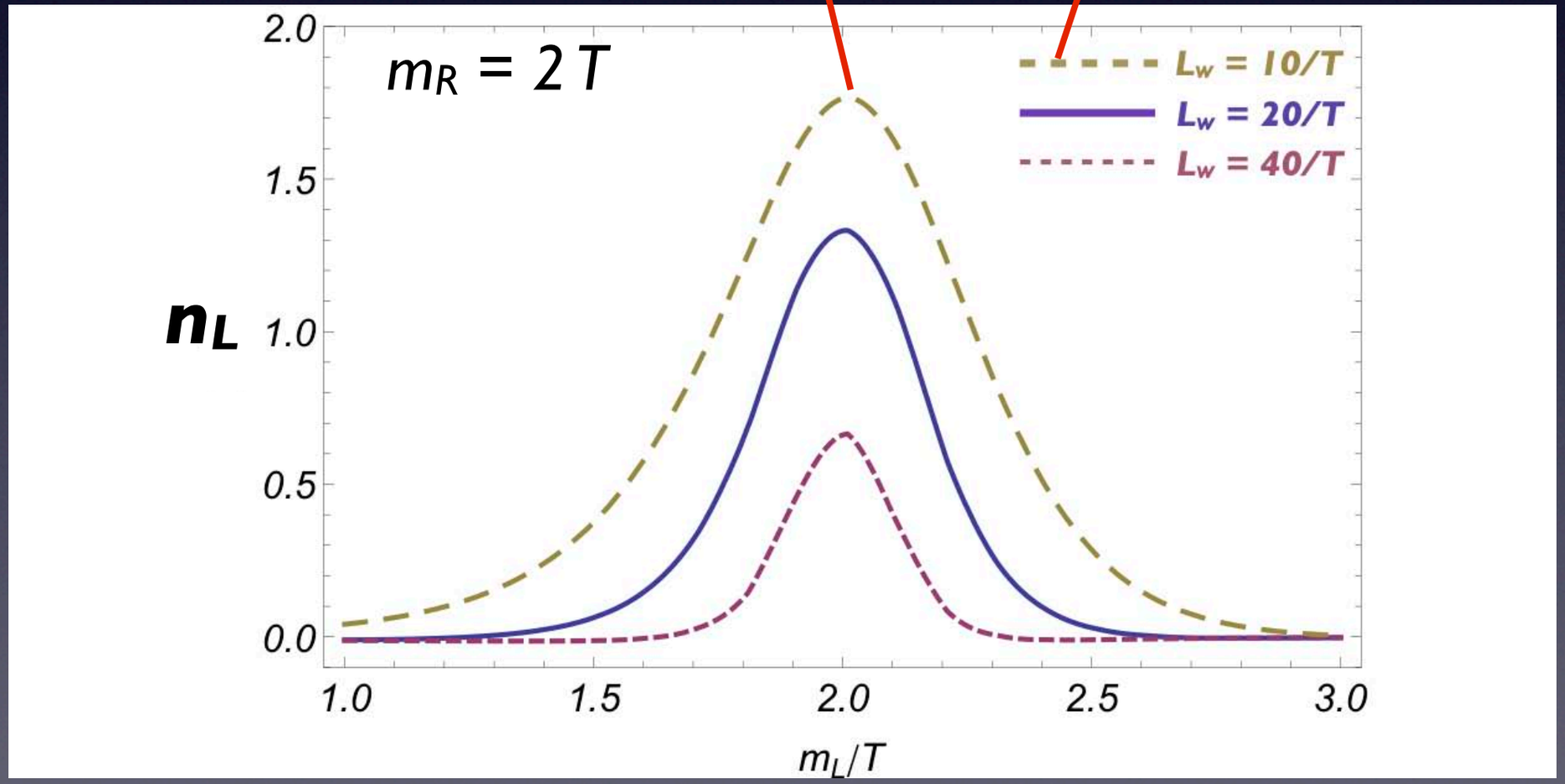
$$n_{L,R}(z) = \int d^3k(p_0 \pm p_z)(k,z)$$

