When BSM physics fails to calculate and badly needs YOUR help

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

VIIth International Conference
“Models in Quantum Field Theory”

LEIMI, Saint Petersburg, Russia

Outline

1. Introduction to the problem
2. Examples in particle physics: when BSM meets QCD
3. Examples in cosmology: violent dynamics

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Standard Model extensions:

we cook them ourselves

Naturally, the new ingredient can be treated perturbatively

(... technicolor)

However, sometimes it happens that...

...the invironment is strongly coupled

...processes are violent

...particle description fails

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Examples of interesting processes

In particle physics QCD at the scale ~ 1 GeV

- light scalar decays into hadrons
- light vector production by a proton beam
- ...

Lattice? ... Effective descriptions: e.g. pomerons? AdS/CFT ?

In cosmology

- axion dark matter
- dark matter and leptogenesis in νMSM
- instant reheating in healthy Higgs inflation
- ...
- reionization (not BSM actually)

New methods are needed

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Widely accepted statements

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- We definitely need New particle physics
  - neutrino oscillations
  - baryon asymmetry
  - dark matter
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- New Heavy particle contribution to the Higgs boson mass lifts it up but miraculously $m_h \sim E_{EW}$

Guesswork: a logically possible option

- All the new particles are at (below) E_{EW}
  then quantum contributions to $m_h \sim E_{EW}$ are safe
- Why so far no evidences for such light New Particles ?
- They are only feebly coupled to the Standard Model
  - they are SM gauge singlets (not a GUT)
  - new Yukawa-type couplings ?
  - portal-like couplings ?

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There are no general theoretical motivation for the New Particles to be of (sub)GeV mass

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Main task

- Moreover, there are many concrete BSM theories which suggest such theoretical motivations
- Then the problem is
  how to properly account for the new particle (SM gauge singlet) effective coupling to the SM strongly-interacting states
  - for $m \gg 1$ GeV it couples to partons
  - for $m \ll 1$ GeV it couples to hadrons
  - how to calculate
    the new particle production and decay rates for $m \simeq 1$ GeV ?
  - in the concrete models
    "parton" and "hadron" answers often mismatch
- Eventually we must predict the signal rate 'in observed particles': pions, kaons, etc

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Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- Scalar portal: SM Higgs doublet H and hidden scalar S

  the simplest dark matter

$$\mathscr{L}_{\text{scalar portal}} = -\beta\, H^\dagger H S^\dagger S - \mu H^\dagger H S$$

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \varepsilon H^*$ and hidden fermion N

  sterile neutrino !!

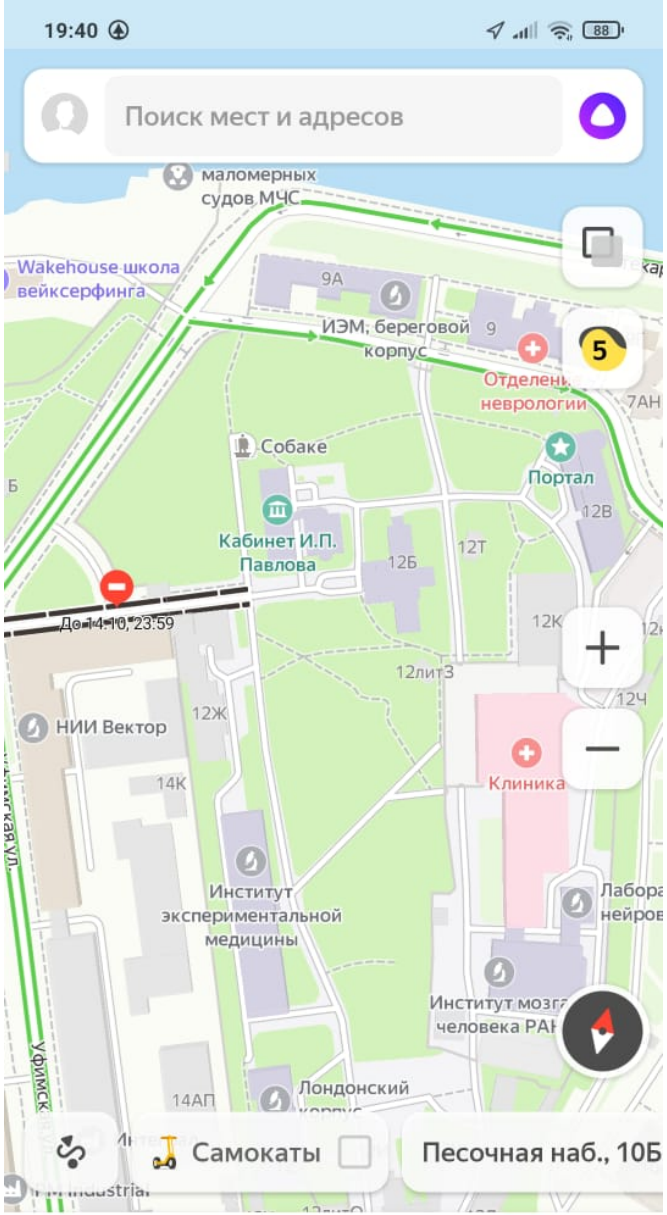
$$\mathscr{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

  hidden photon

$$\mathscr{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B^{U(1)_Y}_{\mu\nu} B^{U(1)'}_{\mu\nu}$$

The nearest portal…



Renormalizable inflaton at GeV scale

0912.0390

$$S_{X\mathrm{SM}} = \int \sqrt{-g}\, d^4x \left(\mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\mathrm{ext}} + \mathscr{L}_{\mathrm{grav}}\right),$$

$$\mathscr{L}_{\mathrm{ext}} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 - \frac{\beta}{4} X^4 - \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2\right)^2,$$

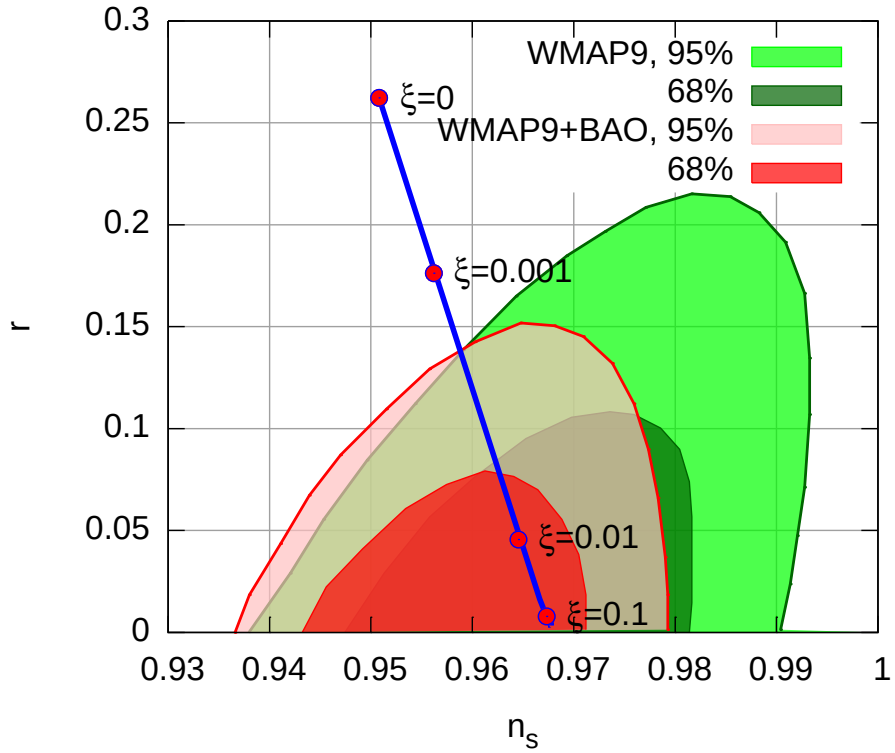
$$\mathscr{L}_{\mathrm{grav}} = -\frac{M_P^2 + \xi X^2}{2} R,$$

inflaton mass

$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}} = \sqrt{\frac{\beta}{\lambda \theta^2}}.$$

phenomenology is fixed by
mixing with Higgs

$$\theta^2 = \frac{2\beta v^2}{m_\chi^2} = \frac{2\alpha}{\lambda}.$$



QCD modes: claimed uncertainties upto 10^2

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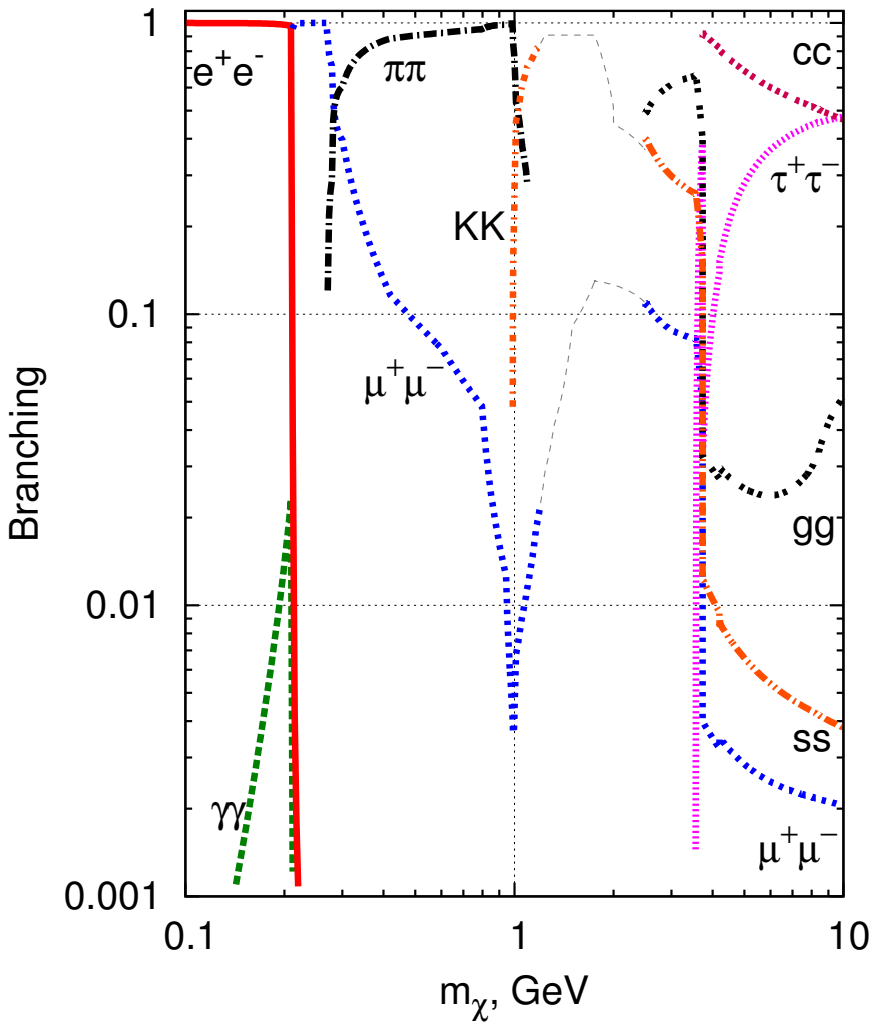

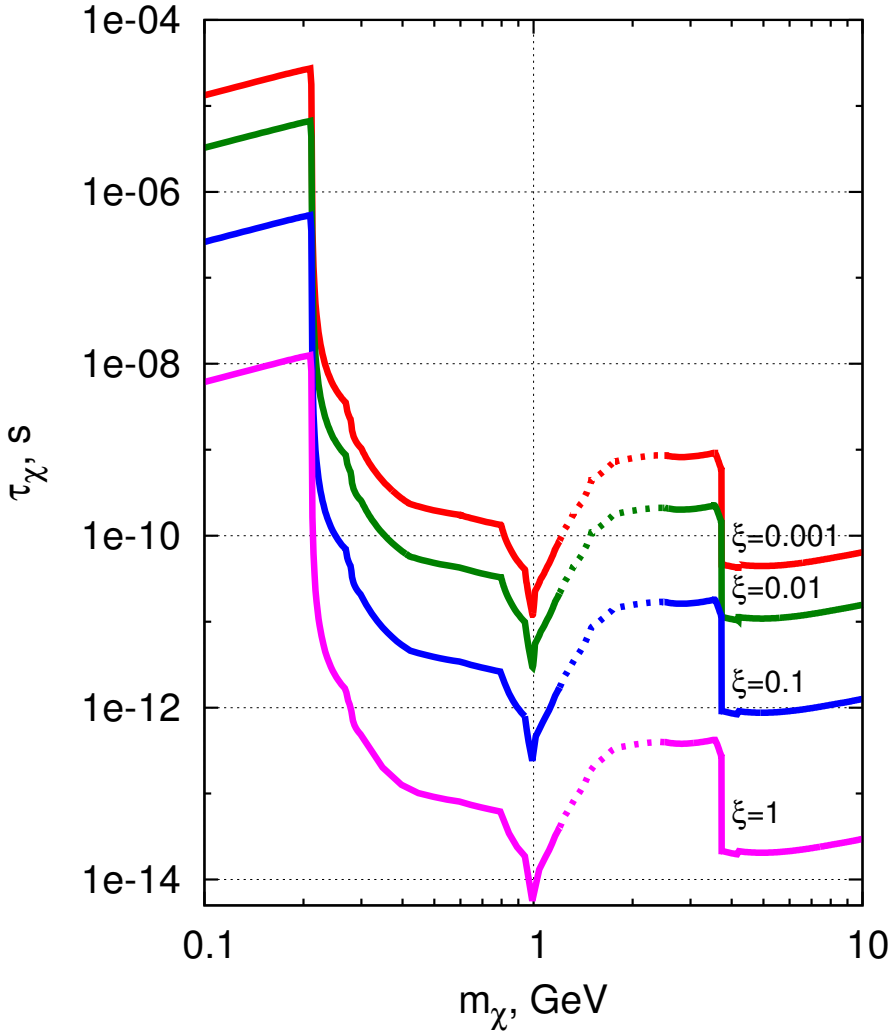

Interaction among the final hadronic states

following J.Donoghue, J.Gasser and H Leutwyler (1990)

