Particle Production in High-Intensity Lasers*)

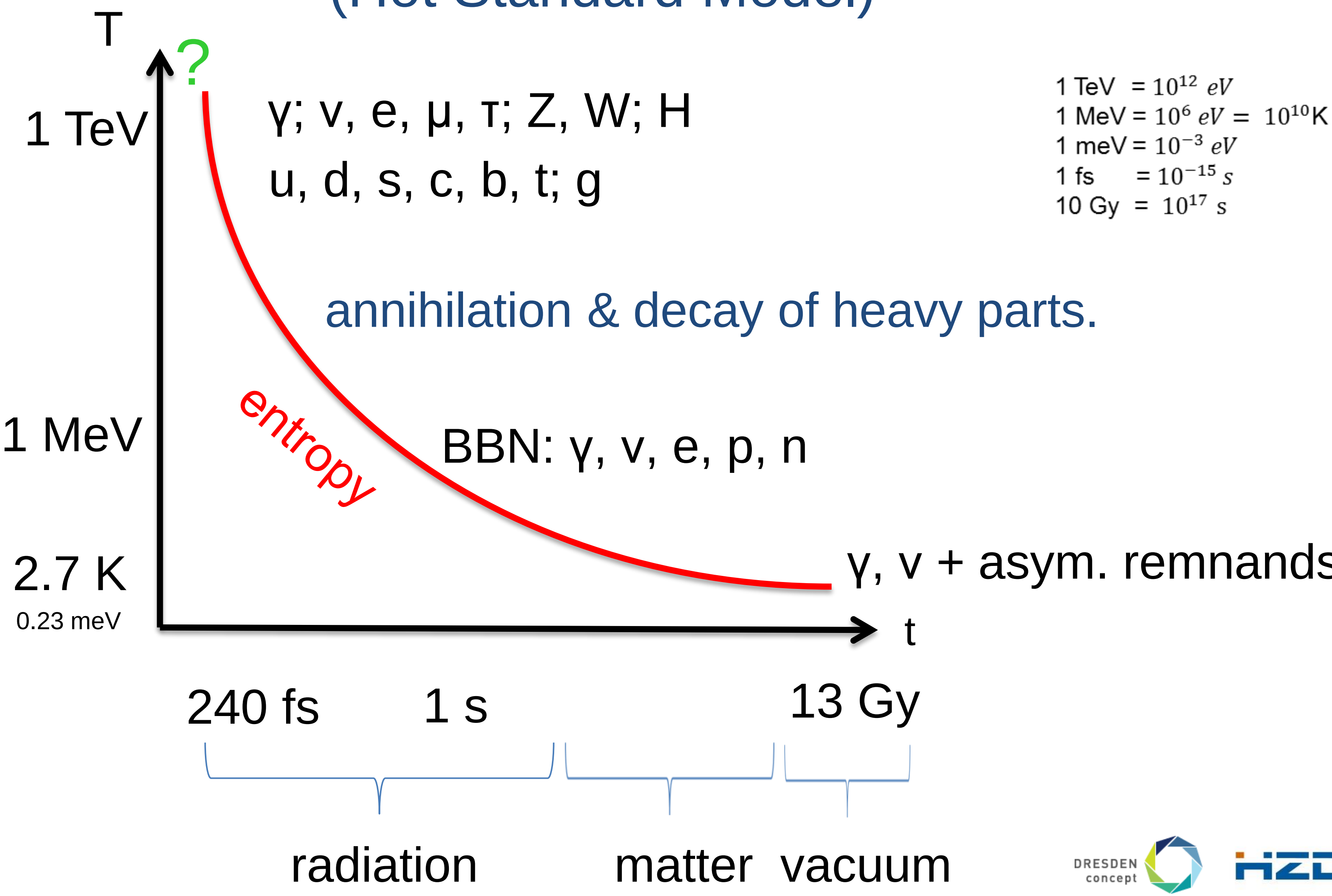
B. Kämpfer

Helmholtz-Zentrum Dresden-Rossendorf
Technische Universität Dresden

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)

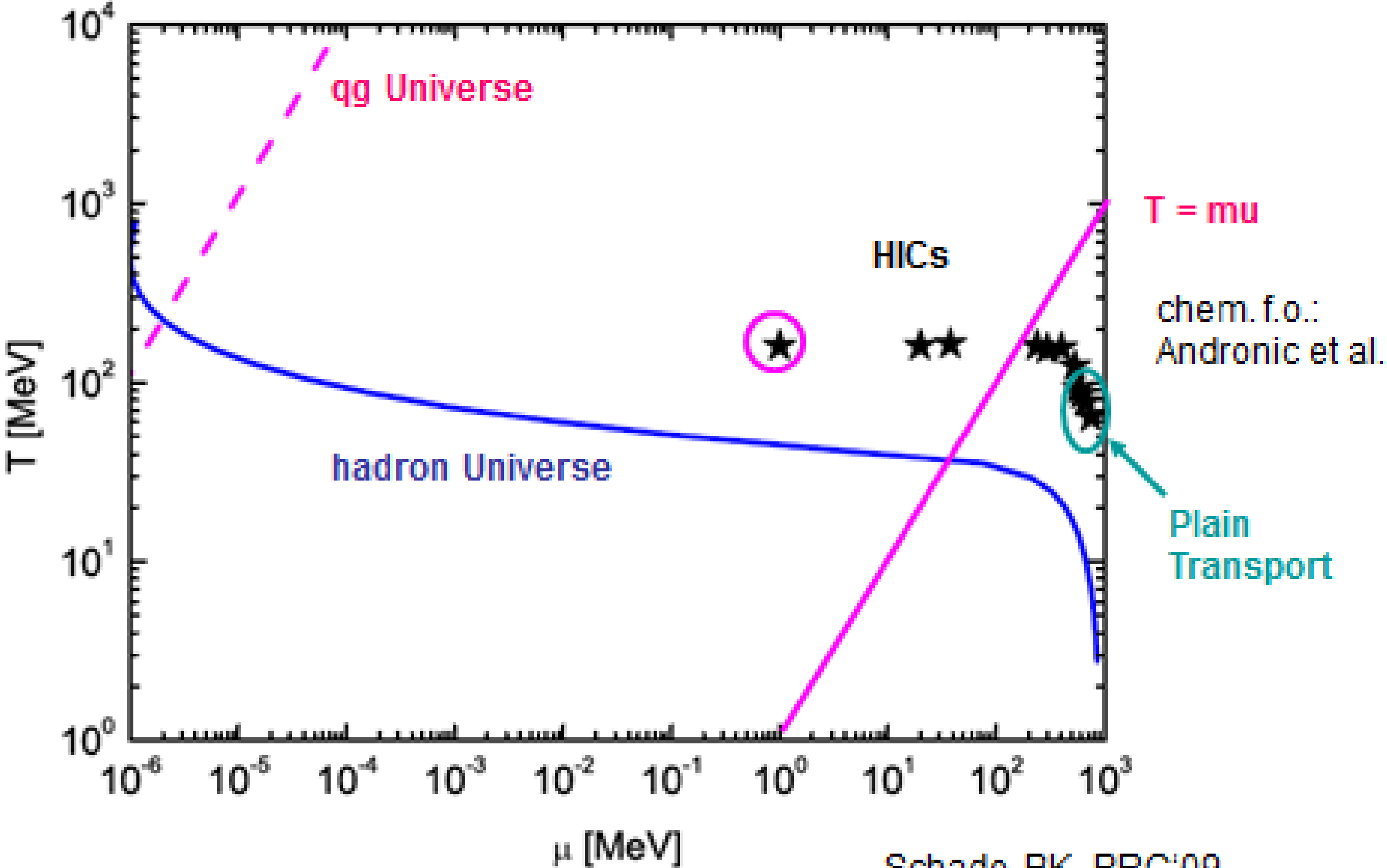
Particle Destruction in the Universe (Hot Standard Model)



1 TeV $= 10^{12}\ eV$
1 MeV $= 10^{6}\ eV = 10^{10}$K
1 meV $= 10^{-3}\ eV$
1 fs $= 10^{-15}\ s$
10 Gy $= 10^{17}\ s$

Disapparence of Anti-Matter in the Universe

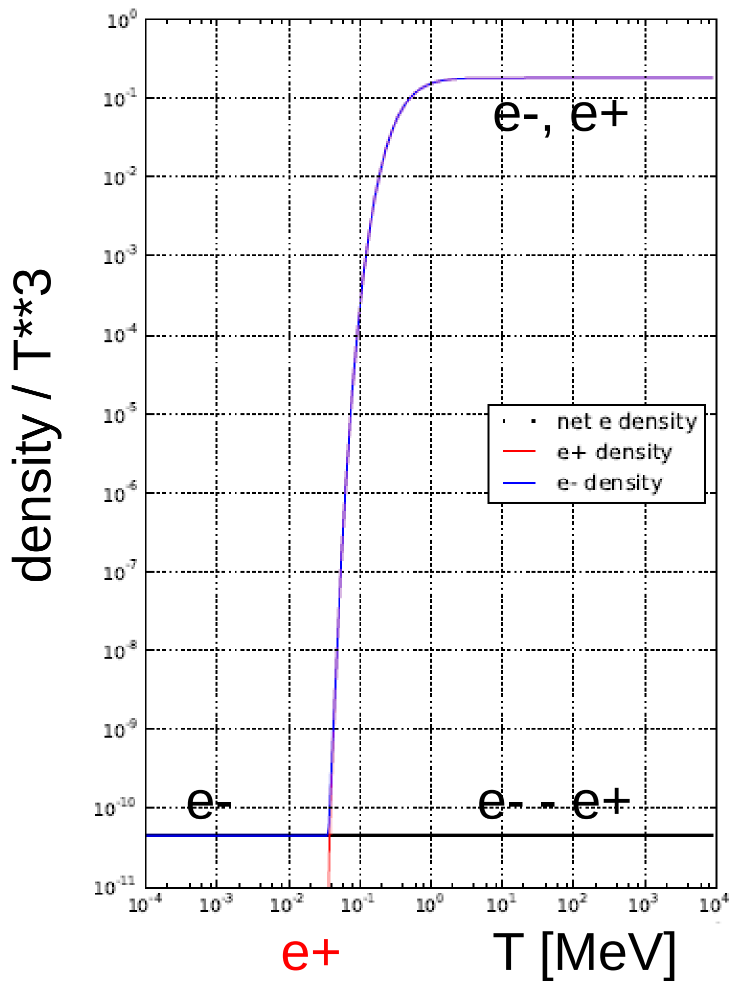
(i) T ~ 40 MeV: annihilation of anti-nucleons **cosmic swing**

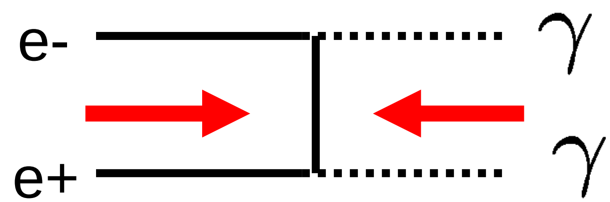


Schade, BK, PRC'09

Disapparence of Anti-Matter in the Universe

(ii) T ~0.5 MeV: annihilation of positrons





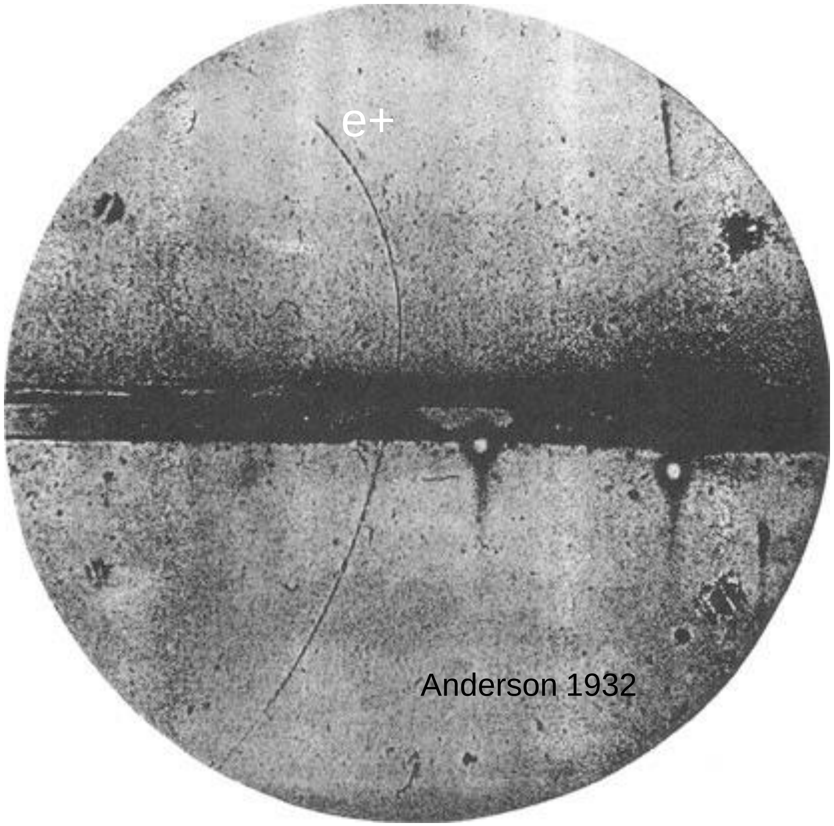
t ~ 15 s, T ~ 3 x 10^9 K

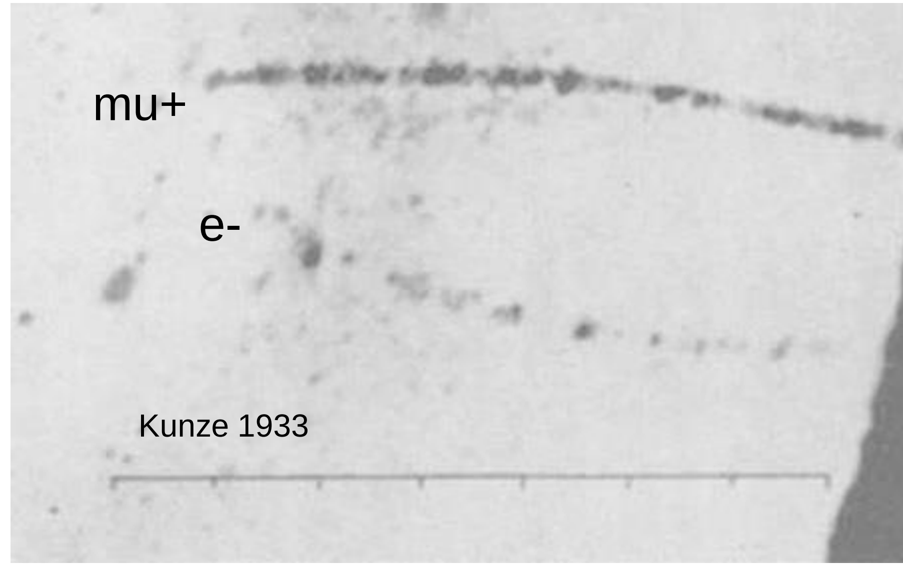
from $\eta = 10^{-10}$
and charge neutrality

mystery: high-energy e+ from AMS

13 Gy later: discoveries of the positron

first detection:Skobelzin 1929



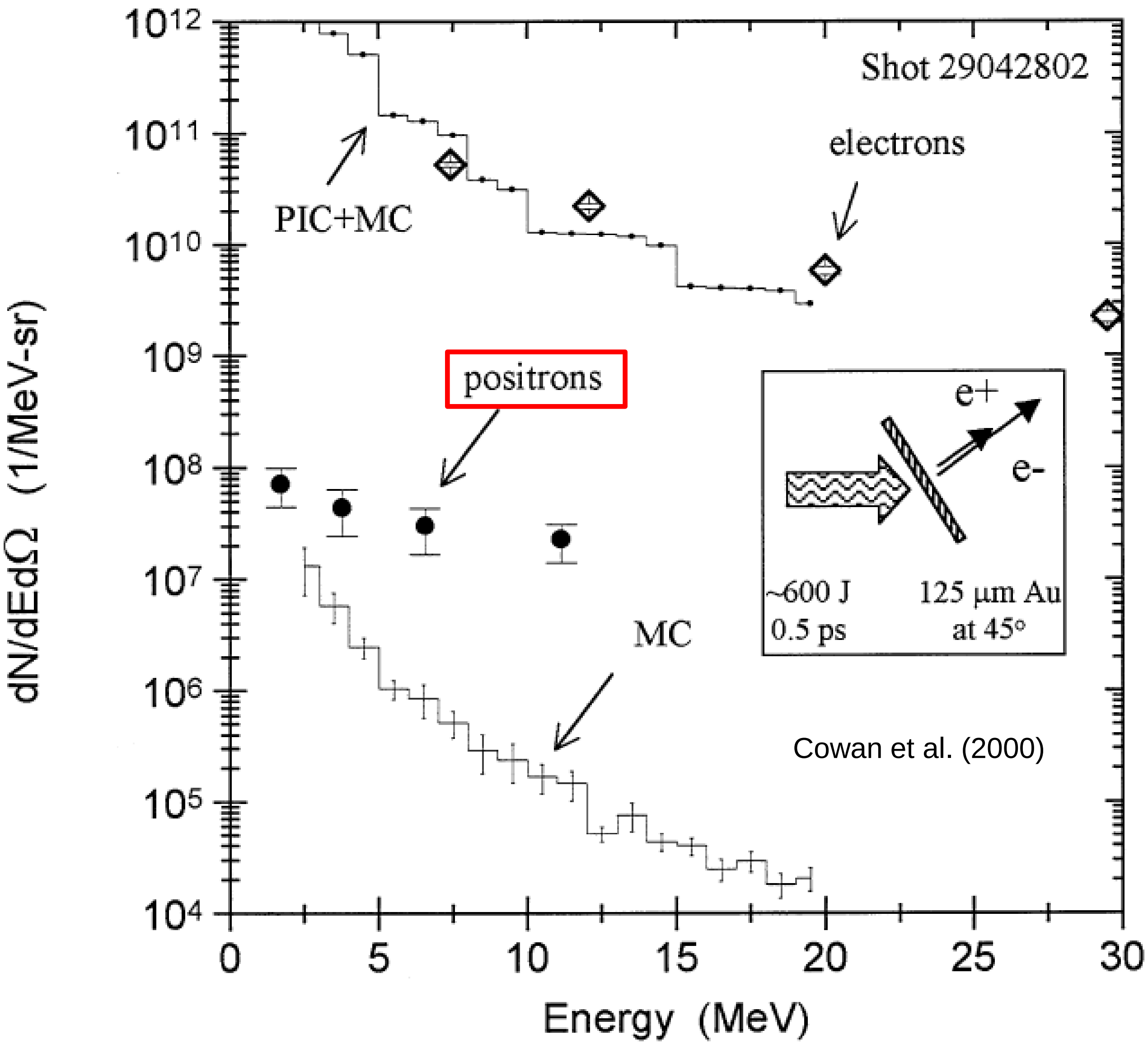


Dirac (1928): e+ and e-

Matter & Antimatter

Laser-Matter Interaction → Antimatter

Cowan et al. (1999): using Nova at LLNL



Engines of Particle Production

gravity: R(t) in expanding universe; tunneling from vacuum

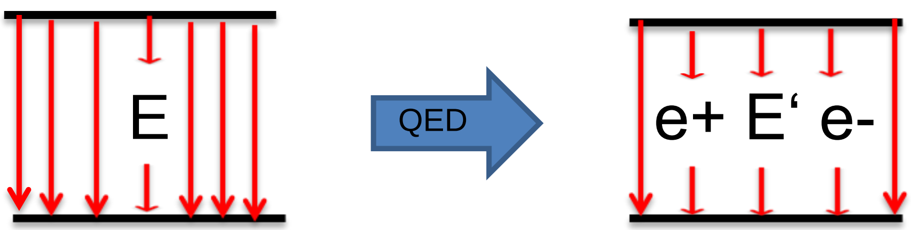
…, Baseler, BK (1988)

chiral mass shift: m(t) from strong interact.

Michler, Greiner (2013)

electric field: A ~ t, E = const

Schwinger (1951), Sauter (1931)



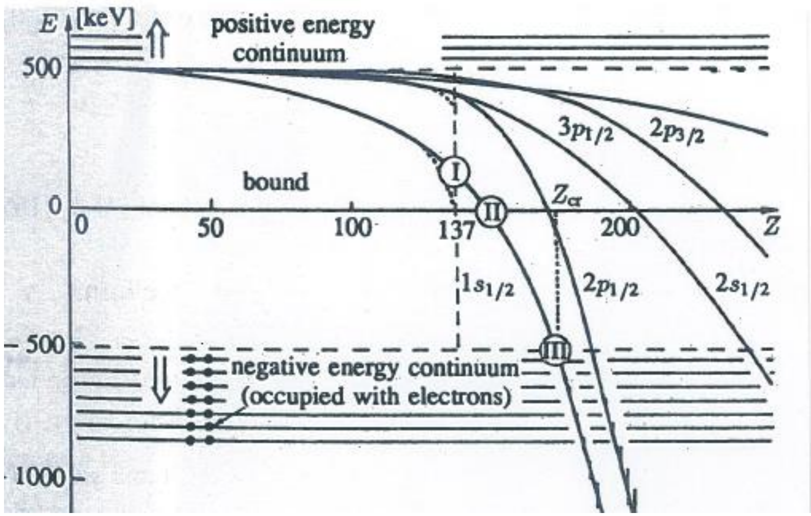
decay of the vacuum

alternating e.m. field (laser): dyn. Schwinger effect

Brezin, Itzykson (1970)

super-critical fields

Greiner et al. (> 1970)



E(R) = Ze /R^2

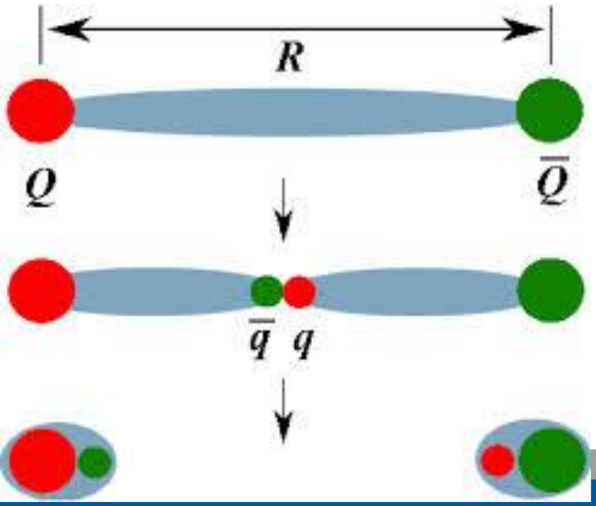
~ 2000 Ec for Uranium

vacuum breakdown

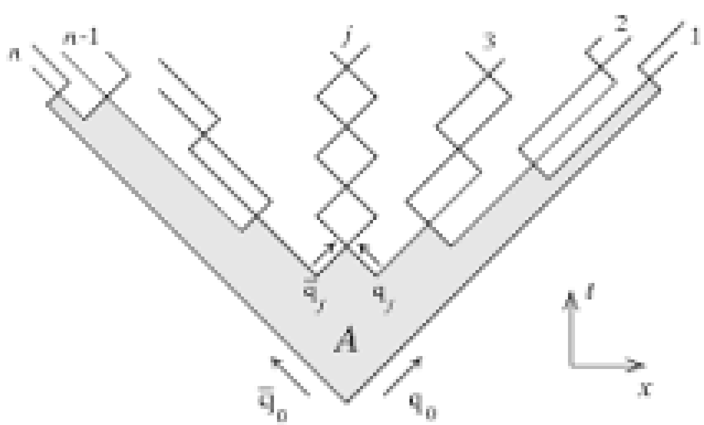
Lund string model: hadron production

Casher, Neuberger, Nussimov (1979)
Andersson et al. (1977)

string breaking



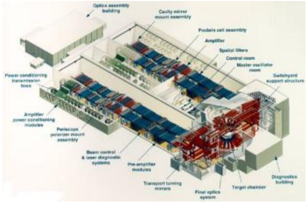
yo-yo

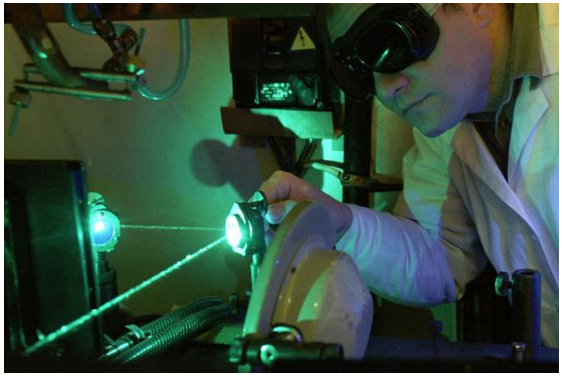


task: recreation of anti-matter (by lasers)

1. (optical) laser facilities

ultra-intensity: projects = ELI, HiPER, IZEST, …,
high-energy: NIF, XCELS/Sarov/Nishni Nowgorod





Helmholtz (Dresden-Rossendorf): Draco, Penelope

150 TW / PW Ti:Saphir Laser

optical photons: O(1 eV)

Texas Petawatt Laser

pulse containes186 J of energy, 167 fs in duration
based on optical parametric chirped pulse amplification
and mixed Nd:glass amplification. (2008)

POLARIS in HIJ

Visions: ILE appolon $10^{24}\,\frac{W}{cm^2}$ from 10 PW
HiPER 10^{26} W/cm^2 from 100 PW

Member of the Helmholtz Association
B. Kampfer I Institute of Radiation Physics I www.hzdr.de

2. XFELs x-ray photons: O(1-10 keV)

LCLS, SACLA, Europ. XFEL @ Desy (Helmholtz), …

LCLS (former SLAC)

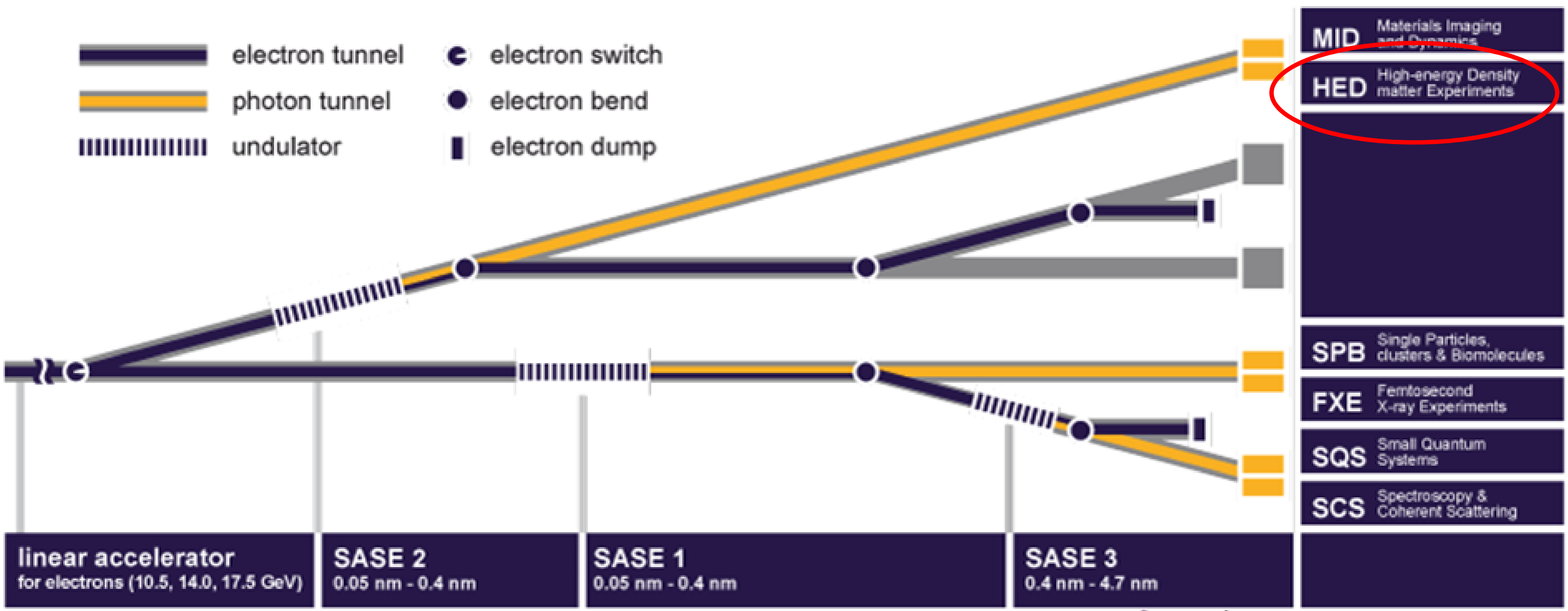
European XFEL in Hamburg/Desy

Total length	3.4 kilometres	The facility will run from the DESY site in Hamburg in a northwestern direction to the border of the town of Schenefeld (Schleswig-Holstein).
Number of sites	3	The three sites are: DESY-Bahrenfeld (ca. 2 hectares), Osdorfer Born (ca. 1.5 hectares) and Schenefeld (ca. 15 hectares). The research campus will be located in Schenefeld.
Depth of the tunnels	6 to 38 metres	The tunnels are covered by at least 6 metres of soil.
Construction costs including preparation and commissioning	1.15 billion euro (price levels of 2005)	As the host country, Germany (Federation, Hamburg, and Schleswig-Holstein) covers 58% of the construction costs. Russia takes over 27% and the other international partners between 1% and 3% of the construction costs each.

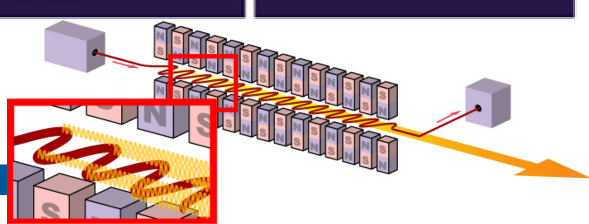
The European XFEL will provide light sources (beamlines) for X-ray flashes with different properties.