Dependence on Mass Spectrum

Size of total integrated left-handed density generated outside the wall depends on mass spectrum:

resonant enhancement for $m_L = m_R$

smaller wall length leads to efficient "non-adiabatic" production



Status and Outlook

- Extension to fermions in progress
  - Then: conversion of left-handed fermion density into baryon density by sphalerons
  - Phenomenology in a realistic model of EWB
    - could already study squark-driven EWB
- Work in progress to converting full kinetic equations to simpler diffusion equations
  - Connect to earlier pre-2006 estimates
    - ***preliminary***: source for baryon asymmetry similar in size to our group's estimates from 2006 *V. Cirigliano, CL, E. Passemar (2013)*

Lessons Learned

- CP-violating flavor oscillations can be the largest source responsible for asymmetry in left-handed fermion density $\boldsymbol{n_L}$ and thus for BAU
- Maximal **resonant** generation of asymmetry for small mass differences and thus large oscillation wavelengths
- **Consistent power counting of full two-flavor distribution functions essential**
- **Most reliable predictions to date for quantum transport in EWB**

Additional Slides

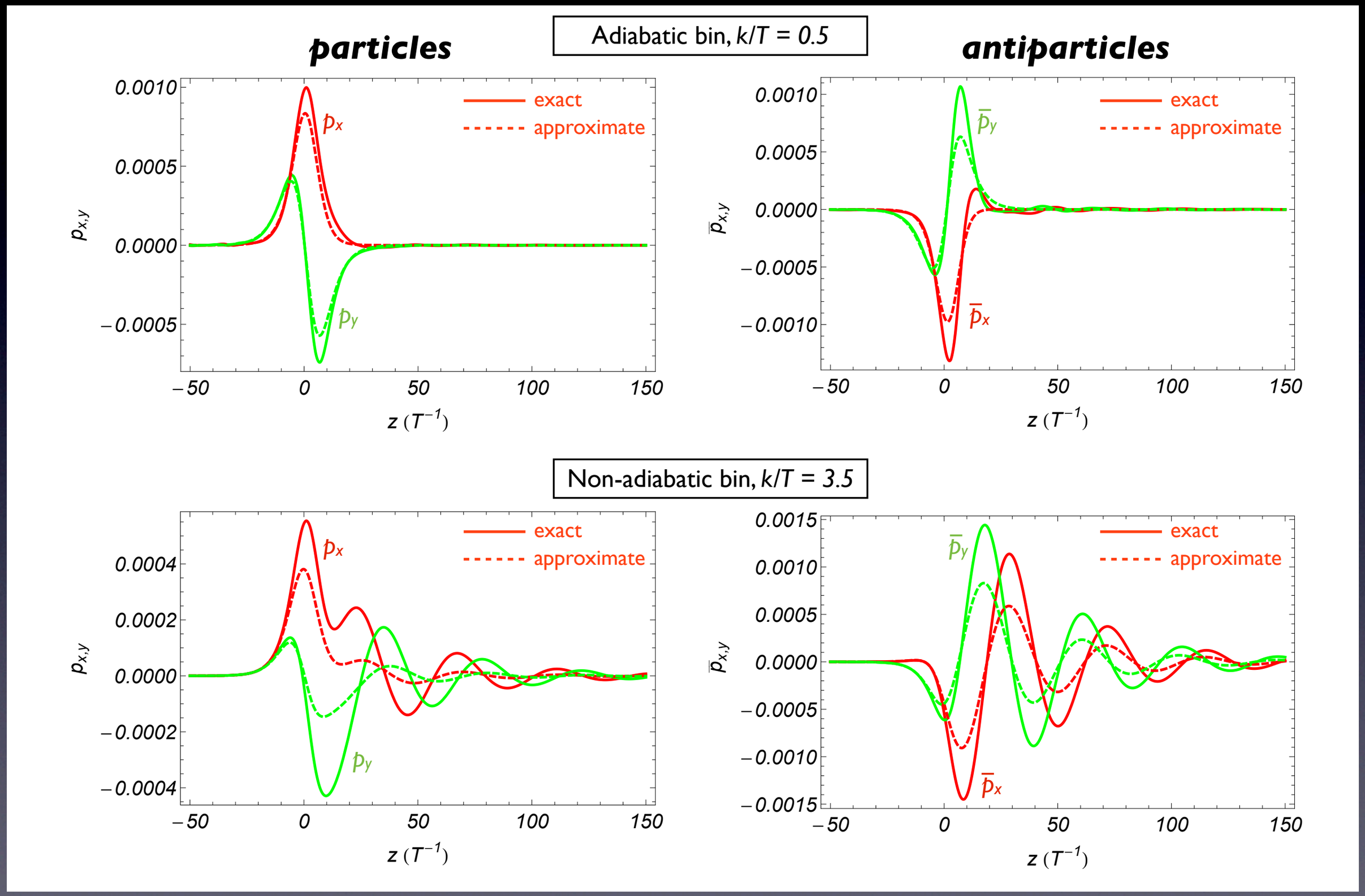
Viability of MSSM Baryogenesis

- First-order phase transition requires Higgs mass $m_H \lesssim 127 \text{ GeV}$ and a light stop $m_{\tilde{t}} \lesssim 120 \text{ GeV}$ Carena, Nardini, Quiros, Wagner

- LEP2 bound: $m_H \gtrsim 114 \text{ GeV}$
  - First-order EWPT with higher m_H possible with extra scalars (e.g. *next*-to-minimal supersymmetric extension of the Standard Model)

- CP-violating phases $\mu = |\mu| e^{i\phi_\mu}$ $A_t = |A_t| e^{i\phi_A}$ allowed by electric dipole moment searches to be large enough to generate $\eta \sim 6 \times 10^{-10}$

Comparison to previous work



solutions for $p_{x,y}$ agree slightly better

In terms of the Magnetic Analogy

$$\frac{d\vec{p}}{dt} = (\vec{B}_0 + \vec{B}_\Sigma) \times \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}$$

exact

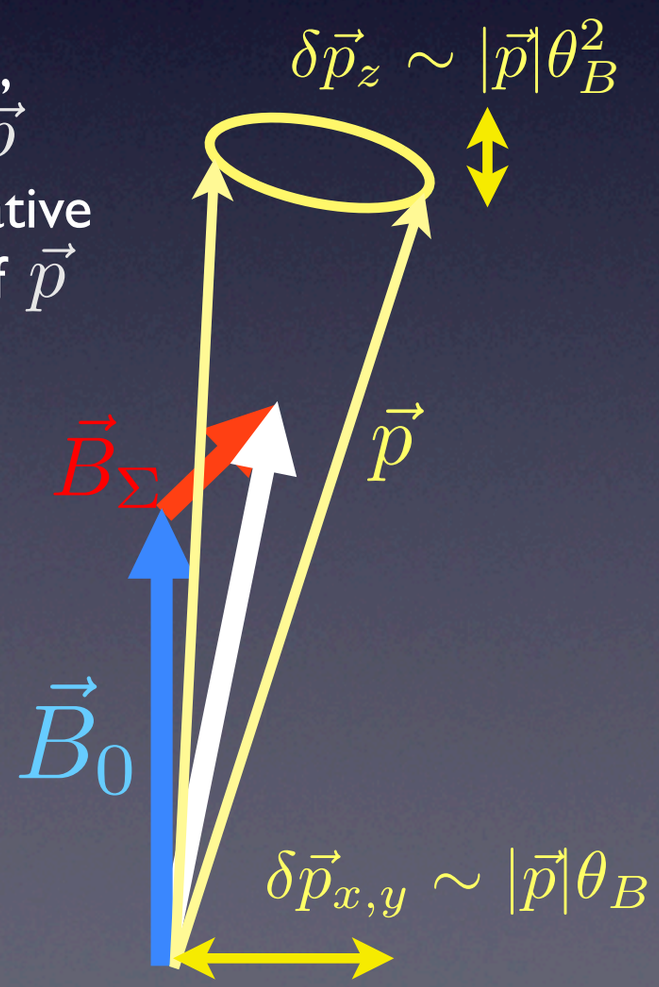
$$\frac{d\vec{p}}{dt} = \vec{B}_0 \times \begin{pmatrix} p_x \\ p_y \\ 0 \end{pmatrix} + \vec{B}_\Sigma \times \begin{pmatrix} 0 \\ 0 \\ p_z^{\rm eq} \end{pmatrix}$$

approx $\left(dp_z/dt = 0\right)$

"Magnetic field" in *z*-direction in absence of wall: $\vec{B}_0 = (0, 0, \omega_1 - \omega_2)$

