Saturday Morning Physics 2008 at A&M: From the Micro-World to the Universe

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SMP-2008 Lecture 7
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Outline

1.) Overall Structure of SMP08 Lectures

2.) From Particles+Forces to the Universe

- Force Properties and Proton Structure
- The Role of Fundamental Forces in the Cosmos

3.) Gravity and Dark Matter

4.) Weak Force and Universality

5.) Nucleosynthesis, Stars and the Universe's Fate

- Supernovae: Nuclear Burning + Expansion of the Universe
- Neutron Stars

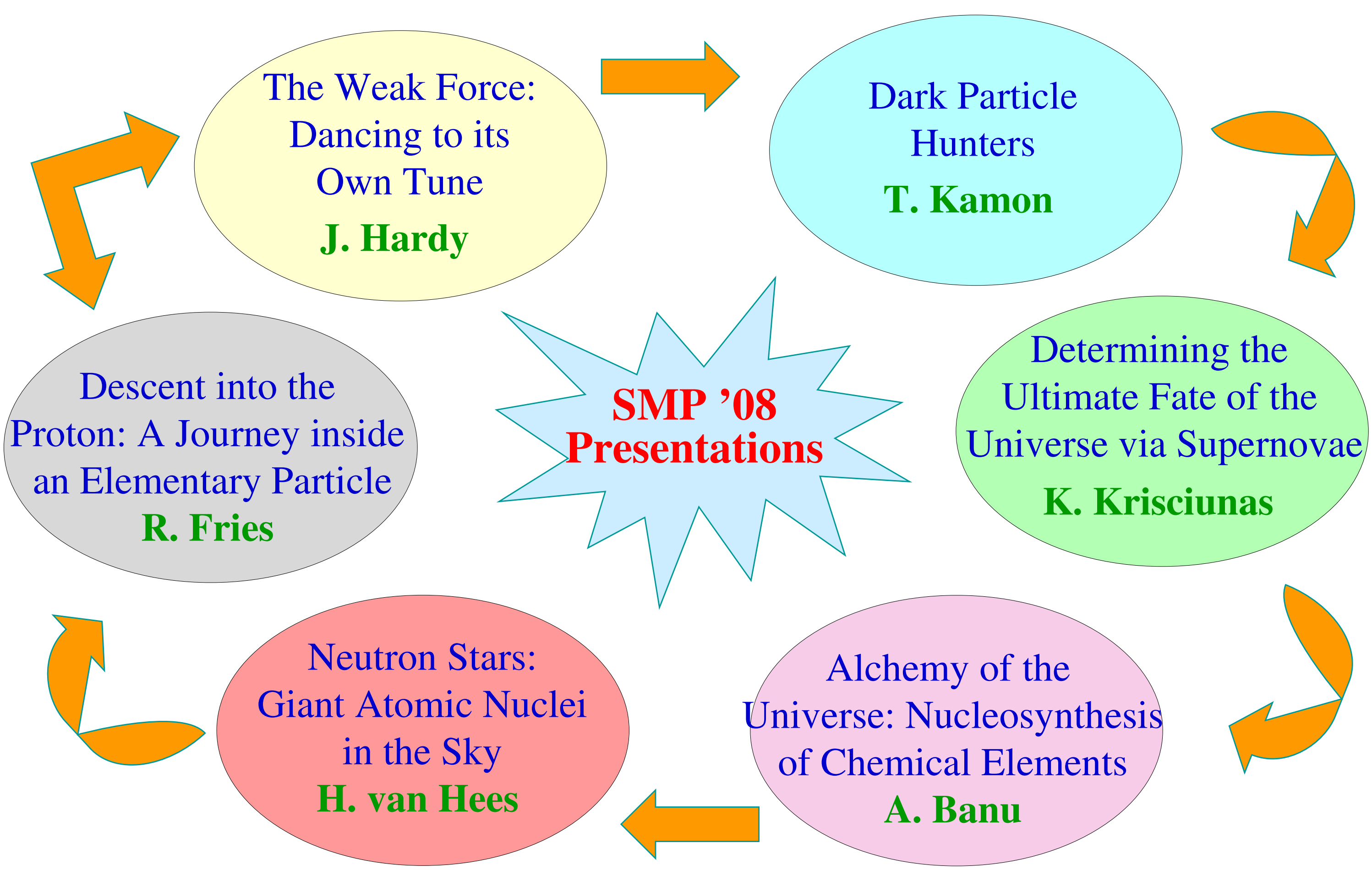
6.) Concluding Remarks

1.) From the Smallest to the Largest

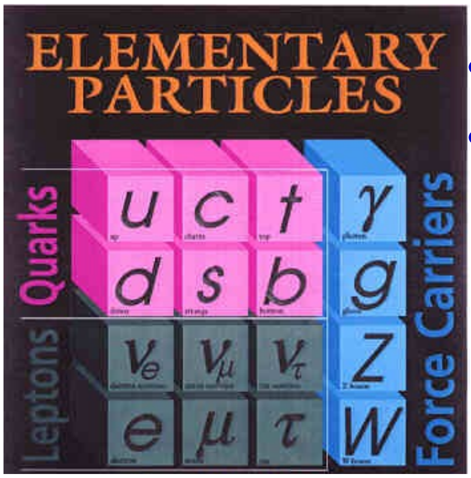
- 20th (and 21st ?!) century: tremendous progress in our understanding of elementary particles + their interactions
- Also true for the origin and evolution of the Universe
- Intimate relations between the subatomic and the cosmic world unraveled
- early example (17th century): Newton discovered the connection between the falling apple and planetary motion (universality of gravity!)

