Pair Production in High-Intensity Lasers*)

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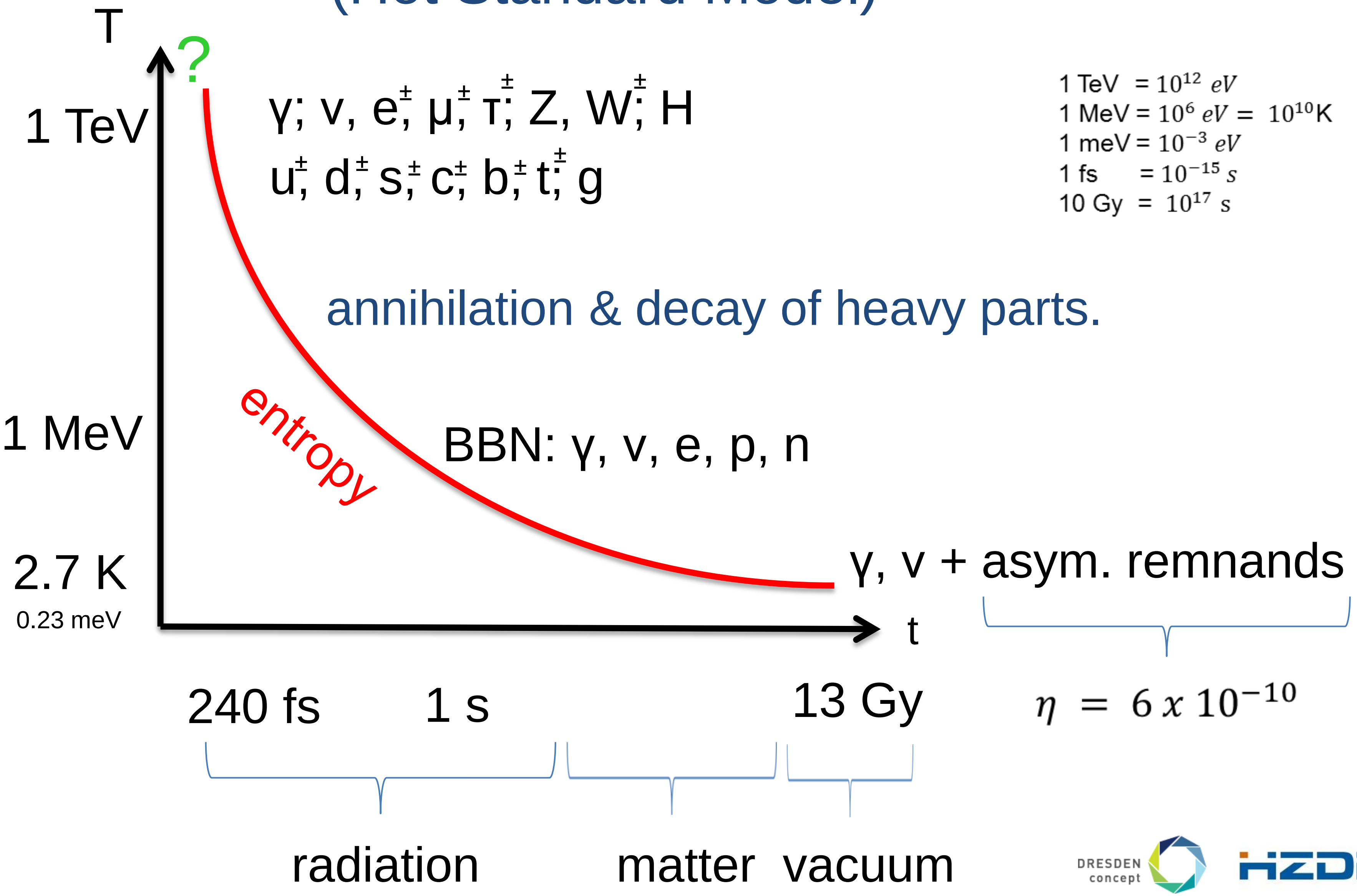
with A.I. Titov, H. Takabe, A. Hosaka, et al.
D. Blaschke, S. Smolyansky, S. Schmidt et al.
D. Seipt, T. Nousch, A. Otto, H. Oppitz et al.

*) Schwinger, Breit-Wheeler
(Short & Strong Laser Pulses)

Particle Destruction in the Universe (Hot Standard Model)



§ 1: Schwinger § 2: Breit-Wheeler Compton

E1(vt) + E2(Nvt)

A1(kx) + A2(Nkx)

periodic
fite duration
pulse shape

kinetic eqs.
(Bogolyubov transf.)

probe photons (pert.) + sQED
(Furry: Volkov)

motivation:

HIBEF at European XFEL/Hamburg:
PW-class laser(s) + XFEL

1. Dynamically Assisted Schwinger Process (Pair Production from „Vacuum“)

quantum kinetic eqs.

e.g. Grib, Mamaev, Mostepanenko (1988) Eq. (9.73)

$$\dot{f}(\boldsymbol{p},t) = Q(\boldsymbol{p},t)\int_{t_0}^{t} \mathrm{d}t'\, Q(\boldsymbol{p},t')\left[1-\eta f(\boldsymbol{p},t')\right]\cos 2\left[\Theta(\boldsymbol{p},t)-\Theta(\boldsymbol{p},t')\right]$$

= 2 for spin ½ Fermions
(→ Pauli blocking)

$$f = \frac{d\ N}{d^3p\ \ d^3x}$$

$$\Theta(\boldsymbol{p},t) = \int_{t_0}^{t} \mathrm{d}t'\, \omega(\boldsymbol{p},t')\ ,$$

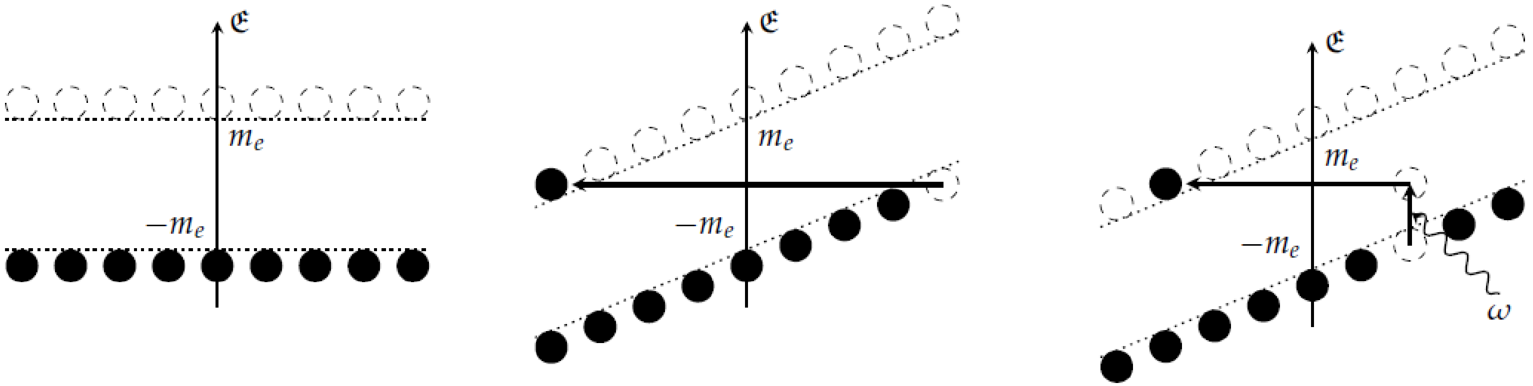
dyn. phase, non-Markovian process

$$\omega(\boldsymbol{p},t) = \sqrt{\epsilon_\perp^2 + \left(p_{||} - eA(t)\right)^2}$$

quasi-energy

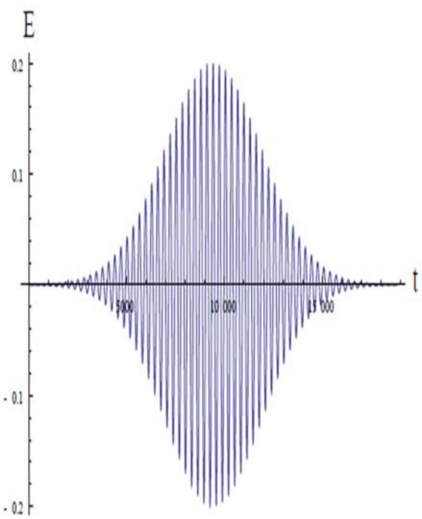
$$Q(\boldsymbol{p},t) = \frac{eE(t)\epsilon_\perp}{\omega^2(\boldsymbol{p},t)}\ ,$$

amplitude of vacuum decay

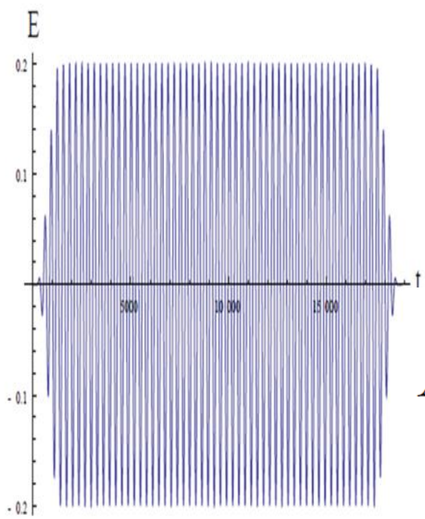


from
C. Schneider (2015)

Schutzhold, Dunne, Gies (2008): tunneling + multi-photon



Smolyansky et al. 2015



Otto et al. 2015

specific to our work (Laser + XFEL):

$$A(t) = \left(\frac{E_1}{\nu} \cos(\nu t) + \frac{E_2}{N\nu} \cos(N\nu t) \right) \underbrace{K(\nu t)}_{C^\infty}$$

$$K(\tau) = \begin{cases} 0 & \text{for } \tau < 0 \\ & \text{smooth transition} \\ 1 & \text{for } \tau_{\text{ramp}} < \tau < \tau_{\text{ramp}} + \tau_{\text{f.t.}} \\ & \text{smooth transition} \\ 0 & \text{for } \tau_{\text{pulse}} < \tau \end{cases}$$

simply field doubling

$$\underbrace{w \sim \exp\{-\pi \frac{E_c}{E}\}}_{\text{very very small}} \quad \text{vs.} \quad \underbrace{\exp\{-\pi \frac{E_c}{2\,E}\}}_{\text{very small}}$$

enhancement by $\exp\{+\,\pi \frac{E_c}{2E}\}$

Narozhny et al. (2004) multiple beams at XCELS

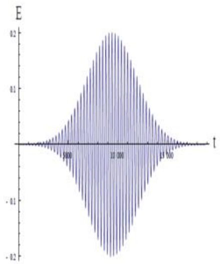
more than field doubling: Orthaber+ (2011), Kohlfurst+ (2013), Sicking (2013), Hebenstreit+ (2014), Akal+ (2014), Otto+ (2015)

