Saturday Morning Physics 2007 at TAMU: Program Summary + Perspectives

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Outline

1.) Our Objectives

- The Idea(s) behind, and Pillars of, the Program

2.) The Nuclear/Particle Micro-Cosmos

- The Standard Model: Elementary Particles + Forces
- The Strong Force: Quark Confinement, Mass Generation
  New Phases of Matter, Early Universe

3.) Nuclear/Particle Physics and the Universe

- Gravity in Extremis: Black Holes and General Relativity
- Dark Matter and beyond the Standard Model

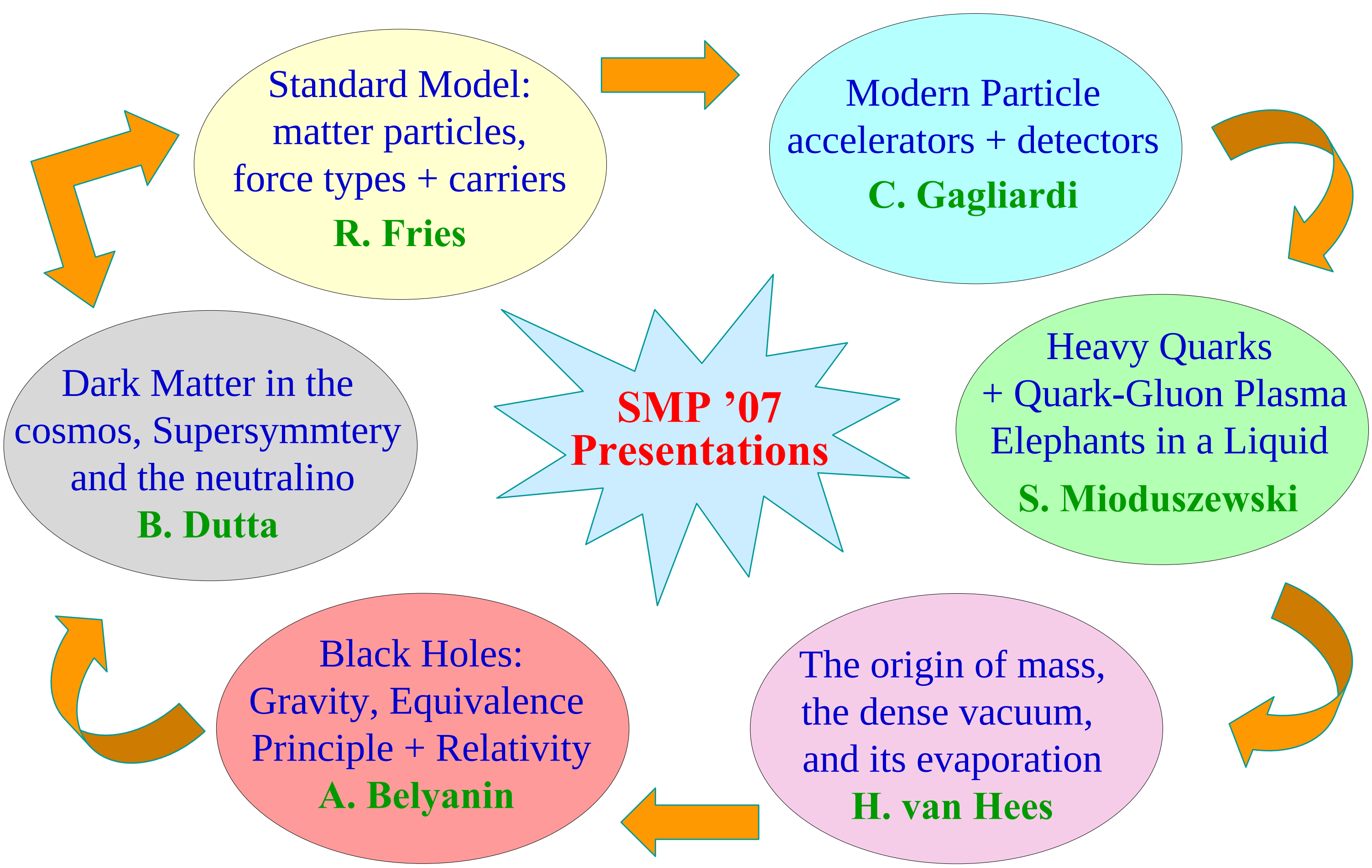
4.) (Your) Perspectives

- Expanding Your Knowledge; College, or even Physics as a Job?

1.) Our Objectives

- Give high school students (teachers) the opportunity to learn about frontier science in Nuclear Physics
- Provide education
- Use understandable language
- Convey the excitement of ongoing research
- Dispel prejudices about Nuclear Physics
- Reveal perspectives for choosing university-physics study as (beginning of) career path
- Hands-on experience
- Have fun!   (and donuts …)

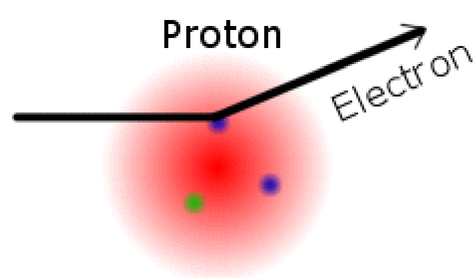
1.2 Pillars of Saturday Morning Physics 2007



2.) The Discovery of the (Sub-) Atomic World

- **Rutherford's α-scattering (1911):**
  - most of the atom is "empty space"
  - mass is concentrated in the atomic **nucleus**

- nucleus itself has structure:
  made of **protons (+), neutrons (0),**
  held together by **"strong" force**

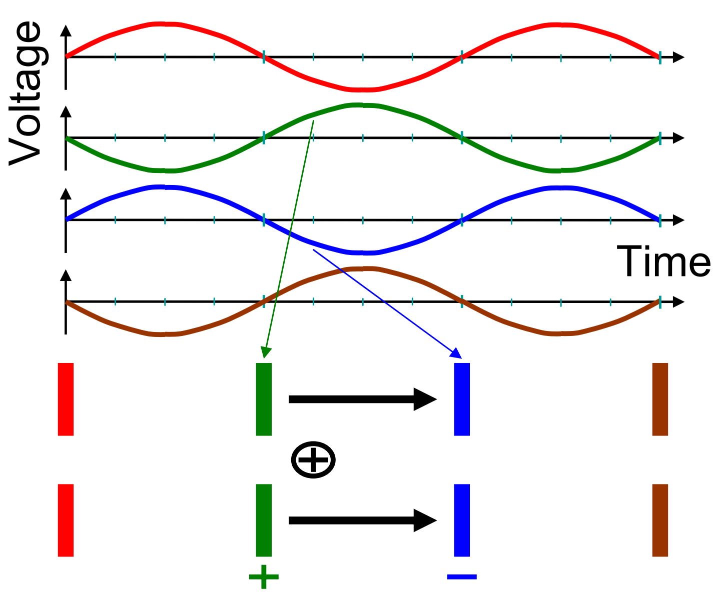


- "Rutherford Scattering" 1968 (**SLAC**):
  yet smaller constituents in the proton
  → "**quarks**" and the **Strong Force**!
- 1984: **p-p** Scattering Exps. at **CERN**:
  discovery of heavy bosons
  → **W** and **Z**: **Weak-Force** carriers!

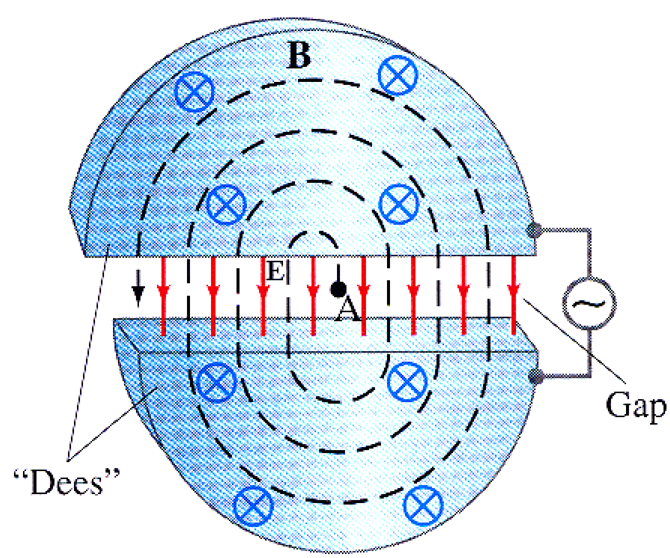
2.2. Particle Accelerators and Detectors

- probe the properties of particles and matter by exciting them
  ⇒ accelerate particles and collide them,
  interpret the reaction products (recall **Rutherford 1911**!)

