Dynamical Dark Matter

A Status Report

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Work done in collaboration with **Brooks Thomas**

- arXiv: 1106.4546
- arXiv: 1107.0721
- arXiv: 1203.1923
- arXiv: 1204.4183 (also with Shufang Su)
- arXiv: 1208.0336 (also with Jason Kumar)
- arXiv: 1306.2959 (also with Jason Kumar)
- arXiv: 1406.4868 (also w/ J.K. & David Yaylali)
- arXiv: 1407.2606 (also with Shufang Su)

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Mitchell Workshop on Collider & DM Physics
Texas A&M University
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Dark Matter = ??

- Situated at the nexus of particle physics, astrophysics, and cosmology
- Dynamic interplay between theory and current experiments
- Of fundamental importance: literally 23% of the universe!
- Necessarily involves physics beyond the Standard Model

→ One of the most compelling mysteries facing physics today!

Traditional view of dark matter:

- One or several dark-matter particle(s) χ which carry entire DM abundance: $\Omega_\chi = \Omega_{CDM} = 0.26$ (WMAP).
- Such particle(s) must be hyperstable, with lifetimes exceeding the age of the universe by many orders of magnitude $\sim 10^{26}$ s.
- Most DM scenarios take this form.

Indeed, any particle which decays too rapidly into SM states is likely to upset BBN and light-element abundances, and also leave undesirable imprints in the CMB and diffuse photon/X-ray backgrounds.

Stability is thus critical for traditional dark matter. The resulting theory is essentially "frozen in time": Ω_{CDM} is constant, etc.

Dynamical Dark Matter (DDM):

Let's suppose the dark matter of the universe consists of N states, with N>>1 ... an entire *ensemble* of states!

- No state individually needs to carry the full Ω_{CDM} so long as the sum of their abundances matches Ω_{CDM}.
- In particular, individual components can have a wide variety of abundances, some large but some small.

But a given dark-matter component need not be stable if its abundance at the time of its decay is sufficiently small.

A sufficiently small abundance assures that the disruptive effects of the decay of such a particle will be minimal, and that all constraints from BBN, CMB, etc. will continue to be satisfied.

DDM therefore rests on an alternative concept ---

a balancing of decay widths against abundances:

States with larger abundances must have smaller decay widths,
but states with smaller abundances can have larger decay widths.
As long as decay widths are balanced against abundances across our entire dark-sector ensemble, all phenomenological constraints can be satisfied!

Thus, dark-matter stability is no longer required!

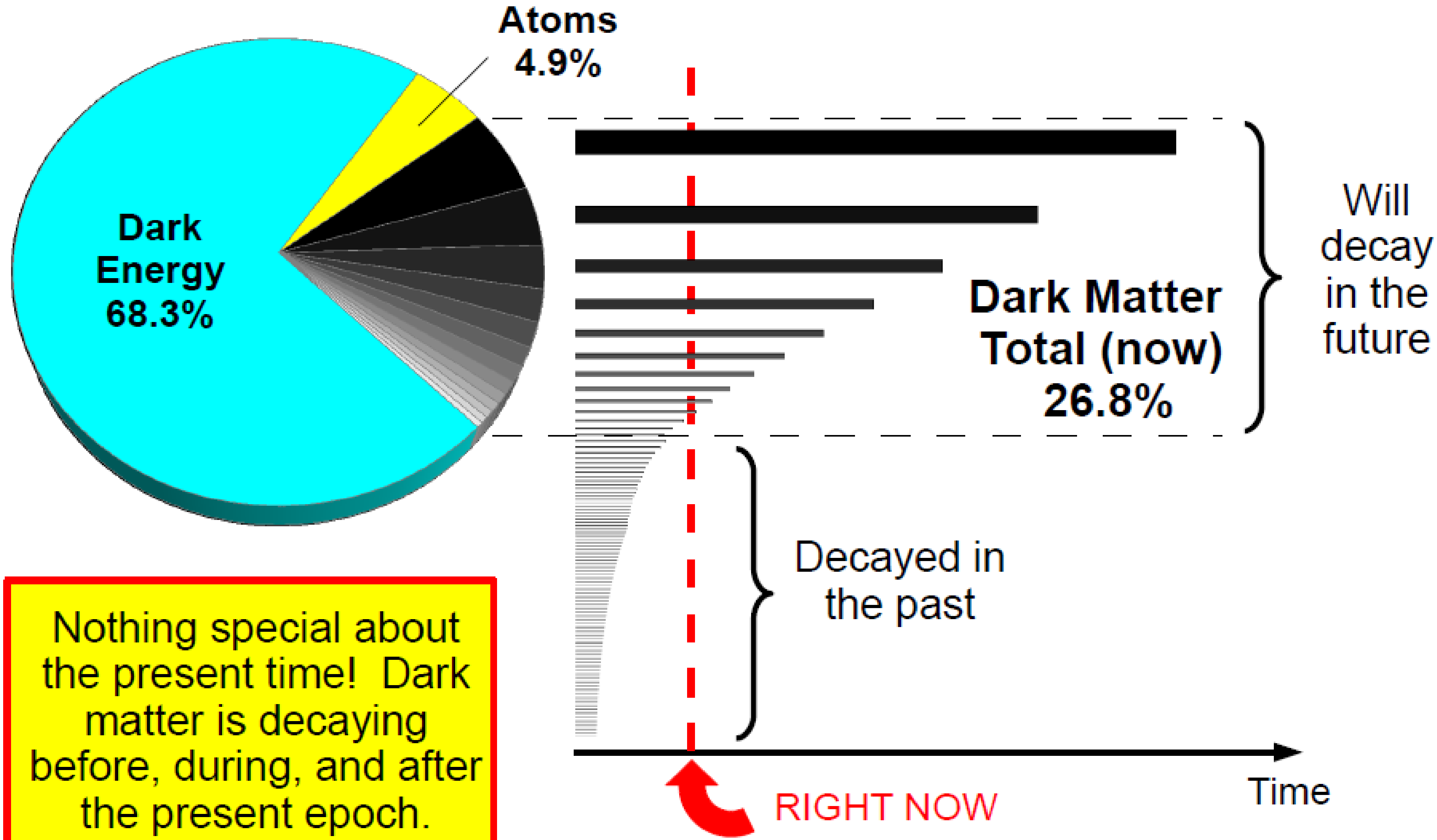
<u>Dynamical Dark Matter (DDM)</u>: an alternative framework for dark-matter physics in which the notion of dark-matter stability is replaced by a balancing of lifetimes against cosmological abundances across an ensemble of individual dark-matter components with different masses, lifetimes, and abundances.

This is the most general dark sector that can be contemplated, and reduces to the standard picture of a single stable particle as the number of states in the ensemble is taken to one.

Otherwise, if the number of states is enlarged, ***the notion of dark-matter stability generalizes into something far richer: a balancing of lifetimes against abundances.*** ***The dark sector becomes truly dynamical!***

"Dynamical Dark Matter": The Basic Picture:

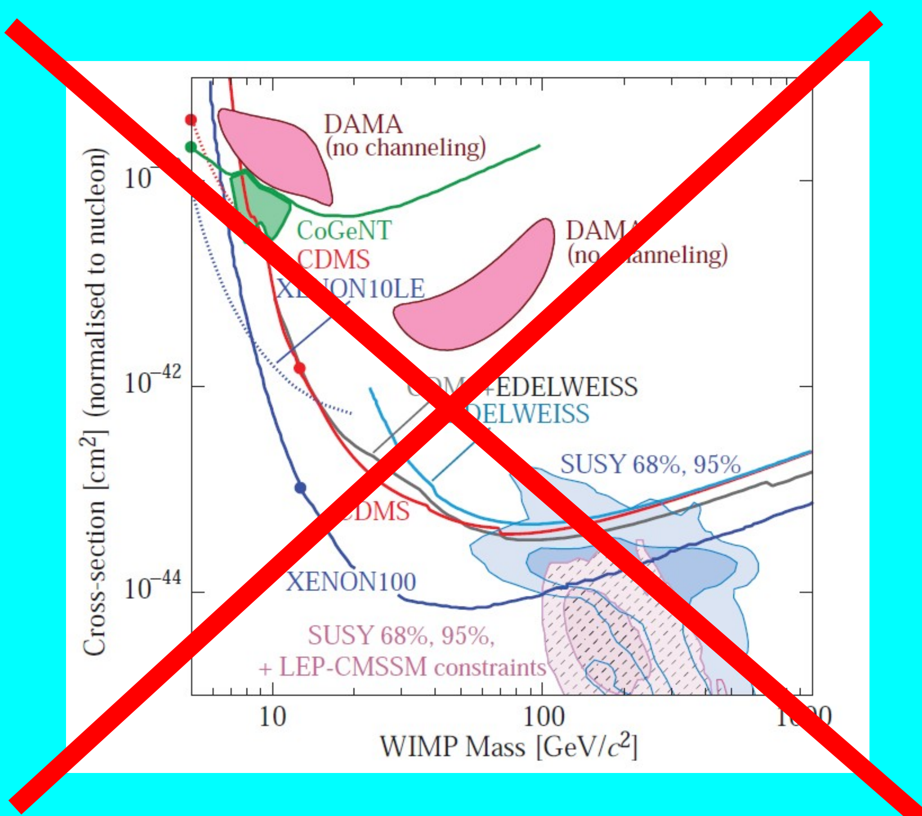
A Snapshot of the Cosmic Pie: Past, Present, and Future



Nothing special about the present time! Dark matter is decaying before, during, and after the present epoch.

Because of its non-trivial structure, the DDM ensemble --- unlike most traditional dark-matter candidates --- cannot be characterized in terms of a single mass, decay width, or set of scattering amplitudes.

→ The DDM ensemble must therefore be characterized in terms of parameters (e.g., scaling relations or other internal correlations and constraints) which describe the behavior of its constituents as a whole.



As a consequence, phenomenological bounds on dark matter in the DDM framework must be phrased and analyzed in terms of ***a new set of variables*** which describe the behavior of the entire DDM ensemble as a collective entity with its own internal structures and/or symmetries.

We must move beyond the standard WIMP paradigm.

This is clearly a major re-envisioning of the dark sector, and calls for re-thinking and re-evaluating much of what we currently expect of dark matter.

- KRD & B. Thomas, arXiv: 1106.4546
- KRD & B. Thomas, arXiv: 1107.0721
- KRD & B. Thomas, arXiv: 1203.1923
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- KRD, J. Kumar & B. Thomas, arXiv: 1306.2959
- KRD, J, Kumar, B. Thomas & D. Yaylali, 1406.4868
- KRD, S. Su & B. Thomas, arXiv: 1407.2606 .....

- Dark-matter equation of state: do we still have *w=0* ? No, much more subtle...
- Are such DDM ensembles of states easy to realize? Yes! (extra dimensions; string theory; axiverse, etc. In fact, DDM is the kind of dark matter string theory gives!)
- Can we make actual explicit models in this framework which really satisfy *every* collider, astrophysical, and cosmological bound currently known for dark matter? Yes! (and phenomenological bounds are satisfied in new, surprising ways)
- Implications for collider searches for dark matter? Unusual and distinctive collider kinematics. Invariant mass spectra, MT2 distributions, ...
- Implications for direct-detection experiments? Distinctive recoil-energy spectra with entirely new shapes and properties!
- Implications for indirect detection? e.g. positron excess easy to accommodate, *with no downturn in positron flux expected*... a "plateau" is actually a smoking gun for DDM!

Experimental signatures of DDM

How can we distinguish DDM...

- at colliders (LHC)
- at the next generation of direct-detection experiments
  (e.g., XENON 100/1T, SuperCMS, LUX, PANDA-X)
- at indirect-detection experiments (e.g., AMS-02, ...)

... relative to more traditional dark-matter candidates?

KRD, S. Su, and B. Thomas, arXiv: 1204.4183
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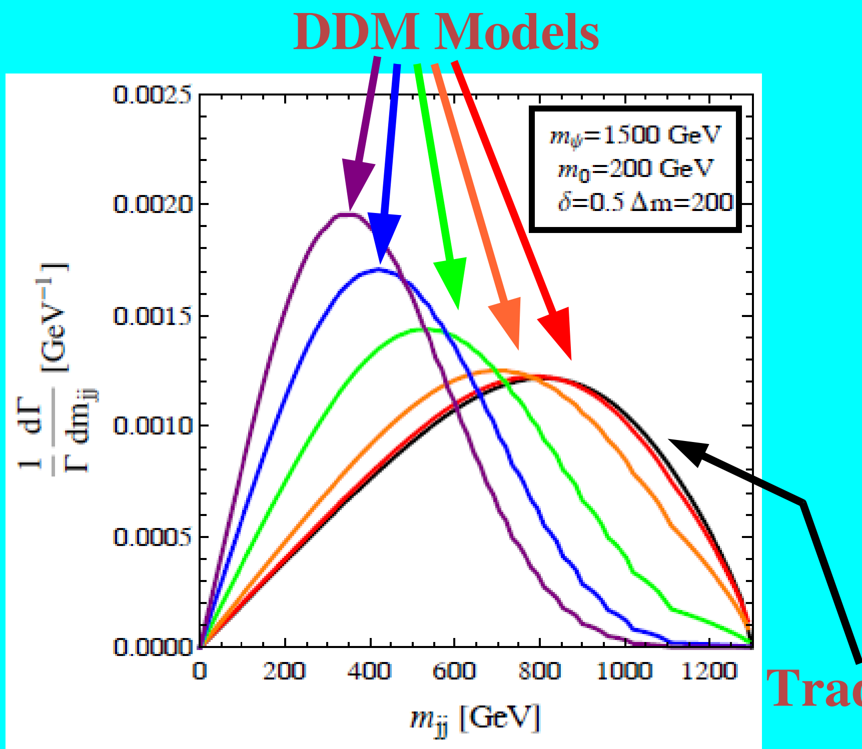
This can indeed be done --- both at collider experiments...



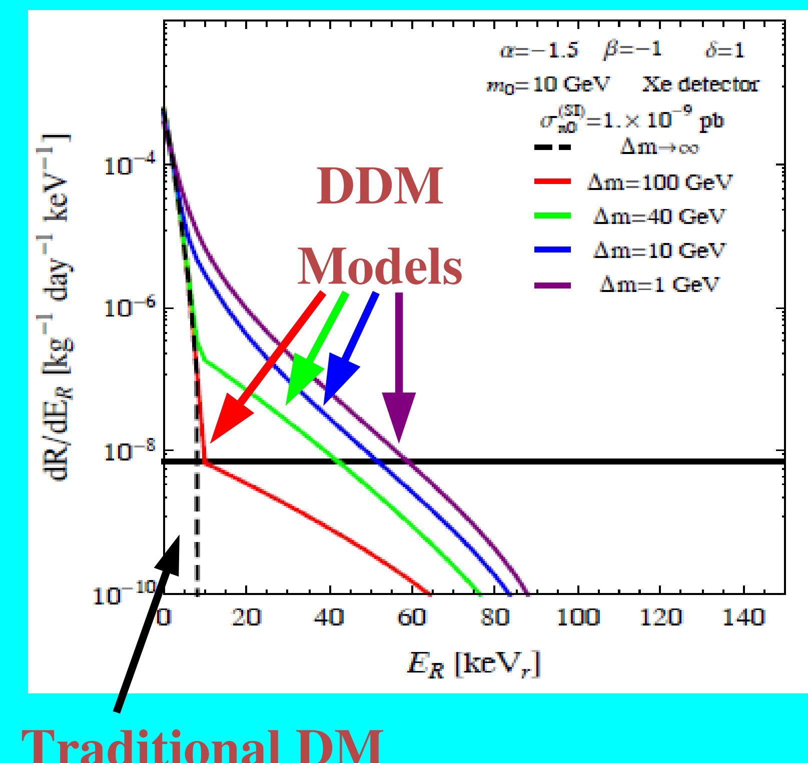
- KRD, S. Su, and B. Thomas, arXiv: 1204.4183

- In many DDM models, constituent fields in the DDM ensemble can be produced alongside SM particles by the decays of additional heavy fields.
- Evidence of a DDM ensemble can be ascertained in characteristic features imprinted on the invariant-mass distributions of these SM particles.

... and at direct-detection experiments.

- KRD, J. Kumar and B. Thomas, arXiv: 1208.0336

- DDM ensembles can also give rise to distinctive features in recoil-energy spectra.



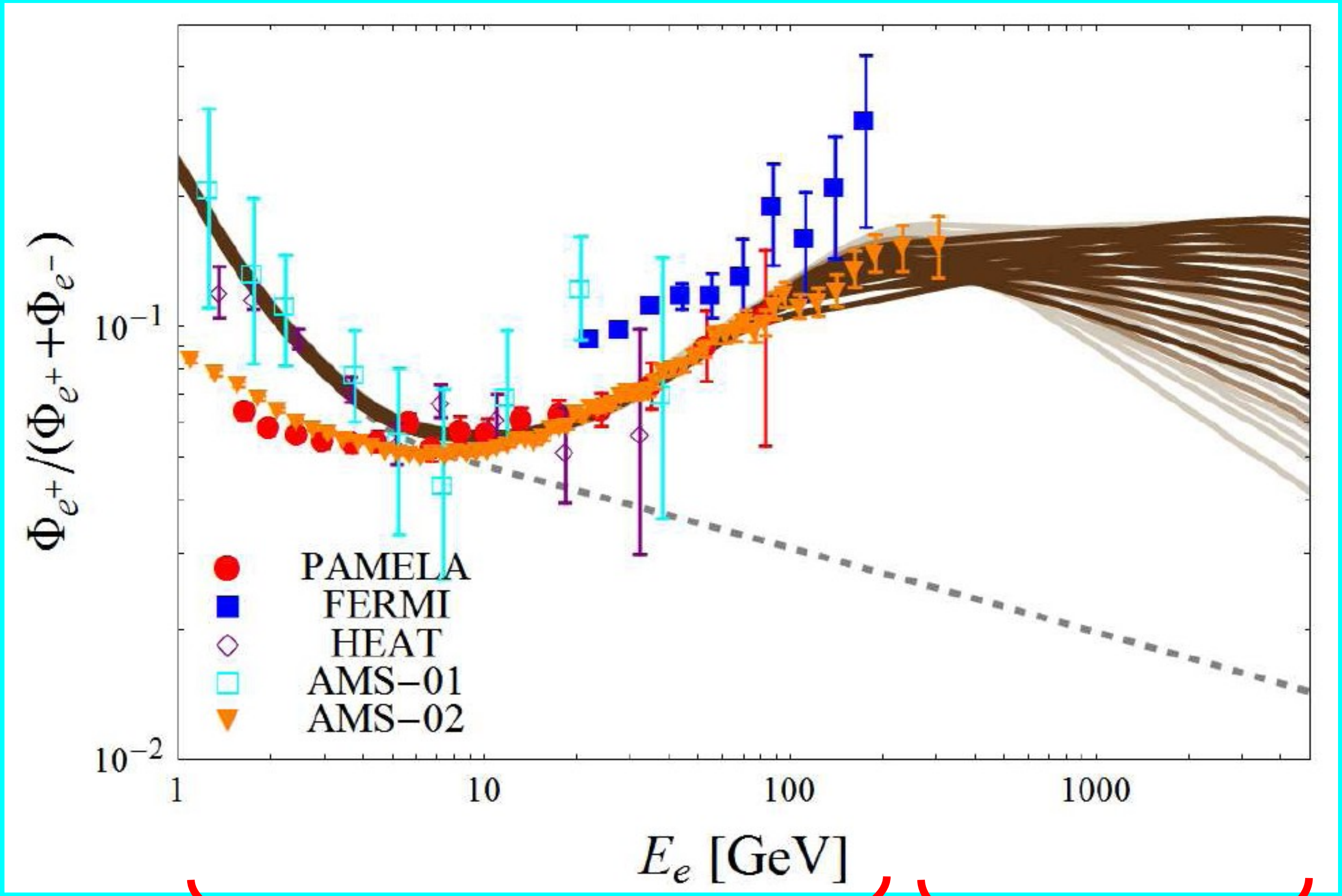
These examples illustrate that DDM ensembles give rise to **observable effects** which can serve to distinguish them from traditional DM candidates.

DDM also makes predictions for indirect-detection experiments…

• KRD, J. Kumar & B. Thomas, arXiv: 1306.2959

All curves also satisfy other constraints from...

- Comic-ray antiproton flux (PAMELA)
- Diffuse gamma-ray flux (FERMI-LAT)
- Synchrotron radiation (e^+/e^- interacting in galactic halo with background magnetic fields)
- CMB ionization history (Planck)
- Combined electron/positron flux (FERMI-LAT)



DDM: Fully consistent with positron excess observed thus far [AMS-02]

DDM prediction: no downturn at higher energies! Flat plateau...

A "smoking gun" for DDM!

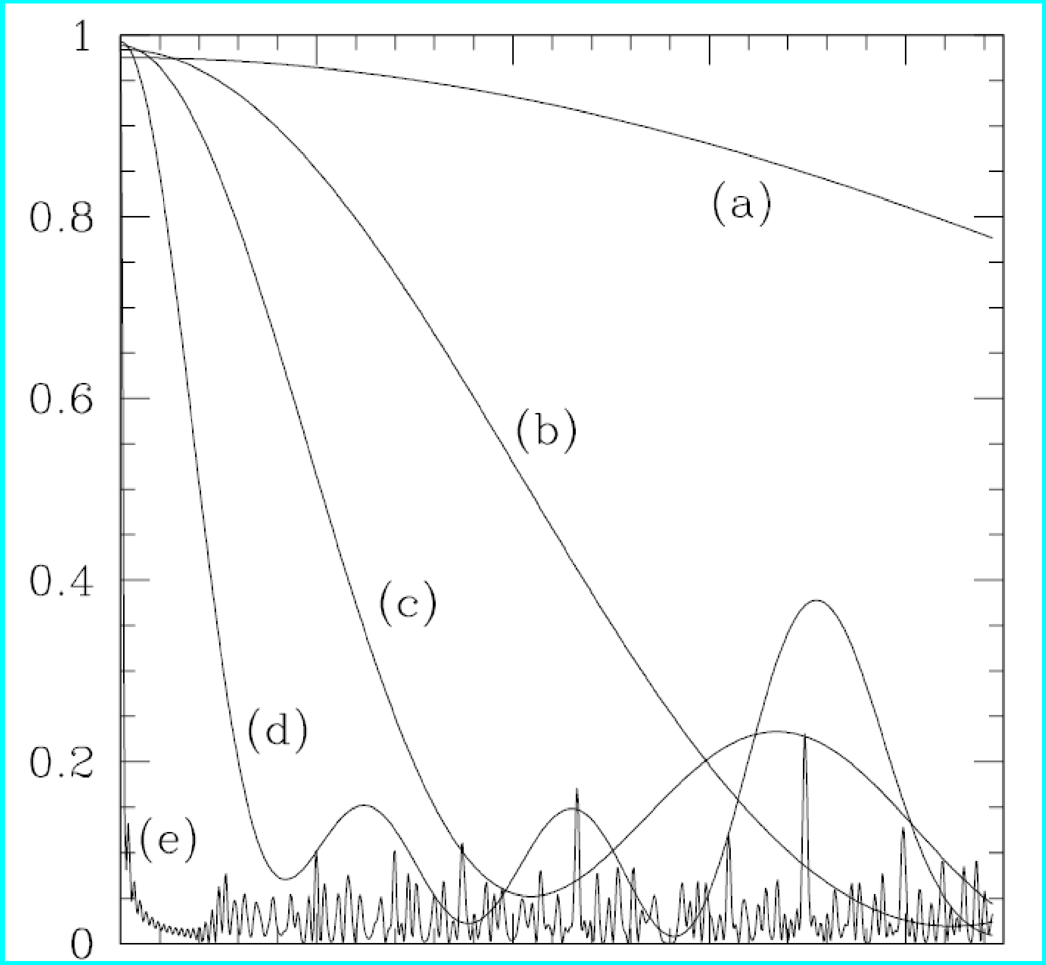
DDM also has new ways of helping the dark sector stay dark!

In many DDM constructions, the SM couples to only one combination of ensemble fields with different masses...

$$\phi' \equiv \Phi(y)\Big|_{y=0} = \sum_{k=0}^{\infty} r_k \phi_k$$

However, once ϕ' is produced (in laboratory, in distant astrophysical sources, etc.), it rapidly ***decoheres*** and does not reconstitute in finite time...

This novel effect provides yet another mechanism which may help dark matter stay dark, and leads to different signature patterns from those which characterize purely 4D scalars and traditional single-component dark-matter candidates.



KRD, E. Dudas, T. Gherghetta (1999)

Over the past year, many other DDM projects have been completed, or are actively in progress...

all with **Brooks Thomas** and ...

- New strategies for probing non-minimal dark sectors at colliders: interplay and correlations between different kinematic variables, their distributions, and potential cuts.

w/ Shufang Su 1407.2606

- New effects in direct detection: velocity suppression --- normally believed to render pseudoscalar couplings irrelevant --- can be overcome through special nuclear-physics effects. Thus direct-detection experiments can indeed be sensitive to pseudoscalar DM/SM couplings, especially if isospin-violating effects are included.

w/ Jason Kumar & David Yaylali 1312.7772

- Enhanced complementarities for multi-component dark sectors

w/ Jason Kumar & David Yaylali 1406.4869 (PRL)

- Cosmology with multiple scalar fields: Mixing, mass generation, and phase transitions in the early universe
  - Mixing effects can enhance and/or suppress dissipation of total energy density and alter distribution across different modes (isocurvature)
  - Parametric resonances and other non-monotonicities emerge
  - *Re-overdamping*: new behaviors beyond pure vacuum energy or matter.

w/ Jeff Kost

And also...

all with
Brooks Thomas
and ...

- Other realizations of DDM ensembles
  - "Deconstructed DDM" --- resembles KK towers but with numerous unexpected discretization effects with new phenomenologies.
  - "Random-matrix DDM" --- ensembles from large hidden-sector gauge groups --- new scaling behaviors emerge
- DDM in string theory: not just KK states, but also string *oscillator* states!
  - Density of states grows *exponentially*
  - Hagedorn behavior, phase transitions, etc.

  Moreover, this is mathematically equivalent to a strongly coupled dark sector with DM ensemble = hadron-like bound-state spectrum.
- Designing DDM ensembles via new *thermal* freezeout mechanisms.
- General decay constraints on multi-component dark sectors.
- DDM effects on
  - Structure formation: complex behavior for Jeans instabilities
  - Non-trivial halo structures

w/ Barath Coleppa & Shufang Su

w/ Jake Fennick & Jason Kumar

w/ Fei Huang & Shufang Su

w/ Jake Fennick & Jason Kumar

w/ Jason Kumar & Pat Stengel

(just Brooks & me!)

Indeed, we are only at the tip of the iceberg...

Almost every traditional line of investigation in dark-matter physics can be re-evaluated in this context (from structure formation to collider phenomenology, and everything in between).

The Dynamical Dark Matter framework is rich and we have only begun to explore its properties. DDM provides new, non-minimal, “dynamical” ways to think about old problems and challenges in dark-matter physics.

But perhaps most importantly...

The Take-Home Message

Dynamical Dark Matter ***is*** the most general way of thinking about the dark sector...

- ***Stability and minimality are not fundamental properties of the dark sector!***
- All that is required is a phenomenological balancing of lifetimes against abundances. A much richer *dynamical* dark sector is possible!
- The resulting physics can satisfy all astrophysical, cosmological, and collider constraints on dark matter, and yet simultaneously give rise to new theoretical insights and new experimentally distinct signatures.

It is time we shed our theoretical prejudices and embrace all the possibilities that dark-sector non-minimality and instability allow!

A Tale of Two Timescales:

Mixing, Mass Generation, and Phase Transitions in the Early Universe

Keith R. Dienes

work with Jeff Kost and Brooks Thomas

Thanks, Jeff, for the slides!

[arXiv: 1505.xxxxx]

Scalar DDM Ensembles

- One important class of dark-matter candidate consists of **scalar singlets**.

- In fact, scalar singlets appear in many theories beyond the Standard Model, e.g.

    - **axions,** to solve the strong CP problem
    - string **moduli,** involved in compactification, etc.

- As a result, scalar fields play an important general role in early-universe cosmology...

  What is the cosmology of a DDM ensemble of scalar fields?
  What is the cosmology of multiple scalar fields more generally?