news on Schwinger/pairs: (i) speakers in session „pair creation“ at ExHILP

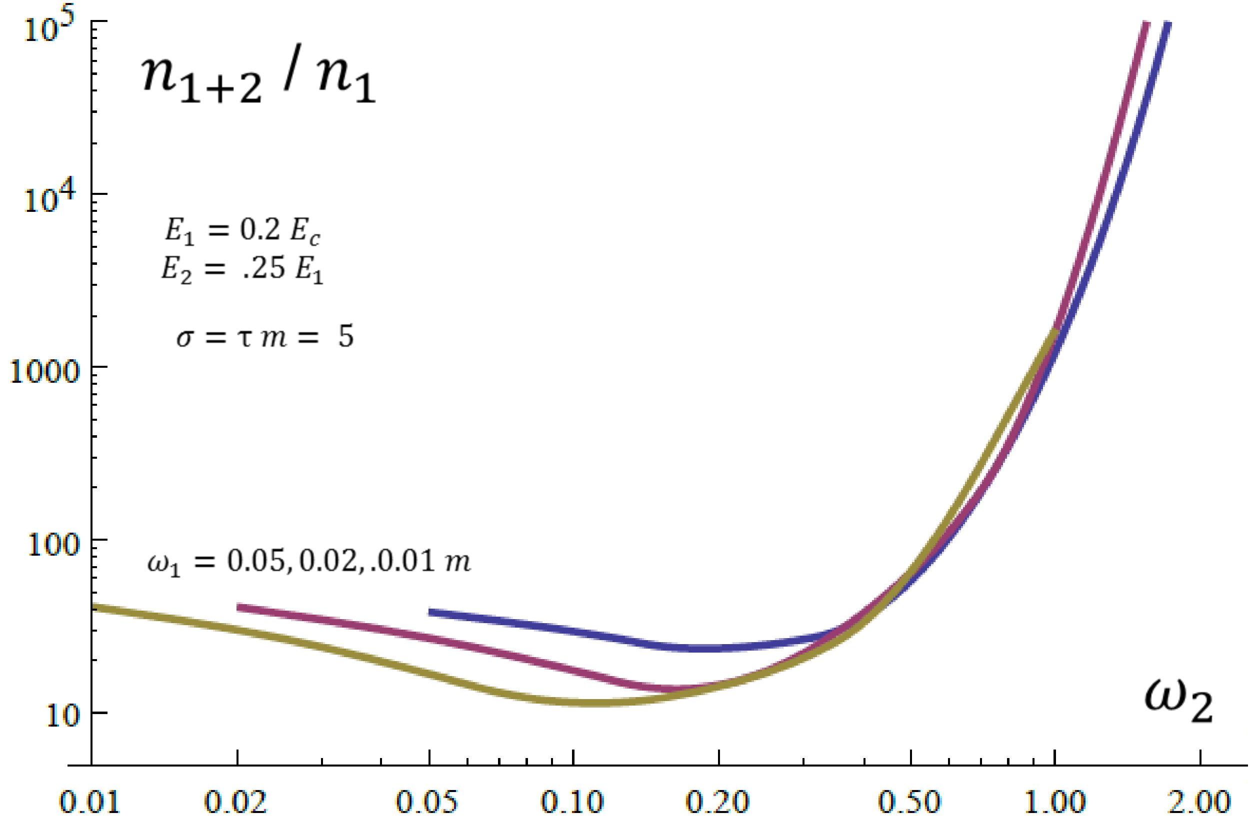
(ii) Dabrowski, Dunne (2014), Fey, Schutzhold (2014), Dumlu, Dunne (2011), Schneider, Schutzhold (2014), Ilderton (2014)

(iii) a few more relevant authors

Gauss envelope



$$E(t) = (E_1 \cos\ \omega_1 t + E_2 \cos \omega_2 t)\, \exp(-t^2 / 2\, \tau^2)$$



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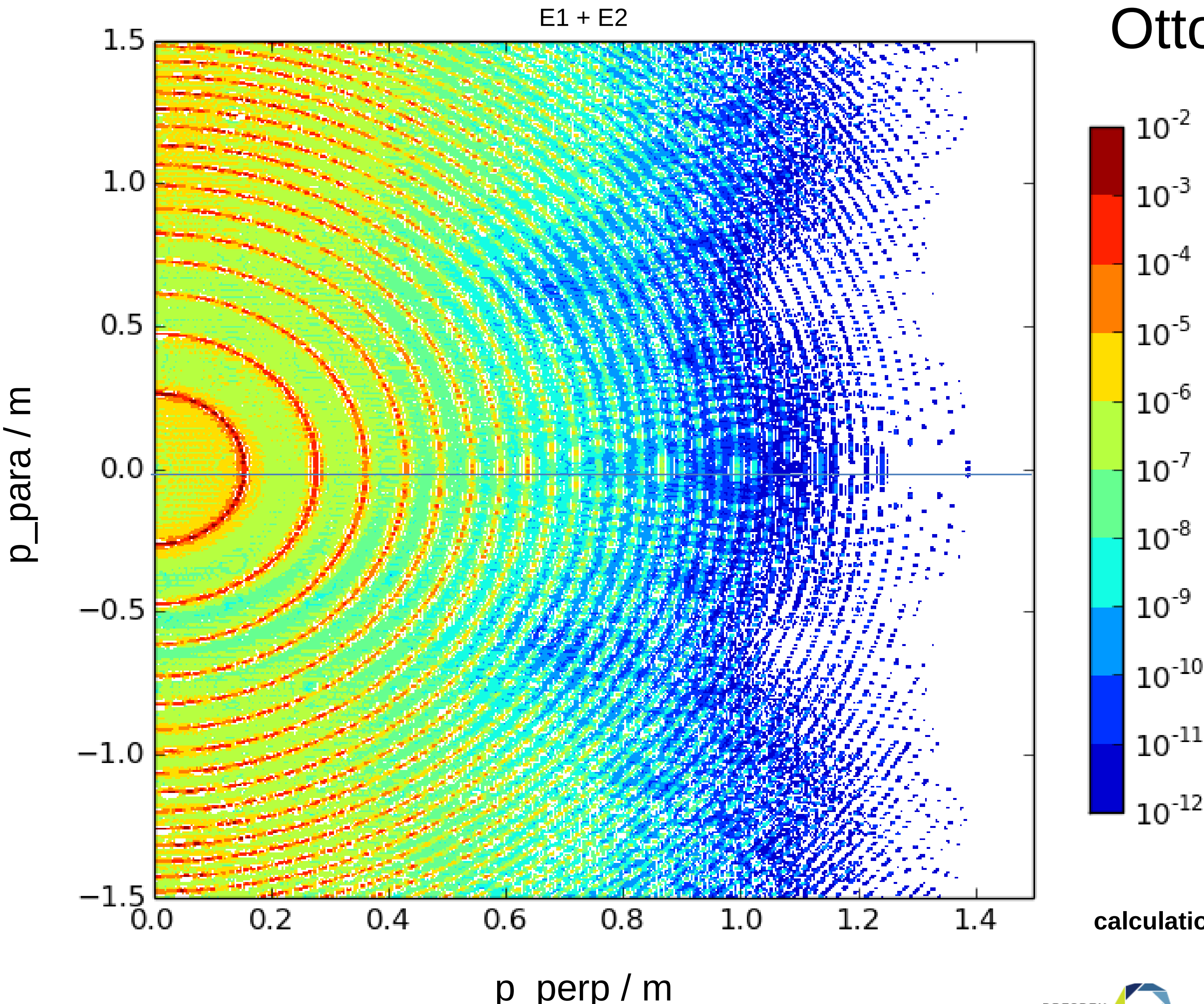
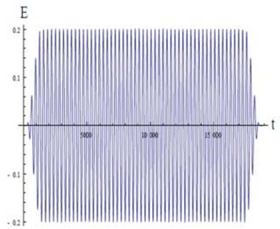
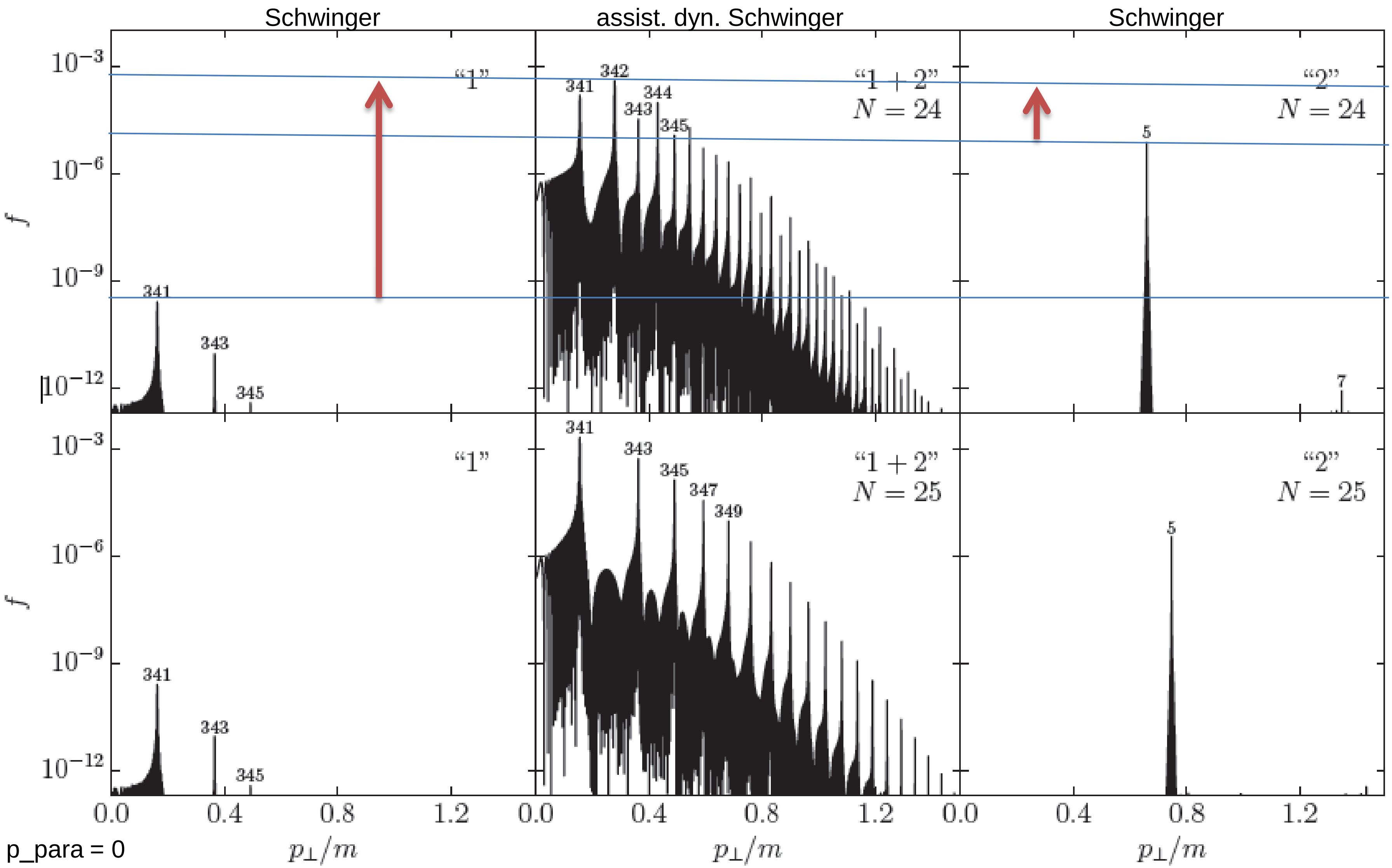
Otto pulse