- SMP2008 was an attempt to illuminate some of these fascinating discoveries in Nuclear/Particle/Astrophysics (and exhibit open problems …)

1.2 Topical Structure of SMP08



2.) Known Particles + Forces in the Universe



- "Standard Model of Particle Physics"
- based on symmetry principles:
  matter particles interact via **force carriers**

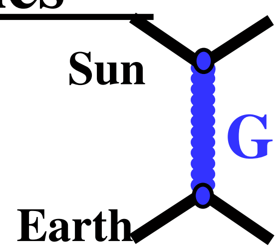
  - stable matter: **u , d , e⁻ , ν$_e$**
  - 2 more "generations" (heavier + short-lived)
  - bare masses: **$m_{u,d}$ = 5 MeV … m_t = 175 GeV**

	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

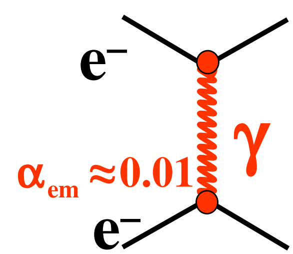
- **forces differ by**
  - exchange particles
  - charge content
  - range
  - strength

2.2 Fundamental Force Properties

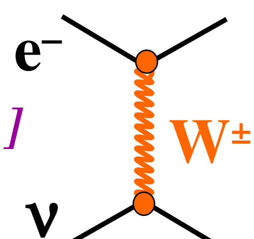
- **Gravity (graviton** exchange)
  - static force law (Newton): $F_G(r) = -G_N \frac{m_1 m_2}{r^2}$
  - extremely small coupling
    but only one charge ⇒ long range!



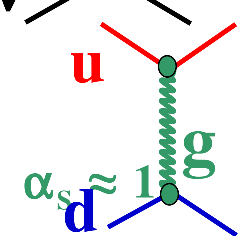
- **Electromagnetism (photon** exchange)
  - static force law (Coulomb): $F_G(r) = G_C \frac{q_1 q_2}{r^2} \sim \frac{\alpha_{em}}{r^2}$
  - small coupling, 1 anti-/charge
    ⇒ medium range



- **Weak Force (W-,Z**-boson exchange)
  - static force law (Fermi,GSW): $F_w(r) \sim \frac{\alpha_w}{r^2} \exp[-m_W r]$
  - small coupling, 2 anti-/charges
  - massive carriers ⇒ extremely short range

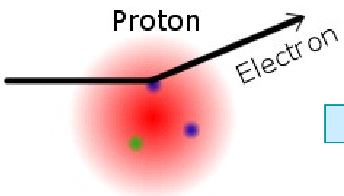


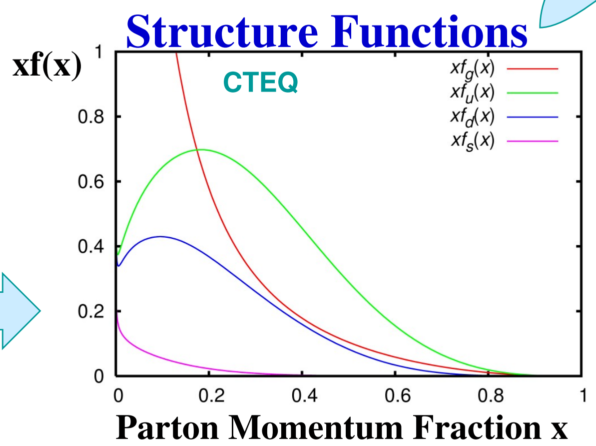
- **Strong Force (gluon** exchange)
  - static force law (QCD): $F_s(r) \sim -\alpha_s / r^2 - \sigma$
  - large coupl., 3 anti-/charges, short range, confinement!

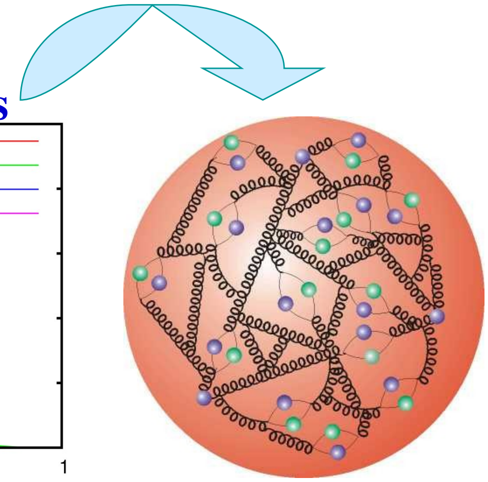


2.3 Proton Structure

- **Deep-Inelastic Electron Scattering**







- **Spin Structure of the Proton**

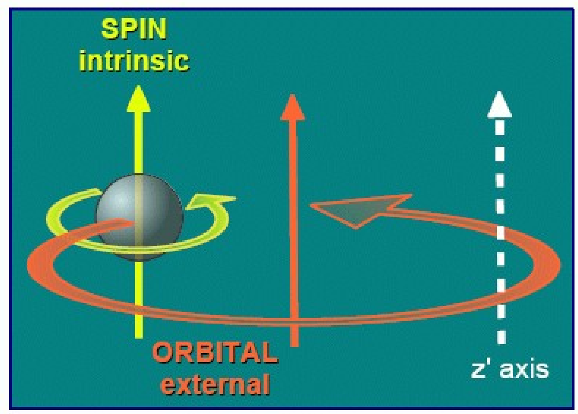
$$\langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle = \frac{1}{2}$$

quark spin

gluon spin

quark orbital angular momentum

gluon orbital angular momentum

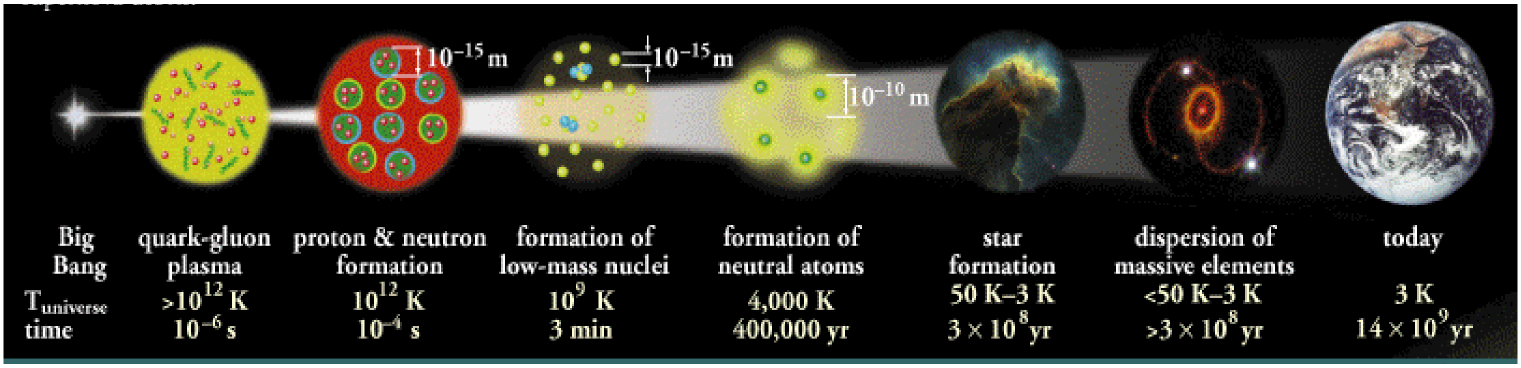


- quark- and gluon-spin contribution small
- quark orbital angular momentum?!