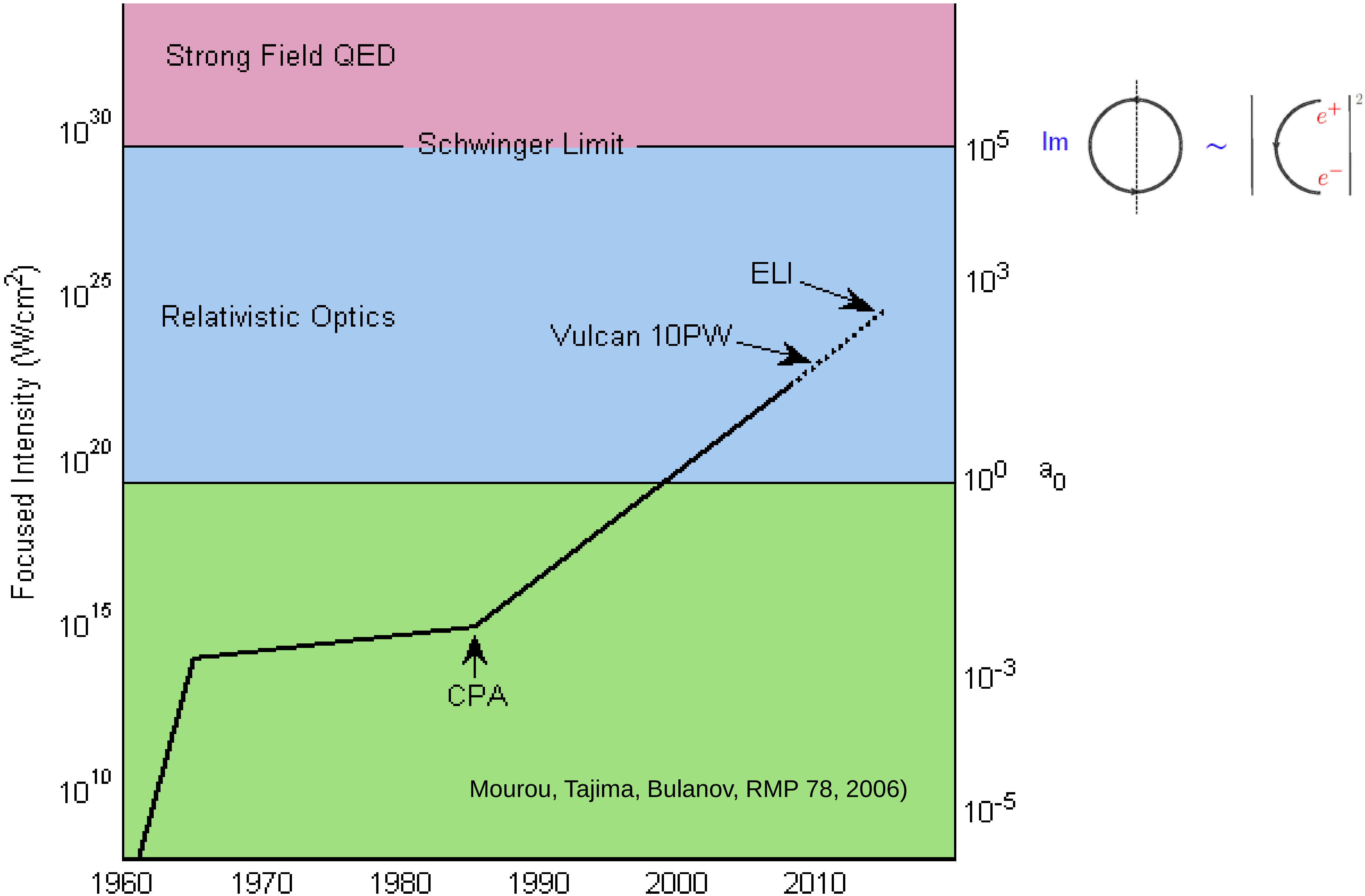
When electron bunches are induced to follow a slalom course in the magnet arrangements – the so-called undulators – of the European XFEL, they emit flashes of X-ray radiation. The European XFEL will comprise different undulators, i.e. different light sources providing X-ray flashes with different properties.

HIBEF collab.:
400 members
(lead inst.: HZDR)



sase = Self Amplified Spontaneous Emission




Strong Field QED
Schwinger Limit
Relativistic Optics
ELI
Vulcan 10PW
CPA
Mourou, Tajima, Bulanov, RMP 78, 2006)
Focused Intensity (W/cm2)
10^30
10^25
10^20
10^15
10^10
1960
1970
1980
1990
2000
2010
10^5
10^3
10^0
10^-3
10^-5
a0
Im
~
e+
e−
2

$$a_0 = \frac{ea}{m} = \eta/2 = \xi$$

$$A = a g(\phi)(\epsilon_1 \cos\phi + \epsilon_2 \sin\phi)$$

circc. pol.

$\Phi = k.x + \Psi$

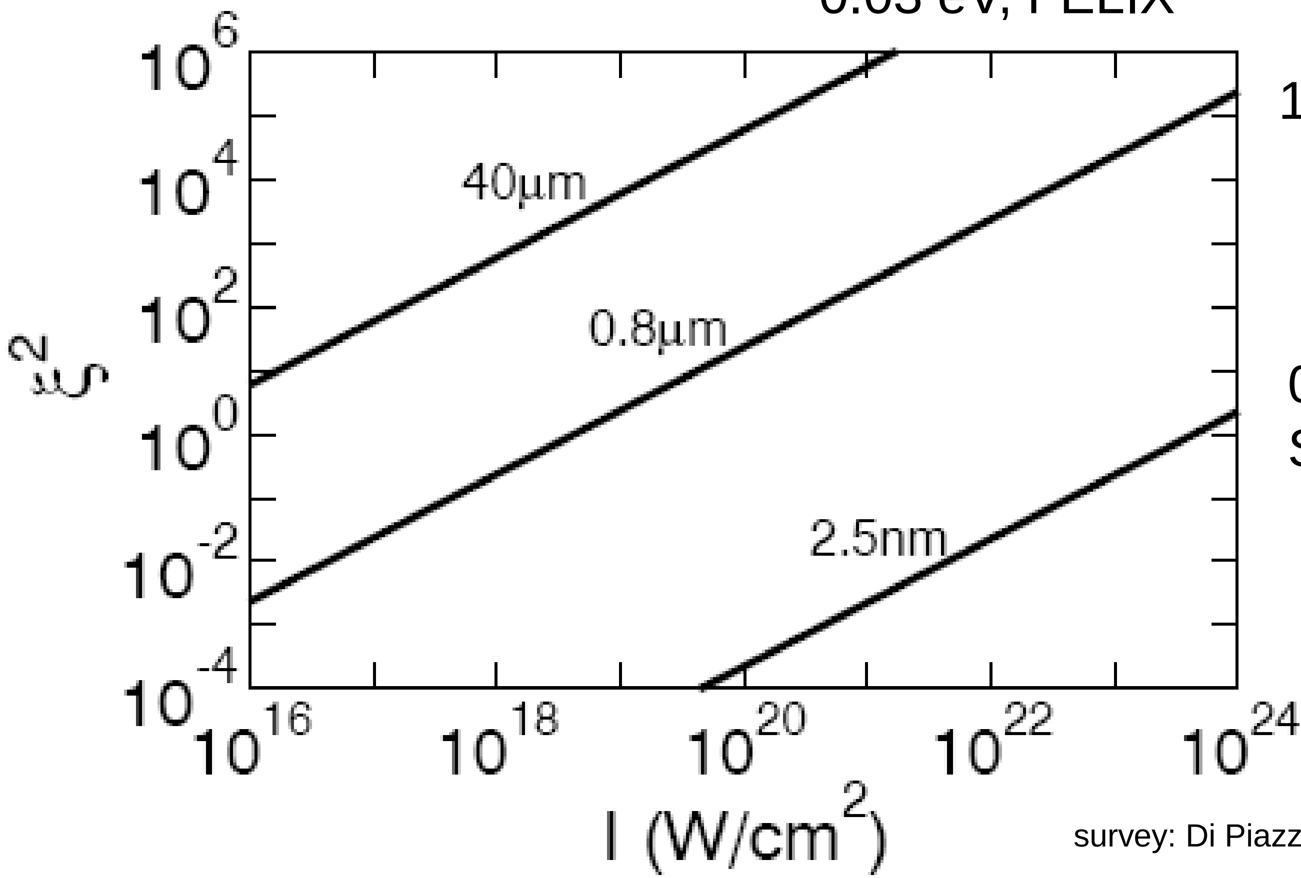
$k.x = \omega t - KX$

$$m^* = m\sqrt{1+\xi^2}$$

0.03 eV, FELIX

1.55 eV, Ti:Sa

0.5 keV,
SLAC x-ray FEL



survey: Di Piazza et al. Rev. Mod. Phys.2012

Titov, BK, Takabe, Hosaka PRD 2011

$$a_0 = 7.5 \sqrt{I_L \,/\, 10^{20} \frac{W}{cm^2}} \frac{eV}{\omega_L}$$

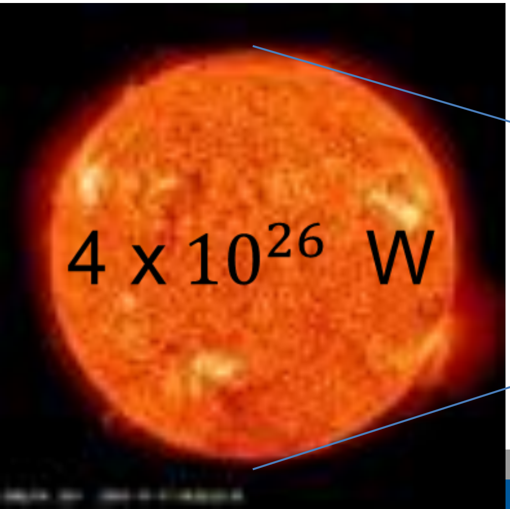
inv. Keldysh parameter:
a0 << 1: weak-field regime → pQED
a0 > 1: strong-field regime → sQED
(Furry picture)

$$\kappa = 6\ 10^{-2} \sqrt{I_L \,/ 10^{20} \frac{W}{cm^2}} \frac{\omega_1}{GeV}$$

Ritus parameter for pair production

2005: the Vulcan laser was the highest-intensity focussed laser producing a Petawatt laser beam with a focused intensity of 10^21 W/cm^2

max. = 10^22 W/cm^2



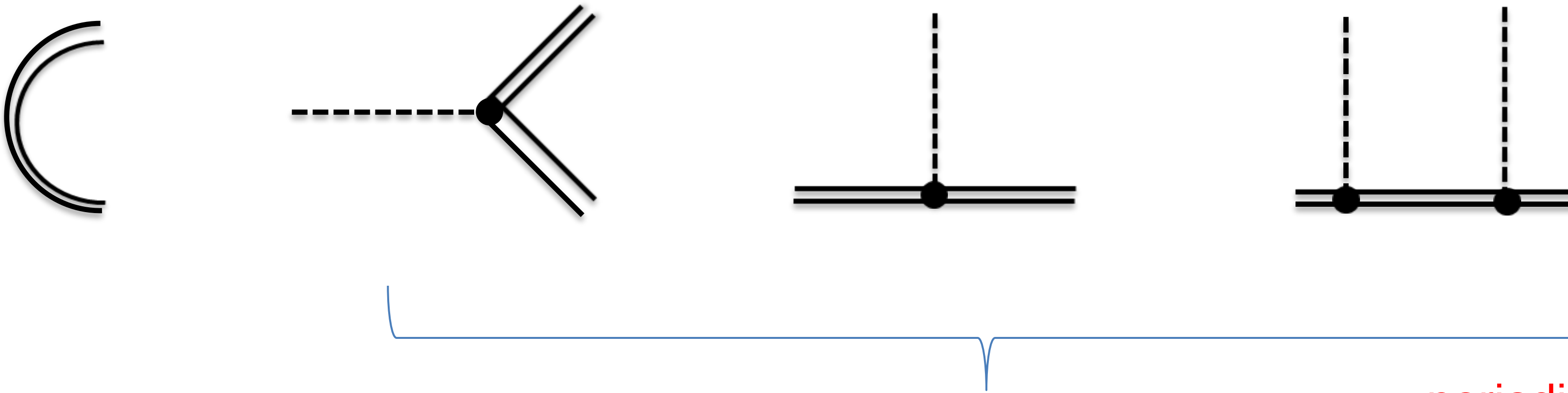
$= 10^{20}\ W/cm^2$

20 m x 20 m

laser beams focussed in space & time

$I_c = 4.3 \times 10^{29}\ W\,/\,cm^2$

§ 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)

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

quantum kinetic eqs.

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

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

η = 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

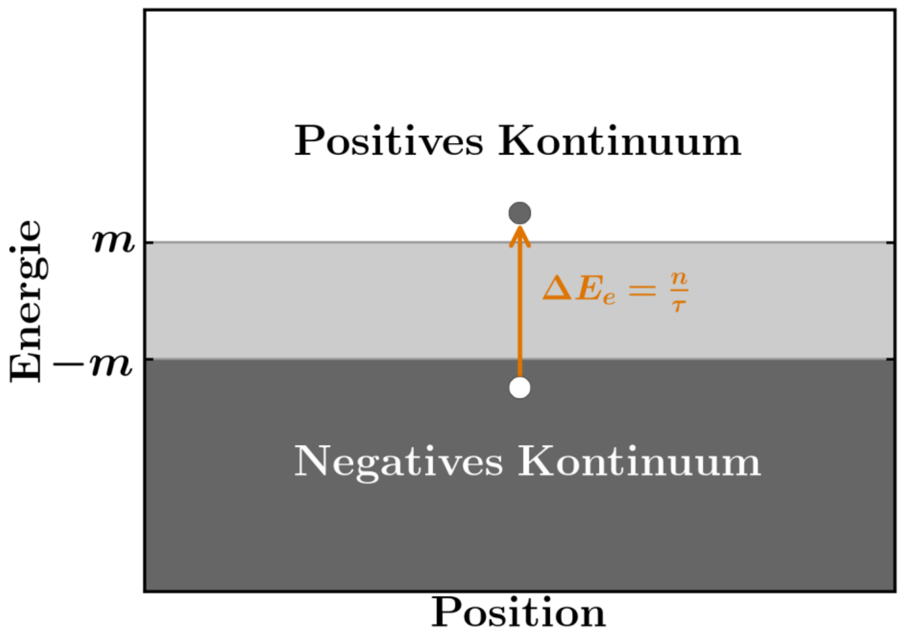
$$Q(\boldsymbol{p},t) = \frac{eE(t)\epsilon_\perp}{\omega^2(\boldsymbol{p},t)} \, ,$$

amplitude of vacuum decay

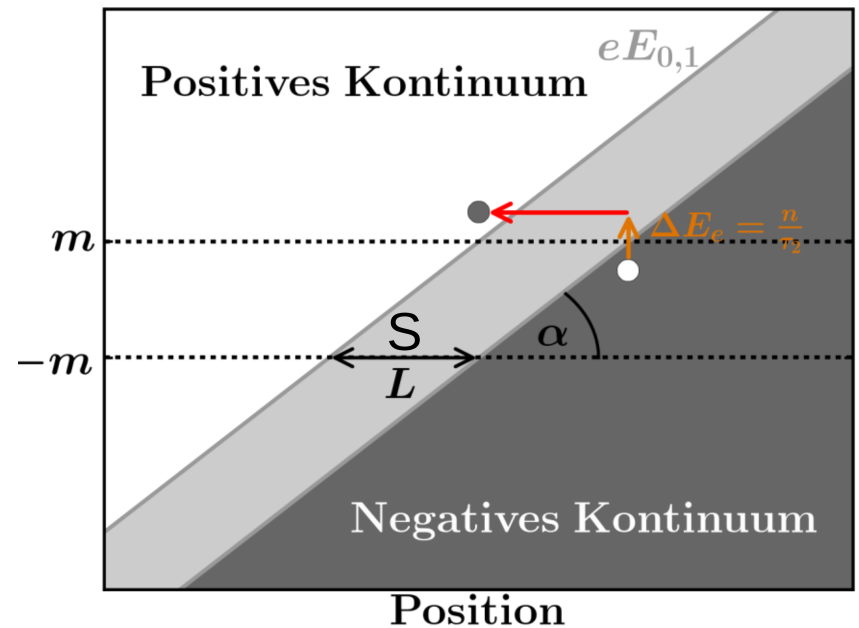
Dynamically assisted Schwinger effect

Schutzhold, Gies, Dunne (2008)
Dunna, Gies, Schutzhold (2009)

multi-photon

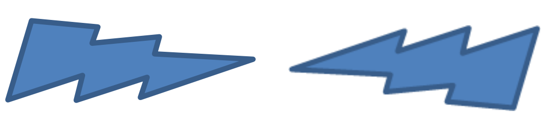


Schwinger   dyn. assist. Schwinger



E(t) in homogeneity region of anti-nodes
of counter-propagating laser beams (lin- pol.)

part. 3-momentum =
good quant. numb.



Heros: Dirac & Bogolyubov

$$\{\gamma^\mu [i\partial_\mu - eA_\mu(x)] - m\}\Psi = 0$$

4 x 4 | 1st order PDE | not a safe exp. param. | renorm. mass | 4 components

In theoretical physics, the Bogoliubov transformation is a unitary transformation from a unitary representation of some canonical commutation relation algebra or canonical anticommutation relation algebra into another unitary representation, induced by an isomorphism of the commutation relation algebra.
The Bogoliubov transformation is often used to diagonalize Hamiltonians, which yields the steady-state solutions of the corresponding Schrödinger equation. (Wikipedia)

a few technicalities in solving the Dirac eq.

H. Oppitz 2013

$$\Psi(\vec{r},t) = \int \mathrm{d}^3p \, \langle \, \vec{r} \mid \vec{p} \, \rangle \langle \, \vec{p} \mid \Psi \, \rangle = \int \frac{\mathrm{d}^3p}{(2\pi)^3} \mathrm{e}^{i\vec{p}\cdot\vec{r}} \phi(\vec{p},t)$$

mode expansion
if E(t)

$$\phi(\vec{p},t) = \sum_{j=1}^{2} \Big(u_j(\vec{p},t) a_j(\vec{p}) + v_j(-\vec{p},t) b_j^\dagger(-\vec{p}) \Big)$$

2nd quantisation,
suitable spinor basis

Hamiltonian is not diagonal → Bogolyubov transormation to time-dependent operators

$$A_j(\vec{p},t) = \alpha(\vec{p},t) a_j(\vec{p}) - \beta^*(\vec{p},t) b_j^\dagger(-\vec{p})$$
$$B_j^\dagger(-\vec{p},t) = \beta(\vec{p},t) a_j(\vec{p}) + \alpha^*(\vec{p},t) b_j^\dagger(-\vec{p})$$

$$|\alpha(\vec{p},t)|^2 + |\beta(\vec{p},t)|^2 = 1$$

unitary transformation

$$\phi(\vec{p},t) = \sum_{j=1}^{2} \Big(U_j(\vec{p},t) A_j(\vec{p},t) + V_j(-\vec{p},t) B_j^\dagger(-\vec{p},t) \Big)$$

not unique

$$\hat{H}(t) = \int \frac{\mathrm{d}^3p}{(2\pi)^3} \bar{\phi}(\vec{p},t) \Big(\vec{\gamma} \cdot \vec{\pi}(\vec{p},t) + m \Big) \phi(\vec{p},t)$$

$$= \int \frac{\mathrm{d}^3p}{(2\pi)^3} \sum_{j=1}^{2} \omega(\vec{p},t) \left(A_j^\dagger(\vec{p},t) A_j(\vec{p},t) + B_j^\dagger(-\vec{p},t) B_j(-\vec{p},t) \right)$$

$$\dot{\alpha}(\vec{p},t) = \frac{1}{2}Q(\vec{p},t)\beta(\vec{p},t)\mathrm{e}^{2i\Theta(\vec{p},t_0,t)},$$

$$\dot{\beta}(\vec{p},t) = -\frac{1}{2}Q(\vec{p},t)\alpha(\vec{p},t)\mathrm{e}^{-2i\Theta(\vec{p},t_0,t)}$$

evolution eqs. for Bogolyubov coeffs.

$$\rho(\vec{p},t) = -2\,\mathrm{Re}\left(\alpha^*(\vec{p},t)\beta(\vec{p},t)\mathrm{e}^{2i\Theta(\vec{p},t_0,t)}\right),$$

$$\xi(\vec{p},t) = -2\,\mathrm{Im}\left(\alpha^*(\vec{p},t)\beta(\vec{p},t)\mathrm{e}^{2i\Theta(\vec{p},t_0,t)}\right)$$

aux. functions

$$\dot{f}(\vec{p},t) = Q(\vec{p},t)\rho(\vec{p},t),$$

$$\dot{\rho}(\vec{p},t) = Q(\vec{p},t)\big(1 - f(\vec{p},t)\big) - 2\omega(\vec{p},t)\xi(\vec{p},t),$$

$$\dot{\xi}(\vec{p},t) = 2\omega(\vec{p},t)\rho(\vec{p},t).$$

system of ODEs, equivalen to Integro-diff. Eq.

time dependent vacuum & Bogoyubov transformation

$$A_j(\vec{p}, t_{-\infty})\,|0\rangle = a_j(\vec{p})\,|0\rangle \qquad = 0,$$

$$B_j(-\vec{p}, t_{-\infty})\,|0\rangle = b_j(-\vec{p})\,|0\rangle \qquad = 0$$

$$\rightarrow \quad A_j(\vec{p}, t)\,|\Omega(t)\rangle = B_j(-\vec{p}, t)\,|\Omega(t)\rangle = 0$$

$$\frac{\langle\Omega(t)|\, n_j^{e^-}(\vec{p})\,|\Omega(t)\rangle}{V} =: f_j(\vec{p}, t) = \frac{|\beta(\vec{p}, t)|^2\delta(0)}{V}$$

definition of diribution function

exact solutions

(cf. Hebenstreit 2011)

parab. cylinder functs.

Schwinger: E = const, A = - E t → f(t) = p(t) /x – y/^2

Sauter: E = E0 /cosh^2 t/T → f(t) = P(t) /X – Y/^2

Narozhny, Nikishov 1974

confl. hypergeom. functs.

B. Kampfer I Institute of Radiation Physics I www.hzdr.de

equivalent formulations (approximations)

- two or three ODEs
- Riccati eq. → quantum scattering fomulation with
  eff. pot. ~ ω
- world line formalism
- density matrix, Wigner formalism
- ….
- WKB approximation

Member of the Helmholtz Association
B. Kampfer I Institute of Radiation Physics I www.hzdr.de

The uncritical „critical field strength“

Schwinger (1951): w ~ exp{- π Ec / E} + …

Sauter-Schwinger: $$E_c = \frac{m^2}{e}$$ in natural units

$= 1.3 \times 10^{16}$ V/cm

qualitative picture:
virtual e+e- fluctuations are lifted on mass shell

scales

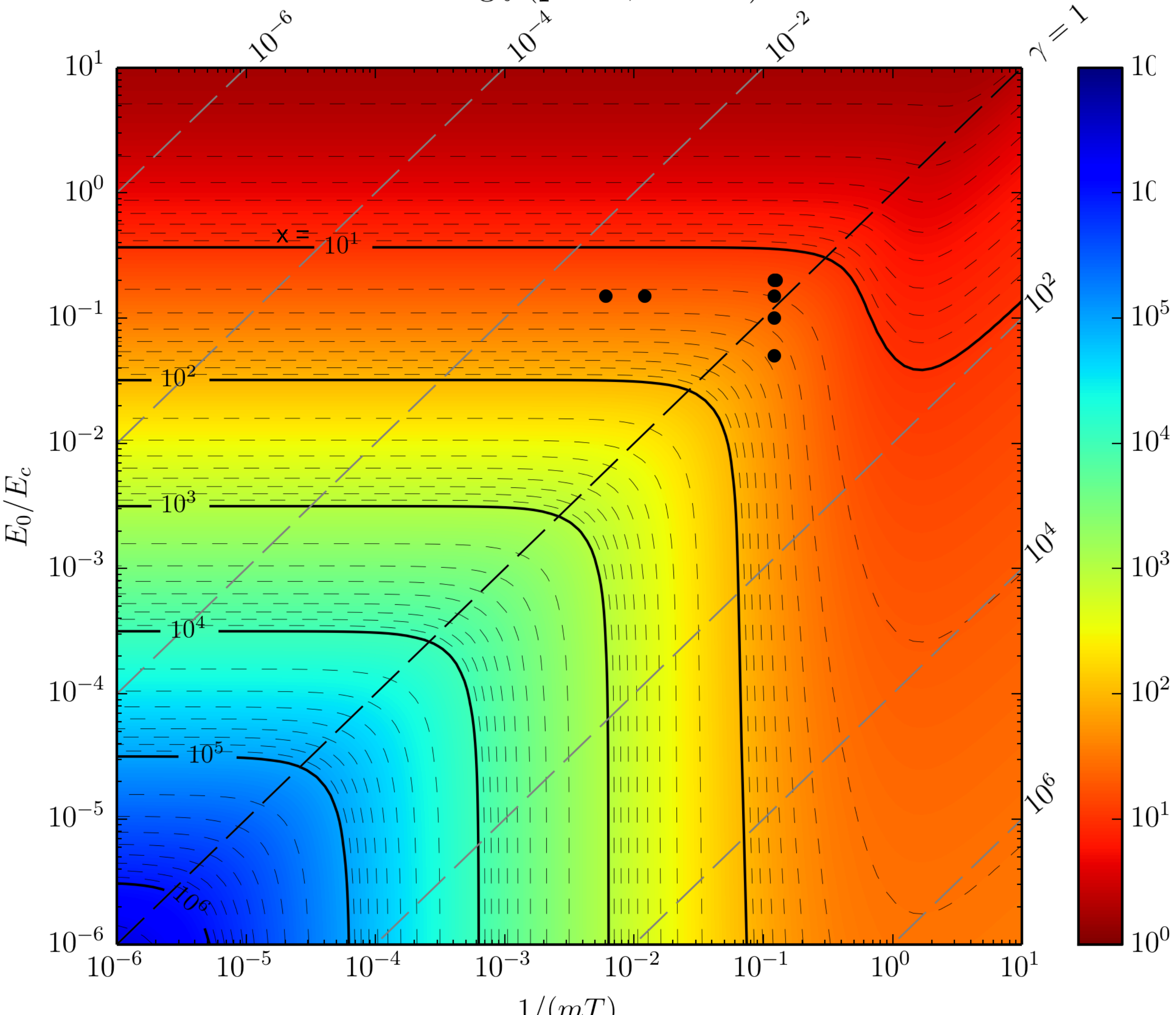
	L	XFEL	m	
	1eV	1 KeV	1 MeV	→ energy

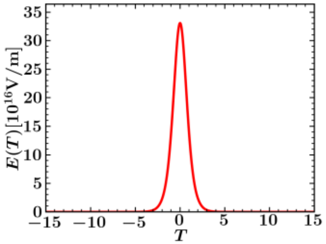
Keldysh parameter $$\gamma = \frac{E_c}{E}\,\frac{\omega}{m}$$

Member of the Helmholtz Association
B. Kampfer I Institute of Radiation Physics I www.hzdr.de

Sauter : $-\log f(\mathbf{p}=0, t\to\infty) + \text{const}$

$E(t) = E_0 \, cosh^{-2}(t/\tau)$





$f \sim e^{-x}$

simply field doubling

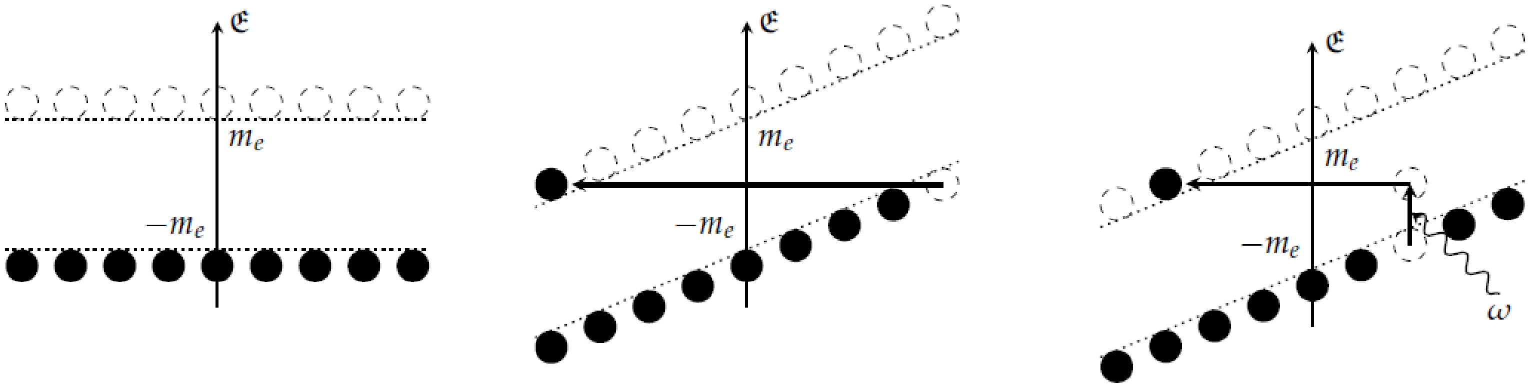
$$w \sim \exp\{-\pi \frac{E_c}{E}\} \quad \text{vs.} \quad \exp\{-\pi \frac{E_c}{2\,E}\}$$

very very small — very small

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

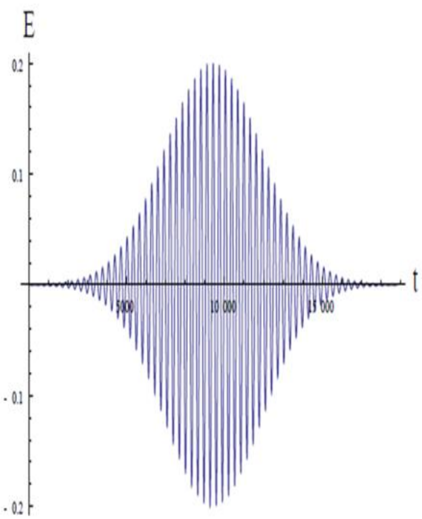
Narozhny et al. (2004) multiple beams at XCELS

DRESDEN concept HZDR

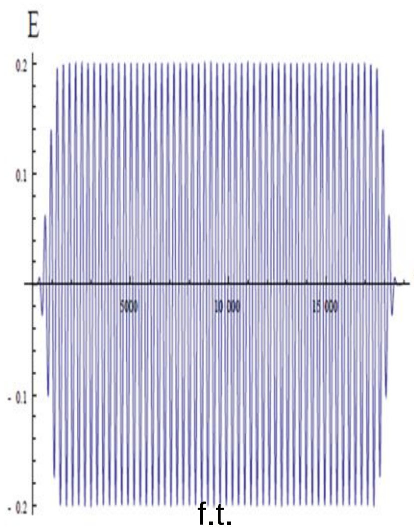


from
C. Schneider (2015)