calculations: A. Otto



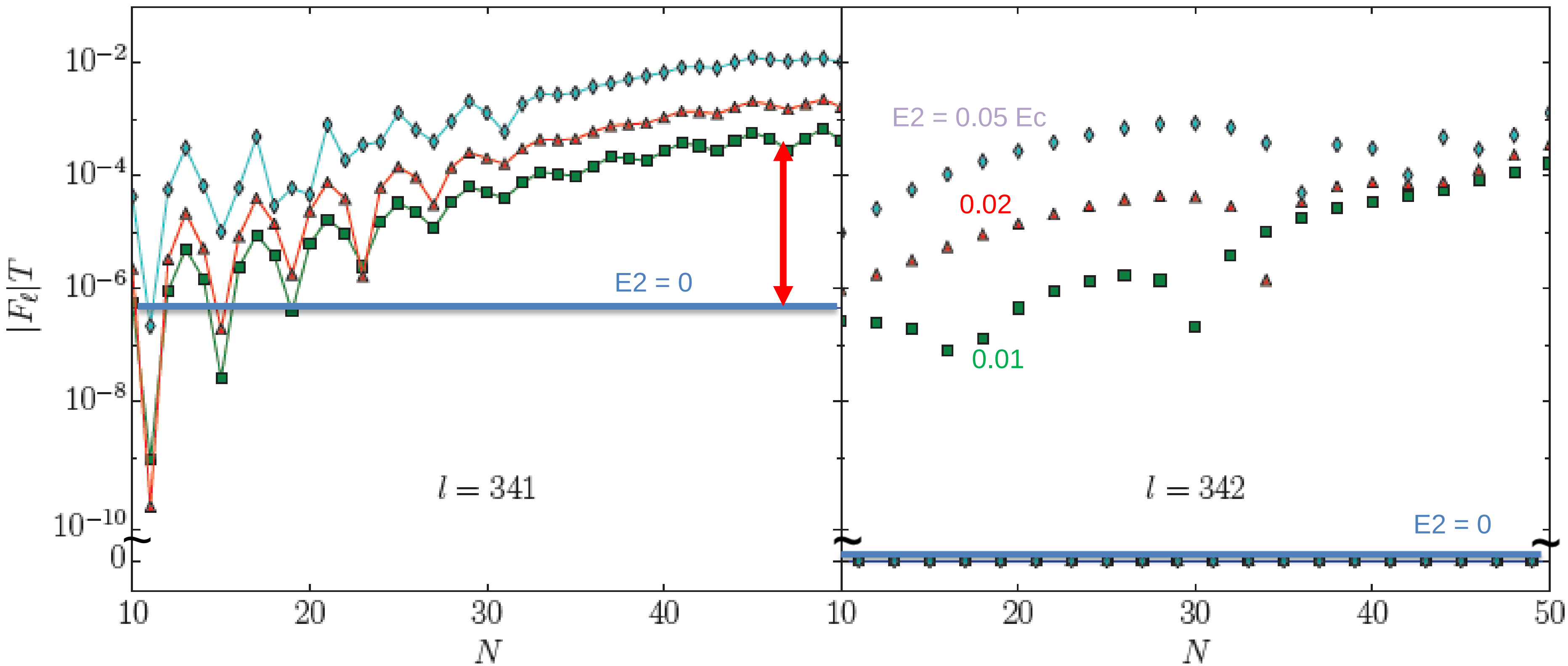
slow strong field „1“
E1 = 0.1 Ec
v = 0.02 m
g1 = 0.2 -> tunnel.

flat top: 50 T
ramping: 5 T
g = (Ec/E) (v/m)

fast weak field „2“
E2 = 0.05 Ec
g2 ~ 10 -> m.p.

$$n \approx 2\pi^2 \sum_{\ell=\ell_{\min}}^{\infty} p_\perp^{(\ell)\,2} / |\Omega'(p_\perp^{(\ell)},0)|\, \underline{|F_\ell(p_\perp^{(\ell)},0)|}^2 \underbrace{t_{\mathrm{f.t.}}}_{}$$

linear due to shell shrinking



low-density approximation (= w/o Pauli blocking)

$$f(\boldsymbol{p},t) = \frac{1}{2}\left|I(\boldsymbol{p},t)\right|^2 ,$$

$$I(\boldsymbol{p},t) = \int_0^t \mathrm{d}t' \, \frac{eE(t')\epsilon_\perp}{\omega(\boldsymbol{p},t')^2} \, \mathrm{e}^{2i\Theta(\boldsymbol{p},t')}$$

N = integer: Fourier + Fourier

$$I(\boldsymbol{p},t) = \sum_\ell \underbrace{iF_\ell(\boldsymbol{p})}_{\text{shell occupation}} \frac{\mathrm{e}^{-i(\ell\nu - 2\Omega(\boldsymbol{p}))t} - 1}{\underbrace{\ell\nu - 2\Omega(\boldsymbol{p})}_{\text{kinematics, shell structure}}}$$

shell width shrinking

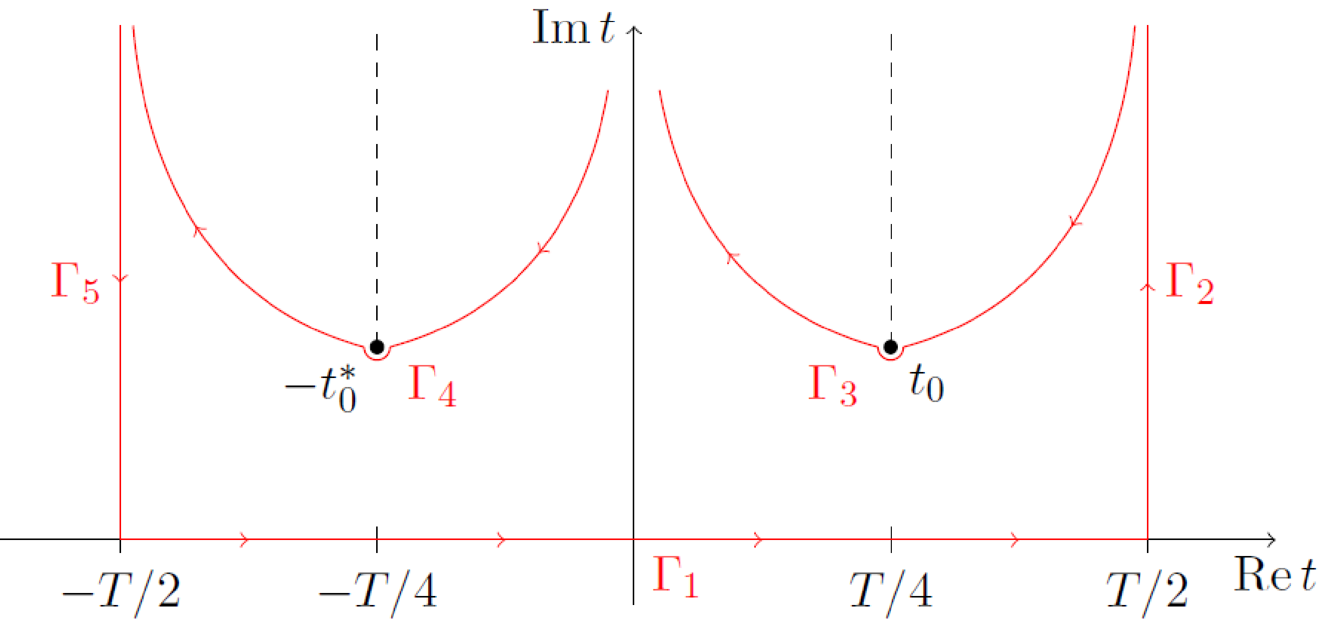
$$F_\ell(\boldsymbol{p}) = \frac{1}{T}\int_0^T \mathrm{d}t \, F(\boldsymbol{p},t)\mathrm{e}^{i\ell\nu t} \qquad \Omega(\boldsymbol{p}) = \frac{1}{T}\int_0^T \mathrm{d}t \, \omega(\boldsymbol{p},t)$$ = Fourier zero mode

$$f(\boldsymbol{p}^{(\ell)},t) = \frac{1}{2}\left| iF_l(\boldsymbol{p}^{(\ell)})t + \sum_{k\neq\ell} iF_k(\boldsymbol{p}^{(\ell)}) \frac{\mathrm{e}^{i(k\nu - 2\Omega(\boldsymbol{p}^{(\ell)}))t} - 1}{k\nu - 2\Omega(\boldsymbol{p}^{(\ell)})} \right|^2$$

$$= \frac{1}{2}\left|F_\ell(\boldsymbol{p}^{(\ell)})\right|^2 t^2 + \underbrace{G(\boldsymbol{p}^{(\ell)},t)t + H(\boldsymbol{p}^{(\ell)},t)}_{\text{transient}},$$

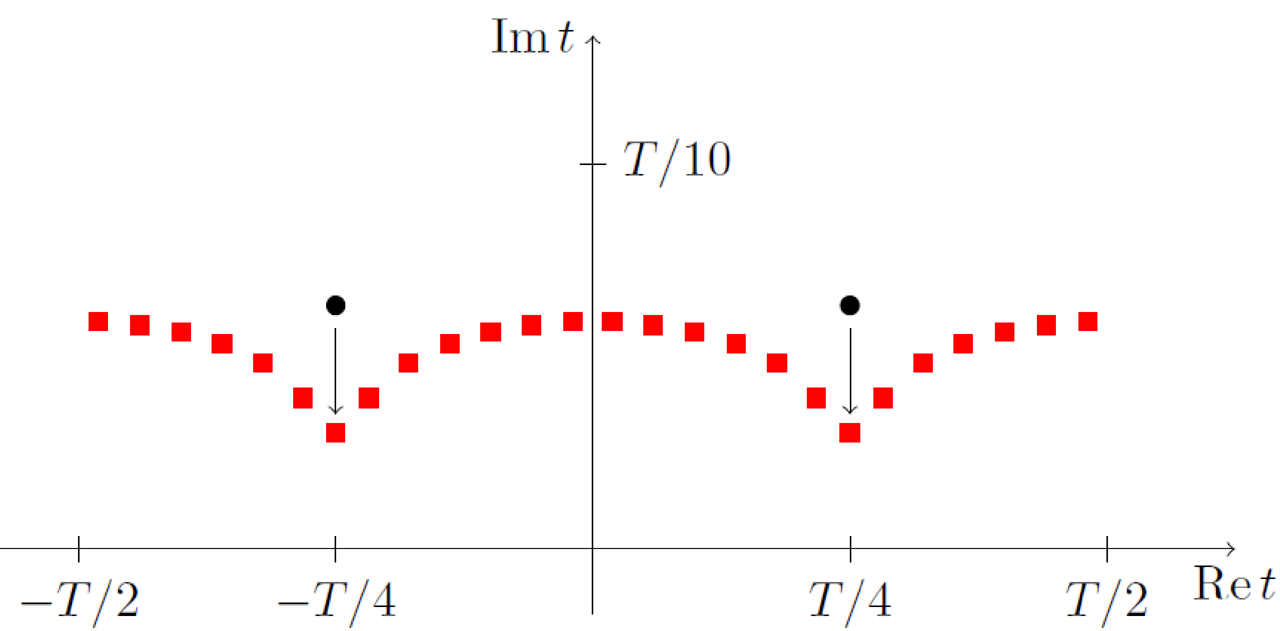
flat-top time

details of Fourier coeff.