2.4 The Role of Particles + Forces in the Evolution + Structure of the Universe

- **Gravity** (long range)
  - large scale structure (galaxies, galaxy clusters)
  - star formation and collapse, black holes
- **Electromagnetism** (medium range)
  - neutralization of electrons/nuclei 400,000y after Big Bang
  - cosmic microwave background $\mathbf{T_{Universe}=2.73^{o}K}$
  - **γ**-ray bursters (the largest fire crackers in the Universe)
- **Weak Force** (very short range)
  - generation of bare masses $\mathbf{10^{-11}s}$ after Big Bang
  - star cooling (neutrinos), element transmutation (**p↔n**)
- **Strong Force** (short range)
  - generation of visible mass $\mathbf{10^{-6}s}$ after Big Bang
  - star burning and explosion, neutron-star structure

Nuclear Physics and the Universe



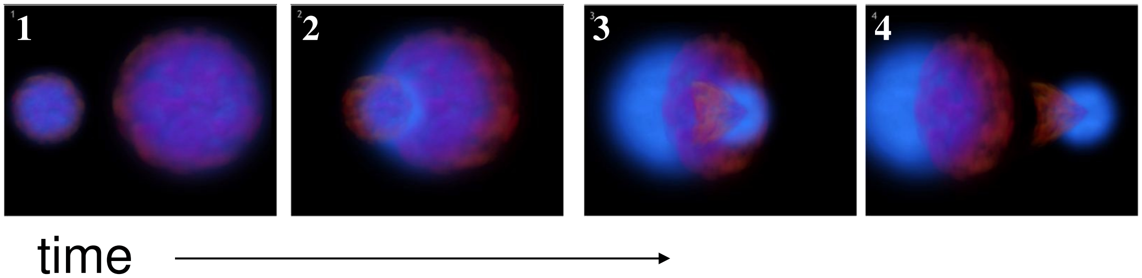
- **Quark-Gluon Plasma: T>200MeV (<0.000001 sec.)**
- **Phase transition to Hadronic Matter (Mass Generation, Quark Confinement), T≈170MeV (0.00001 sec.)**
- **Low-mass nuclei: H (p), d (pn), ^{3}He, ^{4}He, ^{7}Li (3 min.)**
- **Heavy elements in star collapses: supernovae (still today)**
- **Exotic forms of (quark) matter in neutron stars (still today)**

3.) Gravitational Force and Dark Matter

- Evidence for Dark Matter
- Supersymmetry?!
  (Neutralino!)

3.1 Dark Matter Evidence and Properties

Cosmic collision of 2 galaxy clusters: DM unaffected!



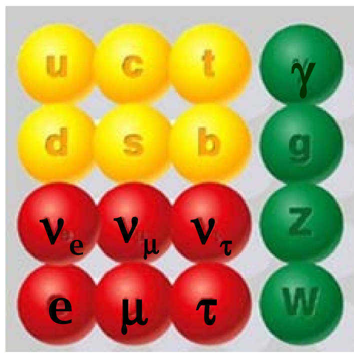
Dark Matter Properties: - very weakly interacting, charge-neutral
- slowly moving ("cold"), stable+heavy particle

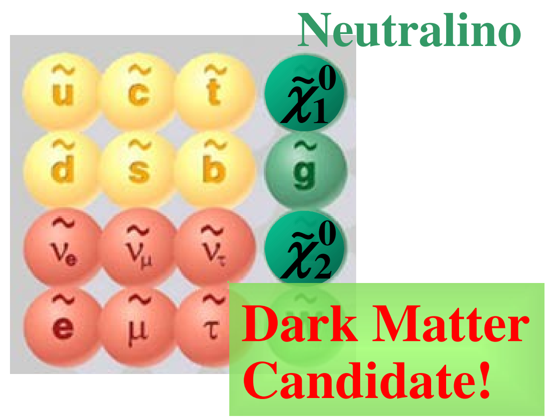
⇒ no such particle in the Standard Model, new idea needed!

Supersymmetry:

- fermion↔boson partners for all standard-model particles
- Supersymmetry "broken":

$m_{stand} << m_{super} \sim 1TeV/c^2$

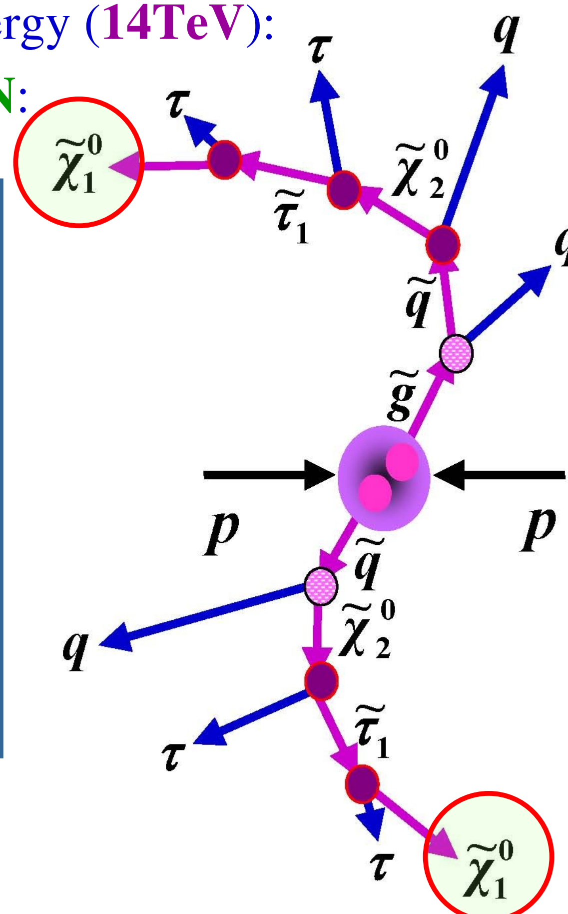




3.2 How to Measure Dark Matter in the Lab?

- proton-proton collisions at the highest energy (**14TeV**):