Scalars in the Early Universe

- One important question naturally arises for all such scalar fields:

→ What early dynamics can occur that would significantly affect the **late-time abundances** (energy densities, i.e. the sizes of the slices of the cosmic pie) of these fields?

ARIZONA

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Let us briefly review each of these...

① Mass-Generating Phase Transitions

In a flat cosmology, where spatial variation in the fields is assumed negligible, they evolve according to the **equation of motion**:

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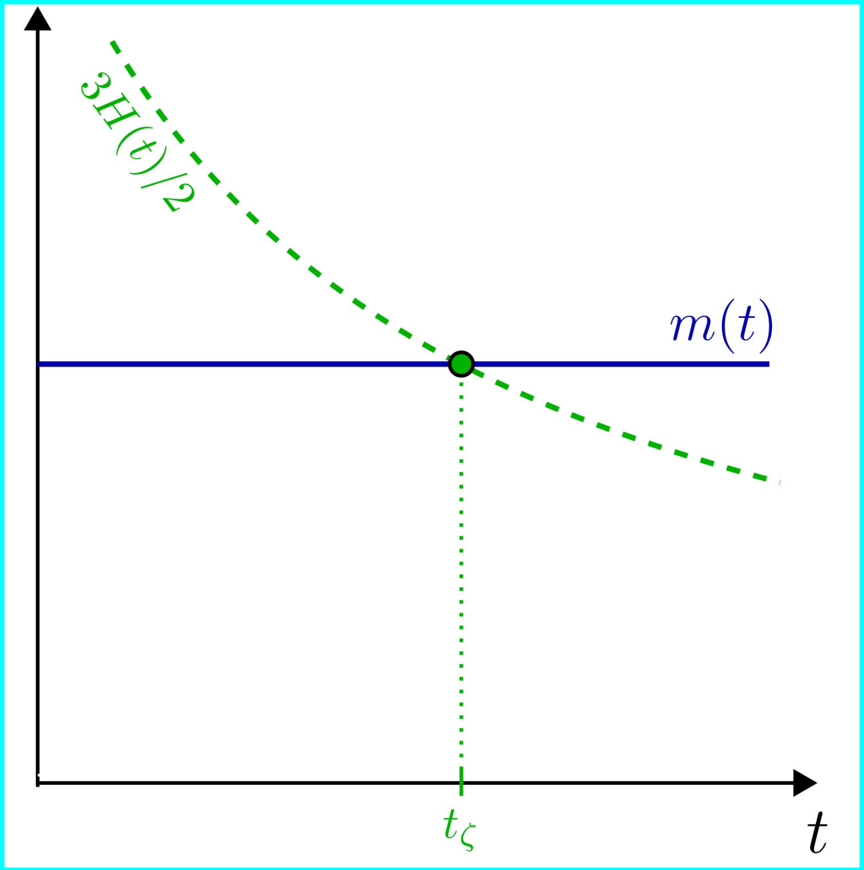

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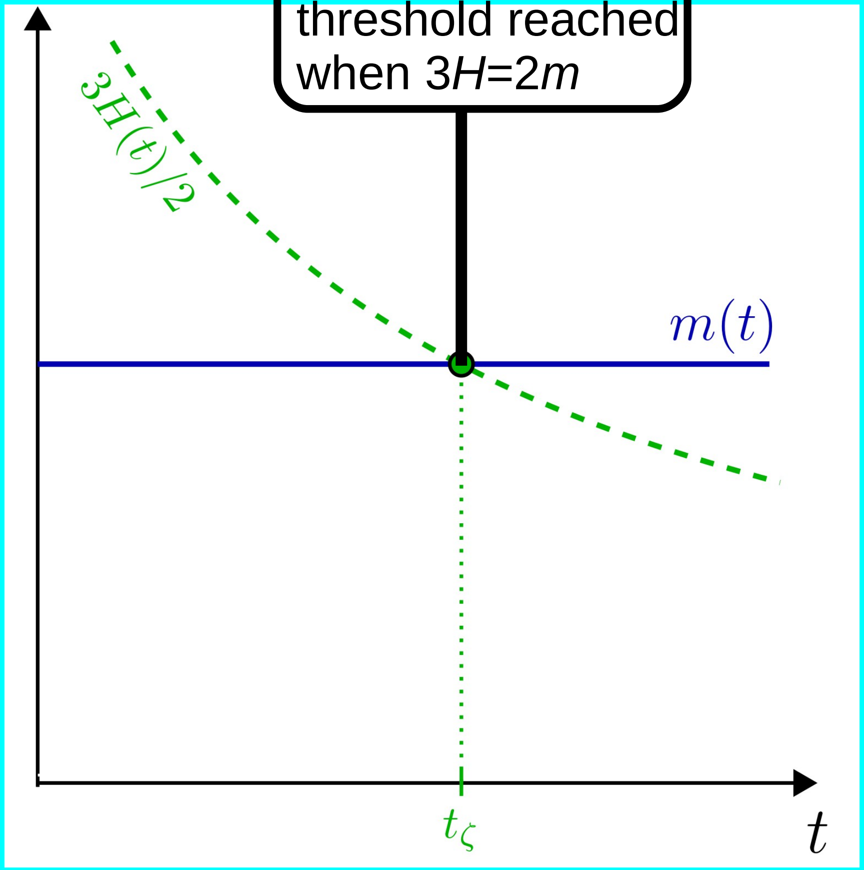
critical damping threshold reached when 3*H*=2*m*



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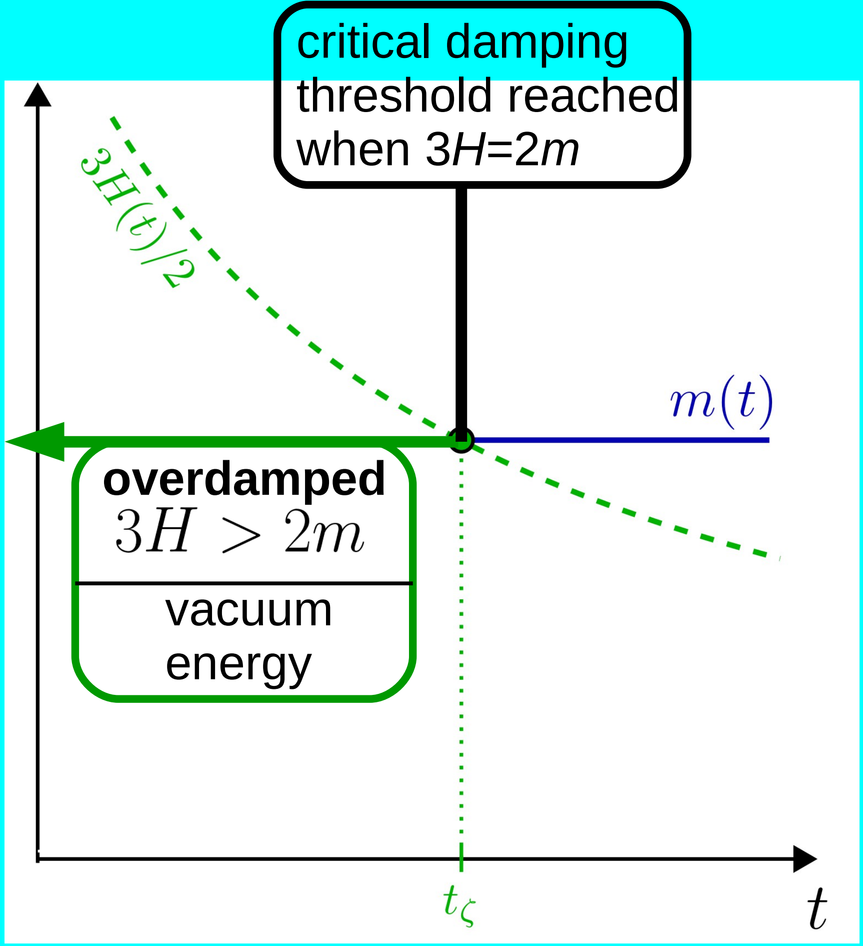

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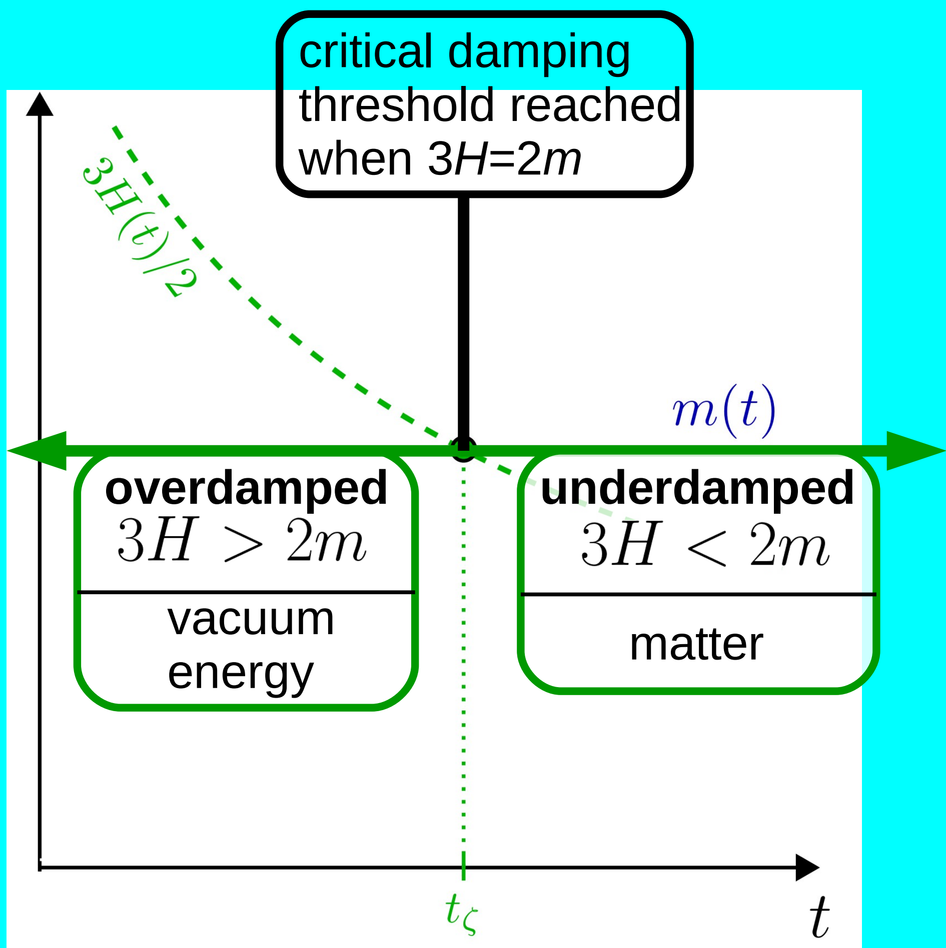

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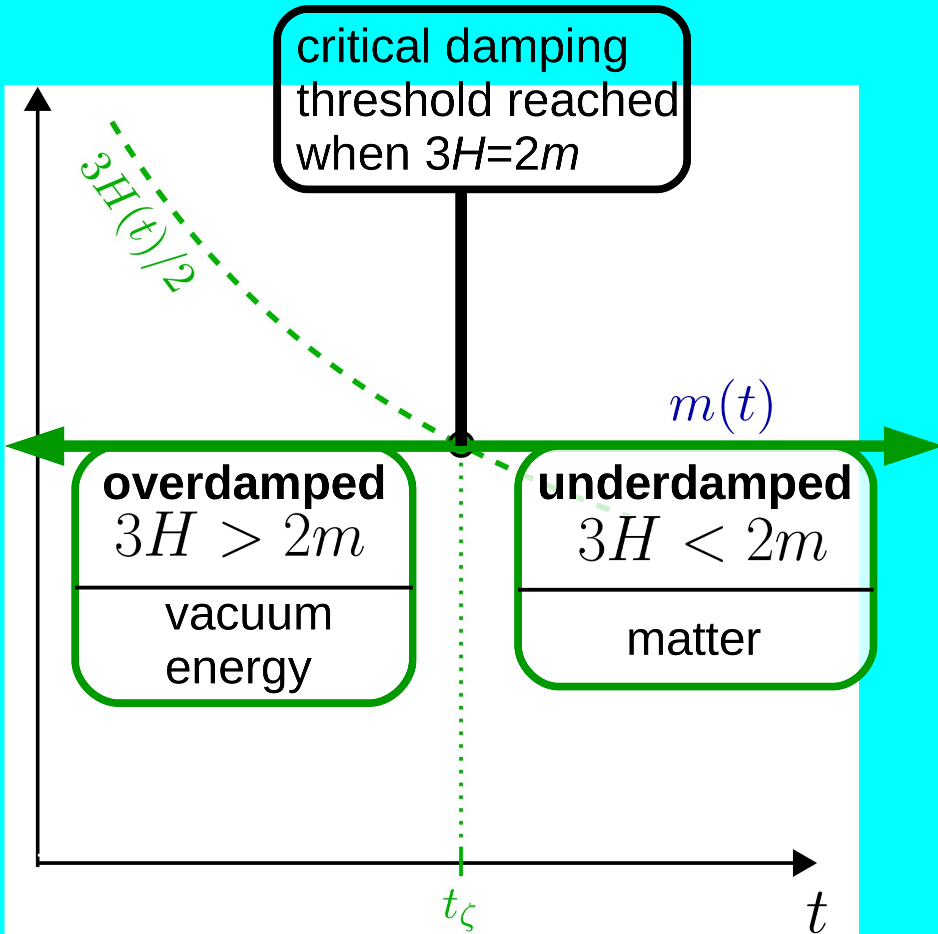

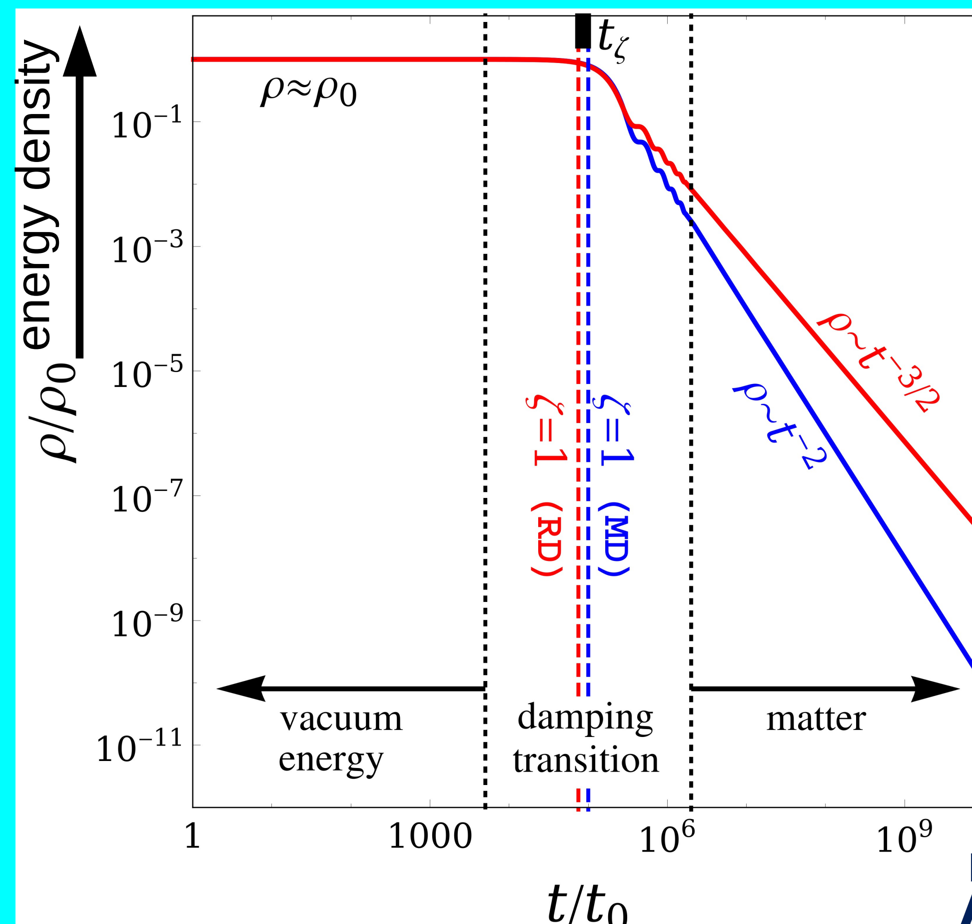

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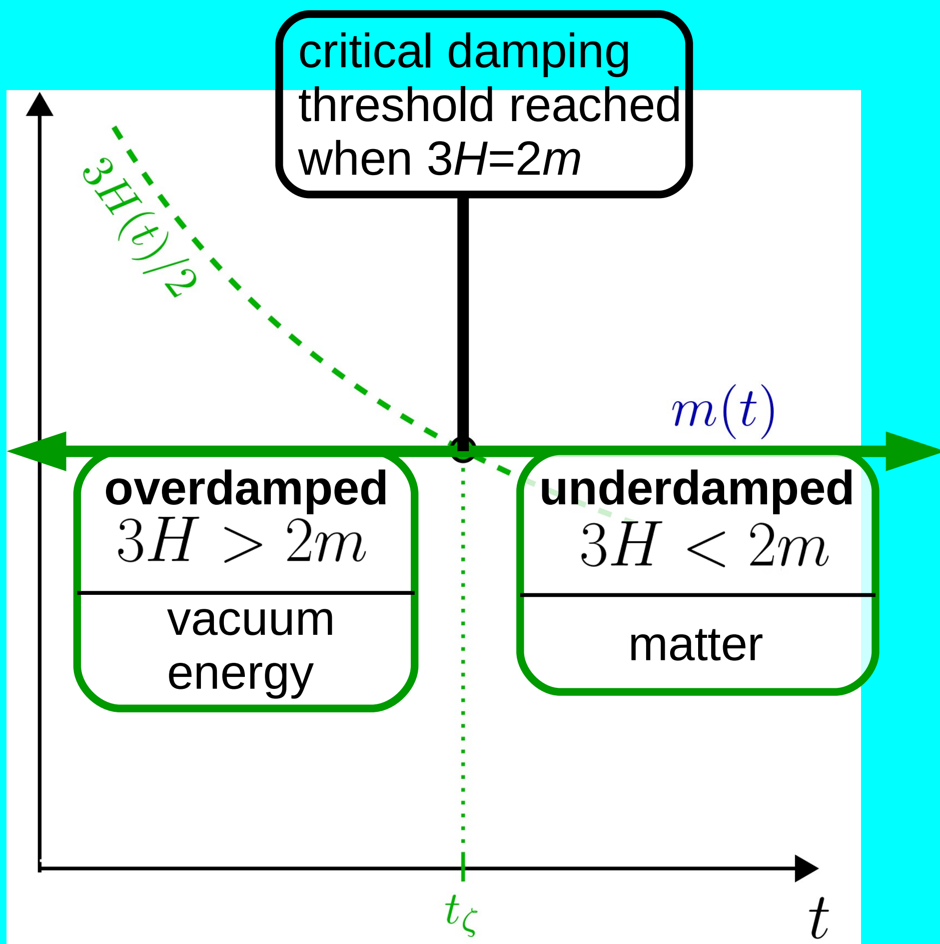

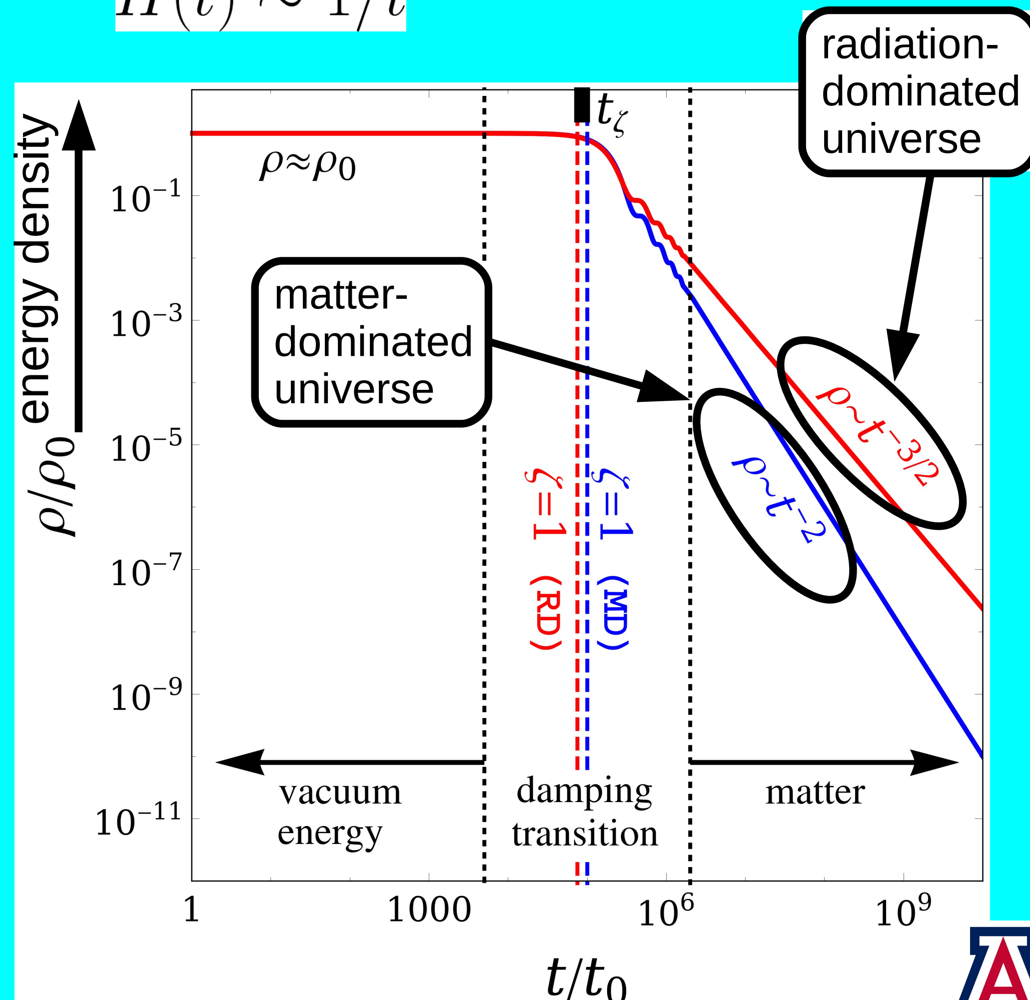

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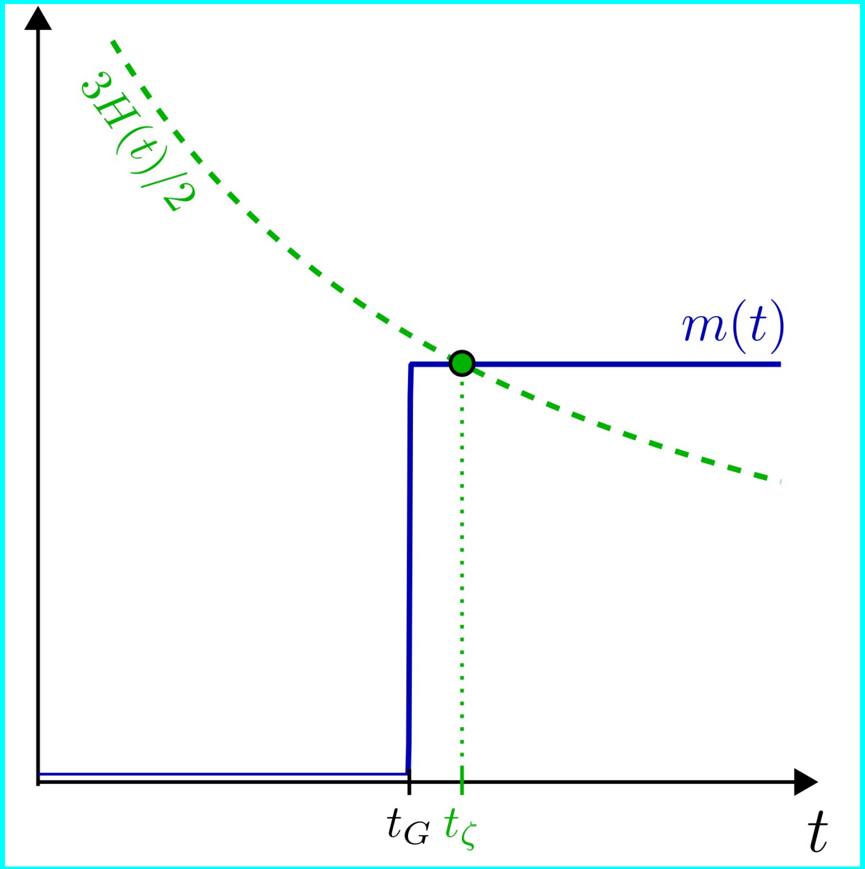

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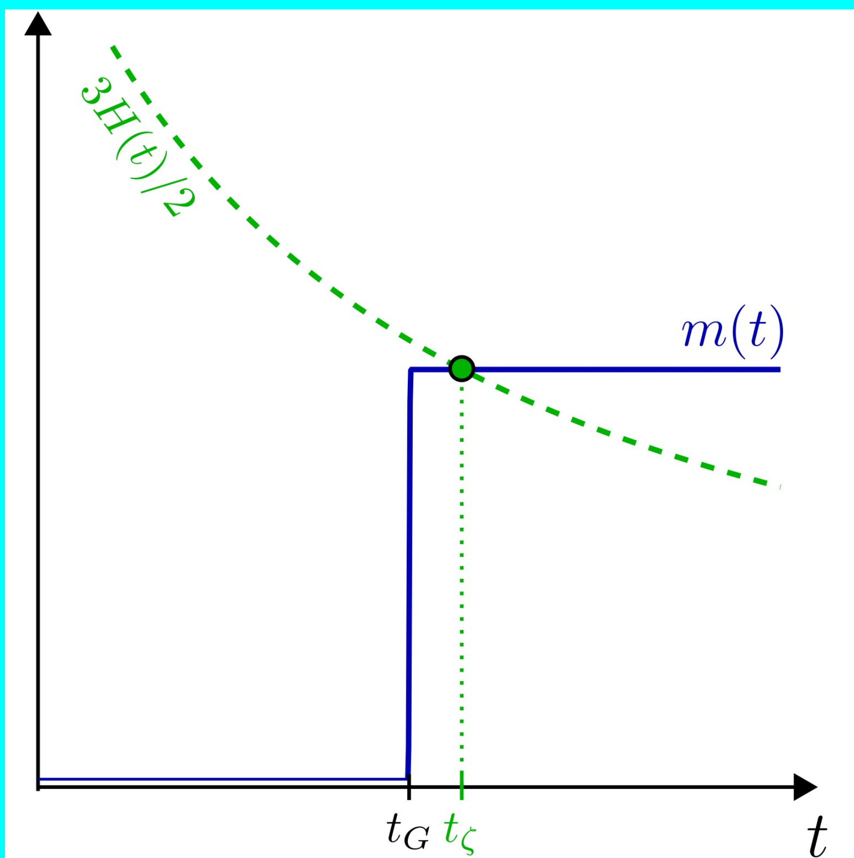

- Energy density remains zero until mass is generated at t_G.
- Otherwise, evolution is similar to the constant-*m* scenario.