one field

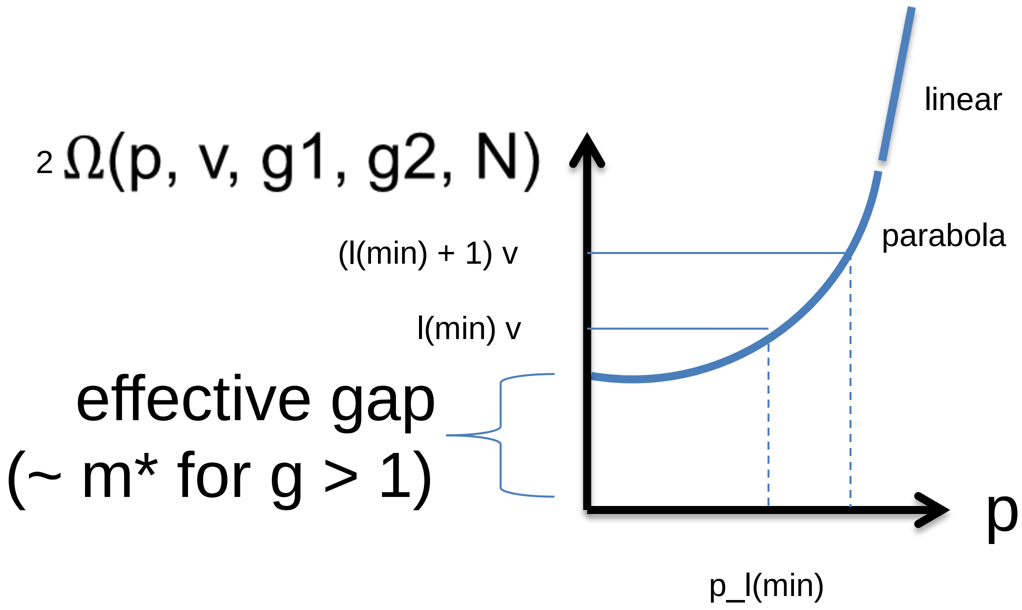
● = zeroes of $\boldsymbol{\omega}$(t)



two fields

kinematics (shell positions)

$\Omega = Fourier\ zero\ mode\ of\ \omega$



slow strong field: g1 < 1
dominates

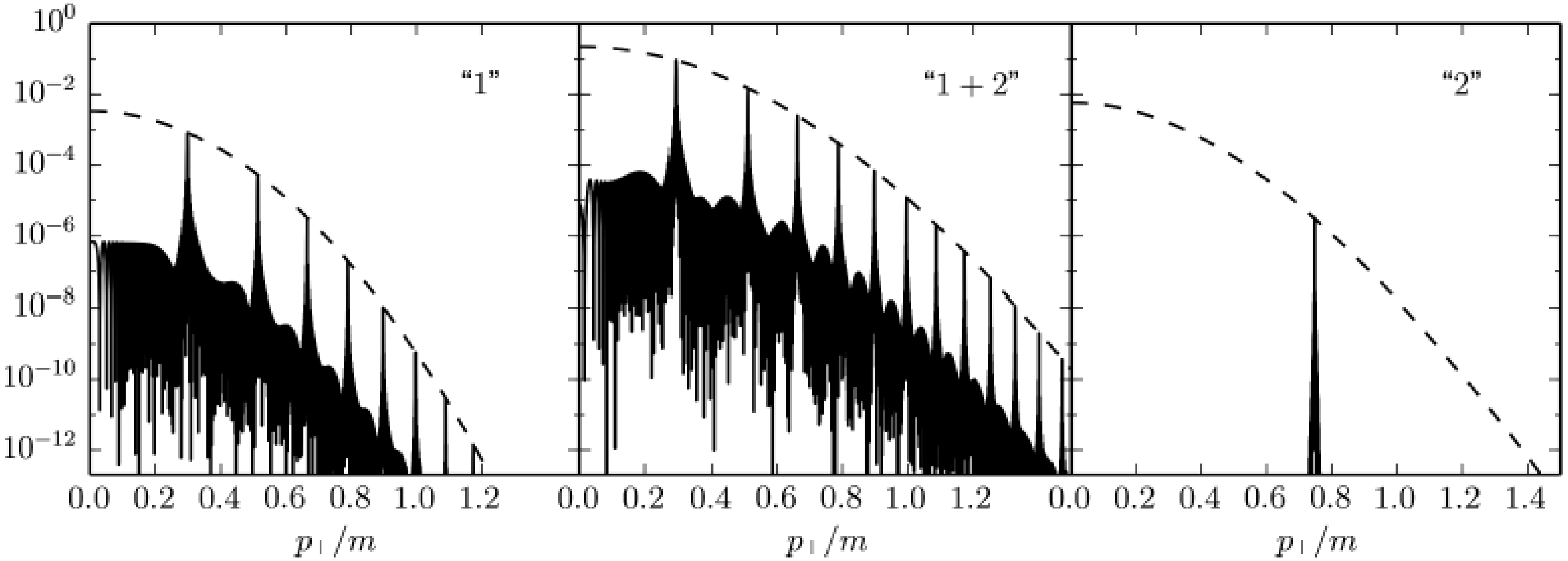
fast weak field: g2 > 2
corrections

analog to channel closing in ATI

increasing E1 or E2 or both → up-shift of parabola

Popov (1973, 1974): 1 periodic field

defining the spectral envelope ------------



---------- at p = 0: a good guidance

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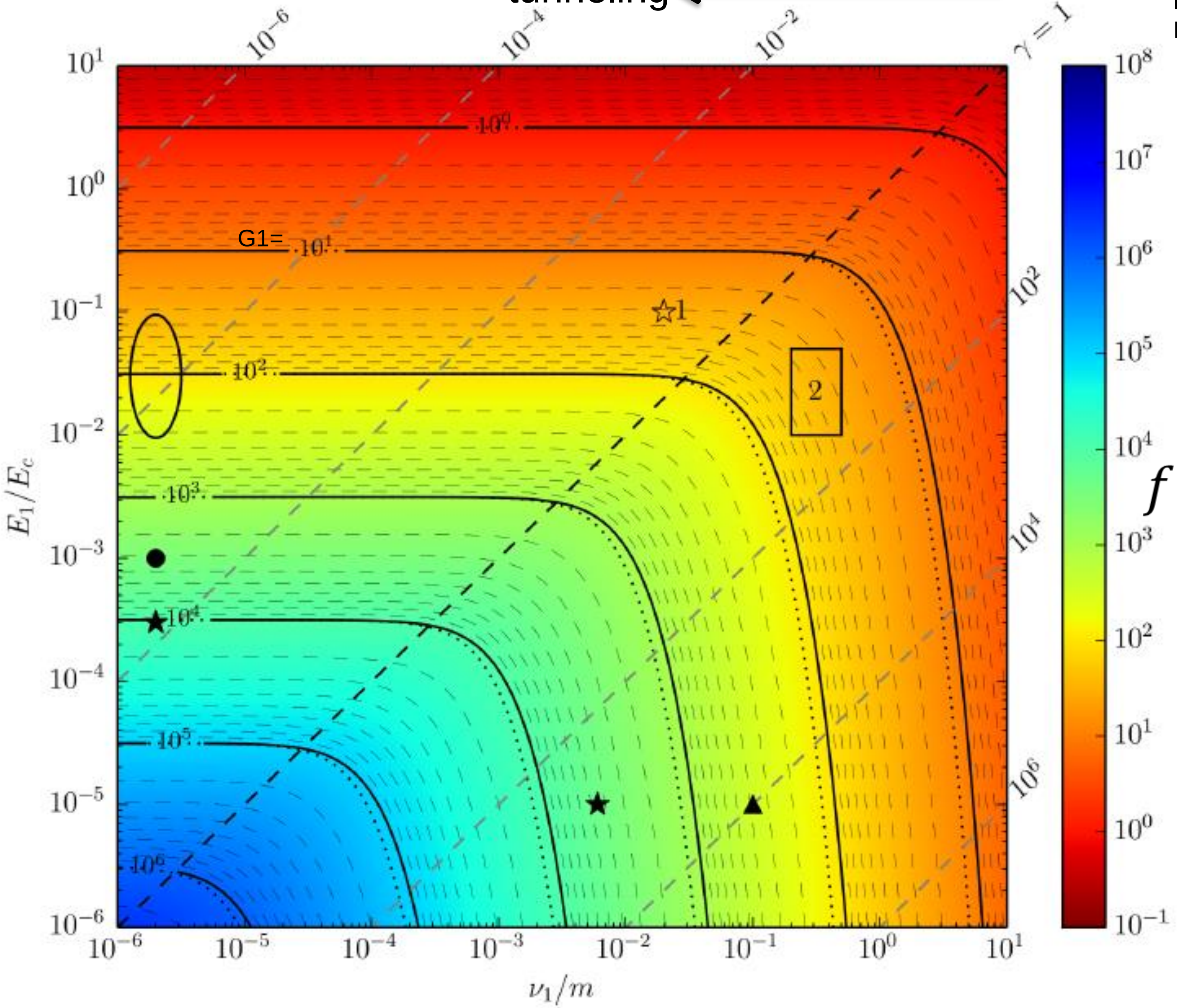
tunneling