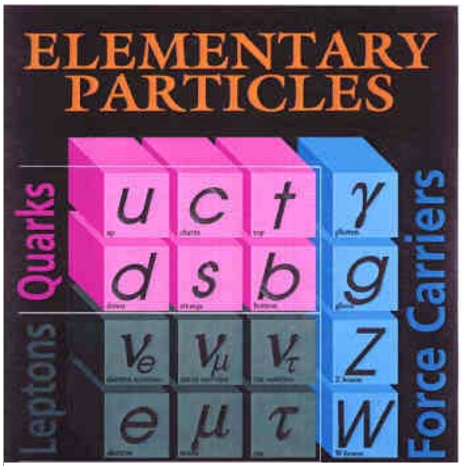
Accelerate with Alternating Voltage



Bend Particles with Magnetic Fields



2.3 The Standard Model of Elementary Particles

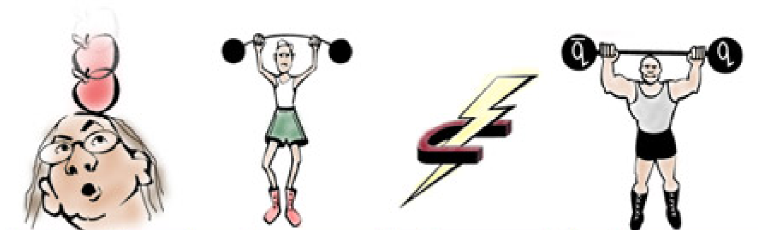


• based on symmetry principles:
matter particles (fermions: half-integer spin)
interact via **force carriers (bosons: integer spin)**

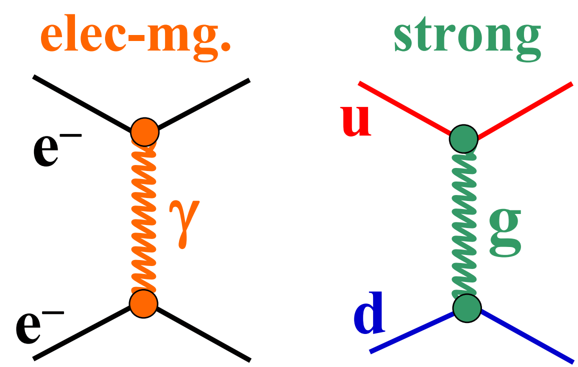
• stable matter: **u , d , e⁻** , ν_e

• 2 more "generations" (heavier + short-lived)

Force Carriers and Strength



	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	$W^+ W^- Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ W^-$	Quarks and Gluons



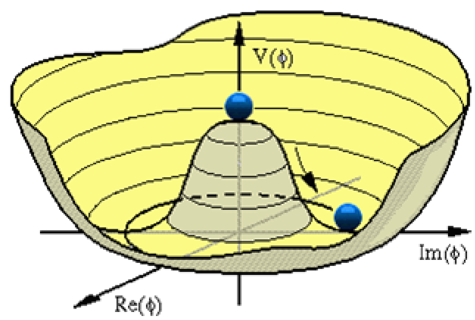
$\alpha_{em} \approx 0.01$ $\alpha_S \approx 1$

2.4 Unsettled Problems of the Standard Model:

Where do the particle masses come from?

• **1. generation: "light" up/down** quark, electron: $m_{u,d,e} \approx$ **0.5-5 MeV/c^2**

• **2.+3. generation: medium/heavy weight ($m_{s,c,t}$=100-170,000 MeV)**



Current Theoretical Prediction:

Higgs Boson and Celebrity effect:

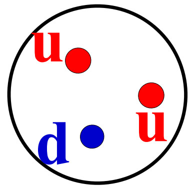
• Higgs Field condenses (lower energy)
+ fills all space ("symmetry breaking")
$\langle 0|\phi|0\rangle \neq 0$ **Higgs Condensate**

• elementary particles have to "**plough**" through "condensate" = **mass**!

• **Higgs Boson** not (yet?) discovered!

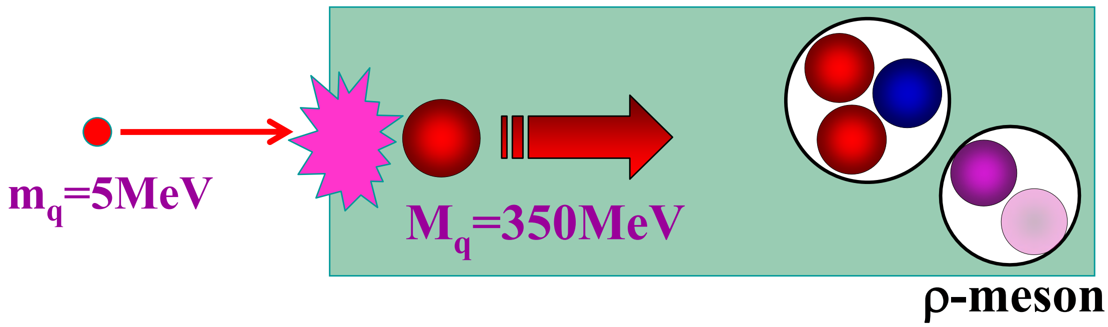
2.5 Unsettled Problems of the Strong Force

protons+ neutrons made of **3 quarks**:



up/down quark: mass $\mathbf{m_{u,d} \approx 5MeV/c^2}$

but: **proton mass** $\mathbf{m_{p,n} = 940MeV/c^2}$



Quark-antiquark pair condensate:

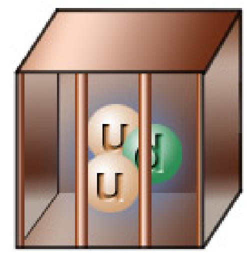
$\langle 0|\bar{q}q|0\rangle \approx 5\,fm^{-3}$

The vacuum is very dense!

2 Mysteries of the Strong Force:

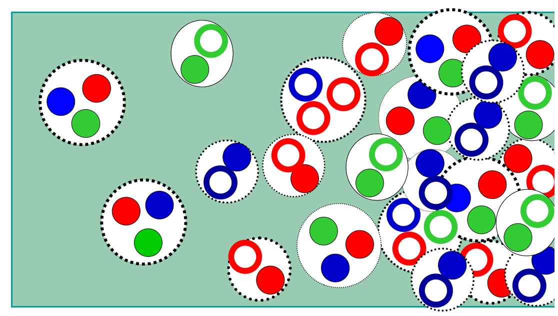
- How can we test the **vacuum** and **>98%** of the **visible mass?**
- Why are quarks not observed in isolation (**Confinement**)?
  rather "glued" together:

$F_s(r) = const$



2.5.2 From Nuclei to the Quark-Gluon Plasma

Heat and evaporate the Vacuum!

