Muon Catalyzed Fusion

David McKeen
TRIUMF

μinneapolis workshop

December 8, 2023

Work* with Patrick Draper

Muon Capture Constraints on Sterile Neutrino Properties

David McKeen[1,*] and Maxim Pospelov[1,2,†]
[1] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*

Reducing cosmological small scale structure via a large dark matter-neutrino interaction: constraints and consequences

Bridget Bertoni, Seyda Ipek, David McKeen and Ann E. Nelson

Department of Physics, University of Washington, Seattle, Washington 98195, USA

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Constraints on muon-specific dark forces

Savely G. Karshenboim,[1,2] David McKeen,[3] and Maxim Pospelov[4,5]
[1] *Max-Planck-Institut für Quantenoptik, Garching, 85748, Germany*
[2] *Pulkovo Observatory, St. Petersburg, 196140, Russia*
[3] *Department of Physics, University of Washington, Seattle, WA 98195, USA*
[4] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
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Cosmological constraints on dark matter interactions with ordinary matter

Manuel A. Buen-Abad [a,b,*], Rouven Essig [c], David McKeen [d], Yi-Ming Zhong [e]

[a] Department of Physics, Brown University, Providence, RI, 02912, USA
[b] Dual CP Institute of High Energy Physics, C.P. 28045, Colima, Mexico
[c] C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794, USA
[d] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada
[e] Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA

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Neutron Star Internal Heating Constraints on Mirror Matter

David McKeen,[1,*] Maxim Pospelov,[2,3,†] and Nirmal Raj[1,‡]
[1] TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada
[2] School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA
[3] William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA

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Gravitational wave constraints on extended dark matter structures

Djuna Croon,[1,*] Seyda Ipek,[2,†] and David McKeen[3,‡]
[1]Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom
[2]Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada
[3]TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada


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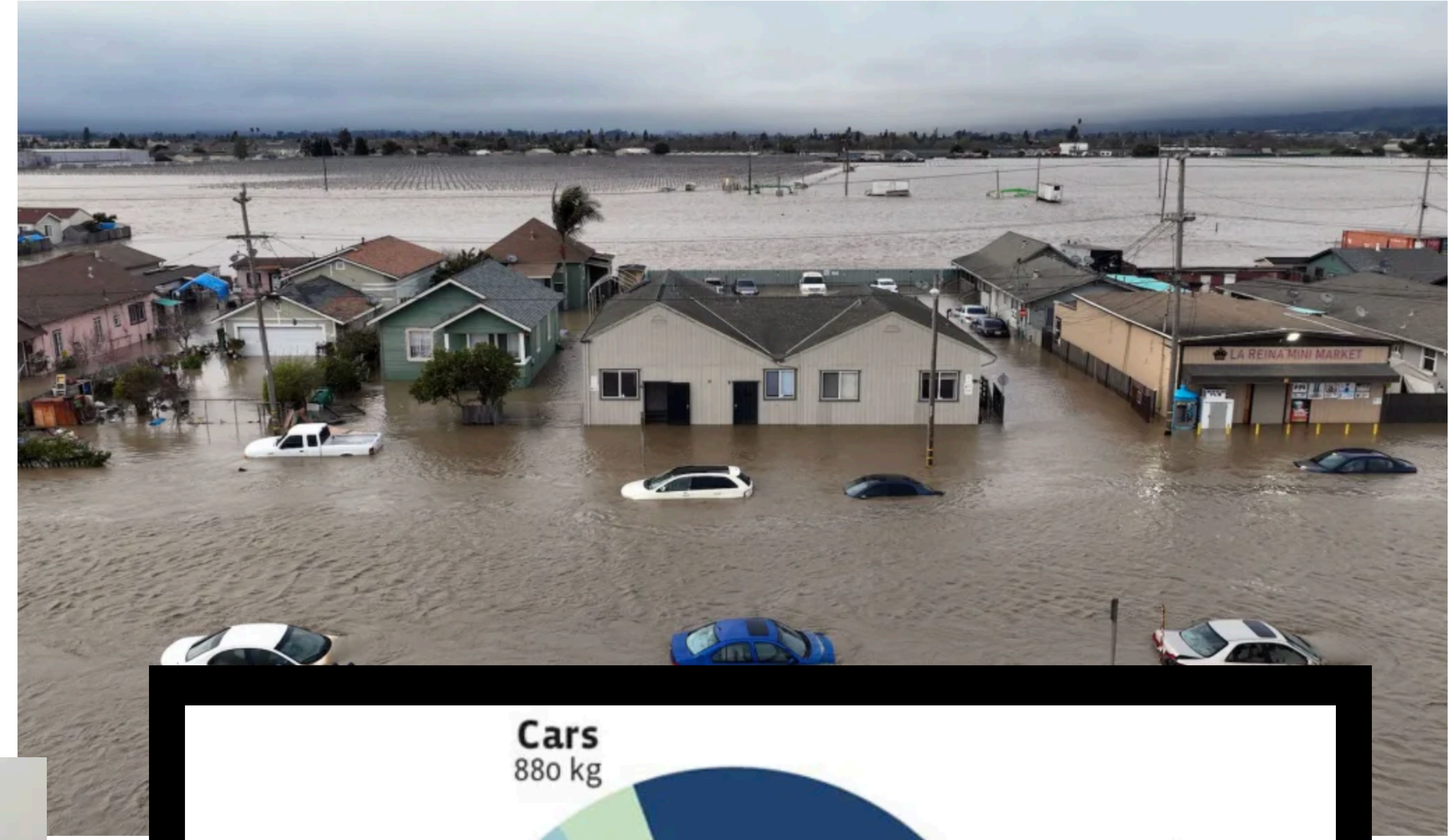
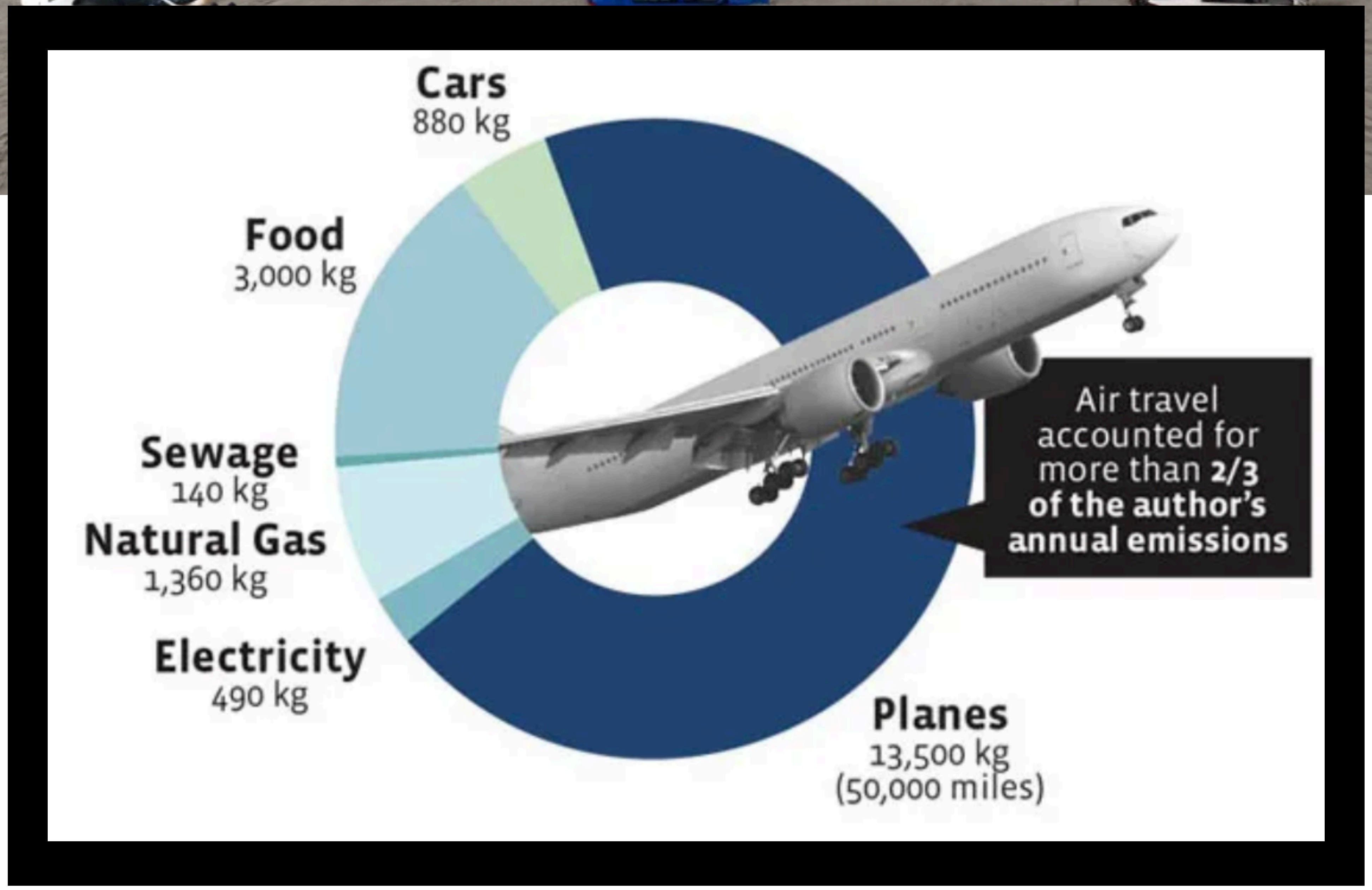