naming scheme:
Brezin, Itzykson 1970

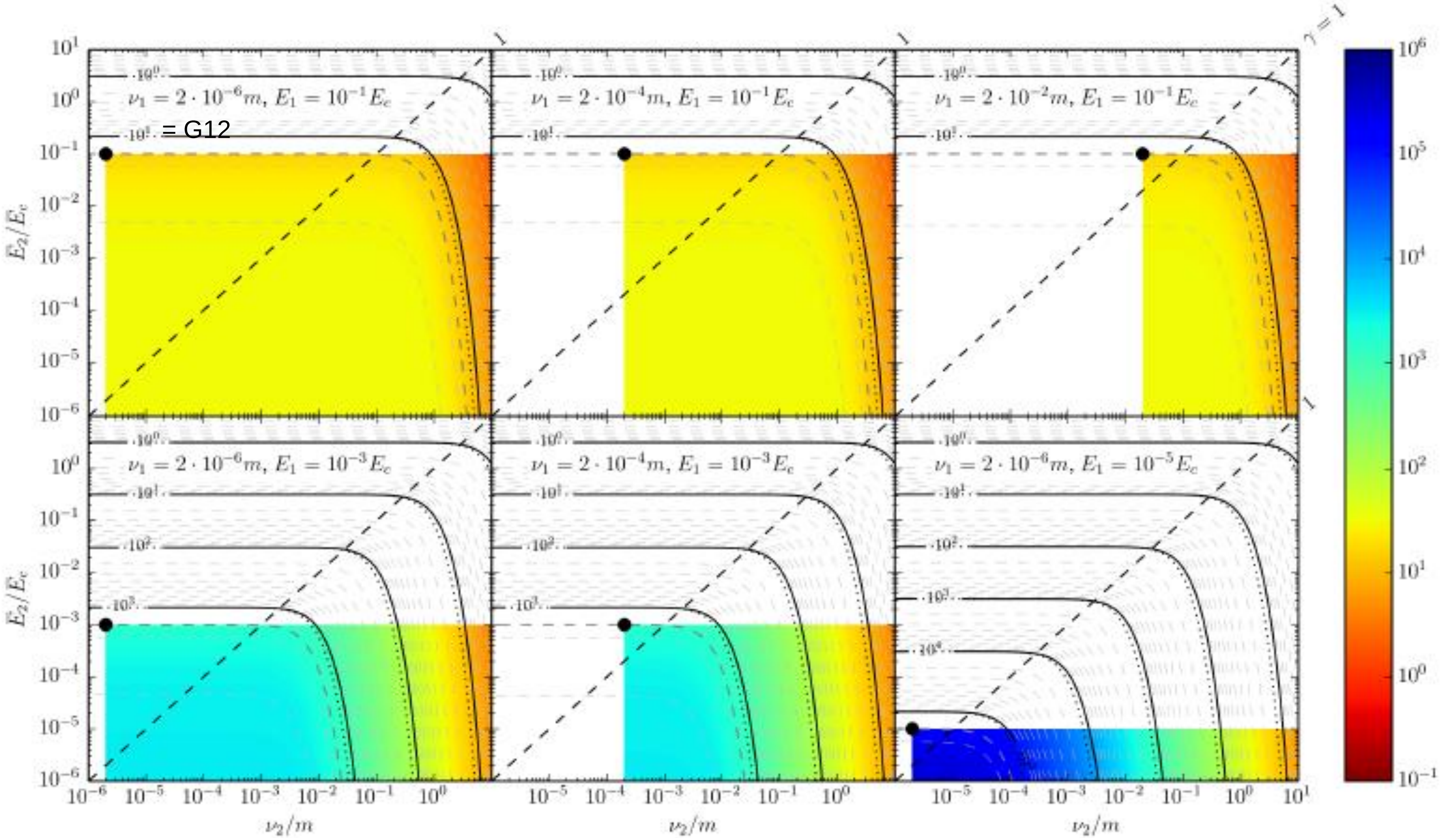


multi-photon

$$f \sim e^{-\#\, G1}$$

envelope

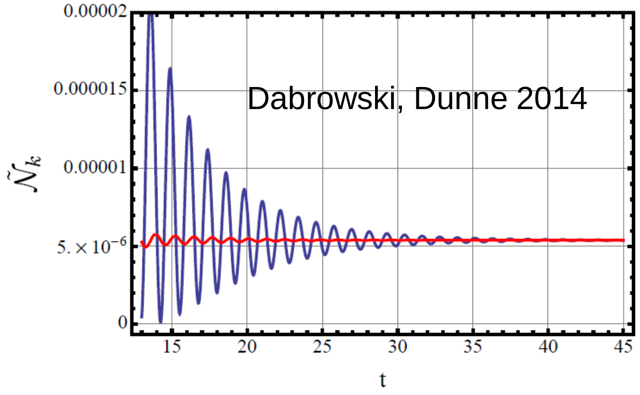
$$\gamma = \frac{E_c}{E}\,\frac{\omega}{m}$$

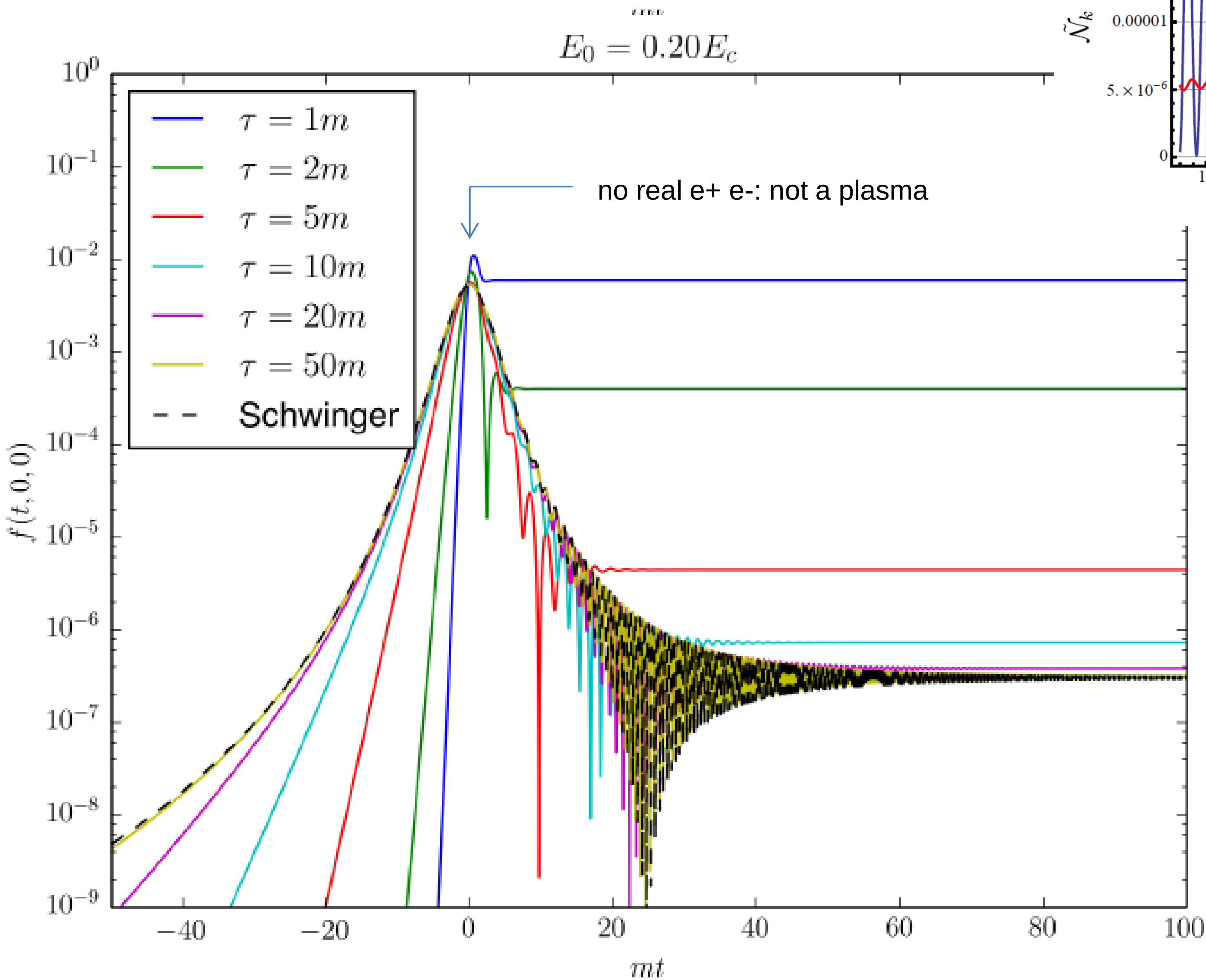


envelope of f ~ exp{ - # G12}

Dynamics (disclaimer: only t → infty is relevant)