Limits from LHCb

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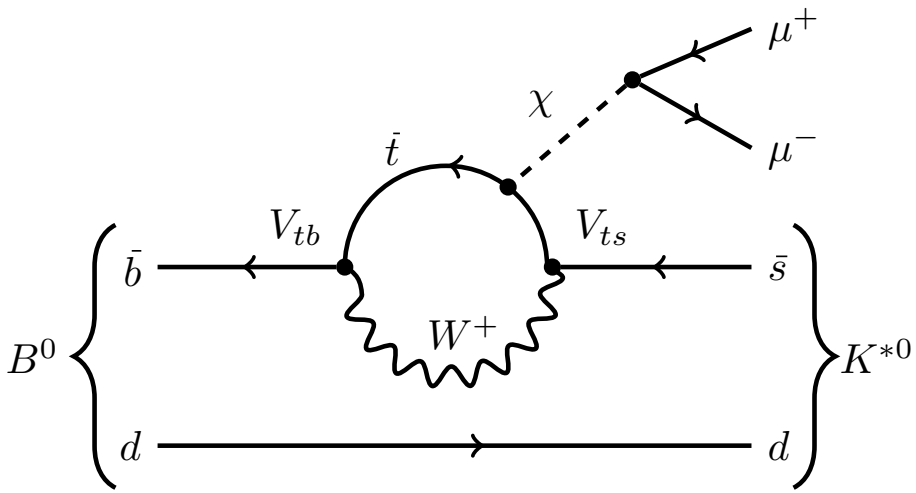
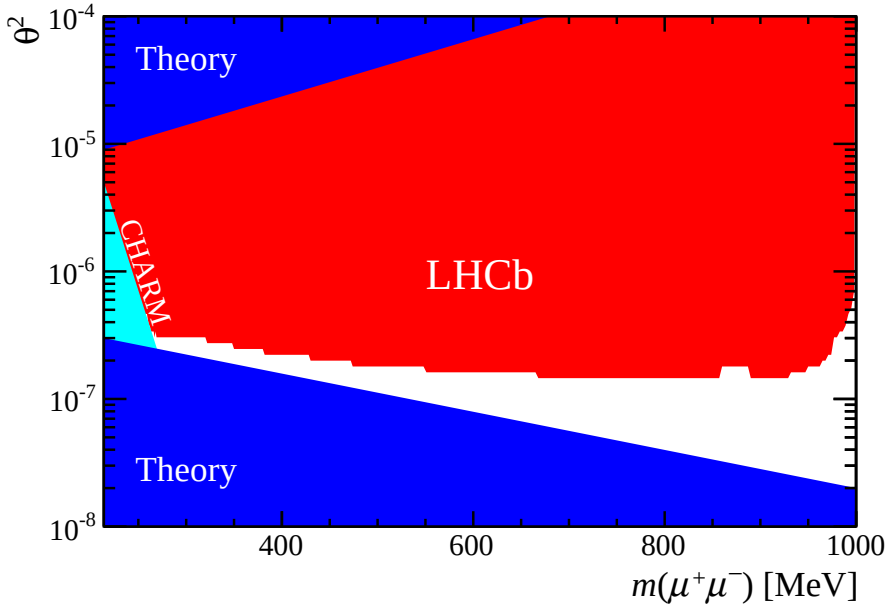
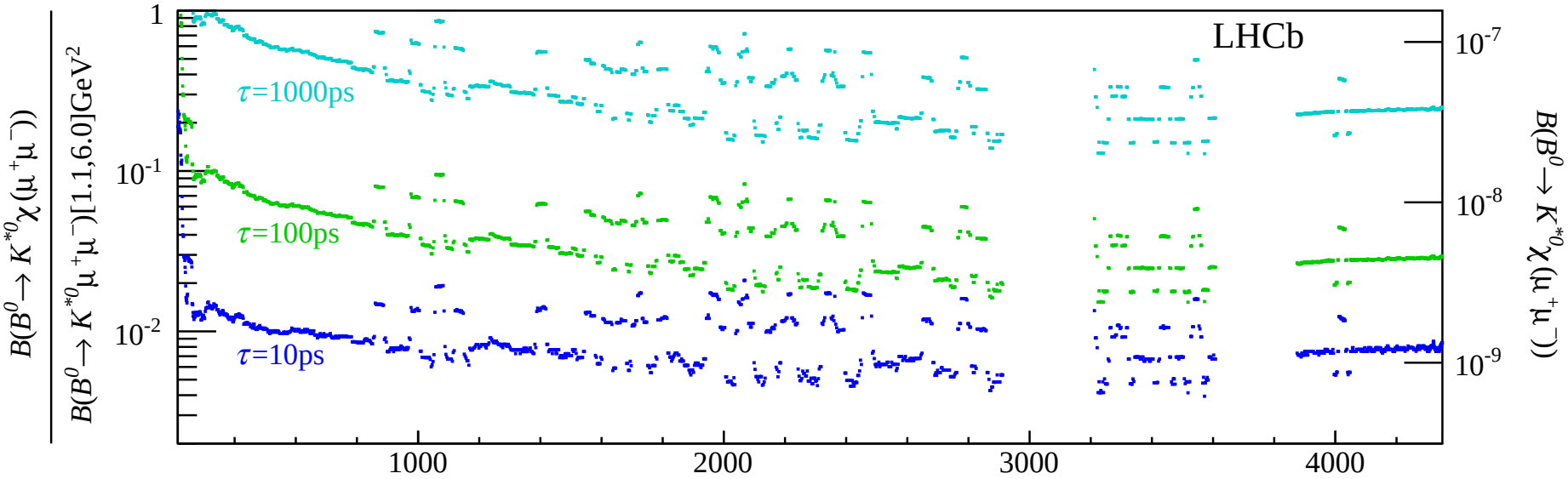






We need to know the scalar form factors

$$\mathscr{L} = -\theta \sum_f \frac{m_f}{v} \bar{\psi}_f \psi_f S, \quad \longrightarrow \quad \theta \frac{\alpha_s}{v} G_{\mu\nu} G^{\mu\nu} S$$

all meson channels are interesting, $\pi\pi$, KK, $\eta\eta$, 4π, etc

$$\langle \pi^i(p)\pi^k(p')| T^\mu_\mu |0\rangle \equiv \Theta_\pi(s)\delta^{ik},$$

$$\langle \pi^i(p)\pi^k(p')| m_u \bar{u}u + m_d \bar{d}d |0\rangle \equiv \Gamma_\pi(s)\delta^{ik},$$

$$\langle \pi^i(p)\pi^k(p')| m_s \bar{s}s |0\rangle \equiv \Delta_\pi(s)\delta^{ik},$$

$$G_\pi(s) = \frac{2}{9}\Theta_\pi(s) + \frac{7}{9}\left(\Gamma_\pi(s) + \Delta_\pi(s)\right).$$

At small $s = (p+p')^2 = M_S^2$ we can compute them within LO ChPT

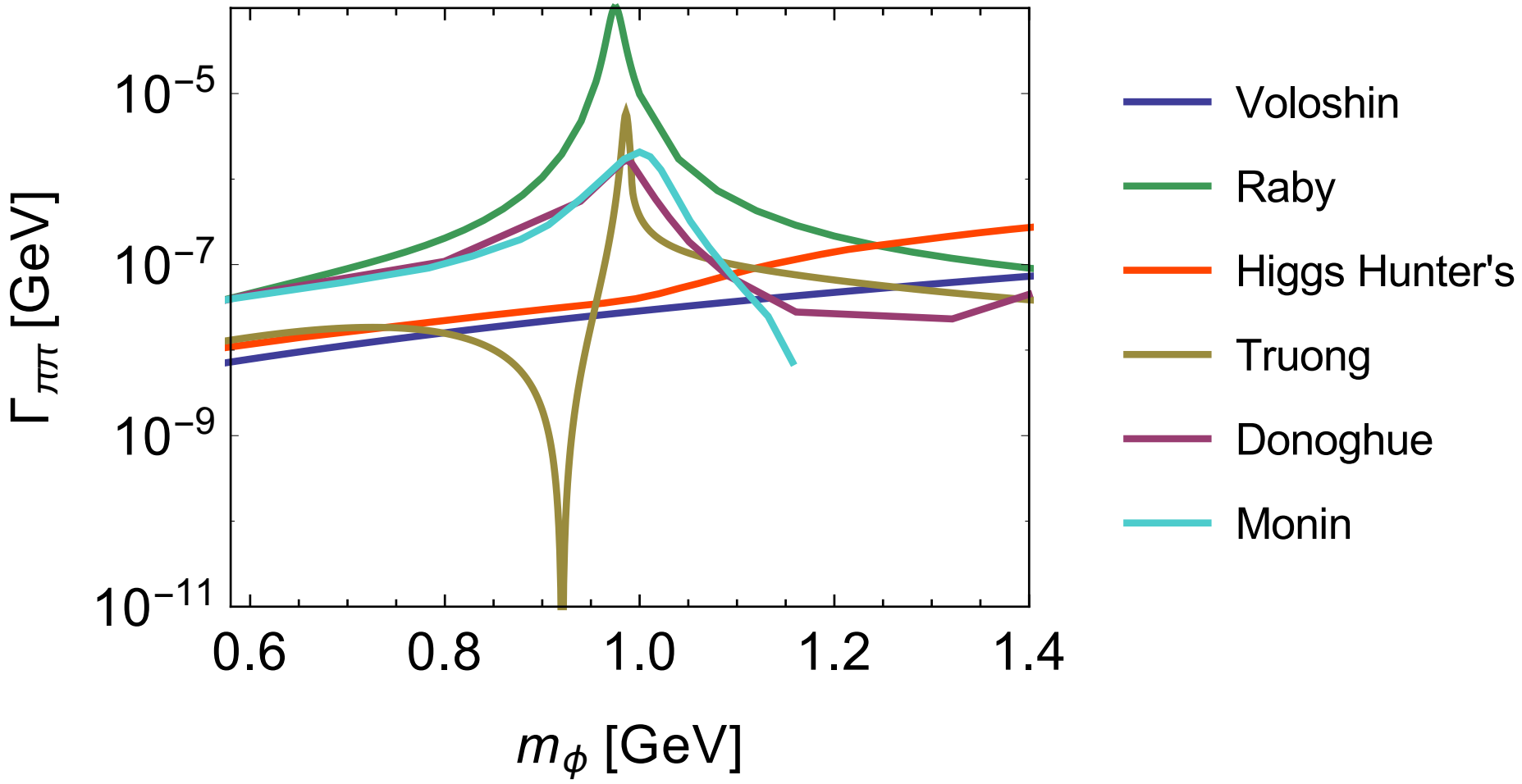
$$\Theta_\pi(s) = s + 2m_\pi^2, \qquad \Theta_K(s) = s + 2m_K^2,$$

$$\Gamma_\pi(s) = m_\pi^2, \qquad \Gamma_K(s) = \frac{1}{2} m_\pi^2,$$

$$\Delta_\pi(s) = 0, \qquad \Delta_K(s) = m_K^2 - \frac{1}{2} m_\pi^2.$$

The estimates BSM people use

1809.01876



Physics: Final State Interaction: $\pi\pi \to \pi\pi$

These estimates are based on dispersion relations

There are several issues, e.g. 1812.08088

- Unitarity requires $\Theta(\infty) = 0$, while $\Theta(s) \propto s$
  — ignore (why not important for low s ?) J.Donoghue, J.Gasser, H.Leutwyler (1990)
  — make $\Theta(\infty) = 0$ by hand (changes or not low s, always changes high s behaviour)
- There are many channels, but people typically reduce to the 2-channels system, $\pi\pi$, KK
  — we need more to make predictions
  $\eta\eta$, 4π, ... hep-ph/9909292
  — the truncation is not justified
  some channels are strongly coupled,
  e.g. $\mathrm{Br}(f_0(1500) \to \pi\pi) \simeq 35\%$, $\mathrm{Br}(f_0(1500) \to 4\pi) \simeq 50\%$,
  results depend on the way one adds a new channel 1809.06867
- Nobody calculate the uncertainty of their results:
  30% (like typically in ChPT), 'factor of 2', '10' ?

We badly (over 10 years for BSM) need to calculate:

$$S \to \pi\pi \ : \ \langle \pi\pi | \int d^4x\, S(x) G_{\mu\nu} G^{\mu\nu}(x) e^{iS_{QCD}} | S \rangle = \ ???????? \pm ???$$

$$\langle \pi\pi | T^{\mu}_{\mu} | 0 \rangle \equiv \Theta_{\pi}(s)$$
$$\langle \pi\pi | m_u \bar{u}u + m_d \bar{d}d | 0 \rangle \equiv \Gamma_{\pi}(s)$$
$$\langle \pi\pi | m_s \bar{s}s | 0 \rangle \equiv \Delta_{\pi}(s)$$

$$\langle KK | T^{\mu}_{\mu} | 0 \rangle \equiv \Theta_{K}(s)$$
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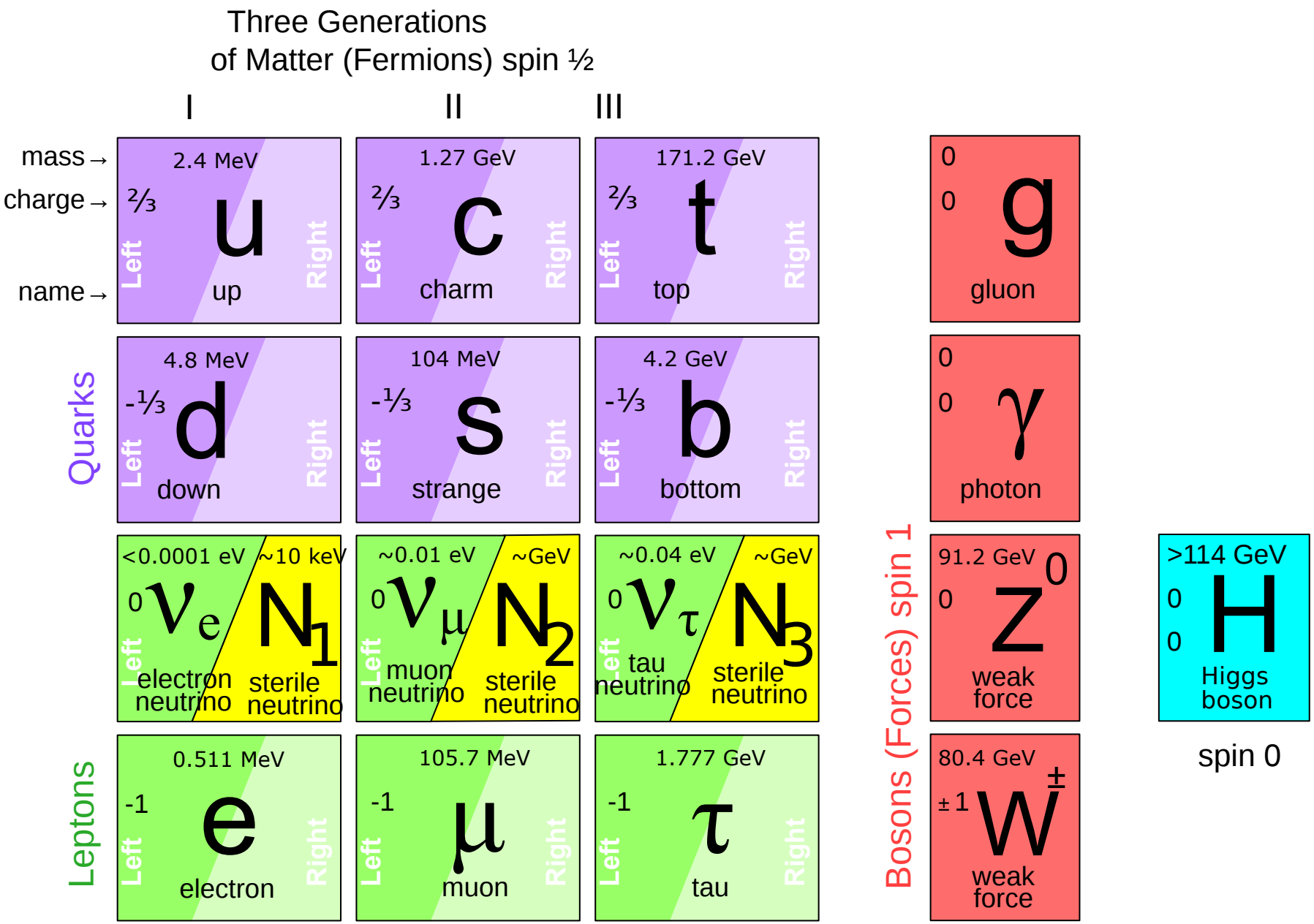

Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
Left
Right
1.27 GeV
⅔
c
charm
Left
Right
171.2 GeV
⅔
t
top
Left
Right
0
0
g
gluon
Quarks
4.8 MeV
-⅓
d
down
Left
Right
104 MeV
-⅓
s
strange
Left
Right
4.2 GeV
-⅓
b
bottom
Left
Right
0
0
γ
photon
<0.0001 eV
~10 keV
0
νe
N1
electron neutrino
sterile neutrino
Left
~0.01 eV
~GeV
0
νμ
N2
muon neutrino
sterile neutrino
Left
~0.04 eV
~GeV
0
ντ
N3
tau neutrino
sterile neutrino
Left
Leptons
0.511 MeV
-1
e
electron
Left
Right
105.7 MeV
-1
μ
muon
Left
Right
1.777 GeV
-1
τ
tau
Left
Right
Bosons (Forces) spin 1
91.2 GeV
0
0
Z0
weak force
80.4 GeV
±1
W±
weak force
>114 GeV
0
0
H
Higgs boson
spin 0

Seesaw type I mechanism: $M_N \gg m_{active}$

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

where $I = 1,2,3$ and $\alpha = e,\mu,\tau$ $\quad \tilde{H}_a = \varepsilon_{ab} H_b^*$

When Higgs gains $\langle H \rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathscr{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.} = \frac{1}{2}\left(\overline{\nu}_\alpha\,,\overline{N}_I^c\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_\alpha^c\,,N_I\right)^{\mathsf{T}} + \text{h.c.}$$

Then for $M_N \gg \hat{M}_D = v\,\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues:

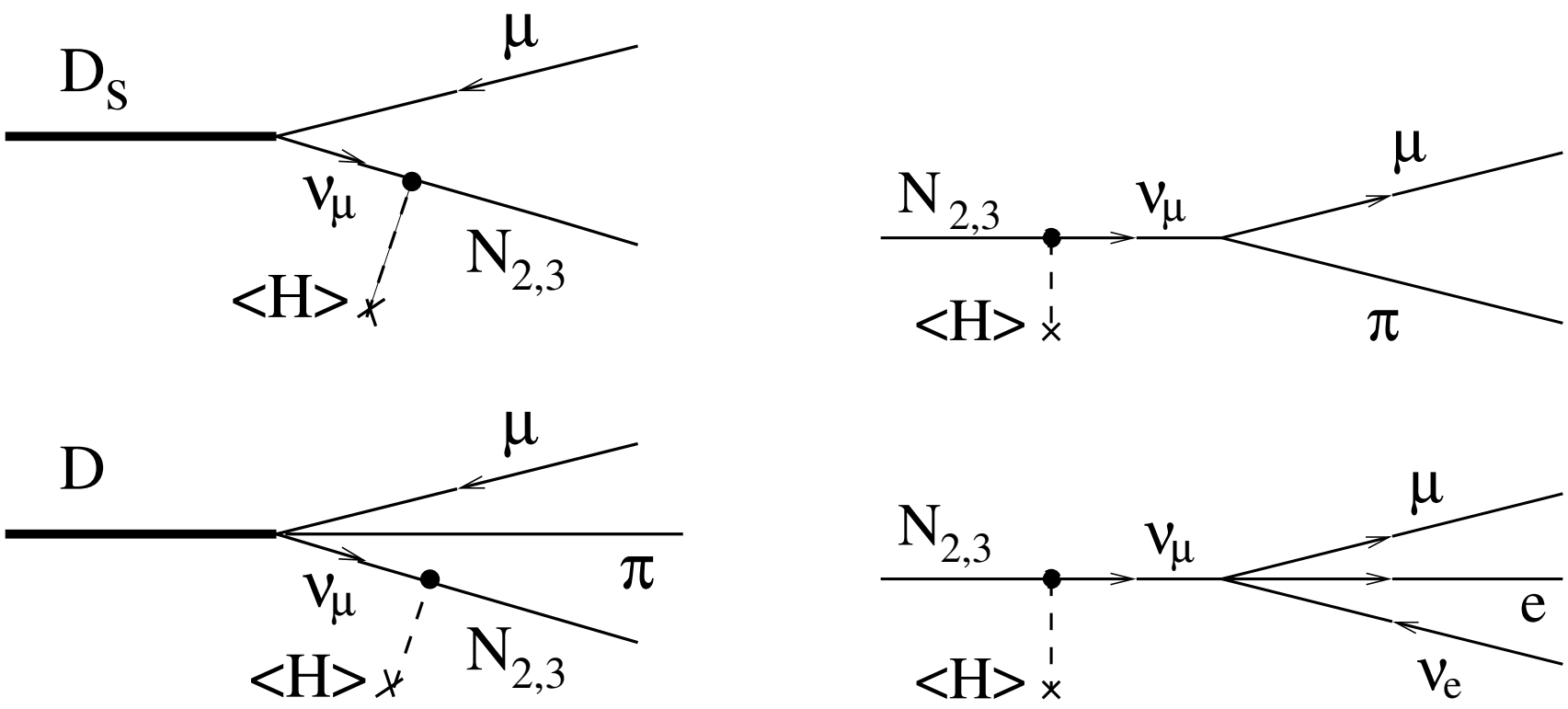
$$\simeq \hat{M}_N \qquad \text{and} \qquad \hat{M}^\nu = -\hat{M}_D\frac{1}{\hat{M}_N}\hat{M}_D^T \propto f^2\frac{v^2}{M_N} \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

active-active mixing: (PMNS-matrix U) $\qquad U^T\hat{M}^\nu U = diag\,(m_1\,,m_2\,,m_3)$

active-sterile mixing: $\qquad \theta_{\alpha I} = \frac{M_{D_{\alpha I}}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$

Sterile neutrinos: production and decays

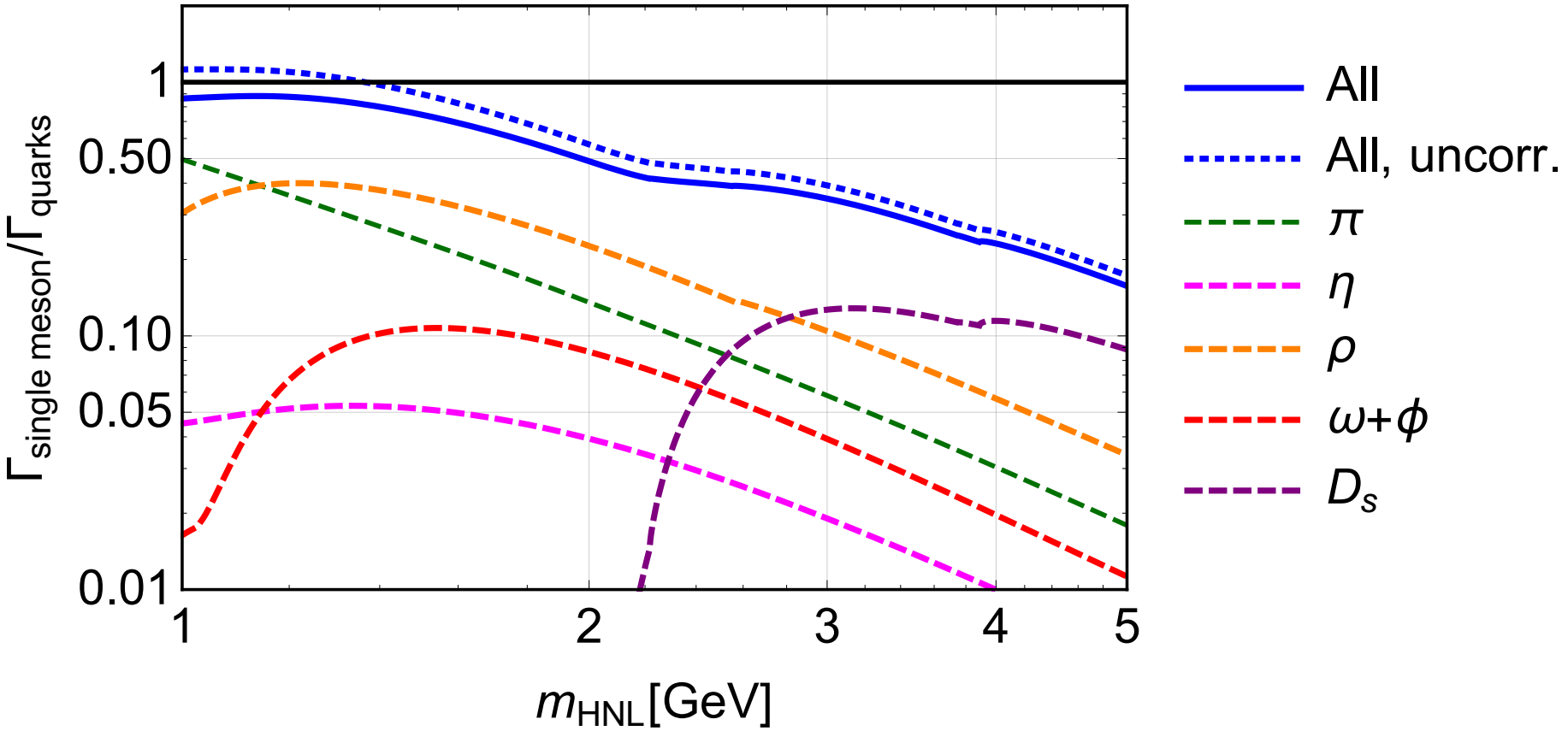


Interaction via neutral and charged weak hadronic currents

Do we need multimeson modes?

Actually not: 20% to production...

1805.08567



Decay modes normalized to quarks with QCD-corrections from $\tau \to \nu + \text{hadrons}$

And we use hadronic form factors...

Massive vectors (paraphotons)

NA64

Vector portal to a secluded sector: e.g. with Dark matter Ψ

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector 0711.4866

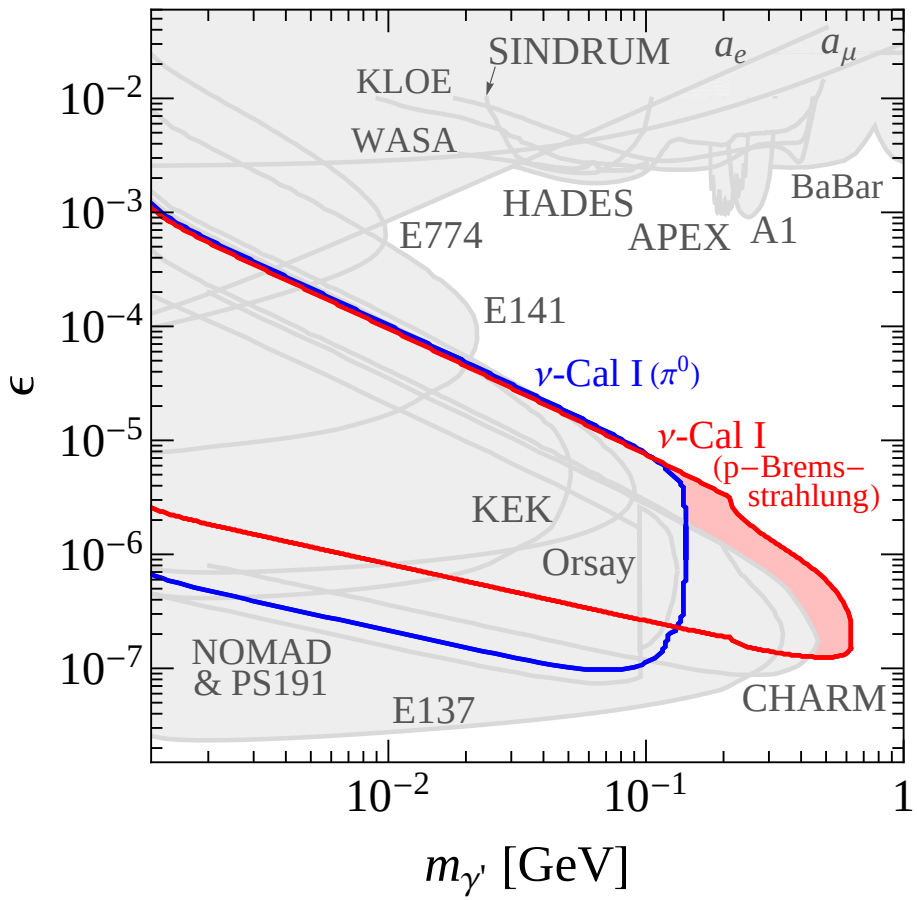
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1\,\text{GeV}$

- limit from BBN:

$$\tau_V < 1\,\text{s}, \implies \varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-21}$$