Cars
880 kg
Food
3,000 kg
Sewage
140 kg
Natural Gas
1,360 kg
Electricity
490 kg
Planes
13,500 kg
(50,000 miles)
Air travel accounted for more than 2/3 of the author's annual emissions

Caveats

This isn't my area of expertise

I haven't thought about it extensively and this is work* in progress

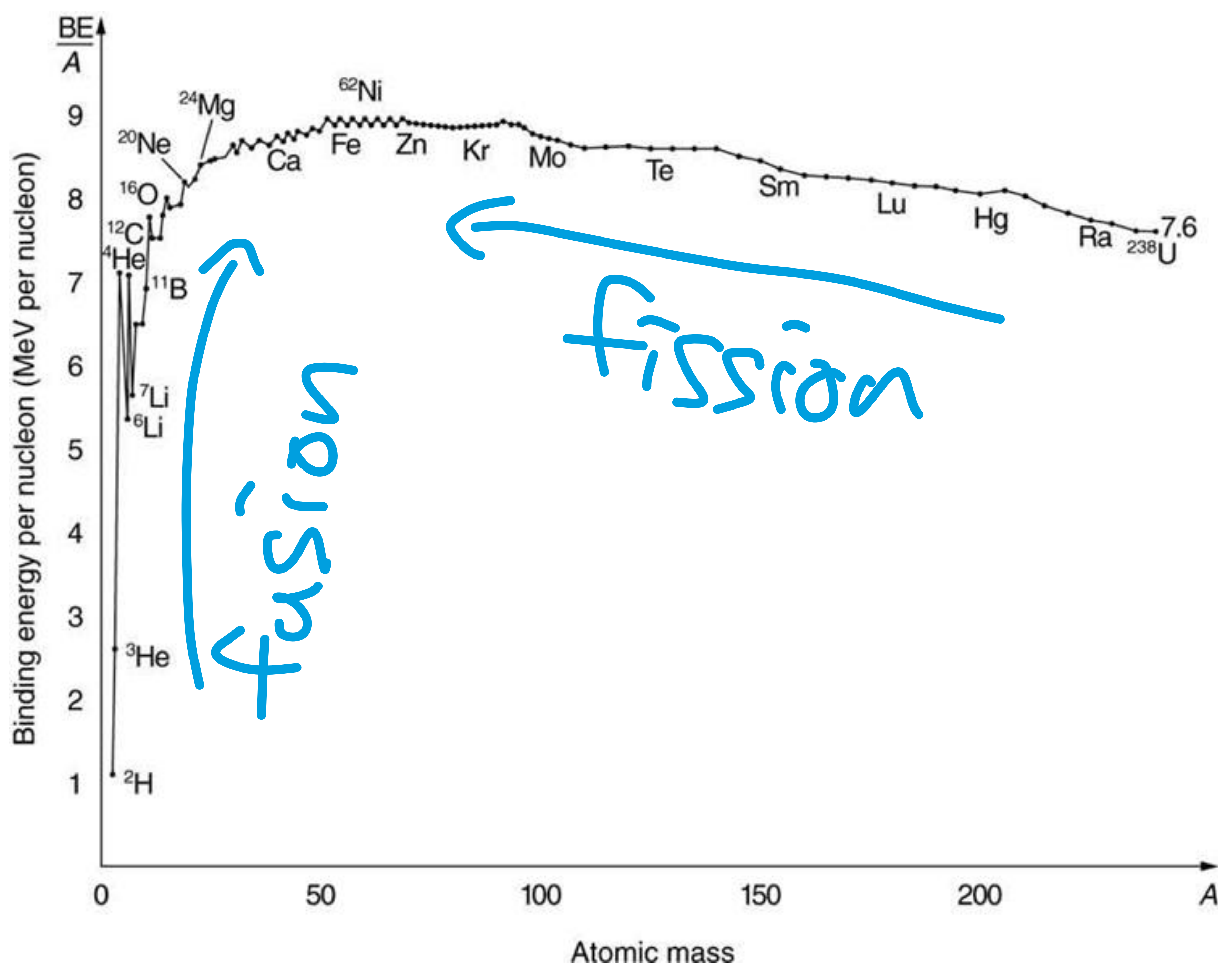
In recent years I've mostly considered new physics because of muons, not with them

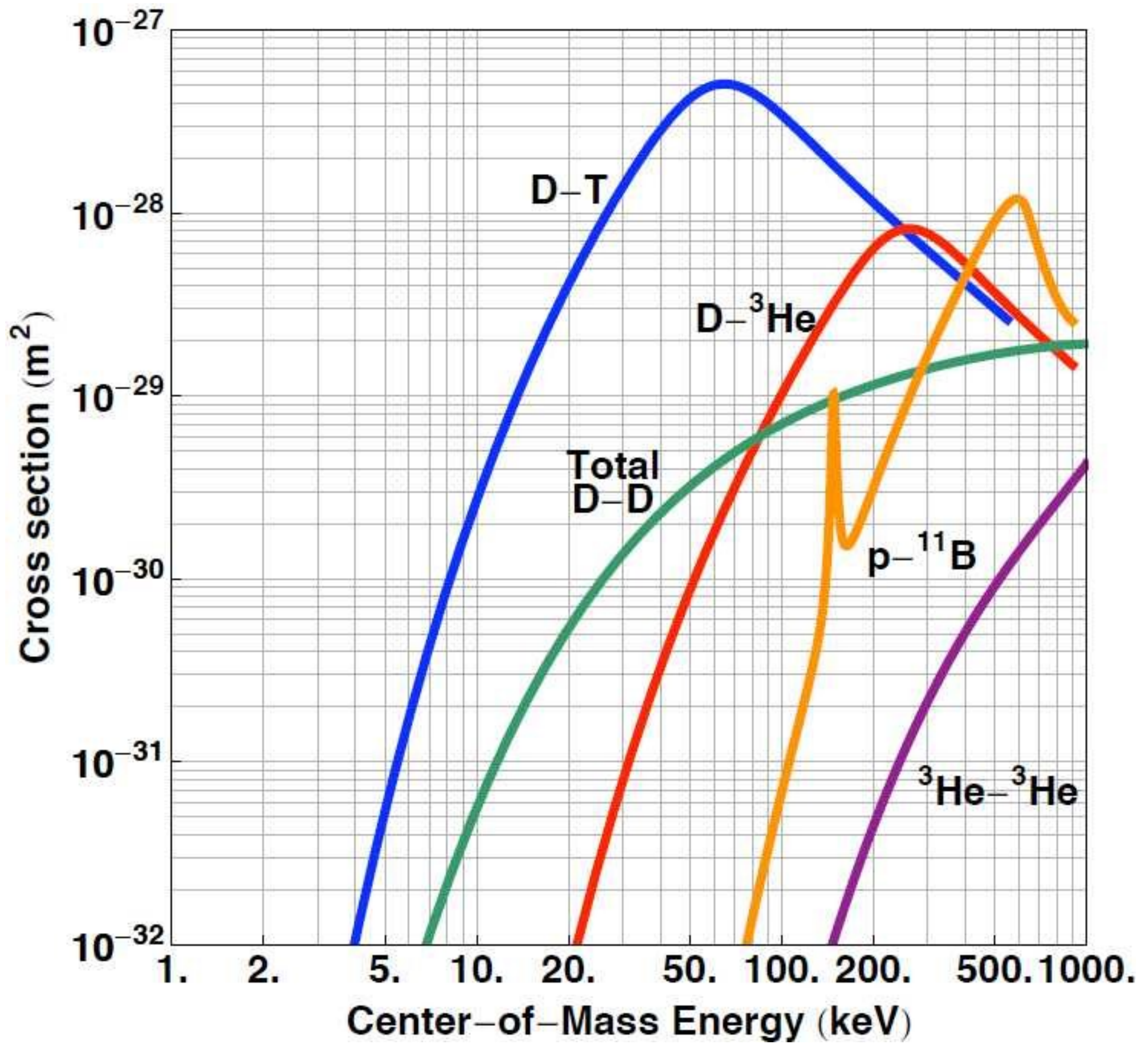
It's an area where it can be hard to determine good science