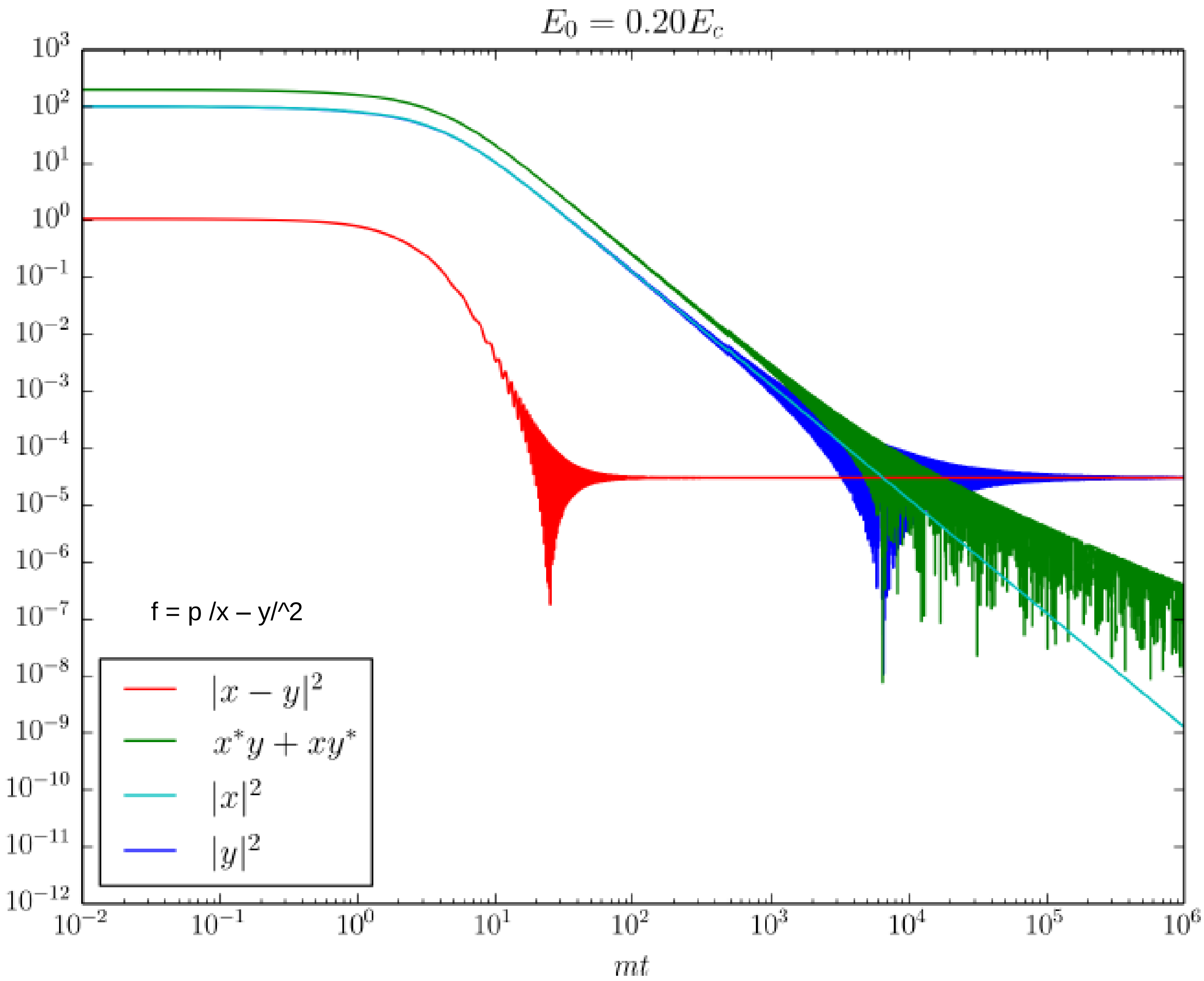
Sauter → Schwinger





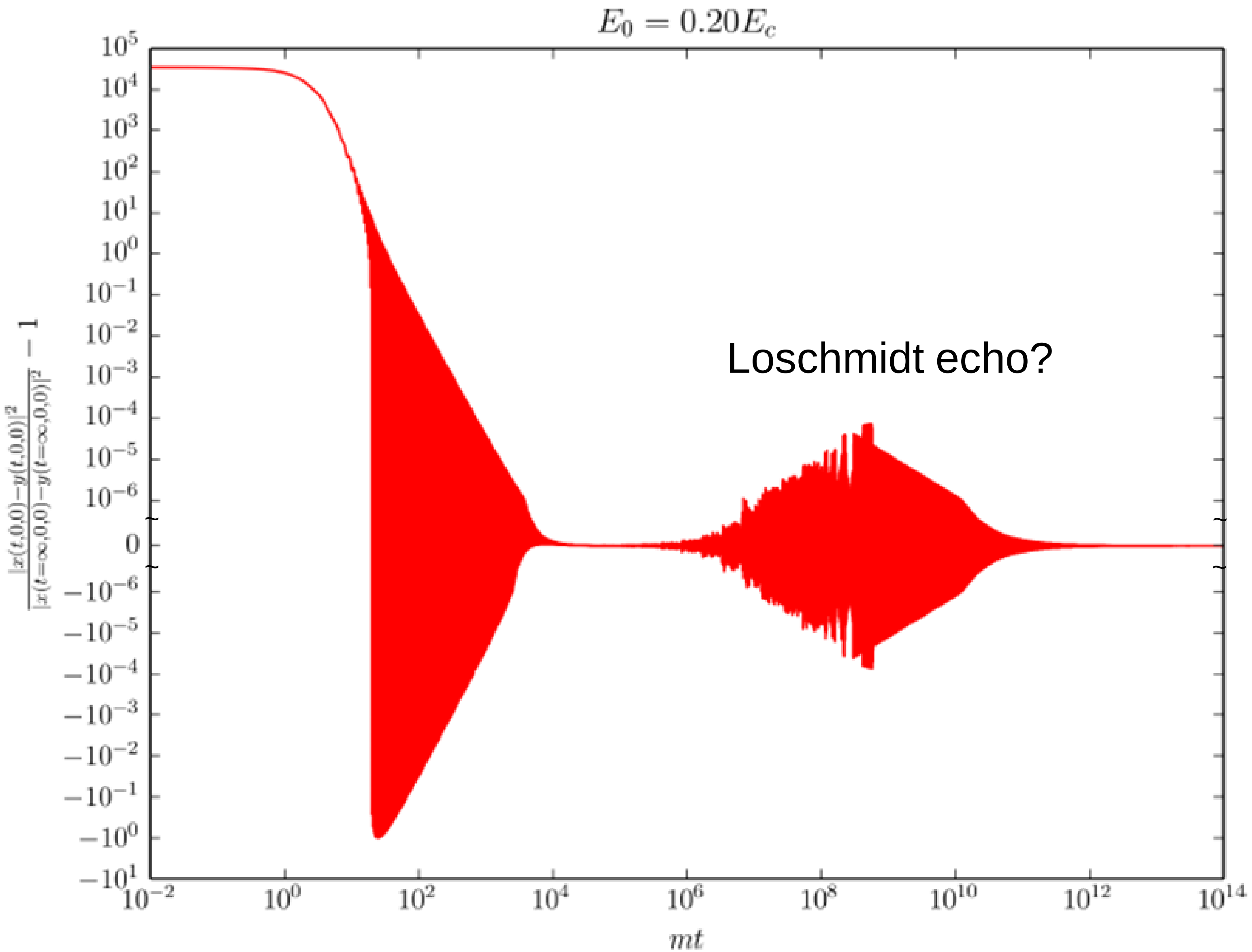
exact solutions:
Narozhny, Nikishov 1974
Hebenstreit 2011

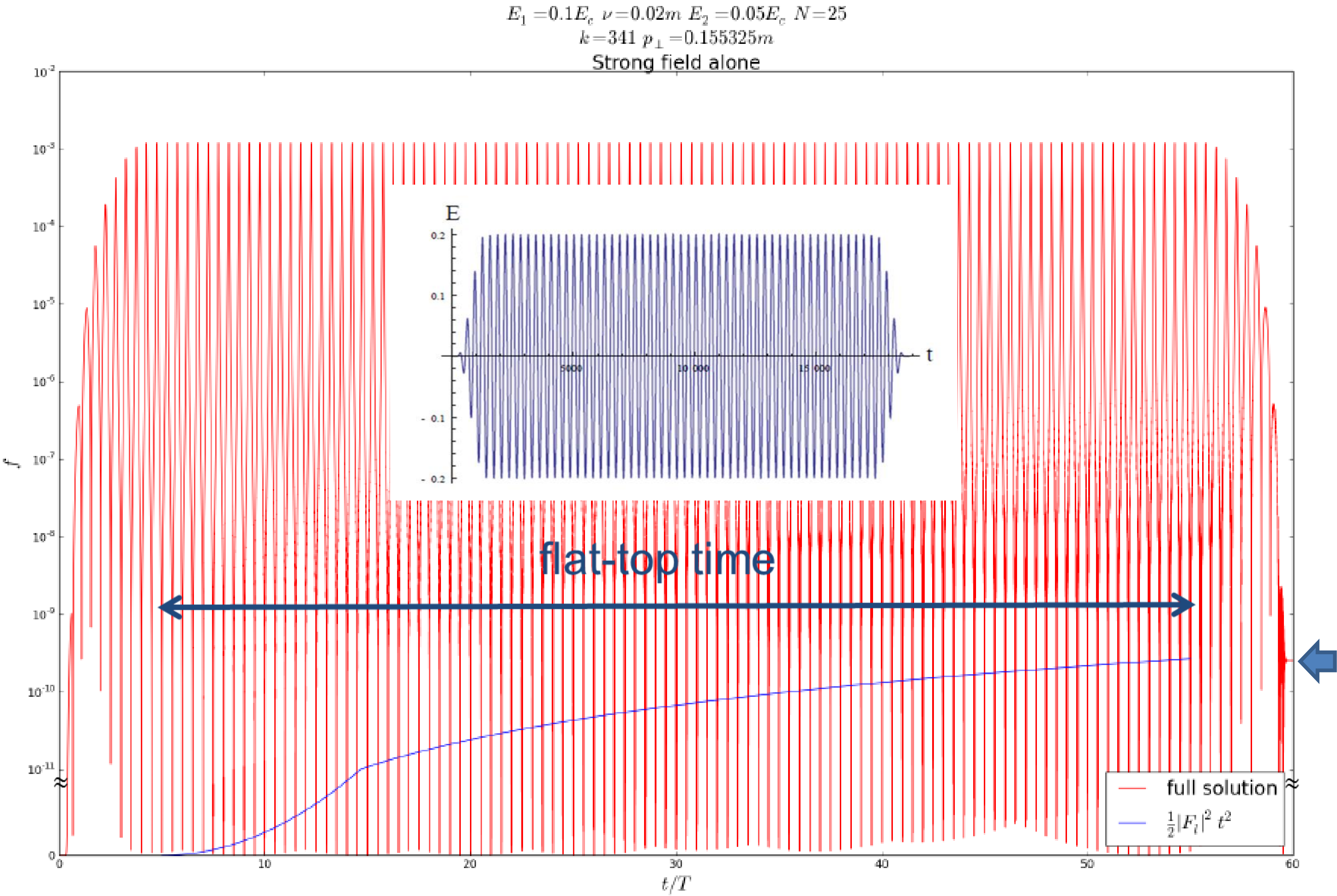
Schwinger



f = p /x – y/^2

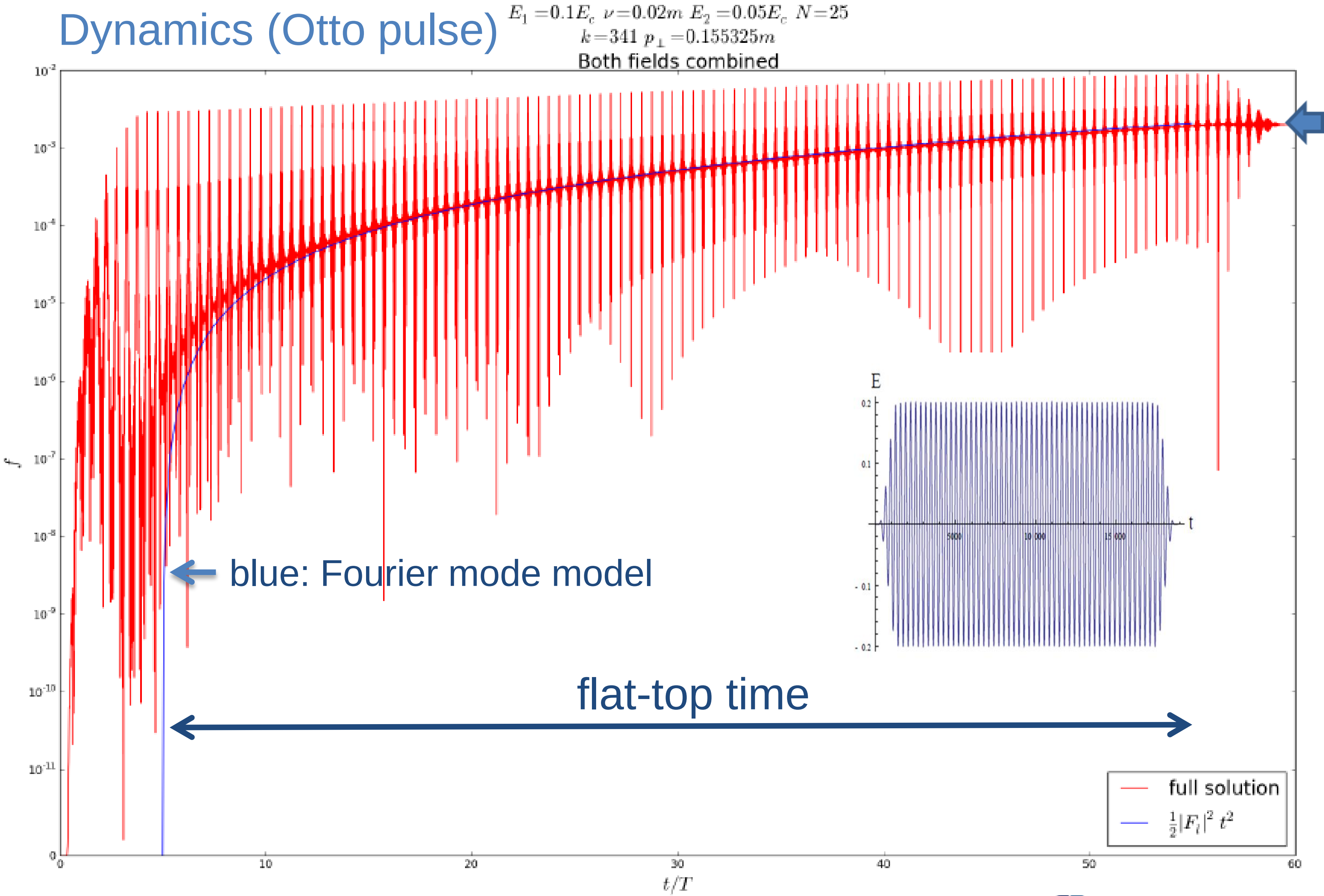
Schwinger: long-term evolution



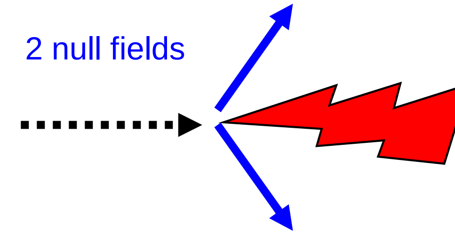


Dabrowski, Dunne (2014): transient f(t) depends on basis

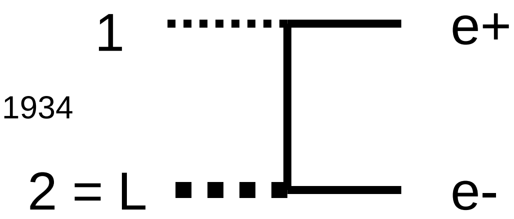
Dynamics (Otto pulse)