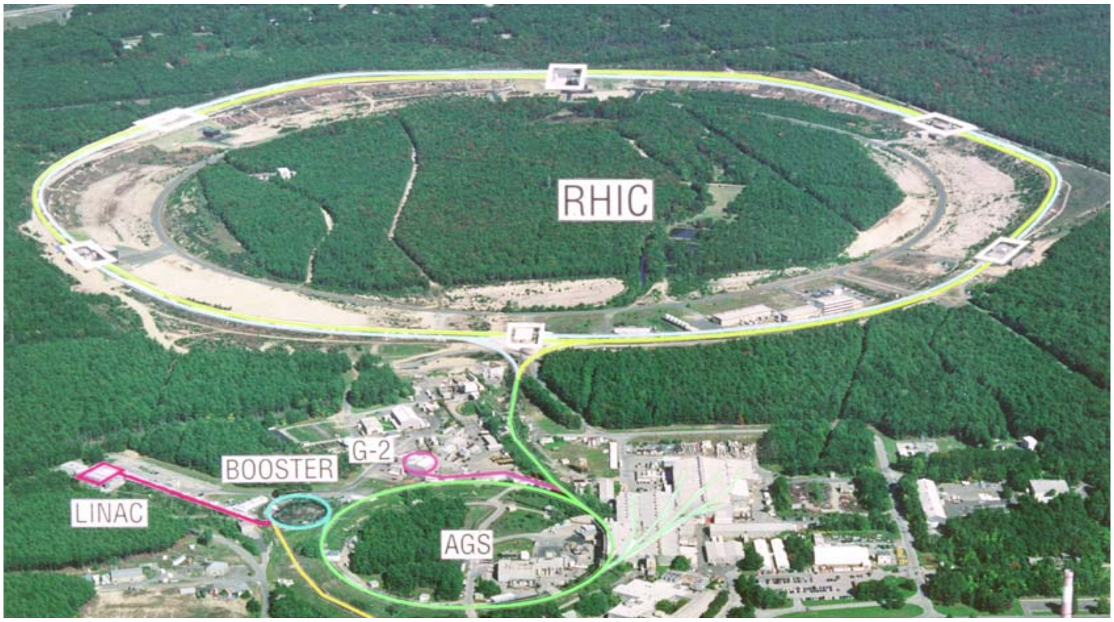


Nuclear Matter dissolves into the **Quark-Gluon Plasma (QGP):**

- hadrons overlap, quarks are liberated ⇒ **Deconfinement!!**
- $\langle\bar{q}q\rangle$ condensate "evaporates", $M_q \rightarrow m_q$ ⇒ **Mass dissolves!!**
- required temperature **~200MeV ≈ 4·10^12 °K (1μs after big bang)**

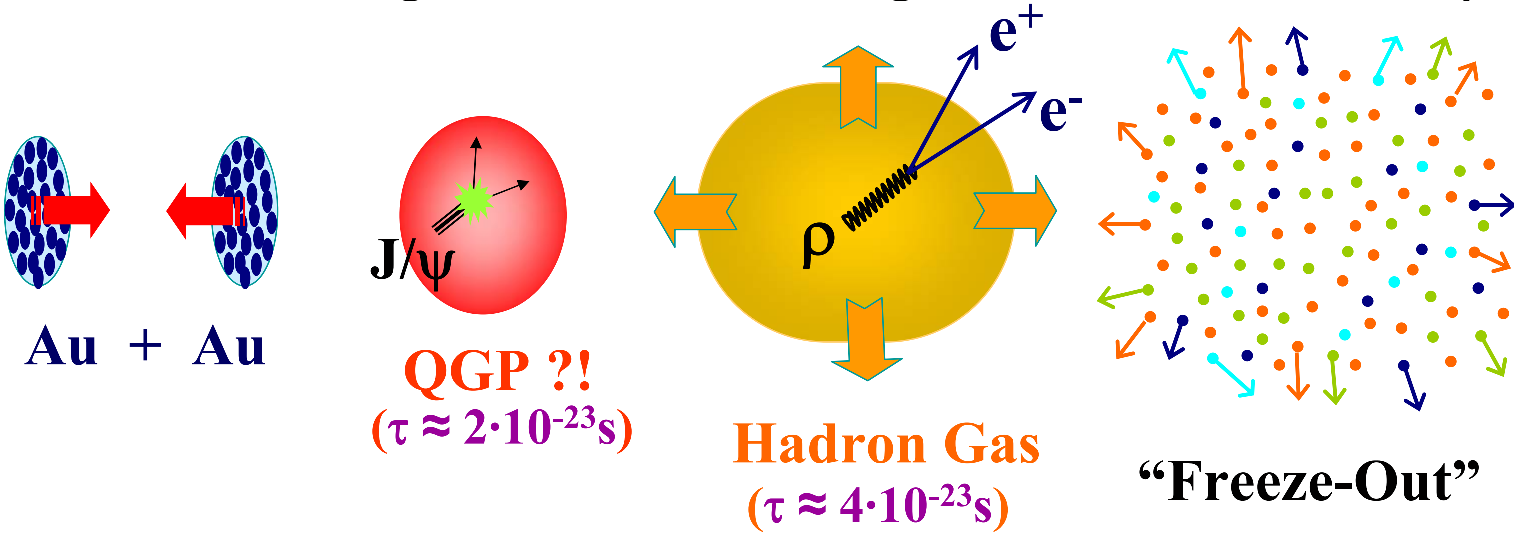
How do we pump this enormous amount of energy into the vacuum??

Answer: The Relativistic Heavy-Ion Collider!!



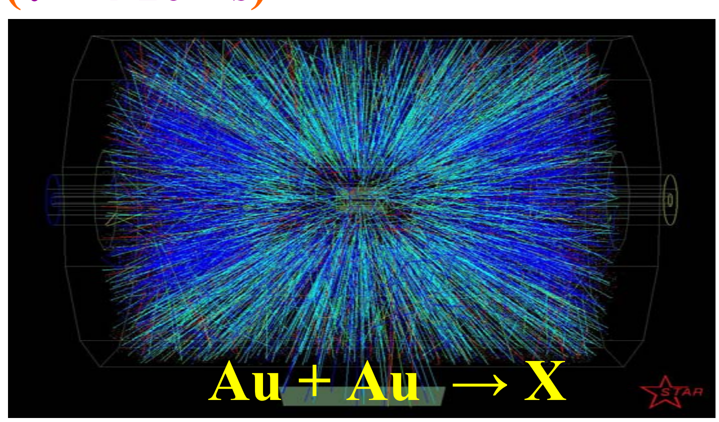
Accelerate Gold-Nuclei to **100GeV/nucleon** and collide them!

2.6 Recreating the "Little Bang" in the Laboratory

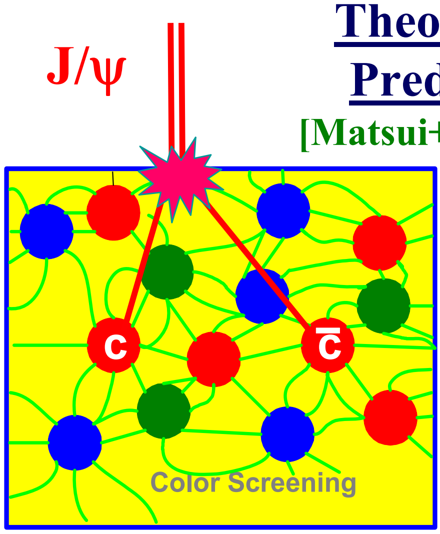


How to look for particles inside the matter?

