Prospectives DPhP 16/10/2017

thème/groupe: thèmes pas traités dans les autres thématiques (!)

- Quelques idées de départs
  - experiment proposal to investigate the Black Hole Information Loss Paradox
  - table top experiment for the search of Planck scale signals (spacetime roughness at Planck scale)

- Appel à idées/inputs supplémentaires

→ plusieurs propositions en retour

beaucoup relevant en principe de thèmes/groupes déjà existants (saveur, neutrino, matière noire, multi messager, cosmologie ….) ou bien relevant en principe plus du DEDIP :

- $\mu \rightarrow e\gamma$ (MEG), $(g-2)\mu$ } Saveur (?)
- neutron oscillations, neutron edm
- étude de l'interaction faible courant neutre cohérente } Neutrino, Matière noire
- Ptolemy (relic neutrino detection, DM)
- matière noire directionnelle avec TPC gazeuse (MIMAC), SHIP Matière noire
- ondes gravitationnelles stochastiques (transition de phase 1er ordre) avec LISA Multi messager
- tests de la relativité générale par effets gravitomagnétiques Multi messager ?
- inflation observational tests (B-mode cosmology) Cosmologie
- polarimétrie X et gamma (techniques de TPC)

Prospectives DPhP 16/10/2017

thème/groupe: thèmes traités dans les autres thématiques (!)

Choix de se concentrer sur

- Experiment proposal to investigate the Black Hole Information Loss Paradox
  Accelerating Plasma Mirrors to Investigate the Black Hole Information Loss Paradox,
  P. Chen, G. Mourou PRL 118 (2017) 045001

  Réunion (JFG, MB) avec G. Mourou et P. Chen (Skype) à l'École Polytechnique le 15/9/2017

- Tabletop experiment for the search of Planck scale signals
  Is a tabletop search for Planck scale signals feasible?
  J.D. Bekenstein† (1947-2015), PRD 86 (2012) 124040, Found. Phys 44 (2014) 452

Μηδὲν ἄγαν !

Experiment proposal to investigate the Black Hole Information Loss Paradox

Experiment proposal to investigate the Black Hole Information Loss Paradox

P. Chen, G. Mourou, Accelerating Plasma Mirrors to Investigate the Black Hole Information
Loss Paradox, PRL 118 (2017) 045001 (see more references in the backup)

CEA - Saclay

- **does Hawking evaporation violate unitarity, and therefore results in the loss of information ?**

  i.e. evolution of quantum-mechanical pure states into mixed states ?

- **how the black hole information is retrieved ?**

  - as the black hole loses mass through evaporation, its temperature rises → this would lead to explosive disappearance of the black hole shortly after its - mass reached a value on the order of the Planck mass

  - Wilczek (based on Carlitz and Willey - see bibliography in backup) → partner modes of the Hawking particles would be trapped by the horizon until the end of the evaporation where they would be released and the black hole initial pure state recovered with essentially zero cost of energy

  - or would these partner modes be released in a burst of energy ?

- **observation of either a burst of radiation or zero-point fluctuations** and measurement of entanglement between these modes and Hawking particles (and its evolution)
  → should help to shed light on the black hole information loss paradox

Experiment proposal to investigate the Black Hole Information Loss Paradox

- use **analog system for black hole evaporation**

  → **i.e. accelerated mirrors** (relativistic)

  - accelerated reflecting wall away from a distant observer

  - observer sees a flux of particles generated in consequence of the accelerating boundary

  - if acceleration is constant observer sees a thermal flux exactly analogous to the flux deduced in Hawking's original work (remember also the Unruh effect)

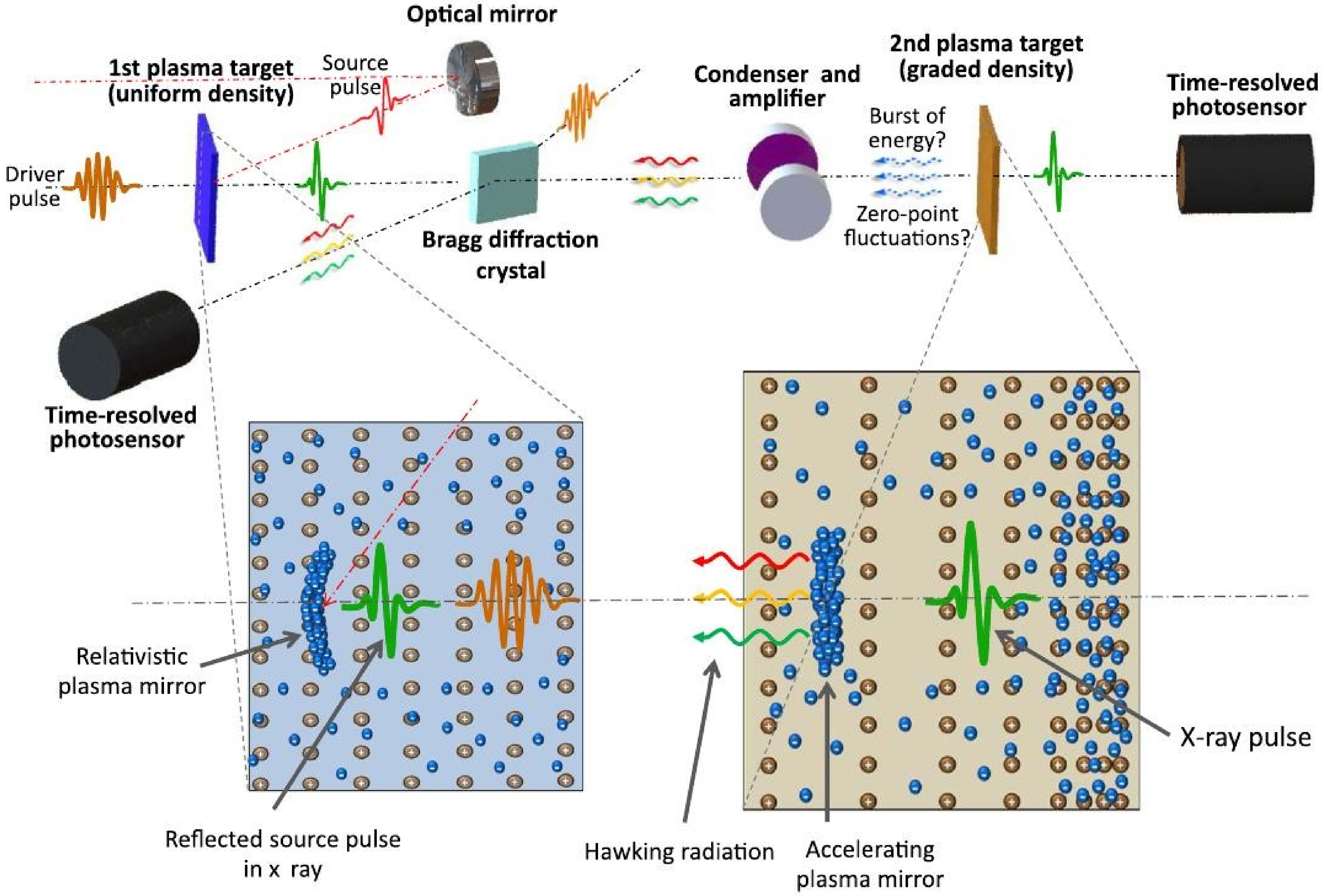
  - abruptly stopped mirrors analogous to the late time evolution of black hole Hawking evaporation

- **relativistic plasma mirror** induced by an intense X-ray beam traversing a solid plasma target with increasing density and sharp termination **can be accelerated drastically and stopped abruptly**

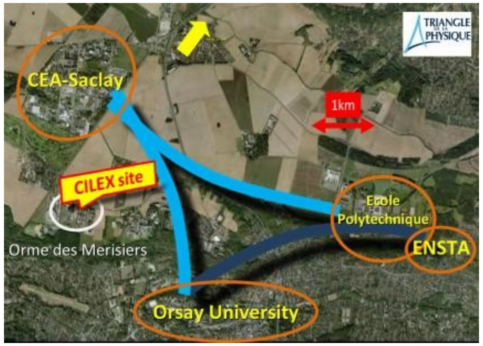
  → Hawking evaporation at its late stage mimicked by **accelerating plasma mirrors based on state-of-the-art laser** (ultrashort highpower - 10 PW) **and** nano-fabrication technologies (for the density gradient target)

Experiment proposal to investigate the Black Hole Information Loss Paradox

(see backup for more details)



Experiment proposal to investigate the Black Hole Information Loss Paradox



- **10 PW green laser** (can be tailored and send reflections at different places)
  - Appolon laser at Saclay (CILEX site at CEA-Saclay) as a starting point
  - at the moment ~ 1shot/mn , ~1000 shot to get 1 photon (if 100 % efficiency)

    new development → Coherent Amplifier Network (several years time scale)

    plan to have 100PW laser in the future (Shanghai)

- **Detect photons in the 0.1 – 1.6 eV range** (near IR, visible)

  in the future aim to reach up to 10 eV (UV)

  photosensors → solid state cryogenic detectors (get rid off thermal bckgnd)

  femtosecond (even lower !) level timing from autocorrelation techniques (''usual laser experts techniques'')

- **Step by step approach**
  - R&D on graded density 2nd target from nanotechnology (Taiwan – Condensed Matter Department)

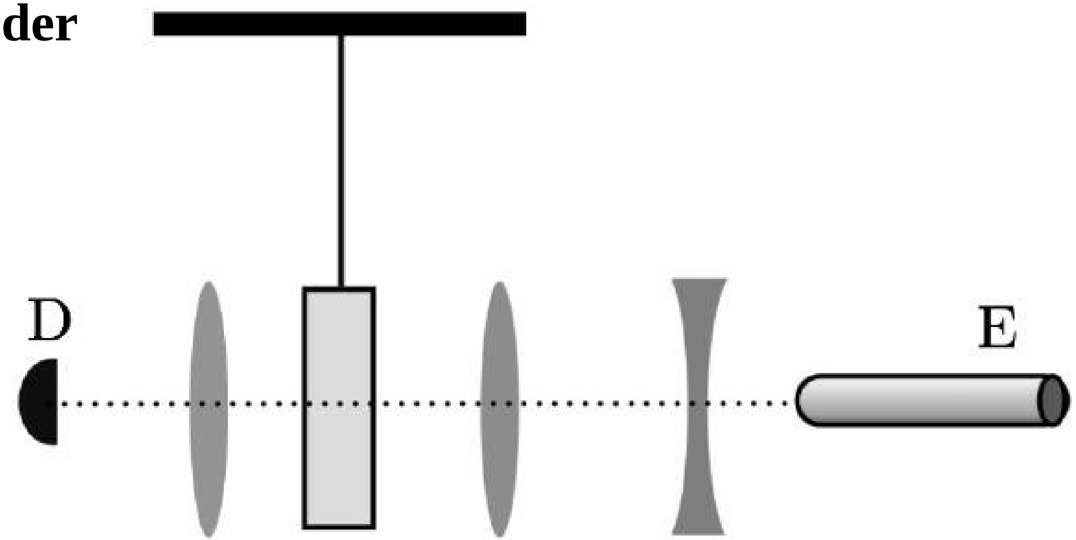
    Annabelle international collaboration
  - demonstrator with 1 PW – 3 PW laser with gaseous target in capillaries as 2nd target (Kansai, Kyoto)
  - validate mirror acceleration with graded density target
  - theoretical and simulation (including plasma simulation), specify the Hawking signal, correlation/entanglement signal
  - detect Hawking radiation from accelerated mirror
  - detect entanglement signals (correlation between Hawking partcl. and partner – energy and polarisation)

Tabletop experiment for the search of Planck scale signals

Tabletop experiment for the search of Planck scale signals

J.D Bekenstein (1947-2015), Is a tabletop search for Planck scale signals feasible? PRD86 (2012)124040, Found. Phys. 44 (2014)452

- use a **single optical photon** which traverses a dielectric block to **engender a translation** of the block which can be arranged to be **of the order of the Planck scale**