If $B_\Sigma \ll B_0$, deviations in $\vec{p}$ are suppressed relative to magnitude of $\vec{p}$

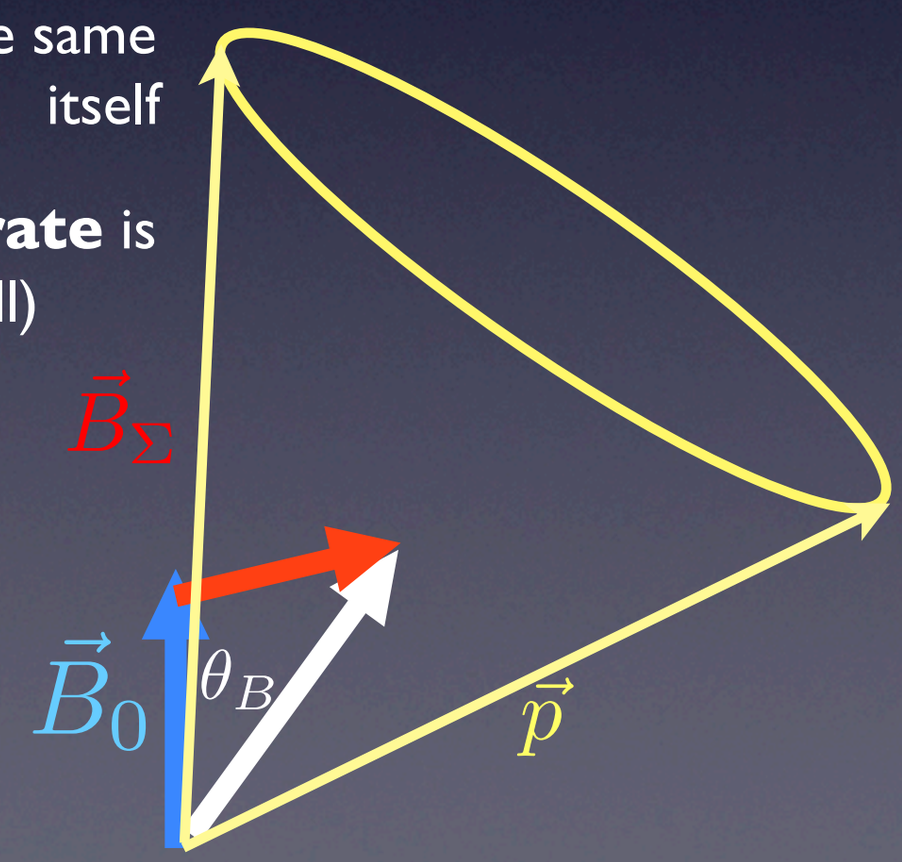
$$\theta_B \sim \frac{\epsilon_w}{\epsilon_{\rm osc}}$$



But if $B_\Sigma \sim B_0$, deviations are same order as $\vec{p}$ itself

(precession **rate** is still small)

$$\theta_B \sim 1$$



Transport Equation for Baryon Density

- Left-handed fermion density biases sphalerons to produce net baryon density:

$$\partial_t \rho_B(x) - D_q \nabla^2 \rho_B(x) \propto -n_F \Gamma_{\rm sph} n_L(x)$$

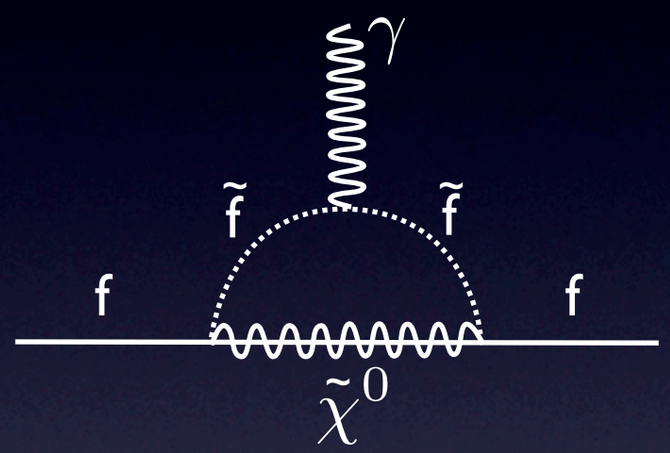
- Processes generating nonzero n_L faster than weak sphaleron rate $\Gamma_{\rm sph}$: derive and solve transport equations for n_L first

