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U.S. DEPARTMENT OF ENERGY | Office of Science

On “Ultimate” Energy Frontier Colliders

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"Dream" Collider: Choices

- Far Future "Energy Frontier" assumes
  - 300-1000 TeV (*20-100 × LHC*)
  - "decent luminosity" (TBD)
- Surely we know:

1. For the same reason there is no circular ***e+e-*** collider above Higgs-F there will be no circular ***pp*** colliders beyond 100 TeV → **LINEAR**

2. Electrons radiate 100% *beam-strahlung* (<3 TeV) and in focusing channel (<10 TeV) → ***μ+μ-*** or ***pp***

circular collider

$$L \propto \frac{\eta P_{wall}}{E^3} \frac{\xi_y}{\beta_y}$$

linear collider

$$L \propto \frac{\eta_{\text{linac}} P_{wall}}{E} \frac{N_\gamma}{\sigma_y}$$

"Phase-Space" is Further Limited

- "Cost Feasibility": for 20-100 × LHC
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

→New technology should provide >30 GeV/m @ total component cost <1M$/m (~NC magnets now)

SC magnets equiv. ~ 0.5 GeV per meter (LHC)

3. Only one option for >30 GeV/m known now: dense plasma→ that excludes *protons*→ only *muons*

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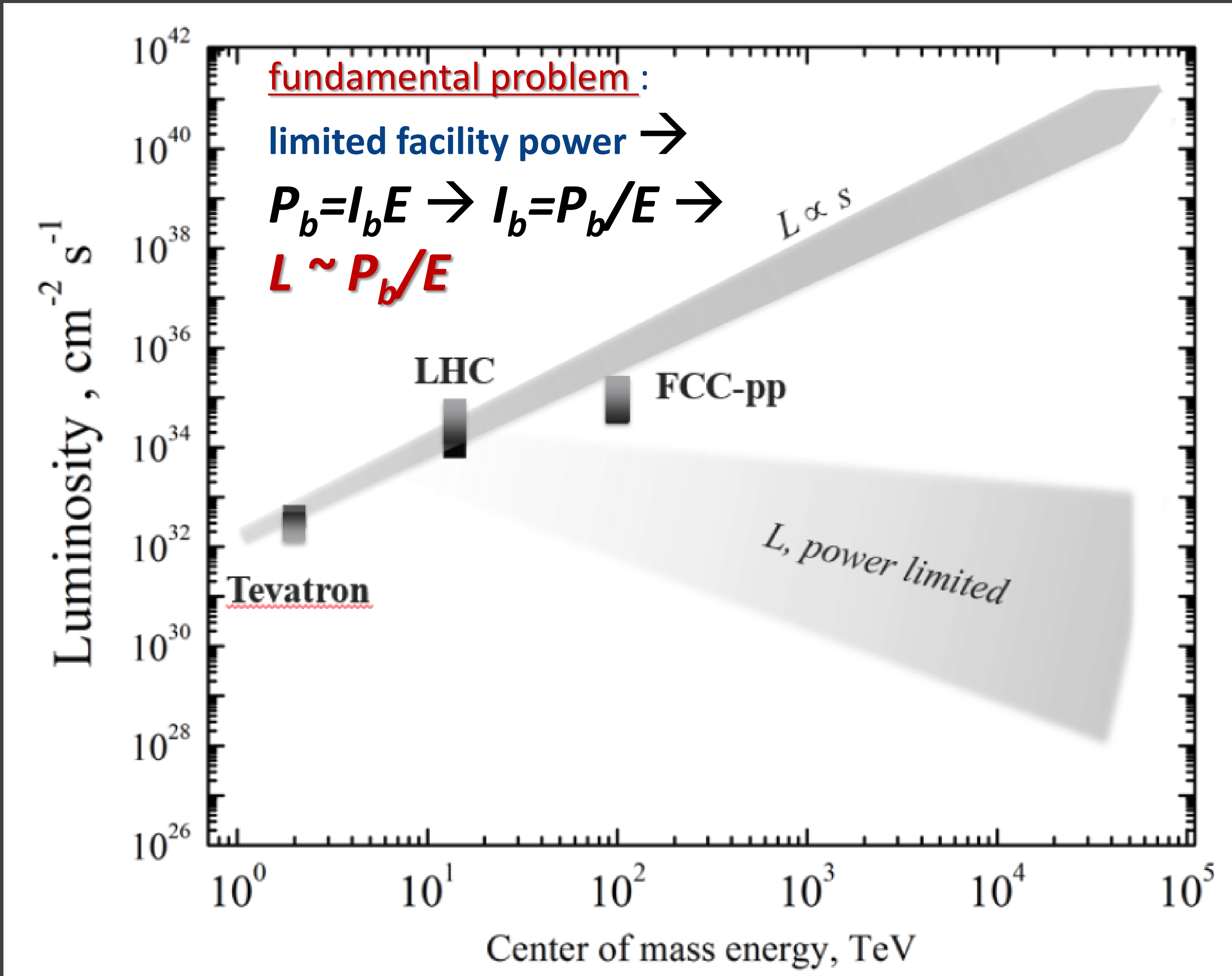
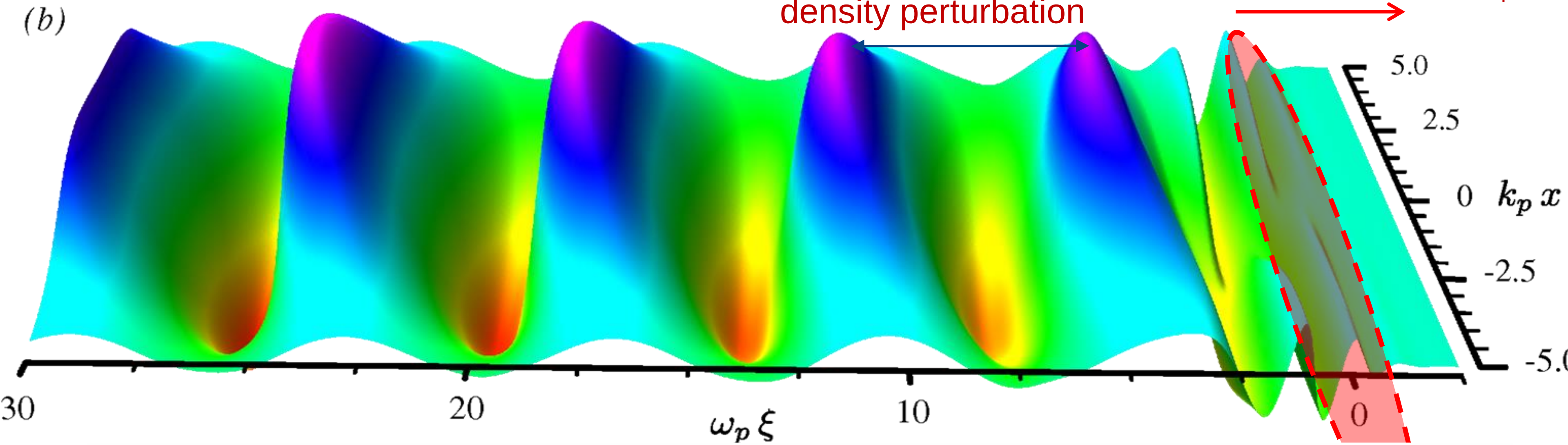
Paradigm Shift : *Energy* vs *Luminosity*



New Technology- Plasma

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Option A:

Short intense e-/e+/p bunch

Few 10^{16}cm^{-3}, **6 GV/m** over 0.3m

Option B:

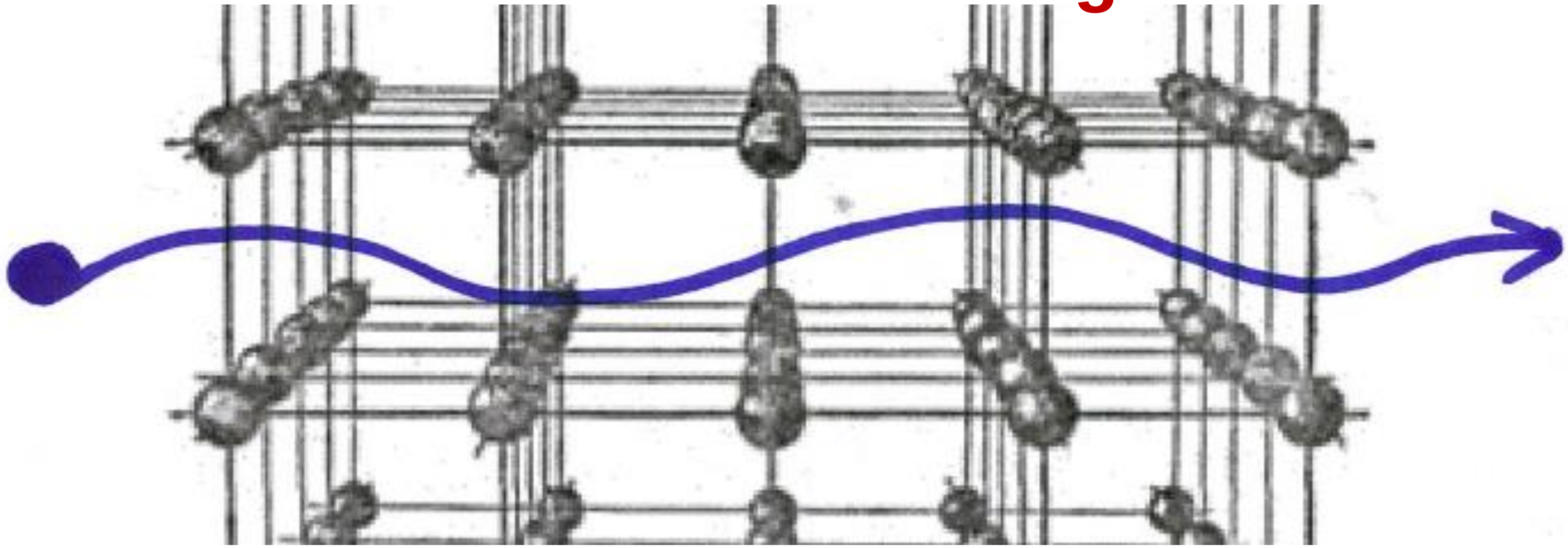
Short intense laser pulse

~10^{18}cm^{-3}, **50 GV/m** over 0.1m

First looks into "Plasma-Collider": **staging kills ! <*E*>~2 GV/m,*ε***

New Approach:

Acceleration in Continuous Focusing Channel



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

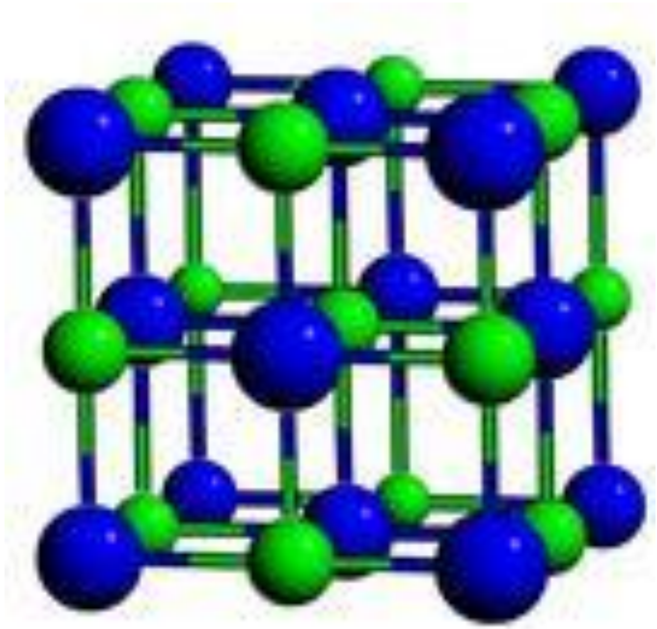
10^{22} cm^{-3} → 10 TV/m, λ_p~0.3µm

10^{24} cm^{-3} → 100 TV/m, λ_p~0.03µm

Synchtrotron radiation losses balance energy gain:
0.3TeV for positrons
10 000 TeV for muons (+)
1000 000 TeV for protons

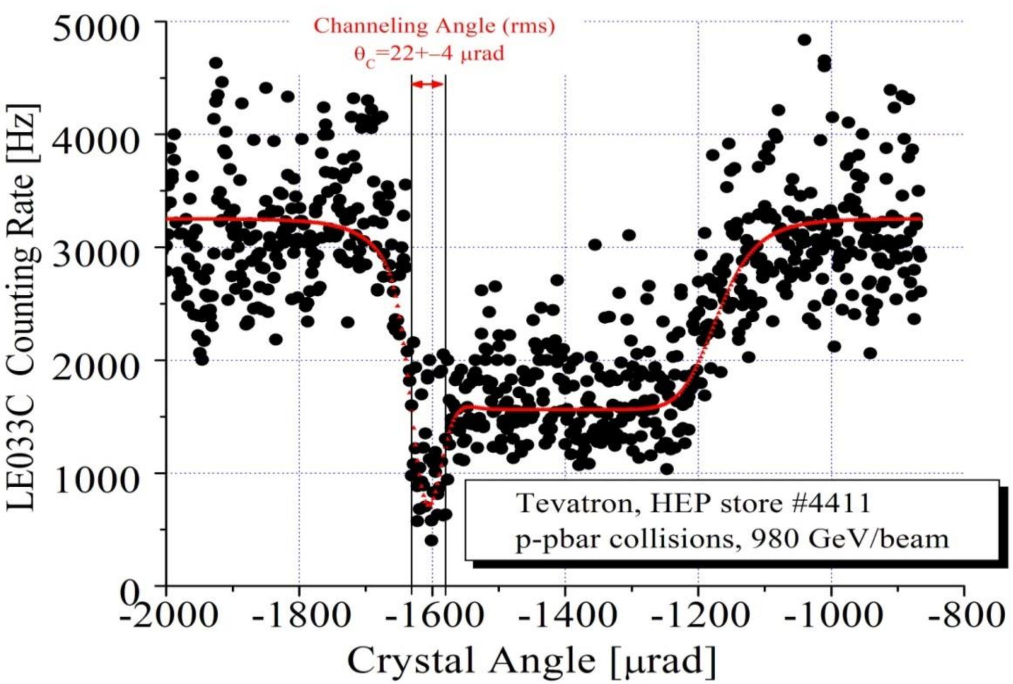
Chen P, Noble R J *AIP Conf. Proc.* **398** 273 (1997)

What Do We Know about Crystals?



$$l_d\,[\mathrm{m}] \sim E\,[\mathrm{TeV}]$$

T980 experiment at Tevatron, *N.Mokhov et al JINST 6 T08005 (2011)*

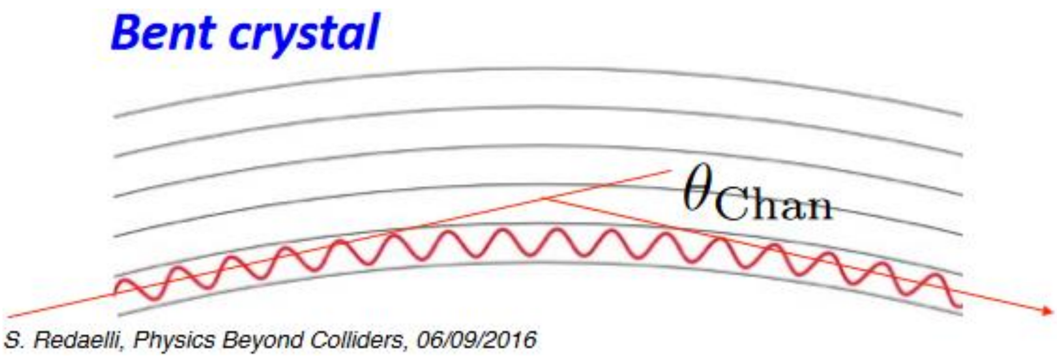


- Strong inter-planar electric fields ~10V/A=1GV/cm
- Very stable, can be used for
  - deflection/bending (*works*)
  - focusing (*works*)
  - acceleration (*if excited*)