Large Hadron Collider (LHC) at CERN:



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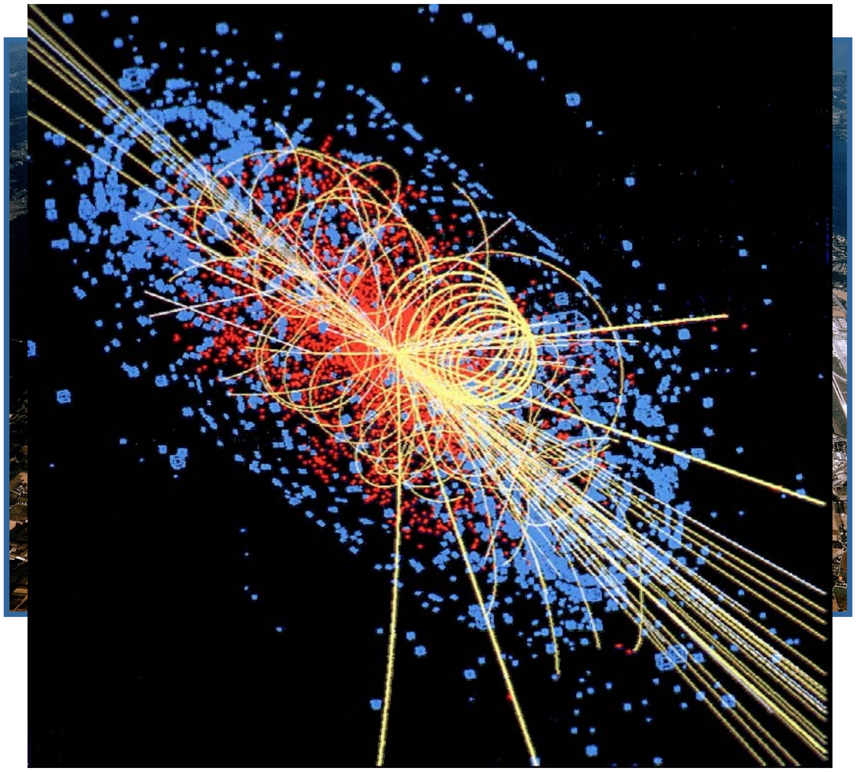
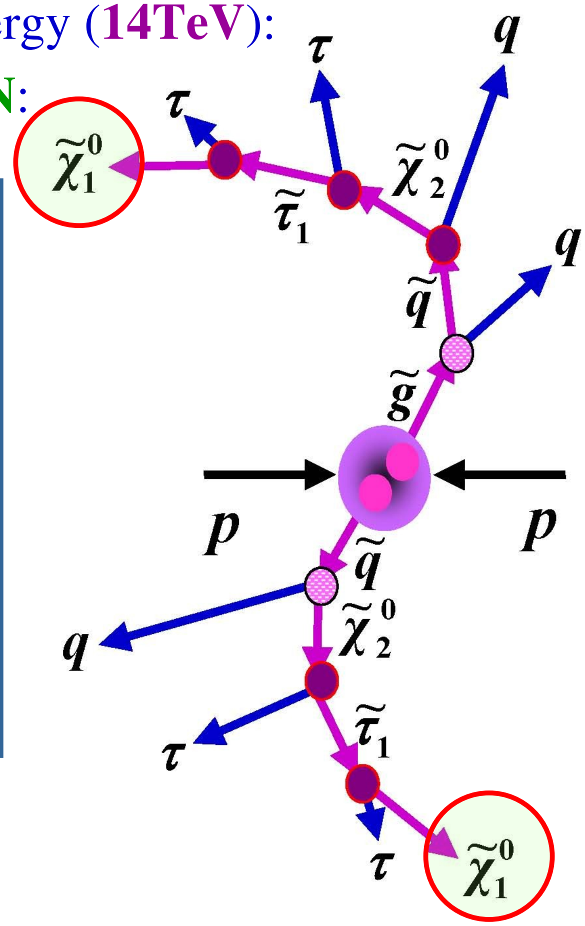




4.) Precision β-Decay: Testing the Weak Force

Recall: around ~1700 Sir Isaac Newton realized the universality of gravity

Is the Weak Force universal, too?

Use precision measurements of nuclear beta-decay to check

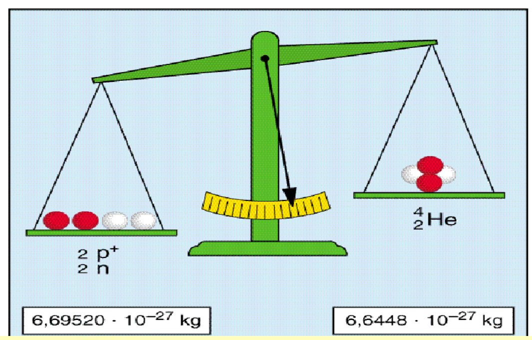
We know now that ...

1. The weak force (vector component) is constant in nuclei to 0.026%.
2. We can also test full universality of the weak force -- including the decay of other particles like the kaon -- but the jury is still out on this one!
3. Nuclear physics is the source of key data for these tests, the most precise ones available.