But it deals with one of the most important problems facing humanity

Enough with the apologies…

Fusion of light elements

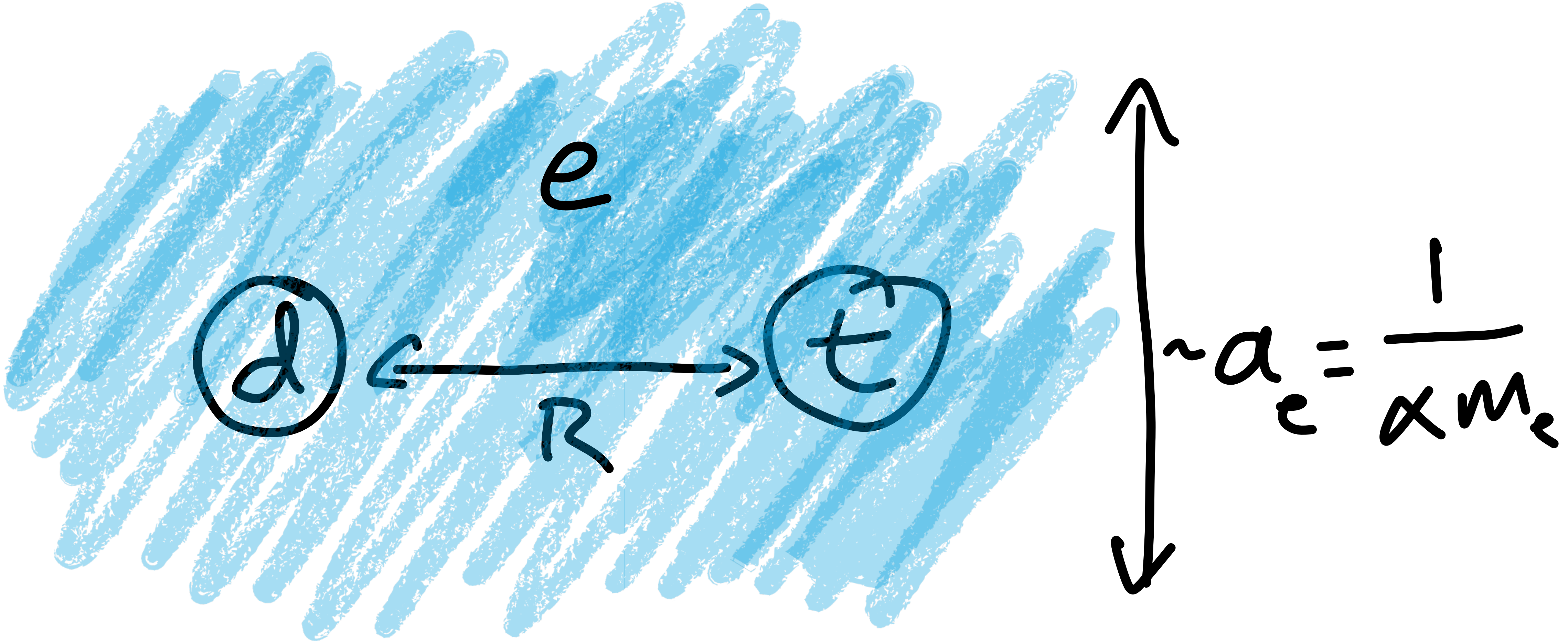


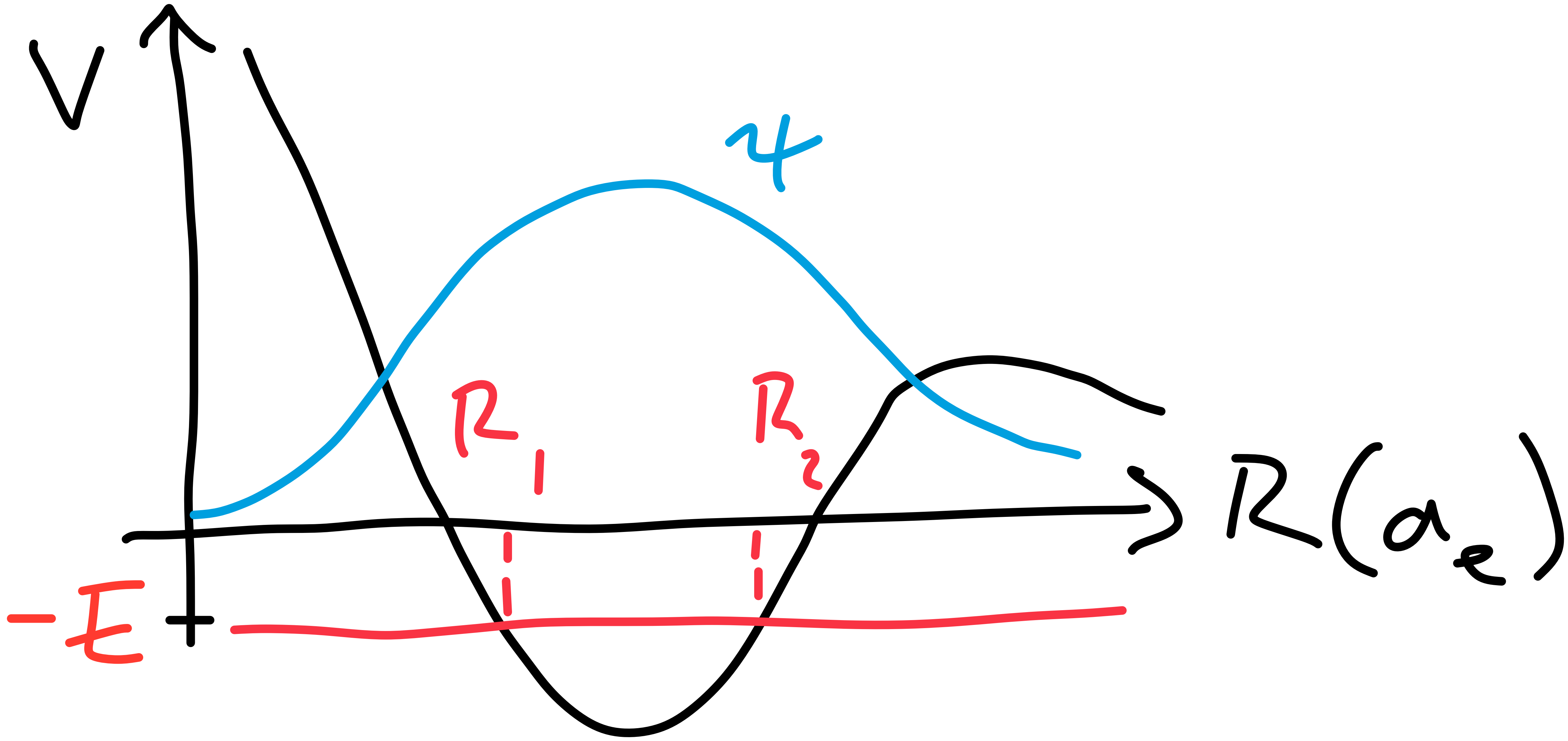


$$d + d \to t + p \qquad Q = 4.0 \text{ MeV}$$
$$d + d \to^3 \text{He} + n \qquad Q = 3.3 \text{ MeV}$$
$$d + t \to^4 \text{He} + n \qquad Q = 17.6 \text{ MeV}$$

^{5}He* resonance enhances d t fusion rate by $\mathcal{O}(1000)$ compared to naive expectation