~92.5+-5% efficiency

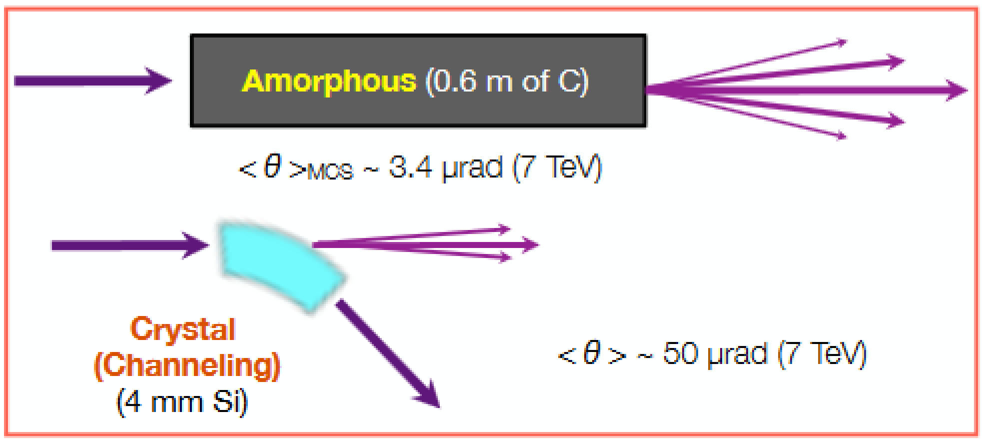
Or *l_d* ~ 5mm/0.025 < 0.2m

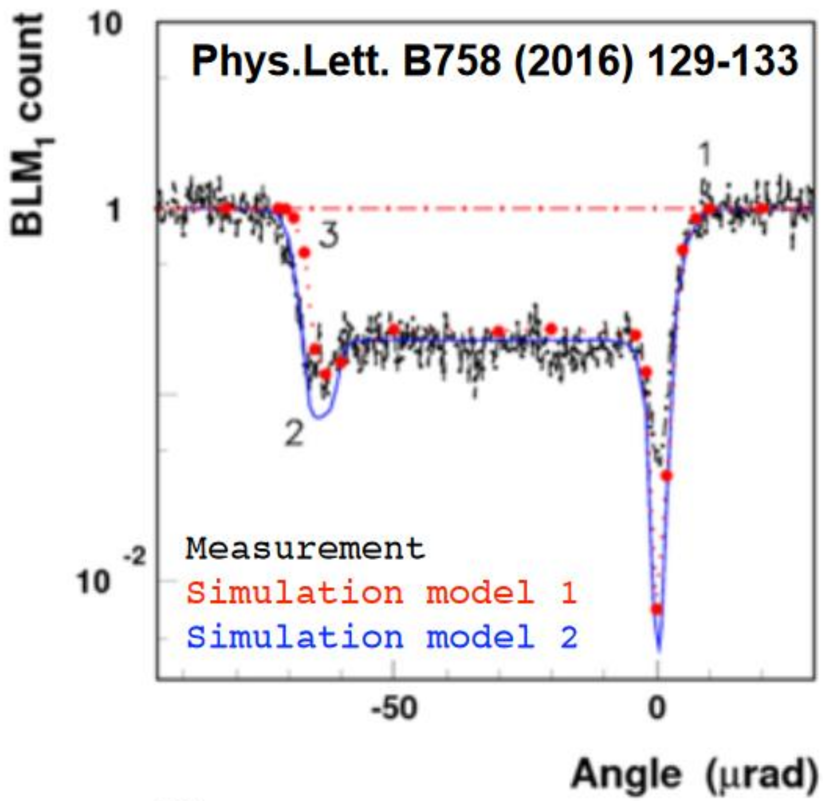
4 mm Si in LHC



~2 mrad at 7 TeV

Equivalent magnetic field for **50μrad** at **7 TeV** proton beams: **310 T** (4 mm crystal)





~99.5% efficiency

Or *l_d* ~ 4mm/0.005=0.8m

Collider considerations

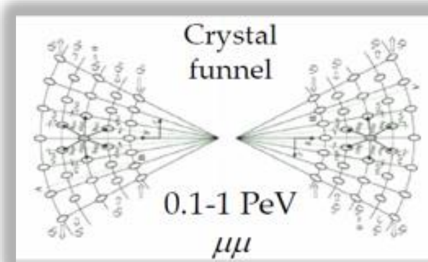
$$dN/dt = -N/\gamma\tau_0 \qquad \frac{N}{N_0} \approx \left(\frac{m_\mu c^2}{E}\right)^{\kappa}$$

$$\kappa = (m_\mu c/\tau_0 G) \ll 1/\ln(E/m_\mu c^2)$$

i.e. irrelevant

$$A \sim 1\ \text{Å}^2 = 10^{-16}\ \text{cm}^2 \qquad N_0 \sim 10^3 \text{ particles}$$

$$L = fN^2/A = f \times 10^{16} \times 10^6\, n_{ch}\ [\text{cm}^{-2}\ \text{s}^{-1}]$$



$$L\,[\text{sm}^{-2}\,\text{s}^{-1}] \approx 4 \times 10^{33\text{–}35}\, \frac{P^2\,[\text{MW}]}{E^2\,[\text{TeV}]\, f n_{ch} [10^8\ \text{Hz}]}$$

Table 4. Options for future particle colliders.

Collider type	Dielectric based	Plasma based	Crystal channeling
Accelerating media	Microstructures	Ionized plasma	Solid crystals
Energy source: option 1 option 2	Optical laser e^- bunch	e^- bunch Optical laser	X-ray laser
Preferred particles	Any stable	e^-, μ^-	μ^+, p^+
Max accelerating gradient, GeV m^{-1}	1 – 3	30 – 100	100 – 10^4
CM energy reach in 10 km	3 – 10	3 – 50	10^3 – 10^5
Number of stages/10 km: option 1 option 2	10^5 – 10^6 10^4 – 10^5	~ 100 10^3 – 10^4	~ 1

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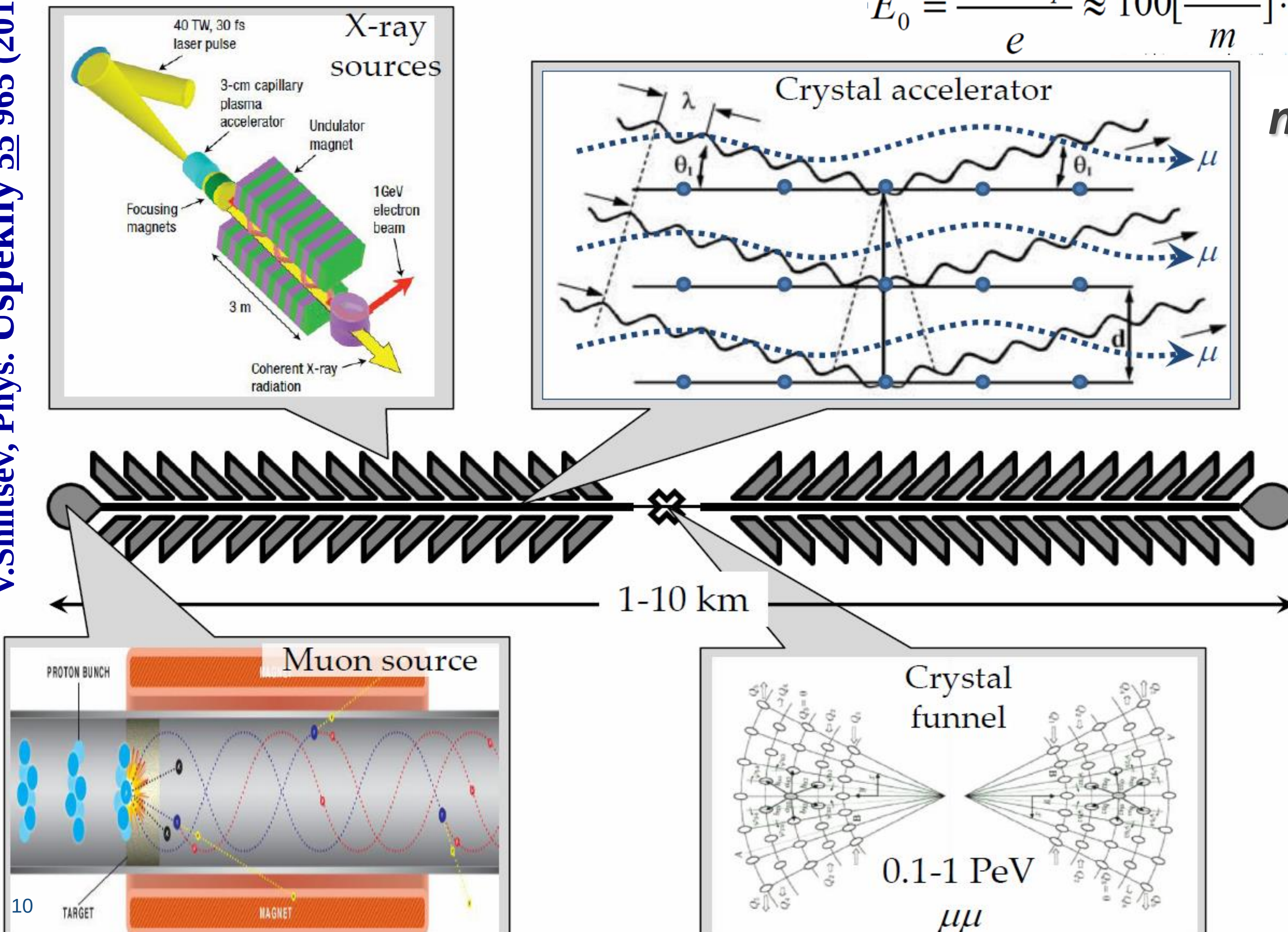
"Dream" Collider = Muons + Acceleration in Crystals + Continuous Focusing (Channeling)

V.Shiltsev, Phys. Uspekhy 55 965 (2012)