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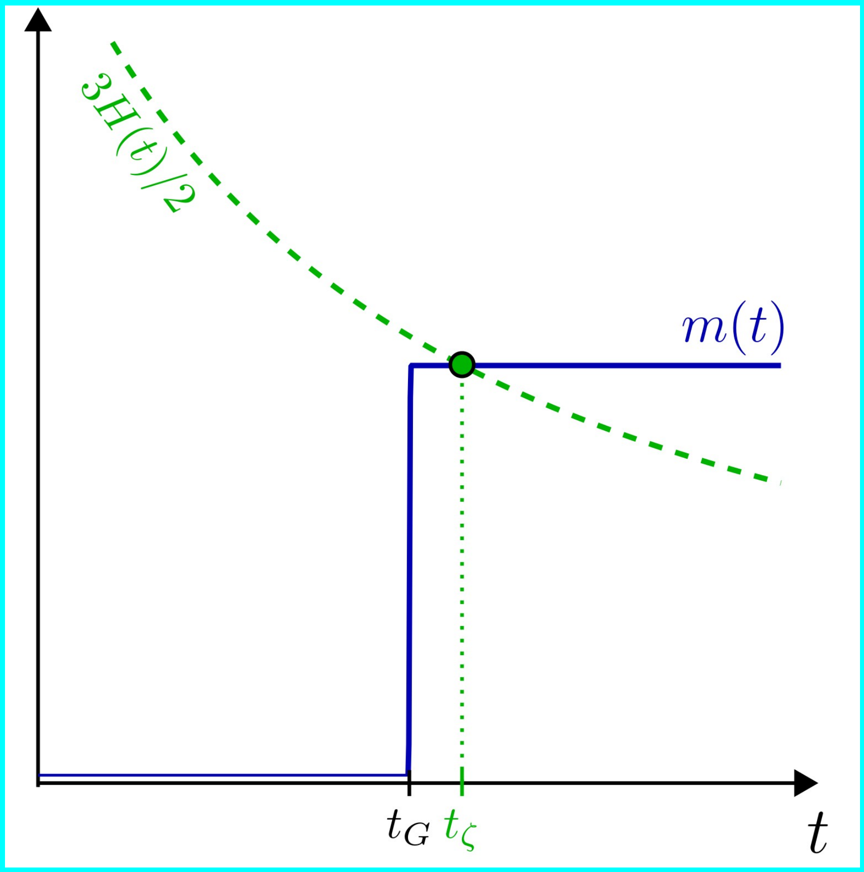
Allow a non-zero **generation timescale** Δ_G



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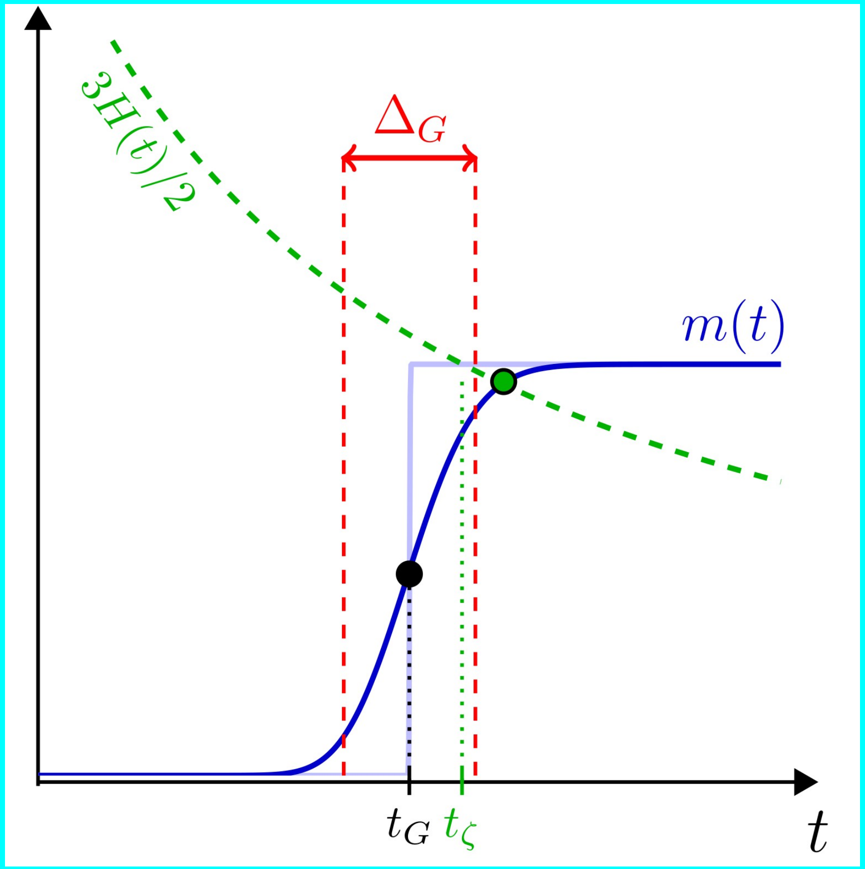

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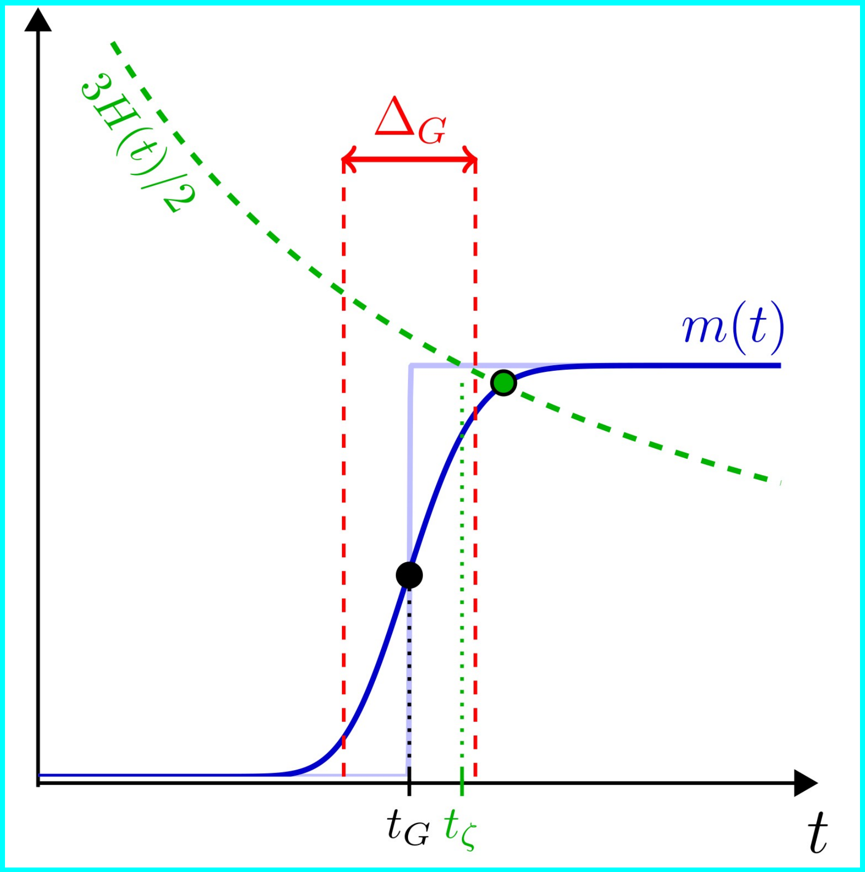

non-zero Δ_G typically leads to ***suppression*** of late-time abundance as compared to an instantaneous transition, in the specific models where it has been studied thus far.

Turner, 1986

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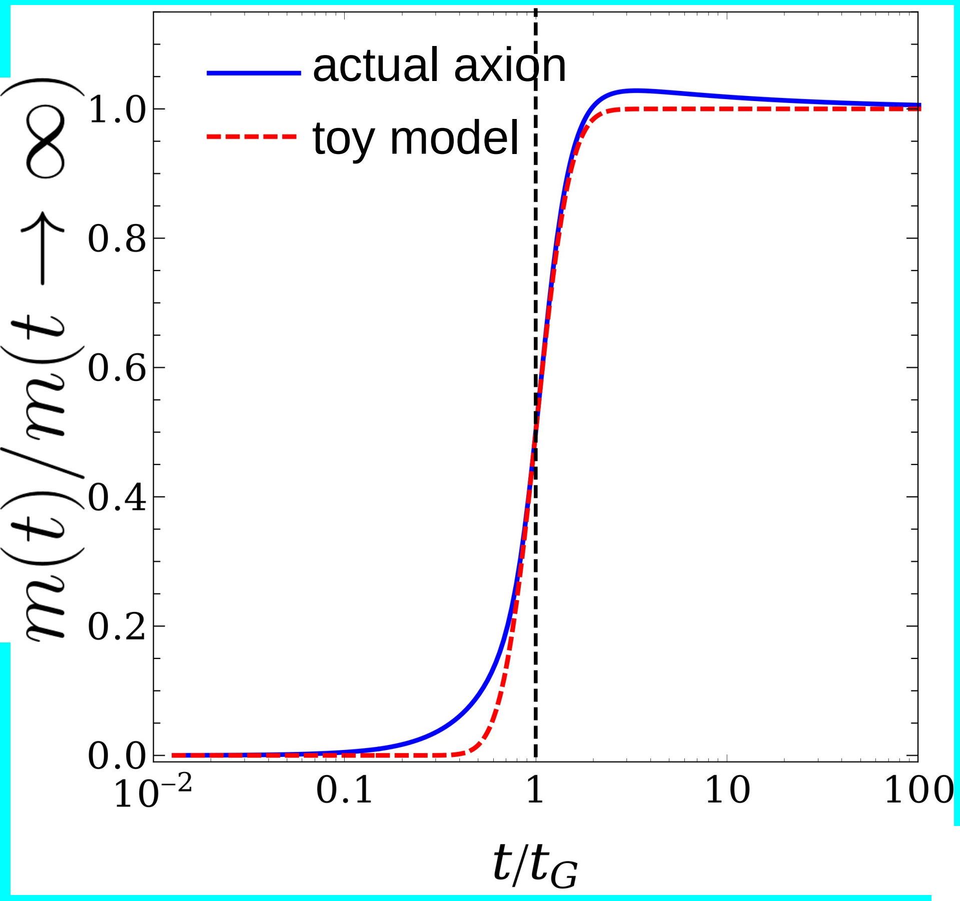
Allow a non-zero **generation timescale** Δ_G

For example, in the case of the QCD axion, this function has been explicitly calculated...:

- A combination of detailed lattice studies and a variety of other approaches have helped determine the axion mass as a function of temperature near its mass-generating phase transition at $T = \Lambda_{\rm QCD}$.

[most recently Wantz, Shellard (2010)]



② Non-Trivial Mixing Amongst the Fields

In scenarios with **multiple scalars**, there can be non-trivial mixing amongst the fields, coupling the equations of motion:

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➡ also found to ***suppress*** their (total) cosmological abundance, in the case of axions under certain cosmological circumstances.

KRD, Dudas, Gherghetta, 1999

The Question...

Both of these effects have occasionally been studied in isolation, but what happens when we introduce them *simultaneously, as would occur in a DDM ensemble?*
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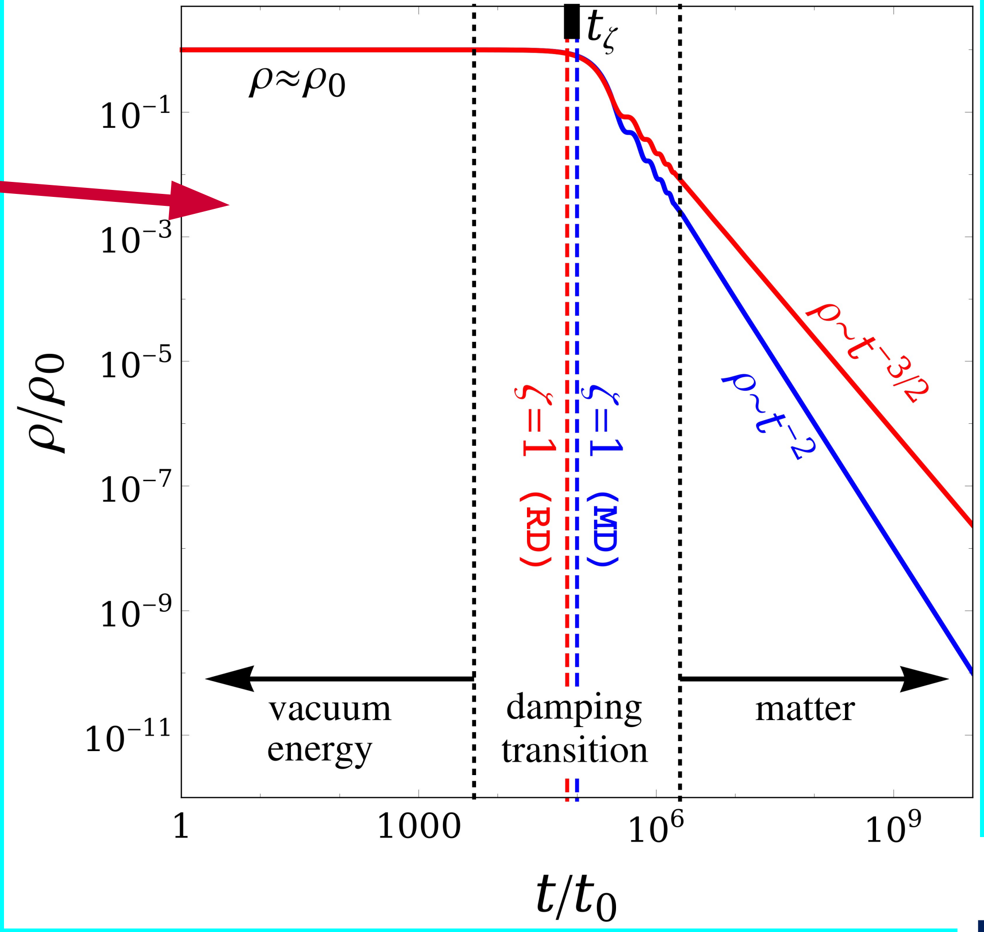
Both of these effects have occasionally been studied in isolation, but what happens when we introduce them *simultaneously, as would occur in a DDM ensemble?* Do any new phenomena emerge?

- A tacit assumption might be that the general picture is essentially unchanged for each mass eigenstate.

To what extent is such an assumption true?

- **This is the fundamental question we shall now explore.**



A Toy Model

- To study these issues, rather than restricting ourselves by focusing on a specific model, we construct a **general toy model.**

- Our toy model is *simple* enough to be tractable, yet *rich* enough to incorporate all the effects of interest:

  1. a mass-generating phase transition with non-zero width
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  2. non-zero mixing between its fields.

- To do this, we require only ***two*** real scalar fields ϕ_0, ϕ_1 with an explicitly time-dependent potential:

$$V(\phi_0, \phi_1; t) \;=\; \sum_{k,\ell} \frac{1}{2} \phi_k \mathcal{M}^2_{k,\ell}(t) \phi_\ell$$

(time-dependent) mass matrix

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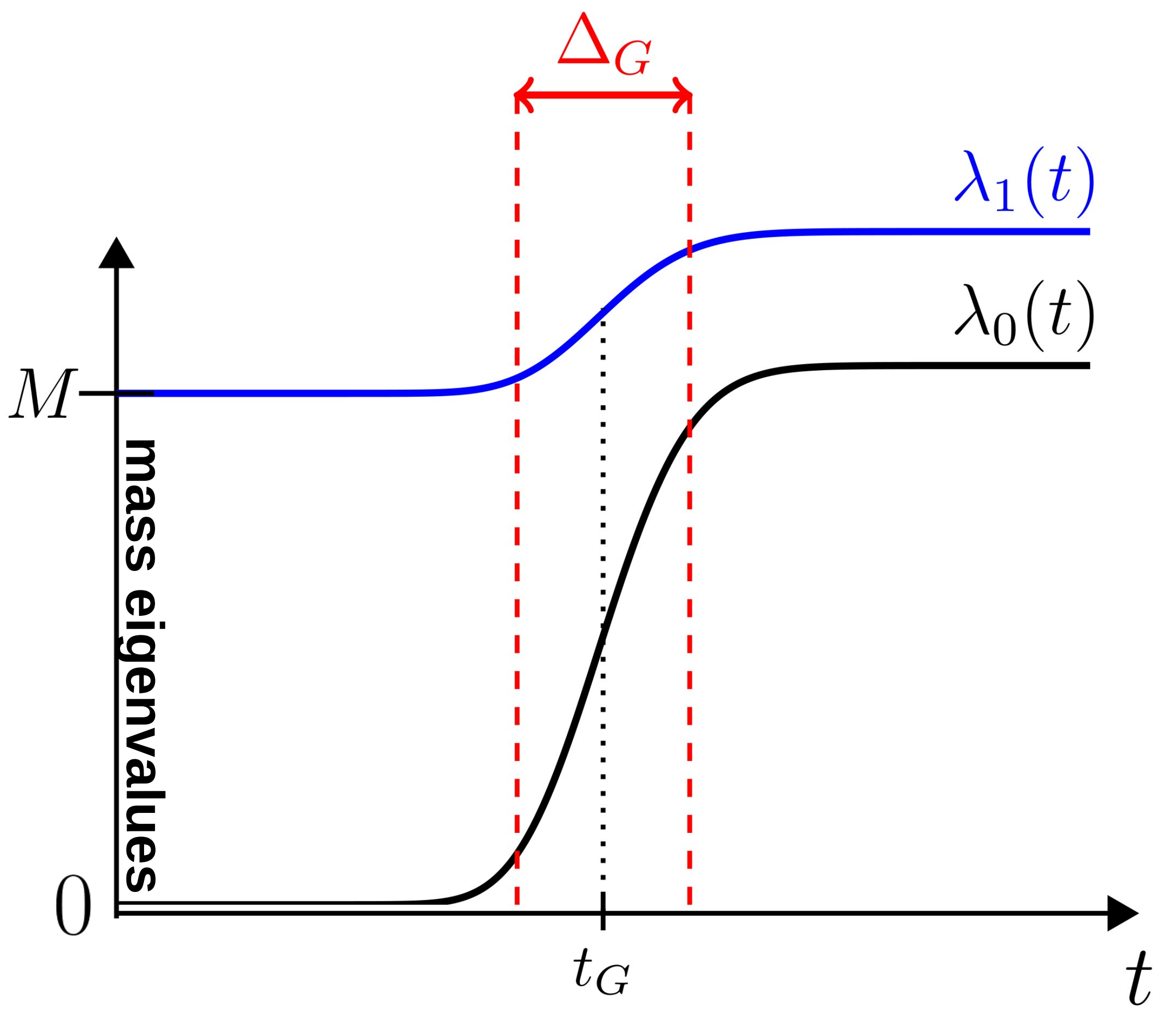
A Toy Model



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$$\mathcal{M}^2 = \begin{pmatrix} 0 & 0 \\ 0 & M^2 \end{pmatrix}$$

at early times, allow for
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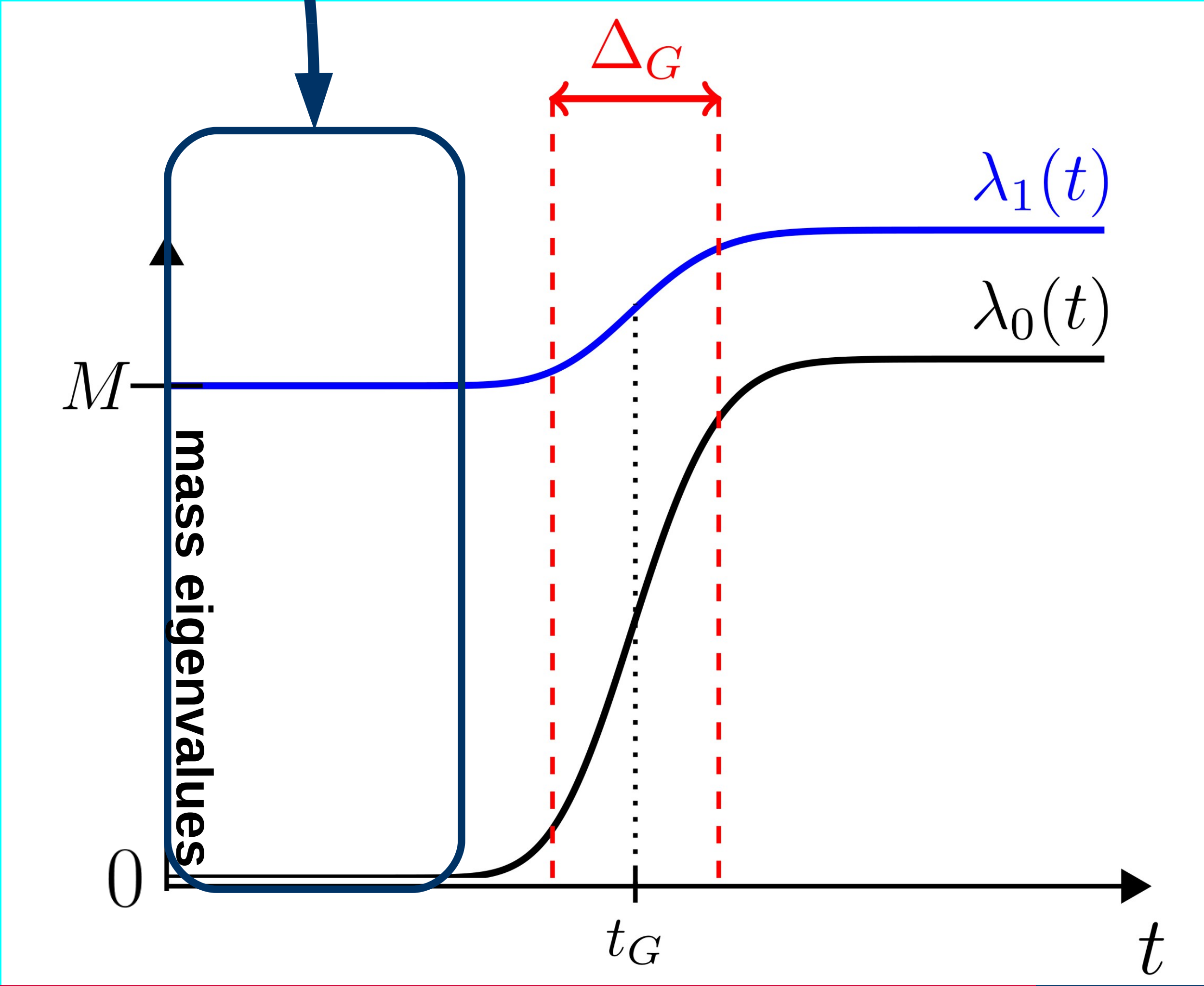

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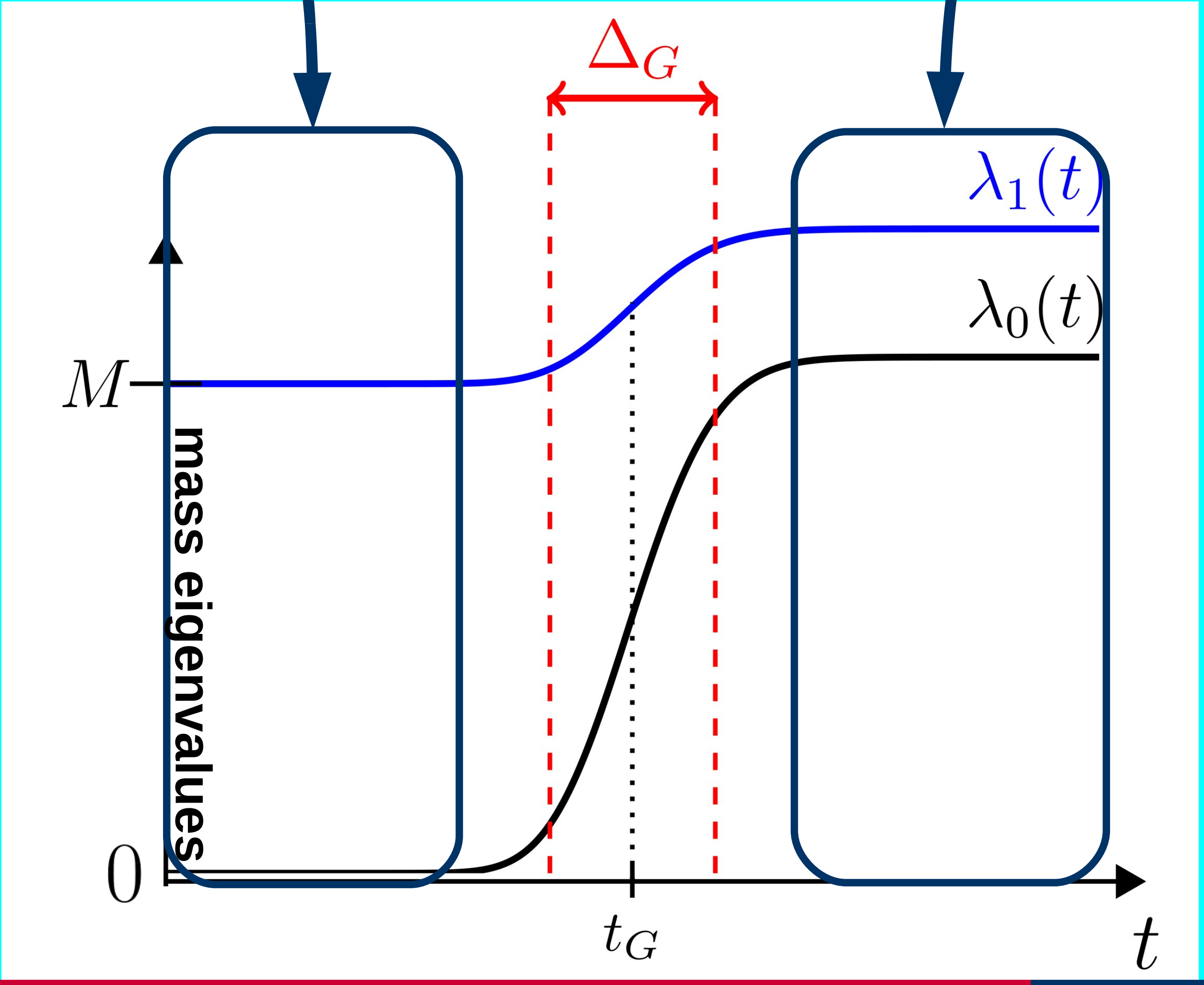
generated mass
components



Evolution of the Mass Matrix

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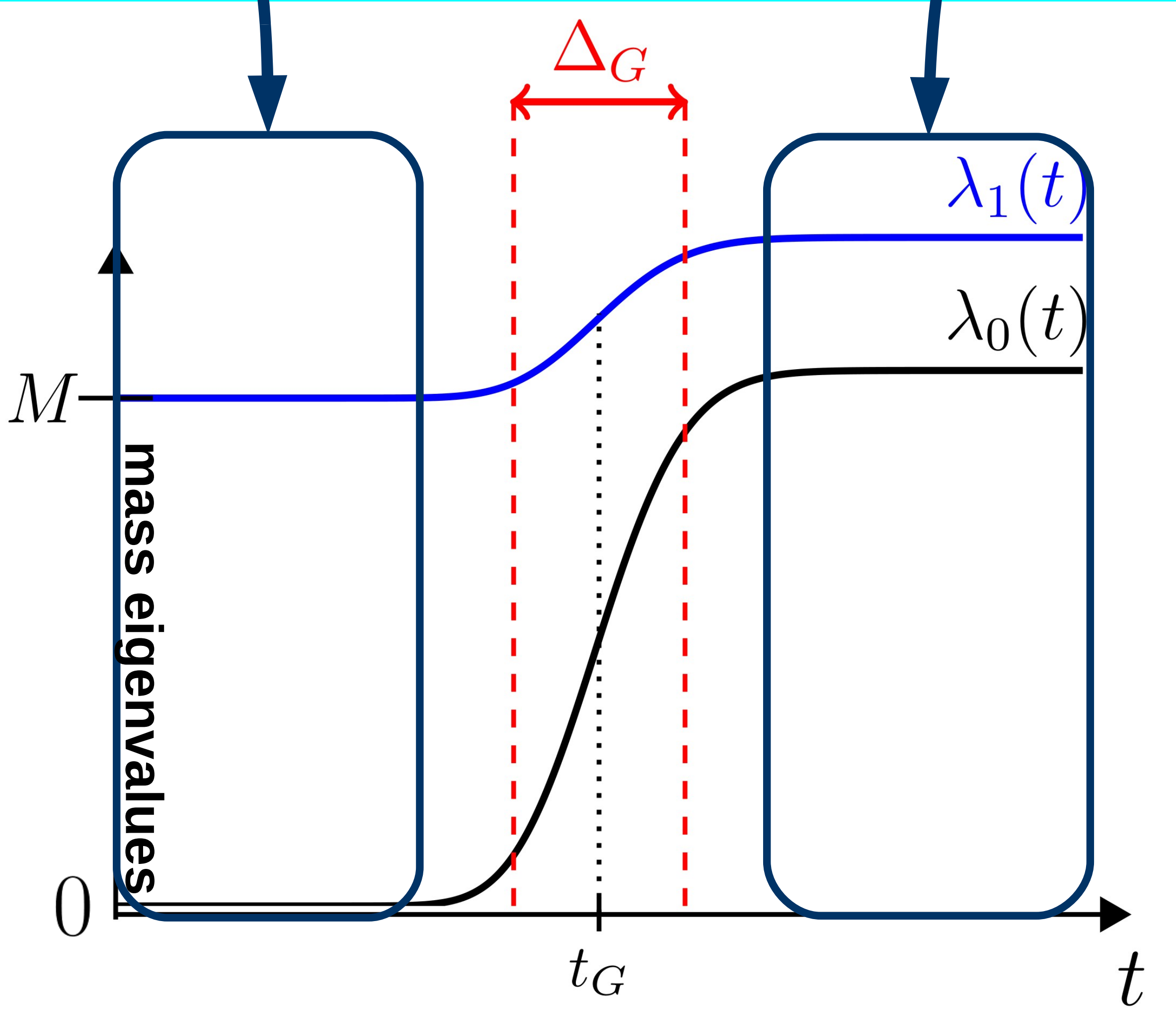