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



Smolyansky et al. 2015

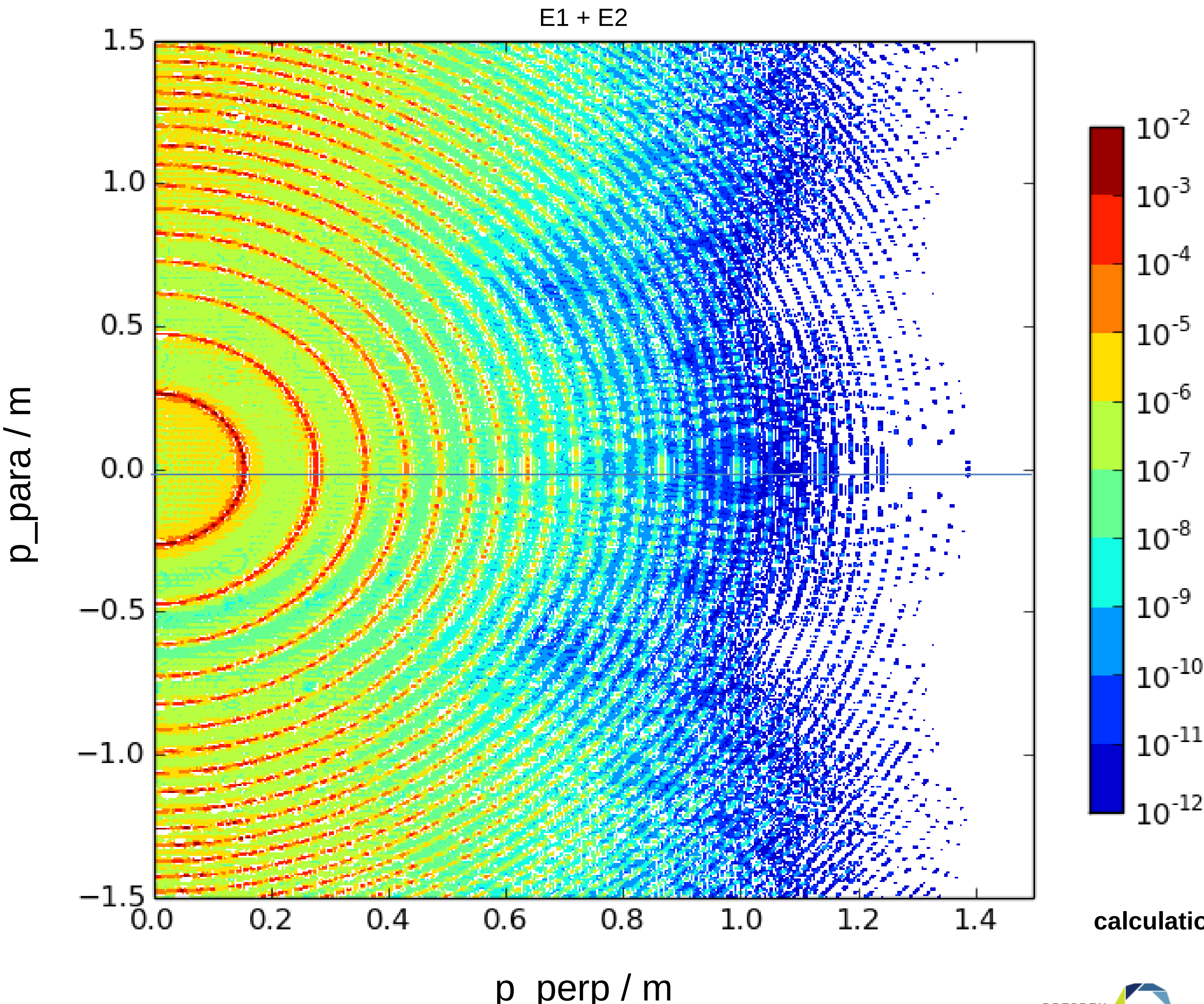


Otto et al. 2015

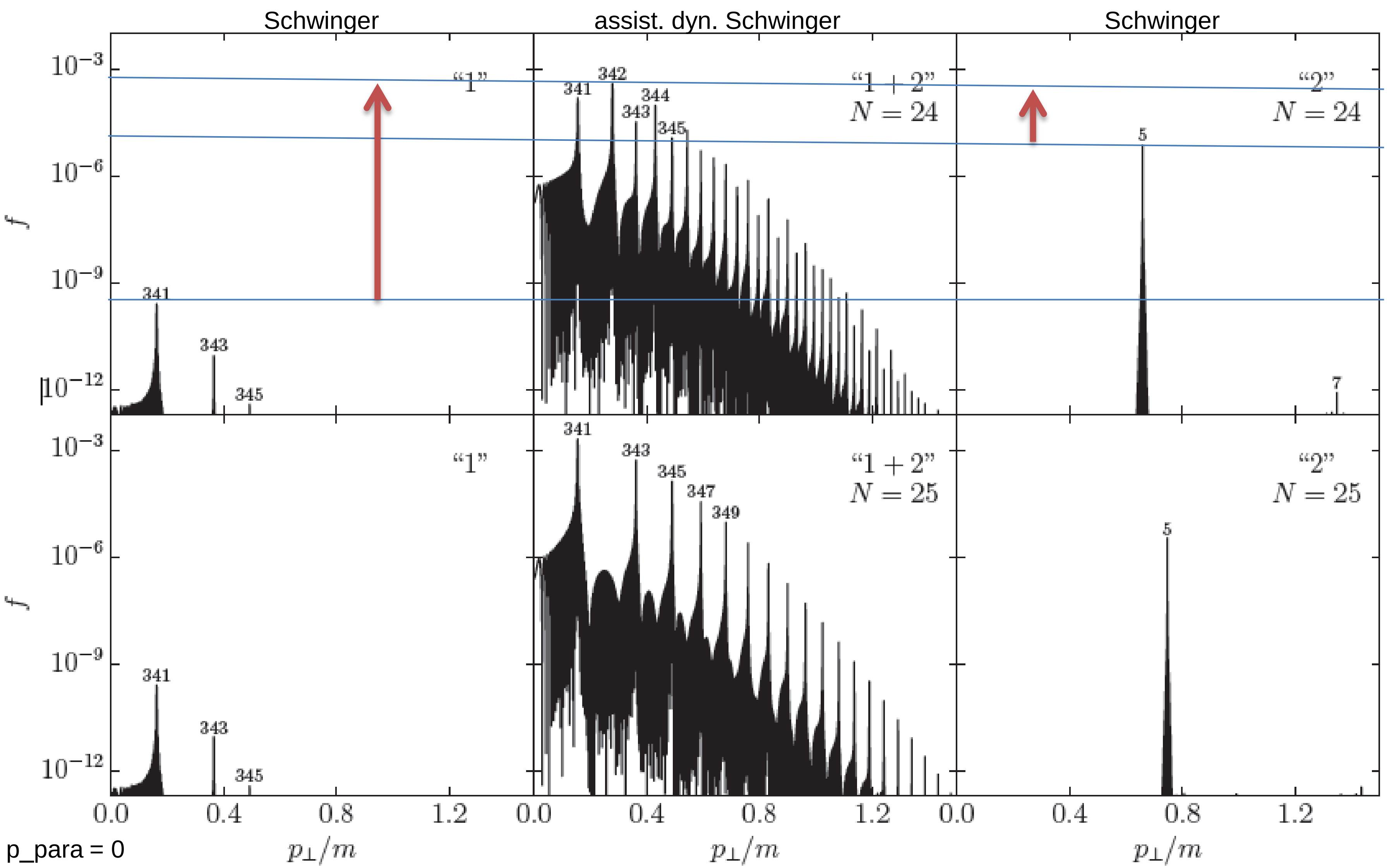
specific to our work (Laser + XFEL):

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

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



calculations: A. Otto



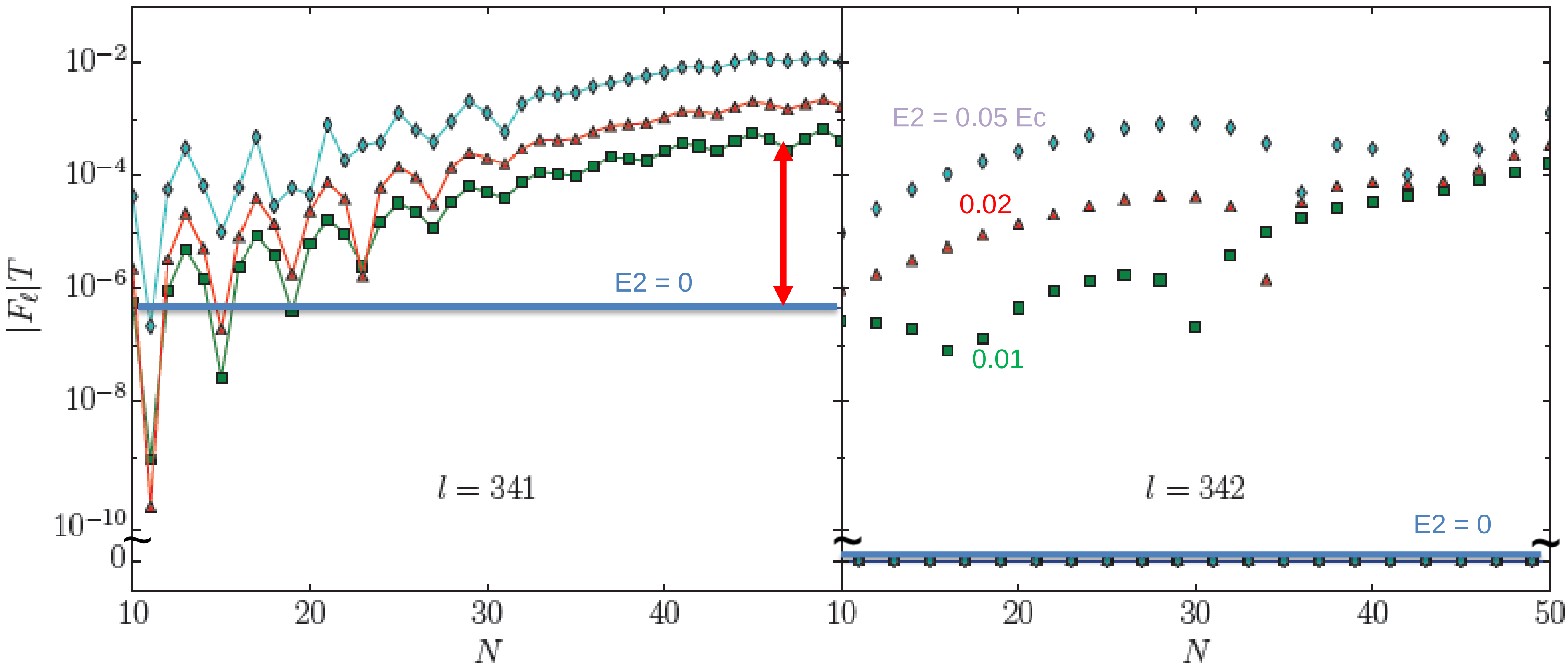
slow strong field „1“
E1 = 0.1 Ec
v = 0.02 m
g1 = 0.2 -> tunnel.

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

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

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

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

$$I(\boldsymbol{p},t) = \sum_\ell iF_\ell(\boldsymbol{p}) \frac{\mathrm{e}^{-i(\ell\nu - 2\Omega(\boldsymbol{p}))t} - 1}{\ell\nu - 2\Omega(\boldsymbol{p})}$$

shell width shrinking

shell occupation ($iF_\ell(\boldsymbol{p})$)

kinematics, shell structure ($\ell\nu - 2\Omega(\boldsymbol{p})$)

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

$$\Omega(\boldsymbol{p}) = \frac{1}{T}\int_0^T \mathrm{d}t \, \omega(\boldsymbol{p},t)$$ = Fourier zero mode

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

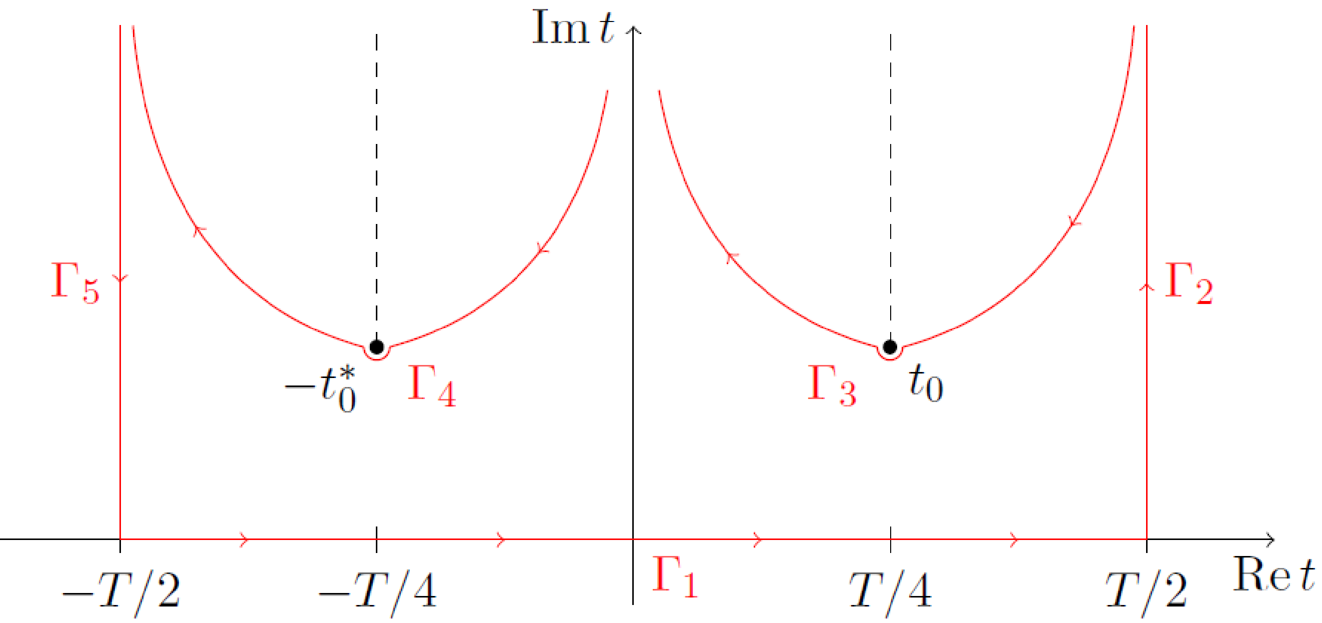
$$= \frac{1}{2}\left|F_\ell(\boldsymbol{p}^{(\ell)})\right|^2 t^2 + G(\boldsymbol{p}^{(\ell)},t)t + H(\boldsymbol{p}^{(\ell)},t),$$

flat-top time (t^2)

transient ($G(\boldsymbol{p}^{(\ell)},t)t + H(\boldsymbol{p}^{(\ell)},t)$)

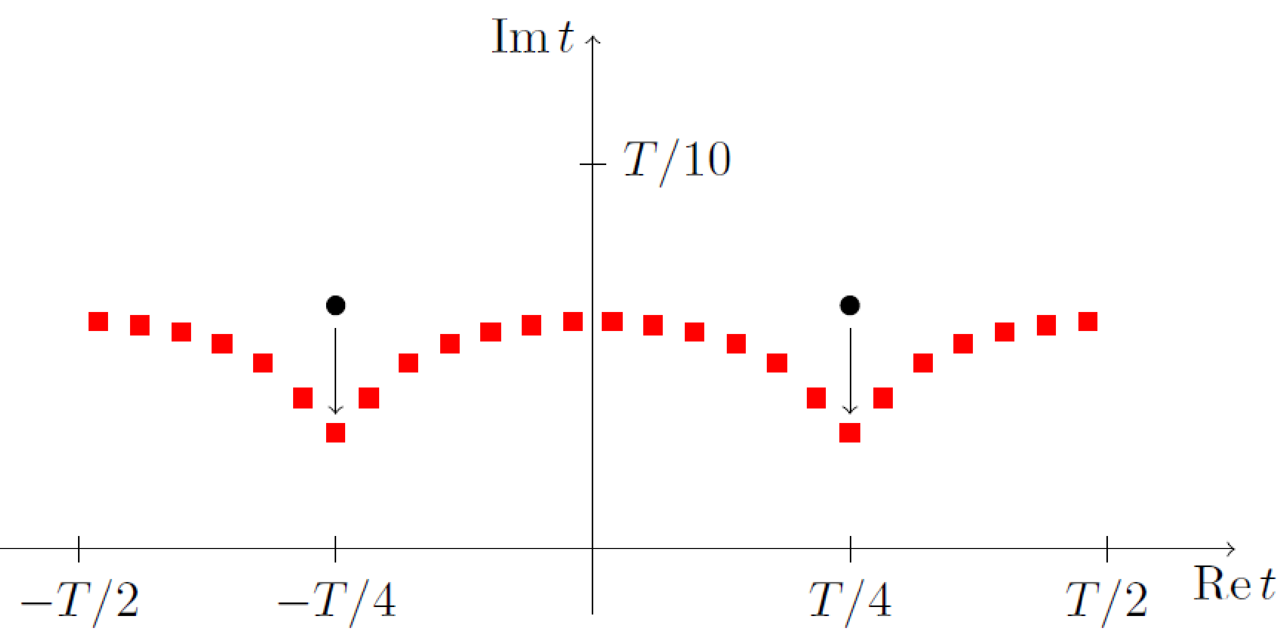
DRESDEN concept HZDR
Member of the Helmholtz Association
B. Kampfer I Institute of Radiation Physics I www.hzdr.de

details of Fourier coeff.

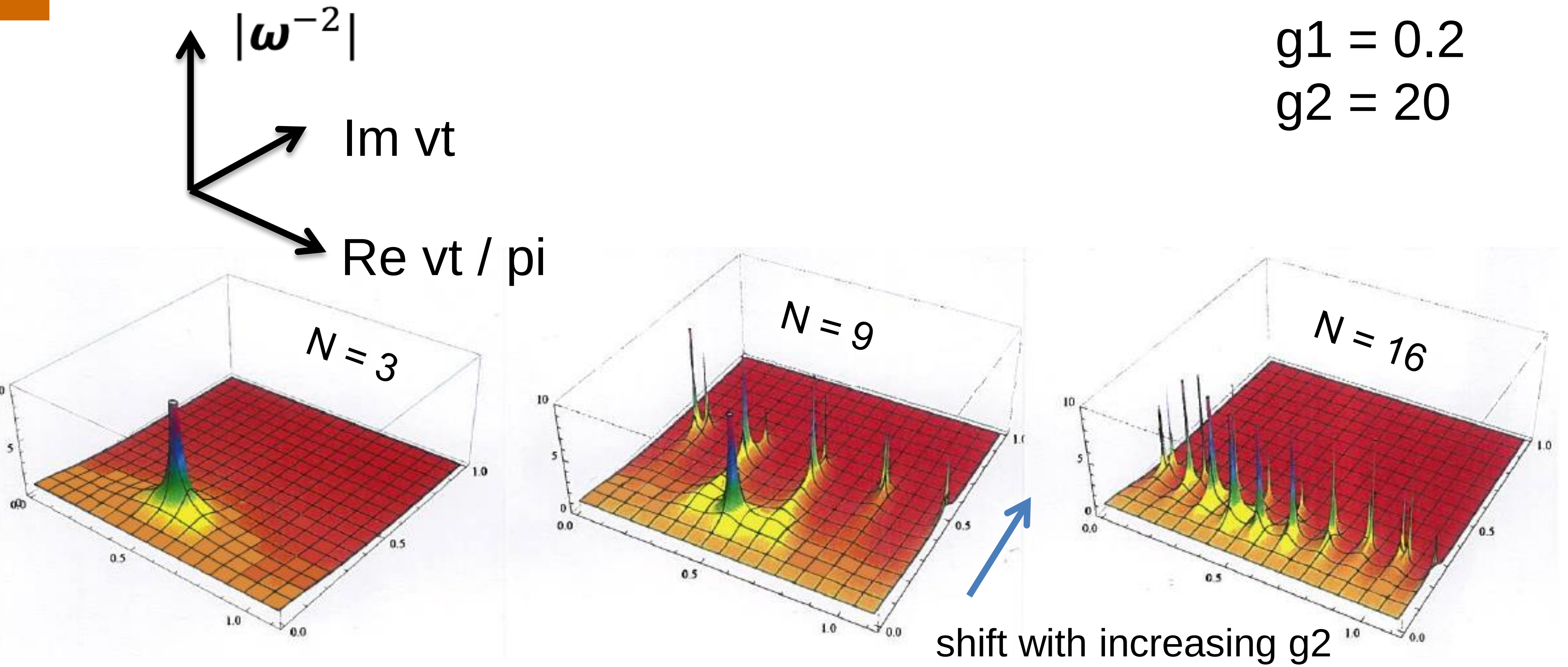


one field

● = zeroes of Ω (t)



two fields

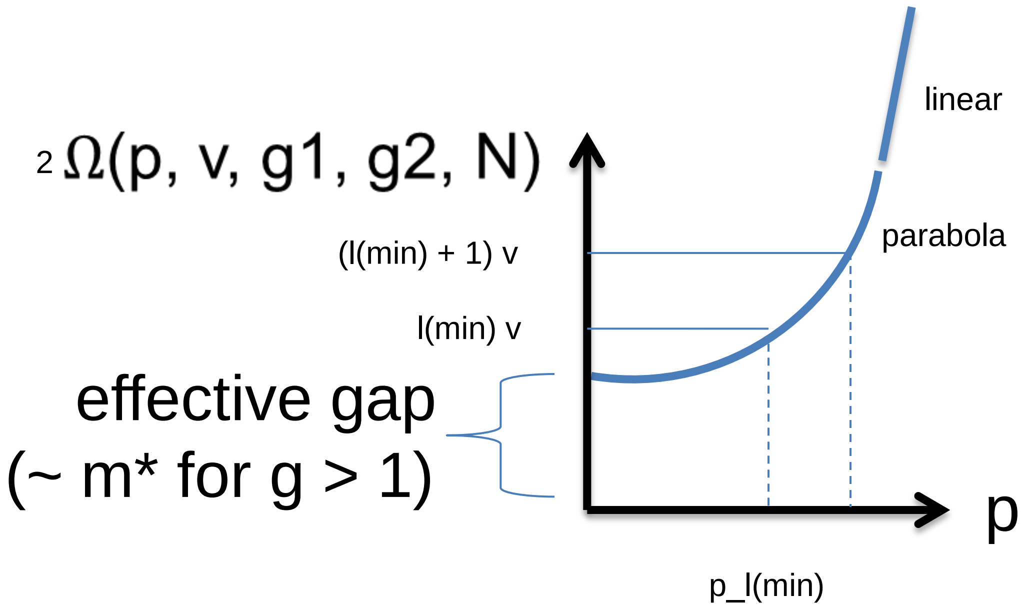


Brezin, Itzykson (1970): 1 periodic field (stat. phase, steepest desc.)

→ 1 pole with Re vt = pi/2, Im vt = arsh g

kinematics (shell positions)