DT Molecule

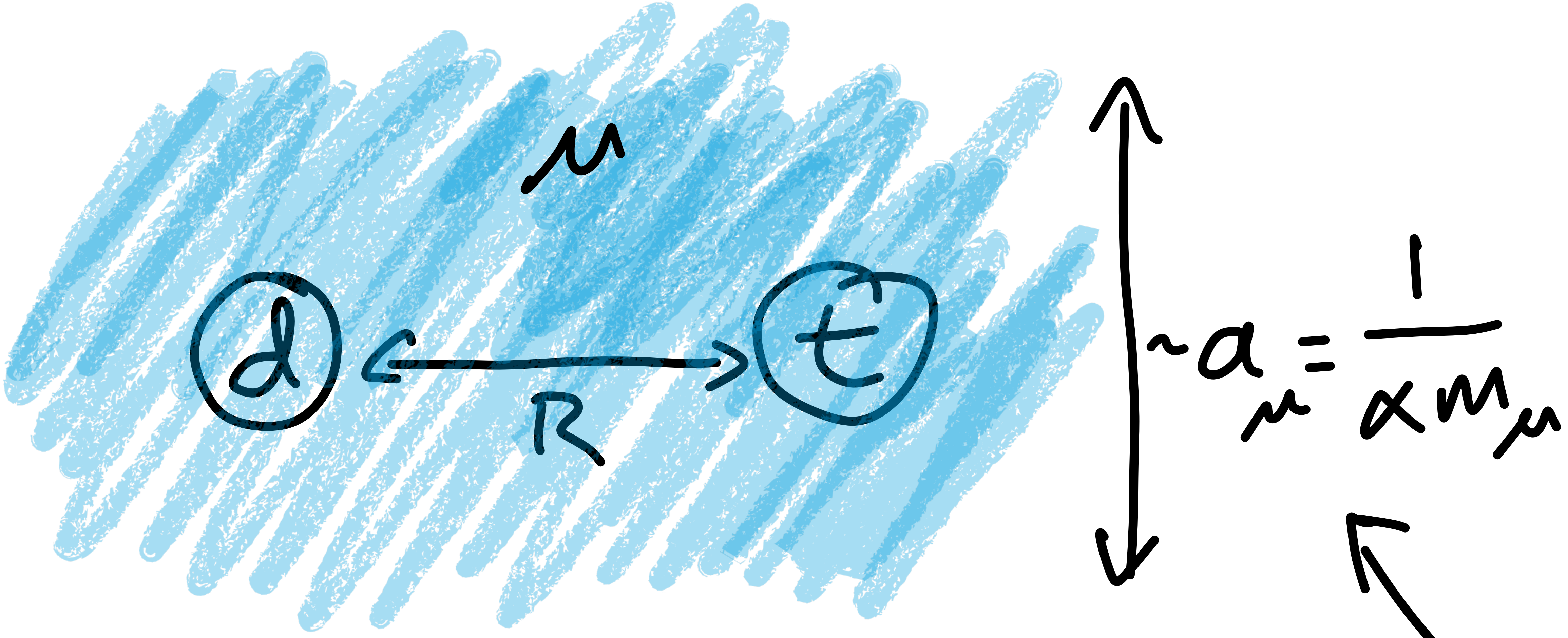


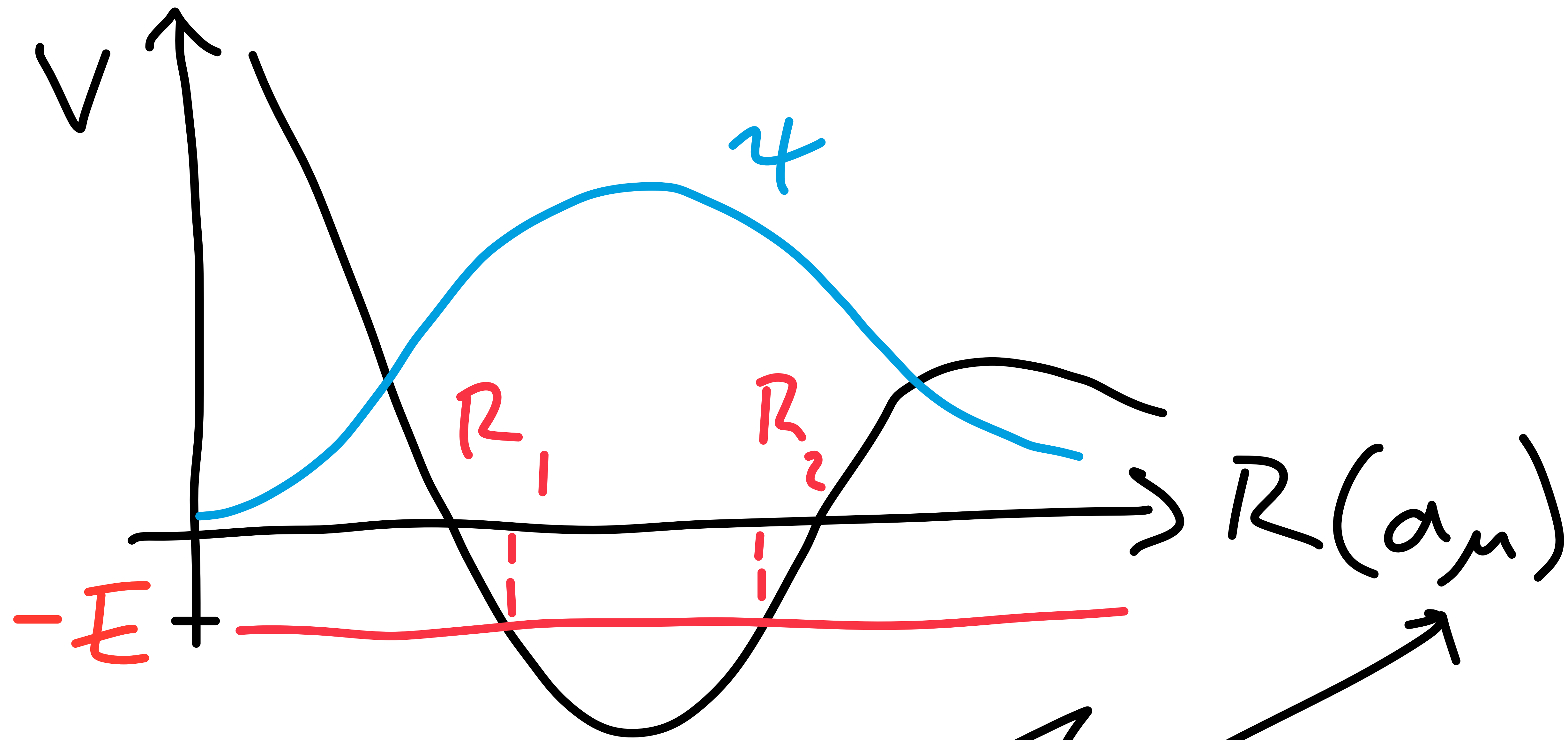


$$\Gamma \sim \sigma v \left| \psi(R=0) \right|^2$$

WKB: $\psi \sim \exp\left[-\int_0^R dx \sqrt{2M(V-E)} \right]$

Muonic DT Molecule





$$\Gamma \sim \sigma v \left| \psi(R = 0) \right|^2$$

length scale ~200 times smaller in $d\mu t$ molecule than det

WKB: $\psi \sim \exp\left[-\int_0^R dx \sqrt{2M(V-E)}\right]$

$\Rightarrow$ rate very large: $\Gamma\ 10^{-12}\ s^{-1}$

Catalysis of Nuclear Reactions by μ Mesons*

L. W. ALVAREZ, H. BRADNER, F. S. CRAWFORD, JR., J. A. CRAWFORD,† P. FALK-VAIRANT, M. L. GOOD, J. D. GOW, A. H. ROSENFELD, F. SOLMITZ, M. L. STEVENSON, H. K. TICHO, AND R. D. TRIPP

Radiation Laboratory, University of California, Berkeley, California

(Received December 17, 1956)