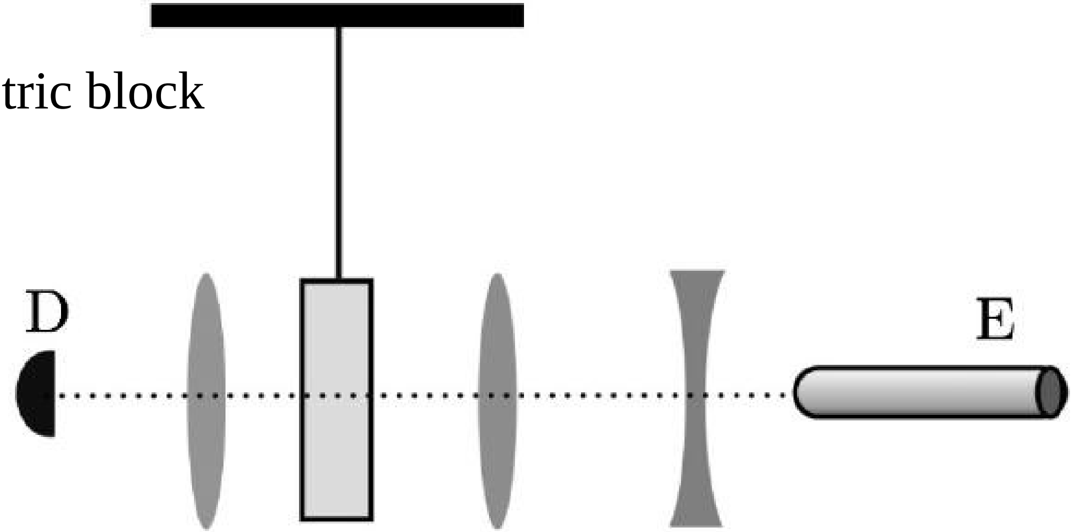
- check that the tiny translation actually occurred :
  - → from detecting the photon after transit through the block
  - → relying on momentum conservation

- translation by a distance of order Planck length is expected to be impeded with some probability
  - → series of single photon experimental runs
  - → if the rate with which the photon is found to get through the block falls short of expectations (from the block' s classical transmission coefficient, multiple back reflection, absorption…), this may **signal that spacetime is 'rough/foamy' at the relevant scale (Wheeler's conjecture)**

Tabletop experiment for the search of Planck scale signals

J.D Bekenstein (1947-2015), Is a tabletop search for Planck scale signals feasible? PRD86 (2012)124040, Found. Phys. 44 (2014)452

- take photon wave length 445 nm (2.78 eV)



- take macroscopic probe → rectangular dielectric block

  dimensions L1 x L2 x L2

  mass M

  crystalline or amorphous

  transparent to optical em waves

  dielectric is supposed to be optically isotropic

- take

  $M = 0.15\ 10^{-3}$ kg

  $L1 = 10^{-3}$ m , $L2 = 5\ 10^{-3}$ m

  $n = 1.6$ (relevant for lead glass at 445 nm)

in original rest frame the block c.m. has moved → $\Delta X = 1.98\ 10^{-35}$ m

Tabletop experiment for the search of Planck scale signals

- **as long as experimental parameters are such that $\Delta X \gg$ Planck length**

→ consider spacetime as endowed with usual symmetries under translation, rotation and Lorentz boosts

→ **no impediment to the translation is expected in that case**

- **however on scales comparable to Planck length, vacuum quantum fluctuations of metric expected to be large**

→ **expect such fluctuations to impede translation of the block c.m. by distances $\Delta X \sim$ Planck length**

→ translation impediment with some probability π^*

→ when block's motion impeded, photon might be prevented from crossing the block (momentum conservation)

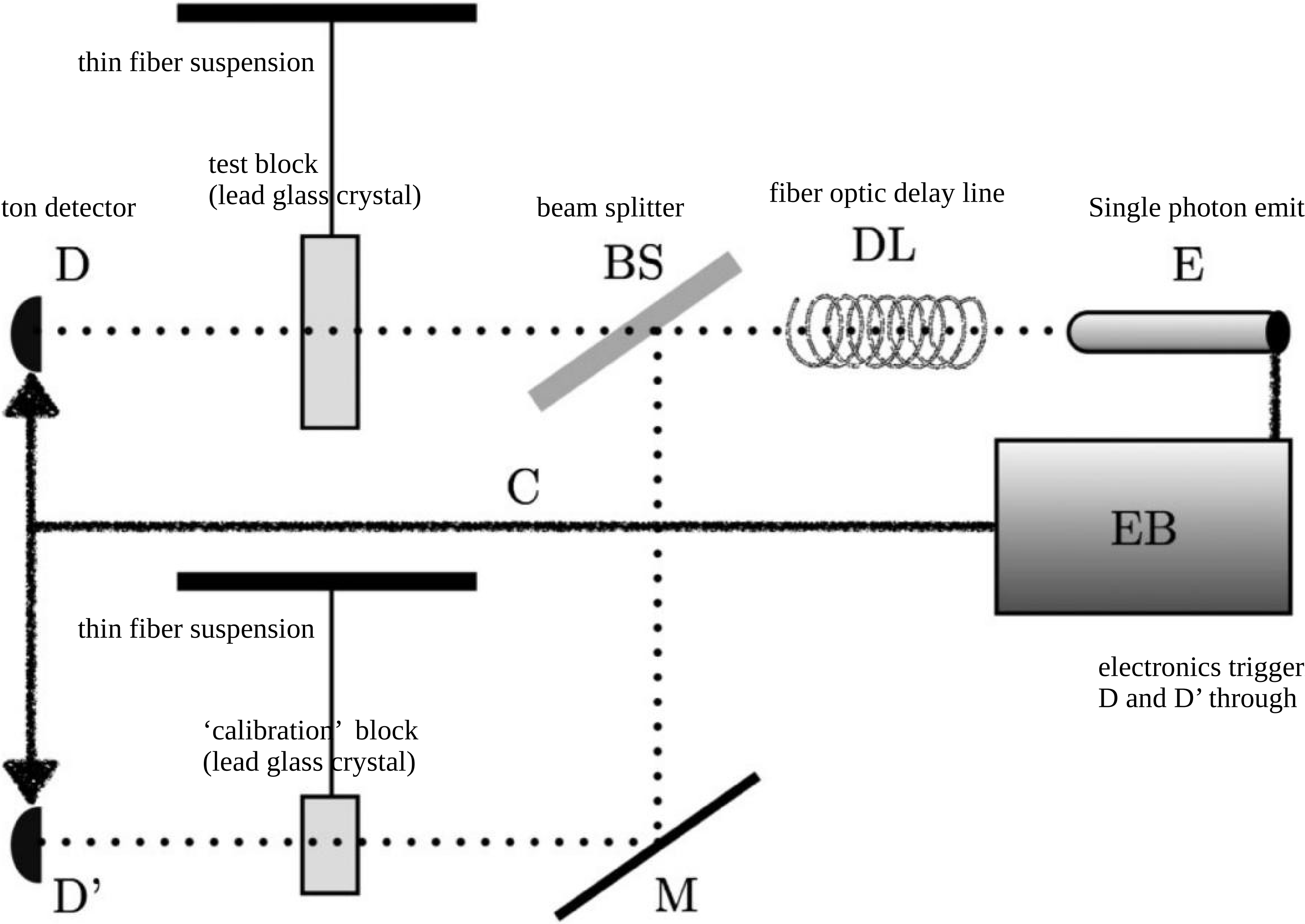
→ with probability π^*, the photon will be backreflected by the block or absorbed
this in addition to that required by Fresnel's formulas (or their extension to account for imperfect transparency)

→ **if** after multiple runs and accounting for the quantum efficiency of the photon detector
find that the **direct photon is detected significantly less frequently than expected**
from Fresnel's formulas expectations, this **may signal 'roughness' of spacetime at Planck scale**

→ **without making specific hypotheses about quantum spacetime, cannot estimate π^***
however by varying $n-1$, $L1$ or M, it is possible to determine critical scale above
which the situation corresponds to a smooth spacetime (providing a check on Wheeler's conjecture)

Tabletop experiment for the search of Planck scale signals

more realistic setup (2 different blocks side by side and about 0.2 m apart)



thin fiber suspension

test block
(lead glass crystal)

single photon detector

beam splitter

fiber optic delay line

Single photon emitter

thin fiber suspension

electronics triggering detectors
D and D’ through cable C

‘calibration’ block
(lead glass crystal)

single photon detector

Tabletop experiment for the search of Planck scale signals

more realistic setup

- supplement the basic setup with a 2nd comparison block of identical composition
  - high-lead glass, density $6\ 10^{3}$ kg/m^{3}, n=1.6
  - suspended side by side with 1st (also by a thin fiber)
  - followed by its own single-photon detector D'

- dimensions of 2nd block such that the corresponding ΔX for the same wavelength as earlier is much longer than Planck length

  - **1st block**: L1 = 10^{-3} m, L2 = $5\ 10^{-3}$ m, M = $0.15\ 10^{-3}$ kg , $\mathbf{\Delta X = 1.98\ 10^{-35}}$ **m**

  - **2nd block:** L1 = L2 = 10^{-3} m, M = $6\ 10^{-6}$ kg , $\mathbf{\Delta X = 4.96\ 10^{-34}}$ **m**
    i.e. ~ 30 times Planck length

- Newtonian force between the two blocks set 0.2m apart is $1.5\ 10^{-18}$ N

  → over the course of the photon transit : impart either block a momentum $8\ 10^{-30}$ kg m s^{-1}
  i.e. factor of 70 below the momentum acquired from the photon

  → mutual gravitation can be kept from being disruptive

Tabletop experiment for the search of Planck scale signals

Background and requirements

- High quality lead glass crystal (dispersion in the block material)

  Schott N-SF2 lead crystal

- most troublesome background source : thermal jitter of the block (atom hit)

  need a ultrahigh vacuum O(1 m^3) volume
  → atom hit probability reduced to 1 % at 10^{-11} Pa (~10^{-15} Pa desirable)

- background light → shielding, cooling (thermal optical background), narrow band filters at detector's inputs

  need to cool the volume down to 4K or lower
  → thermal photon noise 1% of signal at 4K

- background from cosmic ray hits, solar neutrinos, dark matter not found to be a problem

- sismic noise ? (not discussed in the paper)

Summary

- **Experiment proposal to investigate the Black Hole Information Loss Paradox**

- very fundamental and exciting forefront physics

- on-site CEA-Saclay experiment → use Appolon Laser facility (2018-2019 at Ormes des Merisier)

- Laser world experts involved (founding father of Appolon) → flagship exp. for Appolon (?)

- physics at interface of several domains

- several DRF institutes could be involved/interested : Irfu (DPhP), Iramis (Lidil) … ?
Irfu : solid state cryogenic detectors (near IR, visible) ?

- collaboration building up (very keen to welcome new and young collaborators) :
IZEST Ecole polytechnique, LeCosPA Taipei (+SLAC), Kansai-Kyoto, Shanghai Jiao Tong U, LLR (?), IRFU (?) ….

- unique opportunity

- **Tabletop experiment for the search of Planck scale signals**

- very fundamental and exciting physics

- on-site Irfu tabletop experiment (in one room ?)

- several Irfu department could be involved/interested : DPhP, DACM … ?