$\Gamma_{\rm sph} \sim \kappa \alpha_w^5 T^4$ in electroweak symmetric phase Moore

$\Gamma_{\rm sph} \sim e^{-4\pi/\alpha_w}$ in broken phase at T=0

Electric Dipole Moments

- EDMs generated at one loop in MSSM

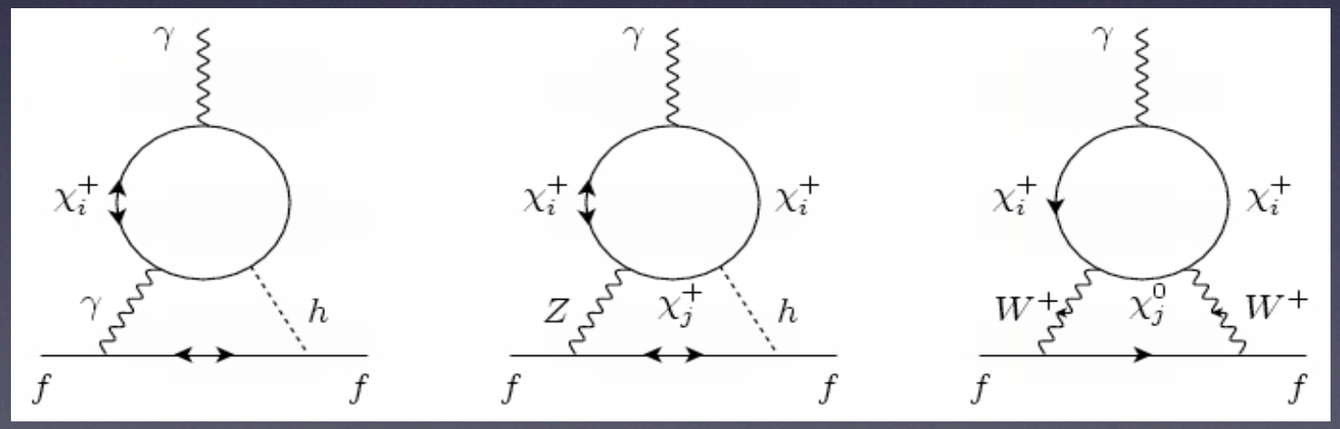


Ibrahim, Nath

but suppressed for large sfermion masses $m_{\tilde{f}}$

- Two-loop graphs important for large sfermion masses

Chang., Chang, Keung; Pilaftsis; Giudice, Romanino

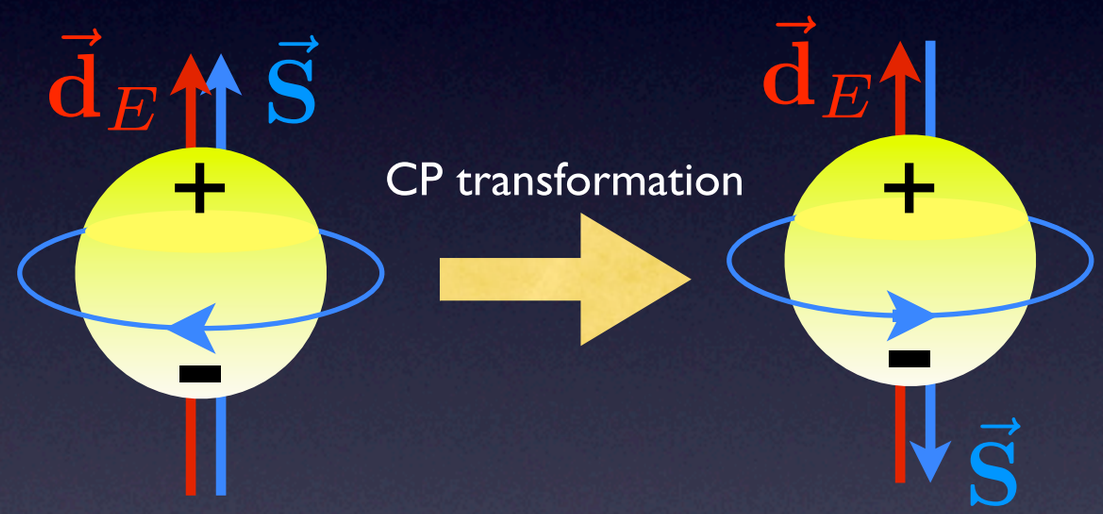


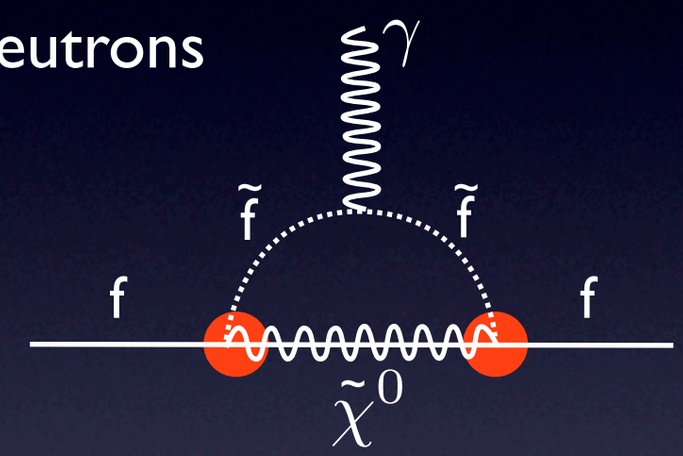
independent of $m_{\tilde{f}}$; dominant for $m_{\tilde{f}} \gtrsim 2 \text{ TeV}$