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



slow strong field: g1 < 1 dominates

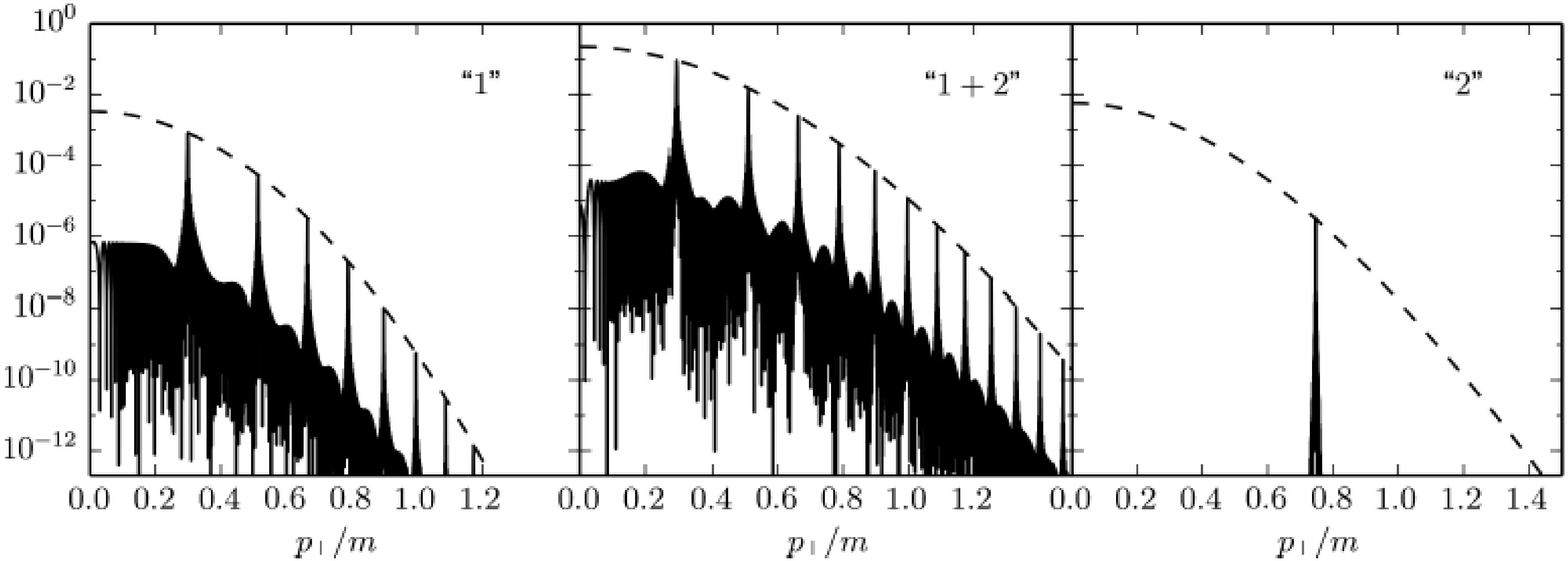
fast weak field: g2 > 2 corrections

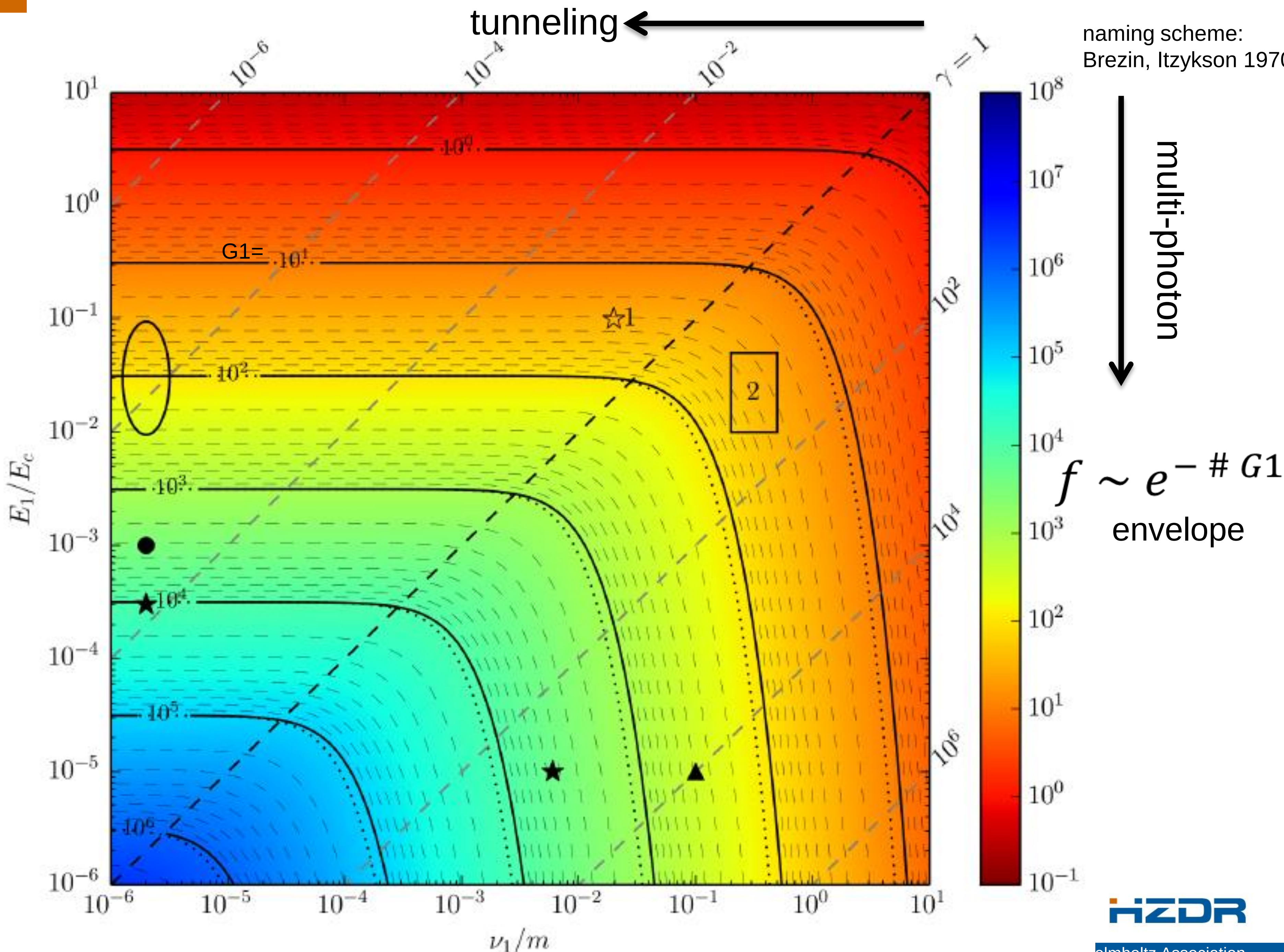
analog to channel closing in ATI

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

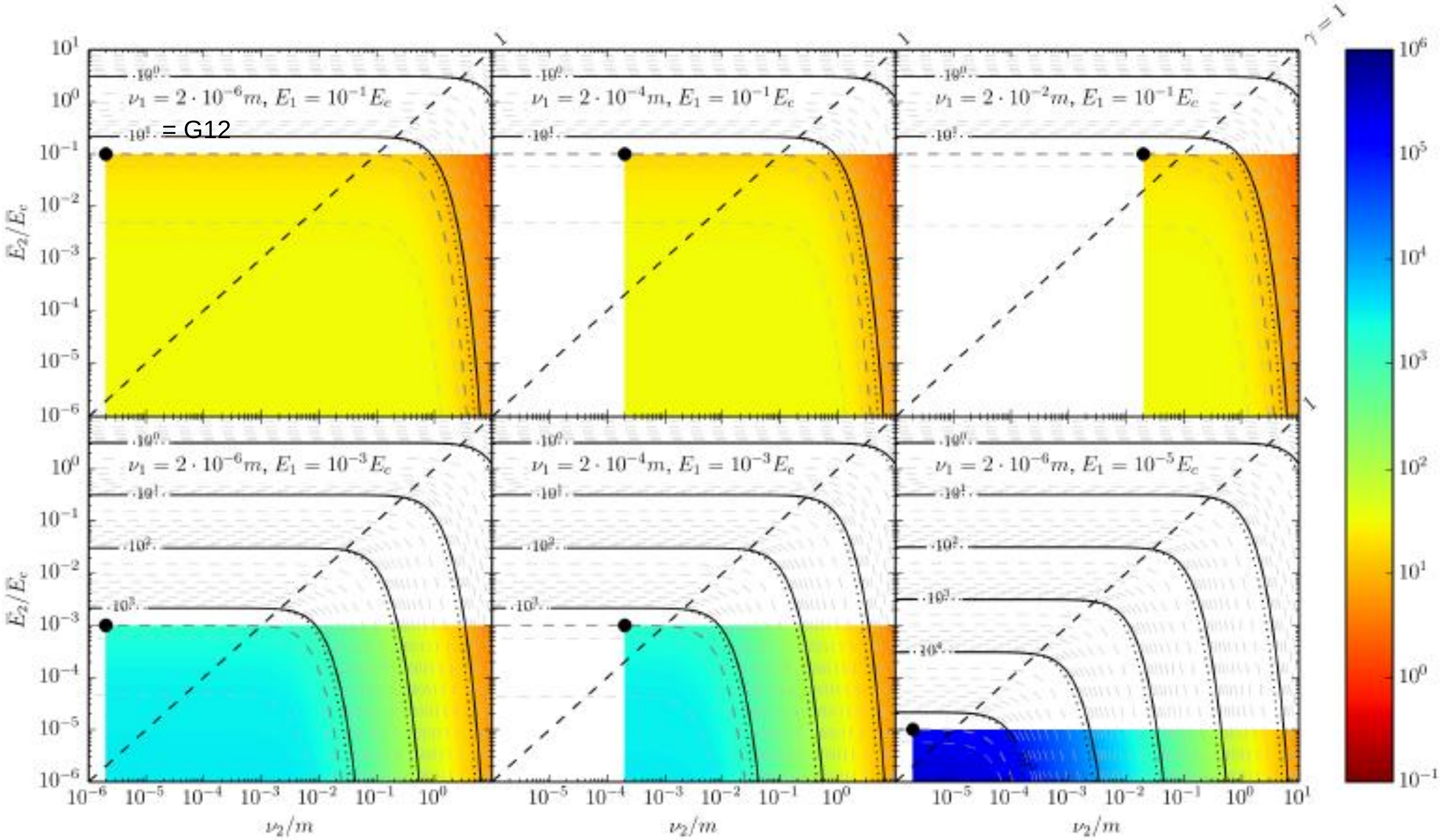
Popov (1973, 1974): 1 periodic field

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

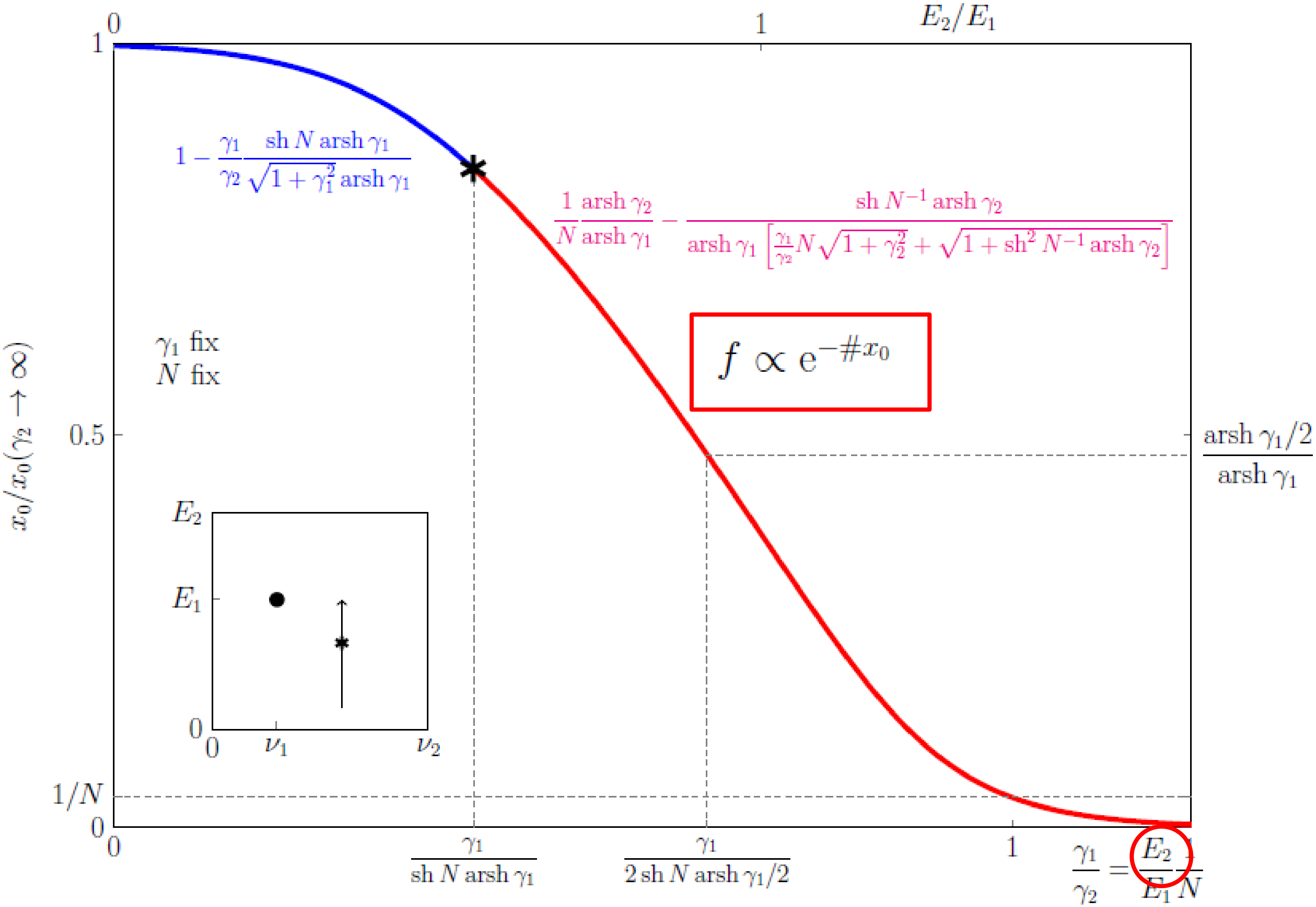




tunneling
naming scheme:
Brezin, Itzykson 1970
multi-photon
$f \sim e^{-\#\,G1}$
envelope
G1=
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{-6}
10^{-4}
10^{-2}
$\gamma = 1$
10^{2}
10^{4}
10^{6}
1
2
E_1/E_c
ν_1/m
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1}

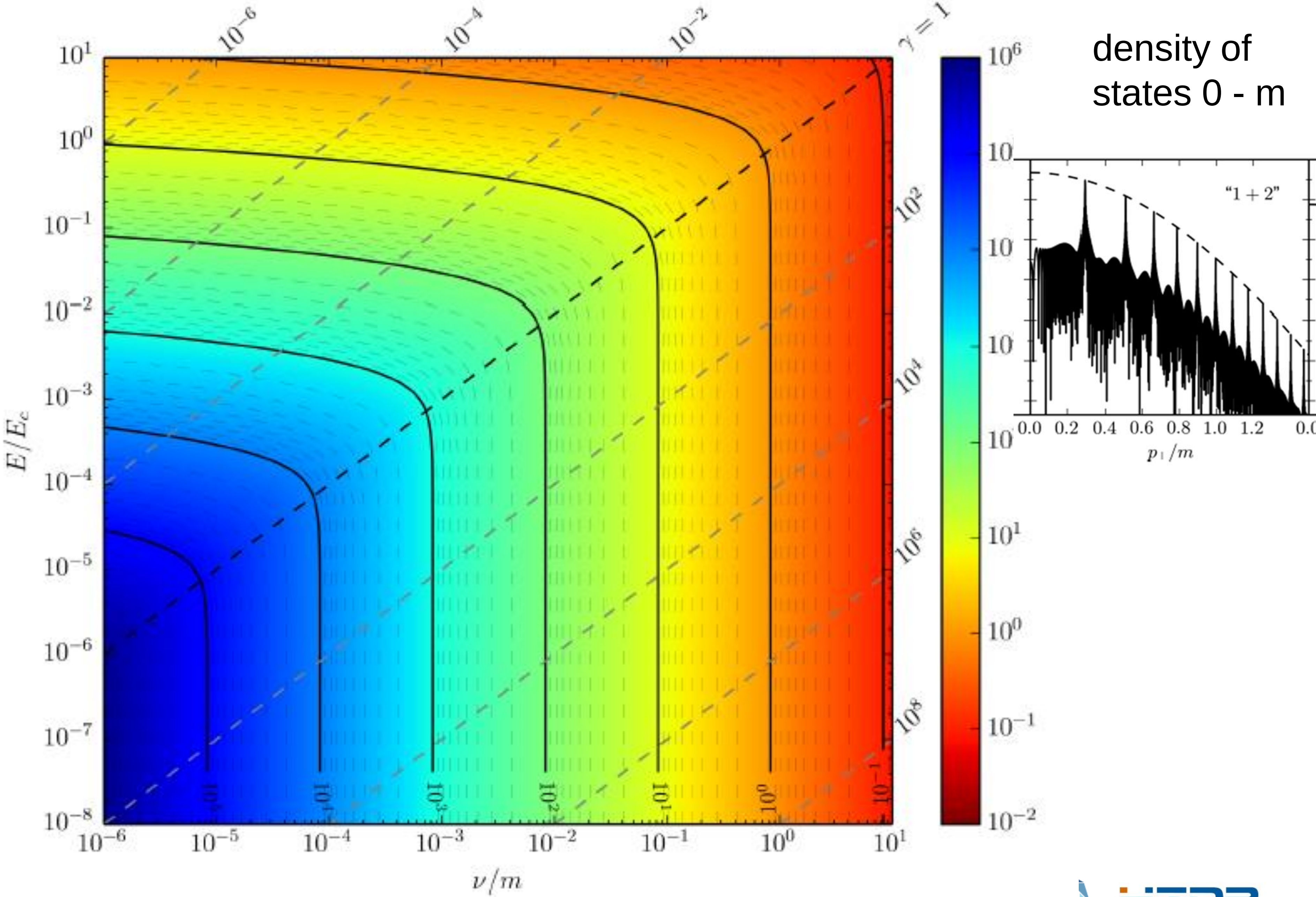


envelope of f ~ exp{ - # G12}



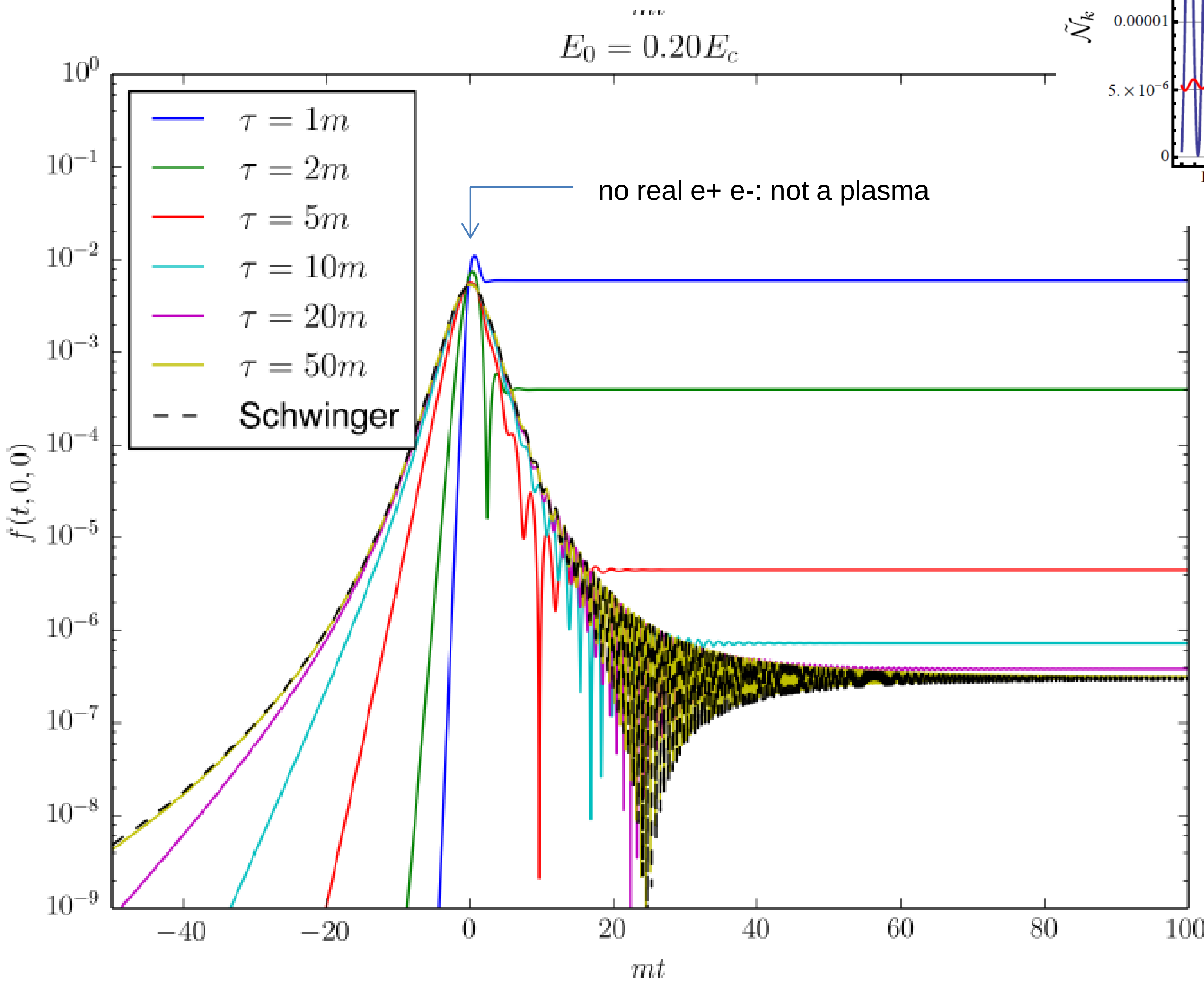
E_2/E_1
$1 - \frac{\gamma_1}{\gamma_2}\frac{\mathrm{sh}\, N \,\mathrm{arsh}\, \gamma_1}{\sqrt{1+\gamma_1^2}\,\mathrm{arsh}\,\gamma_1}$
$\frac{1}{N}\frac{\mathrm{arsh}\,\gamma_2}{\mathrm{arsh}\,\gamma_1} - \frac{\mathrm{sh}\, N^{-1}\,\mathrm{arsh}\,\gamma_2}{\mathrm{arsh}\,\gamma_1\left[\frac{\gamma_1}{\gamma_2}N\sqrt{1+\gamma_2^2}+\sqrt{1+\mathrm{sh}^2\, N^{-1}\,\mathrm{arsh}\,\gamma_2}\right]}$
$f \propto e^{-\# x_0}$
γ_1 fix
N fix
$x_0/x_0(\gamma_2 \to \infty)$
$\frac{\mathrm{arsh}\,\gamma_1/2}{\mathrm{arsh}\,\gamma_1}$
$1/N$
$\frac{\gamma_1}{\mathrm{sh}\, N\,\mathrm{arsh}\,\gamma_1}$
$\frac{\gamma_1}{2\,\mathrm{sh}\, N\,\mathrm{arsh}\,\gamma_1/2}$
$\frac{\gamma_1}{\gamma_2} = \frac{E_2}{E_1}\frac{1}{N}$
E_2
E_1
ν_1
ν_2

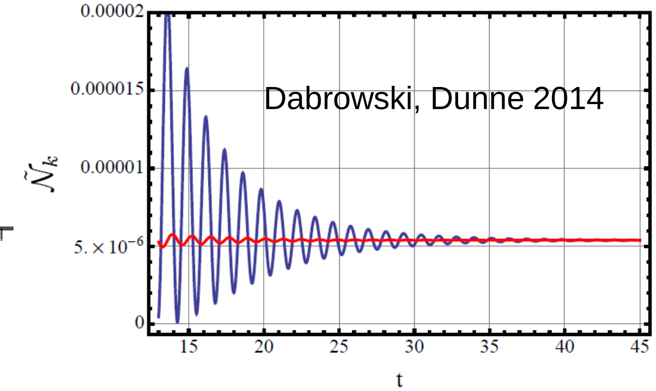
density of states 0 - m



Dynamics (disclaimer: only t → infty is relevant)

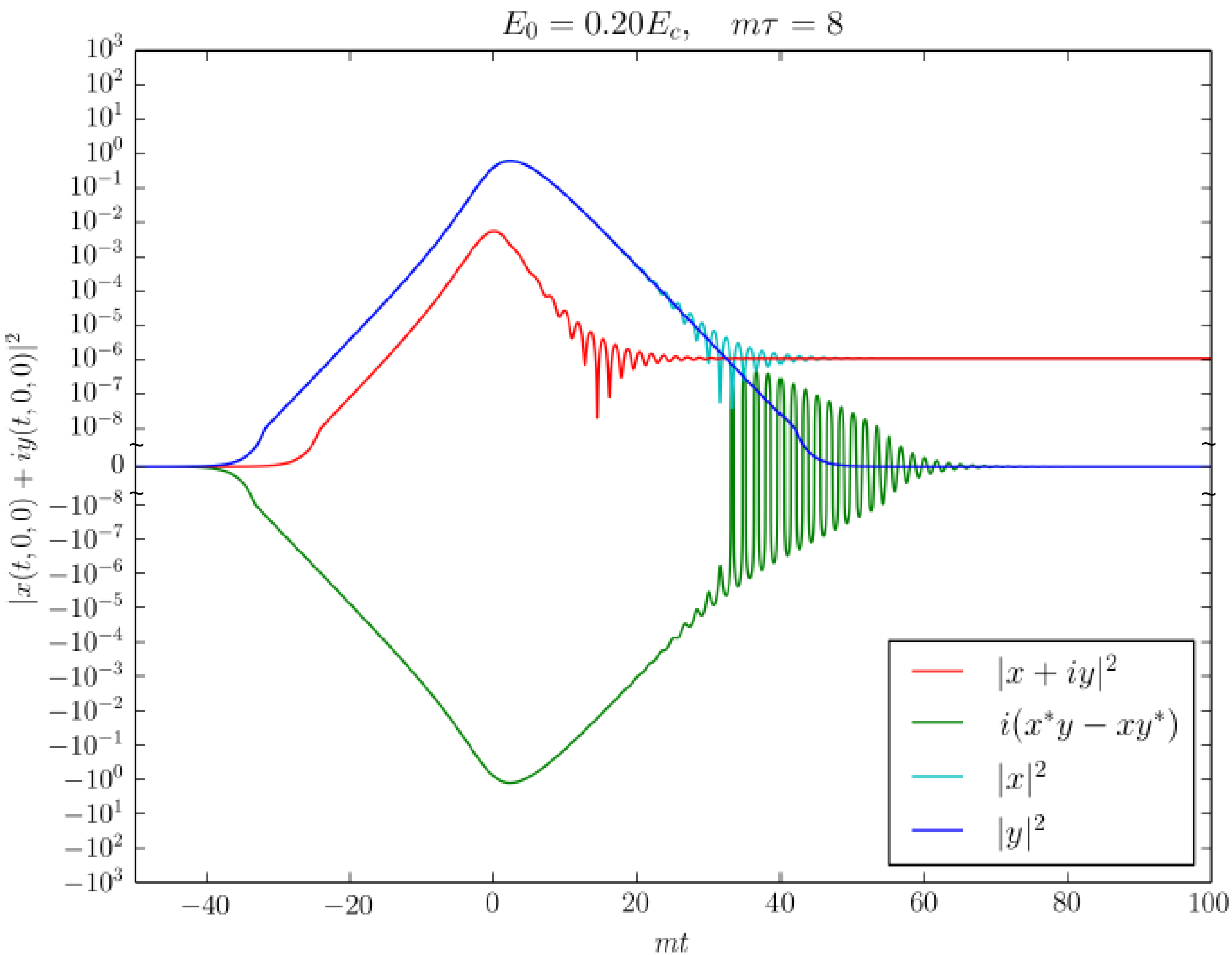
Sauter → Schwinger



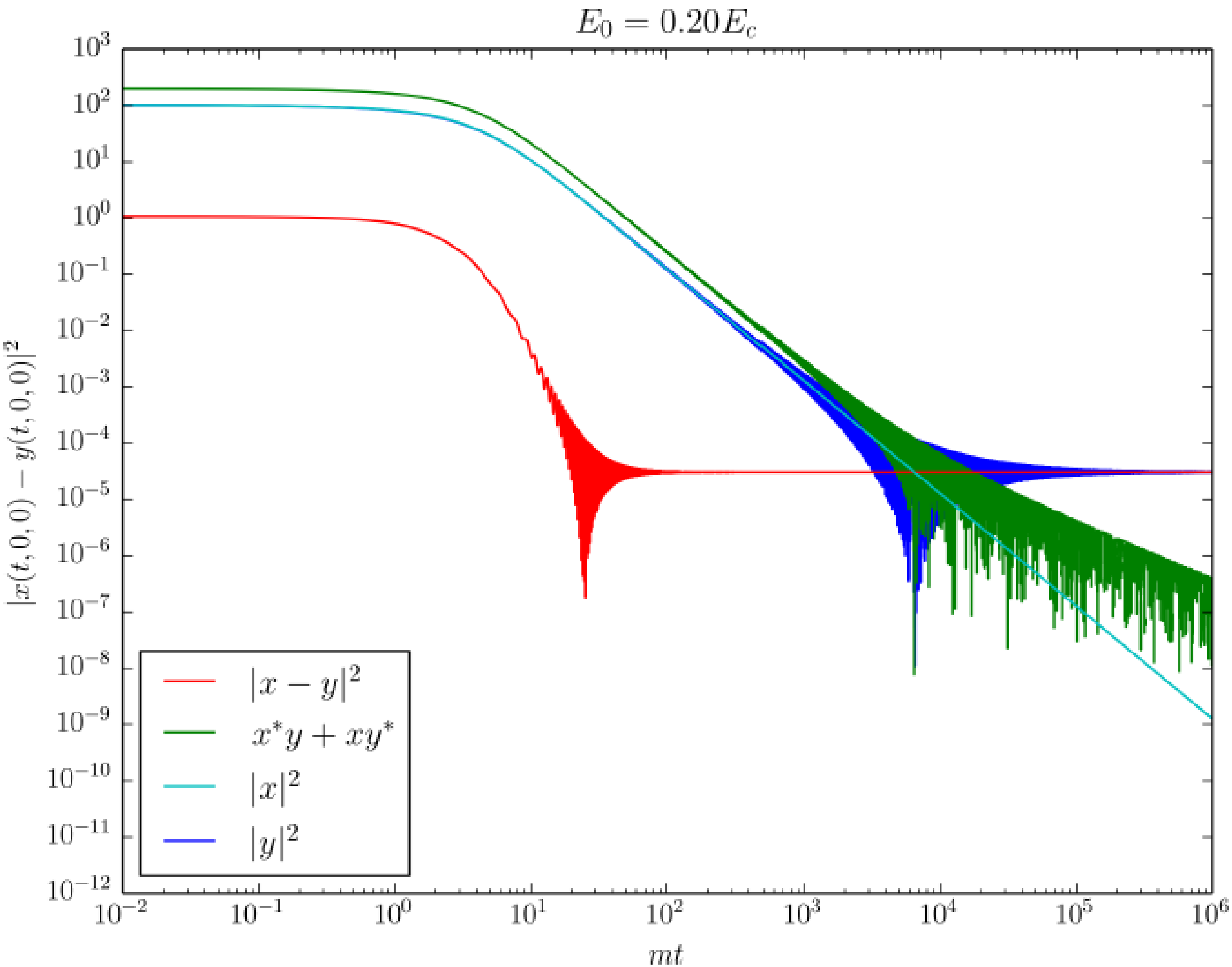


miracles of the time evolution

Sauter: f = P /X – Y/^2

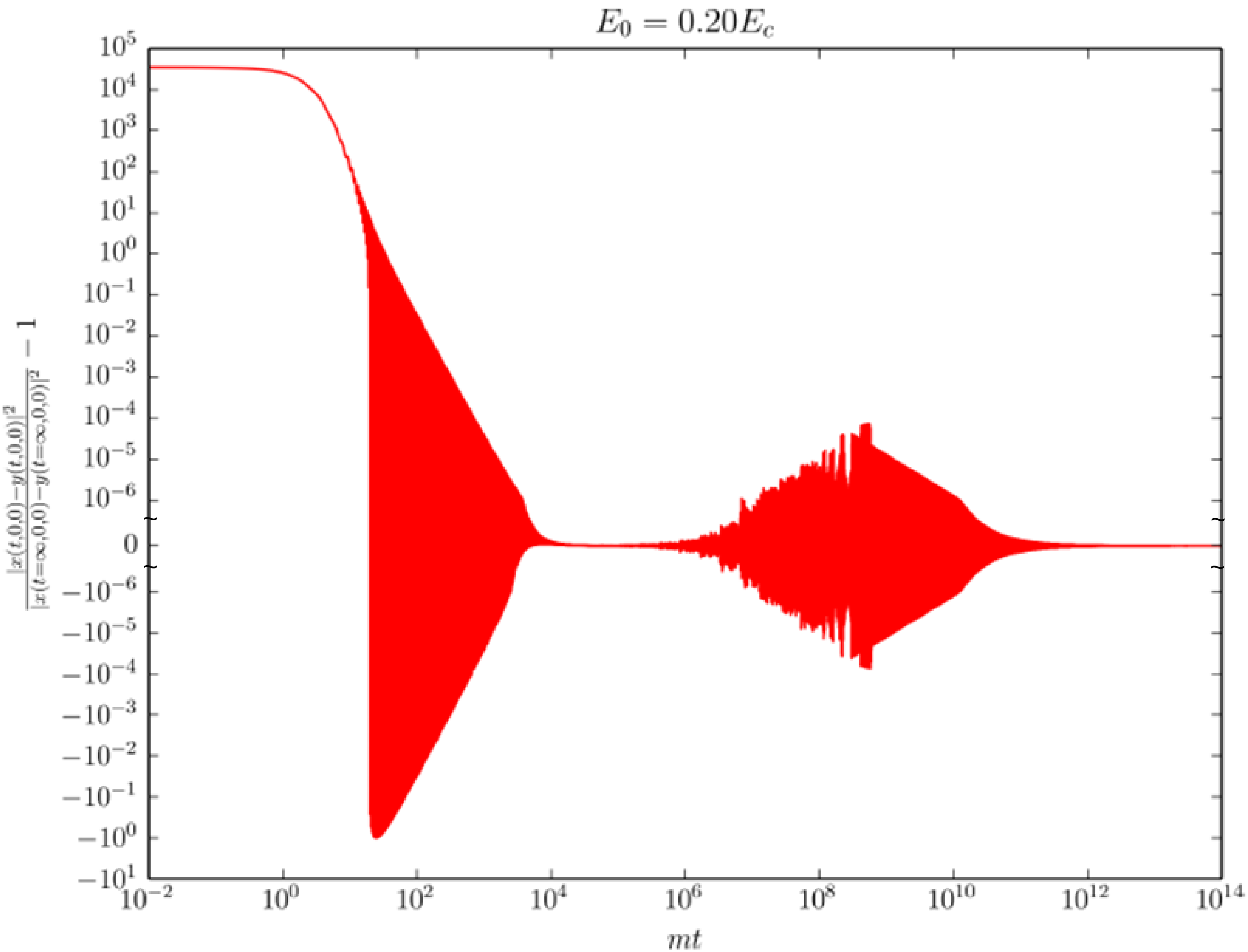


Schwinger

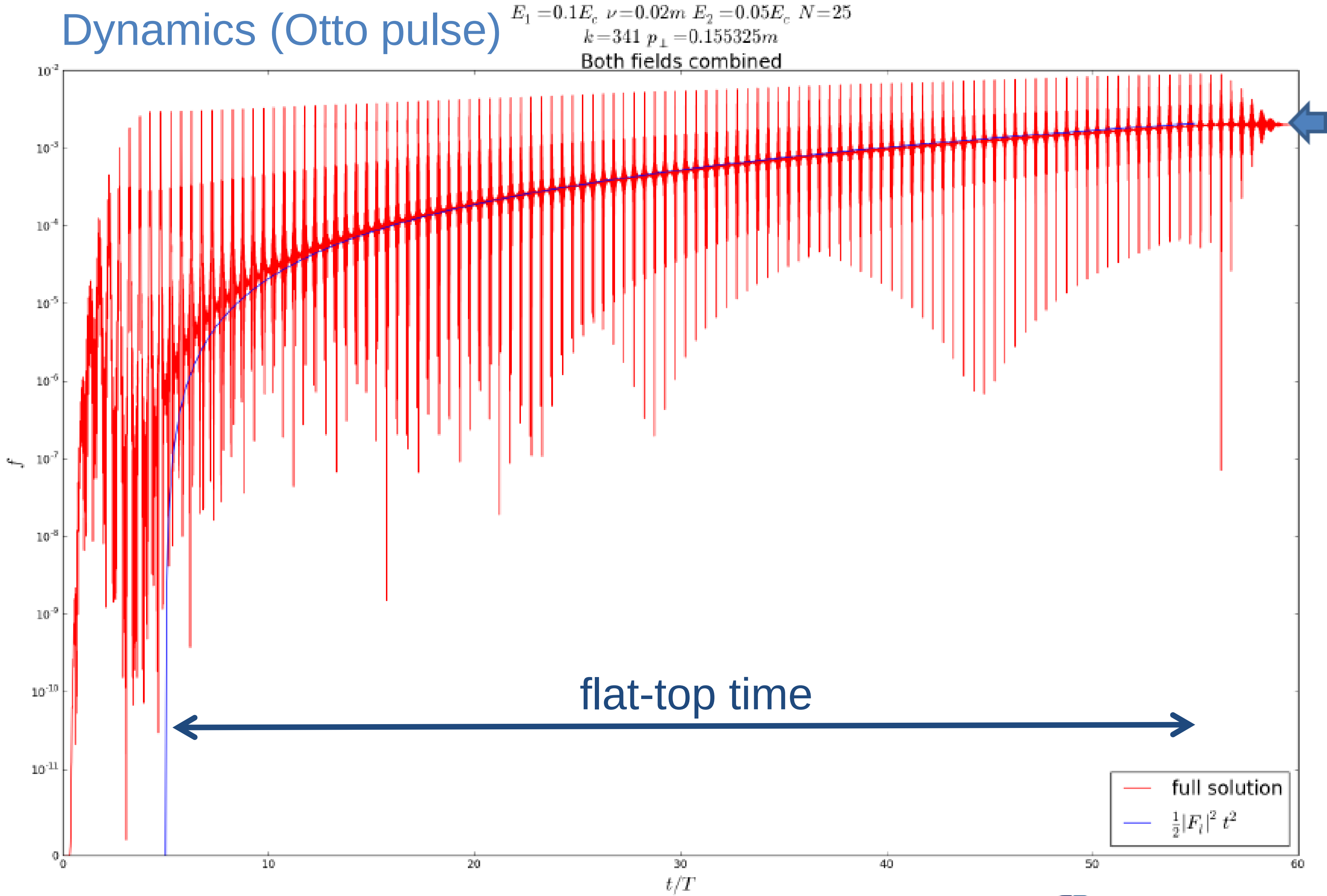


$E_0 = 0.20 E_c$
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$|x(t,0,0) - y(t,0,0)|^2$
$|x-y|^2$
$x^*y + xy^*$
$|x|^2$
$|y|^2$
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
mt