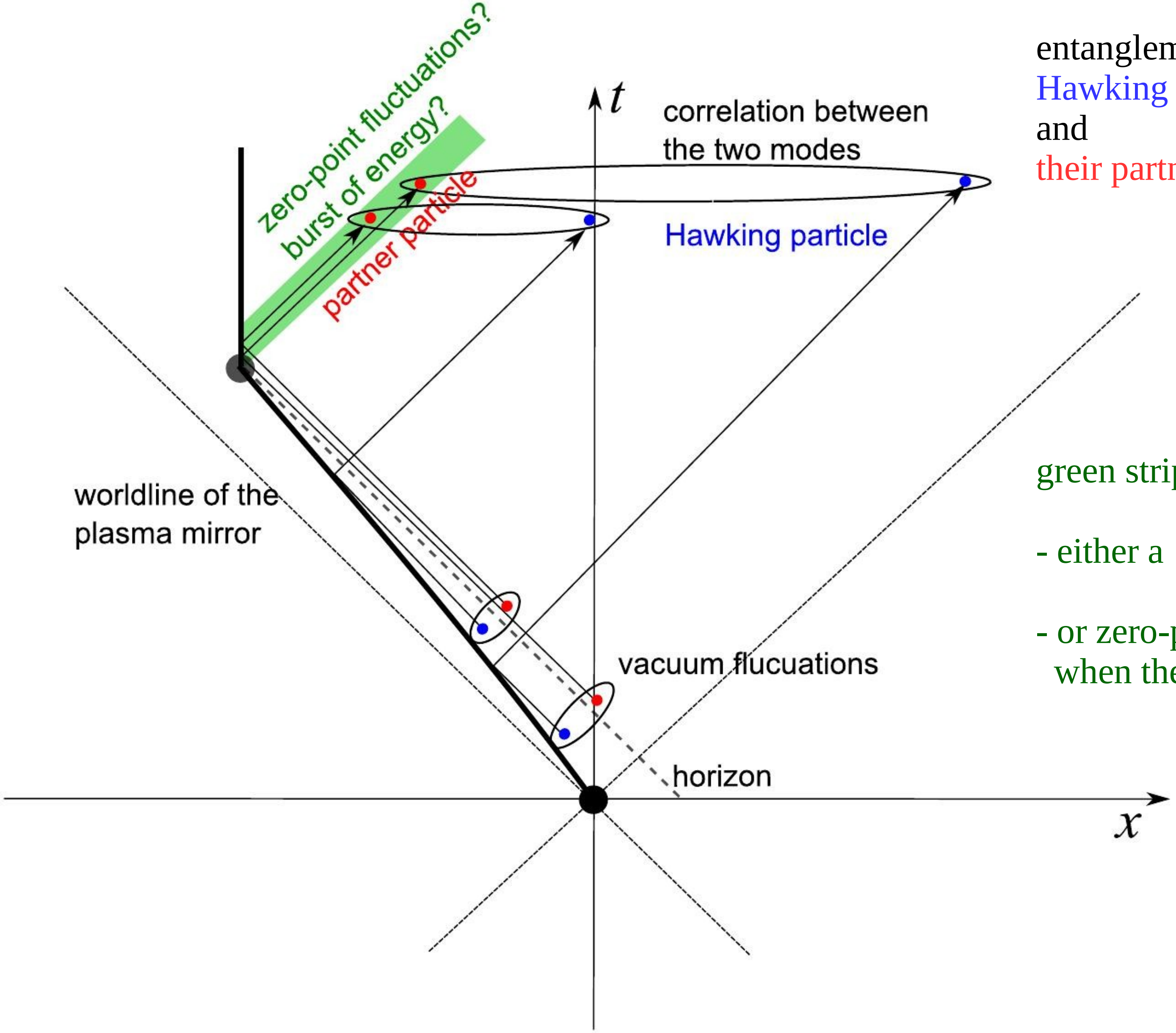
- much shorter time scale than a LHC experiment, very likely to be much less costly

- opportunity (nowhere else than in Irfu ?)

backup

worldline of the accelerating plasma mirror and thespacetime evolution of the entangled vacuum fluctuating pairs (vacuum fluctuations around the horizon)

the partner modes of the Hawking particles are temporarily trapped by the horizon and would presumably be released when the mirror stops abruptly

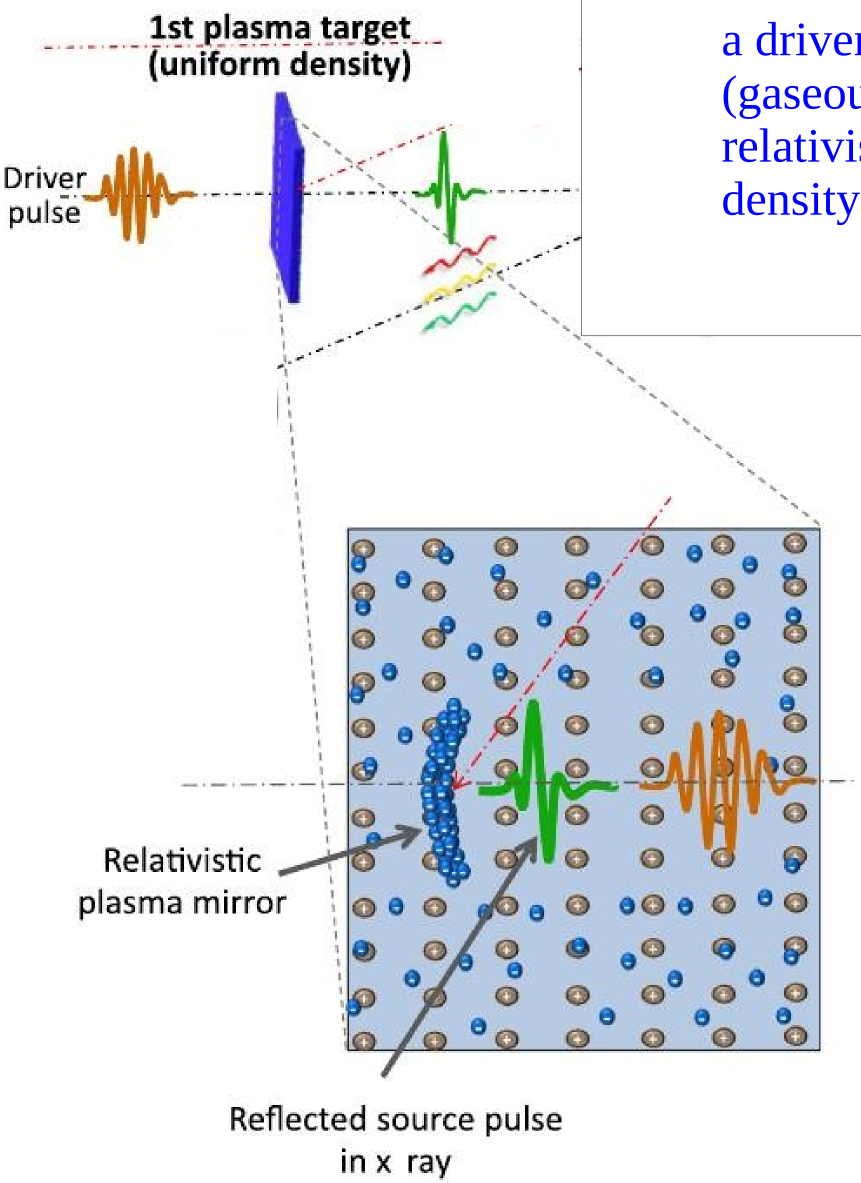


entanglement between :
Hawking particles (blue) emitted at early times
and
their partner particles (red) collected at late times

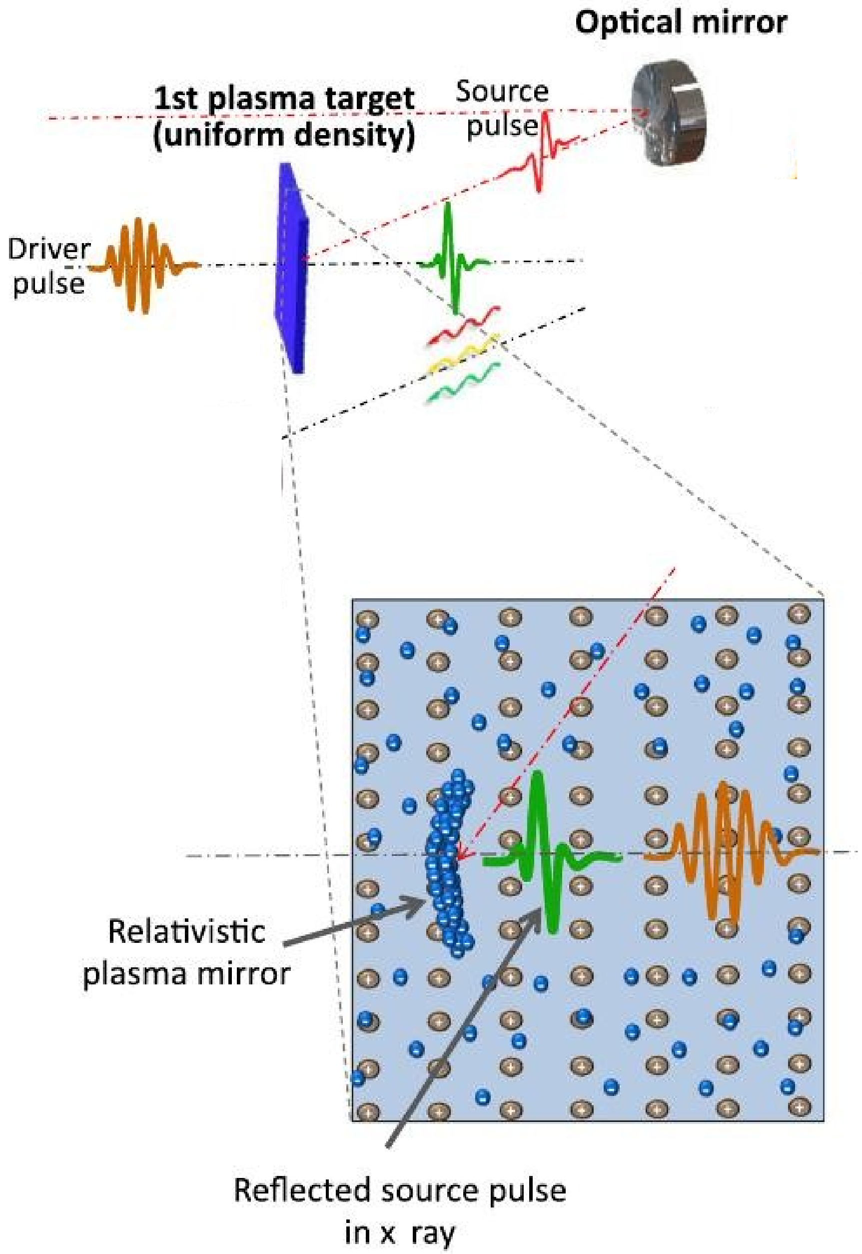
green strip represents

- either a burst of energy

- or zero-point fluctuations emitted when the acceleration stops abruptly

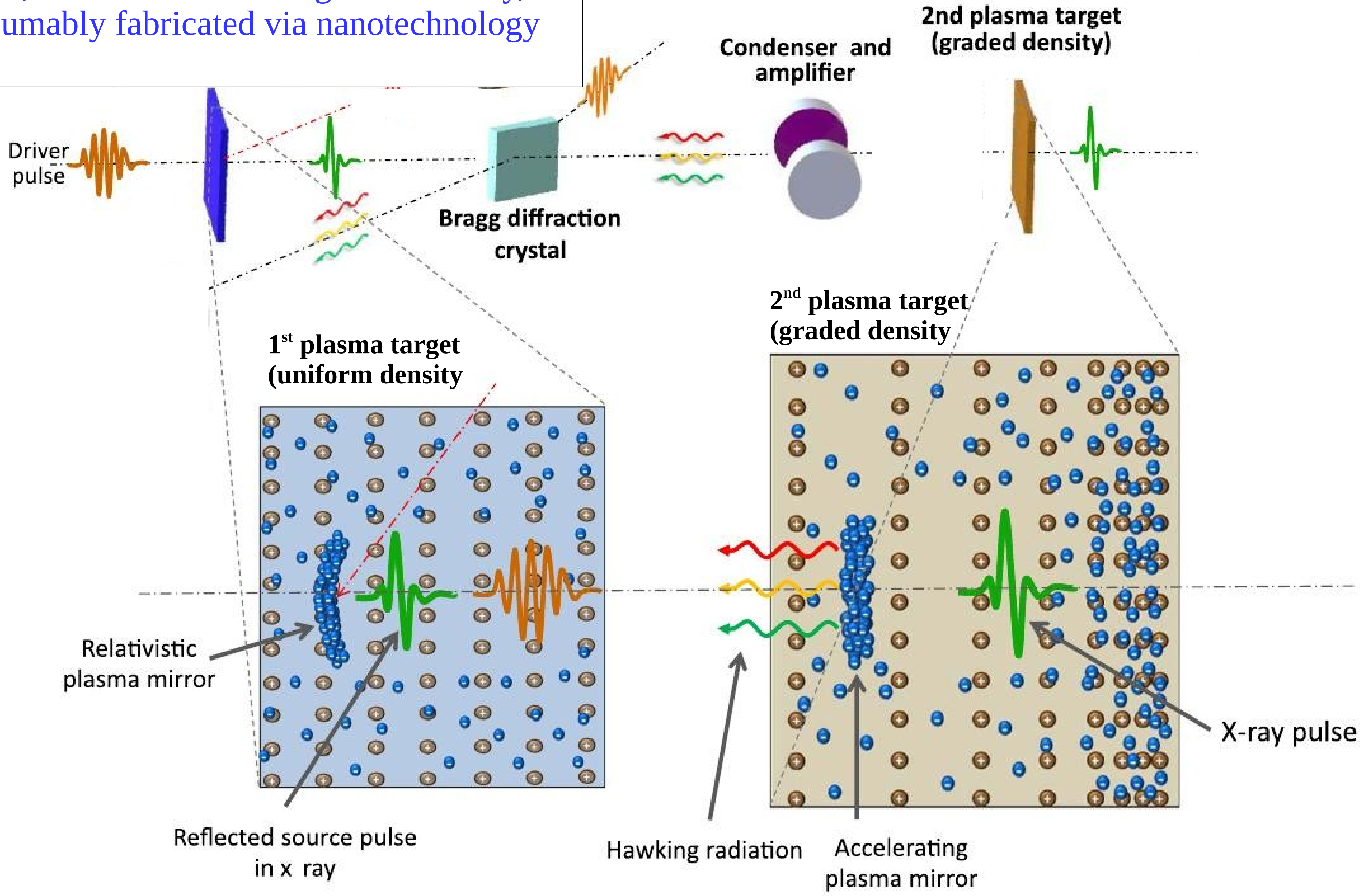


a driver pulse from an optical laser traverses the first (gaseous and uniform) plasma target, which creates a relativistic plasma mirror with a concave transverse density distribution