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$



***n*~10²² cm⁻³,**

10 TeV/m

→

1 PeV = 1000 TeV

n_μ ~1000

n_B ~100

f_{rep} ~10^6

L ~$10^{30\text{-}32}$

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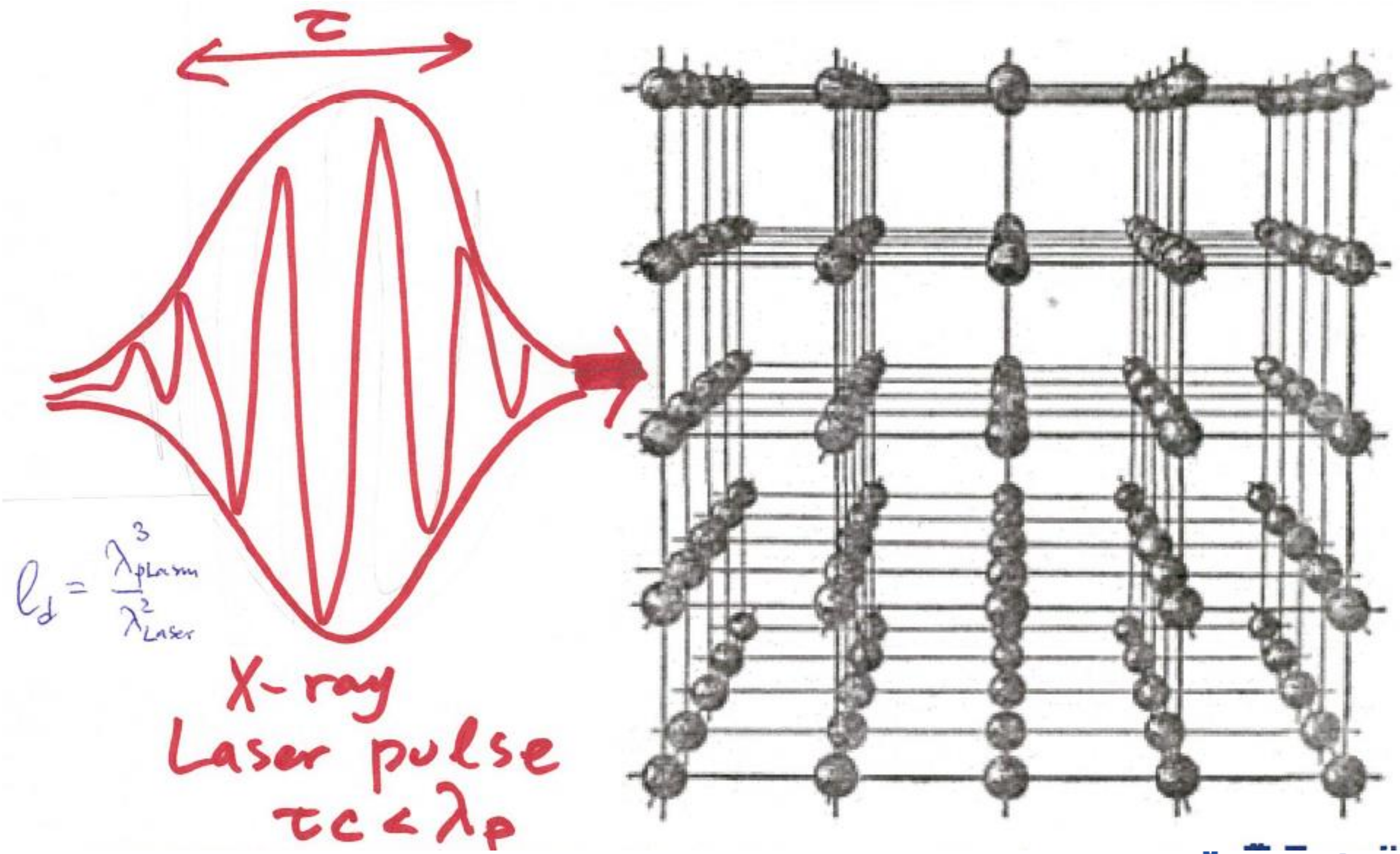
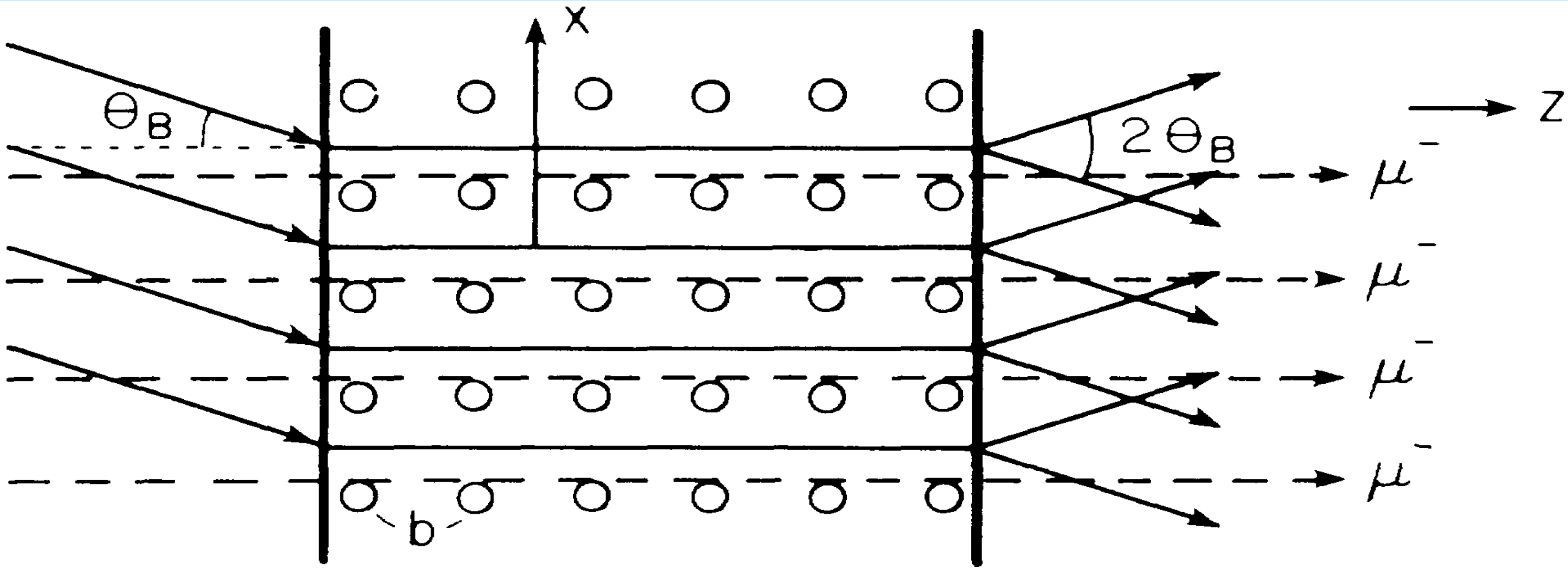
Ways to excite the crystal (1)