2. Breit-Wheeler and Beyond



Berit, Wheeler 1934

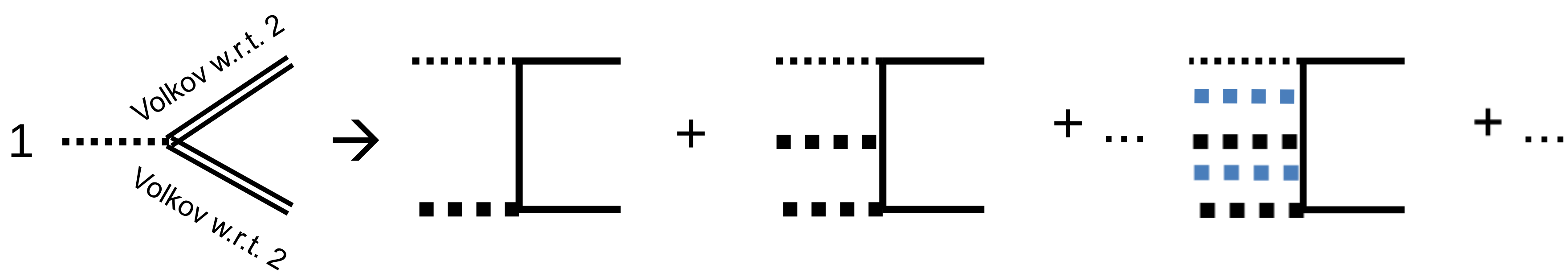


2 → 2: s, t
crossing of Compton
time reversed annihilation

Mandelstam: $s = 2\omega_1\omega_L(1 - \cos\Theta_{\vec{k}_1\vec{k}_L})$

threshold: $s_{th} = 4\,m^2 \rightarrow \sigma_{BW}\,(\,s < s_{th}\,) = 0$

sub-threshold pair production: non-linear BW (multi-photon) Nikishov, Ritus > 1960



sQED (Furry) Breit-Wheeler n.l. Breit-Wheeler/higher harmonics

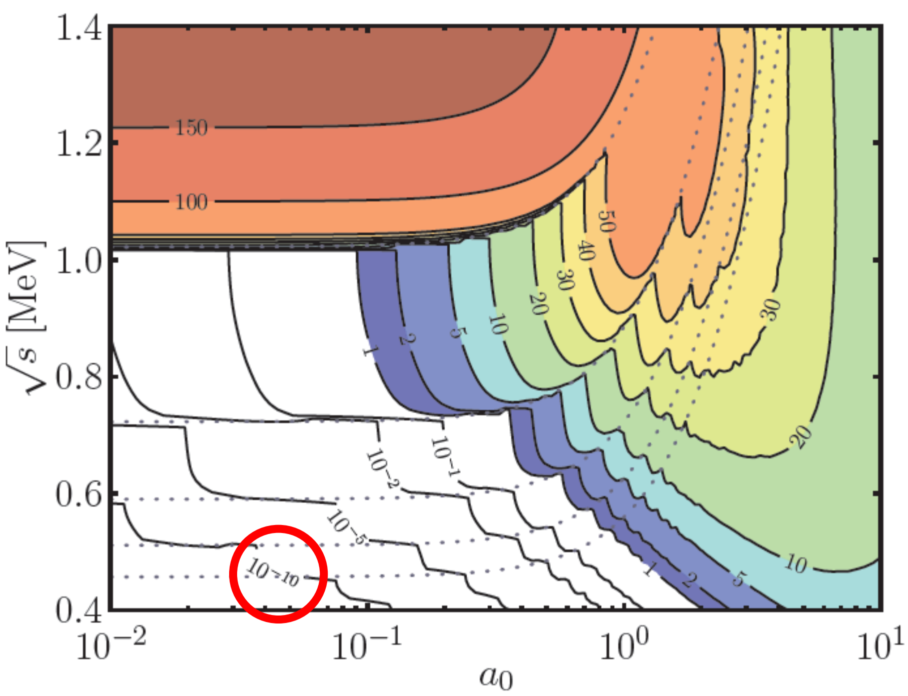
emphasis on short pulses & intensity effects:
Nousch, Seipt, BK, Titov PLB (2012), Titov, Takabe, BK, Hosaka PRL (2012), PRA (2013)

Pair Production in Ultra-Short Laser Pulses

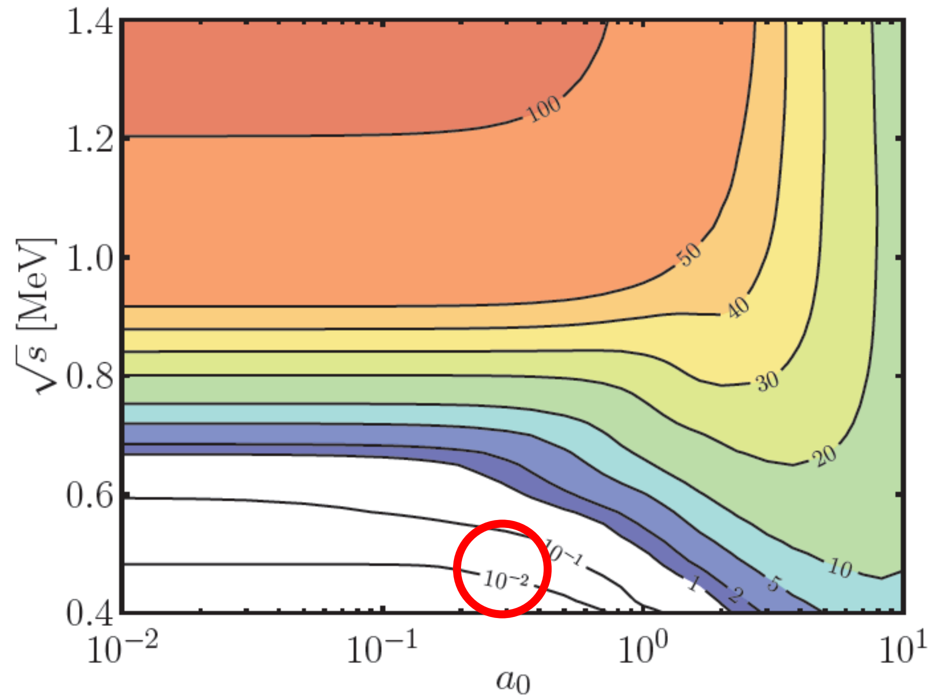
lin. polarization, sigma [mb]

pulse shape: $g(\varphi) = cos^2(\varphi/2\,N)$

IPA

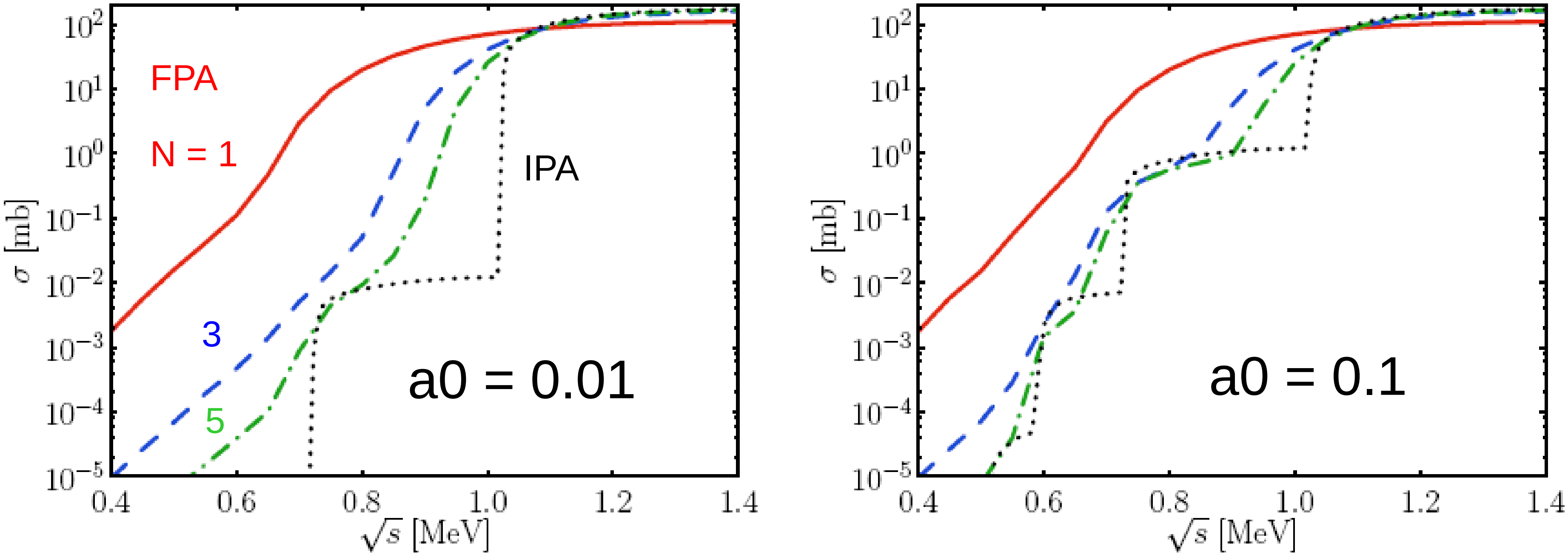


FPA, N = 1



Nousch, Seipt, BK, Titov PLB (2012), Titov, Takabe, BK, Hosaka PRL (2012)