- **suppression of J/ψ particles in QGP (deconfinement!)**
- **electron-positron decays of the ρ(770)-meson (mass!)**



2.7 J/ψ Suppression in the Quark-Gluon Plasma

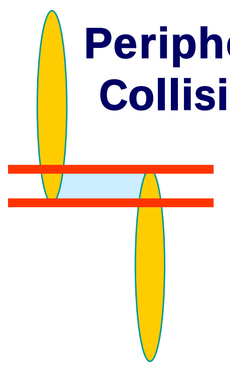


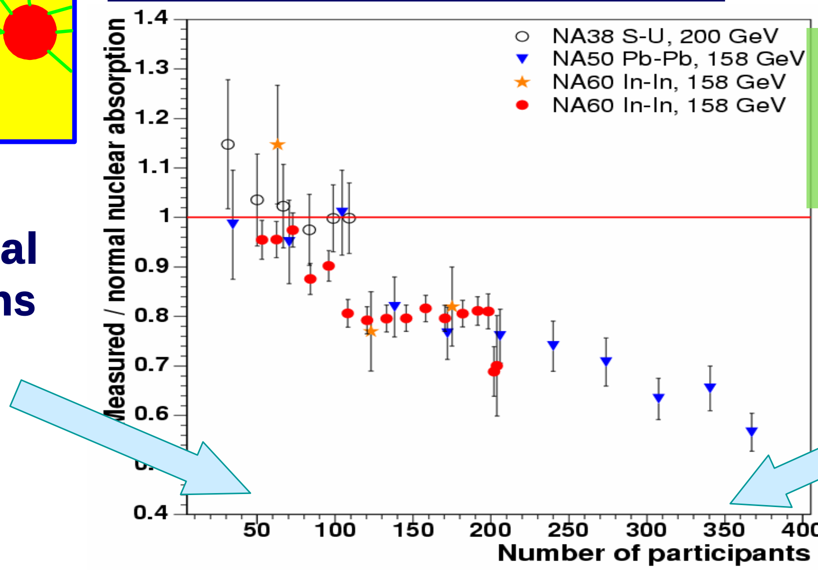
Theoretical Prediction:
[Matsui+Satz 1986]

- J/ψ dissolves in the QGP
- If QGP is formed in Heavy-Ion Collision J/ψ production should be suppressed
- quantify: "Nuclear Modification Factor"

$$R_{AA} = \frac{J/\psi \ \text{yield in Au-Au}}{J/\psi \ \text{yield for p-p}} \begin{cases} =1 & \text{no suppression} \\ <1 & \text{suppression!} \end{cases}$$

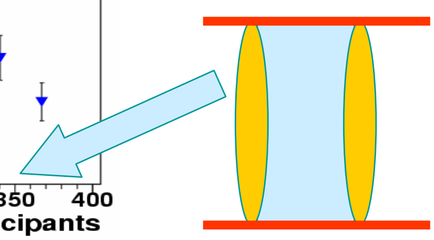
Peripheral Collisions





Suppression confirmed in CERN Exps.!

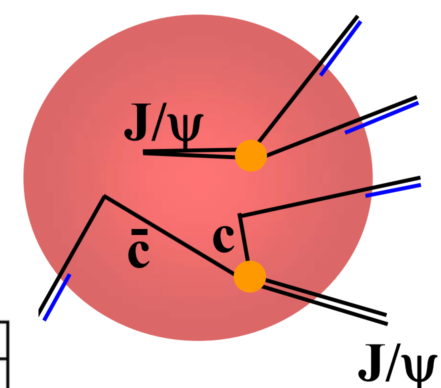
Central Collisions



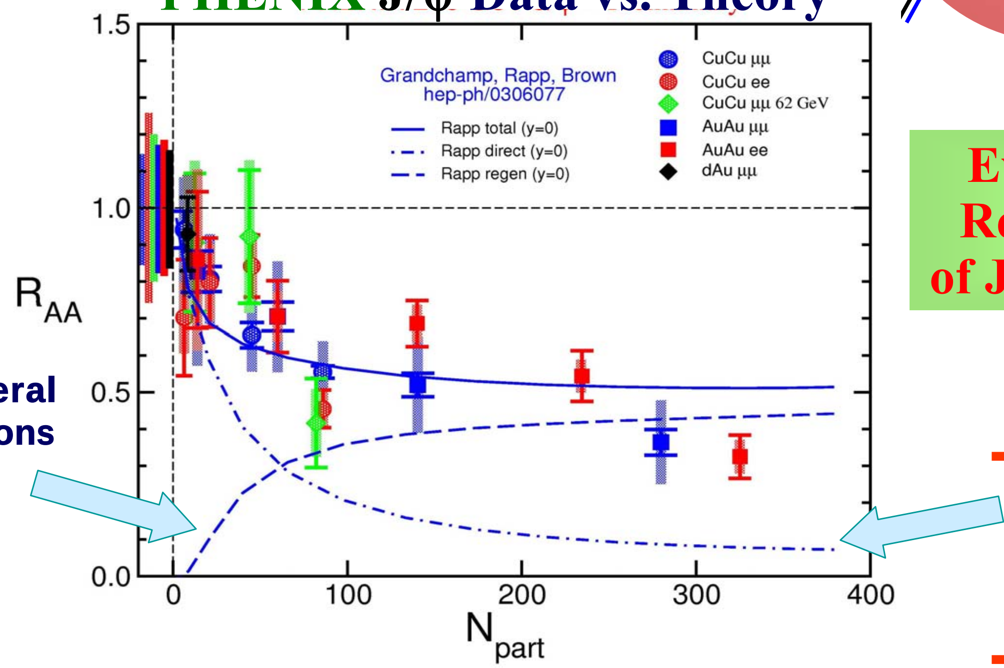
2.7.2 J/ψ at Higher Energies: RHIC Experiments

Central Au+Au at RHIC:

- very hot QGP ⇒ strong J/ψ suppression!
- but: ~20 $c\bar{c}$ pairs ⇒ regeneration $c+\bar{c} \rightarrow J/\psi$

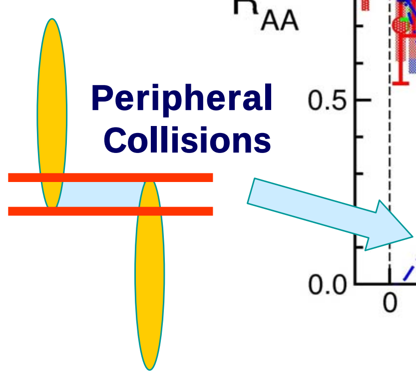


PHENIX J/ψ Data vs. Theory

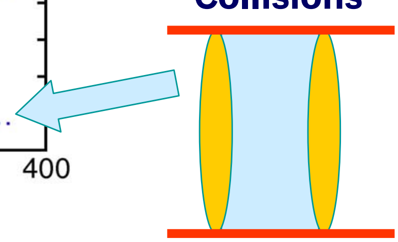


Evidence for Regeneration of J/ψ in QGP?!

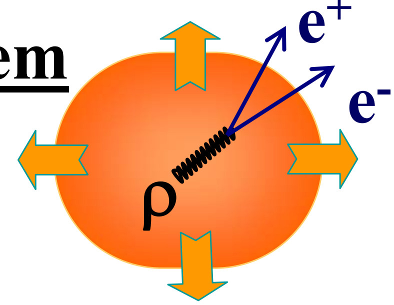
Peripheral Collisions



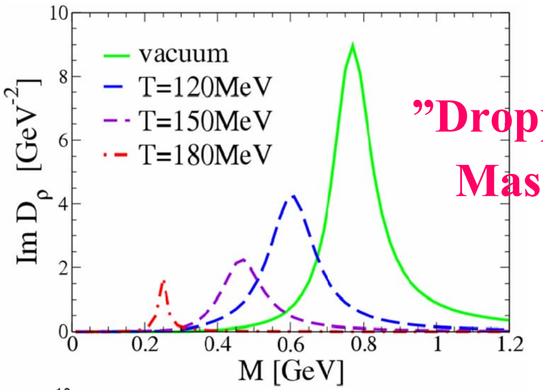
Central Collisions



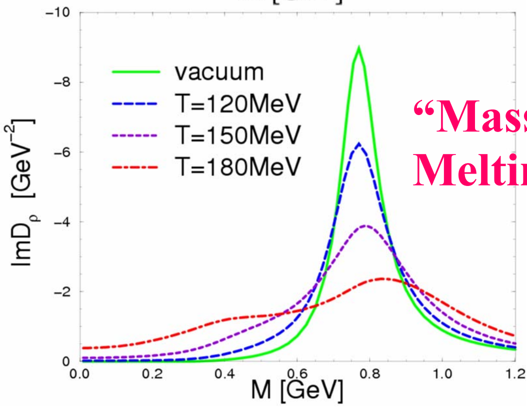
2.8 e^+e^- Spectra and the "Mass" Problem



• calculate $\rho \to e^+e^-$ decays in the "fireball"