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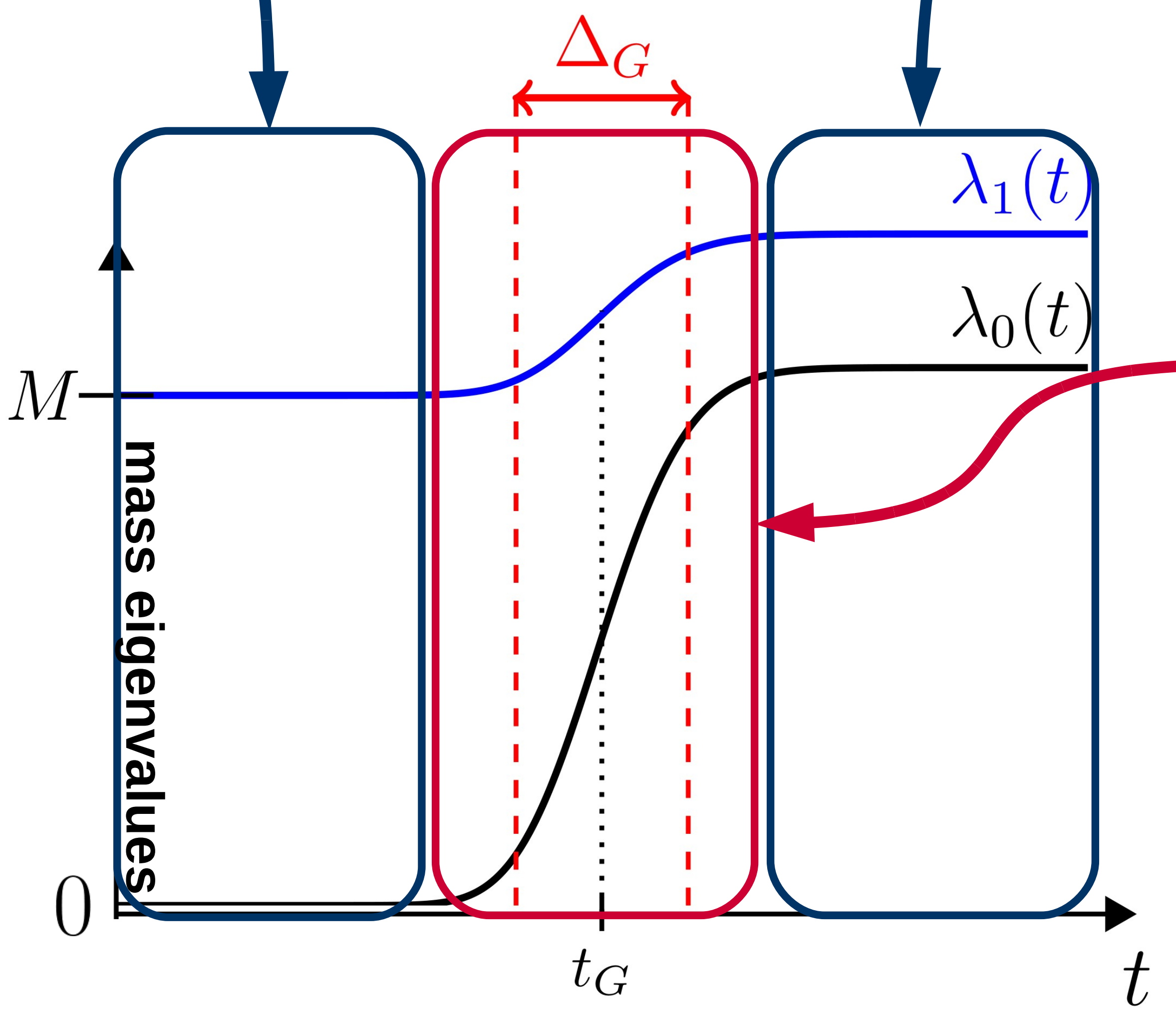

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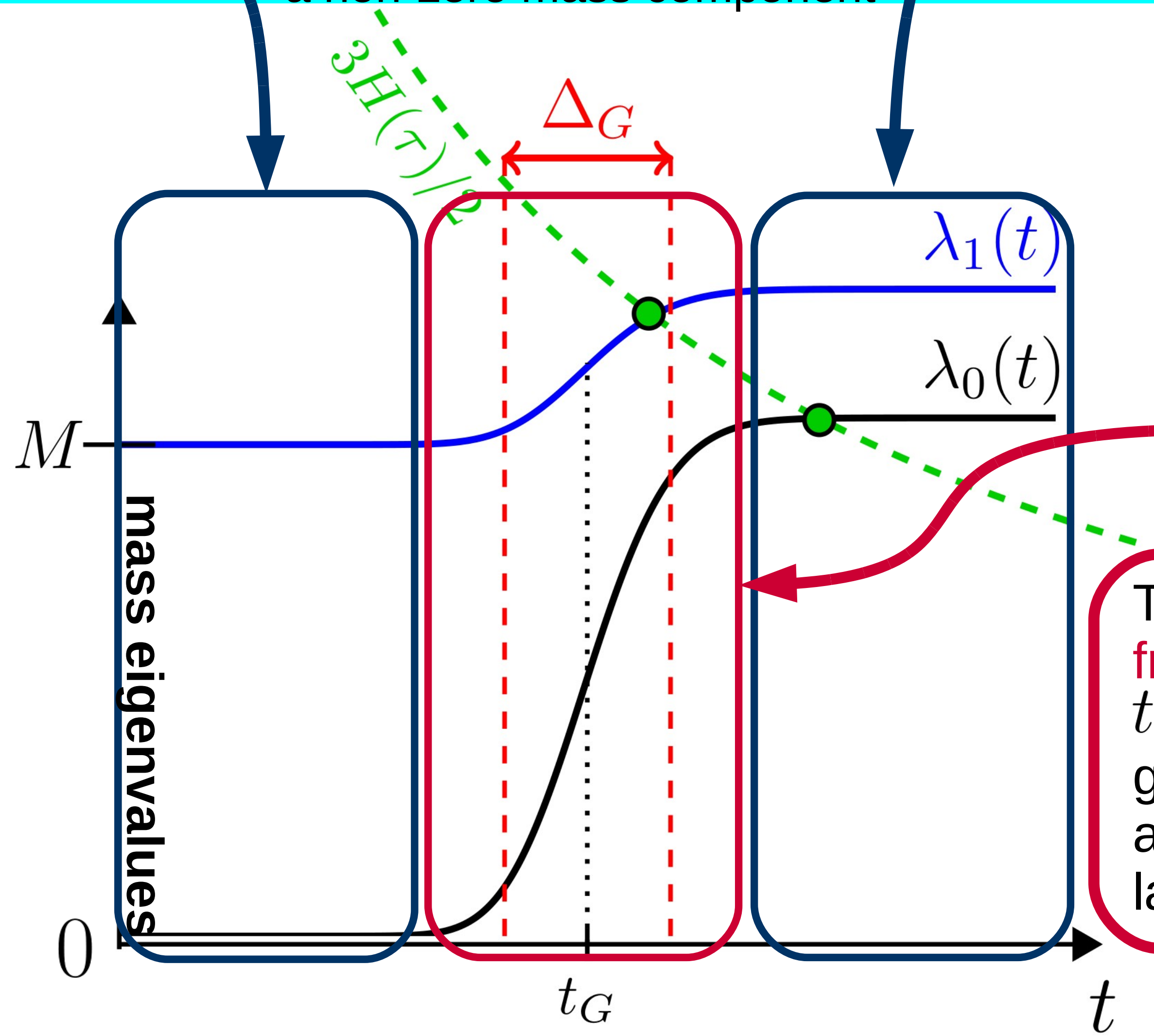

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Thus, model is equipped with free parameters: θ , Δ_G, and t_G (in addition to other generated mass parameters), all of which can impact the late-time abundance.

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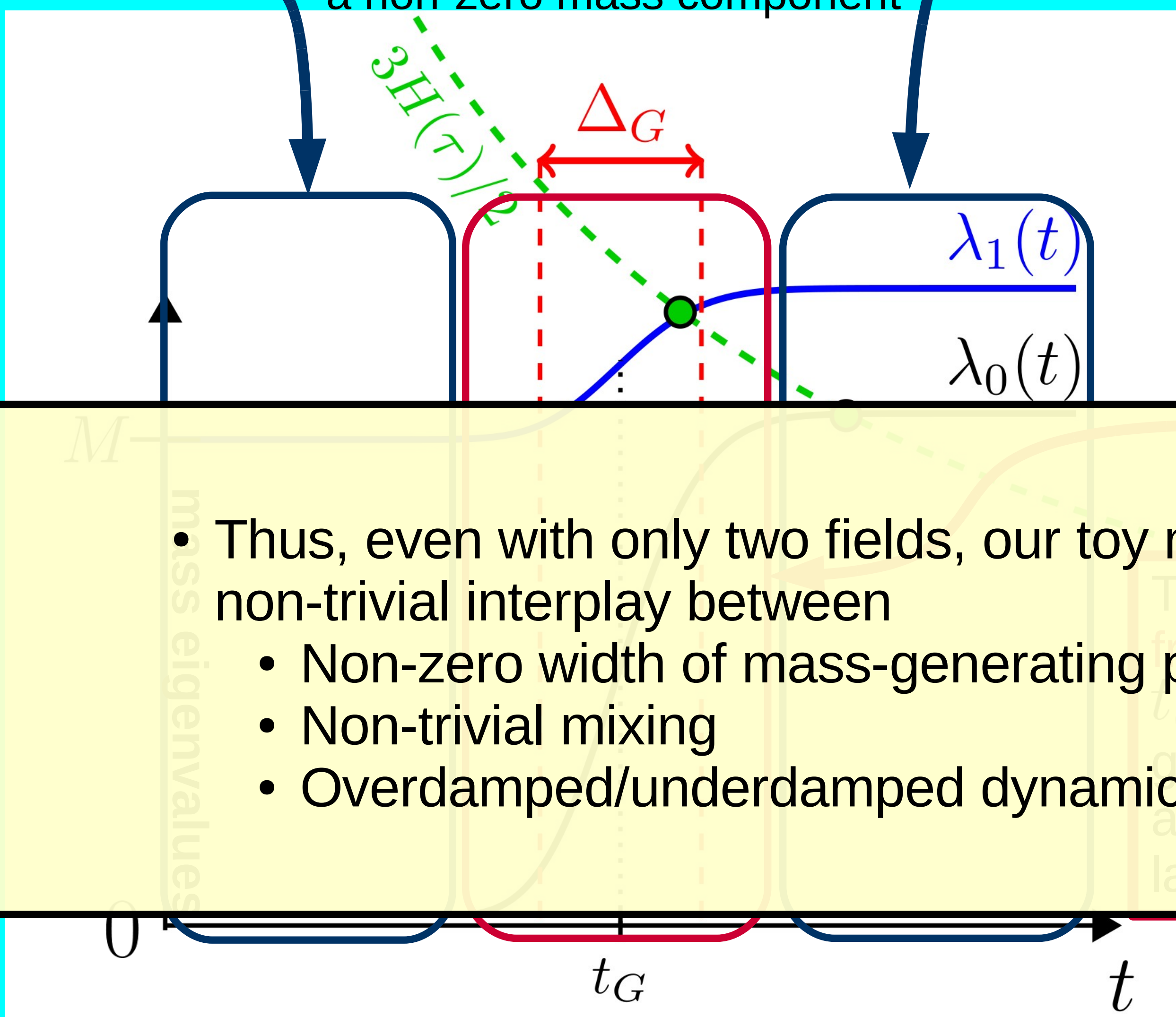

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Thus, model is equipped with free parameters: θ, Δ_G, and t_G (in addition to other generated mass parameters), all of which can impact the late-time abundance.

- Thus, even with only two fields, our toy model captures the non-trivial interplay between
  - Non-zero width of mass-generating phase transition
  - Non-trivial mixing
  - Overdamped/underdamped dynamical transition

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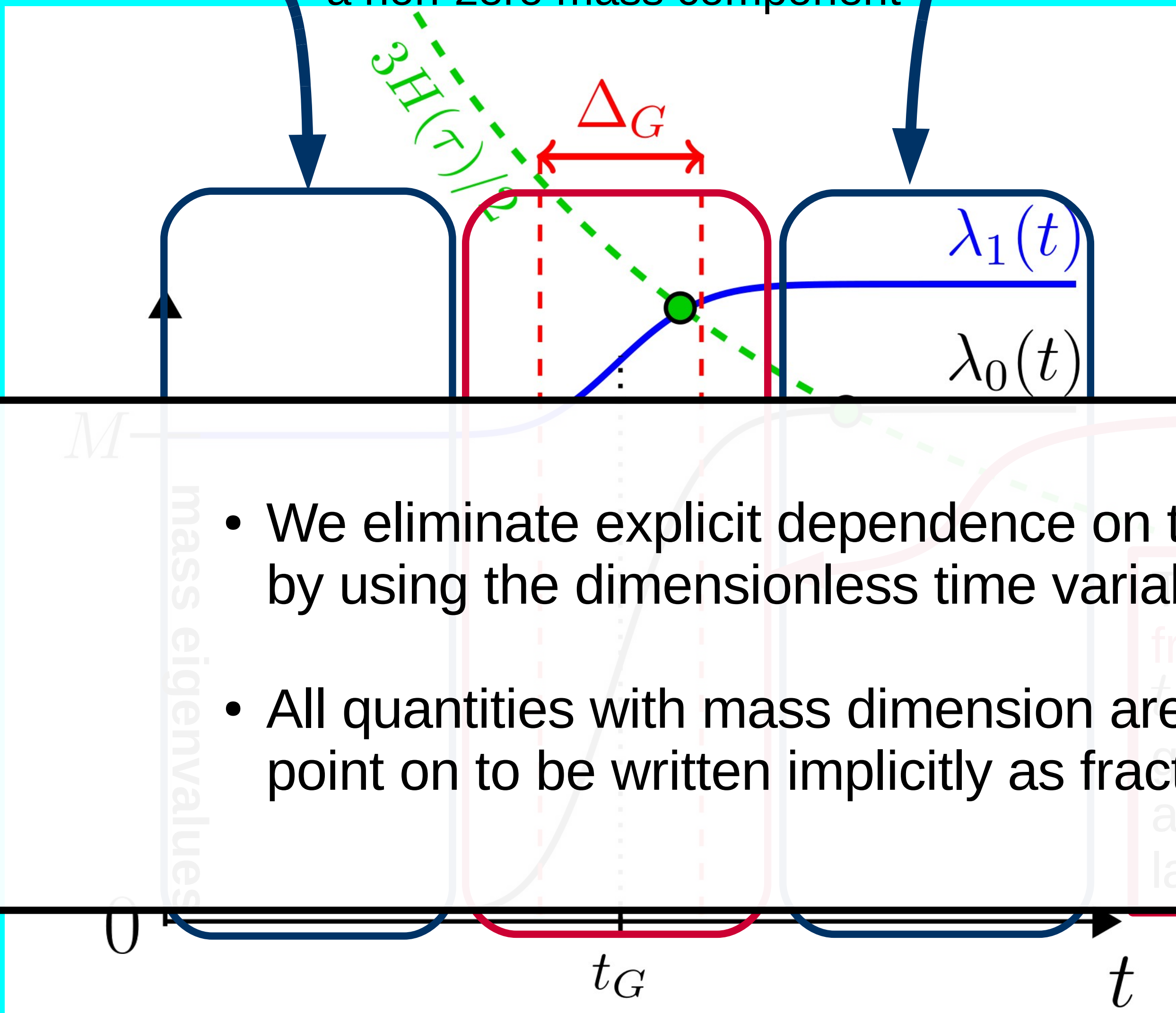
generated mass components

parameterize the mixing that is generated, by some angle θ



smoothly interpolate between the early and late regimes, with some

- We eliminate explicit dependence on the constant mass *M* by using the dimensionless time variable $\tau \equiv Mt$
- All quantities with mass dimension are understood from this point on to be written implicitly as fractions of *M*.

Performing Calculations

- The time-dependence in the mass^2 matrix (in the region of the phase transition) restricts our ability to find analytical solutions, so we solve this system numerically in most scenarios.

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This requires a considerable amount of numerical work:

- Our system can be "**stiff**", depending on its mass spectrum and the damping phase of the fields (which are both time-dependent).
- Must therefore use a combination of implicit and explicit methods ("Runge-Kutta-Fehlberg" and multi-step "Backwards Differentiation Formula" in a predictor-corrector form) to ensure stability of solutions.
- Field solutions will be evaluated at "**late times**" --- this requires a careful definition in our implementation, to ensure that asymptotic behavior has truly emerged.
- An **adaptive error** algorithm must be employed to ensure efficiency, due to the stark changes in behavior that the fields undergo before and after the phase transition, damping transition, etc.

What to Calculate?

- Only interested in how the late-time energy density varies compared to various **benchmarks** (i.e. zero mixing, zero phase transition width).

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- Only interested in how the late-time energy density varies compared to various **benchmarks** (i.e. zero mixing, zero phase transition width).
- Concentrate on two particular quantities in what follows:

$$\overline{\rho}/\widehat{\rho}(\overline{\xi} = 0)$$

Total (late-time) energy density, normalized to what it would have been with **zero mixing** and **zero phase transition width**

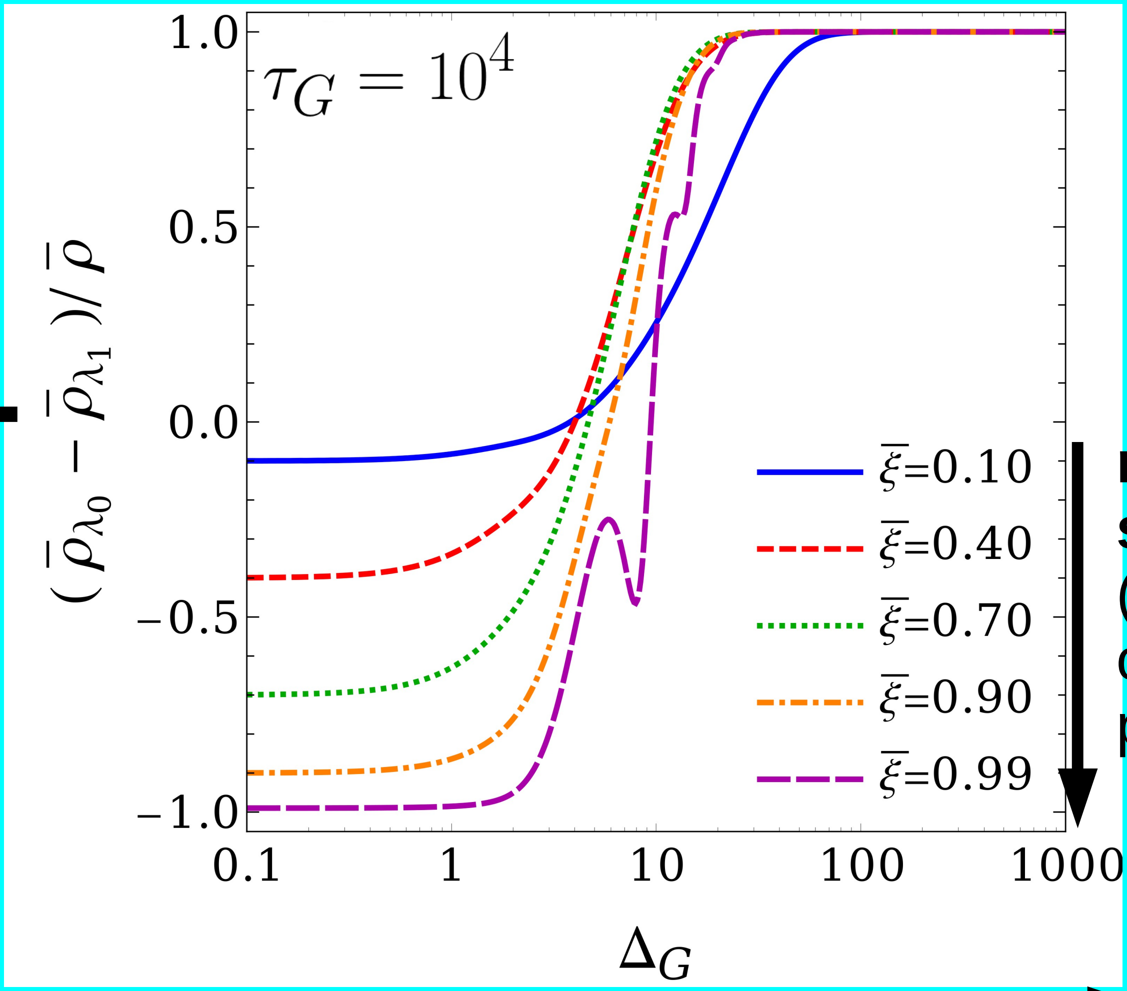
$$(\overline{\rho}_{\lambda_0} - \overline{\rho}_{\lambda_1})/\overline{\rho}$$

Tells how total energy density is apportioned between fields

Distribution of Components

lighter field dominates

heavier field dominates



mixing saturation
(fraction of maximum possible mixing)

phase transition timescale

Distribution of Components

As the width of the phase transition is increased, energy density **shifts completely** to lighter field!

lighter field dominates

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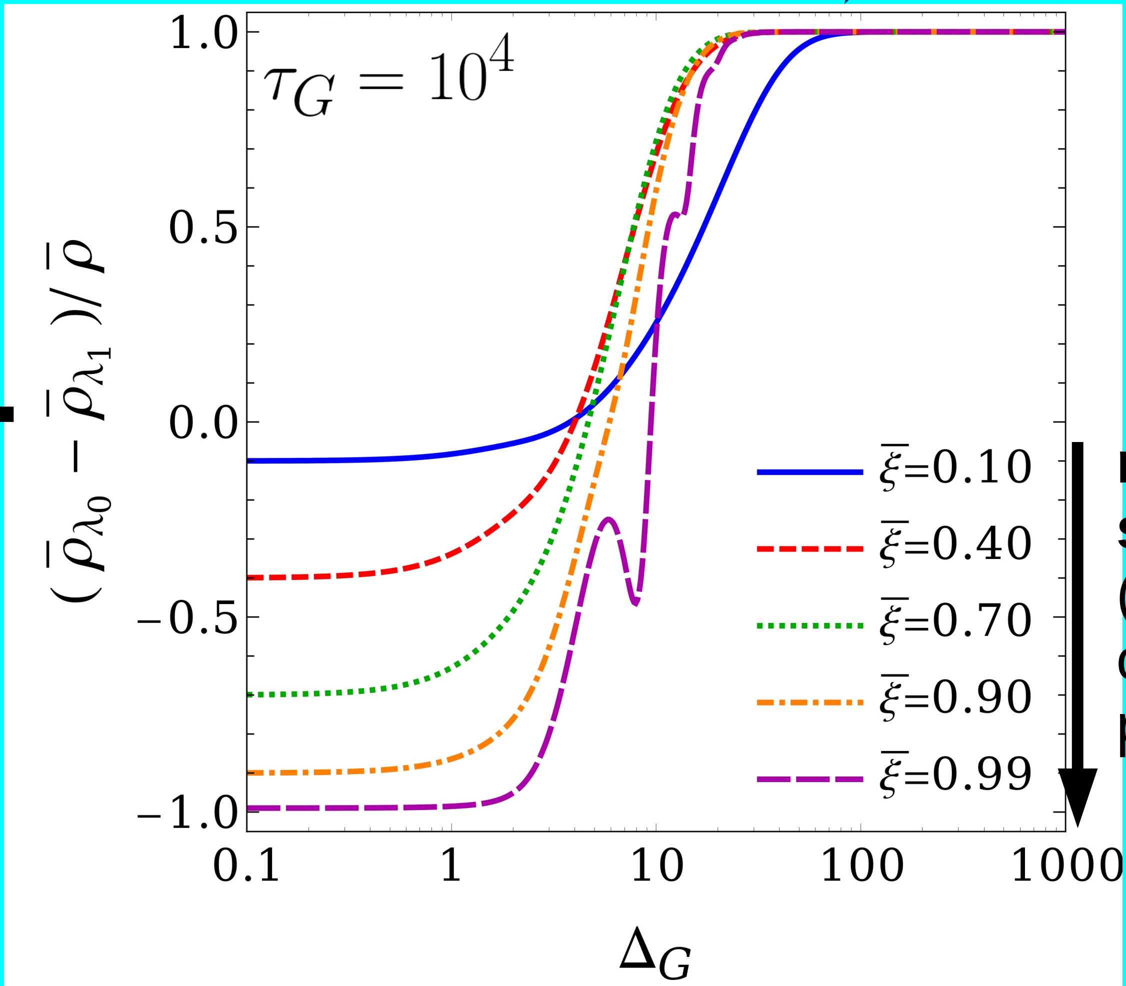

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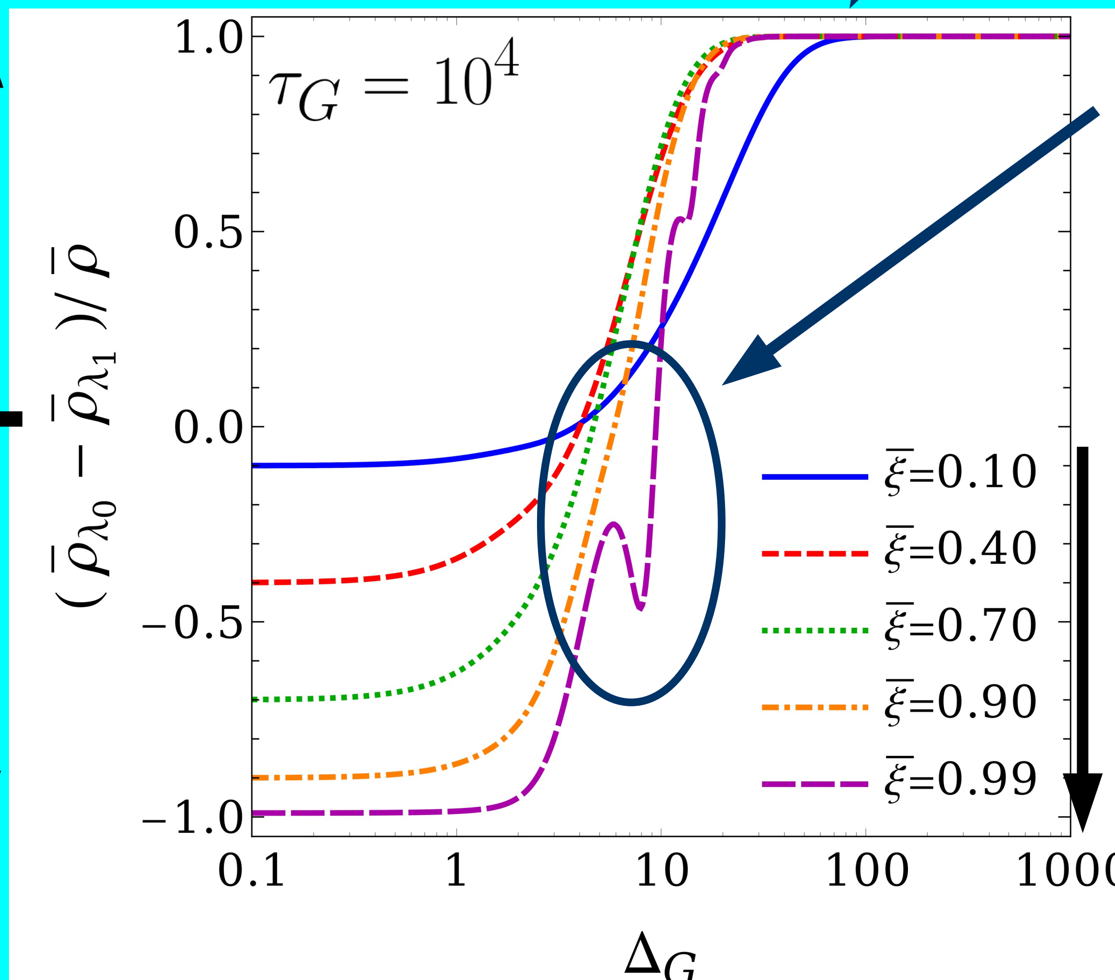