Crystal Excitation by X-Rays

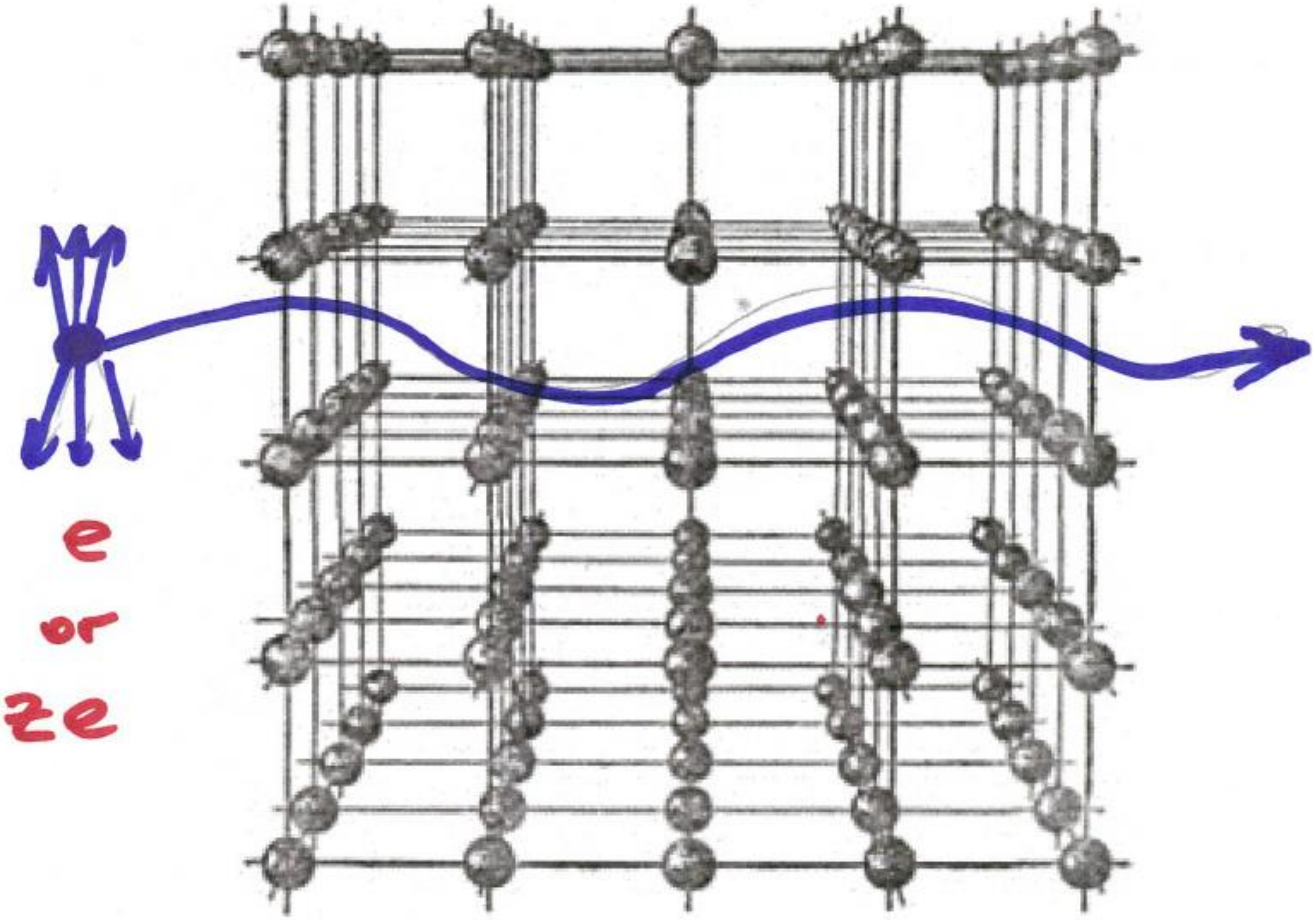


Tajima,Cavenago, Phys. Rev. Lett. 59 (1987), 1440

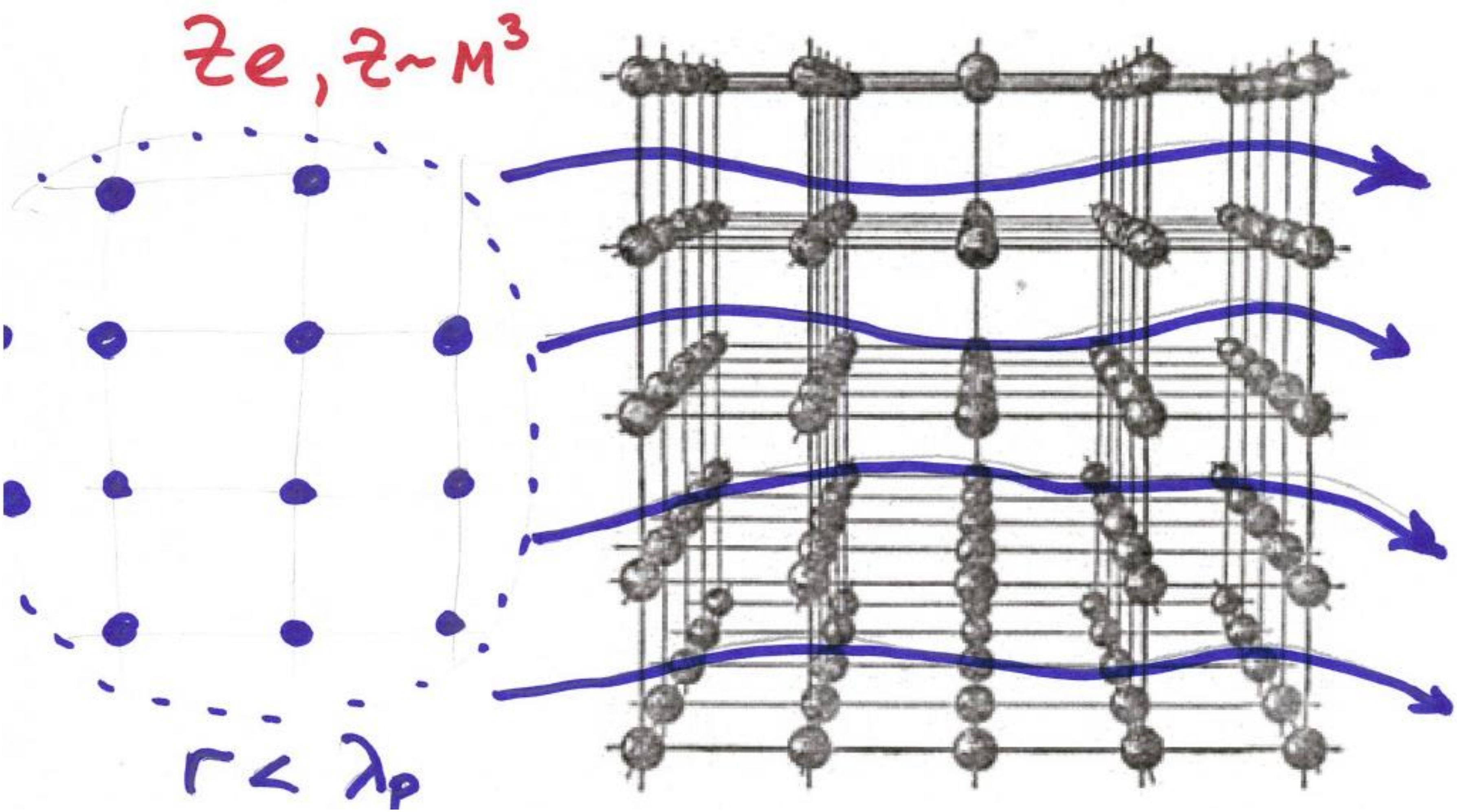
FIG. 1. Bormann anomalous transmission. When the x rays are injected at the Bragg angle, the Bormann effect takes place. Particle beams are injected along the crystal axis.

- Need 40keV high peak power x-rays
  - now available from SASE FELs like LCLS
- Gradients >1GV/cm
- Muons preferred
  - No bremstrahlung, no nucl.
- μ+ rad length 10^9 cm
  - total energy~10^9 GeV

Ways to excite the crystal (2)

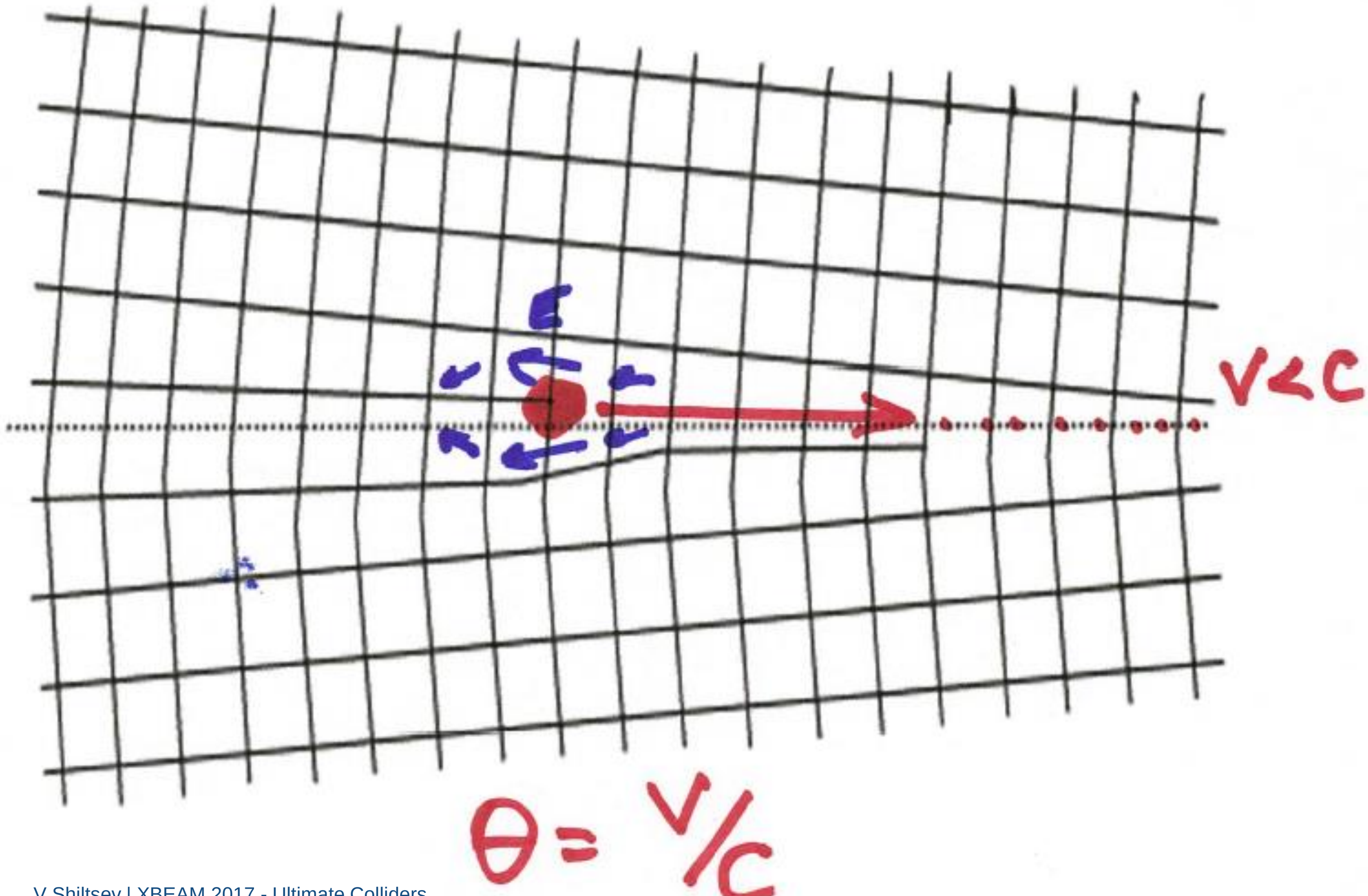


Ways to excite the crystal (3)