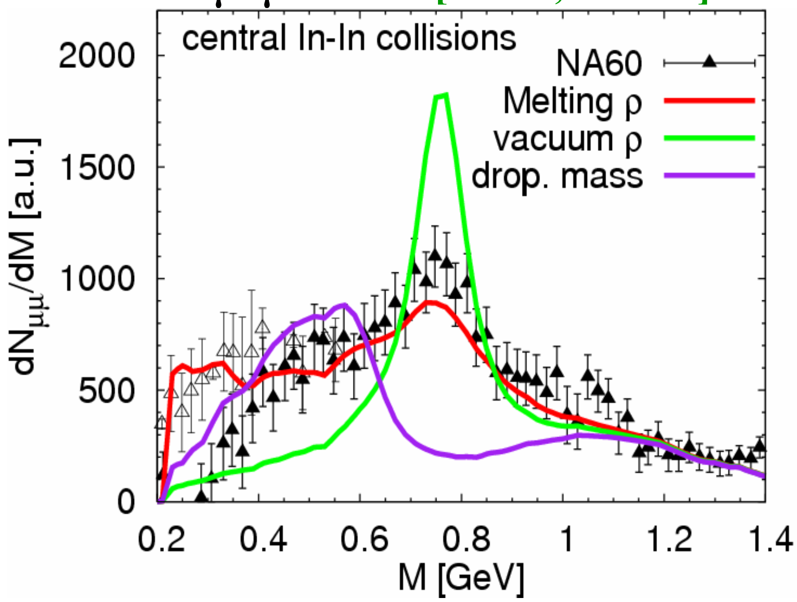


"Dropping Mass"



"Mass Melting"

$\mu^+\mu^-$ **Data** [NA60, CERN]



Experimental data presently favor the "Melting" scenario

But what about the Gravitational Force?

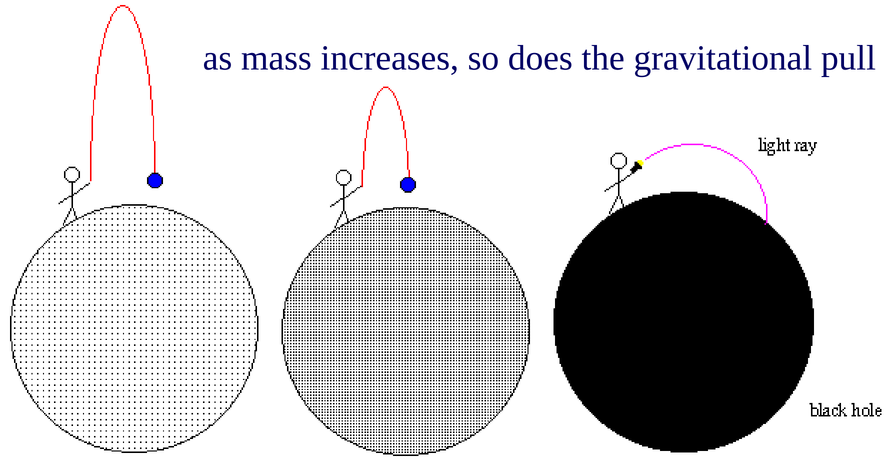
• Irrelevant in the Microcosmos (?!)
• Essential in the Universe!

3. Gravity in Extremis: Black Holes

Objects so massive that not even light can escape!

Newtonian Mechnanics:

$$K=\frac{1}{2}mv^2, \quad U=-\frac{GMm}{R}$$



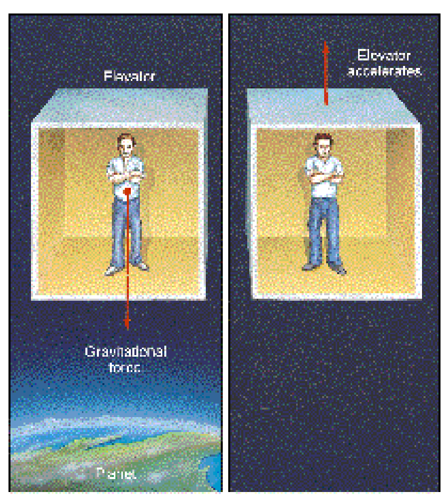
$$K=|U| \quad \Rightarrow \quad v_{esc}=\sqrt{\frac{2GM}{R}} \qquad\qquad v_{esc}=c \quad \Rightarrow \quad R_s=\frac{2GM}{c^2}$$

- Result **accidentally** correct!
- Newtonian Mechanics not applicable for speed close to **c**
- Need theory of special/general relativity!

3.1 Theory of General Relativity

Albert Einstein

- **Equivalence Principle**:
  The effect of the gravitational force in an inertial frame is equivalent to introducing an accelerated frame with no gravitational force

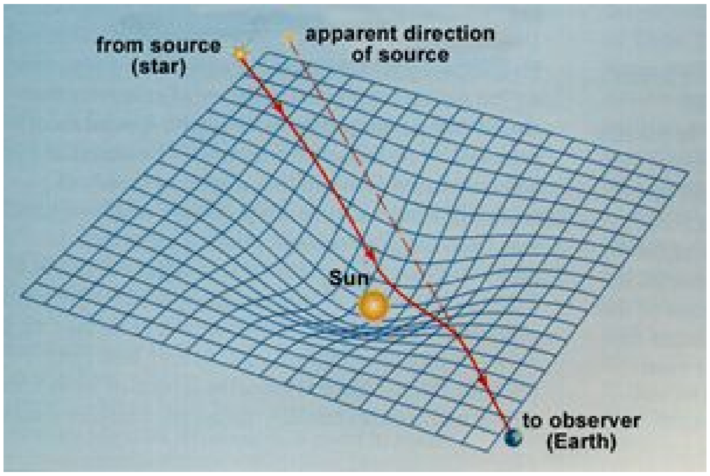


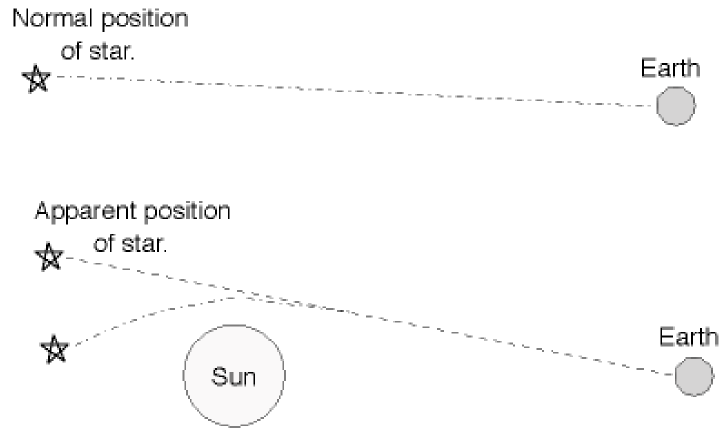
$\Rightarrow$ e.g., person in freely falling elevator does not feel gravitational force

$\Rightarrow$ re-interpretation of gravity as a “geometric” effect!
$\Rightarrow$ the presence of mass induces a “curvature” of space-time
$\Rightarrow$ also light rays should experience: deflection, slowing down!

3.2 Experimental Verification of General Relativity

• **Bending of Light from a Star through the Sun's Gravity**



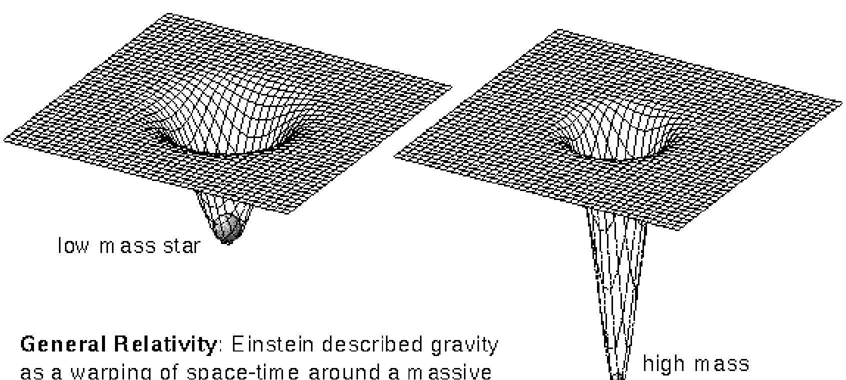


Further Confirmations:

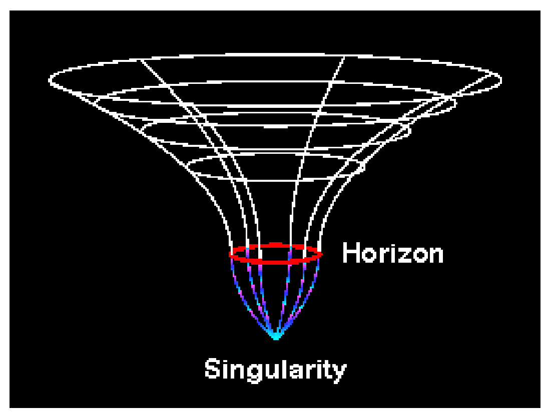
• Redshift of light when climbing out of gravitational field

• Precession of mercury's orbit (long-standing discrepancy!)