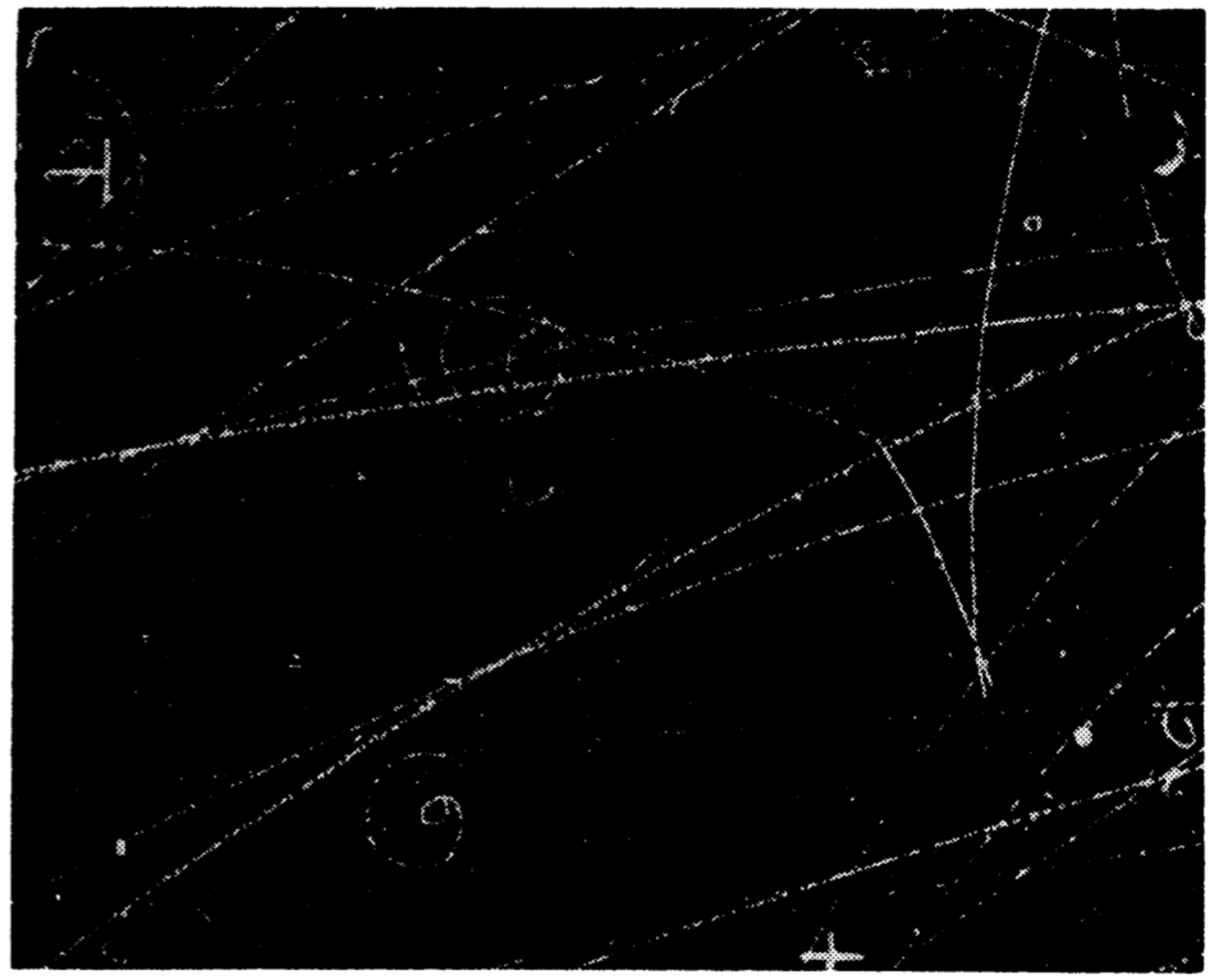


FIG. 1. Example of H-D reaction catalyzed by μ^- meson. The incident meson comes to rest, drifts as a neutral mesonic atom, is ejected with 5.4 Mev by the H-D reaction, comes to rest again after 1.7 cm, and decays.

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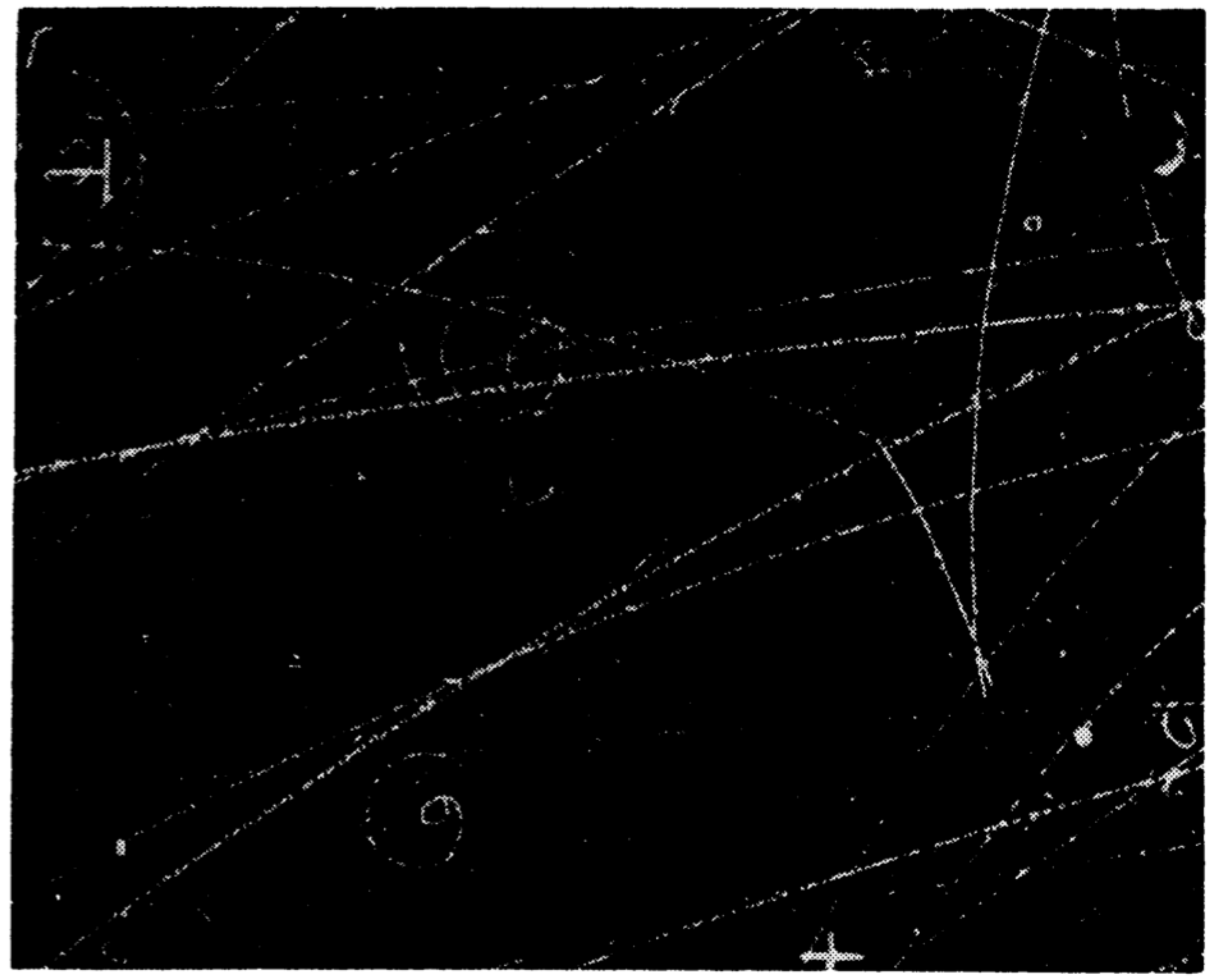

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PHYSICAL REVIEW VOLUME 106, NUMBER 2 APRIL 15, 1957

Catalysis of Nuclear Reactions between Hydrogen Isotopes by μ^- Mesons

J. D. Jackson*

Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received January 10, 1957; revised manuscript received February 4, 1957)

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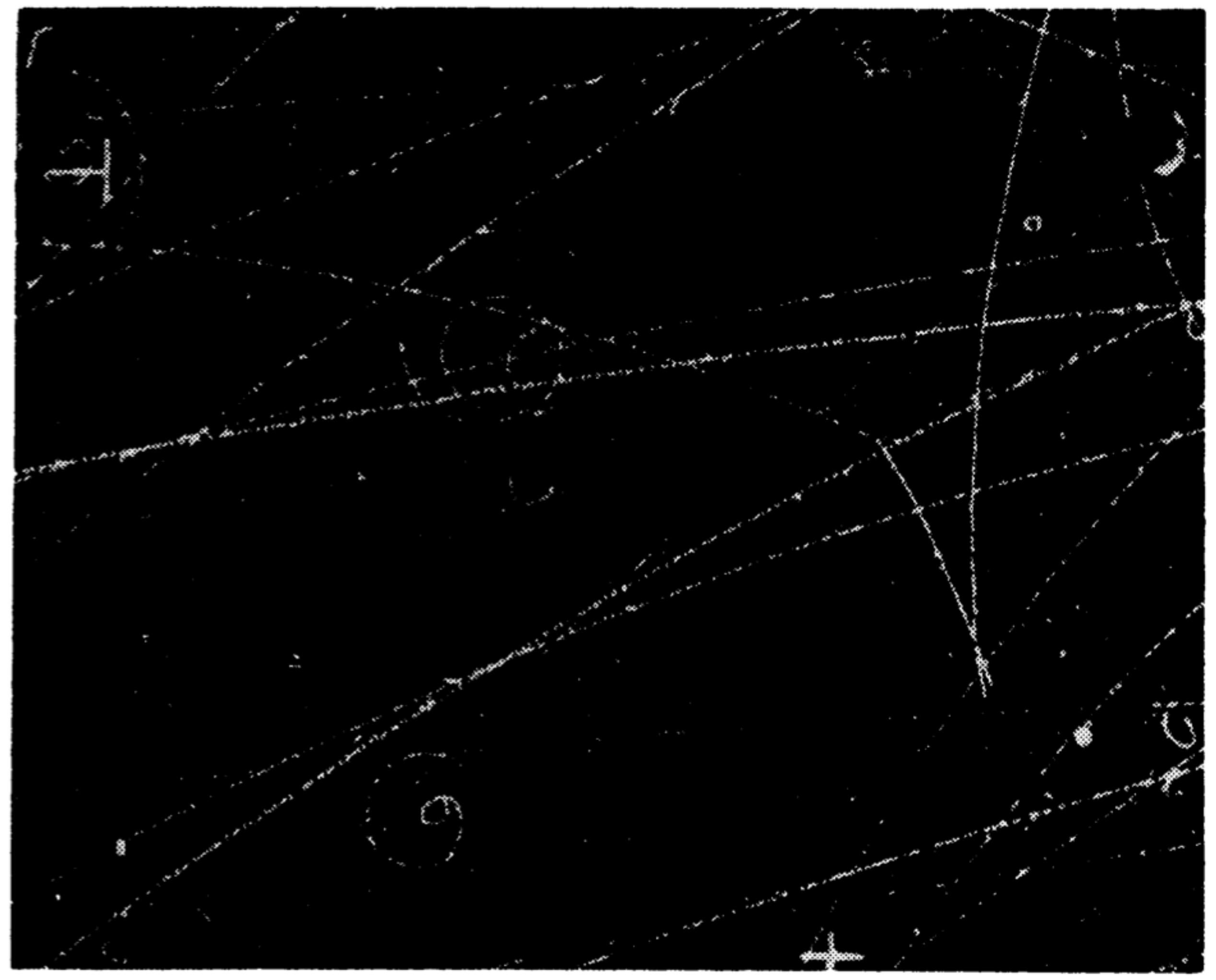