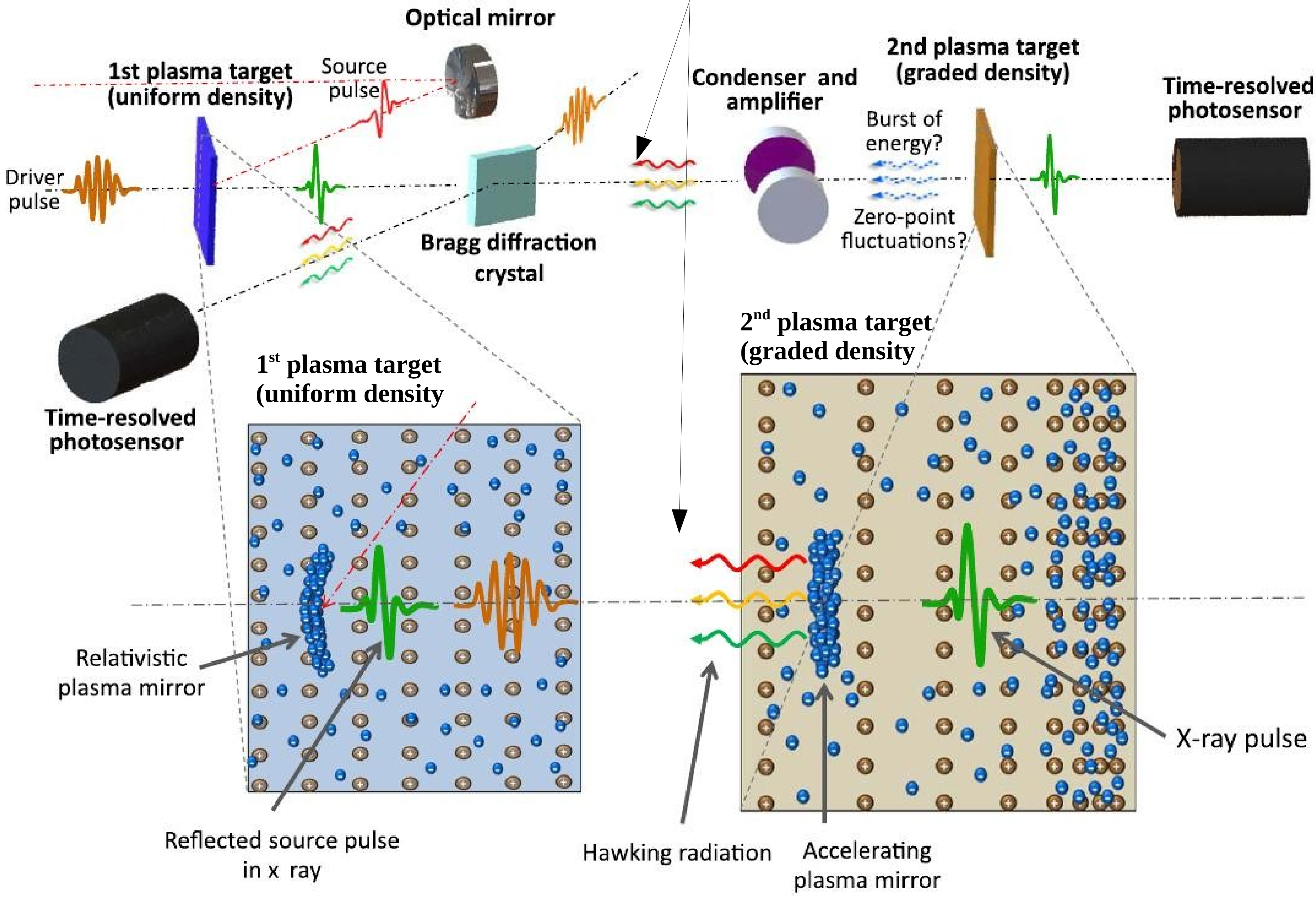


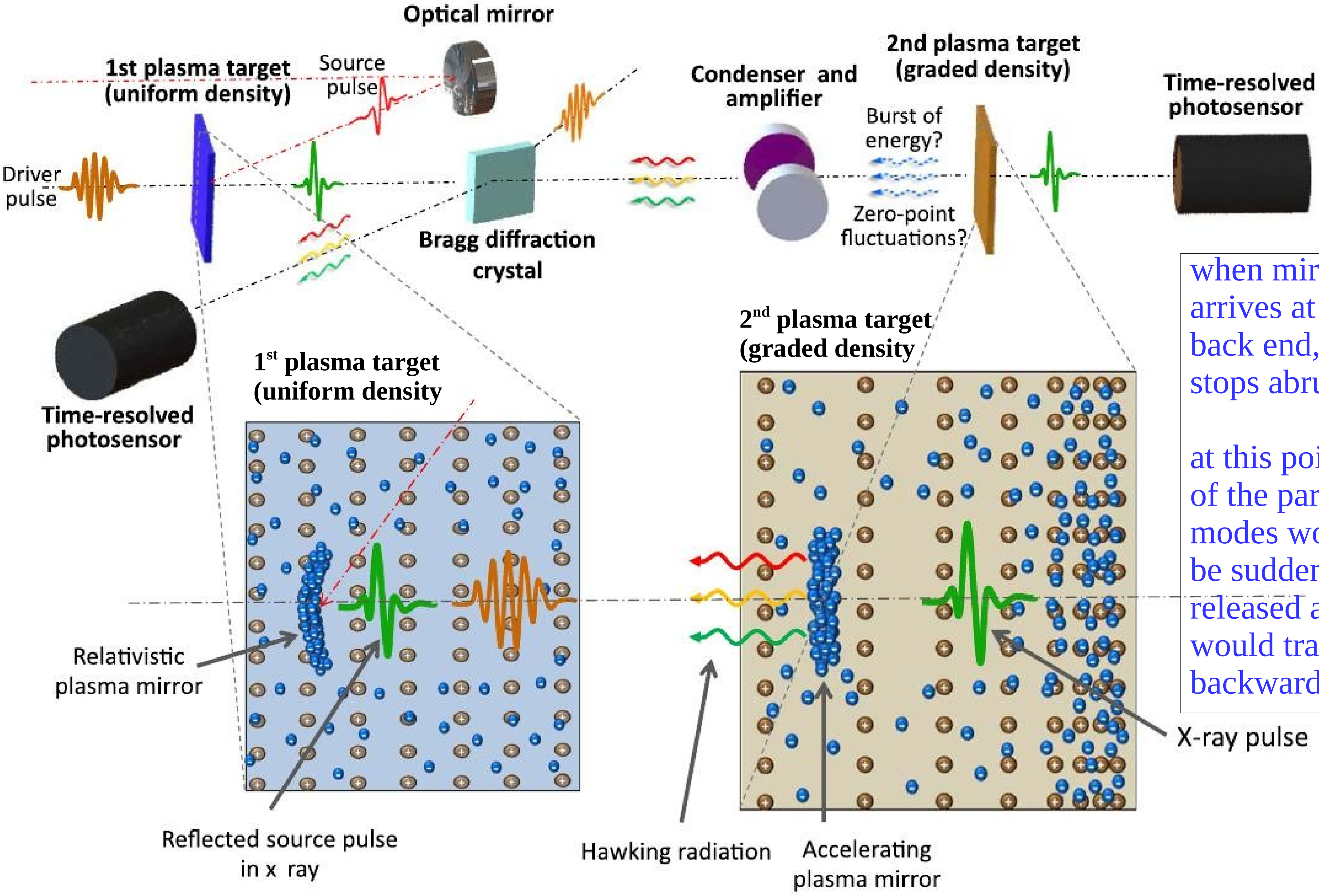
a source pulse, prepared by the same laser, is reflected by the plasma mirror, with frequency increased by a factor of $4\gamma^2$ where γ is the Lorentz factor of the first mirror this x-ray pulse will pass through a Bragg diffraction crystal to arrive at the 2nd plasma target, which is solid with graded density, presumably fabricated via nanotechnology

the driver pulse, on the other hand, can be diffracted to a different path



this second plasma mirror accelerates due to the density gradient and emits the high-frequency part of the analog Hawking radiation which propagates in the backward direction.