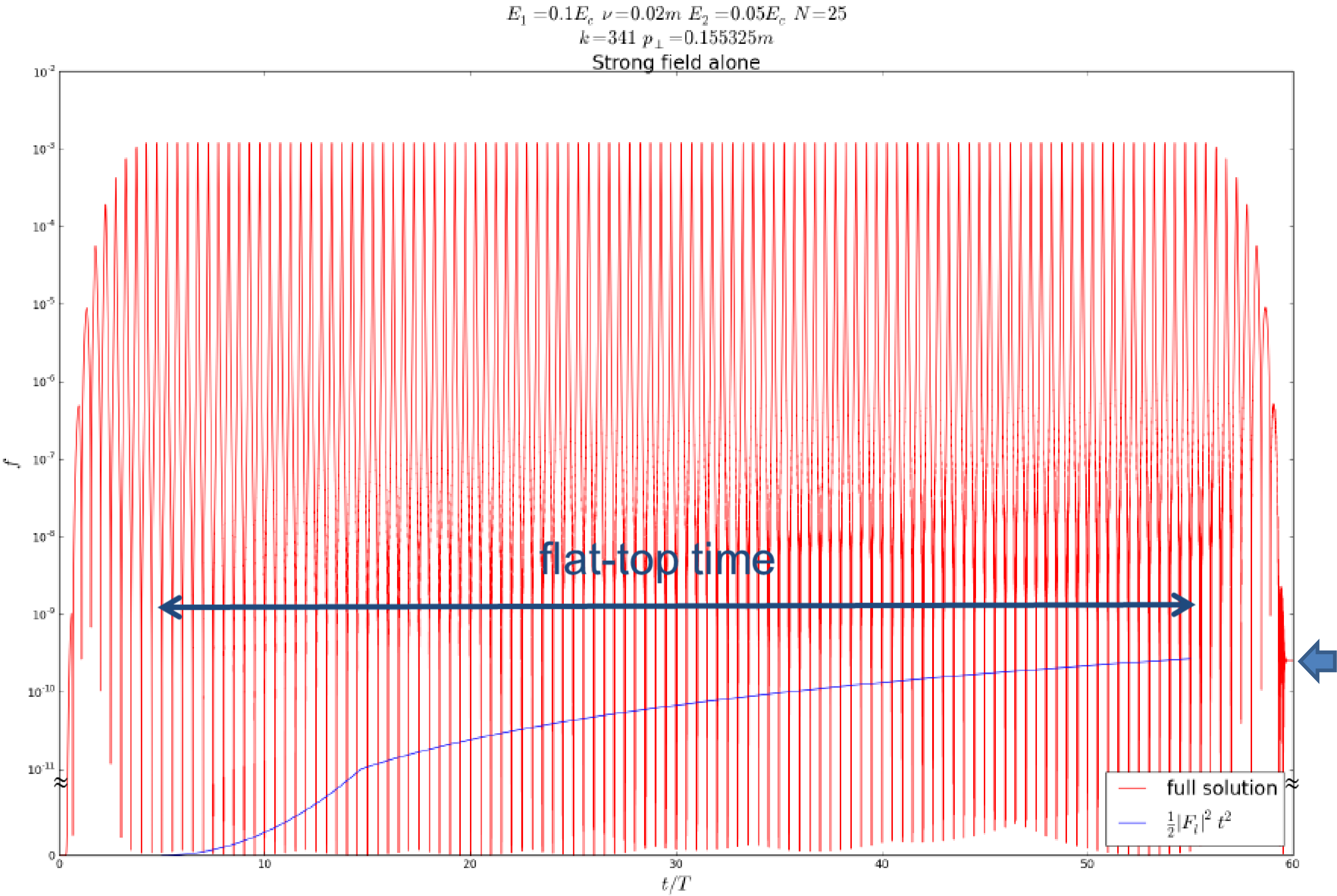
Schwinger: long-term evolution



Dynamics (Otto pulse)

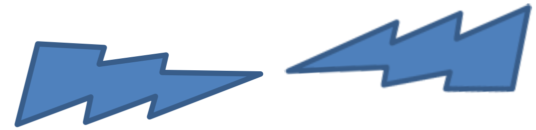


analog to "quark number" in chiral mass model with m(t) (C. Greiner, Micheler)



Dabrowski, Dunne (2014): transient f(t) depends on basis spatial focussing → gradients: E(t, x)

rotating E fields



Circ. Pol.

twisted photons

Schwinger process as prototype for
Hawking radiation, Unruh effect,
cosmological particle production

Interim Summary of §1: Schwinger pairs

1. Huge enhancement of „nearly nothing“
   by assisted dyn. Schwinger effect
   is mostly not enough, unless

2. E1 is sufficiently large (or „not too small“)

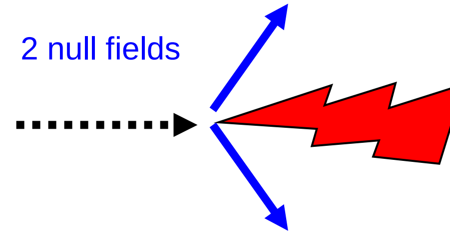
   AND

   w2 is O(m)

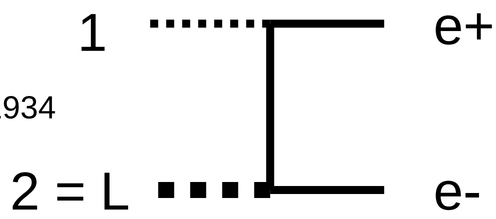
3. Optimization theory is useful for scanning
   the parameter space Orthaber,…, Alkofer (2014)

B. Kampfer I Institute of Radiation Physics I www.hzdr.de

2. Breit-Wheeler and Beyond



Berit, Wheeler 1934

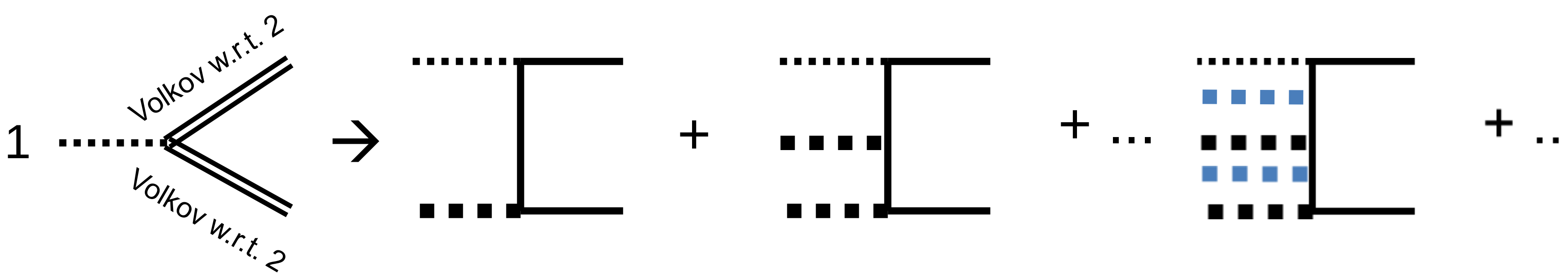


$2 \rightarrow 2$: s, t
crossing of Compton
time reversed annihilation

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

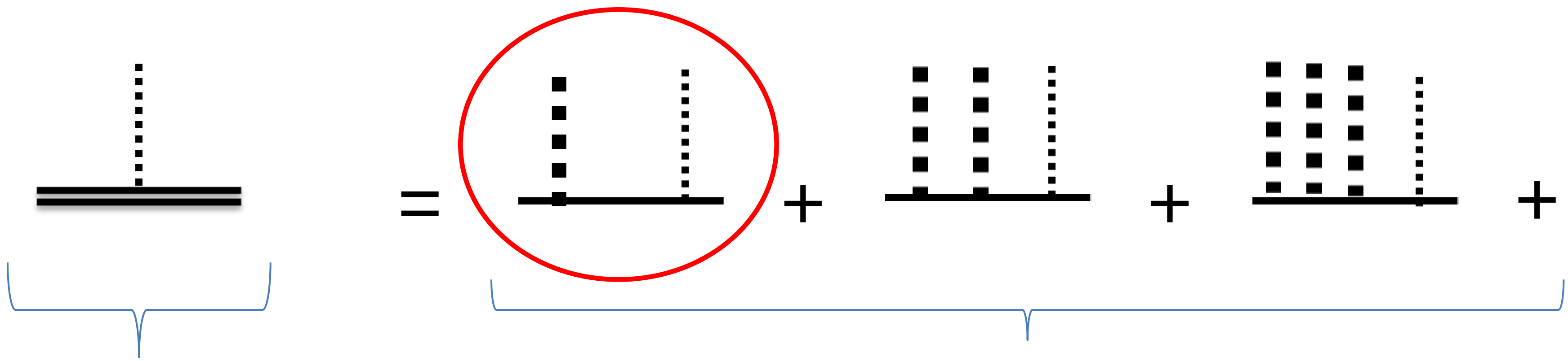


sQED (Furry) Breit-Wheeler n.l. Breit-Wheeler/higher harmonics

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

aside: Compton scattering in Furry picture

exact solution of Dirac eq. in external (class.) field, for plane waves = Volkov solution (1934) (propagator analog)



sQED (Furry) pQED

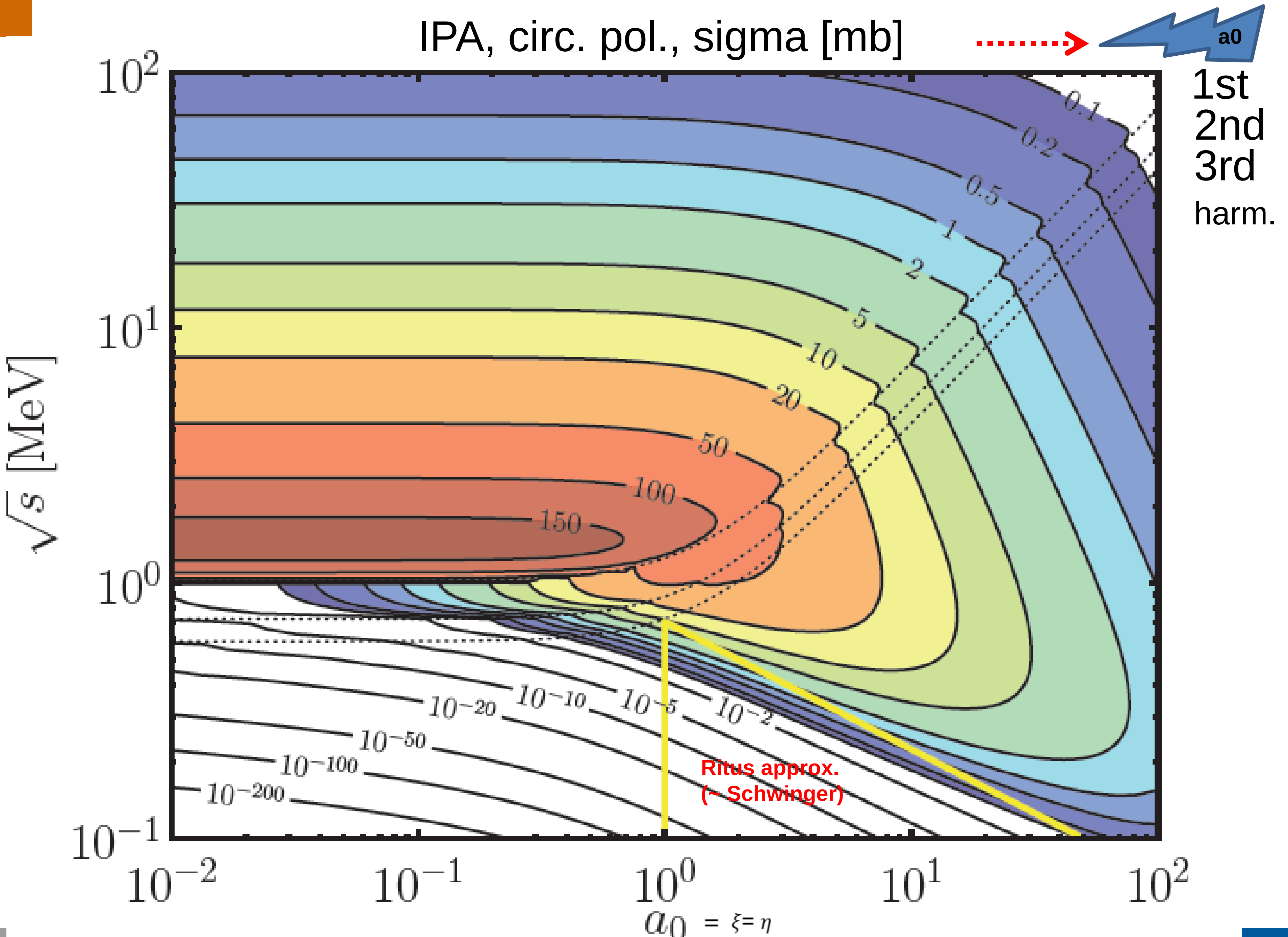
pioneers: Nikishov, Ritus, Narozhny > 1964, Goldman 1964

class. analog:
e- in e.m. wave,
emission via Lienard-Wiechert

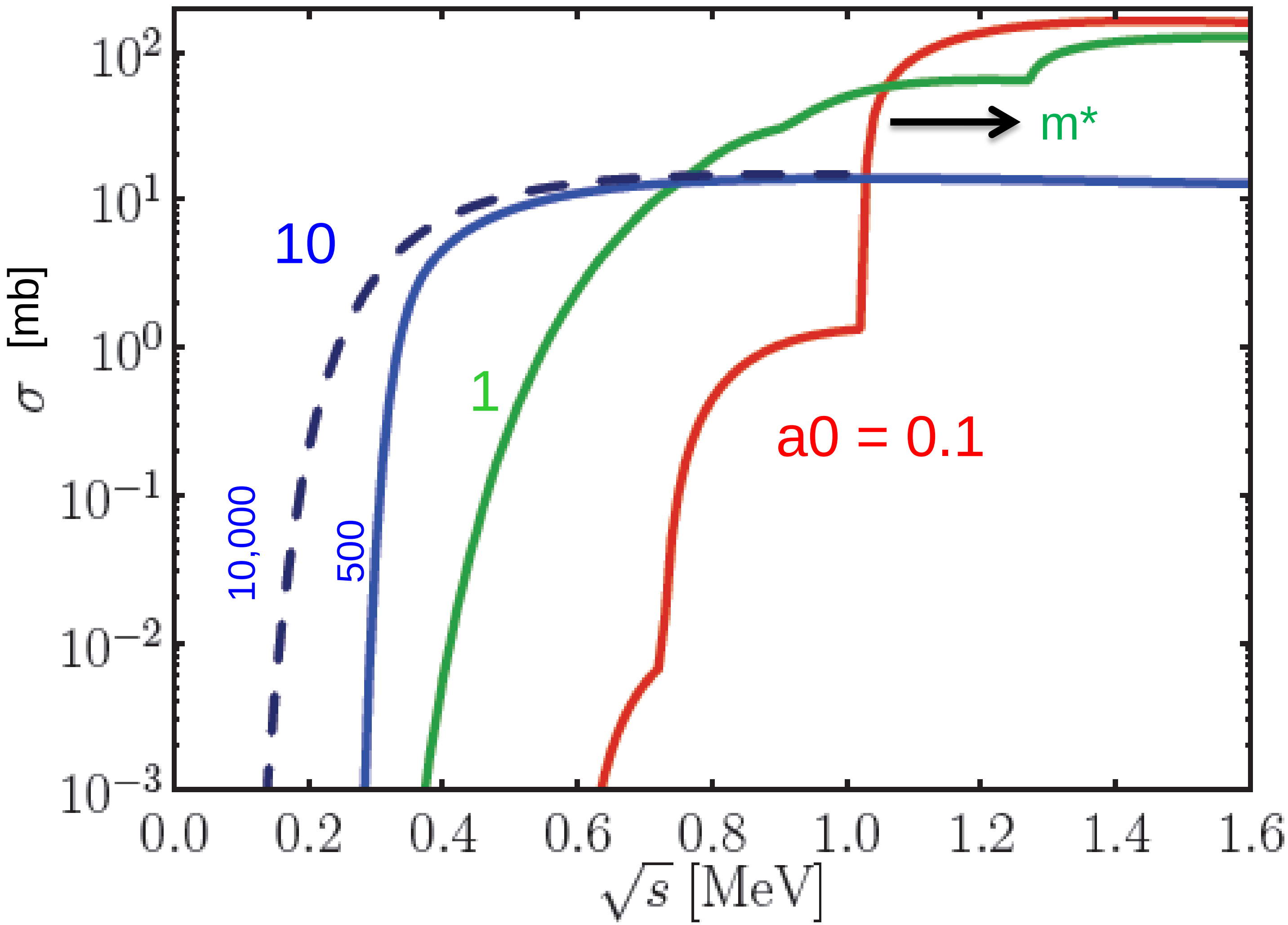
$$W = e^2 m^2 \sum_{s=1}^{\infty} W_i$$

W_1 ($\xi << 1$) = Klein-Nishina

IPA, circ. pol., sigma [mb]



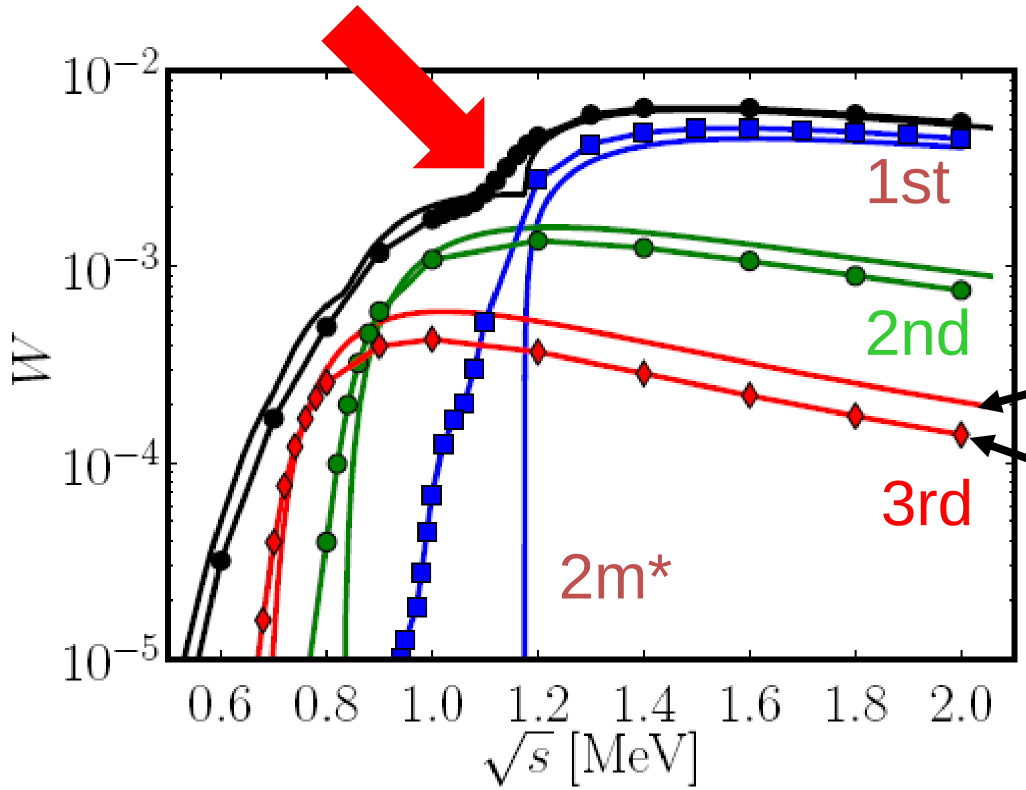
IPA



IPA: infinitely-long pulse approx. (plane wave)

Pair Production in Short Laser Pulses

FPA: finite pulse approx. (plane wave)



Ritus 1985: IPA

$a_0 = 0.8$

$\tau = 25$: FPA

# of oscillations

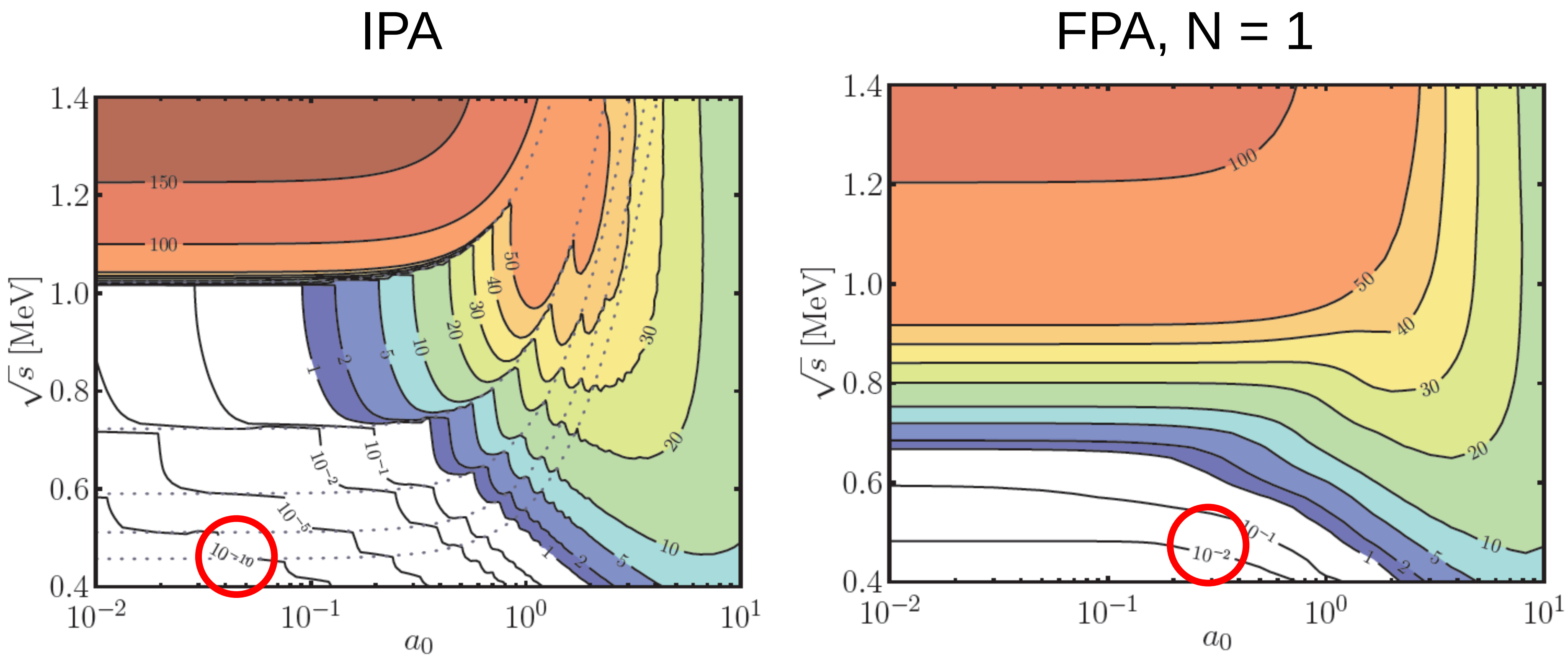
T. Nousch, diploma thesis, Dresden 2011
supervisor: D. Seipt

Pair Production in Ultra-Short Laser Pulses

lin. polarization, sigma [mb]

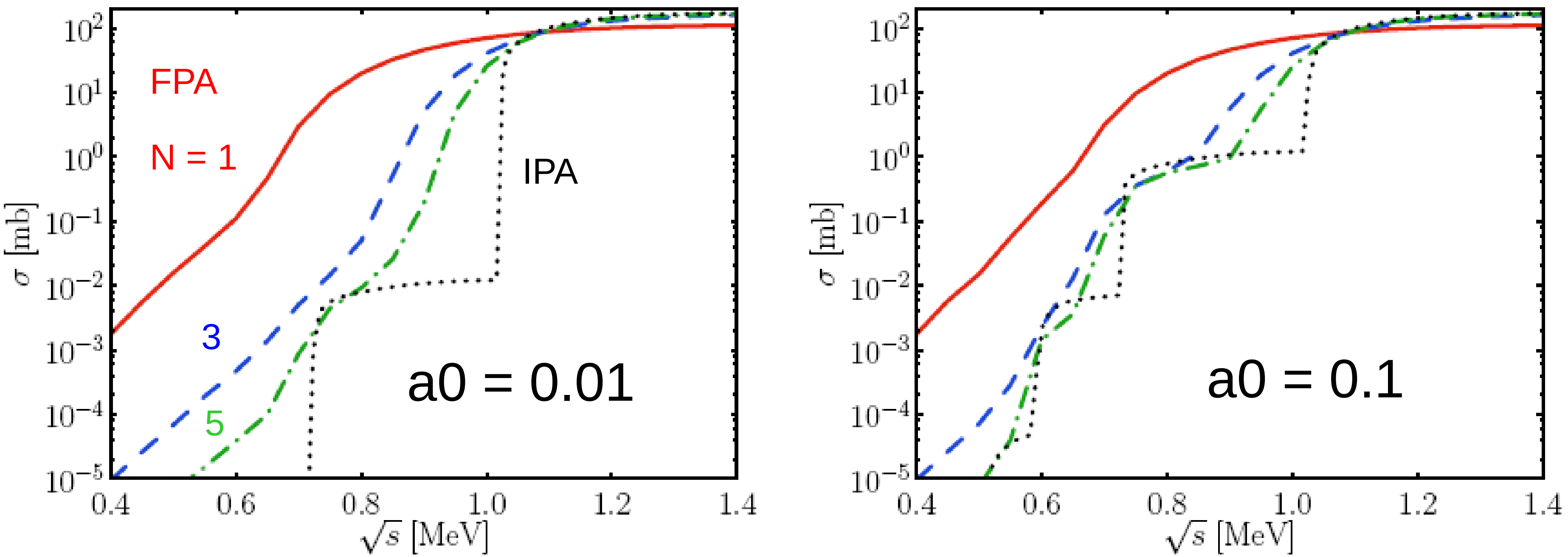
pulse shape: $g(\varphi) = cos^2(\varphi/2\,N)$