Searches at Low Energy

Manifestation of New Physics and symmetry violation through virtual quantum effects in *low-energy precision* experiments

e.g. intrinsic electric dipole moments of electrons, neutrons

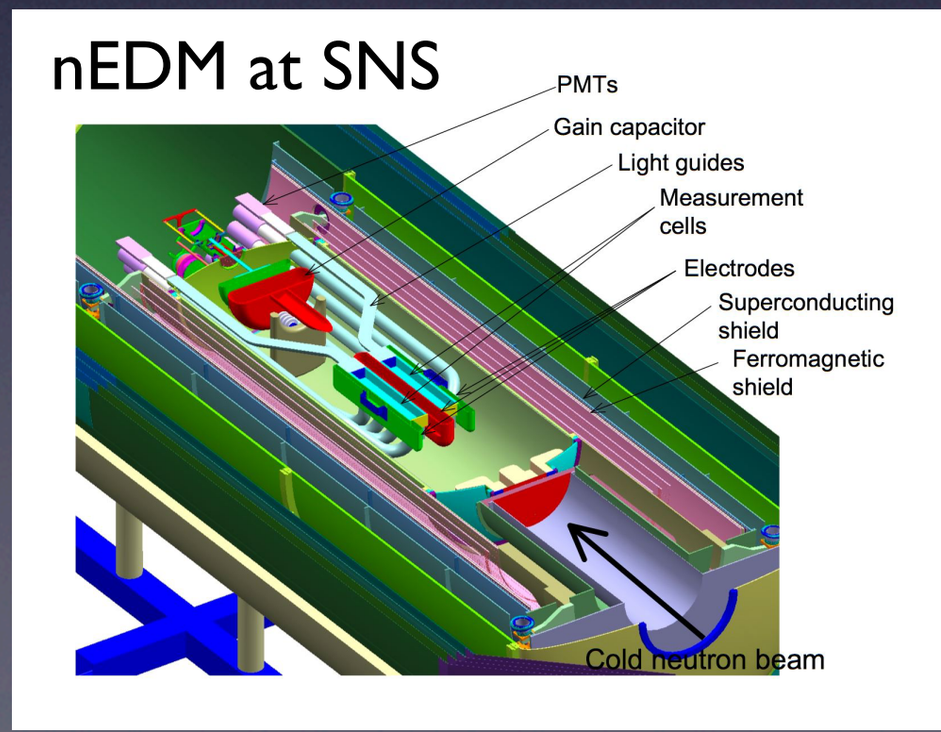




e.g. CP-violating supersymmetric interactions

Sizes of Electric Dipole Moments:

- Neutron EDM = 10^{-30} e cm in Standard Model
- Current best experimental limit < 3 x 10^{-26} e cm
- Baryogenesis implies neutron EDM > 10^{-28} e cm
- New experiments will have sensitivity down to 10^{-28} e cm