3.3 Space-Time Singularities: Black Holes



General Relativity: Einstein described gravity as a warping of space-time around a massive object. The stronger the gravity, the more space-time is warped.



$$R_s = \frac{2GM}{c^2}$$

If an object with given mass is contracted below it's Schwarzschild radius, everything - even light - has not enough energy to escape!

⇒ The object is a space-time singularity, i.e. a Black Hole !!

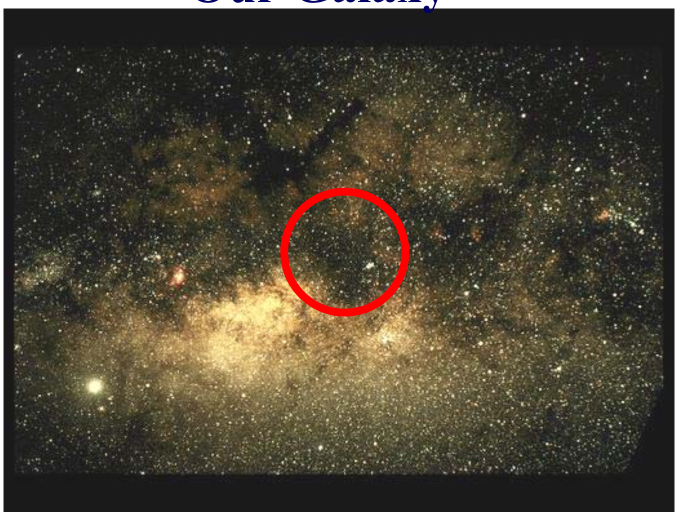
3.4 Black Holes in the Universe

- Supermassive **BHs** in galactic centers (**~10^6 M$_{sun}$**)
- Collapse of massive star (**~10 M$_{sun}$**)
- Early Universe?

Schwarzschild Radii

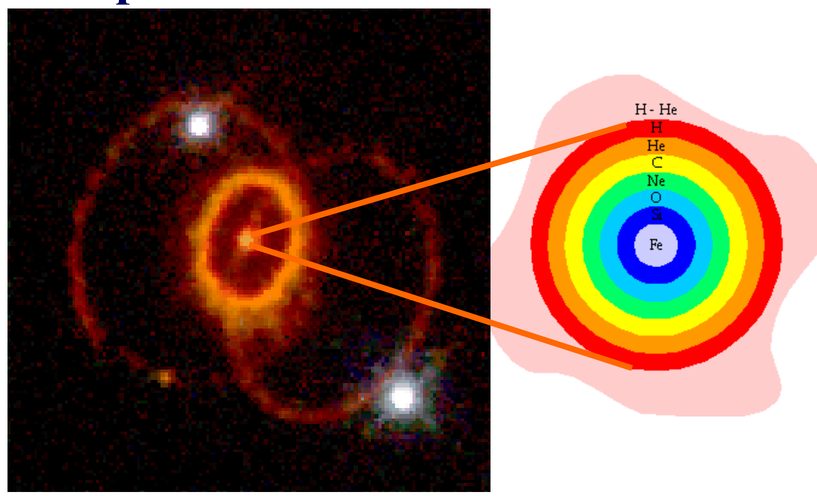
Object	Mass ($M_\odot$)	R_S
Star	10	30 km
Star	3	9 km
Star	2	6 km
Sun	1	3 km
Earth	0.000003	0.9 cm

Our Galaxy



Motion of stars close to BH!?

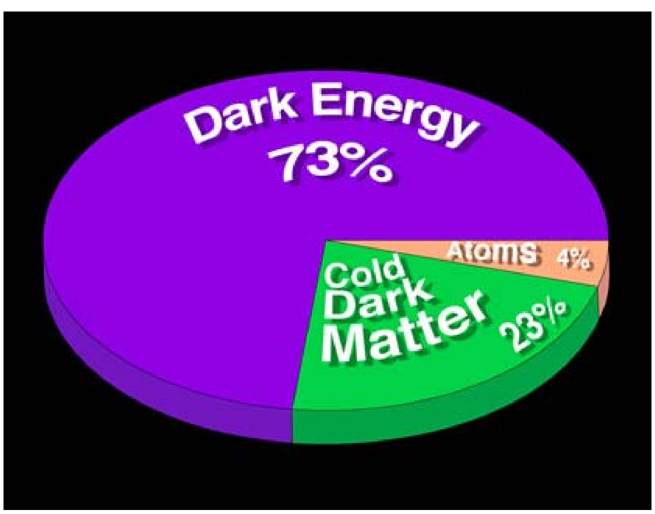
Supernova 1987A

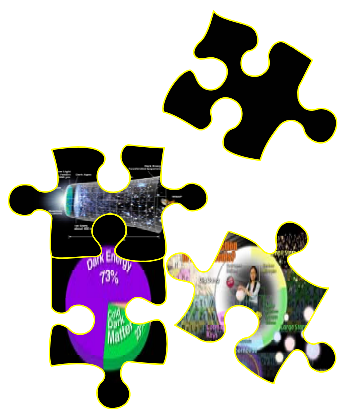


Binary BH - star system?

But there is more "Invisible"

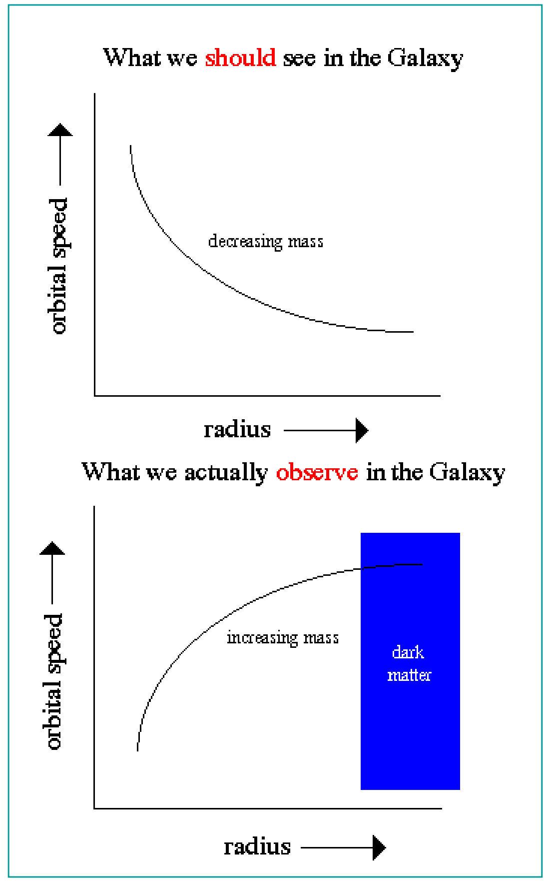
Matter + Energy in the Universe





Dark Puzzles of the Universe …

3.5 Evidence for Dark Matter

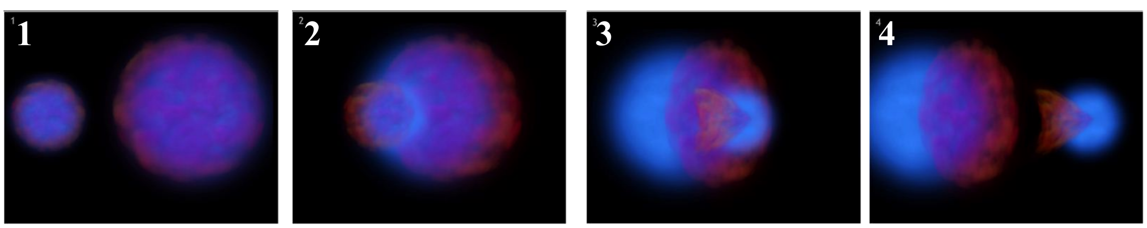


- motion of stars within galaxies: there must be more matter than we "see" (emits light)