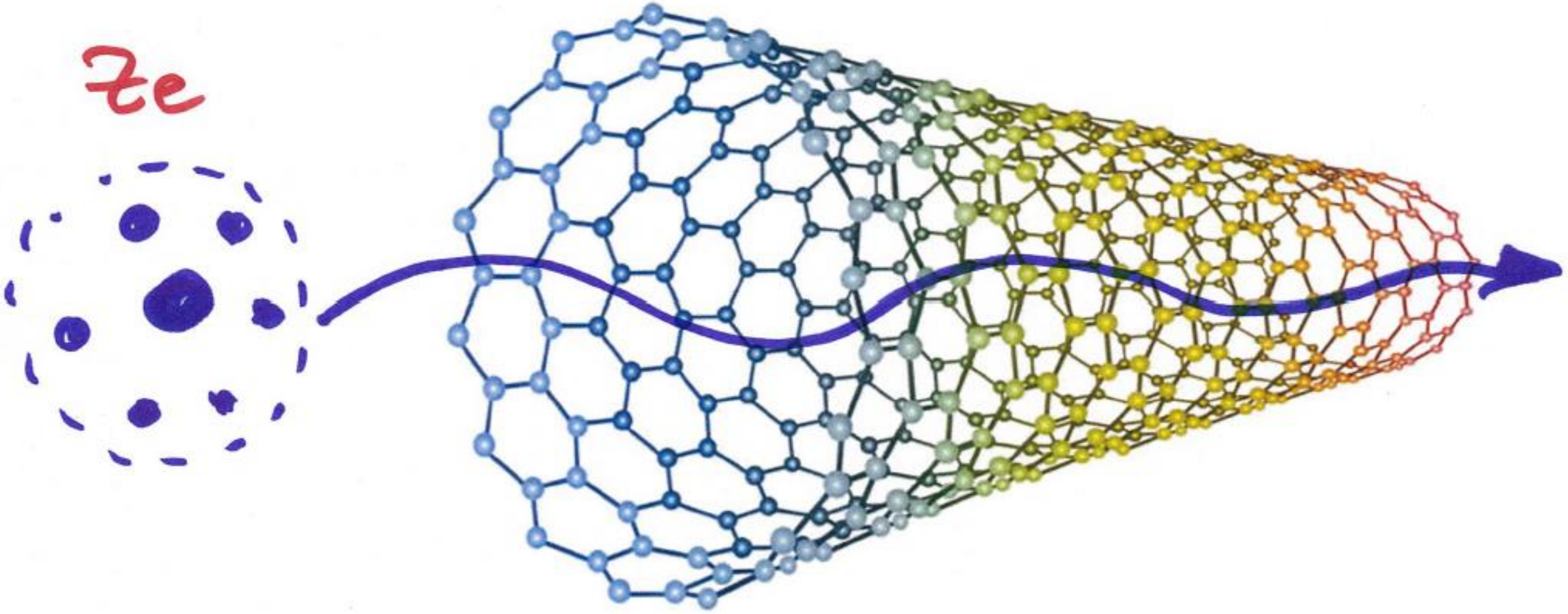
Ways to excite the crystal (4)

Controlled generation of dislocations

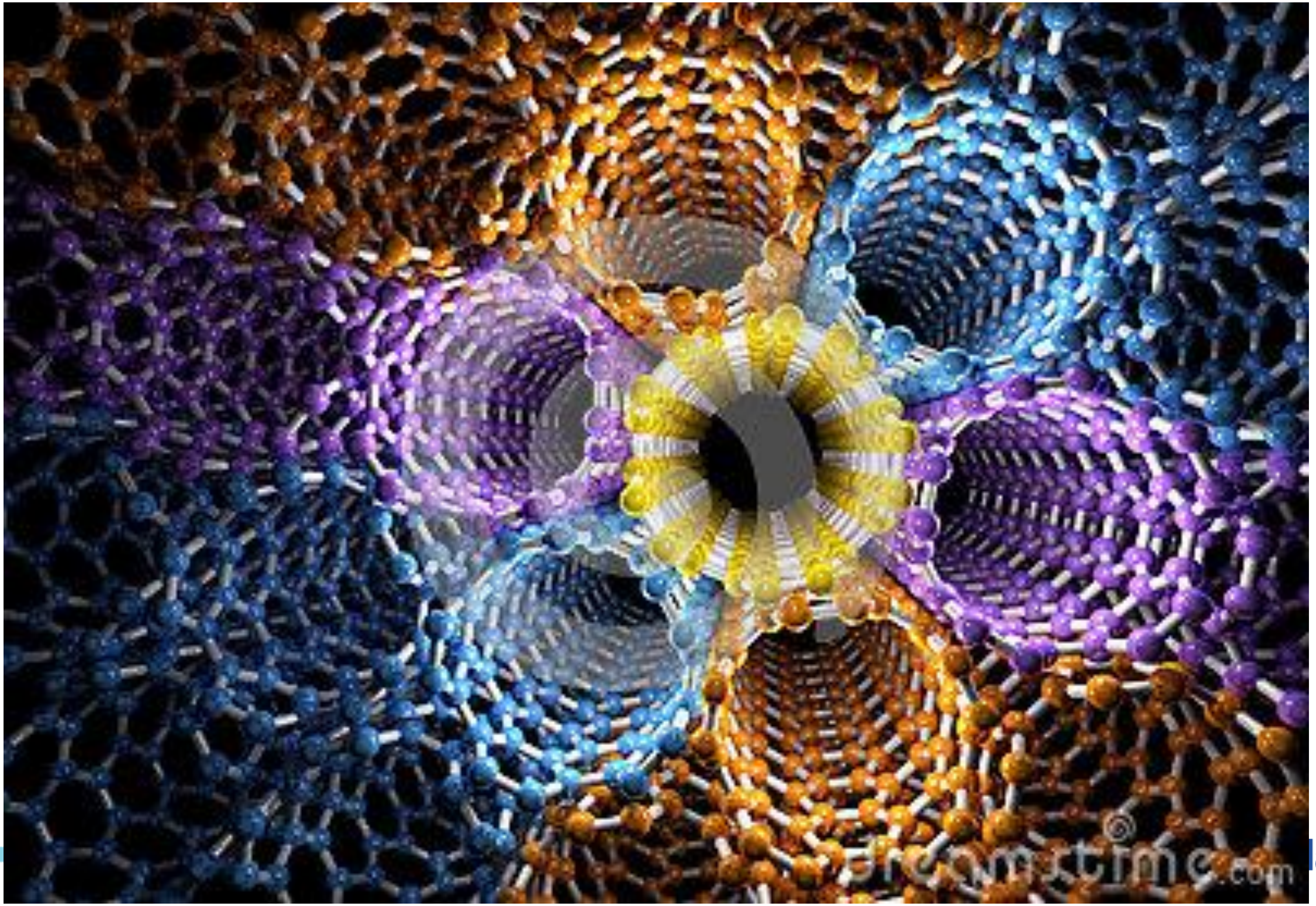


lab

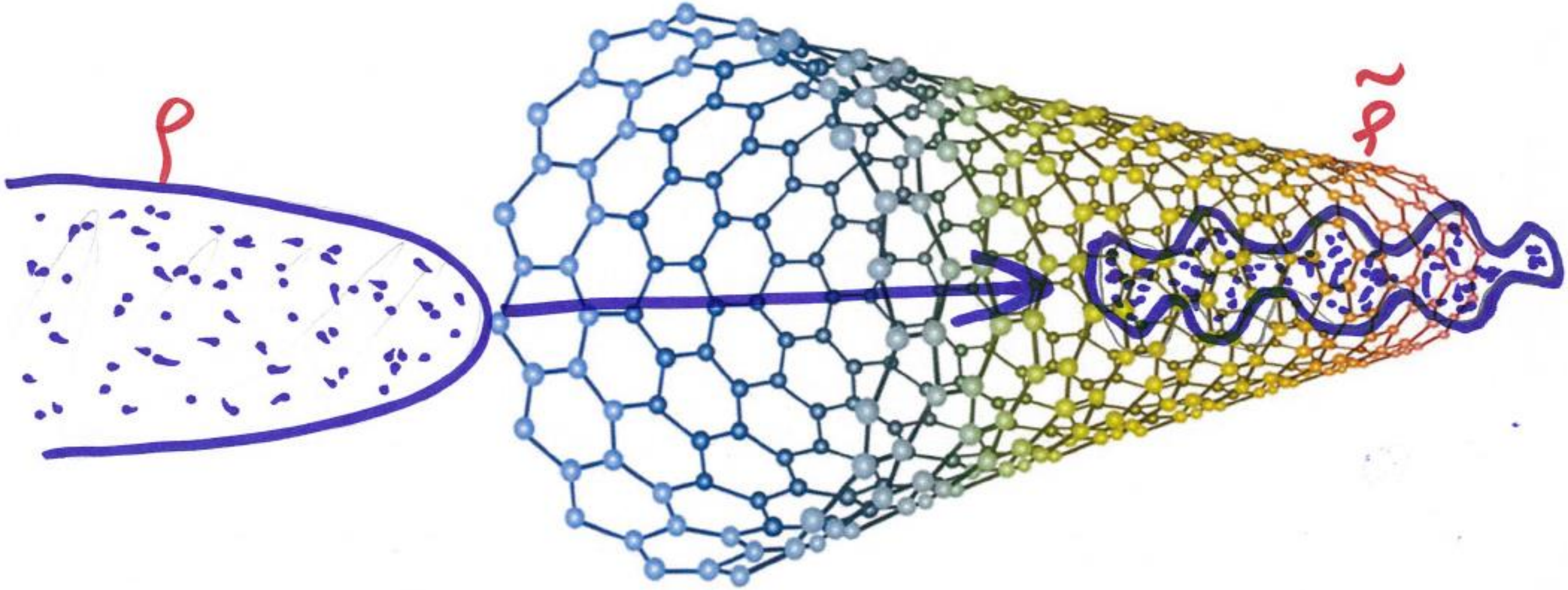
Nanotubes(1)