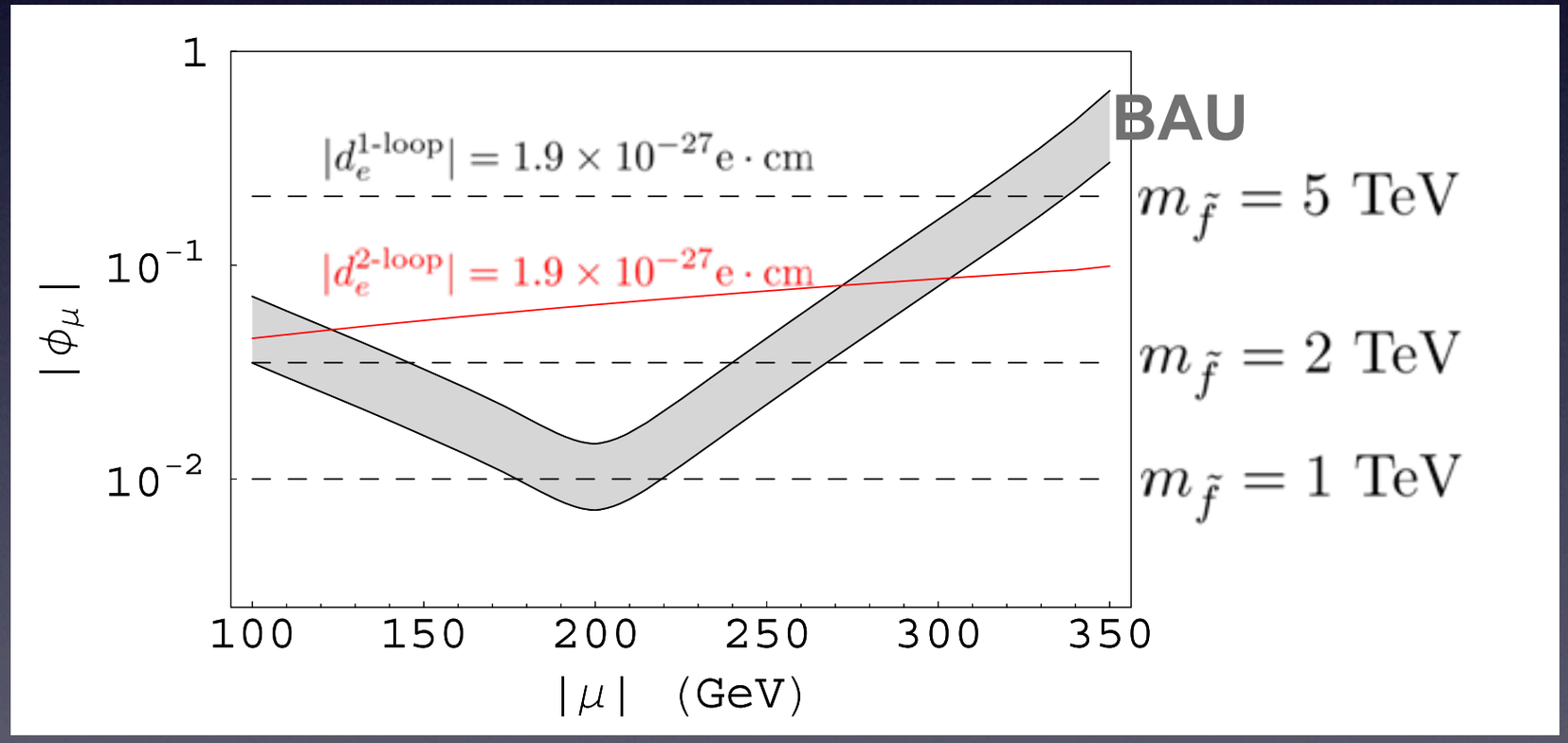


Combined BAU & EDM constraints

Cirigliano, CL, Ramsey-Musolf, Tulin
(in vev insertion approx)