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Reactions produced by μ mesons in hydrogen

Ya. B. Zel'dovich and A. D. Sakharov

P. N. Lebedev Physics Institute, Acad. Sci. USSR

(Submitted 8 February 1957)

Zh. Eksp. Teor. Fiz. **32**, 947–949 (1957) [Sov. Phys. JETP **5**, 775–777 (1957). Also S1, pp. 7–10]

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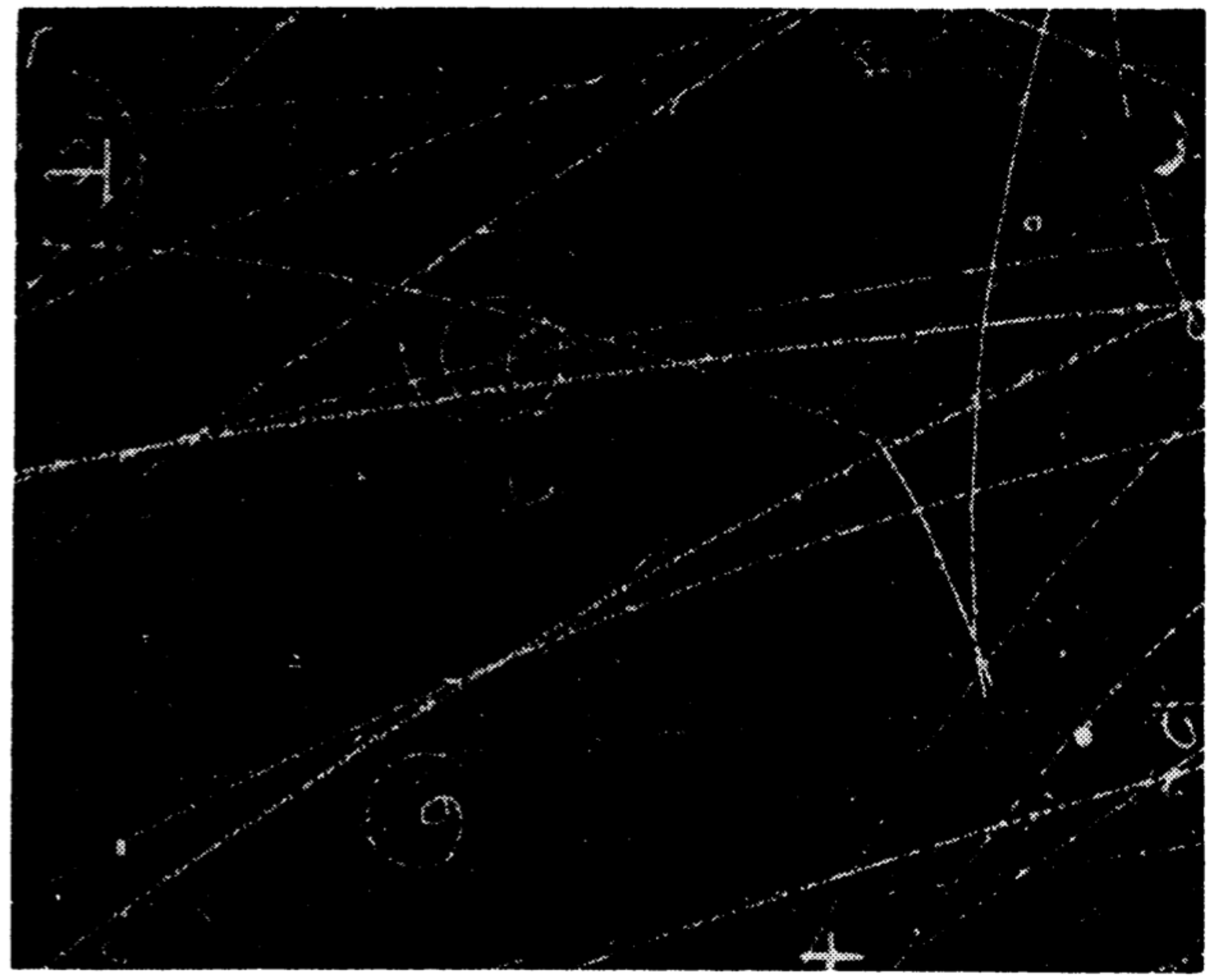

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October 18, 1947 NATURE

HYPOTHETICAL ALTERNATIVE ENERGY SOURCES FOR THE 'SECOND MESON' EVENTS

By Dr. F. C. FRANK, O.B.E.
H. H. Wills Physical Laboratory, University of Bristol

$$H_1^1(e^-) + Y^- \rightarrow H_1^1(Y^-) + e^- + 2{,}700 \text{ eV.}$$
$$H_1^1(Y^-) + D_1^2 \rightarrow H_1^1 D_1^2(Y^-) + 500 \text{ eV.}$$
$$H_1^1 D_1^2(Y^-) \rightarrow He_2^3 + Y^- + 5{\cdot}46 \text{ MeV.}$$

where Y^- and Y^+ denote negative and positive mesons.

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Alvarez Nobel Speech

"We had a short but exhilarating experience when we thought we had solved all of the fuel problems of mankind for the rest of time. A few hasty calculations indicated that in liquid HD a single negative muon would catalyse enough fusion reactions before it decayed to supply the energy to operate an accelerator to produce more muons, with energy left over after making the liquid HD from sea water. While everyone else had been trying to solve this problem by heating hydrogen plasmas to millions of degrees, we had apparently stumbled on the solution, involving very low temperatures instead."

NY Times Dec. 30 1956

Cold Fusion of Hydrogen Atoms

Discovery of a revolutionary way to fuse nuclei of hydrogen atoms without the multi-million-degree temperature required in the thermonuclear hydrogen fusion process was announced Friday at the winter meeting of the American Physical Society at Monterey, Calif., by a team of twelve scientists at the University of California headed by Prof. Luis W. Alvarez.

000,000 degrees Centigrade. (This is the fusion reaction that takes place in the hydrogen bomb.) The second method is that of fission, the splitting of a heavy element such as uranium, by neutrons, into two lighter elements (the method used in the atomic bomb and in atomic power plants). The third method is to bombard an element with nuclear particles fired from