IPA | FPA, N = 1



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

N dependence



harmonics & finite bandwidth effects →

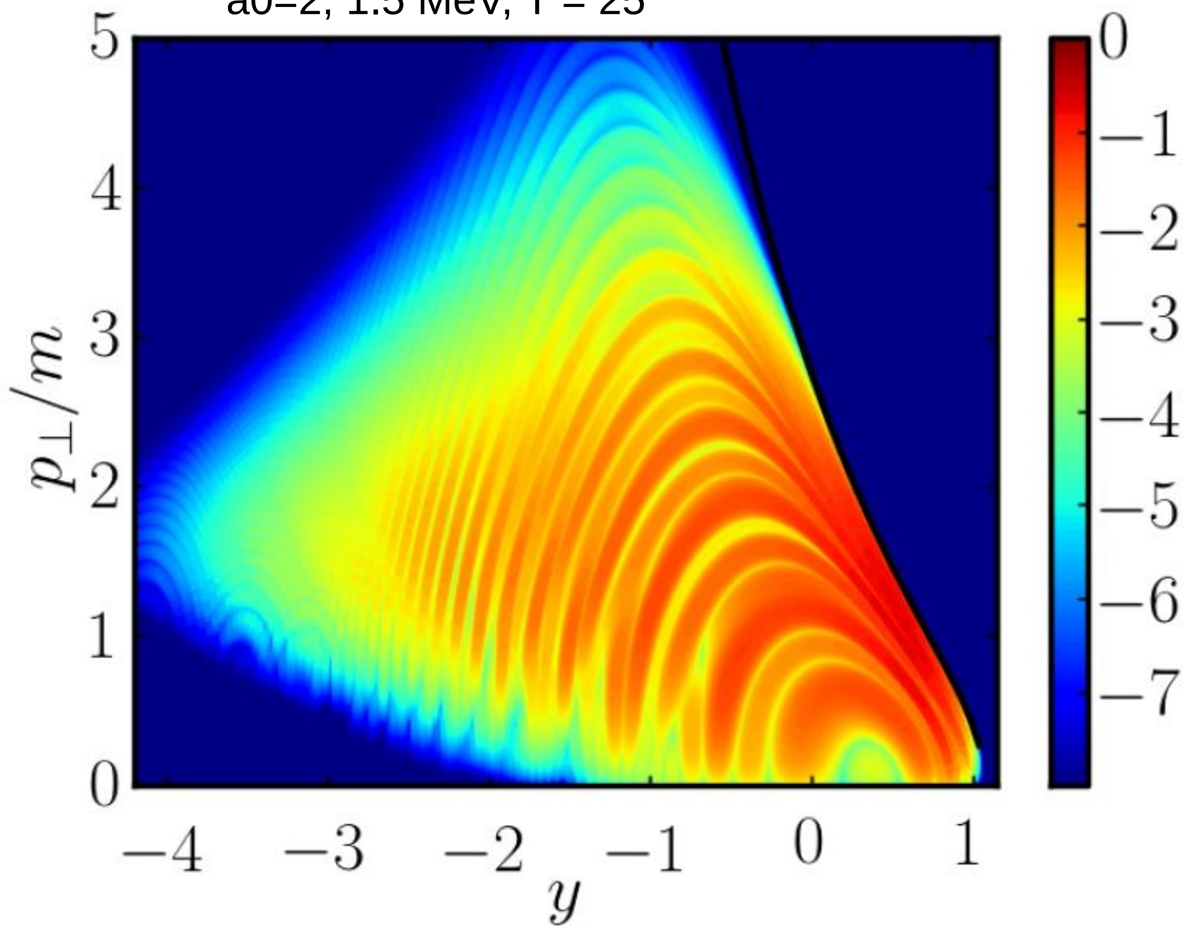
$\omega = \omega_L$ +- Δ

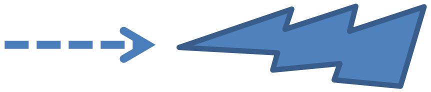
laser enabled subthreshold production

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

IPA & FPA: Asymmetry in Longitudinal Direction

a0=2, 1.5 MeV, T = 25



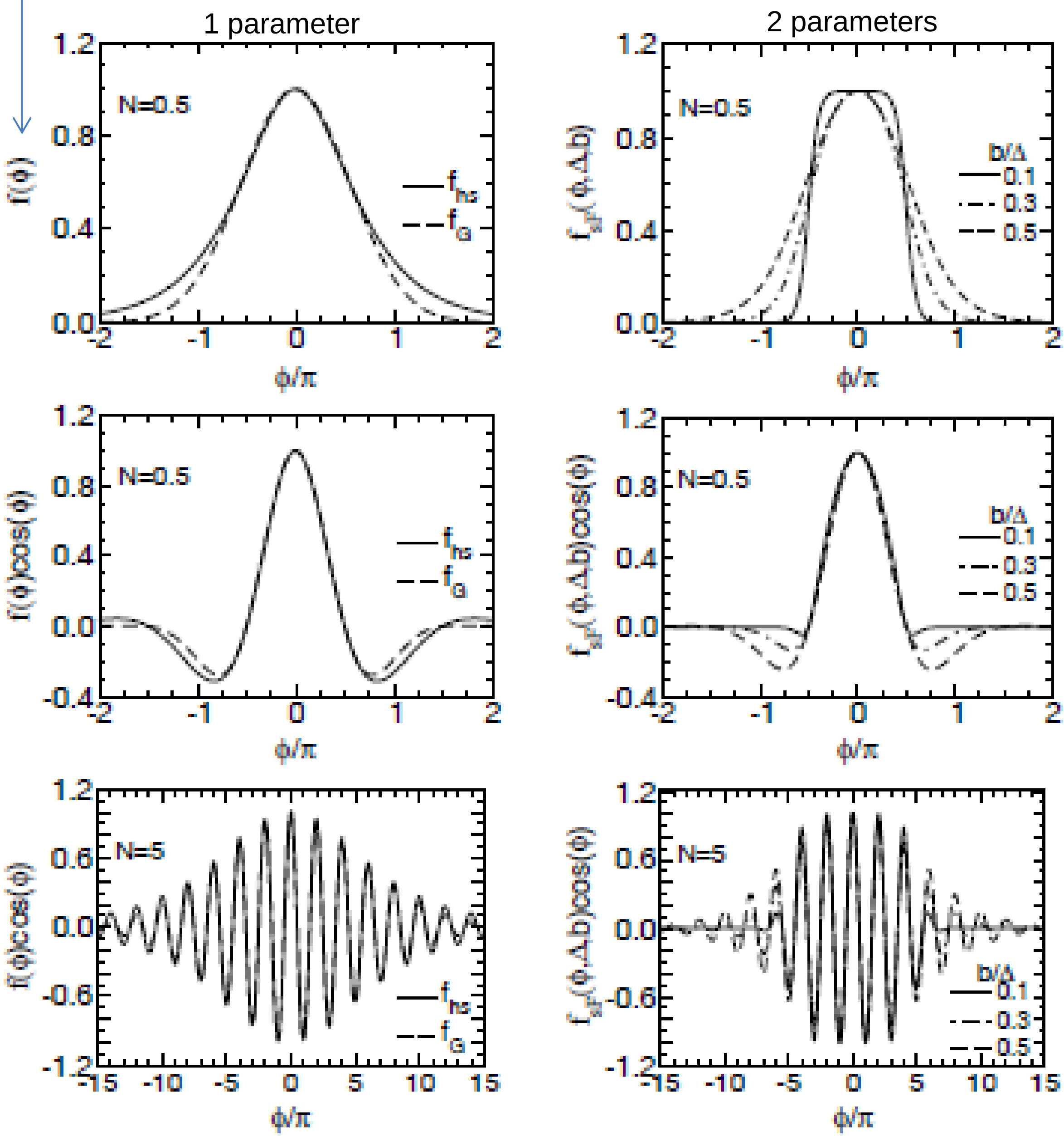


beam shape effects

T. Nousch, diploma thesis Dresden 2011

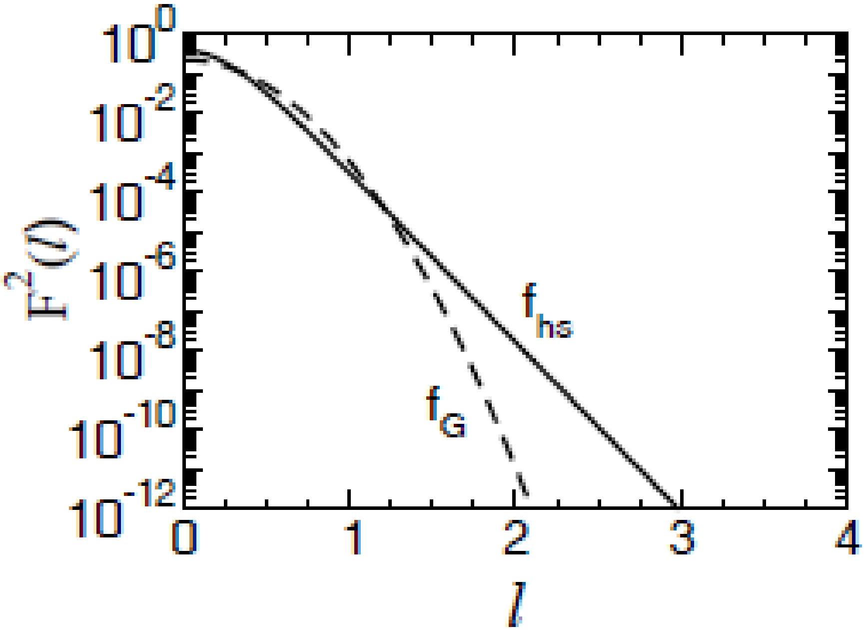
cf. Heinzl et al., PLB 2011

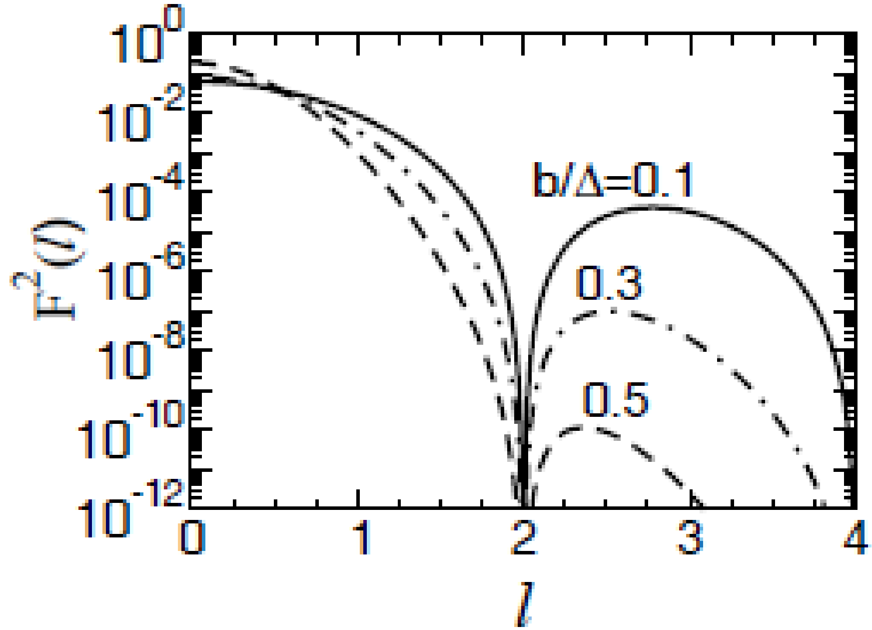
Pulse Shapes



Titov, BK, Takabe, Hosaka
PRA (2013)

Fourier Transforms





$$F_{\rm hs}(l) = \frac{\Delta}{2\cosh\frac{1}{2}\pi\Delta l}\ ,$$

$$F_{\rm G}(l) = \frac{\tau_{\rm G}}{\sqrt{2\pi}}\exp\left[-\frac{1}{2}\tau_{\rm G}^2 l^2\right]\ ,$$

$$F_{\rm sF}(l) = \frac{1+\exp\left[-\frac{\Delta}{b}\right]}{1-\exp\left[-\frac{\Delta}{b}\right]}\,\frac{b\,\sin\Delta l}{\sinh\pi b l}\ .$$

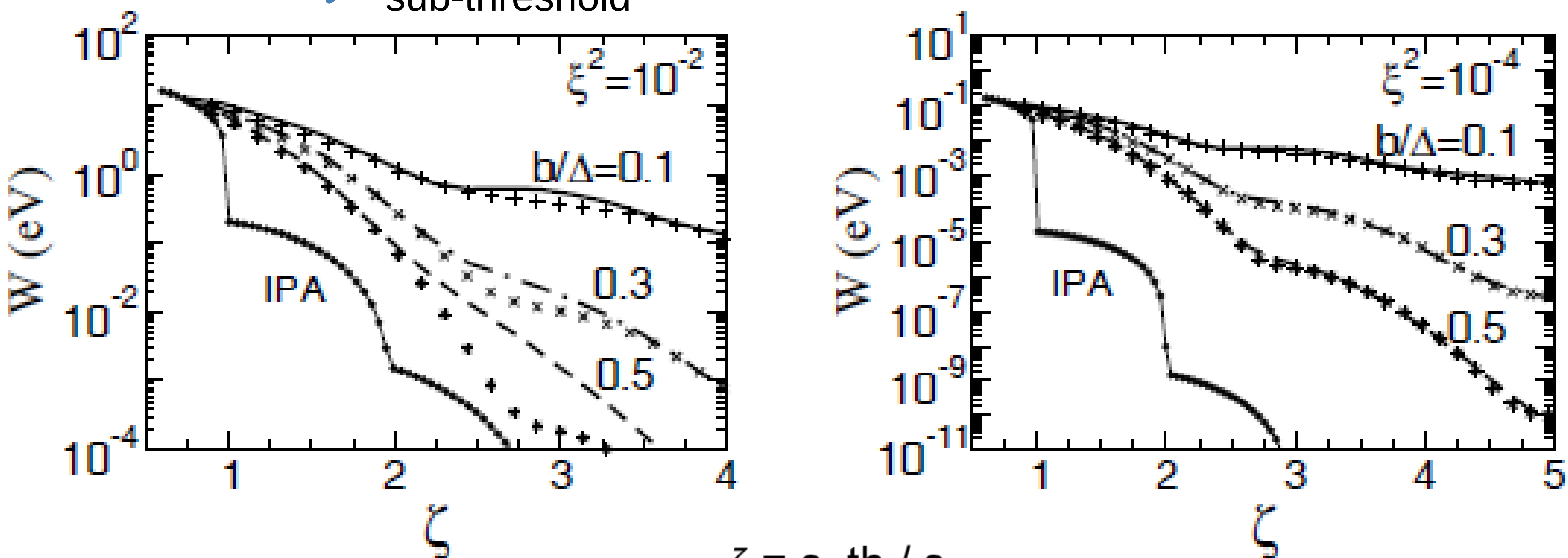
1 parameter: width

2 parameters:
flat-top section + ramping

$$dW = \frac{\alpha \zeta^{1/2}}{2\pi N_0 M_e} \int_{\zeta}^{\infty} dl \, |M_{fi}(l)|^2 \frac{d\vec{p}}{2p_0} \frac{d\vec{p}'}{2p'_0} \delta^4(k' + lk - p - p') \, .$$

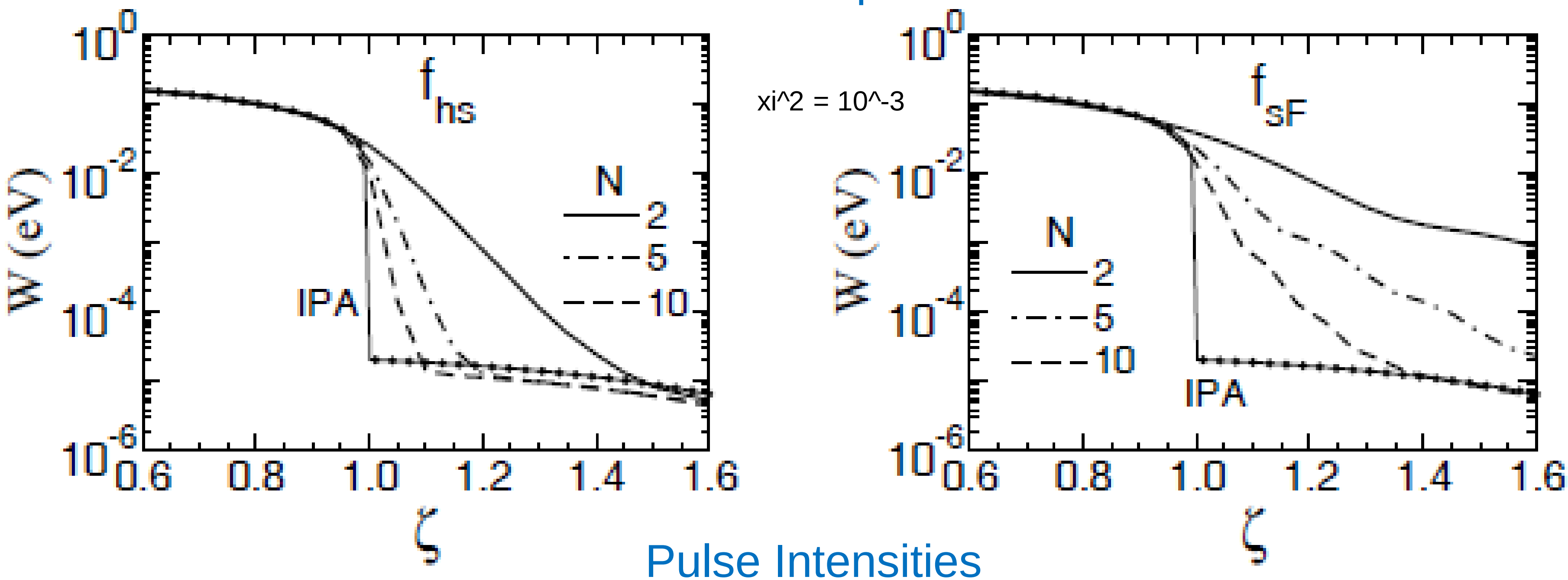
$$N_0 = \frac{\int_{-\infty}^{\infty} S \, dz \, (\mathrm{E}^2_{FPA} + \mathrm{B}^2_{FPA})}{\int_0^{\lambda} S \, dz \, (\mathrm{E}^2_{IPA} + \mathrm{B}^2_{IPA})} = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\phi \, (f^2(\phi) + f'^2(\phi)),$$

sub-threshold

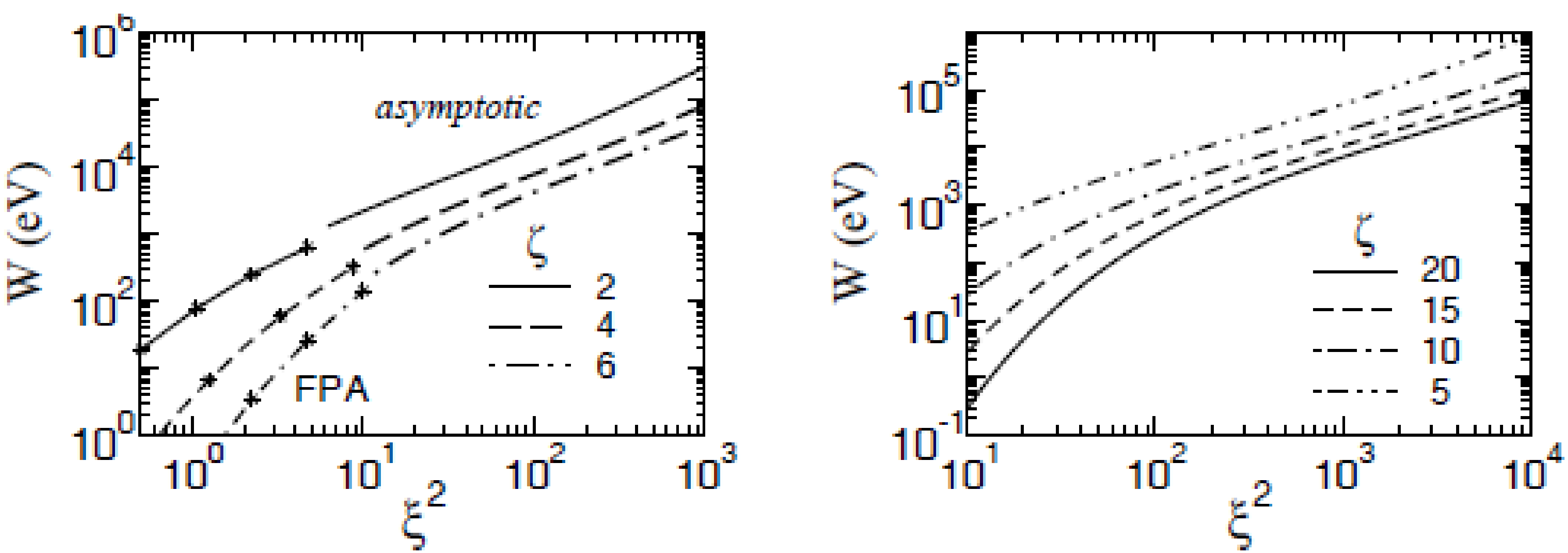


ζ = s_th / s

Pulse Shapes



Pulse Intensities



two regimes:

(i) $\xi\varsigma \ll 1$ $N < 2$: *high Fourier components enhance* W

ξ ↑ *intensity*, ς ↑ s_{th}/s

(ii) $\xi \gg 1$ *pulse shape and duration unimportant (dominant contribution from central pulse section)*

FPA $\sim$ *IPA*

(iii) $\xi \sim 1$ *complicated interplay of all effects*

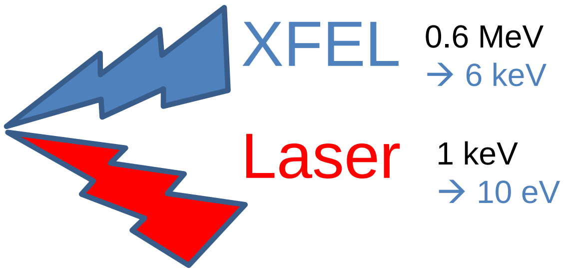
Titov, BK, Takbe, Hoska PRA (2013)

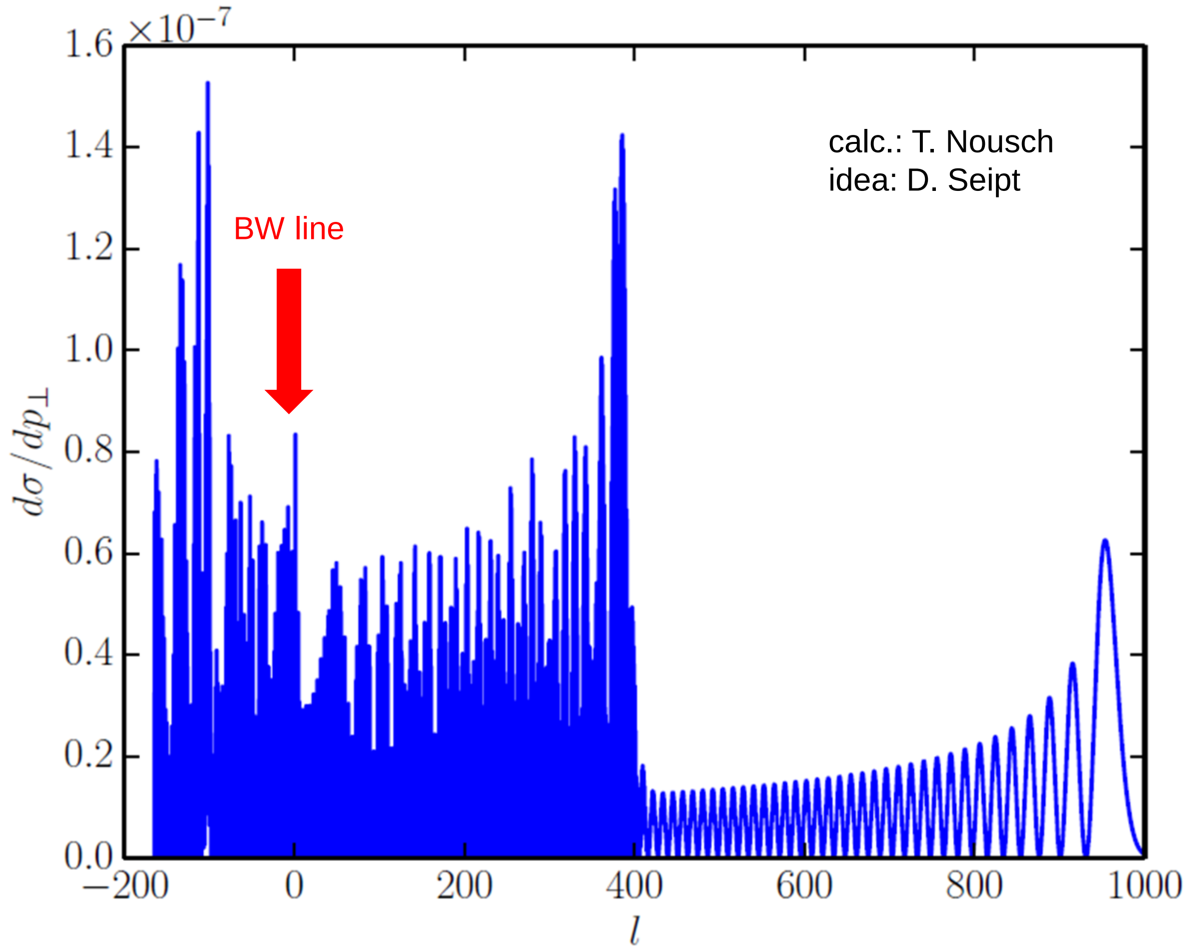
work in progress (T. Nousch):

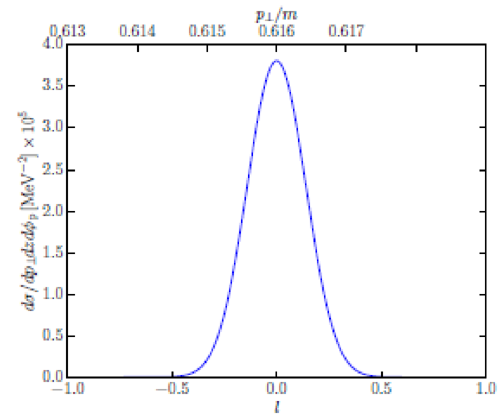
IPA: Jansen, Muller (2013), Wu, Xue (2014)

0.6 MeV
→ 60 MeV

Compton backscattering







w/o laser

caustics = stat. phase points
(quasi-class. motion after creation
with interferences)
redistribution in phase space by FSI

Caustics in laser assisted Breit-Wheeler process

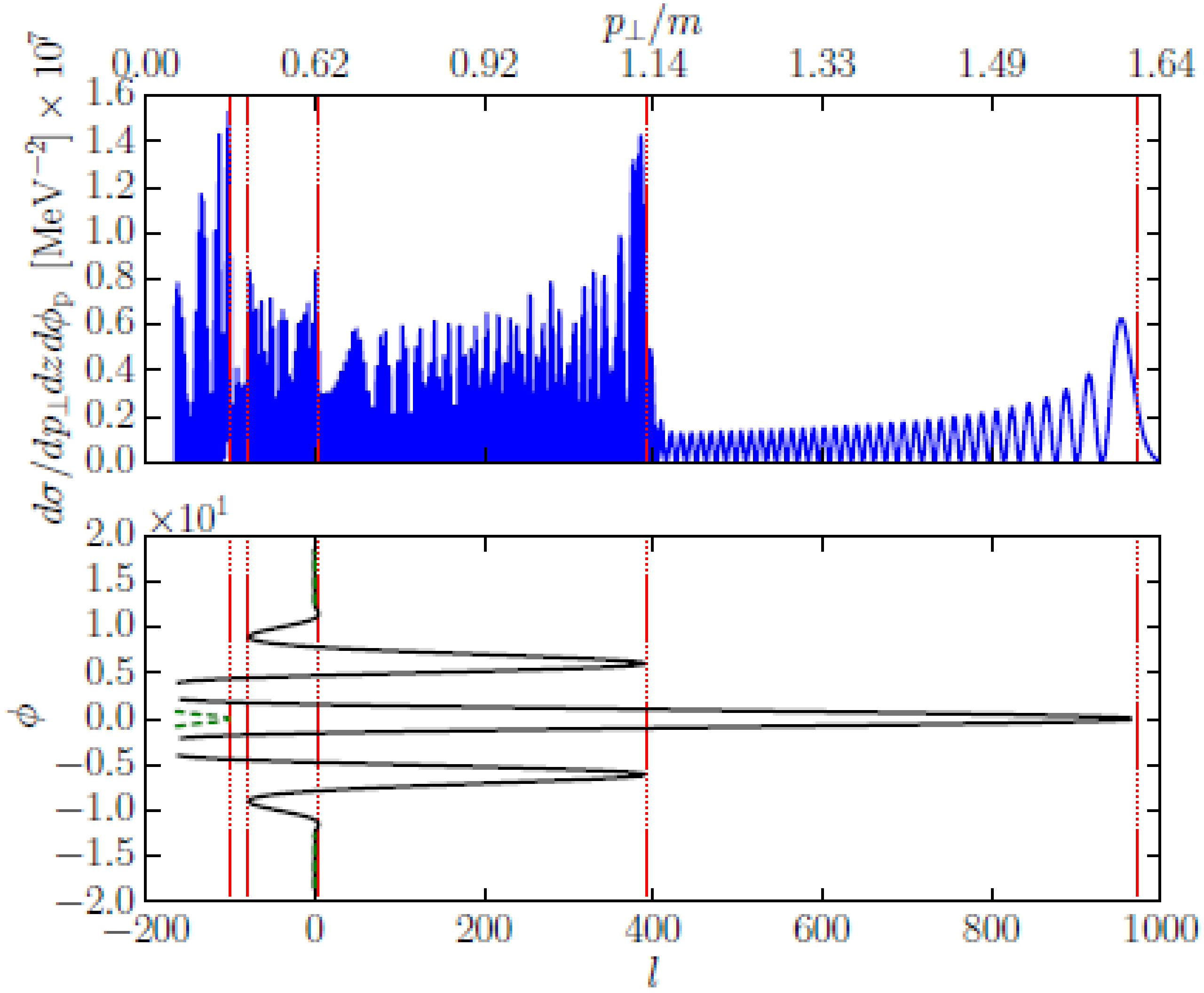
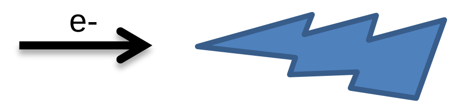


Figure 1: $a_{0L} = 1$, $a_{0X} = 10^{-5}$, $\sqrt{s} = 1.2$ MeV, $\omega_{ph} = \omega_X = 0.6$ MeV, $\omega_L = 1$ keV, $\tau_L = 4\pi$, $\tau_X = 5.1/\kappa$, $\kappa = \omega_L/\omega_X \simeq 1.67 \times 10^{-3}$, $g_L = \cos^2$, $g_X =$ Gauss, lineare Polarisation, $\phi_{pos} = \pi$, $z = 0$

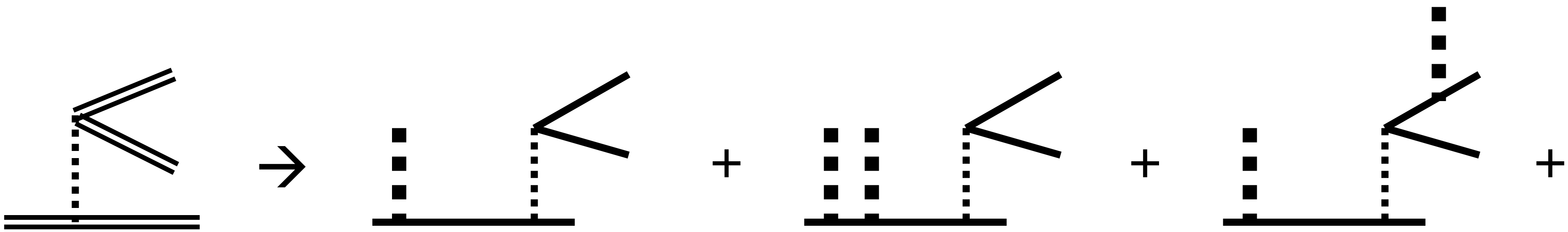
Trident Process

(= Virtual Compton Process)

E-144 at SLAC

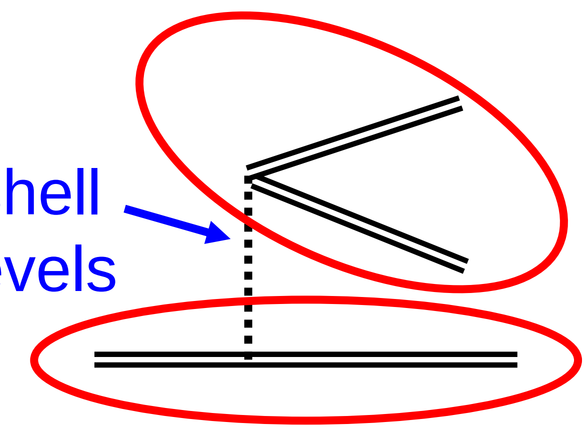


(= Cross Channel of Moller/Bhabha Scattering)



Di Piazza et al., PRL 2010
Ilderton, PRL 2011

photon propagator: on-shell + off-shell
→Oleinik divergences/Zeldovich levels



pair prod.

Compton

first step in cascades: avalanches of e+ e- pairs → plasma

Member of the Helmholtz Association
B. Kampfer I Institute of Radiation Physics I www.hzdr.de

QED cascades and ultimate electric field?

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 054401 (2011)

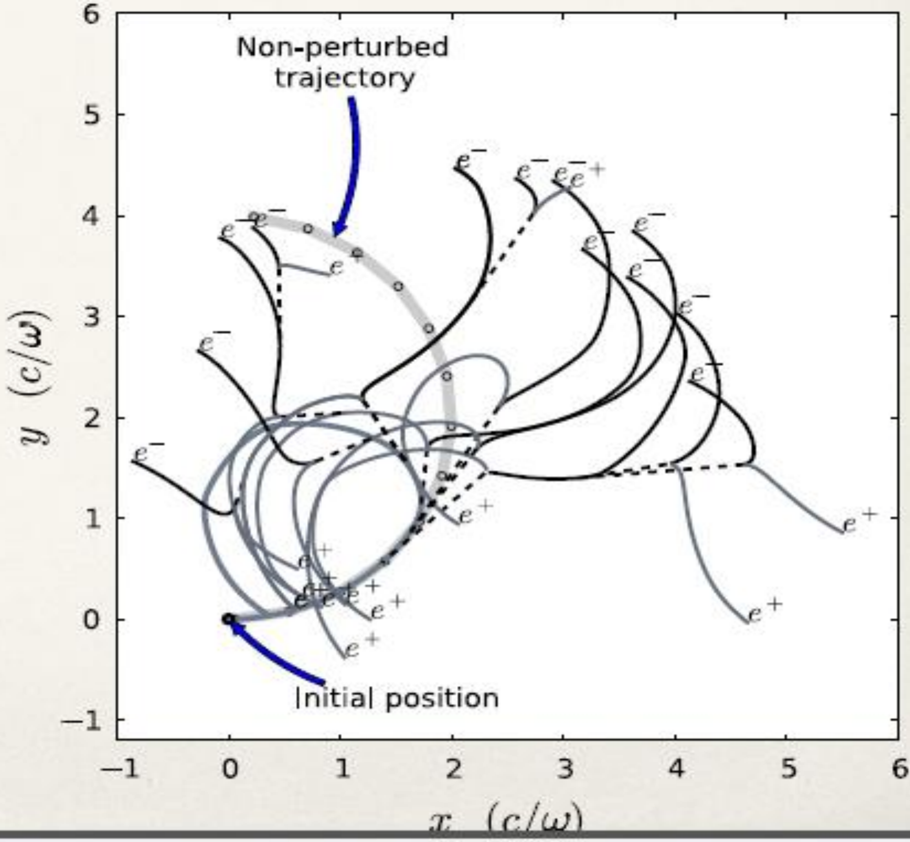
QED cascades induced by circularly polarized laser fields

N. V. Elkina,[1] A. M. Fedotov,[2] I. Yu. Kostyukov,[3] M. V. Legkov,[2] N. B. Narozhny,[2] E. N. Nerush,[3] and H. Ruhl[1]
[1]*Ludwig-Maximilians Universität München, 80539, Germany*
[2]*National Research Nuclear University MEPhI, Moscow, 115409, Russia*
[3]*Institute of Applied Physics, Russian Academy of Sciences, 603950, Nizhny Novgorod, Russia*
(Received 22 October 2010; published 12 May 2011)

Monte-Carlo simulations

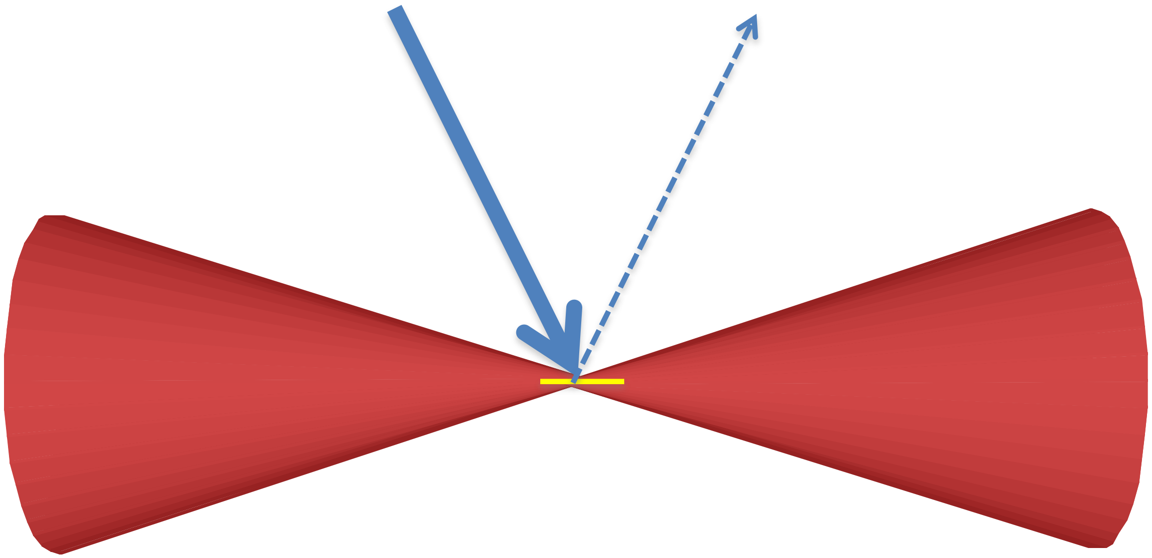
includes radiation friction

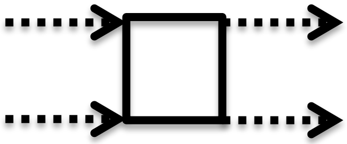
fully quantum treatment needed



from G. Dunne, PIF 2013

Photon-Photon Scattering
Quantum- Reflection



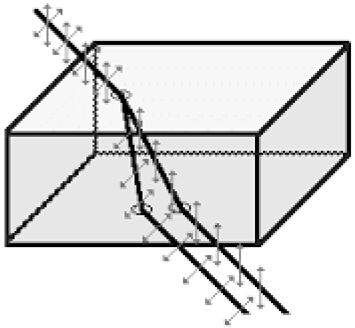


- Use different wavelengths, polarisation
- Ensure good vacuum
- Eliminate shots with ions present.