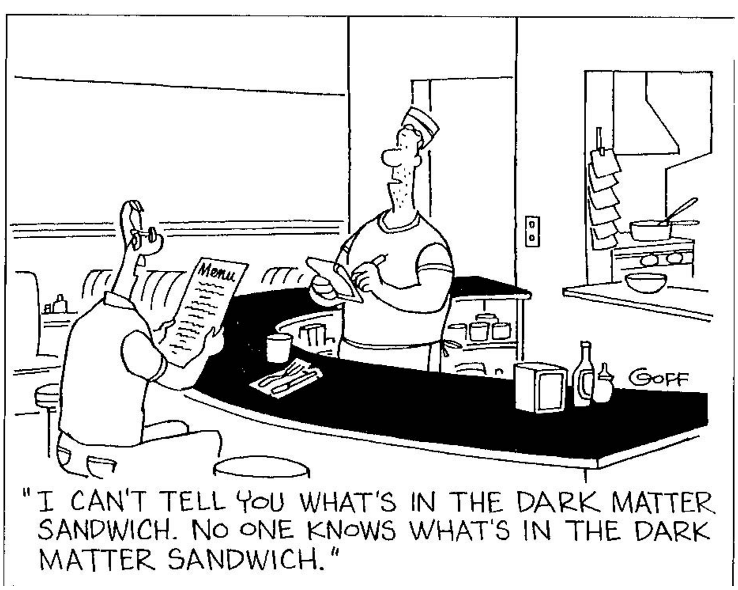
  ⇒ **Dark Matter**:
  - "background"?
  - new particles?

3.6 More Evidence + Dark Matter Properties

Cosmic collision of 2 galaxy clusters: DM unaffected!



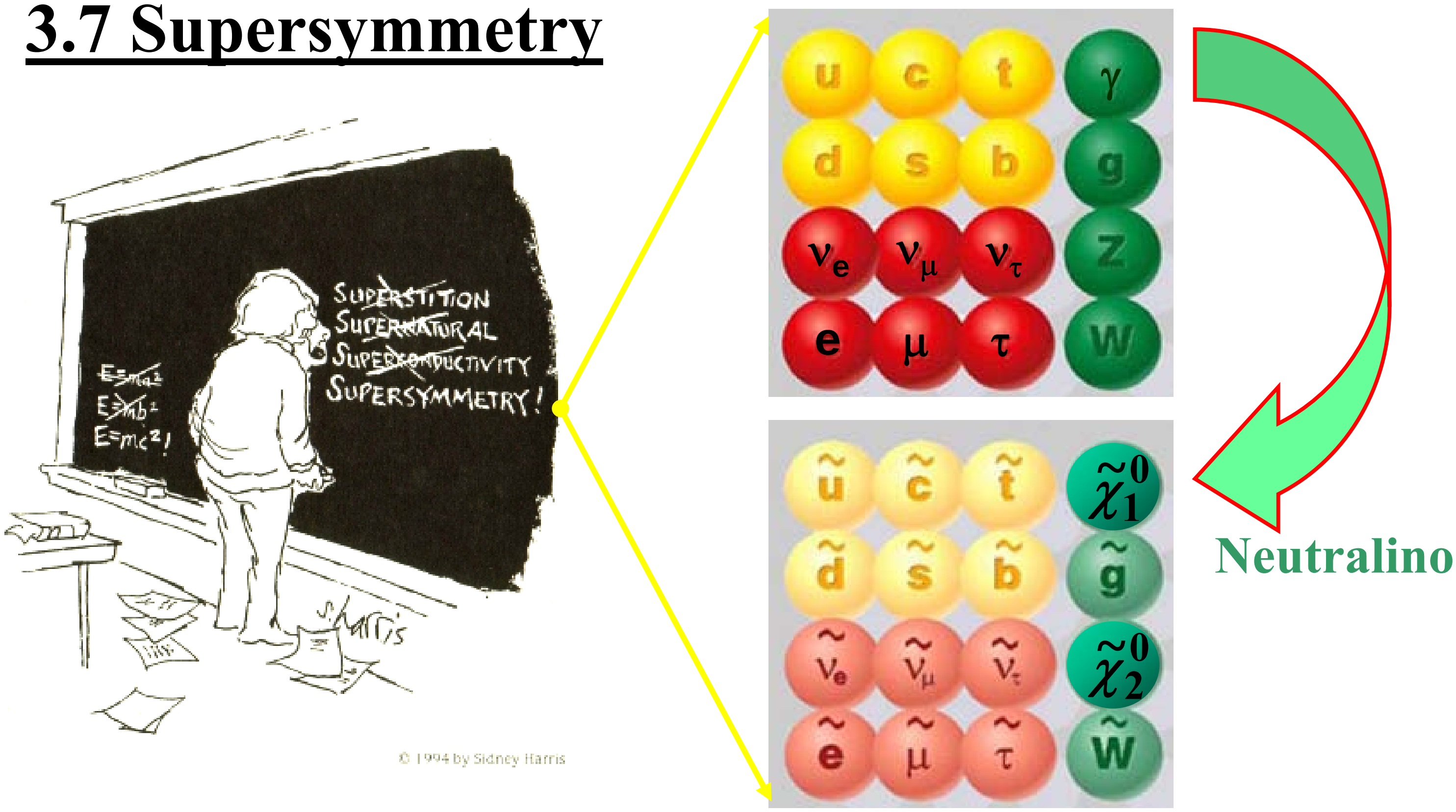
time →



The **Dark Matter Sandwich**:
- very weakly interacting
- charge-neutral
- slowly moving ("cold")
- long-lived heavy particle

⇒ **no such particle in the Standard Model! New idea needed!**

3.7 Supersymmetry



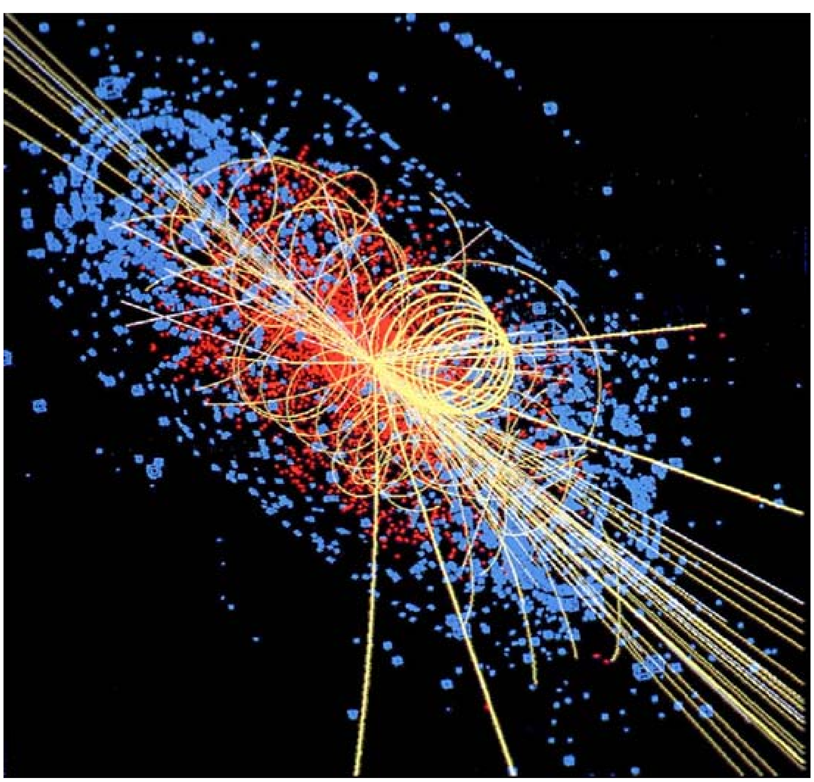
- Standard-Model particles $\leftrightarrow$ **supersymmetric** partners (fermion$\leftrightarrow$boson)
- Supersymmetry "broken": $\mathbf{M_{stand} << M_{super} \sim 1TeV/c^2}$
- one stable supersym. particle: **neutralino** (heavy, neutral)