- light for $(g-2)$
- light for Pamela, Fermi, etc



1311.5104

Production by virtual photon $\sigma \propto \varepsilon^2$

Decay through virtual photon, $\Gamma \propto \varepsilon^2$

$V \to e^+e^-$, $\mu^+\mu^-$, etc

Massive vectors: decays are under control

Decay into SM via mixing with photon

into leptons

$$\Gamma_{A'}^{l^+l^-} = \frac{1}{3}\alpha_{\rm QED} m_{A'} \varepsilon^2 \sqrt{1-\frac{4m_l^2}{m_{A'}^2}}\left(1+\frac{2m_l^2}{m_{A'}^2}\right),$$

into hadrons

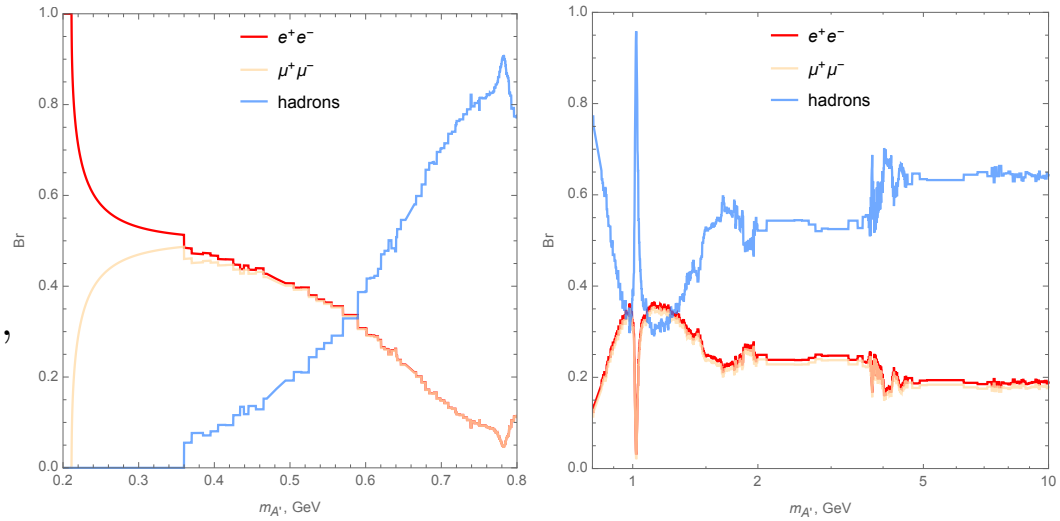
$$\Gamma_{A'}^{\rm hadrons} = \frac{1}{3}\alpha_{\rm QED} m_{A'} \varepsilon^2 \cdot R(m_{A'}),$$

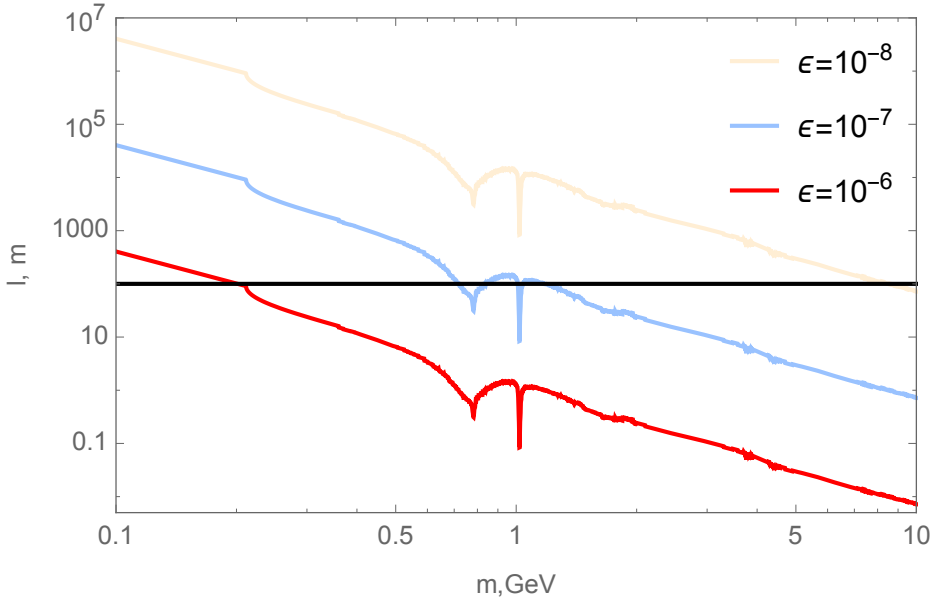
where

$$R(\sqrt{s}) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

and

$$\Gamma_{A'}^{\rm tot} = \Gamma_{A'}^{e^+e^-} + \Gamma_{A'}^{\mu^+\mu^-} + \Gamma_{A'}^{\rm hadrons}$$





1411.4007

Massive vectors: production by protons

- decays of π^0, η^0 and $\rho^\pm$, ρ^0, ω

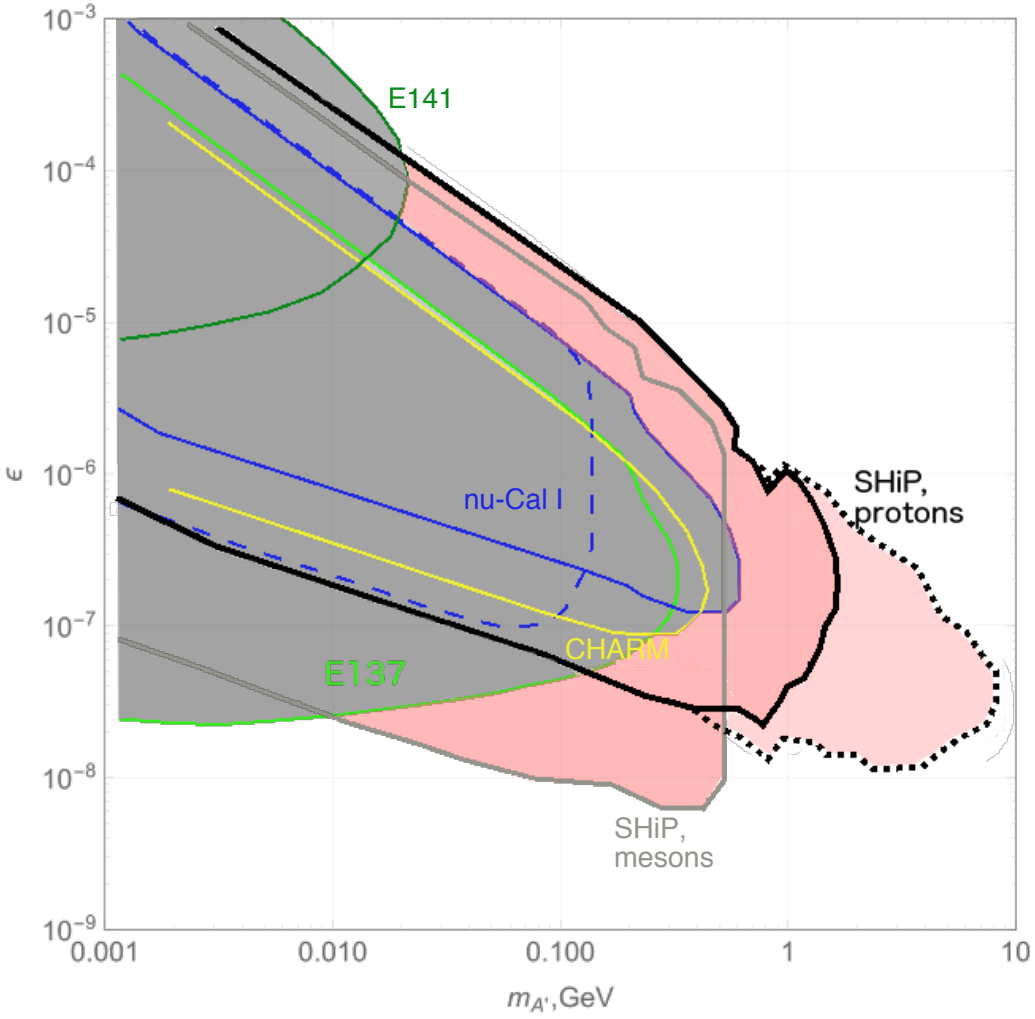
$$\mathrm{Br}_{\pi^0\to A'\gamma} \simeq 2\varepsilon^2 \left(1-\frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{Br}_{\pi^0\to\gamma\gamma}$$

- proton bremsstrahlung
  concervatively corrected by the Dirac (electric) form factor of proton

$$F_1 = \frac{1}{\left(1+\frac{q^2}{m_D^2}\right)^2} \to \frac{1}{m_{A'}^4}$$

  with Dirac mass squared $m_D^2 = 12/r_D^2$ and the Dirac radius $r_D \approx 0.8\,\mathrm{fm}$

- quark bremsstrahlung ??
  still under study...



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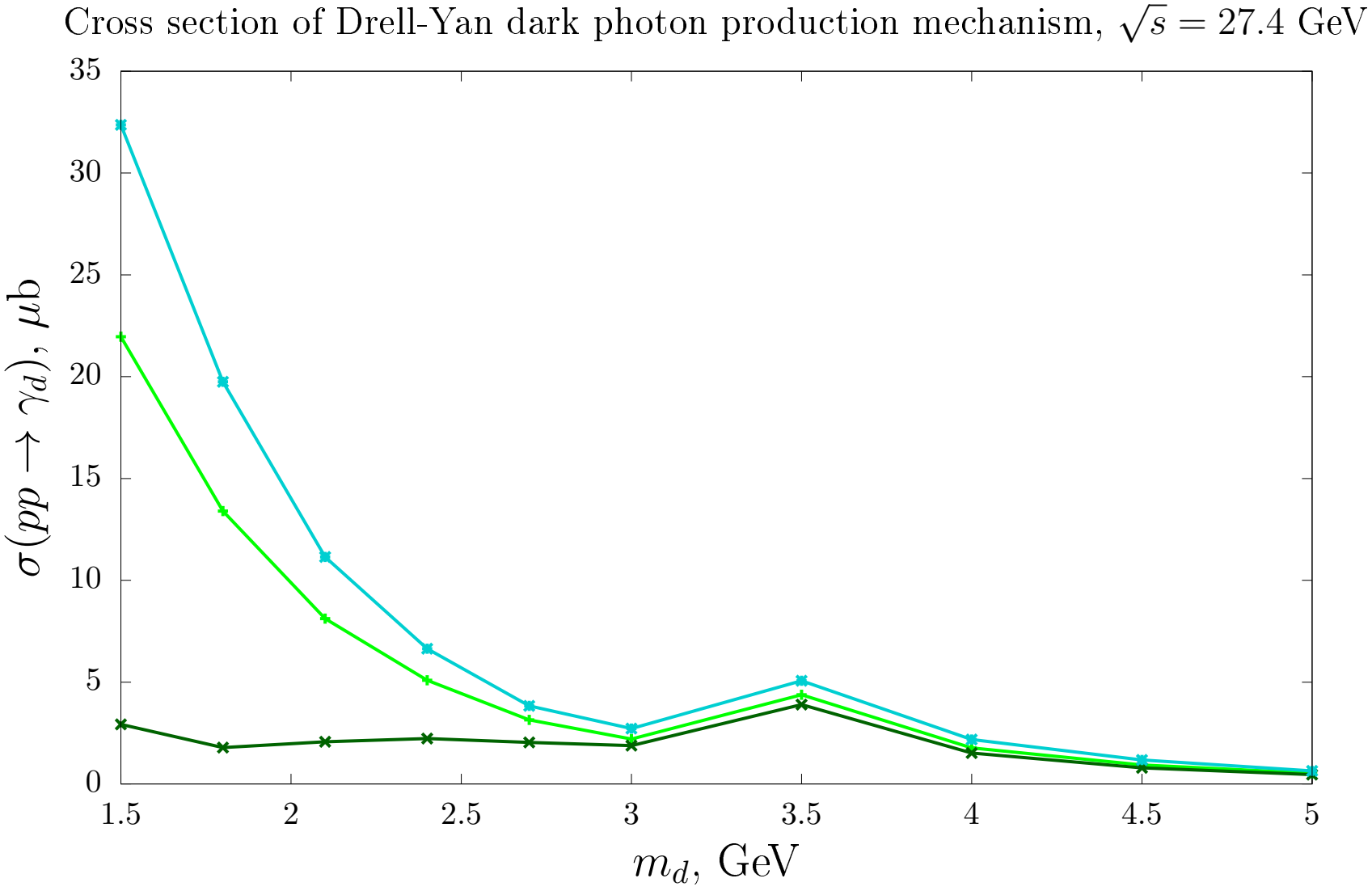
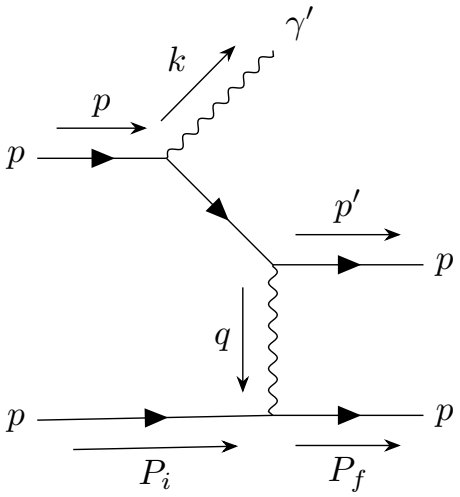
Massive vectors: QCD NNLO calculation