5.) Nucleo-Synthesis, Stars + the Universe

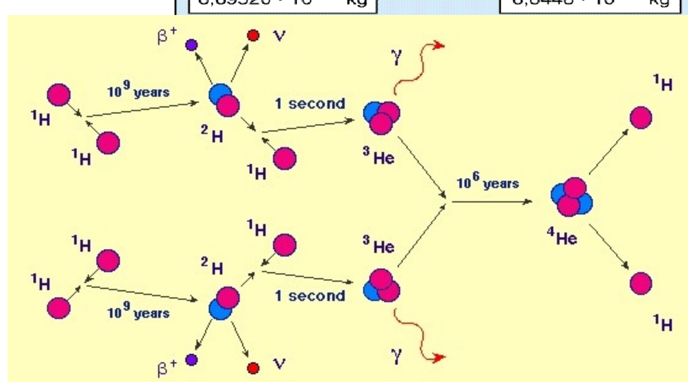
- Nuclear Burning
- Supernovae
  - White-Dwarf Explosions (type-Ia)
  - Heavy-Star Explosions (type-II)
- Fate of the Universe
- Neutron Stars

5.1 Nuclear Burning



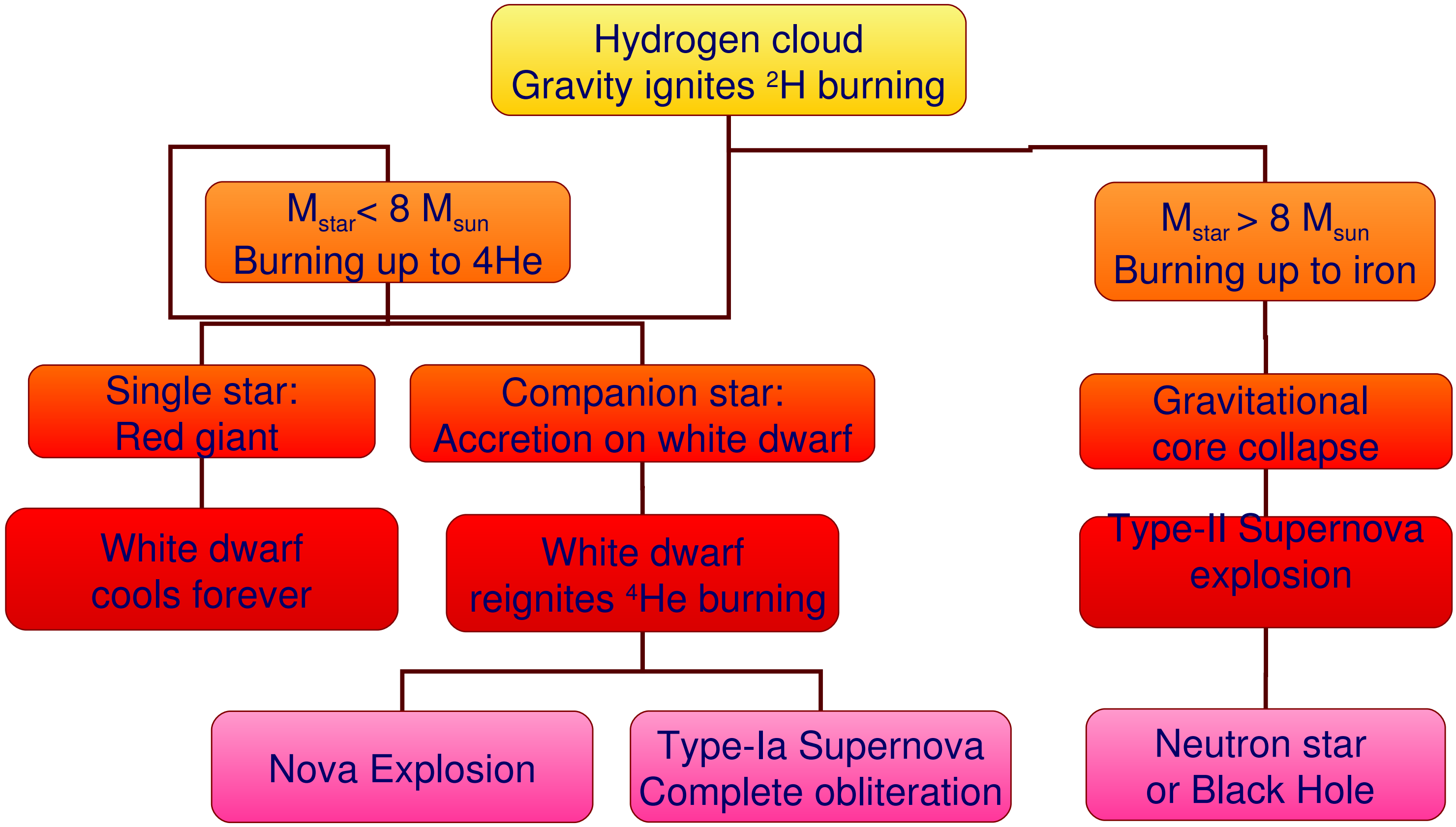
- Principle: large energy gain if light nuclei "fuse": **A + B → C + binding energy**

  $E_B = [\,(M_A+M_B)-M_C\,]\,c^2$
- "problem": Coulomb repulsion between **A** and **B**
- **A** and **B** need to "touch" to feel strong force and bind
- large temperature and density required for nuclear fusion (burning)!



- Big Bang: rapid expansion, only up to mass **A=7** (**Li**), gaps at **A=5,8**!
- much later: gravity-driven star formation
  - Sun ($M \sim M_\odot$) **p+p→ d +p→^{3}He +^{3}He→^{4}He+2p**
  - heavy stars: **3^{4}He →^{12}C +^{4}He→^{16}O +^{16}O→^{4}He+^{28}Si +^{28}Si→^{56}Co→^{56}Fe**
  - star collapse and explosion: all elements beyond **A=56** (no energy gain)