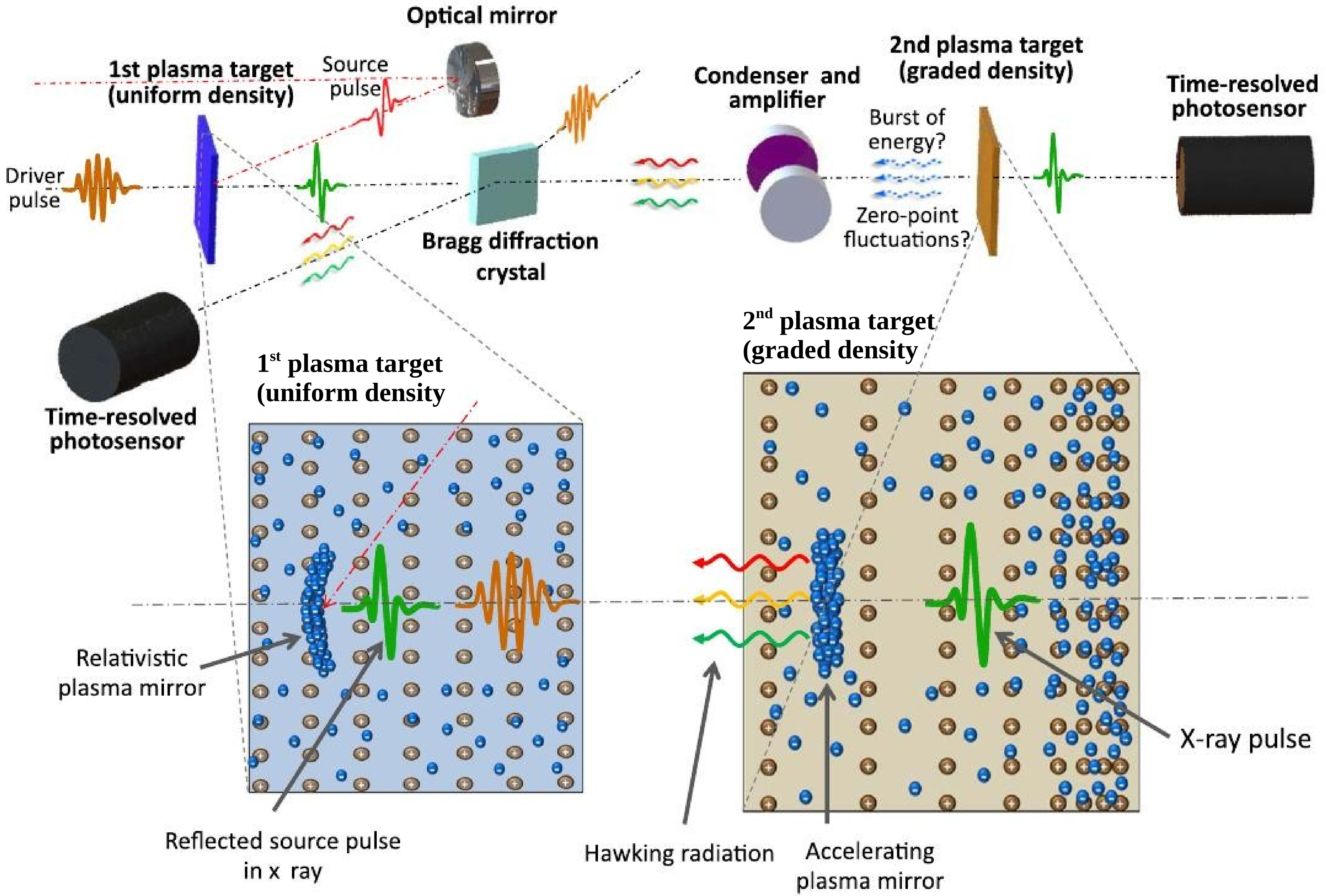




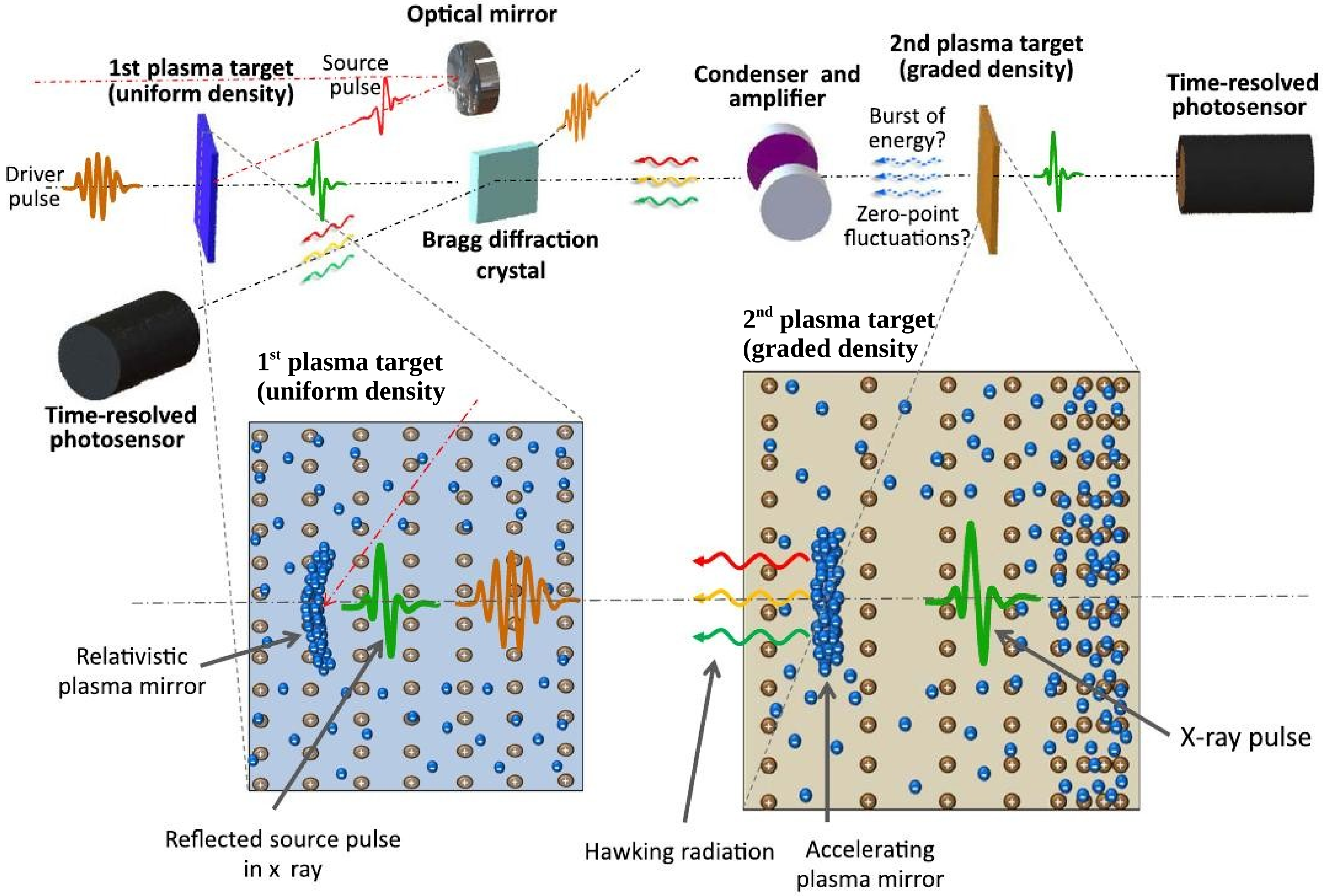
when mirror arrives at the back end, it stops abruptly

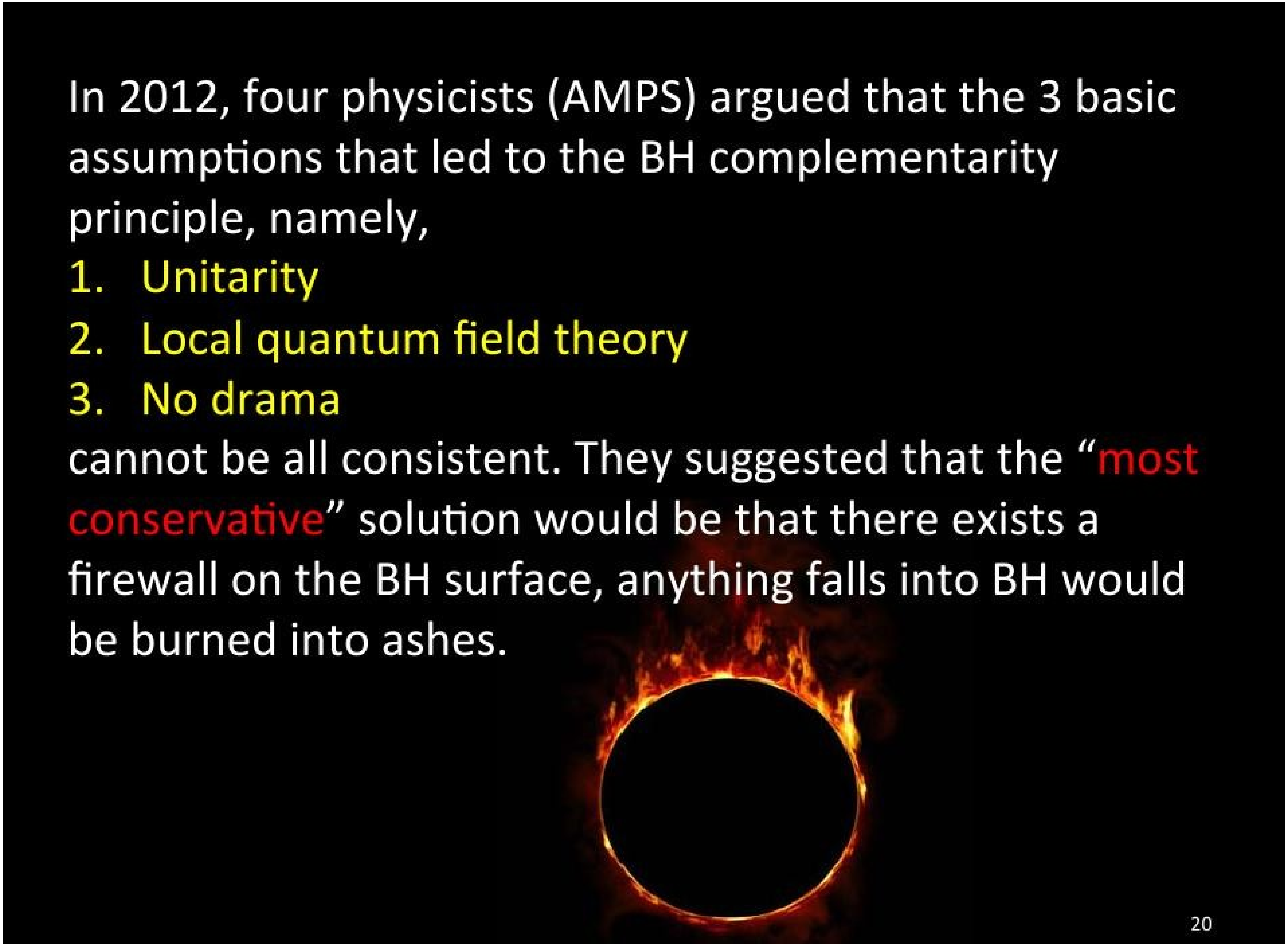
at this point all of the partner modes would be suddenly released and would travel backwards upstream of the second target, the supposed zero-point fluctuations will be measured by condensers and amplifiers,

while the Hawking and the partner particles (if real), sufficiently lower in frequency than that of the X-ray, will be Bragg diffracted to a time-resolved photosensor



time resolution should be much finer than the penetration time i.e. **~a femtosecond,** such that the final burst of partner particles can be distinguished from the Hawking photons





In 2012, four physicists (AMPS) argued that the 3 basic assumptions that led to the BH complementarity principle, namely,

1. Unitarity
2. Local quantum field theory
3. No drama

cannot be all consistent. They suggested that the "most conservative" solution would be that there exists a firewall on the BH surface, anything falls into BH would be burned into ashes.

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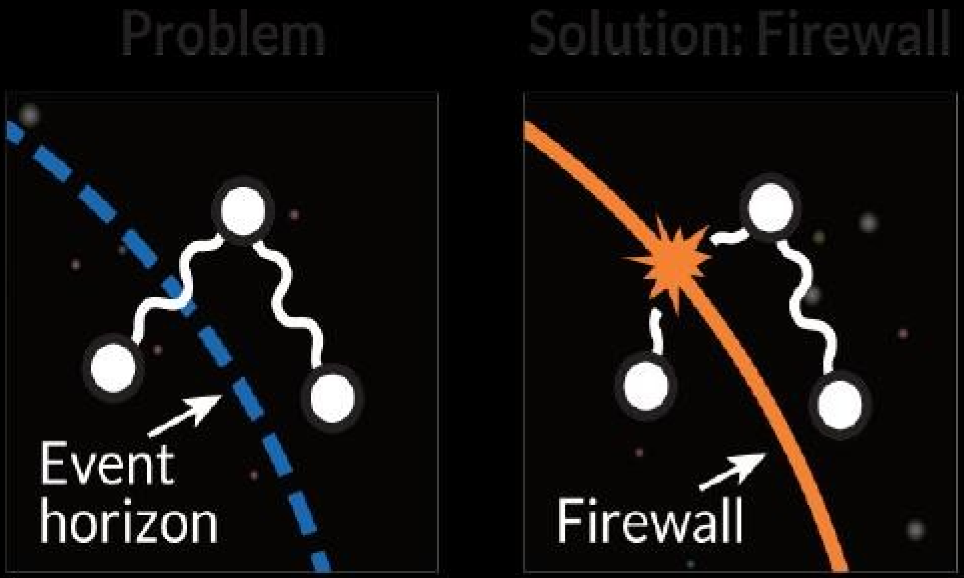
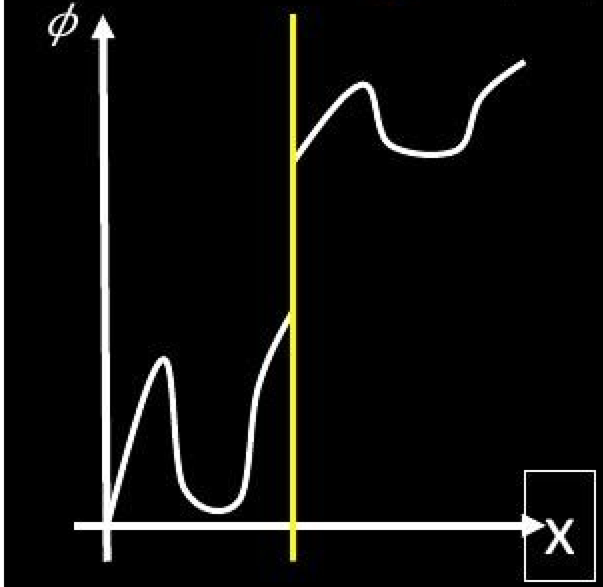
AMPS black hole firewall





The intensity of a quantum field is Determined by the rate of change of the field

For disconnected spacetimes, the magnitudes of the quantum field need not be continuous.