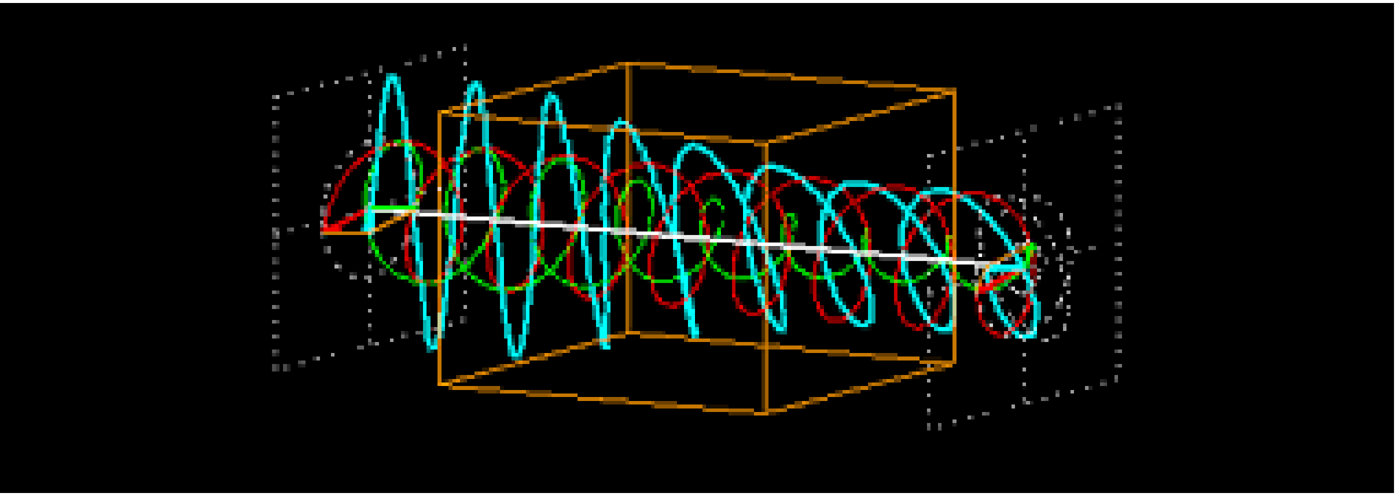
- Reflectivity from refractive index variation due to intense laser focus.
  - Giess, Karbstein, Seegert on [arXiv:1305.2320]
- Reflectivity about 10^{-19} for 200TW laser focus
- Few photons refelected per shot for 200TW class lasers

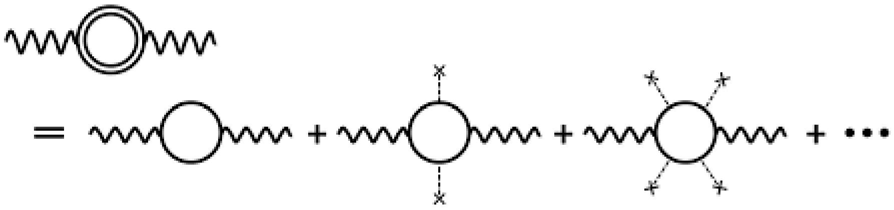
from M. Zepf PIF 2013

Vacuum Birefringence



rotation of polarization in external (laser) field
(test of „material properties“ of vacuum)





a project at HIBEF
key: polarizers (HIJ)

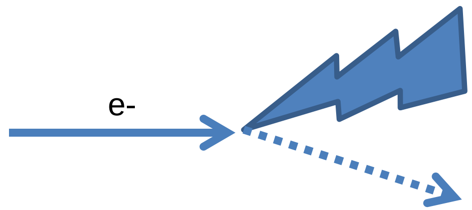
Member of the Helmholtz Association
B. Kampfer I Institute of Radiation Physics I www.hzdr.de

Interim Summary of § 2: Breit-Wheeler Process

light → matter + anti-matter

- finite pulses → bandwidth effects
- higher harmonics
- intensity effects

Breit-Wheeler = crossing channel of Compton



X rays for pump probe exps.

Summary

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

Schwinger: strong assistance by 2nd field

Breit-Wheeler: sub-threshold, pulse length, pulse shape, intensity

elementary 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)

Outlook

single line	free electron / positron	pQED
double line	laser dressed (Volkov)	sQED
triple line	laser + Coulomb	sQED

double line → spatio-temporal structure

$$QED_{light}:\ \gamma, e^{\pm} \longrightarrow QED_{heavy}:\ \gamma, e^{\pm}, \mu^{\pm}, \tau^{\pm}$$

$$QED:\ \gamma, e^{\pm}, \mu^{\pm}, \tau^{\pm}, hadrons/quarks$$

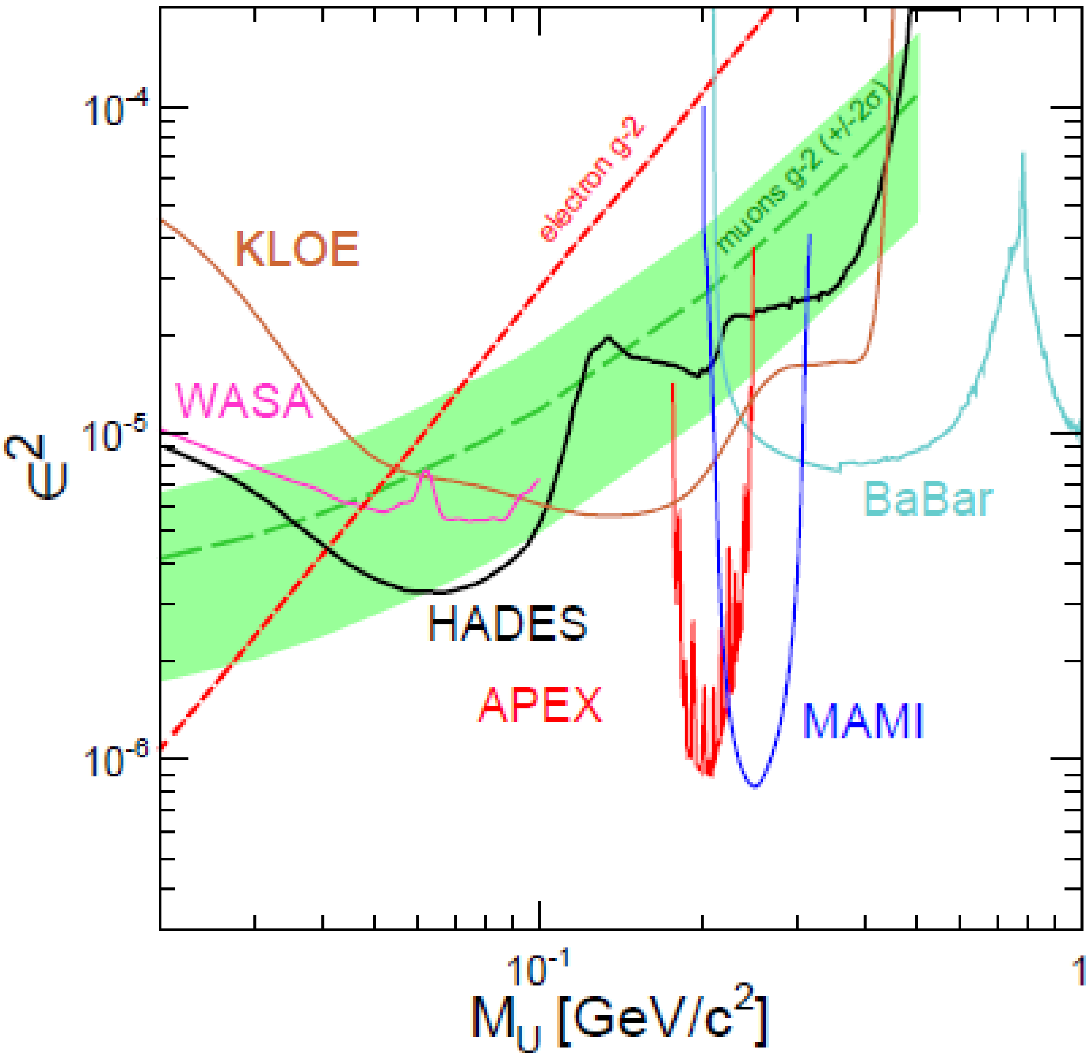
$$QED_{e.w.}:\ \gamma, Z^0, e^{\pm}, \mu^{\pm}, \tau^{\pm}, hadrons/quarks, W^{\pm}, \nu$$

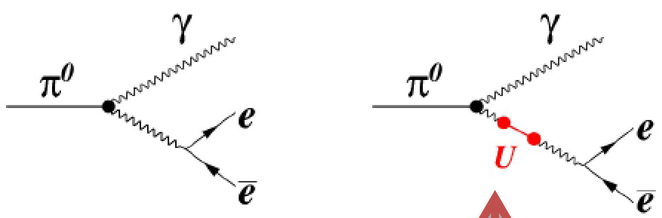
What is beyond QED? $\mathcal{L} = -\frac{1}{4}F^2 + j \cdot A + ?$, 4D → XD

$U(1) \otimes SU(2) \rightarrow ?$, new couplings, new fields, …

Searching a Dark (U) Photon

HADES, Phys.Lett. B731 (2014) 265





Dark Matter candidate beyond SM

$\Omega = 1$

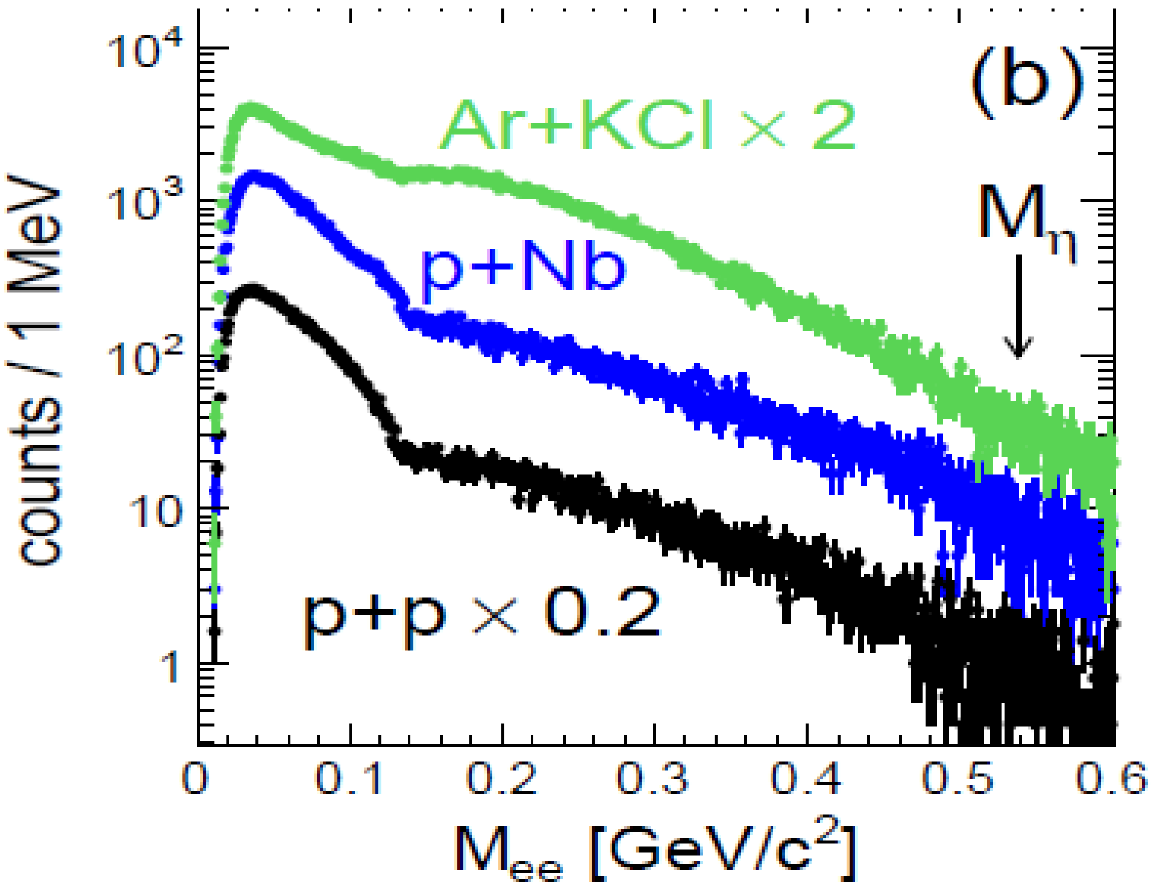
$\Omega_{DE} = 0.75$ (Λ ?)

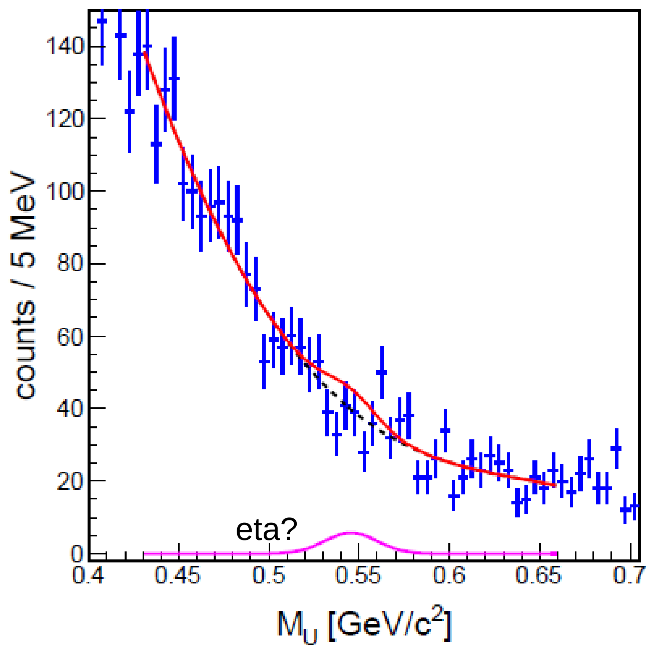
$\Omega_{DM} = 0.20$

$\Omega_B = 0.05$

excluding more and more

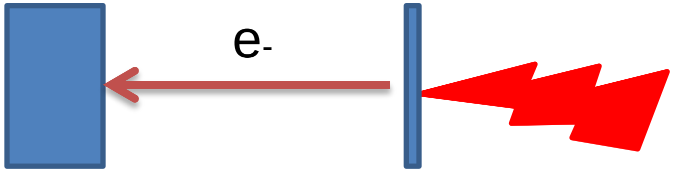
searching a signal in background



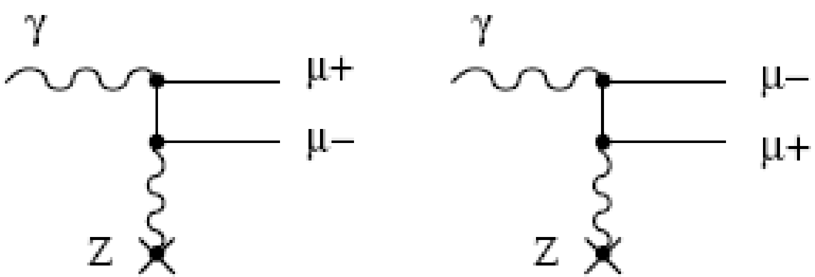


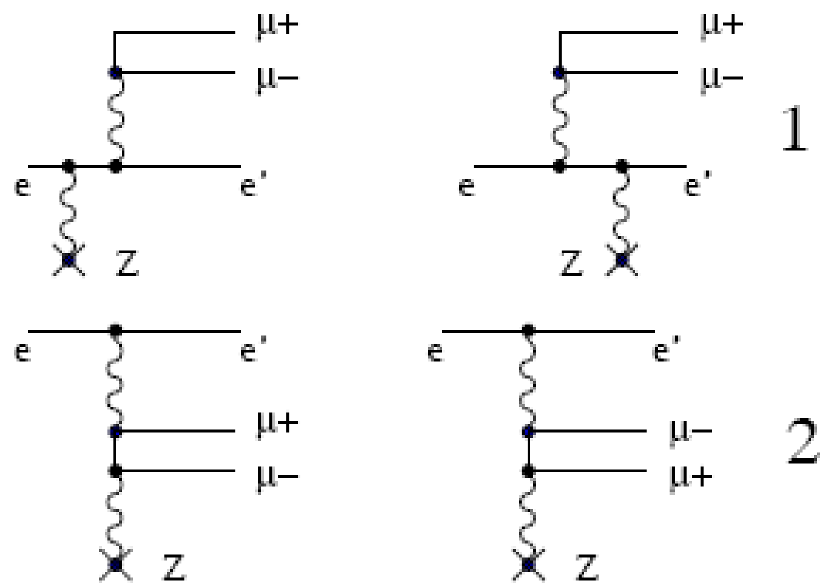
Kolomogorov-Smirnov test, Cousins-Feldman method

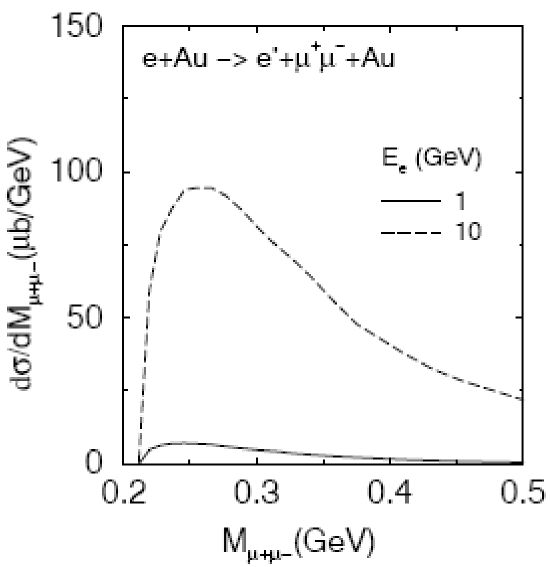
Muon Pair Production

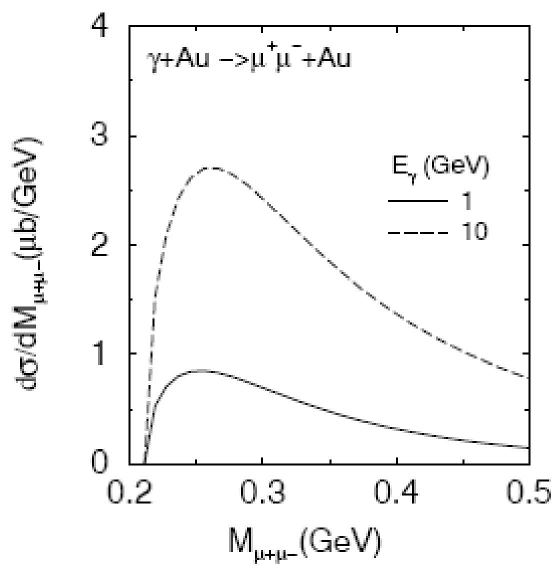


Bethe-Heitler



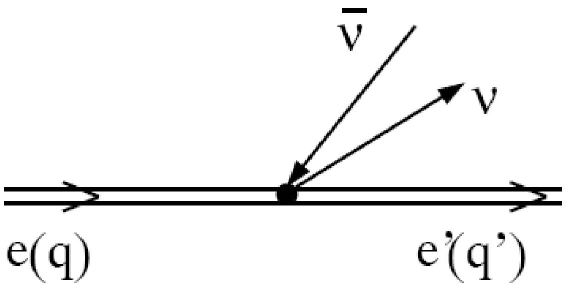






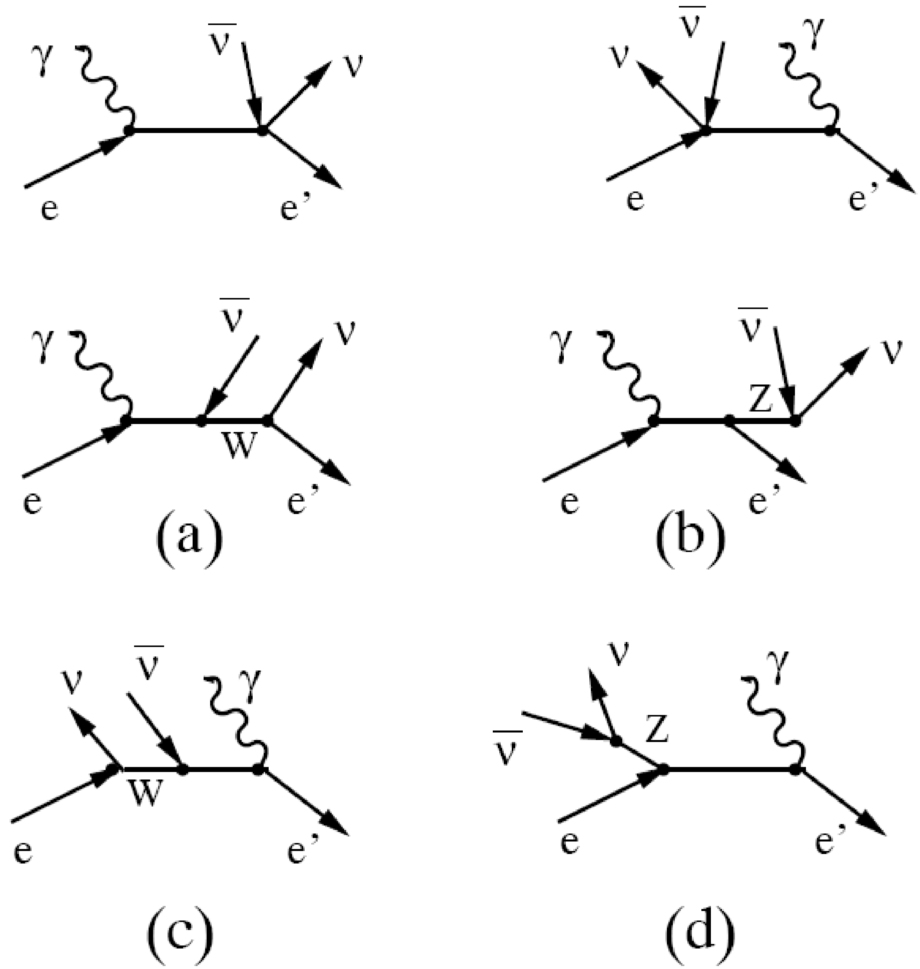
Titov, BK, PR ST AB 2009

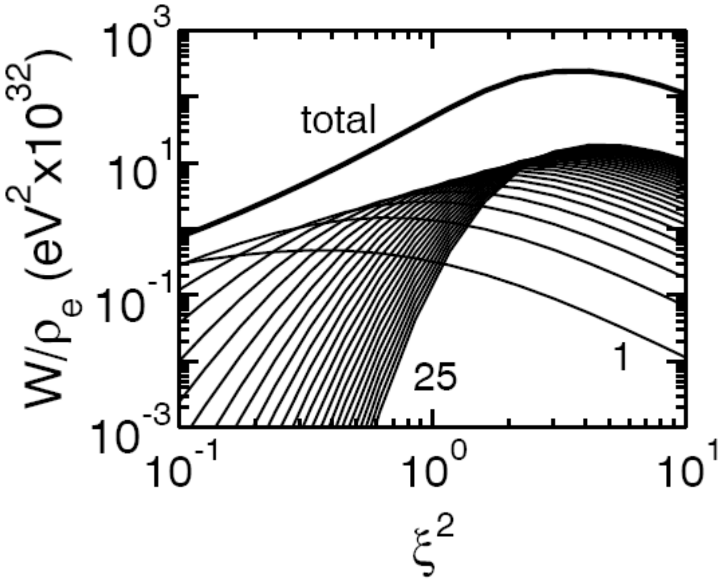
Neutrino Pair Production



→

→





Titov, BK, Hosaka, Takabe, PRD 2011

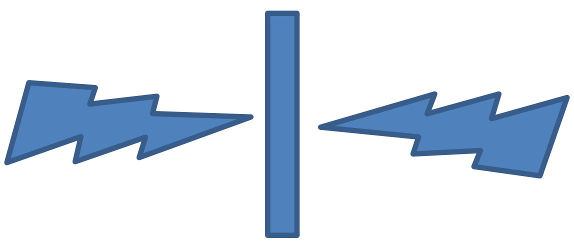
e+ e- Nano Droplets

I. Kuznetsova, J. Rafelski, arXiv:1109.3546
L. Labun, J. Rafelski, arXiv:1107.6026;
I. Kuznetsova, D. Habs, J. Rafelski, PRD 2010
I. Kuznetsova, D. Habs, J. Rafelski, PRD 2008
A.G. Aksenov, R. Ruffini, G.V. Vereshchagin, PRE2010
R. Ruffini, G. Vereshchagin, She-Sheng Xue, Phys. Rept. 2010
A.G. Aksenov, R. Ruffini, G.V. Vereshchagin, PRD 2009

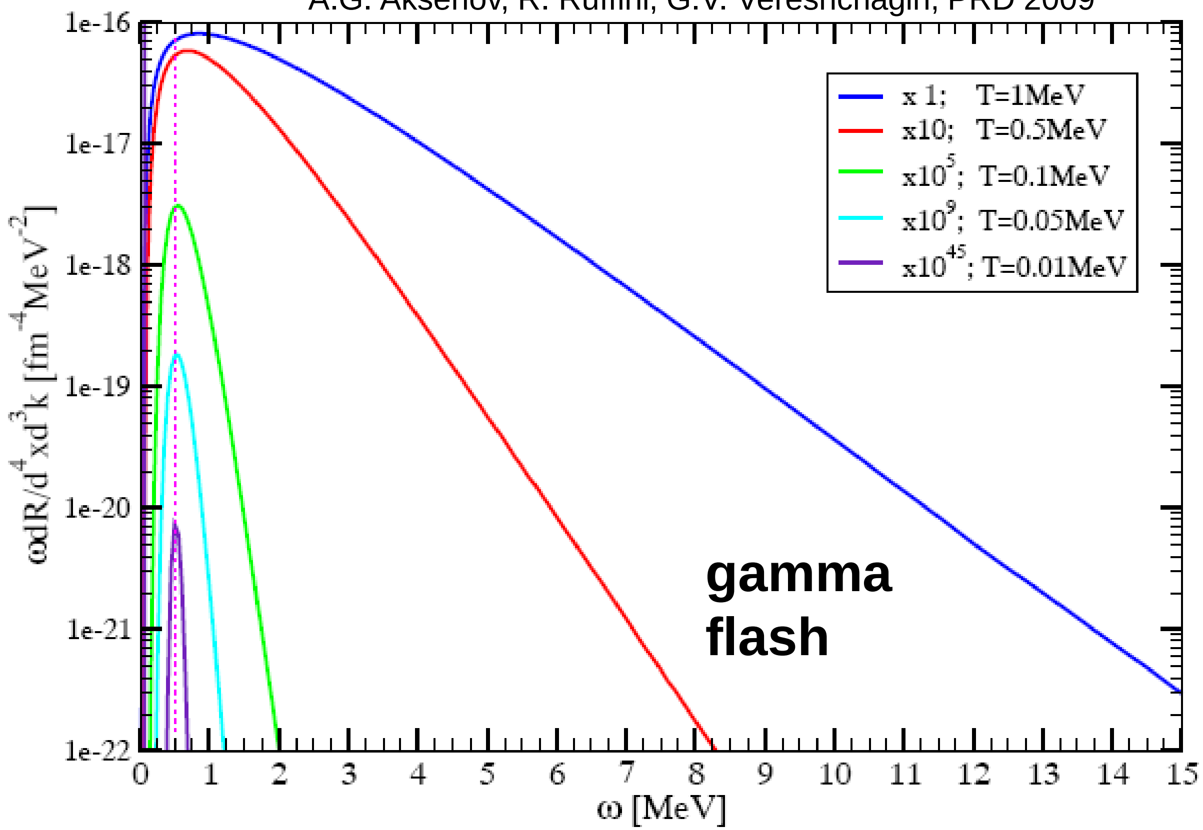
Yaresko, Munshi, BK, Phys. Plasma 2011
Munshi, BK, PRA 2009

QED Avalanches

Fedotov et al., PRL 2010
Nerush et al., PRL 2011
Elkina et al., PR ST AB 2011
Sokolov et al., PRL 2010
Bell, Kirk, PRL 2008
Bulanov et al., NIM 2011

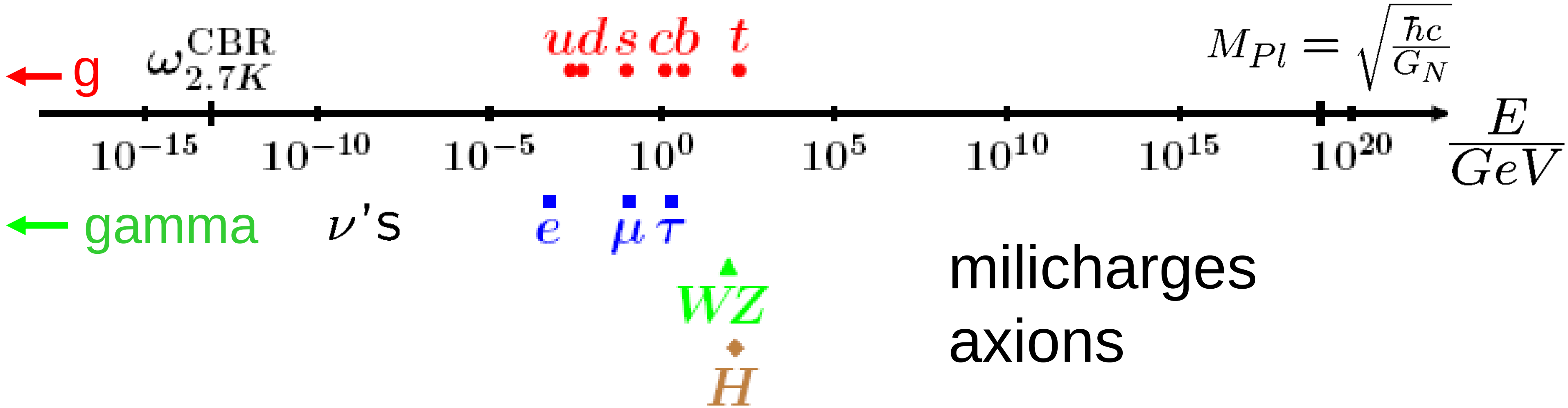


Shen, Meyer ter Vehn, PRE 2002

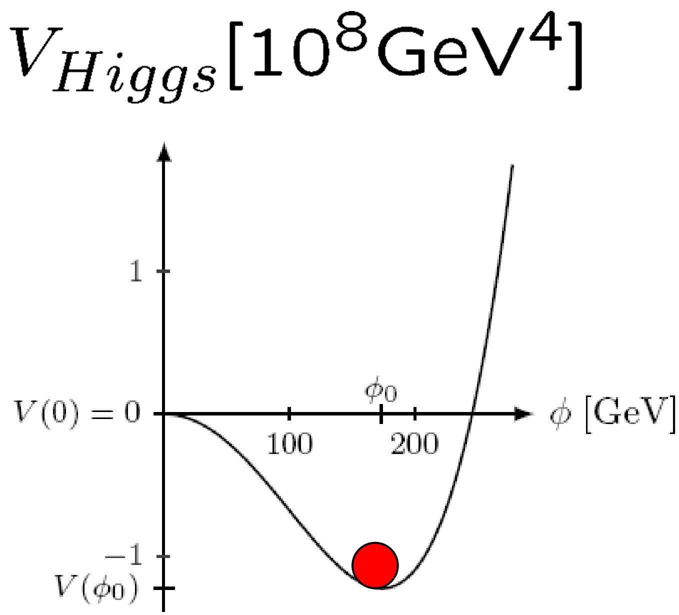


analog to early universe: e+ e- annihilation

SM Higgs: Mass Matters (Die Masse macht‘s)



milicharges
axions
....