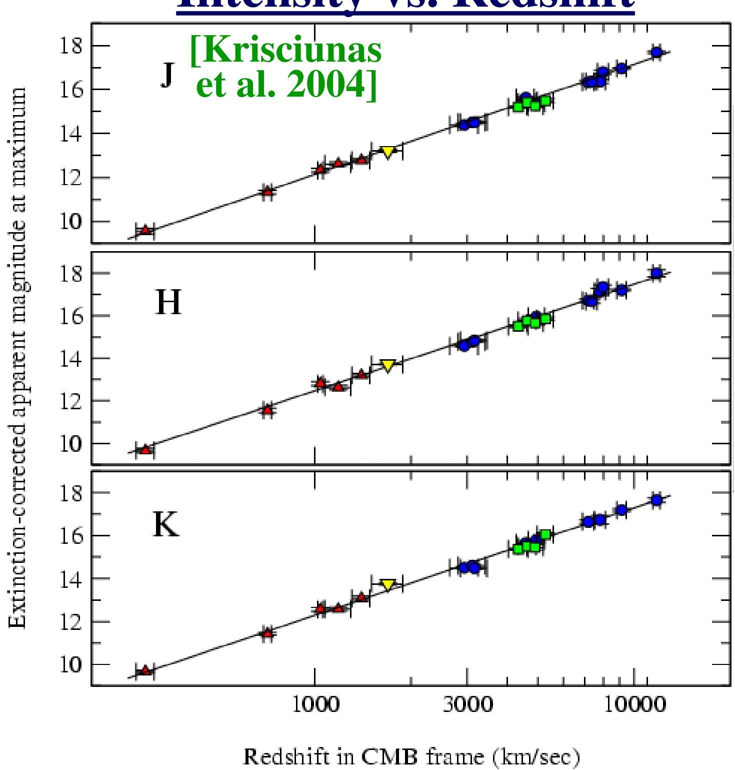
5.2 Star Evolution Chart



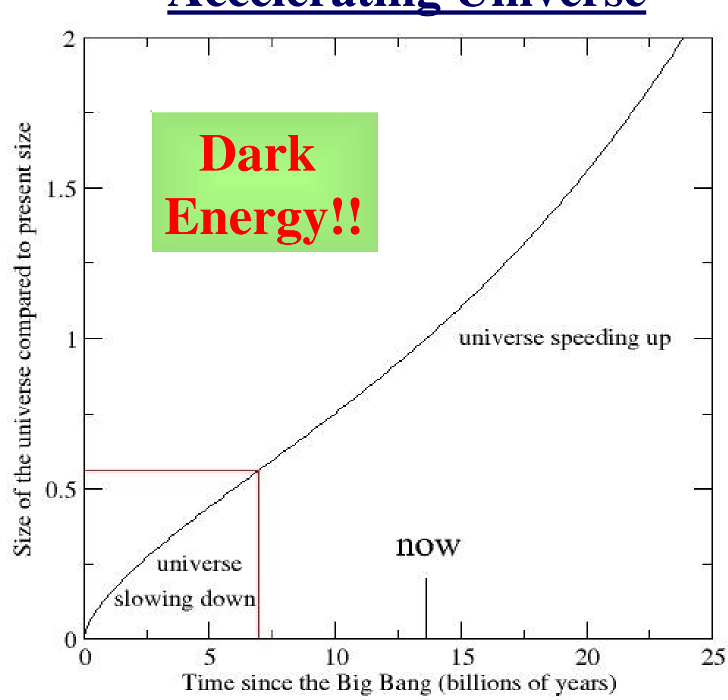
5.3 SN-Ia Candles + Expansion of the Universe

- accurate light output I_0, intensity $I(r) = I_0/4\pi r^2$ ⇒ **precise distance r(I)**
- Doppler (red-) shift of spectral lines ⇒ **recession velocity, v_r, of source**