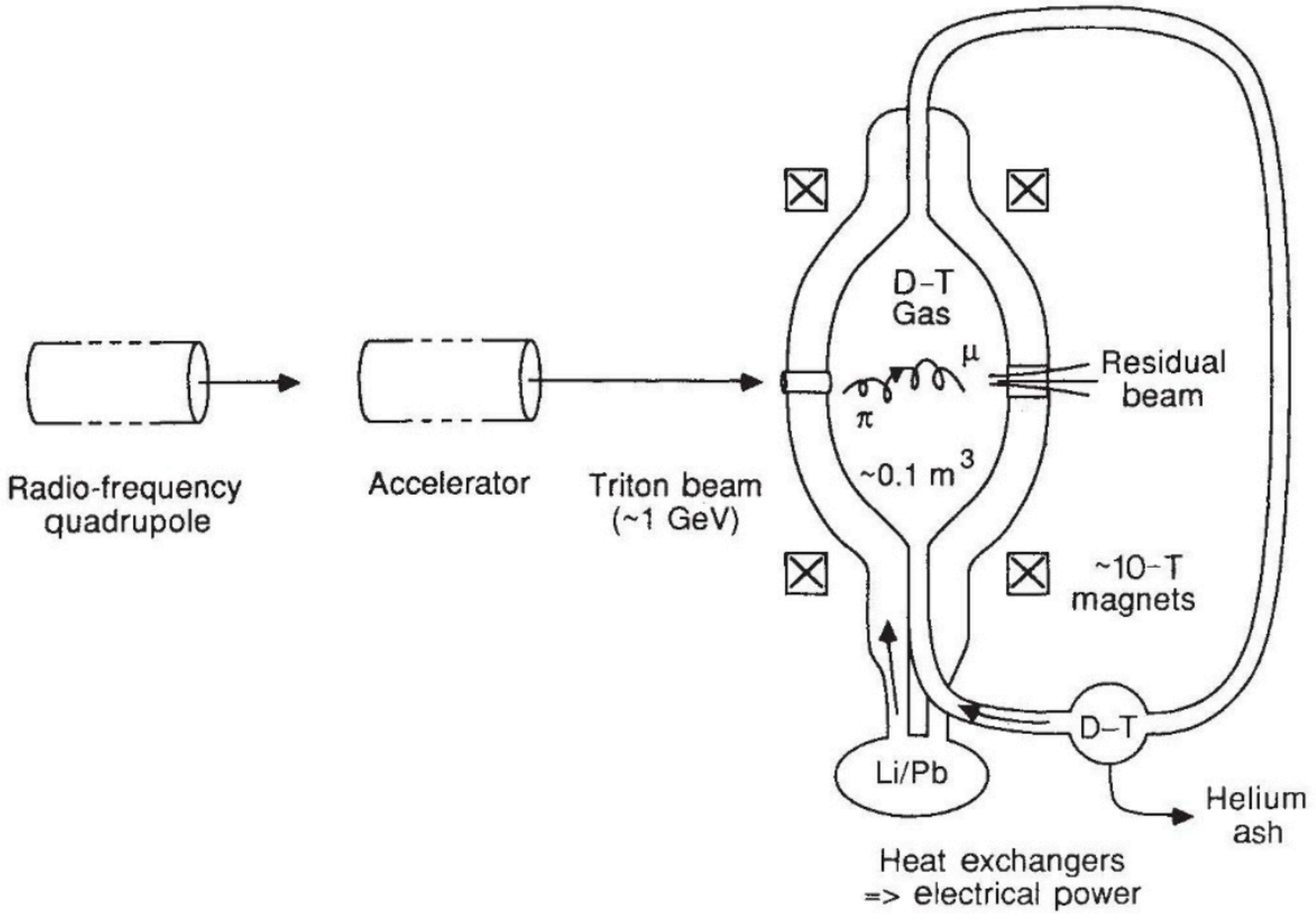


Fig. 6 A conceptual muon-catalysed fusion system, showing detail of a modular reaction vessel where muon-catalysed d–t fusion occurs.

Energy Accounting

number of μ^-/beam particle

efficiency in making beam

number of reactions/μ^-

$$Q_{\rm fus} = \frac{\text{energy out}}{\text{energy in}} = \frac{f_\mu E_{\rm fus}}{E_b/\epsilon_b} \times N_{\rm cat} \simeq \left(\frac{f_\mu}{0.5}\right)\left(\frac{3\ \text{GeV}}{E_b}\right)\left(\frac{\epsilon_b}{40\,\%}\right)\left(\frac{N_{\rm cat}}{1000}\right)$$

beam energy

$$d + t + \mu^- \to (^4\text{He}\mu^-) + n$$

$$N_{\rm cat} = \frac{\tau_\mu}{\tau_{\rm fus}}\left(1 - p_{\rm stick}\right)$$

primarily controlled by molecular formation

$N_{\rm cat} \sim \mathcal{O}(100)$ observed

Depends on density, pressure of d, t mixture

How can this be improved?

More efficient production of μ^-

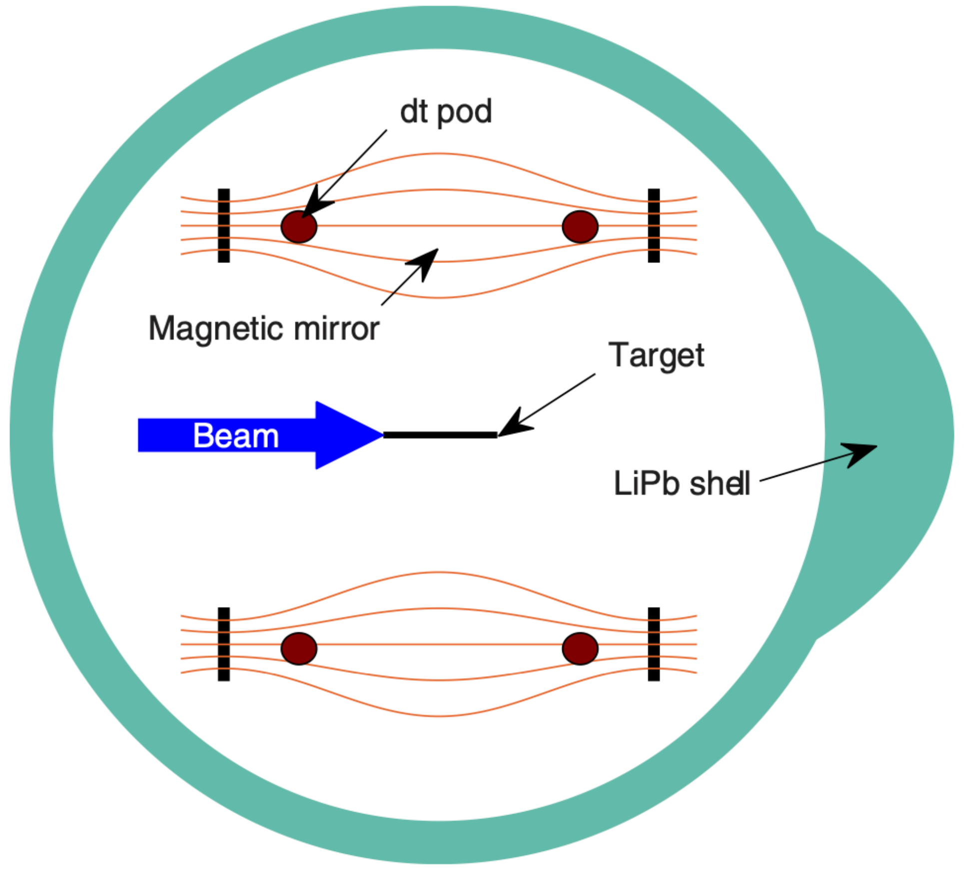
Neutron beams? Storage ring?

Will muon collider R&D help here?

Higher pressures, temperatures? (still cold?)

Fancy targets?

Kelly et al., J. Phys. Energy **3** 035003



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Muon Catalyzed Fusion

F. Dyson
D. Eardley
S. Koonin
C. Max
R. Muller
M. Rosenbluth
S. Treiman

October 1990

JASON
The MITRE Corporation
7525 Colshire Drive
McLean, Virginia 22102-3481
(703) 883-6997

The DOE theoretical program is mixed and, in some ways, lags that in the Soviet Union. Overall, the field has been characterized by a strong and generally healthy interplay between theory and experiment. Theorists, including some supported by the DOE, are guiding experiments and are working to understand quantitatively many aspects of the data. However, other DOE work involves speculative schemes to improve the feasibility of MCF; some of these were mentioned above and are discussed in the following sections. These schemes often have an air of desperation about them, caused in part (we suspect) by the programmatic nature of the funding. While new ideas are certainly to be encouraged, they must be worked out with sufficient detail to be evaluated critically. This can be done more rapidly, and with less effort, than is presently the case.