- Ahmed Almheiri, Donald Marolf, Joseph Polchinski, James Sully, "Black Holes: Complementarity or Firewalls?", JHEP 1302 (2013) 062.
- Ahmed Almheiri, Donald Marolf, Joseph Polchinski, Douglas Stanford, James Sully, "An Apologia for Firewalls", JHEP 1309 (2013) 018.

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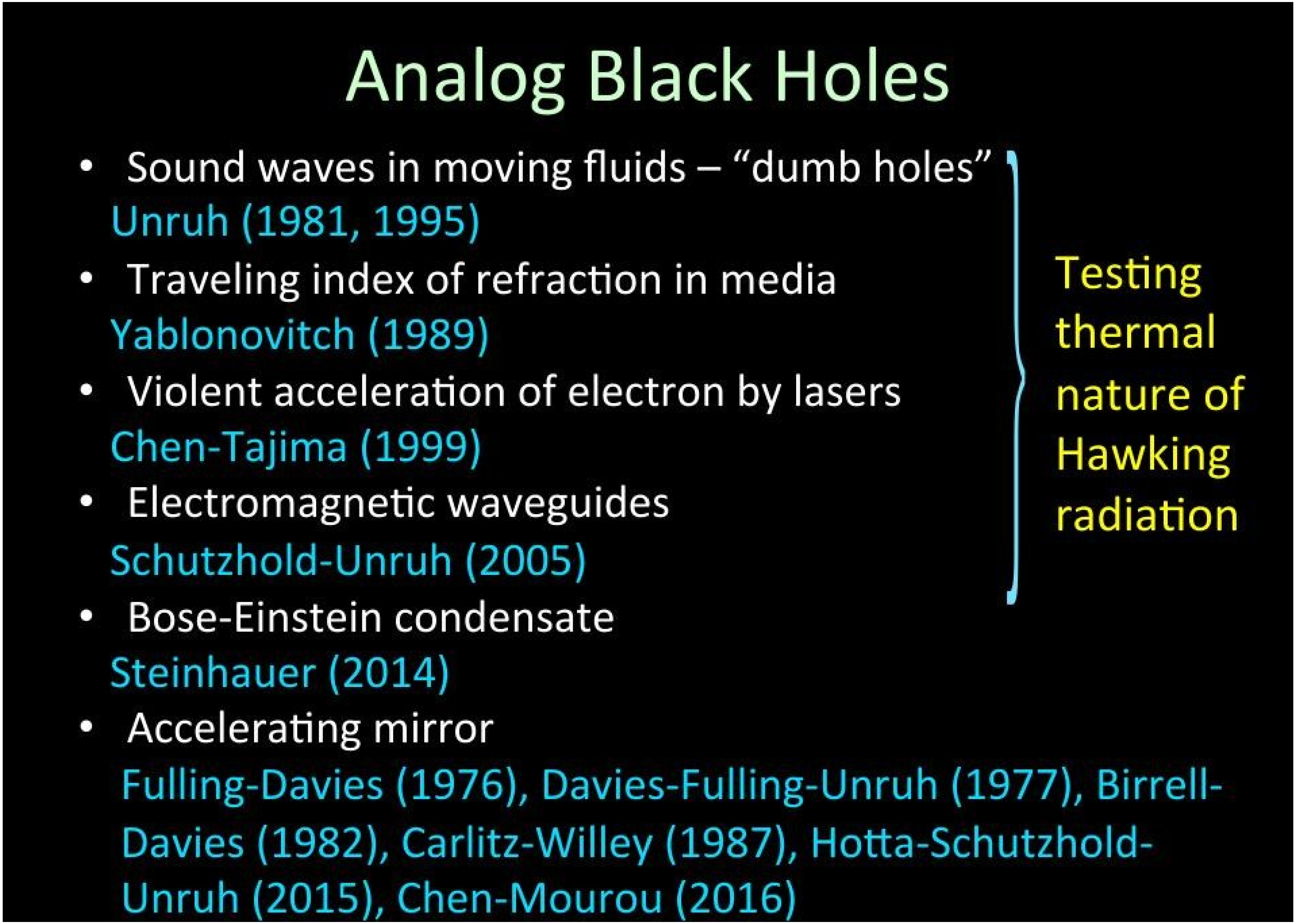

Analog Black Holes

- Sound waves in moving fluids – “dumb holes”
  Unruh (1981, 1995)
- Traveling index of refraction in media
  Yablonovitch (1989)
- Violent acceleration of electron by lasers
  Chen-Tajima (1999)
- Electromagnetic waveguides
  Schutzhold-Unruh (2005)
- Bose-Einstein condensate
  Steinhauer (2014)
- Accelerating mirror
  Fulling-Davies (1976), Davies-Fulling-Unruh (1977), Birrell-Davies (1982), Carlitz-Willey (1987), Hotta-Schutzhold-Unruh (2015), Chen-Mourou (2016)

Testing thermal nature of Hawking radiation

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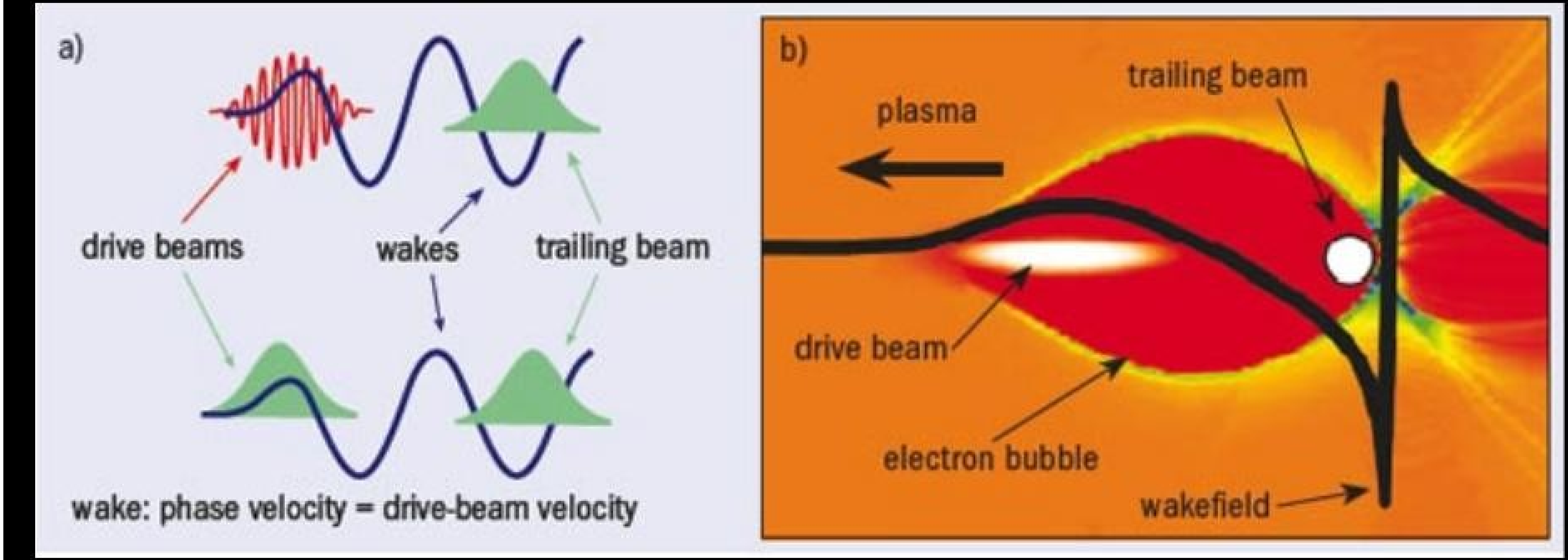
Plasma wakefield acceleration

Tajima-Dawson (1979)- Laser driven (LWFA)

Chen-Dawson-Huff-Katsouleas (1985)- Particle beam driven (PWFA)



SLAC & LBL- Acceleration of O(100) GeV/m observed!

AWAKE- A new experiment at CERN

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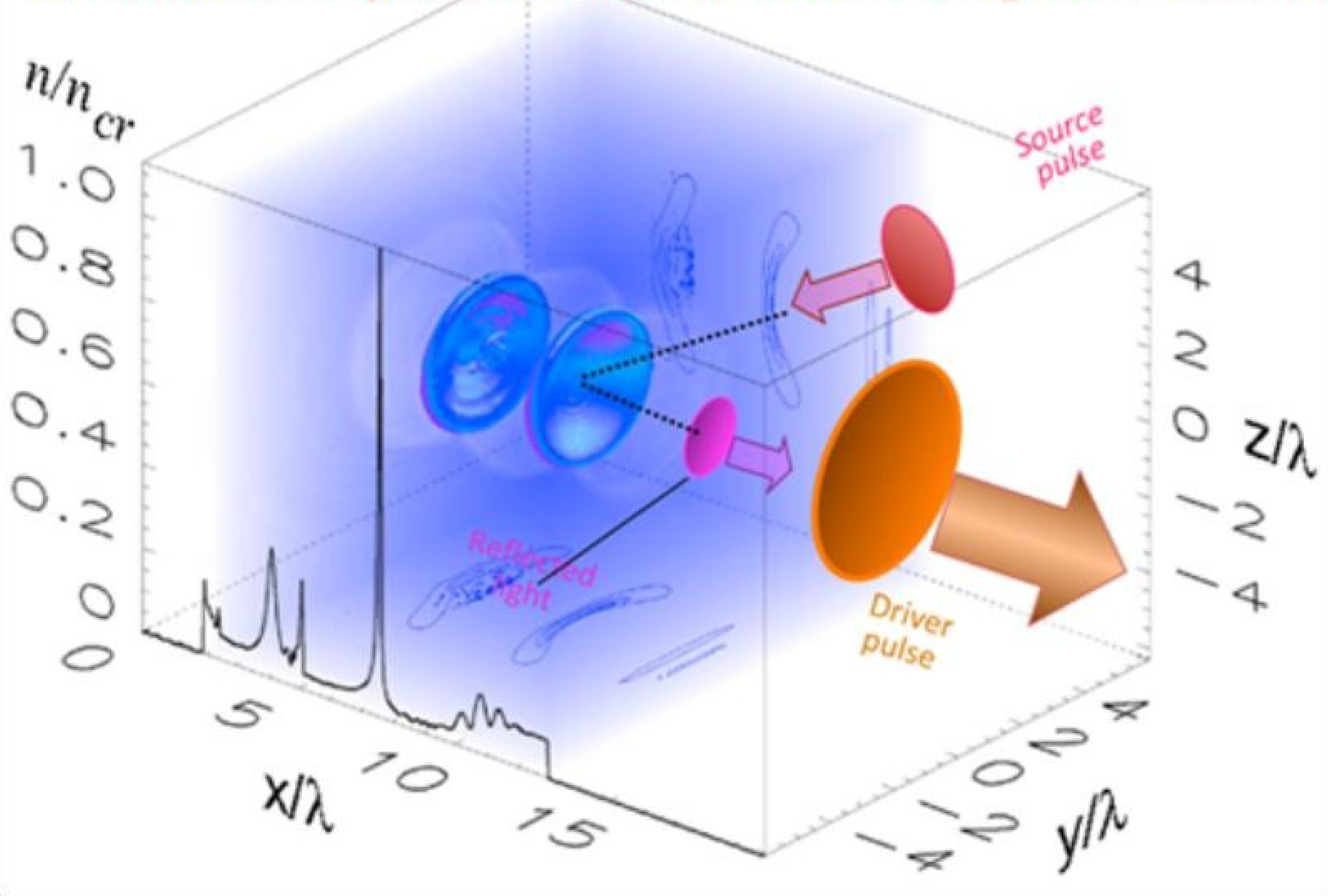
Relativistic Plasma Mirror

Bulanov (2001), Bulanov, Esirkepov, Tajima (2003), Mourou-Tajima-Bulanov (2006)

Reflected laser pulse Lorentz-boosted and tighter-focused.