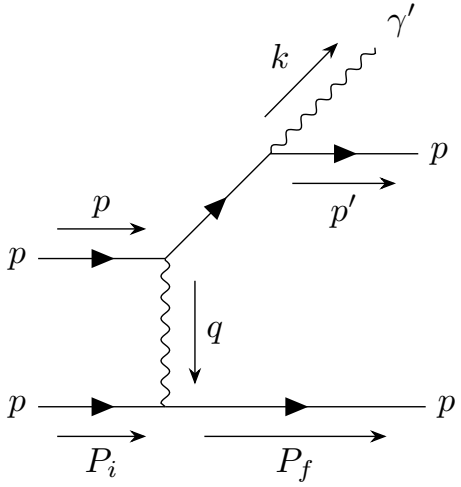
with E.Kryukova



Massive vectors: Pomeron-based calculation

with E.Kryukova





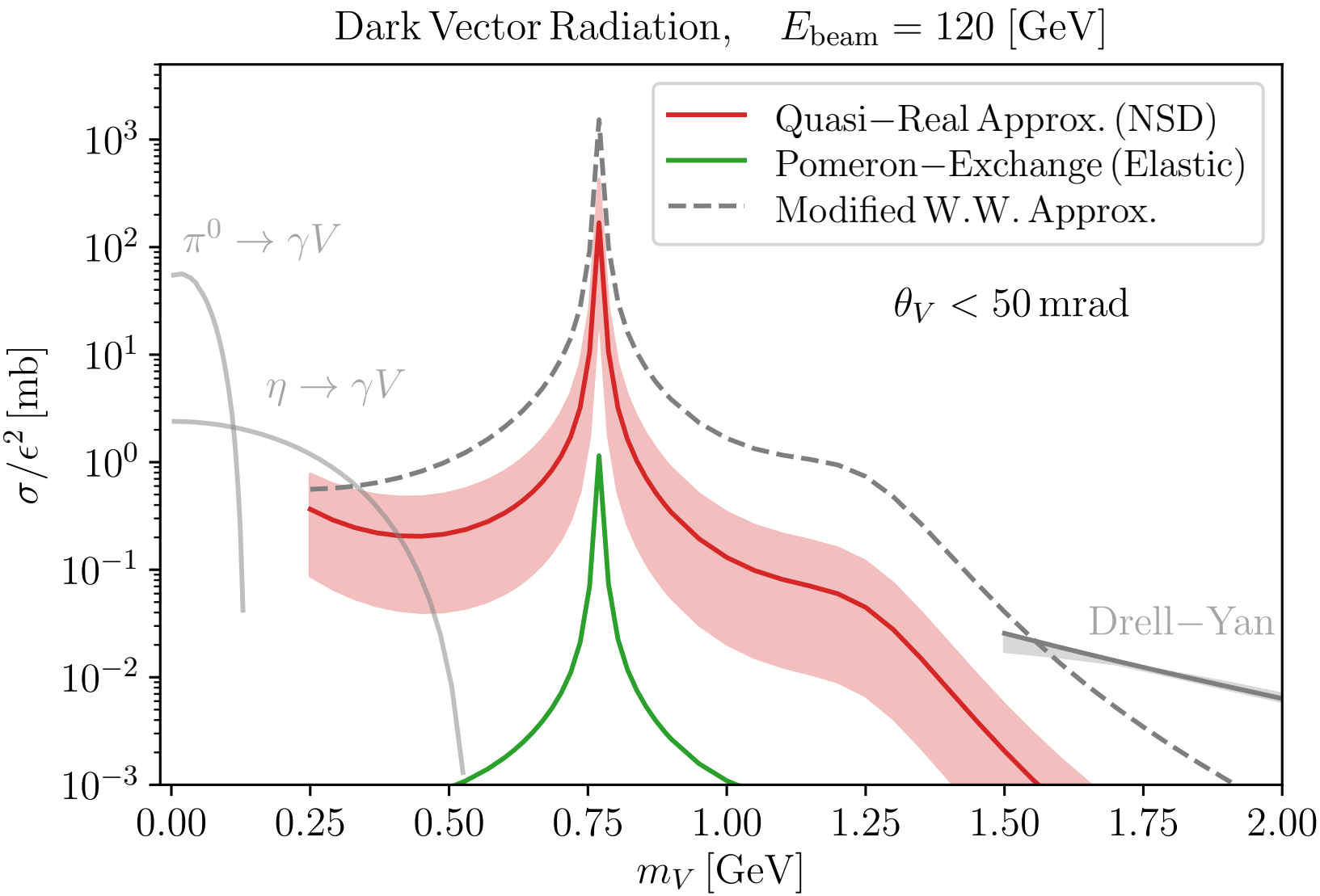
$$i\mathscr{M} = -i\varepsilon e Q_b^2 L^\nu \frac{-i}{q^2} g_{\nu\lambda} J^\lambda,$$

$$L_\nu = \varepsilon^{*\mu}_{\gamma'}(k)\bar{u}(p')\left(\gamma_\nu \frac{\hat{p}-\hat{k}+M}{(p-k)^2-M^2}\gamma_\mu + \gamma_\mu \frac{\hat{k}+\hat{p}'+M}{(k+p')^2-M^2}\gamma_\nu\right)u(p).$$

which can be related with elastic *pp* scattering cross section

Massive vectors: various attempts

2108.05900



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Higgs-driven inflation

F.Bezrukov, M.Shaposhnikov (2007)

$$S^{JF} = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R - \xi H^\dagger H R + \mathscr{L}_{SM}\right)$$

In a unitary gauge $H^T = \left(0, (h+v)/\sqrt{2}\right)$ (and neglecting $v = 246\,\text{GeV}$)

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2 + \xi h^2}{2}R + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda h^4}{4}\right)$$

slow roll behavior due to modified kinetic term even for $\lambda \sim 1$

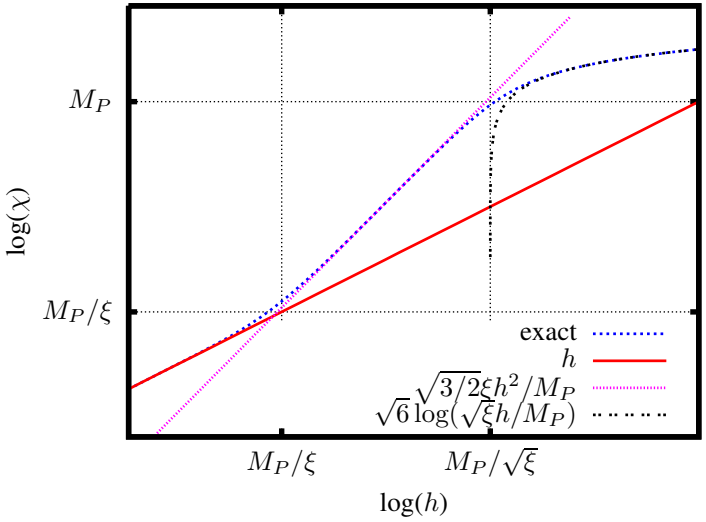
Go to the Einstein frame: $(M_P^2 + \xi h^2)\, R^{JR} \to M_P^2 R^{EF}$

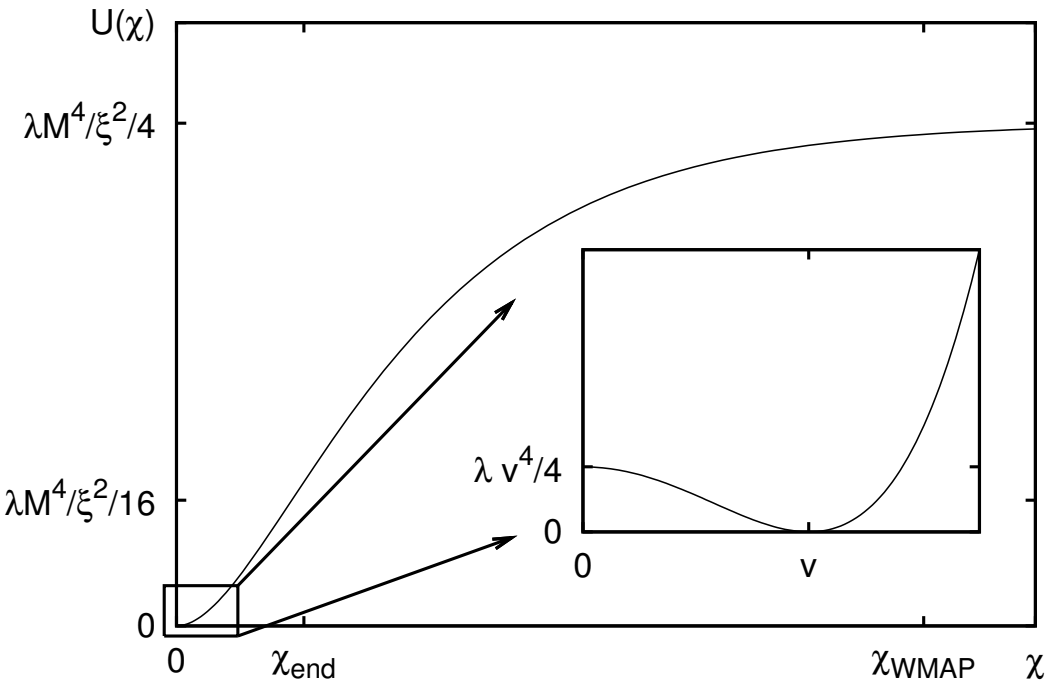
$$g_{\mu\nu}^{JF} = \Omega^{-2}\tilde{g}_{\mu\nu}^{EF}\,, \qquad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

with canonically normalized χ: interval ds^2 changes !

$$\frac{d\chi}{dh} = \frac{M_P\sqrt{M_P^2 + (6\xi+1)\xi h^2}}{M_P^2 + \xi h^2}\,, \quad U(\chi) = \frac{\lambda M_P^4 h^4(\chi)}{4(M_P^2 + \xi h^2(\chi))^2}\,.$$

we have a flat potential at large fields: $U(\chi) \to \text{const}$ @ $h \gg M_P/\sqrt{\xi}$





Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

effective dynamics : $h^2 \to \chi$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

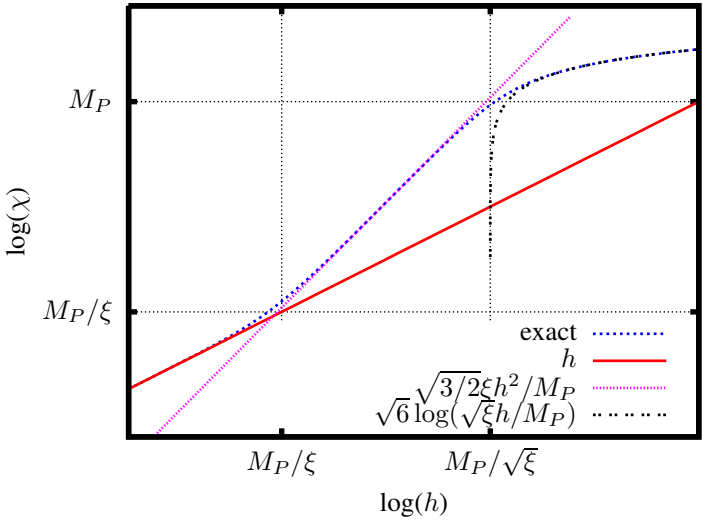
Advantage: NO NEW interactions
to reheat the Universe
inflaton couples to all SM fields!

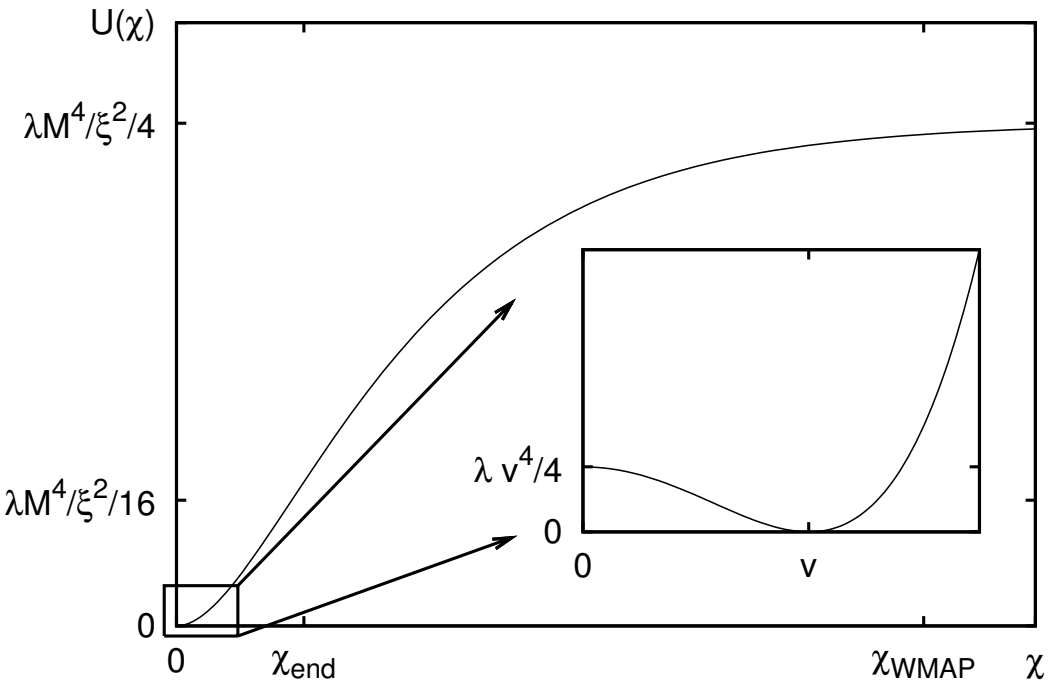
exponentially flat potential! @ $h \gg M_P/\sqrt{\xi}$:

$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

NO NEW d.o.f. 0812.3622, 1111.4397
Different reheating temperature...

from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$





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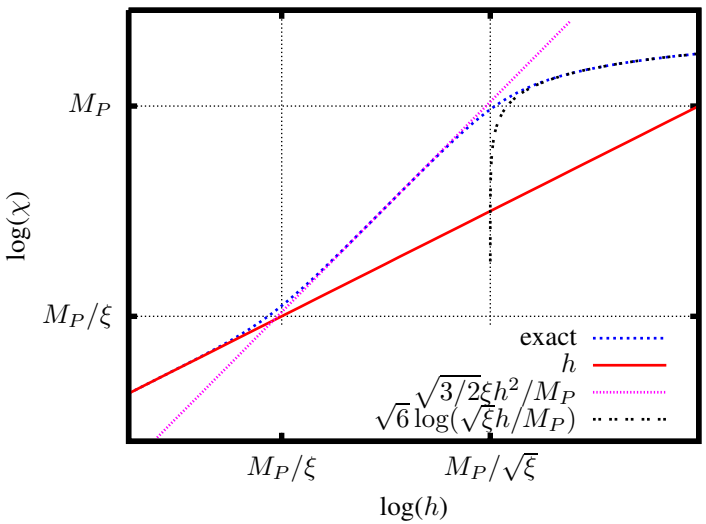
F.Bezrukov, D.G., M.Shaposhnikov, 0812.3622



$$m_W^2(\chi) = \frac{g^2}{2\sqrt{6}} \frac{M_P |\chi(t)|}{\xi}$$

$$m_t(\chi) = y_t \sqrt{\frac{M_P |\chi(t)|}{\sqrt{6}\,\xi}} \operatorname{sign} \chi(t)$$

reheating via W^+W^-, ZZ production at zero crossings

then nonrelativistic gauge bosons scatter to light fermions

$$\chi \to W^+W^- \to f\bar{f}$$

Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

Hot stage starts almost from $T = M_P/\xi \sim 10^{14}$ GeV:

effective dynamics : $h^2 \to \chi$

$$\mathscr{L} = \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

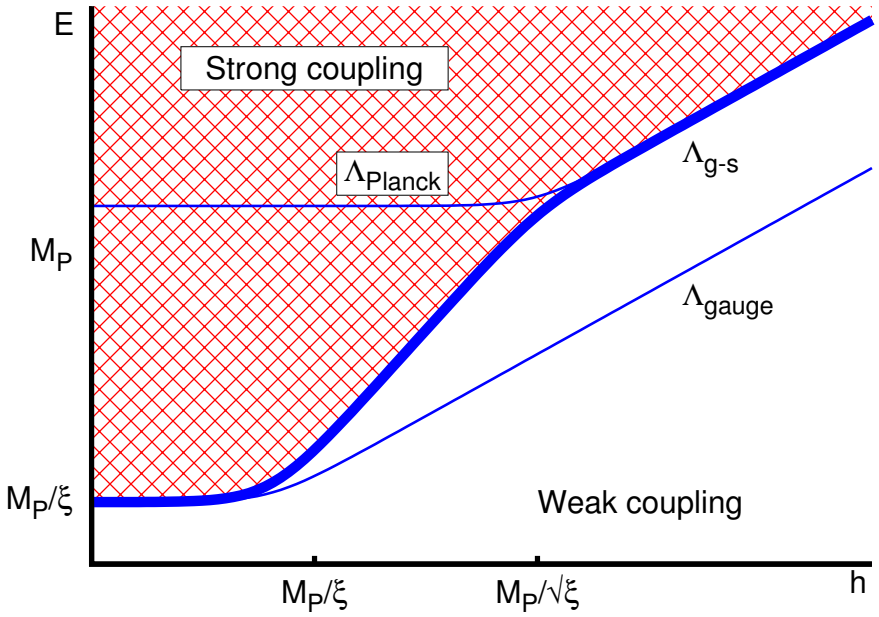
$$3.4 \times 10^{13}\,\text{GeV} < T_r < 9.2 \times 10^{13} \left(\frac{\lambda}{0.125}\right)^{1/4} \text{GeV}$$

Advantage: NO NEW interactions
to reheat the Universe
inflaton couples to all SM fields!