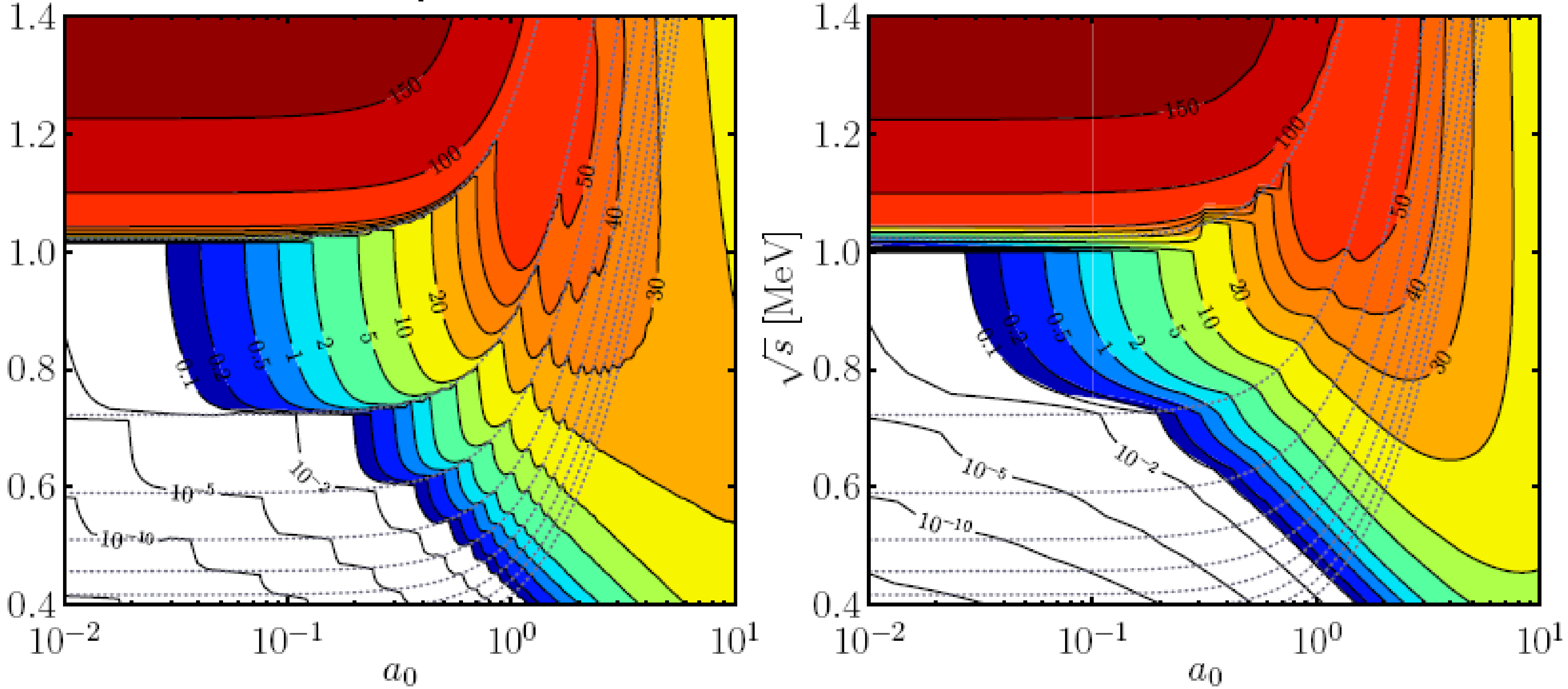
vacuum parameters:

$$e = V(\phi_0) = -1.22 \times 10^8 \,\mathrm{GeV}^4$$
$$\phi_0 = 174 \ \mathrm{GeV}$$
$$m_\phi = 126 \ \mathrm{GeV}$$

the new ether?

σ [mb]

IPA, lin. pol. — IPA, circ. pol.



$$a_0 = 7.5 \sqrt{I_L / 10^{20} \frac{W}{cm^2}} \frac{eV}{\omega_L}$$

$$\kappa = 6\ 10^{-2} \sqrt{I_L / 10^{20} \frac{W}{cm^2}} \frac{\omega_1}{GeV}$$

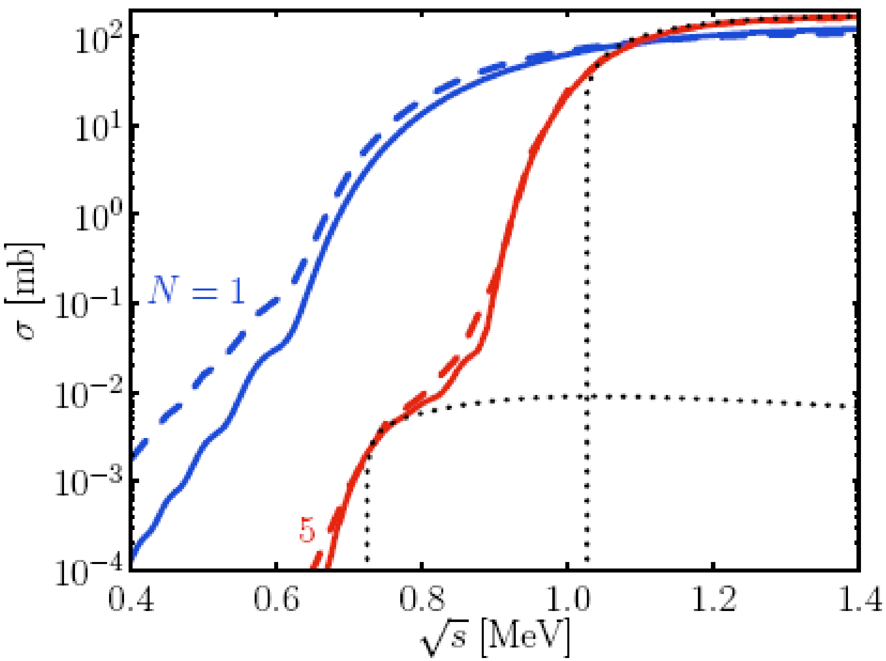
D. Seipt: Folding Model (i)

Fourier transform of g

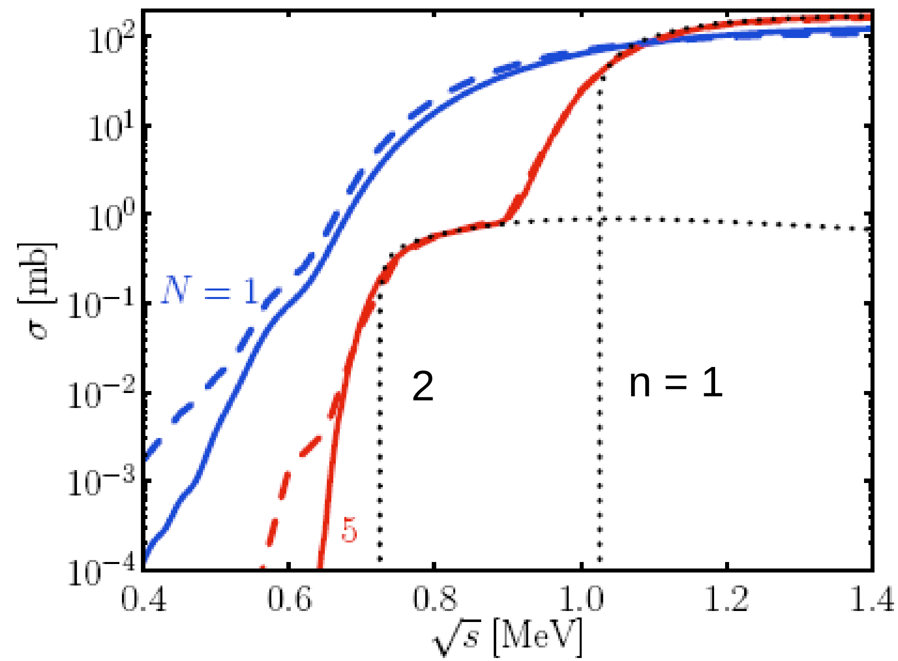
weak field harmonics

$$\langle \sigma_n \rangle (s) = R_n \frac{\int_0^\infty d\ell \, G(\ell - 1)^{2n} \sigma_n^{(0)}(\ell s)}{\int_0^\infty d\ell \, G(\ell - 1)^{2n}},$$

a0 = 0.01



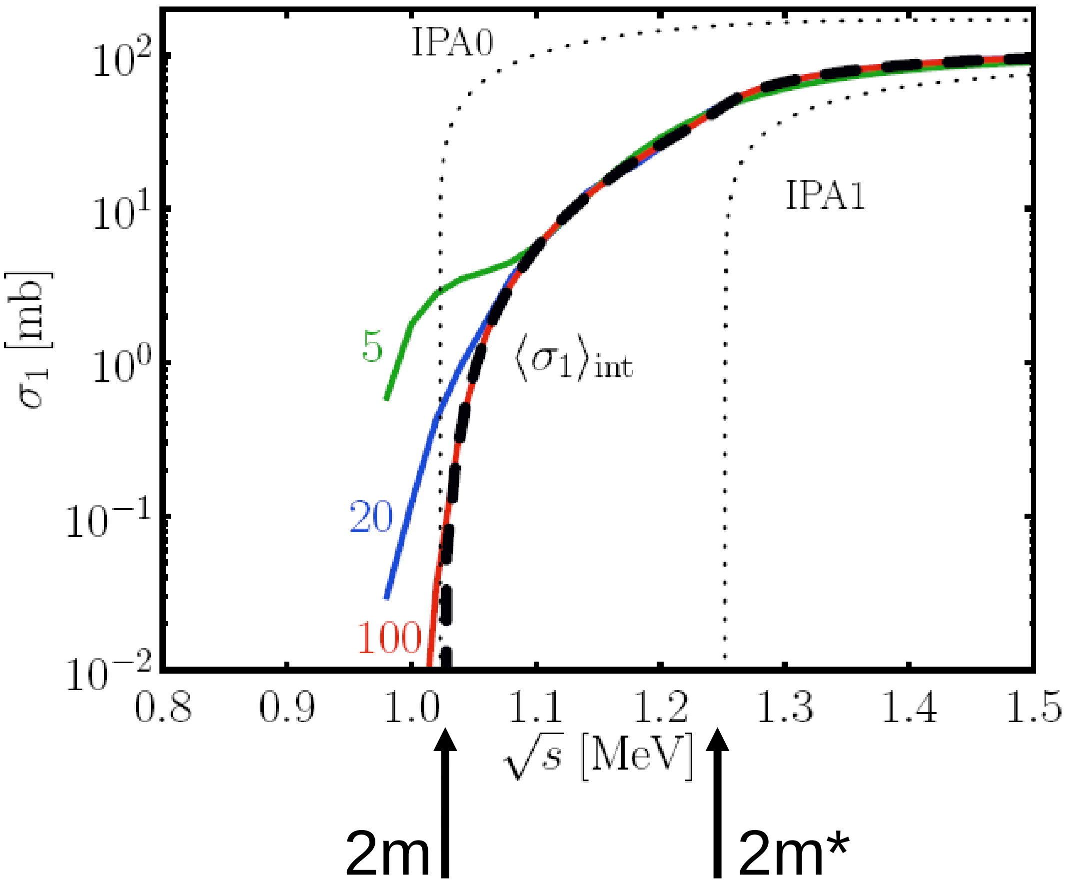
a0 = 0.1



D. Seipt: Folding Model (ii)

IPA, 1st harmonic

$$\langle \sigma_1 \rangle_{int} = \frac{\int d\phi\, g^2(\phi)\, \sigma_1(a, a_0 \to a_0 g(\phi))}{\int d\phi\, g^2(\phi)}$$



$N^{-1} > a_0^2$:

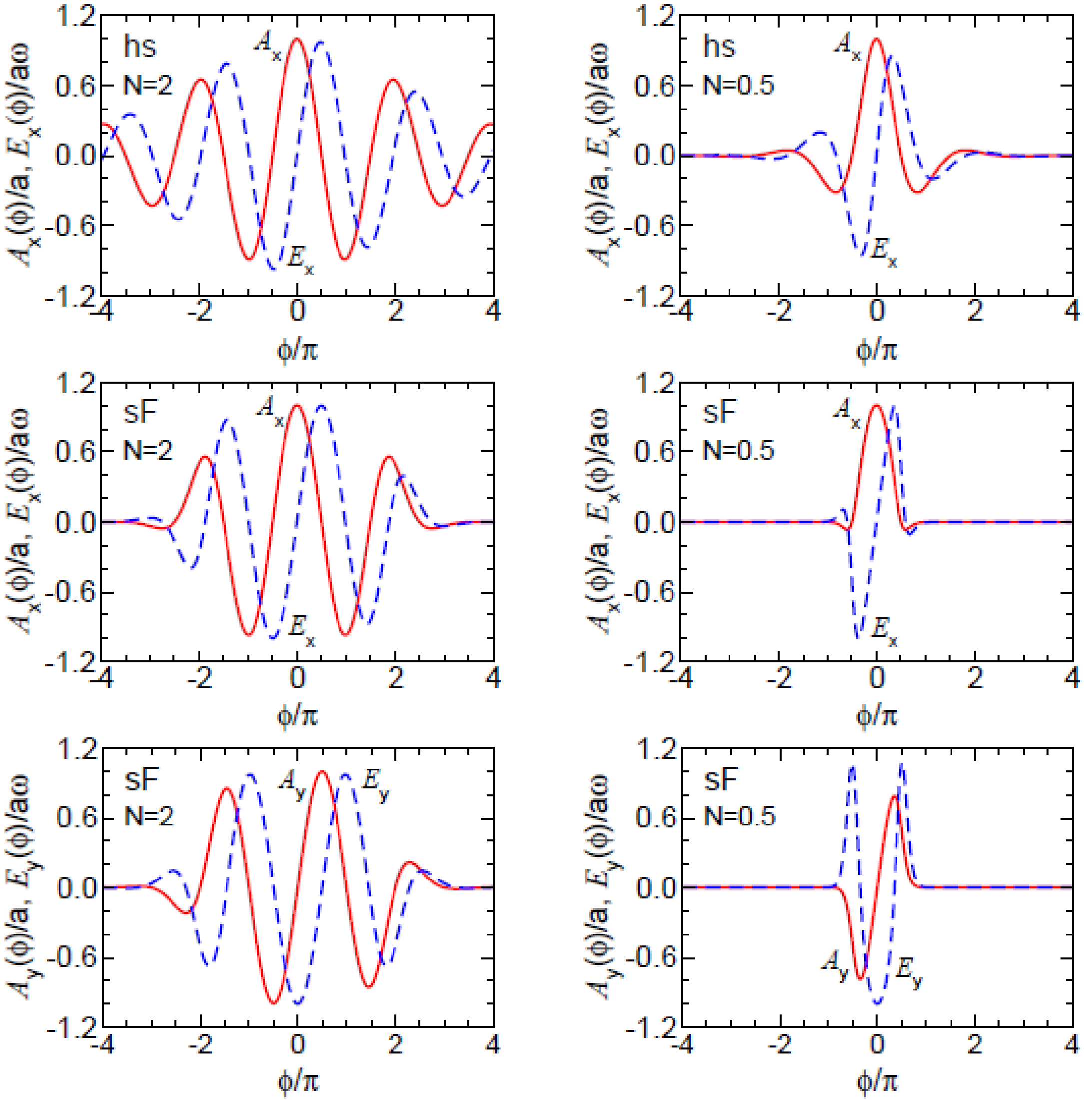
frequency distr. → spectrum

$N^{-1} < a_0^2$:

intensity variation → spectrum

3. Compton: ultra-short pulses

$$\vec{A}(\phi) = f(\phi)\left(\vec{a}_1 \cos(\phi + \tilde{\phi}) + \vec{a}_2 \sin(\phi + \tilde{\phi})\right)$$

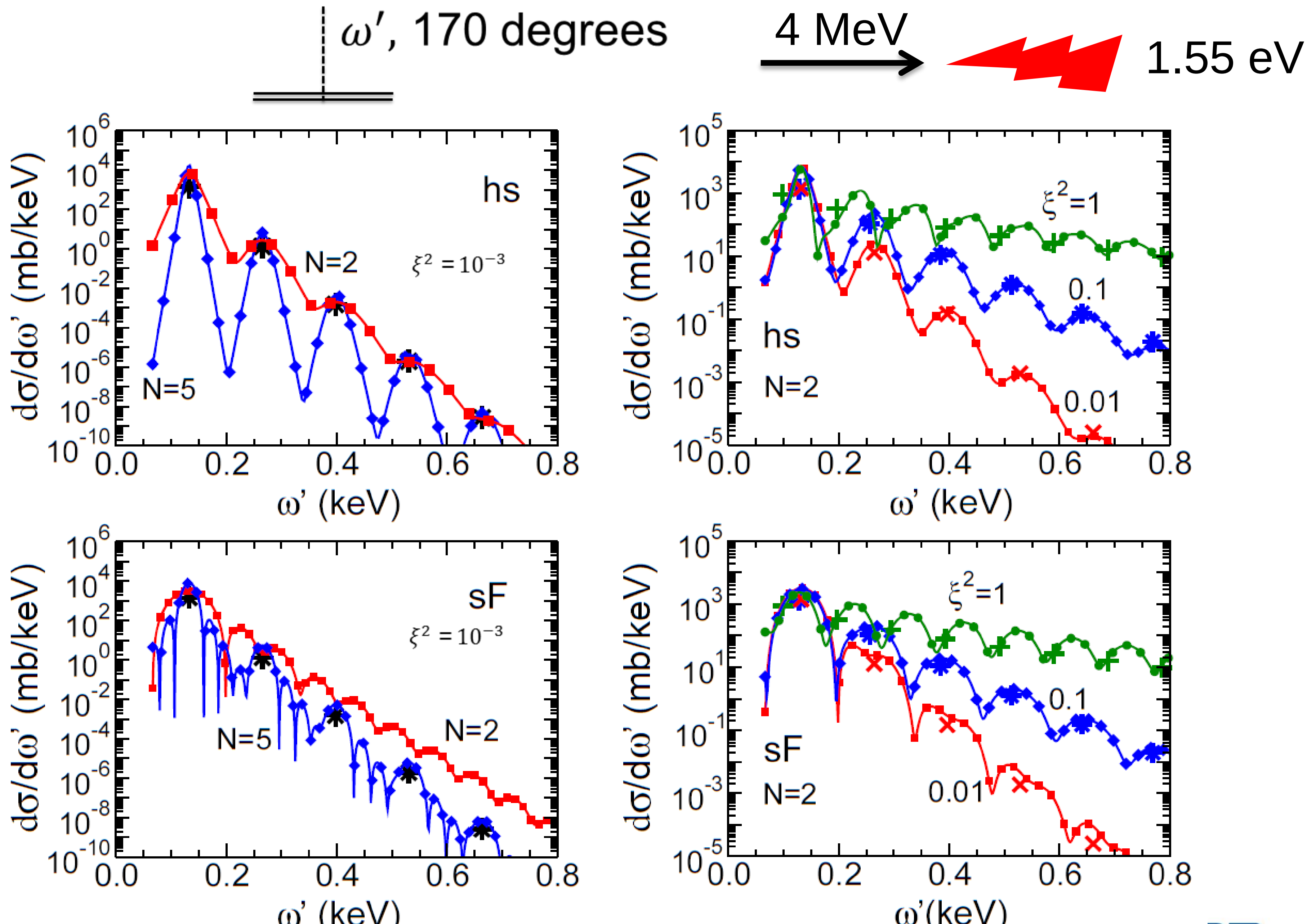


$$f_{\mathrm{hs}}(\phi) = \frac{1}{\cosh \frac{\phi}{\Delta}}$$

$$f_{\mathrm{sF}}(\phi) = \frac{\cosh \frac{\Delta}{b} + 1}{\cosh \frac{\Delta}{b} + \cosh \frac{\phi}{b}}$$

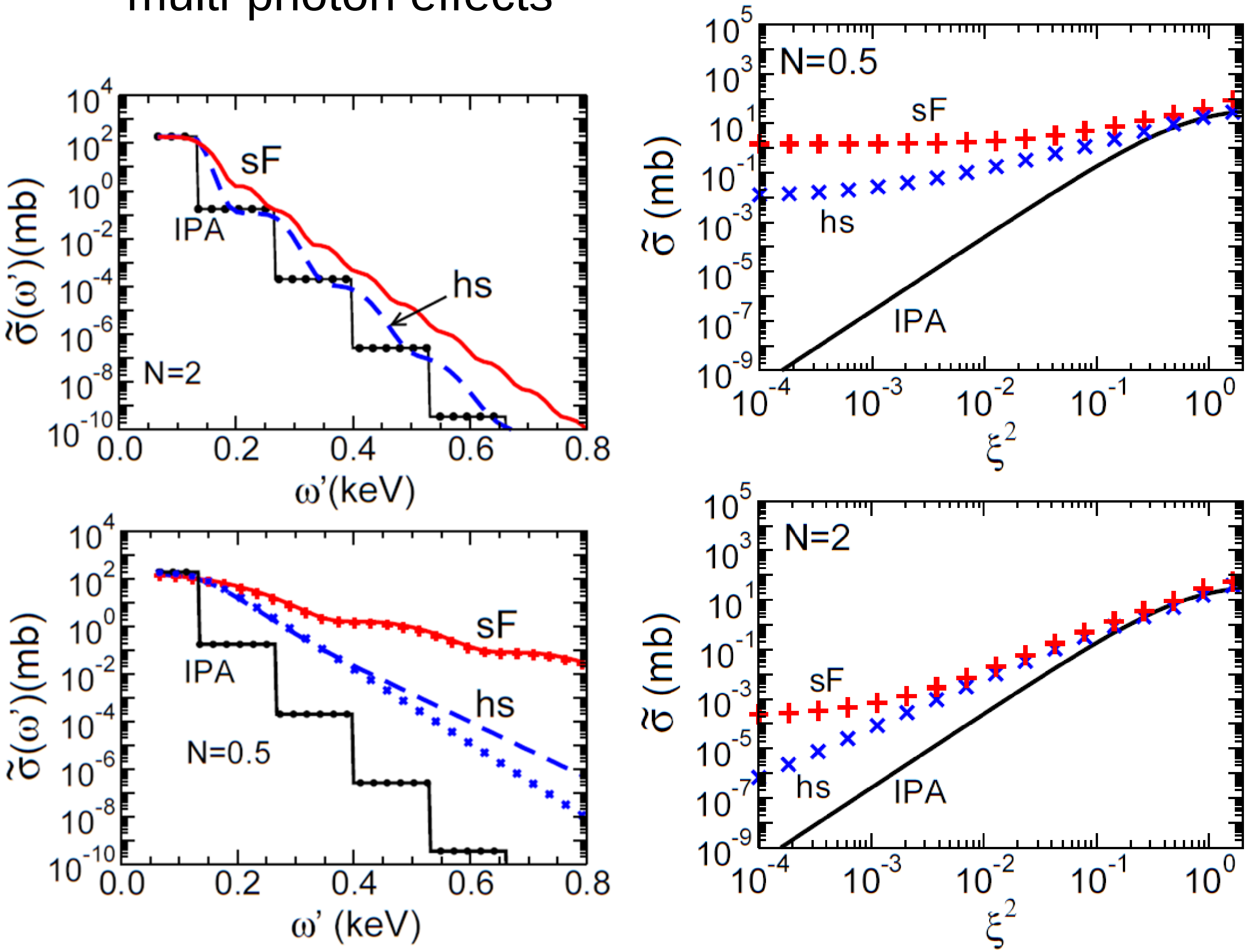
N = Delta/pi

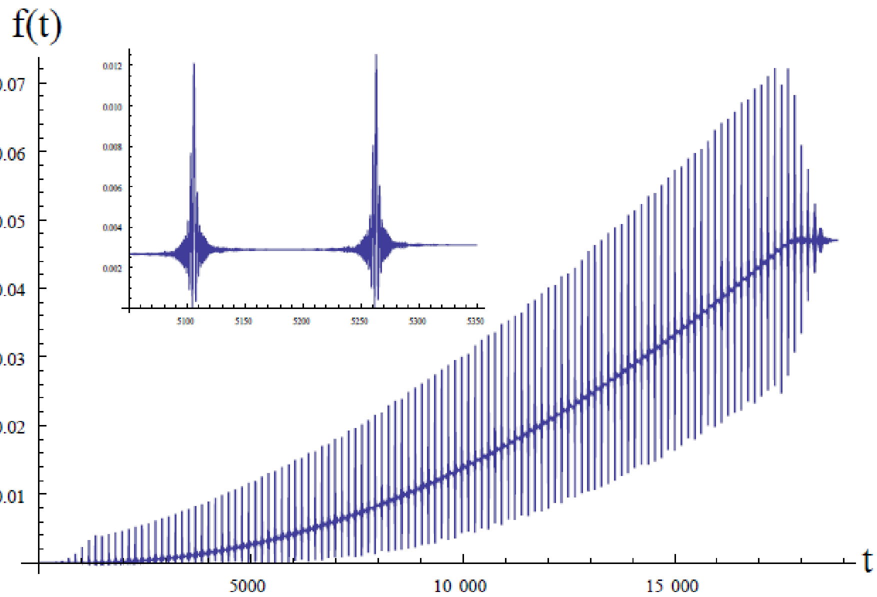
Titov, BK, Shibata, Hosaka, Takabe
1408.1040

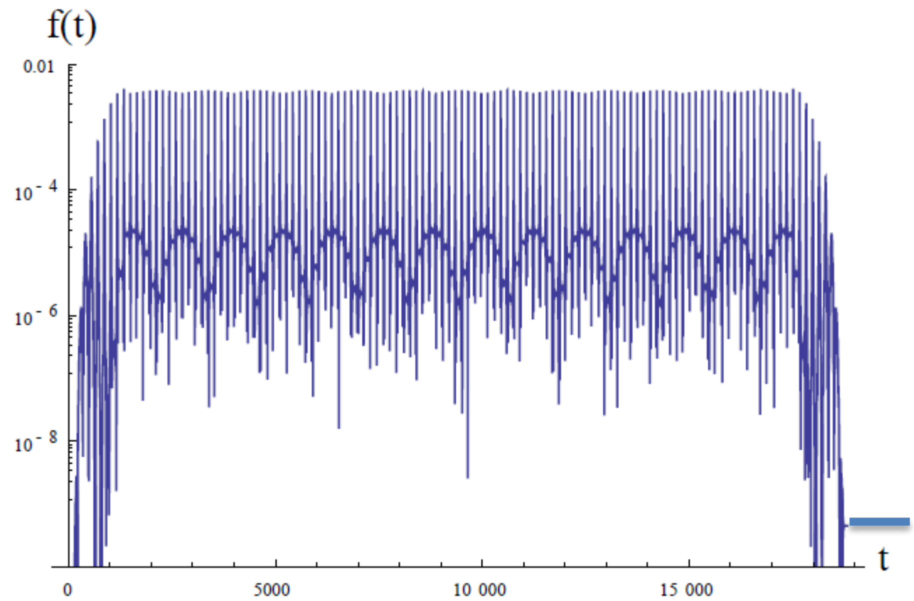

ω′, 170 degrees
4 MeV
1.55 eV
hs
N=2
$\xi^2 = 10^{-3}$
N=5
dσ/dω' (mb/keV)
ω' (keV)
ξ^2=1
0.1
0.01
hs
N=2
sF
$\xi^2 = 10^{-3}$
N=5
N=2
ξ^2=1
0.1
sF
N=2
0.01
ω'(keV)

highlighting multi-photon effects

$$\tilde{\sigma}(\omega') = \int_{\omega'}^{\infty} d\bar{\omega}' \frac{d\sigma(\bar{\omega}')}{d\bar{\omega}'} = \int_{l'}^{\infty} dl \frac{d\sigma(l)}{dl}$$







Member of the Helmholtz Association
B. Kampfer I Institute of Radiation Physics I www.hzdr.de