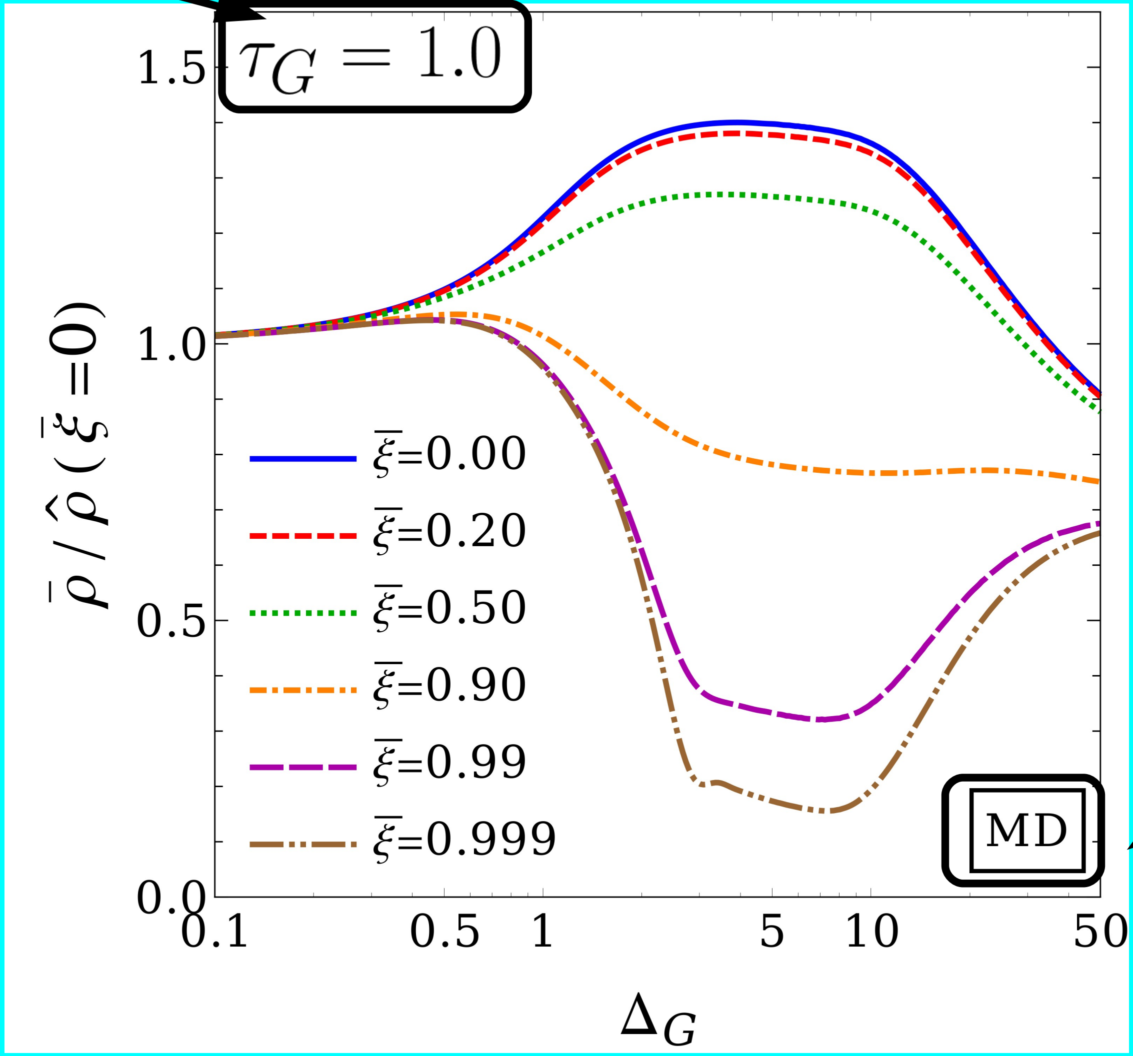
non-monotonicities appear in highly saturated mixing regime!

mixing saturation (fraction of maximum possible mixing)

phase transition timescale

Late-Time Total Energy Density Comparison

not all fields oscillating immediately at mass generation



matter dominated epoch

phase transition timescale

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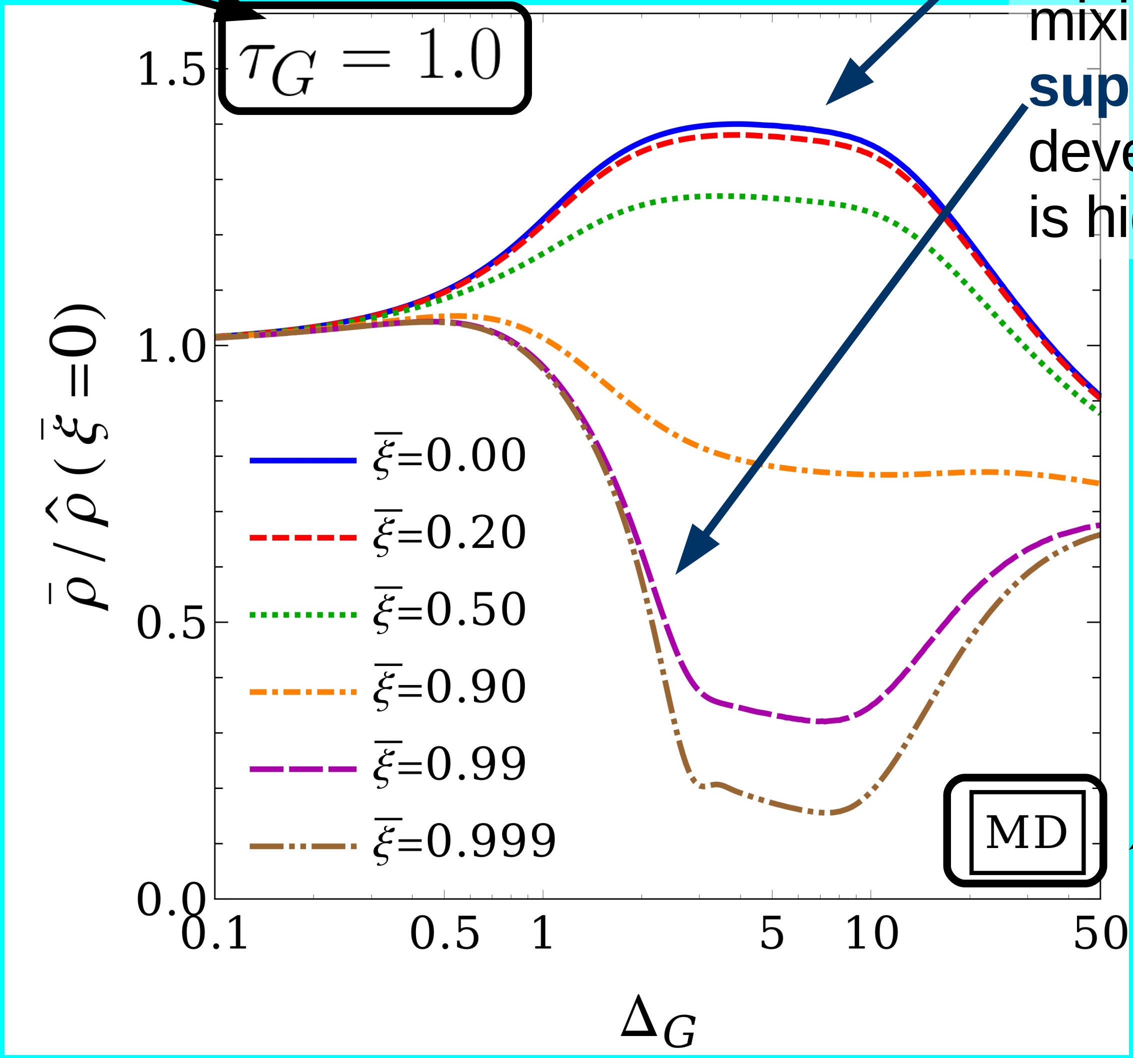
an **enhancement** develops for small mixing, while a **suppression** develops when mixing is highly saturated!



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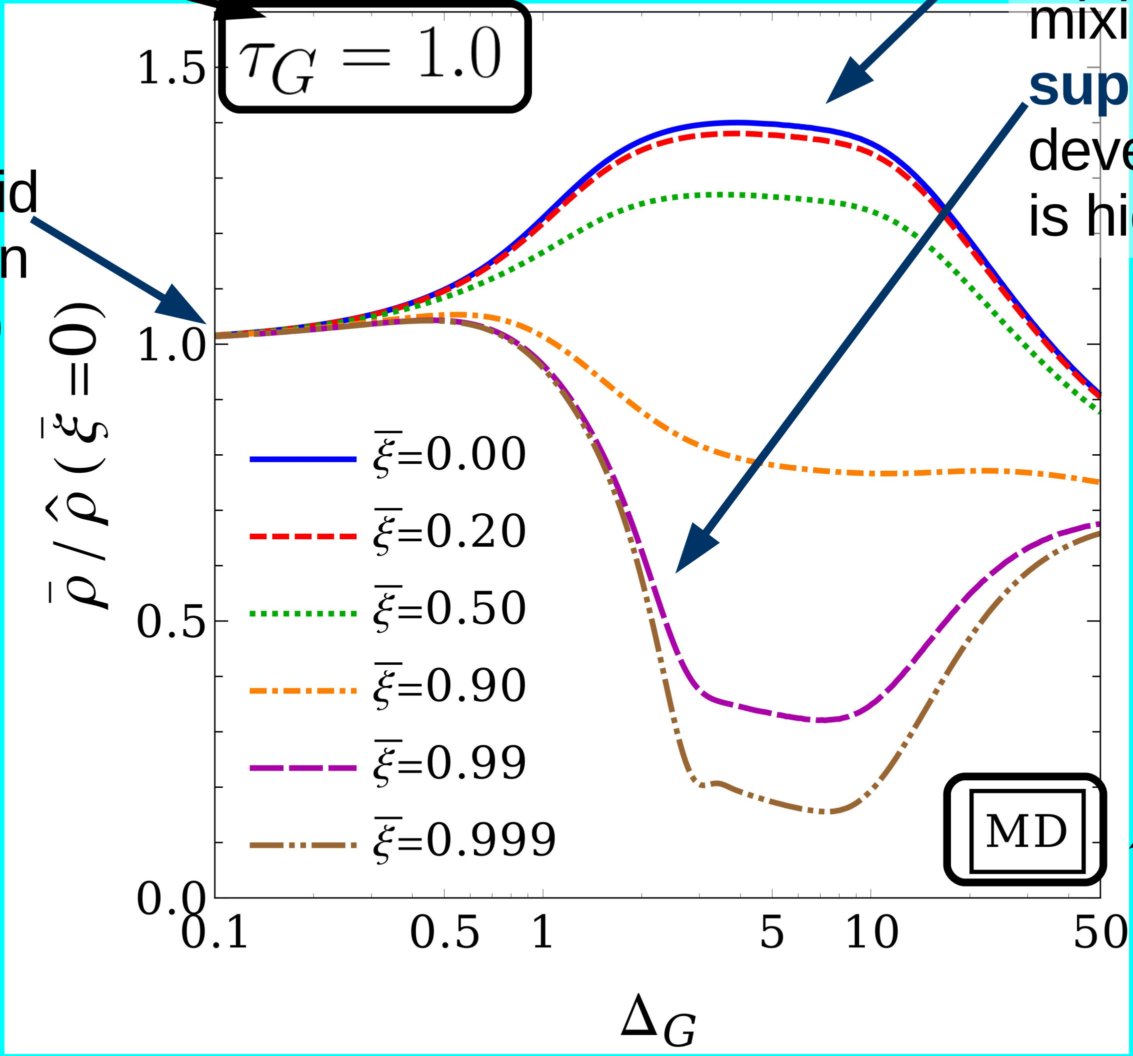

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Late-Time Total Energy Density Comparison

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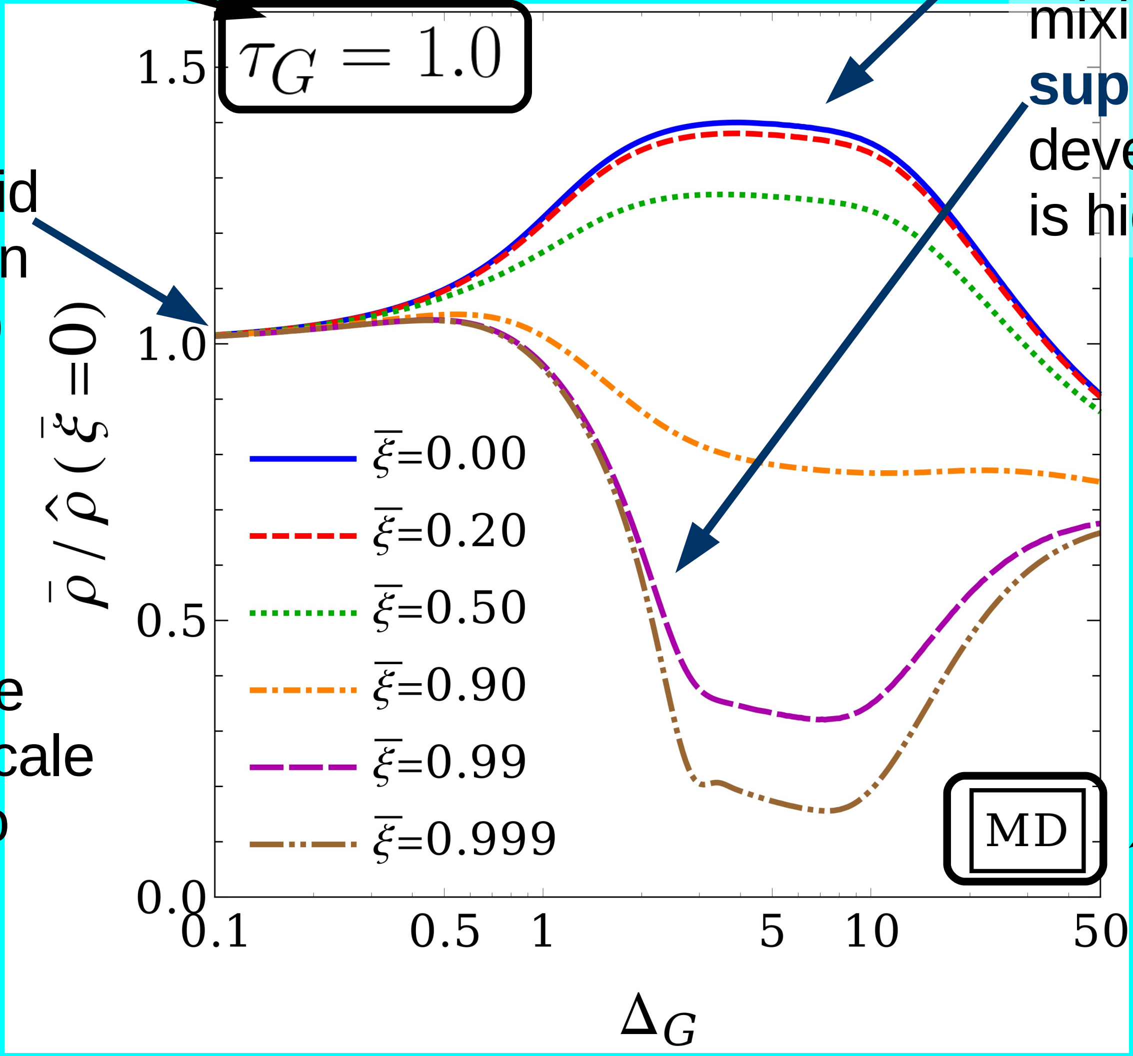
non-trivial phase transition timescale *allows* mixing to leave imprint at late times!



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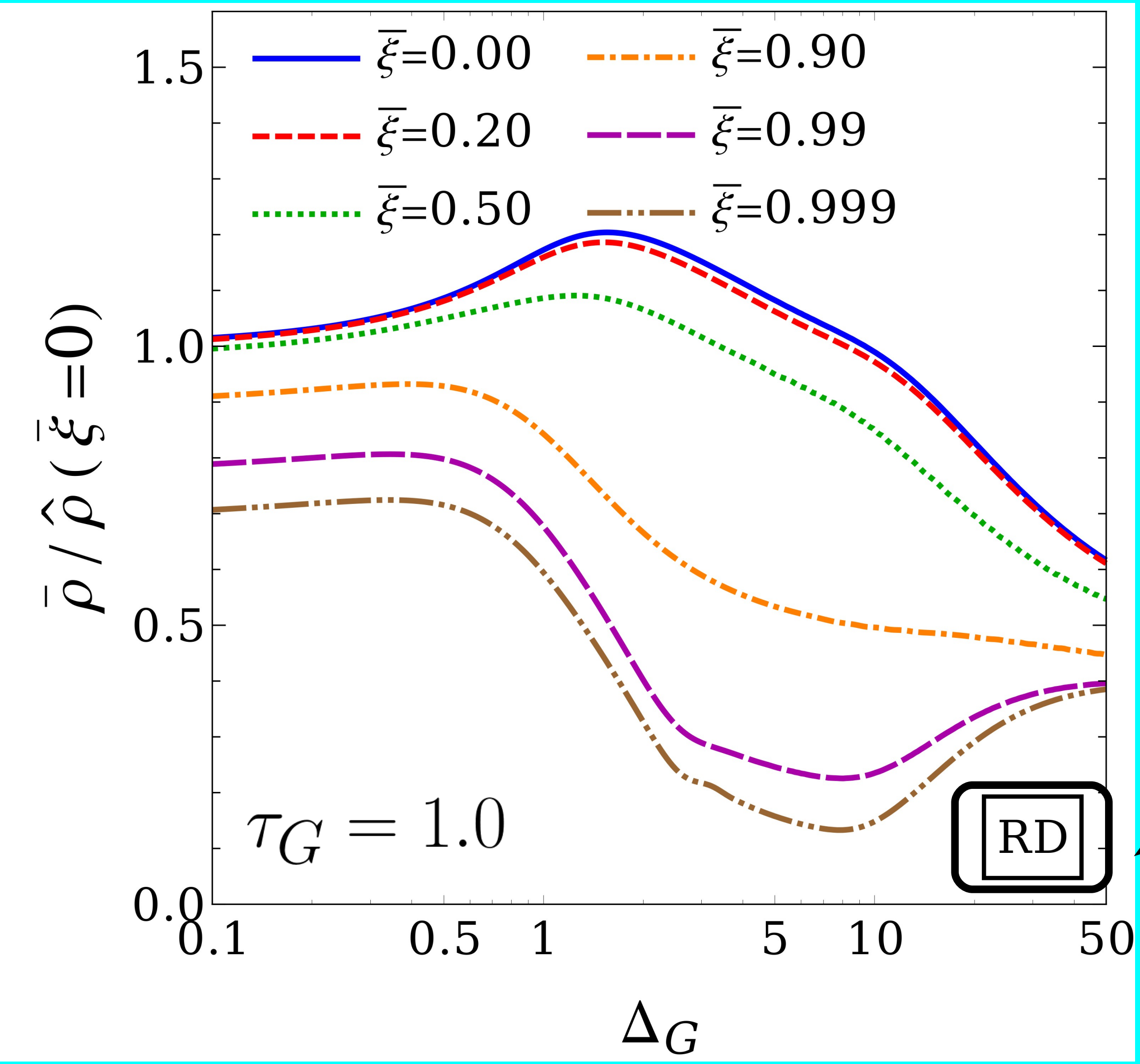
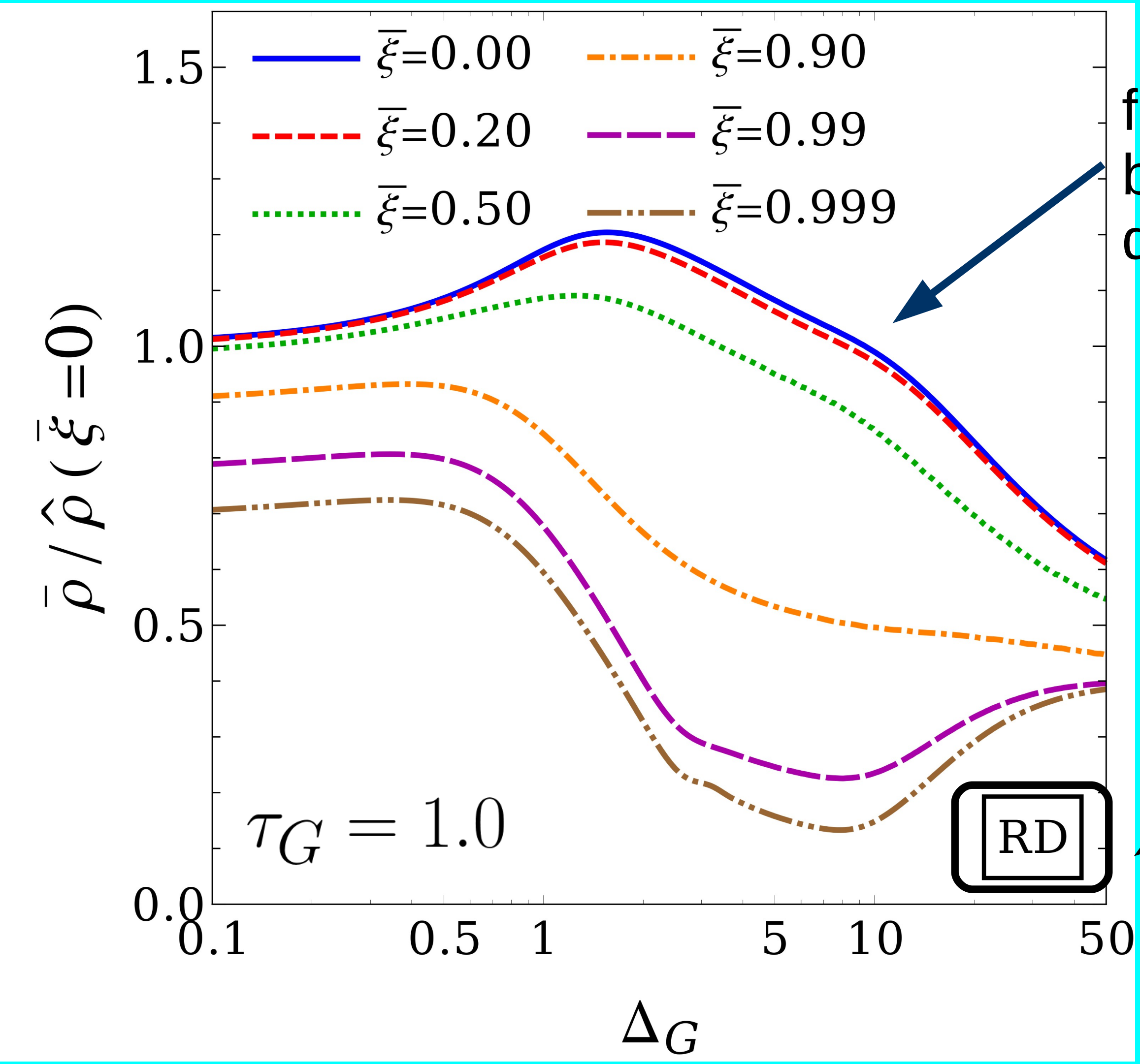


radiation dominated epoch

phase transition timescale

Late-Time Total Energy Density Comparison



follows similar behavior to matter-dominated epoch

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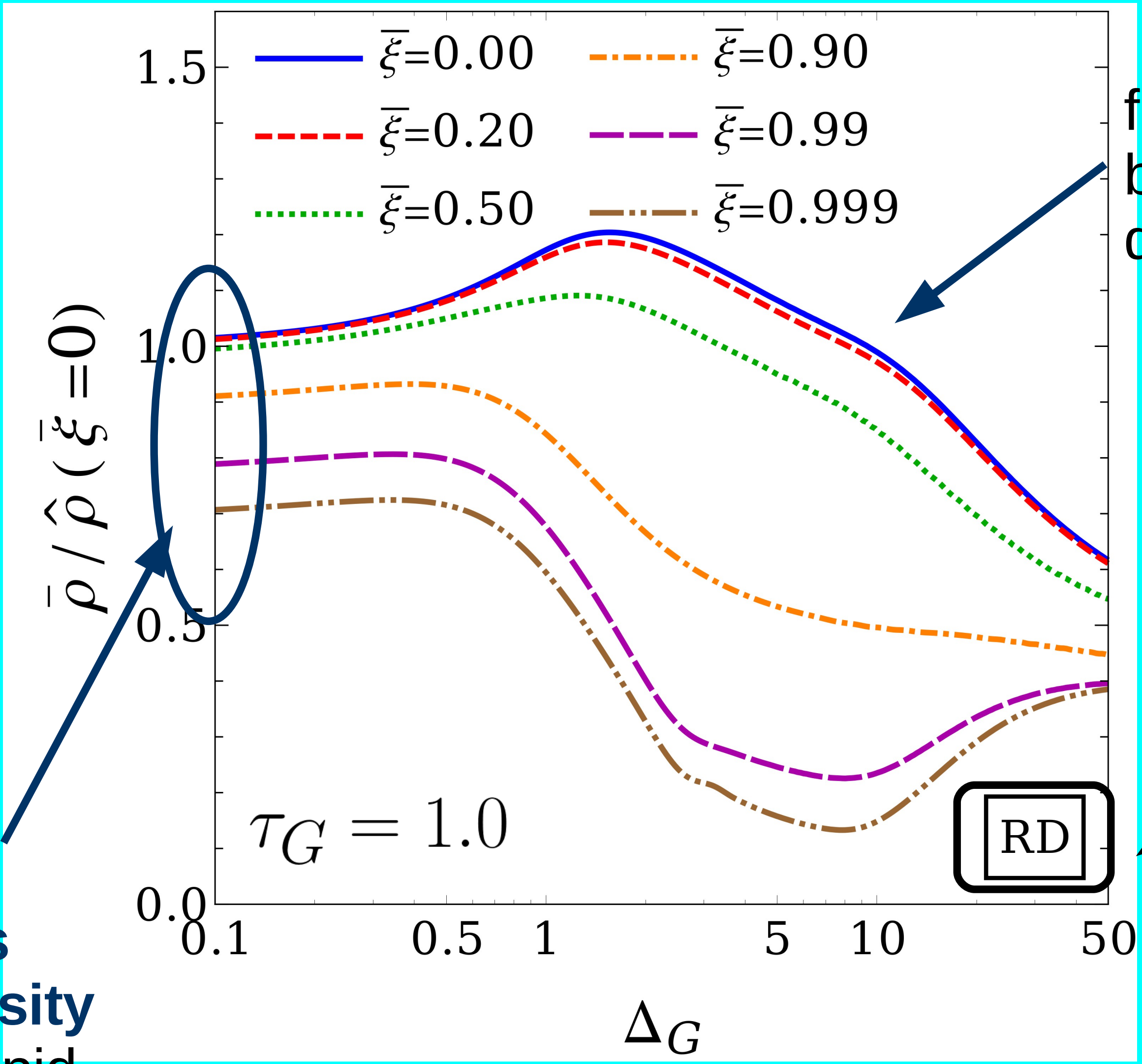
phase transition timescale