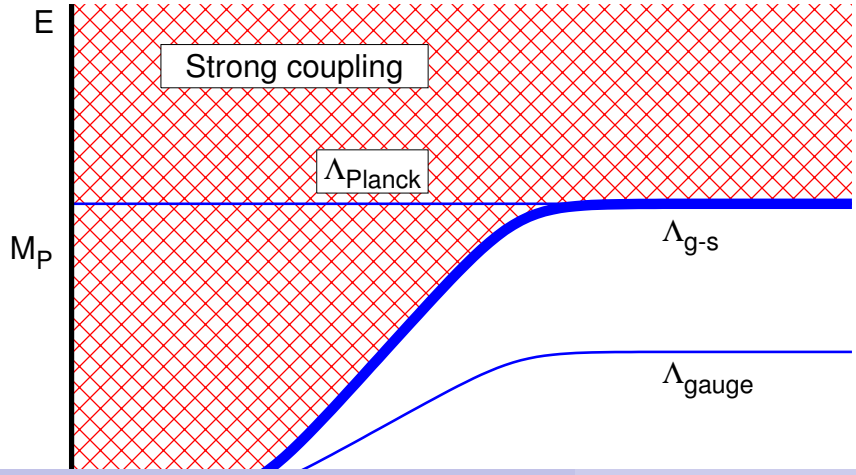
$n_s = 0.967$, $r = 0.0032$ F.Bezrukov, D.G.,

Strong coupling in Higgs-inflation

Jordan frame



Einstein frame



However, the reheating is almost instant

1609.05209, 1810.01304

We made an error, solving

$$\left(m_W^2(h(t)) + \Box\right) W_\nu^\pm = 0$$

while the true equation is

$$W_\nu^\pm m_W^2(h(t)) + \partial_\mu W_{\mu\nu}^\pm = 0$$

We fixed the gauge covariantly, $\partial_\mu W^\mu = 0$ ...

And the reheating is almost instant

1609.05209, 1810.01304

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$$W_\nu^\pm m_W^2(h(t)) + \partial_\mu W_{\mu\nu}^\pm = 0$$

the $\partial_\mu W_\mu^\pm = 0$ gauge does not go through the equation...

So, the longitudinal components of vector boson get contributions $\omega_L^2 \propto \dot{m}_W, \ddot{m}_W$
instant reheating well inside the strong coupling domain...

Natural completion with R^2

Y.Ema (2017), D.G., A.Tokareva (2018)

$\xi h^2 R$ induces R^2-term

hep-th/9510140

$$S_0 = \int d^4x\sqrt{-g}\left(-\frac{M_P^2+\xi h^2}{2}R+\frac{\beta}{4}R^2+\frac{(\partial_\mu h)^2}{2}-\frac{\lambda}{4}(h^2-v^2)^2\right).$$

introduce a Lagrange multiplier L and auxiliary scalar $\mathscr{R}$

$$S = \int d^4x\sqrt{-g}\left(\frac{(\partial_\mu h)^2}{2}-\frac{\lambda}{4}(h^2-v^2)^2-\frac{M_P^2+\xi h^2}{2}\mathscr{R}+\frac{\beta}{4}\mathscr{R}^2-L\mathscr{R}+LR\right).$$

integrate out $\mathscr{R}$

$$S = \int d^4x\sqrt{-g}\left(\frac{(\partial_\mu h)^2}{2}-\frac{\lambda}{4}(h^2-v^2)^2+LR-\frac{1}{\beta}(L+\frac{1}{2}\xi h^2+\frac{1}{2}M_P^2)^2\right)$$

$$\xi \to \xi^2/\beta$$

with

$$\beta \gtrsim \frac{\xi^2}{4\pi}$$

everything here look healthy

Further transformations...

Y.Ema (2017)

introducing scalaron ϕ with $m = M_P/\sqrt{3\beta}$

$$g_{\mu\nu} \to \Omega^2 g_{\mu\nu}\,, \quad \Omega^2 \equiv \frac{2L}{M_P^2}\,, \quad L \to \phi \equiv M_P\sqrt{\frac{2}{3}}\log\Omega^2\,.$$

and setting $M_P = 1/\sqrt{6}$

$$S = \int d^4x\sqrt{-g}\left(-\frac{R}{12} + \frac{1}{2}e^{-2\phi}(\partial h)^2 + \frac{1}{2}(\partial\phi)^2 - \frac{1}{4}e^{-4\phi}\left(\lambda h^4 + \frac{1}{36\beta}(e^{2\phi} - 1 - 6\xi h^2)^2\right)\right)$$

both gravity and scalar sector are weakly coupled up to M_P with $\beta \gtrsim \xi^2/(4\pi)$

And one more...

D.G., A.Tokareva (2018)

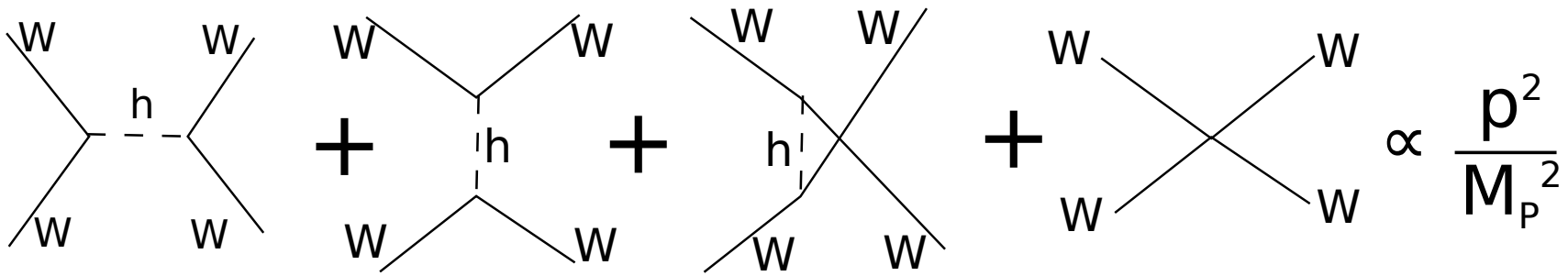
$$h = e^{\Phi}\tanh H,\ \phi = e^{\Phi}/\cosh H,$$

The scalar sector becomes

$$L = \frac{1}{2}\cosh^2 H(\partial\Phi)^2 + \frac{1}{2}(\partial H)^2 - \frac{\lambda}{4}\sinh^4 H - \frac{\lambda}{144\beta}(1 - e^{-2\Phi}\cosh^2 H - 6\xi\sinh^2 H)^2.$$

and the Higgs coupling to gauge bosons, e.g.,

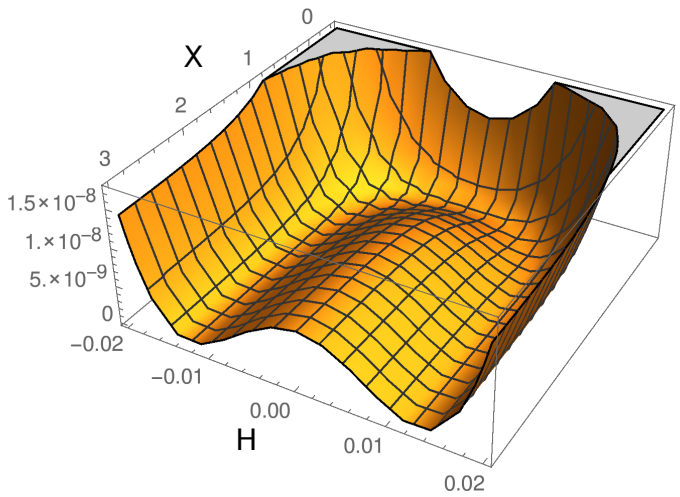
$$L_{gauge} = \frac{g^2 h^2}{4} e^{-2\phi} W_\mu^+ W_\mu^- = \frac{g^2}{4}\sinh^2 H\ W_\mu^+ W_\mu^-.$$

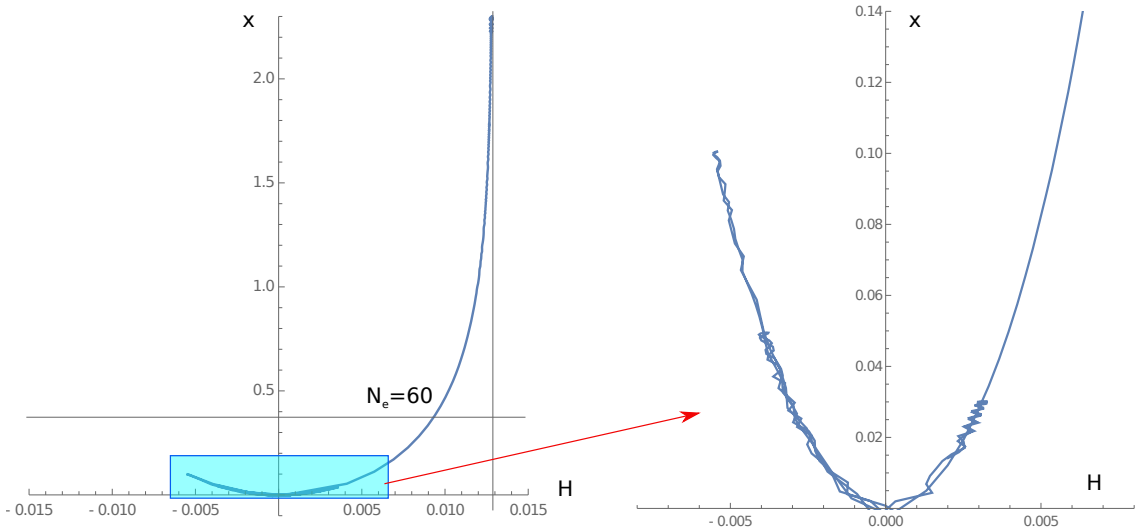


$$\mathscr{A} \sim \frac{g^2 p^2}{m_W^2}\left(\frac{4}{g^2}\left(\frac{dm_W(H)}{dH}\right)^2 - 1\right) \to \mathscr{A} \propto \frac{p^2}{M_P^2}$$

Cosmological spectra

D.G., A.Tokareva 1807.02392





Scalar perturbations:

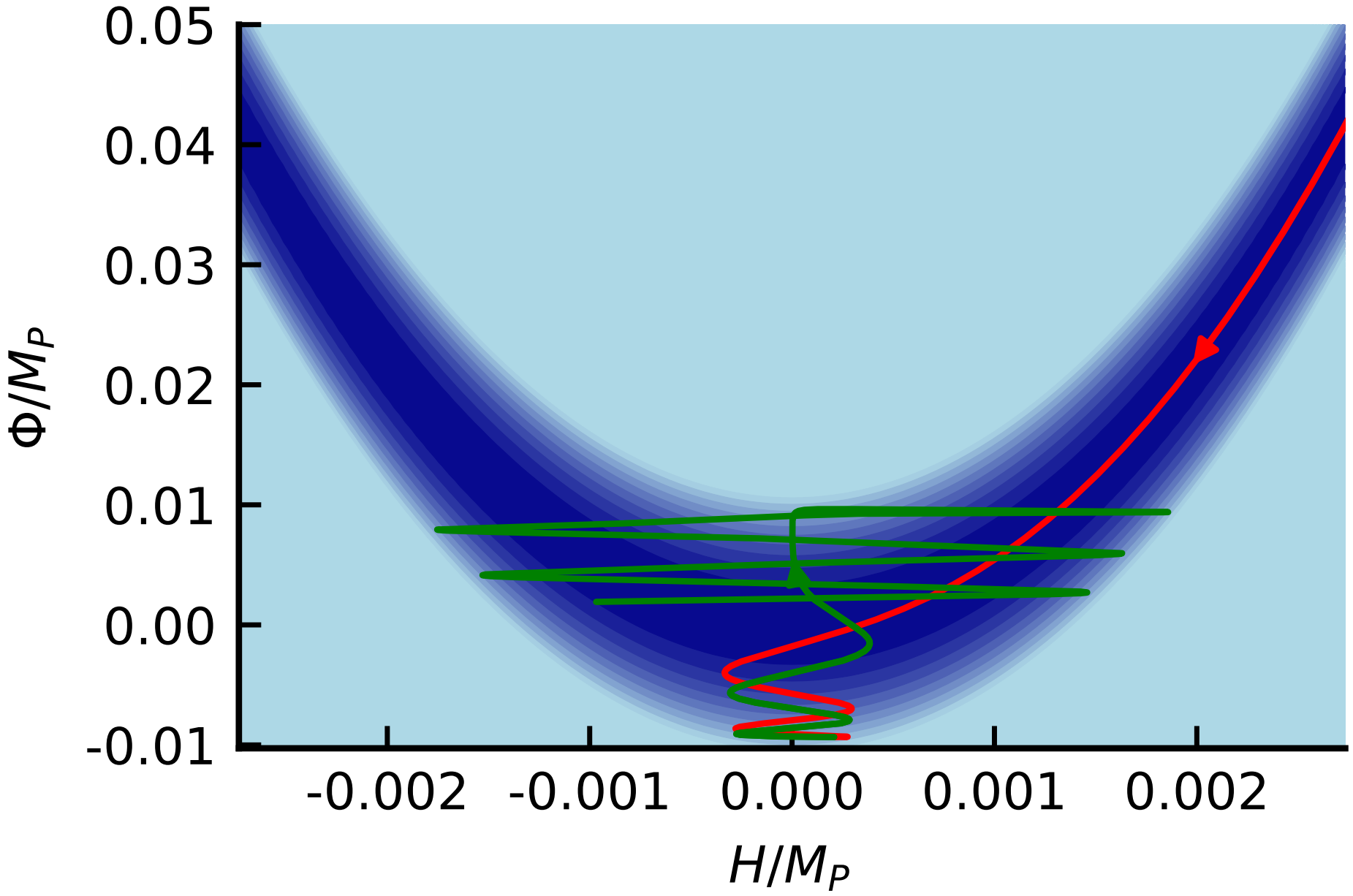
1701.07665

$$\beta + \frac{\xi^2}{\lambda} \simeq 2 \times 10^9$$

At small β like in the Higgs-inflation

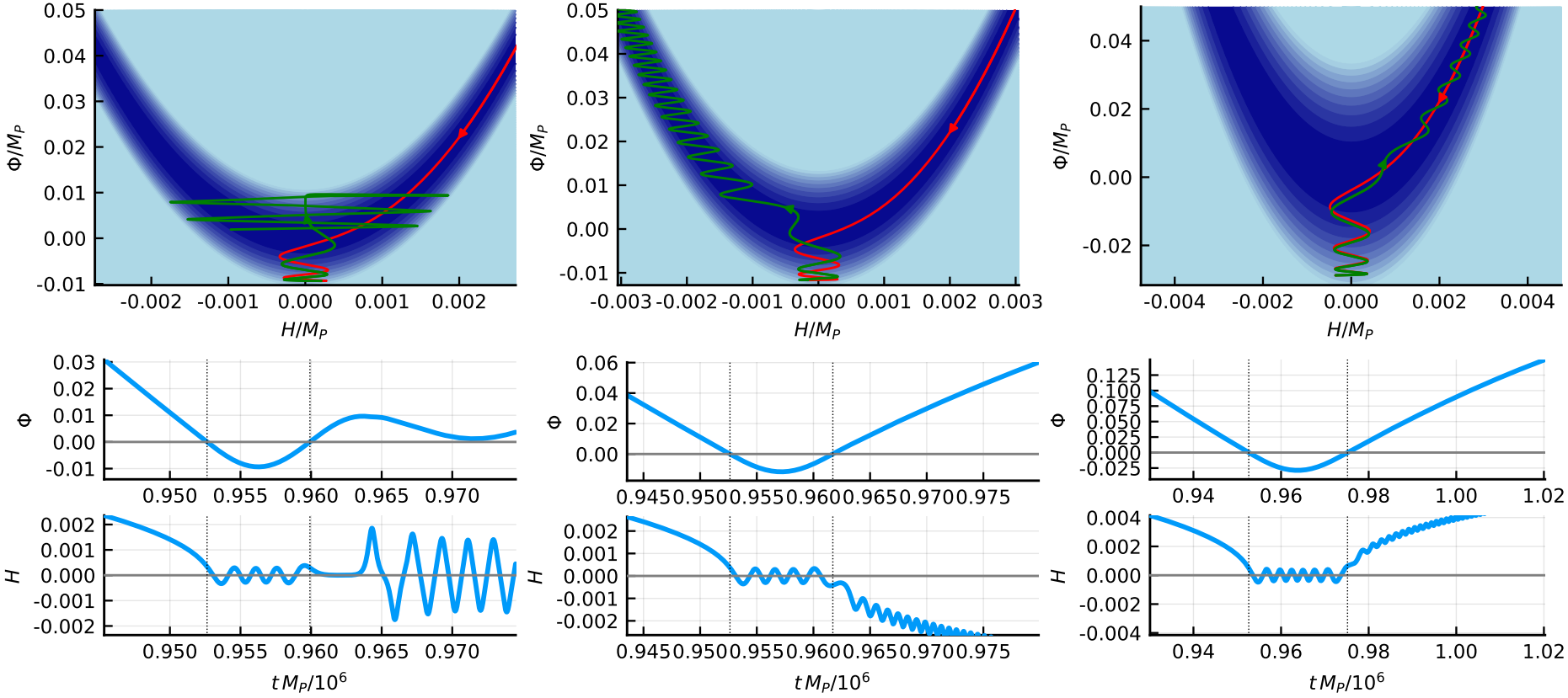
heavy scalaron is integrated out

$$\frac{\xi^2}{4\pi} < \beta < \frac{\xi^2}{\lambda} \quad \rightarrow \quad 5 \times 10^{13}\,\text{GeV} < m < 1.5 \times 10^{15}\,\text{GeV}$$


0.05
0.04
0.03
0.02
0.01
0.00
-0.01
Φ/M_P
-0.002
-0.001
0.000
0.001
0.002
H/M_P

Scalaron Φ and Higgs H evolution after inflation

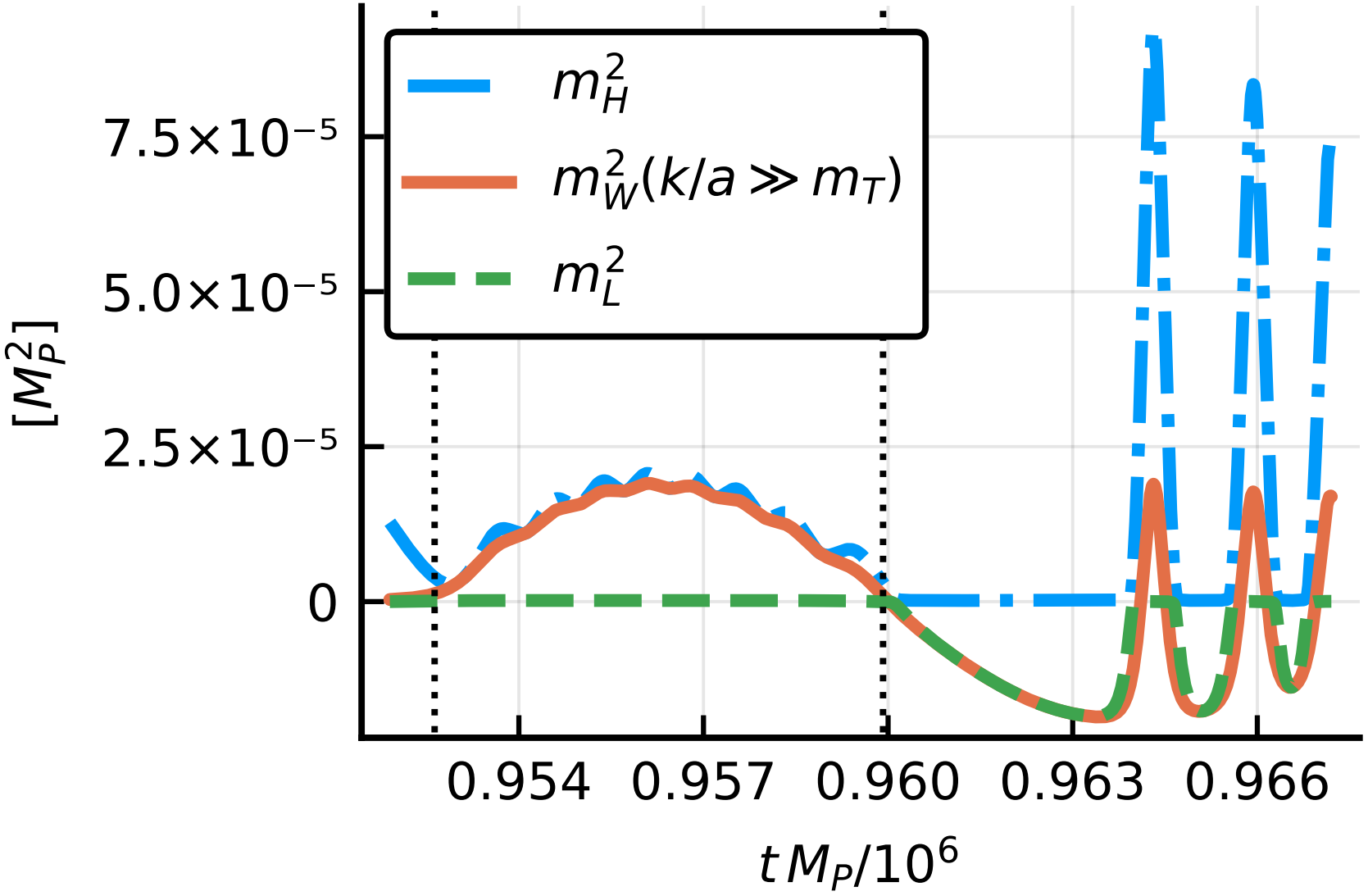
Homogeneous modes (mixing in kinetic sector), $\dot{\Phi} < 0$, $\dot{\Phi} > 0$



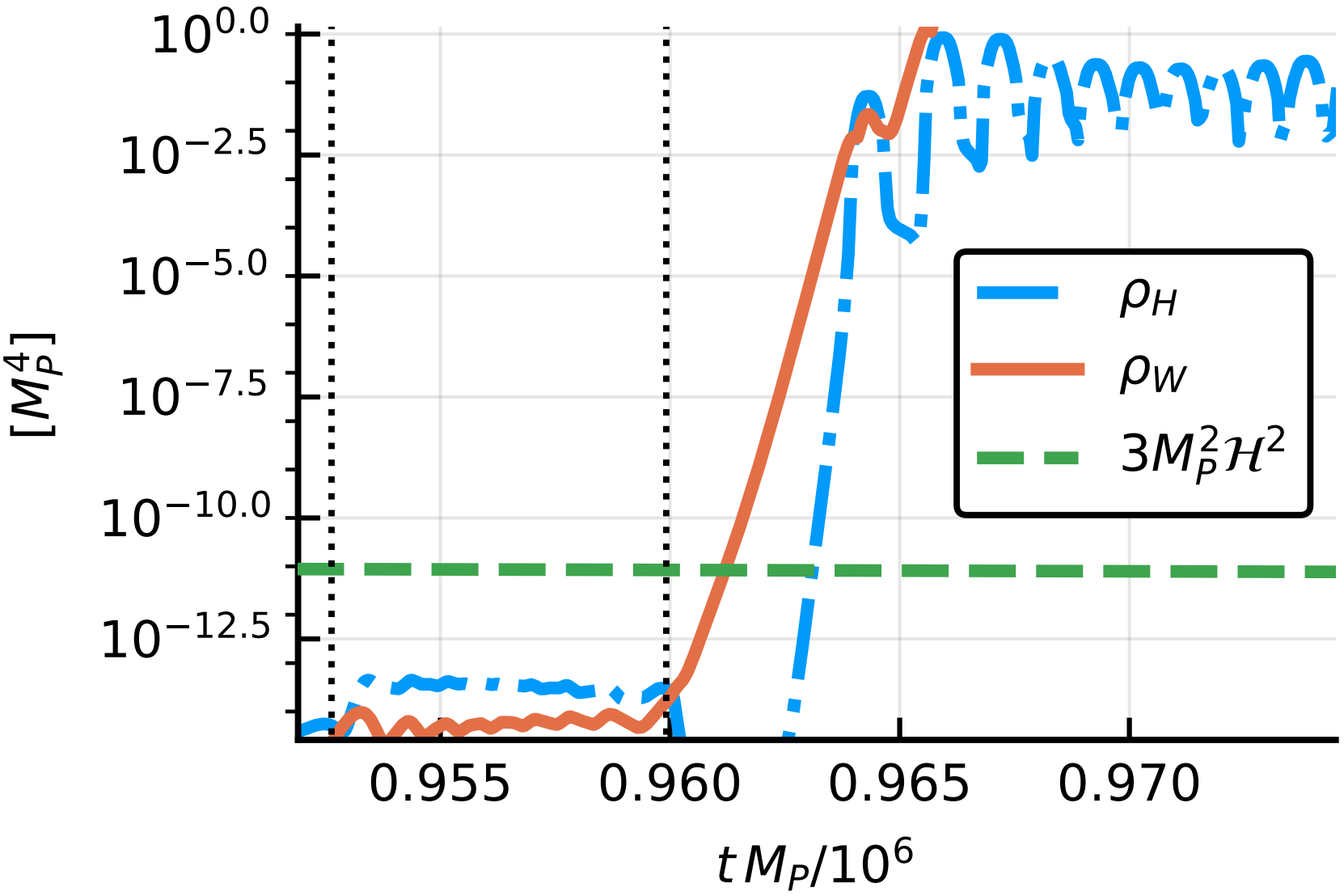
$\beta = 1.869 \times 10^6$ $\beta = 2.9 \times 10^6$ $\beta = 18 \times 10^6$

$$V(H,\Phi) = \frac{1}{4}\left(\lambda + \frac{\xi^2}{\beta}\right) H^4 + \frac{M_P^2}{6\beta}\Phi^2 - \frac{\xi M_P}{\sqrt{6}\beta}\Phi H^2 + \frac{7}{108\beta}\Phi^4 + \frac{\xi}{6\beta}\Phi^2 H^2 - \frac{M_P}{3\sqrt{6}\beta}\Phi^3$$