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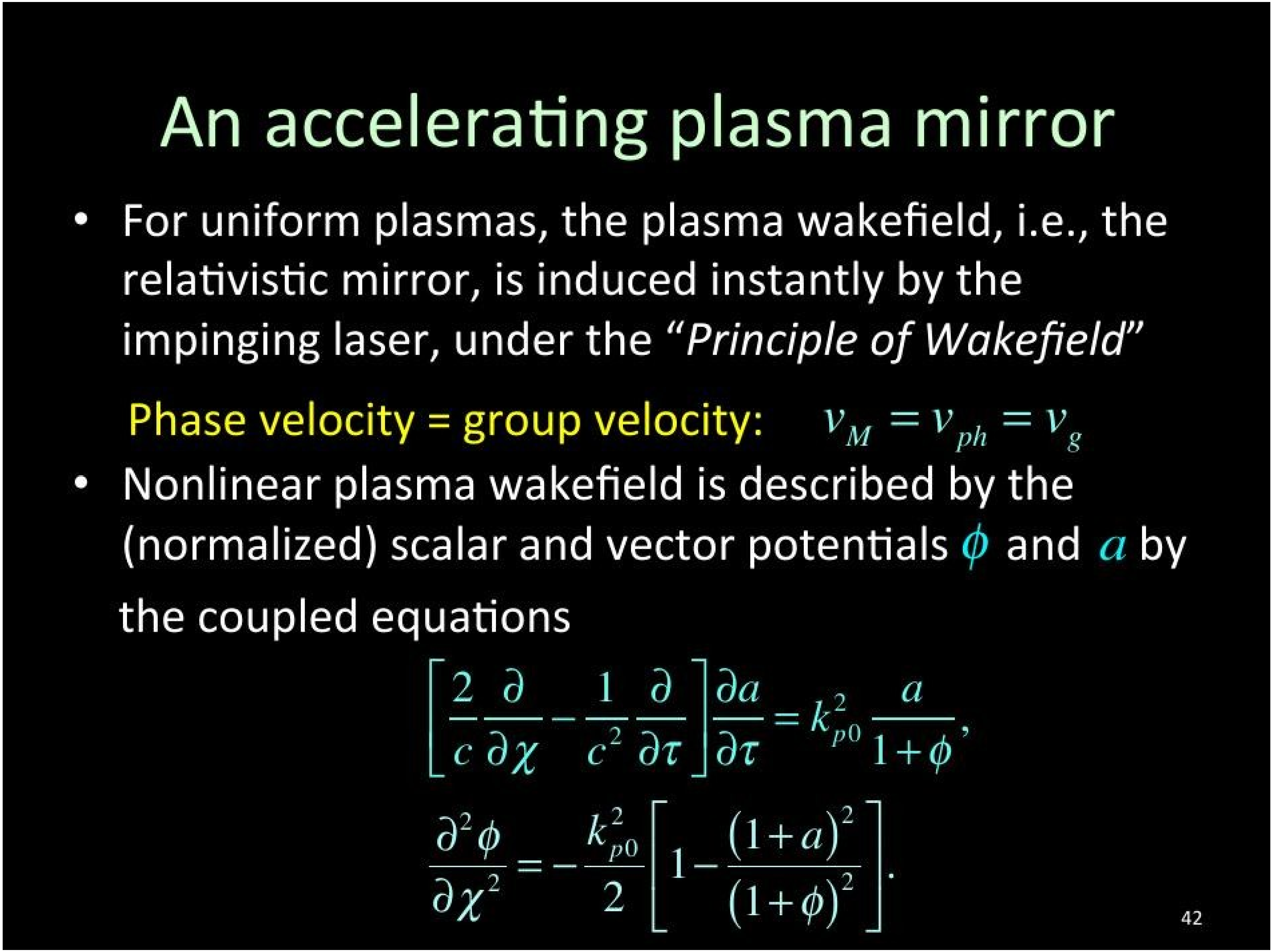

An accelerating plasma mirror

- For uniform plasmas, the plasma wakefield, i.e., the relativistic mirror, is induced instantly by the impinging laser, under the "*Principle of Wakefield*"

Phase velocity = group velocity: $v_M = v_{ph} = v_g$

- Nonlinear plasma wakefield is described by the (normalized) scalar and vector potentials ϕ and a by the coupled equations

$$\left[\frac{2}{c}\frac{\partial}{\partial\chi} - \frac{1}{c^2}\frac{\partial}{\partial\tau}\right]\frac{\partial a}{\partial\tau} = k_{p0}^2\frac{a}{1+\phi},$$

$$\frac{\partial^2\phi}{\partial\chi^2} = -\frac{k_{p0}^2}{2}\left[1 - \frac{(1+a)^2}{(1+\phi)^2}\right].$$

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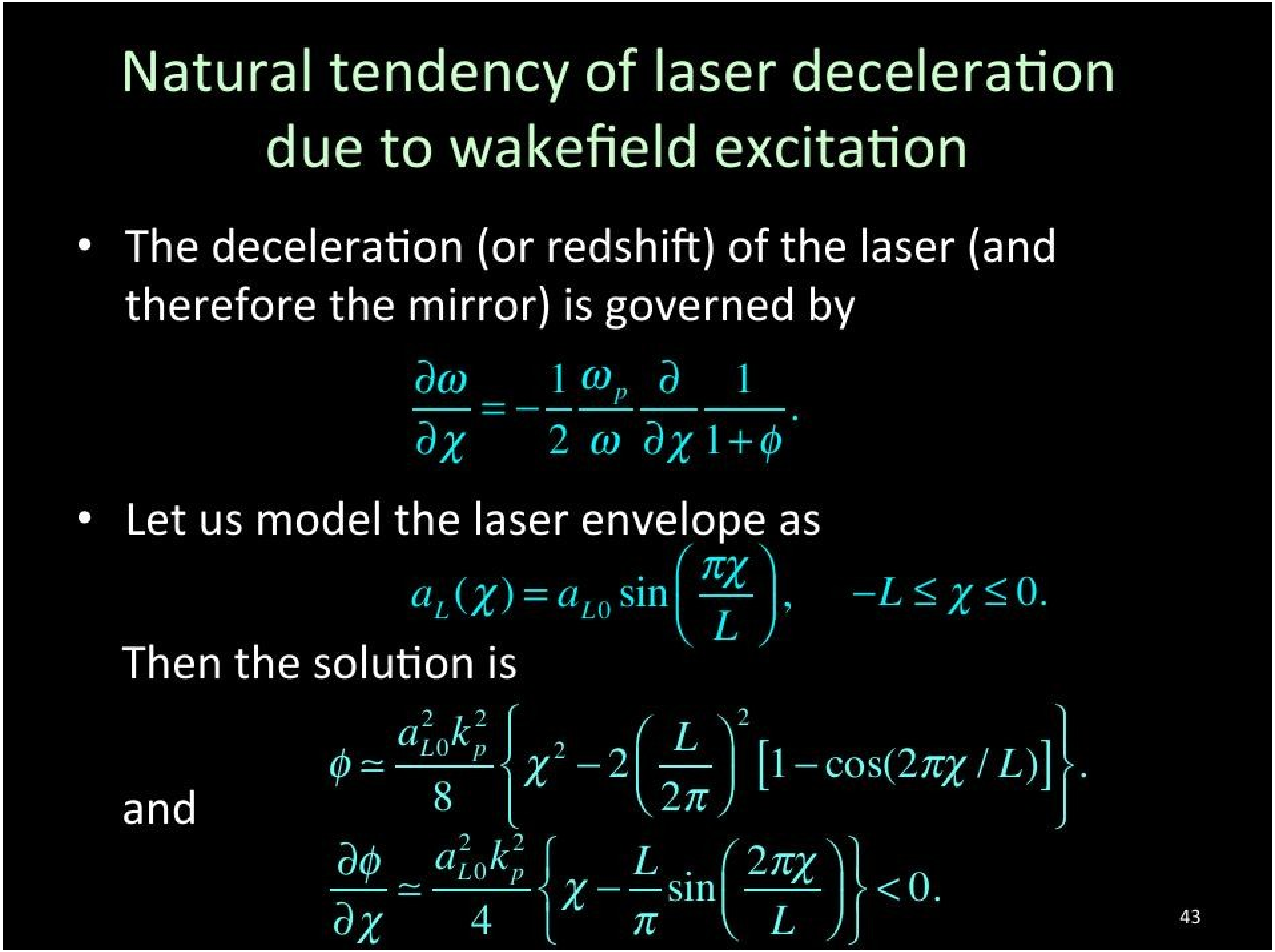

Natural tendency of laser deceleration due to wakefield excitation

- The deceleration (or redshift) of the laser (and therefore the mirror) is governed by

$$\frac{\partial \omega}{\partial \chi} = -\frac{1}{2}\frac{\omega_p}{\omega}\frac{\partial}{\partial \chi}\frac{1}{1+\phi}.$$

- Let us model the laser envelope as

$$a_L(\chi) = a_{L0}\sin\left(\frac{\pi\chi}{L}\right), \qquad -L \le \chi \le 0.$$

Then the solution is

$$\phi \simeq \frac{a_{L0}^2 k_p^2}{8}\left\{\chi^2 - 2\left(\frac{L}{2\pi}\right)^2\left[1-\cos(2\pi\chi/L)\right]\right\}.$$

and

$$\frac{\partial \phi}{\partial \chi} \simeq \frac{a_{L0}^2 k_p^2}{4}\left\{\chi - \frac{L}{\pi}\sin\left(\frac{2\pi\chi}{L}\right)\right\} < 0.$$

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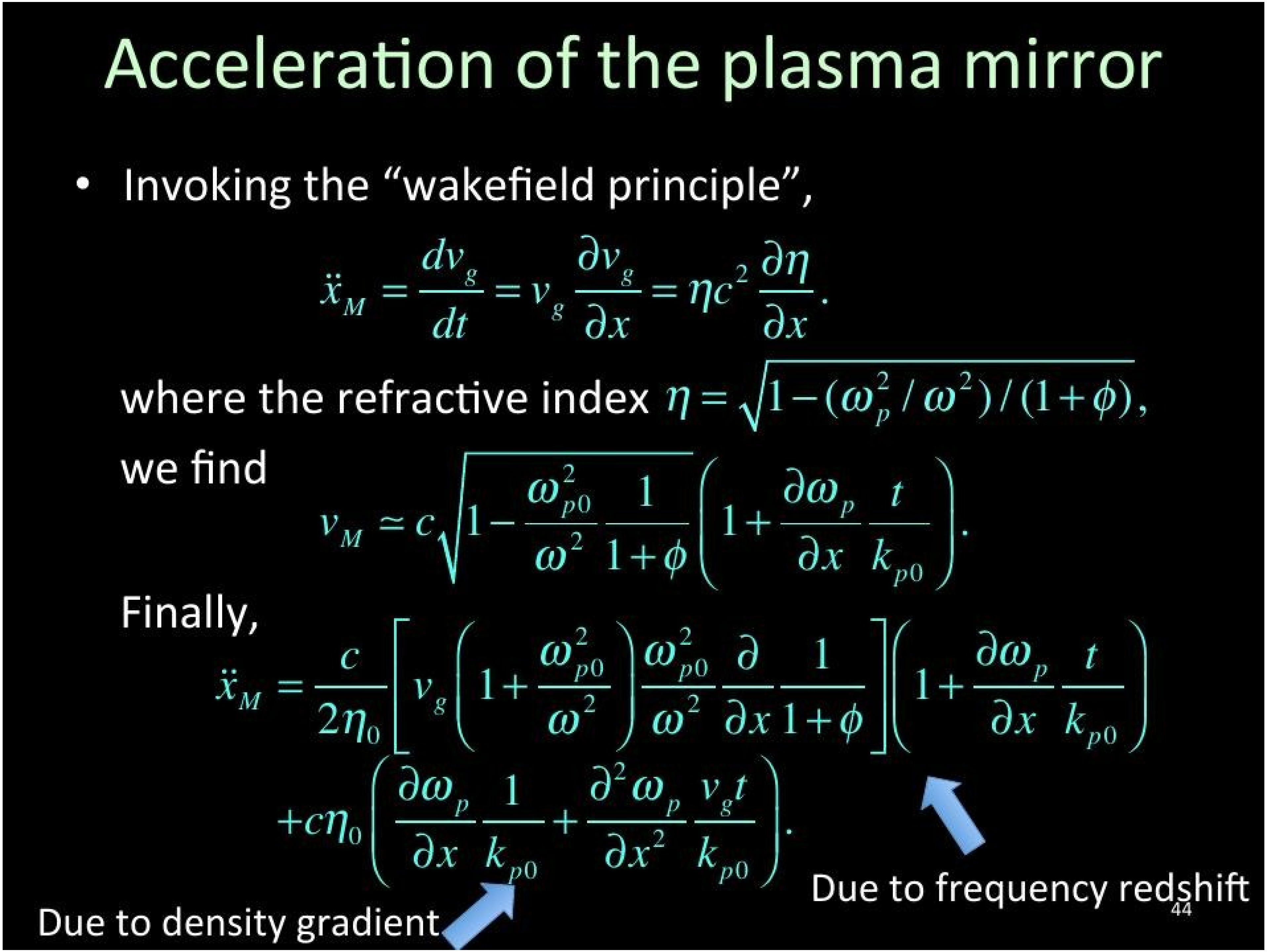