Late-Time Total Energy Density Comparison



follows similar behavior to matter-dominated epoch

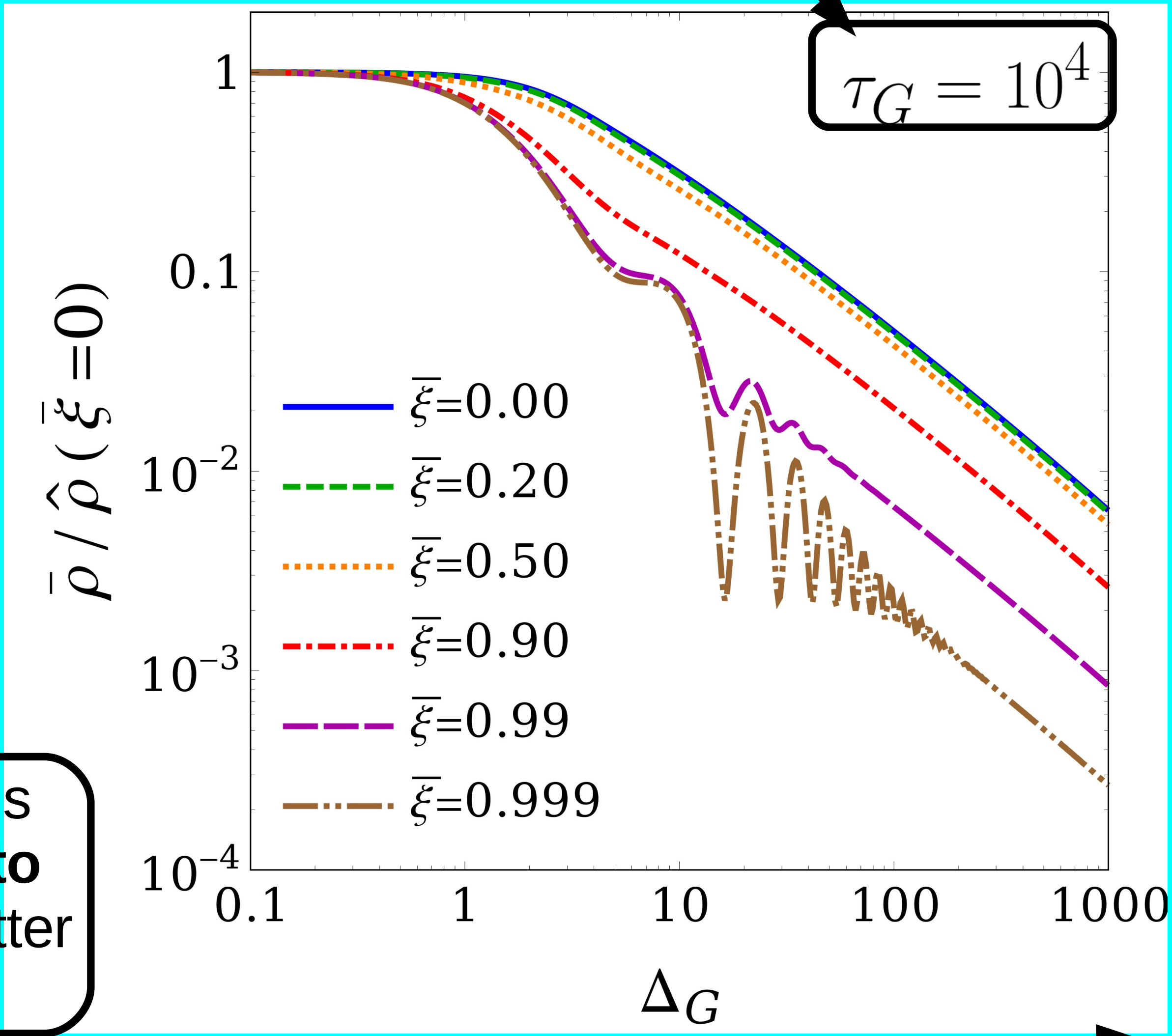
radiation dominated epoch

mixing now **suppresses energy density** even with rapid phase transition!

phase transition timescale

Late-Time Total Energy Density Comparison

fields immediately begin oscillating at mass generation



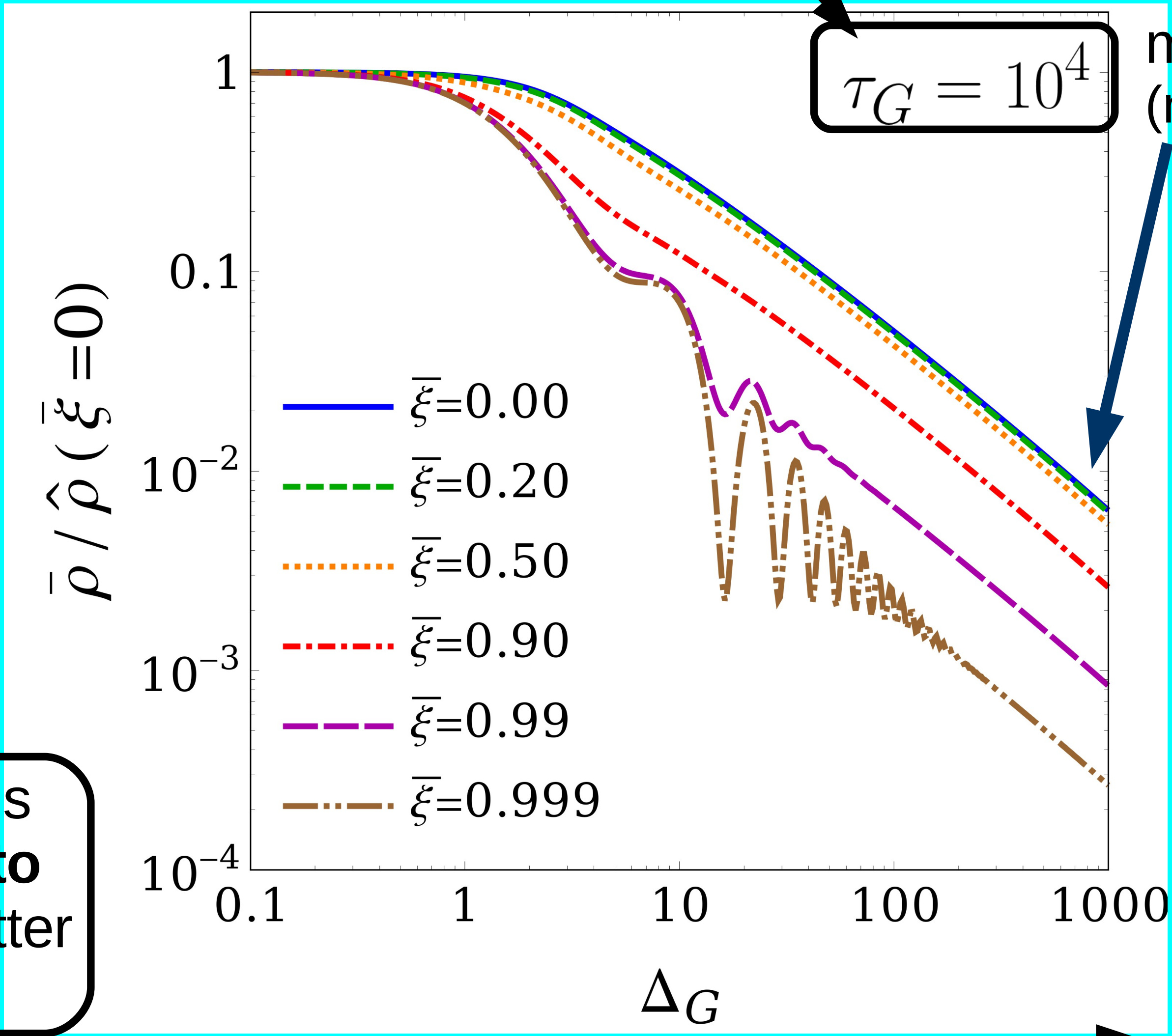
This regime is **insensitive to** radiation/matter domination

phase transition timescale

Late-Time Total Energy Density Comparison

fields immediately begin oscillating at mass generation

large suppressions: become increasingly dramatic as the mixing is saturated! (note this is a log-plot)



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Late-Time Total Energy Density Comparison

mixing again has **no effect** when the phase transition is rapid.

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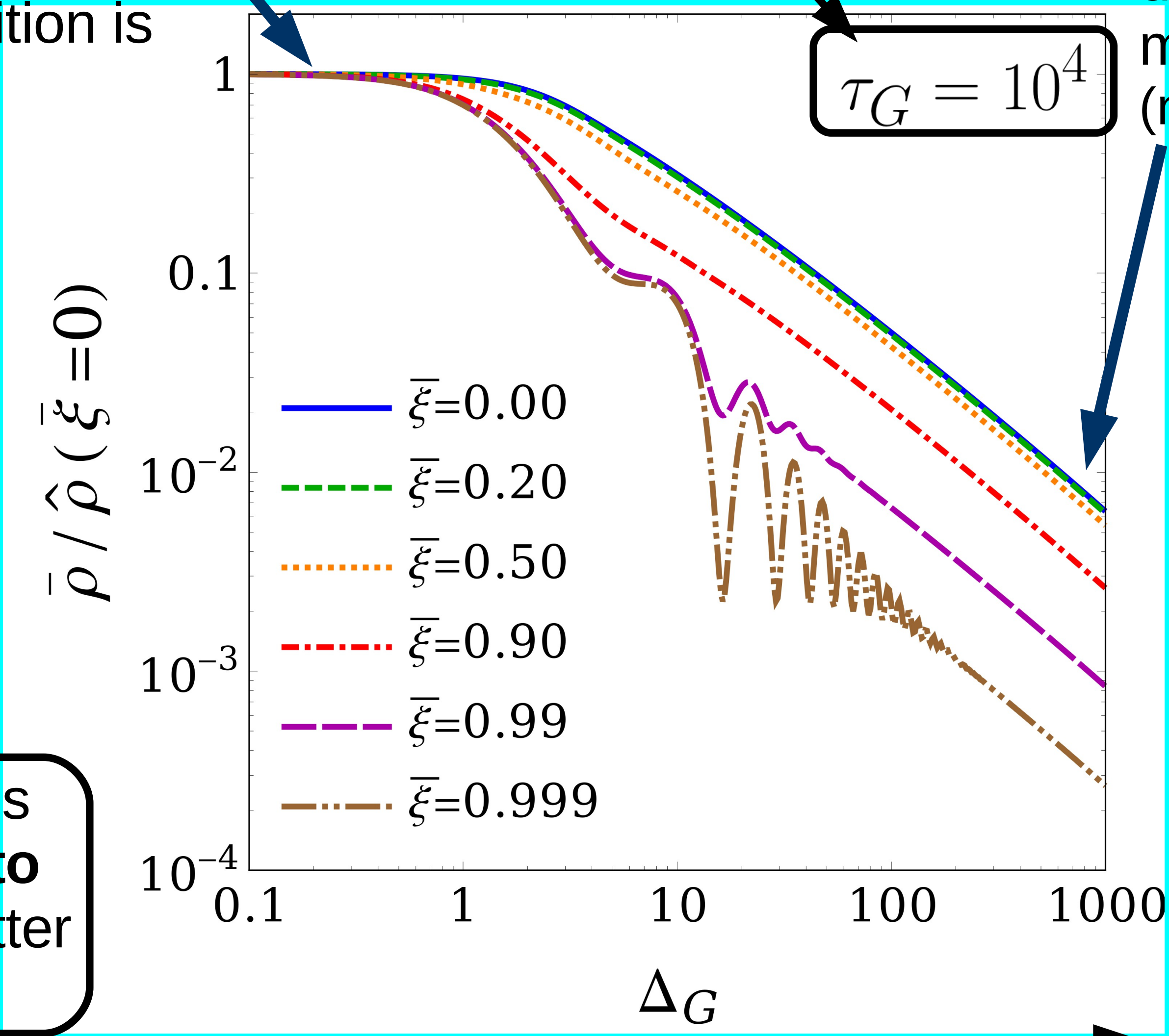

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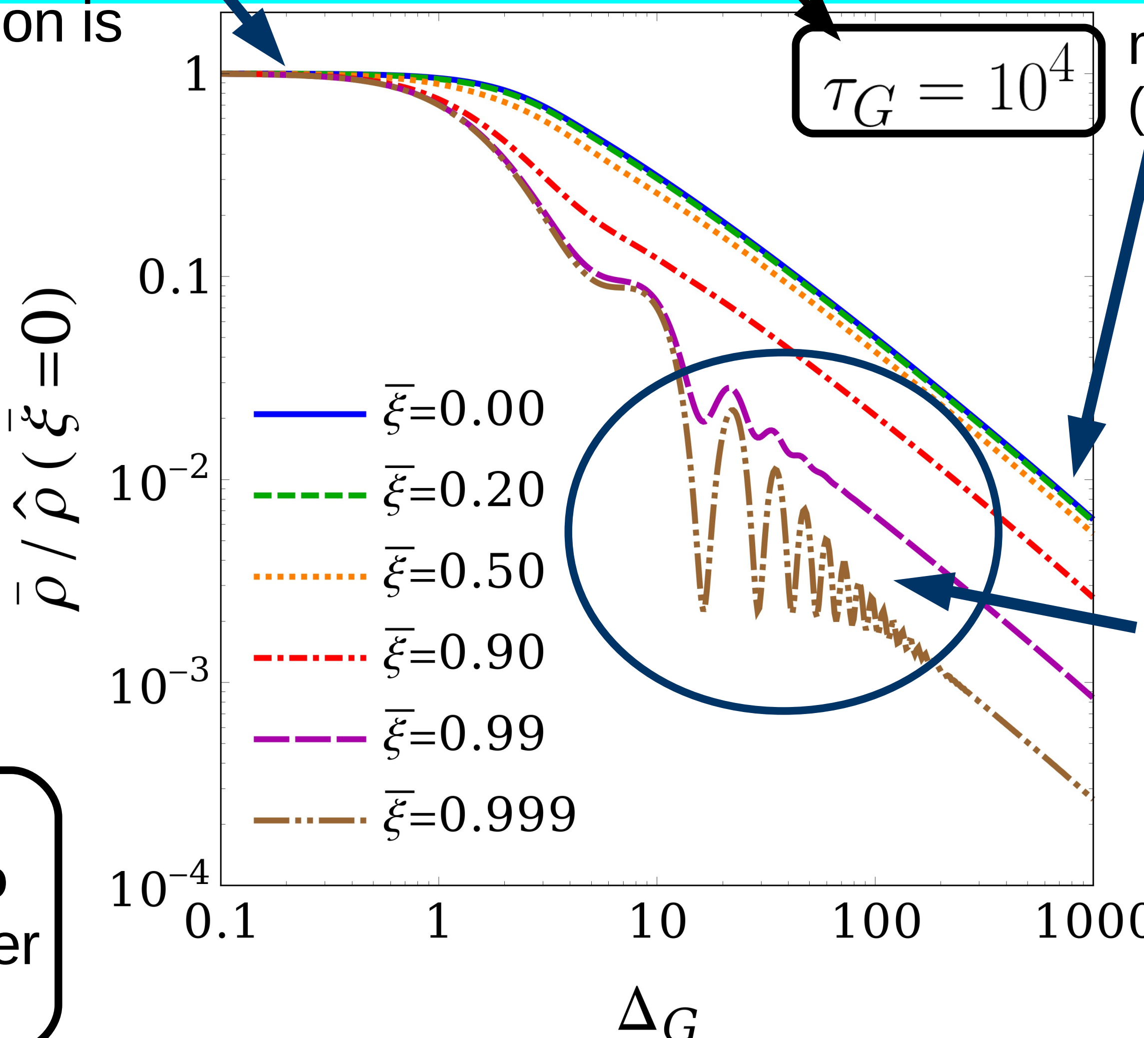


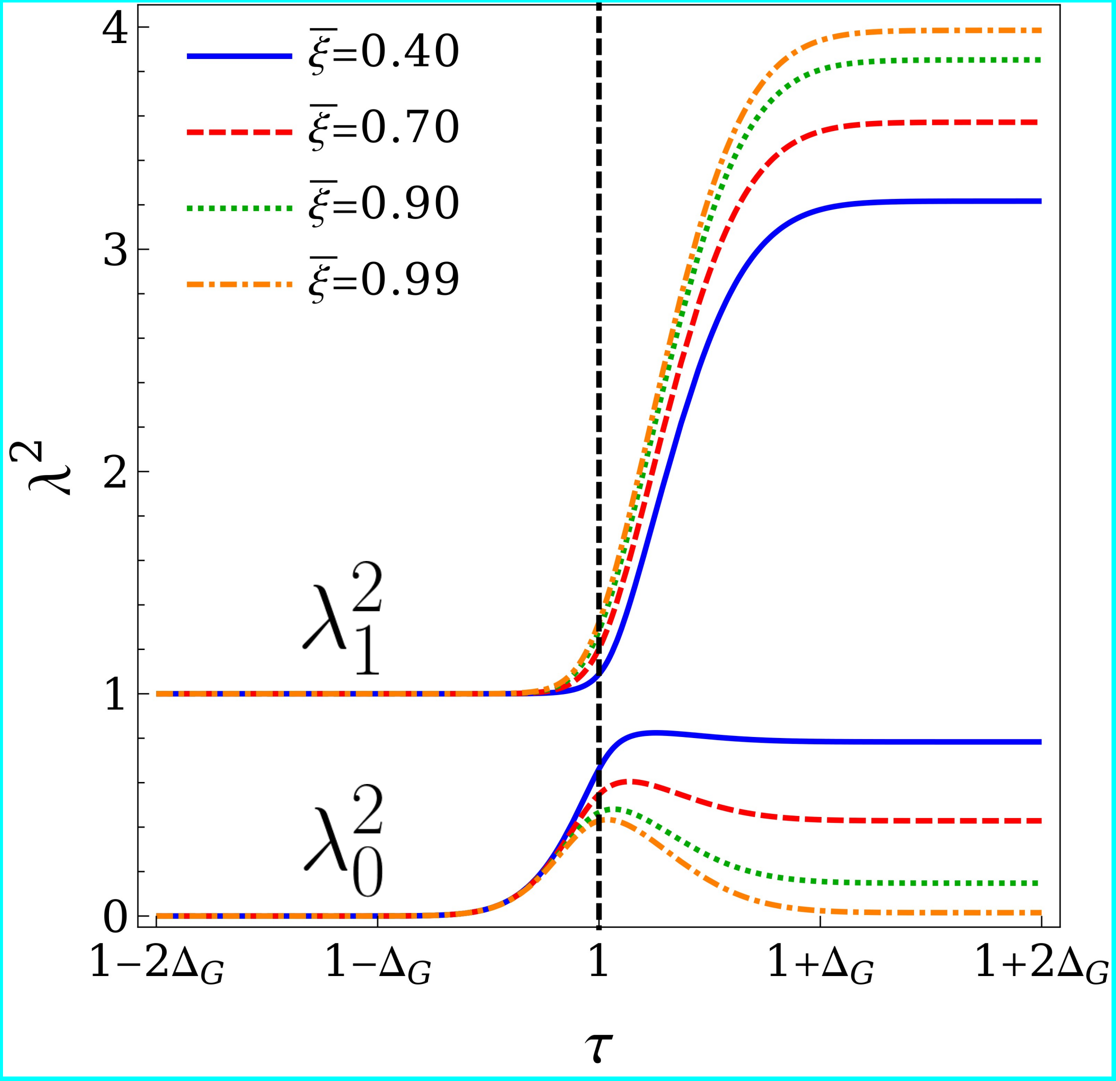
again, a sequence **non-monotonicities** in the saturated mixing regime!

This regime is **insensitive to** radiation/matter domination

phase transition timescale

Origin of Non-Monotonic Behavior

- The non-monotonicities seen in the highly mixing saturated curves are due to a special property of the mass spectrum in this regime:



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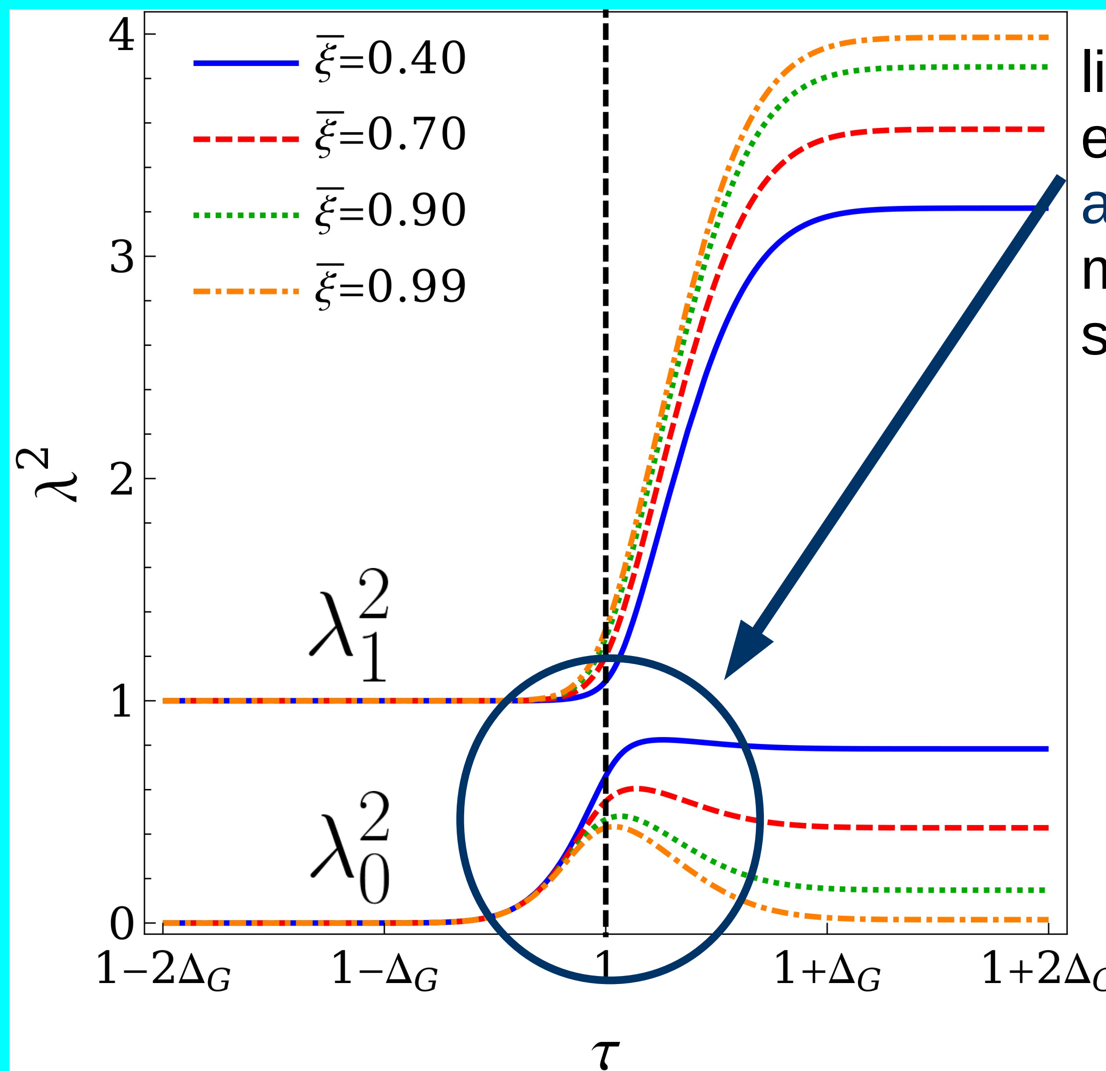


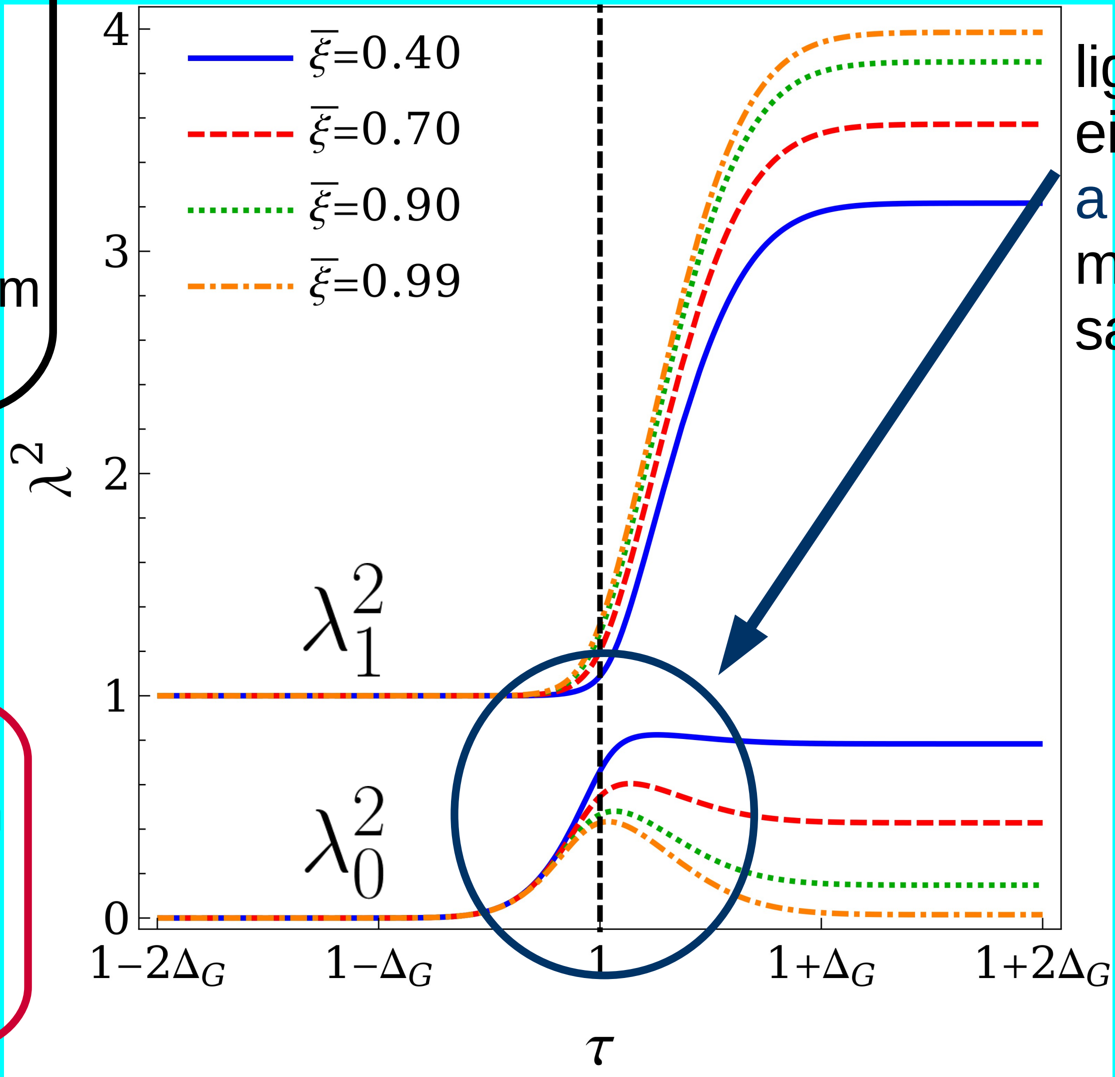
lighter mass eigenvalue develops a "pulse" when mixing is highly saturated

Origin of Non-Monotonic Behavior

- The non-monotonicities seen in the highly mixing saturated curves are due to a special property of the mass spectrum in this regime:

produces an effective **parametric resonance** in the lighter field for a whole discrete spectrum of widths Δ_G

resonant **enhancement** in energy density associated with the lighter field!