Numerical results: mass squared

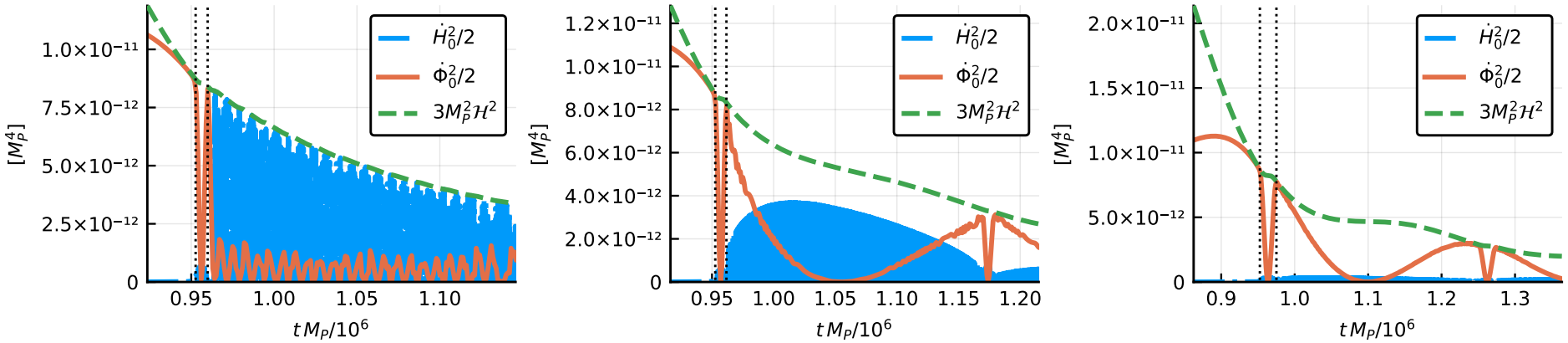


Energy in perturbations: back reaction is needed

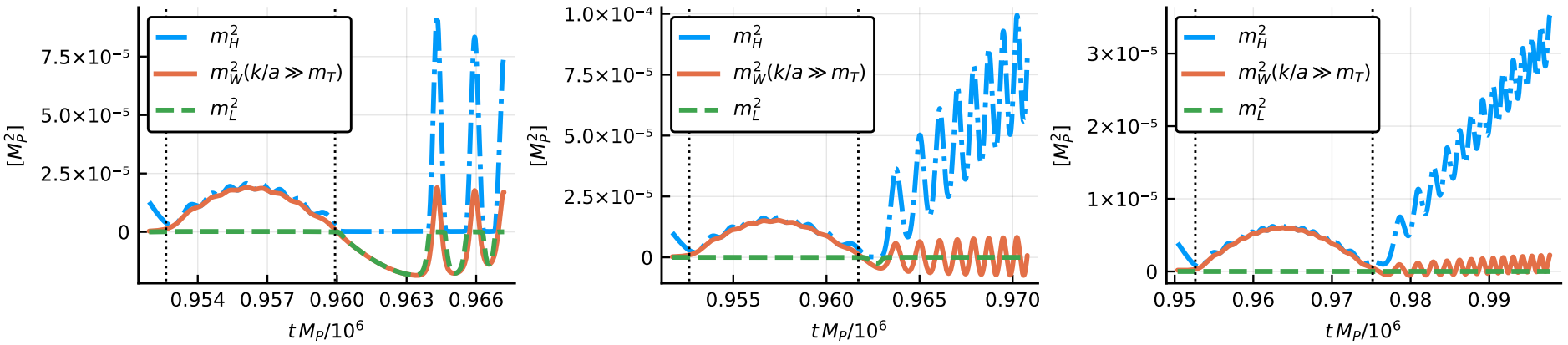


Numerical results for perturbations

energy distribution over homogeneous modes

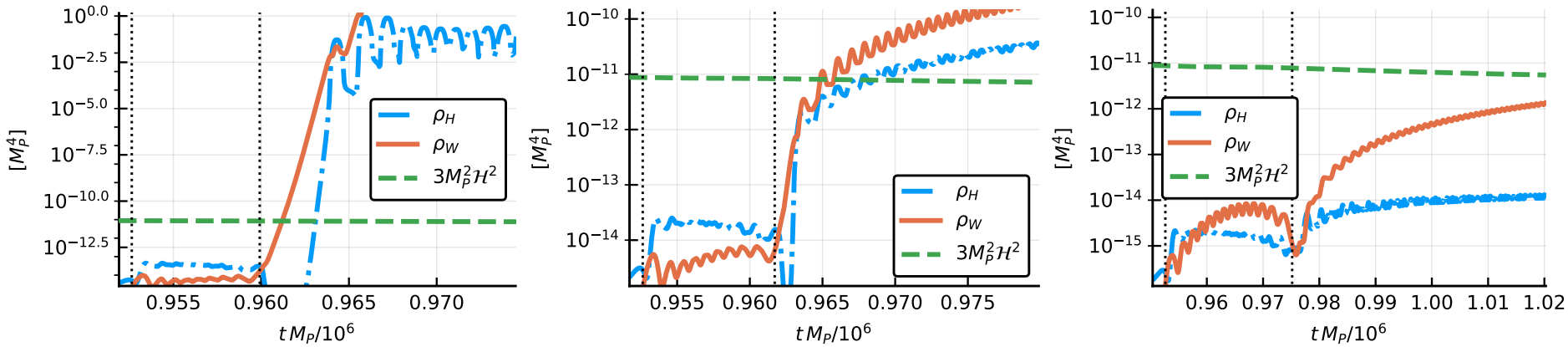


mass squared for the relevant perturbations

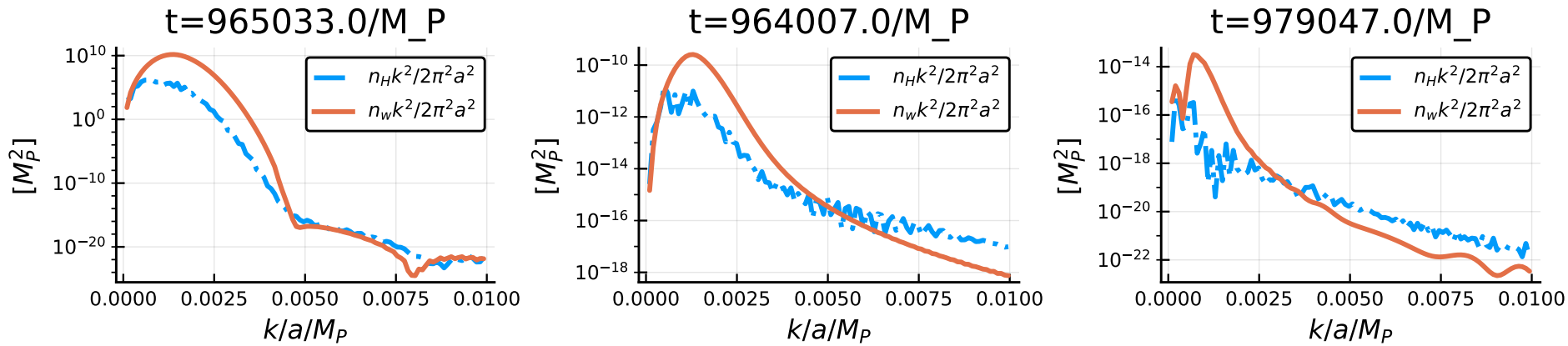


Specra and energy density of produced particles

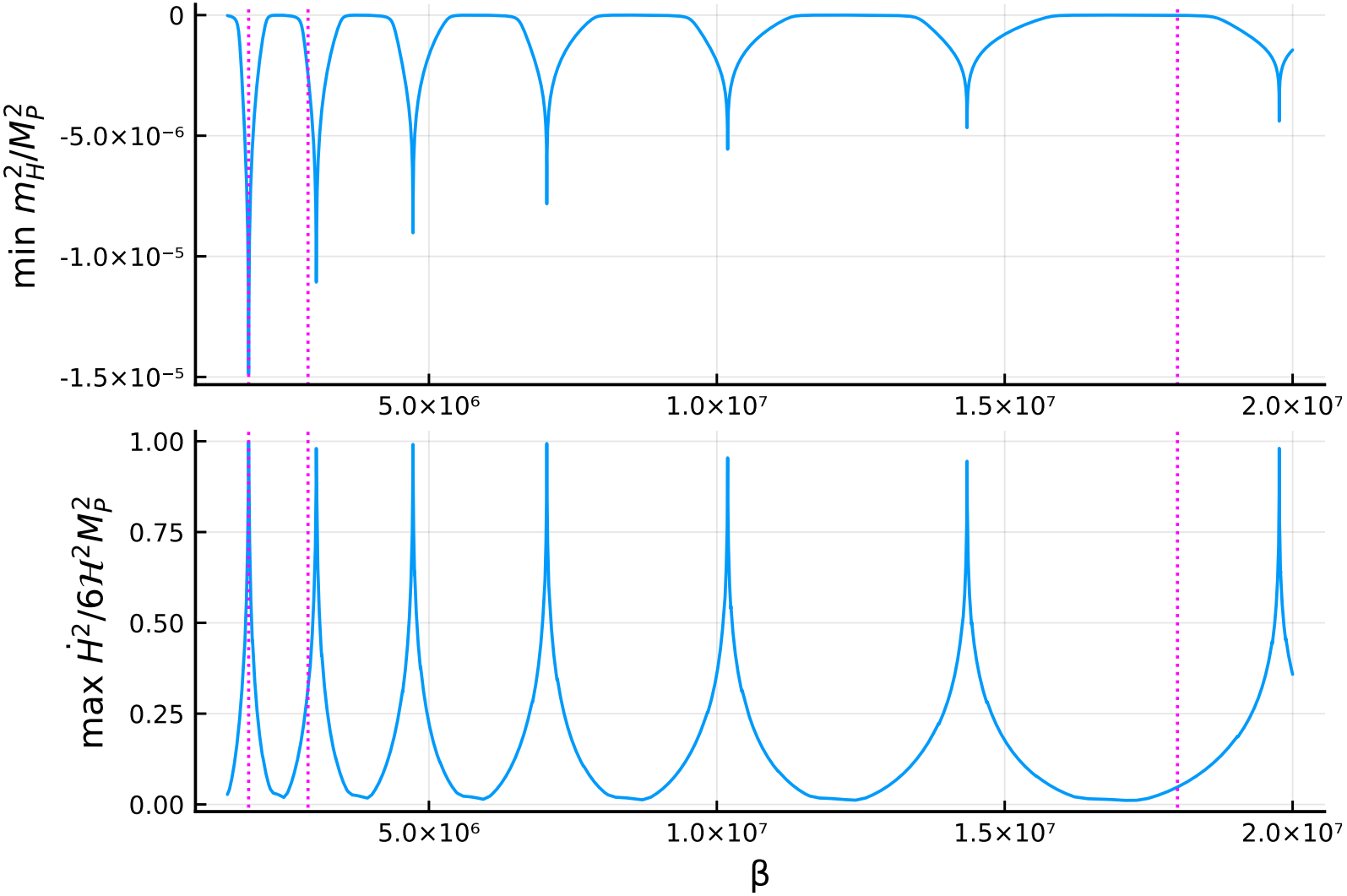
neglecting the adiabaticity conditions... and backreaction



spectra at a reference moment



The resonance positions and energy in Higgs between two zero crossings are correlated



New methods are needed !!

– Higgs frequency is much and
scalaron frequency is significantly higher than the expansion rate:
It seems that the reheating is almost instant

$$N_e = 59, \quad n_s = 0.97, \quad r = 0.0034.$$

- only for specially chosen values of β
- even there we need backreaction and there :
  – semiclassical approach is not applicable
  – Hartree–Fock does not work
- violent processes may induce
  – gravitational waves as a signature
  – black holes production, and their remnants as dark matter

Summary

WE NEED HELP

- If some exotics even feebly couples to QCD-stuff
- QCD-effects MUST BE properly accounted for
- help from QCD-people are welcome !!
- we must describe violent reheating like in Higgs+R^2 ...

HELP IS NEEDED

Backup slides

Dispersion system truncated

$$F_1(s) = \sum_{j=1}^{N} \int \frac{ds'}{\pi} \frac{T^*_{1j}(s')\sigma_j(s')}{s'-s} F_j(s') + \left\{ \sum_{j=N+1}^{M} \int \frac{ds'}{\pi} \frac{T^*_{1j}(s')\sigma_j(s')}{s'-s} F_j(s') \right\}$$

$$F_2(s) = \sum_{j=1}^{N} \int \frac{ds'}{\pi} \frac{T^*_{2j}(s')\sigma_j(s')}{s'-s} F_j(s') + \left\{ \sum_{j=N+1}^{M} \int \frac{ds'}{\pi} \frac{T^*_{2j}(s')\sigma_j(s')}{s'-s} F_j(s') \right\}$$

. . . . . .

$$F_N(s) = \sum_{j=1}^{N} \int \frac{ds'}{\pi} \frac{T^*_{Mj}(s')\sigma_j(s')}{s'-s} F_j(s') + \left\{ \sum_{j=N+1}^{M} \int \frac{ds'}{\pi} \frac{T^*_{Nj}(s')\sigma_j(s')}{s'-s} F_j(s') \right\}$$

Light sgoldstinos in SUSY models

SUSY is spontaneously broken

breaking of $SU(2)_W \times U(1)_Y$ by the $\langle H \rangle = v$

Goldstones bosons couple to all massive fields

(Goldberger–Treiman formula like for pion)

$$\mathscr{L} = \frac{1}{v} J^{\mu}_{SU(2)_W \times U(1)_Y} \partial_\mu H$$

breaking of SUSY by $\langle F_\varphi \rangle = F$

Goldstone fermion: goldstino

$$\mathscr{L}_\psi \propto \frac{1}{F} J^{\mu}_{SUSY} \partial_\mu \psi$$

Goldstino supermultiplet: (boson φ (sgoldstino), fermion ψ (goldstino))

~~SUSY~~ $\longleftrightarrow$ $F \equiv \langle F_\varphi \rangle \neq 0$ $\quad \Phi = \varphi + \sqrt{2}\theta\psi + F_\varphi \theta\theta$ $\quad \frac{1}{\sqrt{2}}\left(\varphi + \varphi^\dagger\right) \equiv S$ — scalar

sgoldstino: $\mathscr{L}_{S,P} \propto \frac{M_{soft}}{F}$ $\quad F \sim (\text{~~SUSY~~ scale})^2$ $\quad \frac{1}{i\sqrt{2}}\left(\varphi - \varphi^\dagger\right) \equiv P$ — pseudoscalar

M_{soft}: MSSM soft terms

superpartner masses and trilinear couplings,

massless at tree level

naturally may be light...

gauginos:

$$M_\lambda \lambda\lambda \longrightarrow \frac{M_\lambda}{F} S F_{\mu\nu} F^{\mu\nu}, \quad \frac{M_\lambda}{F} P F_{\mu\nu} \tilde{F}^{\mu\nu}$$

squarks, sleptons:

$$A_{ij} h_u \tilde{q}_i \tilde{u}_j \longrightarrow \frac{A_{ij}}{F} S h_u q_i u_j, \quad \frac{A_{ij}}{F} P h_u q_i u_j$$

Direct coupling to gluonic tensor

- For $M_S \ll 1$ GeV estimate coupling to pions through the triangle anomaly in $T_{\mu\mu}$
  M.Voloshin, V.Zakharov (1980)

$$-\langle\pi\pi\left|\frac{bg_s^2}{32\pi^2}G^a_{\mu\nu}G^a_{\mu\nu}\right|0\rangle = \langle\pi\pi\,|\,T_{\mu\mu}\,|\,0\rangle = q^2\varphi^\alpha_\pi\varphi^\alpha_\pi/2$$

  hence we get an amplification 1511.05403

$$\Gamma(S\to\pi^0\pi^0) \approx \frac{\alpha_s^2(M_3)}{\beta^2(\alpha_s(M_3))}\frac{\pi m_S^3 M_3^2}{4F^2}\sqrt{1-\frac{4m^2_{\pi^0}}{m_S^2}},$$

- For $M_S \gg 1$ GeV we have gluons and a suppression $g_s^2 G^2_{\mu\nu}$ is a renorm-invariant

$$\Gamma(S\to gg) = \left(\frac{\alpha_s(m_S)\beta(\alpha_s(M_3))}{\beta(\alpha_s(m_S))\alpha_s(M_3)}\right)^2\frac{m_S^3 M_3^2}{4\pi F^2}.$$

- The two rates mismatch by orders...