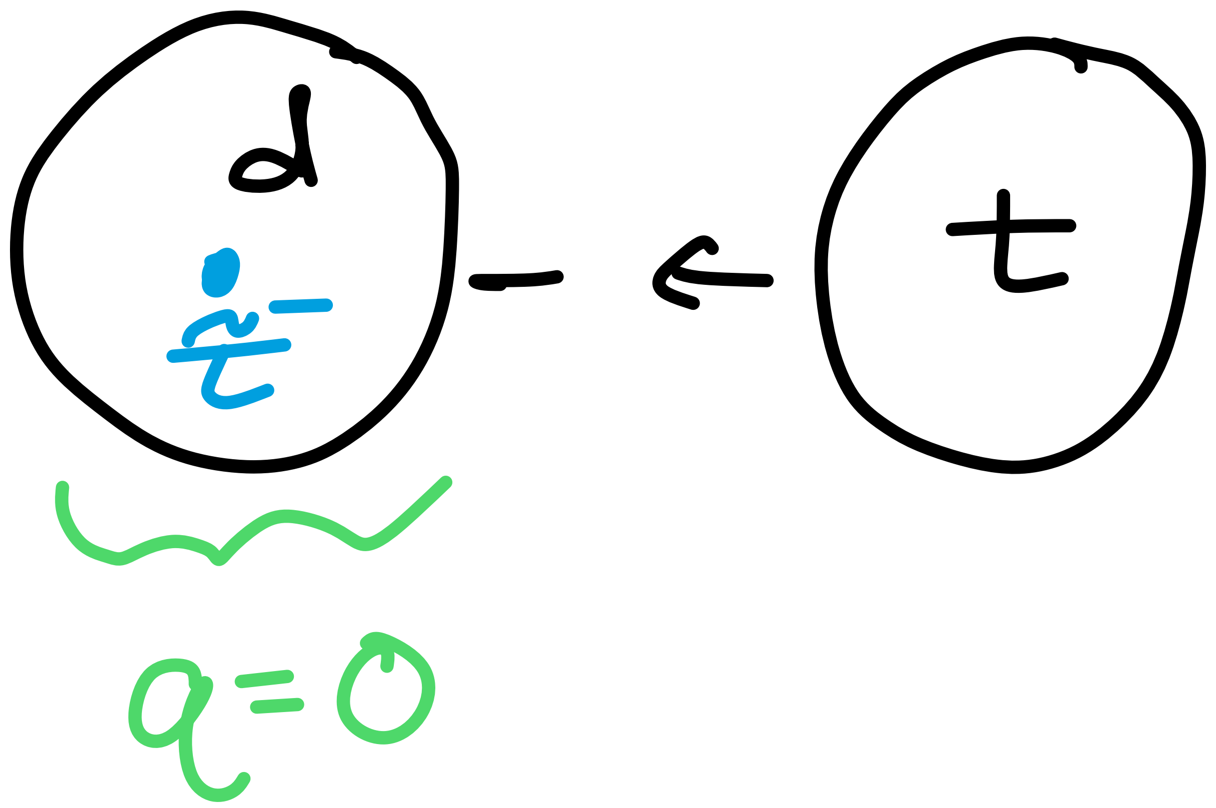
Other ideas

Stau-catalyzed *d*-*t* Nuclear Fusion

Koichi HAMAGUCHI[1,2], Tetsuo HATSUDA[1,3], Masayasu KAMIMURA[3] and Tsutomu T. YANAGIDA[1,2]

in SUGRA $\tilde{\tau}$ can be NLSP

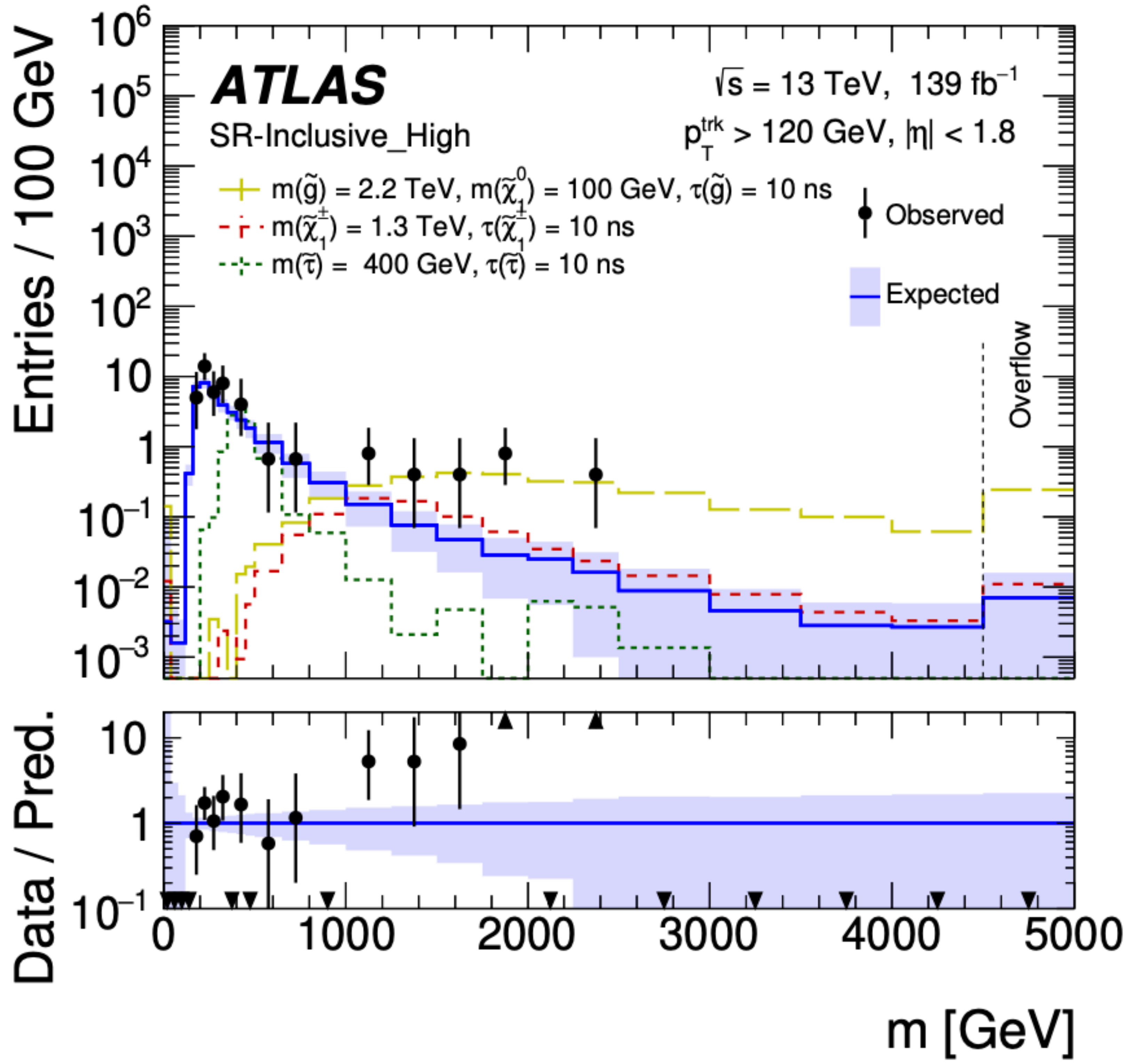
decays to $\tilde{g}$ slow (gravity) so $\tilde{\tau}$ long-lived ($\tau_{\tilde{\tau}} \sim 1$ yr)



Now sticking $[d + t + \tilde{\tau}^- \to ({}^4\mathrm{He}\tilde{\tau}^-) + n]$ becomes rate-limiting process and $p_{\mathrm{stick}} \sim 0.1\,\% \;\Rightarrow\; 12\ \mathrm{GeV}/\tilde{\tau}^-$

Other ideas

Search for heavy, long-lived, charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment and the full Run 2 dataset



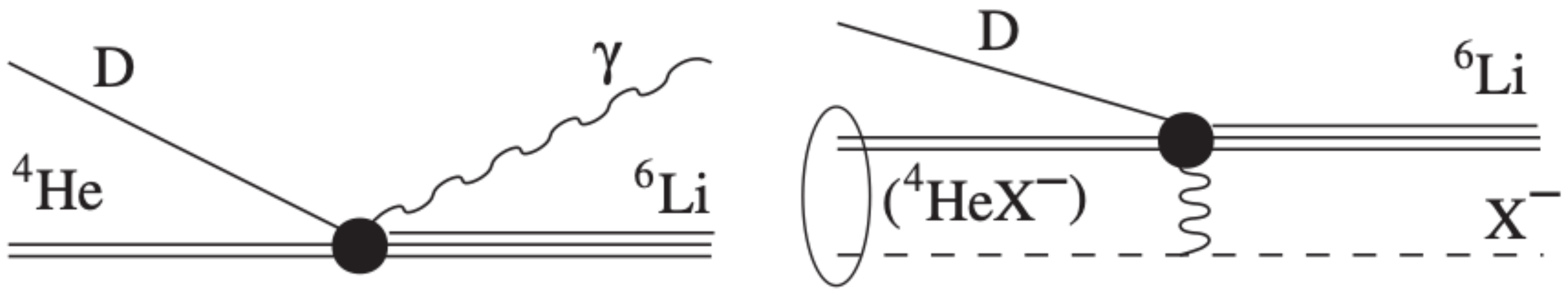
Particularly interesting in light of excess in ATLAS search for LLPs using dE/dx measurement

Other ideas

Particle Physics Catalysis of Thermal Big Bang Nucleosynthesis

Maxim Pospelov[1,2]
[1]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2J 2W9, Canada*
[2]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, V8P 1A1 Canada*
(Received 1 July 2006; revised manuscript received 9 November 2006; published 4 June 2007)

BBN is a probe of charged relics through their catalysis of some reactions



$$n_{X^-}/s \lesssim 2.5 \times 10^{-17}.$$

Can also catalyze reactions that destroy $^7\mathrm{Be}$ ($\rightarrow ^7\mathrm{Li}$) to address “lithium problem”

Wrap up

Muons catalyze the fusion of light nuclei by helping to overcome Coulomb barrier

Using this process to produce useful energy is challenging

Muons are a very hot topic now, can new ideas here help?

We face difficult problems, as a species and as physicists, we need to think!

Sometimes it's cool to listen to the oldies