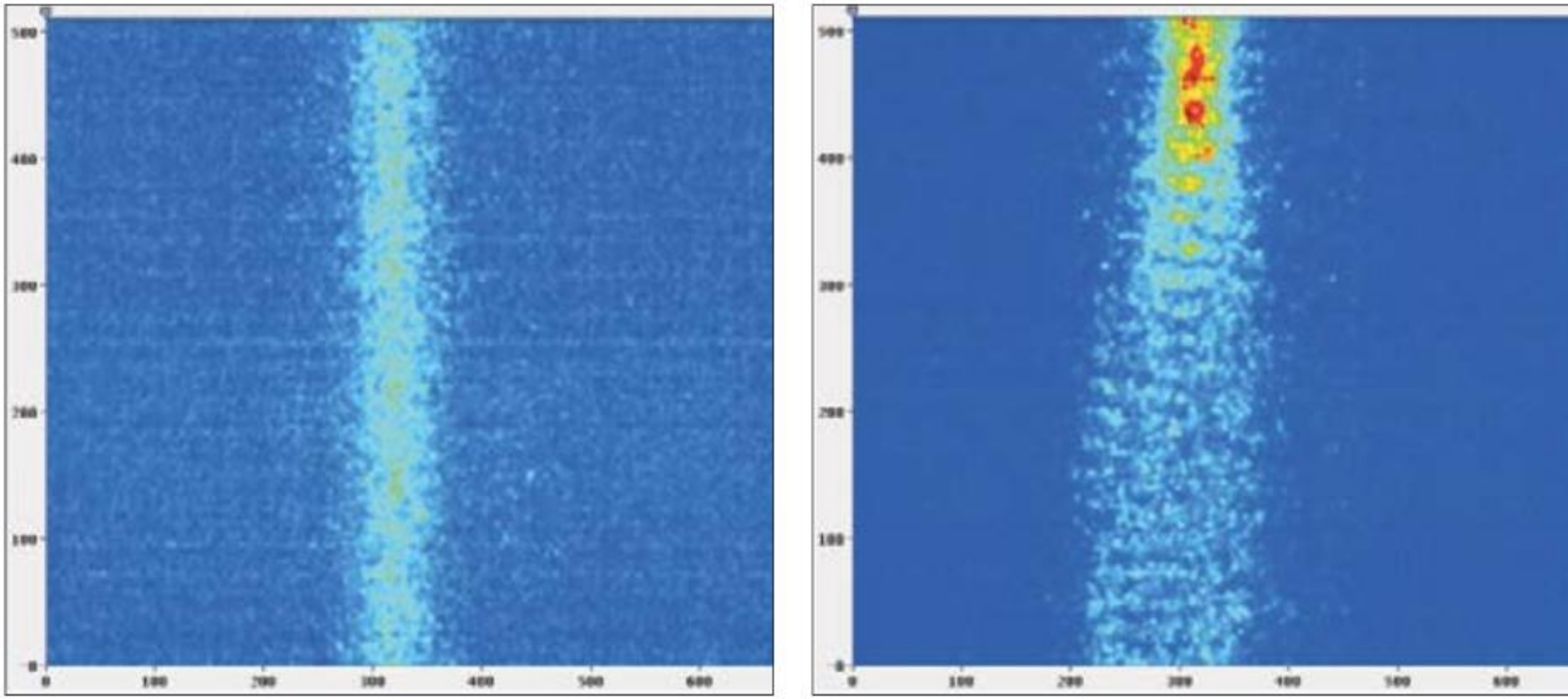


Nanotubes (2)



Excite nanotubes





A Petrenko/CERN

Comparison of the proton-bunch longitudinal profile (left, no plasma) with the profile for a bunch passing through plasma (right), showing the strong modulation of the bunch.

ACCELERATOR TECHNOLOGY

AWAKE makes waves

CERN COURIER
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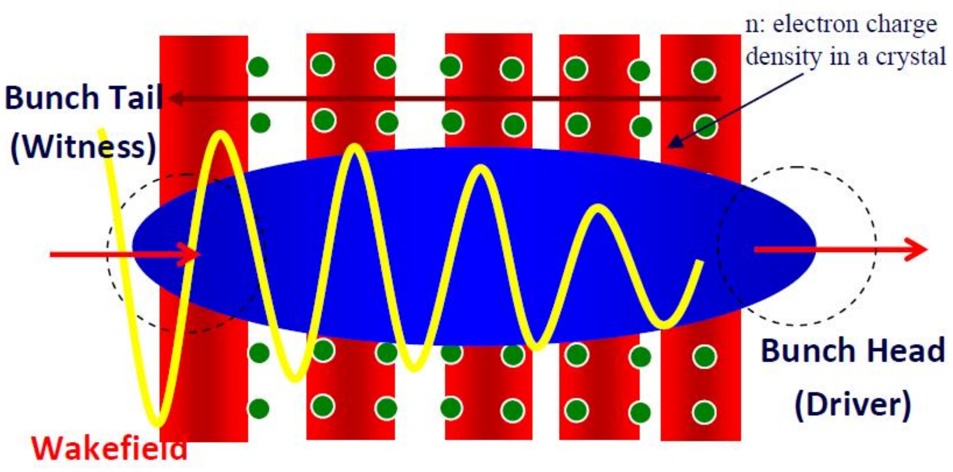
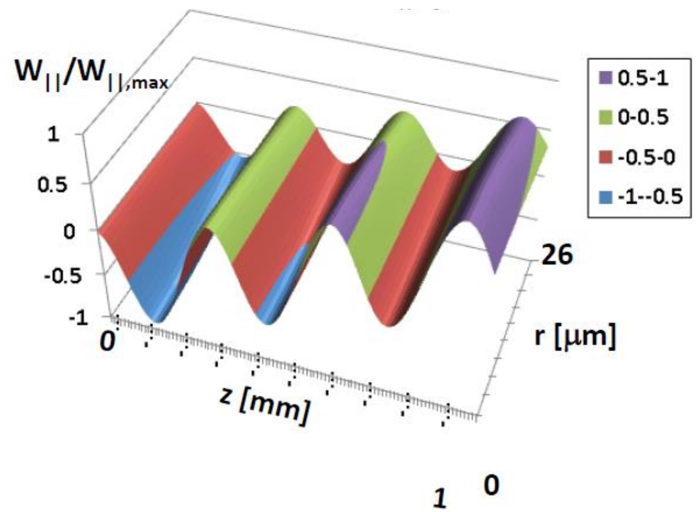
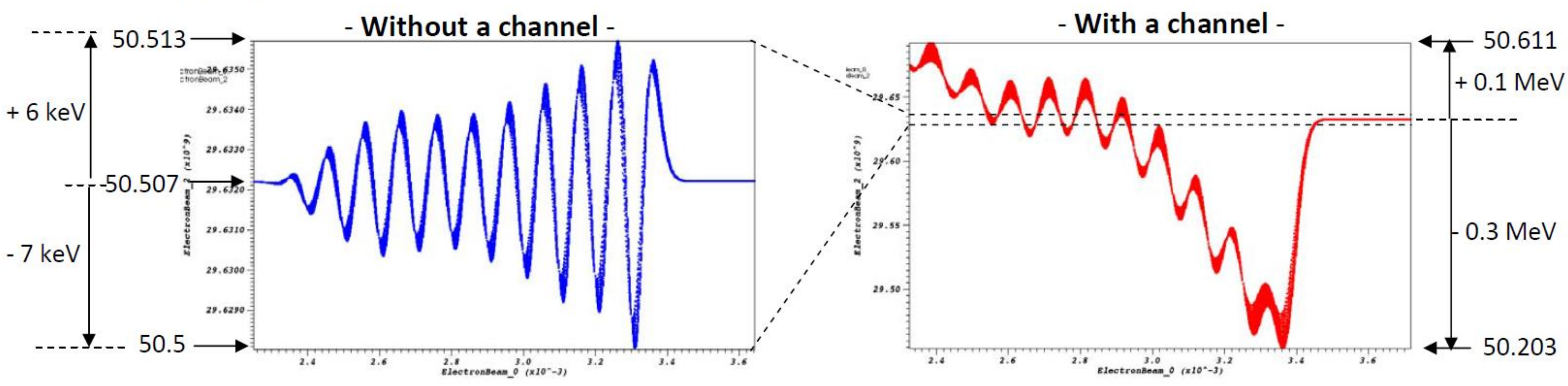
Proof-of-principle test of acceleration in Crystals/Carbon Nano Tubes (CNTs)