N dependence



harmonics & finite bandwidth effects →

$\omega = \omega_L \pm \Delta$

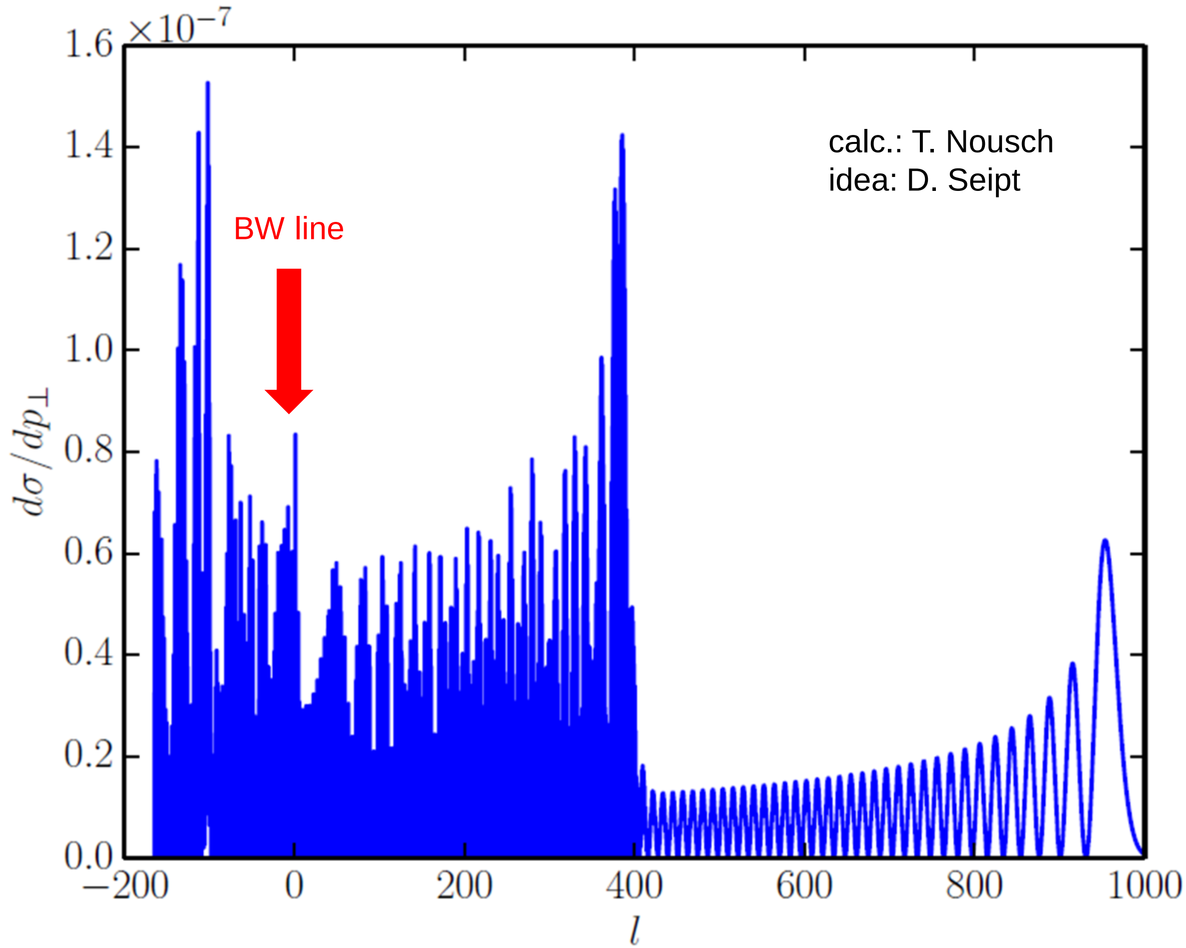
laser enabled subthreshold production

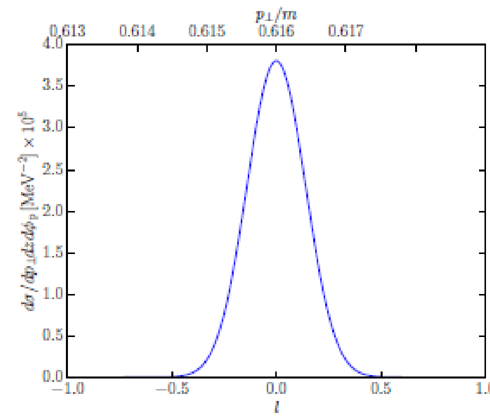
Seipt, BK, PLB 2012: folding model(s) - intensity vs. frequency variation → spectrum

laser assisted Breit-Wheeler process

work in progress (T. Nousch):

IPA: Jansen, Muller (2013), Wu, Xue (2014)



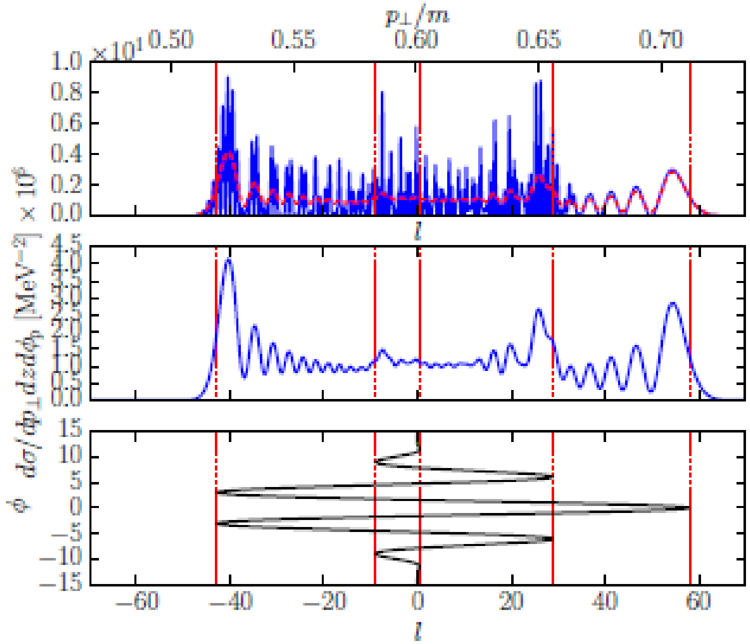


w/o laser

caustics = stat. phase points
(quasi-class. motion after creation
with interferences)

redistribution in phase space by FSI

(analog to Meuren etal. 201 5)

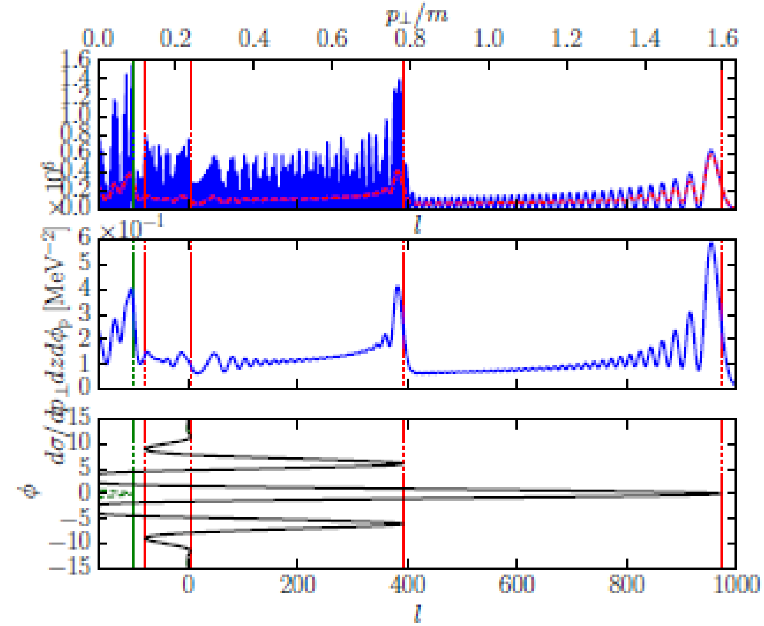


(a) $\tau = 4\pi$

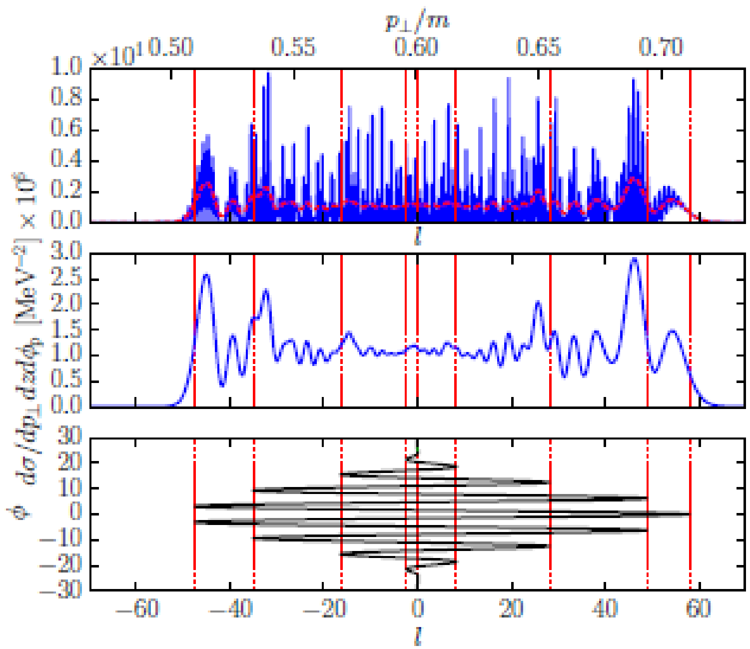
T = 4 π

a0 =0.1

a0 = 1

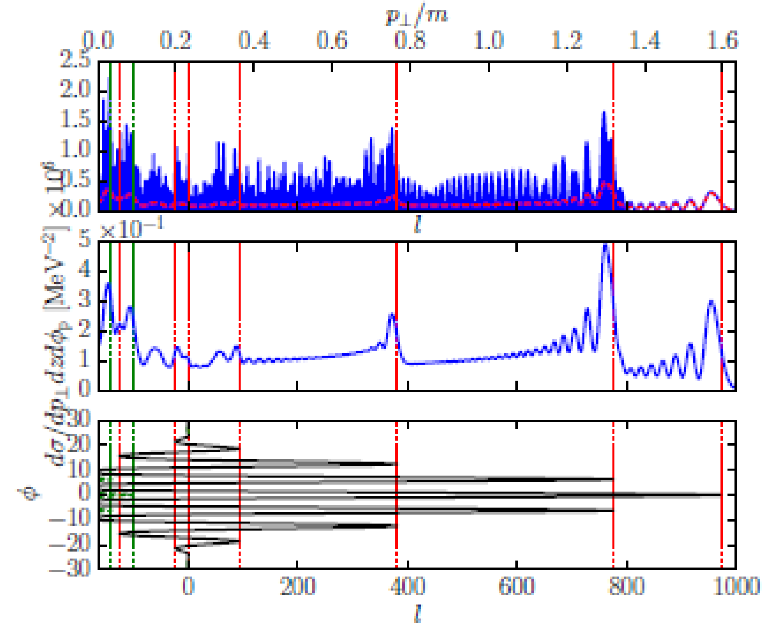


(a) $\tau = 4\pi$



(b) $\tau = 8\pi$

T = 8 π



(b) $\tau = 8\pi$

Summary

pairs = particles & anti-particles (anti-matter)

Schwinger: conditions for stark assistance by 2nd field

Breit-Wheeler: sub-threshold, pulse length, pulse shape, intensity,
assistance by 2nd field (spectral caustics)

*e*lementary processes – prospects for laser matter interaction

Compton: ultra-short pulses, probing multi-photon effects

laser-assisted scattering of x-rays: Seipt, BK PRA (2014)
entangled 2-photon emission: Seipt, BK PRD (2012)

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