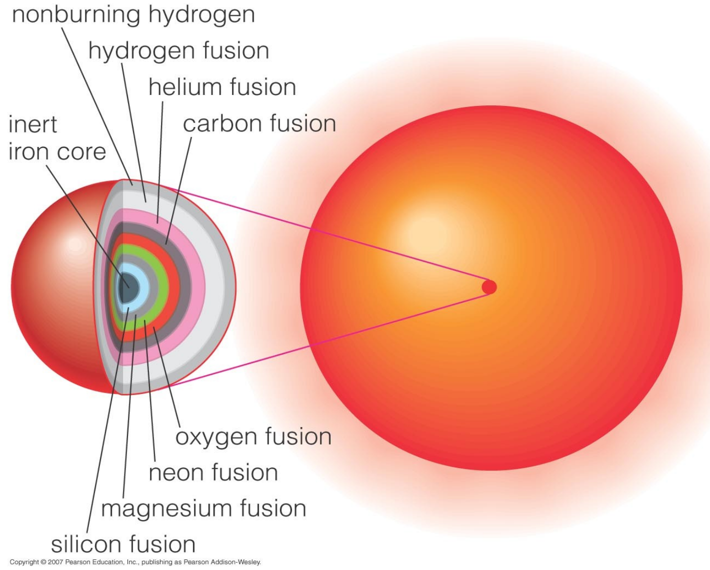
Intensity vs. Redshift



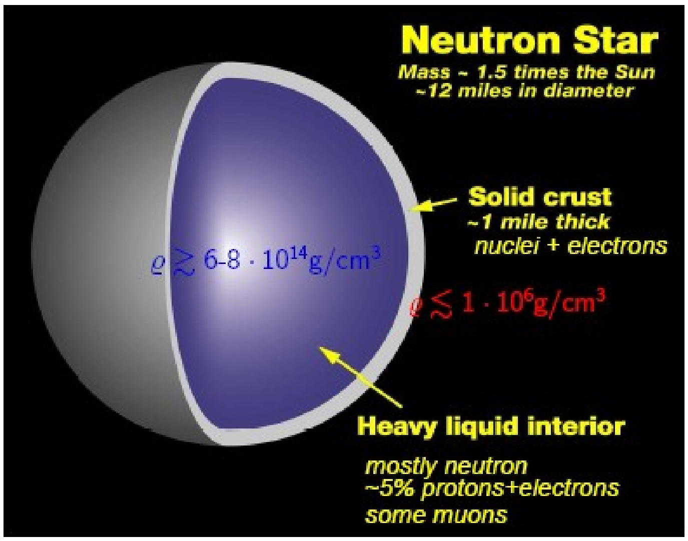
Accelerating Universe



5.4 Type II Supernovae

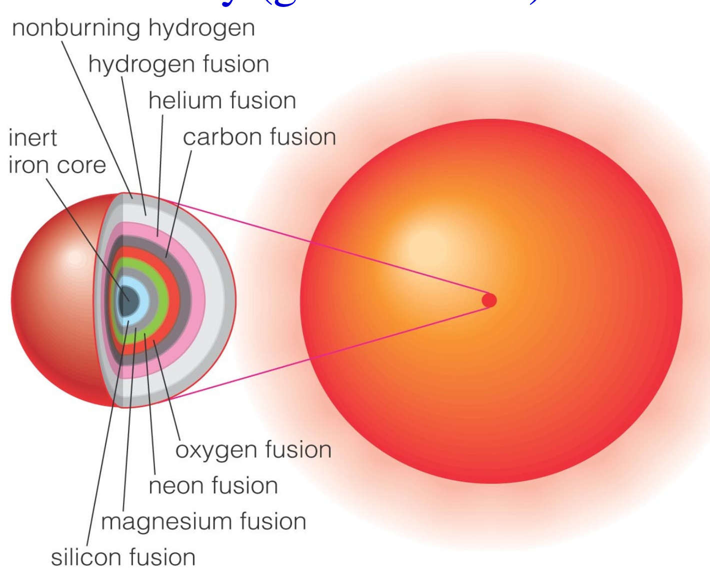


- High-mass star ($M_{star} > 8M_\odot$),
- burns fast (~50 My), up to ^{56}Fe
  - ⇒ **core collapse**
  - ⇒ **type-II supernova explosion**
- produces all known heavy elements
- leaves behind moving+rotating NS/BH



- $M_{NS} \approx 1.4\, M_\odot$, but **R=15km**
- **up to 5-10 times density of nuclei!!**
- study cold nuclear equation of state (quark plasma, color-superconductor …)
- rotation: lighthouse (mag. field), glitches
- γ-ray emission (bursters?)
- general relativity (grav. waves?)

5.4 Type II Supernovae



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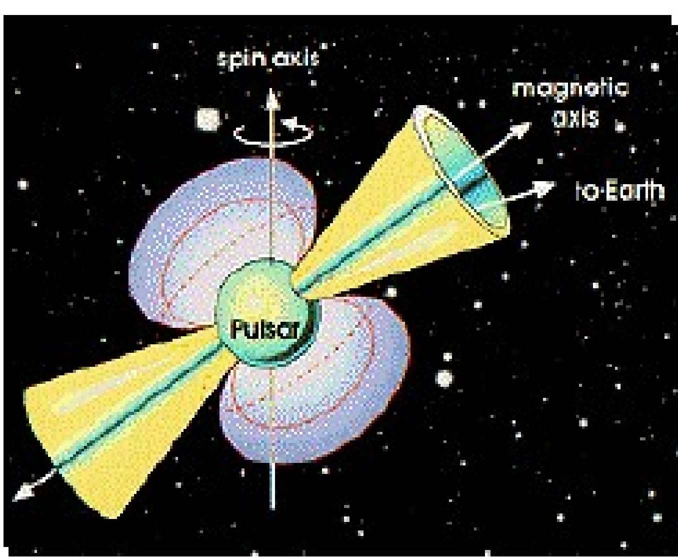

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6.) Some Perspectives for You

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:

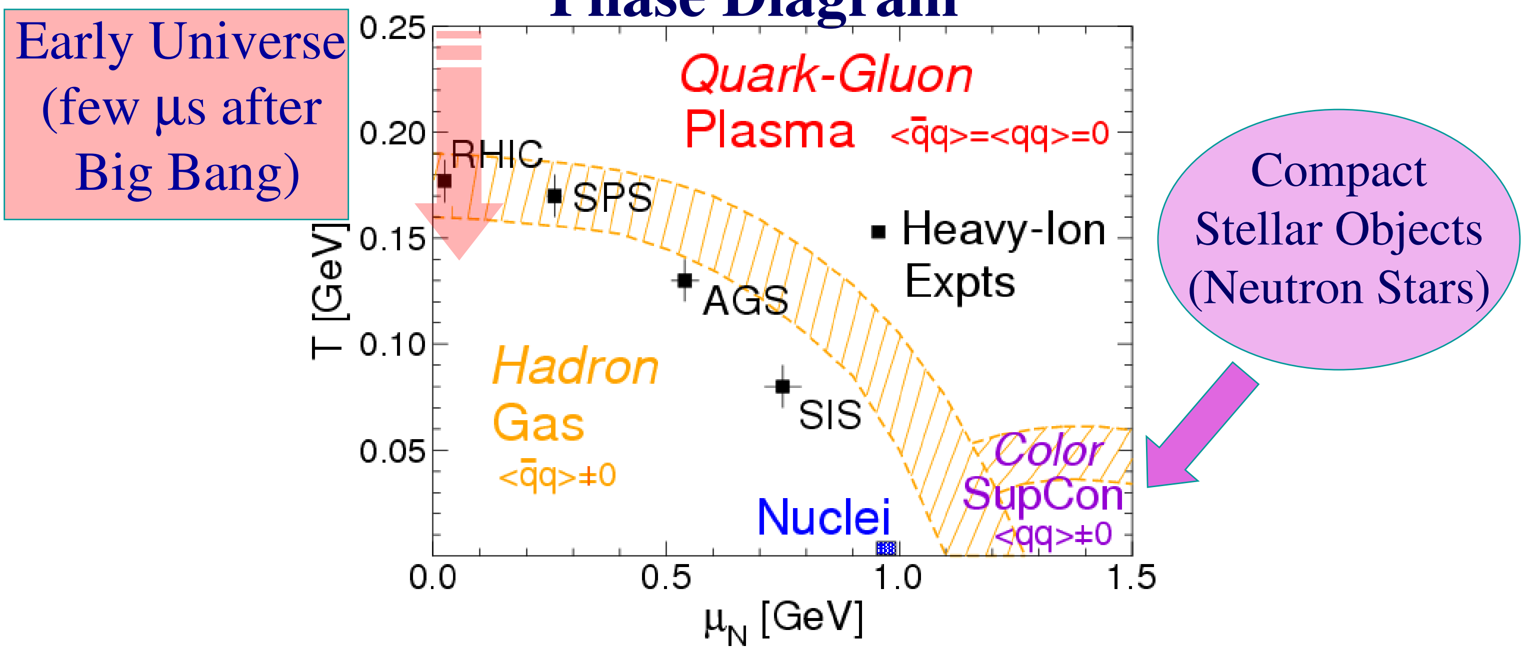
- Watch out for future SMP Series at A&M (2+ more)
- Consider enrolling in the Physics Undergraduate Program at A&M
- Inform yourself about future career paths in Physics