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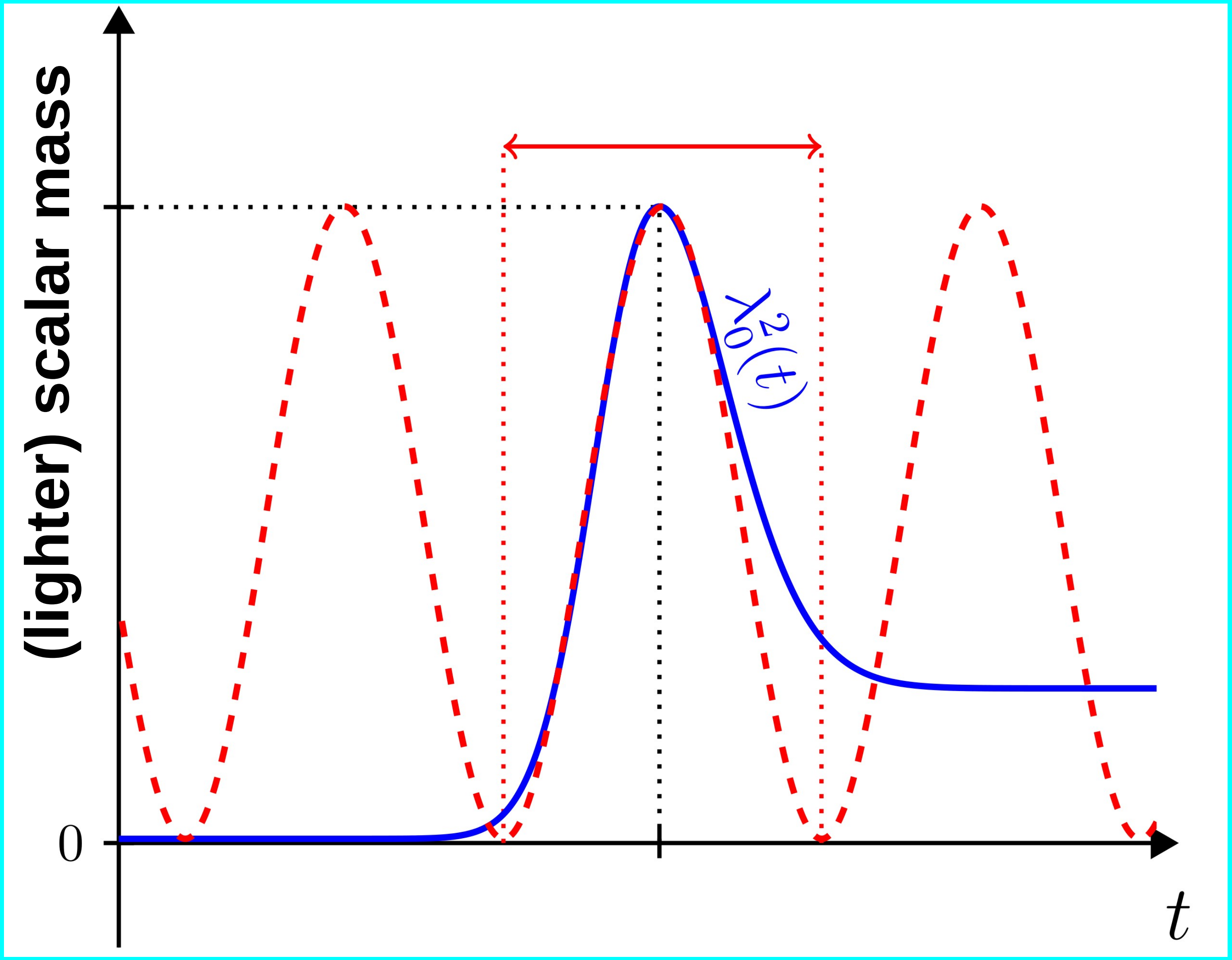
- Recall: a parametric resonance occurs when a parameter in the system modulates at frequencies that are certain (integer) multiples of the natural frequency.



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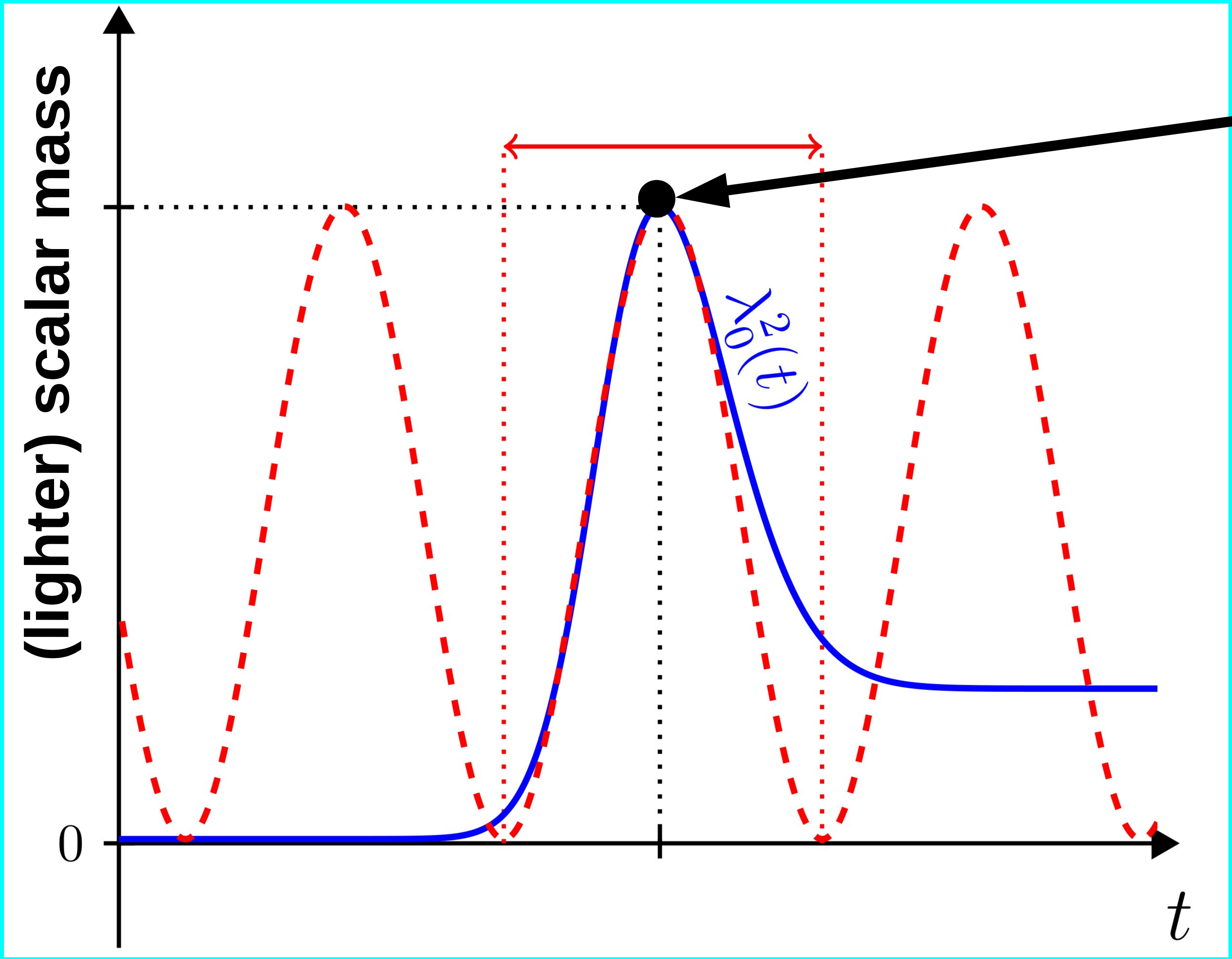

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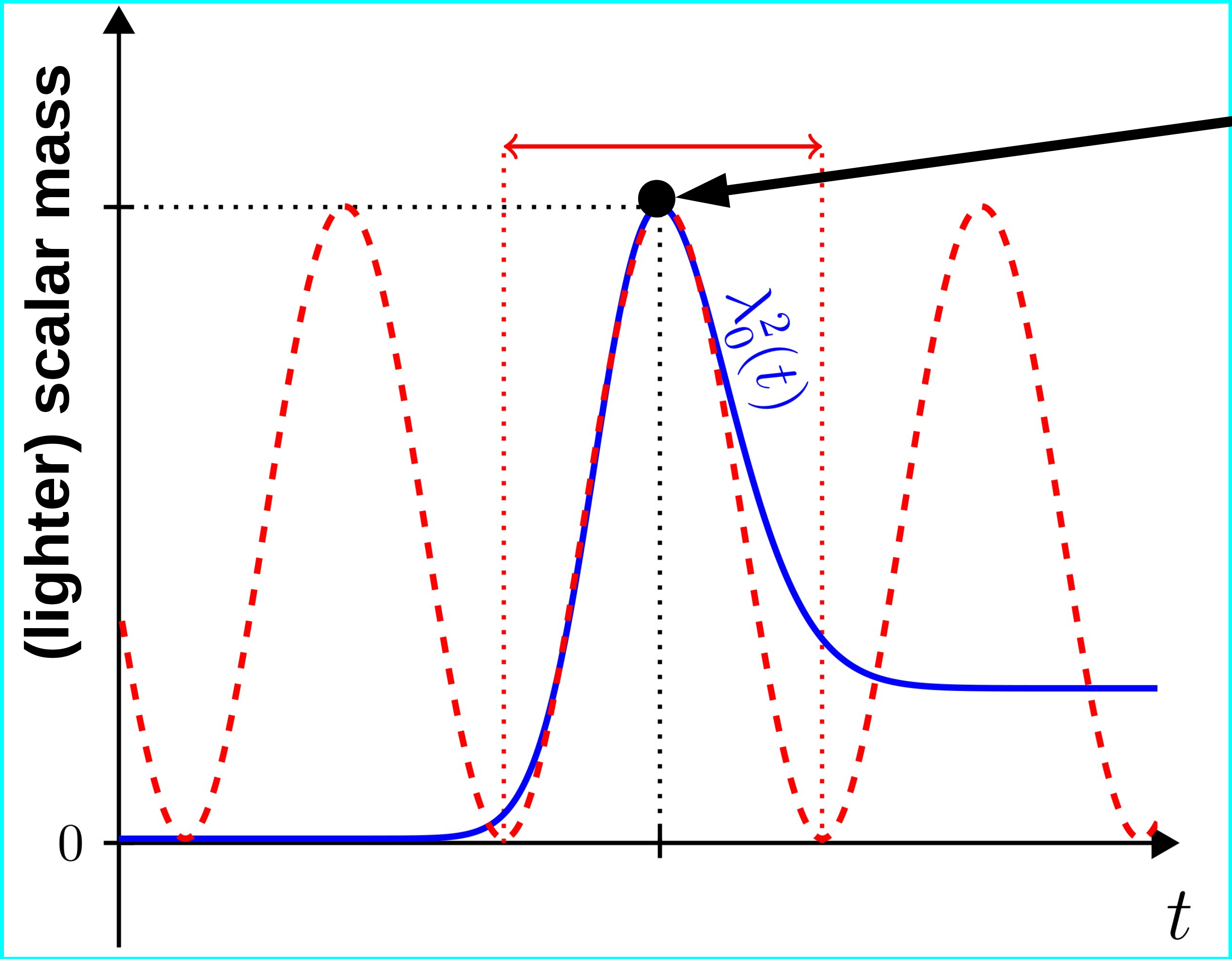


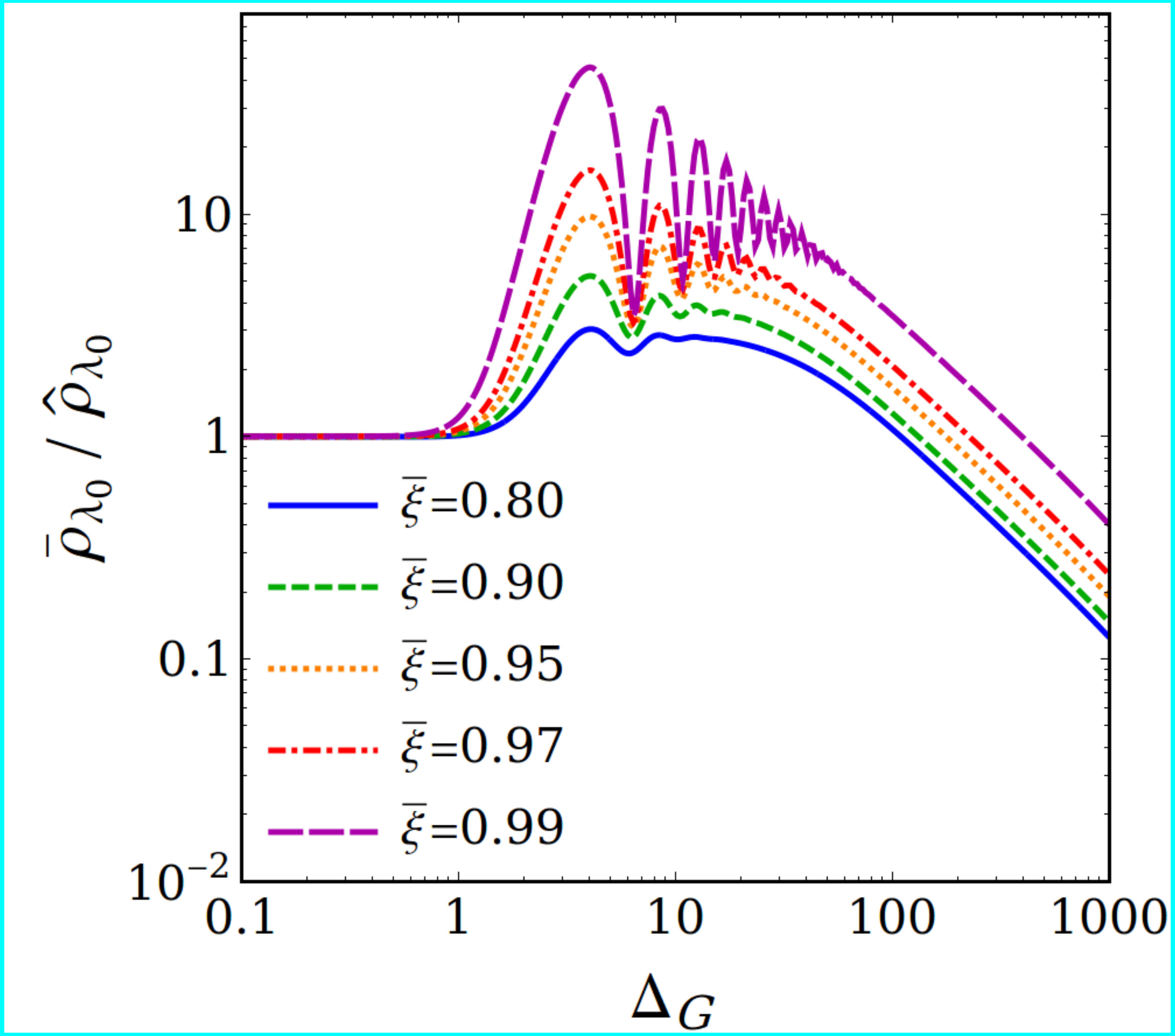
- Locally, the pulse *appears* periodic, with some effective frequency $\omega_{\rm eff}$.
- A resonant enhancement is produced when

$$\omega_{\rm eff} = 2\lambda_0/n$$

where n is an integer.

The Resonant Enhancement on the Lighter Field

- These resonances can be quite dramatic, e.g. for the **lighter field**:



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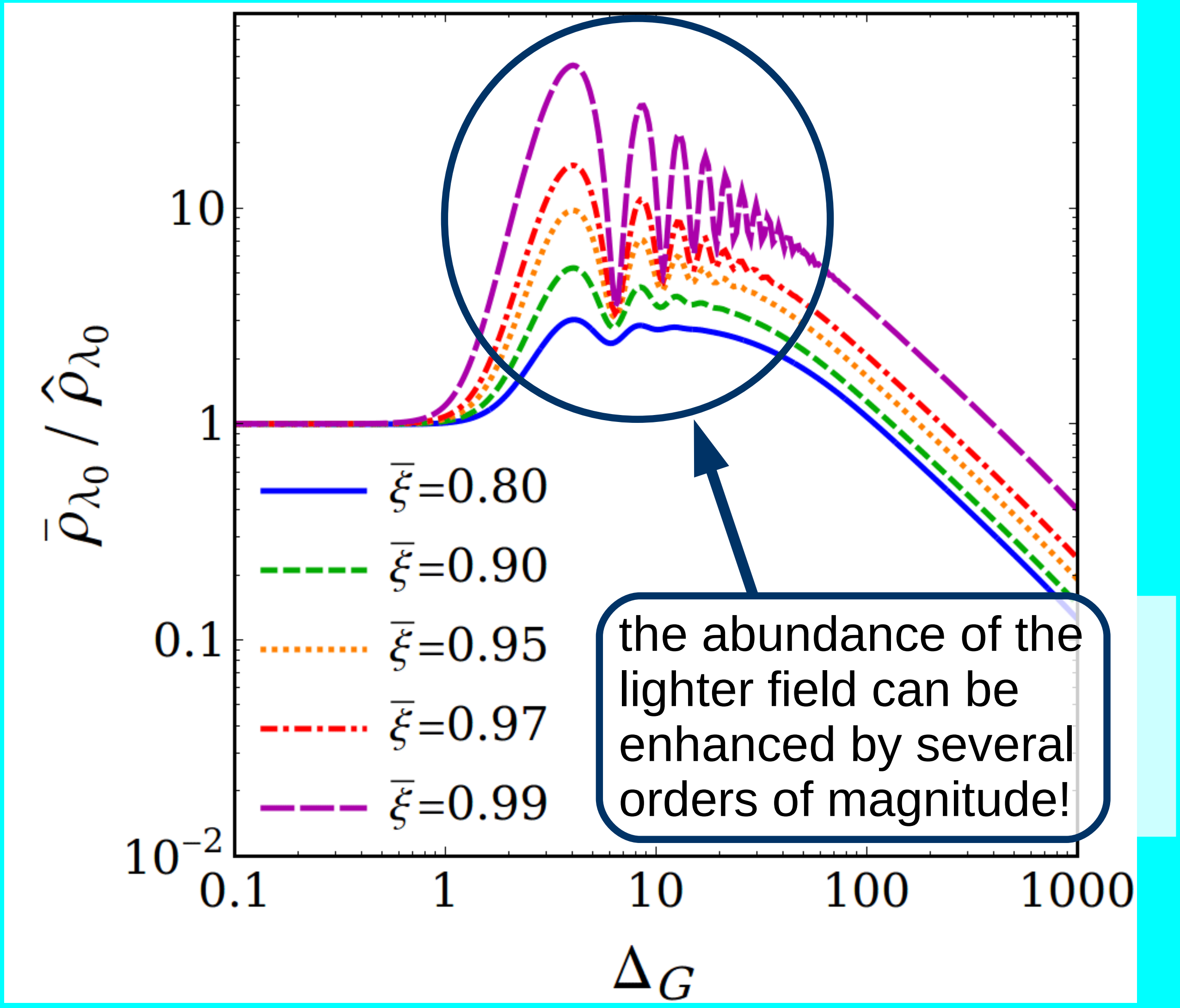
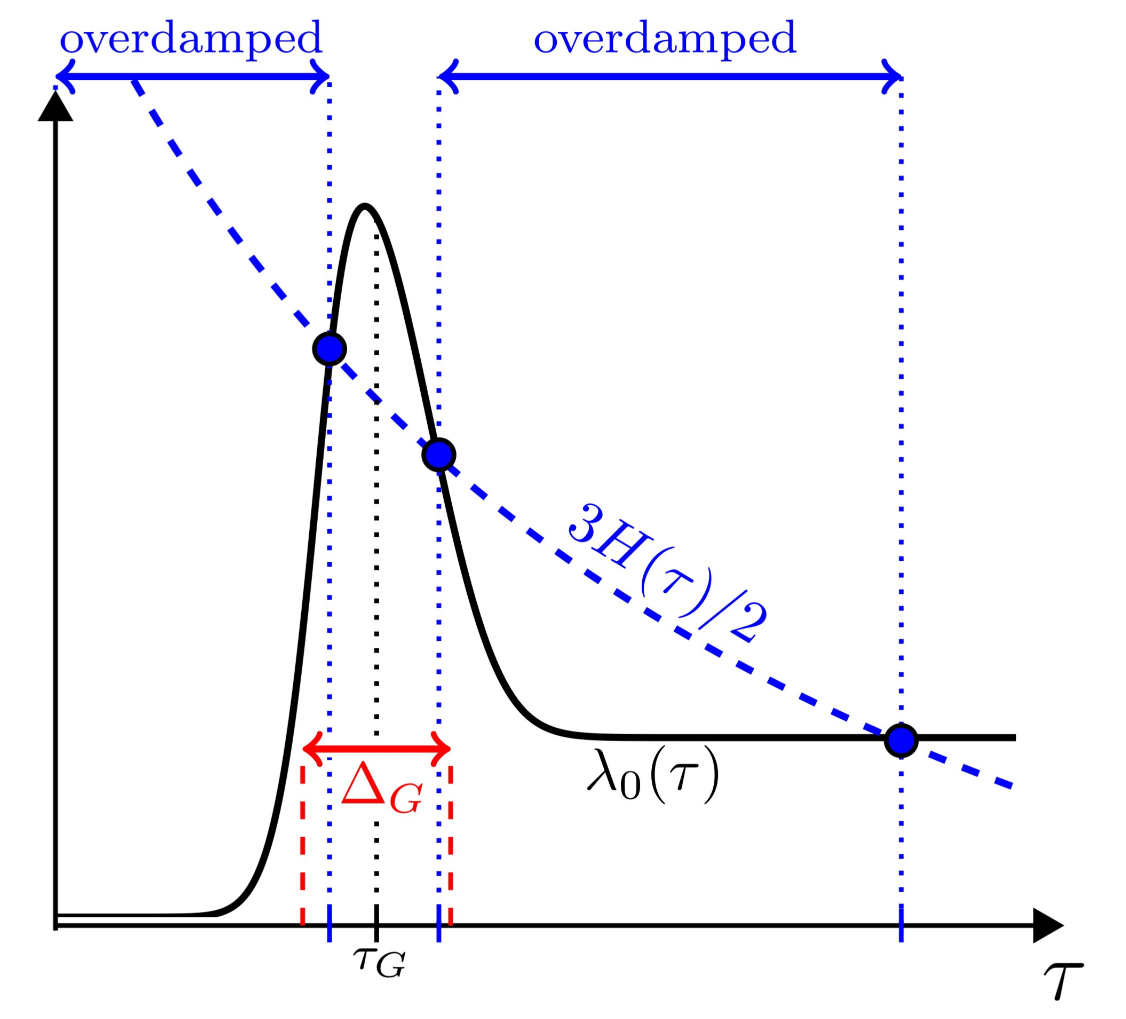


A "Re-Overdamping" Phenomenon

- This pulse also has other implications:



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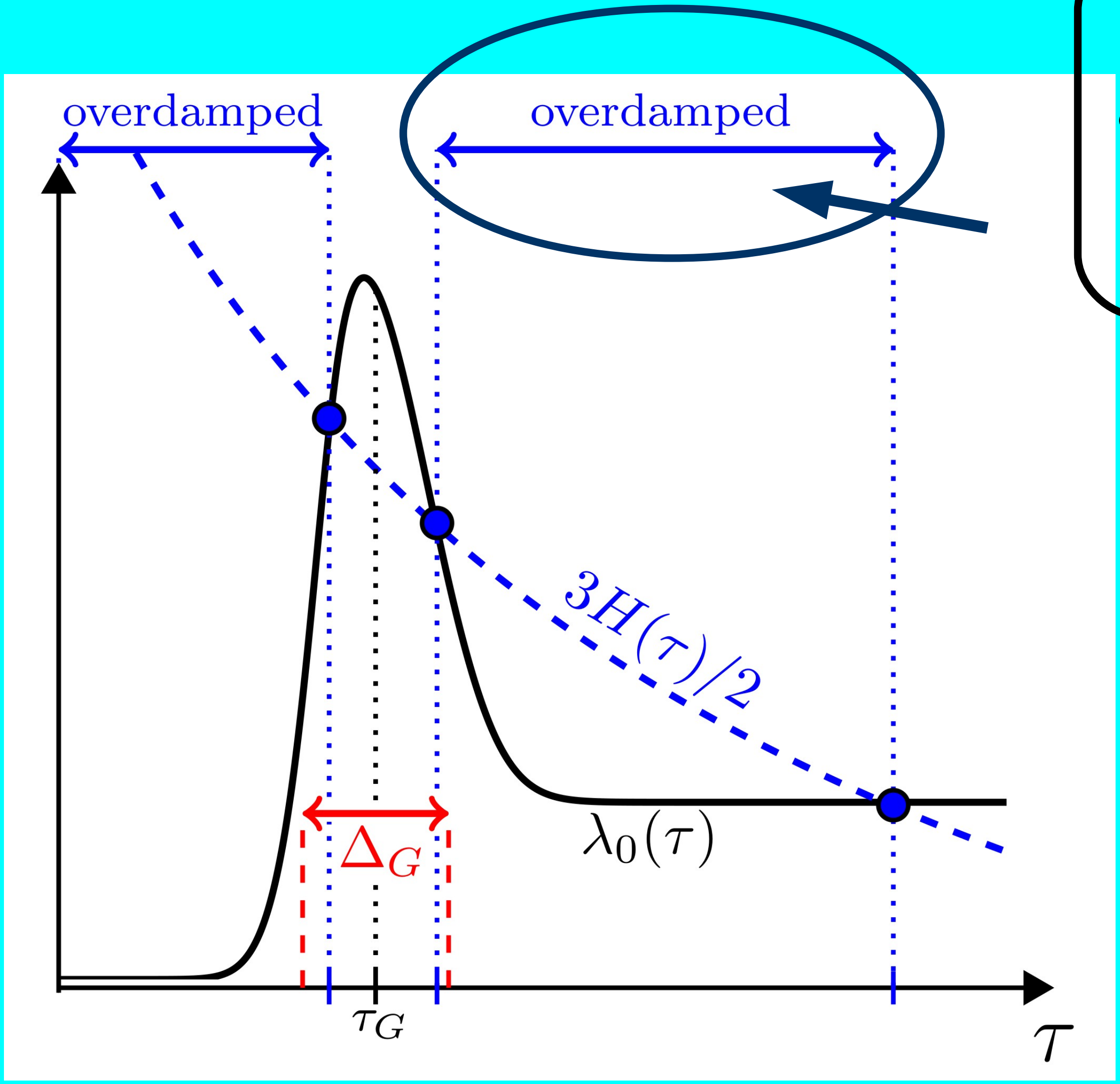

"Re-overdamping":

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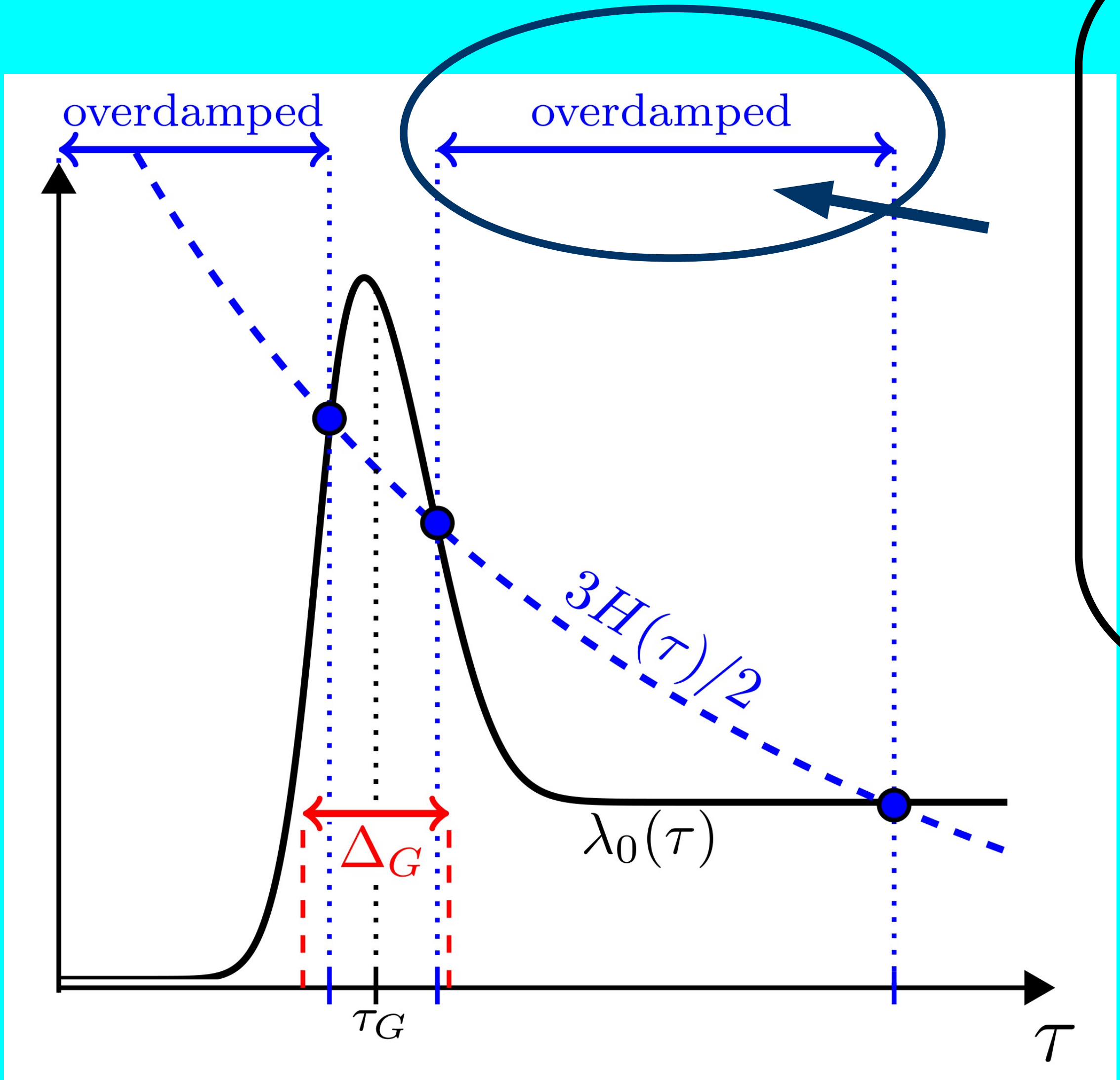