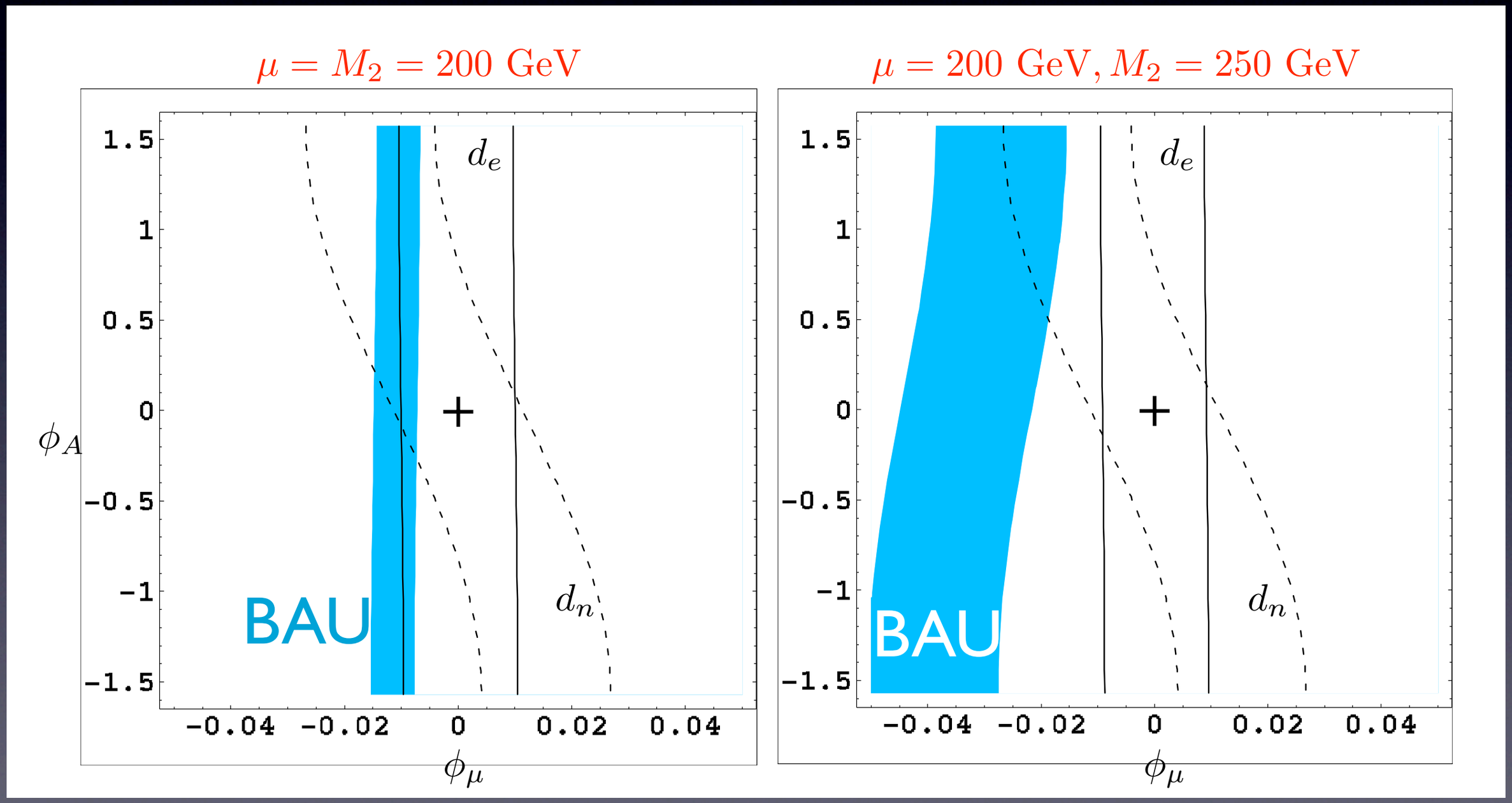
- CP-violating phase needed to generate observed BAU:

$$M_2 = 200 \text{ GeV}$$



Combined BAU & EDM constraints (2006)

Cirigliano, CL, Ramsey-Musolf

EDM present limits:
$d_e < 1.9 \times 10^{-27}$ e cm Berkeley Tl (2002)
$d_n < 3.6 \times 10^{-26}$ e cm ILL UCN (2006)

Projected future limits:
$d_e \sim 10^{-30}$ e cm LANL...
$d_n \sim 10^{-28}$ e cm ILL, SNS UCN...