Y.M.Shin(NIU/FNAL), V,Shiltsev, C.Thangaraj (FNAL), et al



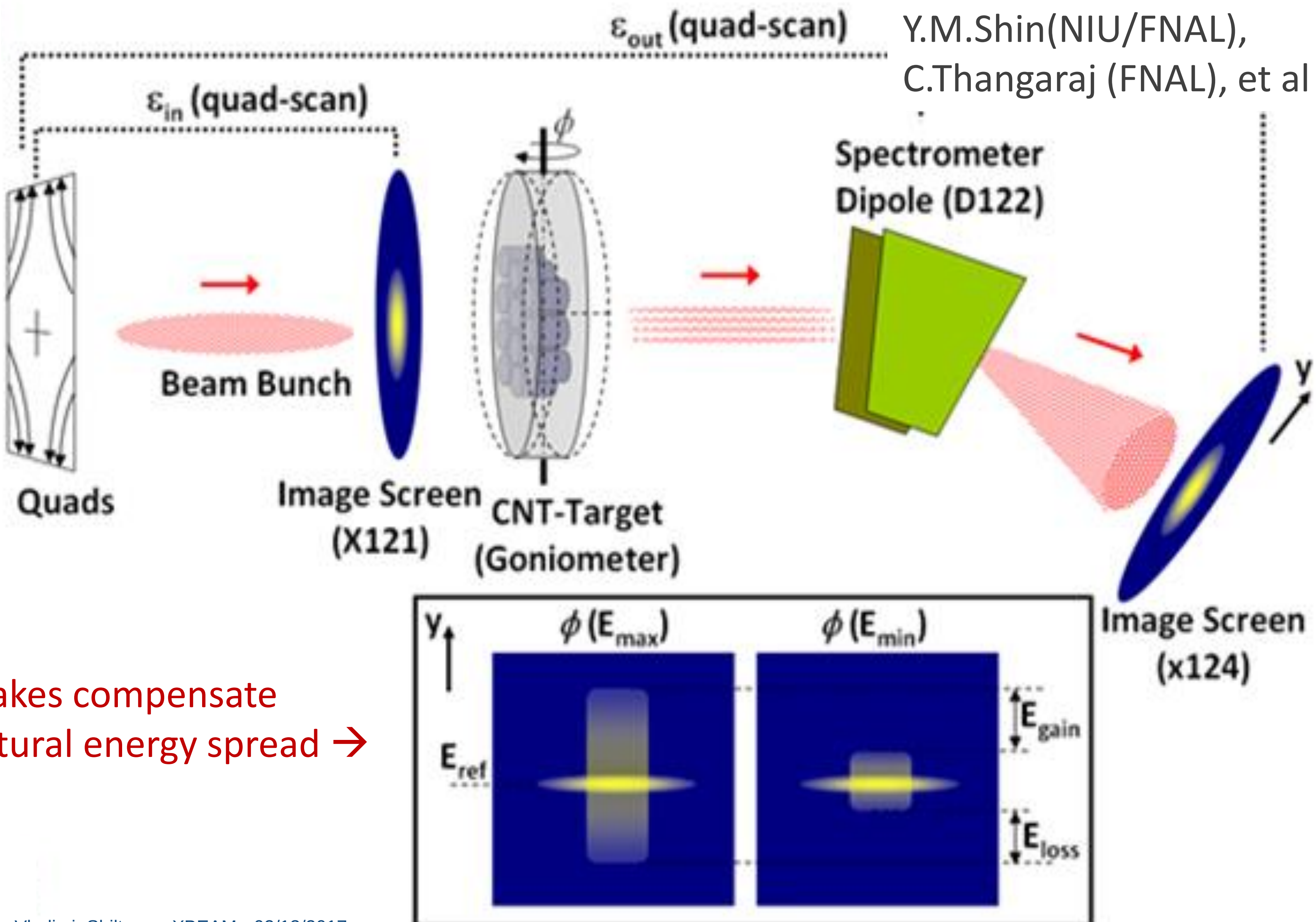


- 50 MeV (1 nC)



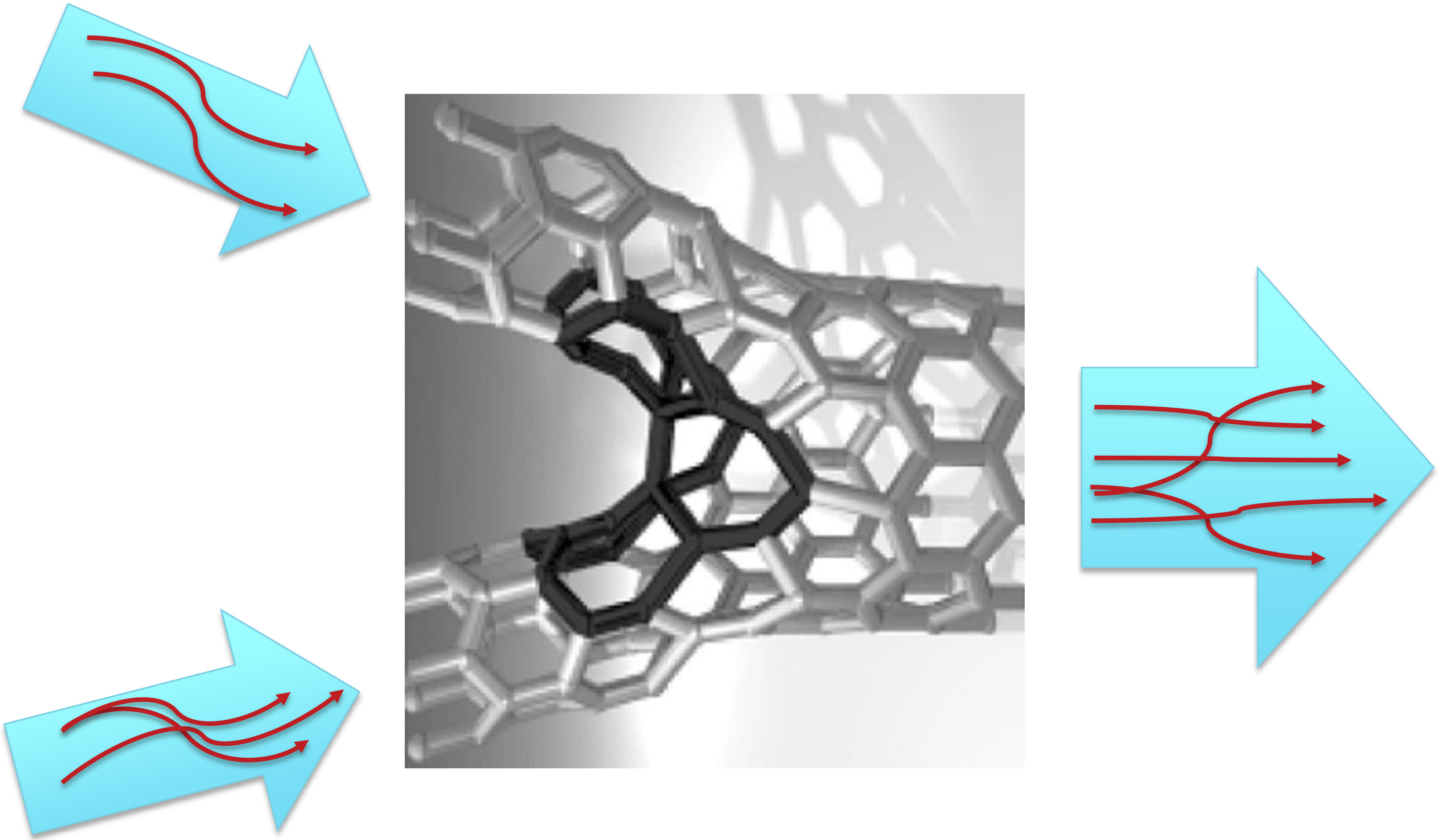
Outline of Proposed Experiment at ASTA

Y.M.Shin(NIU/FNAL),
C.Thangaraj (FNAL), et al



Wakes compensate
natural energy spread →

Combine (funnel) Channels



Bright Future

HEP's "Far" Future

- **Good News**
  - options **EXIST**
    - 300-1000 TeV muons in plasma/crystals
- **Bad News**
  - It will be

High

Energy

Low

Luminosity

Thank You for Your Attention!

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