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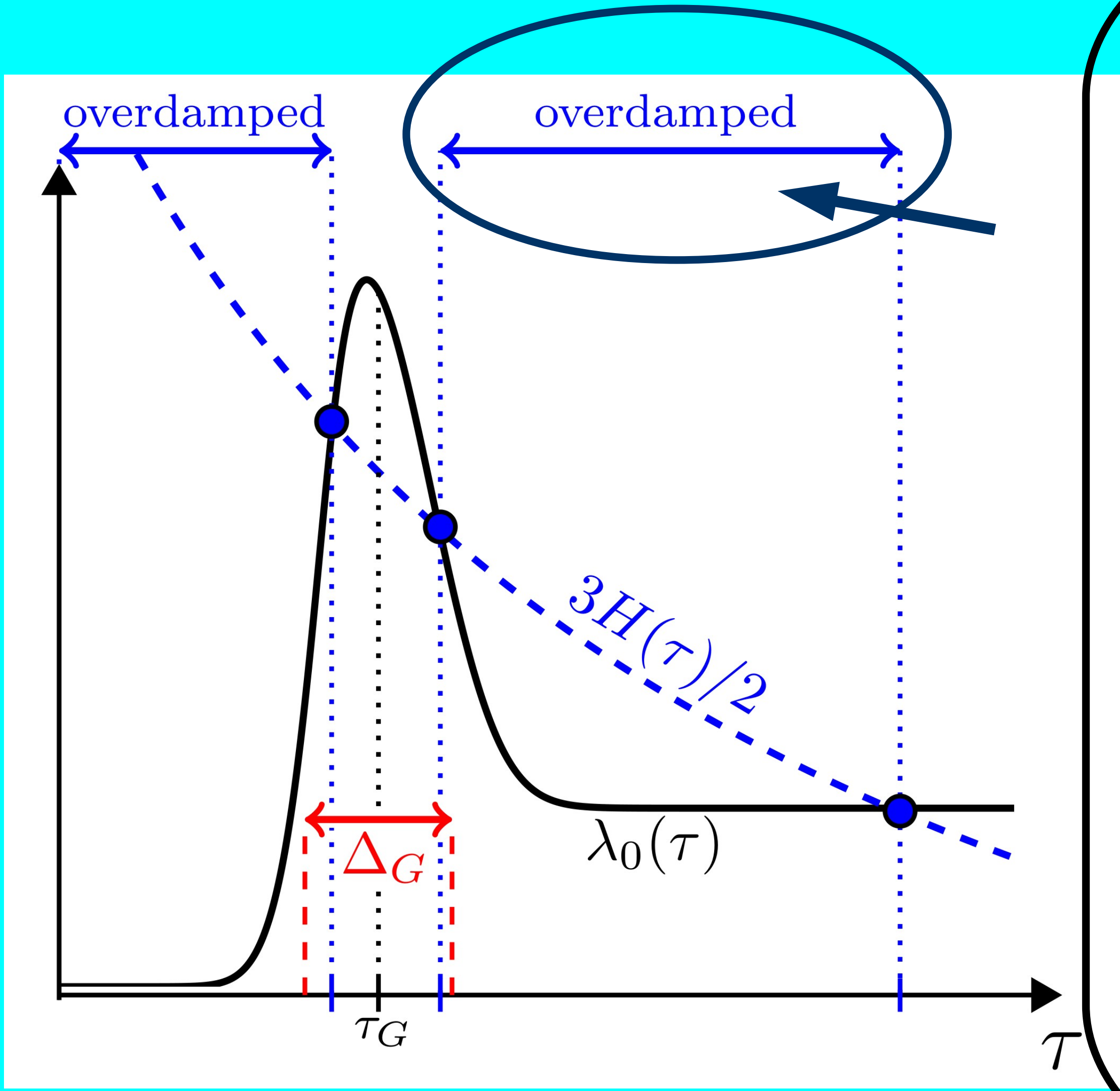
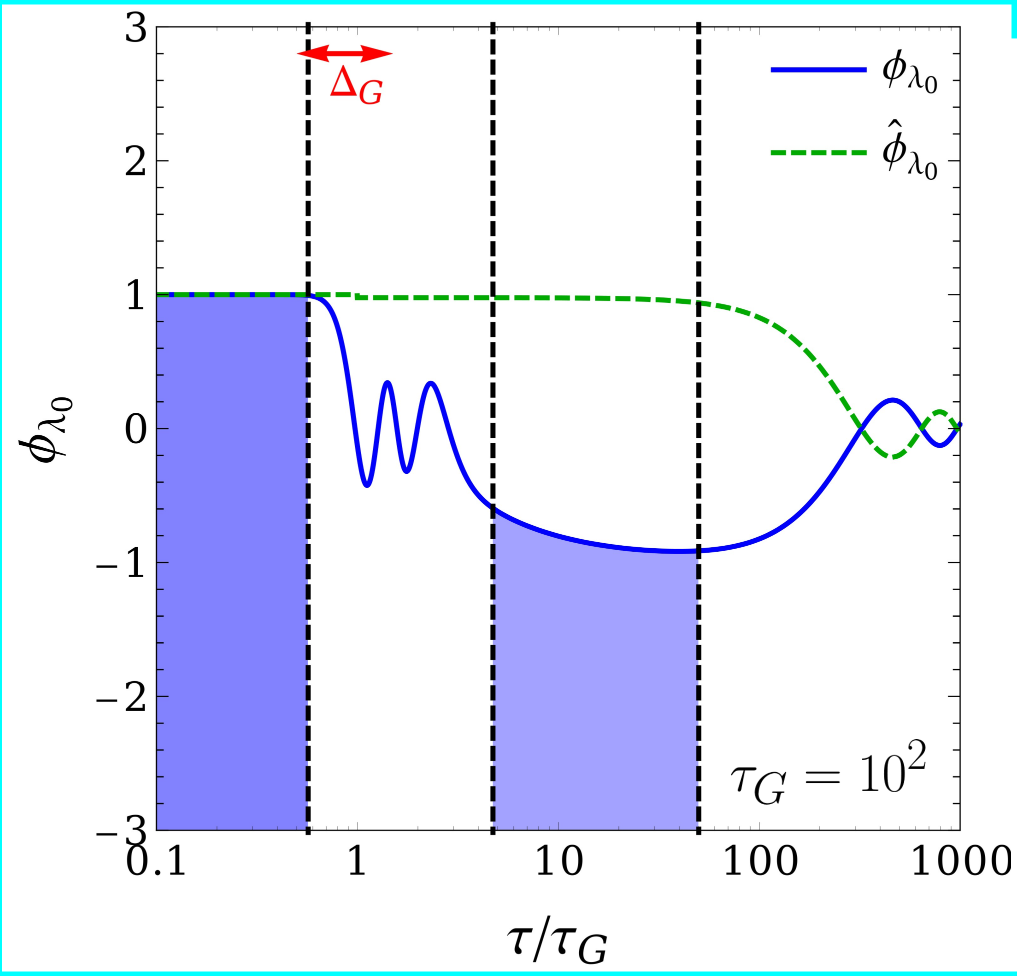
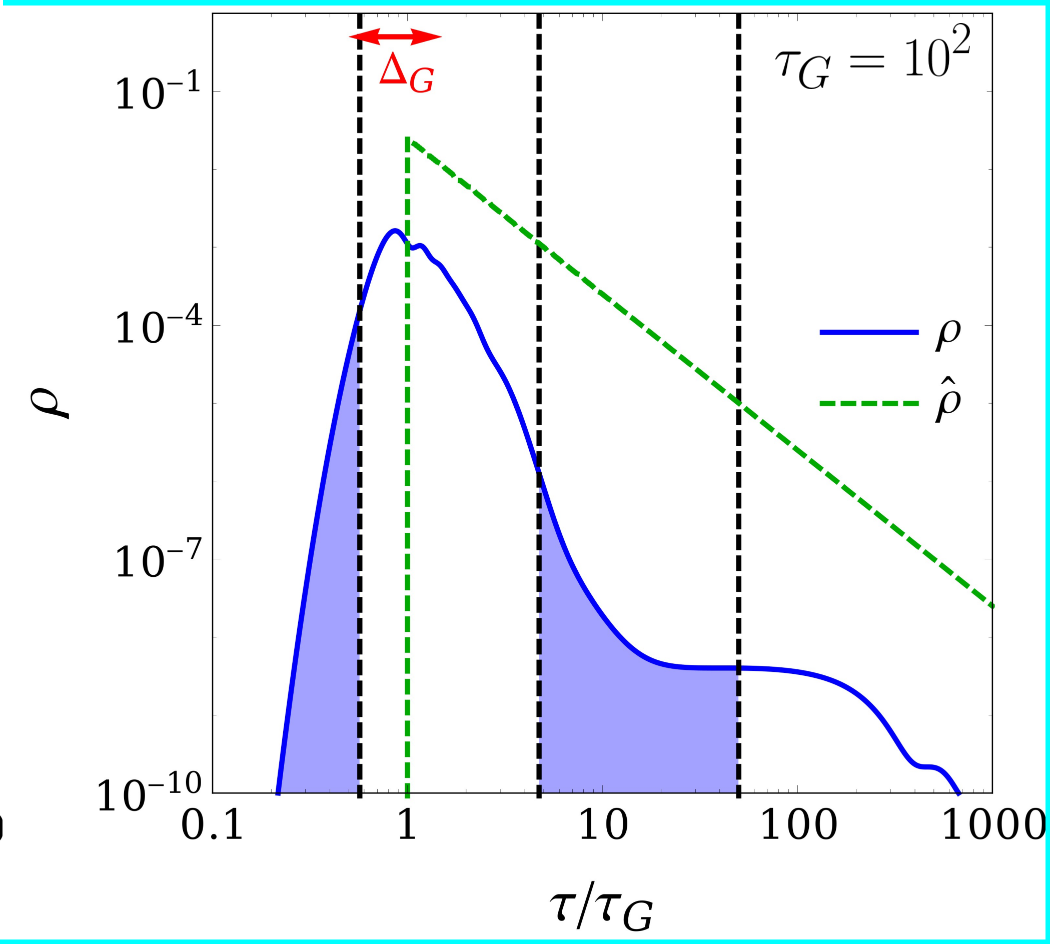


"**Re-overdamping**":

- The field which has already commenced oscillations returns to an *overdamped* state!
- Field ceases oscillation -- acts as different state of energy (not quite vacuum energy, not quite matter).
- The timescale over which this lasts can potentially be **much longer** than the phase transition itself...a new kind of "matter" between traditional pressureless matter and vacuum energy?

A "Re-Overdamping" Phenomenon

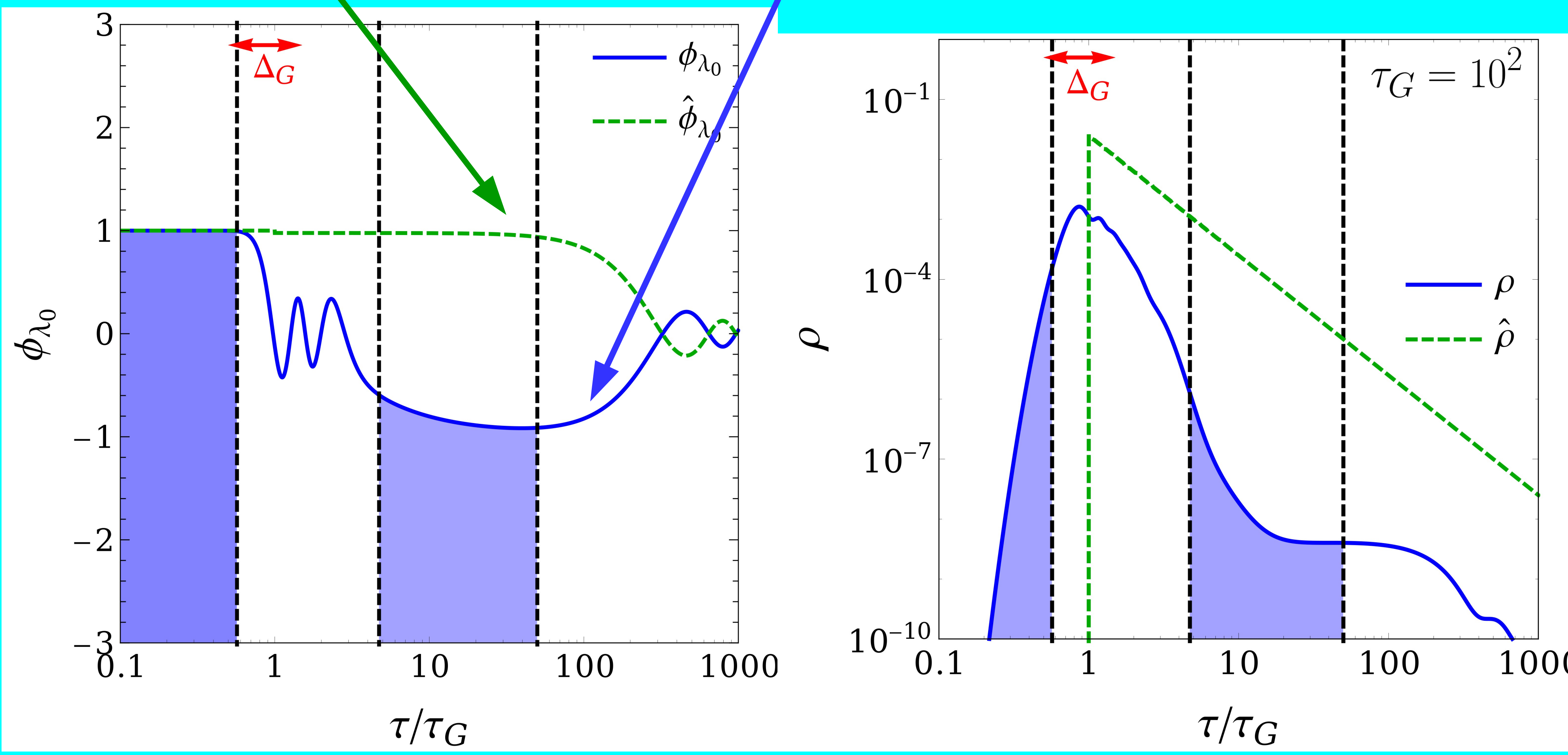




A “Re-Overdamping” Phenomenon

Field behavior if phase transition had been instantaneous.

True field behavior for $\Delta_G = 10^2$.



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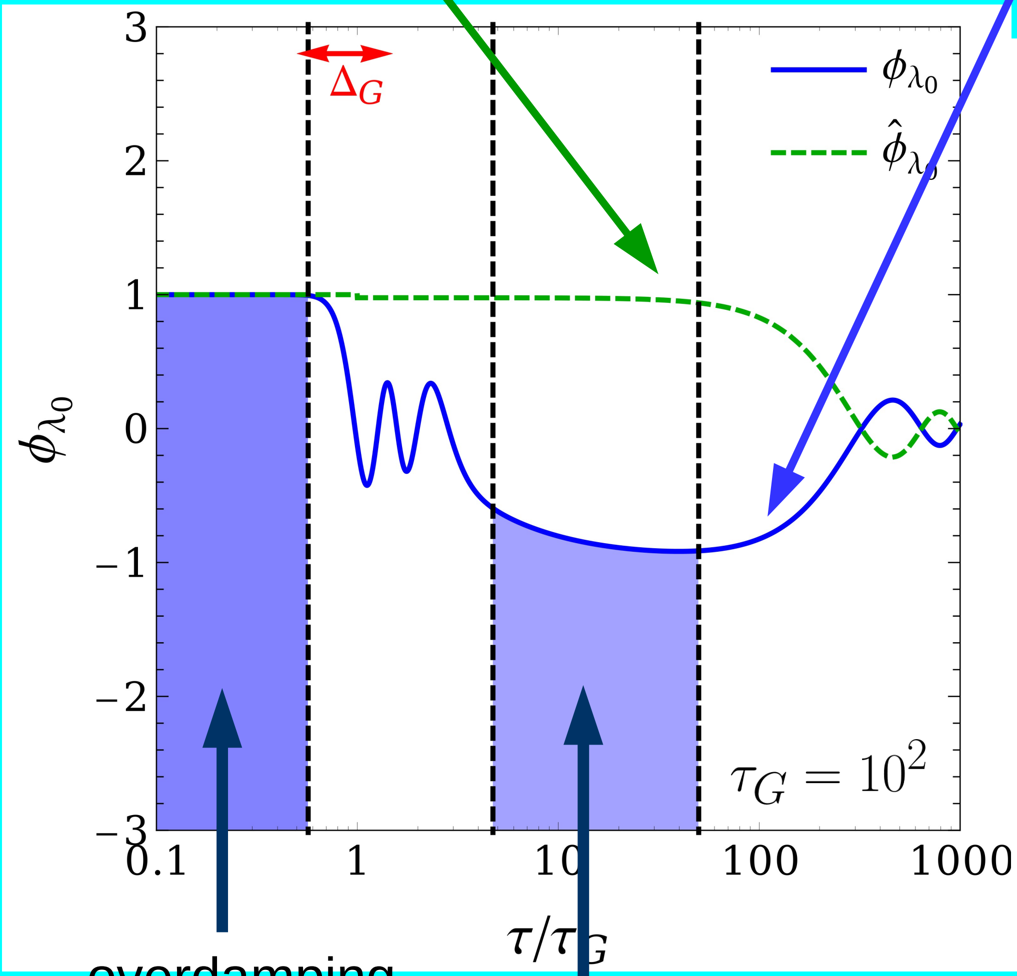

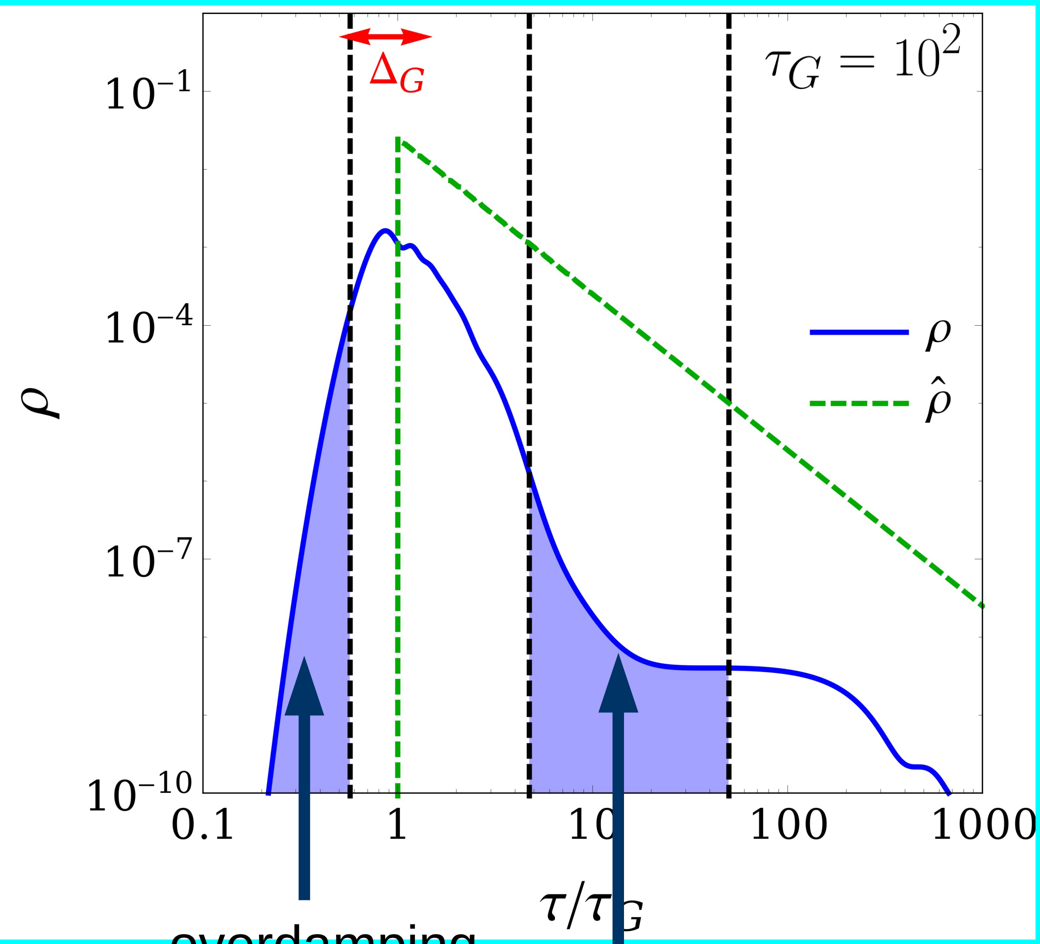

overdamping

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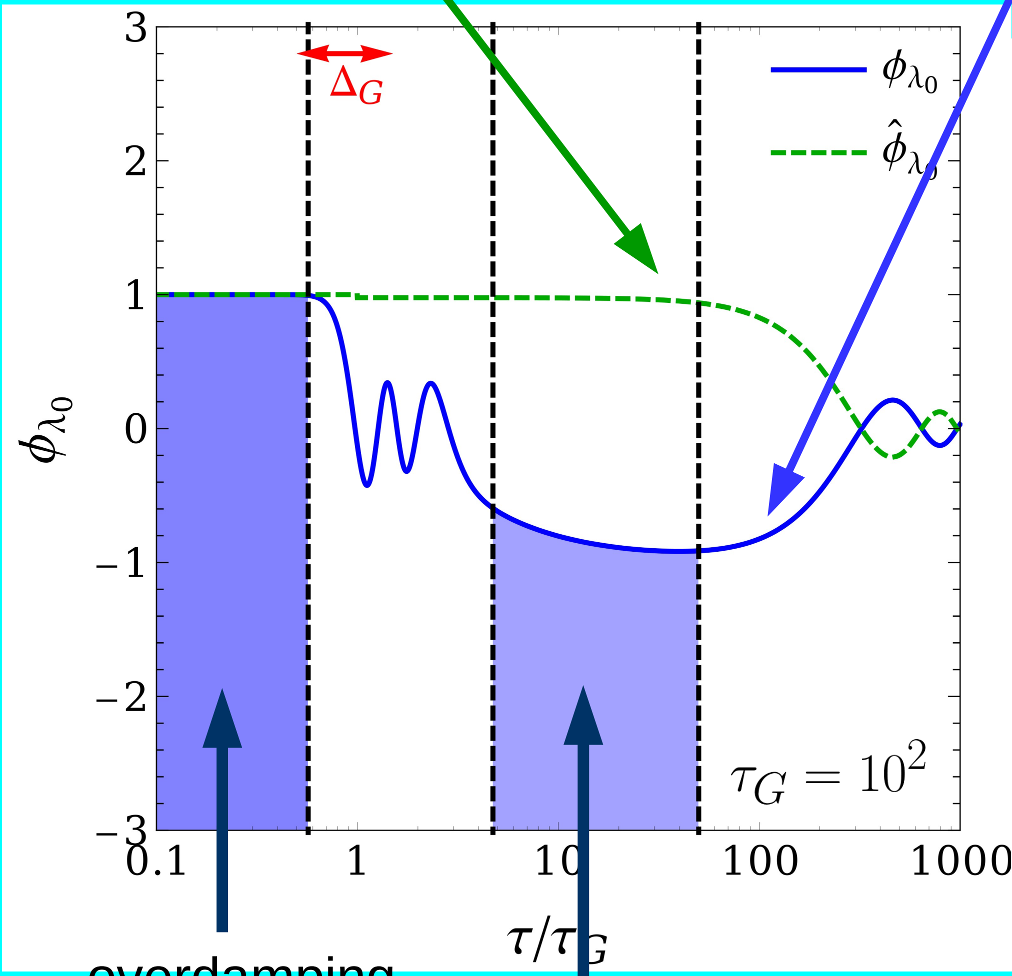

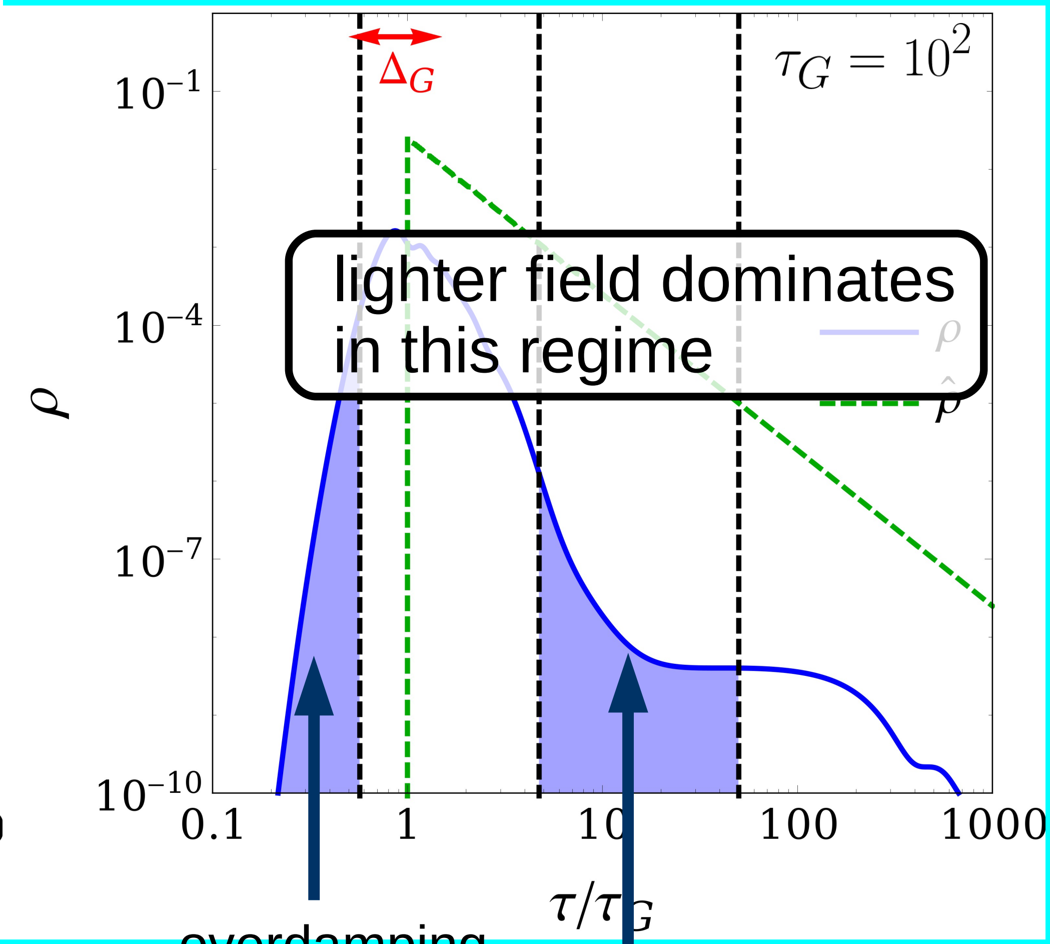

lighter field dominates in this regime

overdamping

re-overdamping

overdamping

re-overdamping

Conclusions

- For a simple two-component toy model we have found a rich set of phenomena that emerge from the non-trivial interplay between the width of mass generating phase transitions, non-trivial mixing, and overdamped/underdamped behaviors.
  - Unexpected suppressions and/or enhancements in late-time energy densities.
  - Shifts in energy density from lighter to heavier modes, simply by increasing timescale of phase transition.
  - Effective parametric resonances that cause energy densities to fluctuate by several orders of magnitude.
  - Surprising "re-overdamped" phases and unexpected field behaviors.
- These effects can potentially be even more dramatic in a full model, with more than two modes included (KK systems, axiverse, multiple string moduli, …).

The cosmology of such systems may be *far richer* than we have previously imagined. Many new possibilities for phenomenology and model-building exist.

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