Acceleration of the plasma mirror

- Invoking the “wakefield principle”,

$$\ddot{x}_M = \frac{dv_g}{dt} = v_g \frac{\partial v_g}{\partial x} = \eta c^2 \frac{\partial \eta}{\partial x}.$$

where the refractive index $\eta = \sqrt{1 - (\omega_p^2 / \omega^2)/(1+\phi)}$,

we find

$$v_M \simeq c\sqrt{1 - \frac{\omega_{p0}^2}{\omega^2}\frac{1}{1+\phi}}\left(1 + \frac{\partial \omega_p}{\partial x}\frac{t}{k_{p0}}\right).$$

Finally,

$$\ddot{x}_M = \frac{c}{2\eta_0}\left[v_g\left(1 + \frac{\omega_{p0}^2}{\omega^2}\right)\frac{\omega_{p0}^2}{\omega^2}\frac{\partial}{\partial x}\frac{1}{1+\phi}\right]\left(1 + \frac{\partial \omega_p}{\partial x}\frac{t}{k_{p0}}\right)$$
$$+ c\eta_0\left(\frac{\partial \omega_p}{\partial x}\frac{1}{k_{p0}} + \frac{\partial^2 \omega_p}{\partial x^2}\frac{v_g t}{k_{p0}}\right).$$

Due to frequency redshift

Due to density gradient

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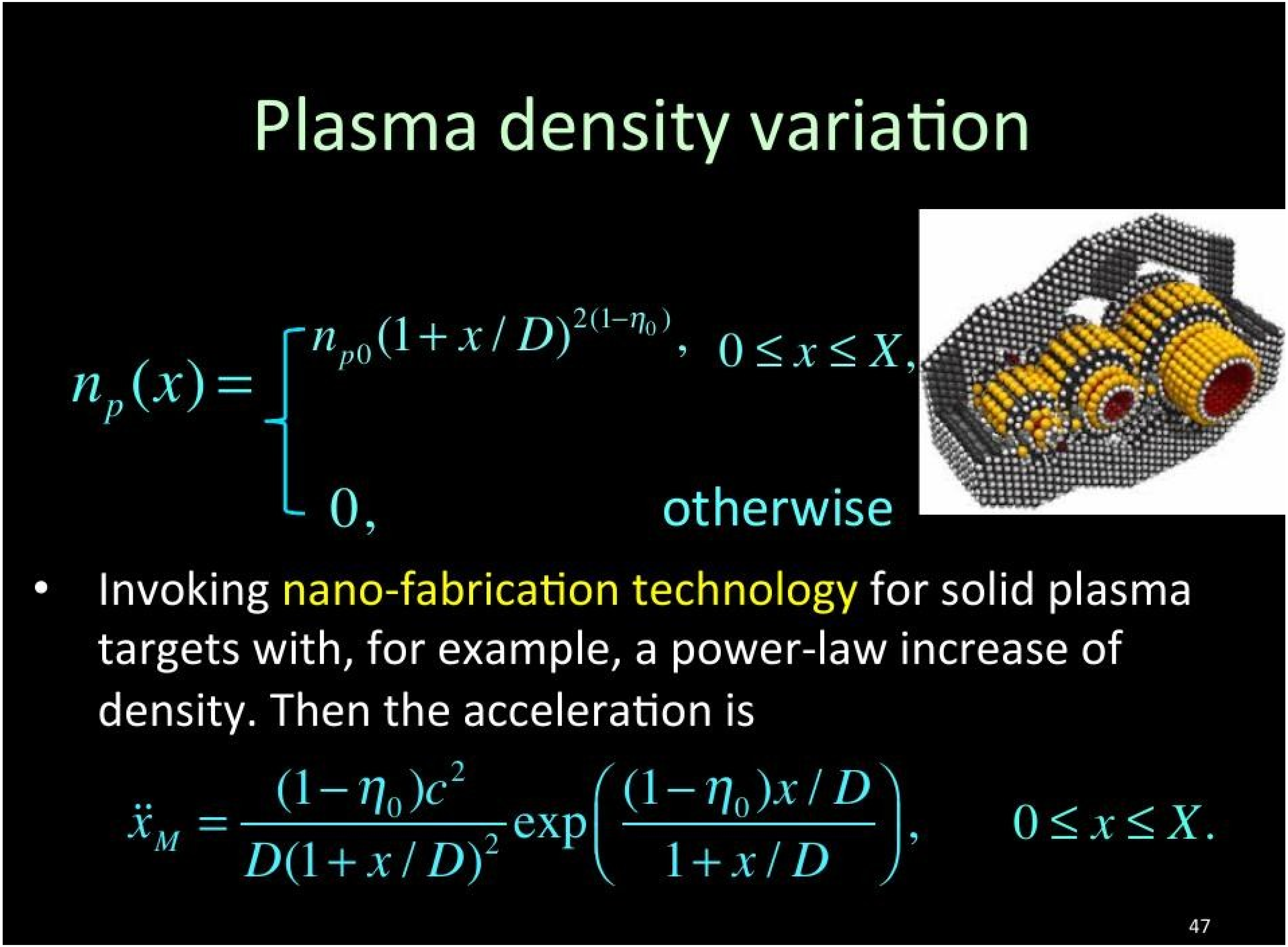

Plasma density variation

$$n_p(x) = \begin{cases} n_{p0}(1 + x / D)^{2(1-\eta_0)}, & 0 \le x \le X, \\ 0, & \text{otherwise} \end{cases}$$

- Invoking nano-fabrication technology for solid plasma targets with, for example, a power-law increase of density. Then the acceleration is

$$\ddot{x}_M = \frac{(1-\eta_0)c^2}{D(1+x/D)^2}\exp\left(\frac{(1-\eta_0)x/D}{1+x/D}\right), \qquad 0 \le x \le X.$$

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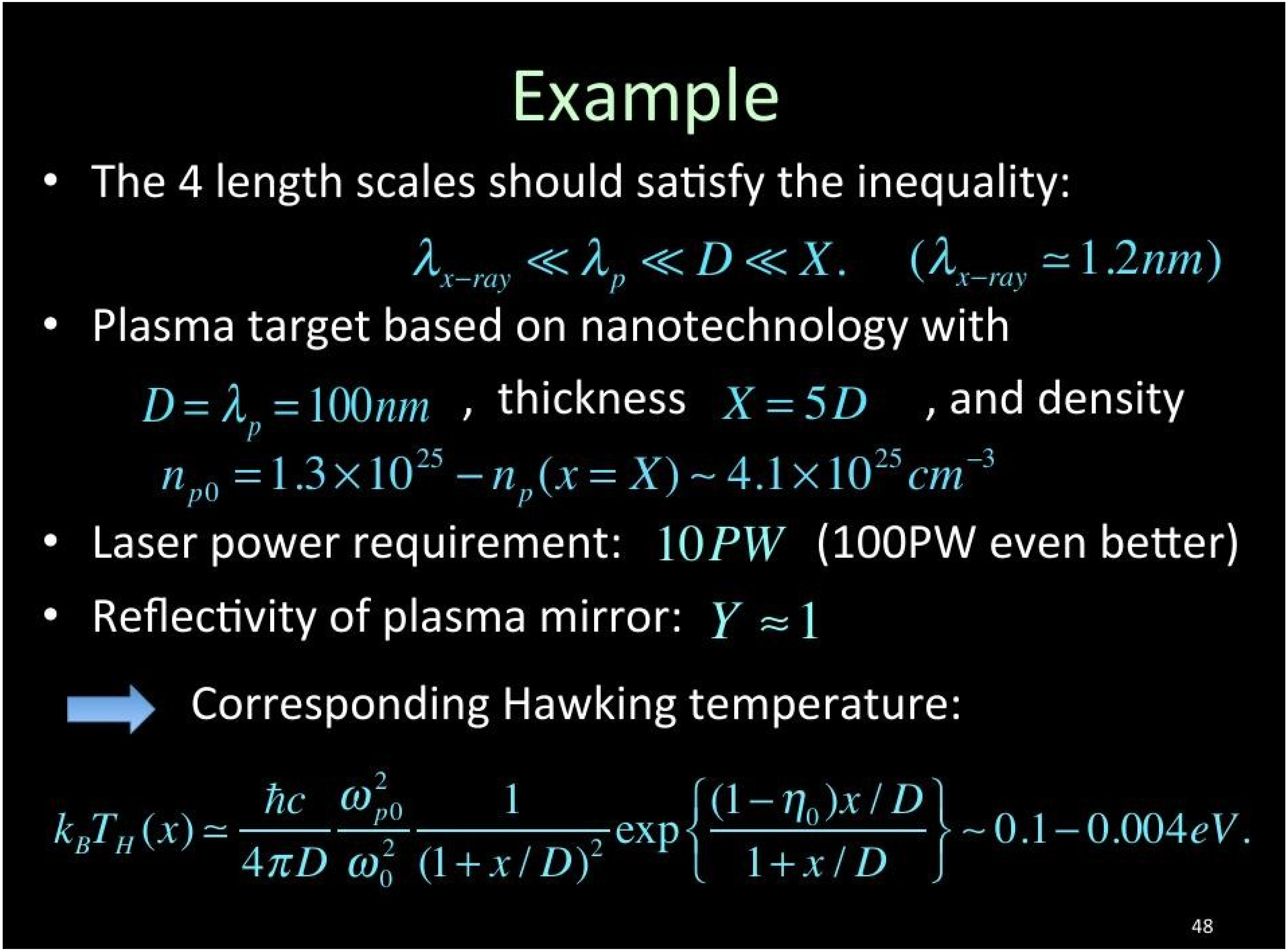

Example

- The 4 length scales should satisfy the inequality:

$$\lambda_{x-ray} \ll \lambda_p \ll D \ll X. \quad (\lambda_{x-ray} \simeq 1.2nm)$$

- Plasma target based on nanotechnology with

$D = \lambda_p = 100nm$, thickness $X = 5D$, and density

$$n_{p0} = 1.3\times10^{25} - n_p(x = X) \sim 4.1\times10^{25}\,cm^{-3}$$

- Laser power requirement: $10PW$ (100PW even better)
- Reflectivity of plasma mirror: $Y \approx 1$

➡ Corresponding Hawking temperature:

$$k_B T_H(x) \simeq \frac{\hbar c}{4\pi D}\frac{\omega_{p0}^2}{\omega_0^2}\frac{1}{(1+x/D)^2}\exp\left\{\frac{(1-\eta_0)x/D}{1+x/D}\right\} \sim 0.1-0.004eV.$$

From P. Chen seminar LLR 3/4/2017

Selected bibliography for :
The experiment proposal to investigate the Black Hole Information Loss Paradox

P. Chen, G. Mourou, Accelerating Plasma Mirrors to Investigate the Black Hole Information Loss Paradox, PRL 118 (2017) 045001

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