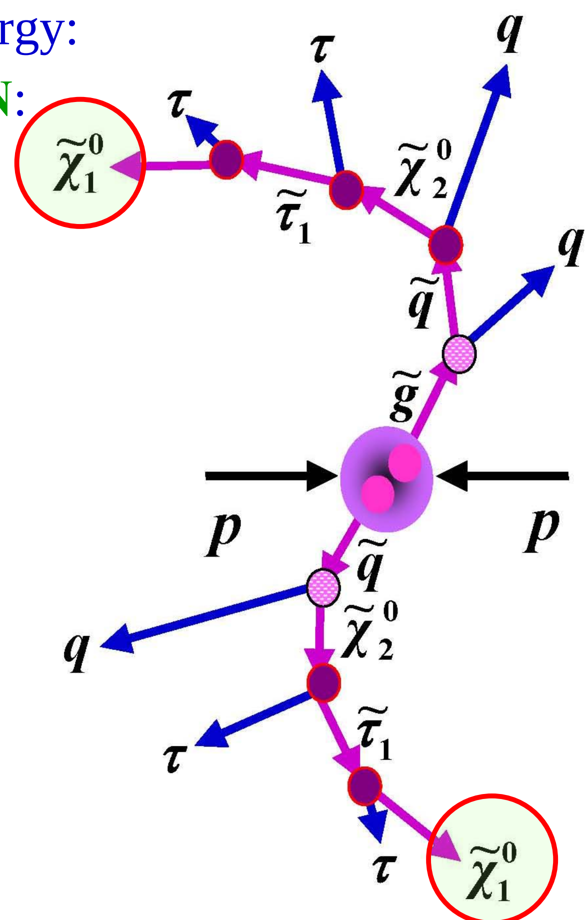
Dark Matter Candidate!

3.8 How to Measure Dark Matter in the Lab?

- proton-proton collisions at the highest energy:

Large Hadron Collider (LHC) at CERN:





4.) Some Perspectives for You

If you

- Enjoy / are excited by Physics / Science
- Tend to be curious
- Like to try things out AND/OR like math, computers

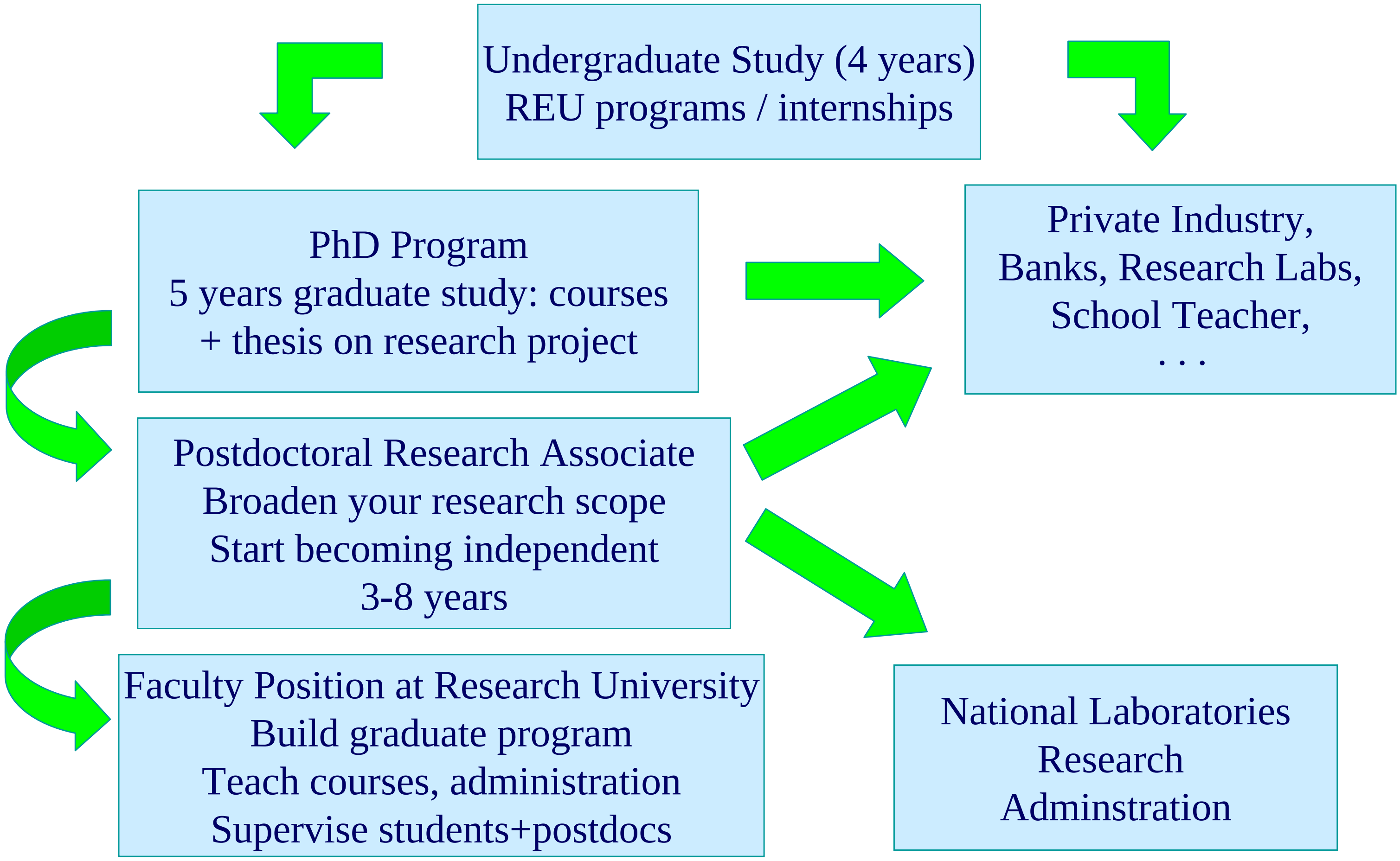
then we recommend to:

- Watch out for future SMP Series at A&M
- Consider enrolling in the Physics Undergraduate Program at A&M
- Inform yourself about future career paths in Physics

4.2 Future Plans for SMP at TAMU

- At least 3 more series planned (one per year; spring or fall?)
- Expand the coverage of forefront Nuclear Physics topics:
  - compact stellar objects (neutron stars, supernovae, gamma ray bursters, …)
  - nuclear astrophysics (formation of elements)
  - (quark-gluon) structure of hadrons + their interactions
  - nuclear structure, nuclear energy …
- New colleagues will join the Cyclotron this fall
- Connect to other SMP programs in the US and Europe (e.g. the heavy-ion research center (GSI) in Darmstadt, Germany)
- Extend to other fields in physics (Quantum Optics, Condensed Matter, …)

4.3 Physics as a Job (Passion?!)



5.) Thanks to:

- **You! (students/participants)**
- **Our supporting high-school teachers !**
- **Our lecturers: Rainer Fries, Carl Gagliardi, Saskia Mioduszewski, Hendrik van Hees, Alexey Belyanin, Bhaskar Dutta**
- **The “technical” support team: Kendra Beasley, Shana Hutchins, Sharon Jeske, Bruce Hyman, Tony Ramirez, Robert Tribble (Cyclotron Director)**
- **The SMP organizing team (Daniel Cabrera, Hendrik van Hees, Lorenzo Ravagli, Xingbo Zhao)**