6.2 Thanks to:

- **You! (students)**
- **Our high school teachers!**
- **Our lecturers: Profs. John Hardy, Teruki Kamon, Kevin Krisciunas, Hendrik van Hees, Rainer Fries, Dr. Adriana Banu**
- **The staff support team: Kendra Beasley, Shana Hutchins, Bruce Hyman, Leslie Spikes, Sharon Jeske, Tony Ramirez, Jerry Deason**
- **The SMP organizing team: Hendrik van Hees, Xingbo Zhao, Trent Strong, Saskia Mioduszewski, Rainer Fries + Adriana Banu**
- **Financial Support: U.S. National Science Foundation, Texas A&M Cyclotron Institute + Physics Department**

2.1 Hot+Dense QCD Matter in Nature

Phase Diagram

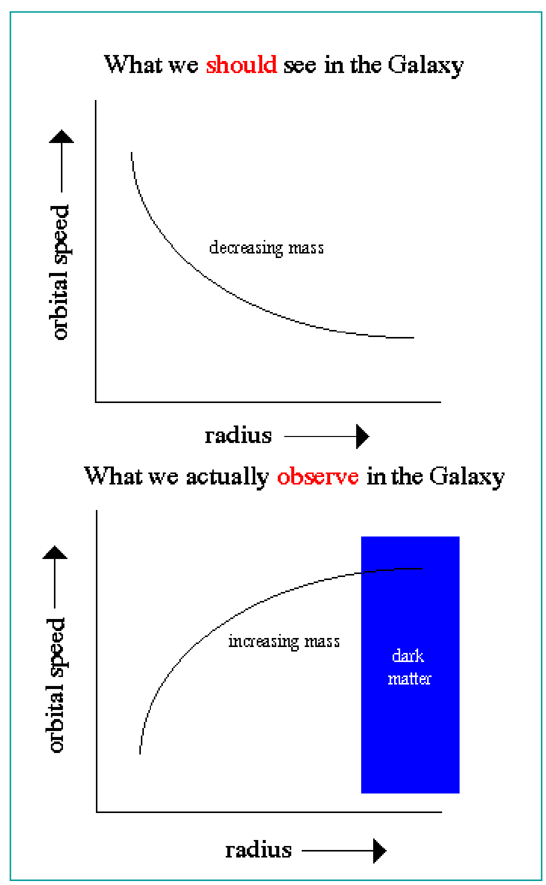


In the laboratory: high-energy collisions of heavy nuclei!

Objective: to create matter at temperatures $T > T_c \approx 170MeV$

and energy densities $\varepsilon > \varepsilon_c \approx 1GeVfm^{-3}$

3.1 Evidence for Dark Matter I



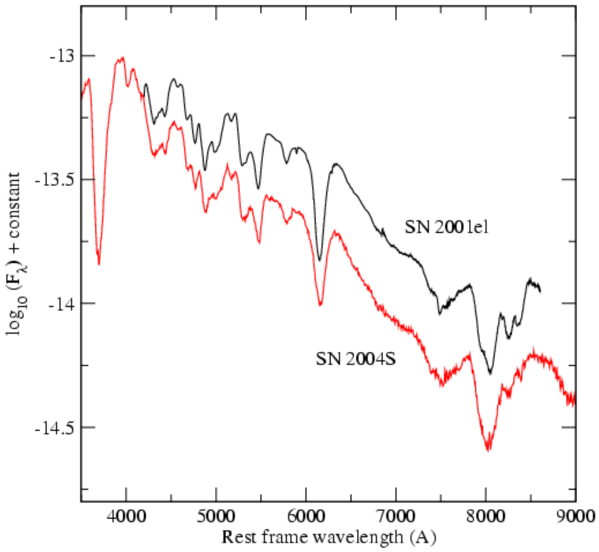
- motion of stars within galaxies: there must be more matter than we "see" (emits light)

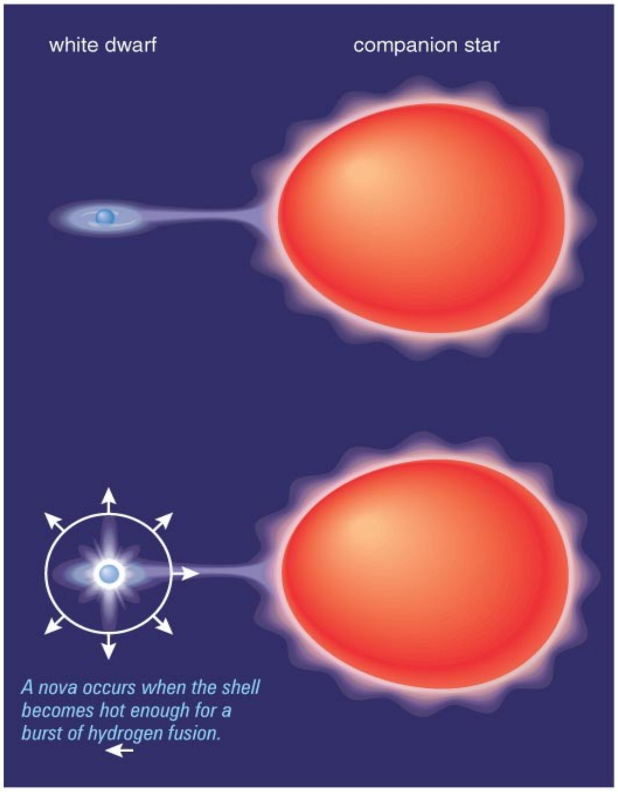
  ⇒ **Dark Matter**:

  - "background"?
  - new particles?

5.3 Novae and Type-Ia Supernovae

- White dwarf accretes matter from red-giant companion (binary system)
  - (i) helium burning ignited on surface
    - ⇒ **Nova** explosion
  - (ii) mass accretion up to **1.4 $M_\odot$**
    - ⇒ **Type-Ia Supernova** explosion,
    - **extremely regular light output:**





a Diagram of the nova process.